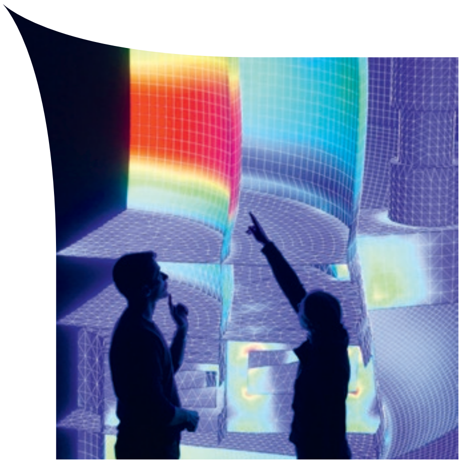
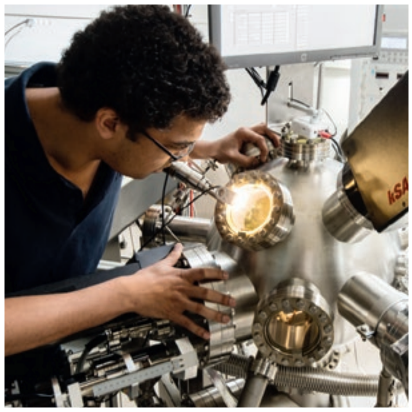
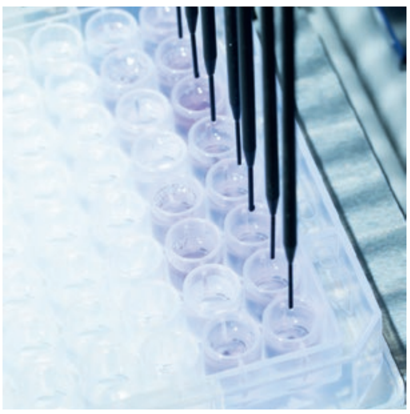


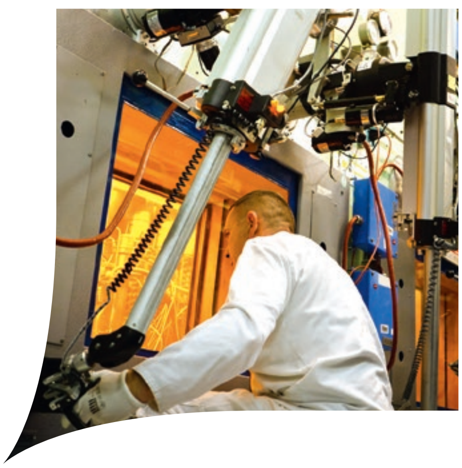
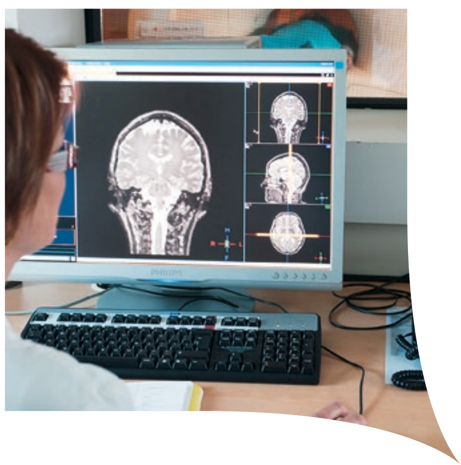



THE CEA
AT THE HEART OF GREAT NEW CHALLENGES

ANNUAL REPORT 2016





FROM RESEARCH TO INDUSTRY

cea

KEY FIGURES 2016

4,938
PUBLICATIONS
in peer-review journals

1,147
DOCTORAL STUDENTS
AND 211
POST-DOCTORAL RESEARCHERS
at the CEA

422
EUROPEAN PROJECTS
including 194 FP7 projects and 228 H2020 projects

743
PRIORITY PATENTS FILED
(the CEA holds fourth place in the National Institute of Industrial Property (INPI) ranking of public and private patent applicants)

OVER
6,100
PATENT FAMILIES IN FORCE

195
STARTUPS
created since 1972 in the field of innovation and technological development,
132 since 2000

OVER
600
INDUSTRIAL PARTNERS

55
FRAMEWORK AGREEMENTS
in force with **universities and graduate colleges**

30
COMPETITIVENESS CLUSTERS,
of which
17 are administered by the CEA

51
RESEARCH UNITS
co-supervised by the CEA and academic partners
(45 UMR, 5 UMS, 1 USR)

16,010
EMPLOYEES

9
CENTRES

5
REGIONAL TECHNOLOGY TRANSFER PLATFORMS

4.1 billion Euros
CIVIL AND DEFENCE BUDGET

CORPORATE GOVERNANCE

(AS AT 1ST JUNE 2017)

GENERAL DIVISION

- Chairman: **Daniel VERWAERDE**
- Deputy Chairman: **Christophe GÉGOUT**
- Chief of Staff and Performance Director: **Dominique MONVOISIN**
  - Security-Safety Delegate Director: **Edwige BONNEVIE**
  - Renewable Energy Delegate Director: **Jean THERME**
  - International Cooperations Director: **Gabriele FIONI**
  - Sustainable Development Director: **Françoise TOUBOUL**
  - Compliance and Internal Control Director: **Éric CAPELLE**
  - Special Adviser Director: **Hervé BERNARD**
- High Commissioner for Atomic Energy: **Yves BRÉCHET**
- Chief of Staff: **Claire KERBOUL**
- National Institute for Nuclear Science and Technology: **Philippe CORREA**
- General and Nuclear Inspection Division: **Xavier VITART**

OPERATIONAL DIVISIONS

- Military Applications Division: **François GELEZNIKOFF**
  - Cesta Centre: **Jean-Pierre GIANNINI**
  - DAM Île-de-France Centre: **Pierre BOUCHET**
  - Gramat Centre: **Jehan VANPOPERYNGHE**
  - Le Ripault Centre: **Serge DUFORT**
  - Valduc Centre: **François BUGAUT**
- Nuclear Energy Division: **François GAUCHÉ**
  - Cadarache Centre: **Christian BONNET**
  - Marcoule Centre: **Philippe GUIBERTEAU**
- Fundamental Research Division: **Vincent BERGER**
  - Paris-Saclay Centre: **Michel BÉDOUCHA**
- Technological Research Division: **Stéphane SIEBERT**
  - Grenoble Centre: **Philippe BOURGUIGNON**

FUNCTIONAL DIVISIONS

- Strategic Partnerships and Sales Division: **Franck LÉNA**
- Strategic Analysis Division: **Jean-Philippe BOURGOIN**
- Central Safety Division: **Edwige BONNEVIE**
- Central Safety Division: **Xavier CLÉMENT**
- Programmes and Financial Division: **Marie-Astrid RAVON-BERENGUER**
- Legal Affairs Division: **Florence TOUÏTOU-DURAND**
- Nuclear Safety and Protection Division: **Jean-Marc CAVEDON**
- Internationales Relations Division: **Anne LAZAR-SURY**
- Human Resources and Social Relations Division: **Philippe SANSY**
- Information Systems Division: **Louis ARRIVET**

GOVERNANCE OF THE CEA

CEA's administrative headquarters.
© AM. Gendre–Peter/CEA

The CEA—*Commissariat à l'énergie atomique et aux énergies alternatives,* the French Atomic Energy and Alternative Energies Commission—is a public agency devoted to scientific, technical and industrial research and development, under the authority of the Ministries of Energy, Research, Industry and Defence. Its statutes and missions are defined in Articles L. 332-1 to L. 332-7 of the Research Code, and are made law by Decree No. 2016-311 of 17 March 2016 concerning the organisation and operation of the CEA.

At its head, the Administrator-General, who is responsible for the overall running of the entity, is largely empowered to act in its name, and represents it officially. The Administrator-General appoints the Directors, who supervise the operational execution of the agency's missions, prepare the meetings of the Board of Administration, and see that the Board's decisions are carried out. The Administrator-General serves the French government's control of the nuclear deterrent and the management of the nuclear assets required for defence.

The High Commissioner for Atomic Energy acts as scientific and technical advisor to the Administrator-General, and can be tasked by the latter, or by a Government Minister, to take charge of various missions of consultancy and expertise in areas of interest to the CEA, and missions concerning National Defence and Education. Both are officially named by government appointment through the Council of Ministers.

GOVERNANCE AND CONTROL BODIES

The **Board of Administration** oversees the general organisation of the CEA, the contract of objectives and performance, the annual activity programme, the budget, the annual financial statements, the creation of subsidiaries, projects for contracts, procurement, transactions, international agreements, and participation in incorporated organisations. It may also be consulted by the Government Ministers under whose authority the CEA operates on any matter lying within the CEA's domain of competence. It is informed of all important events affecting the CEA.

The Board of Administration's **Investment Committee** examines—including the financials—matters arising from the CEA's strategic investments and commitments, and its annual planning. This committee is responsible for dovetailing civil programmes, strategic investments and financial resources, and ensuring the smooth advancement of the civil programmes.

The **Atomic Energy Committee** is the body with the longest history at the helm of the CEA and France's civil and military nuclear sector. It sets the body's research, production and work programme, and examines all matters that concern the CEA, as ordered by the Board of Administration, the Administrator-General or the High Commissioner for Atomic Energy. The Investment Committee reports to it, and it can be convened by the relevant Government Ministers concerning any projects for legislation and regulation that affect the CEA's mission or organisation. It is chaired by the Prime Minister to discuss civil activities, and the Minister of Defence for defence-related matters.

The Atomic Energy Committee delegates authority to the **Armed Forces–CEA Joint Committee** to examine, particularly in their financial aspects, matters concerning the execution of the nuclear weapons programmes for which the CEA is accountable.

The **Scientific Council** is chaired by the High Commissioner for Atomic Energy, whom it assists by shaping recommendations on the future directions to be taken by the CEA and on its scientific activities. It advises on the relevance of the CEA's scientific activities and investments with regard to its mission. It is informed of the execution of the CEA's programmes and evaluates their results. The Scientific Council's advice, recommendations and reports are passed on to the Board of Administration, the Atomic Energy Committee, and the relevant Government Ministers.

The CEA's finances are state-controlled, through an **Inspection Mission** under the official general economic and financial monitoring body.

Its reports are passed on to the Administrator-General and addressed to the relevant Government Ministers and the Minister in charge of the Budget. The annual financial report, where necessary with the consolidated statements, and the CEA's annual report, are submitted to the Inspection Mission.

THE CEA'S MISSIONS

THE CEA IS A KEY PLAYER IN RESEARCH, DEVELOPMENT AND INNOVATION IN FOUR MAIN AREAS: DEFENCE AND SECURITY, NUCLEAR AND RENEWABLE ENERGY, APPLIED TECHNOLOGY RESEARCH FOR INDUSTRY, AND FUNDAMENTAL RESEARCH (PHYSICAL SCIENCES AND LIFE SCIENCES).

Virtual reality platform.
© P. Stroppa/CEA

DEFENCE

The CEA leads action frameworked under the French nuclear deterrent programme. The nuclear defence mission is governed by a 15-year programme within a 30-year national defence strategy, set by the President of France, and made law by the Military Planning Act. The CEA also provides France with technology to strengthen security in the face of new hazards such as terrorism and cyberattack, and to upgrade response to earthquakes and tsunamis.

LOW-CARBON ENERGIES

A gold-standard agency for energy research, the CEA mobilises its expertise and multidisciplinary competencies to propose innovative technological solutions to address major societal challenges, such as energy transition, nuclear and renewable low-carbon energies, and understanding the mechanisms underpinning climate change.

The CEA offers public authorities and industrial operators expertise and innovative ideas for the production of nuclear power that is sustainable, safe and economically competitive, and contributes to national and international nuclear safety policies. It also follows a research strategy encompassing the whole energy system, focusing simultaneously on means of electrical power production, both nuclear and renewable (solar), more efficient energy storage, and dynamic adjustment of supply and demand response through energy storage (batteries), the use of hydrogen as an energy vector, and smart power grids.

