Inauguration of Spiral2 at Ganil

Thursday, November 3, 2016 in Caen

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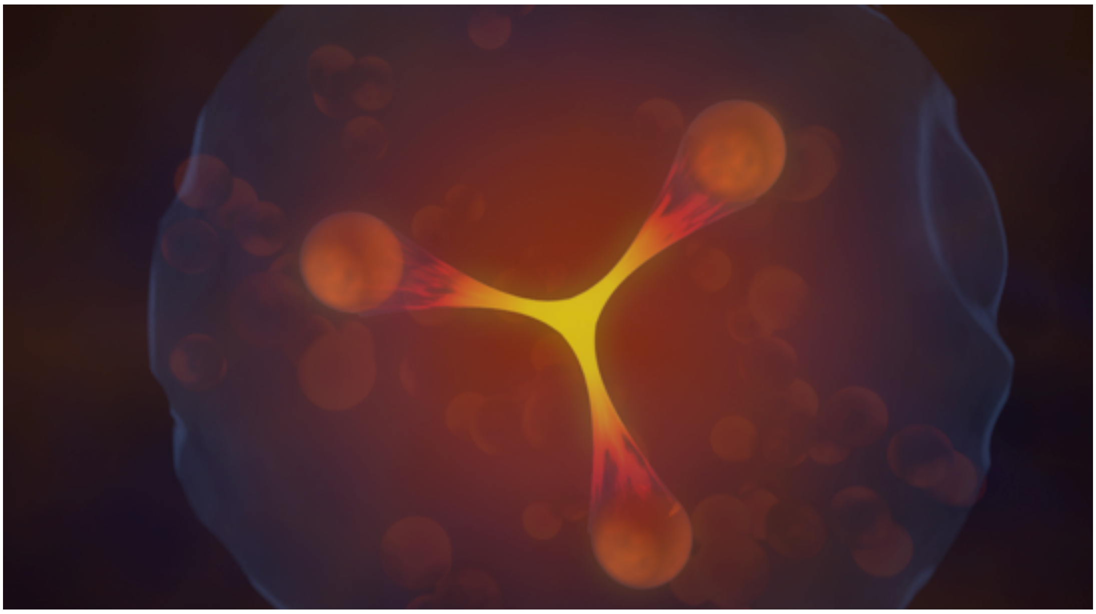

Artist's impression of the inside of a proton © Frédéric Durillon/Animéa/CEA

France doubles its experimental capability in nuclear physics

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1. WHY DID WE NEED A NEW ACCELERATOR AT GANIL?

At the cutting edge of research on exotic nuclei (so-called because they do not naturally exist on Earth), Ganil, the Large-scale Heavy-Ion Accelerator, is a very large research infrastructure jointly developed by the CNRS and the CEA and located in Epron (approx. 21 hectares), Caen (10.5 ha) and Hérouville-Saint-Clair (4.3 ha). It is now one of the five major laboratories in the world used to synthesize and study the properties of these new nuclei. This field of research emerged in the 1980s and has proved to be an incredibly rich mine of information.

Ganil, key figures

- **€30 million** budget (including payroll);
- **250 permanent members of staff** (physicists, engineers, technicians, administrative staff, etc.);
- **700 researchers** from 30 different countries and 65 foreign laboratories and universities come to Ganil each year to carry out experiments and attend conferences and seminars;
- **3,020 scientific papers** written by researchers at Ganil since it first opened.

Everything we knew about the structure of the atomic nucleus and its thermal and mechanical properties, and about exotic nuclei, has been radically thrown into doubt by the results obtained in recent years at Ganil, with profound consequences on our understanding of the cosmos.

Examples of discoveries made using Ganil

- Through experiments on atomic nuclei composed of 20 neutrons and 14, 16 or 20 protons, researchers at Ganil demonstrated for the first time in history, in March 2014, that the structural properties of the atomic nucleus are strongly dependent on the density of matter at the center of the nucleus. The effect was characterized in an atypical nucleus, silicon-34, for which the same team of physicists have recently shown, in a study published recently in *Nature*, that its center is unusually hollow. The physicists expect that, in super-heavy nuclei, the very high number of protons will give rise to the formation of a "bubble" similar to the interior of such nuclei, accompanied by changes in their structure and impacting on the position of the "stability island" sought for so long. It remains to be seen what new possibilities Spiral2 will open up.

The quest for super-heavy nuclei

Last March, the International Union of Pure and Applied Chemistry officially confirmed the discovery of elements 113, 115, 117 and 118, thereby adding four new elements to the periodic table (used to organize all known chemical elements). Thanks to Spiral2, Ganil will be able to be part of the quest for and study of "super-heavy" elements, so-called because they contain more than 104 protons. Above all, the physicists hope to be able to probe them in the most minute detail to reveal the secrets contained within these super-heavy nuclei, and discover their physical and chemical properties. How many protons and neutrons can an atomic nucleus contain?

- In May 2015, physicists using ion sources at Ganil discovered a new process responsible for the production of very low-energy electrons during collisions between ions and molecules. This is a phenomenon which could have far-reaching implications in radiobiology. The future S^3 experimental facility will improve the study of the processes involved in atomic collisions between very intense stable ion beams.

- One other example, in the healthcare sector this time: last March, using the beams delivered by Ganil, a team of researchers from other French laboratories were able to better assess the effects of irradiation in hadrontherapy (cancer treatment using mainly carbon-ion and proton beams) compared to conventional radiotherapy techniques (treatment using X-rays). Spiral2 will provide an opportunity to pursue this kind of research in the healthcare sector. The impact of neutrons on living tissue, and the production of radioactive isotopes that may potentially be used in nuclear medicine, will be important areas of research carried out in the NFS facility, due to come into service in mid-2017.

Ganil, key dates

- **1976**: Set up by the CNRS and CEA
- **1983**: The first experiment
- **1992**: Ion beam intensity increased
- **2001**: The first Spiral beam
- **2005**: Spiral2 Project launched
- **2006**: Spiral2 agreement signed
- **2011**: Construction of Spiral2 started
- **2014**: Spiral2 buildings delivered
- **Dec 2015**: First proton beam pre-accelerated in the Spiral2 injector

