



MINISTÈRE
DE L'ENSEIGNEMENT
SUPÉRIEUR,
DE LA RECHERCHE
ET DE L'INNOVATION

*Liberté
Égalité
Fraternité*



Edition
2021

French national **strategy**

on research
infrastructures





French national
strategy

Edition
2021

on research
infrastructures

Foreword



Frédérique VIDAL
Minister of Higher
Education,
Research
and Innovation

The COVID-19 pandemic has shown how much our society depends on research and innovation to find solutions to large-scale problems. However, scientific and technological breakthroughs and the response to the major challenges of our time increasingly require the use of research infrastructures at the highest level. In many more disciplinary fields than in the past, infrastructures have become incredible engines of knowledge and innovation, attractors of talent, catalysts of interdisciplinarity, image and scientific prestige carriers. At the service of the scientific community, they are essential tools for the competitiveness of national research and innovation. As promoters of new practices, they are also an ideal vector for the transfer of knowledge and technology towards the socio-economic world.

Research infrastructures are not like other working tools. They represent a precious asset in which France is investing to build its future in the field of research and innovation and to support the major transitions in which we are engaged. The longevity of the infrastructures, their ambitions, their costs are all particularities whose value must be regularly assessed at the end of strategic reflections such as those which led to the publication of this Roadmap.

The renewal of the national strategy for research infrastructures is part of a much broader movement aimed at giving French research its rightful place in the world, in full consistency with the Research Programming Law for the years 2021 to 2030. Infrastructures are called upon to push back the frontiers of knowledge ever further, and to participate fully in the dynamics of recovery and transition driven by the France 2030 Plan and the PIA4.

At the European level, the structuring of the infrastructure landscape continues through Horizon Europe and the European Strategy Forum on Research Infrastructures (ESFRI), allowing for a decidedly coherent approach to pan-European infrastructure policy-making.

Our country can only congratulate itself for supporting, over more than twenty years now, the development of national and European infrastructures which have transformed the practices of the scientific communities. Their attractiveness relies mainly on the excellence of the highly qualified personnel, researchers, engineers, technicians and administrators who operate them. I would particularly like to thank the operational teams of the 108 infrastructures of this new edition of the national Roadmap for the quality of the actions and support for research that they provide on a daily basis.

The infrastructures of the French national roadmap must appear without any complex at the top of the European agenda, with the certainty that equipment of excellence supports ambitious and innovative French and European projects at the best international scientific level.

Summary

The various types of research infrastructures	p. 8
Research infrastructures and the Roadmap	p. 10
1. Astronomy and astrophysics	p. 19
2. Biology and health	p. 43
3. Energy	p. 87
4. Nuclear and high-energy physics	p. 99
5. Social sciences and humanities	p. 125
6. Material sciences and engineering	p. 137
7. Digital and mathematics sciences	p. 163
8. Earth system and environment	p. 177
9. Digital infrastructures and services	p. 211
Research infrastructures and open science	p. 253
Research infrastructures index.....	p. 264

Introduction



Claire GIRY
Director-General
of Research
and Innovation
– Ministry of
Higher Education,
Research
and Innovation

The role of infrastructures in research and innovation has been growing over the years. It is fair to say that they are now the backbone of research in a very large number of disciplines.

The infrastructures are at the service of excellence in research, in fields as diverse as nuclear and high-energy physics, material sciences, astrophysics and astronomy, high-performance computing, environmental observation, climatology, biology, and the social sciences and humanities. They are increasingly interdisciplinary in nature, resulting in a growing interdependence between research actors at national, European and international levels. The use of research infrastructures has become, in most disciplines, an imperative condition for scientific competitiveness and international influence. Moreover, they are often surrounded by significant economic, industrial and even technological sovereignty issues.

National and European strategies in the field of research infrastructures are set out in “roadmaps”. This new French roadmap is the fifth edition since 2008. It differs from the previous ones by the will to display a more developed strategic analysis of the research infrastructures landscape, as well as by a reinforced attention to the transversal issues of open science and data, in accordance with France’s commitments in this area. It demonstrates France’s determination, through its major research and higher education establishments, to respond to the ever-changing demands of knowledge and

innovation. It also aims to maintain an essential complementarity with the European strategy in the field of research infrastructures, which has recently evolved through the 2021 update of the ESFRI roadmap.

This new National Roadmap was developed with one main objective in mind: to express a clear vision of the essential infrastructures for French research and innovation, positioned in a strategic analysis of the research infrastructure landscape.

The strategic analysis of the infrastructure landscape is a real innovation of this new National Roadmap and aims to highlight:

- Major scientific questions and societal challenges that require the use of infrastructure;
- The positioning of each infrastructure in the Roadmap in relation to research developments, community needs, competing facilities, and possible interfaces and complementarities between infrastructures;
- The potential gaps to be filled, as well as the orientations for the next five years, trying to identify priorities and objectives in terms of impact, and identifying new synergies to be developed, also considering budgetary sustainability;
- Open science and data practices of the infrastructures.

This analysis, produced by the Directorate-General for Research and Innovation (DGRI) after consultation with national thematic research alliances, research institutes and universities, now serves as a reference for explaining the French State’s strategy in the field of research infrastructures to other ministries, members of Parliament, the National Court of Audit, research organisations, institutions and communities, our foreign partners and international institutions (European Commission, OECD, etc.). It may inform future funding policy decisions and the selection of

new projects, by ensuring their relevance to this overall strategic framework.

Beyond DGRI services, this national Roadmap update has mobilised a whole range of important actors, whom I would like to thank for their essential contributions:

- The national thematic research alliances, organisations and universities concerned by research infrastructures, which were consulted in thematic groups coordinated by the DGRI;
- The infrastructures called upon to apply;
- The High Council for Research Infrastructures (HC-IR), which has been asked to inform the strategic discussions within the Steering Committee for Research Infrastructures (CD-IR) that I have the pleasure of chairing.

With a renewed strategy for research infrastructures, France is ready to meet the research and innovation challenges of the coming years.

The various types of research infrastructures

A RICH AND VARIED LANDSCAPE

The present National Roadmap for Research Infrastructures has identified 108 objects of extremely varied form and content. These infrastructures are not limited to large-scale facilities located on a single site, but can also take distributed forms. They are also influenced, to varying degrees, by the new capabilities of information and communication technologies. Finally, they reflect organisational methods that are highly dependent on the thematic communities and the techniques they share.

WHAT IS A RESEARCH INFRASTRUCTURE?

A research infrastructure is characterised by essential facilities, resources or services that are unique and of national or even European or international scope, the purpose of which is to conduct and support excellent research activity. It includes scientific equipment, resources such as scientific collections, archives and data, digital services and infrastructures, and any other essential tool to support research and innovation at the highest level.

An infrastructure of the National Roadmap...

- must have an identified, unified and effective governance and strategic and scientific steering bodies;
- must be open to research communities wishing to use it, accessible on the basis of peer-reviewed projects; it must therefore have adequate evaluation bodies;

- may conduct its own research and/or provide services to one or more user communities including actors of the economic sector. These communities may be present on the site, come to carry out work on an ad-hoc basis, or interact remotely;
- must have a multi-annual budget plan and submit a formalised budget to the relevant bodies;
- must be part of a dynamics of open science and control of the life cycle of data it produces and uses.

FOUR CATEGORIES OF OBJECTS

This National Roadmap includes four categories of objects defined according to the following principles:

- International scientific organisations (IOs) are legally based on an intergovernmental convention, which specifies, among other things, the objectives of the organisation, the conditions of membership, the operating bodies and the modalities for the contribution of member States;
- RIs* (called VLRI – very large research infrastructures - in previous editions of the National Roadmap¹) are infrastructures which, although under the scientific responsibility of research operators, are part of a national policy and are subject to specific budgetary allocation by the Ministry in charge of research, for financial and/or ministerial scientific policy reasons;
- The RI category includes infrastructures whose scientific strategy and budgetary monitoring are the responsibility of research operators;

¹ The qualifier “very large” in the VLRI label was inappropriate, as some “small” VLRI, in terms of size, coexisted with very large RIs.

- Projects, under construction or already productive but not yet fully mature according to the criteria mentioned above, have an importance in the French research landscape that justifies inclusion on the Roadmap. This status is of a transitory nature and will be the subject of a new analysis during the next update of the Roadmap.

It should be noted that according to the criteria presented above, test infrastructures and demonstrators used in the framework of major equipment programmes (energy, transport, buildings, food-processing, space, nuclear, defence, etc.), which may carry out research but without external access, are not intended to be included in this Roadmap.

Research infrastructures and the Roadmap

INCLUSION ON THE ROADMAP

The National Roadmap determines the major frame for public intervention in the strategic management of research infrastructures. This exercise, carried out on a regular basis by the Ministry of Research, in consultation with the thematic research alliances and research organisations, affirms the French State's desire to structure the landscape of infrastructures of at least national scope. The inclusion of a research infrastructure on the national roadmap represents a quality label and recognition of its strategic importance for France. It is necessary to support French positions within major European or international research projects, without weakening support for national facilities, which often remain the first point of access for our researchers. This ambition presupposes a strong requirement in the governance of research infrastructures, which must be applied at all levels, through: a selective and hierarchical choice of projects to be supported, a good evaluation of construction costs but also the control of operating costs, which is the only way to guarantee their long-term sustainability, as well as the necessary consideration of their economic, societal and cultural impact.

NATIONAL AND EUROPEAN ROADMAPS

The work on updating the national roadmap was carried out in close connection with the work done on the revision of the European Strategy Forum on Research Infrastructures (ESFRI) roadmap.

Designing and developing pan-European and international infrastructures requires consultation at European level, in particular when choosing host countries. Indeed, infrastructures play a driving role in the construction of the European Research Area and are an integral part of Pillar 1 "Scientific Excellence" of the Horizon

Europe Framework Programme. The clear definition of its national choices allows our country to effectively influence orientations at the European and international levels. The numerous French participations in European infrastructures are mentioned in this document.

THE PROCESS OF UPDATING THE NATIONAL RESEARCH INFRASTRUCTURE ROADMAP

The previous editions of the national research infrastructure strategy were published in 2008, 2012, 2016 and 2018. The 2021 edition is the result of a collective process, in which the thematic alliances and research institutions have been major players, under the guidance of the DGRI.

A national launch webinar with more than 300 participants (representatives of infrastructures, institutions and research communities, etc.) took place on November 4th 2020 to explain the issues, objectives, process and timetable for the renewal of the National Roadmap.

A first wave of consultation with research organisations and alliances took place from November 2020 to January 2021, within thematic working groups corresponding to each of the major scientific fields using infrastructures. These working groups, led by scientific experts from the DGRI, made it possible to draw up a preliminary version of the strategic analysis of the infrastructure landscape and to draw up the list of infrastructures invited to submit their applications to the new Roadmap.

These pre-selected infrastructures then filled in an online survey in February 2021, via a platform developed by the ministerial statistical service for education and research (SIES). The survey aimed to explain all the important points of analysis, such as the nature of the infrastructure, its scientific and technological design, its governance, its

possible European/international dimension, its data management, its open science practices, its indicators in terms of openness and use, scientific production, training, innovation and socio-economic impact. In March 2021, and on the basis of the data collected, a second wave of working group meetings made it possible to assess the evolution of the infrastructures listed in previous editions of the Roadmap, to study the characteristics of new projects and to refine the strategic analysis of the overall landscape. Two cross-disciplinary working groups on open science and data practices of infrastructures also worked to enrich the overall strategic analysis.

The High Council for Research Infrastructures (HC-IR), a consultative body bringing together 15 high-level scientific personalities with experience in the field of large-scale facilities and representative of the various research sectors, was asked to analyse the applications in April 2021. The HC-IR interviewed the coordinators and leaders of the working groups in May 2021, and delivered a report giving detailed opinions on the applications and the overview of the infrastructures in June 2021.

The Steering Committee for Research Infrastructures (CD-IR), chaired by the Director General of Research and Innovation and comprising the CEO of CNRS, the Administrator General of CEA, the presidents of the five national thematic research alliances, representatives from the Ministry of Foreign Affairs and the Ministry in charge of the Budget, met on July 13th and October 1st 2021 to examine the list of infrastructures considered for the new Roadmap in the light of the opinions of the HC-IR and the strategic analysis of the infrastructure landscape. At the end of these discussions, the Director-General decided on the list of infrastructures retained on the new national Roadmap.

The strategic analysis of the infrastructure landscape was finalised and the individual

sheets presenting each infrastructure were produced in autumn-winter 2021. The publication of the new National Roadmap led to the organisation of a webinar for infrastructures and representatives of research institutions and communities on March 8th 2022.

Table of research infrastructures

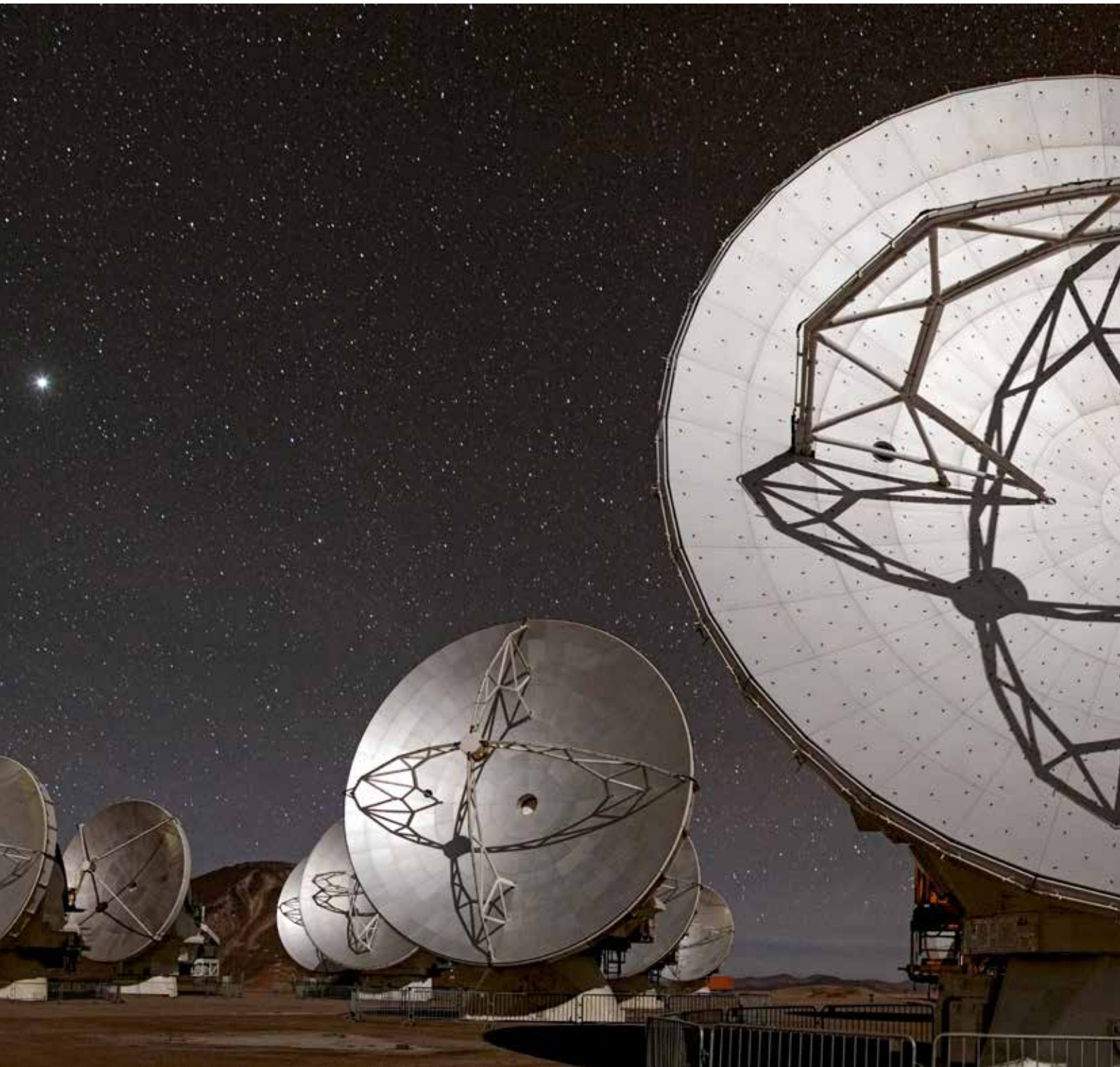
MAIN RESEARCH FIELD	SECONDARY RESEARCH FIELD(S)	ACRONYM	FULL TITLE OF THE INFRASTRUCTURE:	TYPE	ESFRI STATUS
Astronomy and astrophysics		ESO	European Southern Observatory	IO	ELT: ESFRI landmark
		ESO/ALMA	Atacama Large Millimeter/Submillimeter Array		
		SKAO	SKA Observatory	IO	ESFRI landmark
		CFHT	Canada-France-Hawaii Telescope	RI*	
	Nuclear and high-energy physics	CTA	Cherenkov Telescope Array	RI*	ESFRI landmark
		IRAM	Institute for Millimeter Radio Astronomy	RI*	
		CDS	Strasbourg Astronomical Data Centre	RI	
	Nuclear and high-energy physics	HESS	High Energy Stereoscopic System	RI	
		Instrum-ESO	Instrumentation for ESO's large telescopes	RI	
		LOFAR/NenuFar	International Low Frequency Radio Array Telescope – LOFAR FR	RI	
		PARADISE	Platform for Applied Research and Development Activities in Ground and On-board Instrumentation	RI	
Biology and health		EMBL	European Molecular Biology Laboratory	IO	
		CALIS	National Consumer-Food-Health Research Infrastructure	RI	
		Celphedia	National Infrastructure for the Creation, Breeding, Phenotyping, Distribution and Archiving of vertebrate models	RI	INFRAFRONTIER: ESFRI landmark
		ChemBioFrance	Bioactive molecules discovery platform to explore and cure living organisms	RI	
		CONSTANCES	Cohort of consultants at health examination centres	RI	
		ECELLFrance	National platform for regenerative medicine based on adult mesenchymal stem cells	RI	
	Earth system and environment	EMBRC France	National Centre for Marine Biological Resources	RI	EMBRC: ESFRI landmark
		EMERG'IN	National Research Infrastructure for the control of animal and zoonotic emerging infectious diseases through <i>in vivo</i> investigation	RI	
		FBI	France-BioImaging	RI	Euro Bioimaging: ESFRI landmark
		F-CRIN	National Platform of Clinical Research thematic expertise	RI	ECRIN: ESFRI landmark
		FLI	France Life Imaging	RI	

MAIN RESEARCH FIELD	SECONDARY RESEARCH FIELD(S)	ACRONYM	FULL TITLE OF THE INFRASTRUCTURE:	TYPE	ESFRI STATUS
Biology and health		France Cohortes	France Cohortes	RI	
		France Génomique	National Genomics and Associated Bioinformatics Infrastructure	RI	
		FRISBI	French Infrastructure for Integrated Structural Biology	RI	INSTRUCT: ESFRI landmark
	Earth system and environment	IBISBA France	Industrial Biotechnology Innovation and Synthetic Biology Acceleration	RI	ESFRI project
		IDMIT	National Infrastructure for Human Infectious Disease Modelling and Advanced Therapies	RI	
		IFB	French Institute of Bioinformatics	RI	ELIXIR : ESFRI landmark
		Ingestem	National Pluripotent Stem Cell and Tissue Engineering Infrastructure	RI	
		Laboratoire P4 Jean Mérieux	Research Infrastructure dedicated to highly infectious diseases - Inserm Jean Mérieux BSL4 Laboratory	RI	ERHINHA : ESFRI landmark
		LiPh@SAS	Livestock Phenotyping for Sustainable Agricultural Systems	RI	
		MetaboHUB	French distributed infrastructure for metabolomics and fluxomics dedicated to innovation, training and technology transfer	RI	
		NeurATRIS	Translational Research Infrastructure for innovative therapies in Neuroscience	RI	EATRIS: ESFRI landmark
		NEUROSPIN	Research center for innovation in brain imaging technologies	RI	
	Earth system and environment	Phenome-Emphasis France	French Plant Phenomics Infrastructure	RI	EMPHASIS: ESFRI project
		ProFI	Proteomics French Infrastructure	RI	
		CAD	Data Analyser Collector	Project	
		EBRAINS-FR	European Brain ReseArch INfrastructureS-France	Project	EBRAINS: ESFRI project
	FR Exposome	FRANCE EXPOSOME	Project	EIRENE: ESFRI project	
Energy		ECCSEL	European Research Infrastructure for CO ₂ Capture, Utilisation, Transport and Storage	RI	ESFRI landmark
		FR Solaris	French Research Infrastructure for Concentrated Solar Power	RI	EU Solaris : ESFRI landmark
		THEOREM	Network of Hydrodynamic Test Facilities for Marine Renewable Energies	RI	MARINERG-i : ESFRI project
		WEST	W(Tungsten) Environment for Steady-state Tokamaks	RI	

MAIN RESEARCH FIELD	SECONDARY RESEARCH FIELD(S)	ACRONYM	FULL TITLE OF THE INFRASTRUCTURE:	TYPE	ESFRI STATUS
Nuclear and high-energy physics		CERN	European Organization for Nuclear Research	IO	
		CERN LHC	Large Hadron Collider	RI*	HL-LHC: ESFRI landmark
		DUNE / PIP-II	Deep Underground Neutrino Experiment/ Proton Improvement Plan II	RI*	
	Astronomy and astrophysics	EGO-Virgo	European Gravitational Observatory - Virgo	RI*	
		FAIR	Facility for Antiproton and Ion Research	RI*	ESFRI landmark
		GANIL-SPIRAL2	Large National Heavy Ion Accelerator – 2nd Generation On-line Radioactive Ion Production System	RI*	SPIRAL2: ESFRI landmark
		AGATA	Advanced GAMMA Tracking Array	RI	
		JUNO	Jiangmen Underground Neutrino Observatory	RI	
	Astronomy and astrophysics	KM3NeT	Kilometre Cube Neutrino Telescope	RI	ESFRI project
		LSM	Modane Underground Laboratory	RI	
	Astronomy and astrophysics	LSST	Legacy Survey of Space and Time	RI	
Astronomy and astrophysics	PAO	Pierre Auger Observatory	RI		
Social sciences and humanities	Scientific information	HUMA NUM	Very Large Research Infrastructure for Digital Humanities	RI*	DARIAH: ESFRI landmark
		PROGEDO	Data Production and Management	RI*	ESS: ESFRI landmark CESSDA: ESFRI landmark SHARE: ESFRI landmark GGP: ESFRI project
	Scientific information	RnMSH	National network of Maisons des Sciences de l'Homme	RI	
	Material science and engineering	E-RIHS FR	European Research Infrastructure for Heritage Science – France	Project	E-RIHS: ESFRI Project
Material science and engineering		Apollon	Apollon laser	RI*	
		ESRF	European Synchrotron Radiation Facility	RI*	ESRF-EBS: ESFRI landmark
		ESS	European Spallation Source	RI*	ESFRI landmark
		European XFEL	European X-ray Free Electron Laser	RI*	ESFRI landmark
		ILL	Max von Laue – Paul Langevin Institute	RI*	ESFRI landmark
		SOLEIL	SOLEIL synchrotron	RI*	

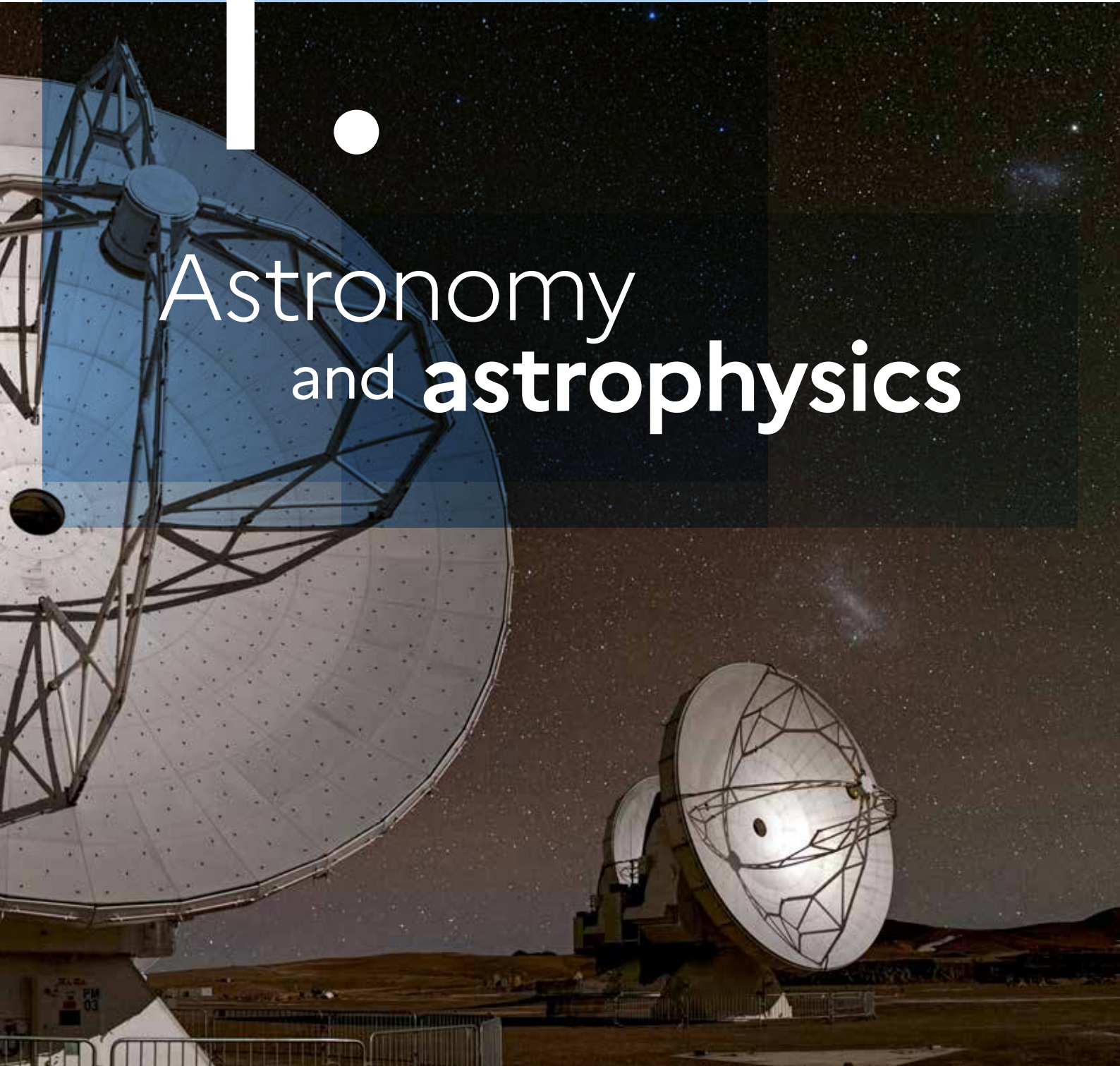
MAIN RESEARCH FIELD	SECONDARY RESEARCH FIELD(S)	ACRONYM	FULL TITLE OF THE INFRASTRUCTURE:	TYPE	ESFRI STATUS
Material science and engineering	Nuclear and high-energy physics	EMIR&A	National Accelerators Network for the Irradiation and Analysis of Molecules and Materials	RI	
		Infranalytics	National Research Infrastructure Network for High-Field NMR, EPR and FTICR	RI	
		LMJ-PETAL	Megajoule – PETawatt Aquitaine Lasers	RI	
		LNCMI	National Laboratory for High Magnetic Fields	RI	EMFL: ESFRI landmark
		METSA	National Research Infrastructure Network for Electron Microscopy and Atomic Probe	RI	
	Astronomy and astrophysics	REFIMEVE	Metrological Fibre Network with a European Vocation	RI	
		RENATECH	National Network of Nanofabrication Technology Centres	RI	
Digital and mathematics sciences		CONTINUUM	Collaborative Continuity from Digital to Human	RI	
		ROBOTEX 2.0	The Coordinated Infrastructure of Robotics Platforms in France	RI	
		SILECS	Infrastructure for Large-Scale Experimental Computer Science	RI	SLICES: ESFRI project
Earth system and environment		ECMWF	European Centre for Medium-Range Weather Forecasts	OI	
		CONCORDIA	CONCORDIA – French-Italian Antarctic Research Station	RI*	
		ECORD/IODP	International Deep Sea Drilling Programme/ European Consortium for Ocean Drilling Research/International Ocean Discovery Program	RI*	
		EURO-ARGO-Fr	In-Situ Ocean Observation Network/European contribution to Argo program	RI*	EURO-ARGO: ESFRI landmark
		FOF	French Oceanographic Fleet	RI*	
		ICOS-Fr	Integrated Carbon Observation System	RI*	ICOS: ESFRI landmark
		ACTRIS-Fr	Ecosystem Analysis and Experimentation – France	RI	ACTRIS: ESFRI landmark
		ANAEE-Fr	Analyse et Expérimentation sur les Écosystèmes – France	RI	ANAEE: ESFRI landmark
		CLIMERI-Fr	National Research Infrastructure for Modelling the Earth's Climate System	RI	
		DATA TERRA	Data hubs and services for the Earth system	RI	
		eLTER-Fr OZCAR	Critical Zone Observatories, Application and Research	RI	eLTER: ESFRI project
		eLTER-Fr RZA	Réseau des Zones Ateliers – Socio-Ecosystems Infrastructure	RI	eLTER: ESFRI project

MAIN RESEARCH FIELD	SECONDARY RESEARCH FIELD(S)	ACRONYM	FULL TITLE OF THE INFRASTRUCTURE:	TYPE	ESFRI STATUS
Earth system and environment		EMSO-Fr	European Multidisciplinary Seafloor and water column Observatory – France	RI	EMSO: ESFRI landmark
		IAGOS-Fr	In-Service Aircraft for Global Observing System	RI	IAGOS: ESFRI landmark
		ILICO	Marine Coastal and Nearshore Research Infrastructure	RI	
		IN AIR	National Infrastructure of Aircraft Instrumented for Research	RI	
		IN-SYLVA-Fr	In-Sylva France National research infrastructure for adaptive forest management	RI	
		PNDDB	National Biodiversity Data Centre	RI	
		RARe	Agronomic Resources for Research	RI	MIRRI: ESFRI landmark
		RECOLNAT	French national network of naturalist collections	RI	DiSSCo: ESFRI project
		RESIF/EPOS-FR	French seismological and geodetic network/ European Plate Observing System	RI	EPOS: ESFRI landmark
	RéGEF	French Geochemical and Experimental Network	Project		
Digital services (computing and networking)		GENCI	National High-Performance Computing Equipment	RI*	PRACE: ESFRI landmark
		RENATER	Public Interest Grouping for the National Electronic Communications Network for Technology, Education and Research	RI*	
	Nuclear and high-energy physics	CC-IN2P3	IN2P3 Computing Centre	RI	
		CINES	National Computer Centre For Higher Education	RI	
		France Grilles		RI	
Scientific information		CollEx-Persée	Collections of Excellence for Research – Persée	RI	
		HAL+	Next-generation open archive	RI	
		Métopes	Methods and Tools for Structured Publishing	RI	
	Social Sciences and Humanities	OpenEdition	Open Science Communication in the Humanities and Social Sciences	RI	OPERAS: ESFRI project
		ISTEX	Scientific and technical information of excellence	Project	
		Software Heritage		Project	



1.

Astronomy
and **astrophysics**



Astronomy and astrophysics

Astronomers have been studying the sky since ancient times. Astrophysics aims to study and understand the universe and its constituents. Astronomy is based on three fundamental pillars: observation/detection, theory/modelling and simulations. Progress in astrophysical observation is dependent on the large research infrastructures that are the observatories on the ground or in space. The increase in the size of ground-based telescopes, the opening up of the entire field of electromagnetic waves made possible by space telescopes, and more recently the possibilities of detecting cosmic particles and gravitational waves have opened up new windows on the universe, which pose new questions for our understanding of the cosmos.

THE MAJOR CURRENT SCIENTIFIC ISSUES AND THEIR LINKS TO RESEARCH INFRASTRUCTURES

Structuring of the Universe

The hypothesis that the universe went through a very hot and dense phase and then expanded and cooled was formulated almost 100 years ago. This model, known as the Big Bang, explains the expansion of the universe observed by the rate at which galaxies are moving away from each other; it explains the appearance of elementary particles and the nucleosynthesis of light nuclei. It explains the blackbody radiation that has reached us since the time when the universe became transparent through the recombination of nucleons and electrons to form atoms. This is called the Cosmic Microwave Background (CMB). No other model is capable of explaining all these observations. However, three additional hypotheses must be included. To reproduce the quasi-homogeneity of the universe, it is necessary to assume a very rapid exponential expansion phase, called inflation, which occurred very early on. Several inflation models have been proposed, but their physical basis remains uncertain. Secondly, the composition of the universe predicted by the Big Bang model has two main components that raise questions: dark energy,

which is responsible for the current acceleration of the expansion of the universe, and dark matter, which governs the dynamic evolution and structuring of the universe. Dark energy accounts for about 68% of the energy in the universe, dark matter for 27%. Their nature remains unknown, despite extensive research through both astronomical observations and direct detection physics experiments. In this universe, the matter of which we are formed, the so-called baryonic matter, represents only 5% of the universe's content.

Observations of the CMB provide information about the state of the universe at the time of recombination. Observations by the WMAP (NASA, 2001) and Planck (ESA, 2009) satellites have made it possible to determine the precise temperature of the cosmological black body, as well as the scale of the density fluctuations that gave rise to the large structures of the universe. The polarisation of these radiation fluctuations can tell us about the processes that took place during the inflationary period. The measurement of this polarisation is the aim of future projects that are still far off, such as the Japanese Litebird satellite and the American CMB-S4 project on the ground. The observation of Ia type supernovae in distant galaxies made it possible in 1996 to determine the second acceleration of

the expansion rate of the universe due to dark energy (Nobel Prize in Physics 2011), which started 5 billion years ago. This result has since been confirmed by other independent means: observations of the CMB and observations of the large-scale distribution of dark matter by observing distortions in the images of distant galaxies due to gravitational lensing, what is known as gravitational shear. These have been conducted from the ground with wide-field telescopes, such as **CFHT**, and soon with **LSST**, and will be conducted with even greater precision by the European satellite **EUCLID**, to be launched in 2023. In the next few years, gravitational shear to map large-scale dark matter with **LSST** and **EUCLID** will be the main focus of observational cosmology.

The future of cosmological research will be to find direct tracers of phenomena that occurred before the recombination. Two candidates exist. Neutrinos decouple before photons, and could give a diffuse cosmological neutrino background that could be detected by studying the ultra-high energy cosmic rays with observatories such as the **Pierre Auger Observatory (PAO)**. Low frequency gravitational waves could be generated during inflation. They are difficult to observe from the ground, but they will be one of the goals of the European Space Agency's **LISA** project (2030+). Another approach would be to better understand the formation of large structures just after recombination, before stars and galaxies form and illuminate the universe. The matter is then in the form of clouds of atomic hydrogen, which can be observed in radio. This is one of the main aims of the **SKA** radio astronomy observatory, in which France has just decided to participate and which will be operational around 2030.

Formation and evolution of galaxies

From primordial density fluctuations, matter in the Universe is structured into dark matter filaments by gravity and expansion. At the intersection of these filaments, dark

matter halos are formed in which baryonic gas is trapped. It cools by radiation, allowing the formation of the first stars and galaxies. The evolution of the properties of these galaxies over cosmic time has been studied in detail based on numerous observations from the ground (**CFHT**, **VLT**, **ALMA**, **DESI**) and from space (**XMM-Newton**, **Herschel**). It raises many theoretical questions on the processes that govern it and require new observational diagnostics, which will be accessible with the next generation of observatories on the ground, such as the **ELT**, and soon in space with **EUCLID** and the **JWST**.

A key aspect of understanding the diversity of galaxy properties is the ability of feedback processes to regulate the gas within the structures. Supernovae, and supermassive black holes at the centre of galaxies, are responsible for propelling galactic winds and modulating the accretion of gaseous matter in galaxies. Observatories such as **ALMA** offer a better understanding of the origin of these winds by characterising the cold gas in galaxies and its kinematics. The shocks generated by supernovae and relativistic jets from active galactic nuclei are the site of particle acceleration, cosmic rays (**CTA**, **KM3NeT**, **PAO**) which can be used to deduce some properties of the formation of these winds. A better knowledge of the coevolution of supermassive black holes (**ATHENA**, **LISA**) with their galaxy will also allow to better characterise their activity.

Knowledge of the properties of intergalactic gas is of major interest and will be taken a step further with the new generation of observatories. Whether in cosmic filaments through their Lyman-alpha emission (**VLT**, **ELT**) and their properties in absorption of the radiation emitted by the most distant galaxies (**VLT**, **ELT**), or that of the hot X-ray emitting gas in galaxy clusters, probed in X-rays with the **XMM-Newton** satellite (**ATHENA** in 2030+), and in radio with **LOFAR (SKA in 2030+)**, these studies make it possible to place indirect obligation on the cosmological models.



Finally, the study of the content of our Milky Way and its satellite environment by the GAIA satellite can provide information on the way our galaxy has assembled over time.

Since galaxy formation is a fundamentally multi-scale and multi-physics phenomenon, purely analytical theoretical approaches are ineffective. Numerical modelling, backed by robust physical models, offers a unique theoretical approach that massively parallel computers have made possible. Astrophysical simulations are among the major spin-offs of **GENCI** and **PRACE**.

Star and planet formation

Within galaxies, the interstellar medium, from its most dilute to dense phases, is the reservoir of material for the formation of new stars and their planetary systems. The outline of star formation by gravitational collapse was drawn several decades ago, but the quantitative understanding of the formation processes is still an open question. This process involves the complex physics of matter, including its turbulent dynamics, interactions with radiation, the magnetic field and the energetic particles that make up cosmic rays. These different mechanisms operate simultaneously and none can be neglected. Furthermore, newly formed stars, and in particular massive stars, have a significant effect on their environment and thus contribute through this feedback to the regulation of large-scale star formation, but feedback also plays a critical role in the formation of planetary systems. Studies on star formation and the interstellar medium benefit from advances in numerical simulations based on multi-scale modelling of physical and chemical phenomena, supported by numerous interdisciplinary studies with physicists and chemists. Space missions in the infrared and submillimetre domains, such as Planck and Herschel, and the millimetre observatories on the ground, **IRAM** and **ALMA**, have enabled a detailed characterisation of the structures and

confirmed the critical role of the magnetic field. The challenge is now to characterise turbulence and the magnetic field from the largest scales of galaxies to those of planetary systems. France is well positioned thanks to its participation in **ESO**, the **IRAM** and **ALMA** radio telescopes. The Gaia stellar surveys provide essential information for obtaining a statistical view of the phenomena. Access to low-frequency radio telescopes such as **LOFAR/NenuFAR** and **SKA** will provide a unique means of 3D magnetic field characterisation. Access to high angular resolution is absolutely necessary to visualise the structure, composition and dynamics of circumstellar disks and to understand how the diversity of planetary systems emerges, and how interstellar matter in the form of gas or dust is incorporated into planet embryos.

From stars to compact objects

Depending on their mass, stars will evolve very differently, in isolation or in binary systems, and on time scales of a few million years to several billion years. Massive stars have a strong influence on their environment by ionising and chemically enriching the interstellar medium through their wind. It is the ultimate phases of stars that produce the heaviest elements from silicon to iron and beyond during explosive supernova nucleosynthesis and eject this enriched material into the interstellar medium. The shock structure generated (supernova remnant) heats the interstellar medium to tens of millions of degrees, accelerates particles and generates turbulence. The energy released is considerable, from some 10^{50} to 10^{53} ergs for hypernovae, and is the cause of retroaction phenomena on the formation of stars and the evolution of galaxies. Different types of explosion occur, but two main categories can be distinguished: thermonuclear explosions (SN Ia), and the gravitational collapse of the iron core of a massive star with the formation of a compact object (neutron star/pulsar or black hole). Long

gamma-ray bursts are thought to originate from these massive progenitors, while short gamma-ray bursts are thought to originate from the merger of neutron stars (kilonovae) in binary systems. The challenge is to understand the physics of the explosion, the nature of the progenitors, the formation of the compact object, the jets and the supernova remnant, and their impact on the ecosystem of galaxies. What critical role do neutrinos and instabilities play in triggering the explosion, the properties of the compact object and their afterglow? How are particles accelerated in the shocks, how is turbulence generated and the magnetic field amplified? To make progress, this requires advanced numerical simulations and observations over a wide multi-wavelength spectrum from radio with **LOFAR** and **SKA**, to optical-near-IR with **ESO**, to X-rays in space, gamma rays with **HESS** and **CTA** but also multi-messenger (neutrino, cosmic rays and gravitational waves). These systems play a key role in our understanding of the formation of stars and planetary systems, the evolution of galaxies and the chemical enrichment of intergalactic gas.

Planets and astrobiology

The questions of the existence of life in the Universe, its emergence and the conditions necessary for its maintenance have been important areas of research since the detection of the first extrasolar planet around a nearby star (Nobel Prize in Physics 2019). These fundamental questions are grouped under the heading of astrobiology and overlap with those of planetology and solar-terrestrial relations. This research mobilises very important efforts in the world. They are interested in objects in the solar system such as Mars, which may have harboured life in the past, or moons of Jupiter and Saturn such as Europa and Enceladus, which contain oceans of liquid water under a layer of ice, but also Earth-like planets located in the so-called habitable zone around other stars. Considerable progress has been made

over the past 25 years. More than four thousand planets have been detected, showing how common planetary systems are and paving the way for the study of their formation and evolution, and offering new perspectives on the conditions for the appearance of life. The great progress made in ground-based and space-based observation methods has led to the detection of an increasing number of telluric exoplanets in the habitable zone of their star, and the measurement of their atmospheric composition will become possible with the **ELT** or **JWST**. Returning to the Solar System, our knowledge of the early Earth has greatly evolved and it is possible that life appeared very quickly more than 4 billion years ago. Organic matter has been detected on comet Churyumov-Gerasimenko 67P by the Rosetta probe and on Mars by Curiosity, along with traces of water and methane. Future or ongoing sample returns from Mars or the Ryugu and Bennu asteroids will allow further analysis to understand the contribution of organic matter to Earth and the potential existence of life elsewhere in the solar system. The study of the Sun-Earth relationship, but also of potential collisions with small bodies, will shed light on the evolution of conditions conducive to life in the only case known today where it has been able to develop. In support of these observations, important theoretical and laboratory activities aim to study the chemical and biochemical mechanisms at work in the transition from inert to living and the identification of bio-signatures.

The new astronomies

From radio waves to ultra-high energy X-rays and gamma rays, multi-wavelength astronomy has developed, partly thanks to progress in space, throughout the second half of the 20th century, revealing very energetic objects, but also very cold components, unobservable by traditional astronomical means. France is a major player in this development, both in high-energy astrophysics with its involvement in the X-ray and Gamma-ray satellites



(SIGMA, XMM-Newton, INTEGRAL) and the ground-based Cherenkov observatories, **HESS** and soon **CTA**, as well as in the field of the cold universe, with **IRAM** and **ALMA**, but also in space with major involvement in the ISO, Planck and Herschel satellites.

Since the beginning of the 21st century, new windows on the universe have been opened by cosmic particles and gravitational waves. More than a century after their discovery, the origin and composition of ultra-high-energy cosmic rays remain a mystery. The **Pierre Auger International Observatory** in Argentina, in which France participates, is being upgraded and should reach a higher level of performance in 2021. The very large astrophysical neutrino detectors saw a significant advance in 2017 with the very likely detection of an active galaxy by the IceCube observatory in Antarctica, and thus the beginning of neutrino astronomy. The new generation of neutrino projects will detect gravitationally collapsing supernovae at distances well beyond the Large Magellanic Cloud. France is involved in the **KM3NeT** project, which is being built in the abyss of the Mediterranean Sea, and contributes to the Global Neutrino Network.

The first direct detection by LIGO of the passage of a gravitational wave in 2015 from a merger of two black holes (Nobel Prize in Physics 2017), marked the birth of gravitational wave astronomy. This was followed in 2017 by the observation by LIGO and **EGO/Virgo** of the signal from a merger of two neutron stars, which marked the birth of multi-messenger astronomy since an electromagnetic component could be associated with this event, which had considerable implications for astrophysics, cosmology and fundamental physics. Major upgrades are expected to bring these two detectors to the limit of their capacity by 2024, and studies are underway to determine the next generation of gravitational wave detectors, such as the Einstein Telescope project in Europe.

The universe is a laboratory for applying and testing theories of physics and chemistry in situations that are impossible to obtain on Earth.

Some theories, such as general relativity, can only be tested using astrophysical methods, for example by studying the surroundings of black holes. The early phases of the universe or the observation of ultra-high-energy particles allows new studies of particle physics. Moreover, interstellar chemistry offers a privileged laboratory for studying chemical reactions and the formation of aggregates in very dilute media. This is one of the reasons why many theoretical physicists and high-energy physicists are interested in collaborative work with astrophysicists. These collaborations have been going on for a long time, but they are becoming more and more important. Finding ways to make them even more effective is one of the keys to making ground breaking discoveries such as a new theory of gravitation or theories beyond the standard model of particle physics.

POSITIONING AND IMPORTANCE OF CURRENT LANDSCAPE INFRASTRUCTURES IN RELATION TO RESEARCH DEVELOPMENTS

Advances in astrophysics have always coincided with improvements in instrumentation and the introduction of new fields of observation. For example, in the optical field, the gain in collecting capacity, from the few centimetres in diameter of Galileo's telescope to the 10 m of today's telescopes and soon the 39 m of the **ELT**, has made it possible to go from observing the planets of the solar system to detecting the first galaxies formed after the Big Bang. Astronomy is now multi-wavelength, and is becoming multi-messenger. This evolution could only have occurred through the commissioning of new infrastructures dedicated to a specific type of observation. What might appear to be a multiplication of resources is a scientific necessity. Each of these messengers signals different physical processes, the understanding of which is necessary to grasp the entirety of the systems observed. New infrastructures, which are synonymous with potential progress, must

not be limited, but must be designed, from the outset, at the right European or global level to avoid duplication and control expenditure.

The 20th century also saw the birth of the computer revolution, which increased observation, data processing and digital simulation capacities tenfold. From an astronomy that was often limited to a few objects, we moved on to a statistical astronomy that was indispensable for dealing with certain subjects such as the analysis of the dark sector of the Universe or the evolution of galaxies. Data have consequently become more complex and massive, requiring new approaches and generating interdependencies with data science. As users of large observational infrastructures, astronomers have also become users of large infrastructures for calculations and data. Not to mention that they are also users of physics infrastructures for laboratory studies, and for the analysis of extra-terrestrial materials.

NATIONAL, EUROPEAN AND INTERNATIONAL DIMENSIONS OF THE INFRASTRUCTURES

European cooperation for the development of observatories began in 1962 with the creation by five countries, including France, of an intergovernmental organisation, the European Southern Observatory, **ESO**. Today **ESO** has 16 European member states and a strategic partnership with Australia. Thanks to **ESO**, European astronomers have been able to develop a coherent programme, with increasingly innovative and efficient telescopes, which now place them ahead of American astronomy. The awarding of the Nobel Prize in Physics in 2019 to the Swiss scientists Michel Mayor and Didier Queloz for their discoveries of exoplanets, and in 2020 to the German astrophysicist Reinhard Genzel for his work on the black hole at the centre of the Milky Way, is largely based on the work they have done using **ESO** telescopes.

The contribution of French astronomers to **ESO**'s programmes has been decisive in many areas, especially in the development of adaptive optics and interferometry systems. On the **VLT**, the multi-object spectrograph **MUSE**, the very high spatial resolution camera **SPHERE**, or the interferometric instrument **GRAVITY**, which have French PIs or Co-PIs, have no equivalent in the world. The impetus given by **ESO** has also facilitated the development of other projects, the **CFHT** with Canada and the **IRAM** with Germany and Spain.

The cost of astrophysics research infrastructure is now reaching the limits of what can be expected from a purely European programme. Several current projects have been set up on a global scale. The first was the **ALMA** millimetre radio astronomy network installed in Chile in 2011, the result of a collaboration between Europe (**ESO**), the USA, Canada, Japan, Taiwan and South Korea. The **Cherenkov Telescope Array, CTA**, currently under development, brings together scientific teams from 31 countries. The **SKA** low-frequency radio astronomy project was conceived from the outset as a global project and a new intergovernmental organisation, **SKAO**, was created in 2020. France has started the process of joining **SKAO** in 2021.

In order to manage such projects, astronomy very quickly acquired the necessary tools to carry out strategic analyses and define priorities. Since the 1970s, the INSU of the CNRS has conducted a foresight exercise every five years involving all the French players. At the European level, the ERANET ASTRONET, which brings together the main European astrophysics research organisations, was created in 2005. It is leading an exercise to define an RI roadmap for astrophysics, both on the ground and in space. The first one was published in 2008, and updated in 2014 and 2022. A similar process also exists in Europe for astroparticle physics. The scientific priorities presented in this document are part of this broader context.



SIZE OF THE SCIENTIFIC COMMUNITIES INVOLVED; POSSIBLE INTERCONNECTION WITH OTHER DISCIPLINARY FIELDS

The scientific communities concerned are mainly grouped in universities, the CNRS, the Paris and Nice observatories and the CEA/IRFU. They work within UMRs, which are themselves often part of Observatoires des Sciences de l'Univers (OSU). The astroparticle community includes, in addition to part of the staff working in laboratories labelled astronomy-astrophysics and attached to the INSU, staff working in laboratories of other CNRS institutes, especially IN2P3, but also INP and in smaller numbers at CEA. The CNRS/INSU/AA staff includes 805 researchers and academics, 411 CNRS ITAs and 245 from other organisations, as well as 166 fixed-term contracts. About 150 students start a thesis each year and there are some 250 postdoctoral researchers. This represents about 2,500 people. The male/female split is 23% among permanent researchers and 30% among PhD students. The CNRS/IN2P3 workforce in the field of astroparticle and cosmology includes 246 researchers and academics, about 60 postdoctoral researchers and about 100 PhD students. It should be noted that with 6% of the members, France is the second country after the United States in terms of the number of astronomers who are members of the International Astronomical Union.

Astrophysics is interdisciplinary in nature. For the past twenty years, the most important collaboration has been with theoretical physicists and high-energy physicists. Several infrastructures are supported by the three communities, such as the **Pierre Auger Observatory**, **CTA** or the **Vera Rubin Observatory (LSST)**. But even purely astronomical observatories such as **SKA** or the **ELT** will have spin-offs in fundamental physics. More recently, active collaboration with chemists has

developed for the study of the interstellar medium. A new field, astrobiology, is also emerging, involving geologists, chemists and biologists in addition to astrophysicists.

RI in astrophysics are at the cutting edge of technology in many fields, optics, mechanics, detectors, computing. The French community is particularly active in the development and exploitation of innovative focal instruments, for ground and space. The **Instrum-ESO** infrastructure is specifically dedicated to the involvement of French teams in instruments for **ESO**. It is fundamental for the French contribution to the **VLT** instruments and even more so for those of the **ELT**. A networking of the integration and test platforms of these instruments, indispensable elements of the instrument development scheme, is proposed as a new infrastructure, called **PARADISE**.

IMPACTS: SCIENTIFIC, SOCIO-ECONOMIC, ON EDUCATION AND TRAINING, ON INNOVATION

Astronomy and all its components are rightly considered pure sciences; that is, their aim is to increase our knowledge of our universe. By attempting to answer fundamental questions, astronomy has a major societal role in advancing our knowledge.

Astronomy also has practical applications. The definition and measurement of legal time originated in astronomical laboratories. Reference location systems are based on measurements of the positions of certain stars. The search for near-Earth asteroids that might hit the Earth and the monitoring of space weather to ensure the quality of radio telecommunications are based on the work of astronomers.

Observation in astronomy is dependent on advances in technology. In turn, techniques developed in astronomy have consequences in other fields, particularly in medicine. All medical imaging systems using scan or

tomography use derivatives of aperture synthesis developed by radio astronomers in the 1960s. More recently, adaptive optics techniques implemented on telescopes have been successfully used in ophthalmology for retinal surgery. Astronomers have always taken into account the value of developments in astronomical instrumentation. The realisation of research infrastructures in astronomy is done with a very important industrial return. The **ELT** project is costing **ESO** 1.3 billion euros. 90% of this budget corresponds to industrial contracts. But, beyond the financial return, these very high-tech achievements push industry to excel. In this way, they acquire new expertise that they can then use in other projects. The REOSC Company, now Safran-REOSC, created by opticians from the Institut d'Optique and the Observatoire de Paris in 1937, has become a world leader in optics thanks in part to the work it has done for all the **ESO** telescopes.

Astronomy is a discipline that attracts many students, not only those who want to do research in astronomy, but also engineers in optics, detection, mechanics or software development, who are attracted by the technical challenges linked to focal instruments and telescopes. Astronomy is also a privileged tool for spreading scientific and technical culture in schools. Flagship operations such as “La main à la pâte” are the result of the concerted efforts of astrophysicists and physicists. Finally, astronomy is of great interest to the public. In 2018, it was estimated that 3.5 million people were reached by the “La Nuit des Étoiles” operation. Amateur astronomers are a very active community. There are over 300 amateur astronomy clubs and 26 permanent amateur observatories equipped to receive the public. Several participatory science programmes to search for transient events, such as meteors with the FRIPON network, or supernova explosions have been initiated. Astronomers devote a significant part of their time to activities related to education and dissemination of knowledge.

DIGITAL NEEDS AND DATA

Astronomy has to use data from a wide variety of observatories. The question of sharing this data arose very quickly, and was resolved by establishing rules and practices to make all these independent databases interoperable. The International Virtual Observatory Alliance (IVOA) is responsible for this aspect. In France, the **CDS** (Strasbourg Data Centre) was one of the pioneers of the virtual observatory and remains a pillar of the IVOA. All major observatories follow the IVOA recommendations, and provide astronomers worldwide with scientifically exploitable observational data archives.

Large observational projects such as **LSST**, or **SKA** and its precursors promise an avalanche of data to be reduced and analysed, which will set new standards in terms of data logistics. These projects will have to deal with massive data by exploiting the best of the existing large architectures (**CC-IN2P3**, **GENCI**) or with dedicated architectures. Consideration must be given to the level of centralisation or grouping of data storage and processing resources (**CC-IN2P3**, Mesocentres) and to the interdisciplinary synergies to be encouraged. To face this digital challenge, the community will need to structure itself around new expertise in scientific computing and new data analysis formalisms (artificial intelligence). It should be noted that some of these data issues also exist for numerical simulations.

Numerical simulation is one of the pillars of our theoretical understanding of the universe. These simulations are largely based on massively parallel computing, requiring tens of millions of computing hours and hundreds or thousands of TB of storage, thus posing numerous technical challenges, whether in terms of operating the computing architectures, or in terms of logistics and making the simulated data available (in the context of open science). Numerical simulations in astrophysics are strongly



structured around community codes (RAMSES, PLUTO, AMRVAC, etc.). Numerical simulations benefit from access to **GENCI** at national level (> 100 million hours/year) and **PRACE** at European level. We can cite the CODA-II project that simulated the reionisation of the universe by exploiting 16,000 GPU cards in parallel or the Extreme-Horizon project to simulate galaxies in the large structures of the universe with a multi-resolution approach. The arrival of new (pre)Exascale architectures imposes new programming paradigms on these simulation codes, calling for new approaches. These changes in architecture require specific technical expertise that is not yet widely available in astronomy laboratories.

OPEN SCIENCE APPROACHES

Astronomy is a pioneer in the development of open access to data, whether raw data from telescopes, data from advanced processing such as object catalogues or processing and analysis software. Almost all major observatories on the ground and in space have an interoperable archive in the framework of the Virtual Observatory (IVOA) allowing the discovery and free access to data after a short embargo period. Bibliometric analyses show a significant percentage (30% for **ESO**) of publications based on the use of these archives. The **CDS** is spearheading these activities in France with its teams of astronomers, computer scientists and archivists. The tools for accessing scientific information developed at the **CDS** are enriched by the analysis of publications within the framework of partnerships with the journal *Astronomy and Astrophysics*, CNES, ESA and **ESO**, and contribute to the international bibliography service NASA Astrophysical Data System. The Virtual Observatory is not limited to data from observations but also includes the provision of data from numerical simulations or modelling. This expertise of the astronomy community is recognised within international actions such as RDA (Research Data Alliance) and working groups

related to open science in France, and in Europe (European Open Science Cloud) and in many European projects (ESCAPE cluster).

THE POTENTIAL GAPS TO BE FILLED, AS WELL AS THE ORIENTATIONS FOR THE NEXT 5 YEARS

Scientific orientation

The major areas that will focus efforts in the coming years will mainly revolve around three themes:

- cosmology: inflation, dark energy, dark matter, and structure formation
- the physics of compact objects, the death of stars and the development of multi-messenger astronomy and transient phenomena
- star and planet formation, comparative planetology, exoplanets and astrobiology.

The main priorities for infrastructure remain unchanged from the 2018 roadmap, in line with the INSU and astroparticle foresight exercises.

The growing importance of numerical aspects, large databases, interoperability, and the need for HPC for exascale numerical simulations, which will become increasingly essential for the modelling and simulation of cosmic phenomena, should be noted.

It is worth noting the French decision not to become a member of the European Solar Telescope in the Canary Islands, an ESFRI-labelled project being pushed by several European countries. Although solar physics is one of the French thematic priorities, the centre of gravity has shifted towards space for very large infrastructures in this field.

Difficulties and possible improvements

The recent evolution of astronomy, the development of fields at the interfaces with other disciplines, the development of multi-messenger astronomy and transient

Fundamental physics	SKA			ESO VLT, ESO VLT, ESO ELT, LSST VRO	CTA	KM3NeT, AUGER	VIRGO		
Primordial universe	SKA, LOFAR			CFHT, ESO VLT, ESO VLT, ESO ELT, LSST VRO	CTA			Simulation GENCI PRACE	
Formation and evolution of galaxies	SKA, LOFAR	NOEMA IRAM	ESO ALMA	CFHT, ESO VLT, ESO VLT, ESO ELT, LSST VRO				Simulation GENCI PRACE	
Formation and evolution of stars		NOEMA IRAM	ESO ALMA	CFHT, ESO VLT, ESO VLT, ESO ELT			VIRGO	Simulation GENCI PRACE	
From stars to compact objects	SKA, LOFAR	NOEMA IRAM	ESO ALMA	ESO VLT, ESO VLT, ESO ELT, LSST VRO	CTA, HESS	KM3NeT, AUGER	VIRGO	Simulation GENCI PRACE	
Planets and astrobiology	SKA, LOFAR	NOEMA IRAM	ESO ALMA	CFHT, ESO VLT, ESO VLT, ESO ELT				Simulation GENCI PRACE	
Technology and support								CDS IVOA	Paradise, Instrum-ESO
	Low frequency radio	Millimetre radio		Visible and infrared	High energy Gamma	Cosmic particles	Gravitational waves	Simulations and data	Instrumentation

- LOFAR Infrastructure in operation
- SKA Infrastructure under development
- VIRGO Infrastructure described in other sections

Astronomy and astrophysics research infrastructures grouped by observational domains and ordered according to research areas. The RIs framed with a solid line correspond to RIs in operation, those with a dotted line to RIs under development. The RIs with a grey background are those described in the Nuclear and High Energy Physics roadmap and in the Digital Services (Computing and Network) roadmap.

phenomena and the explosion of digital technology must be taken into account. The careers of researchers at the interfaces of astronomy must be facilitated. An effort should be made to develop skills at the astronomy-digital interface, especially for HPC, Big Data and Artificial Intelligence.

The cost of projects increases in proportion to the complexity of the instruments and the amount of data they provide. While traditional funding sources are generally adequate to finance the construction of RIs, it is more difficult to fund the upstream

(preparatory R&D) and downstream (scientific exploitation) phases. The interface fields would benefit from better overall governance, taking into account the priorities of the various CNRS institutes involved: INSU, IN2P3, INP.

Although astronomy is a popular science, its societal and economic impact remains poorly known. Astronomy could be better used as a vehicle for scientific and technical culture in high school and early university education, but also to promote women's access to scientific careers and to improve the social diversity of scientific careers.



ESO

European Southern Observatory

ESO is the main European intergovernmental organisation in the field of ground-based astrophysics and has world leadership in the optical and infrared fields. Sixteen European countries are member-states and contribute in proportion to their GNP. A partnership agreement with Australia was signed in 2017. Chile, the host country, is not a member of ESO but benefits from 10% of the observation time. The scientific programmes are very diverse, ranging from planetary science to cosmology. Apart from solar physics and the direct exploration of the solar system bodies, all the major astronomical issues are addressed.



© ESO

The following observatories are part of ESO:

- La Silla Observatory (3.60 m telescope and NTT) ;
- Paranal Observatory (4 telescopes of 8.20 m from VLT, plus 4 telescopes of 1.80 for VLTI, and 2 wide field telescopes);
- ALMA millimetre and sub-millimetre observatory with a 37.5% share, together with North America

(USA and Canada) for 37.5%, Asia (Japan and Taiwan) for 25%, Chile (host country, no direct contribution), comprising 66 antennas (50 antennas of 12 m in diameter for interferometry, 4 antennas of 12 m for full power observations, and a compact network of 12 antennas of 7 m in diameter);

- ELT: a 39 m in diameter visible and infrared telescope project, included in the ESFRI roadmap, with first light expected in 2027.

Relations with economic actors and/or socio-economic impact

ESO is a major actor in high-tech developments, opto-mechanics, detectors, lasers and complex instrumentation, with a significant industrial return of around 60% of the organisation's budget. Many French companies benefit as contract holders or subcontractors. High visibility in the media and dissemination of knowledge. Training programmes at the theses and post-doctoral levels.

Open science and data

- Annual data production: 131 TB
- Infrastructure with a FAIR data policy in application

Category: IO

Type of infrastructure: distributed

Infrastructure location in France: Paris

French supporting institutions: MESRI

- **Director or RI representative in France:** Guy Perrin, Karine Perraut
- **Construction:** 1962
- **Operation:** 1965
- **Stakeholders in France:** CNRS, CEA, ONERA, Observatoire de Paris, Observatoire de la Côte d'Azur
- **Contact in France:** guy.perrin@recherche.gouv.fr, karine.perraut@cnrs.fr
- **Website:** www.eso.org/public/france

International dimension

ESFRI landmark: ESO/ELT

Director: Xavier Barcons

- **Member countries:** AT, BE, CH, CZ, DE, DK, ES, FI, FR, IE, IT, NL, PL, PT, SE, UK
- **Partner countries:** AU, CL
- **Website:** www.eso.org/public/france



ESO/ALMA

Atacama Large Millimeter/Submillimeter Array

The main objectives of ALMA are the study of the molecular gas and dust in the universe.

The main scientific topics are the formation and the evolution of galaxies, from the distant high-spectral-shift universe to the local universe, the physics and chemistry of the interstellar medium and the formation of stars and planetary systems, the study of comets and planetary atmospheres, as well as the small bodies of the solar system.

ALMA is a radio Interferometer comprising 66 antennas (50 antennas of 12 m in diameter for interferometry, 4 antennas of 12 m for full power observations, and a compact network of 12 antennas of 7 m in diameter). The largest available baseline is 14 km, allowing a resolution of 0.007 arc seconds at the highest frequency observed.



© ALMA (ESO/NAOJ/NRAO), A. Marinkovic/X-Cam

Observation time is awarded on open calls for tender to the international community. A single telescope time allocation committee evaluates proposals on their scientific merit; observation time is then allocated in such a way that each partner receives a proportional return on its investment, with Chile receiving 10%.

Relations with economic actors and/or socio-economic impact

ALMA's equipment are mainly built by industry: antennas (Thales), power supplies (Engie), computers (ST-microelectronics) and signal processing. The instrumentation is designed and manufactured in research laboratories, as well as the software. Strong activity, particularly in Chile, for the dissemination of scientific and technical knowledge and training, but also through ESO in Europe.

Open science and data

- The source codes produced by the infrastructure are open on a software forge <https://bitbucket.sco.alma.cl/projects/ASW>
- Annual data production: 500 TB
- Infrastructure with a FAIR data policy in application

Category: IO

Type of infrastructure: single site

Infrastructure location in France: Paris

French supporting institutions: MESRI

- **Director or RI representative in France:** Guy Perrin
- **Construction:** 2003
- **Operation:** 2013
- **Contact in France:** guy.perrin@recherche.gouv.fr
- **Website:** www.eso.org/public/france/about-eso

International dimension

Director: Sean Dougherty

- **Partner countries:** AT, BE, CH, CA, CL, CZ, DE, DK, ES, FI, FR, IE, IT, JP, KR, NL, PL, PT, SE, TW, UK, US
- **Website:** www.almaobservatory.org/en/home

SKAO

SKA Observatory

The SKA project will be one of the largest physics machines built on Earth. The instruments for this radio astronomy observatory were designed between 2012 and 2020 by the SKA Organisation, a company with members from 14 countries (including CNRS) and collaborations with institutes in more than 20 countries.

Today, an intergovernmental organisation based in the UK, the SKA Observatory (SKAO), is managing the construction and will soon manage the operation of the telescopes and the infrastructure needed to provide astrophysicists with the scientific data to be analysed. French President Emmanuel Macron made the announcement of France's membership of the SKA Observatory during his state visit to South Africa in May 2021. In early 2022, the ratification process for French membership is underway.

Construction of SKAO began on July 1st 2021. The result will be an observatory operating two



© SKA Observatory

interferometers consisting of large antenna networks (over 131 000 log-periodic antennas in Australia, SKA-LOW, and just under 200 parabolic antennas of about 15 m diameter in South Africa, SKA-MID), capable of capturing the global electromagnetic radiation emitted by celestial objects between 50 MHz and 15.4 GHz. Over the next few decades, this observatory will make major discoveries in astronomy and fundamental physics.

Relations with economic actors and/or socio-economic impact

Through the work of the SKA-France structure, led by the CNRS and which has seen the direct collaboration of the academic and industrial worlds since 2016, the main French contributions to the construction of SKAO are around major social issues (computing and energy fields). In particular, France is piloting the design and supply of the two SKAO high-performance energy sub-exascale data centres.

Open science and data

- All the publications from projects using the infrastructure are open access
- Annual data production: 700 PB
- The validated and described data are published on a data repository <https://astronomers.skatelescope.org/the-ska-regional-centres>

Category: IO

Type of infrastructure: distributed

Infrastructure location in France: Paris

French supporting institutions: MESRI

- **Director or RI representative in France:** Pascale Delbourgo, Chiara Ferrari, Michel Pérault
- **Construction:** 2016
- **Operation:**
- **Stakeholders in France:** CNRS, CEA, Inria, Observatoire de la Côte d'Azur, Observatoire de Paris, Université de Bordeaux, Université d'Orléans
- **Contact in France:** pascale.delbourgo@recherche.gouv.fr, chiara.ferrari@oca.eu, michel.perault@cnrs-dir.fr
- **Website:** <https://ska-france.oca.eu/fr>

International dimension

ESFRI landmark

Director: Philip Diamond

- **Partner countries:** AU, CA, CH, CN, DE, ES, FR, IN, IT, JP, KR, NL, PT, SE, UK, ZA
- **Website:** <https://france.skatelescope.org>

CFHT

Canada-France-Hawaii Telescope

The CFHT is located at one of the best sites in the northern hemisphere, which allows for observations of high image quality. All fields of astronomy, including planetology and cosmology, are covered. The infrastructure consists of a 3.6 m telescope and a suite of associated high-performance instruments: MEGACAM (wide-field imaging in the visible range), WIRCAM (imaging in the infrared range), ESPaDOnS (spectropolarimeter for the study of the magnetic life of stars), Sitelle (Fourier transform spectrometer in the visible range) and SPIRou (ultra stable infrared spectropolarimeter). The observing time is allocated on the basis of calls for proposals that are evaluated and ranked by a scientific committee. A very large fraction of the observing time (60%) is devoted to "large programmes", with stable instrument configurations, service mode observations and real-time estimation of the signal-to-noise ratio in order to optimise exposure times.



© Jean-Charles Cullandre (CEA-Saclay)

A large part of the telescope time is currently devoted to two major programmes: 1/ the mapping of a large part of the northern sky with the MEGACAM camera to study galaxies and to provide an essential complement to the observations of the Euclid space mission to study dark energy; 2/ the study of exoplanets around low-mass stars, based on infrared spectropolarimetric observations with SPIRou.

Relations with economic actors and/or socio-economic impact

Innovative state-of-the-art instrumentation is necessary and often requires upstream R&D studies. Examples include the Hawaii 4RG detectors for the SPIRou instrument or the large gratings for the echelle spectrographs ESPaDOnS and SPIRou.

Open science and data

- Some of the publications from projects using the infrastructure are open access
- Annual data production: 20 TB
- Infrastructure with a FAIR data policy in application
- The validated and described data are published on a data repository

Category: RI*

Type of infrastructure: single site

Infrastructure location in France: Paris

Other sites in France:

French supporting institutions: CNRS

• **Director or RI representative in France:** Martin Giard

• **Construction:** 1974

• **Operation:** 1977

• **Contact in France:** Martin.Giard@cnrs-dir.fr

• **Website:** www.cfht.hawaii.edu/fr

International dimension

Director: Jean-Gabriel Cuby

• **Partner countries:** CA, FR, US

• **Website:** www.cfht.hawaii.edu/fr

CTA

Cherenkov Telescope Array

CTA is a network of ground-based optical telescopes, which will observe very high-energy gamma photons indirectly by detecting the faint flashes of Cherenkov light emitted by the particle showers created when a cosmic gamma photon interacts with the Earth's atmosphere. In its initial configuration, CTA will consist of more than 60 ground-based Cherenkov telescopes distributed in two networks, one in the southern hemisphere in Chile for observation of the Galactic centre and the other in the northern hemisphere in the Canary Islands. Three types of telescopes are planned: a core of a few large telescopes (~24 m in diameter) for the detection of low-energy showers, a network of intermediate-sized telescopes (~12 m) optimising sensitivities at energies at the TeV scale, and smaller telescopes (~4 m) for observations at higher energies. The distribution of telescope sizes and their number will differ between the northern and southern sites. CTA will improve the sensitivity



© Gabriel Pérez Díaz, IAC

of current observatories by almost an order of magnitude while providing better angular resolution and will extend the energy range, observing from 30 GeV to 300 TeV. CTA will thus enable the discovery of new sources of high-energy photon emission, a better understanding of the mechanisms of their acceleration, the study of gamma-ray bursts, and the detection of possible dark matter signals.

Relations with economic actors and/or socio-economic impact

The construction of CTA has created opportunities for technology transfer to French companies. Numerous partnerships have been formed in the fields of optics, electronics, and mechanics to equip the NectarCAM cameras or to build the small, medium, and large telescopes. These include partnerships for the production of mirrors and the manufacture of telescope arches.

Open science and data

- Some of the publications from projects using the infrastructure are open access
- Annual data production: 2 PB
- The validated and described data are published on a data repository

Category: RI*

Type of infrastructure: distributed

Infrastructure location in France: Paris

French supporting institutions: CEA, CNRS

- **Director or RI representative in France:** Danielle Gallo, Martin Giard, Vincent Poireau
- **Construction:** 2016
- **Operation:** 2023
- **Stakeholders in France:** Aix-Marseille Université, École polytechnique, Observatoire de Paris, Sorbonne Université, Université de Bordeaux, Université Grenoble-Alpes, Université de Montpellier, Université de Paris, Université Paris-Saclay, Université Savoie Mont-Blanc, Université de Toulouse III - Paul Sabatier
- **Contact in France:** danielle.gallo@cea.fr, martin.giard@cnrs.fr, vincent.poireau@cnrs.fr
- **Website:** www.facebook.com/CTA.France

International dimension

ESFRI landmark

Director: Federico Ferrini

- **Partner countries:** AT, AU, CH, CZ, DE, ES, FR, IT, JP, SI, UK
- **Intergovernmental partner organization:** ESO
- **Website:** www.cta-observatory.org

IRAM

Institute for Millimeter Radio Astronomy

IRAM, based in Grenoble, is one of the world leaders in the field of millimeter radio astronomy. It is a Franco-German-Spanish institute in charge of two astronomical observatories: the 30 m antenna at Pico Veleta (Spain) and the NOEMA interferometer with twelve 15 m antennas, located on the Bure plateau (Hautes-Alpes). These instruments are used by the scientific community of the partner countries. The millimeter spectral range allows the observation of the emission of cold matter, molecular gas and dust, which are fundamental elements for the formation of stars and galaxies. IRAM has instruments among the best in the world in their fields, offering unique possibilities in terms of receiver performance, spectroscopic capabilities, field of view extents, or capacity to conduct large multi-year programmes. IRAM actively participates in the worldwide network of EHT observatories whose data are combined



to provide very high-resolution images (image of the M87 black hole). IRAM has also a recognised expertise in the development of technologies and instrumentation in the Terahertz domain and has contributed to the development of several other observatories (e.g. ALMA in the Southern Hemisphere).

Relations with economic actors and/or socio-economic impact

A very large part of IRAM's investment budget is invested in industrial contracts, e.g. for the realisation of the six new 15 m antennas of the NOEMA project over the last few years. These are high-tech developments, often requiring specific R&D efforts.

Open science and data

- Annual data production: 30 TB
- Infrastructure with a FAIR data policy in application

Category: RI*

Type of infrastructure: distributed

Infrastructure location in France: Saint-Martin-d'Hères

Other sites in France: Dévoluy

French supporting institutions: CNRS

- **Director or RI representative in France:** Karl Schuster
- **Construction:** 1979
- **Operation:** 1985
- **Stakeholders in France:** Max-Planck Gesellschaft, MPG, Instituto Geográfico Nacional, IGN
- **Contact in France:** schuster@iram.fr
- **Website:** www.iram-institute.org

International dimension

Director: Karl Schuster

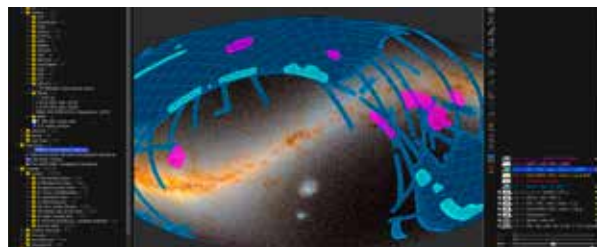
- **Partner countries:** DE, ES, FR
- **Website:** www.iram-institute.org

CDS

Strasbourg Astronomical Data Centre

The mission of the CDS is to collect, standardize and distribute astronomical information for the benefit of the entire international community. The objective is to facilitate the work of astronomers by gathering information, with links to observatory archives, academic journals and other databases, particularly ADS and NED. The CDS is a major player in the development of open science in astronomy, including the development of the astronomical Virtual Observatory (VO), which aims to provide transparent and FAIR access to the full range of online astronomical resources.

The CDS develops services widely used by the community: SIMBAD, the reference database for the identification and bibliography of objects outside the solar system; VizieR, the reference database for large sky surveys, catalogues and tables published in academic journals, and increasingly



for other types of data “attached to publications”; the Aladin interactive sky atlas, a portal that provides access to the CDS reference image collection and to images available in the archives of ground and space-based observatories. The CDS also provides a cross-identification service for very large catalogues. In 2021, the CDS services managed more than 1 500 000 requests per day.

Relations with economic actors and/or socio-economic impact

Long-term contracts to support the open access to the services, including the interested socio-economic partners. Contract with the Astronomy & Astrophysics journal for the publication of data associated with articles. An internship programme for universities and engineering school (12 per year); work at CDS is an excellent preparation for employment for computer science students. CDS services are used by planetariums.

Open science and data

- The source codes produced by the infrastructure are open on a software forge: <https://github.com/cds-astro>
- Annual data production: 150 TB
- Infrastructure with a FAIR data policy in application
- The validated and described data are published on a data repository

Category: RI

Type of infrastructure: single site

Infrastructure location in France: Strasbourg

French supporting institutions: CNRS, Université de Strasbourg

• **Director or RI representative in France:** Mark Allen

• **Construction:** 1972

• **Operation:** 1972

• **Contact in France:** mark.allen@astro.unistra.fr

• **Website:** <http://cdsweb.u-strasbg.fr/index-fr.gml>

International dimension

IVOA/Euro-VO International Virtual Observatory of Astronomy

- **Partner countries:** AR, AM, AU, BR, CA, CL, CN, DE, FR, HU, IN, IT, JP, NL, RU, ZA, ES, UA, UK, USA
- **Intergovernmental partner organization:** ESA
- **Website:** <http://ivoa.net>



HESS

High Energy Stereoscopic System

HESS is an array of atmospheric Cherenkov imaging telescopes located on the Khomas Highlands, near the Gamsberg in Namibia. It is designed to study cosmic gamma rays between a few tens of giga-electronvolts and a hundred tera-electronvolts. The network is composed of 4 telescopes of 12 m in diameter (corresponding to the first phase of the project) and of a 5th telescope of 28 m in diameter since September 2012, allowing to double the sensitivity of the array and to decrease the energy threshold (down to 50 GeV or even 20 GeV).



