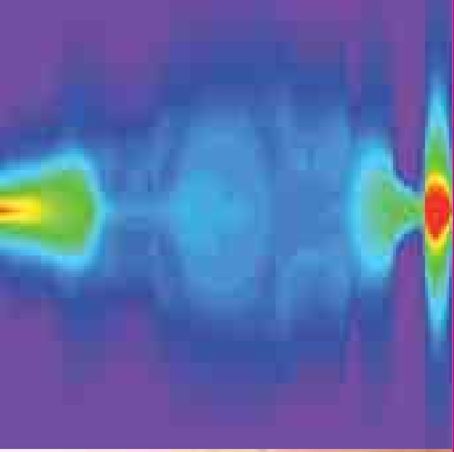
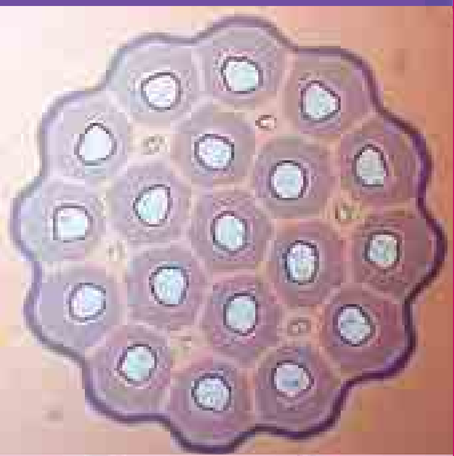




Physical Sciences Division (DSM)

Institute of Research into the Fundamental Laws
of the Universe (IRFU)

Department of Accelerators, Cryogenics and Magnetism

SACM 2010-2012

FROM RESEARCH TO INDUSTRY

cea

Contents

Department of Accelerators, Cryogenics and Magnetism (SACM)

SACM is part of the Institute of Research into the Fundamental Laws of the Universe (IRFU), of the CEA Physical Sciences Division (DSM). It is located on the Saclay center in the premises of the former National Laboratory Saturne, LNS, and the former Department of Instrumental Techniques of Elementary Particles, the STIPE. These premises have been renovated and gathered in a large platform called "Synergium" which occupies a total floor area of 25,000 m^2. SACM which hosts 75 research engineers and 45 technicians has for mission to carry out, with the national and international community, research and development of excellence in the fields of particle accelerators, cryogenic systems and superconducting magnets for use in fundamental research. The Department has played a major role over many years in the construction of the high technology instruments needed for this type of research (LHC, W7-X, SPIRAL2, FAIR, IPHI, ESS).

The expertise of the Department has also been deployed in support of work in associated fields including energy (materials studies for thermonuclear fusion as part of the IFMIF project, qualification of the coils of the Japanese JT-60SA Tokamak), life sciences (the ISEULT ultra high field magnetic resonance imager for NEUROSPIN) and light sources (SOLEIL and XFEL).

SACM also provides management services for major large scale projects and develops the associated test systems. These projects are carried out within the project structure of the IRFU in close association with other departments of the Institute, both physical and technology, particularly the Department of System Engineering, SIS. Finally the technology transfer to industrial partners constitutes a core component of the work of the Department.

SACM brings together strengths in both the design and construction of large scale systems. The expertise of the Department extends to the fields of accelerator theory, ion sources, conventional and superconducting accelerating cavities, superconducting magnets, and the associated cryogenic systems. It is based on a wide range of test systems, from small test stations used to characterize materials to very large scale systems capable of testing entire superconducting coils and cavities. The vitality of SACM is also due in a large part to the contribution of young PhD students and post-doctoral researchers within the R&D teams. This continual influx of new ideas enables the Department to explore new technologies for use in designing and constructing the instruments needed to support advances in applied fundamental research.

The workforce of SACM is divided among five laboratories:

- the Accelerator Design and Development Laboratory (LEDA),
- the Accelerator and Hyperfrequency Systems Engineering Laboratory (LISAH),
- the Cavity and Cryomodule Development and Integration Laboratory (LIDC2),
- the Laboratory for Superconducting Magnet Research (LEAS),
- the Cryogenics Laboratory and Test Stations (LCSE).

A Scientific and Technical Committee, the CSTS, composed of 14 members and 7 international experts from outside the CEA, meets once a year to evaluate ongoing activities and examine new proposals. The CSTS assists the Head of the SACM in defining research and development strategy within the Department.

In the last three years, SACM has scored a number of successes: the injectors of SPIRAL2 and IFMIF have been tested in an operational situation in their bunkers inside the Synergium and have achieved their nominal performance. The 51 tons of superconducting material necessary for the ISEULT project were produced and 170 double pancakes were wound with the required accuracy. The development of innovative antennas for medical imaging has continued with success. Sources of SILHI type will now be industrialized and beam dynamics softwares are marketed worldwide. In October 2012, the JT-60SA cold test station received its imposing cryostat.

Over the next three years efforts will focus on commissioning the IPHI injector, on the industrial phase of XFEL cryomodules assembly, as well as on the construction and testing of two innovative cryomodules: the prototype cryomodule for the IFMIF-LIPAC accelerator, and the technology demonstrator for ESS. SACM will also contribute to the progress of the project CILEX in view of new acceleration techniques and deliver the proton injector FAIR project in Darmstadt. In the field of cryomagnetism the JT-60SA test station will be commissioned in 2014 and will open technological extensions for the ITER program. The spectrometer R^{3}B-Glad will be cryostated and tested. The imaging magnet NEUROSPIN-ISEULT will be cryostated to get its ambitious performances in terms of magnetic field homogeneity and stability. The SACM will also participate strongly to the development of new high-field magnets needed to increase the luminosity and energy of the LHC.

By 2017 and within its complementary activities of accelerators and cryomagnetism, the SACM will be intensely involved in exciting projects equal to the major scientific missions of the CEA. Moreover the SACM will resolutely participate, together with the nearby communities, in the launching and the success of the campus of the Paris-Saclay University.

Antoine Daël, head of SACM

LEDA

The Accelerator Design and Development Laboratory (LEDA) brings together SACM expertise and skills in the design, construction, and testing of systems used to produce, transport, and accelerate charged particle beams. As of December 31, 2012, LEDA employs 20 engineers, seven technicians and one PhD student, working in the following teams:

- a team of experts in beam modeling applied to linear and circular accelerators, in the presence of collective effects such as space charge or wake fields, and in electromagnetic calculations applied to electrostatic, magnetic and radiofrequency systems;
- a technical team experienced in accelerator installation, mechanical assembly and cooling;
- an experimental team specialized in setting up and operating sources and injectors;
- an experimental team of experts for measuring beam parameters involving the design and implementation of innovative diagnostic techniques.

Building the groundwork for future research, LEDA is currently constructing an accelerator for nuclear physics research (FAIR), designing a radio frequency quadrupole (RFQ) for the ESS project, exploring the theoretical and technological aspects of the next generation of particle accelerators (HILUMI, LHC, and CLIC), and studying laser-plasma acceleration for the CILEX project.

In 2013, in addition to the BETSI test system for the development of compact light ion sources and diagnostic tests, the laboratory will make available to future users intense beams of 3 MeV protons after the RFQ of the Iphi project.

LISAH

As of December 31, 2012, the Accelerator and Hyperfrequency Systems Engineering Laboratory (LISAH) employs 13 engineers and five technicians. Their expertise covers the design of high frequency electromagnetic structures and their deployment together with appropriate instrumentation.

The work of the laboratory is mainly concerned with the development of systems for particle accelerators used in physics research (radio frequency quadrupoles, cryomodules with superconducting cavities and power couplers), together with the associated qualification tools including power sources, test platforms and instrumentation. This expertise can be extended to cover applications in other fields such as antennas for high field magnetic resonance imaging.

In carrying out its work, LISAH has access to internal expertise within IRFU in the fields of material sciences, process engineering, mechanical construction, and quality assurance. The laboratory also contributes to other IRFU projects, either by taking responsibility for an entire work package or by providing consultancy services.

LIDC2

The Cavity and Cryomodule Development and Integration Laboratory (LIDC2) is a centre of expertise within SACM in relation to research on superconducting accelerator cavities and the integration of cryomodules.

LIDC2 provides expertise in support of IRFU projects. The laboratory carries out the R&D work needed for the development of cavities from the perspective of both materials (multilayer and polishing) and surfaces (electropolishing and high pressure rinsing). The laboratory participates in the design and development of cryomodules for both French and international accelerators such as SPIRAL2, XFEL and ESS. Responsibility is taken for the integration of these systems from the prototyping stage. The laboratory manages the shared SACM resources allocated to it, including cleanrooms, the installation of chemical treatment systems, material characterization laboratories and assembly halls.

A staff of eleven engineers and seven technicians work within the laboratory to achieve the projects allocated to them.

LÉAS

The **Laboratory for Superconducting Magnet Research** (LEAS) offers its expertise in magnetic fields to IRFU physicists and is staffed by eight technicians, 17 engineers and one PhD student as of December 2012. The laboratory teams are responsible for the design and project management of superconducting magnets for experimental facilities, especially large magnets or those with high magnetic fields.

In the design of superconducting magnets, LEAS applies its expertise to the optimization of coil geometry, conductor design, mechanical, electromagnetic, and thermal calculations, and magnetic protection in the event of quench. In addition to designing magnets, LEAS has the capacity to manage large projects, to develop magnets and integrate them into cryostats, and to provide monitoring for industrial projects. The magnets are inspected jointly with the Cryogenics Laboratory and Test Station (LCSE). Measurement work includes analyses of tests at ambient and cryogenic temperatures, including quench analyses and magnetic measurements.

The R&D work carried out is partly in response to the requirements of construction projects such as the GLAD dipole in the R^3B spectrometer and the ISEULT imager. Also, in view of the future development of the LHC, development work is being carried out on the use of niobium tin (Nb_3Sn) and high critical temperature superconductors. The use of magnesium diboride (MgB_2) conductors is also being studied.