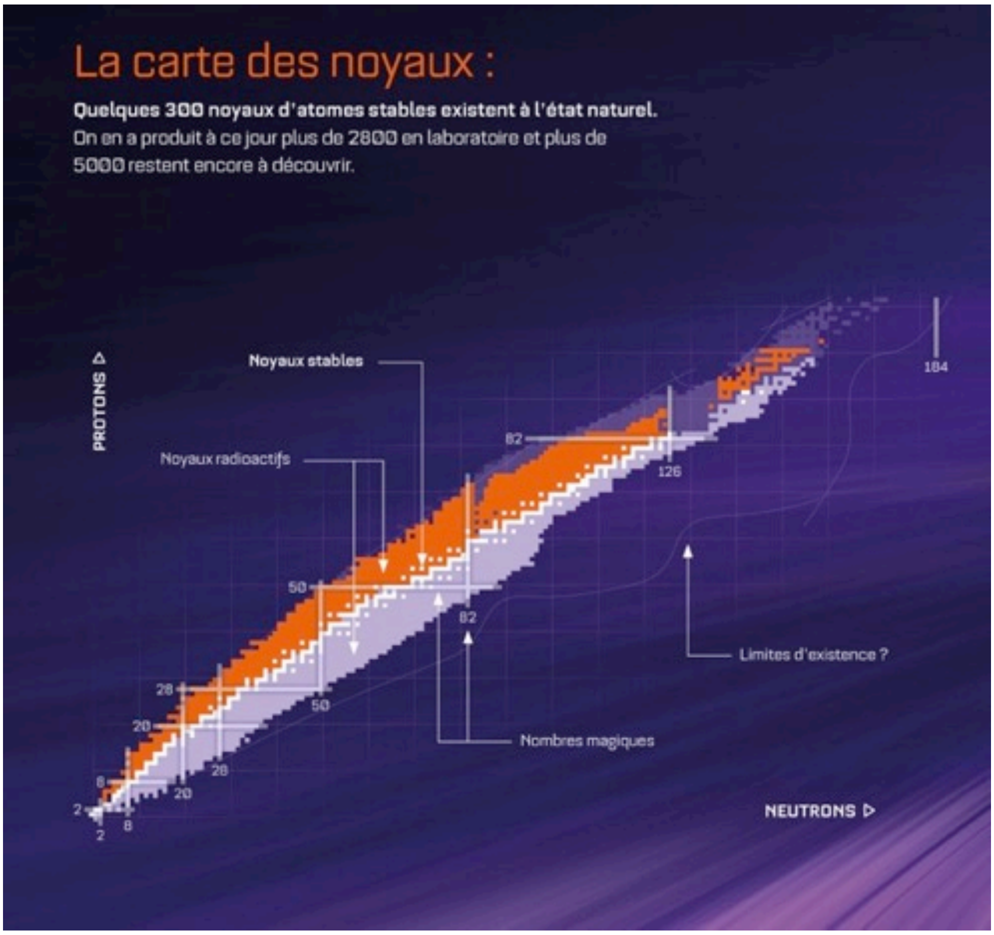
With Spiral2 (standing for "Système de production d'ions radioactifs accélérés en ligne de 2ème génération" - the second-generation system for on-line production of accelerated radioactive ions), the CNRS and CEA now have a more powerful facility for the production of heavier, more proton-rich, exotic nuclei. This new facility will make Ganil highly competitive at the international level for years to come, and give France and Europe a technological and scientific lead.

What scientific breakthroughs can we expect?

Generally-speaking, Spiral2 will be used to study the atomic nucleus, in other words, the very heart of the atom, the very heart of all matter, probing it from every possible angle and in extreme conditions, in terms of imbalance between the number of protons and the number of neutrons (e.g. nuclei that are neutron-deficient or, on the contrary, very neutron-rich), as well as in terms of excitation energy, temperature and pressure. It will be invaluable for revealing the deepest darkest secrets of matter. Exploring the properties of nuclei also entails questioning our origins and finding out more about the sources of energy production and matter in our Universe.

- **Exploring unknown territory within the Chart of the Nuclides**

Spiral2 will make it possible to probe the **limits of the existence of nuclei** by tracking the number of protons and neutrons they contain. This is especially important since it will make it possible to study how nucleons are distributed in a series of shells within these extreme nuclei, and probe the nuclear forces at work. There are a number of different scenarios relating to how matter is created, but they all depend on the properties of the most exotic nuclei, most of which are still undiscovered.



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Each element in this chart represents a nucleus, which is positioned according to the number of neutrons it contains, "from west to east" (x-axis), and the number of protons, "from south to north" (on the y-axis):
- the white elements are the 291 naturally-occurring nuclei found on Earth;
- the orange and light gray areas correspond to the 2,800 nuclei synthesized in laboratories to date.
The rest are the nuclei predicted, in theory, to exist in the Universe. A further 5,000 to 7,000 nuclei remain to be discovered…

Note: The numbers shown indicate the **magic numbers of protons or neutrons** which make nuclei more stable. The structure of the most exotic nuclei does not appear to bear any relation to these magic numbers. Spiral2 will make it possible to systematically track their evolution to the limits of the nuclei's existence in an attempt to understand this as yet unexplained phenomenon.

Thanks to the high intensity of Spiral2's heavy-ion beams, the Ganil will have a **competitive lead in the race to find super-heavy nuclei** (nuclei with more than 104 protons). In particular, it will be used to determine their physical and chemical properties, and their molecular states.

Another major area of research will focus on **the nuclear forces that bind** the nucleus together. The properties of exotic nuclei, their cohesion, size, excited levels, and shape, among other things, are determined by a subtle balance between the forces at work within them. By means of major modeling studies, the results from Spiral2 will help in describing these forces, in particular those at work in neutron-rich nuclei. Indeed, studying collisions between accelerated exotic nuclei and stable nuclei will be used to probe the properties of the cohesive forces acting on nucleons within the nucleus and to study how they evolve in extreme temperature and density conditions.

- **Looking deep into fundamental interactions**

Exotic nuclei transmute into more stable species through beta radioactivity. They may therefore be used to study the fundamental properties of the weak nuclear force which causes this phenomenon.

- **Nuclear astrophysics**

Exotic nuclei are produced during nuclear reactions in the Universe. To understand where these elements come from, and their abundance on Earth, we need to understand the properties of exotic nuclei, and the nuclear reactions which created them. Studying nuclear reactions using high-intensity radioactive or stable light-ion beams will help us understand the origin of heavy elements in the Universe (nucleosynthesis).

The protons and neutrons in a nucleus form a liquid with "extraordinary" density. This neutron-rich liquid makes up the heart of supernovae and neutron stars. Spiral2 will create this kind of matter on Earth, in reactions with highly neutron-rich nuclei normally found in stars and supernovae.

- **Nuclear physics for healthcare (1)**

The neutrons and ions delivered at Spiral2 will be used to study alternative and innovative methods for producing radioelements for medical use. In addition to proton/hadron therapy (treating cancer using ion beams), research will be carried out to study the influence of neutrons on living tissue.

- **Other applications (1) of Spiral2 will include**, for example, testing electronic components for resistance to radiation. Spiral2 will also be used in measuring nuclear data with a view to making nuclear energy ever safer and more environmentally-friendly. In particular, such data will be of use for new-generation fission reactors, fusion technology and nuclear waste transmutation.

(1) For more information, see Section V on the social and economic impact and technology transfer related to research at Spiral2-Ganil.

A positive local, national and international environment - the partners in the project

Since it was set up in 1976, Ganil has consistently received strong support from the local authorities, including Lower Normandy (now Normandy) Regional Council. Spiral2 is funded by the CNRS, the CEA, Normandy Regional Council, Calvados Departmental Council, the Caen la Mer Agglomeration Council and Caen City Council, with support from the European Union, via the EU's Spiral2 - Preparatory Phase project, and international collaboration (*for details of the budget, see Section III on the project's future development phases*).

A national project

Spiral2 is the CNRS' and CEA's national priority project in the field of Nuclear Physics, the outcome of technical and scientific collaboration between many French, European and international laboratories. The following French laboratories, in addition to Ganil of course, have been involved since the outset:

- **ten CNRS associate laboratories**: the Centre d'études nucléaires de Bordeaux Gradignan (CNRS/Université de Bordeaux), the Centre de sciences nucléaires et de sciences de la matière (CNRS/Université Paris-Sud), the Institut pluridisciplinaire Hubert Curien (CNRS/Université de Strasbourg), the Institut de physique nucléaire de Lyon (CNRS/Université Claude Bernard Lyon1), the Institut de physique nucléaire d'Orsay (CNRS/Université Paris-Sud), the Laboratoire de l'accélérateur linéaire (CNRS/Université Paris-Sud), the Laboratoire de physique corpusculaire de Caen (CNRS/Unicaen/Ensicaen), the Laboratoire de physique nucléaire et de hautes énergies (CNRS/UPMC/Université Paris Diderot), the Laboratoire de physique subatomique et de cosmologie (CNRS/Grenoble INP/Université de Grenoble) and the Laboratoire de physique subatomique et des technologies associées (CNRS/Université de Nantes/Ecole des Mines de Nantes);

- at the CEA, several laboratories within the Fundamental Research Division and the Military Applications Division are involved in both component design for Spiral2 and experimental programs.