ALLIANCES

The CEA's research missions make it a stakeholder in a series of national alliances set up to coordinate French research in energy (Ancre), life sciences and health (Aviesan), digital science and technology (Allistene), environmental sciences (Allenvi) and human and social sciences (Athena).

TECHNOLOGICAL RESEARCH FOR INDUSTRY

The CEA serves France's competitiveness by impelling the development of technology, particularly IT, to meet the needs of research, industry and society, transferring knowledge, skills and technology, and mobilising research findings. It forges close ties with academic research and industry, bridging the gap between the worlds of science and the economy.

Doted with unique expertise built on a culture of innovation, the CEA supports big industry and small businesses bringing innovative technologies to market.

In close collaboration with local players, CEA-Tech runs technology transfer platforms (PRTTs) in many French regions: Occitania (Toulouse), New Aquitaine (Bordeaux), Pays de la Loire (Nantes), Great East (Metz), and Hauts-de-France (Lille), and is adding to its activities in the Provence-Alpes-Côte d'Azur region.

THE CEA'S MISSIONS FORM PART OF FRANCE'S MAJOR STRATEGIC POLICY DIRECTIONS:

- **Military Planning Act,**
- **Energy Transition for Green Growth Act,**
- **Paris Climate Agreement (COP21),**
- **New Industrial France Policy,**
- **National Research Strategy.**

FUNDAMENTAL RESEARCH

In the health sector, the CEA is part of the considerable progress made in biology and genomics, and the advances in imaging technology and medical devices. It is readying for the opportunities offered by the statistical processing of big data. The meshing of biotechnologies, nanotechnologies and IT is forming tomorrow's healthcare—more individualised, more home-based, and less invasive.

The CEA leads cutting-edge fundamental research in astrophysics, materials science, cryogenics, nanosciences, and more. It also helps develop and operate a number of internationally renowned research instruments, like the Herschel space observatory or the LHC. It pursues dynamic fundamental research, both in-house and through its many partnerships with other research bodies, local authorities and universities.

With expert status in its domains of competence, the CEA plays a full part in the European Research Area, and is increasingly active internationally.

DEFENCE & SECURITY

THE MISSIONS OF THE CEA INCLUDE DEFENCE AND SECURITY OF THE NATION IN VARIOUS FIELDS: NUCLEAR WARHEADS THAT EQUIP FRANCE'S SEA– AND AIRBORNE DETERRENCE FORCES, NUCLEAR REACTORS (INCLUDING REACTOR CORES) FOR NAVAL PROPULSION OF THE FRENCH NAVY SUBMARINES AND AIRCRAFT CARRIER, AND COMBATTING NUCLEAR PROLIFERATION AND TERRORISM.

The Military Applications Division (DAM) is responsible for:

- the design, manufacture, through-life support and dismantling of the nuclear warheads that equip France's sea- and airborne deterrence forces, with the guarantee of their safety and reliability throughout their lifetime,
- the design and manufacture of the nuclear reactors and reactor cores on French Navy submarines and aircraft carrier, in support of the French Navy with in-service follow-up and through-life support for these reactors,
- procuring strategic nuclear materials required for the nation's deterrence,
- providing technical support to national and international authorities relative to the prevention of nuclear proliferation and terrorism,
- and providing its expertise in conventional weaponry in support of the Ministry of the Armed Forces.

Test Reactor (RES).
© Y. Brandt/Areva TA

DETERRENT WEAPON SYSTEMS

Two types of nuclear warhead are in service:

- the airborne nuclear warheads (TNA), which has been equipping France's strategic air force missiles since 2009;
- the seaborne nuclear warheads: the TN75, which equip the M51 missiles and, since 2016, the TNO, which equip the second-generation M51 missiles.

The safety and reliability of the TNA and the TNO have been guaranteed by Simulation, without further nuclear tests.

NUCLEAR PROPULSION

The French Navy's fleet of nuclear- powered vessels has 12 steam supply systems equipped with nuclear reactor cores in service. This includes 4 *Triomphant*-class new-generation nuclear-powered ballistic missile submarines, 6 *Rubis*-class nuclear attack submarines (SNAs) and the *Charles de Gaulle* aircraft carrier.

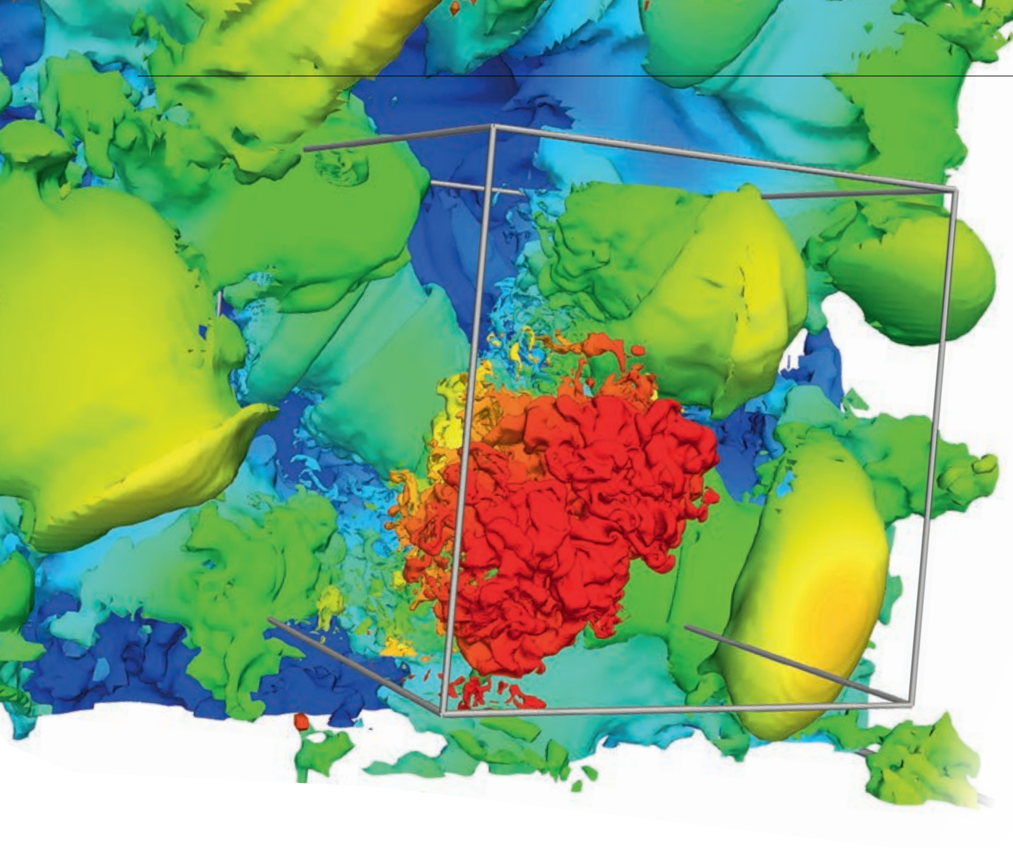
The DAM delivers the French Navy one fresh nuclear core for these on-board steam supply systems per year.

The *Barracuda* programme

France's current fleet of nuclear attack submarines will ultimately be replaced by a new generation. This is the *Barracuda* programme where the DAM is leading the design and manufacture of the nuclear steam supply systems and the associated cores, together with all the logistical resources required for their maintenance.

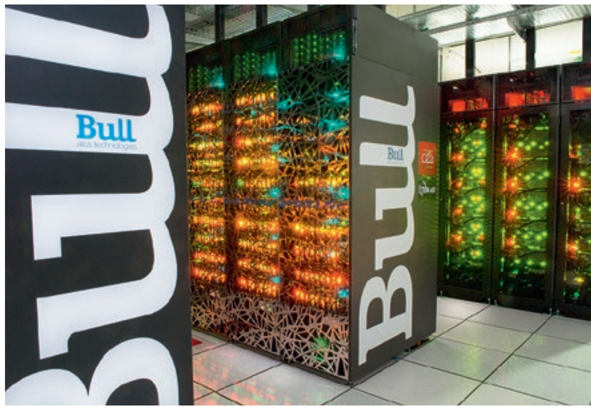
The RES programme

Maintaining availability targets and ensuring high standards in terms of safety is dependent not only on rigorous equipment maintenance, but also on skilled teams and land-based resources, under the



3D simulation of hydrodynamic instabilities occurring in the operation of nuclear weapons.
© CEA

Tera 1000–1 supercomputer.
© CEA



responsibility of the Nuclear Propulsion Unit attached to the DAM Île-de-France Centre and located in the CEA's Cadarache Centre. One such resource is the recently-completed RES test reactor for which core implementation and divergence are pending authorisation from the Defence Nuclear Safety and Radiation Protection Delegate (DSND). The RES is representative of the reactors on-board the French Navy's vessels and their nuclear cores, and offers a matchless simulation tool for their design and through-life support.

THE SIMULATION PROGRAMME

The reliability and safety of French nuclear warheads are now guaranteed without conducting any further nuclear test, through the Simulation programme, launched in 1996. It involves modelling the physical phenomena underlying the functioning of nuclear weapons, equation-solving using supercomputers, and experimental validation in the large facilities Epure and the Megajoule Laser (LMJ).

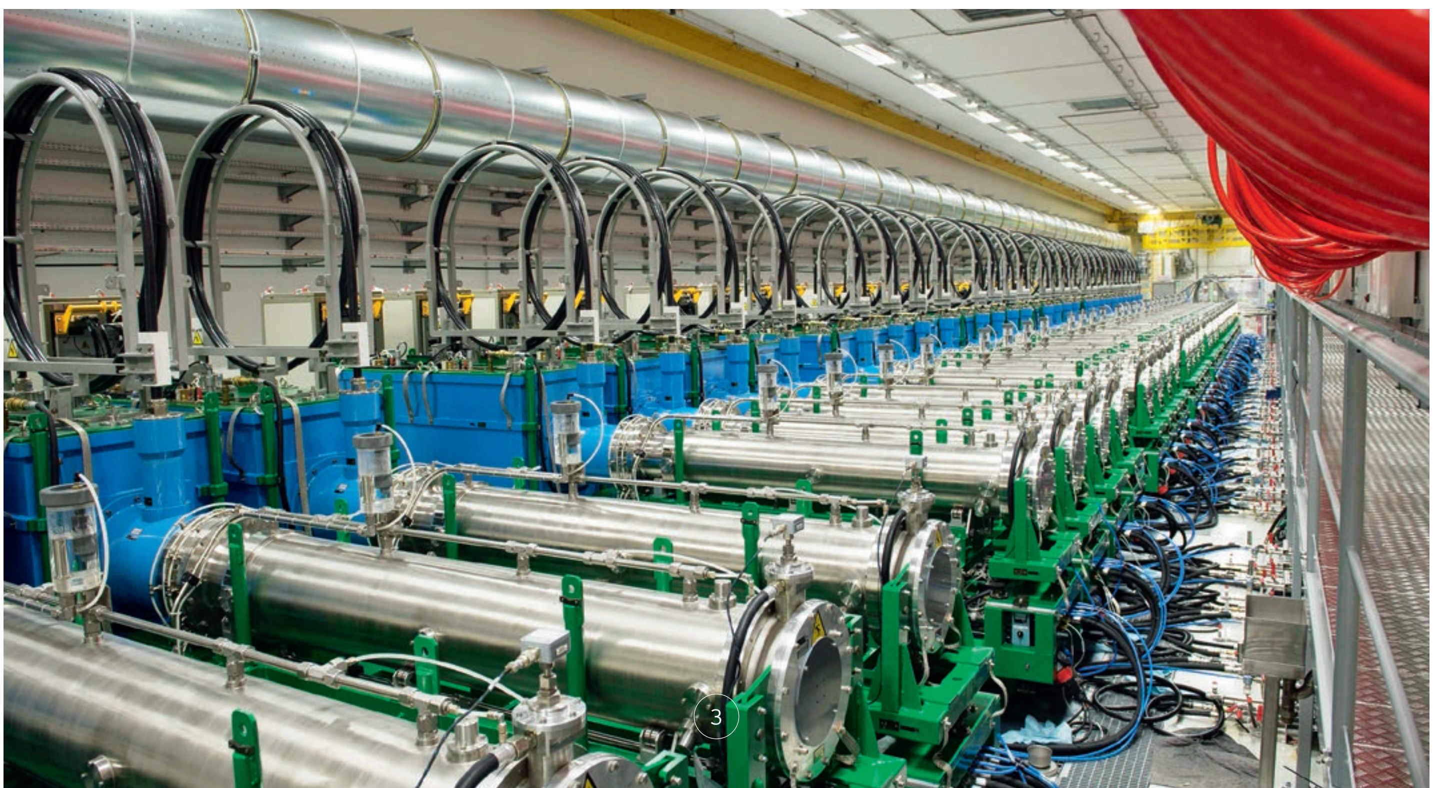
Supercomputers

The supercomputers are sized to meet the design and guarantee specifications of nuclear weapons. The Tera 1000-1 computer, which was commissioned to service in 2016, can perform 2.6 petaflops (million billion operations per second), and its successor Tera 1000-2, currently under development, will achieve 25 petaflops in 2017 with a very high energy efficiency.