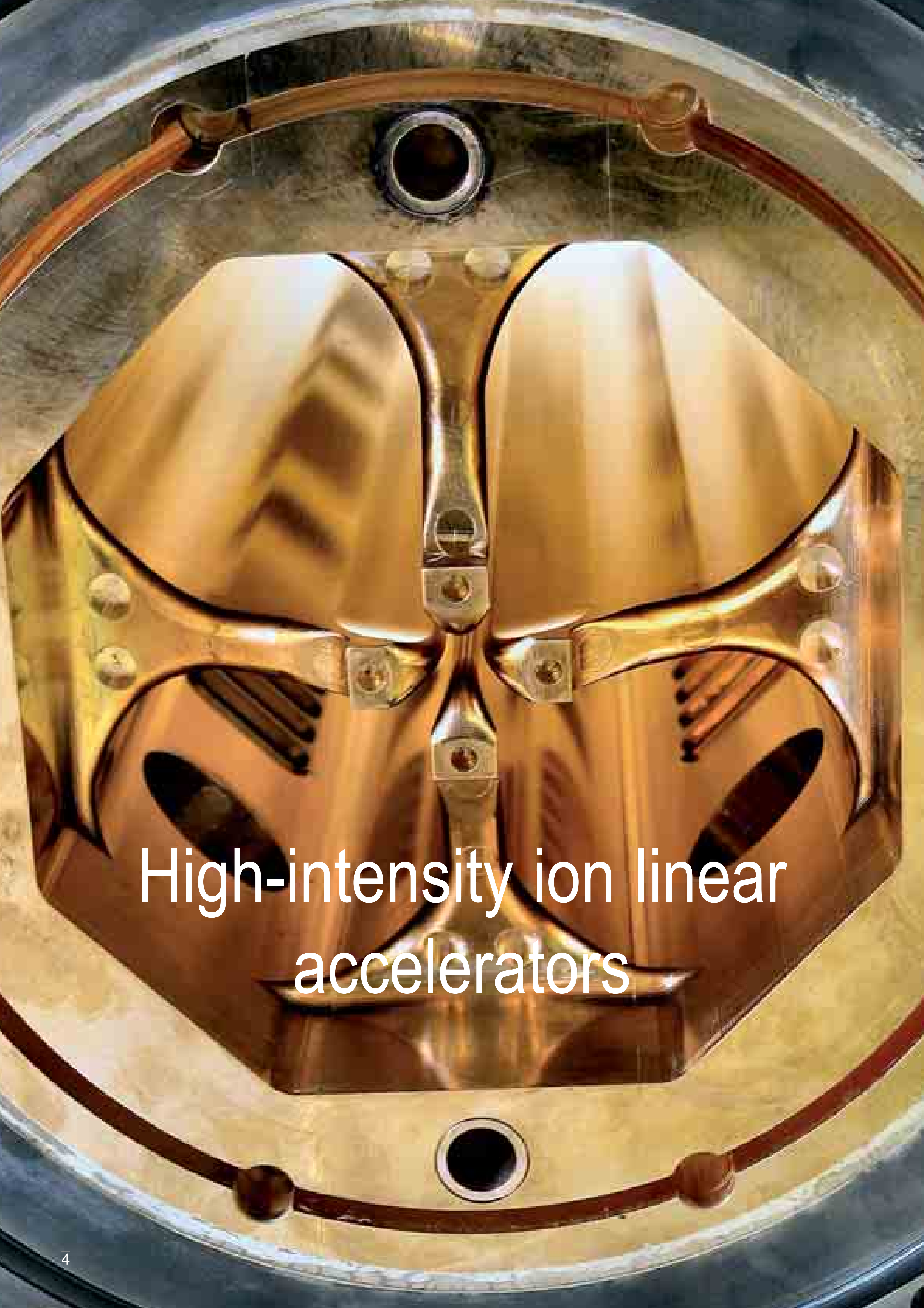
LCSE

The task of the **Cryogenics Laboratory and Test Stations** (LCSE) is to develop expertise in cryogenics technology for superconducting magnets, accelerator cavities, physics detectors (cryogenic target systems, calorimeters), and the production and distribution of liquid helium. This expertise is applied to the design, construction, and operation of cryogenic facilities of various types and sizes. Fluids currently in use include helium, nitrogen, argon and hydrogen. Design and construction work is mainly focused on cryostats and associated cryodistribution systems, together with low temperature refrigeration machines, ranging from cryogenerators to high-power helium refrigerators.

The laboratory operates a number of test and characterization facilities stations offering a total of sixteen distinct systems for the study of the mechanical, thermal and electrical properties of materials such as insulators, composites, metallic alloys and superconductors under the influence of cryogenic temperatures and magnetic fields. Tests of cryogenic samples and subassemblies ranging in size from a few millimeters to several meters can also be carried out under nominal conditions.

A range of R&D activities is also carried out in the fields of low temperature heat transfer (helium II in a porous medium), two-phase flows (convection using helium I, nitrogen, etc.), and instrumentation development.

As of December 31, 2012, the laboratory had a staff of thirteen engineers, thirteen technicians, and one PhD student.



High-intensity ion linear accelerators

The SPIRAL2 project

Following a preliminary design phase, in which SACM played a leading role, the SPIRAL2 project has now entered a phase of construction and consolidation. IRFU is responsible for the construction and installation of the light ion injector at Saclay, with the aim of facilitating the final installation of the lines at the Large Scale Heavy Ion Accelerator (GANIL) in Caen. IRFU is also undertaking the production of the radio frequency quadrupole from design and development through to construction, together with the testing of twelve low beta cryomodules and their delivery to GANIL, and the development of the S^3 spectrometer.

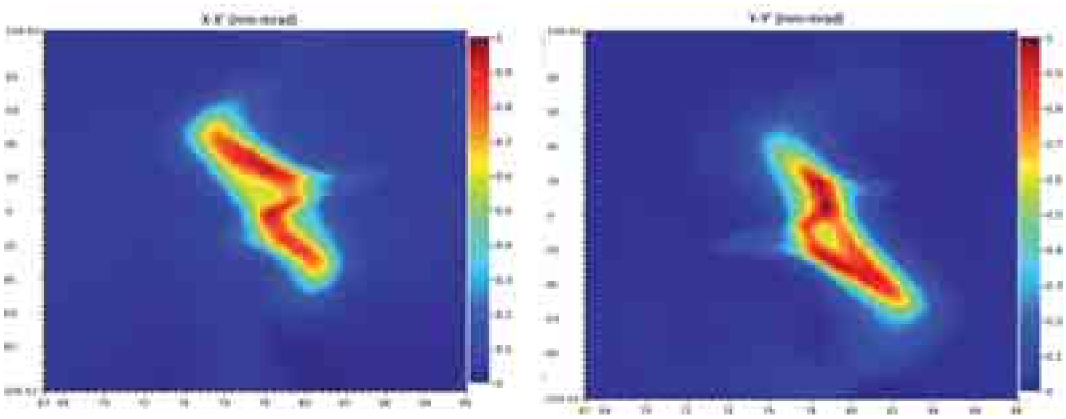
The light ion injector

SACM has undertaken a project covering the three main aspects of the work; beam dynamics, adjustment procedures and the associated control and instrumentation systems, and beam experiments. The proton and deuteron injector, including the source and low energy beam lines, has been fully installed and tested at Saclay. The light ion injector provided up to 5 mA of protons and deuterons, in both continuous and pulsed modes, which are intended to be injected into the radio frequency quadrupole (RFQ) of SPIRAL2 in Caen.

The SPIRAL2 light ion injector in its bunker at SACM.

The injector has been built in a number of stages over a period of two years in order for the beam characteristics to be measured at various points along the line. This work was completed at the end of July 2012 with a range of diagnostic tests carried out at the exact position to be occupied by the RFQ within the injector. The readings obtained were then used in a simulation model in order to estimate the beam characteristics at the exit from the RFQ. This is certainly the first time that a high intensity beam has been measured at the exact point of injection into an RFQ and then tracked through it using a simulation. The results obtained have confirmed the original design and the program of tests carried out on the SPIRAL2 injector at IRFU.

The injector is currently being rebuilt in the SPIRAL2 accelerator building at GANIL. The next step will be to restart the installation and inject the beam into the RFQ cavity. The beam characteristics at the exit from the cavity will then be measured and compared with the results predicted by the simulation.



Emittance values from the 5 mA deuteron beam measured at IRFU at the exact position to be occupied by the RFQ within the injector at GANIL, confirming the design and construction of the SPIRAL2 injector.

Radiofrequency quadrupole

The radiofrequency quadrupole is an essential component of all linear ion accelerators. It provides the beam bunching and pre-acceleration functions that are essential for effective energy transfer in the upper stages, while ensuring particle confinement. The RFQ design is optimized with the aim of achieving the most effective bunching possible with the lowest electrical power consumption, while maintaining good performance in terms of breakdown strength. Reproducing the optimized amplitude of the electromagnetic field to within a few per cent requires manufacturing tolerances in the region of a few tens of microns at the pole ends.

First RFQ section.

The SPIRAL2 RFQ operates at a frequency of 88.05 MHz and consists of a single 5 meter long segment. This cavity is used to accelerate the beam with a efficiency of more than 97 % with intensities of up to 5 mA of deuterons at 40 MeV per nucleon under continuous conditions. Each meter long section consists of four copper poles installed in a cylindrical tube. It was designed by SACM and SIS teams, who will also monitor construction. The RFQ has been built to a geometric accuracy of ± 50 µm per section and ± 100 µm for any two consecutive sections. Any remaining geometric inaccuracies are compensated for by 40 pistons, each with a maximum displacement of 123 mm. These pistons are used to achieve the frequency tuning and voltage curve required by the beam dynamics. The RFQ sections are currently being manufactured by Research Instruments GmbH and are due for delivery in 2013.

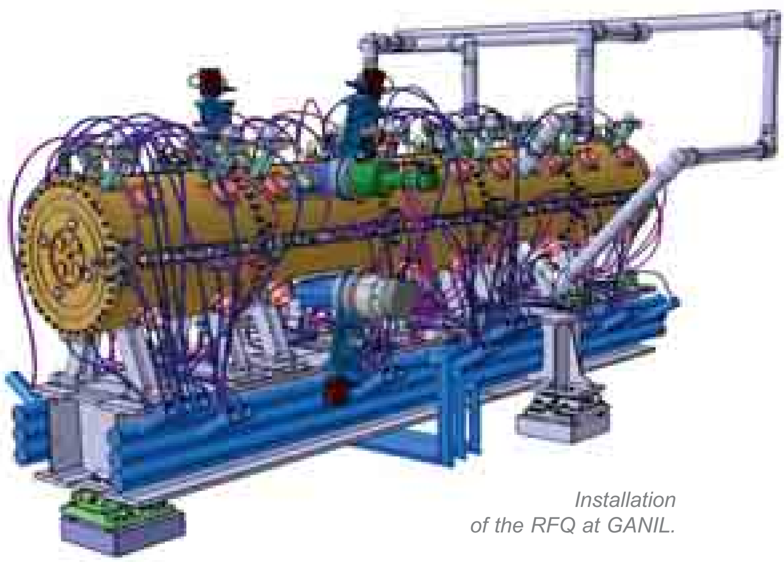
Low-beta cryomodules

The SPIRAL2 superconducting linear accelerator will include two types of cryomodules, each including cavities with optimized geometry for accelerating particles to 7% the speed of light (low-beta cavities: $\beta = 0.07$), and to 12% of the speed of light (high beta cavities: $\beta = 0.12$).

Assembly of the power coupler onto the SPIRAL2 cavity in the cleanroom.

Each low beta cryomodule contains a single cavity, manufactured from solid niobium and fitted with a power coupler capable of injecting 10 kW of continuous maximum radio frequency (RF) power. These couplers are supplied by the Subatomic Physics and Cosmology Laboratory (LPSC) in Grenoble. The cryogenic circuits, together with a thermal screen and multi-layer superinsulation, enable the cavity to be cooled to 4 K, at which temperature it exhibits superconducting properties. A mechanical system is used to adjust the cavity frequency through deformation of the cavity walls at extremely high resolution (to within a few nanometers) over a wide amplitude (2 millimeters).

A qualification cryomodule was built prior to beginning manufacture of the production cryomodules. Initial tests at 4 K carried out in December 2008 showed that a maximum RF power of 10 kW could be achieved. The orders for the production cryomodules were placed during 2009, and all the components, cavities and cryomodules were delivered during 2010. The first assembled cryomodule was tested in 2011 and showed very high levels of cryogenic consumption due to the intense electron emission when the cavity was in operation. This phenomenon was found to be due to contamination in the region of the power coupler. LPSC was able to make the necessary modifications to the installation and preparation procedures so that new



Installation of the RFQ at GANIL.

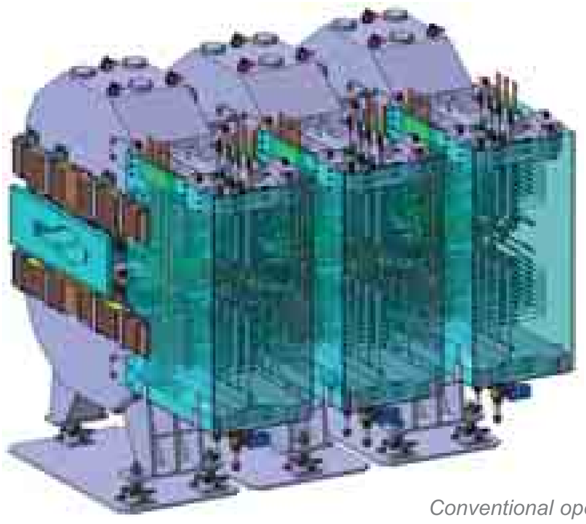
power couplers could be delivered in compliance with suitable cleanliness criteria. During this period, one cryomodule was assembled at SACM with a critically coupled antenna fitted in place of its normal power coupler. This cryomodule was used to carry out qualification tests on all the cryomodule components and functions under the responsibility of SACM.

Cryomodules in the course of assembly after leaving the cleanroom.

At the end of 2012, three assembled cryomodules fitted with new power couplers successfully passed the qualification tests needed for installation on the SPIRAL2 accelerator. A fourth cryomodule was assembled; qualification testing under RF power is due to begin in January 2013. Assembly of a fifth cryomodule is currently making good progress with completion due in early 2013.