Other CEA departments and CNRS laboratories have contributed their expertise and support, especially in the field of nuclear safety and in developing the scientific program.

An international project

Ganil has a long tradition of welcoming physicists from all over the world: its scientific community includes nearly 700 researchers who regularly carry out experiments and attend seminars and conferences here. What's more, 23 countries have collaborated in Spiral2: Belgium, Bulgaria, Canada, China, Czech Republic, Finland, Germany, Greece, Hungary, India, Israel, Italy, Japan, Poland, Romania, Russia, South Korea, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the USA. Around twenty bilateral agreements have been signed to this end since 2002.

Accelerators of comparable capability to Spiral2 in the world

A number of countries have launched major research projects in the field of Nuclear Physics in recent years. **Five accelerators of similar capabilities to Spiral2**, either because of the type of nuclei studied or the production methods used, are currently under construction:

- Air in Canada and HIE-Isolde at CERN, which are due for completion in 2017,
- Fair, the German project led by GSI, which is to be dedicated to hadron physics and particle physics as well as nuclear physics, and the Italian SPES project, both due to be brought online mid-2019,
- the USA is developing FRIB, scheduled to be operational in 2022.

The launch of Spiral2 in 2017 will thus open up a whole new era in fundamental and applied research on atomic nuclei, putting France at the forefront of international research.

II. THE SPIRAL2 FACILITY AND EQUIPMENT

The Spiral2 accelerator and the experimental areas

Spiral2 consists of a linear particle accelerator (Linac) for research in fundamental nuclear physics and interdisciplinary research, together with three experimental areas called NFS, S^3 and Desir. The facility will produce beams unlike any other in the world, primarily in terms of beam intensity. The kind of exotic nuclei that nuclear physicists are keen to study will be generated by the interactions between these beams and specific targets.
There are 8,000 cables in the facility, giving a total length of 240 km spread within 7,200 m^2, i.e. as many as in the original Ganil facility. For the purposes of radiation protection, the entire facility is buried at a depth of around 10 meters underground. The heat generated in all the equipment is dissipated in six 13-meter high cooling towers with total capacity of 7.6 MW (1).

The sources: generating ions

The Spiral2 operators have two different sources that can be used to produce either light ions (protons, deuterons and alpha particles) or heavy ions (from carbon to uranium).

Each source, known as ECR (Electron Cyclotron Resonance) sources, comprises a vacuum cavity in which atoms are injected in gaseous form (a pure gas or gas composed of several types of atoms, or a heated metal vapor). The cavity is subjected to a strong microwave field which causes collisions between free electrons and the gas atoms, resulting in ionization of the gas atoms. The ultimate form of charged particle, ions are sensitive to electrical and magnetic fields. On exiting the ECR source, they have kinetic energies of up to a maximum of 60 keV (1).

Forming ions into a beam, accelerating and guiding them

As they exit the source, the ions are subjected to a series of electromagnetic fields which bunch them together and accelerate them through a 40-meter long linear path: the ions pass first through a cavity made of pure copper into a quadrupole magnet in which a radiofrequency wave groups them into "bunches". Their kinetic energy can increase up to 750 keV per unit mass.
They are then accelerated by passing through 26 superconducting cavities made of niobium, increasing their kinetic energy up to 40 MeV in the case of deuterons (and 33 MeV in the case of protons).
This accelerator produces **beams of up to 200 kW** (1), much higher than the power of the beams currently produced at Ganil.

Accelerator cryomodules

The first twelve cryomodules each have one superconducting cavity, while the next seven have two each. The cavities contain an intense electromagnetic field, required to accelerate the ion beam. The cryomodules have been specially-designed for Spiral2 by teams at the CEA and CNRS which specialize in superconducting cavities, the same teams that were involved in the design and development of the CERN's LHC accelerator components.

Cooling the superconducting cavities

The Spiral2 cryogenic facility maintains the cavities in the cryomodules in the superconducting state at an operating temperature of –269°C, which is close to absolute zero. It includes a helium condenser. Liquid nitrogen is used for pre-cooling and functions with coolants and exchangers in a vacuum vessel. Its job is to produce liquid helium at a temperature of 4.5 K which is supplied to the cryomodules and maintains the superconducting cavities at the correct operating temperature.

Guiding the beam to the experimental areas

Along its path, in the Linac and then on toward the experimental areas, the ion beam is focused by quadrupole magnets and guided by dipole magnets. The ion beam is carried inside tubes maintained under very high vacuum conditions (10^{-11} bar (3)).

The experimental areas

Spiral2 has three large areas housing experimental systems.

- Neutrons: Protons and deuterons accelerated by the Linac can generate extremely intense neutron beams through reaction with a target or interaction with a converter. The NFS (Neutrons For Science) facility uses these neutrons in fundamental physics experiments and a great many applications.
- Nuclei that are heavier than uranium: The Spiral2 Linac will accelerate very high-intensity stable ion beams. These unparalleled intensities open up new opportunities in many areas of physics, primarily in the study of very heavy and "super-heavy" ions that do not occur naturally on Earth. The Super Separator Spectrometer, known as the S^3 separator, is dedicated to research on these types of nucleus.
- Coupling Spiral + Spiral 2 beams together: The Desir facility (Decay, Excitation and Storage of Radioactive Ions) uses low-energy beams generated by Spiral (part of the original Ganil facility) and from the S^3 facility (or, in the future, from the Spiral2 production building). By combining spectroscopy, mass spectrometry and ion-trapping measurement techniques, these beams can be used to try and answer questions in the fields of nuclear physics, weak-interaction physics and astrophysics.

Converting the beam prior to an experiment (Phase 2)

In the second phase of the Spiral2 project, the complex will be equipped with a "production building", which will be used to couple together Spiral2 and Spiral. The beam produced by the Spiral2 Linac, by irradiating a target, will produce low-energy neutron-rich heavy exotic nuclei (from zirconium to mercury). An ion source will then be used to ionize and accelerate these new nuclei, which will be characterized, sorted and transported to the Desir facility or to the existing Spiral facility to undergo post-acceleration before being sent to the experiment chambers.

From Spiral to Spiral2

The new science complex is called Spiral2 although it is based on a linear accelerator. It is being developed as an addition to the Spiral facility (Système de production d'ions radioactifs accélérés en ligne - system for on-line production of accelerated radioactive ions). Spiral is the first facility for the production and acceleration of exotic nuclei built in France (2001).
The acronym, Spiral, is also a reference to the shape of the trajectory taken by radioactive ions post-accelerated in CIME, the Spiral cyclotron. The original Ganil facility delivers heavy-ion beams, from carbon through to uranium.

Spiral2 will make it possible to **deliver light-ion beams (protons, deuterons, helium, etc.), and heavy-ion beams which are of 10 times higher intensity than anything currently available**. Beam intensity may be up to 5 mA in the case of light-ion beams and up to 1 mA in the case of heavy-ion beams. These levels mean that the facility will be one of the most powerful in the world.