The Epure facility

The Epure facility, which is gathering momentum at the Valduc Centre, falls within the context of the Teutates Treaty between France and the United Kingdom, signed in 2010, related to sharing radiographic facilities for the purposes of their respective deterrence programmes. Ultimately including three high-power radiographic axes, its commissioning

Flash X-ray generator (Airix radiography machine) at the Epure facility.
© CEA



Kerguelen Islands, radionuclide monitoring station, part of the International Monitoring System of the Comprehensive nuclear Test BanTreaty (CTBT).
© CEA

with a first radiographic axis, since end 2014, makes it possible to characterise, to the highest level of precision, the state and hydrodynamic behaviour of materials, under the conditions encountered in the pre-nuclear phase of weapon functioning.

The Megajoule Laser

The Megajoule Laser at the Cesta Centre is an indispensable tool for simulating the physical phenomena involved in the nuclear phase of weapon functioning, and for certifying the expertise of physicists in charge of weapons design. Since its commissioning by the Prime Minister of France at the end of 2014, the first experimental campaigns of weapon physics were successfully conducted.

COMBATTING NUCLEAR PROLIFERATION AND TERRORISM

The DAM provides its expertise, based on its knowledge in nuclear science and technology and its skills in detection and identification technologies, in combating nuclear proliferation and terrorism.

To inform the French authorities in the event of a nuclear test, the DAM participates in the implementation of the means for verifying compliance with the Comprehensive Nuclear Test Ban Treaty (CNTBT). The observance of this treaty is verified by the analysis and characterisation of data collected by the 321 stations of the International Monitoring System, in which the DAM is strongly involved. Supported by its competencies in geophysics, the DAM is also responsible for the French Tsunami Early Warning Centre for the Mediterranean and North-East Atlantic (Cenalt). The Cenalt's mission is to alert the French authorities responsible for protecting the population. The authorities of the countries bordering on the Mediterranean or North-East Atlantic that subscribe to Cenalt's services are informed simultaneously. As part of the CEA's national security research mission, the DAM is entrusted by the French authorities and Defence with managing the inter-ministerial R&D programme on CBRN-E (chemical, biological, radiological, nuclear, and explosive terrorism) and the R&D programme on cybersecurity.

CONVENTIONAL DEFENCE

The DAM, mainly at the Gramat Centre, provides project management assistance to the French Defence Procurement Agency (DGA) for conventional defence activities, making use of its expertise on the effects of weapons and weapon system vulnerability.

Megajoule Laser (LMJ) facility.
© MS–CEA

NUCLEAR AND RENEWABLE ENERGY

Shielded lines for studies on the reprocessing of spent nuclear fuel.
© S. Le Couster/CEA

NUCLEAR FISSION ENERGY

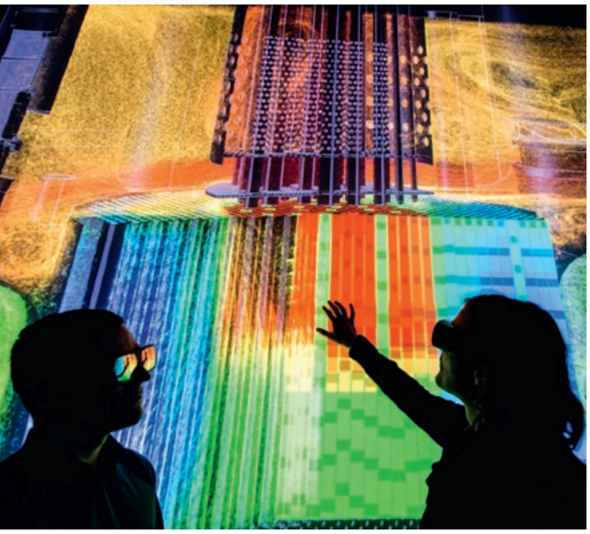
THE CEA PROVIDES THE FRENCH GOVERNMENT AND THE INDUSTRY WITH ITS TECHNICAL EXPERTISE AND INNOVATION TO DEVELOP SUSTAINABLE ENERGY THAT IS BOTH SAFE AND ECONOMICALLY COMPETITIVE. ITS R&D PROGRAMMES COVER TWO DIFFERENT TIME SCALES: TODAY WHICH INVOLVES SUPPORTING THE CURRENT FLEET OF INDUSTRIAL-SCALE NUCLEAR FACILITIES, AND TOMORROW WHICH ENTAILS A LONG-TERM VISION TO PREPARE THE FUTURE GENERATIONS OF NUCLEAR SYSTEMS. LARGE EXPERIMENTAL DEVICES AND EXTENSIVE SIMULATION TOOLS ARE NECESSARY TO CARRY OUT SUCH ACTIVITIES. THE CEA ALSO MANAGES AND UPGRADES ITS OWN FLEET OF NUCLEAR FACILITIES THROUGH CONSTRUCTION, REFURBISHMENT, CLEAN-UP AND DISMANTLING PROGRAMMES.

OPTIMISING THE CURRENT FLEET OF INDUSTRIAL-SCALE NUCLEAR FACILITIES

The CEA provides support to its industrial partners, whether for their current fleet of facilities or for new build. Its programmes cover a broad range of R&D topics in the fields of reactors and the fuel cycle, with considerable effort being devoted to developing the simulation tools needed for such research. With respect to reactors, objectives of competitiveness, service life, performance level, availability and nuclear safety must be met. Research is also carried out to support Areva in the fuel cycle field. This involves optimising or adapting the processes both for spent fuel reprocessing at La Hague plant, and for MOX fuel fabrication at the Melox plant, as well as keeping the Areva plants in good working condition. Actions also focus on improving the performance of processes used for the selective extraction of uranium, followed by its purification and then its conversion. The CEA supports Andra by providing scientific and technical data for the deep geological repository called Cigéo for which Andra is the project owner. It is helping to elaborate the technical and material specifications for high-level (HLW) and long-lived intermediate-level (LL-ILW) waste packages, as well as to define the safety measures applicable to waste disposal in the Cigéo facility.

DESIGNING NUCLEAR SYSTEMS FOR THE FUTURE

The CEA is working on a long-term outlook for the future generations of nuclear reactors and their fuel cycles. It is helping EDF to optimise its pressurised water reactors like the EPR, while contributing to discussions on small modular reactors (SMR). The French State has also given the CEA the task of carrying out research on innovative nuclear reactor systems called 4th generation. Within this scope, the CEA is the owner of a project to build a sodium-cooled fast reactor demonstrator called ASTRID, which stands for Advanced Sodium Technological Reactor for Industrial Demonstration. It also maintains a multi-sector technology watch and R&D on the range of systems and technologies relevant to this 4th generation. In line with these studies, the CEA is also preparing the future fuel cycle by developing advanced processes for the multiple recycling of spent fuels. Keeping this in mind, the CEA has studied different industrial scenarios for



Modelling to support Astrid reactor design activities.
© P. Stroppa/CEA

deploying fast reactors in collaboration with its partners EDF and Areva. With respect to the fuel cycle, the objective is to transition smoothly from the current fleet with once-through recycling to a fast reactor fleet that opens the way to multiple recycling.

IMPLEMENTING LARGE EXPERIMENTAL DEVICES AND SIMULATION TOOLS TO SUPPORT NUCLEAR DEVELOPMENT

The type of research carried out by the CEA requires extensive predictive tools to model the different nuclear systems. In this context, the CEA is developing software platforms and computational codes in the key fields of nuclear energy (neutronics, thermal-hydraulics, mechanical and thermal behaviour, fuels, fuel cycle chemistry, and materials) to model the complex phenomena occurring during normal or accident conditions in a nuclear reactor or facility. This is mostly done in partnership with the main players in the French nuclear sector (EDF, Areva, IRSN, etc.). Experimental tools are needed to confirm the validity of the models and computational calculations. These tools can be: experimental platforms, hot laboratories (to study irradiated objects), research reactors, and critical mock-ups (very low power reactors to conduct experimental neutronic studies). Some of these facilities are reaching the end of their service life after more than 40 years of operation. Renewing or refurbishing these facilities remains a key issue for the CEA. This is why the Jules Horowitz reactor (JHR) is currently under construction on the CEA Cadarache site. Once completed, it will provide a unique tool for studying materials and fuels under irradiation to support current and future nuclear reactors. It will also be used to produce a sizeable fraction of the radioisotopes needed for medical purposes.

MANAGING NUCLEAR CLEAN-UP AND DISMANTLING

As a nuclear operator, the CEA is responsible for dismantling its nuclear facilities and managing the waste generated by such activities. A specificity of the CEA is that it has a broad range of facilities to dismantle: research reactors, chemistry laboratories, and effluent and waste treatment plants. The dismantling of each facility gives rises to a specific case each time, thus feedback cannot generally be used for the next case (no standardised operations). Over the years, the CEA has gained significant experience, both in project ownership and in the methodologies and expertise required for the implementation of such dismantling projects. Whenever possible, these operations rely on standard techniques that have been adapted to a nuclear environment, yet it is often also necessary to develop specific tools and technologies. In this context, the CEA is running several pioneering R&D programmes in this field with the objective of reducing the overall costs and waste volumes, while improving the working conditions on dismantling sites.

Checking the radiological condition and conformity of radioactive waste packages.
© L. Godart/CEA

ZOOM ON...

IMPACT ON HEALTH AND THE ENVIRONMENT

The Fundamental Research Division conducts research on the impact of radionuclides and ionising radiation on populations or the environment.
In 2016, division teams demonstrated that there is a gene involved in radiosensitivity. This gene, called *Trail*, has three genetic forms, two of which were linked with serious skin complications in breast cancer patients treated with radiotherapy.
Division scientists are also investigating the intrinsic toxic potential of cobalt oxide particles, which can get inhaled in cases of accidental contamination in the nuclear industry, and remain trapped in the lungs. They showed *in vitro* that cobalt particles have genotoxic effects on human lung cell DNA. *In vivo* toxicity studies are now needed to define the mutagenic potential of these particles following inhalation.

POLYMERS UNDER IONISING RADIATION

Polymers casked in intermediate-level long-lived waste packages may release hydrogen under irradiation. The CEA's chemical scientists have shown that hydrogen production decreases rapidly with dose, as the energy gets trapped inside radiation-induced flaws in the plastic (polyethylene) film.

NUCLEAR FUSION BY MAGNETIC CONFINEMENT

The CEA, as part of the Euratom community, contributes to the European programme for research on magnetic confinement fusion, which aims to show the feasibility of producing cheap, safe and sustainable energy from fusion plasmas. ITER, the thermonuclear fusion reactor being built at the Cadarache site, is of strategic importance for the CEA and its partners. The test platform West (Tungsten Environment in Steady-State Tokamak) achieved its first plasma at Cadarache in late 2016 and is set to test critical equipment components for ITER, along with sophisticated diagnostics for fine-grained characterisation of the fusion plasma (spatial and temporal temperature profiles).
The CEA has pressed ahead with its input to ITER's extended Approche programme for the future Japanese tokamak JT-60SA, including taking delivery of the cryogenic plant, toroidal coils and their electrical powerfeeds.