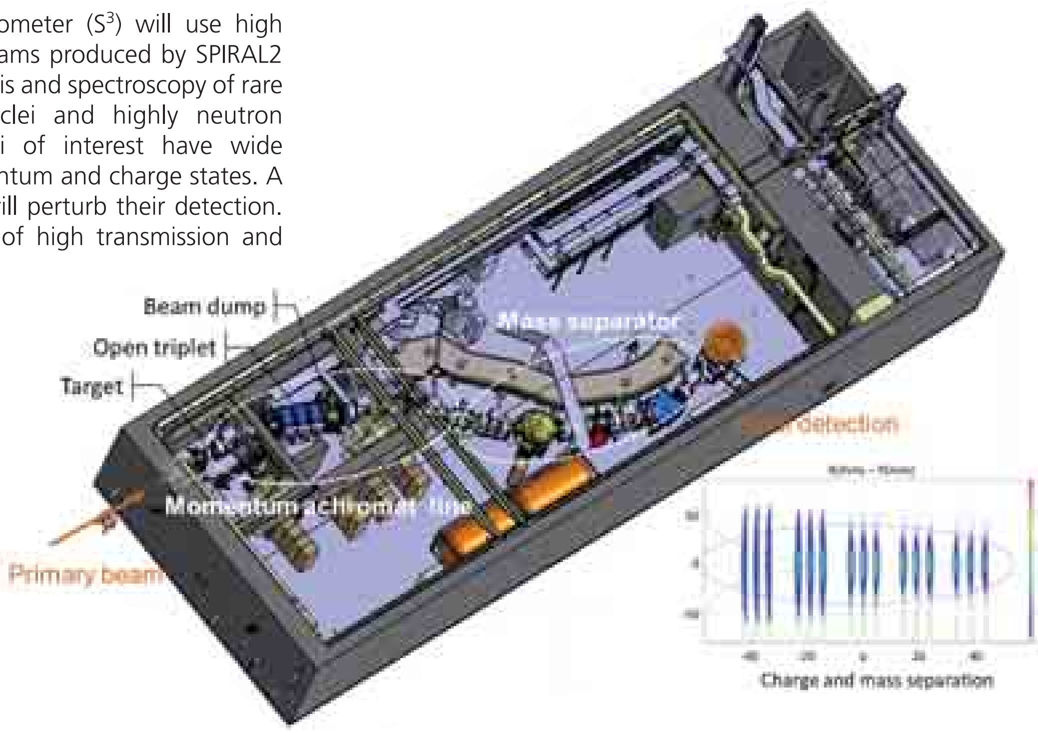
S^3 spectrometer

The Super Separator Spectrometer (S^3) will use high intensity stable heavy ion beams produced by SPIRAL2 at GANIL to study the synthesis and spectroscopy of rare nuclei, including heavy nuclei and highly neutron deficient nuclei. The nuclei of interest have wide distributions of angle, momentum and charge states. A majority of parasitic nuclei will perturb their detection. S^3 will offer a combination of high transmission and excellent selectivity.



Conventional open quadrupole triplet.

The spectrometer optics is realized with groups of three superconducting quadrupoles. Simulations carried out by SACM in collaboration with GANIL and the Argonne National Laboratory (ANL) show that any aberrations can be corrected by means of hexapoles and octupoles superimposed on the quadrupoles. The spectrometer is divided into two separation stages. The first one is a momentum achromat using two magnetic dipoles. Its purpose is to reject most of the parasitic nuclei, including the primary beam. SACM has investigated the conventional open multipoles which allow the selection and stopping the primary beam. SIS is working on beam stop blocks subject to high incident power levels. The second one is a mass separator, combining electrostatic and magnetic dipoles in order to separate and identify the nuclei. S^3 is expected to enter service in 2014 along with the first beams from SPIRAL2.



Installation of the spectrometer in the S^3 experimental area. Bottom right: final focusing plane.

The IPHI high-intensity proton injector

A high intensity proton accelerator provides an intense source of secondary beams, including neutrons, muons, neutrinos, and radioactive nuclei. The characteristics of these beams open new fields of study and applications in both fundamental and applied research. Building and testing a prototype of these next-generation accelerators, especially the low-energy components, should provide a conceptual and experimental framework for future technical choices. The construction of IPHI, a high-intensity proton injector, meets this objective. IPHI is a joint project between the Physical Sciences Division (DSM) of the CEA, the CNRS National Institute of Nuclear Physics and Particle Physics (IN2P3), and CERN.

IPHI is a proton injector prototype which accelerates a continuous 100 mA beam to an energy of 3 MeV. The main components of the system are a high intensity light ion source (SILHI) together with the associated low energy (95 keV) beam transport, a radio frequency quadrupole (RFQ) accelerator cavity that increases the beam energy to 3 MeV, and a diagnostic line intended to measure all the characteristics of the beam leaving the RFQ to the highest possible accuracy.

The SILHI source

The SILHI source has been in problem-free operation since 1997. It is used as a test bench for demonstrating the production of a 100 mA proton beam at 95 keV over a prolonged period. During these operating periods, the beam is used to test new non-interceptive diagnostic systems for intense beams, including residual gas ionization profile monitors and tomographic measurements of the transverse beam profile.

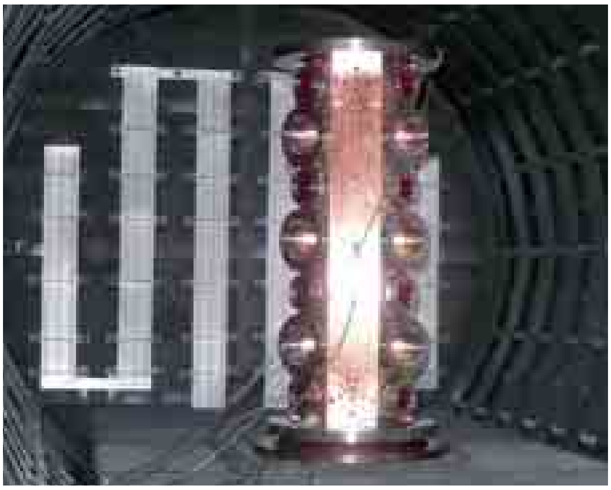
View of the tomographic beam profile analyzer on the SILHI transport line.

Construction of the RFQ accelerating cavity

View of the radio frequency measurement system on an IPHI section.

The RFQ accelerating cavity constitutes the heart of this accelerator. When this type of cavity resonator is excited by a radio frequency wave (352 MHz in the case of IPHI), it collects the continuous beam from the source with practically no loss, and simultaneously accelerates and focuses it. However, these exceptional qualities are balanced by the severe technological difficulties associated with the manufacture of the cavity.

The cavity consists of six sections, each around one meter in length. Each separate section is machined in four parts known as electrodes. The shaped profile of these electrodes must be manufactured to an accuracy of ± 20 micrometers. Longitudinal cooling channels are machined to a length of one meter with a positional accuracy of ± 200 micrometers. Radio frequency measurements are carried out on the assembled section in order to check that these tolerances have been met. The selected material is ultra pure oxygen-free copper, hot forged in three dimensions, then stabilized by a thermal cycling process. Following the roughing phase (to within + 1 mm), each pole is subjected to another thermal cycle in a vacuum



View of an IPHI section in the oven immediately prior to vertical brazing.

at 800 °C. In order to relieve the mechanical stresses induced by the milling tool. After final machining, the four poles and their associated operating sub-components (flanges, pump nozzles and tuning piston channels) are assembled by vertical brazing at 800 °C in a vacuum oven. The manufacture of the production sections began in 2004. Technological advances during the course of the project have forced the CEA to specify a new manufacturing methodology. This new technological approach has resulted in a partnership between the IPHI team and two industrial partners, each with defined responsibilities. Machining operations are carried out by Mécachrome, cleaning is the responsibility of the IPHI team, and Bodycote undertakes the brazing operations. The mechanical specification is agreed between the partners. Three finished sections had been delivered to the CEA by the summer of 2010. The final three were delivered at the end of 2012. The geometry of the sections is checked by making a series of three-dimensional measurements, the quality of the accelerator field is quantified by RF measurements, and the vacuum seal is tested by carrying out leakage tests.

Installation at the Saclay site

Work on installing the IPHI in the halls formerly housing the SATURNE accelerator at the Saclay site began in 2003, with the assembly of the proton source and biological shields. The cooling system and the RF power generators (klystrons from CERN) were tested. The safety infrastructure systems (access control and radiation detection) are operational. The diagnostics line used to characterize the beam has been assembled and placed under vacuum. All instrumentation and control systems have been tested. The RF power transmission windows were conditioned in 2011. The assembly of the sections onto the supporting beam began in 2012 with the RF adjustments to the RFQ cavity complete with the six sections, and the initial assembly of the pumping system.

View of the complete IPHI RFQ (six sections) on the supporting beam together with the radio frequency adjustments.

View of the initial stages of attaching the pumping system to the RFQ.

The IPHI will be tested in three phases over a period of around two years.

- The first phase will consist of a start-up and power ramp-up period culminating in the achievement of the nominal performance required for demonstration operation with the European Spallation Source (ESS) beam characteristics.
- The second phase will consist of a similar demonstration operation, this time with the EUROTRANS beam characteristics and reliability testing at reduced intensity.
- During the third phase, the power will be increased to achieve the nominal characteristics of the IPHI demonstrator.

The European Spallation Source (ESS)

The European Spallation source (ESS) will be the most powerful spallation source in the world (5 MW) and will produce its first neutrons in 2020 at Lund in Sweden. The neutron source consists of three main sub-assemblies; the linear accelerator, the target, and a suite of instruments installed around the target. The linear accelerator will include in its low energy part a radio frequency quadrupole (RFQ) and a drift tube linac (DTL). The high energy section consists of superconducting cavities capable of accelerating the protons up to 2.5 GeV. There are three families of superconducting cavities. The first of these are spoke cavities operating at 352 MHz and optimized for proton beams at fifty percent of the speed of light (β = 0.50) with energies of between 80 MeV and 200 MeV. The second and third families are elliptical cavities operating at 700 MHz, one with β = 0.67 and energies of between 200 MeV and 650 MeV, and the other with β = 0.86 and energies of between 650 MeV and 2.5 GeV.

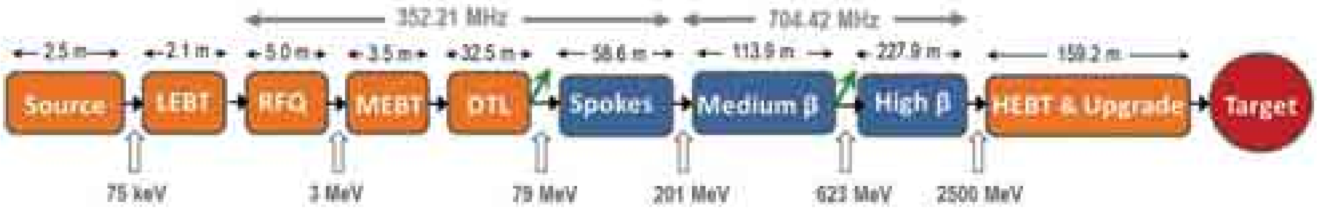


Diagram of the ESS accelerator. The sections including superconducting cavities are shown in blue.

The agreement between France and Sweden covers the accelerator design update (ADU) phase running from 2010 to 2012, and preparation for the construction phase beginning in January 2013. The agreement is broken down into eight separate projects, five of which are the responsibility of IRFU, with two being undertaken by the Orsay Institute of Nuclear Physics (IPNO) and one joint collaborative project involving the two organizations. The eight projects are listed below:

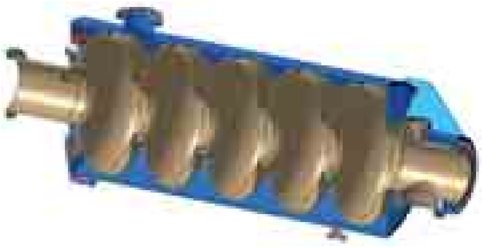
- Project 1: Injector reliability test.
- Project 2: Installation of a bunker for conditioning couplers at 352 MHz.
- Project 3: Assembly and testing of eight superconducting elliptical cavities.
- Project 4: Contribution to the Technical Design Report (design of the RFQ).
- Project 5: Contribution to the mechanical studies.
- Project 6: Spoke cryomodule (IPNO).
- Project 7: Installation of new infrastructure for the superconducting cavities (IPNO).
- Project 8: Design, realization and test of a prototype elliptical cavity cryomodule (joint IRFU - IPNO).