© Mathieu de Naurois

The two main features of the installation are the simultaneous observation of particle cascades caused by gamma rays entering the Earth's atmosphere, from different angles, and the combination of several telescopes into one larger system to increase the effective area of gamma-ray detection and improve their characterisation. Thanks to the high sensitivity thus achieved (a few thousandths of the flux of the Crab

Nebula, the reference source), HESS makes it possible to study high-energy cosmic phenomena with remarkable precision: cosmic rays, interstellar medium and scattering, compact objects, gamma bursts, jet physics, cosmology, dark matter, etc.

HESS could remain operational until the CTA Southern Hemisphere site has taken over. An extension of operations until September 2024 has been agreed.

Relations with economic actors and/or socio-economic impact

The construction involved numerous companies specialising in civil engineering, mechanics (metallic structures), microelectronics (ASICS), automatism and photon detection.

Open science and data

- All the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure are open on a software forge <https://github.com/gammapy/gammapy>
- Annual data production: 1 Po
- The validated and described data are published on a data repository www.mpi-hd.mpg.de/hfm/HESS/pages/dl3-dr1

Category: RI

Type of infrastructure: single site

Infrastructure location in France: Paris

French supporting institutions: CEA, CNRS

Director or RI representative in France:

• Mathieu de Naurois

• **Construction:** 2002

• **Operation:** 2003

• **Stakeholders in France:** Aix-Marseille Université, École polytechnique, Observatoire de Paris, Sorbonne Université, Université de Bordeaux, Université de Montpellier, Université de Paris, Université Paris-Saclay, Université Savoie Mont-Blanc

• **Contact in France:** denauroi@in2p3.fr

• **Website:** www.mpi-hd.mpg.de/hfm/HESS/HESS.shtml

International dimension

Director: Stefan Wagner, porte-parole de la collaboration

- **Partner countries:** AM, AT, AU, DE, FR, IE, JP, NA, NL, PL, SE, UK, ZA
- **Website:** www.mpi-hd.mpg.de/hfm/HESS

Instrum-ESO

Instrumentation for ESO's large telescopes

The mission of the infrastructure is to coordinate and accompany the realisation of the instruments that will be placed at the focus of the different ESO telescopes; nowadays the 4 telescopes of 8 metres of the Very Large Telescope (VLT), including its interferometric mode of operation (VLTI), the specialised telescope for large surveys VISTA, and, in the future, the Extremely Large Telescope (ELT) of 39 metres. This action aims in particular to support the completion of the current developments of the VLT (MOONS) and VLTI (MATISSE), the continuation of the VLT and VLTI developments (instruments of the VLT-2030 plan: GRAVITY+, BlueMuse and SPHERE Upgrade), the participation in the VISTA instrumentation (4MOST) and the developments of the ELT instrumentation (HARMONI, MICADO, MAORY, METIS, MOSAIC and HIRES), including the preparatory R&D for the future instruments. These instruments,



© ESO

identified as priorities by the French astrophysics community in particular during the CNRS/INSU foresight exercises, operate in the visible and infrared. They cover all fields of astrophysics: planetary science, extrasolar planets, stellar physics, galactic physics, extragalactic physics, cosmology, etc. They are prepared in international consortia.

Relations with economic actors and/or socio-economic impact

The RI has 45 non-academic partners, including, since 2006, 3 with astronomers as founders. In particular, high-tech developments, opto-mechanics, detectors, lasers, complex instrumentation are the subject of collaborations between laboratories and industry.

Open science and data

- Some of the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure are open on a software forge: <http://gitlab.lam.fr/efisoft>
- Infrastructure with a FAIR data policy in application

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Paris

Other sites in France: Marseille, Meudon, Nice, Saclay, Saint-Genis-Laval, Saint-Martin-d'Hères, Toulouse

French supporting institutions: CNRS

Director or RI representative in France: Martin Giard

Construction: 2005

Operation: 2005

Stakeholders in France: Aix-Marseille université, CEA, ENS de Lyon, Institut d'Optique Graduate School, Observatoire de la côte d'azur, Observatoire de Paris, ONERA, Sorbonne Université, Université Claude Bernard - Lyon 1, Université de la Côte d'Azur, Université de Grenoble Alpes, Université de Paris, Université Paris-Saclay, Université de Toulouse III - Paul Sabatier, Université de Franche-Comté

Contact in France: Martin.Giard@cnrs-dir.fr

Website: www.eso.org/public/france

LOFAR/NenuFAR

International LOFAR (Low Frequency Array) Telescope – NenuFAR

LOFAR, the first large “digital” radio telescope, extends radio observations to the lowest frequencies (10 to 240 MHz) and highest angular resolution accessible from the ground. Its main objectives are cosmology, galaxy clusters, cosmic magnetic fields, cosmic radiation, the Sun, the planets, and the variable universe (pulsars, black holes and high-energy sources, planets and exoplanets). It consists of 52 stations (38 in the Netherlands, 14 in Germany, France, Ireland, Latvia, Poland, Great Britain, and Sweden). Each station consists of 96 low-frequency antennas and 96 high-frequency antenna tiles, connected at high speed (3 Gb/s) to the central correlator. NenuFAR, based in Nançay, consists of 96 mini-networks (MRs) of 19 antennas each, specifically optimised for the entire 10-80 MHz band. In addition, there are six remote MRs for imaging. It can simultaneously be connected to LOFAR as a replacement for the French low-frequency antennas, acting as a



© Laurent Denis/Station de Radioastronomie de Nançay

superstation for LOFAR, greatly increasing its sensitivity and other characteristics. By splitting the signal from the antennas before entering the processing chains, NenuFAR will operate independently and simultaneously as an autonomous instrument with specific scientific programming. LOFAR will be upgraded to LOFAR 2.0 in 2023.

Relations with economic actors and/or socio-economic impact

LOFAR was built abroad; its installation in Nançay relied on French companies. The realisation of NenuFAR called upon subcontractors in France, for the construction and for the installation: calculator with the development of a high-performance computing card, coaxial links, electronic systems of analogical phasing of the telescope and other subcontracting for fibre optics, electronic racks, etc.

Open science and data

- Infrastructure with open science policy
- All the publications from projects using the infrastructure are open access
- Infrastructure with a FAIR data policy in application

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Station de Radioastronomie de Nançay, Cher

French supporting institutions: CNRS, Observatoire de Paris, Université d’Orléans

Director or RI representative in France: Philippe Zarka

Construction: 2011

Operation: 2011

Contact in France: philippe.zarka@obspm.fr

Website: www.obs-nancay.fr/lofar

International dimension

ILT

Director: Rene Vermeulen

- **Partner countries:** DE, FR, IE, LV, NL, PL, SE, UK
- **Website:** www.lofar.org

PARADISE

Platform for Applied Research and Development Activities in Ground and Space-based Instrumentation

PARADISE (Platforms for Applied Research and Development Activities in Ground and Space-based Instrumentation) is a research infrastructure that aims to federate at the national level the main existing integration and test facilities for instrumentation in the sciences of the universe in order to offer all the actors in the field a complete range of expertise, services and the means to carry them out:

- Integration hall and clean rooms;
- Environment simulators;
- Optical, mechanical, thermal and electronic test facilities...

PARADISE responds to a need linked to the increasing complexity of instruments in general, their integration and testing in particular, and of the consortia that carry them out, requiring strong national coordination of project set-up. PARADISE also aims:

- To share expertise on a national scale in order to improve quality;



© Image composites par M. Ollivier à partir de plusieurs images prises sur les sites internet des plateformes

- To consolidate the link between laboratories and instruments to optimise involvement in instrumental projects within international consortia;
- To coordinate the development, operation and maintenance of test facilities on a national scale in order to ensure their long-term operation and the associated expertise;
- To promote integration between the academic and industrial worlds.

The RI relies on the facilities of six existing sites in Paris-Saclay, Meudon, Marseille and Toulouse.

Relations with economic actors and/or socio-economic impact

PARADISE enables industrialists, via its facilities and personnel on its six sites, to carry out integration and testing of instruments or instrumental sub-systems for space or other extreme environments. Integrated in its ecosystem, each site has its own economic model, based on the principle of services or more direct partnership with industry.

Open science and data

- Annual data production: 1 TB
- The validated and described data are published on a data repository

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Gif-sur-Yvette, Guyancourt, Marseille 13^e, Meudon, Orsay, Toulouse

French supporting institutions: CNRS

• **Director or RI representative in France:** Marc Ollivier

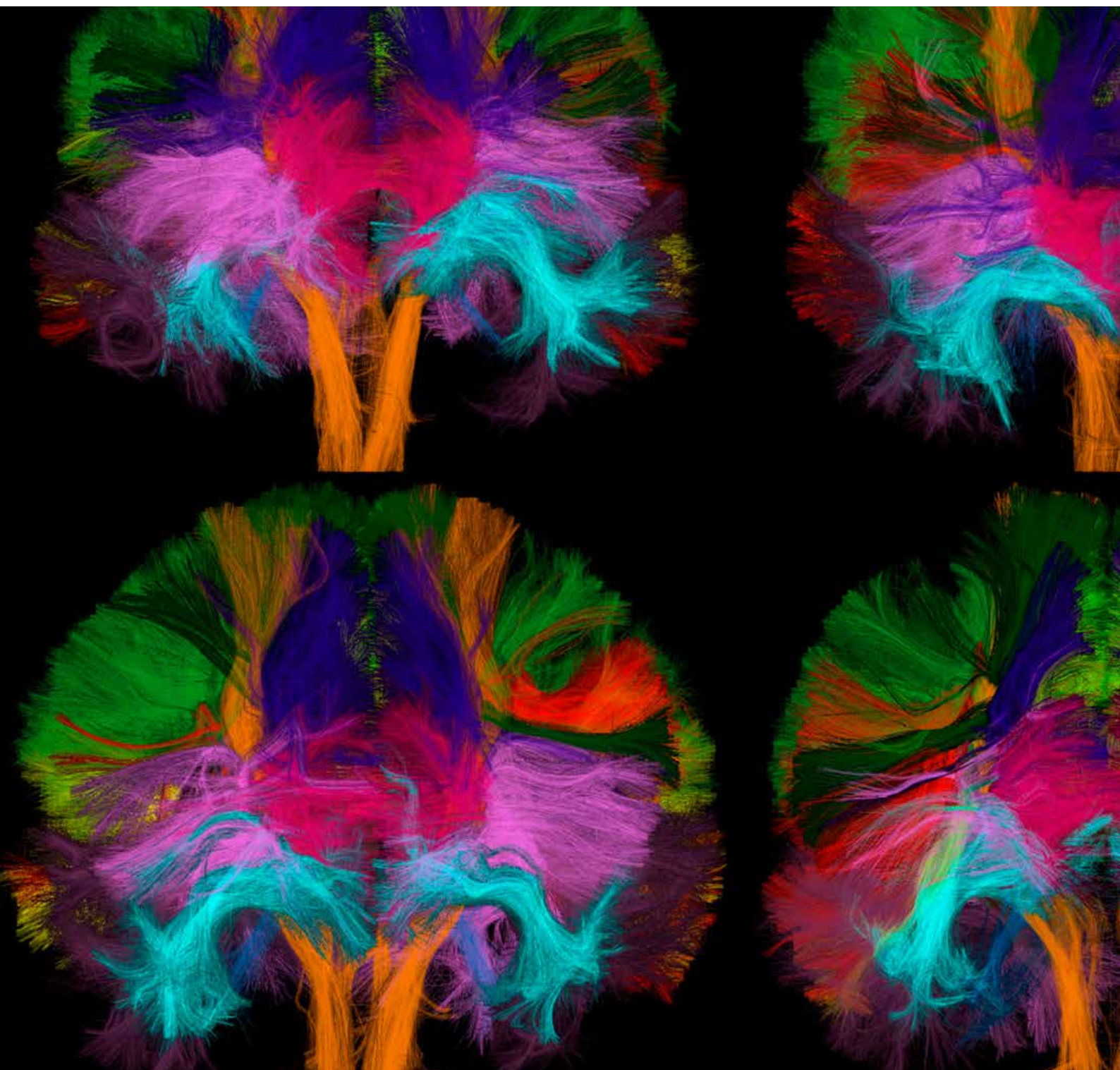
• **Construction:** 2019

• **Operation:** 2019

• **Stakeholders in France:** Aix-Marseille Université, CEA, CNES, Observatoire de Paris, Université de Paris, Université Paris-Saclay, Université de Versailles Saint-Quentin-en-Yvelines, Sorbonne Université, Université Toulouse III - Paul Sabatier

• **Contact in France:** marc.ollivier@universite-paris-saclay.fr

• **Website:** www.gis-paradise.fr



2.

Biology
and **health**



Biology and health

Research in “Biology and Health” has benefited in recent decades, and increasingly rapidly, from the massive arrival of new technologies allowing the exploration of living organisms. These have led to a change of scale in the approaches used and have made it possible to address scientific questions through a set of efficient complementary approaches (multimodality). Research infrastructures, often built around these new technologies, have enabled scientific communities to access larger equipment and devices that are often of high technology and require real scientific and technical expertise, provided as close as possible to the users by exceptionally competent and dedicated staff and often associated research teams.

MAJOR SCIENTIFIC QUESTIONS AND SOCIETAL CHALLENGES THAT REQUIRE THE USE OF RESEARCH INFRASTRUCTURES

The infrastructures proposed for inclusion in the roadmap (Figure 1) fall into two main categories: those based on generic and technological approaches (“generic and technological” RIs) and those whose activities are more in line with societal themes or specific fields of application (Object RIs).

This typology is also found at European level.

Some major scientific and societal issues have been identified and the infrastructures that are or could be mobilised to address them have been compiled. Some elements of the European strategies and missions and of the acceleration strategies currently being developed at the national level have been included without aiming at exhaustiveness. The correspondences between the infrastructures that are candidates for inclusion in the roadmap and these scientific and/or societal items are listed as precisely as possible in the data charts 1 and 2.

It must be noted that in practice the typology of “generic and technological” vs. “object”

RIs is not really discriminating and that all infrastructures fall into both categories simultaneously. Moreover, the density of the correspondences illustrates the capacity of infrastructures to address these two aspects in a complementary manner and, in particular, to contribute to meeting societal challenges. It also undoubtedly imposes the need to improve their visibility and ensure their outreach.

Two aspects are critical to address societal issues as well as major scientific questions: exploiting the complementarity between infrastructures and promoting their agility (i.e. their capacity to adapt). Two examples illustrate the dimension of complementarity:

- Several infrastructures cover the production of large-scale data (omics) on living systems (structural biology data, proteomics, sequencing, metabolomics, imaging, etc.) and only their integration can allow for a fine and complete multi-scale and multimodal analysis of living systems. Bioinformatics plays an important role in this integration of data and in their curation. The most spectacular results are achieved by crossing techniques and their mutual



Figure 1: Infrastructures proposed for inclusion in the 2021 roadmap. The infrastructures are classified into four sets that represent a continuum from the structure of the molecule to the individual and to human populations, and the correspondences with the infrastructures listed on the ESFR (European Strategy Forum on Research Infrastructures) roadmap are indicated outside the circle. Infrastructures that were candidates for inclusion in the national or ESFR 2021 roadmaps have a light background. The five national infrastructures, E-BRAINS, and EIRENE were selected through the process. The stars indicate the ESFRs in the Health and Food domain of which the French infrastructure is only partially the national node (Instruct ERIC) or of which France is not a member (Openscreen).

contributions. The necessary link between “omics” type platforms, imaging and bioinformatics has been clearly reinforced, as shown by several recently funded Equipex+ projects. These themes represent an important part of the development of digital biology. A considerable effort is being made to build similar approaches in the field of health data with their specificities (sensitive data, context of anonymisation and collection of informed consent) and opens the way to more precise and personalised medicine. The exploitation of the complementarity of the two approaches, biological and medical, is also progressively taking place;

- The sharing of experience between the **P4 Jean Mérieux laboratory** (a high-security laboratory dedicated to the study of highly pathogenic agents)

and **Emerg’In** (an infrastructure for the study of infectious processes in domestic animals and wildlife) on infectious diseases and pathophysiology, as well as the coordination between these two RIs at the national and European levels, help to ensure that France has a leading position in the field of emerging infectious diseases, which is particularly strategic and sensitive in terms of public and veterinary health.

At the European level, this complementarity between infrastructures can also be illustrated by the rapid development of an alliance (Alliance of Medical Research Infrastructures (AMRI)) between the three ERICs involved in medical research: **EATRIS** (translational medicine), **BBMRI** (biobanks) and **ECRIN** (clinical research). By joining forces, the three pan-European RIs aim to facilitate users’ access to their services and support



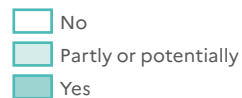
INFRASTRUCTURES ON THE 2018 ROADMAP	SCIENTIFIC ISSUES								
	Single cell	Bio-production and cell factory. Metabolic pathways	Information processing in biology. Cognition	AI	Populations, social complexity	Integration of scale from the infinitely small to a higher level	Resources and integrity	Very fine and very large scale phenotyping	Intrinsic variability in complex systems, limit of measurement
Functional exploration									
ChemBioFrance									
FBI									
FLI									
France Génomique									
FRISBI									
MetaboHub									
NEUROSPIN									
PROFI									
Model organisms and resources									
Celphedia									
EMBRC France									
Emphasis France									
IBISBA France									
Ingestem									
From pre-clinical to clinical									
ECELL France									
F-CRIN									
P4 Jean Mérieux Laboratory									
Emerg'in									
IDMIT									
NEURATRIS									
Bioinformatics, cohorts, databases									
CONSTANCES									
IFB									
CAD									
Potential new infrastructures									
CALIS									
EBRAINS-FR									
France Cohortes									
FR Exposome									
LiPh@SAS									

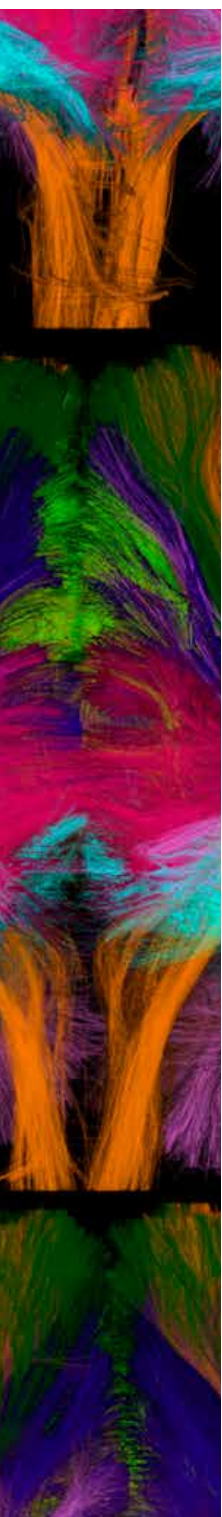
Data chart 1 Links between infrastructures and some major scientific issues. The green and light green backgrounds correspond to strong and medium links respectively.

- No
- Partly or potentially
- Yes

INFRASTRUCTURES ON THE 2018 ROADMAP	SOCIETAL ISSUES								
	Impact on the bioeconomy	Interactions with industry	Health and quality of life, nutrition	Degenerative diseases	Cancer	Chemical exposome and toxicology	Emerging and re-emerging infectious diseases, antibiotics	Global health	Digital health
Functional exploration									
ChemBioFrance									
FBI									
FLI									
France Génomique									
FRISBI									
MetaboHub									
NEUROSPIN									
PROFI									
Model organisms and resources									
Celphedia									
EMBRC France									
Emphasis France									
IBISBA France									
Ingestem									
From pre-clinical to clinical									
ECELL France									
F-CRIN									
Laboratoire P4 Jean Mérieux									
Emerg'in									
IDMIT									
NEURATRIS									
Bioinformatics, cohorts, databases									
CONSTANCES									
IFB									
CAD									
Potential new infrastructures									
CALIS									
EBRAINS-FR									
France Cohortes									
FR Exposome									
LiPh@SAS									

Data chart 2 Links between infrastructures and some major societal issues. The green and light green backgrounds correspond to strong and medium links respectively.





the development of common tools, services and approaches. Such a reflection would undoubtedly be useful at national level.

A single example, the recent Covid 19 epidemic, may suffice to illustrate the necessary agility of Biology and Health RIs. In response to this challenge, the vast majority of RIs in the roadmap, and particularly in Biology and Health, have mobilised, either directly or through their participation in ESFRIs, and have adapted their offer to the new constraints (remote work, adapted user training), prioritised access to teams involved in research on this new pathology, and made resources available to support teams in methodological or thematic reorientation (increased use of bioinformatics). More generally, however, RIs in the Biology and Health domain must respond to the twofold change in scale brought about by the development of the equipments and of the digital technologies: on the one hand, access to very high definition that opens up prospects in structural biology at the limits of measurement and the intrinsic variability of measurement, and on the other hand, access to massive data of various kinds that make it possible to approach the complexity of populations.

One of the strong points of the “Biology and Health” infrastructures is their openness to both the academic scientific communities and the private sector. Some of these RIs are dedicated to translational research in biotechnology or bio-manufacturing, which makes it possible to deal with projects at high Technology Readiness Level (TRL). These interactions and access to the technological developments carried out in the national infrastructures in Biology and Health are essential to guarantee the international competitiveness of our industries in Health, Food, Environment and many other sectors.

Life sciences research infrastructures were first included in the roadmap of national infrastructures in the field of Biology and Health in 2008. However, most of the infrastructures really took off within the framework of the “investment for the future” programme (PIA) and its “Health – Biotechnologies” action following two calls for tenders opened in 2010 and 2011. These calls have enabled France to equip itself with 4 pre-industrial demonstrators and 23 national large-scale and highly competitive infrastructures (INBS) and to finance them potentially until 2020.

Following a mid-term evaluation, 18 of these infrastructures as well as three new infrastructures (**IBISBA France, ChemBioFrance and Neurospin**) and one project (**CAD**) formed the core of the 2018 roadmap in the Biology and Health domain.

The support provided to the INBSs after the mid-term evaluation has had an extremely positive effect on most of the infrastructures, in terms of visibility, structuring and user satisfaction.

An explicit reference to the European positioning and the ESFRI (European Strategy Forum on Research Infrastructures) roadmap was included in the calls for projects and it is very satisfying to see that the national infrastructures represent very active nodes of the ESFRIs and that they are increasingly benefiting from this European articulation (Figure 1).

POSITIONING OF EACH INFRASTRUCTURE IN THE LANDSCAPE

The “Biology and Health” infrastructures presented are numerous and their overall size is very significant,

both in terms of mobilisation of resources and number of users¹.

To simplify the reading of the landscape, RIs have been categorised according to an organisation in four clusters, which represent a continuum from structures of molecules to the individual, and to human populations²:

- **Analytical and functional exploration RIs**, which include technologies for studying the different scales of life (intra-cellular components, cells and tissues, organs, individuals, etc.);
- **RIs of model organisms, resources** that provide a set of biological resources necessary for the study of life and for bio-production;
- **Pre-clinical and clinical RIs**, which aim to transfer strategies developed in basic research to care;
- **RIs dealing mainly with data and associated processes: bioinformatics, cohorts support and cohorts, e-infrastructures.**

Analytical and functional exploration infrastructures

One of the ultimate goals of biology is to study the different levels of organisation of living organisms, from the molecule to the individual or even the population, in order to understand the mechanisms governing its functioning and dynamics. This research requires the integration of a range of approaches and spatio-temporal scales supported by functional exploration infrastructures. These infrastructures develop multi-modal services and innovations, based on approaches that are at increasing resolution in space and time, at ever higher throughputs and for increasingly varied types of biological samples, which is

made possible by advances in technologies, particularly in digital technologies. These approaches are accompanied by services for data processing and data understanding as well as processes for making data FAIR, allowing the integration of scales for the understanding of living phenomena. The integration of data from various experimental and observational sources (structural and functional) is indeed a major challenge for studying multiscale phenomena in biology. These infrastructures are therefore largely dependent on the development of bioinformatics, as well as efficient data archiving, processing and calculation services.

Structural and imaging approaches are developed in **FRISBI** for integrative structural biology, **FBI** for cellular imaging, **NeuroSpin** (developing an 11.7T MRI for humans, the only one of its kind in the world, for the purpose of understanding the brain) and **FLI** for in vivo imaging.

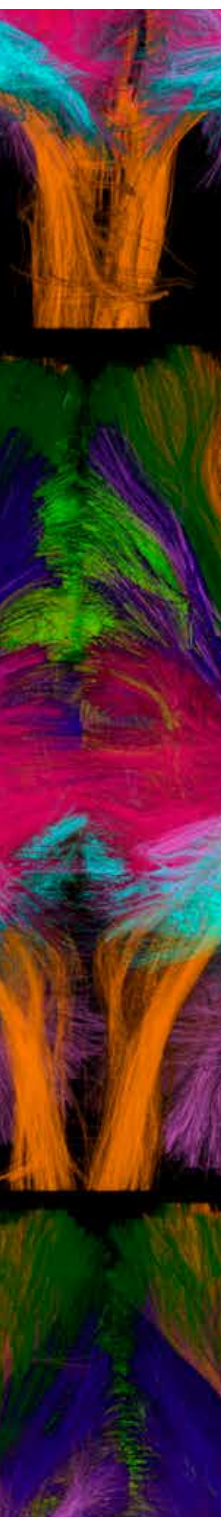
The “omics” approaches are supported by dedicated infrastructures: **France Génomique** for genomics, **PROFI** for proteomics and **MétaboHUB** for metabolomics and fluxomics.

Beyond their technological excellence, one of their shared objectives is to contribute to the integration of their data. One of the major current challenges is to establish relationships between imaging data, multi-omics and phenotypic descriptions, and the structural and morphological parameters of systems in a normal or pathological context. All these approaches contribute to making the search for bioactive molecules more efficient.

This is the objective of the **ChemBioFrance** infrastructure, which is developing high-throughput screening, chemo-informatics and synthetic biochemistry approaches.

¹ Around 1500 ETPs are directly involved in these RIs and the final evaluation of the INBSs identified the need to recruit around 150 ETPs to ensure the sustainability of the INBSs, of which almost 100 have been pledged by the agencies. More than 20,000 national users were identified by the roadmap RIs in 2017.

² Population approaches to other taxa are best dealt with in the field of Earth System Science and Environment.



Finally, high-throughput monitoring using a range of analytical approaches for various human samples should enable the exposome to be characterised more finely.

Model organisms and resources infrastructures

Developments in modern biology make it necessary to have access to referenced and qualified biological resources in terms of sanitary conditions and genetics. Referencing and qualification are essential elements in contributing to an open science policy, particularly for access to these resources, transparency and the reproduction of results. They help to guarantee the integrity of the work. This approach requires in particular the development of technologies allowing deep and precise phenotyping and/or high throughput. The purpose of the resources and model organisms RIs is to propose these resources, to create them if necessary, in particular through genome editing technologies, and to ensure the reproduction and conservation of lines with a defined sanitary status.

Some RIs in this section are also dedicated to innovative experimentation on model organisms involving functional exploration or phenotyping technologies. High-throughput phenotyping of cultivated plants is developed by **Emphasis France** in the context of adaptation to global changes, while **Celphedia** ensures the creation, breeding and phenotyping of animal models.

These resources are also dedicated to bio-production, the technologies and processes of which are the responsibility of dedicated RIs ; for induced pluripotent stem cells and organoids (**Ingestem**), for marine organisms and blue biotechnologies (**EMBRC-France**), but also potentially for plant species (**Emphasis France**) and for white biotechnologies (**IBISBA-France**). In the context of these more process-oriented entities, the characterisation of resources is also a major challenge.

Finally, they include technological developments that make it possible to go beyond the “model” phase and go directly to the target species to be studied (**Emphasis France**).

Preclinical and clinical infrastructures

Research conducted for the health of populations, mainly in Europe, and for the benefit of patients, requires the development of multiple technologies and approaches at the interface between experimental approaches, molecular and cellular biology engineering, and understanding of the dynamics of the health of individuals and populations. Backed by technologies and resources offered by functional exploration RIs and bio-resources, these RIs in preclinical and clinical research offer services, expertise and know-how in drug development, whether molecular, cellular or genetic, as well as the medical expertise associated with the mastery of regulatory aspects and the required quality controls. They thus enable the confirmation of proof of concept in humans and the commitment to clinical investigation.

Specific expertise in the bio-production of “drug cells” is provided by the **ECCELLFrance** infrastructure for the production and preclinical and clinical qualification of mesenchymal stromal cells (MSCs), which are the basis for essential therapies in the treatment of major chronic diseases in public health, such as diabetes, autoimmune diseases and cardiovascular diseases.

NeurATRIS is exclusively dedicated to the four major neurodegenerative diseases and neurodevelopmental deficits. It offers services and research on a range of methodological developments including cellular, gene and drug therapies, and in vivo functional assessment.

The **IDMIT** infrastructure ensures the development of ad-hoc models of

human diseases, in particular on non-human primates, and the research of new therapeutic approaches in vaccinology and immunotherapies against various infectious diseases.

Research on emerging infectious diseases requires biosafety level 4 laboratory containment, both for resource conservation and experimental approaches, due to the dangerous nature of certain pathogens. The **P4 Jean Mérieux laboratory** is the infrastructure dedicated to the study of these highly pathogenic agents. The study of infectious processes in domestic animals and wildlife is provided by the **Emerg'In** infrastructure, which offers experimental and conservation services on pathogens and their vectors where appropriate. The **P4 Jean Mérieux Laboratory** and **Emerg'In** share their experience.

Finally, the **F-CRIN** infrastructure occupies a unique national positioning by ensuring the coordination of the actors of clinical research on one hand, and those of the medicine or care world and industry on the other.

Infrastructures dealing mainly with data and related processes: bioinformatics, cohort support and cohorts, e-data infrastructures

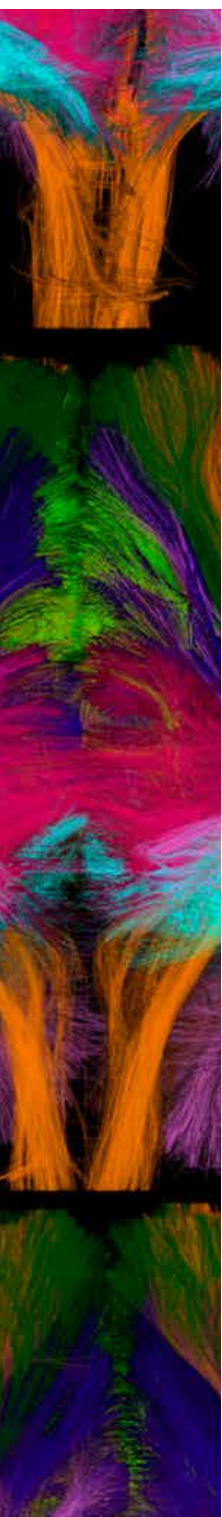
As indicated in the introduction, the integration of all types of data produced by increasingly efficient technologies is one of the major challenges for the life sciences and their applications in health, ecology, agronomy and bio-production. This challenge requires the recognition of dedicated e-infrastructures that can provide data and resource services, as well as innovations (new algorithmic approaches, digital twins, etc.) whose impact may extend beyond the fields concerned. This field is particularly concerned by the issues of open science and of making data FAIR, which make it possible to increase the use of data and improve

the reproducibility of results, thus amplifying the potential impact of research in response to economic and societal issues. Thus, in each of the RIs in the Biology and Health domain, we are witnessing the creation and development of upstream digital components (the data acquisition pipeline), processes for organising, characterising and accessing data (DMP) and downstream services for advanced data processing. Depending on the ethical and regulatory constraints (e.g. for health data), the access modalities are as open as possible, and as closed as necessary. Indeed, RIs dedicated to the collection, archiving and analysis of individual data and health states of individuals and human populations (**CAD**, cohorts, etc.) must both open up services to researchers and make their data accessible, but also maintain a level of protection that corresponds to citizens' expectations.

The provision of services and methodological developments for the analysis of "omics", imaging and structural data to a large user community is largely provided by the **IFB**. Thanks to the funding obtained for the MuDiS4LS-IFB project (within the framework of the ESR/Equipex+ call for projects), this RI will extend its service offer in terms of data (data management plan (DMP), warehouse portal, referencing, accessibility, etc.), thus structuring, along with the **Data Terra** RI, the landscape of essential national-scale e-infrastructures, whose mission is to consolidate France's position in a highly competitive European context (EOSC).

The **France Cohortes** project, whose objective is to be a national platform of services for cohorts, is also part of this transverse support strategy (collection, hosting, processing and provision of data, regulatory and administrative support, etc.).

The study of the relationships between data from various sources (health, behavioural, social and environmental factors, including working conditions, biological and genetic data, etc.) and different health conditions



is carried out by **CONSTANCES**, a very large epidemiological cohort in the general population (several hundred subjects overall). **CONSTANCES** contributes to the monitoring of the public health system in France and to the study of the distribution of the main health determinants in the general population. It supports health research and public health authorities.

Finally, at the heart of the France Genomic Medicine Plan, the **CAD** infrastructure acts as a national centre for hosting and analysing genomic data from the plan, and aims to improve knowledge of pathologies (rare diseases, cancer, etc.) and to develop innovative diagnostic or therapeutic approaches, first and foremost in genomic medicine (by making data, tools and algorithms available, which it can also help to develop).

Interfaces with other areas of the national roadmap

Most of the research questions in “Biology and Health” are inter- or transdisciplinary. Thus, several infrastructures are listed at the interface between two domains of the national roadmap. It should be noted that this trend towards inter-sectorial positioning is also evident at the European level: of the eight projects recently submitted to ESFRI in the Health and Food sector, six are under double evaluation – two in DIGIT (Data, Computing and Digital Research Infrastructures), one in ENV (Environment), two in PSE (Physical Sciences and Engineering) – and one is under triple evaluation – ENV (Environment) and SCI (Social and Cultural Innovation).

Infrastructures at the interface with the Earth System and Environment domain

For research at the interfaces between the physical and living environments, some infrastructures are shared with the Earth System and Environment domain.

- Dedicated to the phenotyping of plants and model species, the **Phenome-Emphasis-France** RI complements, for agronomists and ecologists, “omics” platforms such as the **MetaboHUB** RI and the **France Génomique** RI.
- Two other RIs are of great interest to the environmental sciences: **IBISBA France**, which is positioned between the environment/energy/biology-health fields. Its centre of gravity is synthetic biology and biotechnologies but with applications in different fields such as waste recovery (bio-control, waste treatment in the circular economy, biomass recovery) and **EMBRIC France** for marine biological resources.

Furthermore, it should be noted that **RARe**, which is dealing with canine and microbial genetic resources (consortia representing microbiomes), is of interest to the biomedical and health field.

Infrastructure at the interface with the Energy domain

IBISBA-France joins the concerns of the Energy domain for the bio-production of carbon energy and the use of biotechnologies in the circular carbon economy.

Interface with Chemistry and Physics

The development of new approaches, both technological and digital, in biology, has revolutionised approaches to living systems and has largely contributed to the development of new knowledge on how they function, from the atomic scale to the organism without discontinuity and in their native state. These approaches constitute real bridges between physicists, chemists, digital specialists and biologists to develop new concepts and in return allow the improvement of instrumentation. Thus, approaches as varied as massive data analysis, multi-scale modelling approaches, high-throughput screening and chemo-informatics have

become essential for modern biology. In this perspective, the relationships between infrastructures such as **FRISBI** and **FBI** with **SOLEIL** and **METSA**, to give just one example, must be strengthened in the years to come, to enable a community as broad as possible to address the fundamental questions posed by life sciences today.

Impact on education and training/ socio-economic benefits

All of these aspects were addressed in the recent evaluation of the RIs funded under the PIA (future investment programme). The training of users but also of engineers in the field (including, of course, those not directly involved in the RIs) contributes to a better use of existing equipment and ensures a scientific and technical watch for all. The analysis of the economic impact can be seen both in the desire to find and welcome new users from industry who can contribute to the financial equilibrium of the RIs and to establish partnerships for instrumental developments. The mobility of actors between RIs and private partners is an important element in the dissemination of technologies and expertise for mutual enrichment.

Impact on public policies

The current crisis linked to COVID 19 has naturally mobilised several of the infrastructures of the Biology and Health roadmap and their role and impact in the definition of public policies must be underlined. But beyond that, the impact of **CALIS** (health/food), of the **CAD** (genomic medicine), of the support of **France Cohorts** to the more specialised/thematic cohorts, of the **F-CRIN** network, without forgetting, of course, **CONSTANCES**, are central to the question of the impact on public policies. The involvement and interest of other ministries or agencies in given infrastructures or projects is also increasingly evident.

Open Science

The Open Science dimension of the infrastructures in the Biology and Health domain was analysed according to the five axes proposed by the transverse working group (Open Science Strategy, Data Governance Actors, Maturity of Data Practice, Open Code and Software Policy, Open Publication Policy). A very wide range of services is provided to users and the infrastructures very often benefit from the services of digital support infrastructures (**IFB**, more marginally **Data Terra**, etc.).

The open science approach is widely taken into account (with advanced practices on code, data and/or publications), but is still emerging and needs to be generalised. It is still too rarely part of a global strategy.

The proposal to systematically use an identifier for funding institutions and agencies (Funder registry) seems to be an interesting mean to explore in order to identify the role of infrastructures both in the dissemination of data and codes and publications.

Clusters of infrastructures in Biology and Health face common problems in setting up a solid Open Science policy: important regulatory component for infrastructures generating or exploiting sensitive data (health data, personal data...), qualification of samples (for biological resources infrastructures), problem of multiple scales of resolution and multi-modularity (omics). It would be appropriate to define practices/ standards of description common to infrastructure clusters. This effort must be part of a more global perspective and has often been initiated at the ESFRI level (Elixir, Alliance of Medical Research Infrastructures (AMRI), which includes **EATRIS**, **BBMRI** and **ECRIN**, **EOSC** life, etc.).

The existence of a User Committee is an important element in strengthening the open science approach. Of the 22 infrastructures in the 2018 version of



the Biology and Health roadmap, eight have this dialogue tool fully operational and eight are in the process of setting it up.

STRATEGY: POTENTIAL GAPS TO BE FILLED AND DIRECTIONS FOR THE NEXT 5 YEARS

Several cross-cutting needs are shared by some of the infrastructures in the roadmap: single-cell approach or molecular and cellular engineering (which now makes it possible to produce biological entities (plants, animals, organoids) that are purposely defined for the creation of genotypes and their functional exploration) without potentially being effectively met by new infrastructures or even needing to. There is an urgent need to establish cross-cutting exchange structures at national level on these issues, for example through support for initiatives such as Research Networks or Thematic Schools. Visibility and agility of RIs are again central to facilitating the development of these techniques. The driving role of IBISA and Aviesan in this context should be highlighted.

The model of knowledge sharing, good practice and consideration of ethical and regulatory components developed by **France Cohortes** could also be transposed to effectively address these common concerns.

But some of the needs of the research communities can only be met by the creation of new national infrastructures. The increase in the number of projects in this field clearly reflects this very strong dynamic.

New infrastructure proposed for entry on the roadmap

Five new research infrastructures are proposed for inclusion in the 2021 roadmap:

- The **CALIS** (Consumer/Food/Health) project aims to coordinate the main platforms involved in the field of human nutrition. The infrastructure is structured

around three poles: a consumer pole (processing and management of data relating to consumer behaviour), a food pole (food quality and structural and functional characterisation of food components and foods), and finally a health pole (role of the microbiota, characterisation of the nutritional properties of foods and their impact on human health). The functional exploration of nutrition in humans will enable a dialogue that is essential for the development of innovations in the context of sustainable food for health. Governance is organised to provide added value at each stage of the development of technological solutions for the food chain and/or public policies. The science of food consumption will thus be able to benefit fully from technological advances in a strategic field for France in the European context. **CALIS** is involved in the ESFRI **Food Nutrition and Health-RI** infrastructure project;

- **France Cohortes**, a national platform, is an infrastructure project of digital and computer technologies at the service of cohorts. It is equipped with tools to guarantee security, traceability of processing and avoid data dissemination, as well as to document GDPR compliance in a centralised manner. The main users are national cohorts that are well established in the public health research landscape. The solution for hosting and making data available is organised in a secure environment that complies with the security guidelines of the national health data system (SNDS);
- **LiPh@SAS** (Livestock Phenotyping for Sustainable Agro ecoSystems) is an infrastructure for the phenotyping of production animals (cattle, pigs, fishes) in a context of adaptation of livestock farming to global changes and societal demand for livestock farming

that respects animal welfare and the environment. This RI is particularly open to European academic teams since France is coordinator of the three European infrastructures in the field (supported by INFRAIA calls). It develops technologies contributing in particular to the 3R approaches, in order to offer access to original animal lines for horizontal or vertical phenotyping and characterisation of genetic resources in breeding conditions adapted to the new requirements of sustainable agro-ecological systems;

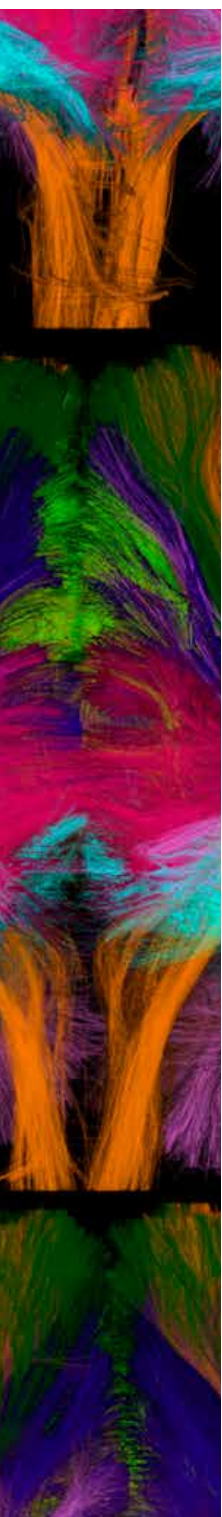
- **EBRAINS-FR** is the French node of the ESFRI **EBRAINS** infrastructure project led by France. The project is an expression of the evolution of certain technologies insofar as this RI combines services of accessibility to reference data (atlases, image databases), high performance computing and algorithmic and neuromorphic process innovation. **EBRAINS** aims at modelling the human brain, with spin-offs in different fields such as neurobiology, medicine and in parallel computational sciences and algorithms. **EBRAINS-FR** comprises a combination of digital platforms dedicated to the analysis and processing of large and complex brain data sets allowing the elaboration of models and simulations of brain functions. It is therefore transverse with several other RIs focused on data acquisition. This is another example of the need to exploit the complementarity of infrastructures in a given scientific field, if only by formalising a network. The **EBRAINS-FR** project, mainly in Biology and Health, is also very directly linked to the field of Digital Sciences and Mathematics;
- The **FR Exposome** project for an infrastructure for analysing the human chemical exposome is part of both the National Environmental Health Plan and the European project Human

Monitoring for Europe HBM4EU, an initiative in which France plays a major role, particularly in terms of new technologies, as well as the ESFRI **EIRENE-RI** (Research Infrastructure for Environmental Exposure assessment in Europe) project, submitted by the Czech Republic, which is part of the ESFRI 2021 roadmap. The creation of the national infrastructure aims to consolidate the French position by organising, as a first step, an offer for human biomonitoring of chemical contaminants and access to technical platforms in this field. The project is in an active consolidation phase. Exchanges are underway between the actors and the supervisory bodies concerned in order to clarify the respective positions of **MetaboHUB** and **FR Exposome**, but generally speaking, the consideration of environmental exposure issues at the national level, in one form or another, will be necessary for France to be able to play its full role in the construction of EIRENE. It is necessary to launch a real dynamic and build synergies for an inclusive approach;

- ESFRI, in its press release on the inclusion of new research infrastructures in its 2021 roadmap, made a point of emphasising that the **EIRENE** project (in the development of which **FR Exposome** should be associated) is part of the key priority Health at European level and that **EBRAINS** (of which **EBRAINS-FR** should be the French node) is part of the two key EU priorities Digital Transition and Health.

Strengthening and sustaining national infrastructures

It is crucial to continue to foster the evolution of national infrastructures to enable them to adapt to new user needs, reach out to new communities, and thus enable them to develop and/or make



available new technologies and scientific approaches that will bring additional benefits to the user community.

The sustainability of research infrastructures requires a good adaptation to the end of the “National Infrastructures in Biology and Health” investment programme.

Most of the infrastructures created by the PIA have been favourably evaluated by the Steering Committee of the Health and Biotechnology Action based on the opinions of an international jury.

This evaluation made it possible to confirm the support of the supervisory authorities and to take into account the need for the infrastructures to develop their economic models. 75 millions of euros (for the period 2021-2025) were provided.

The role of infrastructures in Biology-Health, recognised ten years ago, has proved to be central in many aspects of national policies and in the rise of many scientific fields. France must find ways to maintain them at the best level and not run the risk of no longer being internationally competitive and of losing its power of attractiveness, which has been restored thanks to the actions carried out over the last ten years.

EMBL

European Molecular Biology Laboratory

EMBL is one of the world's leading centres of excellence in basic biological research. The long-term commitment of its 27 member states enables it to integrate and coordinate scientific activities on a European scale. In addition to the headquarters in Heidelberg and its research laboratories, the EMBL is spread over five sites covering specific areas of biology: structural biology in Hamburg and Grenoble, bioinformatics in Hinxton, neurobiology and epigenetics in Rome and tissue biology and disease modelling in Barcelona.

About 100 excellent young scientists are selected as leaders of research teams and departments (for 5 to 9 years).

EMBL provides scientists with access to essential scientific services (large biological databases, synchrotron facilities, advanced imaging and experimentation).

The training aspect of EMBL is extensive: PhD programme in Life Sciences (250 students from



© EMBL, ATC, Heidelberg campus

more than 40 countries), hosting of post-doctoral programme, ARISE (Career Accelerator for Research Infrastructure Scientists) programme, short-term stays and a wide portfolio of highly regarded courses and conferences.

In its next programme, Molecules to Ecosystems (2022-2026), EMBL aims to develop new areas of research, including planetary biology, microbial ecosystems, human ecosystems and infection biology.

Relations with economic actors and/or socio-economic impact

EMBL is committed to the promotion and dissemination of its knowledge to industry. Its exclusive technology transfer partner (EMBLEM GmbH - Enterprise Management Technology Transfer) manages a portfolio of more than 250 patents and copyrights (technological innovations, programme developments, databases). One of the objectives is the development of inventions and technologies to commercial maturity.

Open science and data

- All the publications from projects using the infrastructure should be put on open access
- Annual data production: 10 to 15 PB
- Infrastructure with a FAIR data policy in application

Category: IO

Type of infrastructure: distributed

Infrastructure location: Heidelberg (Allemagne)

Other sites: Grenoble (France), Hambourg (Allemagne), Barcelone (Espagne), Monterotondo (Italie), Hinxton (Royaume-Uni)

French supporting institutions: MESRI

• **Construction:** 1974

• **Operation:** 1974

• **Contact in France:** Anne Paoletti, anne.paoletti@recherche.gouv.fr; Elena Hoffert, elena.hoffert@recherche.gouv.fr

• **Website:** www.embl.fr

International dimension

Acronym of the European/international infrastructure: EMBL

Director: Edith Heard

- **Partner countries:** AT, DK, FR, DE, IL, IS, IT, NL, SE, CH, UK, FI, GR, NO, ES, BE, PT, IE, HR, LU, CZ, MT, HU, SK, ME, PL, LT; AU (pays associé); EE (pays prospect); LV (pays prospect)
- **Website:** www.embl.org

CALIS

National Consumer-Food-Health Research Infrastructure

The Consumer-Food-Health research infrastructure (CALIS) is based on the grouping and national coordination of accredited platforms and experimental systems that have been in operation for many years. These entities are organised into 3 clusters for better readability and more efficient governance: (i) the "Food" cluster dedicated to the design and characterisation of foodstuffs, (ii) the "Consumer" cluster, specialising in the study of food choices and consumption behaviour, and (iii) the "Health" cluster, which focuses on the repercussions of food on the physiology and health of humans (including their microbiota). CALIS offers services to both the public and private scientific communities, based on technological developments, the provision of data and experimental materials and training activities. The strategic interest of grouping these entities into a distributed infrastructure is to be able to address research questions on sustainable food for health in



© Exclusive-design - Adobe Stock

a multidisciplinary manner by integrating the entire value chain from agricultural raw materials and their transformation into food to the effect on human health, including consumer choices and preferences. CALIS thus groups together fourteen platforms or experimental facilities spread throughout Metropolitan France, representing a collective of 189 ETPs.

Relations with economic actors and/or socio-economic impact

The CALIS research infrastructure is developing a very strong activity in support of industry. The CALIS entities sign about 160 contracts each year, mainly with the food-processing and pharmaceutical industries. Over the last few years, CALIS entities have filed 30 patents, designed 7 software programs and created 3 start-ups (Enterome, Maat Pharma and Novobiome).

Open science and data

- Some of the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure are open on a software forge <https://forgemia.inra.fr>
- Annual data production: 200 TB
- The validated and described data are published on a data repository

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Rennes

Other sites in France: Clermont-Ferrand, Dijon, Grenoble, Ivry-sur-Seine, Montpellier, Nantes, Paris 13^e, Pierre-Bénite, Rennes, Saint-Genès-Champanelle

French supporting institutions: INRAE

• **Director or RI representative in France:** Didier Dupont

• **Construction:** 2020

• **Operation:** 2020

• **Stakeholders in France:** Inserm, Anses, Universités: Paris-Saclay, UCA, Claude Bernard – Lyon 1, Sorbonne Paris Nord, UJM, Université de Paris, UGA, Université de Nantes, Sorbonne U, UBFC, Université de Montpellier, CNAM, AgroParisTech, Institut Agro, AP-HP, CHUs de Saint-Étienne, de Grenoble-Alpes, de Nantes, de Clermont-Ferrand, HCL.

• **Contact in France:** Didier Dupont

• **Website:** www.inrae.fr/calis

International dimension

FNH-RI project

Director: K. L. Zimmermann

- **Partner countries:** NL, IT, BE, IE, SK, BG, MK, ES, PT, SI, RS, ME, HU, DK, UK, IS, NO, SE, FI, CA, DE, GR, CZ, PL
- **Website:** <https://fnhri.eu>

Celphedia

National Infrastructure for the Creation, Breeding, Phenotyping, Distribution and Archiving of vertebrate models

Model organisms are essential for basic research and for veterinary and biomedical progress. They are key for understanding integrative physiology or the expression of a genetic trait. Indeed, these biological processes result from the interaction of the genome with its environment. The measurement of the clinical phenotype requires the use of certified resources, validated, robust and standardised methods, and a study design that guarantees the statistical power and reproducibility of the results. This approach meets the ethics of animal research, expressed in the 3Rs rule, with the reduction of the number of animals, the refinement of the tests, and can only be done when all alternative studies have been done, also by choosing the model organism according to the scientific question asked.

CELPHEDIA has defined 5 strategic objectives, guaranteeing breakthrough progress in animal research and better reproducibility of data:



© composite

- 1) By the quality of material resources,
- 2) By controlling the environment, the exposome, to understand the phenotype, particularly during ageing,
- 3) By qualified and robust experimental methods, cross-validated between centres,
- 4) By the necessary control of multi-scale transitions
- 5) And by making all the models and phenotyping data available to the scientific community and training.

Relations with economic actors and/or socio-economic impact

CELPHEDIA maintains specific relationships with the socio-economic world, with more than 60 audited suppliers, of which more than two thirds are in France. It contributes to the development of sixty-three biotech, start-ups and service companies in the field of animal research.

CELPHEDIA has established cooperation agreements and strategic alliances with a dozen industrial groups.

Open science and data

- Annual data production: 200 TB
- Infrastructure with a FAIR data policy in application
- The validated and described data are published on a data repository www.mousephenotype.org

Category: RI

Type of infrastructure: distributed

Localisation du siège de l'infrastructure): Illkirch-Graffenstaden

Other sites in France: Clermont-Ferrand, Gif-sur-Yvette, Lyon, Marseille, Nantes, Niederhausbergen, Orléans, Paris, Rousset, Strasbourg, Toulouse

French supporting institutions: CNRS

• **Director or RI representative in France:** Yann Herault

• **Construction:** 2008

• **Operation:** 2008

• **Stakeholders in France:** Institut national de la santé et de la recherche médicale, Université de Strasbourg, ENS de Lyon, Université Claude Bernard – Lyon 1, Université Toulouse III – Paul Sabatier, ENVT, AMU, Inrae, Université Paris-Saclay, Université de Nantes

• **Contact in France:** Yann Herault

• **Website:** www.celphedia.eu

International dimension

INFRAFRONTIER, ESFRI landmark

Director: Martin Hrabé de Angelis et Daniel Lahne

• **Partner countries:** DE, FR, CZ, GR, FI, SE

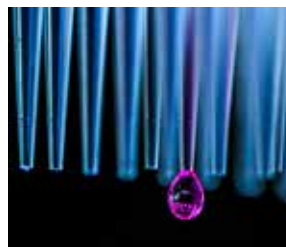
• **Website:** www.infracfrontier.eu

ChemBioFrance

Bioactive molecules discovery platform to explore and cure living organisms

ChemBioFrance's mission is the discovery of small molecules to understand and treat living organisms. Specifically, it aims to offer academic laboratories resources (molecules, software, cell lines, etc.) and instruments (technical platforms) for identifying small bioactive molecules intended to understand living organisms, and thus to develop diagnostic and treatment tools in the fields of health and the environment. ChemBioFrance needs to integrate into a single research infrastructure

- i) the National Chemistry Library of 60,000 compounds and 15,000 extracts;
- ii) a network of 21 screening platforms distributed throughout the country;



© Philippe Jaffret, membre de ChemBioFrance

- iii) a cheminformatics platform distributing physical chemistry, modelling and virtual screening software;
- iv) a network of preclinical study platforms in ADME and Toxicology.

Relations with economic actors and/or socio-economic impact

ChemBioFrance offers services to academic and private project leaders for the development of molecules. 165 ADME services per year, 180 screening services per year. 50 patents licensed to companies, 10 industrial contracts in 2019, 350 publications and 60 conferences given by ChemBioFrance members in 2018-2020.

Open science and data

- All the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure are open on a software forge <https://github.com/JordiMa/L-G-Chimio>
- Annual data production: 10 TB

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Illkirch-Graffenstaden, Montpellier

Other sites in France: Gif-sur-Yvette, Grenoble, Illkirch-Graffenstaden, Lille, Marseille, Montpellier, Paris, Roscoff, Toulouse

French supporting institutions: CNRS

Director or RI representative in France: Jean-Luc Galzi

Construction: 2018

Operation: 2018

Stakeholders in France: CNRS, CEA, Inserm, INRA, Institut Pasteur, Institut Curie, MNHN, INSA Lyon, Rouen, Rennes, Universités Strasbourg, Haute Alsace, Paris Sud, Paris V, Orléans, Caen, Lyon1, Grenoble, Reims, Nantes, Aix-Marseille, Clermont Ferrand, Versailles, Rouen, Toulouse III, Amiens, le Mans, Nice, Bordeaux, Mulhouse, Lille, de Lorraine, Tours, Montpellier, Paris Est, Sorbonne, Toulon; Écoles d'ingénieur de chimie Lyon, Montpellier, Rennes, Centrale Marseille, SIGMA Clermont, l'École supérieure de physique et de chimie industrielle de Paris.

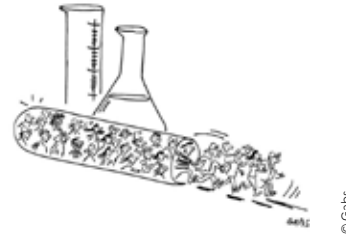
Contact in France: contact@chembiofrance.org

Website: www.chembiofrance.fr

CONSTANCES

Cohort of consultants at health examination centres

Constances is an epidemiological cohort of 220,000 subjects representative of the population aged 18 to 69 years. Inclusion takes place in health examination centres in 21 departments, including a health examination, the constitution of a biobank and questionnaires (health, lifestyle, socio-professional factors). Follow-up is active (annual self-questionnaire, examination every 4-5 years), and passive by annual linkage with the SNDS and Cnav databases. The main data collected concern health, healthcare use, biological and physiological parameters, a biobank, socio-demographic characteristics and occupational factors. A control cohort of more than 400,000 people is followed in the national databases to enable the adjustment of prevalence estimates in the general population. It is an “immaterial” infrastructure whose mission is essentially to collect individual data from participants in a prospective manner from multiple



sources. Through calls for projects, the cohort database is open to the French and international research community, and more than one hundred projects have been validated by the Constances International Scientific Council. Constances is the largest French cohort, and participates in several national and European consortia.

Relations with economic actors and/or socio-economic impact

We have contracts with drug and wellness companies. Regarding the socio-economic impact, Constances is used by ministries and health agencies thanks to the provision of data on the health of the French population: CESE, Ministry of Health, Ministry of Labour, Interministerial Mission for the fight against drugs and addictive behaviours, Mildeca.

Open science and data

- Annual data production: 2 TB
- Infrastructure with a FAIR data policy in application

Category: RI

Type of infrastructure: single site

Infrastructure location in France: Villejuif

French supporting institutions: Université Paris-Saclay

- **Director or RI representative in France:** Marie Zins
- **Construction:** 2011
- **Operation:** 2013
- **Stakeholders in France:** Université de Paris, CNAV, UVSQ, CNAM, INSERM
- **Contact in France:** Marie Zins
- **Website:** www.constances.fr

ECELLFrance

National platform for regenerative medicine based on adult mesenchymal stem cells

The mission of ECELLFrance (ECF) is to develop mesenchymal stem cell (MSC)-based therapies to regenerate damaged tissues in many age-related or/in chronic/inflammatory diseases currently without viable curative treatment.

ECF, federating 7 sites, integrates 11 technological platforms and brings together internationally recognised national experts in the following fields: osteoarticular, autoimmune, neurovascular, dermatology and ischemia diseases. This expertise will be extended to other cell therapies such as CAR-T cells and NK lymphocytes mediated immunotherapies.

ECF fully coordinates all services from MSC bioproduction to the development pipeline including: project validation, preclinical studies, regulatory support, bioproduction of Advanced Therapeutic Medicine Product (ATMP), safety and activity testing, clinical trials and immunomonitoring.



© Didier Deslats

The clinical transfer of MSC-mediated therapies will be strengthened by:

- i) the introduction and automation of bioreactors;
- ii) the new generation of MSCs (genetically modified, generated from iPS, with an enhanced biological effect);
- iii) identification of MSC subtypes (single cell array, methylome of phenotyped subpopulations);
- iv) characterisation of extracellular vesicles secreted by MSCs.

Relations with economic actors and/or socio-economic impact

ECELLFrance is at the origin of:

- 10 patents
- 2 spin-offs created in 2018: MedXCell Science in Montpellier, which bioproduces MSCs to treat osteoarticular diseases, and Cell Easy in Toulouse, which bioproduces adipose-derived MSCs for allogeneic therapies

Open science and data

- All the publications from projects using the infrastructure are open access
- Annual data production: 75 TB
- Infrastructure with a FAIR data policy in application

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Montpellier

Other sites in France: Besançon, Clamart, Créteil, Grenoble, Rennes, Toulouse

French supporting institutions: Université de Montpellier

Director or RI representative in France:

Christian Jorgensen

Construction: 2011

Operation: 2012

Stakeholders in France: EFS, CNRS, Inserm, CHU Montpellier, CHU Rennes, Université Toulouse III - Paul Sabatier, UGA, Centre Hospitalier Universitaire de Grenoble-Alpes, Centre de Transfusion Sanguine des Armées

Contact in France: www.ecellfrance.com/home/contact-us

Website: www.ecellfrance.com

EMBRC France

National Centre for Marine Biological Resources

The National Centre for Marine Biological Resources (EMBRC-France) is a national Research Infrastructure (RI), winner in 2010 of the call for projects "National infrastructures in biology and health" of the "Investment for the future" programme. EMBRC-France is the French node of the European Marine Biological Resource Centre (EMBRC-ERIC). The Infrastructure is coordinated by Sorbonne University (SU) and the National Centre for Scientific Research (CNRS). EMBRC-France integrates the services and expertise of the 3 SU - CNRS stations, the Observatoire Océanologique de Banyuls-sur-Mer, the Institut de la Mer de Villefranche-sur-mer and the Station Biologique de Roscoff.

EMBRC-France's mission is to provide access, on site or by expedition, to marine ecosystems and biological resources, as well as to provide users with a high-level scientific and technological environment. The services offered by EMBRC-France are classified as follows:



© David Luquet (Institut de la Mer de Villefranche)

Provision of marine biological resources (stabling and/or culture, collections of planktonic organisms, model organisms and provision of genetic and genomic resources), Access to marine ecosystems, Technology platforms, Support services and Training. The RI aims to facilitate this access to the academic and industrial communities, in order to support the research projects of the whole French community.

Relations with economic actors and/or socio-economic impact

Relations with the economic world are managed by the development services of the supervisory bodies, SU and CNRS. The RI has a Council of Territorial Authorities, with representatives from the Regions of Brittany, Occitania and the South, and from the two Pôles Mer, Méditerranée and Bretagne-Atlantique. The RI is very attentive to the Regions' Smart Specialization Strategy and to its good insertion in the local innovation ecosystems.

Open science and data

- Annual data production: 2 PB
- The validated and described data are published on a data repository www.ebi.ac.uk/ena

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Banyuls-sur-Mer, Paris 5^e, Roscoff, Villefranche-sur-Mer

French supporting institutions: Sorbonne U, CNRS

Director or RI representative in France:

Gemma Giménez Papiol

Construction: 2011

Operation: 2014

Contact in France: www.embrc-france.fr/fr/qui-sommes-nous/contact

Website: www.embrc-france.fr

International dimension

EMBRC, ESFRI landmark

Director: Nicolas Pade

Partner countries: FR, BE, ES, GR, IL, IT, NO, PT, GB

Website: www.embrc.eu

EMERG'IN

National Research Infrastructure for the control of animal or zoonotic emerging infectious diseases through *in vivo* investigation

EMERG'IN is a distributed research infrastructure for the control of animal or zoonotic emerging infectious diseases by *in vivo* investigation on a wide variety of animals (model and production animals, wildlife, arthropod vectors). The infrastructure consists of 5 complementary experimental platforms belonging to INRAE, ANSES and CIRAD.

The ambition of EMERG'IN is to provide France with a national coordination instrument to increase upstream knowledge and to accelerate the marketing of means of control and diagnosis of infectious diseases (vectorised or not) capable of affecting human and animal health. To this end and with the support of the Carnot Institutes (France Futur Elevage, AgriFood Transition), EMERG'IN is developing public-private partnerships. EMERG'IN offers (1) a wide range of A2/A3/I2 devices, (2) animals with controlled health status, (3) isolators (poultry, rodents) to study the impact



of microbiota on the physiopathology of infections, (4) *in vivo* imaging and surgical devices to monitor infectious processes and (5) telemetry equipment to analyse physiological and behavioural data acquired during experiments. EMERG'IN, in partnership with various research actors, is also working on new alternative methods to *in vivo* experimentation and its refinement.

Relations with economic actors and/or socio-economic impact

EMERG'IN maintains close and regular contact with all public (universities, research organisations) and private actors in animal health via services and research contracts (national/ANR, European/Horizon Europe or private). The socio-economic impact of EMERG'IN concerns public health, animal production sectors, the food production chain, public policies and citizens.

Open science and data

- Some of the publications from projects using the infrastructure are open access
- Annual data production: 5 TB
- The validated and described data are published on a data repository <https://dataverse.cirad.fr/dataverse/astre>

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Nouzilly

Other sites in France: Jouy-en-Josas, Montferrier-sur-Lez, Nouzilly, Ploufragan

French supporting institutions: INRAE

• **Director or RI representative in France:** Fabrice Laurent

• **Construction:** 2018

• **Operation:** 2018

• **Stakeholders in France:** Anses, Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail, Cirad, Centre de coopération internationale en recherche agronomique pour le développement.

• **Contact in France:** emergin@inrae.fr

• **Website:** www.emergin.fr

International dimension

VetBioNet

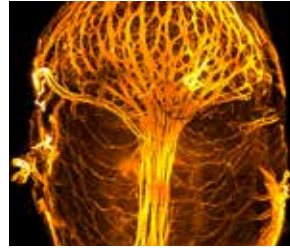
- **Partner countries:** FR, NL, DE, UK, ES, PL, DK, IE, CH, IT
- **Website:** www.vetbionet.eu

FBI

France-BioImaging

France-BioImaging provides access to the entire national community to the latest innovations in life science imaging. FBI is a multidisciplinary infrastructure that:

- explores new venues in bio-imaging and encourages their application in biological sciences.
- It is a tool for research in many fields, from plant biology and stem cell research to preclinical and translational studies on cancer and neurodegenerative diseases;
- aims to promote the technological transfer of innovations produced by its expert R&D teams to its facilities. It aims to accelerate access, while ensuring the quality control and sustainability of the acquisition systems and the data produced;
- is a gateway for private/public projects in the field of advanced microscopy, in particular for the screening and development of therapeutic drugs and active ingredients, for instance in cosmetics;



© Orestis FAKLARIS / Nicolas CHEVALIER / IJM / FranceBioImaging / CNRS Photothèque

- is a resource centre for training and education. FBI supports dissemination activities in biological imaging, organises and participates in national and international training programmes (FBI-AT; EMBO courses and workshops, Elmi meetings, CNRS schools...);
- is the French node of the ERIC Euro-BioImaging and is involved in European and international networks and programmes (Global BioImaging, COST projects...).

Relations with economic actors and/or socio-economic impact

France-BioImaging maintains relations with the industrial world through services and research collaborations. The infrastructure also has an industrial committee with which it develops joint actions in the field of imaging. This committee includes major companies in the field, numerous French SMEs that develop innovative systems and national start-ups.

Open science and data

- Some of the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure are open on a software forge <https://github.com/France-Bio-Imaging-Data>
- Annual data production: 12 PB
- The validated and described data are published on a data repository <https://cid.curie.fr>

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Montpellier

Other sites in France: Bordeaux, Gif-sur-Yvette, Marseille, Nantes, Rennes

French supporting institutions: CNRS

Director or RI representative in France:

• Edouard Bertrand

• **Construction:** 2011

• **Operation:** 2012

• **Stakeholders in France:** AMU, IP, Inria, Inserm, Université de Paris, UB, UM, Curie PSL, ENS PSL, École polytechnique (X), Université de Rennes 1, Université de Nantes

• **Contact in France:** contact@france-bioimaging.org

• **Website:** <https://france-bioimaging.org>

International dimension

Euro-Bioimaging, ESFRI landmark

Director: John Eriksson

- **Partner countries:** AT, BG, CZ, DK, FI, FR, HU, IT, ISL, NL, NO, PL, PT, SE, SI, UK
- **Website:** www.eurobioimaging.eu

F-CRIN

National Platform of Clinical Research thematic expertise

F-CRIN is a national infrastructure for clinical research. Its mission is to identify, support and structure French clinical research in order to strengthen its performance, and therefore its attractiveness and visibility on the international stage. As a transversal organisation that brings together the main operators in clinical research, whether academic, hospital or industrial, its aim is to federate the medical, methodological, statistical and operational expertise, which is available in France for clinical research in the promising and cutting-edge fields of human health. F-CRIN currently has 21 components, including 16 national thematic networks specialized in research and clinical investigation, 3 targeted expertise networks, 1 platform of advanced services in clinical



research, and a national coordination unit which has the dual function of representing the Infrastructure and providing central support services for all the components.

Relations with economic actors and/or socio-economic impact

In total, since its inception, F-CRIN has participated in over 671 clinical research projects of which 4% are international in scope. Almost half of these projects involve or are promoted by industry (with a recruitment of over 62,000 patients). More than 1,350 scientific publications mention F-CRIN or one of its components. Finally, F-CRIN coordination has organised 70 training modules involving almost 1,800 participants.

Open science and data

- The validated and described data are published on a data repository www.fcrin.org

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Paris, Toulouse

Other sites in France:

French supporting institutions: Inserm, AP-HP, CHU Saint-Étienne, CHU Toulouse, Université Toulouse III - Paul Sabatier, Centre Hospitalier de Bordeaux, Centre de recherche en nutrition humaine "Rhône-Alpes".

• **Director or RI representative in France:** Olivier Rascol

• **Construction:** 2012

• **Operation:** 2012

• **Contact in France:** Vincent Diebolt

• **Website:** www.fcrin.org

International dimension

ECRIN, ESFRI landmark

Director: Jacques Demotes

- **Partner countries:** FR, IT, ES, IE, NO, CZ, DE, HU, PT
- **Website:** <https://ecrin.org>

FLI

France Life Imaging

France Life Imaging (FLI) is a National Health Biology Infrastructure created in 2012. It brings together in a coordinated network more than 35 in vivo imaging platforms for biomedical research in France. The network of expert laboratories in image management and analysis has set up a software infrastructure for the management, analysis and availability of images generated in the framework of clinical and preclinical research projects. Finally, FLI animates the scientific community through the exchange of expertise between laboratories in critical imaging research fields, in order to facilitate the emergence of innovations. FLI's missions are as follows:

- To coordinate in vivo imaging platforms for biomedical research, distributed throughout the country, in order to provide access to state-of-the-art imaging equipment in all modalities for academic and industrial researchers, as close as possible to their laboratory;



© FLI et I. Aguilu, ASAP

- To offer services for the storage and analysis of images and the opening of imaging data to the community;
- To strengthen the expertise of imaging research laboratories in four key areas of imaging research, imaging agents, instrumentation and technology innovation, interventional imaging and multi-modal data processing;
- To offer training adapted to the needs of platform personnel.

Relations with economic actors and/or socio-economic impact

France Life Imaging provides academic and industrial researchers with highly innovative imaging equipment and the expertise of associated laboratories. To facilitate access to the platforms for industrialists, FLI has forged links with the regional competitiveness clusters in the field; regional platforms and hubs are members of Carnot institutes. FLI has close relations with the learned societies in the field of imaging.

Open science and data

- Some of the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure are open on a software forge <https://project.inria.fr/fli/en>
- Annual data production: 300 TB
- The validated and described data are published on a data repository

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Montpellier, Saclay

Other sites in France: Bordeaux, La Tronche, Marseille, Nancy, Nantes, Paris, Rennes, Saint-Aubin, Strasbourg, Toulouse, Villeurbanne

French supporting institutions: CEA

- **Director or RI representative in France:** Vincent Lebon

- **Construction:** 2012

- **Operation:** 2012

- **Stakeholders in France:** CNRS, Inserm, Inria, AMU, UBx, Université Claude Bernard - Lyon 1, UGA, Université de Paris, Université Paris-Saclay, Université de Nantes, Université de Rennes 1, Université de Lorraine, Université de Strasbourg, Université de Montpellier, Université Toulouse III - Paul Sabatier

- **Contact in France:** www.francelifeimaging.fr/contact-3

- **Website:** www.francelifeimaging.fr

France Cohortes

France Cohortes

France Cohortes develops and pools services and a secure IT infrastructure certified as a “health data host”, to support research teams carrying public health cohorts in the consolidation and processing of their data (from collection to reuse), while respecting the confidentiality of participants.

French cohorts provide essential data for research and studies in human health, over long periods. France Cohortes is setting up a resource and service centre for researchers, in order to enhance and perpetuate projects and the scientific exploitation of data produced by public health cohorts, thus promoting the emergence of useful knowledge for the prevention of diseases and the improvement of care, in all or part of the population.



© Igor Vitomirov (Adobe Stock)

By 2024, France Cohortes will integrate several cohorts affiliated to the initial scope of the infrastructure. Beyond that, the services will be open to new cohorts based on scientific and institutional eligibility criteria.

Relations with economic actors and/or socio-economic impact

Cohorts, supported by public funding, are now strongly identified by the national and international scientific community. The France Cohortes initiative should allow their perpetuation via the various services provided, and to accompany the opening of the cohort databases to the research community.

Open science and data

- All the publications from projects using the infrastructure are open access
- Annual data production: 10 TB
- The validated and described data are published on a data repository <https://epidemiologie-france.aviesan.fr>

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Aubervilliers, Paris, Paris 12^e, Villejuif

French supporting institutions: Inserm

- **Director or RI representative in France:** Grégoire Rey
- **Construction:** 2020
- **Operation:** 2020
- **Stakeholders in France:** Université Paris-Saclay, Sorbonne U, Université de Paris, INED
- **Contact in France:** <https://francecohortes.org/contact>
- **Website:** <https://francecohortes.org>

France Génomique

National Genomics and Associated Bioinformatics Infrastructure

France Génomique's mission is to offer to the public and private scientific community access to French platforms providing the best expertise in genomics, capable of supporting them efficiently in the realisation of their projects.

The establishment of a single governance and entry point for the management of large and medium-sized projects, as well as the sharing of equipment and skills, enables all scientists in the field to structure themselves in order to reach the critical mass necessary to meet the growing needs for sequencing, storage and data processing.

The infrastructure's mission is also to remain at the forefront of international advances thanks



© Get-PlaGe, INRAE

to intensive monitoring and innovative developments in technologies and methodologies and to contribute to their dissemination through training activities, workshops, symposium, etc.

Relations with economic actors and/or socio-economic impact

At the heart of the technological revolution in genomics, France Génomique offers French research the possibility of maintaining its competitiveness with permanent access to the best state-of-the-art in this field. France Génomique is thus a key player in major genomics projects with a high socio-economic impact, in all areas of life sciences: human genetics and medicine, environment and ecology, agronomy.

Open science and data

- Annual data production: 0,5 PB
- Infrastructure with a FAIR data policy in application
- The validated and described data are published on a data repository www.ebi.ac.uk/ena/browser/home

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Évry-Courcouronnes

Other sites in France: Auzeville-Tolosane, Clermont-Ferrand, Illkirch-Graffenstaden, Montpellier, Marseille, Paris, Valbonne

French supporting institutions: CEA

- **Director or RI representative in France:** Patrick Wincker et Denis Milan
- **Construction:** 2011
- **Operation:** 2011
- **Stakeholders in France:** CNRS, INRAE, INSERM, Institut Curie - Curie, Institut Pasteur, AMU, ENS ULM, Université de Strasbourg, Université Lille 1 - Sciences technologies
- **Contacts en France:** Marie-Thérèse Bihoreau, Patrick Wincker, Denis Milan
- **Website:** www.france-genomique.org



FRISBI

French Infrastructure for Integrated Structural Biology

Integrated Structural Biology allows, through the combination of different approaches, to access structural and dynamic information at various size and time scales and thus to improve the understanding of the dynamic interaction of biological macromolecules and their functional complexes, of pathogens with their environment and thus to understand the mechanisms that govern the functioning of healthy cells and to document the link between molecular deregulation and pathology. The French Infrastructure for Integrated Structural Biology, FRISBI, distributed across 5 centres (Strasbourg, Grenoble, Montpellier, Marseille and Paris Saclay) offers the academic and industrial, national and European research community access to a range of cutting-edge technologies and expertise adapted to integrated structural biology projects (<http://frisbi.eu>) in the fields of:

- Sample production in eukaryotic, prokaryotic and in vitro systems
- Biophysical characterisation;
- Crystallisation;



© Bruno Klaholz

- Crystallography including links with ESRF and SOLEIL synchrotrons;
- Electron microscopy;
- Super-resolution fluorescence microscopy;
- NMR;
- Spectroscopies.

FRISBI has a training mission in Integrated Structural Biology, which is carried out through the ReNaFoBis initiative (National training network in integrative structural biology) for the training of young researchers at PhD and post-doc level (www.renafobis.fr).

Relations with economic actors and/or socio-economic impact

FRISBI is an infrastructure whose access is open to industry. Partnerships have been set up for technological development such as the automation of image collection in electron microscopy. Collaborations and services have been established with SMEs and large pharmaceutical and biotechnology companies for the use of the FRISBI platform. Start-ups have been created, patents and licences filed.

Open science and data

- The source codes produced by the infrastructure are open on a software forge
- Annual data production: 3 PB
- The validated and described data are published on a data repository www.ebi.ac.uk/pdbe/emdb

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Gif-sur-Yvette, Grenoble, Illkirch-Graffenstaden, Marseille, Montpellier

French supporting institutions: CNRS

• **Director or RI representative in France:** Bruno Klaholz

• **Construction:** 2011

• **Operation:** 2011

• **Stakeholders in France:** CEA, Inserm, Université de Strasbourg, Université de Montpellier, Université Paris-Saclay, UGA, AMU, EMBL

• **Contact in France:** contact@frisbi.eu

• **Website:** <http://frisbi.eu>

International dimension

Instruct-ERIC, ESFRI landmark

Director: Harald Schwalbe

- **Partner countries:** UK, FR, BE, IT, ES, IL, CZ, FI, PT, NL, SK, LT, LV, EMBL
- **Website:** www.instruct-eric.eu

IBISBA France

Industrial Biotechnology Innovation and Synthetic Biology Acceleration

IBISBA (Industrial Biotechnology Innovation and Synthetic Biology Acceleration) is a distributed European research infrastructure that supports research and innovation in biotechnology for industry and the environment. Its activity is therefore part of the development of technologies for the circular bio-economy and the fourth industrial revolution. The originality of IBISBA in the French landscape is both its multidisciplinary and its ambition to carry out translational research. Thus, as an integrator, IBISBA assembles fundamental knowledge from research in biology, process engineering and digital sciences to create a continuum between fundamental research on the one hand and industrial R&D on the other. In fact, IBISBA actively participates in pre-competitive research projects and in partnership with socio-economic players.