Fresnel–reflector concentrated solar powerplant.
© P. Avavian/CEA

RENEWABLE ENERGY

Work hosted at the Liten[1] covers solar energy as a priority (thermal and photovoltaic) and its integration in housing (at the National Institute of Solar Energy—INES), batteries for stationary applications and transport, the production of vector hydrogen, and waste-to-energy solutions. It develops the tools needed to grid-connect renewable energies.

SOLAR ENERGY

Its research in the field of **solar photovoltaics** aims to address two big challenges: cutting the power costs and increasing the energy efficiency of the solar cells and the complete photovoltaic system. The Liten is working in particular on very-high-conversion-yield, bifacial, communicating, self-diagnosing premium-quality modules. In parallel, it is developing integrated, functionalised modules for specific applications: boat decks, mall roofs, roadways, and more.

It is developing cutting-edge technologies to control and manage **thermal solar energy:** capture (collectors), storage for later use—in industry for instance–, or distribution via heat networks. It has already developed innovative thermal energy storage systems.

It supports industrial operators seeking to install **thermodynamic concentrated solar powerplant systems** by developing technologies, software and tools for sizing these installations, which are capable of powering seawater desalination plants, for example.

ELECTRICITY STORAGE

In the field of electrochemical storage, work is directed not only to on-board applications (electric vehicles and mobile devices) but also to stationary storage, which is vital for the development of intermittent renewable energy sources.

Efforts are being focused in particular on improving the performance and lifespan of Li-ion batteries, and on developing a battery management system to improve reliability.

In parallel, the Liten is driving the development of disruptive technologies for new applications: sodium-ion batteries and easily-recyclable biomass-derived organic batteries, both of which are cheap yet promising solutions for stationary a pplications, or lithium-sulphur batteries, which are particularly geared to applications in aeronautics.

Further upstream, research teams from the Fundamental Research Division are looking for ways to improve the performance of lithium-ion batteries. One of the teams studied battery ageing by picosecond-pulse radiolysis, which highlighted the role of solvated electrons interacting with the electrolyte. Another identified the mechanisms limiting the performances of nickel and manganese oxides for use as positive electrode in lithium cells. These materials could ultimately sustainably replace the materials currently in use.

Pilot-scale lithium battery assembly line.
© D. Guillaudin/CEA

ZOOM ON...

SENSITISED SOLAR CELLS

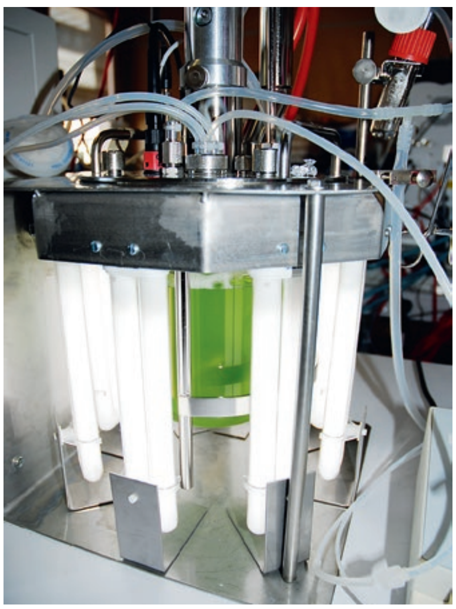
Scientists at the CEA propose a way to improve the efficiency of solar cells by 'sensitising' them using a dye contained in a porous layer of titanium dioxide (TiO_2), which improves electron contact while preventing the charge recombination reaction. The porous layer could be replaced by nitrogen-doped TiO_2 nanoparticles.

1. Liten: Laboratory of Innovation for Sustainable Energy Technologies and Nanomaterials.

BIORESOURCES

The Liten's Genepi platform is helping to develop innovative, high-performance production of syngas from solid bioresources, such as residues from agriculture and household waste. The bioresources are converted into synthetic gas by high-temperature treatment. The resulting biogas can, for example, be converted into synthetic natural gas. In parallel, the Liten is developing alternative processes for the treatment of wet waste, such as sewage plant slurries, by hydrothermal liquefaction.

Chemical scientists at Iramis[2] are seeking to extend recycling to actual chemical molecules by 'taking apart' polymers sourced from forestry waste or plastics using depolymerisation processes working at ambient temperatures and pressures, using metal-free catalysts. The molecules thereby obtained could be re-used to make plastics, food additives, or cosmetics.



Photobioreactor cultivation of microorganisms producing energy-rich substances.
© G. Lesénéchal/CEA

2. Iramis: CEA-Saclay Institute for Radiation and Matter.

Pegase facility designed to host thermal biogas purification.
© P. Avavian/CEA

PRODUCTION OF HIGH-ENERGY-VALUE SUBSTANCES

Certain micro-organisms can make fuel—scientists are hoping to use them to support the renewable energy commodity chain, primarily to develop rare-metal-free catalysts to produce hydrogen, or to develop processes to produce lipids for biodiesel fuel. In particular, the biologists have shown that an ancient signalling pathway that was inherited from bacteria affects growth and development in plants. Understanding how this mechanism works has the potential to lead to the development of new strategies for protecting crops from climate change and for enhancing photosynthesis to create biofuels and other valuable products. Researchers have also injected years of effort into mimicking natural enzymes in order to produce hydrogen. In 2016, they proposed a system mimicking nickel-iron hydrogenases, getting closer to reality. These hydrogenases naturally catalyse the production of dihydrogen.

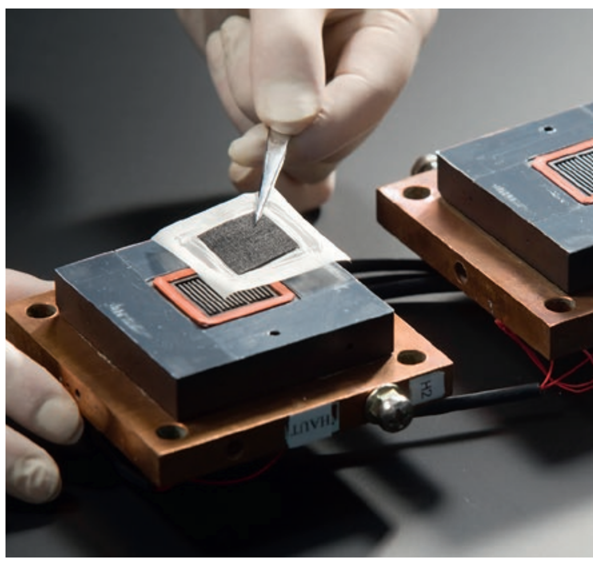
HYDROGEN AND FUEL CELLS

Hydrogen as an energy vector will play a major role in many sectors, in particular for extending the range of electric vehicles by means of fuel cells. The CEA's work in this field focuses especially on reducing the quantity of platinum needed, lengthening the lifespan of the proton exchange membrane fuel cell (PEMFC) system, and new bipolar plate coatings, so as to propose economically viable alternatives to current solutions.

For oxygen reduction, fuel cells could gain benefit from a new stable, efficient catalyst, based on a nanostructured graphene, free of rare or toxic metals such as the platinum used today.

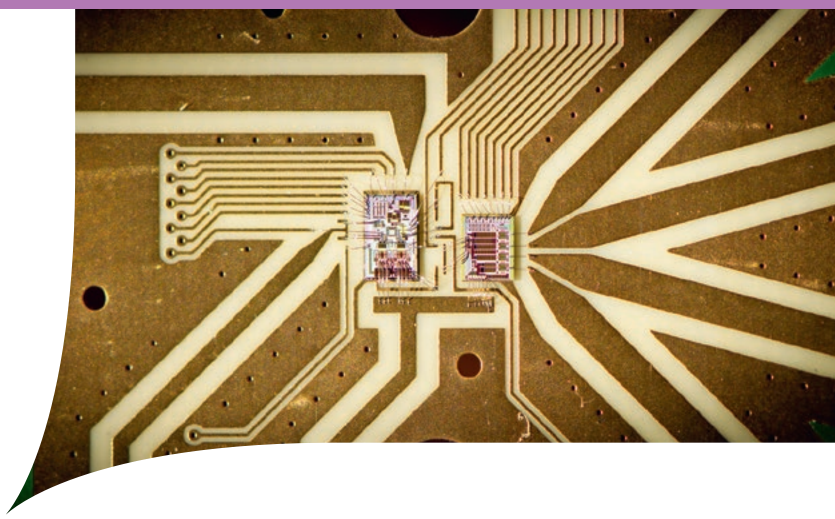
In parallel, the Liten has developed a reversible hydrogen production system by high-temperature electrolysis of water vapour (HTE or steam electrolysis), opening up new prospects at ecodistrict scale, in addition to its usefulness for smoothing fluctuations in renewable energy availability. This same system can also work in co-electrolysis mode (CO_2, H_2O) to generate a syngas.

Phases in PEMFC fuel cell preparation and lay-up.
© P. Stroppa/CEA



TECHNOLOGY RESEARCH FOR INDUSTRY

FOR INDUSTRY THE CEA SERVES FRANCE'S COMPETITIVENESS BY DRIVING TECHNOLOGICAL DEVELOPMENT AND KNOWLEDGE, SKILLS AND TECHNOLOGY TRANSFER TO INDUSTRY, IN PARTICULAR AT REGIONAL LEVEL, AND BY MOBILISING ITS OWN RESEARCH FINDINGS.



Power amplifier chip and associated matching circuit chip in SOI technology.
© CEA–Leti

MICROELECTRONICS

In the domain of microelectronics and microtechnologies, the Leti1 is conducting research in close cooperation with industrial operators and the scientific community as a whole.

Its priorities are:

- **Ultimate miniaturisation of microelectronics, or "More than Moore"**

To this end, the Leti is developing new substrates with Soitec and advanced FD-SOI components with STMicroelectronics and GlobalFoundries (Dresden). It is also leading research into tomorrow's non-volatile memories, which are essential for microcontrollers, which work at low voltage and are revolutionising the architecture of integrated circuits.

In tandem with the CEA's Fundamental Research Division, it is also studying original transistor structures such as the single electron transistor (SET), components for silicon quantum computers and nanowire transistors.

- **Diversification of components, or "More Than Moore".**

The Leti is studying the chip-scale integration of mechanical, chemical, biochemical and photonic functions. Through the use of innovative SoC (System-on-Chip) assembly techniques using 3D integration (including the monolithic 3D technology called CoolCube™ that stacks two layers of transistor circuitry), the chips can integrate not only computing capabilities (CMOS components and memories), but also micro- and nano-sensors and actuators, local energy sources, and radiofrequency (RF) or optical communication modes. Innovative devices derived from this research benefit from nanoscale miniaturisation, the introduction of new materials, and novel associated properties. These components can help meet the needs of new communicating systems and services for many sectors of activity, such as telecommunications, healthcare, and more generally what we call the Internet of Things (IoT). These developments are being conducted in partnership with numerous French, European and international industrial operators.

NANOTECHNOLOGIES AND NANOSCIENCES

The nanosciences and nanotechnologies took shape in the 1980s with the development of new atom-scale manufacturing, measurement and characterisation tools. These tools, such as tunnel-effect microscopes and tomography, allow not only observations at atomic or even subatomic scale, but also three-dimensional reconstitution of the localisation and displacement of atoms.

The nanosciences connect the nanometric-scale structure of objects to their electrical, optical, and mechanical properties—and their chemical reactivity. Nanosciences are opening fast-expanding perspectives for applications across the board, including nanoelectronics, energy sources (photovoltaics, fuel cells, hydrogen, and more) and the life sciences.

Chemistry is becoming an increasingly important vector for conferring form and function to nano-objects. However, it is equally important to optimise their implementation and conceptualise new architectures to host them. These strategic research efforts need to follow into more technology-driven developments in order to obtain an original device system with firmly-controlled properties.

One illustration is semiconductor nanowire

1. Leti: Electronics and Information Technology Laboratory.

Immersive virtual reality with force feedback assembly operation.
© C. Meireis/CEA

'brushes' that could spot-cool hot points on microelectronic circuits—or even convert the lost heat into useable electricity. Another illustration comes from the fields of nanophotonics and quantum sensors, where semiconductor quantum dots, used as single photon sources, give signal by a spectral shift identical to the application of a mechanical stress.