Injector reliability test

The injector reliability tests will be carried out on the IPHI platform using the ESS beam structure. The ESS project has contributed to the finalization of the IPHI injector, and the RFQ in particular, in order to ensure that the tests can begin as soon as possible in 2013 with a reliable beam using the ESS beam structure.

Installation of a bunker for conditioning couplers at 352 MHz

The bunker for conditioning the power couplers at 352 MHz, known as the IFMIF-ESS bunker, has been installed in Building 126 at CEA Saclay, with the waveguides connected to the IPHI klystrons. IPNO will install in this bunker during 2013 the conditioning system for the 352 MHz couplers used in the spoke cavities for which they are responsible. The bunker is large enough to enable the testing of large-scale cryomodules such as the prototype ESS and IFMIF cryomodules.



Cross-section of the ESS elliptical cavity.

Design of the radio frequency quadrupole

The design of the RFQ was based on specifications that were changed in the summer of 2012 at the request of ESS. The design work in progress at that time was temporarily suspended. The only work still to be carried out in order to finalize the design at that time was the thermo-mechanical studies. The new specifications were received in December 2012. Design work can now begin on the four meter long RFQ to replace the original five meter design.

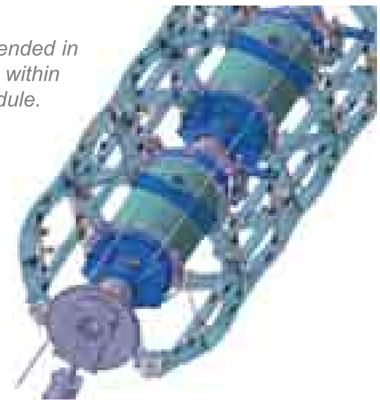
Assembled superconducting elliptical cavities

The design of the $\beta = 0.86$ elliptical cavities has now been finalized and a prototype cavity has been ordered from each of two different suppliers. They are due for delivery in June 2013. These cavities will be fitted with a power coupler and a piezoelectric tuning system already developed and successfully tested by SACM as part of the High Intensity Pulsed Proton Injector project (HIPPI). The preliminary design of the magnetic shielding has been finalized. This component is the third of the elliptical cavity sub-assemblies to be supplied as part of Project 3. The detailed design of the shielding, couplers and tuning systems will be finalized in early 2013 prior to the start of manufacturing of these components.

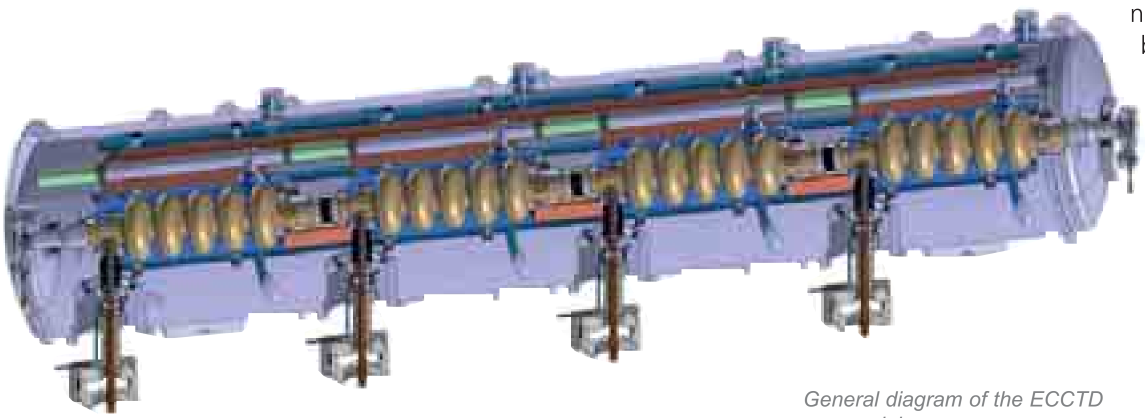
ESS cavity fitted with the power coupler and frequency tuning system.

Prototype elliptical cavity cryomodule

Project 8 required an amendment to the original Franco-Swedish agreement, and work could not begin until April 2012. The project covers the design, construction, assembly and radio frequency power testing of the prototype Elliptical Cavity Cryomodule Technology Demonstrator (ECCTD). The ECCTD contains four superconducting elliptical cavities operating at f = 700 MHz and $\beta = 0.86$. The mechanical design of the cryomodule was carried out by IPNO. The cavities, power couplers, tuning systems and magnetic shielding are to be delivered, tested and qualified by SACM as part of Project 3. The remaining components of the cryomodule will be supplied by IPNO. Assembly will take place at IRFU in the new cleanroom to be built during the first half of 2013. It will then be tested in the IFMIF-ESS bunker.



Cavity string suspended in the space frame within the cryomodule.



General diagram of the ECCTD cryomodule.

The IFMIF prototype accelerator

As part of the wider approach to ITER, IRFU is responsible for delivering the French contribution to the International Fusion Material Irradiation Facility (IFMIF) project which will enable the testing of materials developed for future nuclear fusion installations. The initial Engineering Validation and Engineering Design Activity (EVEDA) phase will consist of the construction and characterization of a full scale prototype of the low energy section (up to 9 MeV). This will then be used to validate the design of such a machine.

World record for a deuteron injector

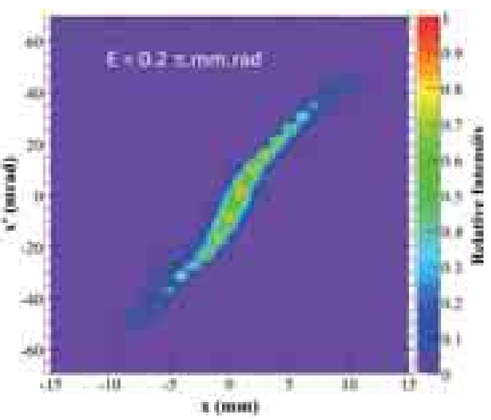
The first component of the IFMIF-EVADA accelerator, the injector, has been designed and constructed by SACM teams in collaboration with the SIS. This injector was installed in the hall of Building 126 at CEA Saclay in early 2011. The injector consists of an electronic cyclotronic resonance (ECR) ion source installed on a high voltage platform capable of delivering 100 kV, together with a grounded transport line fitted with solenoids, electrically driven pumps and diagnostic systems. The entire system is installed in a concrete radiological protection bunker.

The IFMIF injector. From left to right: Source, accelerator tube and low energy transport line.

Beam characterization in progress.

During November 2012, in the presence of delegates from the Japan Atomic Energy Agency (JAEA) and the European Fusion for Energy group (F4E), the IFMIF-EVEDA injector achieved almost all of the required performance criteria, both in terms of the beam characteristics and the machine and personnel protection systems. The control system was also approved. The results obtained represented a world record for this type of beam. In continuous mode, the beam power reached 17 kW at the exit from the source (170 mA of deuterium ions at 100 kV), and the D^+ ion current reached 140 mA, i.e. 14 kW, immediately behind the radio frequency quadrupole (RFQ) feed horn. In pulsed mode, the emittance measurements carried out with beams of between 100 and 150 mA showed that the beam quality met with the requirements at the entry to the RFQ accelerating cavity.

Following delivery and acceptance of the various systems and conditioning of the injector, a beam of hydrogen ions was generated and guided along the transport line at energies of between 50 and 100 keV in both pulsed and continuous modes. More recently, the first deuteron beam has been extracted at an energy of 100 keV with a duty cycle of 1% (10 ms – 1 Hz). The duty cycle was progressively increased to 10%, 30% and 50% before entering continuous mode. During these stages, the beam was measured and analyzed using diagnostic systems specially developed for this application.



Emittance of a pulsed beam at 140 mA - 100 keV.

On completion of these tests, F4E, JAEA and the project manager decided to transfer the injector to the Rokkasho site in Japan in early 2013. The injector will be the first accelerator component to be installed at the Japanese site. The installation will be carried out by a team from JAEA with the active participation of CEA personnel. The beam is expected to go live again in the late summer of 2013.

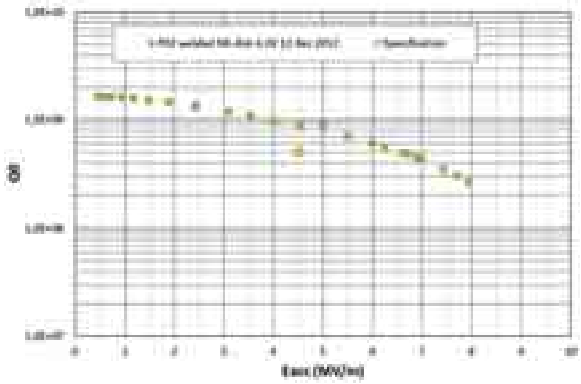
The cryomodule

The cryomodule of the IFMIF prototype accelerator is intended to accelerate the deuteron beam exiting the RFQ from 5 MeV to 9 MeV. It consists of eight superconducting cavities operating at 175 MHz, equipped with power couplers that continuously transfer 70 kW of power to the beam. Eight superconducting solenoids are fitted between each cavity to focus the beam. The Spanish laboratory and collaboration partner Ciemat is responsible for the solenoids and their current feeds.

General view of the IFMIF/EVEDA accelerator cryomodule.

Prototype niobium half-wave resonator (HWR) cavities were delivered to the CEA at the end of 2010. A number of additional studies involving interconnected RF and thermal simulations were carried out at the same time as the first radio frequency tests in a vertical cryostat. In addition, new mechanical studies have been carried out with the aim of ensuring that the cavity complies with the Japanese regulations for equipment under pressure. Following these studies, the design of the frequency tuning system was changed to a system based on the elastic deformation of the cavity, similar to the technique used in SPIRAL2. A prototype cavity compatible with this type of tuning system was qualified in December 2012, demonstrating a level of performance well in excess of the specifications. The accelerator field achieved 8 MV/m (specification: E = 4.5 MV/m), and the nominal quality factor was obtained (specification: $Q_0 = 5 \times 10^8$ at 4.5 MV/m).

Modified prototype cavity.



Results of the tests on the modified prototype cavity.

At the same time, a number of modifications to the cryomodule were made, including an increase in the length of the cryomodule, optimization of the pumping circuit, and changes to the alignment system. The detailed design of the cryomodule was released following these changes.

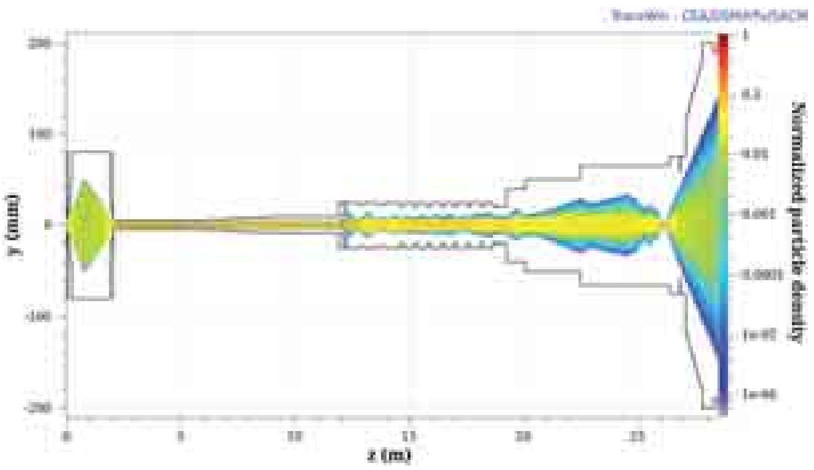
The call for proposals for the design and construction of the set of power couplers was issued in 2009 and the contract was awarded to the American company CPI. SACM was responsible for overseeing the design, construction and characterization of the components, and prototypes were delivered to the CEA in June 2012. They were then prepared for use in the cleanroom and shipped to Ciemat for the RF power couplers to be conditioned.