The Jules Horowitz Campus

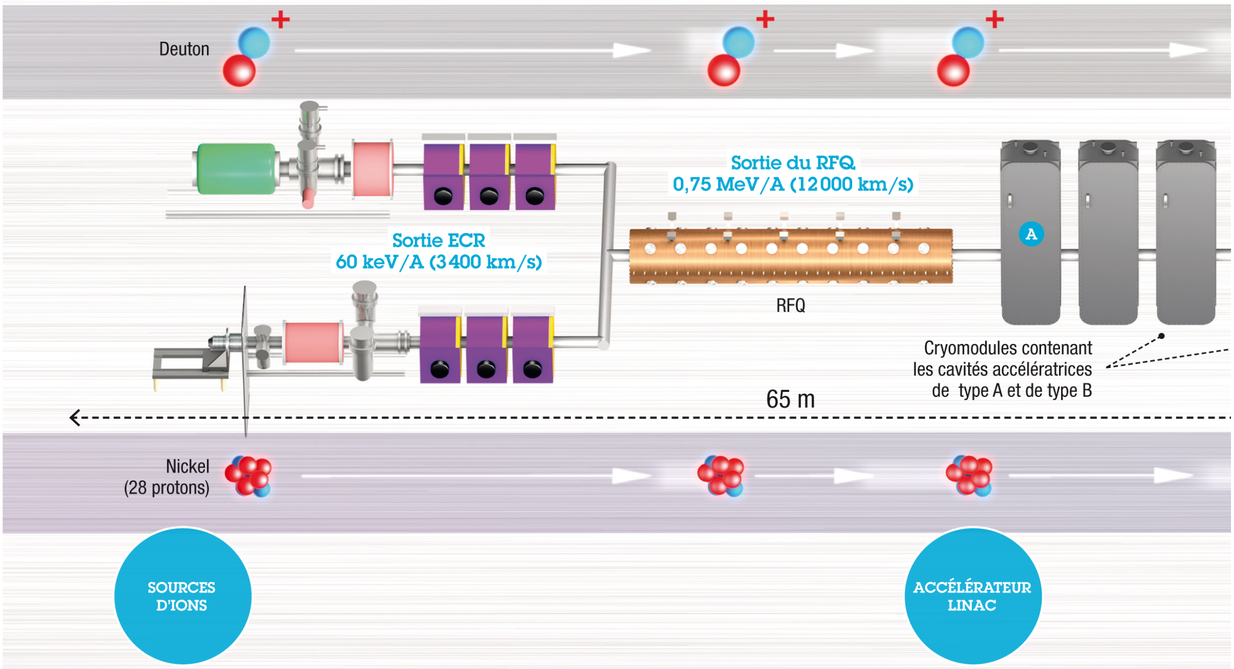
A multidisciplinary science hub has gradually grown up around Ganil to form the Jules Horowitz Campus. Continuing on from the "ion-matter interaction" multidisciplinary science hub formed around Ganil, and in order to enhance synergy between different areas of research, Ganil is a stakeholder in the project to develop a “regional center of excellence in nuclear technology” based on Industry, Education, Training and Research in Normandy.

(1) To give an idea of the orders of magnitude involved in the amount of heat dissipated, a clothes iron dissipates around 1kW and a light bulb around 10 W. 1 kW = 1,000 W. 1 MW = 1,000 kW. 1 watt corresponds to energy flow of 1 joule per second.
(2) When speaking of elementary particles and ions, energy is often expressed in electron-volts (symbol: eV). 1 electron-volt is the kinetic energy to which an electron at rest is subjected under the effect of a 1 volt electrical field. 1 keV = 1,000 eV. 1 MeV = 1,000 keV
(3) 1 bar is atmospheric pressure at sea level (altitude of 0 m)

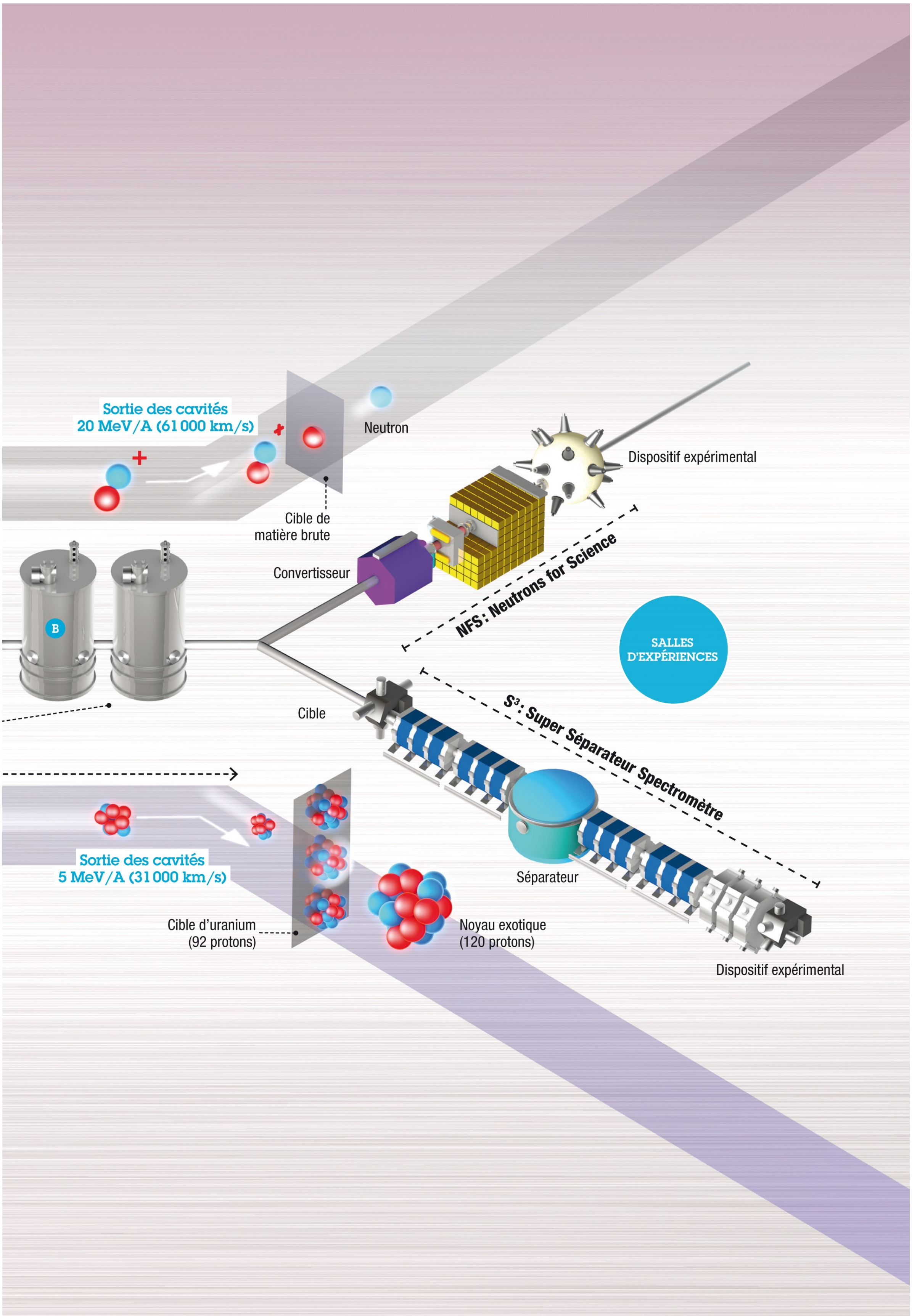
Spiral2

PRINCIPE

Produits par deux sources d'ions, des faisceaux de particules chargées sont guidés et accélérés par les champs électriques et magnétiques d'un accélérateur linéaire, le Linac.
Ils sont ensuite acheminés dans des salles d'expériences où ils sont projetés sur des cibles de matière pour produire des neutrons ou des **noyaux exotiques** utilisés pour des études en physique fondamentale et appliquée.