As a player in biotechnologies for industry and the environment, IBISBA's research aims are numerous,



covering the fields of bioenergy (e.g. bio-methane and bio-H₂), chemicals for industry (e.g. plastics processes), ingredients for the food-processing industry, and compounds for the cosmetics and pharmaceutical industries. IBISBA's research is also aimed at the production of services, such as the bio-recycling of waste or the bio-protection of agricultural crops.

Relations with economic actors and/or socio-economic impact

As a player in translational research in biotechnologies for industry and the environment, IBISBA is a key link in the French R&D&I ecosystem. All IBISBA platforms work in partnership with companies, both to support the activity of innovative start-ups and SMEs and to contribute to projects led by large companies whose activities concern different market sectors.

Open science and data

- The source codes produced by the infrastructure are open on a software forge <https://github.com/search?q=ibisba>
- Annual data production: 10 TB
- The validated and described data are published on a data repository <https://hub.ibisba.eu>

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Jouy-en-Josas, Ramonville-Saint-Agne, Saint-Nazaire, Saint-Paul-lès-Durance, Toulouse, Évry-Courcouronnes

Other sites in France: Bélesta-en-Lauragais, Narbonne

French supporting institutions: INRAE

Director or RI representative in France:

• Michael O'Donohue

• **Construction:** 2017

• **Operation:** 2021

• **Stakeholders in France:** INSA de Toulouse, CNRS, CEA, Université de Nantes

• **Contact in France:** ibisba-fr@ibisba.eu

• **Website:** www.ibisba.fr

International dimension

IBISBA EU, ESFRI project

Director: Michael O'Donohue

• **Partner countries:** FR, IT, ES, GR, UK, BE, DE, NL, FI

• **Website:** www.ibisba.eu

IDMIT

National Infrastructure for Human Infectious Disease Modelling and Advanced Therapies

CEA, Institut Pasteur, Institut National de la Santé et de la Recherche Médicale, Agence Nationale de Recherche sur le SIDA et les Hépatites Virales - Maladies infectieuses émergentes, Université Paris Saclay are the institutional founders of the research infrastructure for the modelling of infectious diseases and innovative therapies (IDMIT) on the CEA site in Fontenay-aux-Roses. This infrastructure is dedicated to preclinical research programmes on vaccines and therapies directed against human infectious diseases. The partners, all international leaders in the field of research, bring their complementary expertise to create an infrastructure that is unique in Europe, equipped with innovative technological platforms for the study of infectious diseases using animal models, particularly non-human primates. The main objective of the consortium is to provide the national and international scientific community with a highly competitive infrastructure to accelerate the transfer of innovation from research to



© CEA, Fontenay-aux-Roses

the clinic. The IDMIT infrastructure includes research laboratories, technological platforms (in vivo imaging in particular) in class 2 and 3 containment, and animal facilities dedicated to experimental infection by class 2 and 3 pathogens (AIDS, yellow fever, whooping cough, dengue, chikungunya, malaria), including respiratory agents (influenza, Covid-19, tuberculosis).

Relations with economic actors and/or socio-economic impact

Since its creation, IDMIT has collaborated with private players (SMEs and Big Pharma) in the field of human infectious diseases, including GlaxoSmithKline, Novartis, Sanofi Pasteur, Merck and Valneva via collaborations or research services. IDMIT is also developing local partnerships with SMEs to accelerate the transfer of technologies resulting from the infrastructure.

Open science and data

- All the publications from projects using the infrastructure are open access
- Annual data production: 10 TB
- Infrastructure with a FAIR data policy in application

Category: RI

Type of infrastructure: single site

Infrastructure location in France: Fontenay-aux-Roses

Other sites in France:

French supporting institutions: CEA, Inserm, Université Paris-Saclay, ANRS Maladies infectieuses émergentes

• **Director or RI representative in France:** Roger Legrand

• **Construction:** 2012

• **Operation:** 2012

• **Stakeholders in France:** ONCODESIGN

• **Contact in France:** infoidmit@cea.fr

• **Website:** www.idmitcenter.fr

International dimension

Transvac2

- **Partner countries:** CH, DE, DK, ES, FR, IT, NL, PT, UK
- **Website:** www.transvac.org/transvac2-about

IFB

French Institute of Bioinformatics

The French Institute of Bioinformatics (IFB) is a distributed national infrastructure that provides support, deploys services, organises training and carries out innovative developments for the life sciences and health communities. The IFB federates 35 regional platforms and associated teams, as well as a coordinating unit, IFB-core (UMS CNRS 3601). The IFB is the French node of the European Bioinformatics Research Infrastructure ELIXIR (<https://elixir-europe.org>).

The IFB's mission is to provide the Life Sciences and bioinformatics communities with access to resources vital to their research, support for projects based on a high level of expertise, and the possibility of participating in ambitious projects at national and international level. The IFB also represents French bioinformatics services within the ELIXIR infrastructure. The services offered by the IFB are of different natures: data, tools, training, support to research



projects and the provision of an IT infrastructure dedicated to life sciences. In order to maintain French research at the highest level of competitiveness and performance in bioinformatics analysis, the IFB anticipates the future needs of the domain and participates in methodological innovations, in particular to meet the challenges of integrative bioinformatics.

Relations with economic actors and/or socio-economic impact

The IFB develops numerous collaborations with researchers from the academic and private world. Between 2017 and 2019, the IFB was involved in 848 services at the national level (including 28 with SMEs) and 247 at the international level, and in 77 scientific collaborations (including 11 with SMEs). The IFB is a key player in large national projects with a strong economic impact (i.e. monitoring and genomics research).

Open science and data

- The source codes produced by the infrastructure are open on a software forge <https://github.com/IFB-ElixirFr>
- Annual data production: 9 PB
- Infrastructure with a FAIR data policy in application
- The validated and described data are published on a data repository <https://ressources.france-bioinformatique.fr/fr/services/donnees>

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Orsay

Other sites in France: Auzeville-Tolosane, Bordeaux, Clermont-Ferrand, Jouy-en-Josas, Montpellier, Nantes, Paris 5°, Paris 13°, Paris 15°, Rennes, Roscoff, Strasbourg, Versailles, Villeurbanne, Évry-Courcouronnes

French supporting institutions: CNRS-INSB

Director or RI representative in France:

• Claudine Médigue

• **Construction:** 2013

• **Operation:** 2016

• **Stakeholders in France:** INRAE, Inserm, CEA, Inria

• **Contact in France:** www.france-bioinformatique.fr/guichet-conseil-orientation/

• **Website:** www.france-bioinformatique.fr

International dimension

ELIXIR, ESFRI landmark

Director: Niklas Blomberg

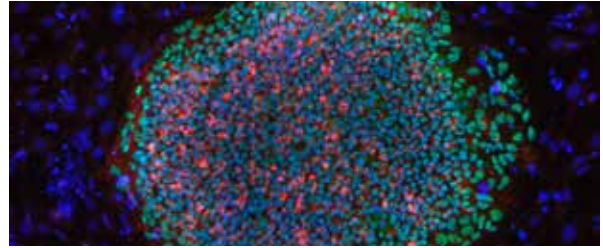
• **Partner countries:** BE, CH, CZ, DE, DK, EE, ES, FI, FR, HU, IR, IS, IT, LU, NO, NL, PT, UK, SL, SE.

• **Website:** <https://elixir-europe.org>

INGESTEM

National Pluripotent Stem Cell and Tissue Engineering Infrastructure

The INGESTEM infrastructure develops medical applications of human embryonic stem cells (ESC) and induced pluripotent stem cells (iPSC). The objective is to accelerate the development of cutting-edge technologies and translational research to model diseases via iPSCs with the aim of developing new cell and gene therapies for future applications, regenerative medicine and cancer. INGESTEM develops innovations and technological resources in partnership with European and international consortia, in cell reprogramming strategies, differentiation protocols and molecular screening strategies, and large-scale culture of clinical grade cell products. iPSC/ESCs are used for genome engineering and organoid generation for innovative therapies and cell-based therapies in the field. iPSC/ESCs derived from animal models are available to evaluate the safety and therapeutic efficacy in vivo of ESC/iPSC-derived cell



© Olivier Féraud

grafts. INGESTEM is currently developing the national iPSC bank "Haplobank" within a university platform at Genopole to generate clinical grade iPSC lines that will allow the generation of "MTI" medicines for innovative therapies, for Phase I/II clinical trials in regenerative medicine and immuno-oncology.

Relations with economic actors and/or socio-economic impact

Since its creation, INGESTEM has trained more than 170 people in cell reprogramming; and participates in European and international consortia such as PreviTox (national), ScreenTox and RESTORE (European) and GAIT, Global Alliance for iPSC Therapies (international). 6 spin-offs have emerged from INGESTEM with 3 iLAB Awards and 11 patents have been filed in the field of iPSCs, including 2 licenses in co-development with industry.

Open science and data

- Some of the publications from projects using the infrastructure are open access
- Annual data production: 100 TB

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Bron, Corbeil-Essonnes, Montpellier, Villejuif

French supporting institutions: Inserm

Director or RI representative in France:

• Annelise Bennaceur

• **Construction:** 2021

• **Operation:** 2021

• **Stakeholders in France:** Université Paris-Saclay, Université Évry-Val-d'Essonne, CHU Montpellier

• **Contact in France:** Annelise Bennaceur

• **Web site:** www.ingestem.fr

International dimension

GAIT

- **Partner countries:** CA, CN, FR, KR, US, UK
- **Web site:** www.gait.global

Laboratoire P4 Jean Mérieux

Research infrastructure dedicated to highly infectious diseases – Inserm Jean Mérieux BSL4 Laboratory

The Inserm Jean Mérieux BSL4 Laboratory is a research infrastructure dedicated to the study of the most dangerous pathogens belonging to Risk Group 4 (RG4).

The state of knowledge concerning Risk Group 4 agents, which are characterised by high mortality, lack of diagnostic tools and therapeutic and prophylactic means, remains very limited. In this context, the P4 laboratory is organised as a major research tool hosting academic or private, national but also European and international teams. As a major player in the European RG4 research capacity, the infrastructure provides the scientific community with cutting-edge operational capacities as well as high-performance scientific and technical services adapted to the implementation of innovative programmes ranging from the very basic to pre-clinical



© Inserm/Patrick Delapierre

trials; and aiming at a better understanding of the physiopathological mechanisms associated with infection by these viruses as well as the development of new prophylactic, therapeutic and diagnostic tools.

Relations with economic actors and/or socio-economic impact

The provision of the infrastructure concerns the provision of scientific and technical assistance for the definition and implementation of projects. Any experimentation can be carried out for the project leaders by the laboratory staff. In this context, the Inserm Jean Mérieux BSL4 laboratory has established solid partnerships with national and European players and within consortia or bilaterally with private players.

Open science and data

- Annual data production: 10 TB
- Some of the publications from projects using the infrastructure are open access

Category: RI

Type of infrastructure: single site

Infrastructure location in France: Lyon

French supporting institutions: Inserm

- **Director or RI representative in France:** Hervé Raoul
- **Construction:** 1999
- **Contact in France:** www.laboratoirep4-jeanmerieux.inserm.fr/contactez-nous
- **Website:** www.laboratoirep4-jeanmerieux.inserm.fr

International dimension

ERINHA, ESFRI landmark

Director: Hervé Raoul

- **Partner countries:** SE, PT, HU, NL, FR
- **Website:** www.erinha.eu

LiPh@SAS

Livestock Phenotyping for Sustainable Agricultural Systems

LiPh4SAS is an infrastructure dedicated to the phenotyping of farm animals (cattle, small ruminants, pigs, fish). It consists of 8 experimental units housing animals, a functional exploration platform and a structure dedicated to the management and provision of the data produced. The phenotypes measured range from the fine exploration of biological functions on small numbers of animals (vertical phenotyping), to non-invasive measurements on large numbers (horizontal phenotyping). The animals have a precisely known health, genetic and physiological status. They are derived from commercial populations or from original populations allowing the study of particular biological functions. The measurements, standardised and robust, are carried out under varied and finely characterised rearing conditions, allowing the study of genotype x environment interactions or the animals' responses to environmental variations. The protocols are designed



© Jean-Pierre Bidanel (Montage)

to ensure the reproducibility of results and are carried out in strict compliance with animal welfare and animal experimentation regulations (3Rs rule – Reduce, Refine and Replace). The infrastructure also has a mission of technological innovation, notably for the development of non-invasive methods, alternatives to animal experimentation, training and technology transfer.

Relations with economic actors and/or socio-economic impact

LiPh4SAS has many links with agricultural technical institutes (scientific collaborations, joint technological units, agreements, etc.). Several collaborations also exist with private sector players, either directly or via research units, in particular within the framework of the Carnot France Futur Elevage, as well as with start-ups/SMEs for the development of phenotyping tools or software.

Open science and data

- Annual data production: 40 TB
- Infrastructure with a FAIR data policy in application
- The validated and described data are published on a data repository <https://data.inrae.fr>

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Castanet-Tolosan, Osmoy, Saint-Genès-Champanelle, Saint-Gilles, Saint-Pierre-d'Amilly, Saint-Pée-sur-Nivelle, Sizun

French supporting institutions: INRAE

Director or RI representative in France:

Jean-Pierre Bidanel

Construction: 2021

Operation: 2021

Contact in France: Jean-Pierre Bidanel

Website: www6.inrae.fr/liph4sas

International dimension

AquaExcel2020/SmartCow/PigWeb

Website: <https://aquaexcel2020.eu>

MetaboHUB

**French distributed infrastructure for metabolomics and fluxomics
dedicated to innovation, training and technology transfer**

MetaboHUB provides French and international researchers with the essential tools and methods for metabolic phenotyping and functional characterisation of the metabolism of biological systems in many research fields (health, plants, biotechnologies). To this end, MetaboHUB develops and transfers to the academic and private scientific community physicochemical analysis methods as well as an ecosystem of digital tools for the analysis of data required for metabolomics and fluxomics approaches (W4M, PeakForest, MetExplore). These technologies (NMR, LC-MS, GC-MS, statistics, bioinformatics) are developed to enable high-throughput and high-resolution biochemical phenotyping from single cell to large sample sets (biological fluids from human cohorts, plant extracts, micro-organisms) and high-throughput metabolic flux measurements in prokaryotic and eukaryotic cells. Since 2019, MetaboHUB has developed projects in partnership with other national



infrastructures in biology and health in order to understand metabolism in an integrative and multi-scale manner. MetaboHUB brings together a network of 5 platforms under the supervision of INRAE and CEA: Bordeaux (INRAE, CNRS and Univ. Bordeaux); Clermont-Ferrand (INRAE, CNRS, Univ. Blaise Pascal); Toulouse, (Univ. Paul Sabatier, INSA, INRAE, CNRS, INSERM); Paris-Saclay, (CEA, INRAE, Univ. Paris-Saclay); Nantes (CNRS).

Relations with economic actors and/or socio-economic impact

As a player in the socio-economic world, MetaboHUB has a strong action of theoretical and practical training of engineers and researchers in the various fields of metabolomics. MetaboHUB is also solicited by industrial players in many sectors of activity such as food-processing, industrial biotechnology, health or the environment. More than 150 companies have already benefited from MetaboHUB equipments and expertises.

Open science and data

- The source codes produced by the infrastructure are open on a software forge <https://github.com/eMetaboHUB>
- Annual data production: 15 TB
- The validated and described data are published on a data repository <https://metabohub.peakforest.org/webapp>

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Toulouse

Other sites in France: Gif-sur-Yvette, Nantes, Paris, Villenave-d'Ornon

French supporting institutions: INRAE

• **Director or RI representative in France:** Fabien Jourdan

• **Construction:** 2013

• **Operation:** 2013

• **Stakeholders in France:** CEA, Inserm, CNRS, INSA de Toulouse, UCA, UBx, Sorbonne U, Université Toulouse III - Paul Sabatier

• **Contact in France:** www.metabohub.fr/contact

• **Website:** www.metabohub.fr

NeurATRIS

Translational Research Infrastructure for innovative therapies in Neuroscience

NeurATRIS is a research infrastructure designed to accelerate the transformation of basic research discoveries into medical innovations for the treatment of nervous system diseases. Based on seven main research centres located in the Paris region and in Nantes, NeurATRIS represents one of the largest concentrations of neuroscience researchers, engineers and clinicians in Europe (around 2,000). NeurATRIS, a distributed infrastructure, brings together MIRCen, SHFJ and Neurospin from the CEA, the Brain Institute, the Henri Mondor, Bicêtre and Robert Debré hospital groups, the INRAE's UMR PANTHER and I-Stem, around high-level skills, expertise and technical platforms specialising in neurology, biotherapy and neurodevelopmental disorders. In these fields, NeurATRIS is positioned as the largest European infrastructure conducting R&D projects and providing services to academics, clinicians and industry. The work carried out by NeurATRIS concerns Parkinson's disease, Huntington's disease, Alzheimer's



© NeurATRIS/APH/UPEC/Julien Valette et Thierry Delzescaux, CEA-MIRCEN/Matrin Carbot-Tano, ICM

disease, multiple sclerosis and neurodevelopmental diseases. The objective of this research is to accelerate the understanding of physio-pathological, biological and developmental mechanisms, to facilitate the implementation of preclinical/clinical trials for the validation of new therapies and to develop innovative approaches to diagnosis and care for these diseases.

Relations with economic actors and/or socio-economic impact

As the French node of ERIC EATRIS, NeurATRIS simplifies access to its platforms for French and European players and improves France's visibility in the field of translational neuroscience research. NeurATRIS develops public and private partnerships aiming at developing new therapies, gathering expertise in a unique structure, giving access to high-level platforms in translational research.

Open science and data

- Some of the publications from projects using the infrastructure are open access
- Annual data production: 1 PB

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Fontenay-aux-Roses

Other sites in France: Corbeil-Essonnes, Créteil, Fontenay-aux-Roses, Le Kremlin-Bicêtre, Nantes, Orsay, Paris, Saint-Aubin

French supporting institutions: CEA

Director or RI representative in France:

• Philippe Hantraye

Construction: 2011

Operation: 2012

Stakeholders in France: Inserm, AP-HP, UPEC, INRAE, ICM

Contact in France: <http://neuratris.com/index.php/ft/neuratris-contact>

Website: www.neuratris.com

International dimension

EATRIS, ESFRI landmark

Director: Antonio L. Andreu

- **Partner countries:** BG, CZ, FI, FR, IT, LV, LU, NL, NO, PT, SI, ES, SE, EE
- **Website:** <https://eatris.eu>

NEUROSPIN

Research center for innovation in brain imaging technologies

NeuroSpin is a research infrastructure that aims to advance knowledge of the brain, particularly the human brain, by developing and exploiting cutting-edge methodologies in brain imaging and neuroinformatics.

NeuroSpin is equipped with 3 MRI scanners for humans (3T, 7T and 11.7T MRI scanners currently being tested, the latter being the only one of its kind in the world) and 3 preclinical MRI scanners for small animals (7T, 11.7T and 17.2T, the latter again being the only one of its kind in the world). NeuroSpin also has a platform for electroencephalography (EEG, 256 channels) and magnetoencephalography (MEG, 306 channels) recordings as well as electrophysiology instruments (Utah arrays, laminar electrodes) and 3-photon imaging (rodent, primates).

NeuroSpin is also equipped with significant computing resources (1 Gb network for 100 workstations, ~1,200 TB of redundant/archived backup space, departmental



© CEA

CATi/NeuroSpin cluster with 500 cores). Finally, it houses technical workshops (electronics, mechanics, chemistry, histology and cell culture), an infrastructure for clinical research and investigation involving healthy or sick volunteers, including children and the elderly (day hospitalization beds, examination and test rooms, medical and paramedical staff), and an infrastructure dedicated to preclinical research.

Relations with economic actors and/or socio-economic impact

NeuroSpin opens its large imaging instruments to the entire French and international physics and neuroscience community to meet three main objectives:

- Study the complexity of the human brain at different scales,
- Understand what makes the human brain unique,
- Identify the markers and mechanisms of certain neurological, psychiatric or neurodevelopmental diseases.

Open science and data

- Annual data production: 1 PB
- Some of the publications from projects using the infrastructure are open access

Category: RI

Type of infrastructure: single site

Infrastructure location in France: Saint-Aubin

French supporting institutions: CEA

Director or RI representative in France:

• Stanislas Dehaene

• **Construction:** 2007

• **Operation:** 2008

• **Stakeholders in France:** INSERM, INRIA, Université Paris-Sud

• **Contact in France:** Stanislas Dehaene

• **Website:** http://joliot.cea.fr/drf/joliot/Pages/Plateformes_et_infrastructures/plateformes_imagerie/plateforme-neurospin.aspx

Phenome-Emphasis France

French Plant Phenomics Infrastructure

Phenome-Emphasis (created in 2012 with ANR-INBS funding) develops equipment for phenotyping thousands of plants, as well as methods for analysing the genetic variability of plant responses to climate change (drought, CO₂, high, high temperatures, emerging diseases). The infrastructure has:

- built or improved facilities in nine French sites in greenhouses, in highly equipped fields and in networks of simpler-equipped fields;
- developed new sensors, robots for data acquisition, processing chains and information systems capable of managing millions of data;
- disseminated the techniques and methods to the French phenotyping community (seed companies, technical institutes, public research);
- promoted the emergence of SME technology providers

Phenome-Emphasis continues these activities, but has also identified new challenges:



© Ph. Burger

- Facilitating the agro-ecological transition with equipment and methods for analysing interactions between plants and other organisms (micro-organisms, insects, other plants);
- Deploying an information system and tools so that the data collected is open and available, with all the necessary information;
- Fully integrate its activities in a European context, in particular with the project.

Relations with economic actors and/or socio-economic impact

Phenome Emphasis contributes to the competitiveness of French seed companies, which use its facilities for the characterisation of their genetic material. The infrastructure is in close contact with a network of SMEs via the joint development of tools and methods, with joint patents or licences. It has helped these SMEs to develop their catalogue, and to market their products in France and abroad.

Open science and data

- The source codes produced by the infrastructure are open on a software forge <https://github.com/OpenSILEX>
- Annual data production: 0,5 PB
- Infrastructure with a FAIR data policy in application
- The validated and described data are published on a data repository <https://data.inrae.fr>

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Montpellier

Other sites in France: Auzeville-Tolosane, Avignon, Beauce la Romaine, Beaucouzé, Bretenière, Castanet-Tolosan, Clermont-Ferrand, Dijon, Mauguio, Montpellier, Nantes, Versailles, Villenave-d'Ornon

French supporting institutions: INRAE

Director or RI representative in France: François Tardieu

Construction: 2016

Operation: 2016

Stakeholders in France: Arvalis institut du végétal, Terres inovia

Contact in France: www.phenome-emphasis.fr/Contact

Website: www.phenome-emphasis.fr

International dimension

EMPHASIS, ESFRI project

Directors: Ulrich Schurr et François Tardieu

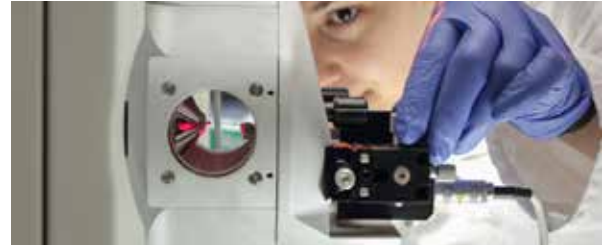
- **Partner countries:** DE, UK, NL, BE, PT, CH, IT, FR
- **Website:** https://emphasis.plant-phenotyping.eu/Plant_Phenotyping

ProFI

Proteomics French Infrastructure

The advancement of knowledge in the field of biology and health is based on the deciphering of mechanisms at the cellular and molecular levels. Proteins, the end product of gene expression, are major players in the functioning and regulation of cellular processes. The National Biology and Health Infrastructure ProFI (Proteomics French Infrastructure) focuses its R&D activity on the development of tools and methods for the structural and functional characterisation of proteins and protein complexes. Proteomic analysis has many applications today, particularly in the fields of medical biology, food-processing and biotechnology.

The ProFI infrastructure was created in February 2012 and brings together three of the main French platforms in France (~70 FTEs in Grenoble, Toulouse and Strasbourg). In addition to its R&D activity, ProFI's mission is to offer proteomic analysis services to the community in the framework of collaborations or services. ProFI participates in the dissemination of its



© P. Avastian/CEA

expertise and the tools it develops within the scientific community through training and communication activities.

The ProFI infrastructure is involved in (i) coordination actions towards the proteomic community (prospective document), (ii) interactions with other infrastructures in biology and health and (iii) large-scale projects at the international level.

Relations with economic actors and/or socio-economic impact

ProFI has strong industrial relationships (> 30 partners), in particular with the pharmaceutical industry (e.g. protein biomarker research, vaccine purity assessment).

The other sectors involved are food, agriculture and bio-production. Some projects are also carried out in conjunction with French competitiveness clusters. ProFI has been closely associated with the creation of start-ups (e.g. Syndivia).

Open science and data

- Some of the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure are open on a software forge <https://github.com/profiproteomics>
- Annual data production: 80 TB
- The validated and described data are published on a data repository www.proteomexchange.org

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Grenoble, Strasbourg, Toulouse

French supporting institutions: CNRS

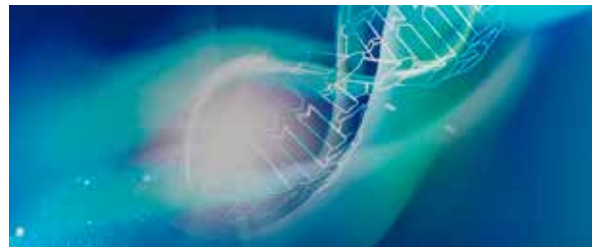
- **Director or RI representative in France:** Myriam Ferro
- **Construction:** 2012
- **Operation:** 2012
- **Stakeholders in France:** Inserm, Université de Strasbourg, Université Toulouse III – Paul Sabatier, UGA, CEA
- **Contact in France:** Myriam Ferro
- **Website:** www.profiproteomics.fr

CAD

Data Analyser Collector

The Central Data Analyser (CAD) project is at the core of the 2025 French Genomic Medicine Initiative. Its ambition is to provide an infrastructure for the collection of genomic data and the provision of services, firstly on the care side to help practitioners interpret the data and have their patients benefit from them, and secondly on the research side to offer the research community the possibility of carrying out a wide range of studies on the data collected in a homogeneous way. It will thus constitute a unique knowledge base.

The CAD will offer several services to the research community: a helpdesk, assistance and advice on project design, access to datasets and tool libraries, provision of virtual machines, hosting of genomic and related data, methodological tools, statistical analysis rendering, and data transfer.



© microm

The research communities that will use the CAD are: genetics/genomics, biological systems at the molecular level, pharmacology, biomarkers and companion tests, pathophysiology and nosology of diseases, clinical research, epidemiology, data science, infrastructure and architecture, software technology and engineering, digital stimulation and modelling.

Relations with economic actors and/or socio-economic impact

The CAD represents a major economic challenge, as it will develop a new industrial sector.

The CAD will offer a unique service to the biotechnology, diagnostic, pharmaceutical and digital industries. This service offer is now in preparation.

Open science and data

- All the publications from projects using the infrastructure are open access
- Annual data production: 5 PB

Category: Projet

Type of infrastructure: single site

Infrastructure location in France: Bruyères-le-Châtel, Montpellier, Paris

French supporting institutions: structure juridique publique à personnalité morale

Director or RI representative in France:

• Franck Lethimonnier

• **Stakeholders in France:** Inserm, CEA, Inria, France Universités, Conférence des Directeurs Généraux de CHRU, Fédération UNICANCER, Groupement de coopération sanitaire SeqOIA, Groupement de coopération sanitaire AURAGEN, MESRI, Ministère des solidarités et de la santé

• **Website:** <https://pfmt2025.aviesan.fr/le-plan/collecteur-analyseur-de-donnees-cad/>

International dimension

Ongoing project in the framework of the European 1+ Million Genomes' Initiative. European "1+ Million Genomes" Initiative

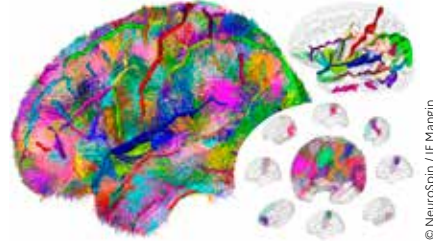
- **Partner countries:** PT, ES, IT, DE, BE, NL, FI, NO, SE, EE, LT, LV, DK, CZ, HU, SI, LU, GR, HR, CY, AT, BG, MT, UK
- **Website:** <https://b1mg-project.eu>



EBRAINS-FR

European Brain ReseArch INfrastructureS-France

EBRAINS-FR est le nœud Français de l'infrastructure de recherche Européenne EBRAINS, inscrite sur la feuille de route du Forum Européen des Infrastructures de Recherche, ESFRI, depuis début juillet 2021. EBRAINS est portée par la France, représentée par le Commissariat à l'Énergie Atomique et aux Énergies Alternatives (CEA). Elle rassemble à ce jour 7 pays Européens, la France, l'Allemagne, l'Italie, l'Espagne, la Norvège, la Suède, la Suisse. La Belgique, le Danemark, les Pays-Bas et le Royaume Uni sont en passe de rejoindre le réseau. EBRAINS a pour mission de faire progresser la recherche dans le domaine des neurosciences computationnelles. Elle émane du programme Européen Human Brain Project. Elle propose donc déjà des services et des outils regroupés en plateformes pour faciliter la recherche sur le cerveau dans les domaines des neurosciences, de la santé (psychiatrie, neurologie, oncologie cérébrale) et des technologies neuro-inspirées, qui seront enrichis au fur et à mesure de sa montée en puissance.



© NeuroSpin / J.F. Margin

EBRAINS-FR rassemble les laboratoires français experts en neurosciences fondamentales, cognitives et computationnelles, afin de proposer une feuille de route de développement des neuro-technologies, d'informatique bio-inspirée, de modélisation et d'émulation du fonctionnement du cerveau à partir du maximum de données possibles pour obtenir des représentations prédictives, efficaces et utiles à la compréhension des fonctions cérébrales et de ses pathologies.

Relations with economic actors and/or socio-economic impact

EBRAINS et EBRAINS-FR ont l'ambition:

- a) de mettre à disposition des plateformes d'analyse et de modélisation des données;
- b) de donner accès à des moyens d'analyse et de calcul à une très large communauté scientifique, de neuroscientifiques, de médecins, de spécialistes des sciences de l'information et des interfaces cerveau-machine...;
- c) soutenir le développement de grands projets en neurosciences pour répondre aux grands défis de Santé.

Open science and data

- The source codes produced by the infrastructure are open on a software forge: <https://github.com/HumanBrainProject>
- Annual data production: 500 TB

Category: Projet

Type of infrastructure: distributed

Infrastructure location in France: Gif-sur-Yvette, Marseille 5^e

Other sites in France: Bordeaux, Gif-sur-Yvette, Nantes, Paris 3^e, Paris 12^e, Paris 13^e

French supporting institutions: CEA

- **Director or RI representative in France:** Philippe Vernier
- **Construction:** 2021
- **Année d'exploitation:** 2021
- **Stakeholders in France:** CNRS, Inserm, Inria, AMU, Université de Paris, UGA, Université de Nantes, Université Paris-Saclay, UBx, Université Claude Bernard - Lyon 1, Sorbonne Université
- **Contact in France:** Philippe Vernier
- **Website:** <https://ebrains.eu>

Dimension internationale

EBRAINS

Director: Paweł Świeboda (CEO EBRAINS AISBL)

- **Pays partenaires:** FR, DE, ES, NO, IT, CH, SE
- **Website:** <https://ebrains.eu>

FR Exposome

FRANCE EXPOSOME

The vocation of France Exposome is to produce excellent research aimed at a better understanding of the associations between chemical exposure and health events.

The five platforms and laboratories that make up Fr-Exposome deploy measurement approaches aimed at the high-throughput characterisation of human internal exposure via targeted approaches allowing the measurement of known chemical compounds and exploratory approaches without a priori whose ambition is to broaden knowledge of the chemical exposome. The general objective of Fr-Exposome is to reach a conceptual, technological and scientific milestone in order to actively participate in this ongoing paradigm shift. Fr-Exposome thus aspires to become a driver of technological and methodological innovation in conjunction with academic and private partners. Fr-Exposome will generate fundamental knowledge related to toxicokinetics to develop new modelling tools



to accompany data interpretation, and will play a major role in the training of users and the new generation of researchers. Fr-Exposome will forge strong links with existing infrastructures in the fields of bio-collections, advanced data processing and bioinformatics tools. Fr-Exposome will interact and develop links with FRANCE GENOMIQUE, PROFI and METABOHUB to address this major public health issue in an integrative way.

Relations with economic actors and/or socio-economic impact

The structures using France-Exposome are public players such as health agencies, national and European research players, hospitals and cancer centres. France Exposome will be solicited by large national companies in the treatment of contaminated environments for the monitoring of health at work, but also by international companies specialising in measurement technologies.

Open science and data

- Some of the publications from projects using the infrastructure are open access
- Annual data production: 30 TB
- The validated and described data are published on a data repository

Category: Project

Type of infrastructure: distributed

Infrastructure location in France:

Other sites in France: Nantes, Paris 6^e, Toulouse, Verneuil-en-Halatte

French supporting institutions: Inserm

● **Director or RI representative in France:** Michel Samson

● **Construction:** 2021

● **Stakeholders in France:** ONIRIS, EHESP, Université de Paris, INERIS, INRAE

● **Contact in France:** Michel Samson

● **Website:** www.france-exposome.org

International dimension

EIRENE, ESFRI Project

Director: Jana Klanova

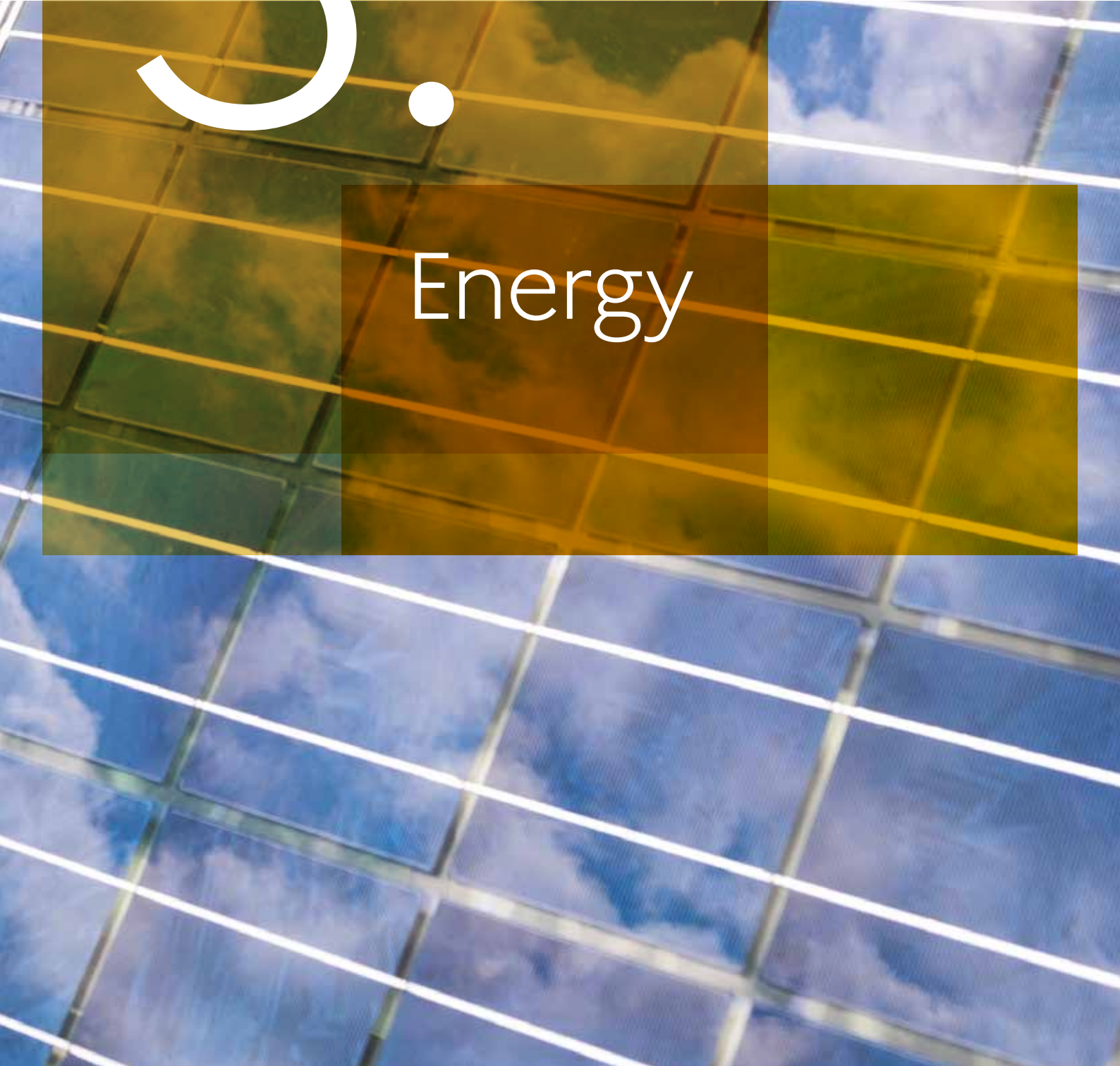
● **Partner countries:** CZ, SI, AT, IT, NL, GR, SK

● **Website:** www.eirene-ri.eu



3.

Energy



Energy

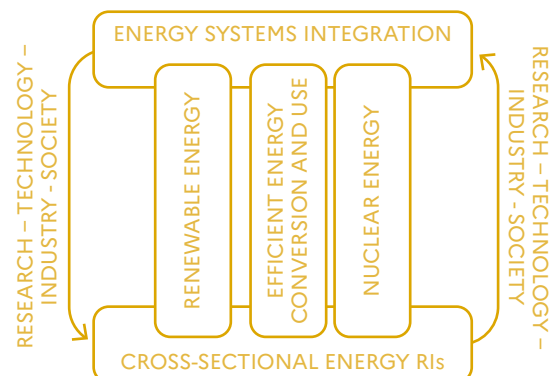


The world of energy must adapt to major changes that are necessary on different scales. Achieving these major changes requires the removal of major scientific and technical barriers, which are increasingly complex and require specific and often new skills as well as research equipment and infrastructures. Thus, the world of energy will have to meet the needs of decarbonisation, which involves the capture, storage and recovery of CO₂, allow the storage of energy at different scales as well as the growing production of renewable energy – solar energy, marine energy including floating wind power – as well as their integration into the networks, and finally meet the major challenges of nuclear energy, particularly fusion.

MAJOR SCIENTIFIC ISSUES AND SOCIETAL CHALLENGES: WHAT CONSEQUENCES FOR THE NEEDS AND USE OF RESEARCH INFRASTRUCTURES?

The fight against global warming, the improvement of air quality, the fight against fuel poverty and simplified access to energy, and the variety of the energy mix are all challenges to be taken up with a view to sustainable development. In the vast majority of cases, these major structuring challenges represent the guidelines drawn up at institutional level either through European directives, particularly those on renewable energy and the implementation of the Green Deal, or at national level (the Law on Energy Transition for Green Growth (LTECV), the Climate Plan, the National Energy Research Strategy, within the framework of the PIA4, etc.). This body of legislation must allow for a sustainable and secure energy supply with a reduced impact on the environment, both on a local/territorial and global scale. Thus, the world of energy must satisfy the increase in demand at the global level and must adapt to the major changes chosen at the national and territorial levels. For example, in France, the trajectories targeted by the LTECV must lead to a 40% reduction in greenhouse

gas emissions in 2030 compared to 1990. De-fossilisation, decarbonisation of the energy mix and diversification of energy supplies are the crucial determinants for meeting the major climate challenges. The 21st century will therefore be one of energy transition. The significant reduction of CO₂ emissions, the mastery of the energy mix and its integration into the networks by 2050 are major challenges of international scope, which lead to very large needs in research and specific equipment. The energy field can be segmented into five major areas: (i) integration of energy systems including networks, energy transport and storage, (ii) renewable energies: solar, wind, geothermal, biomass



energies, (iii) marine energies, (iv) energy efficiency in conversion and use: energy in buildings and industry, Power to G, to X, CCSU, (v) nuclear energy: fission and fusion, and not forgetting cross-cutting issues such as materials, data, simulation and modelling.

Renewable energy

The decarbonisation of the energy mix requires an increase in the use of intermittent and non-intermittent renewable energies: photovoltaic and concentrated solar energy, wind energy (onshore, offshore or floating), marine energy in all its forms (current energy, wave energy, tidal ebb and flow energy, ocean thermal energy, osmotic energy), geothermal energy and biomass. Over the last five years, the cost of some of these renewables has fallen considerably, notably for onshore wind power, and for solar photovoltaics due to the development of new and more efficient concepts and the economies of scale associated with the rapidly growing deployment.

In addition, for many of the renewable options, further significant cost reductions can be achieved through the development of new concepts – new solar cell technologies (tandem, perovskites...), floating offshore wind, turbine performance (>15 MW), biotechnology processes for biomass conversion – again through scaling up of deployment. However, these new concepts may require significant research and development costs, knowledge is dispersed, markets are often global and having research infrastructure is a success factor. In the field of renewable energies, several initiatives have made it possible to have these resources available at European level: Windscanner for wind energy, EU Solaris for concentrated solar energy, to which must be added the EU-IBISBA Infrastructure, which covers some of the concerns regarding the transformation of biomass for energy purposes, but which has a multiple vocation, in particular with a high volume

for the Biology-Health field. At the national level, there is no infrastructure for wind energy and the structuring of the research world, the industrial field and the maturity of developments do not show important needs. In the field of solar energy, concentrated solar power is of great interest and there are hardly any large-scale applications yet, although there are major experimental needs. France is one of the partners of EU-Solaris via FR-Solaris and this participation is important. In addition, EU-Solaris is supporting an ERIC application with France as a partner. In the field of photovoltaic solar energy, there is currently no referenced Infrastructure (the major European projects have not led to the establishment of an RI) but France considers that there is a real need to help and accompany all the major changes in the field. Moreover, France has at its disposal, through the CEA INES and the Institute for Energy Transition IPVF, recognised and efficient means to offer experimental means adapted to the future stages. Consideration should be given to the implementation of an infrastructure on this theme based on these resources. In the field of marine energies, structuring at European level is underway with Mariner-g-i, led by Ireland. France also has test facilities structured as a research infrastructure, the RI THEOREM (associating ECN-CNRS, IFREMER, UGE) offering significant and relevant resources to the major players in the development of marine energies, but also enabling the major obstacles associated with floating wind energy to be addressed. Its continuation and reinforcement are essential, taking into account the growing demand for floating wind energy. In the field of geothermal energy, the needs are more diffuse and difficult to identify. However, the recent problems associated with the development of geothermal wells could give rise to needs. A reflection is to be carried out, probably with the ECCSEL infrastructure on this subject. For the transformation of biomass for energy purposes, the disciplinary spectrum is broad



and is based in particular on the two major fields of biotechnologies and chemistry/ biochemistry/thermochemistry/biocatalysis/ photocatalysis. Concerning the first component, both at the European and national levels, the IBISBA-FR infrastructure, which is supported by the Biology-Health sector, is structured to offer and provide access to the biotechnology research communities to the means adapted to the lifting of major scientific and technological barriers, in a wide range of applications. Concerning the second scientific aspect, it appears that the production of components by means of chemical, thermochemical and catalytic processes, particularly when targeting artificial photosynthesis, cannot currently be based on an existing research infrastructure, even though a growing need is emerging in these disciplines.

A research infrastructure offering means associated with chemistry/ biochemistry/

thermochemistry/ biocatalysis/photocatalysis is important. This is a reflection to be launched by the energy specialists in consultation with their counterparts in the fields of Biology-Health and Environment.

The table below shows the situation of existing research infrastructures and possible developments in relation to renewable energy.

Energy efficiency of processes, energy production and uses

Among the major concerns for controlling and reducing greenhouse gas emissions are conversion processes to produce energy from both fossil fuels and biomass, energy consumption in energy-intensive industries such as cement, steel, ammonia and glass production, to name but a few, and energy efficiency, an area that is now becoming very important; finally, Power to X/Power to Power, another emerging field for which the scope of impact on research infrastructure needs

ENERGY TO CAPTURE	FRENCH RI	STATUS	SUPPORTING/ PARTNER	EUROPEAN RI
Wind turbine	No identified needs			Windscanner
Marine (including offshore, floating et land-based wind energy)	THEOREM	In the 2018 French roadmap	CNRS-ECN, IFREMER, UGE	Marinerg-i, in progress
Concentrated solar power	FR-Solaris	In the 2018 French roadmap	CNRS/Promes	EU-Solaris, ERIC project in progress
Biomass	Biotechnology processing: IBISBA-FR	In the 2018 French roadmap, carried by the Biology and Health sector	INRAE	IBISBA-EU
POSSIBLE FUTURE DEVELOPMENTS				
Photovoltaic solar energy	No RI currently	Reflection to be carried out	CEA (1)/IPVF (2)	No
Biomasses	No RI for non-biotech components	Reflection to be carried out	CNRS	No

(1) CEA INES with Université de Savoie Mont-Blanc

(2) IPVF, ITE associating the CNRS, the Ecole Polytechnique, Air-Liquide, EDF, Horiba Riber, Total

is probably still poorly assessed. For all industrial applications (energy and non-energy), the capture, transport and storage of CO₂ are the short/medium term solution to significantly reduce greenhouse gas emissions, not to mention the reuse and recovery of CO₂. The European research infrastructure ECCSEL, led by Norway, which has ERIC status, with the French node ECCSEL-FR led by BRGM, offers a variety of resources that partly correspond to the needs of all stakeholders. Indeed, ECCSEL FR relies on six major organisations (BRGM, IFPEN, ANDRA, INERIS, CNRS, ARMINES) and three industrialists (EDF, Total Energies, Lafarge Ciments), which allows for a relevant and very significant evolution of ECCSEL, particularly for lower TRL studies, and above all reinforces the great interest of this infrastructure. For non-industrial applications and uses, it is currently difficult to identify precise angles of attack for studies based on research infrastructures. Indeed, the problems are very diffuse and often dependent on the applications. For the time being, it has not been deemed appropriate to pursue investigations in this area, even though it is a key topic. In the future energy landscape, the PtX concept is also likely to develop, but in absolute terms, it can be defined as an aggregation of technological building blocks, most of which are known: energy production, conversion of energy into hydrogen, hydrogen storage and reuse. In France, for example, the Jupiter 1000 project, which is leading to a demonstration stage, is an illustration of this. It can be considered that the experimental scope is or should be covered (see discussion on energy and hydrogen storage). These last two challenges are essential and will lead to the emergence of new needs that must be addressed.

Nuclear energy

Nuclear energy is recognised at European level as one of the components of the climate strategy. Its contribution as a stable, greenhouse gas-free energy

source is a key component in ensuring European energy sovereignty.

This energy is based on two major components: a mature component, fission energy, which is continuing its technological development, and an emerging component for the second half of the century based on fusion energy, the future of which is partly based on the International Thermonuclear Experimental Reactor (ITER) project.

With regard to fission energy, the main scientific and strategic objectives in support of the nuclear industry are to use research to support the operation of the nuclear power plants at the highest level of safety and performance, to prepare for the renewal of part of the plants with new generation reactors, the principle of which is to be decided in 2023, and to carry out the scientific investigation of the CIGEO geological storage project for high-level and long-lived radioactive waste. In addition, the potential of Small Modular Reactors (SMRs) is being evaluated, either to help balance electricity production and demand in the regions, or to extend nuclear production to the supply of heat or hydrogen. The issue of extending the life of existing reactors is fuelling numerous research projects in France and in other countries on the behaviour of materials under irradiation. There is a real need for irradiation tools which will be partially filled by the future French Jules Horowitz reactor under construction (its start-up is planned after 2025) and which could be completed by digital simulation. Research on the transmutation of long-lived actinides, which is arousing interest in certain countries in Accelerator Driven Systems (ADS), is leading Belgium to plan a demonstration of principle in stages with the MYRRHA project selected in the ESFRI roadmap.

Concerning thermonuclear fusion, the first international experimental reactor (ITER) is currently under construction on French soil. This long-term research project aims



to establish the scientific feasibility of thermonuclear fusion of hydrogen isotopes by magnetic confinement (control of the plasma in an ignition situation). Its scale is extraordinary in terms of the technological challenges it represents, the international collaboration gathered around seven major partners (35 countries representing 85% of the world's gross annual product) and its overall cost estimated at more than €30 billion. It will be commissioned in two stages: around 2025-2027 the first plasmas and around 2035, the first tests with thermonuclear plasma.

To guarantee the success of ITER, certain technological obstacles must be overcome by supporting research projects. In this context, the WEST national infrastructure – the only French tokamak – piloted by the CEA and the CNRS, has positioned itself for the choice of a tungsten divertor, an essential component of ITER ensuring, among other things, the extraction of a large part of the heat. WEST's objective is to carry out validation tests at all stages (design, interactions with the plasma, behaviour in service, etc.).

WEST is a world-class infrastructure with a very wide range of experimental possibilities. It has brought together a community of national and international experts and provides training for future specialists.

The European roadmap in the field of fusion is focused on the two large ITER facilities and its successor DEMO, which should demonstrate the possibility of harnessing fusion to provide electricity and thus enable the design of an industrial reactor.

DEMO is planned for the second half of this century. One of the challenges of DEMO is the qualification of materials that will be subjected to 14 MeV neutrons. DONES is a major European infrastructure project that will enable these tests to be carried out.



Tore Supra

Energy system integration

The future European energy system, which will see a strong penetration of renewable energies, needs a strong interaction between the different energy carriers such as electricity, gas, heating and cooling, fuels, stored energy. Such a system requires the control and integration of intermittent renewable energy production, consumption variations (seasonal, territorial...) as well as the control of energy storage which will become an essential brick to stabilise power fluctuations. These major challenges are leading to the development of smart grids, both on a large scale and on a territorial or local scale (micro grids), and to the implementation of energy management systems (EMS). These distribution and network flexibility issues concern the major energy operators. It can be considered that significant RDI needs are necessary to improve decision support tools, for data management, the definition of key indicators, the implementation of intelligent strategies to meet demand integrating energy storage, at different time scales. The issue of storage is becoming one of the keystones of network management and the integration of intermittent energies: storage can take different forms. In general, without being exhaustive, storage is either electrochemical, gravitational, thermal, compressed air, inertial or gaseous. For this last application, it is very often the so-called Power to Gas concept that is used, using the hydrogen vector as the form to be stored (conversion of electricity by

electrolysis). Both at national and European level, strategies to develop a battery industry and to deploy a hydrogen sector are in place. In terms of research infrastructures, energy storage, materials, production technologies, fuel cells, batteries and their systems, needs may arise at both national and European level. Nevertheless, the emergence of the hydrogen sector at world level reveals a short/medium term need for its storage on different scales, particularly its storage in geological form. In this case, the test facilities and skills associated with the ECCSEL infrastructure are likely to be able to answer the questions posed (hydrogen storage in the first instance and opening up to geological energy storage in the second instance). This is a point to be strongly considered at both the level of ECCSEL France and ECCSEL EU, and the recent work of the ERIC ECCSEL shows that this aspect must be integrated into the scope. As things stand, there are no facilities in the sense of research infrastructures dedicated more broadly to energy storage and, as indicated above, a gap could quickly become apparent, firstly concerning the production and storage of hydrogen in all its forms, and then the geological storage of energy in the broad sense. ECCSEL can provide all the answers to these major questions. Finally, for all the technologies associated with batteries, needs will also be felt.

Transversal aspects

Materials for energy: despite the availability of a number of methods and facilities, platforms explicitly dedicated to R&D for materials for energy systems, this is a field in continuous evolution (new materials, new application constraints, etc.) which will require new characterisation means covering a wide spectrum of sizes – from the atomic scale to macroscopic engineering components - and different time scales. There will also be a particular need to develop in situ techniques for characterising materials in operating conditions.

Modelling and simulation: the world of energy is going to be confronted with numerous challenges: flexibility, multi-vector, intermittency, storage, etc., which will have integration as a lock. Indeed, it will be necessary to integrate new concepts, to integrate different energy sources on the networks. All these approaches will lead to a strong demand for modelling and simulation and a strong recourse to artificial intelligence. The connection with the infrastructures dedicated to these problems must be made.

Environment: as the impact of energy production on the environment (air quality, GHGs, waste generation), including safety issues, needs to be reduced, close links are easily established between energy and the research issues addressed by environmental infrastructures.

ECCSEL-FR

European Research Infrastructure for CO₂ Capture, Utilisation, Transport and Storage

In order to mitigate global warming, ECCSEL-FR is a research infrastructure dedicated to the development of technological solutions to reduce CO₂ emissions in industry and power generation and to remove CO₂ from the atmosphere. Its main mission is to accelerate the development of technologies for CO₂ capture, transport, geological storage and recovery (CCS, or CCUS). Its mission now extends to underground energy storage. Synergies with the development of renewable energies and hydrogen energy are also being considered. To this end, ECCSEL-FR offers researchers and engineers from all over the world state-of-the-art sites and experimental platforms made available by five research organisations (Andra, BRGM, CNRS, IFP Énergies nouvelles, INERIS) and two industrial companies (EDF, TotalEnergies). Other organisations are preparing to enrich the infrastructure with other research platforms (ARMINES/Mines Paris,



Lafarge Holcim, etc.). ECCSEL-FR is the French node of the European research infrastructure ECCSEL, which has the status of ERIC. The five founding countries are Norway, which hosts the headquarters, Italy, the Netherlands, the United Kingdom and France

Relations with economic actors and/or socio-economic impact

ECCSEL-FR is building relationships with various private and public actors in research and innovation. In France they are gathered within the Club CO₂, the AVENIA and AXELERA competitiveness clusters, the ANCRE and ALLENNVI alliances, etc. EDF and TotalEnergies are two private partners who wanted to join ECCSEL-FR from the beginning. LafargeHolcim has taken steps to do the same.

Open science and data

- All the publications from projects using the infrastructure are open access
- Annual data production: 20 TB

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Bure, Le Havre, Montpellier, Nancy, Orléans, Pau, Rennes, Rueil-Malmaison, Rustrel, Verneuil-en-Halatte

French supporting institutions: BRGM

- **Construction:** 2017
- **Operation:** 2017
- **Stakeholders in France:** ANDRA, CNRS, IFPEN, INERIS, EDF, TotalEnergies
- **Contact in France:** Isabelle Czernichowski-Lauriol, i.czernichowski@brgm.fr
- **Website:** www.eccsel.org

International dimension

ECCSEL, ESFRI landmark

Director: Sverre Quale

- **Partner countries** FR, IT, NL, NO, GB
- **Website:** www.eccsel.org

FR Solaris

French Research Infrastructure for Concentrated Solar Power

The FR-SOLARIS Infrastructure is supported by the PROMES laboratory: PROCédés, Matériaux & Énergie Solaire, of the CNRS. It brings together most of the national research resources on concentrated solar energy and constitutes a unique set of experimental devices open to research and industry. It allows to work in three main activities:

- Characterisation of materials under extreme conditions at high temperatures: aerospace, automotive, nuclear, etc...
- Synthesis of new materials or surface coatings: semiconductors, refractories, nanomaterials...
- Development of solar energy: production of electricity, synthetic fuels (hydrogen, syngas, etc...), energy storage (thermal or chemical), processes hybridisation, etc...

The research infrastructure is composed by:

- 12 solar furnaces from 1 to 1,000 kW, up to 4,000°C max;
- 1 tower power plant of 5,000 kW
- 1 parabolic trough solar power plant of 200 kW with flexible thermocline storage and ORC turbine.



© Emmanuel Guillot

These large optical facilities are supported by in-lab measurements and specifically adapted technologies for *in-situ* measures: optical temperature measurement by pyro-reflectometry, characterisation of thermoradiative properties such as spectral directional emissivity in temperature, surface chemical properties, etc.

This infrastructure with its team of experienced researchers, engineers and technicians enables early developments from low TRL to tests of industrial pilots and prototypes.

Relations with economic actors and/or socio-economic impact

The FR-SOLARIS Infrastructure is integrated into the socio-economic world in various ways:

- Towards the world of education, via the UPVD or others universities (France, Europe, USA...): visits, internships, training courses, lectures...
- Towards industry, via research contracts: internships, theses, services...
- Towards the tourist environment: exhibition for the general public, heritage days, science festival, panels for visitors...

Open science and data

- Part of the publications from projects using the infrastructure are open access
- Annual data production: 5 To

Category: RI

Type of infrastructure: single site

Infrastructure location in France: Font-Romeu-Odeillo-Via

French supporting institutions: CNRS

• **Construction:** 1950

• **Operation:** 1950

• **Stakeholders in France:** UPVD

• **Contact in France:** Françoise Bataille, francoise.bataille@promes.cnrs.fr

• **Website:** www.fr-solaris.cnrs.fr

International dimension

EU-SOLARIS, ESFRI project

Director: Manuel J. Blanco

• **Partner countries** ES, DE, CY, IT, PT, TR, GR

• **Website:** www.eusolaris.eu

THEOREM

Network of Hydrodynamic Test Facilities for Marine Renewable Energies

The THEOREM Research Infrastructure brings together a set of test facilities and skills from Centrale Nantes, Ifremer and the Gustave Eiffel University, with the aim of supporting research, development and innovation projects in the ocean engineering and marine engineering sectors, and in particular the Marine Renewable Energy industry. The distributed infrastructure integrates in particular:

- the hydrodynamic test facilities of Ifremer and Centrale Nantes, including four wave basins (ECN: traction basin and ocean engineering basin. Ifremer: Deep wave basin and wave and current basin) and two open sea test sites: the SEM-REV open sea test site in Le Croisic (ECN) and the Sainte-Anne du Portzic sea trials platform (ifremer);



© IFREMER/Dugonay; Centrale Nantes; Université Gustave Eiffel

- the mechanical testing facilities on foundations and structures of the Gustave Eiffel University (Geotechnical Centrifuge and cable fatigue bench) and the mechanical testing facilities (testing facilities for cables) and hyperbaric testing facilities for materials and structures in the marine environment of Ifremer

Relations with economic actors and/or socio-economic impact

THEOREM promotes partnership research between universities, technical centres and industry. Combining experimental modelling with numerical modelling, the latter can proceed to de-risking, before moving on to the deployment stage of pre-commercial concepts. In addition to the Marine Renewable Energy sector, our experimental resources are aimed at the offshore oil and naval sector.

Open science and data

- Part of the publications from projects using the infrastructure are open access
- Annual data production: 10 TB
- The validated and described data are published on a data repository <https://data.ifremer.fr/Deposer-Archiver-des-donnees/SEANOE>

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Boulogne-sur-Mer, Nantes, Plouzané

French supporting institutions: Ifremer, ECN, UGE

• **Construction:** 2017

• **Operation:** 2017

• **Contact in France:** Jean-Marc Daniel, Jean.Marc.Daniel@ifremer.fr

• **Website:** <http://theorem-infrastructure.org/version-francaise>

International dimension

marinerg-i

- **Partner countries** IE, ES, PT, UK, DK, NL, DE, FR, IT
- **Website:** www.marinerg-i.eu

WEST

W(Tungsten) Environment for Steady-state Tokamaks

WEST is a major evolution of the Tore Supra tokamak, the first magnetic confinement fusion device to produce plasmas lasting several minutes at high power. Its primary objective is the qualification of the ITER divertor. To this end, a major modification of the magnetic configuration has been carried out by means of magnetic coils in the plasma chamber and the installation of ITER technology tungsten divertor components. It is also equipped with extensive instrumentation, in particular with a system for thermographic measurement of the internal components and plasma measurements in the peripheral zone or for estimating tungsten contamination of the plasma.

The research programme focuses on the following areas:

- Understanding and control of plasma-wall interaction in a metallic environment, erosion/redeposition and retention of plasma fuels; behaviour of materials subjected to these extreme conditions; measurement and interpretation of surface temperatures in



© C. Reux / CEA

reflective 3D environments to allow minimisation of their damage;

- *In situ* qualification of component technologies in relation to ITER plasma;

- Qualification of plasmas operated over long periods of time, with in particular simulation and control tools to be developed for future use on ITER. WEST is one of the tokamaks of the European consortium EUROfusion and collaborates with other international partners.

Relations with economic actors and/or socio-economic impact

WEST generates its own industrial activity, linked to its development (contracts for the supply of components or services) and its operation (mainly framework contracts). After the production of its internal components, which generated about a hundred contracts with industrialists and service providers, WEST entered its scientific exploitation phase in 2018, during which increased recourse to industrialists as operators is sought.

Open science and data

- All the publications from projects using the infrastructure are open access
- Annual data production: 10 TB

Category: RI

Type of infrastructure: single site

Infrastructure location in France: Saint-Paul-lès-Durance

French supporting institutions: CEA

- **Construction:** 2012

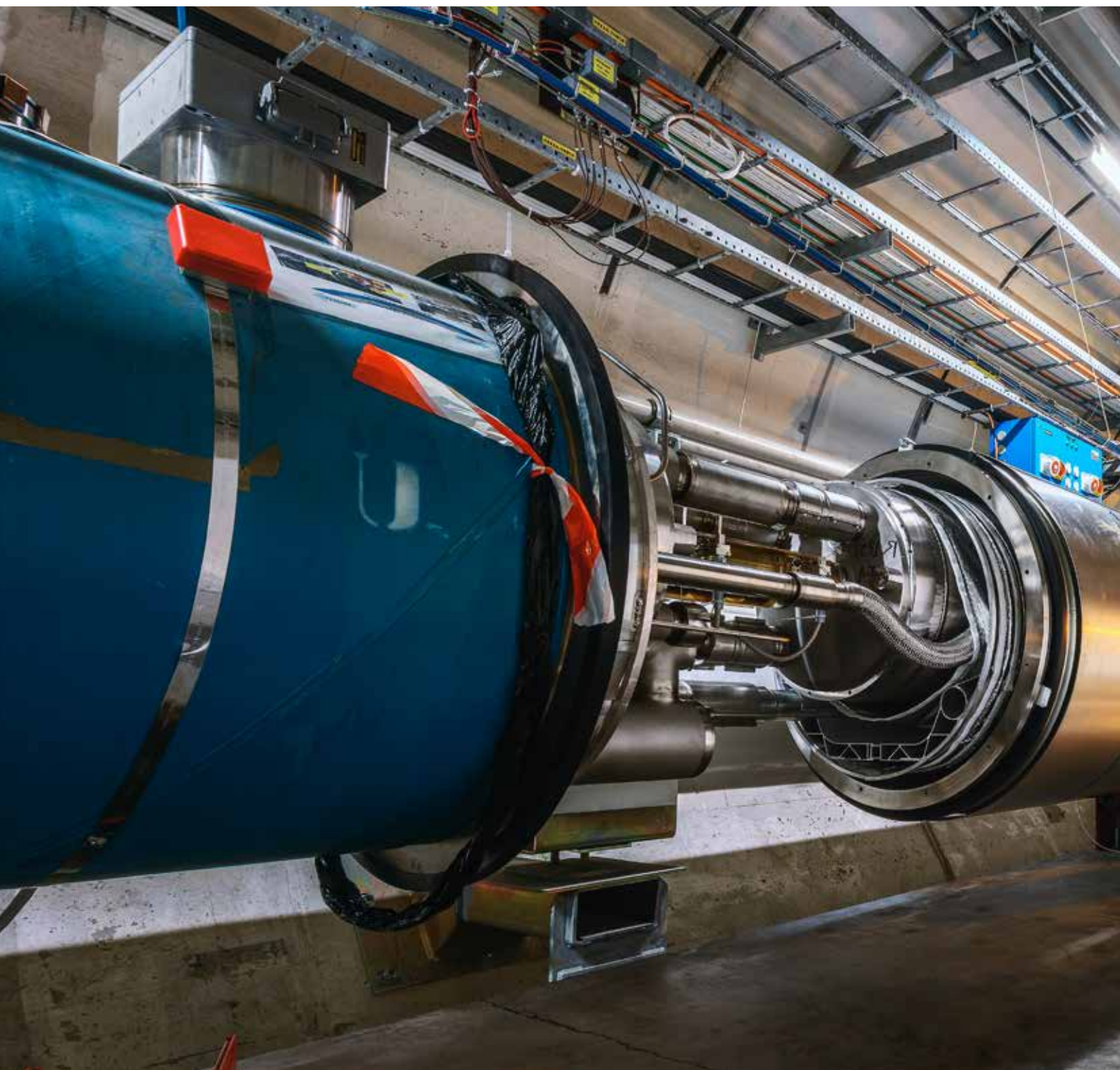
- **Operation:** 2018

- **Contact in France:** Jérôme Bucalossi, jerome.bucalossi@cea.fr

- **Website:** <http://irfm.cea.fr>

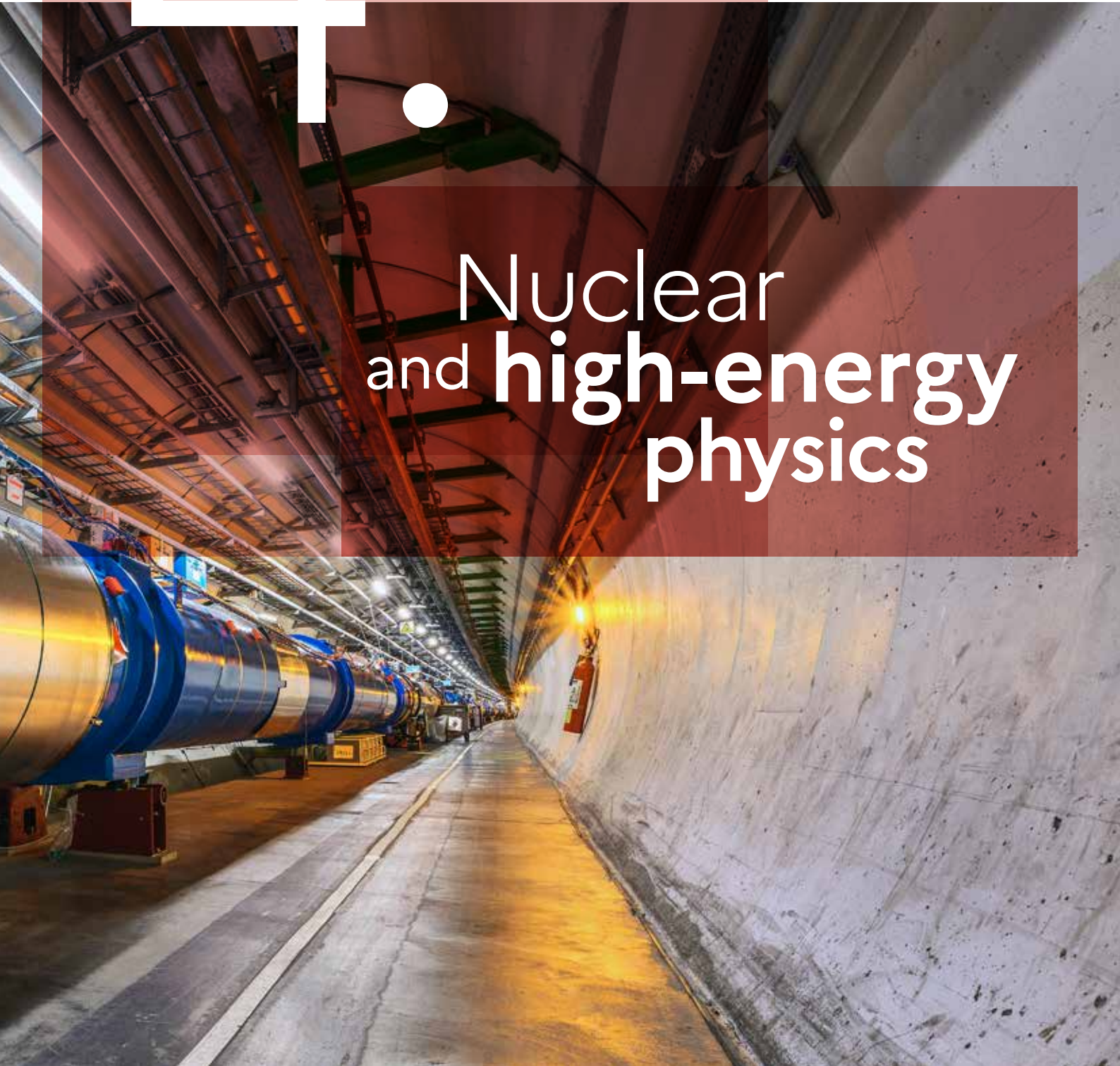
International dimension

- **Partner countries Consortium EUROfusion**



4.

Nuclear and **high-energy** physics



Nuclear and high-energy physics

The objectives of nuclear and high-energy physics are to study the elementary constituents of matter, to describe their interactions and to understand their role in the structuring of space-time and the evolution of the universe.

In these fields, the advancement of knowledge is leading to a growing convergence between research on the two infinities: the **infinitely small**, where physicists study atomic nuclei, nucleons, elementary particles, and the forces and symmetries that govern their interactions; and the **infinitely large**, with the study of astroparticles at very high energies and the cosmological manifestations of particle physics. Both the theoretical and experimental aspects of research on cosmic rays, neutrinos, dark matter, dark energy and gravitational waves, on the one hand, and studies of the elementary constituents of matter, on the other hand, come together to try to answer the same questions of fundamental physics.

Research in nuclear and high-energy physics (PNHE) requires the **implementation of large-scale research infrastructures**, built and operated by international collaborations over several years or even decades. **CERN** is an emblematic example in this regard. Created in 1954 to restore Europe's place in science, **CERN** has become not only an example of international scientific collaboration, a model of organisation for other European cooperation projects – ESA was founded according to the same model in 1975 – but above all the world's undisputed leading laboratory in the field of high-energy physics and associated technologies: superconducting accelerators, particle detectors, massive data processing. The number of **CERN** users is a good measure of the leadership the laboratory has acquired. This number has grown in

a decade from 5 000 physicists to more than 12 500 today, including 8 000 from its 23 member states. French physicists from the CNRS, CEA and universities represent 10% of the users from the member states.

The strategies, necessarily European or even global, for future infrastructures are developed with the participation of CEA and CNRS within European committees (ESPP for particle physics, APPEC for astroparticle physics, NuPECC for nuclear physics, ECFA for future accelerators and associated detectors).

SCIENTIFIC BACKGROUND AND PERSPECTIVES

Particle physics

The search for new particles and interactions, linked for example to dark matter, is one of the priorities of the discipline. In a very complementary way, the other major axis of activities concerns the exhaustive and precise metrology of processes already observed, in particular in the "electroweak" and "flavour" sectors, in order to observe possible anomalies with respect to the predictions of the Standard Model. In this respect, the discovery of the Higgs boson at the **LHC** at **CERN** (Nobel Prize 2013) has opened a new era of detailed studies of the properties of electroweak symmetry breaking, cornerstone of the Standard Model. The **LHC**, and its future so-called high-luminosity phase (**HL-LHC**), which will be operated until around 2038, remains the reference infrastructure for the discipline worldwide.



When the current detector refurbishment phase is completed in early 2022, the **LHC** will resume operation for three years, doubling the amount of data collected. An accelerator upgrade and further improvements to the general-purpose detectors (ATLAS and CMS experiments) will then be installed to kick off the **LHC's** high-luminosity operation phase by 2027, which will last for about ten years. This phase will increase the amount of data collected tenfold, offering greater sensitivity to tests of the Standard Model and to the possible observation of new physics. In view of the anomalies that appear to be emerging in the flavour sector, extended operation of the LHCb experiment for the entire **HL-LHC** phase is now being considered, with additional resources required in this case. This flavour sector is also being studied by the Belle-II experiment at SuperKEKB, the B-factory in Japan, which will continue to take data until 2031.

France has long played a major role in the entire **LHC** programme, from design and construction (accelerators, detectors) to scientific exploitation, and is currently preparing the **HL-LHC**. For 2035 and beyond, the recent **update of the European particle physics strategy** has identified the physics of the Higgs boson as a top priority. Because of its role in the evolution of the universe, the Higgs boson, which is the only scalar particle of the Standard Model, still conceals mysteries that a new machine would make it possible to tackle thanks to measurements that are 10 times more precise. Two architectures, linear or circular, are in the running for a new electron-positron accelerator that could be built in Asia (linear ILC in Japan or circular CEPC in China) or in Europe, where **CERN** is considering either a linear machine (CLIC) or a circular machine (FCC-ee), for which the feasibility study should deliver its results at the end of 2025. If conceivable, this Future Circular Collider with a circumference of 100 km could also serve as a step towards a

longer-term exploratory project that would enable Europe to maintain its leadership in the discipline well into the second half of the 21st century: this is the FCC-hh project, a hadronic collider with an energy seven times greater than the **LHC**. In this context, a sustained R&D programme to develop the technologies needed for such an accelerator – high-field superconducting magnets in particular – appears to be a priority, as well as an upstream programme exploring other acceleration techniques and possibly leading to alternative proposals.

Hadronic physics

Hadronic physics deals with the strong interaction, particularly in its most complex aspects which are necessary to describe the composite objects that are the nucleons such as the proton and the neutron: their structure, the confinement of the quarks and gluons that constitute them, the origin of their mass and their spin.

The **LHC**, like the future **HL-LHC**, can produce ultra-relativistic ion collisions that are suitable for some of these studies, and this infrastructure will remain the spearhead for the study of the quark and gluon plasma for the next decade. The ALICE experiment is dedicated to it, and the ATLAS and CMS experiments exploit as well these data, along with, more recently, the LHCb experiment in a double modality: collider or fixed target. The ongoing upgrade of the ALICE detector will allow it to be used from 2022 to 2030. Both ATLAS and CMS, and possibly LHCb after its refurbishment, could collect data for longer. In addition, a proposal for a new detector to follow ALICE is in preparation – however, the possibility of heavy ion collisions at the **LHC** beyond 2030 is not yet decided.

Complementary to heavy-ion physics at the **LHC**, the Electron Ion Collider (EIC) project was recently prioritised by the US DOE, with construction to begin in 2023 at Brookhaven for a start-up around 2030.



The machine will collide polarised protons or ions with polarised electrons at high energy (20-140 GeV) and high intensity, allowing in particular to better understand the role of gluons in nucleons and nuclei, and even to discover a new state of matter saturated in gluons: the color glass condensate. The scientific community in France is looking forward to the project, as an ambitious continuation of the important work carried out on the structure of nucleons at HERA at DESY, then COMPASS at **CERN** and which will continue until around 2025 at CEBAF at Jefferson Lab.

Baryon-rich hadronic matter, currently studied at GSI (HADES experiment on **FAIR** Phase 0) and at **CERN** (NA61), may be studied after 2027 with **FAIR** Phase 1 (CBM), and with NICA at JINR, a possibility at **CERN** (NA60+) being also considered.

Nuclear physics and astrophysics

The field of nuclear physics is going through a period of many important results from existing facilities. These results have motivated very ambitious efforts worldwide for the production and study of exotic nuclei. In addition to RIBF (Radioactive Beam Factory, RIKEN) in operation since 2007 in Japan, large-scale facilities are emerging in the United States (FRIB), China, South Korea (RAON) and Russia, accompanied by their state-of-the-art instrumentation, and thus demonstrating the enthusiasm for new discoveries in nuclear physics. The recent context of the discovery of gravitational waves and the global opening to multi-messenger astronomy has made the importance of nuclear physics in understanding the universe and its signals even more apparent, as some of the large cataclysmic events detected are the site of nucleosynthesis that allows the creation of the elements that make up our world.

In this rapidly evolving landscape, the French scientific community has a roadmap focused mainly on its national facility, **GANIL** in Caen,

and on **FAIR** in Germany, both of which are ESFRI landmarks, while maintaining an interest in other infrastructures such as RIKEN in Japan, JINR in Russia or FRIB in the USA. **GANIL** and **FAIR** use two different and complementary methods to produce radioactive beams: **FAIR** delivers high-energy beams, far from stability, but with limited optical properties. **GANIL** produces less exotic nuclei, but which can then be re-accelerated into high optical quality, high intensity, and lower energy beams for precision measurements.

FAIR, after its planned start-up in 2027, will have an unrivalled potential for discovering exotic nuclei, as the facility will deliver the most energetic beams compared to other existing facilities. **GANIL**, which is in the start-up phase of its new linear accelerator, will see the deployment of the phase 1 of its upgrade project, **SPIRAL2**, in the next decade. With this new equipment, discoveries are expected in the field of very heavy and super-heavy elements, neutron-deficient intermediate mass elements (with S3 and the Equipex+ NEWGAIN), ground state properties of exotic nuclei and tests of the standard model (with DESIR). In particular, the **GANIL/SPIRAL2** beams will provide precision measurements that are impossible to achieve with the energetic beams of **FAIR**, and the intensities of the heavy beams of the future NEWGAIN injector could make it possible to envisage, in combination with the equipment built within the framework of S3 and DESIR, unprecedented experiments.

Moreover, the experimental programme with the stable and exotic beams produced by **GANIL's** cyclotrons is continuing at the highest level thanks to the intensity of the accelerated beams and the quality of the instruments on site (LISE, VAMOS, ACTAR, INDRA/FAZIA) or hosted for specific periods such as PARIS or **AGATA**. Finally, **GANIL's** scientific programme also includes more immediately applicable fields, whether at NFS or at its cyclotrons:

measurement of nuclear data and study of materials under irradiation stress.