Manufacture of the production couplers is due to begin during 2013 following the RF conditioning of the prototypes, together with the various cryomodule components including the vacuum vessel and thermal screens, helium circuit, magnetic shielding and supporting frame. The procurement of the niobium is currently under way with a view to beginning manufacture of the production HWR cavities.

Prototype power coupler.

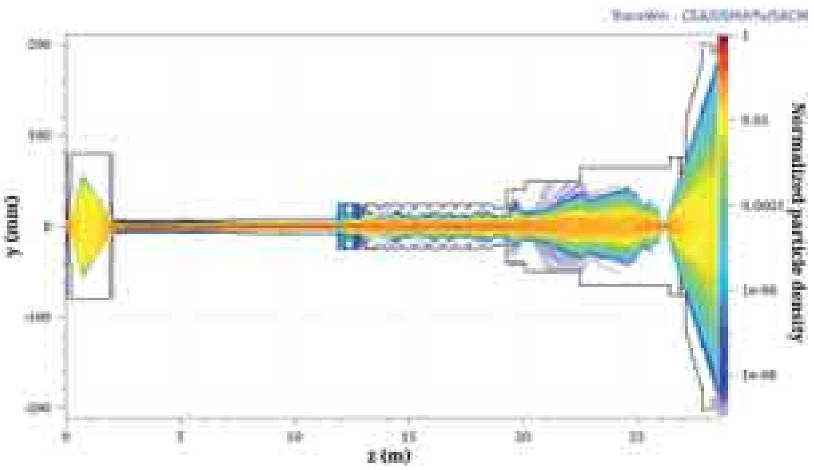
Simulations of the beam dynamics

The deuteron beam from the IFMIF accelerator features two characteristics that have never been achieved before; a power of 5 MW and an intensity of 125 mA in continuous mode. Operation at these levels poses new challenges in the design and optimization of the beam dynamics. These include a required beam loss of less than 10^{-6} times the total beam intensity, non-linear dynamics resulting from strong space charge forces, difficulties relating to the installation of sub-assemblies and diagnostic systems due to a highly compact machine structure. With these constraints in mind, a specific strategy for adjusting the accelerator to achieve minimum beam losses has been implemented through simulation, especially in relation to those sections of the machine in which the beam energy exceeds 5 MeV.



Beam density along the IFMIF-EVEDA accelerator.

Initial studies into the beam dynamics have been carried out separately for each accelerator sub-system including the low energy line (LBE), the radio frequency quadrupole (RFQ), the medium energy line (MBE), the superconducting linac, and the high energy line (LHE). This is followed by a simulation of the entire IFMIF-EVEDA accelerator, from the exit from the ion source to the end of the high energy line (beam stop).



Cumulative beam density for 500 machines with randomly applied errors.

Simulations including the static and dynamic errors for each of the various components of the machine are carried out in order to validate the design and adjustment of the IFMIF-EVEDA accelerator. The static errors include errors in the alignment of the various accelerator components and focusing errors. In this case, errors in the beam trajectory may be corrected by deflectors associated with beam position monitors located at strategic points along the length of the machine. The dynamic errors arise from vibration phenomena or rapid variations in the power supplies. The time constants of these errors are too fast to be corrected. It has been determined that the beam losses remain acceptable, even assuming worst case error values.

Radio frequency test station

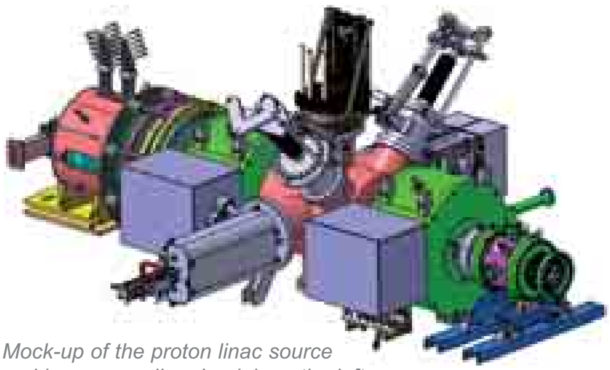
The IFMIF-ESS bunker occupying a floor area of 18 m x 5 m in the hall of Building 126 at CEA Saclay will house the RFQ and cryomodule tests. Biological protection is provided by the 1.5 m thick walls. The installation is supplied with 800 kW of electrical power and 80 m^3/h of cooling water at 22 °C. The bunker will be fitted with a 200 kW RF source operating at a frequency of 175 MHz.

The FAIR linear proton accelerator

The Facility for Antiproton and Ion Research (FAIR) at GSI in Germany addresses several fields of physics research within a single installation. These include the physics of exotic nuclei, hadron physics using proton-antiproton collisions, relativistic heavy ion reactions at a few tens of GeV per nucleon, plasma physics, and atomic physics. SACM is contributed mainly to the FAIR linear proton accelerator, including the development and construction of the ion source and the low energy line, beam position monitors, and magnets for the high energy line. IRFU is responsible for the design and manufacture of the fourteen beam position monitors in the linac, radio frequency design, the supply of preamplifiers and electronic connection cables, and tests using a dedicated test bench at Saclay.

Ion source and low energy transport line

The ion source and its associated low energy transport line are required to generate and transport a 100 mA beam of protons at an energy of 95 keV with an emittance of less than 0.30 π.mm.mrad. The chosen ion source is an electronic cyclotronic resonance type (ECR) operating at 2.45 GHz. The source is based on the design of the SILHI source developed by CEA Saclay. It will operate in pulsed mode at a pulse repetition frequency of 4 Hz.



Mock-up of the proton linac source and low energy line. In pink on the left: The ion source. In green: The two solenoids.

The low energy line is similar to that used in the IFMIF injector. It is very compact and the transport and focusing of the beam are achieved using two solenoids fitted with bipolar correctors in order to optimize the injection of the beam into the radio frequency quadrupole. The low energy line includes a diagnostic system consisting of an emittance meter, Wien filter, profiler and current transformer in order to characterize the generated beam.

Magnets on the high energy line

This work package consists of two dipoles curved through 45°, together with two focusing quadrupoles for the injection line feeding the FAIR SIS18 synchrotron. The specification was written by IRFU on the basis of the GSI specifications, and the contract for the manufacture of the magnets was awarded to

High tension platform on the injector of the proton linac installed at Saclay.

Sigmaphi (France) with production being overseen by IRFU. The magnetic measurements needed to qualify the magnets were carried out by the manufacturer and the magnets were delivered directly to GSI at the end of 2012.

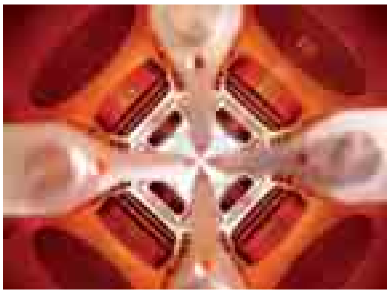
Quadrupole on the high energy transport line (by courtesy of Sigmaphi).

Diagnostics: Beam position monitors

The fourteen beam position monitors to be installed along the length of the linac will be used to measure the transverse beam position, the relative beam current, and its energy using a time of flight method. They are required to be reasonably compacts, to maintain the vacuum, and to have an aperture of 30 mm or 50 mm together with a wideband response. The spatial resolution must be better than 0.1 mm over the entire packet (36 μs), with a phase resolution of better than 1°, corresponding to a temporal resolution of 8.5 ps.

The LINAC4 radio frequency quadrupole

The aim of the LINAC4 project is to build a linear accelerator for H^- ions at 160 MeV to replace the LINAC2 accelerator as injector into the Proton Synchrotron Booster (PSB). This new linear accelerator will double the brightness of the beam out of the PSB, making it possible to increase the current in all the LHC injectors, and ultimately increasing the brightness of the LHC itself. LINAC4 will be installed in a new tunnel and connected to the transfer line to the PSB. It will consist of an H^- ion source, a radio frequency quadrupole (RFQ), a chopper, and a series of accelerating cells occupying a total length of 86 meters. The RFQ was designed by SACM, built by CERN, and adjusted on site by a CEA team. It is currently being conditioned at the 3 MeV test stand prior transfer to its final location, planned for late 2013.



Internal view of section TR1. Some of the tuning slugs (one top right in the foreground and four in the background) have been fitted with loops to measure the RF field. The four vacuum ports can also be seen.

The LINAC4 RFQ operates at 352.2 MHz and should deliver an 80 mA beam at 3 MeV in pulsed mode. Using technology developed for IPHI, it consists of a single three-meter long segment made up of three one-meter sections. Thirty two tuning slugs will be used to obtain the required inter-electrode voltage of 78.27 kV with an accuracy of the order of one per cent. The radio frequency (RF) power is coupled via an iris, fed by impedance ridged waveguide impedance transformer. The injected power will be around 600 kW for a beam power of 210 kW.

This RFQ was designed by SACM and constructed entirely by CERN. Radio frequency checks carried out at each stage of manufacture of the three sections (assembly of the four copper electrodes, initial electrode braze, and flange braze) showed that the operationally critical dimensions were all within the specified tolerances. The actual RF adjustments began in August 2012, and are due for completion in February 2013. They consist essentially of the following five main steps:

- Tuning of end-plates by means of small rods penetrating penetrating into the cavity. Following adjustment, these adjustable aluminum components are replaced by permanent copper ones.
- During the second stage, the thirty two slugs and four dummy RF blocks are adjusted to achieve the required voltage profile (in this case a constant) and frequency.

Section TR2 during radio frequency characterization.

- One of the dummy RF blocks is then replaced by the coupling iris, which dimensions and position inside RFQ cavity are adjusted. The design includes four dummy RF ports for symmetry reason. The permanent coupling iris is then machined from copper, brazed and installed.
- The tuning slugs are then readjusted to compensate for any voltage variations due to the iris.
- The permanent copper slugs are machined and installed, and the resulting RF characteristics are recorded.

The nominal resonant frequency was obtained under vacuum. The refractive index of the air detunes the frequency by around 100 kHz, and this was anticipated correctly. The residual voltage profile errors are around 0.5% for quadrupole component, and 3% for dipole components. Conditioning began using 60 μs pulses, and the nominal power level was achieved. The pulse length was then progressively increased to its nominal value (400 μs). The first tests with a beam are due to take place in 2013.

Copper end-plates and their quadrupole rods.

Electron-positron linear accelerators

The Compact Linear Collider

The Compact Linear Collider (CLIC) is a linear electron-positron collider project for high energy particle physics research. The CLIC collider is a potential candidate to succeed the Large Hadron Collider (LHC). The CLIC has a target collision energy of between 0.5 and 3 TeV with a luminosity of 2×10^{34} $cm^{-2}s^{-1}$ over a distance of 15 to 50 km. The design is based on a new concept in which two high frequency (12 GHz) beams are accelerated with an acceleration gradient of 100 MV/m. This new concept has been studied experimentally using the CLIC Test Facility at CERN.

Experimental validation of the principle of dual beam acceleration

The CTF3 CALIFES electron injector, which simulates the main beam of CLIC, has generated beam energies of 170 MeV to 200 MeV between 2010 and 2012 with increasing reliability and reproducibility. The first acceleration of two beams using a CERN 12 GHz accelerating cavity was demonstrated in December 2010 in collaboration with the University of Uppsala in Sweden. A large number of measurements of the accelerated beam at 12 GHz were made, together with the transmitted and reflected radio frequency power signals. Advanced statistical analyses of the breakdown events in the cavities were carried out over the entire operating period in order to provide a deeper understanding of this new accelerator principle.

Dual beam test bench in the CTF3 experiment hall at CERN (by courtesy of CERN).