Les défis du CEA Novembre 2016 **N°212**
Amélie Lorec, Aude Ganier et Fabrice Mathé (infographie), en collaboration avec Jean-Charles Thomas du Ganil



Sortie des cavités
20 MeV/A (61 000 km/s)
Neutron
Dispositif expérimental
Cible de
matière brute
Convertisseur
NFS : Neutrons for Science
SALLES
D'EXPÉRIENCES
B
Cible
S³ : Super Séparateur Spectromètre
Séparateur
Sortie des cavités
5 MeV/A (31 000 km/s)
Cible d'uranium
(92 protons)
Noyau exotique
(120 protons)
Dispositif expérimental

III. THE PROJECT'S FUTURE DEVELOPMENT PHASES

Schedule and funding

Next milestones

Second half of 2017: Experiments to start in NFS, which will deliver very high-intensity and high-energy neutron beams

Mid 2018: Experiments to start in S^3 and end of Phase 1

2022: Desir, the third experimental area at Spiral2, to start operating

2025 and beyond (subject to funding): Launch of Phase 2 of Spiral2 (the so-called "production" building)

The three major stages (in the diagram below, Spiral2 is shown in purple and Spiral in white)**:**

- Phase 1 (accelerator, NFS and S^3 Equipex): to start operating in the second half of 2017 – mid-2018
- Phase 1+ (including the Desir Equipex): to start operating in 2022
- Phase 2: rescheduled until after 2025

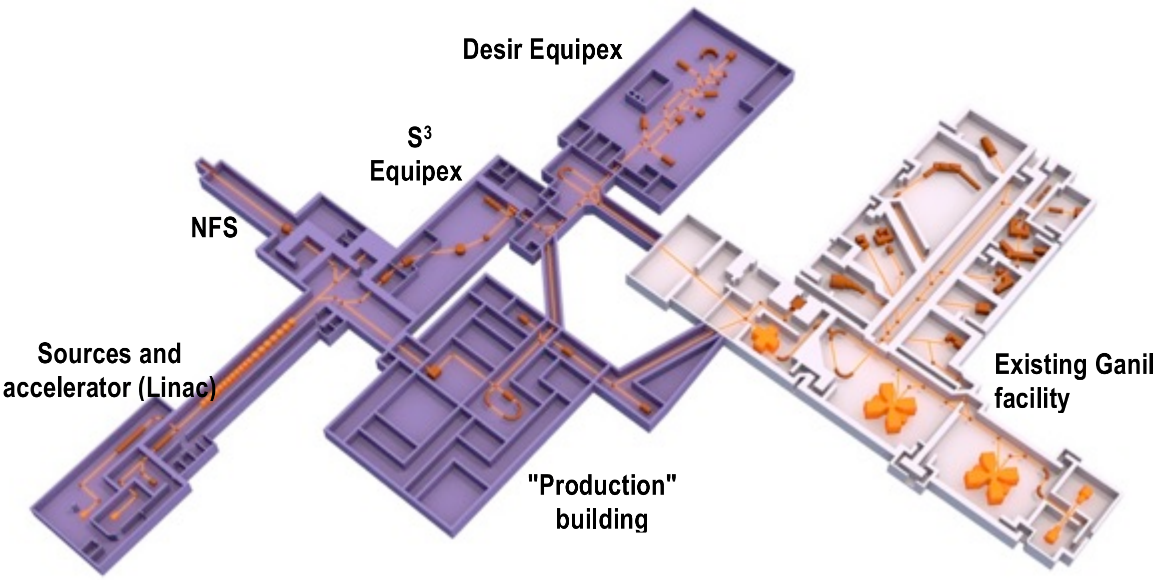


Diagram showing the layout of Spiral2 facilities (purple) and Spiral facilities (white) © Unik studio.

Budget

The total budget of over 138.5 million euro, which will be used to fund Phase 1 and the Desir Equipex at Spiral2 (it does not cover Phase 2) is broken down as follows:

CNRS and CEA	€38.66 million
PIA1 (S^3 and DESIR Equipex)	€17 million
Normandy Regional Council	€28.18 million
Calvados Departmental Council	€12.84 million
Caen la Mer Agglomeration Council	€5.56 million
Caen City Council	€2.80 million
State-Region contract (CPER) 2007-2013	€2.28 million
State-Region contract (CPER) 2015-2020	€4.65 million
Interregional State-Region contract (CPIER) 2015-2020	€1.5 million
FP7 (Europe)	€1.04 million
GSI/FAIR (Germany)	€16.40 million
Other countries (India, Sweden, Belgium, Poland, Czech Rep., Germany, USA, Romania)	€1 million
Ganil	€6,585 million
TOTAL	**€138.5 million**

In addition to this sum, there is also the cost of personnel provided by the CNRS and CEA, at an estimated 60 million euro.

Desir, the Spiral2 low-energy facility

Scheduled to start operating in 2022, Desir (Désintégration, Excitation et Stockage d'Ions Radioactifs - Decay, Excitation and Storage of Radioactive Ions) will be a large experimental area that will receive low-energy beams from Spiral and Spiral2. By combining spectroscopy, mass spectrometry and ion-trapping measurement techniques, these beams can be used to try to answer questions in the fields of nuclear physics, weak-interaction physics and astrophysics.

Desir will thus make use of a combination of innovative and highly-selective ion-trapping techniques employed to prepare ultra-pure radioactive ion beams with systems designed to study how they interact with lasers and observe their transformation processes. The aim is to obtain incredibly precise data on the fundamental properties of atomic nuclei, data that has never been obtained before.

Desir will exploit the huge variety of stable and radioactive ion beams produced by Spiral and Spiral2. In addition to the groundbreaking scientific advances expected in furthering our understanding of the atomic nucleus, the research carried out will be applied in the areas of energy production, primarily by characterizing the decay products of uranium fission, and research on materials. Such advances should also open up new opportunities for technology transfer to industry.

Spiral2: Phase 2

Phase 2 of the Spiral2 project aims to produce beams of radioactive light-ions or neutron-rich ions, at intensities that, once accelerated, will enable them to be used as projectiles to produce even more exotic nuclei.

Beams of radioactive light-ions, which are particularly useful in nuclear astrophysics studies, will be produced in the production building using high-intensity stable ion beams from the Spiral2 linear accelerator (Linac). Beams of neutron-rich radioactive ions will be produced by provoking the neutron-induced fission of uranium targets, generated, as in the NFS facility, by converting a high-intensity deuteron beam delivered by the Linac.

IV. THE PROJECT'S ENVIRONMENTAL IMPACT

Radiological risks

The experiments carried out at Ganil, and this will also apply to Spiral2, produce nuclear reactions and ionizing radiation. However, the quantities of radioactive material used are extremely small (a few milligrams).