A new RI for nuclear physics: AGATA

One of the most accurate probes of the atomic nucleus is its gamma radiation. **AGATA** is a European collaborative project to build and operate a new type of ultra-pure Germanium gamma-ray multi-detector based on the concept of gamma-ray trajectography. This new technique is a technological breakthrough based on modern signal analysis and data analysis techniques, and allows an improved resolution power of one to two orders of magnitude over conventional detection techniques. This quality allows **AGATA** to reveal the structure of the nucleus under extreme experimental conditions, whether with relativistic beams (as at **FAIR**) or with the lower energy exotic beams of **GANIL**. **AGATA** will be used in these two European infrastructures, illustrating their complementary nature. Phase 2 construction of the detector is one of the five priorities of NuPECC's Long Range Plan, after the construction of **FAIR** and **SPiRAL2**, underlining its high discovery potential.

Astroparticle physics

Cosmic rays, both neutral and charged, and gravitational waves are used to study violent, high-energy phenomena in the universe, sometimes at cosmological distances. The laws of fundamental physics governing the infinitely large and the infinitely small are tested under extreme conditions, paving the way for the discovery of new physics or new astrophysical objects.

Gravitational waves

The discovery of gravitational waves (GWs) in 2016 (Nobel Prize in 2017) by the LIGO-Virgo collaboration has opened a new window of observation of the Universe and provides new constraints on quantum theory models of gravitation. Furthermore, the observation by LIGO-Virgo of the GWs produced by

the collision of two neutron stars addresses the question of the equation of state of nuclear matter under extreme conditions of pressure and isospin. The concomitant observation of electromagnetic emission has implications for astrophysics (nucleosynthesis of elements heavier than iron, equation of state of dense matter) and cosmology (independent measurement of the Hubble parameter). This event opens new perspectives for the physics of high-energy multi-messenger astroparticles, which studies violent phenomena in the Universe.

CNRS, INFN and, since the beginning of 2021, Nikhef, as part of the **EGO** (European Gravitational Observatory) consortium, are building and operating the **Virgo** interferometer located in Pisa, Italy. With the improvements underway (**AdvancedVirgo+**), the **Virgo** and LIGO gravitational antennas are so-called second-generation detectors. By 2030, these infrastructures will have benefited from improvements that will bring them to the limit of what is feasible with current dimensions and technologies.

A significant leap in performance, with an order of magnitude gain in sensitivity for the detection of GWs, requires the implementation of a 3rd generation interferometer. In Europe, an innovative concept, the Einstein Telescope (ET), is being developed with the following objectives:

- tests of gravitation and the nature of black holes;
- cosmology (nature of dark energy, and alternative theories of gravitation);
- the physics of supernovae and compact stars (neutron stars), which links the observation of GWs with that of, for example, astrophysical neutrinos.

For the realisation of ET by 2030, a preparatory phase involving R&D studies in partnership with **EGO** is being defined.



In the space domain, the GW LISA (Laser Interferometer Space Antenna) observatory, ESA's L3 mission, should provide measurements in the low-frequency domain from 2032 onwards, complementary to those at higher frequencies measured by ground-based interferometers.

France is one of the leading countries in the world's effort to detect GWs, both with ground-based and space-based instruments. The Advanced Materials Laboratory (LMA) in Lyon has developed a unique technology and expertise in the field of thin films and has designed the mirrors for all the GWs detectors currently in operation (LIGO in the USA, Virgo in Europe and KAGRA in Japan).

Charged cosmic rays

The Pierre Auger Observatory (PAO), covering 3,000 km² in Argentina, is designed to study charged cosmic rays at the highest energies (around and above 10¹⁸ eV). The CNRS/IN2P3 teams have had key roles in the design and construction of the observatory (commissioned in 2008), and have important competences and responsibilities in its operation, in the production of scientific results as well as in the detector improvement project (AugerPrime) now in operation.

Very high-energy gamma rays

The observation of the high-energy Universe is complemented by gamma-ray astronomy, in particular with the construction of the CTA observatory, which will also take over from HESS in the indirect search for dark matter.

HESS is an array of five atmospheric Cherenkov telescopes forming a very high-energy gamma-ray observatory (energy between 20 GeV and 50 TeV), deployed in Namibia. HESS has the most powerful ground-based gamma-ray detection array. A 28-metre Cherenkov telescope, the largest in the world, meets a number

of technological challenges (mechanical precision, signal processing). The lowering of the energy threshold allows continuity in the spectrum observed with the Fermi/Glast satellite and an absolute energy calibration. With the construction of the camera, France was able to demonstrate its leadership in this field. HESS has enabled major advances in high-energy astrophysics, notably in the emission mechanisms of galactic and extragalactic sources (supernovae, pulsars, active galactic nuclei) and their mapping at high spatial resolution in the southern sky.

CTA is a new generation telescope project to increase the sensitivity of current HESS telescopes by more than an order of magnitude. CTA is an array of ground-based optical telescopes using the atmospheric Cherenkov technique for very high-energy celestial gamma rays. Composed of two sites, in the southern and northern hemispheres, this new observatory, with an angular resolution of 2 arcminutes and covering an energy range from 30 GeV to 300 TeV, which is wider than its predecessors, should answer several questions in physics and astrophysics, such as the origin of cosmic rays, the nature of particle acceleration processes in the Universe, in particular around black holes, and their role in the structuring of the interstellar medium, the exploration of physics beyond the Standard Model and in particular the study of dark matter. The phased deployment of the CTA telescopes was launched in 2018 and will be completed by 2027.

Very high-energy neutrinos

The IceCube experiment located at the South Pole is a Cherenkov detector instrumenting 1 km³ of ice in order to detect visible astrophysical sources in the northern hemisphere emitting neutrinos in the energy range from 100 GeV to 1 EeV. IceCube has identified a diffuse neutrino source of extragalactic origin and a first point source of very high-energy cosmic

rays. The **KM3NeT-ARCA** site is currently under construction near Catania in Italy and will be dedicated to high-energy neutrino astronomy. This underwater telescope with a volume of about 1 km^3 will detect Cherenkov light emitted by cosmic neutrinos (between a few tens of GeV and 1 PeV) and will provide essential data on the sky visible from the southern hemisphere, and in particular our galaxy and the galactic centre.

Neutrino physics and dark matter

Following the discovery of neutrino oscillations (Nobel Prize 2015), experiments on neutrino physics aim to clarify the role of this particle in the description of the primordial Universe, in particular by establishing the mass hierarchy of the three families of neutrinos and by revealing CP violation in the neutrino sector. Important advances have been made in this field, the experimental study of which requires several varieties of detectors and sources (accelerators, reactors, cosmic) and only the combination of which makes it possible to constrain the parameters of interest with the required precision.

After the T2K experiment in Japan, very complementary measurements will be made at the future **DUNE** (USA), HyperK (Japan) and **JUNO** (China) experiments. France is investing mainly in the **DUNE** experiment carried out by the DOE and is pursuing measurements from atmospheric neutrinos with the **KM3NeT-ORCA** project, currently being deployed off Toulon, which is complementary to the Italian **KM3NeT-ARCA** site, dedicated to neutrino astronomy. The next generation of experiments is expected to provide answers to experimental questions that are still unanswered today. It remains possible that neutrinos are their own antiparticles, that the matter-antimatter asymmetry in the Universe comes from the fact that CP symmetry is violated in the neutrino sector, or that there are currently unknown types of neutrinos that could be a form of dark matter.

Finally, since neutrinos are not massless, they have a measurable cosmological signature: observations of the cosmic background radiation, large-scale structure surveys, or the measurement of cosmic astigmatism in three dimensions, provide strong constraints on the sum of the masses of light neutrinos.

More than 95% of the energy content of the Universe is "dark", i.e. it does not interact or interacts very weakly with the fields of the Standard Model, and about a quarter of the total is cold dark matter, a form of matter that is as yet unidentified but which plays a major role in the large-scale structuring of the Universe. Experiments searching directly for the WIMP (weakly interacting massive particle) type dark matter require extremely low background levels and share technical characteristics with experiments searching for double beta decay without neutrino emission. They also share the fact that they are installed in the same underground laboratories: Modane Underground Laboratory (**LSM**) and Gran Sasso National Laboratory (LNGS) in Italy.

The French teams are involved at LNGS in the XENON1T dark matter search experiment, which is currently providing world-leading limits in the 10-1000 GeV mass range. The XENON collaboration is continuing its programme to increase the size of their liquid xenon TPC (Time Projection Chamber) detector, with the XENONnT project underway and DARWIN for 2026. The DarkSide experiment and the ARGO project, both based on liquid argon, are also attractive projects for French physicists. It is expected that noble gas detectors will keep the leadership in this field for the next 10 years. In the lower mass range, French contributions are mainly made in the EDELWEISS and DAMIC experiments at **LSM**.

For double beta decay without neutrino emission, French physicists are involved in the SuperNEMO experiment at **LSM**.



The new generation of experiments seeks to cover the phase space of the inverted mass hierarchy and a mass scale of the order of 20 meV for the lightest neutrino. Three technologies (Ge diodes, scintillating bolometers and gas-phase TPC) based on three isotopes (^{76}Ge , ^{100}Mo , and ^{136}Xe respectively) have been identified for experiments of the order of one ton (LEGEND-1000, CUPID and NEXT-HD respectively). For the next generation, aimed at exploring the direct mass hierarchy and masses of the order of 10 meV, R&D is already underway and French operators are playing an important role.

The Modane Underground Laboratory, a new RI for the study of rare phenomena

The **LSM** has been in operation since 1982 and is located along the Fréjus road tunnel. Since 2020, the **LSM** is a national platform administratively attached to the Laboratory of Subatomic Physics and Cosmology (LPSC), which is supervised by the CNRS and the Grenoble-Alpes University (UGA). It is specialised in the implementation of experiments looking for very rare phenomena, limited by the background noise from natural radioactivity. The **LSM**, under 1,700 m of rock, is the deepest underground laboratory in Europe with an experimental site of 400 m². The scientific results obtained in the projects installed at the **LSM** are excellent. These include demonstration detectors for the physics of neutrinoless double beta decay (SuperNEMO, CUPID-Molybdenum, TGV projects), research into the direct detection of cosmic dark matter (EDELWEISS, NEWS-G, DAMIC and MIMAC projects), as well as multidisciplinary projects in microelectronics or biology, involving players from the economic sector. The collaborations in these research programmes are international or national. The **LSM** also has a gamma spectroscopy platform offering a

highly sought-after capacity for radioactive characterisation, particularly in the fields of geosciences, safety (IRSN) and biology.

Inflation physics and dark energy

The discovery of the accelerating expansion of the Universe (Nobel Prize 2011) and the dramatic improvement in the precision of the Planck mission's measurements of the cosmic microwave background have led to the postulation of the existence of dark energy representing about 70% of the energy density of our Universe. The two main projects in preparation are ESA's EUCLID space mission and the *Legacy Survey of Space and Time (LSST)* project at the Vera Rubin Observatory, which will begin operation in 2023 in Chile. CNRS/IN2P3 is participating in the construction of key elements of the **LSST** instrument such as the camera and the filter changer; France is thus the only European country contributing in collaboration with the American DOE teams. France will also play a central role in the processing of **LSST** data at **CC-IN2P3**.

The study of the cosmic microwave background (CMB), initiated by the COBE discovery (Nobel Prize 2006), has reached a state of maturity with the ESA Planck mission, which has confirmed that we understand the birth of these fluctuations through the theory of cosmic inflation. It remains to go beyond the current descriptions and integrate inflation into a complete theory of fundamental interactions. This requires further theoretical efforts but also a way to differentiate the models. It is therefore important to further characterise the seeds of these fluctuations, in particular by trying to measure the CMB polarisation associated with the presence of primordial gravitational waves. French teams are contributing to the ongoing American ground-based Simons Array and Simons Observatory projects and to the LiteBird space mission (Japan, JAXA).

The IN2P3 Computing Centre

French participation in the PNHE experiments relies on the IN2P3 Computing Centre (**CC-IN2P3**), located in Lyon. This RI has 70 permanent CNRS staff and provides French computing resources for nuclear and particle physics experiments by offering transport, storage and processing of huge amounts of data (up to hundreds of Petabytes).

The **CC-IN2P3** is one of the 13 major top-level centres of the *Worldwide LHC Computing Grid (W-LCG)* project coordinated by **CERN**. About 70% of **CC-IN2P3's** resources are used for **LHC** data processing and simulations. In return for funding the resources they need, international collaborations in the field of astroparticles and cosmology can also benefit from **CC-IN2P3** resources. Since 2021, the **CC-IN2P3** is one of the two major data processing centres of the **LSST** project and will have a complete set of data, giving a major advantage to the CNRS teams. It will also be the main component of the French ground segment of the European space mission **EUCLID** and will provide 30% of the total resources. International scientific collaborations using **CC-IN2P3** services also include **GANIL**, **EGO**, **HESS**, **CTA**, **PAO**, **JUNO** and **KM3NeT**, all of which are on the national RI roadmap or on the ESFRI roadmap. In the longer term, the High-Luminosity phase of the **LHC** (2027-2038) will be the major challenge for the **CC-IN2P3**, since it will be necessary to provide storage and computing capacities corresponding to 100 times those currently used for the LHC data.

MAIN PRIORITIES FOR THE COMING YEARS

For the next 5 years, the PNHE priorities in France are clearly established. In particle physics, the exploitation of the **LHC** at **CERN** and the detector upgrade programme for the HL-LHC are the main programmes in the field and will continue to federate

physicists from all over the world. In nuclear physics, the start-up of **SPIRAL2** at **GANIL** will ensure an attractive nuclear physics programme for the French and international communities, and **AGATA** will be crucial for the study of the structure of nuclei under extreme experimental conditions. The **Virgo** experiment at **EGO**, with its **AdvancedVirgo+** upgrade programme, will continue to explore a rapidly growing field through the detection of gravitational waves. In the field of neutrinos, the French contribution to the **DUNE** project in the United States, the start-up of **JUNO** in China and the continued construction of **KM3Net** in France will enable essential research for the understanding of elementary particles and their symmetries. The start-up of the **LSST** experiment will provide a unique programme for understanding dark energy and the accelerating expansion of the universe. In the field of cosmic rays, **CTA** will progressively take over from **HESS** for the detection of very high-energy gamma rays, while **PAO** will continue its programme on ultra-high-energy charged cosmic rays. Finally, the **LSM**, with its very low noise environment, will remain an essential infrastructure for the development of dark matter experiments, while the **CC-IN2P3** will continue to ensure the storage, processing and analysis of most of the PNHE data in France, for which it will develop innovative techniques in close collaboration with international centres in the field.

CONTRIBUTIONS FROM RESEARCH OPERATORS AND UNIVERSITIES

The PNHE field in France counts about 1 250 physicists with a permanent status, 150 at CEA and 1 100 in CNRS laboratories, mainly IN2P3 (including 400 academics). These physicists are spread over 25 laboratories located in the major university centres. About 85% of these physicists are experimentalists and



15% are theoreticians. Highly specialised engineers and technicians support the experiments and infrastructures to which they contribute. In total, these laboratories have about 2 000 technical and administrative staff, 1 500 at the CNRS and 450 at the CEA. In addition, there are 1 150 PhD students, post-doctoral fellows and fixed-term contracts.

TECHNOLOGICAL ISSUES

Research in nuclear and high-energy physics involves innovative instruments that are developed by laboratories, mostly in collaboration with industry.

In the field of **particle accelerators**, the challenge is to master the high-energy and high-intensity beams that allow access to new or rare physical phenomena. Research focuses in particular on the improvement of high-current sources and injectors as well as on the improvement of accelerator gradients, either through better control of the surface states of superconducting radio frequency cavities or through breakthrough technologies exploiting, for example, laser plasma interaction. The French laboratories in the PNHE field have developed significant expertise in accelerators and are major players in the European structuring of this field within the TIARA consortium. This field mobilises about 500 FTEs and excellent infrastructures and platforms, in particular at the Saclay, Orsay, Caen and Grenoble sites. This network of infrastructures is also used for the construction of European accelerators intended for other communities, including, among recent projects, the construction of the **E-XFEL** light source, the construction of the accelerator for the European spallation source **ESS** or the IFMIF-EVEDA neutron source for the qualification of fusion tokamak materials.

In this context, **superconducting magnets** are clearly one of the technological locks

for future **CERN** projects. The Council's recommendations from the European strategy update give impetus to a broad R&D programme aimed at overcoming the current limitations of magnets based on NbTi or NbSn conductors. A roadmap shared between **CERN** and European laboratories is being developed to explore the most promising design and technology paths. The implementation of this roadmap will largely involve European industry. This research on magnets has extensions in the fields of energy (tokamak magnets or energy storage) and life sciences (high-field MRI).

Finally, **innovative instrumentation** for nuclear and high-energy physics is traditionally one of the strong areas of French laboratories. It is a question of meeting the many challenges posed by experiments conducted at the world's major accelerators (**CERN**, **GANIL**, **FAIR**, Fermilab, J-PARC) or outside accelerators (**EGO-Virgo**, **CTA**, **LSST**, **LSM**). The challenges are to have detectors and acquisition chains with increased resolution in energy, time and space in order to respond, through better discrimination, to the increase in accelerator intensities. It is also a question of improving the sensitivities in the detection of rare or tenuous events, in particular for neutrino physics, the detection of gravitational waves or the search for dark matter. All detection techniques are covered by French laboratories, with state-of-the-art developments both in the detectors themselves and in the processing electronics and associated acquisition chains. The next few years will see the emergence of quantum technologies for the two infinities and important innovations in terms of cryogenic detectors, embedded intelligence on detectors and the application of artificial intelligence in detection systems.

INTERCONNECTION AND INTERFACES WITH INFRASTRUCTURES IN OTHER FIELDS

Astronomy and astrophysics

Ion beams are used not only for nuclear physics and for astrophysics, but also to simulate cosmic rays and to understand certain astronomical and astrochemical phenomena, such as the interaction of solar winds on the outer layers of the atmosphere or the creation of complex molecules on the surface of meteorites and interstellar ice by radiolysis. These experiments in our laboratories are of importance for the understanding of space missions and bring together a growing community.

Accelerators for material sciences

CNRS/IN2P3 and CEA/IRFU develop and build accelerators used by other scientific fields. This is the case, for example, of the **E-XFEL** free-electron laser in Germany and the European Spallation Source **ESS** in Sweden, whose users are not in the PNHE field. Ongoing R&D for future accelerators in particle and nuclear physics is essential for the development of techniques and technologies for future light or neutron sources.

Energy, health and environment applications

Because of the large share of nuclear power in the production of electricity, France must have excellent research in nuclear physics, in order to contribute to improving the safety of installations and the economic performance of the sector, and to be able to make proposals for new innovative concepts. Nuclear processes of interest for energy applications are studied at the NFS facility on **SPIRAL2**. **GANIL's** ion beams are also used for experiments on innovative materials, upstream of research on the ageing

of nuclear or space materials. The field of health is also undergoing remarkable development with ion beams to treat cancer. The knowledge of ion-matter interaction in the living environment acquired from accelerators, as well as the instrumentation for beam analysis and dosimetry, is booming in order to define innovative radiotherapy techniques, and has an impact on the protection of man and the environment.

DATA AND OPEN SCIENCE

With the creation of the world-wide-web at **CERN** in 1989, particle physicists were among the first to adopt an open science model, sharing pre-publications (Arxiv and INSPIRE-HEP Archives), and building a deep culture of using and sharing open source software. This practice has been generalised to all the infrastructures of the PNHE perimeter. In France, for example, the import of publications into the national open archive **HAL** from the INSPIRE system at **CERN** has been automated. Thus, most of the publications from the research infrastructures in the PNHE perimeter are available in **open access**.

In general, the data access model for PNHE experiments allows members of the major international scientific collaborations to have exclusive access to the data for a defined period of time before it is made public. The calculation models and data management plans are the responsibility of the international scientific collaborations. In France, the **CC-IN2P3** is the data and analysis centre of the PNHE domain. Together with the other international computing centres, it allows all French users to have access to the data of the scientific collaboration to which they contribute.

Due to the very large volume (hundreds of petabytes per year) and complexity of the data, open access to the data is a real challenge, but this is achieved through



Major scientific challenges in nuclear and high-energy physics.

platforms such as opendata.cern.ch. Experimental data are also made public in the form of catalogues, instant online alerts (multi-messenger astroparticle physics) or uploaded to the hepdata.net website, which shares its metadata with the INSPIRE-HEP archive. These published data all have a unique identifier.

Finally, the physicists and laboratories of the PNHE domain are strongly involved in the coordination of the European EOSC programme and play a leading role in several key EOSC projects, such as EOSC-Pillar, EOSC-hub, ESCAPE or EGI-ACE and soon EOSC-FUTURE



CERN

European Organization for Nuclear Research

CERN was created in 1954 under the aegis of UNESCO by an international treaty, with France being one of the 12 European founding states. It now has 23 member states, 10 associate countries and 3 observer countries. The organisation employs 3,300 people; and 12,800 users from all over the world (including 800 from French laboratories) work there regularly. The main programme is the LHC (Large Hadron Collider), whose aim is to study elementary particles and their interactions. This unique equipment produces proton-proton or ion-ion interactions at the highest energies ever reached in a laboratory. The accelerator, with a circumference of 27 km, is powered by a complex of pre-accelerators built and operated throughout CERN's existence. Other experiments also take place at CERN: at ISOLDE for nuclear physics, at the antiproton decelerator for the study of the effects of gravitation on antimatter, and at the neutrino platform for R&D



© CERN

on future experiments in this field. CERN is also pursuing R&D programmes in instrumentation and acceleration techniques. For the needs of its community, it operates computing infrastructures and plays a key role in structuring the subject in Europe. Following the update of the European strategy, CERN is leading the feasibility study for a possible future very large collider, the FCC.

Relations with economic actors and/or socio-economic impact

This cutting-edge science requires technological innovations: CERN and its partners conduct R&D, train engineers and technicians, and support the rise in technology of industries. Web, medical imaging and proton therapy are exemplary technology transfers. France, as host state, benefits from a significant industrial and financial return, estimated at 500 million euros per year (report 832, National Assembly, 20/03/2013)

Open science and data

- All the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure open on a software forge <https://github.com/cernopendata/opendata.cern.ch>
- Annual data production: 100 PB
- Validated and described data are published on a data repository <https://opendata.cern.ch>

Category: IO

Type of infrastructure: single site

Infrastructure location: Meyrin (CH)

Other sites in France: Prévessin-Moëns

French supporting institutions: CNRS-IN2P3, CEA-DRF

Director or RI representative in France:

• Anne-Isabelle Etievre

• **Construction:** 1954

• **Operation:** 1954

• **Stakeholders in France:** MESRI, MEAE

• **Contact in France:** anne-isabelle.etievre@cea.fr

• **Website:** <https://home.cern/fr>

International dimension

Director: Fabiola Gianotti (directrice générale du CERN)

• **Partner countries:** DE, AT, BE, BG, DK, ES, FI, FR, GR, HU, IL, IT, NO, NL, PL, PT, CZ, RO, UK, RS, SK, SE, CH

• **Website:** <https://home.cern/fr>

CERN LHC

Large Hadron collider

CERN leads particle physics in Europe and operates the world's most important particle physics infrastructure with the LHC. The LHC is currently the world's highest energy particle collider. At four points on the 27 km ring, giant detectors record the products of collisions: ALICE, ATLAS, CMS and LHCb. Following the discovery of the Higgs boson in 2012, the main scientific objectives are now to study the properties of this boson in detail and to search for new physics beyond the standard model. A series of improvements to the accelerator complex will increase the intensity of the particle beams to collect 10 times more collisions that are interesting and achieve greater sensitivity to rare phenomena. This so-called high luminosity or "High-Lumi LHC" phase will start in 2027 and continue for about ten years. This new operating mode requires improvements to the detectors, in which French organisations are involved. The study of the standard model and the Higgs mechanism and the search for new phenomena at the highest energies with ATLAS and CMS, the study of the asymmetry between matter and anti-matter and the search for anomalies in precision measurements



© CERN

with LHCb, as well as the study of the plasma of quarks and gluons with ALICE, are some of the challenges that the LHC will make it possible to take up in the years to come.

Relations with economic actors and/or socio-economic impact

French industries are present at CERN and the LHC (62 industrial contracts worth more than 1 MCHF for a total of 645 MCHF during the LHC construction phase). Nearly a thousand French companies are listed as suppliers to CERN, and many French subcontractors are involved in the construction of detectors in French laboratories. France has an Industry Liaison Officer at CERN.

Open science and data

- All the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure open on a software forge
- Annual data production: 100 PB
- Validated and described data are published on a data repository <https://dphep.web.cern.ch>

Category: RI*

Type of infrastructure: single site

Infrastructure location: Meyrin (CH)

Other sites in France: Prévessin-Moëns

French supporting institutions: CNRS-IN2P3, CEA-DRF

Director or RI representative in France:

Anne-Isabelle Etievre, Laurent Vacavant

Construction: 1994

Operation: 2008

Stakeholders in France: Aix-Marseille Université, Institut Mines-Télécom, Institut polytechnique de Paris, Sorbonne Université, Université Clermont Auvergne, Université Claude Bernard - Lyon 1, Université Grenoble Alpes, Université de Paris, Université Paris-Saclay, Université Savoie Mont Blanc, Université de Strasbourg, Université Toulouse III - Paul Sabatier

Contact in France: anne-isabelle.etievre@cea.fr, vacavant@in2p3.fr

Website: www.lhc-france.fr

International dimension

ESFRI landmark: HL-LHC

Director: Fabiola Gianotti (directrice générale du CERN)

Partner countries: plus de 110 pays contributeurs

Website: <https://home.cern/fr/science/accelerators/large-hadron-collider>

DUNE / PIP-II

Deep Underground Neutrino Experiment / Proton Improvement Plan II

DUNE is an experiment that will study neutrinos and the decay of the proton. It is based on a beam of very high intensity neutrinos produced by a proton accelerator (PIP-II) under construction at Fermilab (Chicago), with these neutrinos being studied 1 300 km away by very large liquid argon detectors. Four detection modules of 10 kt each will be buried at 1 500 m in an underground laboratory (SURF, South Dakota). This project is in the construction phase and is a major U.S. Department of Energy project, supported by CERN and the European Strategy for Particle Physics. The DUNE experiment is scheduled to start taking data in 2028 and be operational for at least 10 years. It will make precision measurements of neutrino oscillations, which allow the mass hierarchy of neutrinos to be determined, the discovery of CP violation in the lepton sector and other precision measurements to constrain the neutrino sector. DUNE will also observe



© CERN

neutrinos from supernova explosions and search for proton decay. All of these measurements will make it possible to explore physics beyond the standard model and to elucidate fundamental problems in cosmology and astrophysics. France is contributing to the construction of the PIP-II proton accelerator and the second module of the far detector.

Relations with economic actors and/or socio-economic impact

The French contributions to the PIP-II accelerator and detector will involve numerous industrial subcontractors in France, with an estimated return of 70% of the contribution to the equipment. The technology on which the cryostats of the four detection modules are based, financed elsewhere, is developed by a French company, GTT, world leader in containment technologies for the maritime transport of liquefied natural gas.

Open science and data

- All the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure open on a software forge <https://github.com/DUNE/>
- Annual data production: 10 PB
- Validated and described data are published on a data repository

Category: RI*

Type of infrastructure: single site

Infrastructure location: Fermilab, Batavia (US)

French supporting institutions: CEA-DRF, CNRS-IN2P3

- **Director or RI representative in France:** Dario Autiero, Olivier Napoly
- **Construction:** 2018
- **Operation:** 2028
- **Stakeholders in France:** Université Claude Bernard – Lyon 1, Université Grenoble Alpes, Université de Paris, Université Paris-Saclay, Université Savoie Mont Blanc
- **Contact in France:** autiero@ip2i.in2p3.fr, napoly@cea.fr
- **Website:** www.dunescience.org

International dimension

Directors: Stefan Söldner-Rembold (porte-parole de la collaboration DUNE), Lia Meringa (cheffe du projet PIP-II)

- **Partner countries:** AM, BR, CA, KR, CL, CN, CO, ES, US, FI, FR, GE, GR, IN, IR, IT, JP, MG, MX, PY, NL, PE, PL, PT, CZ, RO, UK, RU, SE, CH, TR, UA
- **Website:** www.dunescience.org

EGO-Virgo

European Gravitational Observatory – Virgo

The aim of the EGO-Virgo infrastructure is the detection of gravitational waves (GW). The detector, a laser interferometer with 3 km arms, is located near Pisa, Italy. It is hosted and operated by the European Gravitational Observatory (EGO), a consortium founded in 2000 by CNRS and INFN and joined by NWO/Nikhef in 2021. Virgo is an interferometer capable of measuring length variations of the order of one billionth of a billionth of a metre over 3 km. The laser beams are contained in vacuum tubes 120 cm in diameter and are reflected by mirrors (fused silica cylinders 35 cm in diameter with a flatness better than one nanometre) suspended from chains of cascading pendulums, the so-called “seismic superattenuators”. Virgo is part of a worldwide network of GW detectors, which also includes LIGO (two detectors in the USA) and KAGRA (in Japan). Observations of GWs (about 100 sources detected so far) by this network have provided many scientific results,



such as new tests of general relativity, new measurements of the expansion of the Universe, and studies of black hole populations. The detection of the merger of two neutron stars in August 2017 was a new step in so-called “multi-messenger” astronomy. Improvements to Virgo are underway to increase the volume of the observed universe and to gain access to new sources of GW.

Relations with economic actors and/or socio-economic impact

The construction of Virgo is associated with R&D and innovations in the field of lasers, thin film deposition and optical metrology. Several major French companies are contributing to Virgo. The Laboratoire des Matériaux Avancés is producing the optical thin films for the Virgo, LIGO and KAGRA mirrors, making France a world leader in these technologies.

Open science and data

- All the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure open on a software forge <https://git.ligo.org>
- Annual data production: 1 PB
- Validated and described data are published on a data repository www.gw-openscience.org

Category: RI*

Type of infrastructure: single site

Infrastructure location: Cascina (IT)

French supporting institutions: CNRS-IN2P3, CNRS-INP, CNRS-INSU, CNRS-INSIS

- **Director or RI representative in France:** Matteo Barsuglia
- **Construction:** 2000
- **Operation:** 2000
- **Stakeholders in France:** Université Savoie Mont Blanc, Université Claude Bernard, Université de Paris, Observatoire Côte d’Azur, Université côte d’Azur, Université Paris-Saclay, Sorbonne Université, Université Claude Bernard, Université Strasbourg, Université Haute Alsace
- **Contact in France:** barsu@apc.in2p3.fr
- **Website:** www.ego-gw.it/virgodescription/francese/indice.html

International dimension

Director: Stavros Katsanevas (directeur de EGO)

- **Partner countries:** FR, IT, NL
- **Website:** www.ego-gw.it

FAIR

Facility for Antiproton and Ion Research

The FAIR project aims to build and operate a new international facility for antiproton and heavy-ion research in Europe at GSI, in Darmstadt (Germany). The FAIR superconducting synchrotron, with a circumference of 1,100 m, will provide various light and heavy-ion beams. An adjacent array of devices for target production, separators, and, in the longer term, a linear accelerator of protons and storage rings will provide radioactive secondary beams and antiproton beams. These beams of unrivaled quality and intensity are mainly dedicated to research programmes in nuclear physics (strong interaction, hadron structure, plasmas, very strong electromagnetic fields, etc.), but also in many other fields (materials science and biology). The scientists are organized into four major collaborations to build the equipment that will be used at FAIR: APPA (Atomic, Plasma Physics and Applications), CBM (Compressed Baryonic Matter), NUSTAR (Nuclear



© D. Fehrenz, GSI/FAIR

Structure, Astrophysics and Reactions), and PANDA (Anti-proton Annihilation at Darmstadt). This facility will be complementary to GANIL-SPIRAL2, and to ALICE and LHCb at CERN. Some experiments have already been started in the framework of FAIR-Phase 0 with the existing accelerator of GSI, SIS18, using equipment already built by the collaborations.

Relations with economic actors and/or socio-economic impact

France contributes to the construction of FAIR with financial and in-kind contributions. The latter are developed in research laboratories in collaboration with French industries and companies.

Open science and data

- Part of the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure open on a software forge
- Validated and described data are published on a data repository www.hepdata.net
- Annual data production: 75 PB

Category: RI*

Type of infrastructure: single site

Infrastructure location: Darmstadt (DE)

French supporting institutions: CNRS-IN2P3, CEA-DRF

- **Director or RI representative in France:** Danielle Gallo, Marcella Grasso
- **Construction:** 2010
- **Operation:** 2018
- **Contact in France:** danielle.gallo@cea.fr, marcella.grasso@admin.in2p3.fr
- **Website:** <https://fair-center.eu>

International dimension

ESFRI landmark: FAIR

Director: Paolo Giubellino (directeur scientifique de FAIR)

- **Partner countries:** DE, FI, FR, IN, PL, RO, RU, SI, SE
- **Website:** <https://fair-center.eu>

GANIL-SPIRAL2

**Large National Heavy Ion Accelerator – 2nd Generation
On-line Radioactive Ion Production System**

GANIL, a multidisciplinary research platform serving the national and international community, is a laboratory for fundamental and applied research in nuclear physics, atomic physics, astrophysics and condensed matter physics. GANIL offers a wide range of ion beams accelerated by means of 5 cyclotrons in cascade. For fundamental nuclear physics and nuclear astrophysics, it is possible to produce and study nuclei that do not exist on Earth, and in conditions close to certain stellar conditions.

At the international level, GANIL is one of the major laboratories for research with heavy ions.

SPIRAL2 is a new facility composed of a linear ion accelerator and three new experimental rooms: NFS (Neutrons For Science) which produced its first fast neutrons in 2020; S3 (Super Separator Spectrometer)



© Guillaume Lescalle, GANIL

designed to study very rare phenomena thanks to stable beams of very high intensity and DESIR, an experimental room for low energy exotic nuclei, which will receive the beams from SPIRAL1 and S3 for fundamental studies of nuclei and the standard model by high precision techniques.

Relations with economic actors and/or socio-economic impact

SPIRAL2 is currently being commissioned and the socio-economic impact has been estimated for the construction. Of the €150m planned for the completion of the project, 89% is spent in France, 8% in other EU countries and 3% outside the EU. The socio-economic impact of the existing facility includes industrial applications, life sciences and technology transfer.

Open science and data

- All the publications from projects using the infrastructure are open access
- The data produced by the infrastructure are subject to a data management plan
- Each dataset has a unique identifier (DOI)
- Annual data production: 1 PB
- Data is embargoed for 3 years before being made available on demand

Category: RI*

Type of infrastructure: single site

Infrastructure location in France: Caen

French supporting institutions: CNRS-IN2P3, CEA-DRF

- **Director or RI representative in France:** Patricia Roussel-Chomaz
- **Construction:** 1976
- **Operation:** 1983
- **Contact in France:** patricia.chomaz@ganil.fr
- **Website:** www.ganil-spiral2.eu/fr

International dimension

ESFRI landmark: SPIRAL2

Director: Patricia Roussel-Chomaz (directrice du GANIL)

- **Website:** www.ganil-spiral2.eu

AGATA

Advanced GAMMA Tracking Array

The aim of the AGATA collaboration is to provide a new generation instrument for the study of nuclear physics, capable of observing rare events with great precision. AGATA will improve our understanding of nuclear interaction by measuring gamma rays emitted during various nuclear processes. Its high resolution and efficiency make it a powerful tool for probing the electromagnetic signatures of different nuclear matter behaviours and their impact on astrophysical processes, nuclear data and the fuel cycle. AGATA brings together a large community of 300 researchers in Europe. The European collaboration aims to build, maintain and operate this new type of ultra-pure Germanium multi-detector, based on the concept of gamma-ray trajectography. This is a technological breakthrough that allows access to a resolution power that is one to two orders of magnitude better than



© Emmanuel Clément

conventional techniques. A coveted tool, its design allows it to be mobile in order to be used at the best European relativistic beam facilities (such as FAIR, Germany) or exotic beams at GANIL or the National Laboratories of Legnaro (Italy) for high-precision measurements.

Relations with economic actors and/or socio-economic impact

The construction and maintenance of the different elements of the AGATA detector (from Ge crystals to infrastructure elements) are done in collaboration with European companies. AGATA is also a training tool for young engineers and physicists in high-tech fields (electronics, data acquisition and management, algorithms, solid-state physics, nuclear physics and astrophysics...).

Open science and data

- Part of the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure open on a software forge https://gitlab.in2p3.fr/IPNL_GAMMA
- Annual data production: 100 TB
- Validated and described data are published on a data repository <https://cc.in2p3.fr>

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Caen

French supporting institutions: CNRS-IN2P3, CEA-DRF

• **Director or RI representative in France:**

• Emmanuel Clément

• **Construction:** 2003

• **Operation:** 2014

• **Stakeholders in France:** GANIL, Université Claude Bernard - Lyon 1, Université Paris-Saclay, Université de Strasbourg

• **Contact in France:** Emmanuel.Clement@ganil.fr

• **Website:** <http://agata.in2p3.fr>

International dimension

Director: John Simpson (président du comité de pilotage AGATA)

• **Partner countries:** DE, BG, ES, FI, FR, HU, IT, PL, UK, SE, TR

• **Website:** www.agata.org

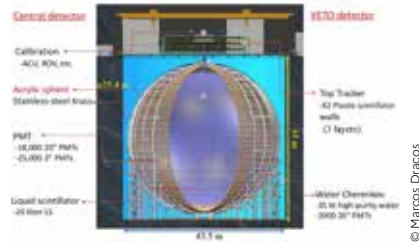


JUNO

Jiangmen Underground Neutrino Observatory

The discovery of oscillations between neutrino flavours opened a loophole in the Standard Model, in which neutrinos are treated as zero mass particles. Since then, several experiments have sought to study the oscillation phenomenon that governs questions of mass hierarchy between the different neutrino flavours.

JUNO is a new generation neutrino detector, which will significantly improve the accuracy of the study of this phenomenon, using the world's largest volume of scintillator liquid, read by more than 40 000 photomultipliers. The detector is located in Kaiping, China, 200 km from Hong Kong. The detector will track anti-neutrinos from the Yangjiang (two 4.6 GWth EPR reactors) and Taishan (six 2.9 GWth cores) nuclear reactors. It is buried at a depth of 700 m to be protected from cosmic radiation. By detecting the flux of anti-neutrinos from the reactors, the experiment will make it possible to measure the oscillation parameters between the different neutrino flavours,



with an unprecedented precision for the study of mass hierarchy.

The experiment may also have an impact on the nature of geo-neutrinos, neutrinos from supernovae or solar neutrinos. The construction of the experimental site began in January 2015 and is now preparing to install the detector, designed and built by an international community, which will operate the experiment from 2023 on.

Relations with economic actors and/or socio-economic impact

Although this project is part of fundamental research, there are close links with industry for the construction of the detector, but also for the R&D phase that preceded this construction. JUNO is also involved in training students from the countries involved in advanced detection techniques and mass data exploitation.

Open science and data

- All the publications from projects using the infrastructure are open access
- Annual data production: 3 PB
- Validated and described data are published on a data repository

Category: RI

Type of infrastructure: single site

Infrastructure location: Jiangmen (CN)

French supporting institutions: CNRS-IN2P3

- **Director or RI representative in France:** Marcos Dracos
- **Construction:** 2014
- **Operation:** 2023
- **Contact in France:** marcos.dracos@in2p3.fr
- **Website:** <http://juno.ihep.cas.cn>

International dimension

Director: Yifang Wang (porte-parole de la collaboration JUNO)

- **Partner countries:** CN, IT, DE, RU, FR, TH, CL, FI, PK, AM, BE, BR, CZ, HR, LV, SK, US, TW
- **Website:** <http://juno.ihep.cas.cn>



KM3NeT

Kilometre Cube Neutrino Telescope

The Kilometre Cube Neutrino Telescope (KM3NeT) is a European neutrino observatory project being installed in the Mediterranean Sea. This infrastructure is designed to detect the very faint light generated by the interactions of neutrinos in water. Two sites are under construction, one off the coast of Toulon in France (Oscillation Research with Cosmics in the Abyss-ORCA), optimised for the detection of low-energy atmospheric neutrinos (3 GeV-100 GeV), and the other in Sicily (Astroparticles Research with Cosmics in the Abyss-ARCA), optimised for high-energy cosmic neutrinos (1 TeV-10 PeV). ORCA, located at a depth of 2500 m, will consist of 115 flexible lines anchored to the seabed at 20 m intervals and carrying detectors (Digital Optical Modules DOM) at 9 m intervals. One of the major objectives of KM3NeT-ORCA is to measure the mass hierarchy of neutrinos. For KM3NeT-ARCA, located at a depth of 3 500 m, the spacing are much wider: 90 m between the lines and 36 m between



© KM3NeT

the DOMs. KM3NeT will follow on from the ANTARES experiment with an order of magnitude improvement in sensitivity and is thus aimed at discovering and studying astrophysical sources of cosmic neutrinos. These permanent deep-sea infrastructures offer important opportunities for synergy with Earth, Marine and Environmental Sciences.

Relations with economic actors and/or socio-economic impact

Within the framework of the development and deployment of the subsea infrastructure, numerous industrial partnerships have been established: Alcatel, AIM, Comex, CREDAM, Cybernetix, Degreane, ECA, Euroceanique, Foselev marine, iXSurvey, iXSea, Genisea, Osean, Orange Marine.

Open science and data

- All the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure open on a software forge <https://github.com/km3net>
- Annual data production: 500 TB
- Infrastructure with a FAIR data policy in application

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Marseille

French supporting institutions: CNRS-IN2P3

Director or RI representative in France: Paschal Coyle

Construction: 2020

Operation: 2020

Stakeholders in France: Aix Marseille Universités, Université de Paris, Université de Strasbourg, Université de Nantes - IMT Atlantique, Université de Caen, Université de Toulon, Université Claude Bernard - Lyon 1, Université Côte d'Azur

Contact in France: coyle@c ppm.in2p3.fr

Website: <https://platforms.in2p3.fr/platform/801/details>

International dimension

ESFRI project: KM3NeT 2.0

Director: Paschal Coyle (porte-parole de la collaboration KM3NeT)

Partner countries: FR, ZA, DE, AU, ES, GE, GR, IT, MA, RO, NL

Website: www.km3net.org

LSM

Modane Underground Laboratory

The LSM (Laboratoire Souterrain de Modane) is a national research platform of the CNRS-IN2P3 dedicated to fundamental research projects and instrumental developments requiring an exceptionally low radioactive environment. Located in the middle of the Fréjus motorway tunnel, with a rock cover of 1,700 m, the laboratory has a cavity of 3,500 m³ protected from cosmic radiation. An area of about 300 m² is dedicated to experimental facilities for national and international scientific collaborations in search of rare events. This site, the deepest in Europe to offer the flexibility of road access, currently hosts the EDELWEISS, DAMIC-M, NEWS-G and MIMAC dark matter experiments, as well as the SuperNEMO, CUPID-Mo and TGV neutrinoless double-beta decay searches. The LSM also hosts a Gamma-ray spectrometry facility, consisting of 18 high-purity Germanium detectors. This facility, which allows the precise measurement



© LSM

of very low levels of radioactivity, is intended for the selection and validation of materials used for the elaboration of experiments for fundamental physics experiments, but is also widely open to scientific teams involved in geosciences and environmental sciences (radiation protection, radioactive dating, etc.).

Relations with economic actors and/or socio-economic impact

The gamma spectrometry platform houses IRSN and CEA instruments dedicated to nuclear safety and offers ultra-low radioactivity measurement services for industry. The possibilities offered by the infrastructure led to the filing of a patent with the Pasteur Institute and the creation of a start-up company, Proceltech, which offers solutions for protecting stem cells from ionising radiation during storage.

Open science and data

- All the publications from projects using the infrastructure are open access
- Annual data production: 1 TB

Category: RI

Type of infrastructure: single site

Infrastructure location in France: Modane

French supporting institutions: CNRS-IN2P3

• **Director or RI representative in France:** Jules Gascon

• **Construction:** 1980

• **Operation:** 1983

• **Stakeholders in France:** Université Grenoble Alpes

• **Contact in France:** j.gascon@ipnl.in2p3.fr

• **Website:** <http://lpsc.in2p3.fr/index.php/fr/lang-fr-plateforme-nationale-lsm-lang-lang-en-lsm-national-facility-lang>

LSST

Legacy Survey of Space and Time

The Legacy Survey of Space and Time (LSST) is a large optical and near-infrared astronomical survey that will be conducted from 2024 and for 10 years by the Vera Rubin Observatory, under construction since 2014 in Chile. It will map the entire visible sky twice a week, providing an accurate picture of the “dynamic universe”. The main scientific goals of LSST are to improve our understanding of energy and dark matter, and to open a new window on the study of the variable universe. The volume of data will also allow us to study all the different structures in the universe, including our solar system and the Milky Way. With no competitor on the ground, the LSST is also essential for space programmes designed to study dark energy, such as the Euclid satellite (ESA project). The telescope used, with a diameter of 8.4 m, is based on a compact design and associated with a dedicated camera with 3.2 billion pixels and covering a field of 9.6° squared, i.e. 40 times the diameter of the full



© Oscar Riviera, Rubin Obs/NSF/AURA

moon. With more than 800 exposures and 20 TB of data produced per night, i.e. about 60 Po at the end of the survey, the survey falls within the scope of Big Data. The images will be analysed in real time and the 10 million anticipated astronomical alerts will be distributed with a latency of 60 seconds. Consolidated catalogues will be produced once a year and made available for analysis.

Relations with economic actors and/or socio-economic impact

The scientific and technological challenges for LSST have led to innovations in France in CCD sensors and their readout electronics, and in the fine measurement of large-scale optics. Developments in the field of large databases and the processing of large volumes of data are leading to partnerships with industrial players and in the field of artificial intelligence.

Open science and data

- The source codes produced by the infrastructure open on a software forge <https://github.com/lstt>
- Annual data production: 7 PB

Category: RI

Type of infrastructure: single site

Infrastructure location: Tucson (US)

French supporting institutions: CNRS-IN2P3

Director or RI representative in France:

• Emmanuel Gangler

• **Construction:** 2009

• **Operation:** 2023

• **Stakeholders in France:** Université Paris-Saclay, Université de Paris, Sorbonne Université, Université de Montpellier, Université Savoie Mont Blanc, Aix-Marseille Universités, Université Grenoble Alpes, Université Clermont Auvergne, Université Claude Bernard - Lyon 1

• **Contact in France:** emmanuel.gangler@clermont.in2p3.fr

• **Website:** <http://lsst.in2p3.fr>

International dimension

Director: Steve Kahn (directeur de LSST)

• **Partner countries:** US, FR, CL

• **Website:** www.lsst.org

PAO

Pierre Auger Observatory

The Pierre Auger Observatory is a high-performance infrastructure located in the Argentine pampas, designed to study cosmic rays at the highest energies, around and beyond 10¹⁸ eV, an energy range inaccessible to accelerators. However, their study is difficult because their flux is too low to allow direct detection. These astro-particles are therefore observed through secondary particle cascades that they generate in the atmosphere, which requires huge detection areas to collect a large number of events. The Pierre Auger Observatory, covering 3 000 km², detects cosmic rays over more than three decades in energy. It allows the characterisation of atmospheric sheaves by detecting the particles arriving on the ground, with a network of 1 660 autonomous detectors, and the fluorescent light they produce in the atmosphere, with 27 telescopes. Its large collection area and its hybrid detection strategy have enabled knowledge of cosmic rays down to the most



© Steven Saffi

extreme energies. Understanding the nature and origin of these cosmic rays remains an open question that the Pierre Auger Observatory is undertaking to solve with AugerPrime, a project designed to improve the characterisation capabilities of atmospheric sprays, through the addition of detectors and high-performance acquisition electronics.

Relations with economic actors and/or socio-economic impact

The research training capacity of students is high, with about 290 PhDs obtained internationally. The AugerPrime project has led to the manufacture of new detectors by companies based in Europe.

The Pierre Auger Observatory regularly welcomes geophysicists and atmospheric specialists on its site, for study projects that have benefited from the existing infrastructure.

Open science and data

- All the publications from projects using the infrastructure are open access
- Annual data production: 50 TB

Category: RI

Type of infrastructure: single site

Infrastructure location: Malargüe (AR)

French supporting institutions: CNRS-IN2P3

Director or RI representative in France: Corinne Berat

Construction: 2000

Operation: 2000

Stakeholders in France: Sorbonne Université, Université Grenoble Alpes, Université Paris Saclay

Contact in France: berat@lpsc.in2p3.fr

Website: <http://auger.in2p3.fr>

International dimension

Director: Ralph Engel (porte-parole de la collaboration Pierre Auger)

Partner countries: DE, FR, AR, AU, BE, BR, CO, ES, IT, MX, NL, PL, PT, CZ, RO, SI, US

Website: www.auger.org



5.

Social sciences
and **humanities**



Social sciences and humanities

In order to face the challenges of the 21st century and to succeed in the major social, economic and environmental transitions, to build fairer, more inclusive, more resilient and more sustainable societies, it is necessary to have robust knowledge on social issues. Access to survey data on beliefs, opinions, ageing, demographic behaviours and markets, for example, is essential to produce science-based analyses and reduce uncertainties and unknowns. Thanks to technological innovations, in particular the digital revolution, it is now possible to store, process, compare and disseminate data and documents of a very diverse nature, whatever the field of study. The digital revolution is also accelerating the involvement of SSH in Open Science practices, by improving, amplifying and stabilising access to data, sources and documents for all researchers.

Social Sciences and Humanities infrastructures therefore address the need to provide the entire scientific community with clearly identified and easily accessible tools and services to pool skills, disseminate innovative practices, familiarise and train users in new instruments and support research based on national and international best practices. They also allow French SSH to be internationally recognised, notably through their contribution to major social European surveys and databases (*SHARE-ERIC*, *European Social Survey ERIC*, *CESSDA-ERIC* and now *GGP*), digital services (*DARIAH-ERIC*) or the EOSC (European Open Sciences Cloud).

Ultimately, infrastructures play a fundamental structuring role in SSH research, whatever the disciplines and thematic fields.

- Some infrastructures are perfectly identified and used by SSH communities (**OpenEdition** and **Huma-Num**). With solid governance and exemplary scientific management, they have led to considerable scientific progress in the field of data, digital humanities, Open Science and publishing. They have become European models.

- Other infrastructures still need to strengthen their governance, management, and scientific positioning to fully achieve their objectives (**PROGEDO**, **E-RIHS-FR** and **RnMSH**). Improving their impact on research communities and clarifying their scientific perimeter are priorities for the next three years.

The infrastructures meet the following needs: data accessibility, support for the digital turn, support for valorisation, support for internationalisation and dissemination.

Today, they carry out different missions:

- development of data culture in SSH (**PROGEDO**, **Huma-Num** and **E-RIHS-FR**);
- development of digital humanities (**Huma-Num**, **PROGEDO** and **E-RIHS-FR**);
- development of open access digital publishing (**OpenEdition**);
- support to heritage sciences (**E-RIHS-FR**);
- territorial distribution of SSH (**RnMSH**) and access to RI*.

Finally, some infrastructures are nodes of European Research Infrastructures:

- RI* **PROGEDO** supports French participation in *SHARE-ERIC*, European

Social Survey ERIC, CESSDA ERIC and now GGP (ESFRI project);

- The RI* **Huma-Num** is the French node of DARIAH-ERIC;
- **OpenEdition** is the French node of OPERAS (ESFRI project);
- **E-RIHS-FR** is the French node of E-RIHS Europe (ESFRI project).

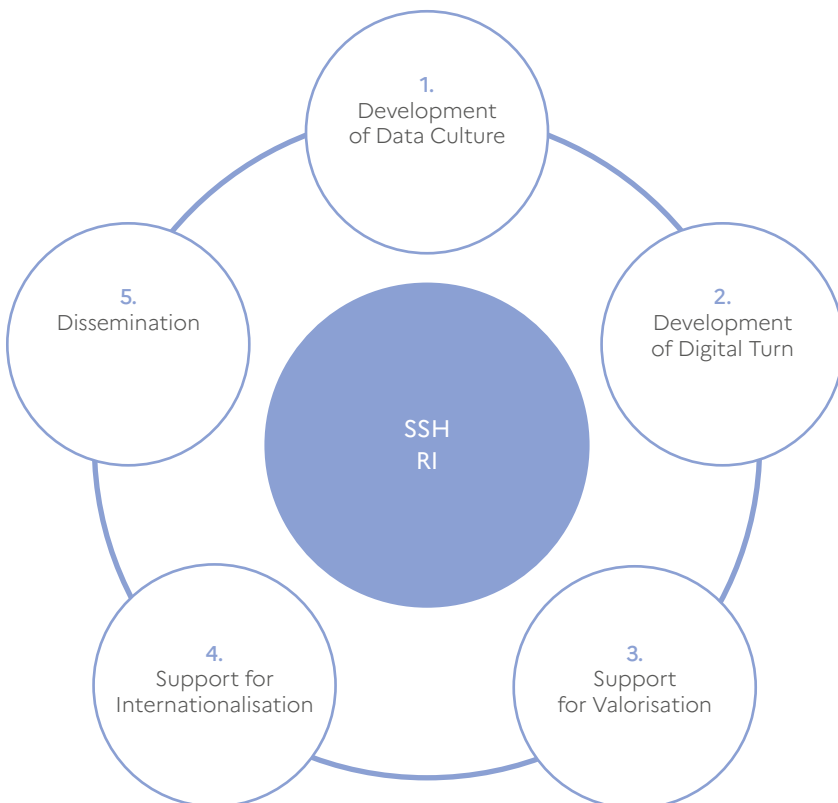
HUMA-NUM: A RI* FOR DIGITAL HUMANITIES

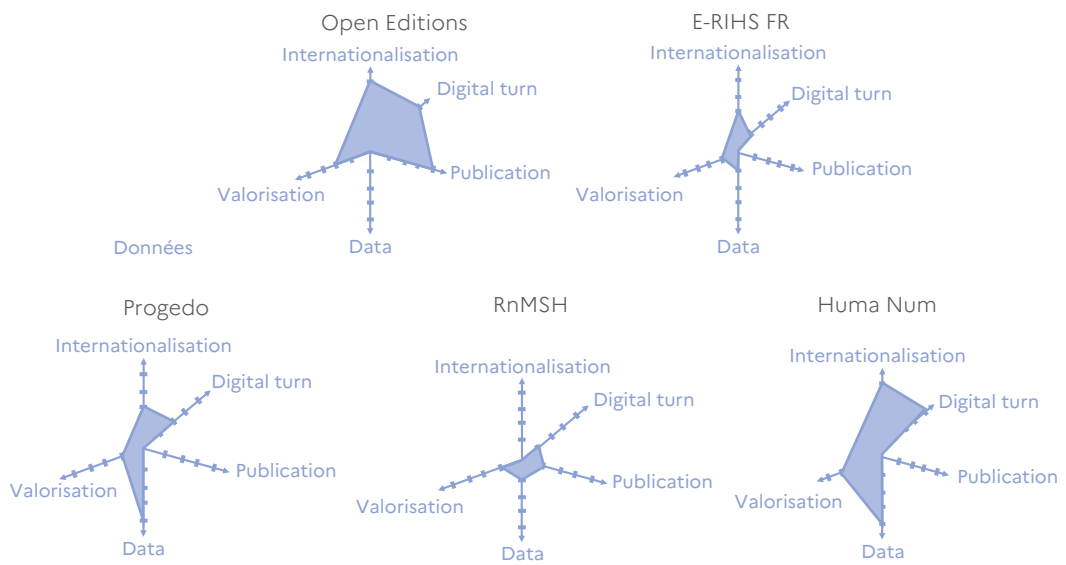
Huma-Num's approach is twofold: making research data available (opening up data and metadata) and making metadata interoperable (standardisation, API, data access interface). Digital

best practice guidelines and white papers, targeted at the needs of SSH research, are also produced.

The digital services and tools of the RI* **Huma-Num** consist of a set of infrastructure technologies (servers) and computer systems made available to research units to share, disseminate and stabilise access to data and documents.

The research programmes likely to use **Huma-Num**'s services and tools are developed with and close to the communities. In 2020, the RI* estimates that there are hundreds of physical users (500 to 1,000), thousands of data producers or users (8,000) and millions of users consulting data and publications.





Analysis of the current SSH research infrastructures landscape based on the survey

In 2021, **Huma-Num**, with the support of the French Ministry of Research and Innovation, opened three “Huma-Num Labs”, which are a pilot experiment associating **Huma-Num** and the *Maisons des Sciences de l’Homme* (MSH).

Huma-Num’s clear and solid scientific project, governance and reporting meet all the requirements for excellence of a RI*. Its role in structuring, training and leveraging communities is established. While the digital humanities are not supported by an institution or a disciplinary community, **Huma-Num** has become the model of a SSH infrastructure and a European champion of the Digital Humanities (with the coordination of the European TRIPLE project and the ERIC OPERAS partnership (*Open Scholarly Communication in the European Research Area for Social Sciences and Humanities*)). The infrastructure is widely supported by SSH communities.

RI* PROGEDO (DATA PRODUCTION AND MANAGEMENT): DEVELOPING A QUANTITATIVE DATA CULTURE IN SSH

PROGEDO’s objective is to support the collection, documentation, preservation and dissemination of a wide range of data needed by the social sciences and humanities. It also supports the implementation and dissemination of major European surveys.

At the national level, **PROGEDO** relies on data platforms deployed in the *SSH Maisons des Sciences de l’Homme*, which provide users with technical assistance.

PROGEDO is also organised to be the funding channel for France’s commitments to major European surveys. This original model makes it possible to group together and manage the ERIC CESSDA (*Council of European Social Science Data Archives*), ESS (*European Social Survey*), SHARE (*Survey on Health,*

Ageing and Retirement in Europe), and GPP (*Generations and Gender Program*) under a single strategic umbrella.

In order to enable SSH to support public policies and public or private actors, and to shed more light on the democratic debate, **PROGEDO** must play a greater role in the dissemination of research results from data processing and surveys to decision-makers or opinion leaders. **PROGEDO** must also increase access to public data, thanks to their anonymization (or semi-anonymization). Finally, the RI* must anticipate the collection and pooling of new data, particularly massive data (collection, processing, representation, etc.), in order to meet the scientific challenges of the future.

To this end, the RI* can develop its relations with SSH units recognised for their expertise on data and collaborations with existing networks. Its visibility among scientific communities must be increased for example, through the "DATA SSH" training weeks, whose number of users has increased significantly since 2019 and measured.

The importance of data culture in SSH gives **PROGEDO** a strategic national and international role. In order to ensure its missions, increase the number of its users, reinforce its sustainability and perpetuate its existence, the RI*'s priorities are to specify its scientific perimeter, reorganise its departments accordingly and equip itself with robust monitoring indicators.

OPENEDITION: AN OPEN DIGITAL EDITION FOR SSH

A national research infrastructure since 2016, **OpenEdition** is a publishing portal in the social sciences and humanities developed by **OpenEdition** Center.

A non-profit public initiative, **OpenEdition's** mission is to develop Open Access digital

publishing, to disseminate uses and skills related to scientific communication, and to promote research and innovation in digital methods of information retrieval and exploitation. **OpenEdition** comprises four platforms: *Revue.org*, *Calenda*, *Hypothèses.org*, *OpenEdition Books*.

This infrastructure is essential for digital publishing in SSH. **OpenEdition** is one of the historical actors in the development of open access at national and international level.

RI **OpenEdition** evolves in a competitive environment composed of private and public actors (e.g. at national level *Cairn* and *Persée*, at international level *Erudit*, *SciELO*, *Jstor*, *OLH*, *PKP*, *PLOS ONE*, *Springer*, *Elsevier*). Compared to these players, **OpenEdition** promotes Open Access by taking into consideration the diversity of publishing structures (bibliodiversity) and by developing a sustainable economic model, *freemium*. The infrastructure has succeeded in its challenge, since 95% of the content distributed by **OpenEdition** is Open Access.

OpenEdition collaborates at national level with *Persée*, *CCSD*, *MSH*, *Métopes* and *Huma-Num*. Its funding model is consolidated by significant successes in national and European calls, which also show that peers recognise **OpenEdition's** work.

In short, the infrastructure fully meets the objectives of the PNSO (National Open Science Plan). Its governance, its scientific project, its financial sustainability (especially its self-financing capacity), its reporting and its visibility are exemplary. In the coming years, **OpenEdition** will have to renew its software and strengthen its human resources in order to build a unified digital environment, accessible through a range of services combining data and publications. It will build on the FAIR principles to provide better services to the scientific communities.



THE NATIONAL NETWORK “MAISON DES SCIENCES DE L’HOMME” (RNMSH)

The *Maisons des sciences de l’Homme* play a role of territorial interface and support for partnerships between universities, National Center for Scientific Research (CNRS) and local authorities. Their history and their inclusion in location make them heterogeneous, whether in terms of size, missions or services they provide. Some **MSHs** aspire to federate SSH research teams on a site, while others are places where interdisciplinarity with non-SSH sciences is built. The **MSHs** are also access points for infrastructures, in particular **PROGEDO** – through the PUDs – and **Huma-Num** (humanum-Lab). The MSH network manages 5 networks of platforms (Scripto, Audio, Data-PUD, Spatio, Cogito). These platforms are a major lever, which must be better exploited and reinforced.

Some **MSHs** play a key role in shared equipment and services for research. Some provide functions related to scientific publishing. Some provide essential training for researchers, academics, PhD students, Research support staff.

The achievement of these objectives and the consolidation of the role of the **MSHs** for the French SSH, in coherence with the status of RI, must be based on a precise perimeter of action and a common scientific project, while respecting their diversity, the specificities of their sites and their own dynamics, and the local needs of the research communities. The potential for shared resources, the benefits of proximity and the visibility that it confers, must be fully grasped over the next three years.

E-RIHS (EUROPEAN RESEARCH INFRASTRUCTURE FOR HERITAGE SCIENCE/FRANCE)

E-RIHS-FR was included in the national roadmap of 2016 under the impetus of the Ministry of Culture (MC). It is

primarily the French node of the E-RIHS EU (ESFRI project). After numerous H2020 projects obtained for more than a decade, the European Commission validated in November 2021 the Step application one which aims at the creation of an ERIC (by 2023 at the earliest).

E-RIHS aims at non-invasive material study of (human) heritage artefacts by physico-chemical measurements and the archiving and/or digital sharing of these measurements. E-RIHS aims to:

- Analysis of degraded and heterogeneous materials (ability to isolate, identify and measure their components and their degradation).
- Analysis of collections, their dating, modalities of their degradation and safeguarding, the understanding of manufacturing processes of artefacts and history of the technical skills of their producers.
- FAIRisation, open publication, archiving and mining of the (potentially) massive data produced by these studies.

E-RIHS is a unique project in Europe and in the world, potentially a vector of a rare transdisciplinary dialogue between materials sciences, humanities and digital technologies. **E-RIHS-FR** is clearly identified as a strategic priority, but still needs to mature in order to meet all the requirements of an infrastructure and address wider communities. It must therefore continue the efforts already undertaken on its organisation and the dissemination of its data, in order to realise the full potential of its scientific project.

In conclusion, the priority objectives for the next three years will be

1. Restructure some RIs to bring them into line with best practices in terms of governance, budgetary management and scientific steering, consolidate their sustainability and ensure their long-term

survival. This will require repositioning and resizing the perimeter of some infrastructures to respect their uniqueness, by clarifying the objects and missions of each to avoid redundancy;

2. To create new modules in certain infrastructures to address recent developments (big data, AI, etc);
3. To increase visibility and access to researchers in SSH, in order to increase the number of users. It will be important to consolidate the monitoring of the infrastructures, in particular through specific indicators.

In addition, the growing needs in terms of valorisation of SSH and transfer to the non-academic world, in particular for expertise, patents and decision making, call for a close thinking of RI evolution.

Supporting and accompanying infrastructures is thus a crucial issue so that they can successfully carry out their transformations and optimise their impact, particularly in terms of access and use for all researchers in SSH.

HUMA-NUM

Very Large Research Infrastructure for Digital Humanities

The main mission of the RI* Huma-Num is to develop, together with the communities and based on scientific guidance, an international level digital infrastructure for the Humanities and Social Sciences. With its consortia, which bring together players from the scientific communities, its regional network of points of presence in the Maisons des sciences de l'Homme, and its project support centre. It supports the SSH in the production, processing and management of research data.

It also hosts, within the Huma-Num Lab, researchers and activities oriented towards research and development, innovation and valorisation.

Huma-Num has a physical infrastructure and implements digital services to develop research programmes – and preserve their data and tools – over the long term in an Open Science context. These services, including the NAKALA repository and the ISIDORE research assistant, are part of the Open Science framework



©CC-IN2F3-HN/CNRS

and, in addition to opening up data, promote their availability with a triple objective of data and metadata quality, inclusion in a life cycle controlled by scholars and, lastly, data sustainability. Huma-Num coordinates French participation in several European infrastructures and is involved in European projects associated with the construction of the EOSC. It is also developing cooperation beyond Europe.

Relations with economic actors and/or socio-economic impact

Huma-Num maintains cooperation and partnerships with the knowledge and data management industries. This is particularly the case for the ISIDORE services and the secure storage infrastructure, or in the case of European projects. Its national and international roadmap foresees a rapid development of these cooperations.

Open science and data

- Part of the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure are open on a software forge: <https://gitlab.huma-num.fr>
- Annual data production: 100 TB
- Infrastructure with a FAIR data policy in application
- The validated and described data are published on a data repository: <https://nakala.fr>

Category: RI*

Type of infrastructure: distributed

Infrastructure location in France: Aubervilliers

Other sites in France: Villeurbanne

French supporting institutions: CNRS

- **Director or RI representative in France:** Olivier Baude
- **Construction:** 2013
- **Operation:** 2015
- **Stakeholders in France:** Campus Condorcet, AMU
- **Contact in France:** secrétaire générale: Ariane Allet ariane.allet@huma-num.fr
- **Website:** www.huma-num.fr, <https://humanum.hypotheses.org>

International dimension

ERIC DARIAH, ESFRI landmark

- **Partner countries** FR, AT, CY, DE, DK, HR, IE, IT, LU, MT, NL, PL, PT, RS, SI, BG, GR, CZ, BE
- **Website:** www.dariah.fr

PROGEDO

Data Production and Management

The RI* PROGEDO aims to define and structure a public data policy for social science research. Its missions aim to develop a data culture, to enable the research community to make the best use of these data, to intensify their use and to make available work useful to society. It supports the implementation and dissemination of major European surveys.

To achieve these objectives, RI* PROGEDO organises support for the collection, documentation, preservation and promotion of a range of data needed by humanities and social sciences disciplines using quantitative methods. It promotes the dissemination of these data for research purposes within a controlled framework that complies with the legislation in force, supports



© Sébastien Oliveau

the carrying out of surveys for research purposes and participates in the setting up of secure systems for access to individual data.

Relations with economic actors and/or socio-economic impact

The infrastructure works to provide researchers with data whose use is legally restricted to research.

The infrastructure works on the production of French components of international surveys whose data are freely available.

Relations with the socio-economic world are therefore limited, as they are not part of the infrastructure's missions.

Open science and data

- Annual data production: 250 GB
- Infrastructure with a FAIR data policy in application
- The validated and described data are published on a data repository:
<https://datacatalogue.cessda.eu>.

Category: RI*

Type of infrastructure: distributed

Infrastructure location in France: Paris

Other sites in France: Paris

French supporting institutions: CNRS

Director or RI representative in France:

Sébastien Oliveau

Construction: 2008

Operation: 2008

Stakeholders in France: CNRS

Contact in France: secrétaire générale:

Claire Vandemoortele, claire.vandemoortele@cnrs.fr

Website: www.progedo.fr

International dimension

ERIC CESSDA; ERIC SHARE; ERIC ESS, GGP ESFRI project

- **Partner countries** AT, BE, HR, CZ, DK, FI, DE, GR, HU, IS, IE, NL, MK, NO, PT, RS, SK, SI, SE, CH, GB
- **Website:** www.cessda.eu

RnMSH

National network of Maisons des Sciences de l'Homme

The RnMSH, a territorial interface infrastructure and partnerships between universities, the CNRS and local authorities, coordinates a network of 22 human science centres, instruments for the transformation of the social and human sciences based on multidisciplinary and interdisciplinarity. It encourages incubation and supports multi and interdisciplinary projects, with a focus on SSH, and runs five platform networks (Scripto, Audio, Data-PUD, Spatio, Cogito). It coordinates actions around priority themes and implements operations to promote and disseminate scientific research. The strategic objectives of the RnMSH's scientific policy, set out in a charter, are to lead a large part of the ESR system of the 22 sites towards the most innovative practices by sharing experiences. The MSHs and their network, in conjunction with the RI* Huma-Num and PROGEDO, and other infrastructures such as Métopes



and OpenEdition, contribute to the digital turnaround in the context of the development of open science and data culture. The RnMSH participates in the evolution of professions and their organisation at both the research and engineering levels, and in strengthening interfaces at the territorial level with civil society and local authorities.

Relations with economic actors and/or socio-economic impact

Through participatory research actions, or through its networks of platform, the MSH and their networks co-construct research projects with territorial players (associations, public structures, private companies). The MSHs are responsible for various mechanisms that enable this research, such as science shops and observatories. They develop recognised scientific expertise.

Open science and data

- Annual data production: 250 TB
- The validated and described data are published on a data repository: www.nakala.fr

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Paris

Other sites in France: Aix-en-Provence, Besançon, Bordeaux, Caen, Dijon, Faaa, Gif-sur-Yvette, Lille, Lyon 7^e, Montpellier, Nancy, Nanterre, Nice, Poitiers, Rennes, Saint-Denis, Saint-Martin-d'Hères, Strasbourg, Toulouse, Tours

French supporting institutions: CNRS, FMSH

- **Director or RI representative in France:** Paul Buléon, Gilles Pollet et Nicolas Thély
- **Construction:** 2006
- **Operation:** 2006
- **Stakeholders in France:** Université de Tours, Université de Lille, Université Lumière - Lyon 2, Université de Lorraine, Université Rennes 2, université Poitiers, université de Clermont Auvergne, université Paris Saclay, Université Sorbonne Paris Nord, Université Paris 8 - Vincennes - Saint-Denis, UFC, UBM, Université de Strasbourg, UGA, UT2, Université Paris 1 - Panthéon Sorbonne (Paris 1), Université Paris Nanterre, UNICAEN, Université Paul-Valéry - Montpellier 3 (UPV), UB, UCA, AMU, Université de Nantes, UPF
- **Contact in France:** Secrétaire générale: Myriam Danon-Szmydt, myriam.danon@cnrs.fr
- **Website:** www.msh-reseau.fr/presentation

E-RIHS France

European Research Infrastructure for Heritage Science – France

E-RIHS France seeks to facilitate the practice of heritage science and improve its impact by promoting research, the development of better technologies and the in-depth study of scientific skills. As the French node of the European E-RIHS infrastructure, E-RIHS France brings together infrastructures from several disciplines and will provide integrated access to equipment, expertise, resources and technologies through a standardised approach that promotes scientific excellence and a culture of multidisciplinary collaboration. This access will be organised around four thematic platforms:

- FIXLAB: access to fixed equipment for synchrotron, ion beam, laser, etc analyses;
- ARCHLAB: access to the network of museum science archives and cultural institutions;
- MOLAB: access to mobile equipment for the study of materials in situ;
- DIGILAB: access to digital data and tools.



© V. Fournier - A. Maigret / C2RM/IF

The ambition of E-RIHS is to use its international status and clear identity to become a cohesive force in the international heritage science community. This unique position will allow it to promote its scientific vision and the values attached to it: scientific excellence, European and international collaboration, innovation, communication and respect for scientific ethics.

Relations with economic actors and/or socio-economic impact

Heritage science is a field of research that spans the humanities, social sciences and experimental sciences. Its practice therefore requires the good collaboration of the cultural and creative industries (heritage institutions, conservation-restoration professionals, etc.) with the different actors of research and innovation, whether from the public or private sector.

Open science and data

- Part of the publications from projects using the infrastructure are open access
- The validated and described data are published on a data repository:

Category: Project

Type of infrastructure: distributed

Infrastructure location in France: Paris

Other sites in France: Cergy, Champs-sur-Marne, Marseille 3^e, Marseille 9^e, Orsay, Palaiseau, Paris 1^{er}, Paris 5^e, Pessac, Saint-Aubin, Toulouse, Versailles

French supporting institutions: FSP

• **Construction:** 2016

• **Operation:** 2023

• **Stakeholders in France:** MESRI, MC, CNRS, Inria, MNHN, Université Paris-Saclay, CY Cergy Paris Université

• **Contact in France:** contact@sciences-patrimoine.org

• **Website:** www.erihs.fr

International dimension

E-RIHS, ESFRI project

- **Partner countries** BE, ES, FR, GR, HU, IT, MT, NL, PT, RO, UK, SI
- **Website:** www.e-rihs.eu





6.

Material sciences
and **engineering**

Material sciences and **engineering**

The objective of the research infrastructures for the sciences of matter is to offer scientific communities exceptional, even unique, research tools to develop knowledge of matter at different scales, from the atom to the macroscopic level, in all its forms (gas, solid, liquid, plasma) and under extreme conditions.

By definition, this field is **transverse** and **multidisciplinary**; it thus concerns most fields of fundamental or applied scientific research (materials science, biology, chemistry, physics, geology, heritage sciences, etc.). Advances in the knowledge and understanding of matter require constantly evolving characterisation techniques with technologies at the cutting edge of scientific excellence. The extremely wide range of probes that they represent (X-rays, neutrons, electrons, lasers, etc.), coupled with constantly improving spatial and temporal resolutions, constitute an important asset for the positioning of French research at international level. These analytical tools are also at the service of numerous societal issues (energy, environment, transport, health, information and communication, etc.).

France has **very large single-site facilities of international scope** requiring very high investments (from 100 M€ to several billion euros) and operating budgets. These instruments (synchrotrons, free electron lasers, neutron sources, lasers) are mostly RI* facilities built and operated by several partner countries. This instrumental landscape is largely completed by numerous distributed characterisation, fabrication or irradiation platforms that allow networking of globally competitive instruments associated with international expertise at the service of the scientific community.

LIGHT SOURCES: SYNCHROTRON RADIATION FACILITIES, FREE ELECTRON LASERS

Since the creation of the Laboratory for the Use of Electromagnetic Radiation (LURE)

in 1971, France has been a pioneer in the **use of synchrotron radiation**. It hosts two excellent synchrotron radiation centres: the European Synchrotron Radiation Facility (**ESRF**) in Grenoble, the first third-generation synchrotron open to users since 1994 – which, after an ambitious and innovative upgrade programme (**ESRF-EBS**), recently became the first fourth-generation high-energy synchrotron – and the **SOLEIL** synchrotron on the Saclay plateau, a national facility open to users since 2008.

These two centres are made up of a set of accelerators that accelerate and store electrons with an energy of 2.75 GeV (**SOLEIL**) or 6 GeV (**ESRF**) in a so-called storage ring, where the inflection of their trajectory by magnetic devices causes them to emit light known as synchrotron radiation, which can range from the far infrared to hard X-rays. These two centres provide photons of different energies: the optimum is 1 keV for **SOLEIL** (soft X-rays) and 10 keV for the **ESRF** (hard X-rays), which makes them complementary.

The global landscape is made up of some fifty synchrotron radiation centres, only three of which being “high-energy”: **ESRF-EBS** at 6 GeV, APS (Argonne, USA) at 7 GeV and SPring8 (Japan) at 8 GeV. In Europe, the user community, estimated at around 30 000 researchers, has 11 synchrotrons in operation, including Diamond in the UK and Petra at DESY in Germany.

A very broad community, covering disciplines such as physics, chemistry, biology, astrophysics, geology, archaeology, palaeontology, materials science and

heritage science, uses the extremely bright light produced by synchrotrons. In particular, these light sources are making a very strong contribution to many of the major societal challenges – and they are set to contribute more and more in the future thanks to the new performance generated by the technological developments in the accelerators and instruments they use. The highlights concern the fields of health (threats of new diseases such as Covid, crystallography of macromolecules with coupled CryoTEM/ synchrotron studies, actions of drugs), environmental sciences (analysis of plants, water, and polluted soils), energy (catalysis, batteries and nuclear materials), and information (quantum materials). Research in biology alone accounts for about 50% of publications at **ESRF** and **SOLEIL**. The number of users is estimated at 4,000 per year for **SOLEIL** on its 29 beamlines and 9,000 for **ESRF**, which has 43 beamlines, including 5 instruments managed by France (the CRG, Collaborating Research Groups). These two centres offer access to around 5 000 French researchers and students per year.

The major technological evolution of synchrotron light sources today consists of integrating the *multi-bend achromats* (MBA) technology, initiated at MAX-IV in Sweden and recently implemented with great success at the **ESRF**, into the storage ring. A reduction of a factor of 10 to 100 in the emittance of the electron beam is then obtained, which is accompanied by a gain in the brightness of the light produced by the same factor, as well as an improvement in its coherence. These new performances, in addition to reducing the duration of experiments and therefore increasing access possibilities, open up new fields of application with previously unattainable spatial resolutions and acquisition times, particularly for experiments carried out *in situ* or *in operando*, as well as for nanoscopy. In the next decade, all excellent synchrotron radiation centres will

be transforming their accelerators using MBA technology. To remain competitive, the **SOLEIL** synchrotron will also have to undergo this upgrade in order to meet the growing needs of the French community for very high spatial and temporal resolution experiments.