12 GHz accelerating structures

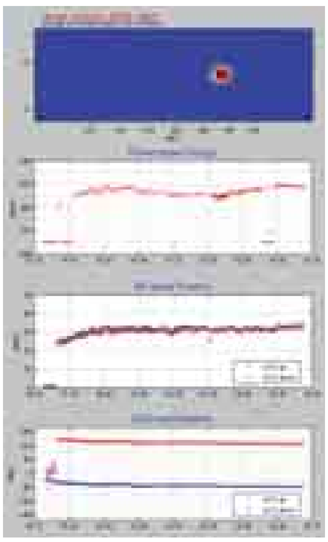
At the same time, two 12 GHz accelerating structures were designed and constructed by teams from SACM and SIS in close collaboration with CERN and the industrial partners Mecachrome and Thales. It was essential that these cavities were very accurately machined and assembled using a highly controlled diffusion process carried out at high temperature in an atmosphere of hydrogen. These two accelerating structures incorporated electron beam position detectors. These detectors, known as wake field monitors, allow to align the accelerating structure to an accuracy of 10 μm and will be essential if the future

Two high gradient 12 GHz accelerating structures following diffusion assembly at 1000°C in an atmosphere of hydrogen at 1 bar.

CLIC machine is to achieve the high level of luminosity demanded. The two structures were put into operation on the CTF3 in September 2012. An acceleration gradient of 80 to 100 MV/m has already been demonstrated experimentally and the first measurements of the signals coming out the wake field monitors are very encouraging.

12 GHz test station

A 12 GHz test station was constructed at CERN between 2010 and 2012. This state-of-the-art facility enables conditioning studies and performance measurements to be carried out on the 12 GHz accelerating structures over significantly long periods of operation. SACM has made a significant contribution to the development and commissioning of this test station, with the supply of the high voltage 400 kV modulator and design of several high power RF components.



Measurement of the acceleration of the CALIFES probe beam by the two 12 GHz accelerating structures using a spectrometer. In this example, an energy gain of 20 to 25 MeV was measured, corresponding to a mean acceleration gradient of 50 to 62.5 MV/m over an active length of 2 x 0.2 m.

The XFEL light source

The European X-ray Free Electron Laser (E-XFEL) project will use a 17.5 GeV electron beam to create an X-ray source that will be a million times more intense than synchrotron-based sources. Located in Hamburg near DESY, the German Electron Synchrotron, it will be used to explore new fields in chemistry, biology, and material science in which there is a requirement for intense and ultra-short (sub-picosecond) beams. IRFU is participating in the construction of the XFEL linear accelerator in association with DESY, IN2P3 and INFN, and is responsible for the overall integration of the 103 accelerating cryomodules at Saclay, together with the manufacture of a third of the beam position monitors.

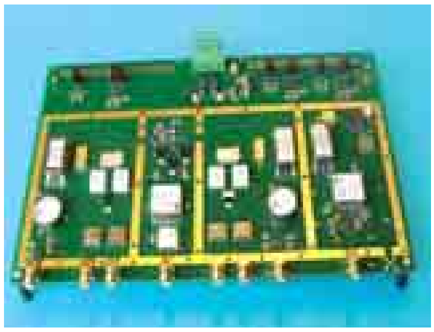
Beam position monitors

SACM is responsible for the design, construction and installation of 31 *re-entrant* beam position monitors (BPM). A *re-entrant* BPM consists of a *re-entrant* cavity fitted with four antennas, together with their analog electronics. As the beam passes through the cavity, it excites electromagnetic modes and generates signals in the four antennas in the cavity. These signals are fed to the associated electronics where they are processed to provide information on the position and intensity of the beam at a given position within the machine.

The monitors will be fitted to a third of the XFEL cryomodules. They will be connected to the quadrupoles in the cleanroom at DESY, then shipped to Saclay for assembly into the cavity string. They must be compatible with the vacuum properties and cleaning procedures in order to work in an ultra-clean environment at a temperature of 4 K. The beam tube is copper plated in order to reduce cryogenic losses. The beam tube is 78 mm in diameter and each monitor has a length of 170 mm.

The system electronics is based largely on an analog signal processing system developed by the CEA. The system is housed in a rack shared by all the XFEL BPMs

Re-entrant BPM fitted to a prototype XFEL cryomodule.



XFEL analog BPM electronics.

that was developed by the Paul Scherrer Institute (PSI). The temporal resolution of around 40 ns is sufficient to make measurements on individual packets. The specified spatial resolution is 50 µm.

With the aim of validating the design of the beam monitors and their electronics, a re-entrant BPM cavity has been installed in a prototype XFEL cryomodule, and another has been fitted to the Free Electron Laser in Hamburg (FLASH) linear accelerator in order to carry out tests with a live beam.

Integration of the cryomodules

In order to provide for the integration of the cryomodules, SACM has developed an assembly infrastructure known as the ‘XFEL Village’. This has been made available to an industrial partner for the three years required for the operation.

The layout of this infrastructure was finalized in 2008 as part of the preliminary manufacturing study carried out by Thales DIS, and extends to three assembly halls. Optimized for the production of one cryomodule per week, the assembly facility consists of a series of seven work stations used to assemble the cryomodule components over a period of seven weeks, beginning with the assembly of eight superconducting accelerating cavities into a twelve meter long string in the large cleanroom. The other work stations are dedicated to the alignment of the cavities, their insertion into the cryostat, and the fitting of the eight radio frequency power couplers.

The installation was qualified in 2011 and 2012 during a prototyping phase involving the assembly of three cryomodules. Part of the industrial team who will begin assembling the modules in March 2013 have been at IRFU since September 2012.

The cavity string fitted with super-insulation, magnetic shielding and frequency tuning system is suspended adjacent to the cryogenic distribution system. The assembly is moved from one work station to another through the doors (shown in red).

The power couplers used to transmit power to the cavity and the beam consist of two sections. The section operating at cryogenic temperatures (shown being handled by the operator) is assembled in the ISO4 cleanroom.

The cryomodule fitted with all its components. The coupler pumping line is currently in operation.

The string consisting of eight cavities, eight bellows, one quadrupole, and one beam position monitor, and isolated by two gate valves, is assembled alternately on the two cleanroom tracks. Electrical, mechanical and leakage tests are carried out throughout the assembly process.

Positron source for the GBAR experiment

The High Intensity Positron Source (SOPHI) is the experimental platform for the Gravitational Behavior of Antimatter at Rest (GBAR) experiment led by physicists from the Particle Physics Department's. This experiment intends to measure the gravitational constant for antimatter. It is accompanied by a trap for accumulating positrons and an analysis line for use in developing materials.

The SOPHI source

The positrons are produced when electrons interact with a tungsten target. They are then collected and guided by a magnetic system. The innovative aspect of the system lies in the low energy of the incident electrons, resulting in a positron beam with high energy and pulse dispersion. The challenge is to capture these positrons and separate them from the electrons, which outnumber them by a thousand to one.

The SOPHI high intensity positron source.

Installed in 2007 in Building 126 at CEA Saclay which used to house the older SATURNE accelerator, the source is fed from a linear accelerator generating electrons at 6 MeV. Based on a concept patented by the physicists Patrice Perez and André Rosowsky, this demonstrator was funded by the French National Research Agency (ANR) in 2005, and by the local authority of the Essonne department in 2006. Following a commissioning process lasting several years, the source entered operation in 2010.

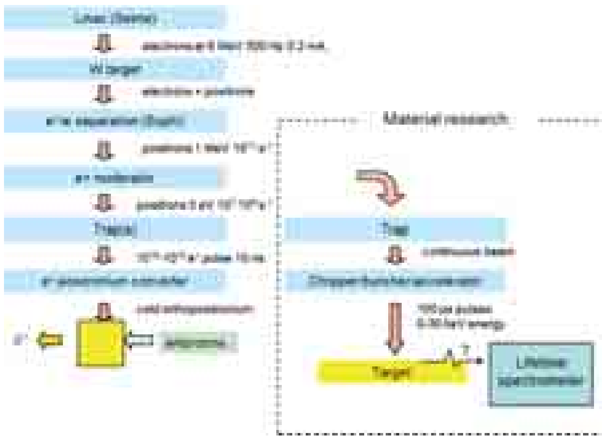
Transport of positrons and magnetic trap

A magnetic guidance system is used to extract the positrons from the radiological protection bunker and to attenuate the pulsed nature of the positron flow resulting from the temporal structure of the electron accelerator.

With funding from the ANR POSITRAP project, a magnetic positron storage trap on loan from the Japanese Riken Institute was installed and recommissioned on the main positron production line in 2011.

Use of positrons in material science

At the same time, a number of studies were carried out in collaboration with the CERN teams led by Professor André Rubbia with the aim of identifying materials capable of generating large quantities of positronium. Positrons are also used in materials science as probes to characterize the size of point defects in crystal structures. The new source may eventually be used to replace the sodium-22 sources that currently supply positrons for materials science applications.



Experimental principles for making antihydrogen and for the materials science applications.

The GBAR collaboration

The ultimate aim of the GBAR experiment is to identify the sign and measure the intensity of terrestrial gravitational acceleration for antimatter. In the extreme cases of models that allow for the possibility of negative acceleration, an atom of antimatter subjected to the Earth's gravity alone would rise rather than fall. The experiment proposal submitted to CERN in 2011 was accepted by the Research Board in May 2012, and a collaborative framework involving twelve European research institutes is currently being established in order to seek funding.

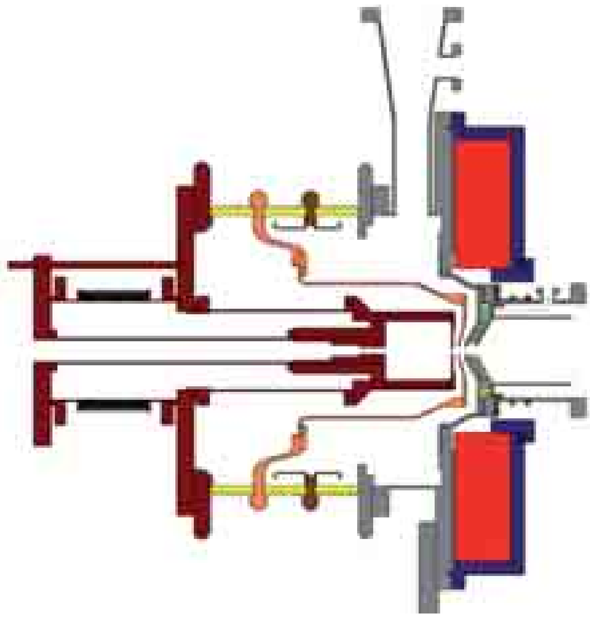
Developments for future particule accelerators

Design and testing of ion sources

Many projects in the field of high current accelerators require high intensity beams of light ions (protons or deuterons). All these machines, whether currently under construction or in the design phase, require a reliable ion source capable of generating intense stable beams of excellent quality. Past development projects have demonstrated the capability of SACM in the design and construction of operational positive ion sources capable of meeting the desired specifications. These excellent results have led to the CEA being chosen to construct the ion sources for the SPIRAL2 and IFMIF accelerators.

Development work must continue in order to carry on making improvements to the optical quality of the beam from these sources, including reducing divergence and emittance. One of the points requiring a deeper understanding is the coupling between the microwave radiation and the plasma. Progress in these fields is being made using the Platform for Research and Optimization of Intense Beams of Light Ions (PROFIIL), together with the BETSI ion source test and research facility, which has been producing and analyzing intense pulsed and continuous beams since 2006.

More recently, the new Advanced Light Ion Source and Extraction System (ALISES) has been developed. This source consists of a single coil referenced to the laboratory potential and has produced encouraging results in terms of the microwave power efficiency, as it can be started with less than 60 W of RF power. This R&D source has been used to test a number of parameters including the influence of the length and radius of the plasma chamber on the production of light ions. The tests were carried out by a PhD student using the BETSI test facility. The large quantity of results has led to the publication of scientific papers and a CEA patent. Some of these results have indicated that it would be possible to adopt a smaller plasma chamber, raising the possibility of a miniaturized ion source. It should also be possible to optimize the coupling between the microwave radiation and the plasma, thereby reducing the required RF power.



Cross-sectional view of the ALISES source. Shown in red: The short solenoid adjacent to the extraction zone that generates a resonance in the plasma chamber.

The ALISES source installed on the BETSI test facility.