When particle accelerators are in operation, the accelerated particles interact with the equipment that intercepts the beam and with the targets used in experiments, generating intense ionizing radiation. The potential immediate consequences related to the beam thus carry a very high risk for any person in close proximity to the beam during operation. However, while this is a major risk, it disappears as soon as the beam is stopped. For this reason, operators and experimenters are prohibited from entering any area in which the beam circulates: all access to them is locked when the beam is present. Furthermore, all the equipment (accelerators, beam transport line and experiment systems) is surrounded by protective concrete and lead shields, as at other particle accelerators such as CERN in Geneva, and the Soleil synchrotron at Paris-Saclay. Lastly, the Spiral2 areas in which the beam travels are buried at a depth of approximately 10 meters underground.

A system of contactors, alarms and radiation detectors is used to monitor the facility at all times from the Spiral2 control room.

The beam causes some of the equipment to become radioactive, particularly the "beam dumps" and certain targets used in experiments. Such equipment is thus subject to residual radioactivity (i.e. which remains after the beam has been stopped). Managing access to such equipment is thus strictly monitored, entailing, as for any radioactive source, the implementation of radiological protection measures designed to reduce radiation flux, radiological inspections carried out by qualified radiation protection personnel, and systematic ambient radiological monitoring in the relevant premises using a dense network of measurement equipment.

All the facilities at Ganil (including Spiral2) are subject to the regulations relative to basic nuclear Installations (INB) and are, therefore, regulated by the French Nuclear Safety Authority (ASN). All the measures, procedures and equipment related to nuclear safety and radiation protection are subject to studies and inspections validated by ASN throughout every stage in the life of the facility, from the design stage, prior to commissioning, throughout operating and until the facility is dismantled. A local information committee (CLI) coordinated by Calvados Departmental Council, involving representatives of the surrounding towns, was set up on 29 December 2008. This committee is in charge of monitoring and public information and consultation processes regarding activities at Ganil.

Computer modeling of Spiral2 surface buildings © Ganil.

Environmental and health risks

A study on the environmental and health impact of the Spiral2 project has been carried out. It concludes that the construction and subsequent operation of the future Ganil facility, consisting of the original facilities and the Spiral2 facility, will have little impact on public health or the environment and will not cause pollution.

Ganil has a radioactive and chemical effluent release permit issued by ASN. The laboratory implements an environmental monitoring program that includes periodic measurements of radioactivity levels and certain chemical pollutants using samples taken in the direct vicinity of the facility.

During normal facility operation, the annual radiological impact on the population most at risk of exposure is less than 4 µSv. This is more than a hundred times lower than the legal annual exposure limit of 1000 µSv (1 mSv) for a member of the public in France (French Public Health Code). It can also be compared to average exposure to background radiation in France, of around 2400 µSv (2.4 mSv) a year.

Conventional safety

Ganil, including Spiral2, is subject to the general regulations applicable to all industrial facilities with regard to conventional risks, including risks relating to electrical, mechanical, cryogenic, etc. systems.

V. SOCIAL AND ECONOMIC IMPACT, AND TECHNOLOGY TRANSFER RELATED TO RESEARCH AT SPIRAL2-GANIL

Industrial applications

The first industrial applications of beams produced at Ganil came about in 1988, with the first experiments to produce microporous membranes by irradiating polymer films using heavy ions, and the first radiation resistance tests on electronic components. Aerospace companies also developed R&D and certification programs for components using Ganil beams.

One of the aims for Ganil is to increase the amount of beam time available to industry, without encroaching on the time devoted to fundamental research and R&D. Spiral2 will thus provide greater capacity for industrial experiments to be performed and extend the spectrum of such applications.

For example, thanks to Spiral2, R&D on innovative radioisotopes for the biomedical sector and the characterization of components and materials subject to irradiation (aerospace, fusion, etc.) will be able to use high-intensity light-ion beams and fast neutron beams.

Microporous membranes

Ion beams produced at Ganil can be used to create controlled defects in polymer films, with a view to manufacturing microporous membranes (filter applications, particularly in the biomedical and agrifood industries). In partnership with a Belgian company, the laboratory has developed equipment that can produce 100 m^2 of membrane per hour. This equipment is mainly used by German, Belgian, Swedish and Chinese companies.

In 2015, a Chinese biomedical company launched a development program aiming to mass produce microporous membranes at Ganil.

Hadron therapy

Since 2013, Ganil has allotted between 150 and 180 hours a year to R&D related to research on hadrontherapy (treating cancer using proton or carbon ion beams). Compared to radiotherapy that uses X-rays, gamma-rays or electrons, hadrontherapy should make it possible to better target irradiation to tumor cells without damaging healthy tissue.

When living tissue is irradiated with electrons, X-rays or gamma-rays, beam energy is absorbed along the beam's path through the tissue. With ions like protons or carbon ions, most of the energy is deposed in the tissue at a depth dependent on initial beam energy. This means that deep tumors can be treated while reducing damage to healthy tissue. Research carried out at Ganil (within the framework of the France-Hadron Project) aims to qualify the method (radiobiology, nuclear physics and dosimetry) with a view to its use in research and medicine.

The Archade Center, devoted to research on hadron therapy, is being built near Ganil. In direct liaison with the François Baclesse cancer care center, it aims to promote the emergence, based in Normandy, of an industry for the design and sale of hadrontherapy equipment. In France there are two centers using proton beams to treat cancer (in Orsay and Nice) but there is no research center specializing in treatment using carbon-ion beams. Compared to proton therapy, the latter technique has the advantage of concentrating even more energy in the tumor and sparing superficial tissue.

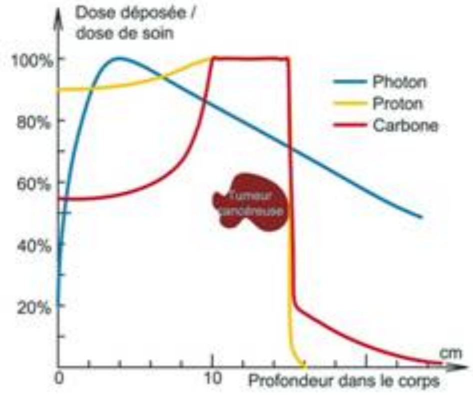


Diagram showing beam energy deposition at different depths in irradiated tissue. In the case of photons (X- or gamma rays) energy deposition is progressive, whereas for protons, and even more so for carbon ions, maximum deposition occurs deep in the tissue, thus avoiding "burning" the superficial tissue surrounding a tumor © France Hadron.

R&D and qualification of components for the aerospace industry

Many companies use the beams produced at Ganil to test certain electronic components used in spacecraft for resistance to radiation: Airbus/Atmel, CNES, EADS, ESA, Infineon, JAXA, ST Microelectronics.

Nuclear industry

Ganil is a member of "Nucleopolis", Normandy's center for nuclear science and its applications in the energy and healthcare industries, set up in 2010. Nucleopolis is a tech cluster that brings together nuclear industry companies, research laboratories and higher education institutions. It promotes economic development through innovation, improving skills and making SMEs more competitive.

Radionuclides for biomedical research, diagnosis and treatment

Since 2014, Ganil has led R&D programs on producing radionuclides that can be incorporated into bioactives (radiopharmaceuticals) used in research as well as in clinical practice. Spiral2 will make it possible to supply such projects with proton, deuteron and heavy-ion beams with higher intensity than the beams currently available to researchers.

Technology transfer

Ganil is involved in many technology transfer projects with its industry partners including, for example, projects on ion sources (with many applications, such as research, ion implantation, developing new materials, hadrontherapy, and radioisotopes) and other innovating technologies.