In addition, the new properties of synchrotron radiation also require new specificities and performances at the level of the instruments, namely: more stability, more efficient detectors, and improved qualitative (use of AI and machine learning) and quantitative (data centre) processing of the data obtained. There are therefore major needs in terms of instrumentation, detection and IT tools in the form of hardware and software. The production of an unprecedented amount of data (**ESRF** plans to produce 60 Petabytes of data in 2026) requires the implementation of innovative processing and storage solutions. **ESRF-EBS**, which became the first renovated operational light source in 2020, has therefore planned the renovation of its beamlines (optics, instrumentation, detectors) and is committed to improving its data management.

XFELs or free electron X-ray lasers are new X-ray sources that offer unprecedented performance for studying the structural and dynamic properties of matter at the atomic scale, for example during a reaction in real time. The **European XFEL (E-XFEL)** project in Hamburg, inaugurated on September 1st 2017, is the most intense coherent X-ray source in the world. This source of photons, produced over a wide energy range (300 eV to 12.4 keV), has a brightness 10 orders of magnitude higher than synchrotron radiation with a pulse duration of less than 100 fs. The operating principle of the **E-XFEL** is based on a 2 km long superconducting linear accelerator (located in a tunnel with a total length of 3.4 km) which confers an energy of 17.5 GeV to electron bunches (technology initially developed for future electron-positron colliders in high-energy physics). These electrons then generate bursts of coherent X-rays through



long undulators, thanks to the phenomenon of self-amplified spontaneous emission (SASE).

XFEL radiation makes it possible to follow, on the scale of a few tens of femtoseconds, states of matter stimulated by light excitation, thermal excitation, a magnetic field, THz excitation, etc. This opens the way to new studies on dynamic phenomena, hitherto unexplored for lack of tools (new manipulations of matter, structure-dynamics-function relationship in structural biology, etc.). XFEL radiation is therefore a unique window on the dynamic knowledge of matter – while in a complementary way, synchrotrons allow the study of systems at longer timescales (> 100 ps). The societal challenges that benefit and will benefit from these facilities are mainly health (small molecules, pharmacology, and enzymes), energy (photosynthesis), information and communication (dynamics of magnetism, quantum matter).

XFELs are sources with unique properties and a growing and diverse user community. Nevertheless, access to these sources remains limited due to the relatively small number of existing installations. In Europe, we can mention the SwissFEL in Switzerland, which is less efficient than the **E-XFEL** in terms of frequency (100 Hz vs. 27 kHz) and energy of the produced X-rays, as well as two installations in the XUV spectral range (soft X-rays), FERMI in Italy and FLASH in Germany, and a free electron laser project in the United Kingdom (UK XFEL), which is well advanced. At the global level, SACLA in Japan, LCLS in the USA, and PAL-XFEL in Korea are also open to the scientific community. In France, **E-XFEL** users come from some forty laboratories associated with various communities working on matter in high energy density conditions, on the physical chemistry of isolated atoms and molecules, on condensed matter (ultrafast dynamics, photo-physics, photochemistry) and on structural biology.

The French strategy in the field of synchrotrons and free electron lasers is to **pursue its commitment to the ESRF (RI*)**, whose

ESRF-EBS upgrade is a great success, to study the possibility of an **upgrade for the SOLEIL synchrotron (RI*)**, to remain competitive and meet user demand for enhanced resolutions and imaging capabilities (*in situ, in operando*), and finally to **strengthen French participation in E-XFEL (RI*)**, the only free electron laser in which France has a stake. France encourages this facility to continue to increase its power and to increase the number of experiments open to users. As the XFEL user community is substantial and growing in number, the relevance of building an XFEL-type source in France could arise in the next decade.

NEUTRON SOURCES

Neutron radiation is used to study and characterise the properties and behaviour of condensed matter, from the atomic to the macroscopic scale, on time scales ranging from 10^{-12} to 1 s. Based on the specificities of the neutron-matter interaction (high penetration in matter, magnetic interaction, sensitivity to light atoms in particular to hydrogen and its isotopes, energy and wavelength close to those of the excitations and relaxations encountered in matter...), it is a powerful and unique tool in a wide range of fundamental research fields, in particular in condensed matter and chemistry (phase transitions, new states of matter, magnetism, solid state chemistry, nanomaterials, polymer and liquid physics, crystal structure, proteins and enzymatic mechanisms, catalysis, solutions, metallurgy, biophysics, etc.) but also in subatomic physics.

Neutron scattering techniques are comparable to those of X-ray synchrotrons. Nevertheless, even if with the evolution of the techniques some overlaps are observed, a majority of the applications of neutrons remain inaccessible otherwise (study of atomic excitations and vibrations, magnetism, non-destructive macroscopic studies of massive parts, imaging and neutronography, structural studies in

physico-chemistry...). Neutron beams thus provide unique information to meet various scientific and societal challenges in fields such as energy (fuel cell membranes, nuclear materials, hydrogen storage, etc.), transport (light materials, mechanical and structural properties, study of tyres, etc.), heritage sciences (non-destructive study by imaging, ageing, etc.), information technologies (complex magnetic materials) or environment (study of foams, understanding of clathrates storing methane, etc.) and health (vesicles as vectors for new molecules, water-protein interaction, biological membranes, etc.), in particular by studying new materials.

The most intense neutron beams are produced either in a nuclear research reactor by the fission reaction of Uranium-235 nuclei, or by the spallation reaction, the principle of which is based on the interaction of a very high energy proton beam (produced by large accelerators) with a heavy metal target (Hg, W or Pb), the neutrons being produced during the decay of the target atoms. Nuclear reactors produce continuous thermalized neutron fluxes ($1 \text{ meV} < E < 150 \text{ meV}$) while spallation sources produce pulsed beams (except SINQ at PSI) over a very wide energy range, and with high peak intensity (while the time-integrated intensity is generally lower than in a reactor).

Europe, the world leader in neutron radiation, has about 6,000 regular users of neutron sources, all disciplines combined, of which about 25% are French (for comparison, the community is about 1,000 people in the USA, probably growing since the rise of SNS, and 800 regular users in Japan). France has the highest rate of publications in neutron science in Europe, along with Germany and the United Kingdom, mainly thanks to the experiments conducted at the ILL and until 2019 at Orphée.

Since the last decade, the European neutron facilities landscape shows a clear decrease in the overall supply due to the progressive shutdown of nuclear reactors, most of them

dating from the 1970s. The last reactors to be shut down are national reactors: BER II in Germany, JEEP II in Norway and Orphée in France, shut down in 2019. This will only be partially offset by the **European Spallation Source (ESS)**, currently under construction in Lund, Sweden, which is based on a 2 MW proton accelerator (eventually 5 MW) and will install 15 instruments in its initial phase. **ESS** is expected to start operation in 2027 and, after several years of ramp-up, to become the world's most powerful neutron source. By the end of the 2020s, the main European neutron sources should be the **ILL** (Grenoble) and FRM2 (Munich) reactors, as well as the SINQ spallation sources at PSI in Switzerland, ISIS in the UK and **ESS** in Sweden. Beyond Europe, neutron science is progressing: China has started up three intense neutron sources in ten years; in the United States, SNS is planning to install a second target, and the NIST and Oak Ridge reactors could be rejuvenated. In addition, Australia has a reactor at ANSTO, Russia will start up the 100 MW PIK reactor and Japan, around the flagship J-PARC facility, is developing numerous small source projects. Europe could thus soon lose its leading position in neutron science despite the advent of the **ESS**.

The French community currently has a single neutron source on its soil, the **ILL** (Institut Laue-Langevin), whose 58 MW **high-flux reactor**, started up in 1971, produces the most intense continuous beams of neutrons in the world. France, Germany and the United Kingdom operate the **ILL** and its shutdown is now envisaged for the early 2030s.

The French community also benefits from five CRG instruments at the **ILL**, operated by various French research organisations. In order to increase the French offer in neutron scattering, the Léon Brillouin Laboratory (LLB) has launched the construction of new instruments by upgrading certain instruments or parts of instruments formerly installed at the Orphée reactor. New CRGs



installed at the ILL and PSI in particular will strengthen the access possibilities for French teams in the coming years. All of these *outstations* will be integrated into the calls for projects already organised by the French Federation for Neutron Scattering (2FDN).

Nevertheless, a major deficit in neutron sources for French users is to be expected. By the 2030s, the number of instrument-days available to the French community will be reduced by at least a factor of 10 compared to before the closure of Orphée if the closure of the ILL is confirmed. A deficit will also be felt at the European level but to a lesser extent, as most of the major countries in the field have at least one national source. In this context, a third way of producing neutrons has recently been developed, using a so-called *stripping* reaction on light targets (Be, Li). The principle is based on the use of a particle accelerator of a few tens of MeV, which is very compact compared to spallation installations requiring very high proton energies, and a small target-moderator system that makes it possible to obtain a neutron beam with a brightness roughly equivalent to that of a medium-power reactor. These compact sources, known as CANS (Compact Accelerator-based Neutron Sources), have the advantage of being less expensive, modular, and capable of being upgraded and pulsed, like spallation sources. These CANS already exist in some countries (USA, Japan) but with very limited performance. With the development of high-current proton accelerators, many projects for such compact sources exist in Europe (Germany, Hungary, Spain, etc.) and in the world (China, Korea, Japan, USA, etc.). Although studies are still needed to solve the target and moderator issues and to optimise the accelerators, it appears that CANS could be promising enough to constitute the neutron sources of the future after 2030. In this context, an innovative project has been initiated by CEA to design and prepare the demonstrator of such a source.

With regard to the French roadmap in the field of neutron radiation, given its importance for the academic and industrial scientific community and its contribution to meeting major societal challenges, the **operation and modernisation of the ILL (RI*)** is a priority. Support for the French instruments developed by the LLB should be continued and increased, in order to strengthen certain areas where there is a lack of supply (diffraction, imaging, etc.). France will continue to **support the construction of the ESS (RI*)**, both on the accelerator and on the instruments; in the long term, the number of instruments must be at least doubled in order to meet the needs of the European community and to achieve an acceptable cost per day of experiment. A future challenge will be to train future generations and to make the best use of the third-generation ESS neutron source, access to which will be highly selective.

LASER FACILITIES

The thematic field of extreme light, marked by the award of a Nobel Prize in Physics in 2018, has been expanding rapidly in the world and in Europe for the last twenty years. France **has two excellent national laser infrastructures, APOLLON and LMJ-PETAL**, as well as very high-level laboratory facilities (about ten in France). The scientific projects concern the physics of ultra-high intensity (UHI) and high energy density (HDE) processes, but also the physics and chemistry of ultra-fast processes. The two French single-site RI facilities, **APOLLON** (Île-de-France) and **LMJ-PETAL** (Nouvelle Aquitaine), meet a criterion that is shared internationally: their laser power exceeds one Petawatt (1 PW = 10^{15} W). These infrastructures combine cutting-edge technologies, large installation size, safety and radiation protection, and project costs that are unthinkable on a laboratory scale.

With plasma physics, generation of radiation sources or particle beams and light-matter interaction as their foundation, **APOLLON**

and **LMJ-PETAL** make it possible to address the major scientific questions currently being asked in UHI physics (including high-field physics, quantum electrodynamics, relativistic plasma mirrors, electron acceleration by laser wake fields, etc.) and in HDE physics (including the basic physics for inertial confinement fusion). Theory, with numerical simulation, as well as R&D on laser technologies are transversal.

The scientific field related to power lasers extends from fundamental research to technology transfer and innovation, with in particular two major French industrial leaders (Thalès and Amplitude) but also SMEs and start-ups. This multi-PW sector is very competitive and many countries have important installations: England (Vulcan 2020), Germany (ATLAS 3000 and PHELIX), Russia (PEARL-X and XCEL), China (SULF and a 100 PW project), Japan (J-Karen), South Korea (CoReLS), the United States (Omega EP and PW TEXAS) and finally Hungary, Romania and the Czech Republic, which are building the ELI project.

The scientific laser community in France is about 500 people, including 200 potential users of the multi-petaWatt facilities, which represents half of the European community identified in the Laserlab Europe consortium. The worldwide laser community is about 3,000 people. The European landscape is very rich, with LaserLab Europe bringing together about 35 leading institutions. Several French facilities are open to users in Bordeaux (CELIA), Marseille (LP3), and on the Saclay area (LIDYL with ATTOLAB, LOA, LULI with LULI2000, ISMO and IJCLab with LASERIX), several of which study the physics and chemistry of ultrafast processes. The reflection initiated by CNRS, École Polytechnique and CEA around the Saclay plateau could be extended to other institutions and to regional sites to develop a national vision of this high-potential science.

In this landscape, the **APOLLON** RI* is a unique tool with its 4 laser beams (10 PW-fs,

1 PW-fs in service, 250 J-nns and probe beam) whose development to reach its nominal characteristics must be pursued as a priority, together with its commissioning and opening to users. Similarly, the **LMJ-PETAL** RI, which has been operational since 2017, must continue its ramp-up. This installation, unique in Europe, is one of the largest in the world, competing with the NIF (National Ignition Facility, Livermore) in the USA. The major impact of these two infrastructures concerns, in addition to national sovereignty, the maintenance of France's scientific excellence on strategic scientific subjects, their role in training excellence on the two sites (Saclay plateau and Bordeaux) and their contribution to the training-research-innovation ecosystem.

INTENSE MAGNETIC FIELDS

Infrastructures that develop and/or operate extremely high magnetic field facilities are used by scientists for research in physics, biology, bioengineering, chemistry, geochemistry, biochemistry, materials science and engineering. In this field, the **National Laboratory for High Magnetic Fields (LNCFM)**, which is part of the European Magnetic Field Laboratory (EMFL) infrastructure together with the HFML Nijmegen (static fields) and the HLD Dresden (pulsed fields), aims to explore exceptional magnetic fields with very high stability and spatial homogeneity. The **LNCFM** is an indispensable analytical infrastructure for the development of new materials essential for many modern technologies such as energy (superconductors, thermoelectric, etc.), high-energy physics, information storage and quantum processing. Its greatest scientific challenge is to understand the electronic structure of highly correlated matter (magnetism, superconductivity).

Furthermore, the development of these magnetic fields raises to a world level the scientific instrumentation dedicated to physical measurements under intense



fields (UV-VIS-NIR-THz spectroscopy, NMR, EPR, magnetisation, transport, etc.), often in combination with very low temperatures. The most remarkable French analytical instruments were until now part of three infrastructures included in the previous roadmap (RMN-THC, Renard and FT-ICR). The merger of these three networks into a single **Infranalytics** infrastructure has enabled them to offer coherent and adapted access to the large community of academic and industrial researchers (approximately 300 users per year). This new infrastructure is unique in Europe. Worldwide, only the NBMFL in the USA has all three techniques in-house. The joint exploitation of high field and high resolution spectroscopy and spectrometry techniques will contribute to technological breakthroughs in a wide range of disciplines, including medicine, structural biology, metabolomics, analysis of complex organic matter, advanced materials, energy production and storage, environment and sustainability.

These two RIs are playing and will continue to play a crucial role in keeping France at the forefront of developments, opening up new opportunities for very high field analytical research and providing access to a large community of academic and industrial users.

ELECTRONIC MICROSCOPY

The use of electron microscopy by the French research community has for many years been at the level of routine use when it comes to classical electron microscopy. However, in parallel, a very high level of electron microscopy has been developing for many years, integrating transmission devices (TEM), atom probe tomography (APT) or cryo-EM devices. The latter are part of the French Integrated Structural Biology Infrastructure (**FRISBI**) providing an integrative approach to structural biology. The other types of instruments are accessible to the community through the RI **METSA**, which includes 13 TEMs and 3 APTs. These instruments are mainly used to study the structure,

chemical composition and physical properties (electronic, electrical, magnetic, optical, etc.) of materials down to the atomic scale, in a way that is highly complementary to synchrotron or neutron infrastructures. **METSA** is aimed at a very broad community including materials sciences (metallurgy, functional materials, etc.), chemistry (catalysis, batteries, etc.), engineering sciences (electronic devices, photovoltaic cells, etc.) and to a lesser extent geology and biology. The use of TEM and APT is at the basis of innovations affecting many current issues, in particular adaptation to global warming, carbon neutrality and information technologies. With almost 50% of the applications made in the context of PhD theses, **METSA** plays an important training role. 10% of its intake is for international applications and two of its platforms are members of the European microscopy network ESTEEM. In the next 5 years, **METSA's** objectives will be to make available emerging techniques of very high technicality (*in situ/operando*, very high resolution spectroscopies, time-resolved, direct detection, etc.), to strengthen internal synergies within its network (between APT and TEM) in order to offer users new means of analysing matter, to strengthen the link with chemistry and to extend its access to the biology community.

For the sake of completeness, it should be noted that certain infrastructures such as **E-RIHS**, which is dedicated to the analysis of heritage materials, also integrate some of the cutting-edge material science characterisation tools (electron microscopy, synchrotrons, lasers, ion beams) in addition to more specific analysis platforms.

IRRADIATION OF MATERIALS

The scientific themes associated with materials irradiation are very varied and concern both fundamental and applied research. Indeed, a better understanding of the role of defects in solids is a major challenge to be able to understand the properties of materials, to design new

ones with innovative properties or to predict their ageing and its consequences. Irradiation can create, in a controlled manner depending on the energy and type of particle, different defects and clusters of defects, but also provoke chemical decomposition phenomena such as radiolysis. Moreover, the control of particle-matter interactions also allows irradiation to create nano-objects, to carry out chemical and structural analyses or, in the industrial sector, to sterilise or to produce radioisotopes for medical imaging.

France has many specialised irradiation facilities but they are not always open to the academic world. **EMIR&A** is a network of particle accelerators for the irradiation and analysis of materials and molecules, accessible to scientific and industrial communities. Its panel of complementary ion and electron accelerators, equipped with *in situ* characterisation instrumentation, constitutes an excellent research tool, as demonstrated by the international access request. Like its counterparts in United Kingdom and Germany, **EMIR&A** is the leading French structure for accelerator-based condensed matter studies. Over the last 5 years, **EMIR&A** has contributed to more than 400 publications in international journals and has built up a substantial user community (450 researchers, 250 students and some 30 industrial partners). In the next 5 years, it is essential to maintain these facilities at the highest level of performance, to open the network to new original tools such as micro-beams and to increase the animation of the community.

On a European scale, IFMIF-DONES is a European infrastructure project led by Spain to enable irradiation with a 14 MeV neutron flux. This project follows on from the IFMIF-EVEDA prototype carried out in the framework of the collaboration between Euratom and Japan (ITER Broader Approach). The main objective of this unique infrastructure will be to study the behaviour of structural materials in future fusion

installations by magnetic confinement (ITER, DEMO) but this type of irradiation will certainly open up to other fields of application such as space. Finally, let us mention the MYRRHA project (Multi-purpose hYbrid Research Reactor for High-tech Applications) under construction in Belgium, which will be the first sub-critical reactor in the world to be driven by a powerful linear particle accelerator (Accelerator Driven System – ADS). This infrastructure will have applications in areas such as nuclear waste, fundamental and applied physics and nuclear medicine.

INFRASTRUCTURES FOR ENGINEERING SCIENCES

Nanotechnologies are used in many scientific fields, in particular in information processing (microelectronics, photonics, telecommunications), which is moving towards quantum technologies and artificial intelligence (quantum processors or neuromorphic computing). A second field of application is biomedical engineering with miniaturised medical analysis devices or organs on chips reproducing biological systems to better understand them. Finally, many other fields need nanofabrication: chemistry with micro-reactors, astronomy with radio or optical detectors for telescopes, miniature instruments for satellites and environmental monitoring (low-cost sensors in large numbers to precisely map territories). Nanofabrication is essential for the realisation of all these devices, in complementarity with other analytical infrastructures (synchrotrons, microscopy, lasers...).

The **RENATECH** network includes 5 “large-scale” nanofabrication centres that allow for the creation of demonstrators and are open to users. This network carries out around 1,000 research projects and around 1,100 publications per year. Similar infrastructures exist in several countries (USA, Japan, Australia, Sweden,



Norway and the Netherlands) and meet the same challenges. **RENATECH** is now also federating 27 smaller “regional” clean rooms to form the **RENATECH+** network, which represents almost all the national clean rooms, and will help to reinforce France’s strengths at the European level, particularly in photonics, spintronics, microsystems and the synthesis of active materials by epitaxy. **RENATECH** is also the leader of the European consortium EuroNanoLab aiming at building a European infrastructure.

In the transverse field of time metrology, the new **REFIMEVE** infrastructure is based on the possibility of distributing, via the **RENATER** fibre optic network, a high stability and accuracy optical frequency developed by the SYRTE (National Time/Frequency Metrology Laboratory). On a national scale, this distribution of time and frequency is envisaged for some thirty laboratories and research infrastructures in a wide variety of fields (**SOLEIL**, **CNES**, **IRAM**, **FEMTO-ST**, **CERN**, **ESR**, etc.) and will enable the best terrestrial clocks to be compared on a European scale. Many disciplinary fields will benefit from the dissemination of this frequency: time/frequency metrology, fundamental physics on Earth and in space, precision spectroscopy applied to the environment and atmospheric physics, etc. In addition, this instrument could be used as a giant gyro sensor and also as a seismic sensor thanks to the presence of a large network of optical fibres throughout the world.

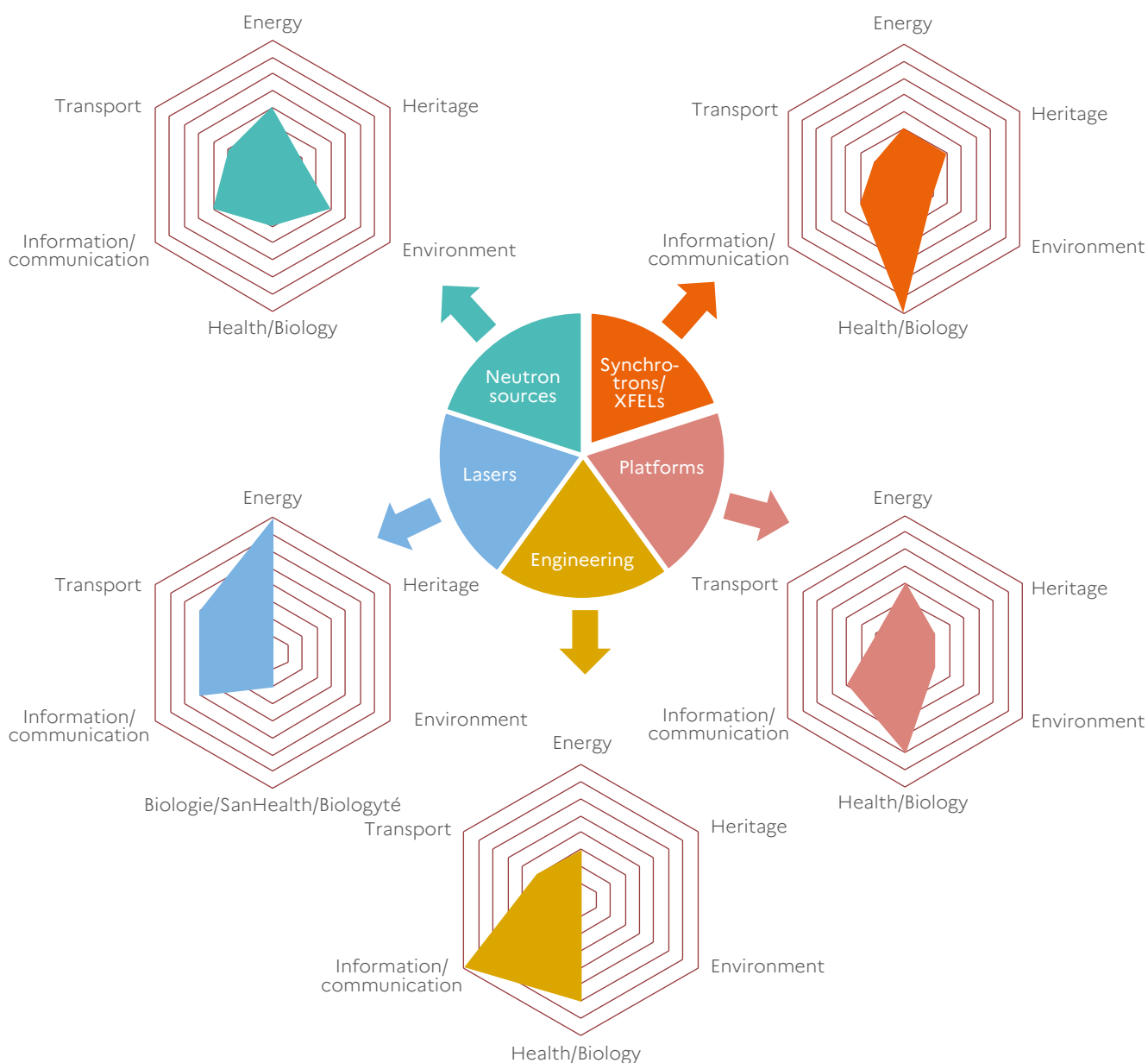
DATA MANAGEMENT AND OPEN SCIENCE

The vast majority of research infrastructures in the sciences of matter and engineering display, in the field of open science, either a genuine policy of openness for the largest and most mature ones, or an interest in and consideration of the stakes of this open approach, at least at the level of data.

With regard to data, almost all infrastructures have a data management policy and are positioned more broadly in a FAIR policy. Most infrastructures have initiated a structuring of resources in order to amplify data engineering and define the standards to be adopted in terms of storage, processing and durability. In particular, for single-site RIs, we note the implementation of unique identifiers attached to each dataset (DOI) and the start of shared storage solutions within specialised centres. In the context of multi-site infrastructures, the situation is more complex and comes up against the absence of data professionals to implement sustainable solutions. For the whole of the material sciences and engineering community, the challenge is now to structure a network of practices around data governance in order to define the right standards, in particular for the description of data sets (samples, acquisition, processing, etc.) and thus enhance their possible reuse.

The open science policy, beyond data, must lead to the emergence of practices for the dissemination of codes or software enabling the processing, simulation or analysis of data. In this area, only a few facilities use collaborative development tools (forge) in order to make shared codes perfectly reusable, and about a third distribute them under free licences. Finally, concerning publications, almost all the infrastructures encourage users to publish in open access or to deposit on open archives.

In order to generalise these good practices, a Funder Registry identifier should be associated with each infrastructure. The citation of this identifier in publications at the level of acknowledgements or co-authors, or associated with software and data sets, would make it possible to trace the use and impact of the infrastructures.



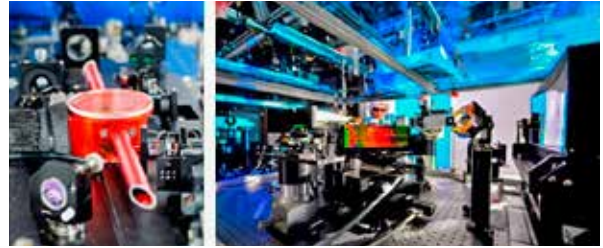
Schematic representation of the use of the infrastructures of the “Material sciences and Engineering” domain for studies related to the societal challenges relevant to this theme (qualitative assessment based on publications from existing infrastructures – the designations “Platforms” and “Engineering” include Infranalytics, METSA and EMIR&A on the one hand and RENATECH and REFIMEVE on the other).

Apollon

Apollon laser

The Apollon research infrastructure, operated by the LULI (Laboratory for the Use of Intense Lasers), aims, thanks to its unique laser sources (1 and, in the long term, 10 PW) and its two experimental rooms, to carry out experiments in a range of laser power that has not yet been explored. Due to its location in the heart of the Saclay plateau, Apollon offers the national and international scientific community a rare scientific environment and unique instruments to develop scientific programmes at the cutting edge of world competition.

Apollon allows innovative studies in plasma physics and quantum electrodynamics, as well as the development of new secondary sources of radiation (X, γ) or particles (electrons, protons, multicharged ions) with exceptional characteristics. This infrastructure thus allows a scientific breakthrough for fundamental research in physics, astrophysics, chemistry, biology



© J. Barande (École Polytechnique), J. Prudent (CNRS) et F. Mathieu (CNRS)

and medicine, and opens the way to numerous multidisciplinary applications. Apollon is also intended to meet technological and societal challenges in the fields of health (diagnostics and therapies), energy and new generation accelerators. Finally, Apollon enables France to position itself as a leading international partner in the field of "extreme light".

Relations with economic actors and/or socio-economic impact

Apollon is a showcase for the R&D of French laser companies (Amplitude, Thales...) by demonstrating the effectiveness of their products on the installation, products often developed in collaboration. Apollon facilitates the creation of joint laboratories (HERACLES3 with Thales). Apollon gives industrialists access to means of characterising optics and mechanical parts, and qualifying components before they are mounted on the installation.

Open science and data

- Annual data production: 150 TB

Category: RI*

Type of infrastructure: single site

Infrastructure location in France: Saint-Aubin

French supporting institutions: CNRS, École polytechnique (X)

Director or RI representative in France:

• Patrick Audebert

Construction: 2010

Operation: 2020

Stakeholders in France: CEA, Institut d'optique graduate school, École nationale supérieure de techniques avancées, Synchrotron SOLEIL

Contact in France: patrick.audebert@polytechnique.fr

Website: <https://apollonlaserfacility.cnrs.fr>

ESRF

European Synchrotron Radiation Facility

A leader in X-ray science, the ESRF is a centre of excellence for fundamental, applied and industrial research, with a wide range of applications in health and biology, the environment, materials physics and chemistry, energy, nanotechnology, geosciences, cultural heritage and palaeontology. Equipped with a brand new generation of high-energy synchrotron (ESRF-EBS), the ESRF is the brightest source in the world, with X-rays 10,000 billion times more intense than those used in hospitals are.



© ESRF/Jocelyn Chauvy

ESRF owes its success to the international cooperation of its 22 partner countries. Every year, more than 10,000 scientists from all over the world come to Grenoble to use the ESRF's X-rays and carry out experiments on one of its 46 beamlines or state-of-the-art laboratories. Thanks to its performance, ESRF-EBS opens up new perspectives for the international scientific community to respond to major societal challenges. ESRF-EBS has already enabled

the implementation of innovative scientific projects, bringing together multidisciplinary international teams, such as the platform of excellence on batteries based on an ESRF-ILL-CEA cooperation agreement, or the project on the imaging of human organs financed by the Chan Zuckerberg Initiative (CZI) Foundation, which is revolutionising bio-imaging down to the cellular level, enabling a better understanding of diseases such as COVID-19 or Alzheimer's.

Relations with economic actors and/or socio-economic impact

ESRF's mission is to share knowledge and technology with the synchrotron community in its member countries, including France, to train the scientists, engineers and technicians of tomorrow and to raise awareness of science among the general public and young people. 98% of the ESRF budget is invested in industrial contracts in its 22 partner countries and 50% in Auvergne-Rhône Alpes. More than 300 companies use the ESRF since 1994.

Open science and data

- The source codes produced by the infrastructure are open on a software forge <https://gitlab.esrf.fr>
- Annual data production: 10 PB
- Infrastructure with a FAIR data policy in application
- The validated and described data are published on a data repository: <http://paleo.esrf.eu>

Category: RI*

Type of infrastructure: single site

Infrastructure location in France: Grenoble

French supporting institutions: CNRS, CEA

- **Director or RI representative in France:** Francesco Sette
- **Construction:** 1988
- **Operation:** 1994
- **Contact in France:** ESRF-Director@esrf.fr
- **Website:** www.esrf.eu

International dimension

ESFRI landmark: ESRF EBS

Director: Francesco Sette (directeur général de l'ESRF)

- **Partner countries** DE, BE, DK, ES, FI, FR, IT, NO, NL, UK, RU, SE, CH
- **Website:** www.esrf.eu

ESS

European Spallation Source

The European Spallation Source (ESS) is a multidisciplinary research infrastructure under construction, which will provide the world's most powerful neutron source for exploring matter in many fields, from materials science to biology, from heritage studies to magnetism. ESS will be about 30 times more powerful than existing facilities and will open up new research possibilities for scientists in the fields of magnetism, ultra-high resolution spectroscopy (10^{-8} eV), and particle physics through the use of ultra-cold neutrons. This facility will also contribute to the fields of health, environment, energy, climate and transport. ESS consists of a 600 m long linear accelerator that delivers 2.5 GeV of energy to protons impacting a tungsten target with a planned beam power of 5 MW. This source will produce long pulses of neutrons (2.86 ms at a frequency of 14 Hz with a peak current



© Perry Nordeng / ESS

of 62.5 mA) corresponding to a peak flux 30 times higher than that of the American spallation source SNS (short pulses). ESS should produce its first neutrons by 2026, welcome first users and then ramp up with the progressive opening of the 15 scientific instruments planned until 2028.

Relations with economic actors and/or socio-economic impact

The creation of a major economic sector around ESS and the MaxIV synchrotron, bringing together research facilities, universities and companies involved in innovation and research. In the context of its construction, more than 90% of the contracts awarded by ESS and its in-kind partners are with companies in the 13 member countries..

Open science and data

- The source codes produced by the infrastructure are open on a software forge <https://gitlab.com/gitlab-org/gitlab>
- The validated and described data are published on a data repository:
- Annual data production: 10 PB

Category: RI*

Type of infrastructure: single site

Localisation du siège de l'infrastructure: Lund (SE)

French supporting institutions: CNRS, CEA

• **Director or RI representative in France:**

• Marie-Hélène Mathon, Sylvain Ravy

• **Construction:** 2014

• **Operation:** 2028

• **Contacts en France:** marie-helene.mathon@cea.fr; sylvain.ravy@cnrs.fr

• **Website:** <https://europeanspallationsource.se>

International dimension

ESFRI landmark: European Spallation Source ERIC

Director: Helmut Schober (directeur général de ESS)

- **Partner countries** DK, SE, CH, CZ, DE, EE, ES, FR, HU, IT, NO, PL, UK
- **Website:** <https://europeanspallationsource.se>

European XFEL

European X-ray Free Electron Laser

The European XFEL in Hamburg, which opened on September 1st 2017, is the world's most intense coherent X-ray source. This source of photons, produced over a wide energy range (300 eV to 12.4 keV), has a brightness 10 orders of magnitude higher than synchrotron radiation and a pulse duration of a few tens of femto-seconds (fs = 10⁻¹⁵ s). The operating principle of the European XFEL is based on a superconducting linear accelerator with a length of 2 km that imparts an energy of 17.5 GeV to packets of electrons. As these electrons pass through inverter, they generate bursts of coherent X-rays through the phenomenon of self-amplified spontaneous emission (SASE).

XFEL radiation makes it possible to monitor, on a scale of a few tens of fs, states of matter stimulated by light (lasers), thermal, magnetic, or THz excitation. This opens the way to studies on dynamic phenomena in matter that were previously unexplored due to a lack



© D. Nölle, DESY

of tools, such as the structure-function relationship in structural biology (photosynthesis); matter under conditions of high energy density; the physical chemistry of isolated atoms and molecules; ultra-fast dynamics in magnetism. It is a unique window on the knowledge of matter. Six instruments are now in operation to meet these challenges and in France, their potential users come from some forty laboratories.

Relations with economic actors and/or socio-economic impact

At the national level, France's contribution to the construction of the infrastructure, led by the CEA and the CNRS, involved the industrial partners Thales (France) and RI-Research Instruments (Germany) for the construction, testing and clean room integration of 824 couplers assembled in 103 cryomodules. The integration of the 103 cryomodules was the subject of an industrial transfer from the CEA to the company Alsyom (France).

Open science and data

- Part of the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure are open on a software forge
- Annual data production: 20 PB

Category: RI*

Type of infrastructure: single site

Localisation du siège de l'infrastructure: Schenefeld (DE)

French supporting institutions: CNRS, CEA

- **Director or RI representative in France:** Maria Faury, Sylvain Ravy
- **Construction:** 2009
- **Operation:** 2017
- **Contacts en France:** maria.fauy@cea.fr, sylvain.ravy@cnrs.fr;
- **Website:** www.xfel.eu

International dimension

ESFRI landmark: European XFEL

Director: Robert Feidenhans'l (directeur du European XFEL)

- **Partner countries** DE, DK, FR, HU, IT, PL, RU, SK, SE, CH, UK
- **Website:** www.xfel.eu

ILL

Max von Laue – Paul Langevin Institute

An international infrastructure, the ILL, with its 58 MW reactor, is a high-flux neutron source that powers 40 of the world's most powerful instruments dedicated to the study of the structure and dynamics of matter. It receives scientists from all over the world (1,500 users/year - 800 experiments/year). Research covers a wide range of scientific fields: biology, chemistry, soft matter, fundamental and nuclear physics, materials science and magnetism.



Today, the ILL remains the world's leading neutron source. To maintain this position, the Endurance modernisation programme was launched in 2016. It involves the upgrading of numerous instrumental projects, the renovation of guides and the improvement of data processing.

The ILL remains unrivalled in its performance, ahead of the most recent European research reactor (FRM-II in Germany), the new American and Japanese spallation sources (SNS and J-PARC) and the British source ISIS. The ESS in Sweden will become the world's most powerful spallation source when it commissions its first instruments in 2026-28 for nominal operation after 2030.

Relations with economic actors and/or socio-economic impact

Development of service contracts with local industry (partnership with CEA-Leti and ESRF (IRT NanoElec)). The ILL is a member of a SATT. The impact of the ILL is to generate (in addition to the 500 jobs at the ILL) 600 induced and indirect jobs in the region and 400 at national level.

Open science and data

- Part of the publications from projects using the infrastructure are open access
- Annual data production: 200 TB

Category: RI*

Type of infrastructure: single site

Infrastructure location in France: Grenoble

French supporting institutions: CNRS, CEA

- **Director or RI representative in France:** Jacques Jestin
- **Construction:** 1967
- **Operation:** 1971
- **Contact in France:** jestin@ill.fr
- **Website:** www.ill.eu/fr

International dimension

ESFRI landmark: ILL

Director: Paul Langan (directeur général de l'ILL)

- **Partner countries FR, DE, UK**
- **Website:** www.ill.eu

SOLEIL

SOLEIL synchrotron

SOLEIL is the French synchrotron radiation facility located on the Saclay plateau. It is a multidisciplinary instrument and a research laboratory whose purpose is to conduct research programmes using synchrotron radiation, to develop state-of-the-art instrumentation on the beamlines and to make these available to the scientific community.

Synchrotron radiation is an extremely bright light emitted by very high-energy electrons (nominal energy of 2.75 GeV) circulating at a speed close to that of light, in a 354 m circumference storage ring.

The Synchrotron SOLEIL, a unique tool for both academic research and industrial applications, opened in 2008.



© CAVOK Productions – Laurent PERSIN

SOLEIL welcomes about 3,000 researchers per year using synchrotron light for their research in a wide range of disciplines such as physics, biology, chemistry, materials science, astrophysics and astrochemistry, environmental and earth sciences, heritage, etc.

Relations with economic actors and/or socio-economic impact

SOLEIL has set up a Strategic and Industrial Orientation Committee (COSIS); the thousandth industrial experiment was hosted in September 2021. SOLEIL offers workshops and visits to pupils from primary school to higher education (partnership with the Rectorat de Versailles) and trains teachers from undergraduate level by putting them in contact with its researchers. SOLEIL also trains 20-30 apprentices per year.

Open science and data

- Part of the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure are open on a software forge <https://gitlab.synchrotron-soleil.fr/public>
- Annual data production: 1 PB

Category: RI*

Type of infrastructure: single site

Infrastructure location in France: Saint-Aubin

French supporting institutions: CNRS, CEA

● **Director or RI representative in France:** Jean Daillant

● **Construction:** 2001

● **Operation:** 2008

● **Contact in France:** jean.daillant@synchrotron-soleil.fr

● **Website:** www.synchrotron-soleil.fr

EMIR&A

National Accelerators Network for the Irradiation and Analysis of Molecules and Materials

EMIR&A is the French network of accelerators dedicated to the study of the irradiation of materials and molecules and/or their analysis by ion and electron beams. It includes 15 ion and electron accelerators coupled with in situ characterisation instruments installed on 11 platforms, spread over 6 sites (Caen, Orléans, Orsay, Palaiseau, Paris, Saclay).

EMIR&A's facilities are complementary to each other in terms of accelerated particles, available energies and associated instrumentation such as Transmission Electron Microscopy, Raman spectroscopy, X-ray diffraction, infrared spectroscopy or optical absorption. This structure offers a unique portal for research in the physics and chemistry of materials and liquids. The accelerators and associated in situ instruments allow fundamental and applied research to be carried out, either to understand the modifications induced by ions and electrons in materials and



© C. Baumier

molecules, or to analyse materials with accelerated ions. The applications are diverse: energy (including nuclear energy), electronics, space, geology, etc. Users have access to the instruments via a single portal, after evaluation of their project by an international evaluation committee. Accelerators for ion beam analysis are also accessible through applications on a rolling basis.

Relations with economic actors and/or socio-economic impact

The accelerators of the EMIR&A network are accessible to actors from the socio-economic world via academic collaborations. These collaborations vary from one platform to another. It is considered to strengthen these links by giving industrialists the possibility of accessing the platforms directly via the EMIR&A portal. We are also studying the possibility of integrating accelerators managed by industrial platforms into our network.

Open science and data

- Part of the publications from projects using the infrastructure are open access
- Annual data production: 330 GB

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Villeurbanne

Other sites in France: Caen, Orléans, Orsay, Palaiseau, Paris, Saclay

French supporting institutions: CNRS

Director or RI representative in France:

Nathalie Moncoffre

Construction: 2014

Operation: 2014

Stakeholders in France: Université de Caen Normandie, Université Paris-Saclay, Sorbonne Université, Université de Paris, École nationale supérieure d'ingénieurs de Caen, École polytechnique, CEA

Contact in France: n.moncoffre@ipnl.in2p3.fr

Website: <https://emira.in2p3.fr/?lang=fr>

Infranalytics

National Research Infrastructure Network for High-Field NMR, EPR and FTICR

Infranalytics is a distributed research infrastructure integrating the most advanced NMR, EPR and FT-ICR MS analytical equipment at very high magnetic fields in a large network of 18 internationally recognised research units. It offers centralised access and expertise to a large community of academic and industrial researchers, experts and non-experts. These instruments offer the possibility of characterising complex molecular structures and structure-activity-function-property relationships in molecular chemistry, materials science or life science with unparalleled precision, resolution and reliability, opening up vast fields of application in the fields of health, the environment, energy, innovative materials, heritage, etc. The network is a place for interdisciplinary exchanges in chemistry, physics, biology and earth sciences at the highest scientific level, where complementary techniques and skills are shared.

The federation's missions are to welcome scientists via expert time requests; methodological,



© (g. à d. haut en bas): Ecole Normale Supérieure, Stéphanie Lecocq, Hervé Vezin, © CEA/ID, Morel, Sylvain Bertina

instrumental and computer development; training; the implementation of a data and open science policy; a coordinated investment policy in order to maintain state-of-the-art instrumentation on French territory.

Some Infranalytics sites are also part of the European infrastructures Instruct-ERIC (ESFRI landmark), iNEXT-discovery, EU FT-ICR MS, PANACEA and MOSBRI.

Relations with economic actors and/or socio-economic impact

The laboratories in the network have multiple relationships with economic players, whether multinationals or local players. The infrastructure has a proactive centralized policy towards industrialists (industrialists' days, participation in R&D meetings for companies). Instrumental or methodological developments are carried out with manufacturers, which result in the opening of new markets.

Open science and data

- Part of the publications from projects using the infrastructure are open access
- Annual data production: 200 TB

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Gif-sur-Yvette

Other sites in France: Grenoble, Marseille, Metz, Mont-Saint-Aignan, Orléans, Orsay, Palaiseau, Paris, Pessac, Strasbourg, Villeneuve-d'Ascq, Villeurbanne

French supporting institutions: CNRS

Director or RI representative in France:

• Carine van Heijenoort

Construction: 2022

Operation: 2022

Stakeholders in France: CEA, École normale supérieure de Paris, École normale supérieure de Lyon, École polytechnique, Université de Lille, Université Grenoble Alpes, Université Claude Bernard - Lyon 1, Sorbonne Université, Université Paris-Saclay, Université de Rouen Normandie, Université de Bordeaux, Aix-Marseille Université, Université de Strasbourg, Université de Lorraine, Centrale Lille Institut, Institut national des sciences appliquées de Rouen Normandie, Université d'Artois, INSERM

Contact in France: carine.van-heijenoort@cnrs.fr

Website: <https://infranalytics.fr>

LMJ-PETAL

MegaJoule – PETawatt Aquitaine Lasers

LMJ-PETAL combines, around the same experimental chamber, the high-energy laser beams of the MegaJoule Laser (LMJ), a very high-power ultra-brief laser beam (PETAL) and a set of measurement resources with very high spatial and temporal resolutions. Together, they constitute an experimental infrastructure unique in Europe, dedicated to the study of the physics of high energy densities. This infrastructure is open, for about 25% of its time, to experimental proposals submitted by the international scientific community through a call for projects.



©CEA - Lilian Marolleau

The MegaJoule Laser was designed by the CEA's Military Applications Directorate (DAM) to meet the needs of the Simulation programme, which is intended to guarantee the safety and performance of French deterrent weapons without any new nuclear test. Commissioned in 2014, the LMJ is steadily increasing its performance towards its full capacity (176 beams, 1.32 MJ); it will carry out its first experiments with

80 beams and 300 kJ in 2022. The PETAL (Petawatt Aquitaine Laser) beam was designed and built by the CEA with funding from the Conseil Régional de Nouvelle Aquitaine, the French government and the European Union. It delivers a light pulse of sub-picosecond duration and 400 J of energy. The very high energy density plasmas created by these laser beams are characterised (in charged particles, neutrons, visible and X-rays) by 18 measuring instruments.

Relations with economic actors and/or socio-economic impact

The primary mission of the LMJ is to provide the experimental data required for the DAM's Simulation programme. In addition, within the framework of the academic experiments that it hosts for 25% of its time, it contributes to research into fusion energy, by the so-called inertial confinement method.

LMJ-PETAL is a catalyst for the ecosystem of the Route des Lasers et des Hyperfréquences competitiveness cluster, of which it is a member.

Open science and data

- Part of the publications from projects using the infrastructure are open access
- Annual data production: 50 GB

Category: RI

Type of infrastructure: single site

Infrastructure location in France: Le Barp

French supporting institutions: CEA

- **Director or RI representative in France:** Jean-Pierre Giannini
- **Construction:** 2005
- **Operation:** 2017
- **Contact in France:** UserLMJ@cea.fr
- **Website:** www-lmj.cea.fr

LNCMI

National Laboratory for High Magnetic Fields

The National Laboratory for high Magnetic Fields (LNCMI) is a research facility that hosts scientists from all over the world for high field experiments. The LNCMI is Europe's largest high-field research facility and the second largest in the world, behind the NHMFL (USA); it is part of the European Magnetic Field Laboratory (EMFL, ESFRI landmark), created in 2015. At the Grenoble site, the LNCMI offers static magnetic fields up to 36 T and at the Toulouse site, pulsed magnetic fields up to 91 T non-destructive and 180 T semi-destructive.



© Julien Billete et Denis Morel, photothèque du CNRS

The LNCMI :

- ensures the development of electro-technical and hydraulic installations, magnets and scientific instrumentation for physical measurements under high magnetic fields;
- provides access to the high-field facilities to users via calls for projects;

- supports the implementation, interpretation and valorisation of experiments. Numerous experiments for physical measurements under high fields are available (UV-VIS-NIRTHz spectroscopy, NMR, EPR, magnetisation, transport, specific heat, etc.).

The main user communities are those of superconductors, semiconductor and nanostructure physics, and magnetism.

Relations with economic actors and/or socio-economic impact

One-off contracts with companies working in magneto-forming, water purification, superconducting cables, watchmaking, high power/high voltage electro-technical components.

Open science and data

- Annual data production: 100 GB

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Grenoble

Other sites in France: Toulouse

French supporting institutions: CNRS

- **Director or RI representative in France:** Charles Simon
- **Construction:** 2009
- **Operation:** 2009
- **Stakeholders in France:** Université Grenoble-Alpes, Université Toulouse III Paul Sabatier, Institut des Sciences Appliquées Toulouse
- **Contact in France:** direction@lncmi.cnrs.fr
- **Website:** <http://lncmi.cnrs.fr>

International dimension

ESFRI landmark: EMFL

Director: Peter Christianen (coordinateur de l'EMFL)

- **Partner countries DE, NL, UK, PL, FR**
- **Website:** <http://emfl.eu>

METSa

National Research Infrastructure Network for Electron Microscopy and Atomic Probe

The CNRS and the CEA, in conjunction with the Ministry of Higher Education and Research, have set up a network of high-level Electron Microscopy and Atomic Probe Platforms with multiple objectives. It must enable:

- to offer academic and industrial researchers in the national and international community access to unique transmission electron microscopy (TEM) and atom probe tomography (APT) resources associated with scientific skills to answer problems (physics, condensed matter science, Earth and universe sciences, environment, biophysics, etc.) that cannot be answered by "conventional" TEM techniques, by covering the costs of using the equipment and the missions;
- to encourage instrumental, methodological and modelling developments specific to TEM and then to make the whole community benefit from them;
- to promote all forms of training (courses, workshops, etc.) and communication (development of a



© Direction de METSa

website, communication operations, scientific and popularisation articles, etc.) on the latest potentialities in the field of TEM;

- to advise, at their request, the supervisory bodies or the project teams on the installation of new TEM equipment and its applications in order to encourage any effort at mutualisation, development and complementarity from the existing environment.

Relations with economic actors and/or socio-economic impact

Researchers from the academic or industrial world can have access to METSa via the twice-yearly call for experimental proposals. Insofar as the committee of experts validates the projects submitted, fundamental studies as well as highly technical analyses in fields directly related to industrial applications can be carried out on the various platforms of the research federation.

Open science and data

- Annual data production: 100 TB

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Orsay

Other sites in France: Caen, Grenoble, Lyon, Marseille, Paris, Rouen, Strasbourg, Toulouse

French supporting institutions: CNRS

• **Director or RI representative in France:**

• Williams Lefebvre

• **Construction:** 2009

• **Operation:** 2009

• **Stakeholders in France:** CEA, Université Paris-Saclay, Aix-Marseille Université, Normandie Université, Université de Strasbourg, Université de Paris, Université de Lyon,

• **Contact in France:** williams.lefebvre@univ-rouen.fr

• **Website:** <http://metsa.prod.lamp.cnrs.fr>

REFIMEVE

Metrological Fibre Network with a European Vocation

Based on a major technological breakthrough, REFIMEVE – Metrological Fibre Network with a European Vocation – is a large national instrument supported by the Laboratoire de Physique des Lasers. It allows the transmission, without degradation, via the fibre optic network of RENATER, of an ultra-stable and accurate frequency signal generated by SYRTE, the National Metrology Institute for time and frequency, with an accuracy of up to 10^{-17} - 10^{-18} . This service will be extended to the dissemination of a high performance time signal. It will benefit a wide range of scientific domains: fundamental physics, quantum technologies, photonics, geodesy and climate, environment, astronomy and VLBI, accelerators, etc.



© Paul-Eric Pottie, Rodolphe Le Targat, Frédéric Meynadier (SYRTE (OPPL, CNRS, SU, LINE))

Thanks to the mutualisation of the RENATER network and the access to SYRTE's metrological references, REFIMEVE has a strong leverage effect by delivering a service that is unique in the world to laboratories and RIs throughout France. Interconnections to several European countries are already operational (CLONETS consortium).

The investments are based on the projects REFIMEVE+ (Equipex, PIA1) and T-REFIMEVE (Equipements Structurants pour la Recherche/Equipex+, PIA3). The national user community is estimated as large as 500 researchers in more than thirty laboratories, not counting future users of the RI* SOLEIL, ESRF, IRAM and CERN.

Relations with economic actors and/or socio-economic impact

Thanks to a successful transfer of knowledge, a consortium of three French SMEs has produced industrial versions of REFIMEVE equipment. Thanks to the REFIMEVE network, they have a showcase for their products and have opened up an international market (EU, USA, and China, in particular) that is expanding fast.

In addition, connections from REFIMEVE to several industrial users are considered in the short term.

Open science and data

- Annual data production: 1 TB
- The validated and described data are published on a data repository:

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Villeteuse

Other sites in France: Besançon, Brest, Gif-sur-Yvette, Grenoble, Lannion, Le Dévoluy, Marseille, Meyrin (CH), Nançay, Nice, Orsay, Palaiseau, Paris, Rennes, Saint Martin d'Hères, Saint-Vallier de Thiey, Talence, Toulouse, Villeneuve d'Ascq

French supporting institutions: Université Sorbonne Paris Nord, Observatoire de Paris, PSL, CNRS

Director or RI representative in France: Anne Amy-Klein

Construction: 2012

Operation: 2015

Stakeholders in France: RENATER, Laboratoire national de métrologie et d'essais, Sorbonne Université

Contact in France: amy@univ-paris13.fr

Website: www.refimeve.fr/index.php/fr

International dimension

Consortium CLONETS

- **Partner countries** FR, DE, IT, UK, PL, ES, CZ
- **Website:** www.clonets.eu

RENATECH+

National Network of Nanofabrication Technology Centres

The RENATECH+ infrastructure is the result of the RENATECH network, comprising 5 large academic nanofabrication centres totalling 8,300 m² of clean rooms, located at C2N (Palaiseau), FEMTO-ST (Besançon), IEMN (Lille), LAAS (Toulouse) and LTM (Grenoble). A second circle of 27 smaller "regional" centres was added to form the RENATECH+ network. Via the RENATECH website, this enlarged network offers any user of nanosciences and nanotechnologies (in France, 4,700 researchers, engineers and technicians and 108 user companies), a micro and nanofabrication service enabling the production of nano-devices, circuits and systems. RENATECH+'s missions are to (i) build and manage a state-of-the-art equipment park, (ii) ensure easy access to its users, (iii) promote the sharing of technical expertise in nanofabrication, (iv) disseminate this knowledge to the general public. The specialised expertise provided by the new partners will strengthen the service to users and the coherence



© Cyril FRESILLON/CNRS Photothèque

of the national nanofabrication system. Their staffs are integrated in the RENATECH technological expert groups. On the international level, RENATECH+ is the leader of the European consortium "EuroNanoLab" (44 partners in 14 countries) aiming at facilitating access to nanofabrication facilities located abroad and at collectively supporting international R&D projects.

Relations with economic actors and/or socio-economic impact

RENATECH+ is a key resource for the socio-economic world, particularly for sectors requiring nanotechnologies (health, IT, telecommunications, transport or security). Each year, the infrastructure is

used by more than 100 companies (large groups and SMEs) in the form of services or scientific collaborations, in order to carry out the demonstrators necessary to start up innovative activities.

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Paris

Other sites in France: Besançon, Grenoble, Palaiseau, Toulouse, Villeneuve-d'Ascq

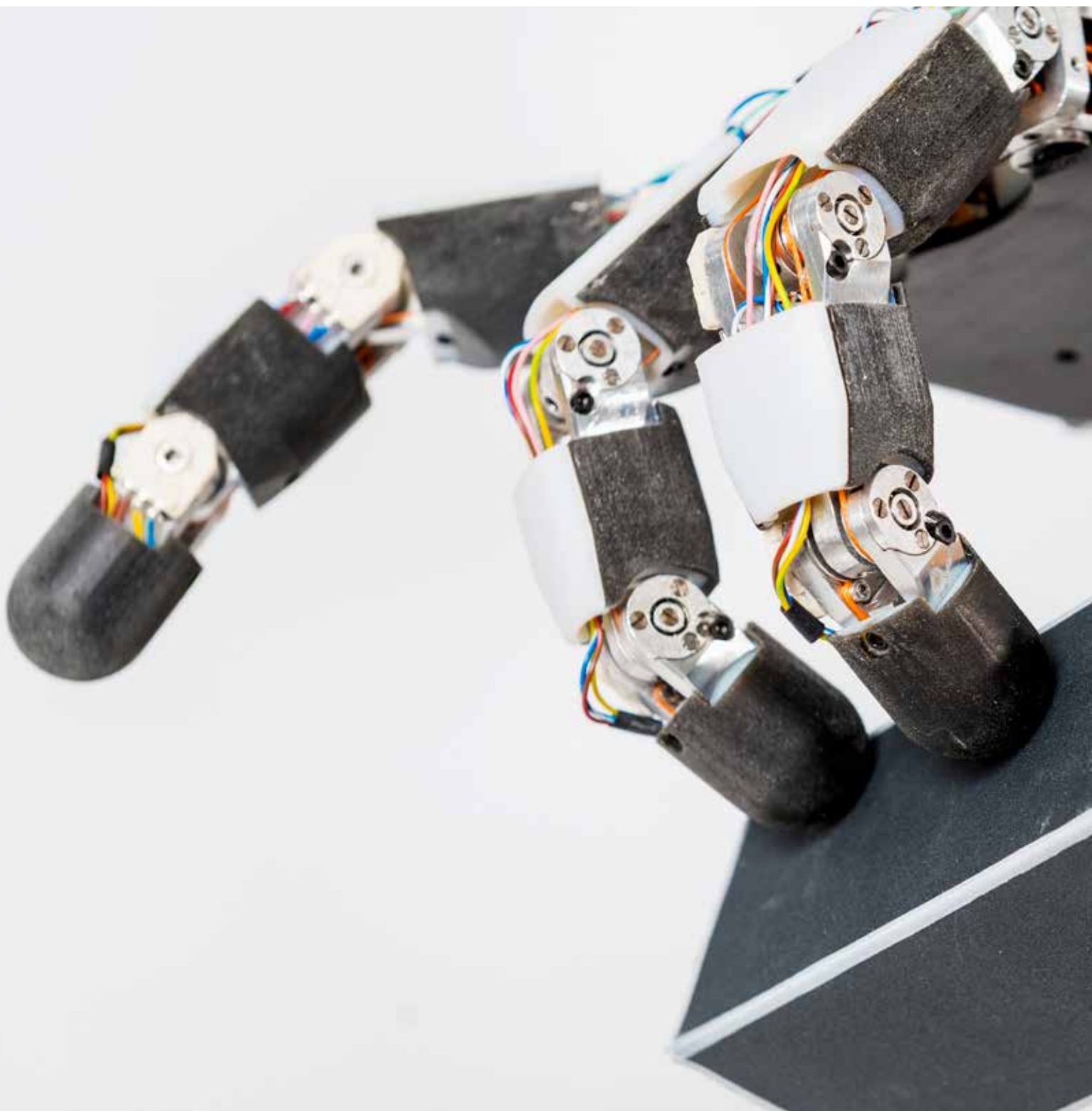
French supporting institutions: CNRS

- **Director or RI representative in France:**
- Michel de Labachellerie
- **Construction:** 2004
- **Operation:** 2004
- **Stakeholders in France:** Université Paris-Saclay, Université Grenoble Alpes, Université de Franche-Comté, École nationale supérieure de mécanique et des microtechniques, Université de Lille, Junia, Université Polytechnique Hauts-de-France, Centrale Lille Institut
- **Contact in France:** michel.labachellerie@cnrs-dir.fr
- **Website:** www.renatech.org

International dimension

Consortium EuroNanoLab

- **Partner countries** NO, SE, FI, EE, LT, LV, NL, CZ, FR, PT, ES, IT, RO, DE
- **Website:** https://euronanolab.eu





7.

Digital
and **mathematics**
sciences

Digital and mathematics sciences¹

Research infrastructures for the digital sciences and mathematics are essential for the accelerated development of scientific and technological breakthroughs, for building the digital technologies and services necessary for the digital transition in the fields concerned, for promoting the optimisation of resources in various industries, and for supporting the various human and environmental sciences in their scientific advances, with increasingly high-performance computing resources and analysis tools that can be accessed locally or remotely.

MAJOR SCIENTIFIC QUESTIONS AND SOCIETAL CHALLENGES REQUIRING THE USE OF RESEARCH INFRASTRUCTURES IN DIGITAL AND MATHEMATICS SCIENCES

In research, as in all areas of society, digital or information and communication technology has become a key factor in economic, industrial, individual and societal development; it is the tool for building tomorrow's society, which is bringing about a new model based on digital technology for the creation, use, access and consumption of various services. This transformation is naturally accompanied by various changes such as the way we work, study, invent, create, innovate and entertain ourselves. Digital transformation is at the heart of developments in various industries; some of them are represented in Figure 1 of the IEEE Institute of Electrical and Electronics Engineers with key digital technologies such as the web, fixed and mobile communications networks, cloud infrastructures, etc. The development of these technologies requires active research in digital sciences and mathematics represented in Figure 2 with the different

research communities in the French national digital sciences and mathematics landscape.

Indeed, digital is a successful conjunction of the culmination of research in the fields of electronic hardware, electrical/electromagnetic/optical signal, computer software, algorithms and programming languages, mathematics, physics and network communication, to provide applications and services for communication, exchange and sharing of various data (multimedia), the web, social networks, intelligent equipment for different industries in the economy and for an increasingly digital society.

Digital technology is also changing the *modus operandi* of scientific research by providing new opportunities for geographically distributed collaboration and data sharing. Data-driven science, with increasingly open access to scientific data and results, will transform not only the way research is conducted (reductionist vs. holistic approach), but also its overall scope as shown in Figure 3.

Investment in research infrastructures for the digital and mathematical sciences is a guarantee of accelerated development of scientific and technological breakthroughs

¹ In this document Digital sciences refer to all research fields of electronic hardware, electrical/electromagnetic/optical signal, computer software, algorithms and programming languages, mathematics, physics and network communication.

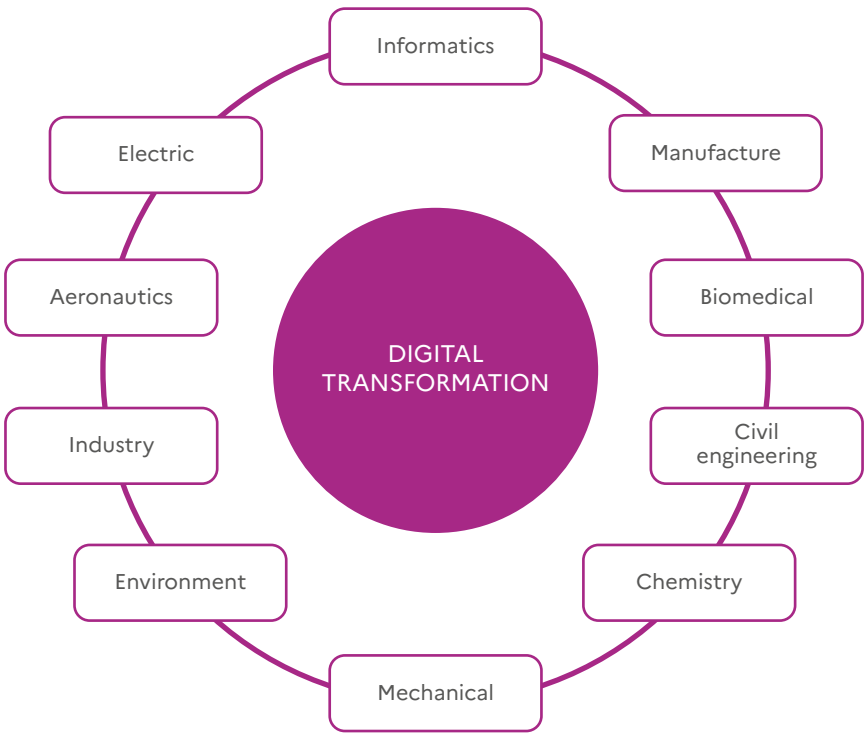


Figure 1: The major industrial fields in digital transformation.

to build the digital technologies and services necessary for the digital transition in the fields concerned, to promote the optimisation of resources in various industries, and to support the various human and environmental sciences in their scientific advances, with increasingly high-performance computing and analysis tools that are accessible locally or remotely. The development of digital technologies to meet socio-technological needs requires an understanding and construction of optimised links between the different levels of digital evolution from hardware, software, communication of information and its use by the individual or communities (groups, organisations, etc.).

POSITIONING OF EACH RESEARCH INFRASTRUCTURE IN THE LANDSCAPE

SILECS²/ESFRI SLICES³

The research community in computer science, networks and communication, distributed systems and transmission with the **SILECS** research infrastructure coordinated by INRIA, is a network connecting different communication, storage and information processing equipment. It deploys different

communication technologies, different hardware and software platforms; unlike communication means (such as **RENATER**, **GEANT**, Internet) and digital infrastructures means (such as **GENCI**, Google Cloud, **OVH** Cloud, etc.), **SILECS** research infrastructure is entirely programmable according to the needs of researchers' experiments. This RI aims to provide the means to experiment with new research approaches for optimising and improving performance and to develop new technological building blocks for digital platforms offering services in production, communication, security and stability of storage, transmission or processing of information. It also aims to solve energy management issues and reduce the carbon footprint of its connected digital devices, as well as to experiment with new ambient energy recovery solutions in collaboration with the research communities in electrical energy creation and management. **SILECS** will also provide an open set of tools for debugging and monitoring at all points to facilitate reproducible research. This Research Infrastructure has also been included in the European ESFRI roadmap in 2021 branded as **SLICES** under the coordination of INRIA and Sorbonne University. Figure 4 provides the elements characterising this research infrastructure.

2 SILECS: Super Infrastructure for Large-scale Experimental Computer Science
 3 SLICES: Scientific LargeScale Infrastructure for Computing/Communication Experimental Studies

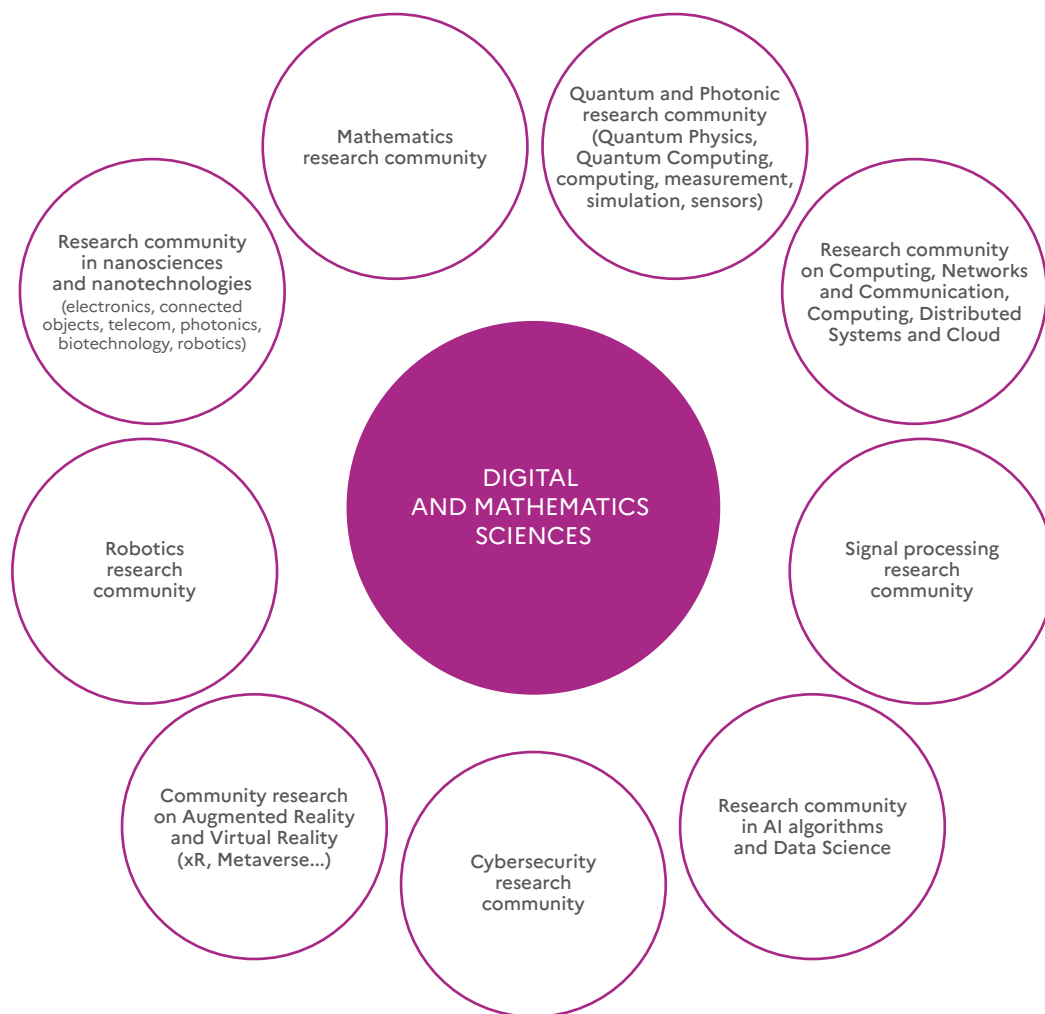


Figure 2⁴: Digital and mathematical sciences landscape according to the digital technologies building blocs⁵ to be developed (3 RI candidates SILECS, Robotex 2.0, CONTINUUM).

Robotex 2.0

The robotics research community, with the **Robotex 2.0** research infrastructure coordinated by the CNRS, aims to develop robotics platforms to support various research experiments. A national coordination of their free access (physical access, digital access, open-data and open software) is planned to gather and federate the research efforts of this community. The research infrastructure is structured in six thematic axes: humanoid robotics, XXL robotics, micronano robotics, autonomous terrestrial

robotics, aerial robotics and medical robotics. In addition to these axes, three transversal axes on Prototyping and Design, Open Infrastructure and Manipulation will irrigate the other thematic axes. Targeted experimental platforms will offer a digital twin for simulation purposes, and sometimes even remote experimental services. Coordination in software development and open access to experimental tests will also be carried out. The figure below provides the highlights of this **Robotex 2.0** RI candidate.

⁴ Representation of research communities according to the needs of common means of scientific experimentation.

⁵ Electronic components, telecom equipment, robotics equipment, HCI equipment, signal processing, network communication, data and simulations, data and AI...

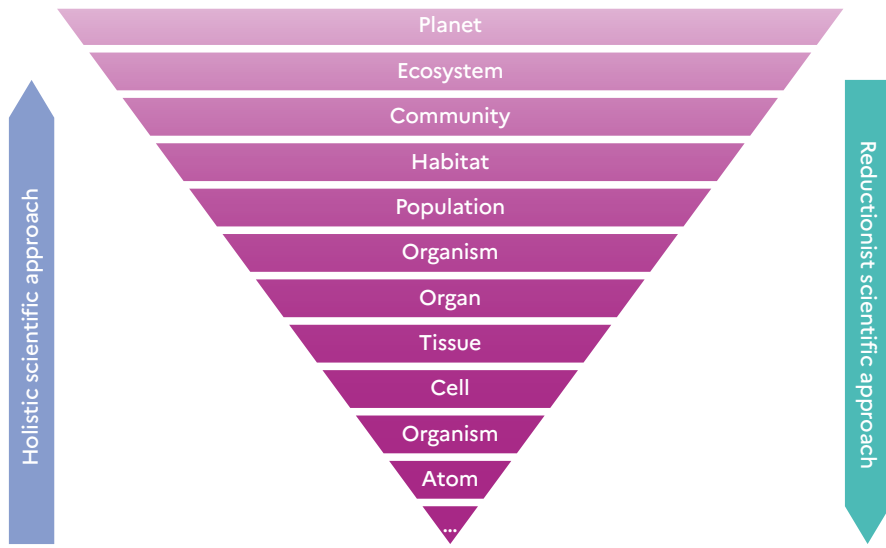


Figure 3: Holistic versus reductionist scientific approaches⁶.

CONTINUUM

The human machine interface research community, with the **CONTINUUM** research infrastructure coordinated by the CNRS, proposes to create a collaborative research infrastructure of 30 platforms distributed throughout France, to advance interdisciplinary research based on the interaction between computer science and human and social sciences. Through **CONTINUUM**, several research teams will develop cutting-edge research programmes focusing on visualisation, immersion, interaction and collaboration, as well as on human perception, cognition and behaviour in virtual/augmented reality, with a potential impact on societal issues. **CONTINUUM** enables a paradigm shift in the way we perceive, interact and collaborate with complex digital data and digital worlds by placing humans at the centre of data processing workflows. **CONTINUUM** will equip scientists, engineers and industry users with a highly interconnected network of high-performance and immersive visualisation platforms for observing, manipulating, understanding and sharing digital data, real-time multi-scale simulations and virtual or

augmented experiences. Figure 5 provides the highlights of the **CONTINUUM** RI.

Other digital and mathematics sciences

The digital and mathematics sciences communities as represented in figure 2 use the research infrastructures of this national roadmap; SILECS, ROBOTEX, CONTINUUM but also the digital infrastructures and e-infrastructures presented in the analysis of the digital services and infrastructures landscape of this French national roadmap. Indeed, according to the needs of research experimentation, researchers use the storage and computing resources made available by the various digital infrastructures such as RENATER, GENCI and the Mesocentres. Other infrastructures specific to the research field, such as the RENATECH research infrastructure, are at the intersection between the sciences of matter and engineering and the digital sciences and mathematics are used by researchers in the electronics, photonics, biotechnologies, nanosciences and nanotechnology. Concerning the mathematics research community, the Times research infrastructure project included in the 2018 roadmap and carried

⁶ National Science Foundation: Science meets Society: Biotechnology, Information technology, Nanotechnology, etc.



Figure 4: Highlights of the SILECS/ESFRI SLICES research infrastructure.

by the CNRS, has been postponed in order to better establish the foundations of this research infrastructure and to more strongly mobilise its partners. Indeed, the presence of a research infrastructure for the mathematical sciences in the landscape of research infrastructures is indispensable, and can be based on the structuring role, recognised by the entire community, of the CNRS INSMI. Such an infrastructure should have the vocation of federating the various tools used by the community as the conference centre (IHP, CIRM), centre of excellence (IHES), organisation for the promotion of mathematical research in developing countries (CIMPA), centre for the dissemination of scientific information (Mathdoc-Mersenne) and agency for the promotion of industrial transfer (Amies). Such a federation would

reinforce the visibility and coherence of the whole, which is an asset for ensuring international leadership. The AI and data science research community already uses the GENCI digital infrastructure and the meso-centres. Specific research experimentation needs would justify the entry in the future of a research infrastructure dedicated to the various scientific needs of data format, storage and processing (in the form of an AI Cloud). Concerning the research community in computer security and cybersecurity, it has started a mapping of platforms to bring out a proposal for a research infrastructure project for experimentation by cybersecurity researchers. This project in the future will be based on the progress of several national and European projects already underway and will reinforce the experimental needs of

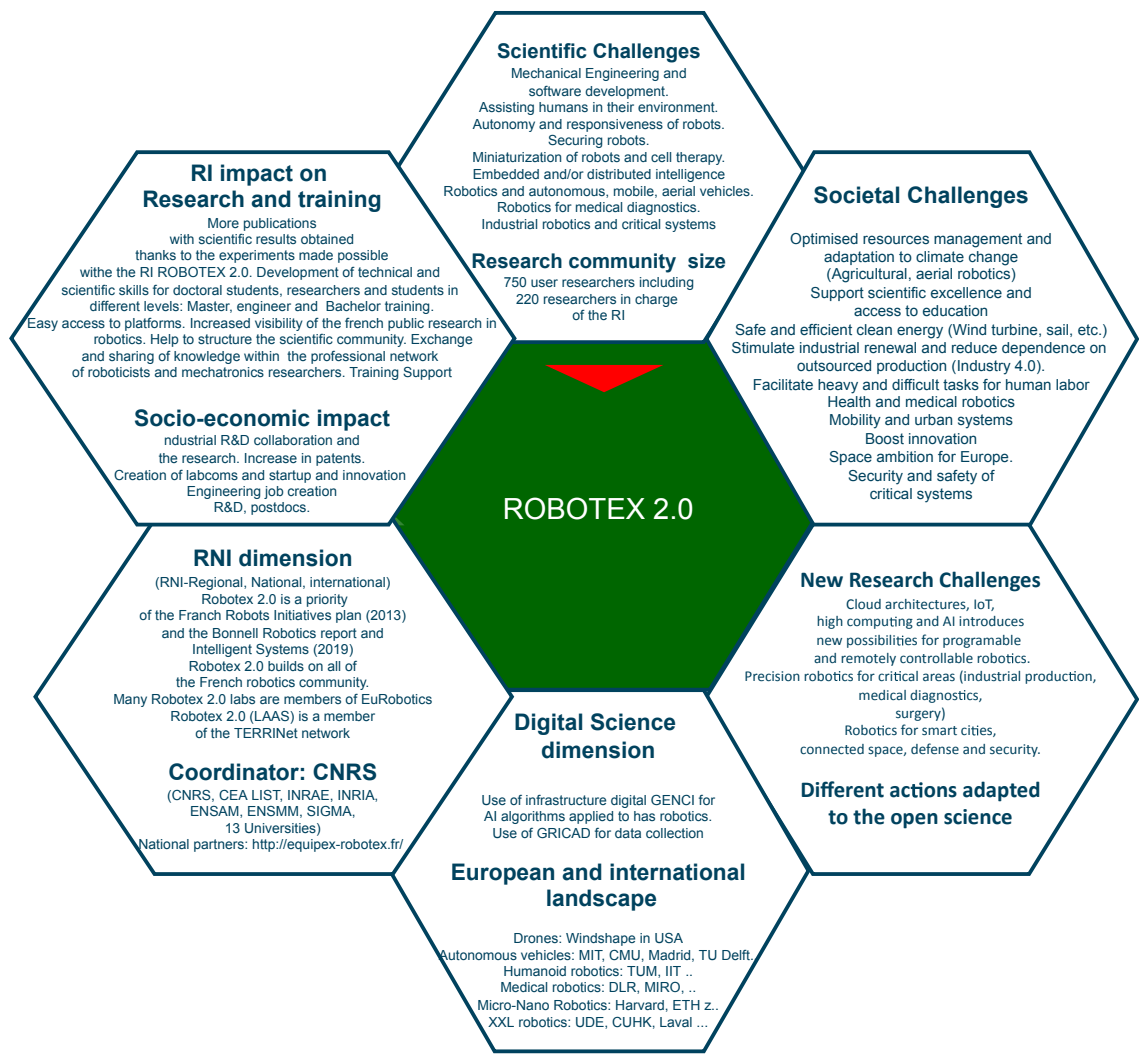


Figure 5: Highlights of the Robotex 2.0 research infrastructure.

researchers active in the priority research programme of the national cybersecurity strategy. Concerning the quantum and photonics research community, it would be important to identify the research experimentation needs and the interactions with other digital infrastructures. It should be noted that at the European level, the Horizon Cluster 4 program is opening up a call for two FPA/SGA Framework Partnerships on the themes of production and test capacities for quantum components; the idea is to set up two consortia and then federate and develop the existing ones in a network. The French version revolves around the clean rooms and other workshops of RENATECH, RENATECH+ and CEA devices (LETI Grenoble and Saclay). On the quantum computing side, there is also EUROHPC QS, with a

French version led by GENCI, which aims to create, within five years, a hybrid computing platform, i.e. a quantum accelerator with at least 100 qubits integrated into two supercomputers (one at the TGCC for France and one in Jülich for Germany); this platform will be "open" via network access and the projects include the software stack, user interfaces and the development of use cases.