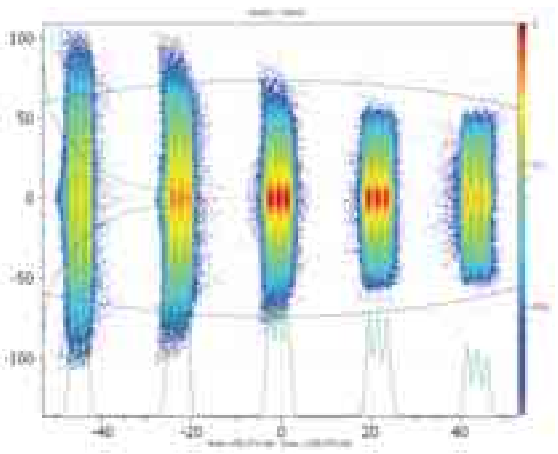
Simulation of the particle beam dynamics

Beam dynamics may be defined as the study of charged particle motion in static or time varying electromagnetic fields. These fields may be external or induced by the particle distribution. In the case of electrons, the effect of synchrotron radiation must also be taken into consideration. Obtaining an accurate model of beam dynamics raises many problems. Examples at the fundamental level include interactions with the residual gas, interactions with solid interfaces, the dynamics of ion source plasmas, beam optics in the presence of high-order electromagnetic components such as hexapoles and octupoles, and the control of halo formation and beam losses for the maintenance of future high-power accelerators. Overcoming these problems involves the development of analytical models and numerical methods that exploit available computer resources to the full. The validity of proposed models must then be tested by comparison with experimental results.

Beam simulation in electron cyclotron resonance sources

The emergence of several projects over the last ten years has prompted the CEA and the CNRS to form a partnership in the field of high-current accelerators, focused specifically on developing a low-energy demonstrator in the form of the IPHI high-intensity proton injector. The projects that led to this collaboration include SPIRAL2 at GANIL, IFMIF which requires deuteron beams, the FAIR project at GSI in Germany, the ESS project at Lund in Sweden, and hybrid reactors requiring a source of protons. Other projects, including SPL at CERN, the Fermilab Proton Driver, and spallation sources, require a source of negative hydrogen ions for injection into the compression rings. All these machines require a powerful and reliable source of ions, which SACM is capable of designing and building.

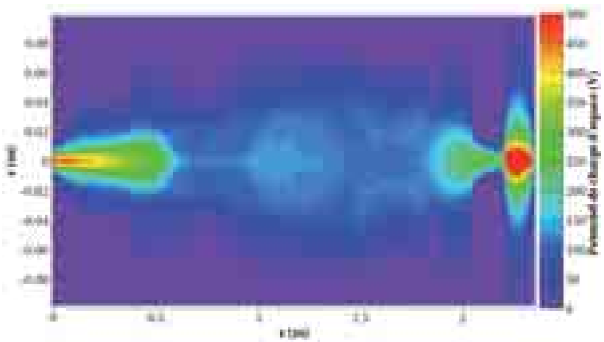
Particle extraction from the source is modeled by calculating the plasma expansion meniscus and beam generation through a multi-electrode extraction system.



Transverse distribution at the final detection plane of the S^3 spectrometer used in the SPIRAL2 project. The separation of three isotopes of a super heavy element (Z = 116 and A = 291, 292 and 293) can be seen in five charge states. Each group of marks represents the three isotopes for a given charge state. The calculation is based on the S^3 geometry with field maps for all components, including the MOSAR magnet.

Particle transport in a low energy line

The low energy line of an accelerator is used to transport the beam from the point of extraction from the ion source, and to optimize its injection into the accelerating sections. In the case of high intensity accelerators such as IFMIF or IPHI, the main problem to overcome is the limitation of losses and increases in emittance during beam transport. The dynamics of these intense beams is dominated by the nonlinear effects of the space charge field. In a low energy line, the beam ionizes the residual gas in the vacuum vessel, leading to a partial compensation of the space charge. The SolMaxP computer code, developed at SACM, is designed to simulate beam transport under space charge compensation conditions.



Map of the space charge potential in the low energy line of the FAIR proton linac. The abscissa z = 0 represents the extraction from the ECR source. The region with no space charge compensation (potential ~ 500V) on the abscissas above 2.2 meters corresponds to the injection of the beam into the radio frequency quadrupole.

The SolMaxP and TraceWin codes were used together to design and optimize the low energy line of the IFMIF deuteron accelerator, and in the preliminary studies for the low energy line of the FAIR proton linac. In both cases, the beam is focused by two solenoids, and the beamline dimensions have been optimized to around two meters in order to limit any increase in the emittance. The characteristics of the beams generated by the IFMIF and SILHI low energy lines have been measured with the aim of providing experimental data to validate the SolMaxP code.

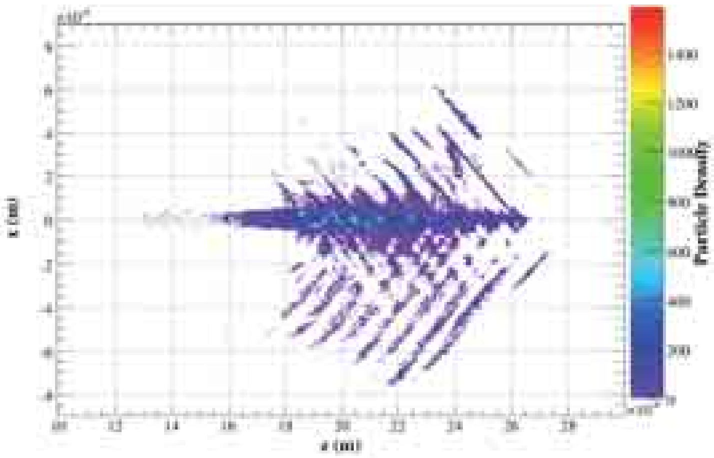
Particle transport in the medium and high energy sections

Beyond the radio frequency quadrupole, the problems caused by the space charge are less significant, but the level of beam losses must still be controlled in order to minimize the power dissipated in the cryostatic components and the activation of the structure. Beam power in high power machines can reach several megawatts, and the main challenge is to develop extremely accurate calculation methods to estimate the probabilities of very low losses, which can often be well below one watt. SACM has focused its efforts on the development of simulation codes that are capable of defining the highest performance accelerators, and on carrying out large scale simulations based on the most realistic description of the accelerator, including tuning and construction errors. The reliability studies must also include an estimation of the impact of the failure of one or more accelerator components, and of any measures taken to reduce the consequences of such failure.

SACM is involved in a large number of projects that demand every aspect of its expertise. These include IFMIF, Betabeam, MYRRHA, EURISOL, LINAC4, SPL, ESS, SPIRAL2, ILC and S^3.

Laser plasma acceleration

SACM is involved in projects in which particles are accelerated by a plasma wave resulting from the wake of a laser beam, such as the Interdisciplinary Center for Extreme Light (CILEX) where the laser is expected to be fired for the first time in 2016. SACM is contributing in two areas: the specification of the transfer lines between the various accelerator stages, together with their associated diagnostics, and simulations of the interactions between the laser and the plasma. The second of these will make use of experience already gained in the development of the Particles in Cell (PIC) codes. Initial simulations have been carried out using the SolMaxP code in order to predict the acceleration of ions when a layer of just a few nanometers is impacted by an intense laser.



Density of electrons of more than 1.5 MeV at t = 107 fs. The target is initially at x = 0. The laser pulse impacts a thin target consisting of 30 nm of hydrogen at an angle of incidence of 30°. The oscillation of the target plasma can clearly be seen. The arrangement of the wave front of the electrons ejected from the target corresponds to the laser wave.

Improvements to the LHC

SACM is contributing to beam dynamics studies aimed at increasing the luminosity of the LHC by a factor of five by 2020. Using the Achromatic Telescopic Squeezing (ATS) approach developed by S. Fartoukh at CERN, this improvement will only require modifications to two interaction regions. One of these modifications requires the replacement of the NbTi quadrupoles in the final focusing triplets with quadrupoles manufactured from Nb_3Sn. The second requires the use of crab cavities in order to compensate the beam crossing angle. SACM is participating in the development of the mesh and has proposed a structure that would reduce the voltage requirement of the cavities by 25%. SACM is also involved in studies to specify the tolerances of the new components, which will affect the long term stability of the beam.

Applications for beam transport software

The development of these codes began in 1995 and since 2000, they have been used by many laboratories in the majority of high intensity accelerator studies throughout the world. The predictability of these codes has been verified by experimental comparisons carried out at SNS in the USA, J-PARC in Japan, and GSI in Germany. This suite of professional software is now distributed under license from the CEA via a download website that promotes the software to internet search engines: http://irfu.cea.fr/Sacm/logiciels/index.php

R&D relating to superconducting radio frequency cavities

Superconductivity is a phenomenon that occurs in the first 50 nm of the surface of a material. Radio frequency cavities are typically manufactured from bulk niobium, the only known superconductor that performs well at radio frequencies. Processing to obtain a good surface quality is essential. R&D work is currently focused on surface treatments, in particular the development of the electropolishing of niobium. It is also necessary to determine the location of any surface defects that could cause a cavity to transit from the superconducting state to the normal state due to local heating (quench) in order to identify the origin of the limitations. Attempts are currently being made to replace complex temperature measurements with a new method for detecting thermal waves in the superfluid helium. New superconductors must also be developed as the maximum magnetic field intensity that niobium can accommodate is approached. In RF applications, it appears that superconducting nanocomposites are the only materials that can accept a higher magnetic field than niobium. At the same time, design of new cavities allows production of the beams required for the recent projects which are very demanding in terms of performance. Examples include the new cavities for the Superconducting Proton Linac (SPL) and the European Spallation Source (SPL).

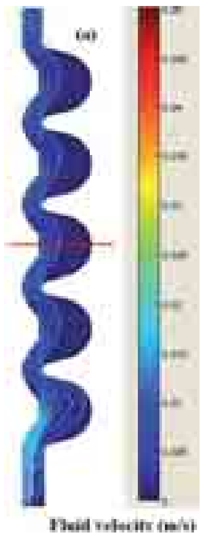
Cavity for the International Linear Collider (ILC) installed in the vertical electropolishing facility prior to treatment.

Electrochemical polishing

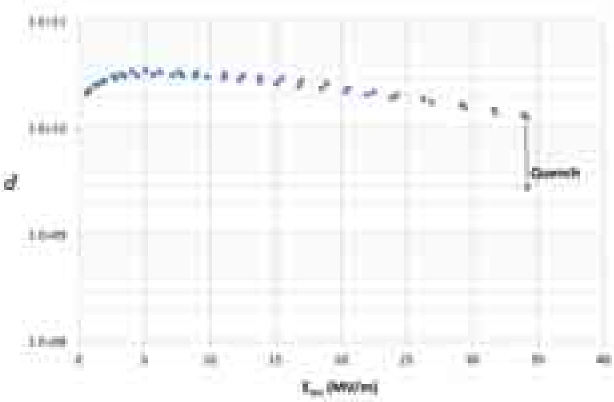
Research into the electrochemical polishing of superconducting niobium cavities has led to the development of an electropolishing setup where the elliptical cavity is placed vertically. The expected benefits of this type of setup include the simplification of the process, making it suitable for use with very large scale cavities, safety improvements, and future extensions of the application to the treatment of large scale resonators. The facility is based on the work carried out at Cornell University, but a number of significant advances have been proposed including improvements of the acid circulation, safety, and automated control, resulting in a reliable process suitable for transfer to industrial use. The process is appropriate for the treatment of the cavities developed for the International Linear Collider (ILC), and for the electropolishing of the cavities developed for the SPL.

The project was carried out in the following three main phases; specifications, detailed design and drawings prepared by Auxitec Ingénierie, and construction by Corelec. The installation of this infrastructure was accompanied by a modeling study carried out using the Comsol Multiphysics software. This involved the simulation of the fluid dynamics and the distribution of the electrical field within the cavity, with the aim of predicting the behavior of the treatment as a function of the type of cavity used. This work revealed the effect of the dimensions of the cavity on the effectiveness of the process, requiring a specific cathode design for each configuration.