Setting up companies

Ganil is a founding member of the "Normandie Incubation" business incubator, in collaboration with the University of Normandy and ENSICAEN Engineering School. Normandie Incubation receives funding from the Normandy Regional Council, the French Ministry of Higher Education and Research, and the European Union (ERDF). Between 2000 and 2014, Normandie Incubation supported 85 research projects which resulted in setting up 66 companies and created 365 jobs in the region.

VI. THE PARTNERS

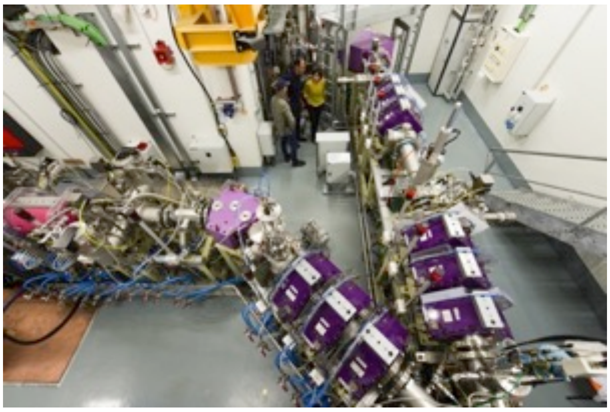
Scientific partners: CNRS and CEA

The project also receives strong support from:

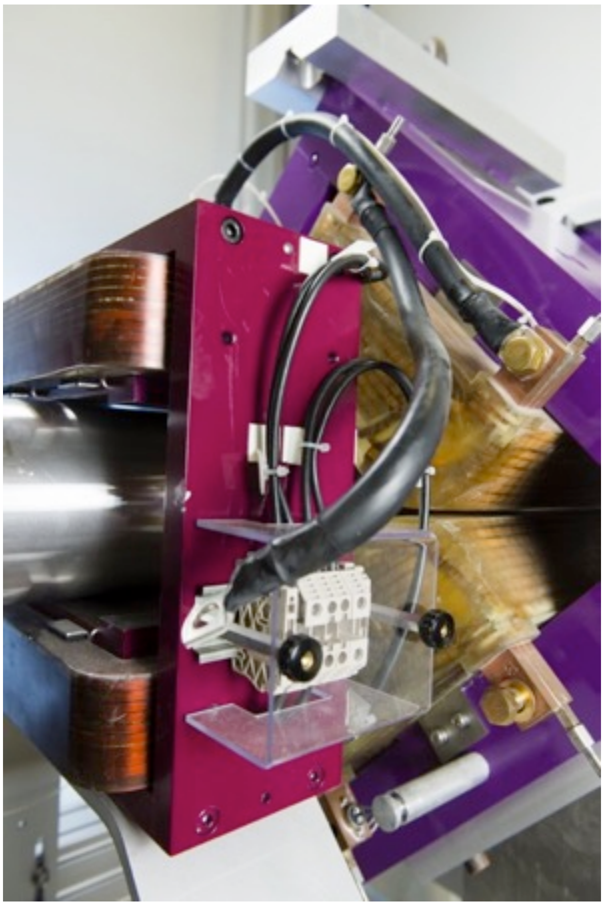
VII. EXAMPLES OF THE IMAGES AVAILABLE

Other images are available at no charge upon request to the CNRS and CEA press offices.

The Spiral2 Linac (LINear ACcelerator) with its superconducting cryomodules enclosing the accelerator cavities.
© Philippe Stroppa/CEA/CNRS



Deuteron / proton source chamber in Spiral2 (the second-generation system for on-line production of radioactive ions).
© Philippe Stroppa/CEA/CNRS



NFS (Neutrons For Science) experimental area being assembled at Spiral2. © Philippe Stroppa/CEA/CNRS

Cryogenic plant where liquid helium is produced for the Spiral2 Linac (LINear ACcelerator). © Philippe Stroppa/CEA/CNRS

Cryogenic plant where liquid helium is produced for the Spiral2 Linac (LINear ACcelerator). © Philippe Stroppa/CEA/CNRS

View of the Spiral2 Linac (LINear ACcelerator). © Philippe Stroppa/CEA/CNRS

Part of the high-energy beam transport line at Spiral2. © Philippe Stroppa/CEA/CNRS

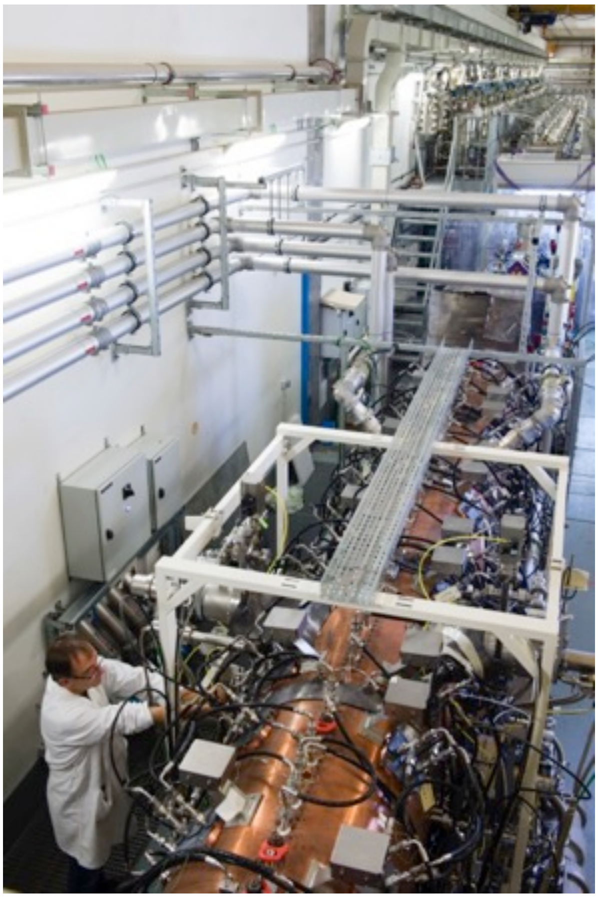
Part of the high-energy beam transport line at Spiral2. © Philippe Stroppa/CEA/CNRS

Spiral2 building, Caen, France. © Philippe Stroppa/CEA/CNRS

Spiral2 building, Caen, France. © Philippe Stroppa/CEA/CNRS

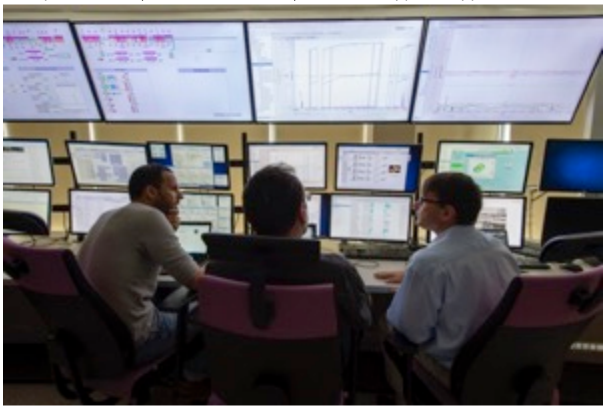
Superconducting cryomodules enclosing the accelerator cavities of the Spiral2 Linac (LINear ACcelerator). © Philippe Stroppa/CEA/CNRS

Superconducting cryomodules enclosing the accelerator cavities of the Spiral2 Linac (LINear ACcelerator). © Philippe Stroppa/CEA/CNRS