In spintronics, "spin valves" have been fabricated with a ferromagnetic alloy of cobalt (CoFe) instead of the usual alloy (NiFe), leading to an order-of-magnitude signal gain and paving the way to applications such as hard-disk read-heads. Finally, a major deadlock has been broken concerning magnetic quasiparticles, which are composed of nanomagnets forming an extremely stable spiral (skyrmions). A team from Inac[2] and the Néel Institute–Grenoble managed to observe these skyrmions at ambient temperature, which paves the way to using them for nanoscale data storage and processing in personal computers.

In quantronics, researchers from the CEA made the world-first observation of the Purcell effect for electron spins in solids. This result was obtained in silicon, and marks a major stride forward towards coherently coupling a single electron spin to microwave cavity photons—a step further towards spin-based quantum information processing.

Note too that an Inac–Leti collaboration has revealed that the very small silicon-on-insulator (SOI) transistors are ideal candidates for making spin-based quantum bits.

ADVANCED MANUFACTURING

The CEA, as a founding member of the Future Industry Alliance, helps companies make their digital transformation. Digital technologies offer tomorrow's production plants the opportunity to gain agility, flexibility, responsiveness and performance.

The solutions developed at List[3] frame and facilitate the work of operators throughout the value chain. Thus tailor-made robotics and cobotics solutions improve their productivity and make tasks less arduous. Virtual reality and augmented reality offer high-performance tools for workstation design, maintenance and training. Innovative sensors and algorithms enhance instrumentation systems. Likewise, non-destructive testing can determine, with unequalled precision, the mechanical integrity of a part, its areas of fragility, its remaining lifespan, or its reliability.

EMBEDDED SYSTEMS

Embedded systems are widely used in many applications by both professionals and the general public. Their levels of safety, security, reliability and performance are crucial. At the European scale, the List is particularly engaged in the KIC EIT[4] Digital initiative, which brings together the major players in the research community (Inria, Fraunhofer, VTT, etc.). In this domain, the List also develops research activities in partnership with major industrial groups such as Renault, STMicroelectronics, Thales, Airbus, Areva and EDF, plus SMEs such as Esterel Technologies, Sherpa Engineering, and All4Tec.

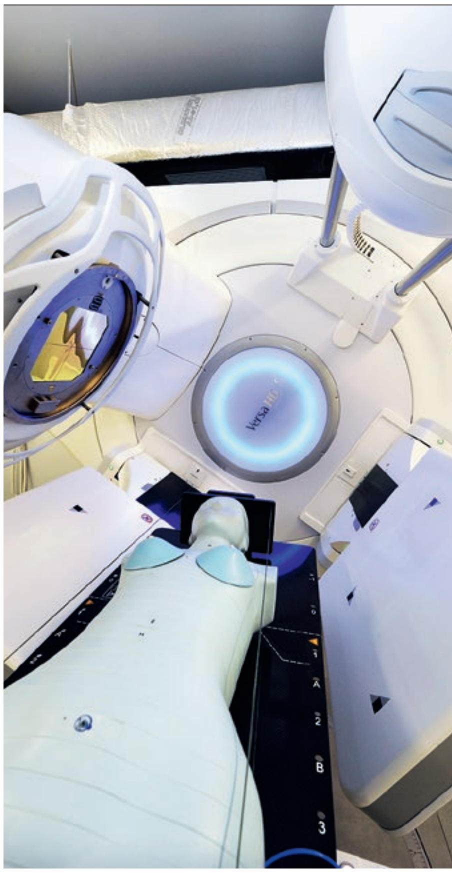
By drawing on several technological levers —design, modelling, computing architectures, and hardware software convergence—, the List has risen to the challenge in sectors from energy and transport to telecommunications, the Internet of Things, and home automation—and of course cybersecurity, a domain in which the CEA enjoys international acclaim.

AMBIENT INTELLIGENCE

How do we extract and transmit useful information from the huge flows of data generated by computer systems and the Internet of Things? How can we secure data using innovative encryption solutions? Researchers at the List are developing new technologies for better management of our environment through vision, geolocalisation, augmented reality, smart processing of big data, and human–machine interfaces. The List is conducting research on ambient intelligence in partnership with industrial operators in transport (Renault), cybersecurity (Thales), energy (Schneider Electric), electronic document management (Bureau Veritas), etc.

Robotic nondestructive testing on a composite part in additive manufacturing.
© A. Calais/CEA

2. Inac: CEA Institute for Nanosciences and Cryogenics.
3. List: CEA Laboratory of Systems Technology Integration.
4. KIC EIC: Knowledge and Innovation Communities of the European Institute of Innovation and Technology.



Doseo platform.
© L. Godart/CEA

TECHNOLOGIES FOR HEALTH

The Fundamental Research Division proposes innovative approaches in the domains of diagnostics, therapy and prophylaxis.

These approaches are helping to develop individualised healthcare, by enabling physicians to prescribe early care for health disorders, avoid treatments that may be ineffective for certain patients, and have access to therapies that are better tolerated.

Medical imaging and radiotherapy

List researchers are working on improving the quality of MRI images and their interpretation. To prepare the ground for the world's most powerful MRI imager (an 11.7-Tesla whole-body system), they pressed ahead with their design engineering work, coming up with increasingly elegant new algorithms to minimise image acquisition times, which get prohibitively longer as precision gets sharper. List physicists also played their part in the characterisation of a red fluorescent protein with record brightness, called mScarlet. They observed its molecular structure and understood what made it so bright - registering a major breakthrough for cell imaging.

The List collaborates with all the players in the domain: industrial partners, clinical centres, researchers, and regulators, in particular as part of the Doseo platform, dedicated to metrology, training and R&D in radiotherapy and imaging.

Thanks to tools for calibration and dose metering, instrumentation and simulation, radiotherapy and X-ray imaging are bringing forth new solutions for individualised medicine, and innovative therapies with better efficacy that are also safer for both patients and carers.

Diagnostics

Biologists can only confirm a diagnosis of neurodegenerative disease post-mortem. The research scientists have developed an *in vivo* magnetic resonance technique to quantify certain morphological signatures of neurons and astrocytes, which are liable to be altered in these diseases. The unit biologists have also taken another step closer to early diagnosis of Alzheimer's disease by engineering two new types of antibodies capable of specifically detecting the amyloid platelets and neurofibrillary tangles that characterise the disease.

The teams also took inspiration from a bacterial protein to design a probe capable of detecting copper in cells, raising prospects for the design of a new diagnostic tool for diseases like Wilson's disease or Menkes syndrome where the normal regulation of copper levels in the body is disrupted.

In the field of therapy

Teams from the Fundamental Research Division have discovered a unique system of acquisition of essential metals in the pathogenic bacterium *Staphylococcus aureus*—the infamous "golden staph"— that represents a new potential target for the design of antibiotics.

They have delivered clinical proof-of-concept for an adjuvant therapy to narcolepsy treatment that the US regulatory agency has designated an orphan drug.

In Alzheimer's disease, they have demonstrated an early and protective role of the brain's active immune defence cells, dubbed microglia. This discovery opens new avenues for potential therapies to slow—or even stop—progression of the disease.

The medical devices platform and trials platform

The Leti is one of France's major actors in the development of healthcare technology, and in particular medical devices. Mobilising a supporting cast of active collaborations with nearly 80 clinical teams across the world, it addresses the domains of in vitro diagnostics, health monitoring and connected healthcare, medical imaging, drug delivery systems, active medical devices and innovative therapies.

For the last two years it has been working on how to deal with the regulatory constraints that apply to the conception, prototyping and clinical trial design for innovative devices. The "Medical Devices platform" enables developers to shorten the bench-to-bedside cycle of tech development to preclinical and clinical trials, and helps industrial partners with conformity for prompt CE marking. With Clinatec, in collaboration with Grenoble university teaching hospital, the Leti places its competencies and technological resources at the disposal of a world-class state-of-the-art preclinical and clinical trials platform. Besides its own research programmes, Clinatec also acts as a project facility, hosting its clinical partners in a hi-tech environment for the duration of their project.

Preparing a slide for histological analysis at the Clinatec platform.
© P. Avavian/CEA

Development of diagnostic and therapeutic antibodies.
© F. Rhodes/CEA

FUNDAMENTAL RESEARCH

THE CEA CONDUCTS RESEARCH IN PHYSICS, CHEMISTRY, MATERIALS SCIENCE, BIOLOGY AND HEALTH.
IT DEVELOPS AND IMPLEMENTS TECHNOLOGIES AND INSTRUMENTATION AT WORLD TOP LEVEL.

Mass spectrometry applied to pharmacokinetics and drug metabolism.
© F. Rhodes/CEA

LIFE SCIENCES

The CEA is breaking new ground in fundamental research in the life sciences to support all its other missions, in particular in the domains of low-carbon energy and new technologies for industry applied to healthcare. This solid foundation covers, among other areas, the molecular basis of immunity, host-pathogen relations and the major cell functions.

CELLULAR SELF-DEFENCE

Cells deploy an array of creative and ingenious strategies to respond to aggression, particularly aggression from free radicals that exert oxidative stress and accelerate cellular ageing. A team from the Fundamental Research Division and its partners has discovered a protein repair mechanism, which raises prospects for better control of oxidative stress-related cellular ageing. By modulating the system that was chaperoning misfolded proteins, they observed that the cell's replicative lifespan was extended by over 50%. This same modulation also reduces protein aggregation. These findings—although still at very fundamental stage—nevertheless offer important insight into ageing-related diseases and their treatment, and for all neurodegenerative diseases characterised by abnormal protein aggregation in the central nervous system. In another study, scientists investigated a cunning strategy used by certain microorganisms as a foil for their defensive weaknesses. Yeast, for instance, resists the effects of oxidative stress by duplicating its copy of chromosome 11, thereby upregulating the genes carried by this chromosome and increasing the antioxidant defences. This cellular adaptation by gene duplication is not just found in micro-organisms—cancer cells also employ it to increase their resistance to free radicals. This research could therefore help better understand cancerisation processes.

Another stressor of living organisms—and especially plants—is excessive light energy. The researchers have identified a new gene that regulates excess light energy-induced cell death in plants. Studying this gene may lead to better plant resistance to environmental stressors.

Integrally-controlled plant growth and measurement chamber.
© L. Godart/CEA

AT THE HEART OP EPIGENETICS

A neuron and a red blood cell come from the same stem cells, which means the same gene pool. A cell's genes can then be expressed one way or another depending on its specialization, its environment, or other factors... and epigenetics sets out to understand how. Each cell type therefore has to tackle the huge challenge of correctly expressing every single one of its genes. An array of cellular mechanisms are at work to meet this challenge, and the chromatin remodellers assist these mechanisms by facilitating or barring access to DNA. Biologists and geneticists from the CEA have revealed how these enzymes work. They have discovered how the mass of genetic material, tightly packaged into the cell nucleus and therefore—in principle—made all but inaccessible, has to be remodelled to enable the cellular machinery to gain access to the genes.

They have also made strides forward in the understanding of largely unexplained epigenetic phenomena. In the plant world, the Leafy protein is necessary to decipher the genetic code responsible for the development of flower buds and their organs.

The team showed that alongside its known role in activating the genes controlling flower development, the Leafy protein also has an epigenetic role, as it can assemble with other congeners to form small Leafy chains that are competent for accessing DNA domains that are normally too compact to be recognised.

Prepping gel electrophoresis to separate proteins for a proteomics study.
© P. Avavian/CEA

BIODIVERSITY

The catalogue of planktonic organisms collected over the course of the Tara Oceans expedition is getting bigger and bigger. The first global vision of the plankton networks driving the oceanic biological pump (carbon sequestration) has highlighted new actors and the primary bacterial functions engaged in this process. Research led by the Fundamental Research Division was instrumental in further showing that the relative abundance of a few bacterial and viral genes can predict a significant fraction of the variability in carbon export down to the ocean floors.