POTENTIAL GAPS TO BE FILLED, DIRECTIONS FOR THE NEXT 5 YEARS

To ensure a smooth evolution of the research infrastructures, it is important to analyse the possible synergies between the three infrastructures as represented in Figure 7. It would also be useful to analyse the possible links on the communication,

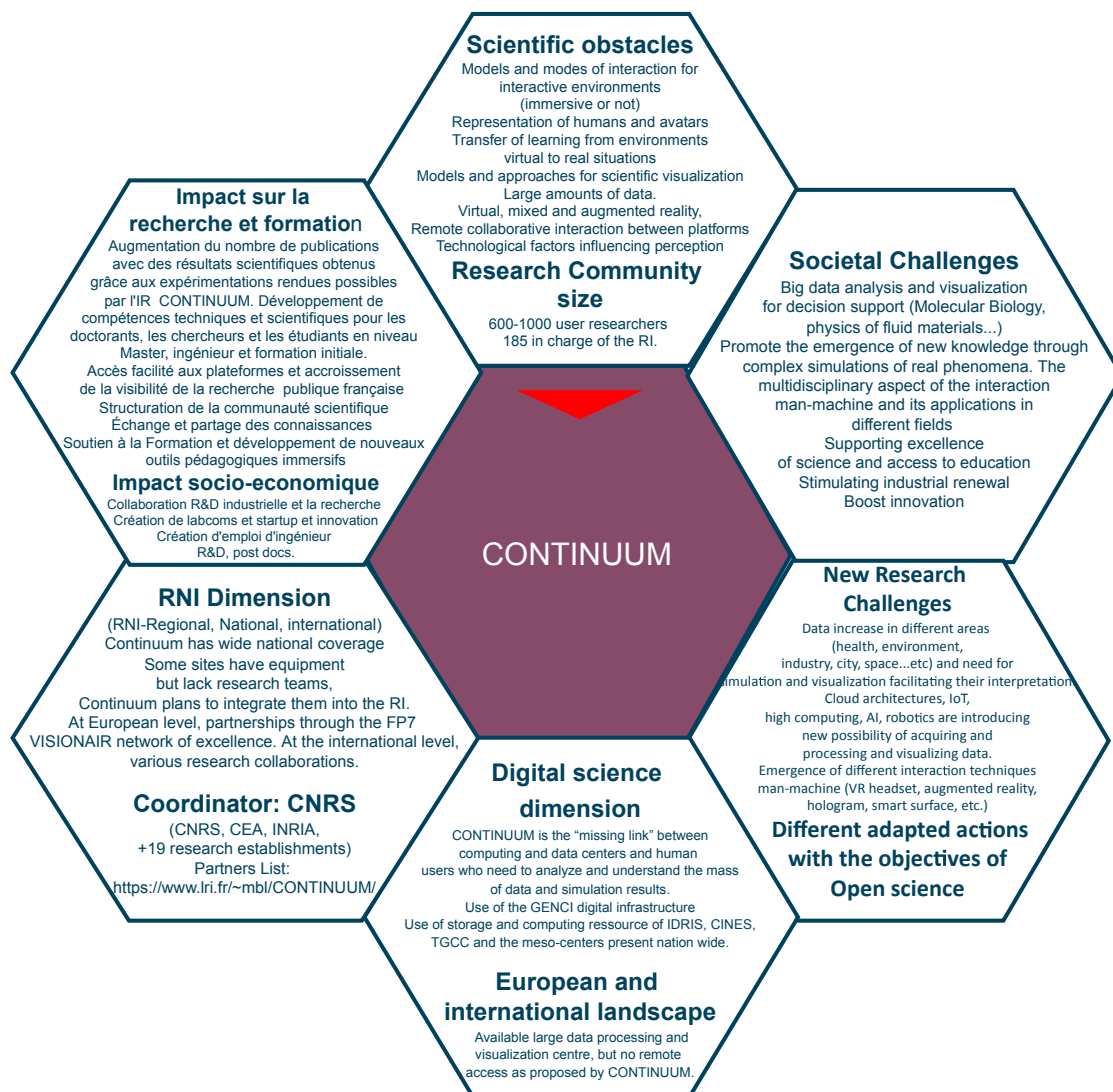


Figure 6: Highlights of the CONTINUUM research infrastructure.

data storage and computing resources part of the ROBOTEX and CONTINUUM research infrastructures and see if the SILECS research infrastructure could meet some of these needs. Conversely, the ROBOTEX and CONTINUUM research infrastructures could provide SILECS with certain use cases with research problems for networks and distributed systems such as reliable and critical communications in robotics or high-speed communications for virtual and augmented reality. On the other hand, research experimentation on simulation data and digital twins is an area of intersection to be analysed between ROBOTEX and CONTINUUM. Finally, the human-machine interface used in ROBOTEX and CONTINUUM should also be brought together where

possible. It would also be interesting to investigate in the future the links with the e-infrastructures GENCI, Mesocentre, and the other research infrastructures of the SILECS, ROBOTEX and CONTINUUM domain for research experiments ranging from the component to the service in order to better ensure the evolution of these research infrastructures and digital infrastructures in order to respond to the needs of scientific experimentation in continuous evolution. The scientific challenges addressed by each of these three research infrastructures evolve according to the scientific needs of each of the fields addressed by each of these infrastructures. Finally, as research experimentation platforms based on simulation or emulation

tools evolve with the physical increase in computing capacity, it is important to see how these equipment-based research infrastructures could interface with emulators and simulators to offer more research experimentation possibilities and possibly reduce certain equipment costs.

The next five years will see the development of several industrial acceleration strategies in France, including the 5G and networks of the future strategy, the Cloud strategy, the cybersecurity strategy, the quantum strategy, the cultural and creative industries strategy, the robotics strategy, phase 2 of the AI strategy, the microelectronics strategy, etc. An analysis of the contribution of these research infrastructures to the scientific research addressed in the research program (aka: PEPR – Priority Research Program and Equipment) of these strategies should be carried out in order to support this research through experimentation and accelerate the results.

A mapping of experimental platforms in other fields such as cybersecurity, AI, quantum, physical instrumentation and measurement, mathematics, would be necessary.

Finally, some elements of information management of the use of research infrastructures would be useful for a better management of the life cycle of these infrastructures. For example, a regular analysis of the statistics on use, exploitation and quality of results would be necessary during the life of these research infrastructures. The organisation of the data management plan, including the listing of experiments and the archiving of the corresponding data, and the implementation of the national open science strategy would accompany the structuring of the networks and the scientific work of these research communities. Given the specific fields of each of these infrastructures, they are indispensable and unique, each for their corresponding research communities. The next five years will see an increase in certain societal and global needs (in order to achieve the UN SDGs), and the digital sciences will be at the heart of the implementation of these objectives. Other research infrastructures may emerge depending on the experimental needs of researchers and the needs of ongoing acceleration strategies such as for cybersecurity and data science.

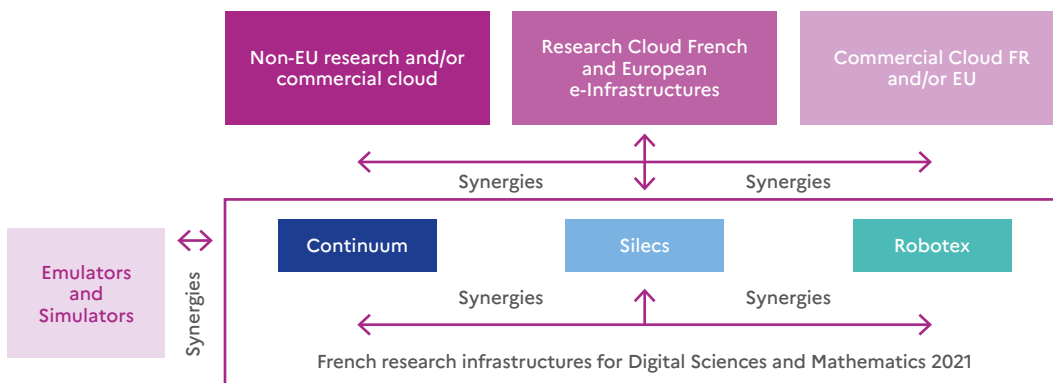


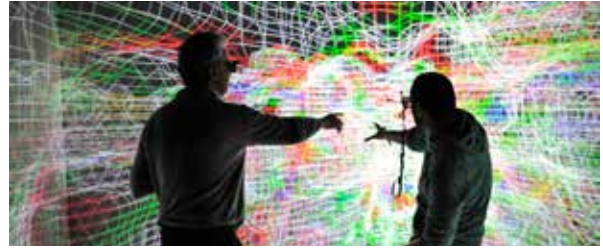
Figure 7: Synergies between the three research infrastructures and external digital resources.

CONTINUUM

Collaborative Continuity from Digital to Human

The CONTINUUM project is creating a collaborative research infrastructure of 30 platforms located throughout France to advance interdisciplinary research between computer science, the humanities and social sciences. Thanks to CONTINUUM, 37 research teams will develop cutting-edge research focused on visualization, immersion, interaction and collaboration, as well as on human perception, cognition and behaviour in virtual/augmented reality.

CONTINUUM is a true digital microscope that enables a paradigm shift in the way we perceive, interact and collaborate with complex digital data and digital worlds by placing human expertise and intelligence at the heart of the data understanding and interpretation processes. The project will provide scientists, engineers and industrial users with a network of high-performance visualization and immersion platforms



© Nicolas Taffin

for observing, manipulating, understanding and sharing digital data, multi-scale simulations and virtual or augmented experiences. All platforms will support remote collaboration and will be equipped with mobile equipment that can be loaned to users to facilitate access to these technologies.

Relations with economic actors and/or socio-economic impact

The wide geographical coverage of CONTINUUM will enable the dissemination of expertise to the economic and social world, in collaboration with innovation transfer players (SATT, competitiveness clusters, Carnot Institutes, etc.). Specific economic models will be developed to allow access to the equipment and to cutting-edge expertise by academics, local authorities and private users.

Open science and data

- Part of the publications from projects using the infrastructure are open access
- Annual data production: 200 TB
- The validated and described data are published on a data repository <http://visionair.ge.imati.cnr.it/ontologies/shapes>

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Gif-sur-Yvette

Other sites in France: Aix-en-Provence, Belfort, Brest, Bruz, Chalon-sur-Saône, Compiègne, Grenoble, Guyancourt, Illkirch-Graffenstaden, Marseille 9^e, Montbonnot-Saint-Martin, Palaiseau, Orsay, Plouzané, Re

French supporting institutions: CNRS

Director or RI representative in France:

• Michel Beaudouin-Lafon

Construction: 2021

Operation: 2021

Stakeholders in France: Inria, CEA, Université de Rennes 1, Université Rennes 2, ENS de Rennes, INSA de Rennes, AMU, UTC, Université de Lille, ENIB, IMT Atlantique, UGA, Grenoble INP, ENSAM, Université de Strasbourg, UTBM, Université Paris-Saclay, Télécom Paris - Institut Polytechnique de Paris, ENS Paris-Saclay, CentraleSupélec, UVSQ

Contact in France: Michel Beaudouin-Lafon, michel.beaudouin-lafon@universite-paris-saclay.fr

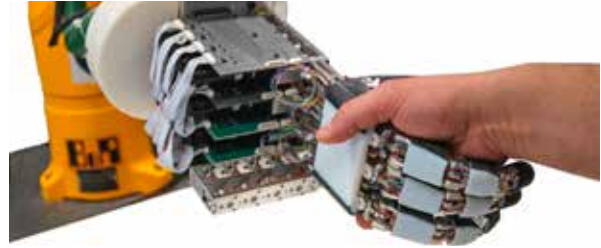
Website: <http://continuum.website>

ROBOTEX 2.0

The Coordinated Infrastructure of Robotics Platforms in France

The Robotex 2.0 coordinated infrastructure brings together the national and regional robotics platforms in France. This research infrastructure relies on more than 1,000 researchers in 32 research laboratories and 5 themes: Humanoid Robotics and Natural Interactions (RHIN), Medical Robotics (RobMed), Land and Air Mobile Robotics (RobMob), Micro and Nano Robotics (MicroRob), Robotics in the Industry of the Future (RobIF). Robotex 2.0 offers robotics researchers a working environment that meets the highest international quality standards and facilitates access to high-level hardware and digital platforms. In collaboration with the GDR Robotics of the CNRS, it aims to:

- promote synergies between research teams in order to remove the scientific obstacles to the autonomy and reactivity of robots, the security of robots, assistance to humans in their environment, etc;
- respond to major societal challenges (Stimulating industrial renewal, Sober resource management



© PPrime, Pascal Seguin et Pierre Laguille

and adaptation to climate change, Clean, safe and efficient energy, Health and well-being, etc.).

The infrastructure allows, among other things, the pooling of technical and human resources with national coordination and thus increases the visibility of public research in robotics. Training, exchange and sharing of knowledge are based on the professional network of roboticists and mechatronics specialists (²RM).

Relations with economic actors and/or socio-economic impact

The Robotex 2.0 laboratories have developed close links with companies in the field, SATTs, competitiveness clusters, IRTs and Carnot institutes. They actively participate in Labexes. Since 2012, its members have also created 12 start-ups and 5 LabComs in the field of robotics and 55 patents with the support of Robotex 2.0 platform equipment.

Open science and data

- All the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure are open on a software forge <https://github.com>
- Annual data production: 20 TB
- The validated and described data are published on a data repository

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Grenoble

Other sites in France: Besançon, Cergy, Clermont Ferrand, Compiègne, Lille, Marseille, Montpellier, Nancy, Nantes, Nice, Paris, Paris-Saclay, Poitiers, Rennes, Strasbourg, Toulouse

French supporting institutions: CNRS

Director or RI representative in France:

- Nicolas Marchand, directeur
- Jean-Pierre Gazeau, directeur adjoint
- Jean-François Kong, coordinateur exécutif

Construction: 2011

Operation: 2012

Stakeholders in France: Inria, CEA, INRAE, ECN, UFC, Sorbonne U, UGA, AMU, Université de Montpellier, Université de Poitiers, Université de Strasbourg, Université de Lille, Université de Lorraine, ENSAM, UCA, UTC, Université de Nantes, ENSMM Besançon, Clermont Auvergne INP

Contact in France: Nicolas Marchand, nicolas.marchand@gipsa-lab.fr
Jean-François Kong, jfkong@unistra.fr

Website: <http://equipex-robotex.fr>



SILECS

Infrastructure for Large-Scale Experimental Computer Science

SILECS (Super Infrastructure for Large-Scale Experimental Computer Science) is a large infrastructure for experimental research on various aspects of distributed computing and networking, from small wireless objects to the large data centres of tomorrow. It enables end-to-end experimentation with protocols at all levels of the software layers, from event capture to data processing and storage, to radio management and dynamic deployment of edge services, allowing reproducible research on clusters and networks that are programmable at all points.

SILECS brings together all French academic actors in networking and distributed systems and represents



© Inria / C. Morel

the French node of the European ESFRI infrastructure SLICES.

Relations with economic actors and/or socio-economic impact

SILECS is supported and used by many private companies, large groups, start-ups and SMEs, either users or suppliers of Cloud or IoT technologies. We can mention OVH, Orange, ATOS, etc.

Open science and data

- All the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure are open on a software forge: <https://github.com/iot-lab/iot-lab.git>
- Annual data production: 20 TB

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Le Chesnay-Rocquencourt

Other sites in France: Biot, Illkirch-Graffenstaden, Lyon, Montbonnot-Saint-Martin, Nantes, Palaiseau, Paris, Rennes, Saint-Martin-d'Hères, Toulouse, Villeneuve-d'Ascq, Villers-lès-Nancy, Villeurbanne, Évry-Courcouronnes

French supporting institutions: Inria

Director or RI representative in France:

• Frédéric Desprez, Nathalie Mitton

Construction: 2018

Operation: 2019

Stakeholders in France: CNRS, IMT, Université de Strasbourg, Sorbonne U, EURECOM, INSA de Lyon, ENS de Lyon, Université de Lille, Université de Lorraine, RENATER, UFTMP, UGA

Contact in France: Frédéric Desprez, frederic.desprez@inria.fr
Nathalie Mitton, nathalie.mitton@inria.fr

Website: www.silecs.net

International dimension

ESFRI SLICES

Director: Serge Fdida, serge.fdida@sorbonne-universite.fr
Christian Perez, Christian.Perez@inria.fr

Partner countries BE, CY, CH, DE, EL, ES, FI, FR, HU, IT, LU, NL, NO, PL, SE

Website: <http://slices-ri.eu>



L'ATALANTE

8.

Earth system
and **environment**



Earth system and environment

The major challenge for research in Earth System & Environmental Sciences is the study of global changes, their determinants and their impacts at all scales of time (from short to very long term) and space (from local to global). The studies are conducted both by major compartments of the Earth System and by major issues, whose interconnections are themselves an object of research.

THE MAJOR SCIENTIFIC QUESTIONS AND SOCIETAL CHALLENGES THAT REQUIRE THE USE OF RESEARCH INFRASTRUCTURES

The environmental issues associated with the knowledge produced by the Research Infrastructures are essential, with the pressure of man and society on the environment at the heart of the subjects: climate change, exploitation and depletion of natural resources, erosion of biodiversity, degradation of air quality, reduction of water resources and degradation of their quality, risks (flooding by river and marine submersion, heat waves, droughts, fires, telluric, industrial and sanitary risks, etc.), changes in land use and degradation, etc.

The research infrastructures (RIs¹) of the Earth System and Environmental Sciences (SST & ENV) domain make a major contribution providing fundamental knowledge on the functioning of the various systems that make up the Earth and their interactions. They support the research of a community of about **20,000 researchers, academics and research engineers**.

These RIs provide access to natural and anthropized environments, manage sample collections and produce large quantities of data from observations, experiments, analyses

and simulations. They provide relevant and validated monitoring indicators, and allow the testing of innovations and predictive numerical models. One of the specificities of observation and experimentation RIs is that they are widely distributed on the national territory and beyond (Europe in particular).

The research data delivered by these infrastructures allow us to:

- understand, model, scenario and predict the evolution of climate, biodiversity and natural resources
- trace air, water and soil pollution and the diversity of their impacts
- study, at different scales, global changes under the two complementary facets of adaptation and reduction,
- respond to the inter- and transdisciplinary scientific challenges posed by the science of sustainability,
- inform decision-making in the framework of public policies,
- contribute to the sustainable development of economic activity.

A major effort has been devoted over the last 10 years in France to the development of information and access systems to data from research, observation and experimentation infrastructures in the field of SST & ENV: one for the physical data of the Earth System (RI

¹ Under the generic term RI, by extension, are considered IO, RI*, RI, Networks, RI in project of the roadmap.

DATA TERRA) and the other for biodiversity (RI **PNDB**). In addition to data management, these two RIs ensure the development of services for research, support to public policies and the socio-economic sector, useful in particular for energy and ecological transitions. In the field of climate, the **CLIMERI-France** RI supports the acquisition and distribution of international global and regional climate simulation data.

POSITIONING OF EACH INFRASTRUCTURE IN THE LANDSCAPE

Understanding and modeling the Earth system and environment requires (Figure 1):

- heavy logistical cross-sectional devices to access certain environments (FOF, ECORD-IODP, CONCORDIA and IN AIR; in orange on Figure 1) and analyses (RÉGEF, RI in project),
- observation or experimental systems and collections of natural, heritage and/or rare samples (in dark blue on Figure 1) to acquire data at different spatial and temporal scales
- e-infrastructures (modeling platforms, data hubs, in light blue on Figure 1).

This synthetic representation of RIs according to the major compartments of the Earth System and by major environmental issues shows their complementarities, but their specificities require a detailed representation by major compartment (see below).

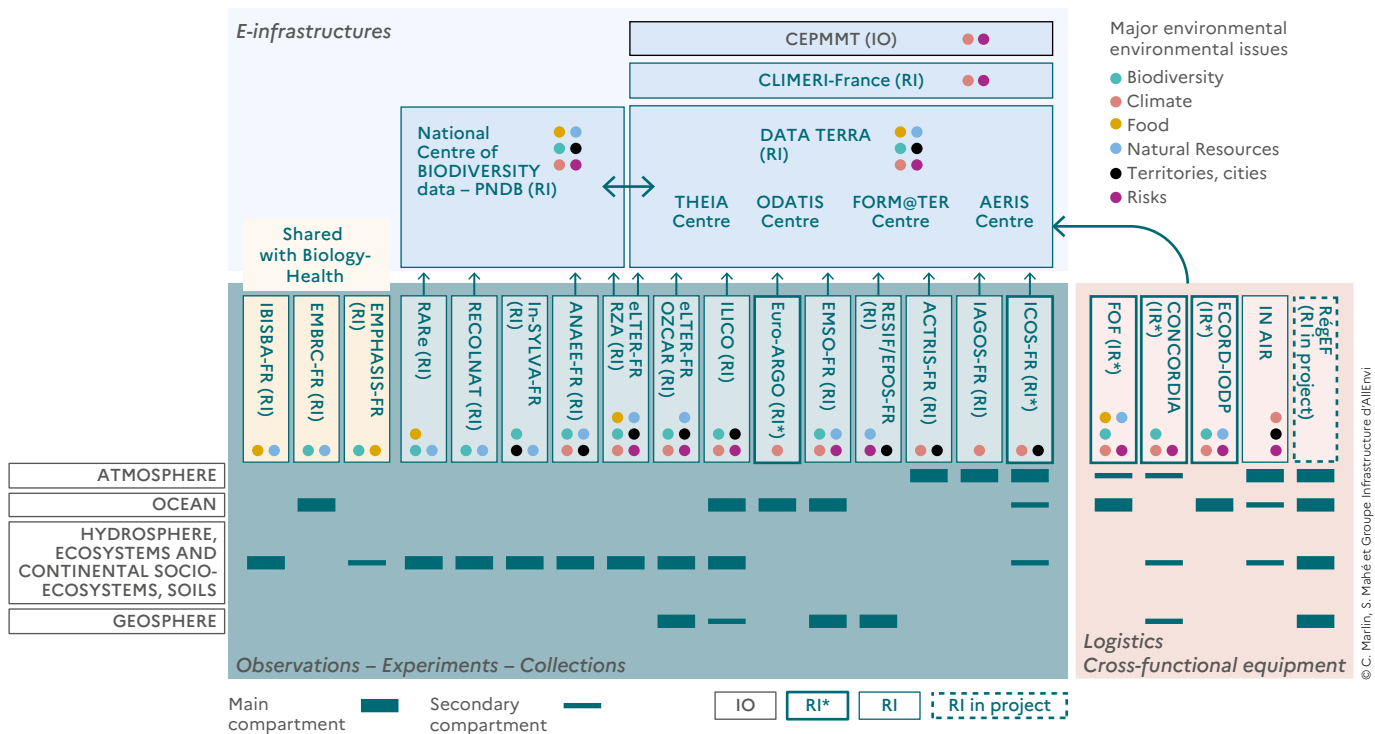


Figure 1: IO/RI*/RI of the SST & ENV domain by major types (observations – experimental – collections, logistics and e-infrastructures), by major compartments of the Earth system (atmosphere, ocean, hydrosphere-ecosystems – continental socio-ecosystems – soils and geosphere) and by major environmental issues (biodiversity, climate, food, natural resources, territories, risks). In yellow are three infrastructures shared with the Biology-Health domain.

© C. Marlin, S. Mahé et Groupe Infrastructure d'AllEnv

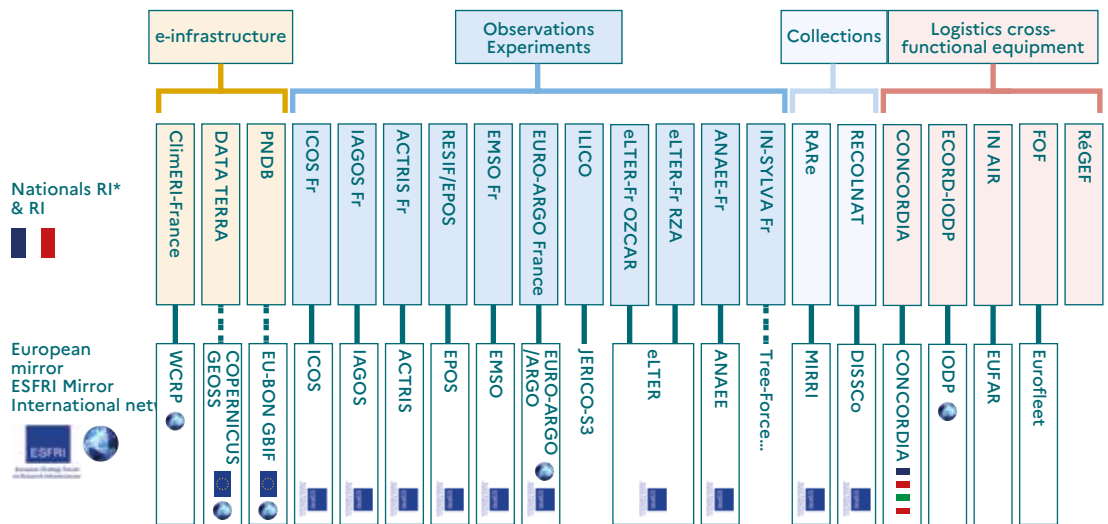


Figure 2: Coherence between French and European or international infrastructures. The infrastructures shared with the Biology-Health domain and the CEPMMT IO are not taken into account here.

The vast majority of French infrastructures in this field are designed on a European scale² (Figure 2).

Logistical infrastructures and transversal equipment

Logistical infrastructures are essential for in situ data acquisition or sample collection in difficult to access environments. These include fleets (RI* **FOF** for oceanographic vessels, RI **IN AIR** for airplanes and balloons), the contribution to the European consortium of drilling ships (RI* **ECORD/IODP**) or polar stations such as RI* **CONCORDIA** in Antarctica, the French part of a Franco-Italian station. In addition, there is the planned RI **RÉGEF**, an infrastructure that brings together measurement, imaging and experimental instruments in geochemistry, petrology and mineralogy.

Observation and experimentation infrastructures

The observation and experimentation infrastructures can be presented

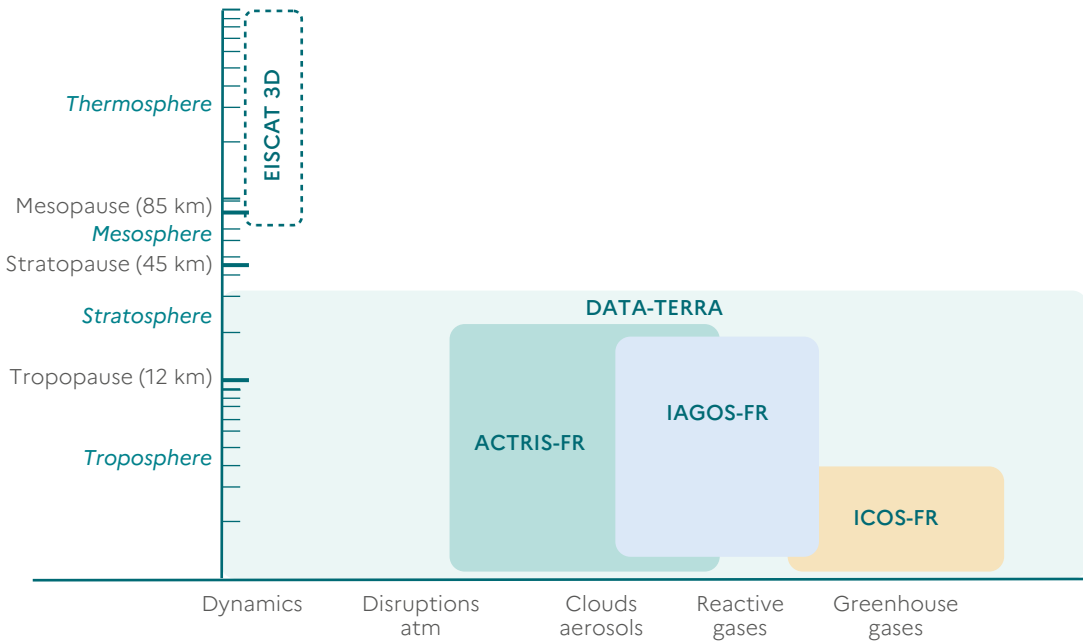
according to the four major compartments of the Earth system, as adopted by the European ESFRI roadmap:

- Atmosphere,
- Ocean and coastline,
- Hydrosphere, continental ecosystems and socio-ecosystems and soils,
- Geosphere.

Atmosphere

The research infrastructures, all French mirrors of ESFRI infrastructures, support scientific activities on climate, atmospheric composition and the carbon cycle, three major issues of SST & ENV (Figure 3). They are carried by communities historically structured around the study of greenhouse gases, via the RI* **ICOS-France**, the composition of the atmosphere at the troposphere/stratosphere level via the RI **IAGOS-France** and the study of aerosols and reactive gases involved in atmospheric chemistry and air pollution via the RI **ACTRIS-France**. The AERIS pole of RI **DATA TERRA** gathers all the pre-existing data centers and databases

² It should be noted that the RI*/logistics RI (FOF, CONCORDIA, ECORD-IODP), the IN-SYLVA-France RI, the planned RI **RÉGEF** as well as the **DATA TERRA** and **PNDB** data clusters are not mirrors of European infrastructures even if they contribute to the European Open Science Cloud (EOSC) initiative.



© C. Marlin, S. Mahé et Groupe Infrastructure d'AllEnvi

Figure 3: French and European research infrastructures in the “Atmosphere” domain. The EISCAT-3D infrastructure is an ESFRI infrastructure without French participation. Logistics infrastructures for access to the atmospheric environment are not shown in this figure.

of **ACTRIS-France**, **IAGOS-France** and **ICOS-France**. In addition to these *in situ* data acquisition infrastructures, France has a climate modelling infrastructure (RI **CLIMERI-France**) which develops French climate models and carries out international numerical simulations as part of the World Climate Research Programme (WCRP).

Ocean and coastline

Marine sciences cover a wide range of spatial and temporal scales, from the global ocean to the microscopic scale, from the century to the second, from the ocean surface to the seafloor, and from the open ocean to coastal environments (Figure 4).

The RIs of the ocean domain (RI* **EURO-ARGO**, RI **EMSO-France**, RI **ILICO**) reflect this diversity and interdisciplinarity.

This domain is closely linked to and dependent on large logistic means (RI* **FOF**, RI* **ECORD-IODP**).

Other infrastructures such as RI* **ICOS-France** and RI **EMBRC-France** or RI **CLIMERI-France** also have an important marine component.

Hydrosphere, continental ecosystems and socio-ecosystems, soils

The RIs of the “Hydrosphere, ecosystems and continental socio-ecosystems and soils”

domain combine instrumented sites (RI **eLTER-France OZCAR** for the hydrological and biogeochemical cycles of the critical zone, RI **eLTER-France RZA** for research on socio-ecosystems, RI **ILICO** for the land-sea interface and RI* **ICOS-France** for the study of greenhouse gas emissions) and experimental sites and platforms (RI **In-Sylva-France** for the forest, RI **AnaEE-France** for the study of ecosystems *in situ* and the study of ecosystems under highly controlled conditions). They cover the main continental ecosystems or socio-ecosystems under different climates, at different spatial and temporal scales (Figure 5).

Geosphere

In the field of the solid Earth, France is very active with two infrastructures, the RI **RESIF/EPOS**, which brings together all the national geophysical resources dedicated to monitoring the hazards and resources of the internal Earth, and the RI **EMSO-France**, dedicated to the observation of the “solid” ocean floor. In addition to the stakes of knowledge on the structure and internal dynamics of the Earth, the societal stakes underlying the field of the geosphere are numerous (natural hazards, energy, raw materials, storage, etc.). In addition, the RI **AnaEE-France** and **ELTER-France OZCAR**

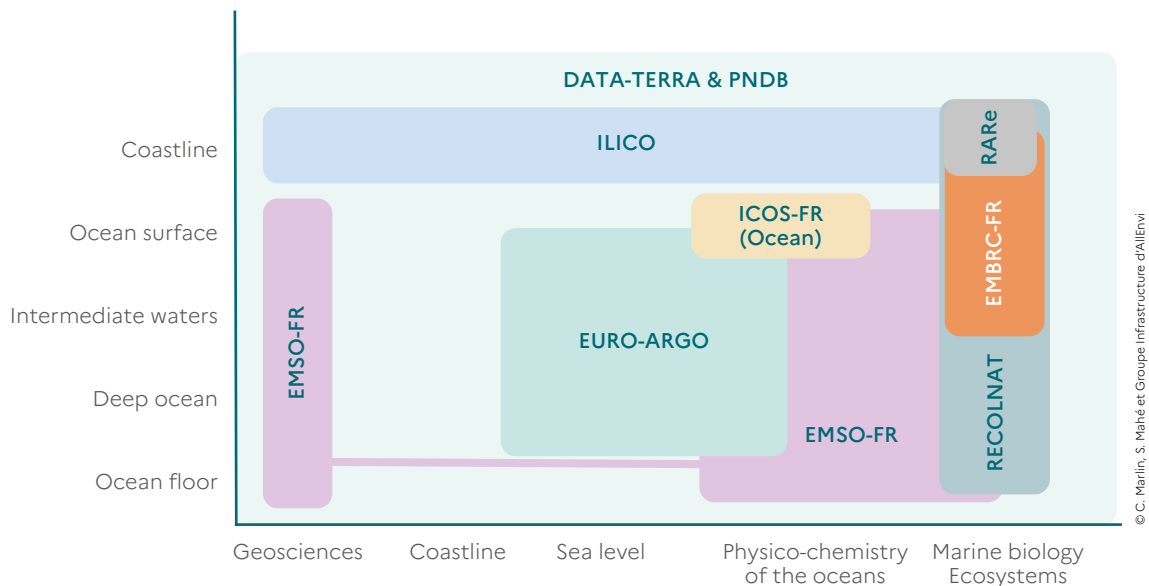


Figure 4: French research infrastructures in the "Ocean and Coastal" domain. The orange box (EMBRC-FR) indicates a common infrastructure with the Biology-Health domain. Logistics infrastructures for access to the oceanic environment are not shown in this figure.

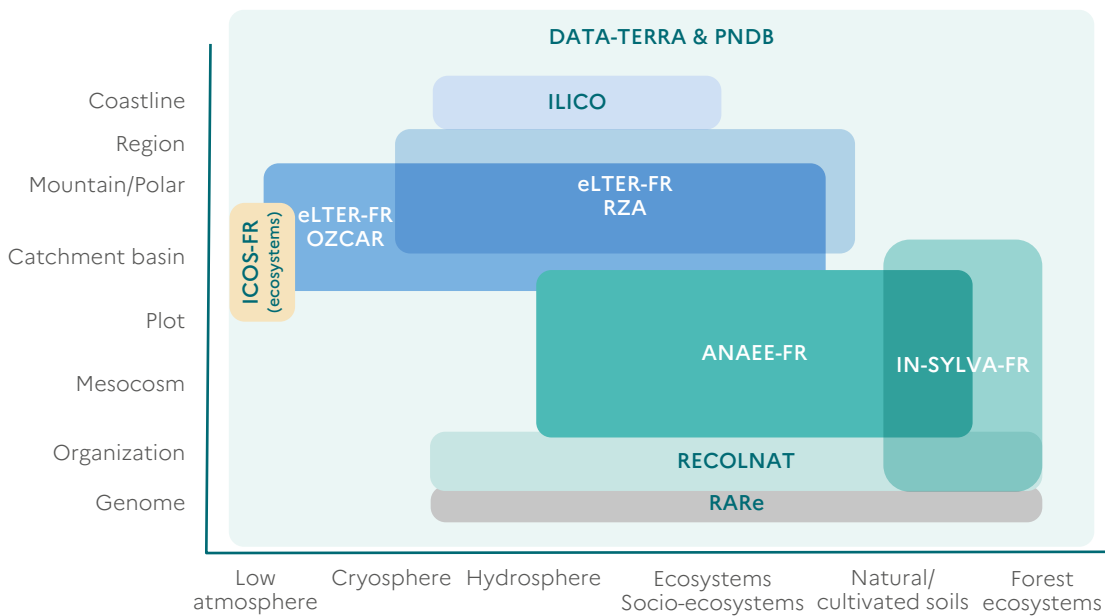
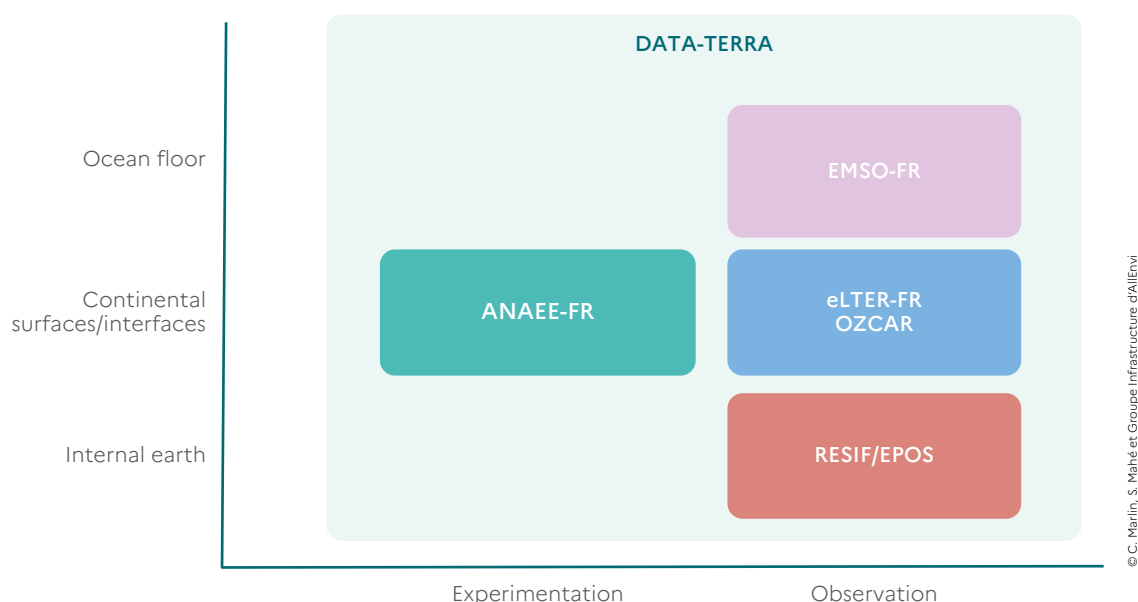


Figure 5: French research infrastructures in the "Hydrosphere, continental ecosystems and socio-ecosystems and soils" domain. Logistics infrastructures for access to the oceanic environment are not shown in this figure.



© C. Marlin, S. Mahé et Groupe Infrastructure of All'Envi

Figure 6: French research infrastructures in the “geosphere” domain. Logistics infrastructures for access to the oceanic environment are not shown in this figure.

respectively provide experiments or observations on soils and the near-subsoil, particularly for aquifers (Figure 6).

Natural sample collections

The sample archiving infrastructures are :

- RI **RARE**, which brings together the animal, plant and microbial biological resource centres dedicated, among other things, to agronomy,
- RI **RECOLNAT**, which brings together naturalist collections. Within the framework of the development of **RECOLNAT**, other disciplines should enrich the offer of images, particularly in zoology and geosciences.

e-infrastructures

Two national data centres gather the data of the domain:

- The **Earth System Data and Services Cluster DATA TERRA** is an infrastructure that is being structured to offer a single portal to the four clusters (AERIS for

the atmosphere, ODATIS for the ocean, FORM@TER for the solid Earth and THEIA for continental surfaces and interfaces) as well as services and tools. It will contribute to major European programs like COPERNICUS and international programs like GEOSS.

- The purpose of the **PNDB RI (National Biodiversity Data Centre)** is to provide access to observation, collection and experimentation data, in connection with the European network EU-BON (*Biodiversity Observatory Network*) and the IO GBIF (*Global Biodiversity Information Facility*).

In terms of modelling, the RI **CLIMERI-France** is responsible for carrying out reference climate simulations. At the national level, it aims to coordinate the models of Météo-France and the Institute Pierre Simon Laplace (IPSL), to facilitate the exploitation of simulation results, especially those of future climate. The data produced in CLIMERI-France are inserted in the international



Earth System Grid Federation database of WCRP reference simulations.

Interfaces with other domains of the national ToR

Research questions in Earth system and environmental sciences are, for the most part, inter- or transdisciplinary. Thus, several infrastructures are registered at the interface between two domains of the national roadmap.

Infrastructures at the interface with the Biology-Health domain

For research at the interface between the physical and living environments, certain infrastructures are shared with the Biology/Health domain.

- Dedicated to the phenotyping of plants and model species, RI **EMPHASIS-France** complements, for agronomists and ecologists, the “omics” platforms supported by Aviesan, such as RI Metabohub and RI France Génomique.
- Three RIs are of great interest for environmental sciences:
 - **IBISBA-France**, which is positioned between the environment/energy/biology-health fields. Its centre of gravity is synthetic biology and biotechnologies, but with applications in various fields such as waste recovery.
 - **EMBRC-France** for marine biological resources.
 - **CALIS** for food production, since agriculture is a major source of greenhouse gas production and a user of natural resources (soil, water, inputs, etc.).

Moreover, it should be noted that the **RARe** RI is also interested in genetic resources of interest in biology and health: canine resources, human microbiota consortia, etc.

Infrastructures at the interface with the SSH domain

The RI **E-RIHS**, an analysis and imaging infrastructure, studies heritage materials, in connection with RECOLNAT, which includes naturalist collections from museums and universities.

Infrastructures at the interface with the Energy domain

The RI **ECSEL-Fr** (*European Carbon Dioxide Capture and Storage Laboratory*) is working on a climate change mitigation technology through the capture, transport and storage of CO₂, which obviously concerns the SST & ENV domain.

Interface with the Digital domain

The reflection on the digital domain concerns all the infrastructures of the SST & ENV domain due to the large amount of data produced and the needs for calculation and simulation. In the long term, France’s ambition to contribute to the development of a digital twin of the Earth (eEarth) cannot be achieved without the support of a global policy on digital technology for all infrastructures in the SST & ENV domain.

Training-Innovation

Numerous links exist between the research infrastructures of the SST & ENV domain and higher education in universities and schools (hosting interns, PhD students, post-doctoral fellows). These links should be intensified or even developed with the hosting of IUT students or apprenticeship students in the infrastructures, for example for long-term internships or summer schools. A form of companionship (a system for training young people in inter-infrastructure relationships) could be developed. In universities, a training/infrastructure/innovation link can also be provided by Fabrication Laboratories – FabLab (instrument or sensor prototyping). These FabLabs could be springboards for innovative technological

developments for the environment.

The growing use of digital technology and “big data” in SST & ENV infrastructures implies new professions, for example the need for “data scientists”. This new field of activity raises the question of the place of digital technology in infrastructures, the associated recruitment profile and the pooling of this type of activity, or even the creation of dedicated companies.

Socio-economic benefits

The infrastructures of the SST & ENV domain play a decisive role in scientific research with major stakes for society (climate change, state of biodiversity, environmental pollution, natural hazards, exploitation and depletion of natural resources, etc.), for the sustainability of the environment and the socio-economic world. All the natural, industrial and health disasters of recent years (floods, droughts, cyclones, fires, heat waves, air pollution, the COVID-19 pandemic, etc.) are examples of strong negative impacts on the economy, society and the environment. Risk prevention as well as research conducted by RI user communities have a positive impact on sustainable agriculture and forestry, bio-economy, blue economy and the emergence of innovative ecosystem services. SST & ENV infrastructures produce a very large amount of essential data for knowledge that also informs public policies and helps public authorities in decision-making.

Moreover, the capacity of scientific communities to document the environment at all scales of time and space cannot be developed without the contribution of innovative technologies and methodologies that concern both measuring instruments, sensors deployed *in situ*, and all the digital tools that are essential for organizing, processing, and modelling the billions of data produced.

DATA AND OPEN SCIENCES

Among the 25 infrastructures of the Earth and Environmental System Sciences domain, 5 produce a volume of data of the order of one Po, 12 of the order of one TB and 8 of the order of one GB, all estimated at about 9% of the total volume of data produced by all the infrastructures of the national roadmap. Observation and experimentation data of the domain are, for a part, stored and shared through Data Terra, the Earth System data and services cluster, organized in four pillars (ODATIS for the ocean, THEIA for the continental surfaces, AERIS for the atmosphere and FORM@TER for the solid Earth) to which is added DINAMIS for space imagery data. Data Terra gathers and manages 40% of the data volume produced by the infrastructures of the domain, excluding the international organization CEPMMT. In addition, there is the PNDB, the biodiversity data cluster, and CLIMERI-France for numerical reference simulations for climate. However, as 86% of the infrastructures in this domain are components of European or international infrastructures, the management and opening of certain nationally acquired data, mainly through distributed devices, can be articulated in a supranational framework (13 international warehouses). The vast majority of research infrastructures in the domain have a data management plan either established (13/25) or in the pipeline (8/25). Four have data management that operates solely on an international or European scale (e.g. CEPMMT, Ecord-IODP, Euro-Argo and ICOS). All of the infrastructures in the domain provide access, through a FAIR approach (16 in application, 7 in preparation/ reflection) to environmental data in the broadest sense to a community of about 20,000 researchers, academics and engineers.

More than 90% of the infrastructures of the Earth System Sciences and Environment are part of an open science approach. This policy of data sharing is well established



in the communities because of the European directives that have long been applied in this field. In detail, if the “Formalized open science strategy”, “publications policy”, “data policy”, and “data governance” components can be qualified as emerging to generalized, the policies of opening codes and software are systematic. A coordination of environmental research infrastructures, through ENVRI-Fair (Environmental Research Infrastructures building FAIR services for research, innovation and society), federates the community with a view to making the services visible in the EOSC (European Open Science Cloud) portal. All the infrastructures encourage the deposit of publications in open archives and the referencing of the infrastructure that produced the data. The communities in the field are also very advanced in terms of governance and data-related professions.

STRATEGY: POTENTIAL GAPS TO FILL AND ORIENTATIONS FOR THE NEXT 5 YEARS

The development of the new roadmap is based on three pillars that should lead to the global modelling of the Earth system, necessary to achieve major transitions and reach the goals of sustainable development:

1. taking into account the evolution of science fronts to answer the major questions posed to environmental sciences,
2. consolidation of national systems with the filling of gaps, the establishment, if possible, of coordination by field or environment, a sharing of procedures (data processing, protocols, etc.) and a common philosophy concerning access to infrastructures (openness, availability, etc.)
3. a strategy of interaction with the European or international level with either a

consolidation of France’s leadership in certain fields or the development of strategic alliances.

Logistics infrastructures and cross-functional facilities

The number and diversity of logistical and cross-disciplinary infrastructures could increase over the next decade with the inclusion in the national roadmap of systems that already exist within organizations or between organizations and that require national visibility. Their inclusion on the roadmap will however have to take into account possible complementarities or overlaps with existing RIs.

In the medium term³, the planned RI RÉGEF (French Geochemical and Experimental Network, coordination CNRS), which constitutes a national system of access to national instruments and thematic analytical networks for mineralogical and geochemical analyses, will have to be fully integrated into the national roadmap as an RI.

In the medium/long term, the lake, continental and glacial coring facilities operated by the CNRS could request a label in the national roadmap.

Observation and experimentation infrastructures

Atmosphere

In the medium term, an “atmosphere” infrastructure of the RI* type should be structured. The joint OBS4CLIM project within the framework of the Equipex+ AAP (PIA3) federating **ICOS-France, IAGOS-France and ACTRIS-France** demonstrates the capacity of these communities to work in synergy and complementarity. However, in order to ensure that the RIs concerned do not lose their European

³ Medium/long term: within the next national roadmap/10 years

visibility, as it currently exists, a coordination organization, without merging the RIs concerned, should be set up as a first step.

Ocean and coastline

An infrastructure dedicated to the open ocean should be built so that **in the medium/long term**, the oceanic domain is entirely covered by the observation infrastructures (RI* **EURO-ARGO**, RI **EMSO-France** and **ILICO** and the high-sea). At the national level, the objective should be the establishment of either a strong coordination between these RI or a single RI FrOOS (French Ocean observing system), in articulation with the data poles DATA TERRA and PNDB.

Hydrosphere, continental ecosystems and socio-ecosystems, soils

In the short/medium term, the RI **eLTER-France OZCAR** and **eLTER-France RZA** should form a single infrastructure (eLTER-France) dedicated to observation and experimentation on hydro-systems, natural ecosystems and socio-ecosystems and the counterpart of eLTER-Europe. The Terra Forma équipex+ (PIA 3) is an additional support to achieve this.

A lack is identified of an infrastructure dedicated to **the observation and environmental modelling of the city, more generally of highly anthropized environments**, although no European mirror infrastructure exists at present. The observation of these environments is currently distributed in several RI but recent initiatives could lead to a national structuring of this field.

Collections of natural samples

In the medium/long term, certain **collections**, not referenced in the national structures and yet organized according to recognized standards, have the characteristics of research infrastructures. Thus, **core libraries**

(sediments, rocks, ice), lithotheques and pedotheques are managed at the local level and a national structuring could be studied.

E-infrastructures

A single infrastructure for Earth system data and services (biological and physical components) resulting from the integration of the DATA-TERRA and associated PNDB RIs in the **GAIA DATA** project (PIA 3/ Equipex+) is expected **in the medium term**.

ECMWF

European Centre for Medium-Range Weather Forecasts

The European Centre for Medium-Range Weather Forecasts is an independent intergovernmental organisation established in 1975 and currently funded by 34 Member States. It is both a research institute and an operational service that develops its global Numerical Weather Prediction model and system, and operates it 24/7 to develop and disseminate its products. Its computing and data centre (and the entire corresponding archive) is accessible to all its Member States for their research activities. As a result, ECMWF is also an important tool for climate research, and in particular carries out re-analyses of recent climate based on its Numerical Weather Prediction system and all available past observations. ECMWF also coordinates and implements the atmosphere



© Anonyme

(atmospheric chemistry, air quality, greenhouse gas emissions) and climate change services of the European Union's Copernicus programme.

Relations with economic actors and/or socio-economic impact

Open science and data

- Annual data production: 85 PB

Category: IO

Type of infrastructure: distributed

French supporting institutions: Météo-France

• **Director or RI representative in France:** H. Roquet

• **Website:** www.ecmwf.int

International dimension

- **Partner countries** AU, BE, HR, DK, EE, FI, FR, DE, GR, IS, IE, IT, LU, NL, NO, PT, RS, SI, ES, SE, CH, TR
- **Website:** www.ecmwf.int



CONCORDIA

CONCORDIA – French-Italian Antarctic Research Station

CONCORDIA is the only permanent European polar research station in the interior of the Antarctic continent. It is located on one of the highest points of the Antarctic ice cap (3,233 m above sea level): Dome C, on the Antarctic continental shelf (75°06'S - 123°21'E), 1,100 km from the French coastal station Dumont d'Urville (DDU) and 1,200 km from the Italian Mario Zucchelli Station (MZS).

The CONCORDIA system includes the station, the land-based supply system from DDU, and the Robert Guillard annex station located near DDU (departure point for land-based logistics convoys). In addition, there are inter- and intra-continental air links via the MZ station, as well as the ship L'Astrolabe, equipped by the French Navy and under the authority of the IPEV during the Antarctic logistical support campaign, which brings the necessary supplies from Tasmania. CONCORDIA, a RI* for Earth and Universe Sciences, has a logistical and observational function (it houses many scientific observatories).



© Institut polaire français/Antarctique / Concordia/Lucie Bonhomme/2018

The construction and operation of CONCORDIA are covered by agreements (signed in 2005, entered into force in 2007, renewed in 2017) for scientific cooperation in Antarctica between the French and Italian research ministries, and between the operators IPEV and Programma Nazionale di Ricerche in Antartide (PNRA).

Relations with economic actors and/or socio-economic impact

The management of RI* has led the Polar Institute to develop unique expertise in collaboration with industrial players in order to meet the challenges imposed by isolation and extreme climatic conditions, particularly in the design/insulation of buildings, the transport of heavy loads on ice or the treatment of waste water. Part of our activities are based on the Tasmanian economic fabric, the starting point of our missions.

Open science and data

- Part of the publications from projects using the infrastructure are open access
- Annual data production: 60 GB

Category: RI*

Type of infrastructure: single site

Infrastructure location in France: Plouzané

French supporting institutions: IPEV

● **Director or RI representative in France:** Chappellaz

● **Construction:** 2005

● **Operation:** 2005

● **Stakeholders in France:** CNRS, CEA, CNES, MF, Ifremer, TAAF

● **Website:** www.institut-polaire.fr/ipev/infrastructures/les-bases/concordia

International dimension

● **Partner countries FR, IT**

● **Website:** www.institut-polaire.fr/ipev-en/support-for-science/antarctica/concordia

ECORD/IODP

International Deep Sea Drilling Programme/European Consortium for Ocean Drilling Research/International Ocean Discovery Program

ECORD is a European consortium (14 European countries and Canada) whose main objective is the scientific exploration of the seafloor where climatic, sedimentary and tectonic events that have affected the planet over its history are recorded. It participates in the IODP programme (International Ocean Discovery Program; 23 countries) which enables scientists to study topics as varied as seismic hazards, climate change, geophysics and geodynamics of the globe, the deep biosphere, ocean acidification, natural resources, chemical exchanges between the oceanic crust and the ocean, biogeochemical and physical processes related to fluid circulation under the ocean floor, etc.).

IODP uses different platforms:

- the conventional drillship JOIDES Resolution operated by the United States;
- the “Riser” vessel Chikyu of the Japanese operator JAMSTEC-MarE3, which can be used to drill very deep and in unstable geological formations;



– Mission-Specific Platforms (MSPs), implemented by ECORD and involving different drilling equipment adapted to scientific needs.

ECORD is a unique infrastructure in Europe and offers a range of activities, including science, technology, education, conservation and data provision. ECORD thus fills a gap in the European scientific landscape.

Relations with economic actors and/or socio-economic impact

Scientific drilling provides essential data to various industrial sectors (oil industry, biotechnologies, mineral resources, water resources, etc.). ECORD and IODP innovate in terms of technological development of drilling equipment and techniques in collaboration with the industrial sector (large companies and SMEs) and in the framework of competitiveness clusters.

Open science and data

- Part of the publications from projects using the infrastructure are open access
- Annual data production: 10 PB
- Infrastructure with a FAIR data policy in application
- The validated and described data are published on a data repository www.marum.de/en/Research/IODP-Bremen-Core-Repository.html

Category: RI*

Type of infrastructure: distributed

Infrastructure location in France: Aix-en-Provence

Other sites in France: Montpellier, Toulouse

French supporting institutions: CNRS

● **Director or RI representative in France:** G. Camoin

● **Construction:** 2003

● **Operation:** 2003

● **Stakeholders in France:** CNRS

● **Website:** www.iodp-france.org

International dimension

ECORD/IODP

- **Partner countries** DE,UK, FR, AU, CA, DK, ES, FI, IE, IT, NL
- **Website:** www.iodp-france.org

EURO-ARGO-France

In-situ Ocean Observation Network/European contribution to Argo program

Argo France brings together all French contributions to the international Argo programme, i.e. scientific and technical coordination, float purchase and deployment, data processing and interfaces with the user community (operational oceanography with Mercator Ocean and research). In addition to processing its own floats, France provides important data processing functions for its European and international partners (Coriolis data centre). Argo-France is coordinated within the Coriolis inter-agency structure (Ifremer, CEREMA, CNES, CNRS/INSU, IPEV, IRD, Météo France, SHOM) and has been labelled as a National Observation Service (SNO) for Research (OSU IUEM) since 2011 by INSU.



© Jean-Jacques Pangrazi

The RI* Euro-Argo includes the national component Argo France and the French contribution to the coordination of the ERIC Euro-Argo. The ERIC (European Research Infrastructure Consortium) Euro-Argo is the European contribution to the international Argo network.

France's ambition is to contribute to about 10% of the Argo programme (i.e. 30% of the European effort) by deploying 80 floats/year distributed as follows: 30 standard floats (T,S-2,000 m), 15 deep floats (T,S,oxygen, 0-4,000 m), 35 biogeochemical floats (BGC, 0-2,000 m), 20 of which with an oxygen sensor only.

Relations with economic actors and/or socio-economic impact

Upstream, RI* Euro-Argo has an industrial partnership with the French profiler manufacturer which is currently one of the two main instrument suppliers. Downstream, Argo is an essential network for operational services operated by Mercator-Ocean, SHOM, Météo-France and, in Europe, the Copernicus Marine Service, and as such has many users. Finally, 10% of Argo publications are made by French teams.

Open science and data

- The source codes produced by the infrastructure are open on a software forge <https://github.com/euroargodev>
- Annual data production: 37 GB
- Infrastructure with a FAIR data policy in application
- The validated and described data are published on a data repository www.ncei.noaa.gov/products/global-argo-data-repository

Category: RI*

Type of infrastructure: distributed

Infrastructure location in France: Plouzané

French supporting institutions: Ifremer

- **Director or RI representative in France:** S. Pouliquen
- **Construction:** 2014
- **Operation:** 2014
- **Stakeholders in France:** SHOM, CNRS
- **Website:** www.argo-france.fr

International dimension

ESFRI landmark

Director: S. Pouliquen

- **Partner countries** DE, ES, FR, FI, GR, IE, IT, NO, NL, UK, BG
- **Website:** www.euro-argo.eu

FOF

French Oceanographic Fleet

The RI* French Oceanographic Fleet (FOF) comprises four offshore vessels; two mid-shore vessels deployed overseas, five coastal vessels and seven station vessels. The FOF vessels are able to carry out studies ranging from general exploration over large areas to site-specific work (deployment of underwater devices such as the remote operated vehicle (ROV) Victor6000 or underwater drones) and the setting up of seabed observatories.

In a European marine science research landscape that is often very fragmented, the French Oceanographic Fleet is a unique integrated infrastructure, in that it combines within a single entity (Ifremer) missions and skills in infrastructure management, operations and technological development, backed up by significant R&D contributions.

The FOF is one of the largest oceanographic fleets in the world, alongside those of the USA, Japan,



© Aker-yards

Great Britain and Germany. In Europe, it is the only one, along with the German oceanographic fleet, to have a global reach and it supports research conducted in the French overseas territories. Finally, the fleet is multi-functional, since it combines an activity oriented towards research, but also training, and expert missions in support of public policies and hydrography.

Relations with economic actors and/or socio-economic impact

In the field of mineral resources, the FOF has long been the vehicle for scientific cooperation with industrialists in the field. It also enables Ifremer to honour France's commitments in the framework of the two contracts for the exploration of deep-sea mineral resources signed with the ISA, and to provide the data required to support the French government's claims to extend the continental shelf.

Open science and data

- The source codes produced by the infrastructure are open on a software forge
- Annual data production: 1 PB
- The validated and described data are published on a data repository <http://donnees-campagnes.flotteoceanographique.fr>

Category: RI*

Type of infrastructure: distributed

Infrastructure location in France: Plouzané

French supporting institutions: Ifremer

• **Director or RI representative in France:** O. Lefort

• **Construction:** 2011

• **Operation:** 2011

• **Stakeholders in France:** CNRS, IRD, Universités marines

• **Website:** www.flotteoceanographique.fr

ICOS-France

Integrated Carbon Observation System

The mission of the ICOS infrastructure is to observe variations in surface-atmosphere fluxes and atmospheric concentrations of greenhouse gases at high spatial resolution and on a daily time step. The infrastructure consists of a high-precision, standardised, long-term monitoring network of greenhouse gas fluxes and concentrations. It integrates standardised observations of the atmosphere, continental surfaces and ocean surface waters. The observations produced by ICOS and made available to the scientific community make it possible to explore the processes behind atmospheric exchanges between oceans and continents, to distinguish between biogenic, geophysical and fossil components and to observe atmospheric transport processes. They contribute to global observations of the Earth's atmosphere and climate. The data produced by ICOS-RI



© M. Ramonet

form the basis for high-resolution spatial temporal monitoring of greenhouse gas emissions. They are applied to the estimation of territorial, regional, national and global greenhouse gas balances and contribute to the verification of energy policies.

Relations with economic actors and/or socio-economic impact

These relationships are deployed with: - the qualification of emissions (cities, industrial sites, port areas, forests, meadows, crops, oil platforms, methanizers, carbon partnerships); - technological innovations and developments; - instrument testing with various industrial companies. They involve in particular the IPSL TRACE chair and several industrial groups and local authorities.

Open science and data

- The source codes produced by the infrastructure are open on a software forge www.cecill.info
- Annual data production: 60 TB
- Infrastructure with a FAIR data policy in application
- The validated and described data are published on a data repository www.icos-cp.eu/data-services

Category: RI*

Type of infrastructure: distributed

Infrastructure location in France: Villenave-d'Ornon

Other sites in France: Saint-Aubin, Thiverval-Grignon

French supporting institutions: ANDRA, CNRS, CEA, INRAE, UVSQ

• **Director or RI representative in France:** D. Loustau

• **Construction:** 2015

• **Operation:** 2015

• **Stakeholders in France:** BRGM, CNES, École nationale supérieure des sciences agronomiques de Bordeaux Aquitaine, École pratique des hautes études, Institut national des sciences et industries du vivant et de l'environnement (AgroParisTech), Institut Pierre Simon Laplace, Météo-France, Avignon Université, Université de Guyane, Université de Lorraine, Université de Montpellier, Université d'Orléans, Université Paul-Valéry - Montpellier 3, Université de Paris-Saclay, Université de Reims Champagne-Ardenne, Sorbonne Université, Université Toulouse III - Paul Sabatier, Université de Grenoble-Alpes, Université de La Réunion, Université Clermont Auvergne, Aix-Marseille Université, IRD, Université des Antilles

• **Website:** <https://icos-france.fr>

International dimension

ESFRI landmark

Director: W. Kutsch

• **Partner countries** FR, BE, DK, CZ, DE, FI, IT, NL, ES, SE, UK, NO

• **Website:** www.icos-ri.eu

ACTRIS-France

Aerosol, Clouds and Trace Gases Research Infrastructure – France

ACTRIS-FR is the French component of ACTRIS for the observation and exploration of aerosols, clouds and reactive trace gases and their interactions. ACTRIS is a distributed pan-European research infrastructure for supporting research on climate and air quality and improving the understanding of the evolution of atmospheric processes and composition.

ACTRIS provides users with high quality data and information on short-lived species and their variability in natural and controlled atmospheres.

ACTRIS operates central platforms (data and calibration centres) and provides services to a large user community working on chemistry/climate models, satellite data validation, or analysis of weather forecasting or air quality prediction.



© François Cheusis

Finally, ACTRIS offers physical and/or remote access to its platforms for the scientific communities and the private sector, thus promoting research, training, and technological innovation.

Relations with economic actors and/or socio-economic impact

Through its access strategy, ACTRIS-FR is resolutely oriented towards the socio-economic world. On average, each year about 320 users from all over the world use the services offered by the platforms, 2,000 ACTRIS-FR data sets are downloaded, 15 collaboration contracts with the industrial sector and 15 theses are identified. The scientific influence and expertise are illustrated by ~150 publications and 60 training activities per year.

Open science and data

- Part of the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure are open on a software forge <https://git.icare.univ-lille1.fr>
- Annual data production: 20 TB
- Infrastructure with a FAIR data policy in application
- The validated and described data are published on a data repository

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Paris

French supporting institutions: CNRS

• **Director or RI representative in France:** S. Sauvage

• **Construction:** 2016

• **Operation:** 2016

• **Stakeholders in France:** CEA, CNES, IMT, INERIS, IPEV, IRD, ENPC, École polytechnique (X), Aix Marseille Université, Université de Lille, Université Clermont Auvergne, Université Grenoble Alpes, Université d'Orléans, Université de Paris, Université Paris-Est Créteil, Université de La Réunion, Université de Versailles Saint-Quentin-en-Yvelines, ENS PSL, Institut polytechnique de Grenoble, Université Sorbonne Paris Nord, Université Toulouse III - Paul Sabatier

• **Website:** www.actris.fr

International dimension

ACTRIS, ESFRI project

Director: E. Juurola

- **Partner countries** AT, BE, BG, CY, ES, FI, FR, GR, IT, NL, PL, CZ, RO, GB
- **Website:** www.actris.fr

AnaEE-France

Ecosystem Analysis and Experimentation – France

The AnaEE France infrastructure provides the scientific community, companies and civil society organisations with access to experimental facilities dedicated to the study of continental terrestrial and aquatic ecosystems and distributed throughout France and its overseas territories. The infrastructure also supports research projects by providing access to data and analytical platforms. Specifically, AnaEE France brings together 33 original devices that allow ecosystems to be manipulated either under more or less controlled conditions or in an open environment by accessing long-term experiments offering differentiated environments and documented histories or by carrying out new experiments, particularly in alpine ecosystems and tropical forests. The AnaEE France platforms offer cutting-edge ecosystem characterisation tools to simultaneously understand state variables relating to living organisms and environments, and material and energy flows.



© AnaEE France (CNRS, INRAE)

The capacity to characterise ecosystems is enhanced within the infrastructure by the provision of seven laboratory or in situ analytical platforms in the field of environmental genomics, soil biochemistry and gas analysis. To enhance the value of the data acquired, the infrastructure proposes an information system allowing open dissemination according to FAIR principles.

Relations with economic actors and/or socio-economic impact

The infrastructure hosts about 10% of projects with private operators with whom it develops a policy of access, licence transfers and expertise transfers. The spin-offs concern ecological engineering and agro-ecology, scenario planning for mitigation and adaptation to global change, food security and the supply of renewable resources for the bio-economy.

Open science and data

- Part of the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure are open on a software forge <https://forgemia.inra.fr/anaee-dev/semdata>
- Annual data production: 10 TB
- Infrastructure with a FAIR data policy in application
- The validated and described data are published on a data repository www.anaee.eu/services/data-and-models-portals

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Paris 16^e, Saint-Pierre-lès-Nemours

Other sites in France: Aix-en-Provence, Cayenne, Cestas, Champenoux, Clermont-Ferrand, Colmar, Dijon, Grenoble, Kourou, Laon, Lusignan, Montferrier-sur-Lez, Montpellier, Moulis, Nogent-sur-Vernisson, Paris 5^e, Rennes, Saint-Michel-l'Observatoire, Saint-Pierre-lès-Nemours, Thiverval-Grignon, Thonon-les-Bains, Villard'Arène

French supporting institutions: CNRS, INRAE, UGA, CIRAD, ENS PSL

Director or RI representative in France: J.-F. le Gaillard, A. Chanzy

Construction: 2012

Operation: 2018

Website: www.anaee-france.fr

International dimension

AnaEE, ESFRI project

Director: M. Boer

● **Partner countries** FR, IT, DK, CZ

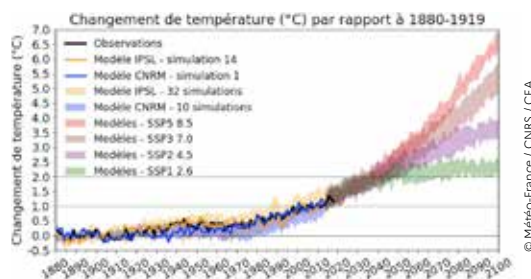
● **Website:** www.anaee.eu



CLIMERI-France

National Research Infrastructure for Modelling the Earth's Climate System

CLIMERI-France is the national research infrastructure for climate modelling. Its mission is to carry out the international numerical simulations of the World Climate Research Programme and to make their results available. These experiments aim to understand the functioning of the climate system, to evaluate the capabilities of climate models, to support studies of mechanisms and processes and to produce projections of future climate change. These experiments serve as a reference for climate science research but also for climate change impact studies in different sectors, and contribute to the preparation of IPCC reports. CLIMERI-France includes the human resources for the development and maintenance of the codes and the tools necessary for their use, the preparation of the reference versions of the codes, the tools for the exploitation of the data produced by the simulations, the computing resources for the international experiments and the data



storage capacities, partly provided by GENCI, as well as the software infrastructure for the management and control of the data and metadata flow. The infrastructure provides digital codes and software tools. It provides a data access service and a platform for analysing the results of global and regional climate models.

Relations with economic actors and/or socio-economic impact

CLIMERI-France prepares and makes available the results of reference climate simulations from French models. These results are used in IPCC reports and for climate change impact studies for different socio-economic sectors (agriculture, energy, water, health...). They serve as a reference for climate services, in particular the Copernicus service on climate change, and for SMEs.

Open science and data

- Part of the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure are open on a software forge
- Annual data production: 3 PB
- Infrastructure with a FAIR data policy in application
- The validated and described data are published on a data repository <https://esgf-node.ipsl.upmc.fr>

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Saint-Aubin

Other sites in France: Bruyères-le-Châtel, Orsay, Paris, Toulouse

French supporting institutions: CNRS, CEA, Météo-France

Director or RI representative in France: S. Jousaume

Construction: 2017

Operation: 2017

Stakeholders in France: Sorbonne Université, IRD, CERFACS

Website: <https://climeri-France.fr>

International dimension

IS-ENES

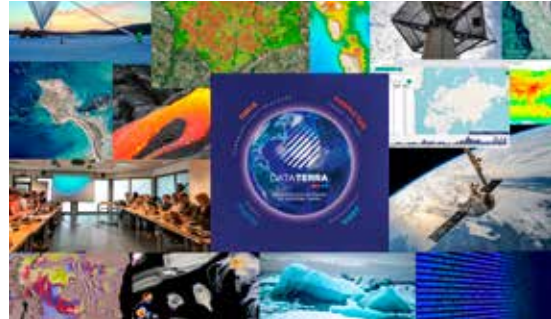
- **Partner countries** UK, DE, IT, SE, ES, NL, NO
- **Website:** <https://is.enes.org>

DATA TERRA

Data hubs and services for the Earth system

The Earth system is a complex system integrating physical and living environments that evolve and interact with each other at different scales. Predicting its evolution, anticipating impacts and warning of environmental risks are major challenges. This requires the collection and cross-analysis of data from observation systems (land, sea, airborne, space), modelling and experimentation. The complexity of the processes studied, the number and increasing precision of observations require the integration of multi-source, multi-scale and multi-type data and a better quantification of their uncertainties.

Data Terra, based on four clusters (continental surfaces, atmosphere, oceans, solid Earth) and crosscutting services, is developing a global system for accessing and processing data, products and services in order to: facilitate access to and use of FAIR data and services, develop services on the entire data cycle and interdisciplinary approaches for scientific communities, public actors and innovation.



© Data Terra - © CNRS 2016.
 crédits: Airbus DS - © Shom, 2018.
 MNT bathymétrique de façade de
 la Guadeloupe et de la Martinique
 (Projet-Homonim) © Pexelis © MTD

This open and interoperable environmental E-infrastructure enables the extraction, cross-referencing and seamless access to multi-source, multi-domain and multi-organism Earth system data. In Europe and internationally, Data Terra contributes to EOSC, space missions and applications, and the implementation of digital twins of the Earth.

Relations with economic actors and/or socio-economic impact

The RI Data Terra is a space dedicated and open to innovation aimed at reinforcing the continuum between research, public action and the economic sphere at all stages of the data life cycle and downstream of the added value chain. Through the numerous interactions and partnerships, the aim is to promote mechanisms for the creation or transfer of value from the world of research to the socio-economic world.

Open science and data

- Part of the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure are open on a software forge <https://gitlab.in2p3.fr/ips/espri/espri-obs>
- Annual data production: 10 PB
- Infrastructure with a FAIR data policy in application
- The validated and described data are published on a data repository www.data-terra.org

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Montpellier

Other sites in France: Paris, Plouzané, Toulouse

French supporting institutions: CNRS, CNES, IRD, INRAE, IFREMER, Meteo-France, IGN

Director or RI representative in France: F. Huynh

Construction: 2016

Operation: 2018

Stakeholders in France: IPG de Paris, CEA, BRGM, ONERA, SHOM, CIRAD, INERIS, Sorbonne Université, École polytechnique (X), Observatoire de Paris, OCA, Université de Lille, Université Toulouse III - Paul Sabatier, UGA, Université de Strasbourg, AgroParisTech, UCA

Website: www.data-terra.org, www.odatis-ocean.fr, www.theia-land.fr, www.aeris-data.fr, www.poleterresolide.fr, www.data-terra.org/category/dinamis

eLTER-France OZCAR

Critical Zone Observatories, Applications and Research

eLTER-France OZCAR is a distributed RI network of sites that instrument the different compartments of the Critical Zone of continental surfaces over the long term: soil, subsoil, water, wetlands and ice. The aim is to continuously measure, model and manage the flows of water, carbon and associated elements. These observatories, which are veritable sentinels of global change, make it possible to address the major scientific issues aimed at a better integrated understanding of the storages and fluxes of energy and matter at the surface of the continents along climatic, topographical, geological or land use gradients.

eLTER-France OZCAR is an essential RI for obtaining a broad and consolidated view of environmental changes on continental surfaces, at the scale of territories ("environments"). It brings together elementary research observatories run by the different research organisations that support them. It offers shared governance and methodology for the study



© Hubert Raguet pour IIR OZCAR

of the functioning and evolution of the Critical Zone at the time of the Anthropocene, for research, public policy support and the economic world.

The services concern the provision of densely instrumented sites, the sharing of their data, the sharing of an instrumental park and technological innovation, and the integrated modelling of the Critical Zone.

Relations with economic actors and/or socio-economic impact

eLTER-France OZCAR is in contact with the stakeholders of the territories where the observatories are located on the issues of water and soil resources, biodiversity, as well as on natural risks. The socio-economic impact of the RI is reflected in the development of innovative environmental sensors to monitor the Critical Zone, environmental expertise and the production of long-term data related to global changes.

Open science and data

- The source codes produced by the infrastructure are open on a software forge <https://github.com/theia-ozcar-is>
- Annual data production: 500 GB
- Infrastructure with a FAIR data policy in application
- The validated and described data are published on a data repository <https://data.icos-cp.eu/portal>

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Paris, Paris 5^e

French supporting institutions: CNRS, IRD, INRAE, BRGM, ANDRA

Director or RI representative in France:

J. Gaillardet, I. Braud

Construction: 2016

Operation: 2016

Stakeholders in France: IPEV, Météo-France, IPG de Paris, Université Grenoble Alpes, Université de Rennes 1, Université de Strasbourg, Université Bourgogne - Franche-Comté, Avignon Université, Université de Caen Normandie, Université d'Orléans, Université de La Réunion, Université Toulouse III - Paul Sabatier, Université de Lyon, Université de Bordeaux, Sorbonne Université, Institut Mines-Télécom, Toulouse INP, CNES, Université Gustave Eiffel, CEA

Website: www.ozcar-ri.org/fr

International dimension

eLTER RI, ESFRI project

Director: M. Mirtl

- **Partner countries** AT, DE, BE, BG, CH, CZ, DK, ES, GR, FI, FR, HU, IL, IT, LV, NO, PL, PT, RO, RS, SE, SI, SK, GB
- **Website:** www.lter-europe.net/elter-esfri

eLTER-France RZA

Réseau des Zones Ateliers – Socio-Ecosystems Infrastructure

The Réseau des Zones Ateliers (RZA, CNRS-INEE) is the embodiment in France of research on socio-ecosystems and the development of sustainability sciences (LTSER platforms). It addresses the functioning and evolution of socio-ecosystems under the influence of the various facets of global change. With strong support from disciplinary approaches within the fields of natural sciences (with a marked emphasis on ecology) and human and social sciences (geography, economics and law, with increasingly strong openings towards sociology, anthropology and the social sciences of politics), the ZAs stimulate truly interdisciplinary approaches and joint research between researchers and territorial stakeholders. The RZA and the diversity of the ZAs that make it up are therefore intended to be both (i) a mosaic of open-air laboratories where these inter- and transdisciplinary approaches can be deployed and tested in order to accompany territories in their transformation towards greater sustainability and (ii) a field for thinking about



© Réseau des Zones Ateliers

the question of changes of scale in inter-ZAs through comparative studies and/or the testing of hypotheses on the functioning and evolution of socio-ecosystems along gradients that may be climatic, anthropogenic or based on the history of researcher-actor relations. The RZA, which became an RI in 2018, contributes with the OZCAR RI to the European ESFRI roadmap via the French node of eLTER.