RFQ (radiofrequency quadrupole) accelerating cavity made of pure copper in the Spiral2 Linac (LINear ACcelerator) Hall. © Philippe Stroppa/CEA/CNRS

RFQ (radiofrequency quadrupole) accelerating cavity made of pure copper in the Spiral2 Linac (LINear ACcelerator) Hall. © Philippe Stroppa/CEA/CNRS



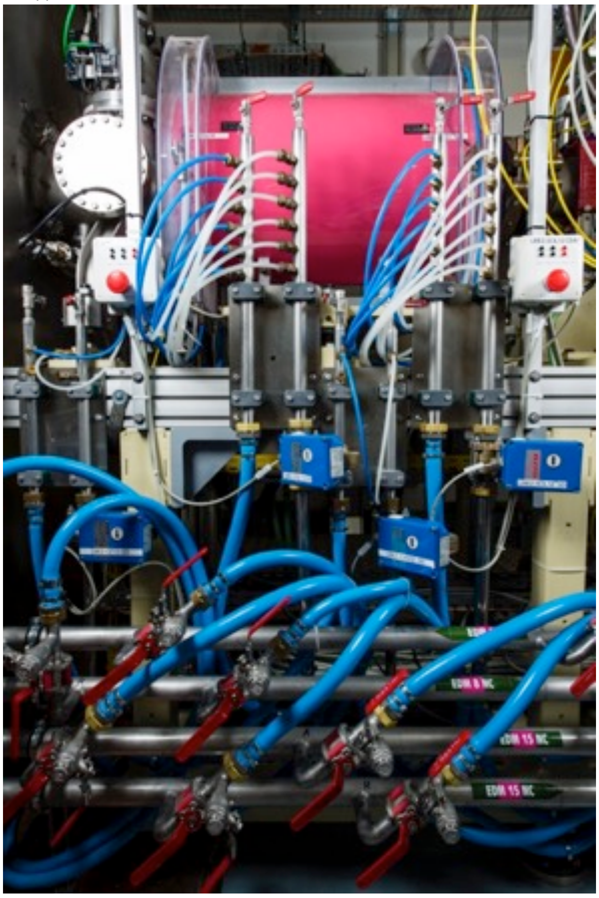
Spiral2 remote control station.
© Philippe Stroppa/CEA/CNRS

Spiral2 High-Frequency hall © Philippe Stroppa/CEA/CNRS

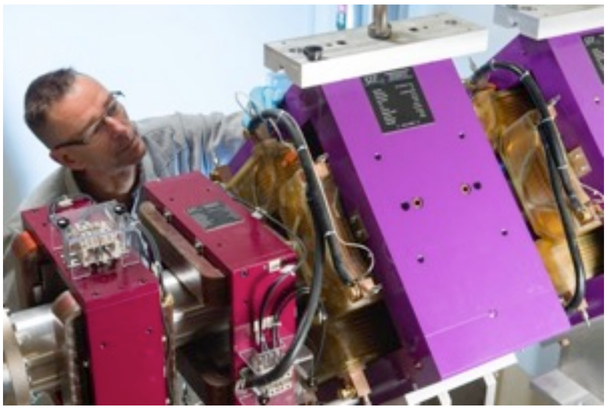

Spiral2 heavy-ion and deuteron / proton sources. © Philippe Stroppa/CEA/CNRS


Spiral2 heavy-ion and deuteron / proton sources. © Philippe Stroppa/CEA/CNRS


Spiral2 heavy-ion and deuteron / proton sources. © Philippe Stroppa/CEA/CNRS

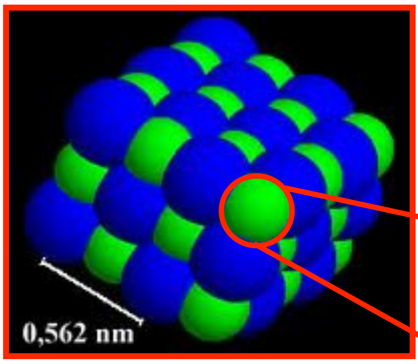

Spiral2 heavy-ion and deuteron / proton sources. © Philippe Stroppa/CEA/CNRS


NFS (Neutrons For Science) experimental area being assembled at Spiral2. © Philippe Stroppa/CEA/CNRS


NFS (Neutrons For Science) experimental area being assembled at Spiral2. © Philippe Stroppa/CEA/CNRS

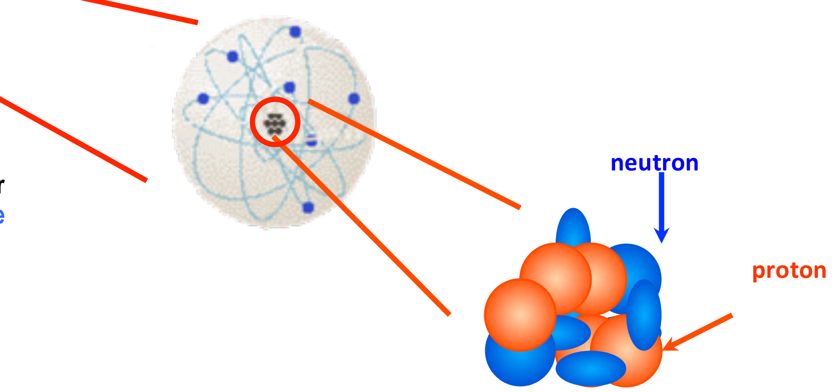
VIII. GLOSSARY

Atom
The basic building-block of matter, with a center made up of nucleons (protons and neutrons) surrounded by electrons.



Example of a salt crystal: regular arrangement of sodium and chlorine atoms.

The atom: a compact core (nucleus) surrounded by electrons



The atomic nucleus: a set of protons and neutrons (protons and neutrons are nucleons)

Electron
Elementary point-like particle (its diameter is considered to be zero), with mass m_e = 9.109x10^{-31} kg, and with a negative charge -e (where e is the elementary charge) = -1.602x10^{-19} C.

Nucleon (proton or neutron)
Nucleons form the atomic nucleus. Protons are electrically charged while neutrons are neutral. The charge of the nucleus, and therefore the element, is defined by the number of protons (1 proton for hydrogen, 6 for carbon, 14 for silicon, etc.). The sum of the number of protons and neutrons gives the total atomic number A, used to define the mass of the nucleus. Nucleons are hadrons (they are made up of quarks) and, to be more precise, baryons (they contain 3 quarks).

Neutron
Electrically neutral (as its name suggests), together with the proton, it forms part of the atomic nucleus, with mass m_n = 1.6749x10^{-27} kg.

Nucleus
The "heart" of an atom, made up of two types of nucleon: protons and neutrons.

Proton

Together with the neutron, it forms part of the atomic nucleus. It has diameter $d_p = 0.8x10^{-15}$ m, mass $m_p = 1.6725x10^{-27}$ kg and a positive charge $+e = 1.602x10^{19}$ C. Neutrons and protons are not elementary particles. We now know that they are made up of quarks.

Quark

The smallest constituent part of an atomic nucleus.

Quarks assemble to form hadrons, such as neutrons and protons, which form stable matter. They interact due to strong-interaction, weak-interaction and electromagnetic forces. The strong-interaction force, known as color confinement, means that they are never found in isolation. They always appear in groups of two (quark-antiquark), forming mesons, which are all unstable, or in groups of three, to form baryons (like the proton and the neutron).