In another study, the CEA and its partners unveiled the workings of an extremophilic bacterium called *Halomonas* that is able to survive in extremely hostile salty environments. It forms a rust, like the one busy destroying the wreck of the Titanic, and survives very hostile saline environments thanks to a compound called ectoin. Neutron scattering experiments have offered up explanations on the mechanisms involved.

Automated 96-well-plate sample preparation.
© P. Avavian£/CEA

ZOOM ON...

HADRON THERAPY: WHAT KIND OF DAMAGE?

A cross-collaboration between several Fundamental Research Division institutes shows that hadron therapy with carbon ions does not cause any more pre-cancer damage to healthy tissues than conventional radiation therapy. The research has helped validate this technique, including for the treatment of recalcitrant tumours that can require radiation doses up to three times higher than normal.

PHYSICAL SCIENCES

Fundamental research at the CEA covers the exploration of the subatomic world (physics of particles and the nucleus), quantum systems (atoms, materials, radiation-matter interactions), and at larger scales, the study of the Earth and the Universe. These disciplines mobilise cutting-edge technologies in accelerators, superconducting magnets, detectors, cryogenics, and more.

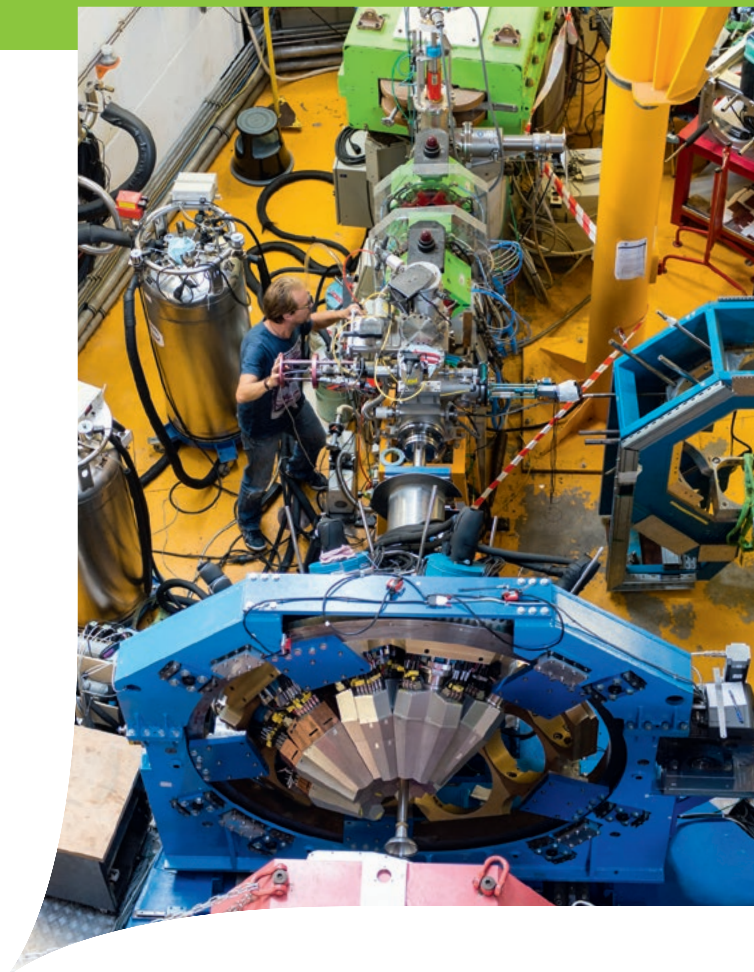
LAWS OF THE UNIVERSE

To drive its research in physics subdisciplines (astrophysics, nuclear physics and particle physics), the CEA designs and custom-builds instruments—detectors, accelerators, magnets—, supported by strong competencies in computing, electronics, magnetics, cryogenics and systems engineering. The very latest Micromegas gaseous particle detector developed for the CERN is designed to measure a neutron beam profile without disrupting it. Other experiments have enabled Ganil[1] and Irfu[2] scientists to better understand certain shape transitions in atomic nuclei. At the Ganil, the experimental campaign programme to support the European gamma-ray tracking spectrometer project Agata has harvested a huge amount of data, and the data analysis underway is expected to enable major progress in understanding manifestations of strong interaction at work in atomic nuclei.

In astrophysics, an Irfu-led team has published a new three-dimensional map of galaxy clusters by surveying the Universe up to distances of 10 billion light-years. The data—much of which was achieved with the X-ray XMM-Newton space observatory—fits uncomfortably with the current cosmological models. Furthermore, analysis of various observations has led to the surprising discovery of a galaxy cluster formed only 'recently', at a new record distance of 11.5 billion light-years, which again shakes up the models.

The Integral gamma-ray space telescope did not register an unusual signal pattern when the gravitational wave reached the Ligo (Laser Interferometer Gravitational Wave Observatory) instrument.

1 Ganil: the national large-scale heavy ion accelerator.
2 Irfu: Institute of Research into the Fundamental Laws of the Universe.



View of the reaction chamber and the beam tube connected to the Ganil-facility cyclotrons.
© P. Stroppa/CEA

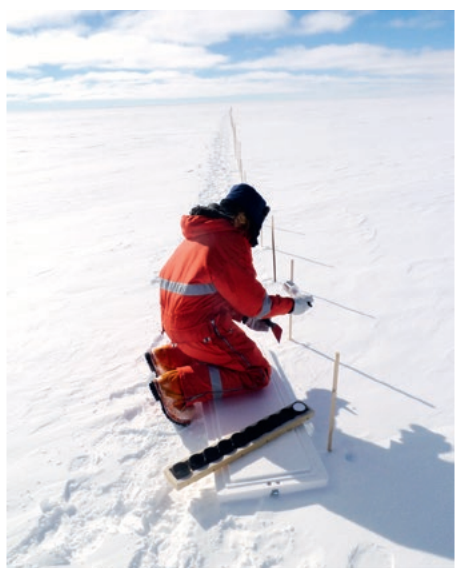
Climate modelling is another core component of LSCE-led research. Preparatory work for the 6th IPCC report involved starting numerical simulations for world climate research programme CMIP6 (Coupled Model Intercomparison Project Phase 6).

This observation further concords towards the scenario of a merger of a pair of black holes that does not emit any gamma signal, just as model theory predicts.

CLIMATE AND ENVIRONMENT

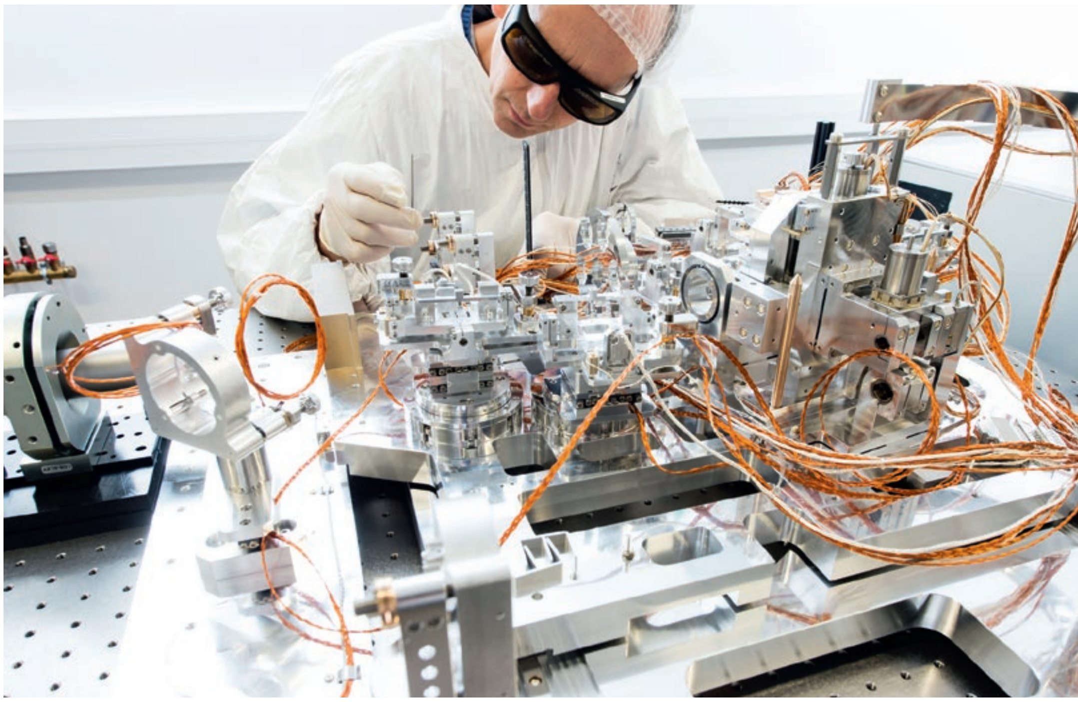
The Laboratory of Environmental and Climate Science (LSCE) is a joint research team (CEA, CNRS and University of Versailles Saint-Quentin-en-Yvelines) coordinated by the Pierre-Simon Laplace Institute (IPSL). It is an active contributor to IPCC (Intergovernmental Panel on Climate Change) assessment and report work. One key focus of research progress is the collection and analysis of natural archives of climate records (ice, sediments, tree rings, etc.). For this purpose, the corer onboard the Marion-Dufresne research vessel extracted exceptionally high-quality marine sediments from between 1,000 and 4,500 metres deep under the Atlantic sea, which will then be analysed to reconstruct the rapid variations in climate system parameters that have occurred over the last forty millennia.

The LSCE is involved in a number of greenhouse gas monitoring networks, and along with its co-partners has published a thorough budget of methane sources and sinks. The methane budget shows that after a period of stabilisation in the early 2000s, methane concentrations have risen fast



Polar ice core extraction and measurement mission in the Antarctic.
© CEA

Assembly of the attosecond-pulse beamline spatial and spectral shaping system equipping the ATTOlab laser.
© P. Stroppa/CEA



ZOOM ON...

GLASSY TRANSITION

The theories are split: some describe glasses as hyperviscous liquids, others as real solids exhibiting an 'amorphous' (non-crystalline) order. Electric susceptibility measurements have just settled the controversy! There is effectively a subtle amorphous order governing glasses, and the phase transition from liquid state to vitreous state belongs to a whole new class of highly-generalized critical phenomena.

since 2007, with no clear explanation. Climate modelling is another core component of LSCE-led research. Preparatory work for the 6th IPCC report involved starting numerical simulations for world climate research programme CMIP6 (Coupled Model Intercomparison Project Phase 6).

The LSCE also boasts acclaimed expertise in radiometric dating methods. Using uranium-series dating, it helped give the intriguing arrangements of stalagmite structures inside Bruniquel cave (Aveyron) a replicated age of 176,500 years, making these edifices among the oldest known constructions made by humans— a discovery that sheds new light on Neanderthal Man. Three volcanic eruptions at 30 km from Chauvet cave were also dated back to between 29,000 and 35,000 years—ages that fit with radiodated spray-shaped signs painted by occupants of the cave, making them the oldest known depiction of these cataclysmic events.

FUNDAMENTAL PHENOMENA IN PHYSICS

The laws of physics are now well-established, yet a few big questions remain unanswered, particularly in the field of complex systems where the behaviour of a set of individuals escapes any attempt to fit it by defining the population's inter-individual interactions.

This complexity is at the heart of thermodynamic processes like self-organisation in the nanosciences. The "animate matter" paradigm starts to probe the frontier between living and dead matter.

LASER-MATTER INTERACTION

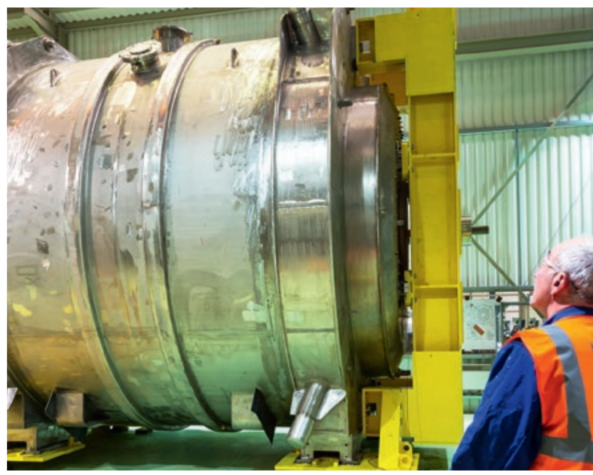
Lasers can probe matter to study its properties in extreme states of electric field intensity, and its atomic and molecular bonds.