Relations with economic actors and/or socio-economic impact

The main service offered by the RZA RI is the co-construction of knowledge between researchers and socio-economic actors to accompany territories in their transformation towards greater sustainability. The RZA researchers thus interact with numerous stakeholders such as associations, managers, agencies (water, biodiversity, etc.), specialists from the world of education or decision-makers.

Open science and data

- Part of the publications from projects using the infrastructure are open access
- Annual data production: 1 To
- The validated and described data are published on a data repository www.indores.fr

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Paris

Other sites in France: Aubière, Auzeville-Tolosane, Besançon, Grenoble, Paris, Plouzané, Rennes, Saint-Pée-sur-Nivelle, Strasbourg, Tours, Vandœuvre-lès-Nancy, Villeurbanne, Villiers-en-Bois

French supporting institutions: CNRS

● **Director or RI representative in France:** O. Ragueneau

● **Construction:** 2018

● **Operation:** 2018

● **Stakeholders in France:** INRAE, CIRAD, IPEV

● **Website:** www.za-inee.org

International dimension

ESFRI project

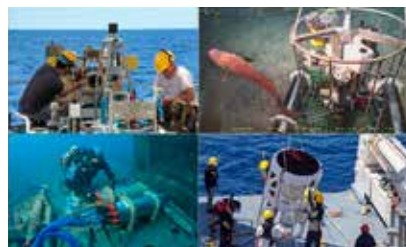
Director: M. Mirtl

- **Partner countries** AT, DE, CH, BE, BG, CZ, DK, GR, ES, FI, FR, HU, IL, IT, LV, NO, PL, PT, RO, RS, SE, SK, SI, GB
- **Website:** www.lter-europe.net/elter-esfri

EMSO-France

European Multidisciplinary Seafloor and water column Observatory – France

EMSO France is the French contribution to the European infrastructure (ERIC) EMSO ('European Multidisciplinary Seafloor and water column Observatory'), which implements multidisciplinary marine observatories distributed in the deep environment around Europe. The objective of the ERIC EMSO is to acquire long and high frequency time series on given locations, both on the ocean floor and in the water column, with the following main scientific objectives: 1) the study of seismic, volcanic, hydrothermal and gravity processes; 2) the study of deep marine ecosystems with a view to fundamental research but also to sustainable management, with regard to anthropic and climatic factors; 3) the contribution to the monitoring of global changes. At each site, the facilities consist in equipment for acquiring observation data in the deep sea, in systems



that ensure two-way communication between the facilities at sea and on land, in platforms on which the acquired data are freely accessible. The EMSO France sites are located in the Azores (since 2010), in the Ligurian Sea (since 1988) and in the Iroise Sea (test site). A project is under study in the Marmara Sea.

Relations with economic actors and/or socio-economic impact

Development of systems and services for monitoring the impact of the ocean resource exploitation, oil & gas, mining or EMR. Establishment of partnership with the industry for the benefit of innovation within the framework of the Brittany Sea Cluster, the Mediterranean Sea Clusters and the Carnot network with the certification of the iC MERS. Offer of access to the sites for the deployment of systems. Contribution to UNEP/GEO, IPCC, OSPAR, DCSSM through the acquisition of essential ocean and climate variables.

Open science and data

- All the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure are open on a software forge <https://gitlab.ifremer.fr>
- Annual data production: 1 TB
- Infrastructure with a FAIR data policy in application
- The validated and described data are published on a data repository www.seanoe.org/data/00311/42182

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Plouzané, Villefranche-sur-Mer

French supporting institutions: CNRS, Ifremer

- **Director or RI representative in France:** L. Coppola, N. Lantéri
- **Construction:** 2014
- **Operation:** 2014
- **Website:** www.emso-fr.org/EMSO-France

International dimension

EMSO ERIC, ESFRI landmark

Director: J. J. Dañobeitia

- **Partner countries** IT, FR, ES, GR, UK, IE, PT, RO, NO
- **Website:** <http://emso.eu>

IAGOS-France

In-service Aircraft for Global Observing System

IAGOS is a European research infrastructure, the only one of its kind in the world, which aims to establish and operate a global network for long-term observation of the composition of the atmosphere: reactive trace gases (ozone, CO, NO_x), greenhouse gases (H₂O, CO₂, methane), aerosols and cloud particles (water droplets and ice crystals) thanks to automatic instruments embarked on a fleet of some 15 airliners (of the Airbus type) belonging to international airline companies. The aim is to build the densest in-situ database with high spatial and temporal resolution over several decades to monitor the evolution of the atmospheric composition involved in climate change and air quality. IAGOS has demonstrated that the commercial aircraft vector is the ideal platform for long-term in-situ measurements in the most critical area of the atmosphere with respect to the greenhouse effect (the upper troposphere-lower stratosphere). The measurements also provide vertical profiles throughout the troposphere between the surface and 12 km altitude of major interest for



air quality issues. At the end of 2021, the database contains more than 63 000 flights covering more than 25 years. These observations are used by the scientific community, weather and air quality forecasting centres, the Copernicus Atmosphere Monitoring Service (CAMS), and more widely by GEOSS.

Relations with economic actors and/or socio-economic impact

In France, part of the IAGOS activities are carried out by aeronautical subcontractors in the Occitania and Aquitaine regions: industrialisation of instrument production by the company LGM, airworthiness certificates by the company Sabena-Technics. In Germany, two aeronautical subcontractors are also involved: enviscope, GmbH and Gomolzig (GFM) for maintenance, logistics and certification of the instruments.

Open science and data

- The source codes produced by the infrastructure are open on a software forge <https://github.com/sedoo/soft-io>
- Annual data production: 150 GB
- Infrastructure with a FAIR data policy in application
- The validated and described data are published on a data repository www.aeris-data.fr/catalogue

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Toulouse

French supporting institutions: CNRS, Météo-France, Université Toulouse III - Paul Sabatier

- **Director or RI representative in France:** V. Thouret
- **Construction:** 2008
- **Operation:** 2008
- **Stakeholders in France:** AERIS
- **Website:** www.iagos-data.fr

International dimension

IAGOS, ESFRI landmark

Director: V. Thouret

- **Partner countries FR, DE, GB**
- **Website:** www.iagos.org

ILICO

Marine Coastal and Nearshore Research Infrastructure

The Marine Coastal and Nearshore Research Infrastructure (ILICO) is the French research infrastructure dedicated to observing and understanding the long-term evolution of marine coastal and nearshore (littoral zone) environments, in France and overseas. Due to its focus on natural environments located at the interface between the continent and the deep ocean, ILICO occupies a strategic position in the observation and research landscape. The Research Infrastructure federates 8 "National Observation Services" (known as "SNO"s) which are permanently accredited inter-agency in-site observation networks. ILICO's mission is also to ensure that the observation data from coastal environments it produces meet societal challenges and scientific issues. It is the guarantor of the interoperability and quality of the observations made by the various observations systems.

ILICO manages a scientific network that ensures cross-disciplinary scientific reflection and forecasting,



and promotes inter-disciplinarity via cross-disciplinary structuring actions. This inter-agency network consists of more than 60 laboratories carrying out research on coastal and nearshore environments throughout metropolitan France and overseas. The RI ILICO is also the French node of the projected European Research Infrastructure JERICO-RI (Joint European Research Infrastructure for Coastal Observatories).

Relations with economic actors and/or socio-economic impact

- Links with government departments responsible for environmental management in metropolitan and overseas France (health of coastal ecosystems, water quality, coastal risks, impacts of global changes);
- Exploratory developments with SMEs and industries (technological development, processing and pooling of resources);
- Developing closer ties with the private sector and/or society around new products/services and facilitation of acquisition methods.

Open science and data

- Annual data production: 5 TB
- Infrastructure with a FAIR data policy in application
- The validated and described data are published on a data repository www.odatis-ocean.fr/donnees-et-services/acces-aux-donnees

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Plouzané

French supporting institutions: CNRS, Ifremer

Director or RI representative in France:

J. Paillet, C. Delacourt

Construction: 2016

Operation: 2016

Stakeholders in France: IRD, SHOM, IGN, Université de Bretagne Occidentale, Sorbonne Université, Aix-Marseille Université, Université Bretagne Sud, Université de Caen Normandie, Université de Lille, Université du Littoral Côte d'Opale, Université de Nantes, La Rochelle Université, Université de Bordeaux, Université Toulouse III - Paul Sabatier, Université de Perpignan Via Domitia, Université de Montpellier, Université Côte d'Azur, Université de Toulon, Université Le Havre Normandie, MNHN, Météo-France, BRGM, CEREMA, OFB

Website: www.ir-ilico.fr

International dimension

JERICO-RI

• **Website:** www.jerico-ri.eu

IN AIR

National Infrastructure of Aircraft Instrumented for Research

IN AIR operates a wide range of instrumented aircraft for a variety of Earth and space observations, as well as validation of technological innovations in aeronautics and space. The aircraft made available to the scientific communities are:

- Laboratory aircraft (ATR 42, Piper Aztec) capable of carrying up to 2 tonnes of scientific cargo;
- Open stratospheric balloons, which are the only way to send several hundred kg of scientific cargo into the stratosphere
- Pressurised balloons, which can be used to carry out measurements lasting several months at the tropopause
- Probe balloons (meteorological balloons), used to probe the troposphere and stratosphere with limited loads
- Tethered balloons used to study the atmospheric boundary layer.

IN AIR provides scientists with its expertise to deploy various equipment from users or from the RI's



© DR SAFIRE

instrumental park. IN AIR's experts prepare and carry out measurement flights, anywhere in the world, according to users' needs. IN AIR's activities are focused on atmospheric physics and chemistry, continental and oceanic surface and interface studies, astrophysics, space weather, medicine, and aerospace research and technology. The flight data are valorised on a centralised database developed in conjunction with AERIS (RI DATA TERRA), the RI's data and services centre.

Relations with economic actors and/or socio-economic impact

As part of its objectives of excellence, IN AIR has numerous and diversified relationships with economic players:

- Balloon envelope R&D;
- Synergy with the promising commercial field of pseudo-satellites;
- Provider of test flights for aeronautics and space industrialists;
- Provider of test flights for SMEs developing measuring instruments;
- Technical expertise for start-ups.

Open science and data

Category: RI

Type of infrastructure: distributed

French supporting institutions: CNRS, CNES, Météo-France

Director or RI representative in France: A. Bourdon

Construction: 2021

Operation: 2021

In-Sylva France

In-Sylva France National research infrastructure for adaptive forest management

In-Sylva France is a distributed National Research Infrastructure (RI) for adaptive forest management. It contributes to an integrated vision of forest management to enable adaptation to climate change, protection of biodiversity and sustainable production of ecosystem services, taking into account the diversity of forest ecosystems and local situations (pedoclimatic, organisation of sectors, local governance). In-Sylva France provides services for forest observation and experimentation to all users (academics and managers) involved in the National Forest and Wood Programme (PNFB). The infrastructure has the experimental networks required for large-scale phenotyping (in-situ services), i.e. over 4,000 ha, i.e. 3,000 sites installed to study the interactions between practices, genetic resources and the environment. It integrates analytical platforms in functional ecology, biogeochemistry, xyloscience and genetics, dedicated



© Laurent Saint-André (INRAE)

to high-throughput sample measurements (In-lab Services) as well as information and analysis systems for data valorisation (In-silico Services). In-Sylva France supports fundamental and applied research in the field of forestry. Its originality lies in its ability to combine forestry, biogeochemical and genetic levers. <https://doi.org/10.15454/1A0P-HE21>

Relations with economic actors and/or socio-economic impact

In-Sylva France is built to serve the forest and wood industries in adapting forests to global changes and their capacity to provide multiple services. Three of its supervisory bodies are linked to the sector: ONF (public forest management); IDF (R&D service for private owners) and FCBA (CTI for the wood processing industries). In-Sylva France has relationships with three competitiveness clusters, including Xylofutur.

Open science and data

- The source codes produced by the infrastructure are open on a software forge <https://forgemia.inra.fr/in-sylva-development>
- Annual data production: 500 GB
- The validated and described data are published on a data repository <https://datadryad.org/stash>

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Champenoux

Other sites in France: Ajaccio, Amiens, Ardon, Aubière, Auzeville-Tolosane, Avignon, Birieux, Boigny-sur-Bionne, Bordeaux, Castanet-Tolosan, Cestas, Chambéry, Champs-sur-Marne, Charrey-sur-Saône, Compiègne, Dijon, Dole, Fontainebleau, Gières, Kourou, Le Ban-Saint-Martin, Lempdes, Marseille 4^e, Mont-Saint-Aignan, Montpellier, Orléans, Paris, Saint-Herblain, Saint-Martin-d'Hères, Saint-Étienne-du-Rouvray, Verneuil-sur-Vienne, Villers-lès-Nancy, Vincennes

French supporting institutions: INRAE

Director or RI representative in France: L. Saint-André

Construction: 2018

Operation: 2018

Stakeholders in France: Université de Rouen Normandie, CIRAD, ONF, Institut technologique Forêt Cellulose Bois Construction Ameublement (FCBA), Centre National de la Propriété Forestière (CNPF)

Website: www6.inrae.fr/in-sylva-france

PNDB

National Biodiversity Data Centre

The PNDB is a national digital infrastructure of the Earth system and Environment, contributing to the open science policy of the Ministry of Higher Education and Research. Since 2020, it has been providing a coherent set of tools and services for the description, provision, validation, analysis and reuse of biodiversity data, particularly for fundamental or targeted research. It aims to contribute to building an integrative scientific framework that takes into account biodiversity over the long term (since the origins of life), at all biological scales (from the molecule to the anthroposystem), and in all its interactions (climate, human activities).

The PNDB aims to provide access to data produced by other infrastructures, by institutions or by scientific communities, and to tools for describing them (metadata) and processing them (data crossing). It thus contributes to promoting the sustainability, interoperability, openness and reuse of biodiversity data, and to increasing the skills of the scientific



© Sandrine Pavoine, MNHN - Jean-Denis Vigne, MNHN

communities concerned. It provides assistance with data banking. It contributes to the animation of communities around open science and stimulates interactions between data producers and users.

The PNDB is part of the landscape of national (SIB, SINP, GBIF France, etc.), European (Lifewatch) and international (GBIF, GEO BON, etc.) biodiversity data infrastructures.

Relations with economic actors and/or socio-economic impact

The PNDB makes use of the data produced by participatory science, in particular those of Vigie-Nature and Vigie-Nature-École. The PNDB provides workflows for calculating biodiversity metrics and indicators, particularly in the context of its involvement in GEO BON. The PNDB makes its services available to consultancy firms, particularly data processing tools such as Galaxy-E.

Open science and data

- Part of the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure are open on a software forge <https://github.com/earnaud/MetaShARK-v2>
- Annual data production: 10 GB
- Infrastructure with a FAIR data policy in application

Category: RI

Type of infrastructure: single site

Infrastructure location in France: Paris

French supporting institutions: MNHN

• **Director or RI representative in France:** J.-D. Vigne

• **Construction:** 2018

• **Operation:** 2020

• **Stakeholders in France:** CNRS, Ifremer, OFB, INRAE, IRD, CIRAD, BRGM, INERIS, Dix universités sont également signataires de la convention inter-établissements (accord de consortium)

• **Website:** www.pndb.fr

RARe

Agronomic Resources for Research

RARe is the reference infrastructure for securing, documenting and distributing the Earth system's biosphere resources. It brings together five networks of Biological Resource Centres (BRCs) managing animal, plant, forest, microbial and complex environmental matrices and associated data (biological, genetic, regulatory and legal). It has a single entry portal to explore these resources. The maintenance of a wide range of resources places BRCs at the heart of many research programmes aimed at exploring life and ecosystems and enhancing biodiversity for agriculture, food, environment and health. The infrastructure aims to improve the visibility of these resources and facilitate their use for research at national and international level. It is a member of the GGBN. The microbial pillar of RARe participates in the MIRRI infrastructure of the ESFRI roadmap. These missions are accompanied by cross-sectoral scientific animation



© photothèque INRAE

and technological developments to preserve and characterise biological resources. The infrastructure pools the skills of its constituent BRCs and harmonises their practices. The development of resources is carried out in accordance with the partnership policies of the supervisory bodies. It offers tools to facilitate the application of the Nagoya protocol.

Relations with economic actors and/or socio-economic impact

The RARe partnership concerns plant, forest and animal production, the agri-food industry, non-food biomass recovery, biotechnology and biocontrol. Some partners come from the health and cryobiology sectors. Companies, producers' associations or technical institutes use the services of the BRCs and build projects in partnership with them.

Open science and data

- The source codes produced by the infrastructure are open on a software forge <https://forgemia.inra.fr>
- Annual data production: 1 TB
- Infrastructure with a FAIR data policy in application
- The validated and described data are published on a data repository <https://eurisco.ipk-gatersleben.de>

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Jouy-en-Josas

Other sites in France: Ardon, Auzeville-Tolosane, Avignon, Beaucauzé, Biot, Bourran, Cestas, Clermont-Ferrand, Dijon, Gouffern en Auge, Jouy-en-Josas, Lusignan, Maisons-Alfort, Marcy-l'Étoile, Marseille, Mignaloux-Beauvoir, Montpellier, Nouzilly, Papeete, Paris, Petit-Bourg, Rennes, Saint-Pierre, Saint-Pierre-d'Amilly, Sinnamary, Sète, Thiverval-Grignon, Versailles

French supporting institutions: INRAE, CIRAD, IRD

• **Director or RI representative in France:**

• M. Tixier-Boichard

• **Construction:** 2015

• **Operation:** 2015

• **Stakeholders in France:** CNRS, AMU, Université de Tours, Université d'Angers, Vetagro-Sup, Institut Agro, AgroParisTech, Anses, Ifremer, Inserm, ENVA, ENVT, ONIRIS

• **Website:** <http://agrobrc-rare.org>

International dimension

MIRRI, ESFRI project

Director: L. Soarez

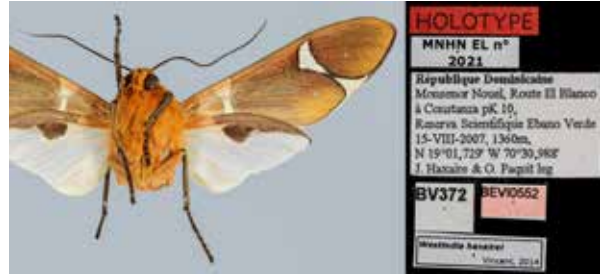
• **Partner countries** BE, ES, FR, GR, IT, LV, NL, PL, PT

• **Website:** www.mirri.org

RECOLNAT

French national network of naturalist collections

The naturalist collections conserved in France incorporate approximately 120 million objects. These archives of biodiversity and geodiversity represent today an irreplaceable heritage and are undeniable assets for present and future scientific research. The general mission of the RECOLNAT infrastructure is to produce, mobilise, collect, harmonise and provide access to naturalist collections and their data. The ambition is to be able to offer scientific communities quality naturalist data, at the right scale, interoperable and in the right format, allowing them to respond to major environmental and societal issues. RECOLNAT also aims to create a network of scientific excellence by bringing together those involved in the conservation and study of naturalist collections. It provides access to data via a portal containing nearly 11 million images from more than 80 institutions (museums, universities, etc.). The participatory science programme "Les Herbonautes", whose community builds



© Marion Depaertere/MNHN/RECOLNAT

up datasets for selected research works, also enriches this corpus. The infrastructure also provides tools for researchers working on digital duplicates of the collections. Led by the Muséum national d'histoire naturelle, RECOLNAT is also the French node of the European infrastructure DiSSCo (Distributed System of Scientific Collections).

Relations with economic actors and/or socio-economic impact

The RECOLNAT infrastructure provides research support to the naturalist community, with a high proportion of systematists and collection specialists. It also feeds societal demand related to expertise, species identification and environmental change. It contributes to enriching the corpus of open data on biodiversity and geodiversity at the international level.

Open science and data

- Part of the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure are open on a software forge <https://github.com/DiSSCo/herbonautes>
- Annual data production: 50 TB
- The validated and described data are published on a data repository <https://inpn.mnhn.fr/espece/cadre/101>

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Paris

French supporting institutions: MNHN

Director or RI representative in France: F. Dusoulier

• **Construction:** 2013

• **Operation:** 2014

• **Stakeholders in France:** UCA, Université Claude Bernard - Lyon 1, Université de Rennes 1, Muséum d'histoire naturelle de Dijon, UB, AMU, Université de Montpellier, CIRAD, Muséum d'histoire naturelle de La Rochelle, Muséum Aquarium de Nancy, Muséum d'histoire naturelle de Marseille, Université de Lorraine, UGA, IRD, Muséum d'histoire naturelle de Lille, Muséum d'histoire naturelle de Toulouse, Sorbonne Université, Muséum d'histoire naturelle de Nantes, Musées de Gaillac, Muséum d'histoire naturelle de Troyes, Université Toulouse III - Paul Sabatier, Office de l'environnement de la Corse, Muséum d'histoire naturelle de Nice, Société botanique d'Alsace, Muséum d'histoire naturelle de Besançon

• **Website:** www.recolnat.org

International dimension

DiSSCo, ESFRI project

Director: D. Koureas

- **Partner countries** FR, DE, AT, BE, BG, DK, ES, EE, FI, GR, HU, IT, LU, NO, NL, PL, PT, CZ, UK, SK, SE
- **Website:** www.dissco.eu/fr-fr/

RéGEF

French Geochemical and Experimental Network

RéGEF is an interdisciplinary research infrastructure built around a network of measurement, imaging and experimental instruments, which implements means to provide data to research programmes, National Observation Services, and other Research Infrastructures.

The importance of geochemical/mineralogical data in our understanding and conceptualisation of the Earth system is considerable. The analytical and experimental means that produce these data represent a major part of the quantification of processes in Geosciences and Environmental Sciences. In this context, the RI RéGEF has two main objectives: (i) to maintain innovation and technological development at the highest level, while (ii) organising access to instruments and data production for the scientific community. The infrastructure is at the heart of the transfer between (i) the development phases and the innovation of tracers and methodologies to reveal new processes, (ii) their use by the community



© R. Pik

to document geological and environmental systems, and (iii) their archiving in an effort to perpetuate and optimise scientific information.

RéGEF is an initiative led by the CNRS-INSU in partnership with the EPST, EPIC and Universities of the UMRs that host the instruments, to ensure and optimise networking and accessibility throughout the national territory.

Relations with economic actors and/or socio-economic impact

RéGEF produces data that are essential to the description and understanding of the Earth system, and that are used by other infrastructures directly concerned with social and economic issues (environment, risk, climate, health, etc.). Its links with the industrialists who develop and market the instruments are also very strong. Part of its activity is carried out in partnership with the R&D departments of major industrial firms.

Open science and data

- Annual data production: 10 TB

Category: Projet

Type of infrastructure: distributed

Infrastructure location in France: Paris

French supporting institutions: CNRS

• **Director or RI representative in France:** R. Pik

• **Construction:** 2017

• **Operation:** 2019

• **Stakeholders in France:** CEA, IRD, IPGP, MNHN, IFREMER, BRGM, France Université et 25 universités

• **Website:** www.regef.fr

Résif-Epos

French seismological and geodetic network/European Plate Observing System

Résif-Epos deploys modern instrumentation in France to understand Earth's internal dynamics, its natural and anthropogenic hazards, and the interaction with the fluid envelopes. The 4.9 Mw earthquake in Montélimar on 11/11/2019 confirmed, through its socio-economic impact, the importance of prevention and management of vulnerability with respect to seismic risk in France. Résif-Epos provides data from instruments (seismometers, GNSS stations and gravimeters) that measure the deformation of the Earth's surface from secular tectonic movements to instantaneous seismic tremors. It thus plays a key role in better understanding the telluric hazards on our territory. More broadly, its array of instruments covering the whole of Metropolitan France opens a new window onto the Earth's interior, in order to better understand its functioning and dynamics. By bringing together expertise in innovative methods of seismic imaging and geodesy, Résif-Epos also provides key data



for a better understanding of the subsoil, to enable its optimised and moderate management. All data from Résif-Epos instruments and derived products are distributed freely and without charge. Résif-Epos is a major French contribution to EPOS (which became ERIC in 2018), coordinating EPOS activities in France and integrating French data and products into the EPOS operating system.

Relations with economic actors and/or socio-economic impact

Résif-Epos improves knowledge of seismicity and the characteristics of seismic wave propagation on French territory and thus contributes to prevention and operations: hazard and risk assessment, rapid damage assessment and crisis management, construction standards, link between building damage and seismicity, reinsurance elements, seismicity induced by human activity, etc.

Open science and data

- The source codes produced by the infrastructure are open on a software forge <https://gricad-gitlab.univ-grenoble-alpes.fr/OSUG/RESIF/>
- Annual data production: 30 TB
- Infrastructure with a FAIR data policy in application
- The validated and described data are published on a data repository <https://seismology.resif.fr/fr/page-daccueil-2/>

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Paris

Other sites in France: Arpajon, Aubière, Besançon, Fontenay-aux-Roses, Gières, Le Mans, Montpellier, Nantes, Paris 5^e, Pessac, Rennes, Saint-Mandé, Saint-Martin-d'Hères, Strasbourg, Toulouse

French supporting institutions: CNRS

Director or RI representative in France: A. Walpersdorf

Construction: 2011

Operation: 2011

Stakeholders in France: BRGM, CEA, CNES, CNRS, IFREMER, Université Gustave Eiffel, IGN, IPG Paris, IRD, IRSN, Observatoire de la Côte d'Azur, Université Clermont Auvergne, Université Grenoble Alpes, Université de Montpellier, Université de Nantes, Université Côte d'Azur, Université Toulouse III - Paul Sabatier Toulouse, Université de Strasbourg

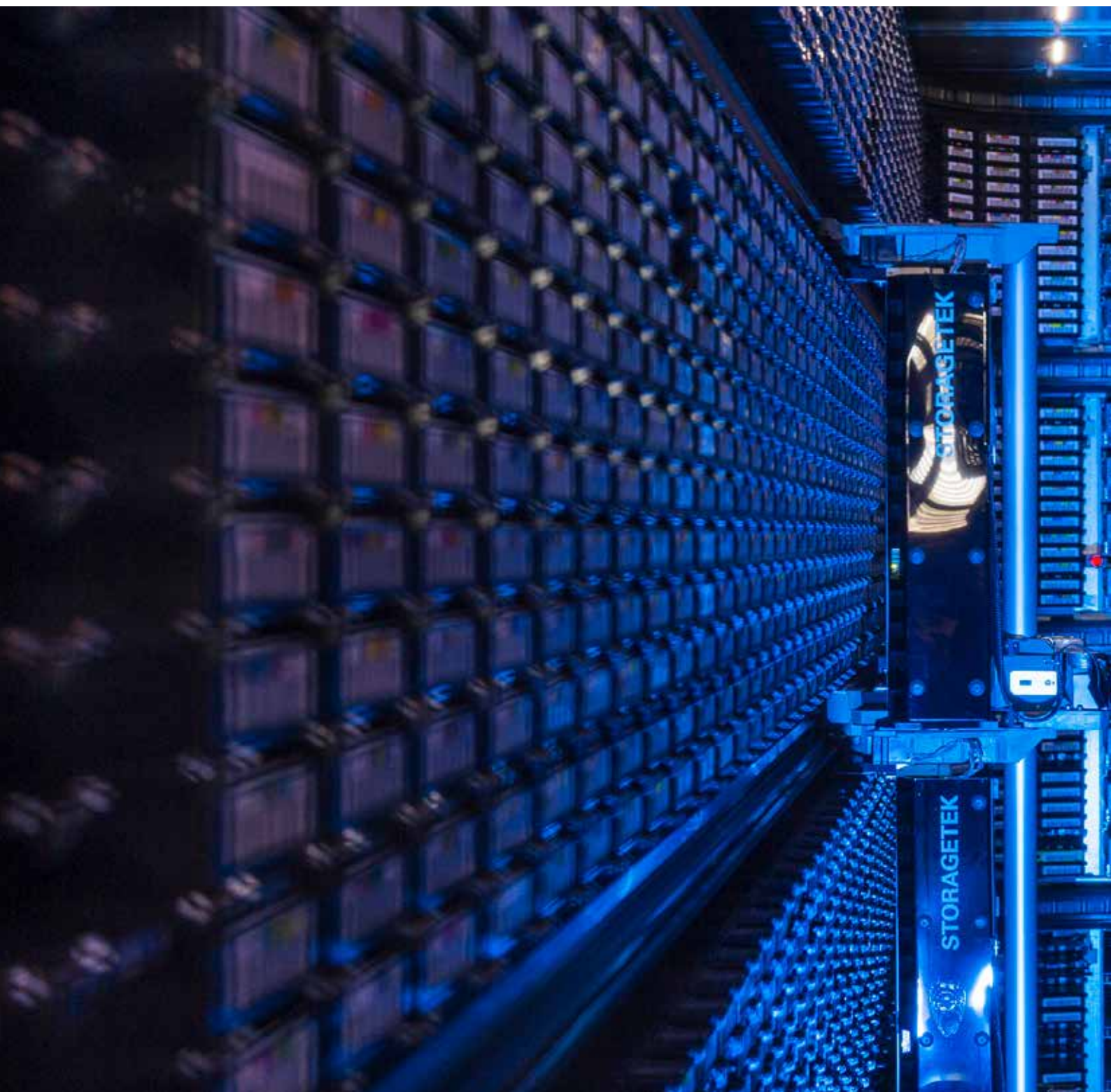
Website: www.resif.fr

International dimension

EPOS, ESFRI landmark

Director: L. Freda

- **Partner countries** BE, DK, FR, GR, IS, IT, NO, NL, PL, PT, RO, GB, SI
- **Website:** www.epos-eu.org






9.

Digital infrastructures
and **services**

Digital infrastructures and **services**



The digital revolution is also taking place within research infrastructures, with an explosion in the volumes of data they handle, but also with the networking of people and content that they involve. The digital revolution is accompanying all scientific fields thanks to the creation of large digitised databases: digitalized archaeological collections, digital herbaria, digitalized libraries, etc. This is also true for the widespread collection of images and data of the health and space sectors, for the management of cities and agricultural resources, and for a wide amount of research in the human and social sciences. This rapid transformation is also reflected in the development in the use of digital twins and in the broad use of artificial intelligence in most sectors. This requires the evolution of the digital infrastructures so as to support these new uses. This is why new storage architectures, computing and data processing resources and the high-speed networks needed for their exchange are strongly and constantly evolving .

At each stage of research projects, there is a digital component that must be maintained at the highest level: data production and acquisition, processing (including calculation), storage, exchange and sharing, dissemination and reuse, preservation and archiving. The proper use of data, in the broadest sense, and the range of digital services that must be developed around it, all depend on the good level of performance, accessibility and robustness of the digital infrastructures that must be supported in view of the competitive stakes for the national scientific offer. Preparing for the reuse and interdisciplinary exchange of these large masses of data requires an anticipated management that is now promoted in the context of open science carried out worldwide by the states and major research institutions facilitate their management and access methods. These are the FAIR principles, which ensure that data is Findable, that it is Accessible, Interoperable and Reusable.

At the heart of the digital infrastructure are the digital services and the generic e-infrastructures for networking, high performance computing and data processing. All the research infrastructures in the “digital services” strand are core infrastructures that offer a service to a wide range of research communities. They allow for the pooling of digital services at the national level, and in most cases are used by several scientific communities.

At the same time, research infrastructures are mostly organised around communities, and sometimes they have organised their digital infrastructures dedicated to their activity. They thus combine access to targeted resources and the development of dedicated services based on the data they manage. The chapter on “the place of data in the roadmap’s infrastructures” describes this diversity of approaches and maturity. Community digital infrastructures deserve particular attention, as they are

very good at scaling the digital resources involved, and are a good example of pooling and rationalisation on a community scale.

The “scientific information” component is a very good example of the digital services that need to be developed and maintained within the strategy of opening up research objects, by integrating a broad spectrum of objects beyond just data.

The need for a global vision of all these systems, ranging from the use of generic digital infrastructures to the interconnection of community digital infrastructures, and taking into account the development of digital services for the publication and conservation of results, leads to the definition of elements for a digital strategy at national level.

This national strategy must necessarily take into account the initiatives in the field at European level. Digital technology is a strategic priority of the Horizon Europe programme, which has just started. With the EOSC (European Open Science Cloud) project, Europe is laying the foundations for a very broad “cloudification”, from infrastructures to services and, of course, for a by-default open science. On the French side, we must organise our participation to this European structuring project, and we must define what an ESRI (higher education, research and innovation) cloud should be, in which research infrastructures will find their place and will benefit to a maximum number of researchers.

The widespread implementation of the FAIR principles, together with powerful, shared e-infrastructures and services, will enable competitive research and enhance the efficiency of research infrastructures.

Digital services, computing, networking



The challenges of digital transformation for research aim in particular at creating a state-of-the-art and eco-responsible digital environment that meets the quality requirements and needs of the various stakeholders, and that reduces the complexity of the digital environment offered to researchers. To achieve this, it is necessary to :

- Host the services, applications, equipment and data managed by the research, in a way that takes into account the requirements associated with all stages of the data life cycle;
- Pooling skills: creating a coherent environment at national level and building on regional skills;
- Give ESRI a visible and legible IT architecture, supporting its participation in major European digital projects and to deploy their French components.

The architecture of digital resources, their interconnection, their efficiency, their robustness and their control are becoming

critical issues that are part of the criteria and requirements for the evaluation of research projects. Moreover, digital technology is constantly evolving and requires everyone to maintain the state of the art of all the layers of digital infrastructure on which research is based and which are schematically represented in Figure 1.

The increase in digital needs at national level must be the subject of particular attention. And it must lead to a coherent and proactive strategy. The dimensioning of digital infrastructures (network, computing and processing capacities, storage and archiving, application services) must enable them to support all the processes implemented throughout the life cycle of data : from their production to their conservation, as well as their dissemination and re-use.

Five infrastructures are included in the 2021 national roadmap. Several, or even all, research communities most often use them. This is the case for **RENATER** and **GENCI**,

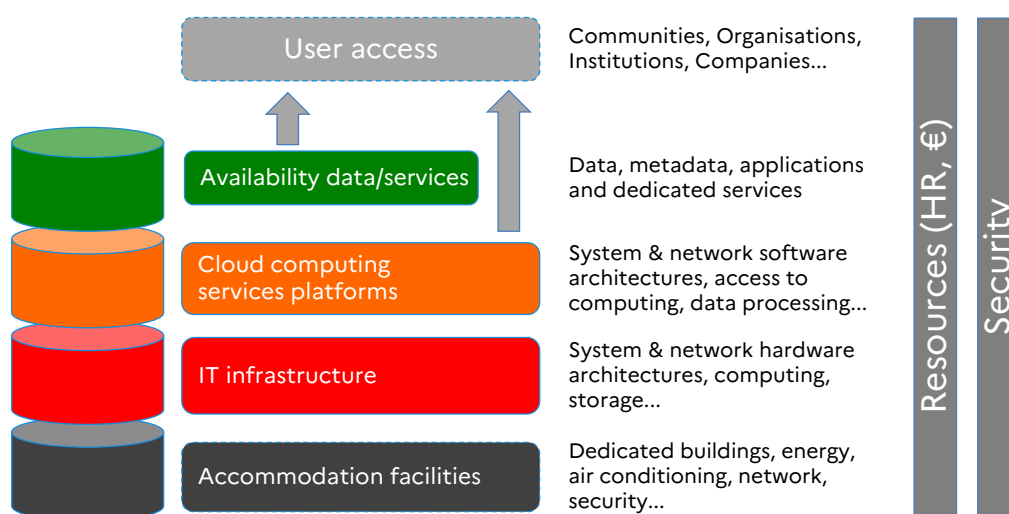


Figure 1: Schematic representation of the different service layers of digital infrastructures or E. Infrastructures

which are both French components of a European infrastructure, respectively GEANT and PRACE (ESFRI Landmarks). The **CC-IN2P3**, **France Grilles** and the **CINES** are also part of this category of e-Infrastructures. The latter will all participate in the digital transformation that directly affects them, and that leads their positioning to evolve, and in some cases leading to an evolution in their missions. The importance of digital in the national landscape with major projects and initiatives at national, European and even international levels, justifies their inclusion on the roadmap as RI.

POSITIONING OF THE FIVE E-INFRASTRUCTURES

The **RENATER** infrastructure provides a digital communication offer, secured at high speed, to all the institutions and communities of Higher Education and Research, as well as

interconnection to European and worldwide networks. It also provides digital services, the basis of sovereign communication tools and secure information exchanges.

The **GENCI** infrastructure provides high-performance computing thanks to the participation of three major national computing centres of the CNRS, CEA and Higher Education: the IDRIS, the TGCC and the CINES. For the past five years, its offer has been extended to include the storage of computational data, and **GENCI** is thus fully involved in the world of massive data. **GENCI** ensures the renewal of the TGCC's computing resources, which are open to the European PRACE collaboration. The latter not only extend the French commitment to this project, but also it prepares the French involvement in the EuroHPC structure.

The **CC-IN2P3**, the **CINES** (outside of its computing mission within GENCI) and France

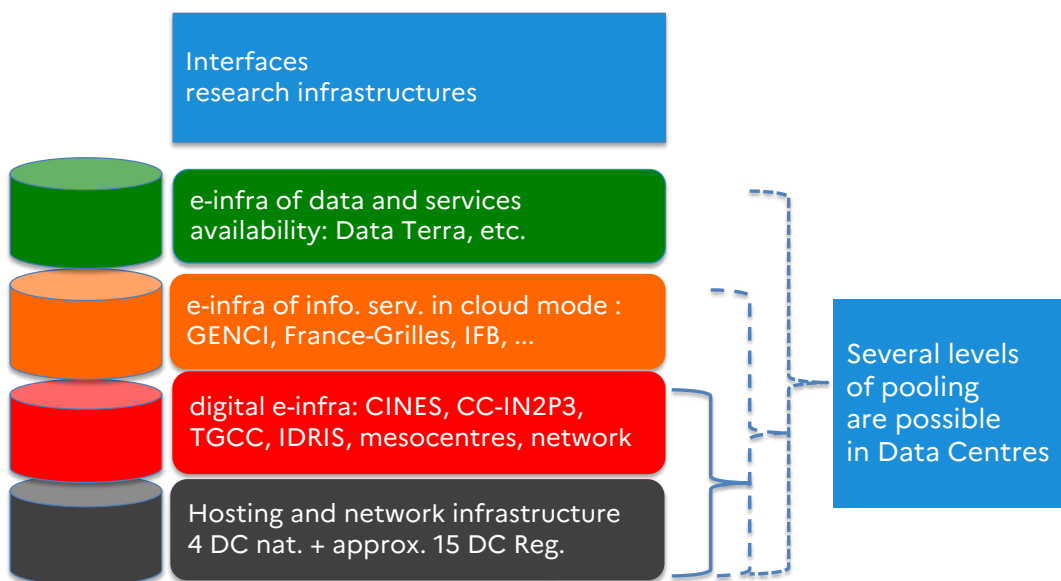


Figure 2: Pooling of the digital resources of research infrastructures



Grilles, at various degrees of mutualisation, provide hosting and distributed digital services and allow the processing and sharing of large volumes of data. The digital services support the management of data throughout its life cycle, from creation to conservation. The CC-IN2P3 is specialized in the storage and processing of massive data from the LHC. But it is also opening up to other large instruments, such as the LSST telescope. France Grilles develops and offers grid and cloud services to hundreds of users from different communities (including users in the long tail of science). France Grilles is the French node of the European Grid Infrastructure (EGI). These players have a key role for France in the European digital landscape, and form the core of the data services infrastructure.

All these infrastructures are part of the EOSC (European Open Science Cloud) partnership.

RENATER – NATIONAL TELECOMMUNICATIONS NETWORK FOR TECHNOLOGY, EDUCATION AND RESEARCH (RI*)

The RENATER is a so-called Public Interest Group (GIP) that provides national and international connectivity to more than 1,400 teaching and research sites in metropolitan France and in the French overseas territories. RENATER is the National Node of the European Research Network (French NREN) and as such is connected to the pan-European GÉANT network. ESRI relies on RENATER to deploy a set of shared network services and infrastructures at the national level. RENATER must provide a reliable, efficient and stable network for the whole ESRI community.

RENATER's activity is spread over several axes:

- A network axis ranging from the evolution of the network architecture and its maintenance in operational conditions, to the interconnection with international networks within the framework of

GEANT and the coordination of regional and metropolitan networks;

- A dedicated network services axis for research infrastructures (LHC, REFIMEVE, SILECS); and specific uses (VPN-establishment, RIE, ITER);
- A shared digital services axis composed of collaborative and secure communication services;
- A security axis: security monitoring, management of security certificates and domain names;
- A service development and integration axis; RENATER contributes significantly to the development of free software.

Future challenges and prospects

RENATER has an essential and strategic role for the ESRI sphere and beyond.

RENATER plays a driving role in the development of core services, such as the identity federation which allows to use secure identification services in France and in Europe, and ensures the mobile connection service "eduroam", as well as other communication, information sharing and collaborative work tools.

It is essential to preserve RENATER's activity on its core business (network, security, communication services) while progressively consolidating its missions in coherence with its competences and its positioning in the French and European ESRI digital landscape (GEANT/EOSC/EuroHPC). It is important to ensure the sustainability and efficiency of the existing organization, while keeping staff growth under control at the right level, and to ensure that the ambitions and priorities are shared among the GIP's members.

GENCI – NATIONAL HIGH-PERFORMANCE COMPUTING EQUIPMENT (RI*)

GENCI acts as the national project manager for high performance computing and computational data storage for research (academic & industrial). As such, GENCI is responsible for the allocation of computing hours based on scientific excellence.

The current aggregate computing power of the three national Tier1 supercomputers (IDRIS, TGCC and CINES) is 50 Pflop/s. In 2020, GENCI resources made it possible to distribute more than 2 billion computing hours to 1,000 open research projects, including 400 in AI. It should be noted that 9% of these projects had industrial support.

At the European level, GENCI is the French representative of PRACE, which includes 26 member countries and concerns seven Tier-0 level computers. It participates in the structuring and implementation of the computing pyramid at national and European level. GENCI also participates in the EuroHPC initiative, in particular on the Governing Board, of which it is the Technical Advisor for France.

GENCI participates in the coordination of regional and university mesocentres that deploy Tier-2 level computers. Thus, in the continuity of the EquipEx “Equip@meso” project of the PIA2 (2011-2020), GENCI coordinated the response to the AMI EquipEx+ of the MesoNET project. This project, which brings together 22 partners, aims at prefiguring a national infrastructure in conjunction with regional players. GENCI is associated with the FITS project submitted by the CNRS to the AMI EquipEx+ to develop a computing and data processing offer based on the complementary skills of the CC-IN2P3 and the IDRIS, linked by a high-speed network (100 Gb/s) and distributed storage between the two centres.

Future challenges and prospects

GENCI’s activity, governed by a strategic plan, is based on data computing and network needs, and the renewal of computing and storage equipment. This plan also aims to contribute to the economic competitiveness of French industry and to promote digital simulation.

Computing resources: HPC, HPDA and AI are major challenges for science, innovation and decision support. The resources deployed by GENCI are supported by national strategies in AI (extension of the Jean Zay AI partition at IDRIS), and in quantum technologies (hosting of the PNCQH National Quantum Computing Platform at the TGCC). The network is crucial for the computing centres: a study with RENATER for a 100 Gb/s loop between the three centres is ongoing, as is another study within the framework of EuroHPC for 400 Gb/s links for exascale.

EuroHPC context

International competition is strong in the field of exascale machines (Japan, China, USA). Faced with this competition, the European response has been organised with the EuroHPC Joint Undertaking, created in 2018. The members of the EuroHPC JU are the European Commission and 32 member states, with the addition of two private members: the associations ETP4HPC and BDVA. The budget for the 2nd phase (2021-2027) is € 3 billions. The main mission of the JU is to set up an excellent HPC/data infrastructure and to support the necessary R&I including training, dissemination and application support.

In its second phase, EuroHPC plans to acquire two exascale supercomputers, one of which will be assembled from European technologies, the latter having been funded earlier by the R&I programme in the previous years. It is in this context that GENCI plans to apply for acquiring and operating an



exascale supercomputer by 2023-2024. That only if the budgetary conditions are met to allowing GENCI to commit on behalf of the French State. In this context, GENCI would be the “Hosting Entity”, in partnership with the CEA/TGCC that could become the French “Hosting site”. This project is accompanied by a study presenting use cases motivating the “exascale” need and a socio-economic impact study.

CC-IN2P3 – IN2P3 COMPUTING CENTRE (RI)

The CC-IN2P3 is a CNRS Support and Research Unit whose core activity is to provide digital services for the needs of research infrastructures and experiments in the field of particle physics, nuclear physics and astro-particles.

At national level, CC-IN2P3 services are provided to about 100 groups of experiments via 4 000 user accounts, including:

- At the IN2P3 institute of the CNRS;
- At the IRFU (Direction de la Recherche Fondamentale du CEA), a laboratory involved in the PNHE field, on a service provision basis and via an agreement;
- About twenty groups from the bioinformatics, chemistry, SSH and ecology communities that use 3 to 4% of the computing and storage resources.

At the European and international level: the CC-IN2P3 is one of the 14 Tier-1s of the WLCG international collaboration network for LHC-related computing at CERN. The French commitment sets a target for the CC-IN2P3 to provide 10% of the world’s resources needed for LHC data processing. More than 70 international experiments involve IN2P3, including those linked to the PNHE infrastructures: CERN-LHC, CTA, DUNE, EGO-VIRGO, GANIL-SPIRAL2, HESS, JUNO, KM3NeT, LSST.

The digital services implemented by the CC-IN2P3 are:

- High-speed computing resources – small HPC farms and GPUs. The current available computing power is equivalent to 500 Tflop/s ;
- Data storage facilities on disks (43 PB) and magnetic tapes (> 100 PB);
- Dry hosting services: IRT BioAster and RI carried by CNRS (Huma-Num, HAL and CCSD) and project management services for connecting IN2P3 laboratories;
- Data management services: the CC-IN2P3 has put in place a Data Management Plan and is working on retention management (living data);
- The CC-IN2P3 offers long-term storage for about 10 PB. 10% of stored data require a perennial archiving which is done in conjunction with the CINES. It should be noted that the remote backup of the perennial archiving of CINES is hosted at the CC-IN2P3.

The CC-IN2P3 team works in a network with similar teams in the IN2P3 laboratories and in the PNHE domain internationally. It conducts research in computer science on the simulation of distributed applications (particularly in connection with the SILECS RI, data structuring for physicists, etc.).

Future challenges and prospects

The CC-IN2P3 has to deal with considerable masses of data to be managed and distributed through the global network. This requires access to additional computing power and an increase in network capacity, all within a controlled cost framework. Exponential growth in computing and storage needs, mainly due to the LHC’s power increase, is expected within 10 years, with storage volumes expressed in Exabytes. Network capacity requirements are expected to rise to 1 Tb/s.

The EquipEx+ FITS project, led by the CC-IN2P3 and in which GENCI is a

partner, will make it possible to set up storage and computing solutions, shared between the CC-IN2P3 and IDRIS, that can be used in a transparent manner. A first use case concerns SOLEIL, which is giving up its own digital infrastructure and will provide funding for this project. CC-IN2P3 and IDRIS are linked by a dedicated RENATER 100 Gb/s link.

FITS could be a component of EOSC-France. The CC-IN2P3 continues its involvement in European projects such as EOSC, with the CNRS which is a member of the AISBL in the framework of the Horizon Europe programme partnerships.

CINES – NATIONAL COMPUTER CENTRE FOR HIGHER EDUCATION – (RI)

The CINES offers services:

- High performance computing (3 billion hours requested over the 9 GENCI calls for 2.5 billion hours awarded since 2017);
- Perennial archiving of data and digital documents (the CINES has the CIAF approval);
- Dry hosting of IT platforms.

The CINES is specifically listed on the roadmap for its activities hosting, services and data storage. The CINES-Calculation activity is attached to the GENCI Infrastructure.

The archiving and preservation of data over time is the specific mission of CINES for ESRI. CINES develops skills and specific solutions (PAC platform ...) for this service of long-term preservation and provides a technology watch in this area. CINES archives all theses defended in France and data from the RI HAL and RI* Huma-Num. It offers an intermediate archiving service and a perennial archiving service. In 2021, the PAC platform switched to VITAM (back office operating in the form of micro-services).

The CINES also offers a dry hosting service, it is one of the four national data centres of ESRI.

The hosting concerns 15 organizations (CNRS, INRAE, INSERM ...), which host part of their digital resources at CINES, which represents a volume of 100 bays in the first quarter of 2021. The CINES also hosts digital resources of regional actors (DSI University of Montpellier, MUSE cluster (330 TF) of Meso@LR, or the HPC cluster of the Federation Balard (chemistry...).

Future challenges and prospects

The CINES has a mission of archiving that is its specificity at the national level. The volumes concerned today by the perennial archiving are relatively small. The perennial archiving of all research data may quickly generate considerable volumes, which requires conducting a sustainable archiving policy. The transition to the VITAM solution for archiving is coordinated with all the ministries concerned and is a major project.

The CINES strengthens its system so as to meet the requirements of security and accreditation, including hosting of health data. The France-Cohortes infrastructure of INSERM and data from the France Genomic Medicine 2025 Plan are hosted at CINES. The CAD (Data Collector Analyser), whose prefiguration is underway will be deployed through the CINES and the TGCC.

CINES is also a partner in the DATA-TERRA and Huma-Num data infrastructures and is a member of the AISBL EOSC and participates in the Horizon Europe project EOSC-Pillar. It is coordinator of the European PHIDIAS project (Prototype HPC / Data Infrastructure for On-Demand Services). The CINES archiving platform is on the EOSC marketplace.

The development of data services, for which the CINES demonstrated expertise and dynamism, has a strategic importance.



FRANCE GRILLES (RI)

The GIS France Grilles provides access to a national-wide distributed infrastructure, which is open to all research communities, and which represents France in EGI (European Grid Infrastructure).

Originally created around CERN's European partners to develop a worldwide distributed computing offering, the grid still represents the majority of the Infrastructure's activity. ISU partners can access a global resource of 1 million cores and 250 PB of storage. French users have harvested 1.3 billion hours of computation since 2014.

France Grilles has extended its activity to the construction of an academic cloud federation and provides access to distributed digital resources. Its cloud offer is dedicated to scientific computing. It is interconnected with the IFB cloud and the EGI cloud and based on open technologies and standards. France Grilles offers a complete catalogue of services for the analysis, processing and management of scientific data dedicated to scientific computing and online scientific portals.

The France Grilles cloud is spread over seven sites in France, all integrated into the EGI cloud. France is one of the four EGI providers. (37 million CPU hours were consumed in 2020). France Grilles is leading a community of experts. There is a predominance of the particle physics community, but it is also open to other communities. There are more than a thousand users of the Academic Cloud, more than 500 for the Grid and more than 1000 users through portals or virtual laboratories. France Grilles is involved in the European projects EOSC and France Life Imaging.

Future challenges and prospects

France Grilles is involved in the following EquipEx+ projects: FITS (federated digital

services for research infrastructures); TERRA FORMA (intelligent observation of territories); GAIA DATA (distributed data infrastructure for the Earth system, biodiversity and the environment) and MuDiS4LS (FAIR data in biology).

France Grilles has 10 years of experience in the cloud and the core skills needed to build EOSC-France. It also has operational tools, and it knows and leads the human networks and scientific communities that are pioneers for its very uses. The need for a computing and data processing Cloud, as an extension of HPC offers, is now well expressed. France Grilles has a role to play in this field.

RI France Grilles has very convincingly demonstrated its key role in building a national grid and production cloud for research. Its skills and leadership are widely appreciated by the scientific community. Its future depends on a reflection on its evolution, which must clarify its position in the national EOSC landscape currently under construction, for which its skills will be appreciated.

THE DIGITAL ORIENTATIONS FOR THE NEXT 5 YEARS

The acceleration of digital uses concerns all ESRI players. It is accompanied by the emergence of new cloud services, by the constant evolution of digital tools, by the growing need for increasingly efficient computing resources, and by a growing volume of data generated, processed and disseminated (personal data, research data, publications and associated data, etc.). Research infrastructures are particularly concerned by the use of digital technology (with 25% of their investments, and 4 to 5% of their operating costs).

For the lowest layers of service, a process of labelling data centres in the regions has been carried out, aimed at encouraging the pooling of secure, state-of-the-art hosting infrastructures, in addition to

the national centres TGCC, CC-IN2P3, CINES and IDRIS. A high-speed network, the backbone of ESRI's digital infrastructures and services, will interconnect all of this. This network of national and regional data centres is intended to be the foundation for hosting research infrastructures.

The need today is to develop the service layers, by continuing to consolidate integrated computing services between HPC, AI and the Cloud, but also to mutualize the services centred on data, which are today often built by individual communities and are too spread out.

ESRI has embarked on a strategy to consolidate the hosting of applications, equipment and data managed by its institutions and communities. This federated system is based on reliable commercial offers. This development should make it possible to build the French component of ESRI's digital resources in the European (EuroHPC, EOSC, ESFRI projects, etc.) and international context, where the orientations of sustained development in the digital field are necessarily of great importance for the national level.

Several RI have already committed themselves to this approach, notably in the framework of the recent PIA3 EquipEx+ call for projects. One of its a section was indeed specifically dedicated to Digital Services and Infrastructures, making it possible to build shared, consolidated, sovereign and eco-responsible digital infrastructures and services.

The main risk in the field of digital technology is under-investment, amplified by the wide spreading of its deployment and its financing methods: the network, computing and data processing resources, and collaborative tools at the service of communities, must all continue to be developed at a sustained rate, with a good level of pooling and rationalisation at each level. These conditions are the key to maximise the effectiveness of the efforts made and the overall sustainability of digital use.

The digital transformation must also be based on the evolution of the skills of the support teams and users. This evolution of skills must enable the deployment of quality digital services developed on recent, secure and competitive technologies. It is also necessary to support the emergence of new professions, so as to enable French research to use the most recent technologies, to benefit from the mass of data at its disposal, and to develop the most advanced applications in each of the fields so as to remain a major and recognized player in Europe and beyond.

Participating to European and international structures and projects (GEANT, EuroHPC, EOSC, etc.) in the digital field, or community projects with significant digital needs (LHC, SKA, EMBL, EBRAINS, etc.) implies a high level of national coordination, that requires institutional support and community involvement.

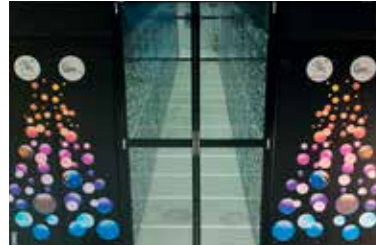
GENCI

National High-Performance Computing Equipment

GENCI is a civil company owned 49% by the State represented by the Ministry of Higher Education and Research, 20% by the CEA, 20% by the CNRS, 10% by the Universities represented by the Conference of University Presidents and 1% by Inria.

GENCI has the following missions:

- Participation in the definition and implementation of national policy in the field of digital simulation by intensive computing and storage/processing of massive data associated with artificial intelligence techniques;
- Project management of the equipment making up the main infrastructures for intensive computing and the processing and storage of massive data
- Promotion of the use of modelling, simulation and intensive computing in fundamental and industrial research
- Participating in the implementation of European initiatives for the development of digital infrastructures



- for intensive computing and massive data processing for research;
- Leading the technology watch carried out with the expert teams of its partners;
- Opening up its teams to all interested scientific communities, whether academic or industrial, national, European or international
- Participating in promoting access for national SMEs to high performance computing resources.

Relations with economic actors and/or socio-economic impact

GENCI provides access to its resources to industrial companies for open research and pilots the SIMSEO programme, which supports small and medium-sized companies and SMEs in the use of digital simulation by providing access to expertise and computing time at regional mesocentres. GENCI has joined the National Competence Center run by Teratec and Cerfacs, the national version of the European project for industry.

Open science and data

- Annual data production: 50 PB
- The validated and described data are published on a data repository:

Category: RI*

Type of infrastructure: distributed

Infrastructure location in France: Paris

Other sites in France: Bruyères-le-Châtel, Montpellier, Orsay

French supporting institutions: CEA, CNRS, Inria, France Universités, MESRI

Director or RI representative in France: Philippe Lavocat

Construction: 2007

Operation: 2007

Website: www.genci.fr

International dimension

PRACE, ESFRI landmark

- **Partner countries** DE, BE, BG, CY, DK, ES, FI, GR, HU, IE, IL, IT, LU, NO, NL, PL, CZ, UK, SK, SI, SE, CH, TR, AT, FR, IE
- **Website:** www.prace-ri.eu

RENATER

Public Interest Grouping for the National Electronic Communications Network for Technology, Education and Research

The purpose of the public interest grouping for the national electronic communications network for technology, education and research is:

- to provide the players of the research and education community with the means of high-speed digital communication and management of related data in France (metropolitan France, the French overseas territories and the COM) on the basis of networks, infrastructures and services
- ensuring that all these resources are secure;
- ensuring interconnection to global research and education networks;
- ensure the work of the networked teams and respond to the advanced and innovative needs of the research and education community;
- to provide advice, expertise, and communication resources or services in its fields of competence



to the State and other French or foreign public entities, insofar as this does not impose obligations on the Grouping that are incompatible with its mission of providing services to the research and education community.

Relations with economic actors and/or socio-economic impact

Participate in the digital transformation of ESRI. Support for innovation and excellence in ESRI.

Relations with the industrial world through purchases according to the rules of public procurement.

Support for the socio-economic development of the territories through facilitated access to education from primary to higher education, to research and to innovation on a national and international scale.

Open science and data

- The source codes produced by the infrastructure are open on a software forge <https://sourcesup.renater.fr>
- Annual data production: 10 TB

Category: RI*

Type of infrastructure: distributed

Infrastructure location in France: Paris

Other sites in France: Cesson-Sévigné, Montferrier-sur-Lez, Saint-Martin-d'Hères

French supporting institutions: MESRI, France Universités, CNRS, CEA, Inria, CNES, INRAE, Inserm, Onera, Cirad, IRD, et BRGM

• **Director or RI representative in France:** Jean Narvaez (par intérim)

• **Construction:** 1993

• **Operation:** 1993

• **Contact in France:** <https://services.renater.fr>

• **Website:** www.renater.fr

International dimension

GÉANT

• **Partner countries voir liste en remarques**

• **Website:** www.geant.org

CC-IN2P3

IN2P3 Computing Centre

The IN2P3 Computing Centre (CC-IN2P3), which is located in Lyon, has 70 permanent CNRS staff. It provides computing resources for nuclear and particle physics experiments by offering transport, storage and processing of huge amounts of data. It is one of the 13 major top-level centres of the Worldwide LHC Computing Grid (W-LCG) project coordinated by CERN. About 70% of the CC-IN2P3's resources are used for LHC data processing and simulations. International collaborations in the field of astroparticles and cosmology can also benefit from CC-IN2P3's resources by financing the resources they need. Since 2021, the CC-IN2P3 is one of the two major data processing centres of the LSST project and will have a complete set of data, giving a major advantage to the CNRS teams. It will also be the main component of the French ground segment of the European space mission EUCLID. International scientific collaborations using CC-IN2P3



© Cyril FRESILLON / CC-IN2P3 / CNRS Photothèque

services include GANIL, EGO, LSST, HESS, CTA, PAO, JUNO and KM3NeT, all of which are on the national RI roadmap or on the ESFRI roadmap. The High-Luminosity phase of the LHC (2027-2038) will be the major challenge for CC-IN2P3 as it will provide 100 times higher capacities.

Relations with economic actors and/or socio-economic impact

Partnership with the manufacturer Dell/EMC, which wishes to contribute, alongside the CC-IN2P3, to a support initiative for massive data processing solutions and computing resources in a scientific context.

Open science and data

- The source codes produced by the infrastructure are open on a software forge <https://gitlab.in2p3.fr>
- Annual data production: 15 PB

Category: RI

Type of infrastructure: single site

Infrastructure location in France: Villeurbanne

French supporting institutions: CNRS

Director or RI representative in France:

• Pierre-Etienne Macchi

• **Construction:** 1986

• **Operation:** 1986

• **Stakeholders in France:** CNRS

• **Contact in France:** contact@cc.in2p3.fr

• **Website:** <https://cc.in2p3.fr>

International dimension

W-LCG

- **Partner countries** Plus de 40
- **Website:** <http://wlcg.web.cern.ch>

CINES

NATIONAL COMPUTER CENTRE FOR HIGHER EDUCATION

The Centre Informatique National de l'Enseignement Supérieur (CINES) is a Public Administrative Institution (EPA) located in Montpellier and placed under the supervision of the MESRI. Benefiting from high performance network access (RENATER regional node), it provides state-of-the-art computing resources through its three national statutory missions in:

- High performance computing: CINES hosts the Adastra supercomputer on behalf of the TGIR GENCI, which is used by 1 500 researchers in 300 research projects. It operates both the supercomputer from a system point of view, but also support its users through a dedicated team of engineers in intensive computing;
- the perennial archiving of digital data: CINES is the archiving centre of ESRI, via an agreement of the Service Interministériel des Archives de France (SIAF), and about twenty institutions archive their electronic documents including the multidisciplinary open archive HAL of the CCSD of CNRS;



© CINES

- Hosting of national and regional IT platforms: CINES hosts in 2021 120 bays for 18 institutions of the ESR, via its hosting service "dry" (provision of the host infrastructure in IaaS mode).

These three missions in synergy allow the RI CINES to offer a catalogue of services FAIR to store, process, disseminate and if necessary archive research data.

Relations with economic actors and/or socio-economic impact

The hosting and archiving services of CINES are open primarily to public institutions of ESRI and MENJ, as part of service provision. The Adastra supercomputer is open via calls for projects organized by GENCI, for public research but also private with an obligation to publish the results.

Open science and data

- The source codes produced by the infrastructure are open on a software forge <https://gitlab.cines.fr>
- Infrastructure with a FAIR data policy in application

Category: RI

Type of infrastructure: single site

Infrastructure location in France: Montpellier

French supporting institutions: MESRI, France Universités

• **Director or RI representative in France:** Boris Dintrans

• **Construction:** 1999

• **Operation:** 1999

• **Stakeholders in France:** GENCI, SIAF, Inserm, CNRS, IRD, Abes, INRAE

• **Website:** www.cines.fr

France Grilles

France Grilles

France Grilles is a multidisciplinary research infrastructure, labelled since 2010 on the Ministry of Higher Education and Research roadmap, which brings together the main players in French public research (CEA, CNRS, France Universities, INRAE, INRIA, INSERM) as well as RENATER within a Scientific Interest Group. It works in close collaboration with the thematic research infrastructures to which it provides distributed computing (grid and cloud) and storage services as well as technical support.



© V. Breton - J. Pansanel - G. Romier

It develops specific services, which are essential for the exploitation of shared data and enables researchers to use these distributed computing and storage resources. Representing France on the board of the European e-Infrastructure EGI, France Grilles now offers its 3,000 users access to a global resource of one million cores and 250 petabytes of storage. It has become an essential element of the digital transformation in France, operating 22,000 cores

distributed via a cloud infrastructure on eleven sites in mainland France.

France Grilles' service offering supports the deployment of open science to facilitate the management, storage and analysis of large volumes of data, either directly on the infrastructure or through virtual research environments. These activities also allow France Grilles to participate actively in the European Open Science Cloud.

Relations with economic actors and/or socio-economic impact

While operating and developing its IT infrastructure for French academic research, France Grilles offers its services to all stakeholders to achieve the vision of science open to all in the French version of the European Research Area. Its relations with the socio-economic world are part of this framework, in collaboration with its European partners in EGI.

Open science and data

- The source codes produced by the infrastructure are open on a software forge <https://github.com/FranceGrilles>

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Paris

Other sites in France: Annecy-le-Vieux, Aubièrre, Bures-sur-Yvette, Castanet-Tolosan, Grenoble, Jouy-en-Josas, Marseille, Montpellier, Nantes, Palaiseau, Paris, Paris 13^e, Paris 14^e, Saint-Aubin, Saint-Martin-d'Hères, Schiltigheim, Talence, Toulouse, Villeneuve-d'Ascq, Villeurbanne

French supporting institutions: CNRS

Director or RI representative in France:

Vincent Jacques Breton

Construction: 2010

Operation: 2010

Stakeholders in France: CEA, France Universités, INRAE, Inria, Inserm, MESRI, RENATER

Contact in France: info@france-grilles.fr

Website: www.france-grilles.fr

International dimension

EGI

- **Partner countries** FR, IT, ES, DE, UK, NL, PT, BE, BG, HR, CZ, EE, GR, MK, PL, RO, SK, CH, TR, HU, AT
- **Website:** www.egi.eu

Scientific information research infrastructures



THE MAIN FUNCTIONS OF SCIENTIFIC INFORMATION

Scientific information infrastructures are **knowledge infrastructures** because they facilitate the transformation of data into information and information into knowledge. Scientific information infrastructures provide tools, services and skills that meet scientific information needs throughout the knowledge production chain, i.e. throughout the life cycle of research, right up to its users and audiences. The functions of scientific information make it possible to articulate several flows of content and services around researchers in the course of scientific activity. In particular, it is a question of supplying researchers with the scientific content they need to produce their research, but also of enabling them to make the results of their research available to scientific communities and the general public. This increasingly goes beyond the historical sector of publications to include objects that enable the construction of knowledge, including data and software/codes, as well as their reuse. These infrastructures ensure or accompany all or part of the functions of scientific information in academic research: 1) collecting and producing, 2) certifying, 3) structuring and linking, 4) maximising impact and 5) ensuring sustainability.

1. Collecting and producing scientific information helps researchers to mobilise data. Researchers are constantly producing data, software and scientific knowledge that they can entrust to scientific information infrastructures and thematic infrastructures. They can also rely on these infrastructures to provide them with data that they collect according to their needs (data discovery, literature review). Digitisation services for heritage collections or research corpuses produce new data (CollEx-Persée). Publication platforms (OpenEdition Books), scientific journals (Persée, OpenEdition Journals, Episciences

of HAL+) and open archives (HAL) promote access to academic literature. They perform a fundamental function of publication and dissemination of knowledge. Being relatively autonomous from the highly concentrated scientific publishing market and, soon, from the scientific data market, scientific information infrastructures constitute pillars ensuring the independence of public research, which must have its own platforms (ISTEX).

2. Certifying scientific information information is the core of the work of this type of infrastructure, as it ensures the transparency and validity of the information. This process involves the qualification of information and its evaluation by human or technical means, the best known of which is peer review. Infrastructures streamline, rationalise and evolve these essential certification mechanisms through internationally standardised expertise and good practices. To make this possible on a large scale and at affordable costs, the scientific information infrastructures deploy tools dedicated to peer review (Episciences, ScienceConf under HAL+). They are also developing services for awarding quality labels, such as the Directory of open access books (DOAB under OpenEdition). Finally, they offer platforms that promote scientific conversation and communication between peers, both upstream and downstream of the publication itself (Calenda, Hypotheses, OpenEdition services), as these elements are essential to scientific processes.

3. Structuring and interlinking scientific information allows the researcher to organise and document his or her scientific results. The process of publishing scientific documents ensures the semantisation of information according to established rules and

the standardisation of public forms of content (Metopes). The management of metadata and identifiers (CollEx-Persée, HAL, ISTEEX and OpenEdition) and the provision of repositories enable the description to be standardised in order to make it intelligible, comparable and classifiable. Metadata allows citation and thus links between content, data, code, research objects, which facilitates access to information (Software Heritage and all other infrastructures).

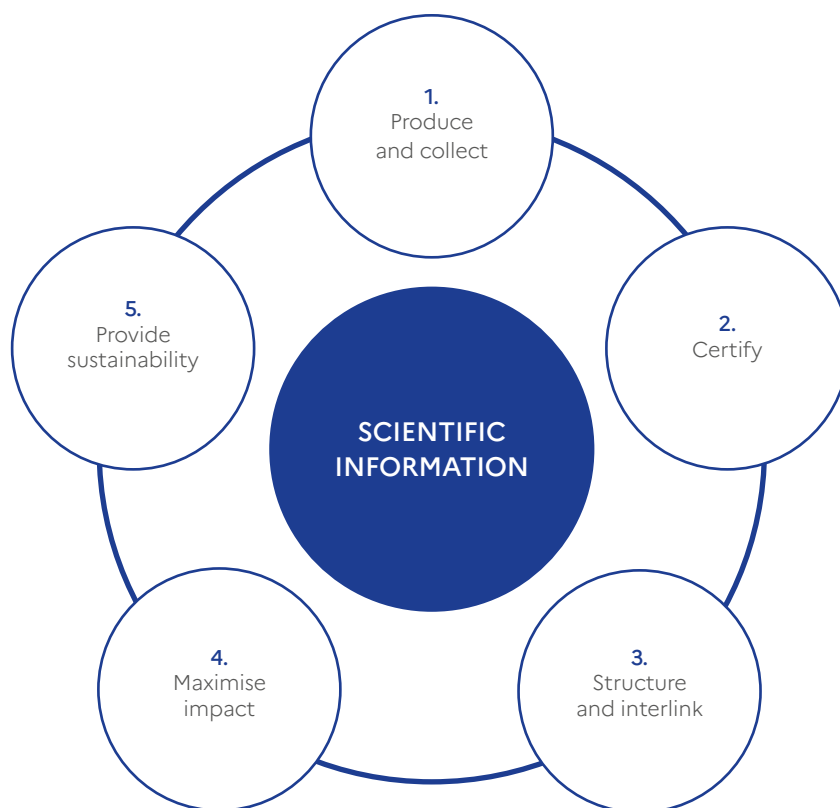
4. Maximising scientific impact is a central objective and function that covers services for disseminating, distributing and promoting information through a number of actions: publishing, reporting, web referencing, optimising visibility (SEO: *search engine optimisation*), compliance with accessibility standards, etc. The aim is to ensure the accessibility of information and data for the widest possible international scientific audience (OpenEdition, CollEx-Persée, HAL+, Métopes, ISTEEX, Software Heritage), but also to ensure visibility for other audiences: public policies, the economic sector, the media, teachers in particular (OpenEdition, HAL+). This requires the inclusion of information in a vast ecosystem, which requires the adoption of clear licences and unique identifiers, based on international standards. Finally, maximising the impact requires the processing of information by mining (ISTEEX) and visualisation tools.

5. Sustainability: scientific information derives from the Library of Alexandria model the imperative need to sustain its action. The functions of hosting, conservation and archiving of scientific information allow the researcher to have a secure and perennial service for the preservation and access to his results (OpenEdition, CollEx-Persée, HAL+, ISTEEX, and Software Heritage). In order to ensure the sustainability of infrastructures

and their contents, a certain number of conditions must be met. It is first of all technological choices, for example the generalization of semantized formats, hosting in data center labelled nationally, permanent archiving at CINES. It is then efficient organizational models, ensuring a good level of mutualisation and provision of highly specialized trades. It is finally the implementation of sustainable economic models, with recurrent funding from the supervisory bodies, but also other models (membership model for HAL, freemium model for OpenEdition ...), depending on the type of activity.

A MAJOR LEVER OF THE NATIONAL PLAN FOR OPEN SCIENCE. SCIENTIFIC INFORMATION MUST BE OPEN OR AT LEAST SHARED

The openness and circulation of scientific information as well as the sharing of scientific data are major issues in the construction of the knowledge society. Producing and using data, evaluating, certifying and publishing research results, validating and ensuring the reproducibility of discoveries, communicating and interacting with society – the life cycle of research is a challenge that was strongly highlighted during the COVID 19 pandemic. This crisis shows the need for private and public actors to base their decisions on the research being done, and the crucial importance of open access to research publications for society as a whole. Open data is also necessary, except when it is sensitive or subject to secrecy. In this case, it is called sharing, which allows controlled access to sensitive information. Code, which now underlies all knowledge production, cannot be forgotten: it is an essential instrument, which goes far beyond the computer sciences and covers all disciplines. It is generally hosted in software forges, which are very numerous and fragile. Software Heritage secures this immense



The five main functions of scientific information infrastructures

computer heritage of humanity, which has no formal scientific limits, the porosity between non-scientific software and that developed within research being total, and allows the production of new knowledge.

Scientific information infrastructures are intended to be the first levers and spearheads of the French National Plan Open Science.

They embody the fundamental principle that research is a common good that must be shared with all. They implement this principle of openness in each of their services and tools, as well as in the organisation of their governance. They have been designed and built to carry the dynamics of open science across all disciplines. They are therefore pillars of open science, even if they can still improve the formalisation of their open science policy, which is sometimes too implicit, and specify their recommendations on the use of licences.

Scientific information infrastructures do not always produce research data directly,

but often metadata and additional layers on top of the data, which must themselves be considered as data. Publications, which are the historical objects of scientific information infrastructures, are in fact treated as data: they are moderated, enriched by metadata whose quality is guaranteed by the management of repositories and identifiers. The role of the data steward can therefore be found in that of moderator and quality controller via repositories, even if the data professions and skills could be better identified and formalised.

Actors of the FAIR principles: the five functions assumed by scientific information require a high degree of maturity in the processes of "Fairisation" of scientific information, i.e. transformation in order to make it **FAIR**: findable, accessible, interoperable and reusable.

Collectively, the mission of these infrastructures is to constitute a coherent

ecosystem, associating methods, data, codes and publications with, in particular, cross-citations between all these objects.

MATURITY AND NECESSARY DEVELOPMENT OF SCIENTIFIC INFORMATION INFRASTRUCTURES: A DYNAMIC, COMPLEMENTARY AND STRUCTURED LANDSCAPE

Major infrastructures that have reached a critical size in terms of content volumes

Scientific information infrastructures now gather such volumes of content that they have become central and indispensable. For software and codes, Software Heritage hosts 9.6 billion source files from 151 million projects. HAL+ provides open access to 865,000 full-text scientific documents, including more than 100,000 theses from all disciplines, and hosts nearly 9,000 conferences. OpenEdition brings together on its various platforms more than one million published scientific documents, 96% of which are available in open access. They include 550 scientific journals, 10,000 e-books and 6,000 research blogs. Finally, ISTEEX provides access to 23 million documents from 30 bodies of scientific literature in all disciplines, i.e. more than 9,314 journals and 348,636 electronic books published between 1473 and 2019.

A powerful vector of international influence and visibility: tens of thousands of producers, tens of millions of users

The scientific communities concerned by the services of scientific information infrastructures are very broad. Upstream, that of content producers, HAL mobilises 72,000 active users from the higher education and research world and OpenEdition nearly 30,000, selected by a scientific council. Software Heritage archives 150 million code projects. All higher education and research communities, all disciplines included, are

therefore active users of these infrastructures. Downstream, that of the users, the success is even more massive and, it is noteworthy, the platforms gather audiences well beyond higher education and research. In 2020, HAL recorded 11.8 million visits and all the OpenEdition services had 96 million visits. Users are also beyond the national community and scientific information infrastructures are a real vector of international influence. In the same year, 51.8% of visits to the HAL infrastructure came from countries other than France and 47.9% of visits to OpenEdition came from outside Europe, led by the United States (4.5 million visits). Making scientific outputs and publications available in open access allows the development of uses by private sector companies as well as by citizens in their personal information practices. OpenEdition has developed an “unexpected reader” detector to identify cases where open access dissemination favours the dissemination of scientific productions in HSS – Humanities and social sciences beyond the expected scientific public: Crédit Mutuel, Dassault, AXA, the automobile sector are thus regular users of OpenEdition. **The impacts of this massive dissemination are therefore both scientific, with stronger connections between disciplines, social with effects on education and training, and socio-economic with consequences on innovation.**

The success of mutualisation and international opening

Four infrastructures have joined forces to build two projects that are now winners of the PIA3 Equipex+ call: HAL with the HALiance project and the alliance of OpenEdition, Huma-Num and Métopes for the COMMONS project. This shows the vitality of the sector and its capacity to organise itself intelligently, by working on the complementarities of each other while preserving the skills and professions of each. It seems necessary to develop other complementarities between infrastructures, for example between



the services of SciencesConf (HAL) and Calenda (OpenEdition). These infrastructures are experiencing a strong international development. The Operas infrastructure (supported by OpenEdition) plays a leading role at the European level and has just been included in the ESFRI roadmap. Links are being strengthened between CollEx-Persée and the European library network. Software Heritage has the vocation to become an international structure whose legal status is being studied, in partnership with UNESCO, with from now on numerous international, private and public financing. HAL is an active member of COAR (Confederation of open access repositories). The international visibility of the infrastructures is particularly taken care of. Google Scholar harvest, for example, HAL, Persée and OpenEdition, as well as OpenAire indexes HAL and OpenEdition. **EOSC is becoming the natural place of exchange and development for all scientific information infrastructures.**

The place of support and training

One of the strengths of these infrastructures is their role in developing a support offer for academic communities, particularly through training (HAL, OpenEdition, ISTE). This upstream support for users (researchers, engineers, publishers) is combined with downstream support (promotion, editorialization, etc.) for the increasingly diversified public that accesses the available content. Support and service are at the heart of these infrastructures. The development of scientific information skills within higher education and research landscape is a fundamental element in the evolution of French research and the implementation of the National Plan for Open Science.