Ultrashort (femtosecond, i.e. 10^{-15} s and attosecond, i.e. 10^{-18} s) pulse lasers like those hosted at the ATTOlab platform and ultra-high intensity lasers like Apollon are invaluable exploration tools for chemistry, biology and high-field physics. Attosecond lasers enable us to study the dynamics of electrons and atomic nuclei in matter in its gaseous and condensed phases.

ACCELERATORS AND CRYOTECHNOLOGIES

The CEA has unique competencies for carrying through large-scale projects, like the new superconducting magnet for the 11.7-Tesla MRI facility to be installed at NeuroSpin (Saclay) in 2017 or the 54 superconducting magnets equipping the future ITER fusion power station demonstrator. An Irfu team has developed "Alises II"—a compact, reliable and robust new high-intensity light ions source designed for neutron production and nuclear physics research. This concept could be adapted to find application such as ion implantation in industry or proton therapy in medicine.

Readying the 11.7-Tesla magnet for transfer from Belfort to Saclay.
© P.Dumas/CEA



ZOOM ON...

LIGHT-DRIVEN ELECTRON ACCELERATION

For the first time, hard evidence of high-energy electron acceleration driven directly by a light wave has just been provided by a Iramis[3] team. Now that this scientific deadlock of 'vacuum' acceleration has been lifted, the only factoring limiting the ability to increase electron energy is the intensity of femtosecond lasers.

3 Iramis: CEA-Saclay Institute for Radiation and Matter.

THE RESEARCH INFRASTRUCTURES (RIS)

Fundamental and applied research both require very large scientific facilities, constructed and run through international collaboration.

The CEA represents France, often alongside the CNRS, in the bodies that coordinate these very large research infrastructures (RIs). It delivers expertise in key areas (nuclear and high-energy physics, materials science, etc.), a broad range of basic skills (accelerators, metrology, vacuum engineering and cryotechnology), and a project-based organisation bringing users and designers together. Their scopes of application and allied instruments are:

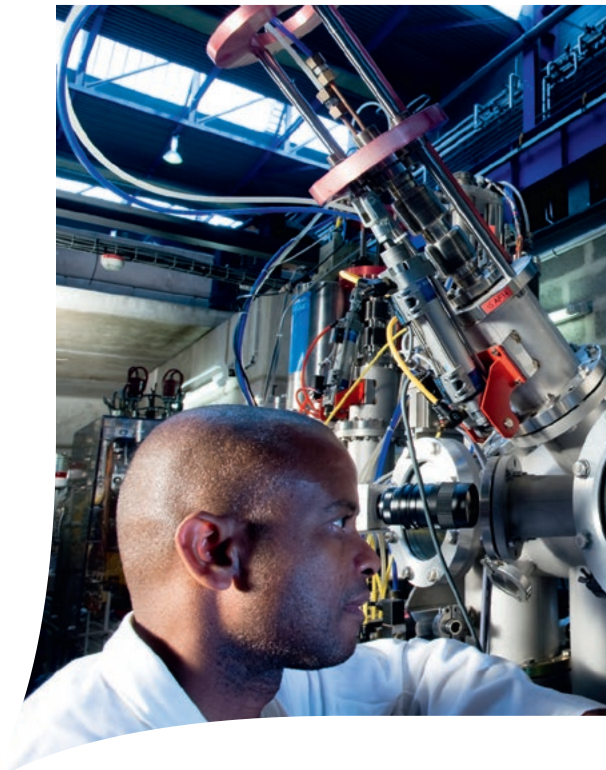
NEUTRONICS ANALYSIS (Orphée-Laboratoire Léon Brillouin, Institut Laue-Langevin, European Spallation Source–ESS)

For the ESS neutron source construction project, the CEA is delivering several work-package contracts for the linear proton accelerator, and taking part in design-engineering six out of the sixteen instruments already selected.

SYNCHROTRON ANALYSES (Soleil, ESRF and E-XFEL, X-ray free electron laser)

Several CEA research teams regularly work on the French and European synchrotron beamlines. X-ray scattering and diffraction, full-spectrum photoemission spectroscopy, EXAFS, spectroscopic analysis, crystallography and imaging are the main techniques employed—particularly for nanoscience research.

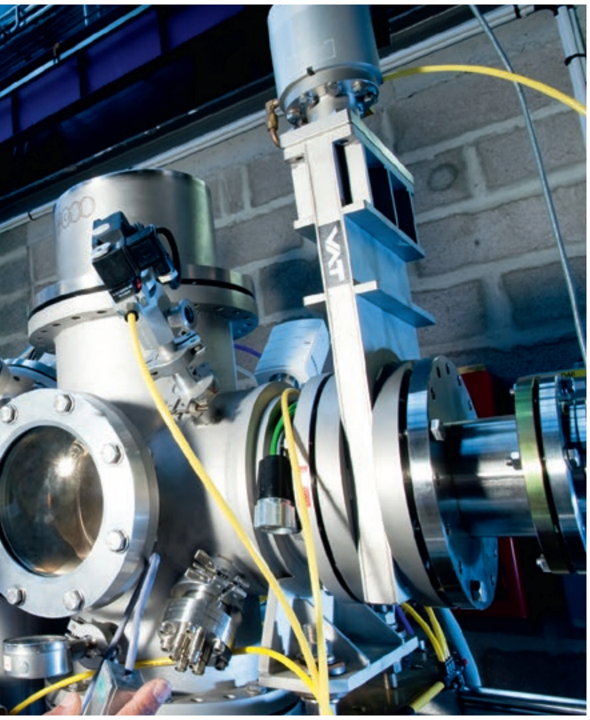
For the E-XFEL facility, the CEA was involved in the construction of the 1.5-km-long superconducting linear electron accelerator by integrating and testing a package of 103 cryomodules alongside industry partner Alsyom.



Ganil experiment chamber.
© P. Stroppa/CEA

Setting up a manipulation in the Institut Laue-Langevin high-flux reactor.
© D. Morel/CEA

The LHCb detector.
© P. Stroppa/CEA



NUCLEAR PHYSICS (Ganil, Spiral2, Cern, Fair)

The Ganil (National Large Heavy Ion Accelerator) facility pioneering the study of exotic nuclei is an economic-interest consortium split 50/50 between its co-founders the CEA and the CNRS. It has just taken delivery of a new facility called Spiral2 (linear radioactive ion accelerator system), engineered through a multipartite technical and scientific collaborations in France, Europe and the world. Its beamlines, which are unique in the world, open up vast new horizons for fundamental nuclear physics and interdisciplinary research.

Analysing vials of air samples in the Icos laboratory.
© F. Rhodes/CEA

HIGH-ENERGY PHYSICS (LHC)

The CEA is a stakeholder in the research conducted at the LHC (Large Hadron Collider), which is exploring the infinitely time matter (elementary particles, antimatter, dark matter, etc.) and the universe milliseconds after the Big Bang.

ASTROPHYSICS (telescopes)

A source accelerating galactic cosmic rays to unprecedented energy in our galaxy has been identified, thanks to analysis of the latest data from the HESS observatory in Namibia. That source is a supermassive black hole at the centre of the galaxy. The century-old enigma of where cosmic background radiation comes from has finally been (practically) resolved.

ENVIRONMENT (Icos)

To study the climate, the LSCE performs atmospheric monitoring via a network of 25 stations, integrated in Icos, the European consortium for monitoring greenhouse gases.

SUPERCOMPUTING (Genci, Prace)

In supercomputing, the first global-run climate simulations with the Dynamico model in planet-ocean configuration have been completed. This new icosahedral grid-based dynamic atmospheric modelling system gives the computation algorithms a huge injection of pace.

HESS system of telescopes, installed in Namibia.
© CEA

PROGRAMME SUPPORT

ALL CEA RESEARCH PROGRAMMES ARTICULATE A CORE SET OF FUNCTIONAL COMPETENCES VITAL TO ALL–ROUND PERFORMANCE: CONTROL OF ACTIVITY CLASS–RELATED RISKS, HUMAN RESOURCES MANAGEMENT, TRAINING AND EDUCATION, BUDGET SCHEDULING FOR STRATEGIC AND RESEARCH ACTIVITIES, INTERNATIONAL RELATIONS, KNOWLEDGE MOBILISATION, COMMUNICATION, AND MORE– ALL COMPETENCIES THAT LET THE CEA STRIDE CONFIDENTLY INTO THE FUTURE.

RISK CONTROL

The CEA operates nuclear facilities hosted in many of its laboratories and research sites, and as such it is responsible for operating them and conducting R&D projects while controlling all the risks inherent to its activities. These risks are identified, assessed and then ranked to provide an annually-updated risk map. This map serves as a reference for implementing the CEA's risk control policy and for setting the programme of audits and inspections, a central part of the CEA's continuous improvement strategy in this domain. Most importantly, it serves to educate and mobilise all CEA personnel around the overriding need to exercise good governance in the protection and monitoring of the environment,

nuclear safety, transport security, health, staff security and radioprotection, protection of sites, facilities and assets, crisis management and the control of legal risks.

HUMAN RESOURCES

The CEA is committed to managing the ongoing development of its permanent and temporary personnel's scientific, technological and other competencies, by means of several levers for forward workforce and skills planning (identification and preparation of skills to meet the needs of future programmes), recruiting and training. The CEA is also committed to favouring constructive dialogue with mandated representatives of its personnel, and to ensuring professional equality and good working conditions.

TRAINING

The INSTN—National Institute of Nuclear Science and Technology is a state-funded higher education establishment and national training organisation administered by the CEA and placed under the joint authority of the government ministries for Industry, Higher Education, and—through its ties to the CEA—Energy. The INSTN has a 60-year history of delivering highly specialised teaching and training to all levels of qualification—from operative agent to engineer and up to research scientist—on the sciences and technologies implemented in industrial and medical applications of nuclear energy.

The INSTN is pursuing an international development strategy, and in 2016 secured International Atomic Energy Agency (IAEA) "Collaborating Centre" status for 'education and training in nuclear technologies—industrial and radiopharmaceutical applications', which makes it the first IAEA-endorsed centre in Europe. This endorsement also credibilises the scientific excellence of the CEA and its activities for the nuclear sector as a whole.

At the INSTN, a brand new immersive 3D space for radiation therapy.
© L. Godart/CEA

PLANNING AND STRATEGY

The CEA signed its goals and performance contract for 2016–2020 with its governing ministers. Drafted by the Strategic analysis division and tracked by the Financial control and programmes division, the purpose of this document is to align the CEA's civilian-sector activities, from research to industry, with the strategic orientations taken by France. It aligns with the multi-year rolling 2015-2025 science programmes schedule as revised and realigned by the Financial control and programmes division working with the operational divisions, and articulates with the CEA's missions and strategic orientations. To ensure its programmes are clearly defined and consistently implemented across all the relevant operational divisions, the CEA has segmented its civil research programmes into major mission areas (nuclear energy—fission and fusion—, technological research for industry, fundamental research grounding). Twenty-six separate segments

Work conference.
© P. Avavian/CEA

have thus been earmarked, of which the scientific, planning and budgetary contents reflect the CEA's strategic vision for the next ten years. All the heads of the scientific segments, under the coordination of the Financial control and programmes division, are responsible for annually re-updating this strategic scientific vision. The Strategic analysis division leads all the analyses necessary to devise, deploy and direct the organisation's strategy. These analyses focally revolve around energy and power systems, digital transformation, and the industrial and business models behind the CEA's major partnership arrangements.

THE CEA IN THE INTERNATIONAL ARENA

The CEA's International relations division advises the government on issues of external nuclear policy, and represents France in international organisations in the nuclear sector, such as the IAEA and the NEA.

It leads and develops cooperation in different domains of activity with counterpart bodies in other countries.

The CEA's European and international policy hinges on several major objectives: deliver backing to support strategic partnerships forged by government; develop its international scientific repute; support France's policy of exporting nuclear energy expertise, in particular through its collaboration with international partners developing civil nuclear power programmes; participate in the construction of the European Research Area.

COMMERCIALISING SCIENTIFIC RESEARCH

When appropriate, the results of research conducted at CEA form the basis of patent applications. In 2016, 743 priority patents were filed, adding to a portfolio of nearly 6,200 patent families in force, and confirming CEA as a leading research organisation for patent submissions to the French National Institute of Industrial Property (INPI). CEA has also achieved prominence in the Clarivate (ex-Reuters) rankings. for 6 years in a row, CEA has appeared on the "*Top 100 Global Innovators*" list identifying "the world's most effective innovators", and it was in second place in the 2016 "*Top 25 Global Innovators–Government*" list of "publicly funded institutions doing the most to advance science and technology".

CEA's large worldwide patent portfolio is mainly exploited via technology transfer activities with industry, leading to over 600 industrial partnerships in 2016.

Our patents also play a driving role in the creation of innovative businesses. Another 8 new startups were created in 2016, consolidating a longstanding trend that has seen 132 companies created since 2000. To support the growth of these fledgling companies, CEA has also engaged in seed funding, an activity that is coordinated by two subsidiaries: CEA *Investissement* and *Supernova* created in 2017.

Also of note is that CEA tech-transfer activities are supported by a strategic marketing group, including a bibliometric/patent research service, whose tried-and-tested expertise helps the labs optimise their commercialisation of scientific research.

COMMUNICATION

The CEA's Communication Division is responsible for keeping the public informed about the organisation's research options and results, and the favourable impact of these on economic wealth creation and employment. Another of the CEA's missions is to propagate the scientific and technical culture underpinning its research and skills.

The CEA at the *Utopiales* international sci-fi festival in Nantes.
© F. Klotz/CEA

SUSTAINABLE DEVELOPMENT

RESPONSIBLE RESEARCH AND INNOVATION FOR A SUSTAINABLE ENERGY MIX

Sustainable development, with the triple goals of environmental protection, economic growth and social equity, is integral to the CEA's mission as a public research agency.

The CEA aligns its research actions with the dynamic strongly supported by the French government : France signed the Paris climate agreement and adopted the UN 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals.

The CEA's mission is entwined with the history of nuclear energy in France, and we have long been vigilantly monitoring the environment, managing waste, economizing material and consulting the local-community populations. The CEA has thus developed activities, processes and a 'socially-responsible' corporate culture that we enforce and apply across everything we do.

THE CEA IS TACKLING THE BIG SUSTAINABLE DEVELOPMENT CHALLENGES THROUGH R&D PROGRAMMES...

The CEA committed to delivering excellence in research on low-carbon energies

The CEA's research on climate modelling enables it to track signals of greenhouse global warming trends, and forward-think the compelling necessity to carbon-neutralize energy production. The CEA is central to the IPCC's science activities.

In 2016, the Laboratory for climate and environmental sciences (LSCE) produced fresh new findings on carbon sinks—including sinks resulting from the degradation of cement materials.
A French-Chinese team with the LSCE on board developed a new methodology for determining the impacts of concrete degradation-driven emissions to atmosphere of greenhouse gases, aerosols and chemically-active compounds on the climate of a whole country.

Valérie Masson–Delmotte, climatologist at the LSCE, and participant on the "Climate Train" rolling outreach exhibition.
© M. Klotz/CEA

As Europe's leading centre for research into clean energies, the CEA is developing the bricks of tomorrow's energy mix, which will blend nuclear with renewable energies in innovative electricity grids and meet optimized power demand.

The CEA is helping to make Provence-Alpes-Côte d'Azur a 'smart region' with the Flexgrid project which is set to showcase the large-scale deployment of French-engineered smart grid technologies.
CEA-Tech, Corsica Sole and it subsidiary Driveco have developed smart charging and grid balancing programmes for solar-powered electric vehicle changing stations, along with the infrastructures needed to territory-scale deployment of these innovative technologies (the first all-solar mobility highway).

The CEA is developing the technologies to shrink the environmental footprint of energy and power systems, both in the nuclear sector (clean-up and dismantling, waste treatment processes) and in renewable energies (saving rare-earth metals, recyclability).

The SFEN presented its award for technological innovation to Onet Technologies and the CEA for the remotely operated laser-cutting technology developed at the CEA and implemented by Onet Technologies in clean-up operations at CEA Marcoule. This promising innovation could be chosen as a solution to remove melted fuel debris from the damaged reactors at the Fukushima Daiichi nuclear power.

Dismantling the Siloé reactor at CEA-Grenoble.
© P. Avavian/CEA

The CEA is developing sustainable nuclear power: the generation-IV fission reactor and fusion reactors (see page 10).

The CEA actively contributing to the economic development of France

The CEA's technological research activity fuels the industrial fabric of France and streams into development areas where this fabric has not yet taken hold. Indeed, the CEA is Europe's number one most innovative research institution, and world number two (in the Clarivate (ex-Reuters) 2016 rankings). It also files more patents than any other public research organisation in France (and ranks 4th all-organisations-included) and generates half of all alliance-based research in France.

The CEA's core R&D in nuclear energy is focused largely on the support of the French nuclear industry and helps re-energise this key sector, representing 220,000 jobs in France (at 2,600 businesses, from multinationals to small and medium-sized enterprises).

CEA research programmes place society first

The CEA plays a lead role in maintaining civil peace and security.

In 2016, the Cenalt (Tsunami Alert Centre) created and operated by the CEA was official accredited part of the backbone tsunami warning system.

2016 also marked the twenty-year milestone of the Simulation Programme designed and led by the CEA to sustain the French nuclear deterrent in the wake of the nuclear test ban treaty.

In the healthcare area, the CEA has partnered the Inserm and the CNRS to further the development of non-energy applications of neutron science and cutting-edge technologies originally developed for microelectronics or defence. It also channels its advanced skills in information and communication technologies into developing technologies that help people at work (virtual reality, cobotics) or in everyday life (for active ageing at home).

The CEA is engaged in a number of major studies on neurodegenerative diseases (see page 19). CEA research has paved the way towards new strides forward towards retinal prostheses for the blind. Note too that the CEA was involved in the discovery of a gene associated with radiation sensitivity and post-radiation-therapy complications, paving the way towards individualised radiotherapy.

The CEA mobilises its technologies to the benefit of developing countries.

The CEA and Morocco-based company MASEN have launched two major projects in Morocco: the "water desalination solutions" project, and the "durability of solar power systems" platform tasked with investigating the durability of thermal solar power infrastructure. Other related backbone research themes are on the table, chiefly in areas tied to smart grid management, hydrogen as vector for energy storage, and district cooling.

.... IMPLEMENTED IN A RESPONSIBLE WAY

Energy consumption and water use

The CEA is located in 9 sites. Two-thirds of its built assets date back to the 1960s and was designed primarily to host research, much of which is nuclear. These facilities have been designed and operated in a way that makes them significant emitters of greenhouse gases. So the CEA decided several years ago to launch an ambitious retrofit programme to refurbish its built infrastructure, destroy its energy-inefficient buildings, and reconfigure its heating systems, opting for gas power, cogeneration or grid connection to district heating.

For water, which is essentially used for industrial purposes (process water, cooling and air conditioning), the CEA uses recycled water and closed-loop water supply systems as much as possible.

Environmental footprint

Most of the CEA's sites are in rural or peri-urban areas. The excellence of CEA research is largely driven by dynamic international scientific collaborations, so transport, whether for business travel or the commute, is a significant item in the CEA's greenhouse gas emissions. The CEA has therefore made arrangements to promote shared mobility solutions (buses or car sharing) or non-mobility (using ICTs), and proposed to privilege the train to the plane. The CEA is in a continual process of optimising its organisational control of the health-hygiene and environmental impacts of all ongoing activities, and of its current or former facilities, whether in terms of managing dismantling and cleanup or managing radioactive, biological or chemical waste and effluent.

Best interests of workforce and stakeholdership

All CEA activities, in-house operations and relations with stakeholders are grounded in and legitimised by 6 core values: public interest, empowerment, engagement, sense of requirement, complexity culture, and solidarity.

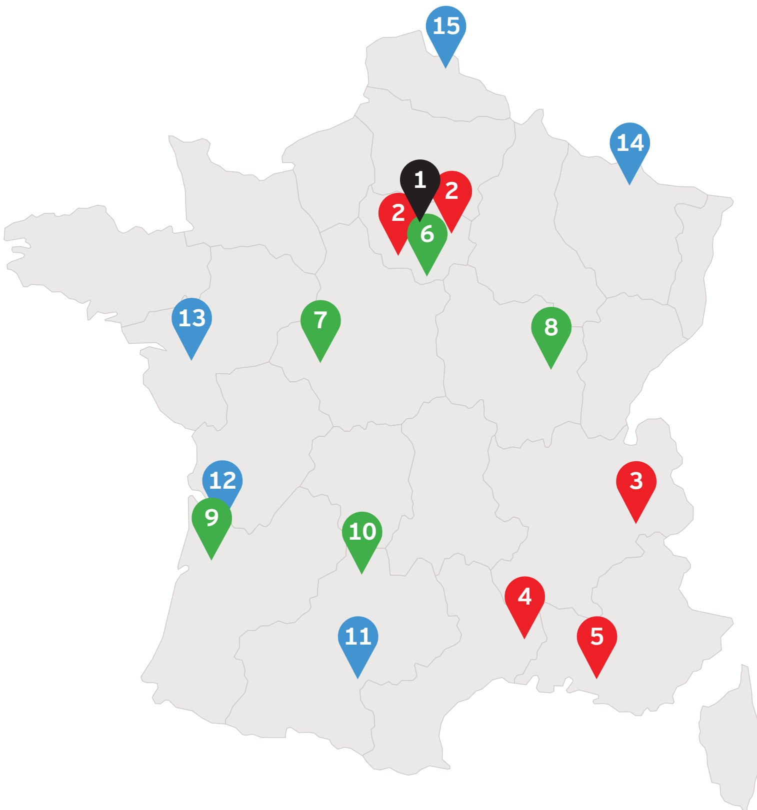
Guided by these values, the CEA pursues goals that help forge national policy on supported employment schemes to help young people, people with disabilities, and seniors in work, and to defend jobs in science.

The CEA is a committed community-aware equal opportunities employer.

In 2016, the CEA–Grenoble centre won awards for its disability inclusion, sustainable development and corporate social responsibility action ('Challenge interentreprises Sport2Job' and 'Trophées RSE Rhône-Alpes' regional CSR awards).

Photovoltaics platform at the INES.
© L. Chamussy/Sipa–CEA

9 CEA'S CENTRES IN FRANCE



1 HEADQUARTER

CIVIL RESEARCH CENTRES

- 2 PARIS–SACLAY
  Fontenay-aux-Roses and Saclay sites
- 3 GRENOBLE
- 4 MARCOULE
- 5 CADARACHE

CENTRES FOR MILITARY APPLICATIONS

- 6 DAM Île-de-France
- 7 LE RIPAULT
- 8 VALDUC
- 9 CESTA
- 10 GRAMAT

REGIONAL TECHNOLOGY-TRANSFER PLATFORMS

- 11 TOULOUSE
- 12 BORDEAUX
- 13 NANTES
- 14 METZ
- 15 LILLE

FROM RESEARCH TO INDUSTRY

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French atomic energy and alternative energy Commission
91 191 Gif-sur-Yvette cedex

www.cea.fr

Cover photos: Left to right and top to bottom: Astrid reactor conceptual design modelling on a video wall - Outdoor test platform for concentrated solar photovoltaics systems - Nanomagnetism experiment - Automated sample preparation in proteomics - Tera 1000-1 supercomputer - Micro-nanosystems and nanoelectronics platform - Remote manipulator work in a shielded process line - Cyceron 3-Tesla whole-body MRI. **Credits:** P. Avavian - P. Jayet - S. Le Couster - P. Stroppa/CEA.
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