ANALYSIS OF SCIENTIFIC INFORMATION INFRASTRUCTURES

HAL+ is an infrastructure whose purpose is to share and archive knowledge. HAL has

seen its role confirmed by the two National Plans for Open Science (2018 and 2021) and in 2020, the Open Science Steering Committee strengthened its governance. Its economic model is being stabilised and its development is ensured by the Equipex+ 2021 project. In addition to HAL, there are two platforms, Episciences for the evaluation and publication of journals, and SciencesConf for the organisation of scientific events. HAL+ covers all scientific fields and the entire publication process (certification, editing, publication, archiving, etc.). HAL+ must succeed in its technical mutation and its interconnection with external contents, manage to satisfy the needs of the researchers as well as those of the establishments, invest in the animation of its network and reinforce its partnerships with the other infrastructures and on the international scale.

OpenEdition provides open access to scientific research results in the form of books, journals, blogs and events. The infrastructure promotes the development of high-level, international digital publishing and places it within the framework of open science. It fully meets the objectives of the national plan for open science, by disseminating research productions in Social Sciences and Humanities (SSH) beyond the scientific public, by developing editorial diversity (bibliodiversity) as well as a sustainable economic model, the freemium. As an Equipex+ 2021 laureate, co-sponsor of the Directory of open access books (DOAB) and of the European OPERAS infrastructure, OpenEdition is structuring the national and European scholarly communication landscape. OpenEdition will have to renew its software infrastructure, strengthen its human resources, increase its science-society dimension and open up at the disciplinary level. It should aim to build a unified digital environment, accessible through a range of services combining data deposited in Recherche Data Govu (under development) and publications.

Métopes' mission is to modernise editorial processes through multi-media management and a structuring function that will bring about transformations for public publishing in the context of open access. Métopes makes it possible to get away from the logic of retro-conversion, which is costly in terms of time, resources and quality. Métopes ensures that content producers have full ownership of their digital holdings, meets the challenge of reasonable open access, and ensures that publications are also data (interoperability and rich metadata). Its small size allows for agility, but it is also a limitation as Métopes needs resources to support complex content, accessibility development, and promotion at national and international levels. Its governance and statutes need to be worked out in relation to its articulation with other structuring functions for public publishing (university presses, distribution).

CollEx-Persée facilitates researchers' access to the collections of research libraries by building up a large pool of research materials. It aims to have a transforming effect by bringing scientific information professionals closer to researchers and engineers in projects with a national impact. It supports a national digitisation policy for research and promotes the development of research services based on the collections. It encourages the production and collection of digitised and natively digital objects, which complement and enrich the collections (digital scientific archives, enriched data, research services, etc.). CollEx-Persée must develop and strengthen its links with other infrastructures, stabilise current programmes and improve their visibility, work on structuring and opening up data, open up to other European and international partners and confirm Persée's central position at the heart of the infrastructure.

Software Heritage is a crosscutting infrastructure, building a universal archive of all software source codes worldwide. It

is aimed at a wider audience than research and has an international vocation. It preserves the scientific and technological knowledge embedded in software source code, which is a precious part of our heritage. By building the largest code base for software research, it promotes better science and enables the development and reuse of software for society and industry. It is an essential building block for replicability, a complement to Open Access and Open Data. The infrastructure is operational with features under development. Solid governance must reinforce this young structure. The monitoring of uses remains to be built.

ISTEX is a platform that offers the entire higher education and research community online access to retrospective collections of scholarly literature in all disciplines, guaranteeing documentary sovereignty, and value-added services to optimise their exploitation by text mining techniques in order to produce new knowledge. The platform has a good technical maturity and strong skills in text mining and data processing. Its visibility needs to be improved and its governance consolidated. The contractual restrictions imposed by the publishers remain an obstacle. The project aims to improve governance and management and to refocus on text mining by developing partnerships.

POTENTIAL GAPS TO BE FILLED, AND DIRECTIONS FOR THE NEXT FIVE YEARS

At the heart of the research process, scientific publishing must be strengthened

The editorial function cuts across all scientific information functions. OpenEdition and Métopes provide structured publishing and open dissemination via efficient services. In spite of this, the actors with publishing missions, university presses and learned



societies, remain too isolated. We need a stronger structuring of the public and semi-public publishing sector in order to coordinate and animate a network of university presses that will set up common actions, synergies and mutualisation. In this context, the issue of diffusion-distribution appears to be a major one in the perspective of knowledge dissemination, and the evolution of FMSH diffusion, its possible articulation with AFPU Diffusion or with other actors, and its possible intervention in the print-on-demand sector will have to be followed closely.

Developing the link between publications and data

Another challenge will be to better ensure the link between publications and data, in order to help improve the conditions for the administration of evidence, to promote scholarly discussion and the comparison of research results, and finally to guarantee respect for scientific integrity in the production and processing of data. The future federated national Recherche Data Gouv platform will contribute to this, as will the EquipEx+ projects.

The need for a research data platform

The Minister Frédérique Vidal announced on December 8th 2020 that the Ministry of Higher Education and Research will “soon” create a warehouse “to store orphaned data known as the long tail, whose weight in bytes may be small, but whose scientific weight may prove to be major”. This warehouse was announced in 2021 in the Second National Plan for Open Science and is due to emerge in 2022 under the name Recherche Data Gouv. Its role will be structural and the question of its inclusion in the future roadmap for research infrastructures will therefore arise. Its mission will then have to be extended to identify the data produced by the other infrastructures and exposed in one of the 3,600 research data repositories in the world.

New objects and services to be developed

Beyond the traditional objects of scientific information, it is now necessary to take into account new or historically considered minor forms. Thus, code and software, scientific archives and video are objects that must be given special attention in the future. They pose essential scientific information questions. The most mature project in this field is Software Heritage, the “Alexandria library of source code”. Initiatives such as Canal-U could eventually play a role in the field of video and educational resources.

Other pooled services are needed, based on crosscutting issues of methods and tools for the quality, dissemination and internationalisation of French research: plagiarism detectors, semi-automatic translation, content submission and peer review workflows, text and data mining systems, interoperability. But also experimentation with new modalities to improve the efficiency of research: open peer review, business models of open access, targeted editorialization.

Text and data mining, a horizon

The very strong development of text and data mining requires that this type of activity be taken into account, based on a combination of vast corpora prepared for this purpose and instruments allowing processing using artificial intelligence. There are many good initiatives in this field, which need to be well coordinated and included in the national strategy on artificial intelligence. In the context of the implementation of new legislation on text and data mining (TDM), the ISTEEX project could serve as a TDM infrastructure for research in France.

An ecosystem to coordinate

This set of infrastructures constitutes a dynamic, complementary and structured landscape without yet forming an ecosystem

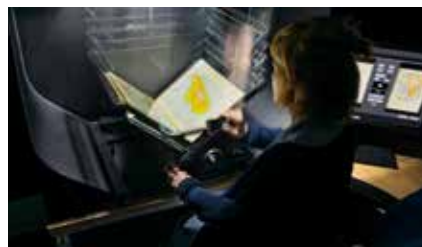
within which the links between publications, data and codes would be developed. As part of its strategy for data, algorithms and source codes, the Ministry of Higher Education and Research proposes to bring together the bearers of these infrastructures in a network of players around the challenge of collectively building the French ecosystem of open science infrastructures. Within this framework, these actors are to develop and implement a national policy of permanent and open identifiers to guarantee a reliable link between research contributors, their productions, their research centres and their institutions. This ecosystem is also intended to become the place for designing and implementing standardised usage statistics tools (e.g. COUNTER 5 type) for all open science infrastructures.

CollEx-Persée

Collections of Excellence for Research – Persée

CollEx-Persée’s mission is to facilitate researchers’ access to the collections of major scientific libraries and to develop the use of the materials they constitute for research, through digitisation and the development of services related to their exploitation and enrichment.

Its action is broken down into programmes dedicated to the listing and accessibility of collections for research, as well as support for the production of digitised and enriched corpora that meet the standards of open science. These programmes also aim to have a transformative effect, by bringing together communities of information professionals and researchers in projects covering a vast field from the identification of deposits to the dissemination and preservation of digital corpora. CollEx-Persée was built on a network of major research institutions and scientific information operators. The UAR Persée plays a central role in this network and is responsible



© Jean-Pierre Rosenkranz

for the national policy of enriched digitisation for research, which aims to coordinate the digitisation activities of ESRI, to pool tools and skills and to promote good practices in digitisation, enrichment, dissemination and preservation. CollEx-Persée thus plays a structuring role in the transformation of scientific information through the coordination it ensures between libraries and the various players in the field.

Relations with economic actors and/or socio-economic impact

Not concerned

Open science and data

- Infrastructure with a FAIR data policy in application

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Strasbourg

Other sites in France: Boulogne-Billancourt, Bussy-Saint-Georges, Lille, Lyon, Montpellier, Nanterre, Orsay, Paris, Paris 2^e, Paris 5^e, Paris 6^e, Paris 7^e, Paris 13^e, Paris 16^e, Pessac, Saint-Denis, Saint-Martin-d’Hères, Toulouse, Vandœuvre-lès-Nancy, Villeurbanne

French supporting institutions: BNU

• **Director or RI representative in France:** Alain Colas

• **Construction:** 2014

• **Operation:** 2017

• **Stakeholders in France:** ABES, BNF, BULAC, Campus Condorcet, CNRS, CTLes, École française d’Athènes, ENS de Lyon, IEP Paris, INHA, MESRI, MNHN, Musée du Quai Branly-Jacques Chirac, Observatoire de Paris, Université Bordeaux Montaigne, Université Claude Bernard Lyon 1, Université de Lille, Université de Paris, Université Grenoble Alpes, Université Paris 1 Panthéon-Sorbonne, Université Paris 3, Université Paris Dauphine - PSL, Université Paris Nanterre, Université Paris-Saclay, Sorbonne Université

• **Contact in France:** Chargée de mission Catherine Désos-Warnier – catherine.desos-warnier@bnu.fr

• **Website:** www.collexpersee.eu

International dimension

- **Partner countries DE – Fachinformationdienst (FID)**

HAL+

Next-generation open archive

HAL+ is an integrated infrastructure ensuring the worldwide dissemination and long-term preservation of research results. It covers all types of scientific publications (articles, preprints, conference communications, theses...) and their link with research data for all scientific fields. In line with the international Open Science movement, HAL+ is built on three complementary platforms.

HAL, the multidisciplinary open archive of French research and all its sub-portals, is the core engine of the infrastructure. Episciences (publication of OA diamond journals) and Sciencesconf (management of scientific events) offer overlay services.

These three platforms have been designed to help researchers and their institutions to make their output available, discoverable, usable and widely shareable over the long term. They also contribute to give back to research communities the control of the scientific communication process. The " Centre pour la



Communication Scientifique Directe " (CCSD) develops and operates them.

HAL+ relies on the CC IN2P3 and the CINES datacentres for IT hosting and data preservation. HAL+ and Software Heritage are partners for the preservation of source codes and software. Finally, HAL+ is interconnected to the major international repositories (arXiv, REPEC, PMC, Zenodo) and the main sources of metadata (ORCID, RNSR, ROR, OpenAire, data.gouv.fr, crossref).

Relations with economic actors and/or socio-economic impact

HAL+ provides open access to scientific literature without any barriers. Open code source and open data enable exploitation by public and private actors. The CCSD, which implements HAL+, collaborates with the software industry to develop new tools and services.

Open science and data

- The source codes produced by the infrastructure are open on a software forge <https://github.com/CCSDForge>
- Annual data production: 1,2 TB
- The validated and described data are published on a data repository <https://data.archives-ouvertes.fr>

Category: RI

Type of infrastructure: single site

Infrastructure location in France: Villeurbanne

French supporting institutions: CNRS, Inria, INRAE.

- **Director or RI representative in France:** Nathalie Fargier
- **Construction:** 2001
- **Operation:** 2001
- **Stakeholders in France:** 124 universités, organismes de recherche et écoles de l'ESR français
- **Contact in France:** ccsd@ccsd.cnrs.fr
- **Website:** www.ccsd.cnrs.fr

International dimension

- **Partner countries Europe:** GR, IT, DE, PL, RO, CZ - USA, IN
- **Website:** www.openaire.eu/openaire-nexus-project, www.coar-repositories.org/notify

ISTEX

Scientific and technical information of excellence

ISTEX houses a unique digital scientific library, providing access to a corpus of 23 million documents (articles, e-books, etc.) covering all scientific fields. These resources are permanent, accessible and usable by the ESR community. As a complement to current subscriptions, the platform meets two needs:

- Document search. The combination of a powerful search engine and integration into local digital environments allows for simple navigation between current resources and retrospective collections;
- Content search. Documents are pre-processed and enriched to facilitate their exploitation. API extraction functionalities allow the generation of corpora on demand.

The main strategic objectives of the infrastructure:

- To open the collection to natively published open access resources and to continue to add to it through an acquisition policy;
- To facilitate the constitution of coherent and enriched corpora, directly exploitable for CT;



- Promote the development of advanced services with the NLP research community;
- To offer corpus exploration and exploitation services accessible to all.

The ISTEX platform is the result of a partnership between the CNRS, the Abes, the Couperin consortium, the CPU and the University of Lorraine. It relies on a system of membership for institutions to finance its software and hardware maintenance.

Relations with economic actors and/or socio-economic impact

The beneficiaries of the infrastructure are members of higher education and research institutions.

Open science and data

- The source codes produced by the infrastructure are open on a software forge <https://github.com/istex>
- Annual data production: 500 GB
- The validated and described data are published on a data repository www.istex.fr

Category: Projet

Type of infrastructure: single site

Infrastructure location in France: Vandœuvre-lès-Nancy

French supporting institutions: CNRS

- **Director or RI representative in France:** Comité de pilotage Istex
- **Construction:** 2012
- **Operation:** 2015
- **Stakeholders in France:** ABES, Consortium Couperin, INIST-CNRS, France Université, Université de Lorraine
- **Contact in France:** copil.istex@services.cnrs.fr
- **Website:** www.istex.fr

Métopes

Methods and Tools for Structured Publishing

Métopes research infrastructure is dedicated to supporting scholarly publishers in their efforts to place their activities and production methods in a resolutely digital context oriented towards open science objectives.

It aims to design, develop and dispense, freely and without charge, through deployment and training actions for public publishers, a set of tools and methods enabling them to organise, in full sovereignty, their print and online production and distribution in a normalized environment, while paying particular attention to the standards and quality of data and metadata's structure.

It is both an observatory and an actor of the evolution of practices in the ongoing mutation of science distribution and communication systems in the context of digital convergence and the transformation of the dissemination-distribution economy.

In short, Métopes aims to be a toolbox for the full integration of digital logics in the construction and exploitation of editorial collections in order to:



© el alce web/Unsplash

- Get away from costly retro-conversion logics;
- Ensure that public data producers have full ownership of their digital collections;
- Take up the challenge of a reasonable open access in full editorial autonomy;
- Raise the skill level of public structures' staffs through training.

Relations with economic actors and/or socio-economic impact

Agreements with partners in the software industry for the co-development of typing and encoding environments, annotation and conversion of normalized structured flows (XML-TEI; JATS; ONIX; ePub3 for accessibility), and in the material publishing and distribution industry for the development of structured flows and scripts for the production of books, ebooks, and the supply of publishing platforms.

Open science and data

- Part of the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure are open on a software forge <https://git.unicaen.fr/metopes>
- Infrastructure with a FAIR data policy in application

Category: RI

Type of infrastructure: single site

Infrastructure location in France: Caen

French supporting institutions: UNICAEN, CNRS-INSHS

Director or RI representative in France:

Dominique Roux

Construction: 2018

Operation: 2018

Stakeholders in France: UniCaen – CNRS-InSHS

Contact in France: dominique.roux@unicaen.fr

Website: www.metopes.fr

OpenEdition

Open Science Communication in the Humanities and Social Sciences

OpenEdition is an infrastructure for academic communication in the humanities and social sciences. It brings together four platforms dedicated to journals (OpenEdition Journals), book series (OpenEdition Books), scientific blogs (Hypotheses) and scientific events (Calenda). A national research infrastructure, OpenEdition is supported by OpenEdition Center, a support and research unit (UAR 2504) of the CNRS, Aix-Marseille University, the EHESS and Avignon University.

Its missions :

- The development of open access digital publishing;
- The dissemination of uses and skills related to academic communication;
- Research and innovation in the field of digital information retrieval and enhancement methods;
- Guaranteeing a high level of reliability and availability of platforms.

OpenEdition is part of the French National Plan for Open Science.



© Lisa George

OpenEdition Freemium is a partnership offered to institutions, which aims to build a sustainable economic model for open access.

OpenEdition hosts R&D projects in the OpenEdition Lab to enable the creation of new knowledge and the deployment of innovative services.

OpenEdition coordinates, with the support of HumNum, the European OPERAS project, part of the ESFRI roadmap, and has created, with the OAPEN Foundation, the DOAB Foundation.

Relations with economic actors and/or socio-economic impact

OpenEdition proposes a programme for the development of Open Access scientific publishing in the field of SSH: OpenEdition Freemium. This partnership for institutions allows to build an innovative and sustainable economic model. All revenues generated by this programme are reinvested in the development of Open Access scientific publishing. 66% of the revenues generated by the programme are returned to publishers.

Open science and data

- 80% of the publications from projects using the infrastructure are open access
- The source codes produced by the infrastructure are open on a software forge <https://github.com/OpenEdition>
- Annual data production: 1 TB
- Infrastructure with a FAIR data policy in application
- The validated and described data are published on a data repository <https://oai-openedition.readthedocs.io/en/latest>

Category: RI

Type of infrastructure: distributed

Infrastructure location in France: Marseille

Other sites in France: Paris, Villeurbanne

French supporting institutions: CNRS, EHESS, AMU, AU

• **Director or RI representative in France:** Marie Pellen

• **Construction:** 1999

• **Operation:** 1999

• **Stakeholders in France:** 170 institutions dans le monde participant aux programmes freemium d'OpenEdition

• **Contact in France:** contact@openedition.org

• **Website:** www.openedition.org

International dimension

Director: pierre.mounier@openedition.org

• **Partner countries** DE, IT, GB, GR, HR, NLD, PR, PT, SI

• **Website:** www.operas-eu.org

Software Heritage

Software Heritage

Software Heritage is a universal archive whose mission is to collect, preserve and make easily accessible the source code of all publicly available software, with all its development history.

Software Heritage contributes to building the software pillar of Open Science, by meeting two key needs: the permanent and public archiving of source code of software produced or used by research, and the accurate referencing of versions used in experiments, thus facilitating reproducibility.

Publicly available source code is collected in several ways:

- Automatically and regularly from code hosting platforms, such as GitHub, GitLab.com or Bitbucket, and package archives, such as Npm or Pypi;
- Following a request on the "Save Code Now" interface;
- By deposit from the multidisciplinary open archive platform HAL.



© Inria

All source code, with its development history, is integrated into a specific data structure, a directed acyclic Merkle graph, and all software artefacts in the archive are associated with intrinsic and persistent cryptographic identifiers, called SWHIDs, which guarantee their integrity.

Relations with economic actors and/or socio-economic impact

Supported by a non-profit organisation, with the aim of becoming an international organisation, Software Heritage is a shared infrastructure, in partnership with UNESCO, which works to preserve and make accessible the source code of all publicly available software, for the benefit of industry, research, culture and society as a whole.

Open science and data

- The source codes produced by the infrastructure are open on a software forge <https://forge.softwareheritage.org>
- Annual data production: 100 TB
- The validated and described data are published on a data repository <https://archive.softwareheritage.org>

Category: Projet

Type of infrastructure: single site

Infrastructure location in France: Paris

French supporting institutions: Inria

Director or RI representative in France:

Roberto Di Cosmo

Construction: 2015

Operation: 2018

Stakeholders in France: CEA, CNRS, DINUM, Inria, MESRI, Université de Paris, Sorbonne U

Contact in France: info@softwareheritage.org

Website: www.softwareheritage.org/?lang=fr

International dimension

- **Partner countries IT (Université de Bologne, Université de Pise), NLD (DANS), UNESCO**
- **Website:** www.softwareheritage.org/support/sponsors

Place of research data in infrastructures



INTRODUCTION

In 2018, the European Commission¹ estimated the cost of the absence of proper scientific data management at €10.2 billion per year, pointing at a variety of sources of efficiency losses (time spent, storage costs), and negative impacts on the major stages of research work (pre-processing and “cleaning” of data, integration of heterogeneous data, data analysis). When compared to the national contribution to the European budget, this loss would amount to €1.32 billion per year for France alone.

Research infrastructures are a central mechanism for the production or processing of data in French research, since they contribute to the research of a community of approximately 100,000 researchers, teacher-researchers and engineers each year. In the context of the renewal of the infrastructure roadmap, data are therefore the subject of particular attention. This attention has evolved, and continues to do so, to better take into account the transformations that have occurred since the publication of the previous roadmap, in 2018: the context of Open Science, which has also been addressed in this report, and the structuring around the FAIR principles allow for a better consideration of data, and require better dissemination and clarification.

As data is present at all stages of research work, it is necessary to understand its place in research infrastructures, in relation to the one it takes within the projects that use these infrastructures, in order to be able to identify the relevant stage to address when considering where the changes in practices or strategy should be addressed. Assessing the maturity of data management

practices, as well as looking for good practices in terms of the digital services deployed (calculation and processing, distribution, storage and archiving, etc.), in each infrastructure or by scientific field, will make it possible to define the relevant scale of an ambitious national strategy.

This overview of data management will enable us to identify infrastructures that are particularly remarkable in terms of both their level of integration of FAIR principles and their integration into the digital transformation strategy for ESRI. The objective is that these infrastructures will make it possible, by relying on them, to disseminate the guiding principles of data management, FAIRification and integration into the EOSC ecosystem that is being developed, both at the French and European levels.

METHODOLOGY

The attention paid to data was assessed through some twenty specific questions on the form filled in by each of the candidate infrastructures, but also through questions related to open science, the French or international positioning of the infrastructure and the organisation, its user communities, its links with research organisations or industrial partners. The analysis was structured along four lines:

- **Production:** assessment of the volumes and types of data produced within the infrastructures, collected or only processed by the infrastructures;
- **Storage of data during processing:** assessment of solutions and policies for data storage in the upstream phase of the life cycle: collection, creation, analysis, processing, calculation;

¹ Cost of not having FAIR research data – <https://op.europa.eu/en/publication-detail/-/publication/d375368c-1a0a-11e9-8d04-01aa75ed71a1>

- **Processing:** assessment of the processing and computing capacities made available or used by the infrastructures;
- **Dissemination:** for data to be disseminable or even reusable by the producing teams, compliance with the FAIR principles is essential.

The assessment of data management practices, through questions on the implementation of a data management plan, compliance with the FAIR² principles and data stewardship and data protection, constitutes a complementary and cross-cutting dimension of analysis for these four areas.

DATA PRODUCTION AND STORAGE

Almost all (95%) of the candidate infrastructures declare that they produce data. This production amounts to **1,255 PB (Petabytes) for the year 2020 alone**.

This production is not evenly distributed among all scientific fields, and some

infrastructures produce hundreds of Petabytes per year, while others produce only a few Gigabytes. Among the 108 candidate infrastructures producing data, production volumes are distributed as follows:

The 31 massive data production infrastructures alone produce 1,250 of the 1,255 PB of data.

For infrastructures with an annual data production of several PB, storage is entrusted to a partner for 2/3 of them. For these 2/3, it is entrusted in equal parts to ESRI's national data centres (**CC-IN2P3, CINES, IDRIS, TGCC**) and to research infrastructures specialising in the scientific field (**IFB, SKA**, etc.).

Infrastructures with a production of an order of magnitude measured in To mostly carry the storage function within them.

The same applies to infrastructures whose production is lower in volume, the tendency to store data in-house being widespread, leading to a scattering of data, scattered in terms of hosting and storage in various premises and on

	PB	TB	GB	MB
Astronomy-Astrophysics	4	6		
Biology Health	9	18		
Energy		5	1	
Scientific information		3	1	
Analytical infrastructures and materials	3	4	3	1
Nuclear and High Energy physics	7	5		
Digital sciences and Mathematics		3		
Social Sciences and Humanities		2	2	
Digital services	3	1		
Earth System and Environment	5	12	8	
TOTAL	31	61	15	1

Data chart 1: Annual data production by order of magnitude and thematic areas. Expressed in number of infrastructures handling each type of volume (PB, TB, GB, MB)

* for digital infrastructures, their own production is reported in this table and not the volume of data

2 FAIR : Findable, Accessible, Interoperable, Reusable

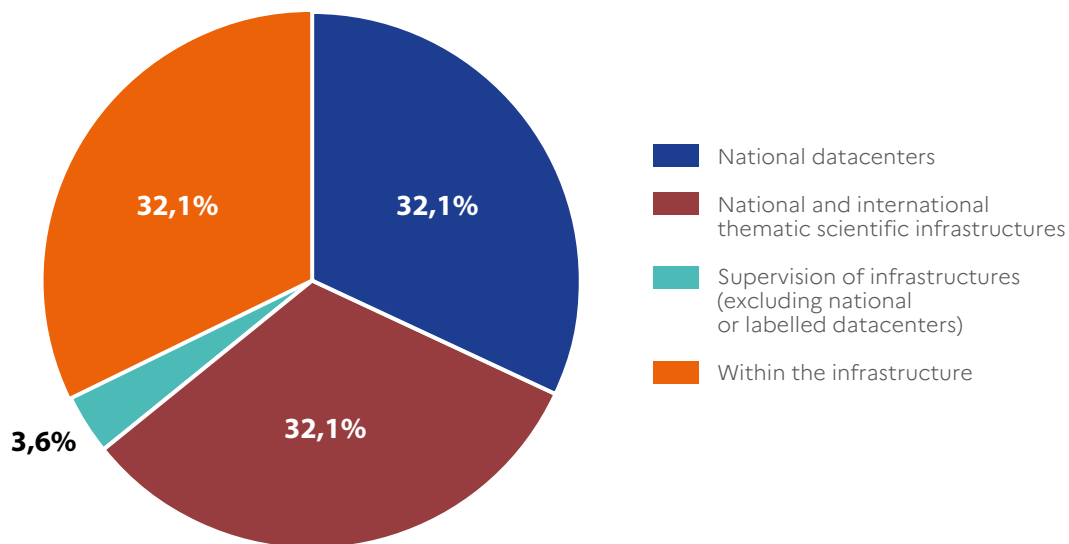


Figure 1: Data storage location for infrastructures producing Petabytes of data

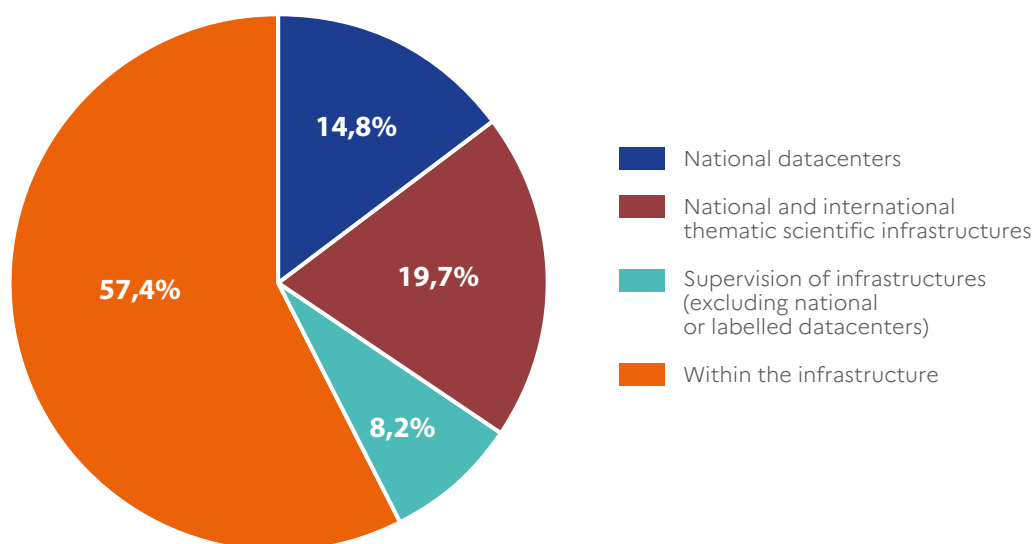


Figure 2: Data storage location for infrastructures producing Terabytes of data

various media, often managed by the research teams, or even by the researchers themselves.

It should be remembered that the scientific value of data does not depend on its volume. This analysis clearly shows that for the 77 infrastructures producing a total of 5 PB of data per year, data storage is fragile because it is operated on non-dedicated and non-backed-up systems, such as the workstations of researchers using the infrastructures.

This analysis confirms that **storage services in support of scientific infrastructures are still mainly operated by the infrastructures themselves, or by their users, which leads either, when they exist, to very fragmented services between scientific fields, or to an absence of data storage and backup services.** In addition to this dispersion, the data correspondents of the thematic infrastructures or the additional information provided by the survey responses describe these services as undersized and needing to be rationalised in order to pool efforts and reduce data loss or the risk of data loss, to control their conservation and to optimise the costs of these resources. Although the questionnaire does not refer explicitly to this, the situation highlighted raises, in addition to the risks of data loss linked to this lack of management, the issue of (cyber) security of data: stored in insufficiently managed locations and on insufficiently managed resources, these data are in fact very exposed to risks ranging from corruption (loss of integrity) to theft.

The importance of the specificity of data by major scientific fields emerges from the testimonies of those who express their unwillingness to use generic services, which are perceived as unsuitable in terms of level of service or cost. To overcome the fragility and dispersion observed, they call for the definition of a data storage service offer that is as close as possible to the needs of researchers, stressing

that this **offer must meet the specific needs of scientific communities.**

The infrastructures were also questioned on the elements of the data storage policy, in order to assess, beyond the systems in place, the care given to data storage between the infrastructures and the projects using the infrastructures.

Although on average only 61% of infrastructures address storage policy issues, some scientific fields seem to give it a more important role or have organised themselves to delegate this policy. These ratios must therefore be read with caution, as they depend on the structuring of infrastructures in each field. Indeed, the fields of **“Nuclear and High Energy Physics”**, **“Earth System and Environment”** and **“Astronomy-Astrophysics”** have structured a landscape of infrastructures by specialising some of them in digital data storage and processing services to support their entire community. Thus, the storage policy may appear to be absent in half of the infrastructures in the **“Nuclear and High Energy Physics”** domain, since those that delegate storage do not need it. The **Biology-Health** domain is taking the same approach by specialising some of its infrastructures by sector in the development of digital services dedicated to storage and analysis (genomics, in particular through the Data Analyser Collector – CAD and the French Institute of Bioinformatics – IFB). The **Social Sciences and Humanities** and **Scientific Information** fields have chosen to rely on the storage policy of the digital infrastructure service specialists (CC-IN2P3 and CINES). However, in order to ensure that storage and analysis services are adapted to the challenges of the scientific domain, the Humanities and Social Sciences have decided to specialise a team of three engineers in charge of specific IT services for the SSH domain, hosted within the CC-IN2P3. Exchanges with the coordinators of the **“Energy”** and **“Digital Sciences”** thematic groups confirm



the need to deploy shared storage policies and devices to control data backup.

Where storage policies have been provided, in the survey responses, they appear to deliver all the guarantees in terms of security and technical preservation of data. However, they never address the issues of standardised data formats, or the definition of the relevant stages at which to store such data.

For other areas in which storage is operated within the production infrastructure itself, the guarantees of storage system backup, and therefore of data security in the medium term, seem more fragile.

It emerges from this analysis of the elements reported by the infrastructures and the thematic groups that a **strategy of pooling and securing hosting and storage offers, taking into account the life cycle of the data, and coupled with the digital transformation strategy would be desirable.**

PROCESSING AND DISSEMINATION

The analysis shows that the **infrastructures are in charge of both data production and processing**, with the exception of a

few fields. The “chemistry and materials” infrastructures offer sample analysis or manufacturing capacities to their users but are not stakeholders in the projects, positioning themselves solely as data processing service providers. The **scientific information infrastructures add a strong dissemination activity to the processing activities**, which is logically at the heart of their action.

Few infrastructures use a third party to process their data. The few cases are concentrated on infrastructures with significant computing needs. The need for a computing and data processing offer adapted to the needs is strongly expressed by scientific fields for which the offers of the large computing centres do not seem to be adapted at this stage. **Intermediate services – in terms of computing hours – are requested**, such as easier access to the France Grilles offer.

The processing of data, as soon as it is acquired, requires particular attention to management and description, so that the processing of stored data is explicit and can then be reused, both by the producers themselves and by researchers from the same community or by the various infrastructure partners.

	Storage policy
Astronomy-Astrophysics	81,8%
Biology Health	77,8%
Energy	16,7%
Scientific information	75,0%
Analytical infrastructures and materials	75,0%
Nuclear and High Energy physics	50,0%
Digital sciences and Mathematics	0,0%
Social Sciences and Humanities	80,0%
Digital services	80,0%
Earth System and Environment	76,9%
AVERAGE	61,3%

Data chart 2: Presence of a data storage policy by infrastructure domain

DATA MANAGEMENT

Data from the point of view of its management was assessed in the infrastructures through the practices of data management plans, the implementation of FAIR principles and the presence of data professions, in particular data protection or data stewards. The function of the data steward is to ensure the organisation of data, the link between IT structuring and the “business-disciplinary” organisation of data and to ensure the quality of information on data, its non-obsolence or its destruction when it is obsolete.

This analysis highlights **that the care given to data in terms of storage and preservation is intimately linked to the scientific domain.** The most advanced communities are those organised in infrastructure ecosystems, those that have deployed operational data stewardship functions. The implementation of a data management plan also reveals the place

given to data, as a simple “consumable” or as a common and precious asset.

The study clearly shows that the implementation of the data management plan (DMP) remains largely in the hands of users, within the framework of their research project, but has not been identified as a structuring tool for good data management within the framework of its acquisition and intermediate storage, during the processing or permanent storage phases. The DMPs provided as attachments to the survey by the few infrastructures that have them at the level of the entire infrastructure show that **data management is taken into account very strongly from the beginning of the data cycle: from acquisition to scientific data validated by processing.** The publication and dissemination of data is linked to successful management upstream.

As with storage, **fields that have structured their infrastructure ecosystem around**

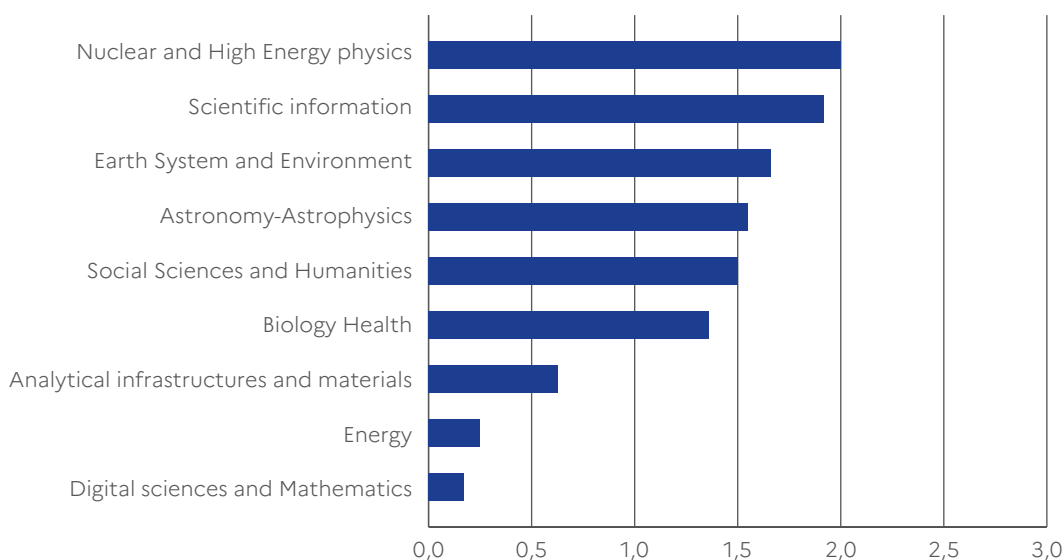


Figure 3: Maturity of data management by scientific field

Maturity is assessed on an axis ranging from 0 to 3 according to the information provided by the infrastructures on the ten or so questions relating to the data management plan, FAIR practices and the data professions. Significance of the value of the axes: 0: No practices and business lines, 1: Emerging practices and business lines, 2: Practices and presence of business lines being generalised, 3: Systematic practices and business lines sufficiently present.

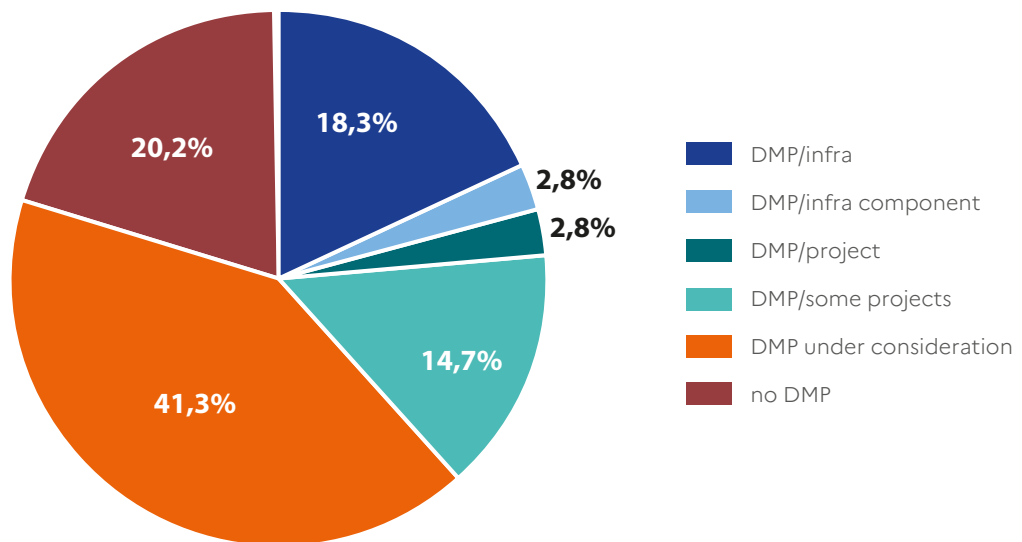


Figure 4: Data Management Plan (DMP)

one or two IT service infrastructures for data storage and processing are the most advanced in terms of data management and, ultimately, in their ability to share and open up data to their research community.

The responses to the survey underline the importance of the emergence or generalisation of data management and FAIRification practices, by scientific field. Encouraging their systematic adoption by infrastructures and imposing these practices on users in the conditions of use or in the selection of projects during calls for projects would be a major contribution to better use and reuse of data. The energy field illustrates this need for practices, not for the opening of datasets linked to publications, but to allow secure storage and sharing of data between all infrastructure partners. Indeed, these infrastructures have constraints on the restricted sharing of data linked to the R&D dimension, attached to the partnership between EPICs and energy industries. If it were still necessary to demonstrate this, this example

illustrates that the data storage systems and policies described contribute to good data management from the beginning of the life cycle and are not just a practice dedicated to infrastructures that have adopted strong openness strategies.

RESEARCH DATA PRESERVATION STRATEGY BY SCIENTIFIC AREA

On the basis of these elements of a shared observation between producers and users, an ambitious national strategy could be drawn up for the sovereign preservation of research data, from their acquisition stage and throughout their processing. **Data storage policies should seek to define, for each scientific field, the relevant stages of data preservation and curation in order to enable economical management of intermediate and long-term storage, taking into account reuse needs while reducing the weight of obsolete and/or useless data.**

It would also provide both the producing teams and the users of the infrastructure

with the capacity and guarantee of re-access to relevant and quality data for further processing, or for integration with other datasets.

The opening up of "citable" datasets constitutes only a small fringe of the research data processed, particularly because they are overwhelmingly associated with publications, whereas "dormant" data, which is difficult to access due to a lack of description, structuring or preservation, leads to an enormous loss of scientific potential and therefore to an obvious economic loss. First and foremost, this lack of care for the data, from the moment it is acquired, leads a large proportion of the research teams producing these data to experience great difficulty in re-accessing their own data, as soon as the person who acquired or processed it has left the laboratory, and the data is not stored on guaranteed and organised devices. When infrastructures are asked about the issue of opening up the data associated with their publications, the first concern expressed is that of preserving/recovering or reusing their own data. These observations call for an urgent and structured response at the ESRI level so that the services offered to researchers are legible through offers that meet their needs.

The regional data center labelling process identifies the regional hosting offer that complements the offer of national centres already used by a significant number of Research Infrastructures. It accompanies the implementation of a mutualisation strategy aimed at deploying secure, state-of-the-art, operated and optimised services. In the medium term, this federation of Datacenters is intended to serve as a deployment base for ESRI's **digital services. In particular, this approach ensures the sovereign and secure preservation of data used and produced by the major scientific fields and Research Infrastructures.** The approach accompanies the transformation of

digital uses and resources deployed for the entire research community.

The communities' support for the modernisation of the deployment of digital resources is a source of substantial savings. It must also make it possible to guarantee the security and sovereignty of data processing and to offer researchers a legible, accessible and competitive IT offer. It must accompany the development of new analysis capacities or the integration of data not yet exploited.

With regard to data services, a tiered approach based on the maturity of each sector would aim to define different levels and types of service offers according to the specific needs of each of the 8 scientific fields. An ecosystem approach of specialised digital service layers based on distributed IT infrastructures and cloud services hosted in approved national and regional data centres would be desirable. This will allow research communities to benefit from specific services while contributing to the reduction of the dispersion of IT resources in scientific infrastructures or in institutions/laboratories. This approach will make it possible to reduce risks, support quality and compliance procedures, and deploy efficient and competitive services at the service of research, thus responding to the loss of efficiency highlighted in 2018 by the European Commission's study in the context of the EOSC initiative.

DATA SERVICE INFRASTRUCTURES AS STAKEHOLDERS IN THE DIGITAL TRANSFORMATION

The necessary consideration of data issues by research infrastructures and the progression of their level of adequacy to the FAIR principles must be done in a strategy aligned with that of digital transformation, as the infrastructures that produce, use and make data available to research communities

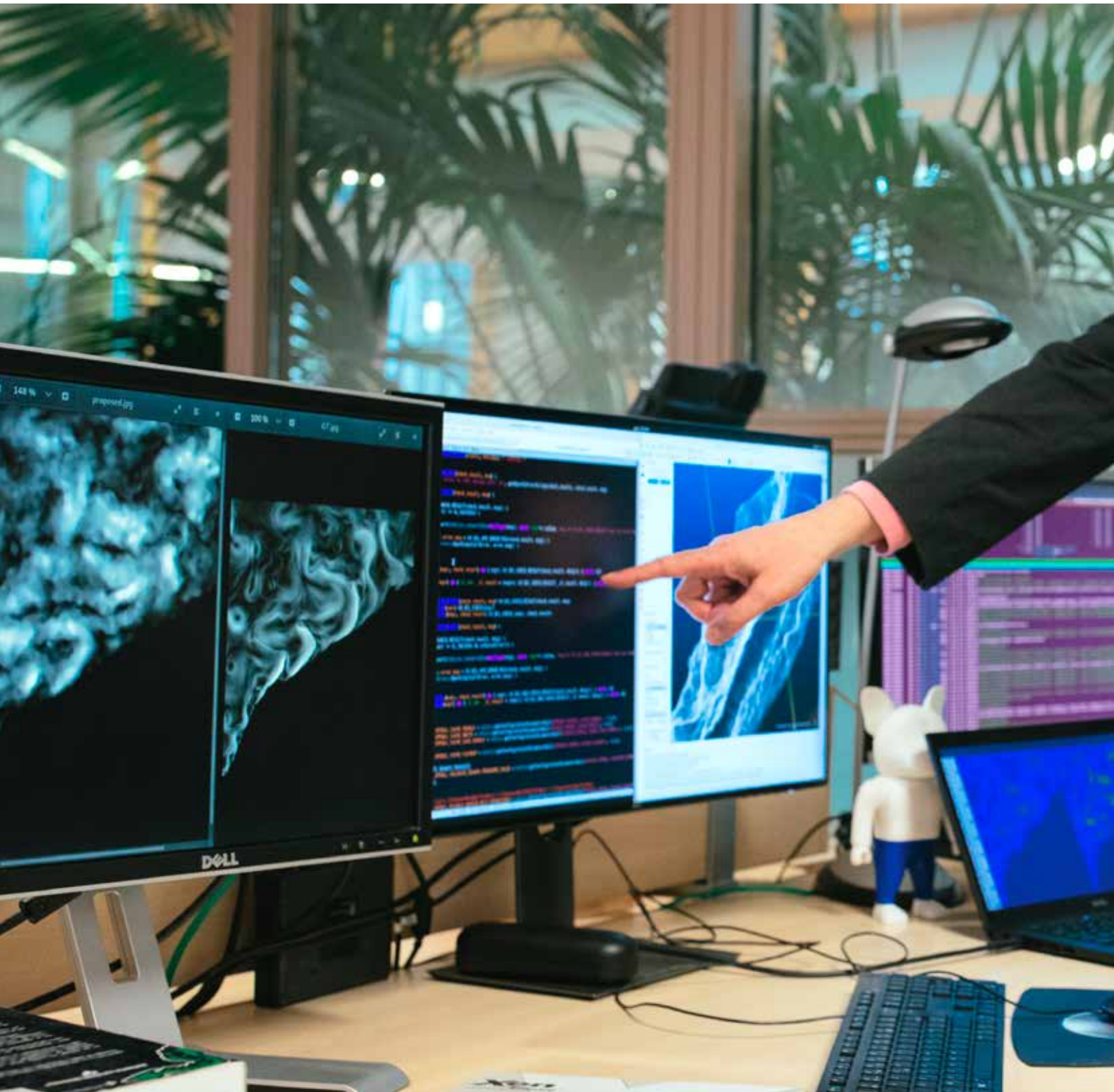


are very consuming of digital resources. The implementation of a strategy is complex, as it requires federating the actors involved, in a logic of rationalisation of efforts and skills. To do this, we intend to rely on the initiatives built by the infrastructures that have the most advanced approaches, and whose central position within the disciplinary fields will provide a very good drive effect.

As we have seen, the diversity of the paths of each disciplinary field prohibits thinking of data service infrastructures as a single model. It is therefore advisable, on the other hand, to try to identify certain core structures, whose action crosses fields, such as the CC-IN2P3 or the CINES, and to aggregate the disciplinary poles according to their relevance, such as DATA TERRA and PNDB, for which the data issue is at the heart of their rapprochement. The CDS and HUMA-NUM, whose action is historical in the fields of astronomy and SSH are also essential. The field of health, due to its progress and the challenges relating to the development of digital processing tools, constitutes a final brick, with the IFB, the CAD and France Cohortes.

Initially, these nine infrastructures will receive special attention, with the aim of substantially improving data services in the framework of this national roadmap.

Finally, let us note the particular role of two infrastructures that are not strictly speaking data service infrastructures, but whose role is particular in this landscape: on the one hand, GENCI, which is in charge of equipping computing centres with computing means and computational data storage, and on the other hand, RENATER, whose network architecture must take into account the main data hosting and storage points.



The image shows two men in a modern office environment. One man, wearing glasses and a dark suit, stands and points towards a laptop screen. The other man, wearing a teal sweater, sits at the desk, looking at the screen. The background features large windows with a view of greenery and a modern interior design. The text is overlaid in the center of the image.

Research
infrastructures
and **open science**

Open science: three main levels of progress in the roadmap infrastructures

INTRODUCTION

The National Open Science Plan and the founding principles of the European Open Science Cloud (EOSC) recall the fundamental principle of open science: research is a common good that should be shared with all. The open science movement is recognised by the scientific community and by governments as the new paradigm that promotes transparency, collaboration and usefulness to society. It is a true accelerator of research and opens up great heuristic potential, i.e. scientific discoveries.

The entire research process needs to be transformed according to the open science paradigm. However, if open access to a publication can be decided of by the researcher at the time of submission of an article to a journal, the opening or sharing of data, code, methods/protocols and software of the research must be considered upstream of the project. Even further upstream, the exploration and use of data and code produced by others could lead to a new approach to the research question, or at least to a reduction in research time and costs.

The challenge is therefore to sustainably transform research practices by integrating open science in a coherent manner throughout the research cycle: from the research question to the dissemination of results. The renewal of the infrastructures' roadmap represents an opportunity to assess, at the level of each of the infrastructures, of the scientific fields and of the infrastructures as a whole, which support the research of several hundred thousand French researchers, academics, engineers and scientific information professionals, the degree of penetration of open science and the transformation of practices.

Furthermore, the adoption of open science by communities has become a criterion of research excellence in EU calls for projects, whereas it was previously

considered more of a technical criterion. Research infrastructures must themselves be the bearers of an exemplary open science strategy and practices in order to offer their users services that are part of this framework of scientific excellence. Infrastructures represent a major vector for this concrete implementation of open science and a massive lever for transforming practices.

METHODOLOGY

The analysis of the dynamics of open science within the infrastructures was based, in the application form, on some twenty questions, which reflect five axes, none of which is optional:

- **Open science strategy:** there is a need for each infrastructure to have a clear, explicit and public policy on the different dimensions of open science, as suggested by the measure in the National Open Science Plan: *"Engage higher education and research actors to develop an open science policy"*;
- **Code and software openness policy:** the code produced by the infrastructures must be part of a development strategy that complies with best practices in the field and, as far as possible, is based on clearly stated public copyright licenses;
- **Open access to publications policy:** Measure 1 of the National Open Science Plan requires each operator to *"Make open access publication of articles and books resulting from publicly funded calls for proposals mandatory"*. Infrastructures cannot be an exception to this principle, which we therefore seek to identify as an element of policy where the infrastructure is suitable;
- **Maturity of the data policy:** data are part of the State's research heritage and have too often been considered as consumables, whereas they are pillars of the capacity to provide scientific

evidence, and potential instruments for new discoveries, through reuse and crosses not initially foreseen. Measure 4 of the National Open Science Plan clearly calls for: *“Implement the obligation to disseminate publicly funded research data”*, which is nothing more than a formulation of Article 6 of the Law for a Digital Republic (2016). For these reasons, it is necessary for each infrastructure producing, collecting or processing data to set up a long-term data policy;

- **Data governance actors:** the complexity of data issues implies having data professionals on site, and in particular people responsible for data governance as well as people in charge of their “fairisation”: compliance with the FAIR principles aiming to make them “Findable, Accessible, Interoperable and Reusable”, these principles being themselves broken down into 16 items.

The assessment of the impregnation of open science concerns the infrastructures that bear scientific stakes or disseminate scientific production and knowledge. So-called “digital services” infrastructures for which open science issues were not relevant are not included in this analysis.

LEVELS OF IMPREGNATION OF OPEN SCIENCE IN INFRASTRUCTURES

While an explicit open science strategy is virtually absent in all the infrastructures, open science policies for publications, code or software and data are emerging in certain scientific fields or are more widespread in others. The responses of the infrastructures reveal strong specificities in the concrete implementation of open science. These specificities are specific to each research field. The methods of producing research data, which vary greatly from one field to another, are a differentiating factor. These policies may have developed before

the concept of open science was forged, in communities where the production of data depended on expensive observation or measurement instruments for which access to researchers is limited. The fields of “Astronomy” and “Nuclear and High-Energy Physics” were pioneers in the sharing of data produced at the scale of their communities, with some researchers working only with data acquired or processed by others.

Whatever the maturity of open science policies, the responses to the questionnaire reveal a common gradient. The story has usually started with open code/software, generally continued with open publications, and finally addressed the complexity of the data issue. This is why we will follow this narrative thread.

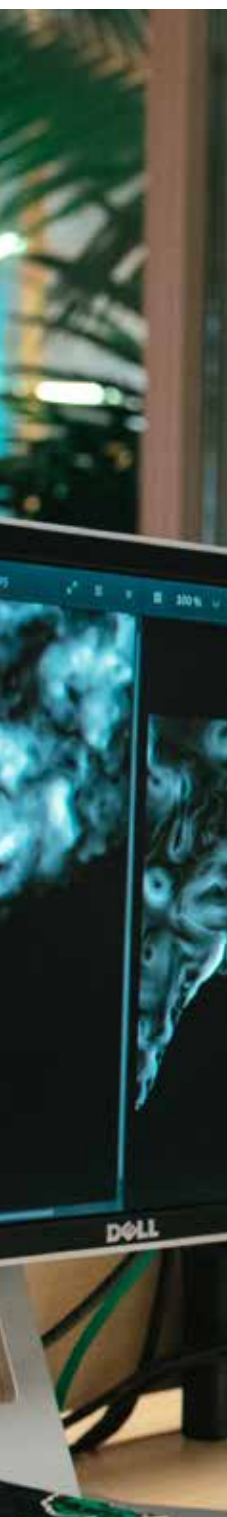
Open science policies according to scientific or thematic areas

All scientific fields are engaged in adopting open science policies, but the landscape of this adoption can be broken down into three groups: policies in the process of systematisation, generalisation or emergence.

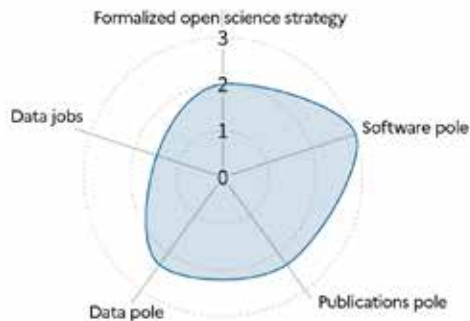
Policies being systematised: “Scientific Information”, “Nuclear and High-Energy Physics”, “Astronomy” and “Earth System and Environment”

A first family of four thematic areas is distinguished by more advanced open science policies. These are “Scientific Information”, “Nuclear and High-Energy Physics”, “Astronomy” and “Earth System and Environment”.

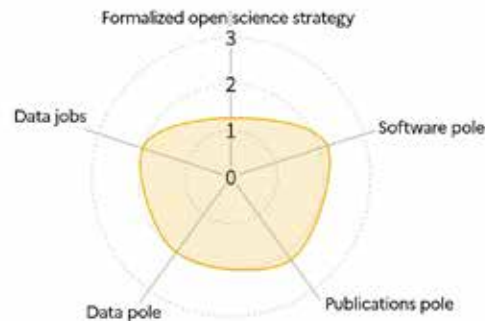
The open science strategy is very advanced in the field of “Scientific Information”, which includes infrastructures such as HAL, Software Heritage or OpenEdition, because the heart of their mission is the most possible universal dissemination of knowledge. They have missions of dissemination, structuring of information, certification and preservation. However, they are also in charge of linking scientific information,



Scientific information



Nuclear and high-energy physics



Earth system and environment



Astronomy

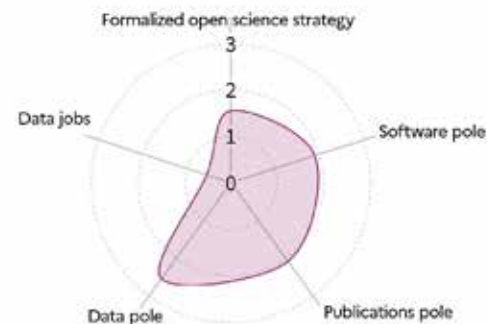


Figure 1: Representation of the impregnation of open science in the infrastructures of the fields of “Scientific Information”, “Nuclear and High-Energy Physics”, “Astronomy” and “Earth System and Environment”.
 Axes: Formalized Open Science Strategy, Software Policy, Publication Policy, Data Policy, Data Governance Trades.
 Significance of the value of the axes: 0: No policy, 1: Emerging policy, 2: Policy being mainstreamed, 3: Systematic policy

particularly through a framework of identifiers and interoperability links. In all other areas, the open science strategy exists rather tacitly through practices or policies already in place, and is not yet formalised as a condition for using the infrastructure.

For the four domains of this family of infrastructures, the gradient of policy maturity that the story explains (codes/software, publication follow-up, and only finally data) is found to a greater or lesser extent. In particular, not all infrastructure software development policies are maximal. The data sharing policies, which have long been in place in the “Astronomy”, “Nuclear and High-Energy Physics” communities, followed by the “Earth System and Environment” sciences community, are clearly visible in the responses from the infrastructures. The specialisation of data professions, particularly through data governance and stewardship functions,

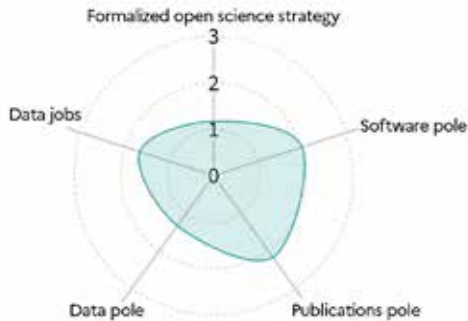
is already well established in environments requiring increased sharing of quality data described for use by heterogeneous communities, beyond that of their producers. This presence, which seems to be less in the field of “Astronomy”, is explained by the diversity of infrastructures in the field – observational instruments that do not store data, the latter being centralised on a single infrastructure, which is the bearer of these functions for the entire community.

Policies being mainstreamed: “Social Sciences and Humanities” and “Biology and Health”

The second family includes the fields of “Social Sciences and Humanities” and “Biology and Health”.

While open science policies are being generalised in these two areas, data-related professions are clearly more present. Personal data, which is very present in these two

Social sciences and humanities



Biology and Health

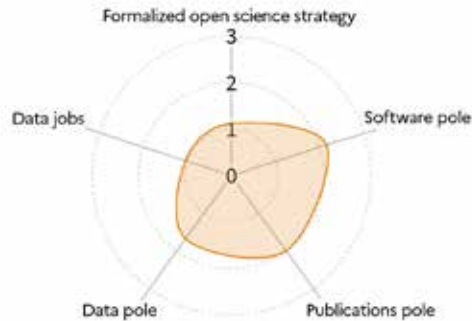


Figure 2: Representation of the impregnation of open science in the fields of “Social Sciences and Humanities” and “Biology and Health”.

Axes: Formalised open science strategy, Software policy, Publication policy, Data policy, Data governance professions.
Axis value significance: 0: No policy, 1: Emerging policy, 2: Policy being mainstreamed, 3: Systematic policy

fields, requires the expertise of the data protection officers of the institutions that own the infrastructures, but also increased mobilisation of the data governance function at the level of each infrastructure to organise and instruct on the issues of controlled access sharing of this data, which cannot be largely open. The obligations and practices of anonymization of personal data are also part of the issues that these two groups of infrastructures could share or mutualise through common approaches. However, it should not be forgotten that these two disciplinary groups also mobilise non-individual data, which are less complex to share.

Emerging policies: “Analytical Infrastructures and Materials”, “Energy” and “Digital Sciences and Mathematics”

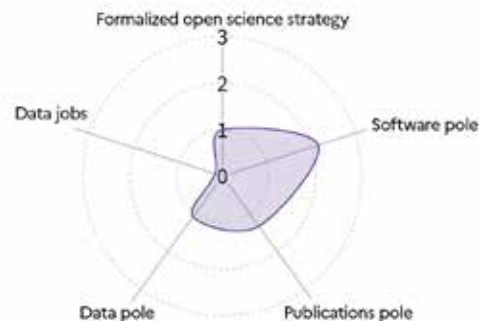
The field of “analytical infrastructures and materials” brings together a set of service infrastructures for research projects in the context of the analysis of their samples or offers of micro and nano manufacturing facilities (clean rooms). This positioning as a service offer does not place these infrastructures at the heart of the research process of each project. As a result, the issues related to data or manufacturing processes are carried out directly by the projects, outside the infrastructures. This helps to explain the varying levels of policy for software, publications and data. The challenge is therefore to define

the conditions of access to the infrastructures, specifying the policies for managing and opening up data and publications.

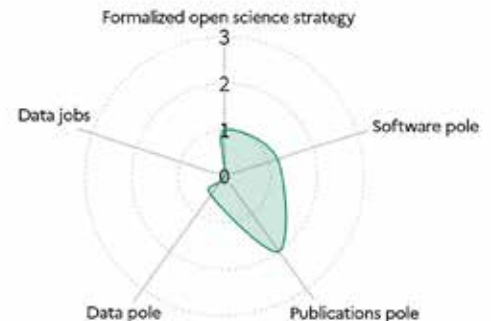
In the field of “energy”, the policy of opening up publications is being generalised, while the policy on codes and data is emerging. Many of the infrastructures in this field are dedicated to R&D and are therefore marked by aspects of intellectual property and secrets that protect processes and technical innovations. This field includes infrastructures often co-sponsored by several EPICs (French public establishment of an industrial and commercial nature) in association with energy industrialists. The challenge in terms of opening up data and code is therefore primarily based, at the level of each infrastructure, on the development of policies for sharing data and code between the infrastructure partners. A certain number of obstacles therefore remain to be overcome in order to meet the challenges of integrating data, models and simulations on a scale that brings together infrastructures dedicated to the various energies: concentrated solar power, photovoltaic solar power, nuclear power, marine energy, etc., and those in the environmental field.

The “digital sciences” are a special case. The three infrastructures in this field cover a wide range of application areas: the visualisation of complex data, distributed computing of connected objects and robotics. The challenge for

Material science and engineering



Energy



Digital sciences and mathematics

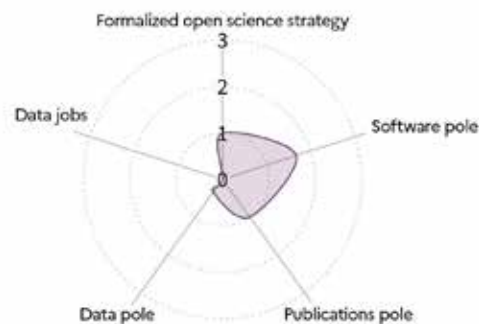


Figure 3: Representation of Open Science impregnation in the fields of “Analytical Infrastructures and Materials”, “Energy” and “Digital Sciences and Mathematics”

Axes: Formalised open science strategy, Software policy, Publication policy, Data policy, Data governance professions. Axis value significance: 0: No policy, 1: Emerging policy, 2: Policy being mainstreamed, 3: Systematic policy.

these infrastructures would be to be able to mobilise data produced by infrastructures in other fields to provide new approaches to data processing or integration. The step forward in terms of open science today lies in the generalisation of good practices in terms of opening up codes and software through the use of public copyright licenses.

Open science policies linked to the coherence of the infrastructure landscape in each scientific field

The maturity of the policies observed in these three families seems to be correlated to the interconnections that exist between the infrastructures within a field. Depending on the scientific field, research infrastructures form a more or less coherent and systemic landscape for their community. From this point of view, three families of organisations emerge:

- an ecosystem of complementary infrastructures ;
- emergence of infrastructure ecosystems by sub-domains;
- dispersed infrastructures.

An ecosystem of complementary infrastructures

The family of infrastructures whose open science policy is being systematised corresponds to a structured landscape of infrastructures in relation to each other within a scientific domain. Indeed, the “Nuclear and High-Energy Physics”, “Earth System and Environment”, and “Astronomy-Astrophysics” scientific groups propose a landscape of interconnected infrastructures that support the research of communities ranging from 12,000 to 30,000 researchers, academics and engineers. The implementation of large

or rare research infrastructures, built and operated by international collaborations over several years or even decades (“Nuclear and High-Energy Physics”, “Astronomy and Astrophysics”) or the understanding and modelling (“Earth System and Environment”), have required the organisation of an ecosystem of complementary infrastructures. Instruments, particularly in physics, astronomy, experimentation or observation and service infrastructures, have been organised to support the storage, processing and even sharing of the data produced.

In each of these thematic areas, the infrastructures produce very large volumes of data, as well as observation and/or longitudinal monitoring data that can only be acquired once. These specificities have led these fields to structure, describe, catalogue and make the data accessible to their community.

The field of “Scientific Information” also offers a coherent and complementary landscape of infrastructures intended to allow the certification, the maximisation of the impact, the linking and the conservation of the knowledge of humanity. Their originality lies in their position at the interface between the scientific world, which produces knowledge, and the scientific world, which consumes knowledge, but also at the interface with non-academic audiences, in particular socio-economic, political and cultural audiences. This importance and diversity of audiences has made it necessary to produce a landscape that is both visible and legible for all audiences. This field cuts across all scientific sectors and thus supports the entire French research community. Even when its “champions” were born in a specific disciplinary field, the trend is towards disciplinary extension.

The structuring of infrastructures in complementarity with each other is a very favourable factor for the development of open science policies and must be encouraged in

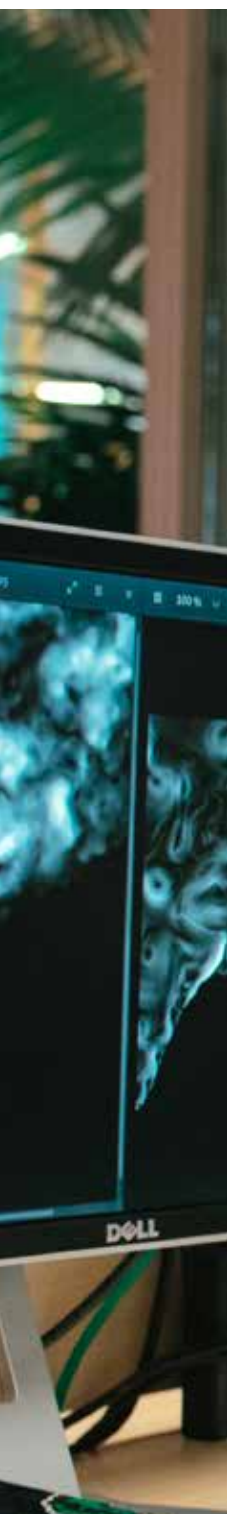
the context of the systematisation of policies at work. This structuring has led the three scientific domains “Nuclear and High-Energy Physics”, “Astronomy and Astrophysics” and “Earth System and Environment” to develop the skills of description, cataloguing and exhibition of research data within one or two infrastructures, which makes it possible to guarantee the homogeneity of vocabularies, metadata catalogues, thesauri, etc., for data description and thus facilitates the integration of multiple datasets from different instruments by projects that have not produced them. These three domains are in fact the most advanced in making their data compliant with the FAIR (“Findable, Accessible, Interoperable and Reusable”) principles, thanks to the development of specific skills. The grouping or networking of data professionals is thus a lever for the sustainable transformation of data sharing and opening policies. This strategy also increases the discoverability of data sets. It also favours the creation of large reference datasets, while reducing the effort required to describe data, protocols and codes in detail.

Emergence of infrastructure ecosystems by sub-domain

The “Biology-Health” and “Social Sciences and Humanities” thematic groups bring together infrastructures which, by thematic sub-groups, initiate or have set up convergences.

In “Biology-Health”, different types of infrastructure clusters are being formed around different services such as the provision of an IT infrastructure dedicated to Life Sciences by the French Institute of Bioinformatics (IFB), or the construction of large reference data sets for health studies and research within the framework of France Cohorts or the Collector, Analyser of Genomic Data (CAD) of the France Genomic Medicine Plan.

In the “Social Sciences and Humanities”, HUMA-NUM has an IT infrastructure dedicated to the entire SSH research



community, which is structuring not only the community but also other research infrastructures in the field such as Progedo.

Within the framework of these two research fields, the IFB and HUMA-NUM infrastructures play a structuring role by providing an IT support service to other infrastructures in their field.

This first stage of structuring by sub-domains contributes to the emergence or generalisation of open science policies on the software, data and publication axes without, however, embarking on the path of integrating data into large reference sets on the scale of a large “biology-health” or SSH community. The path to be investigated would be to evaluate the relevance, in “biology and health” in particular, of a structuring that goes beyond sub-domains (e.g. biomics, cohorts, etc.), which would make it possible to provide data integration and cross-referencing services to researchers.

Dispersed infrastructure by specialisation

The scientific domains “Analysis infrastructures and materials” and “Energy” group together infrastructures or instruments serving very different research projects and do not form an infrastructure ecosystem for an entire community. This dispersion leads to emerging open science policies. Given the contexts of these two fields, linked to the diversity of analyses for the first and to the consortial logic of R&D for the second, an acceleration trajectory could lie in the development of data professions and their networking in order to initiate a common reflection on the data description standards applicable to their fields.

With regard to the “digital sciences”, one way of structuring this research community in support of various application areas could be the creation of an international group within the RDA (Research Data Alliance) to draw up recommendations and standards for these areas of distributed computing.

LEVERS OF ACCELERATION

Even if many cultural, structural or organisational elements lead to different degrees of maturity in the concrete implementation of open science in each scientific field, three acceleration levers seem to benefit all infrastructures.

Formalising open science strategies

Open science practices are at different stages of development depending on the scientific field, but almost all infrastructures share the same lack of formalisation of an open science strategy. Formalising this strategy for the most advanced ones (in particular by displaying a FAIR policy that is already being implemented in practice) or designing one for the others would make it possible to engage in a dialogue with the funding bodies in the context of strengthening data engineering resources, to build dialogue interfaces between infrastructures or infrastructure domains and to sustainably engage infrastructure users in the transformation of their practices.

Dialogue interfaces between infrastructures are being initiated between fields such as the environment and biology-health, notably through the description and opening of plant phenotyping data (Phenome Emphasis – “biology-health”) on the Data Terra infrastructure (“Earth system and environment”), or conversely the use of the French bioinformatics infrastructure (IFB) (“biology-health”) by the RARe infrastructure (agronomy resource centres in the environment field). The formalisation of open science strategies would enable all infrastructures or fields to identify opportunities for dialogue or collaboration: energy-environment links for data integration through the alignment of description vocabularies, common technical approaches to data anonymization between SSH and “biology-health”, etc.

Providing infrastructures with a “funder registry” identifier

Whatever the field, the contribution and impact of infrastructures on scientific knowledge are largely underestimated, as the use of their services by research projects is still not quoted enough in the various research results: publications, software or data. It is proposed to provide each research infrastructure with a unique identifier of the “funder registry” type, as four of the infrastructures (CERN, ESO, AEROSTATS, ECELL FR) have initiated. This will make it possible to generalise a binding policy of quoting the infrastructure by this identifier: in the acknowledgements and metadata of publications as well as in the metadata of data sets and code produced thanks to the infrastructure. “Scientific information” infrastructures should also allow this type of information to be recorded in their metadata, as OpenEdition already does. The Ministry of Higher education and Research could take charge of this action. This implementation should make it easier to monitor the outputs resulting from the use of infrastructures and thus highlight their contribution to the production of scientific knowledge. As some infrastructures have already implemented, the respect of citation by users would also be a contractual condition for the selection of candidate projects during calls for projects launched by the infrastructures.

Reduce the task of data integration by research teams

Data acquisition, processing, description and dissemination systems have often been set up by type of instrument and by field of application. Scientific data, as well as its processing and description, are intimately linked to the research question and the scientific field and cannot be dealt with through a transverse approach to all fields or infrastructures. However, within the same field, certain sectoral approaches

make multidisciplinary studies difficult, such as integrated ecosystem approaches in the environment, ocean/atmosphere or atmosphere/continental surface interactions... At the borders between two fields, the reduction of the impact of energy production on the environment (air quality, greenhouse gases, waste production) by bringing together the R&D work of energy infrastructures and the research questions addressed by infrastructures in the environment field could also be held up as an example, as could the interest of the RARE infrastructure (resource centres in agronomy in the environment field) for genetic resources of interest in “biology and health”.

The data access interfaces offered to users are numerous but, generally, not very homogeneous and use different vocabularies and metadata catalogues. As the *Livre Blanc sur les infrastructures françaises de recherche du domaine des sciences du système Terre et de l'environnement*¹ points out, the task of integrating the data falls to the user scientific team, which makes it very difficult to use. The segmentation of systems and the sectoral approach are a hindrance to the rationalisation of data professions and to the alignment of data sets and their interoperability. For scientific domains that have taken steps to specialise certain infrastructures, a more mature data policy and the development of specialised data professions reveal a greater potential for data use and savings in terms of the effort required to reprocess or describe them.

The thematic groups of this roadmap call for the generalisation of this strategy of strengthening and structuring data professions by scientific field. This would make it possible to support the standardisation of vocabularies for the benefit of data integration on a larger scale, thus facilitating the creation of large data reference sets by field or dialogue between scientific fields.

¹ *Livre Blanc sur les infrastructures françaises de recherche du domaine des sciences du système Terre et de l'environnement* – AllEnvi's strategic vision 2020-2030, november 2019.

Acknowledgements

Were very involved in the production of this document:

- the research and innovation strategy department of the DGRI;
- the department of Large Research Infrastructures of the DGRI;
- the MESRI information and statistical studies service.

Research infrastructures index

A CTRIS-France.....	194	EMBL.....	58
AGATA.....	118	EMBRC France.....	64
AnaEE-France.....	195	EMERG'IN.....	65
Apollon.....	148	EMIR&A.....	154
C AD.....	83	EMSO-France.....	200
CALIS.....	59	E-RIHS France.....	135
CC-IN2P3.....	224	ESO.....	30
CDS.....	36	ESO/ALMA.....	31
Celphedia.....	60	ESRF.....	149
CERN.....	112	ESS.....	150
CERN LHC.....	113	EURO-ARGO-France.....	191
CFHT.....	33	European XFEL.....	151
ChemBioFrance.....	61	F AIR.....	116
CINES.....	225	FBI.....	66
CLIMERI-France.....	196	F-CRIN.....	67
CollEx-Persée.....	236	FLI.....	68
CONCORDIA.....	189	FOF.....	192
CONSTANCES.....	62	France Cohortes.....	69
CONTINUUM.....	172	France Génomique.....	70
CTA.....	34	France Grilles.....	226
D ATA TERRA.....	197	FR Exposome.....	85
DUNE / PIP-II.....	114	FRISBI.....	71
E BRAINS-FR.....	84	FR Solaris.....	95
ECCSEL-FR.....	94	G ANIL-SPIRAL2.....	117
ECELLFrance.....	63	GENCI.....	222
ECMWF.....	188	H AL+.....	237
ECORD/IODP.....	190	HESS.....	37
EGO-Virgo.....	115	HUMA-NUM.....	132
eLTER-France OZCAR.....	198	I AGOS-France.....	201
eLTER-France RZA.....	199	IBISBA France.....	72

ICOS-France	193	P AO	123
IDMIT	73	PARADISE.....	40
IFB.....	74	Phenome-Emphasis France	81
ILICO	202	PNDB.....	205
ILL.....	152	ProFI	82
IN AIR.....	203	PROGEDO.....	133
Infranalytics.....	155	R ARe.....	206
INGESTEM.....	75	RECOLNAT.....	207
Instrum-ESO	38	REFIMEVE.....	159
In-Sylva France	204	RéGEF.....	208
IRAM.....	35	RENATECH+.....	160
ISTEX.....	238	RENATER.....	223
J UNO.....	119	Résif-Epos	209
K M3NeT	120	RnMSH	134
L aboratoire P4 Jean Mérieux.....	76	ROBOTEX 2.0.....	173
LiPh@SAS	77	S ILECS	174
LMJ-PETAL.....	156	SKAO	32
LNCMI	157	Software Heritage.....	241
LOFAR/NenuFAR.....	39	SOLEIL.....	153
LSM.....	121	T HEOREM.....	96
LSST	122	W EST	97
M etaboHUB.....	78		
Métopes.....	239		
METSA.....	158		
N eurATRIS.....	79		
NEUROSPIN	80		
O penEdition	240		

Copyright

Cover: 1st cover: top left: @ CERN – bottom left: © Cyril Frésillon/CC IN2P3/CNRS –right: © ESO – **4th cover:** left: © FT, UMR LEPSE, INRAE Montpellier – top right: c ESRF/S. Cande, 2021 – bottom right: @ Resif-Epos

Foreword: © MESRI – **Introduction:** © MESRI – **p. 18:** © ESO/B. Tafreshi (twanight.org) – **p. 44:** © CEA/I2BM/Neurospin – **p. 88:** © Cyril Frésillon/CNRS – **p. 102:** © European XFEL/Jan Hosan – **p. 128:** © CNRS/Emmanuel LAROZE – **p. 138:** © CERN – **p. 168:** © Cyril Frésillon/CNRS Photothèque – **p. 184:** © Lesbats Stephane (2022). Navire océanographique L'Atalante. Ifremer – **p. 218:** © Cyril Frésillon/CC IN2P3/CNRS – **p. 260:** © Inria/Photo M. Magnin.



**MINISTÈRE
DE L'ENSEIGNEMENT
SUPÉRIEUR,
DE LA RECHERCHE
ET DE L'INNOVATION**

*Liberté
Égalité
Fraternité*