The installation was commissioned and accepted at the end of 2011, and the regular treatment of R&D cavities (mono-cell and nine-cell operating at 1300 MHz) has confirmed the good performance of the facility throughout 2012. Twenty treatments have been carried out to



Modeling of the fluid dynamics during treatment of a cavity for the Superconducting Proton Linac (SPL).



Quality factor as a function of the accelerating field for a vertically electropolished single cell cavity.

date, with a total operating time of greater than 60 hours. The results of these treatments have confirmed the relevance of the preceding work on horizontal polishing with a low electrolysis potential. A low potential together with a high acid flow provides an effective answer to the constraints associated with this configuration, with a reduction in the temperature gradient along the cavity and the efficient evacuation of the gasses resulting from the electrochemical reactions. Initial radio frequency tests on single cell cavities in a vertical cryostat have achieved gradients of between 30 and 34 MV/m.

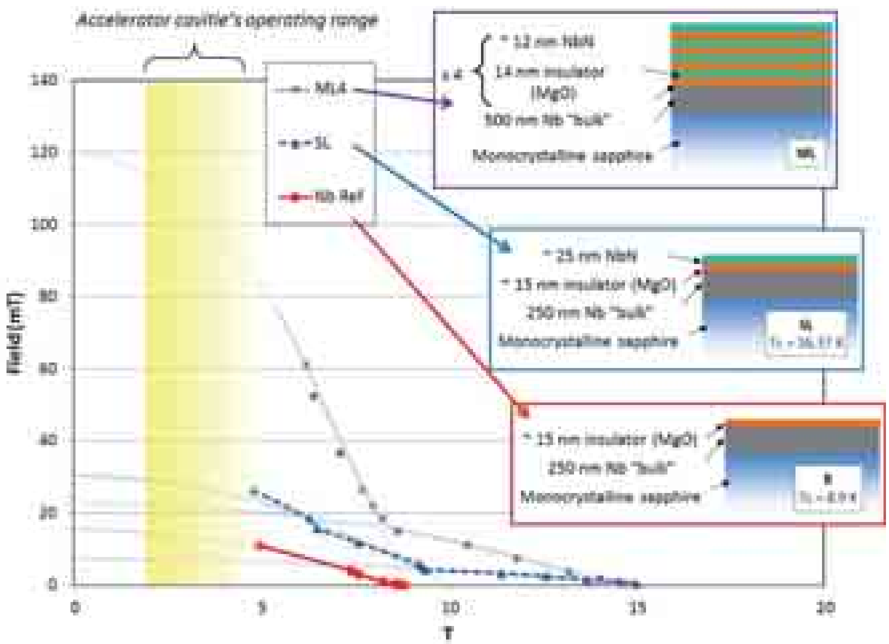
Identifying quench locations using the second sound method

Local heating due to the phenomenon of quench generates a second sound thermal wave in the superfluid helium. This second sound wave is detected by a set of oscillating superleak transducers (OST). The time delay between the arrival of the wave at the various transducers is used to calculate its velocity. This information is then used to calculate the distance of the quench site from each transducer. The position of the quench is then determined by triangulation.

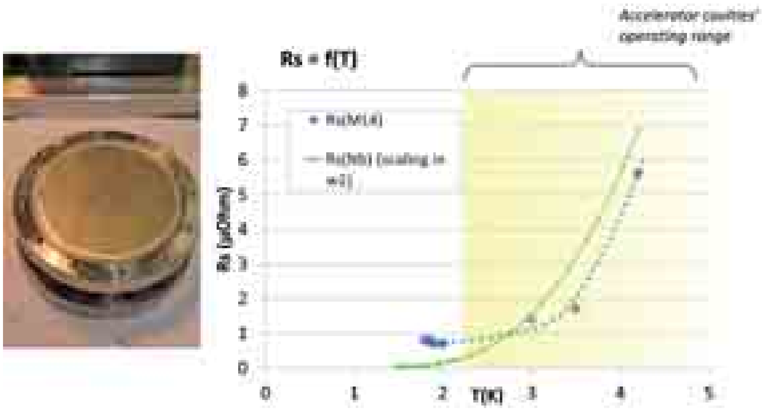
Work on this system began in 2010 with the delivery of eight OSTs and the development of a dedicated electronics board. These transducers were tested on several occasions in single cells in association with a quench location system using a temperature mapping arm. With the new system operational, the first location tests were carried out and the results compared with those produced by temperature mapping. It appeared that the apparent velocity of the thermal wave was not that expected for a second sound wave, differing by up to + 50%. Further investigations were carried out with the aim of gaining a better understanding of the phenomena involved in the superfluid helium and improving the reliability of the technique.

Nanocomposite superconductors

Solid niobium cavities now appear to have reached their performance limit. It is thought that the local power dissipations at high field strengths that lead to quench are caused by the penetration of the lines of the magnetic field, a phenomenon known as vortex. In 2006, the theoretician A. Gurevich proposed a solution in which the surface of the cavity was shielded by a nanometric layer with a thickness less than the depth of penetration of the filed into the superconductor. This would attenuate the field as it passed through the layer, preventing the appearance of any vortex. By building up a sequence of several layers, the field within the niobium could be reduced while increasing the accelerating field in the cavity. Moreover, using a superconductor with a higher transition temperature would reduce the power dissipation in the surface.



Lower critical field of various samples. The layer of pure niobium mimics the behavior of the solid niobium. One for four 25 nm layers of NbN have been tested. It is hoped that the results may be improved by increasing the number and thickness of the layers.



Left: Niobium cover coated with four 25 nm layers of NbN.
Right: The surface resistance of this sample at 3.88 GHz compared with a good cavity in solid niobium (scaled proportional to the square of the frequency).

In collaboration with CEA INAC in Grenoble, SACM has succeeded in depositing NbN (25nm) / MgO (14nm) /… type composites on thick films of niobium deposited on a monocrystalline sapphire substrate. The cathodic pulverization techniques used were developed for the production of Josephson junctions, but a thick dielectric layer of MgO is needed to decouple the various superconducting layers from each other. Similar layers where also deposited on a bulk niobium flat disk suited for radio frequency measurements.

In collaboration with the Italian Nuclear Physics Institute (INFM), SACM has made the first measurements of the vortex penetration field (the lower critical field H_{C1}) using a local field measurement system that is free from the boundary effects normally found in traditional magnetometry. SACM then developed a local magnetometer capable of exploring a wide range of field strengths and temperatures, approaching those found in operating cavities. The results in terms of the critical field are very encouraging. At 6 K, the critical field has been increased by around 50 mT with less than 100 nm of NbN. Apparently an increase about 100 mT could be achieved between 2 and 4 K, corresponding to an accelerating field about 25 MV/m in a cavity, if layers of the same quality were obtained.

In collaboration with the Orsay Institute of Nuclear Physics (IPNO), SACM has also tested a sample of four 4 NbN layers deposited under similar conditions on the bulk niobium cavity cover. The surface resistance of these multi-layer structures can be measured using an accurate thermometric method. With four 25 nm layers, around half the shielding current circulates in the NbN and the remaining half in the niobium. It can be seen, as expected, that the layers dissipate less than the niobium in the high temperature regions under BCS conditions. At lower temperatures, the residual resistance is still quite high. However, no optimization has yet been carried out on this type of sample.

These multilayer structures have a great potential for future superconducting radio frequency cavity technologies. Future R&D work is focused in two main directions; the optimization of the structures in terms of the number and thickness of the layers and the type of superconductor, and the development of deposition techniques suitable for application to cavities.

Accelerating structures for high intensity proton accelerators

The experience gained during the European High Intensity Pulsed Proton Injector (HIPPI) project in the design, technological development and testing of superconducting cavities, RF power couplers, and frequency tuning systems, has enabled SACM to become involved in the development of multi-cellular cavities for high energy protons in the SPL project and, more recently, the superconducting accelerator for the European Spallation Source (ESS).

Half-cells of a 704 MHz cavity with β = 1 during manufacture.

Superconducting electromagnets

The GLAD superconducting spectrometer for R^3B

The European Reactions with Relativistic Radioactive Beams of Exotic Nuclei (R^3B) collaboration brings together 230 physicists from 63 institutes in 21 countries. The group has set up a study at GSI in Darmstadt, Germany to investigate the emerging physics of exotic nuclei with relativistic energies. This program requires the construction of a number of high performance experimental installations in the fields of inverse kinematic reactions, total detection of the reaction products, and momentum resolution. The GSI Large Acceptance Dipole (GLAD), a superconducting spectrometer, will be an essential component of the R^3B detector assembly. The preliminary design for the project was carried out as part of the 5th European research and development framework program (FP5). The decision to fund the construction of the GLAD magnet was taken in October 2005 as part of FP6.

Left: The magnetic structure consisting of six trapezoidal coils. Center: The cold mass of the magnet consisting of the four coil enclosures, connecting plates and cryogenic supports. The electrical junction boxes connecting the superconducting cables are seen here against a blue background. In yellow: The 460 liter tank supplying the 4.5 K indirect cooling tubes in the convection circuit. Right: The cryostat next to its cryogenic satellite providing the external connections. It moves on an air cushion. The total mass of the magnet is 55 tonnes.

Specifications of the spectrometer

The GLAD dipole will have to take numerous constraints into account when analyzing the particles from reactions between radioactive ions and the secondary target. These include:

- A field integral of 4.8 tesla.meters, making it possible to deflect the high magnetic rigidity heavy ions by 18° (typically 15 T.m for $^{132}Sn^{50+}$), and protons by up to 50°.
- A wide angle inlet opening of ± 80 milliradians in both the horizontal and vertical axes, which also provides greater transparency to neutrons that are not deflected by the magnetic field.
- A large momentum acceptance, making it possible to detect protons and heavy relativistic nuclei, at individual nucleon energies of the order of a GeV.
- A negligible leakage field (< 20 mT), especially around the target zone located one meter upstream from the magnet entry face.
- A momentum resolution of 10^{-3} and an angular resolution of 1 mrad reconstructed at the target.

Progress of the GLAD magnet tests

Since the end of 2005, the construction of this magnet has been being partly funded by the European Construction of New Infrastructure – Darmstadt Ion Research and Antiproton Center (CNI-DIRAC) contract under FP6. The design has resulted in a compact and innovative magnet using an active shielding magnetic configuration.

Following a series of mechanical tests carried out on samples of the conductors and a half-scale mock-up of the winding, the mechanical design was finalized and the construction of the coils began in 2009. A prototype coil was built during that year, and six production coils were manufactured during 2010 and installed in their aluminum alloy housings. Electrical and cryogenic tests on the mock-up, also carried out during 2010, confirmed the performance of the conductor and the thermo-mechanical behavior of the winding.

The first coil was delivered at the end of 2010, enabling the start of the cold mass assembly. In addition to the mechanical assembly itself, one of the most important tasks has been to make the electrical interconnections

Installation of a coil in its housing.

between the 28 double pancake coils. The resistance of each connection must be of the order of a few nano-ohms, and each connection must be made with particular care using specific tooling developed for this task. Numerous electrical insulation tests have been carried out on these connections in order to ensure that they have been made correctly. The aluminum heat exchangers were glued to each coil prior to assembly.
The natural circulation of liquid helium in the tubes of the heat exchangers will provide indirect cooling to the entire cold mass. The coil housings are thermally linked to the coils by a total of 344 copper braids for cooling purposes.

The cold mass was placed on its three supporting legs at the end of 2011. Two of the legs are articulated so that the mass is free to retract during the initial cooling process. This assembly was then installed in one of the test cryostats in the W7-X test station in order to verify its behavior during all phases of the operation of the magnet, including initial cooling, current ramping, quench, and warming. The W7-X test station was extensively modified during 2011 in order to accept the cold mass and carry out these functions. A large number of tests have been carried out in order to confirm that its cryogenic capacity was sufficient to allow the operation of the magnet.

Half of the connections, stabilized, brazed, insulated and installed on their cooling plate.

The cold mass was connected to the test station in 2012 and a full range of tests were carried out in order to confirm that the magnet would operate correctly and safely during testing. The first tests with a current flowing were carried out at the end of 2012 and will continue through early 2013 until the nominal current of 3584 A is reached.

The cold mass installed in one of the cryostats in the W7-X test station at Saclay for acceptance testing at the nominal current.

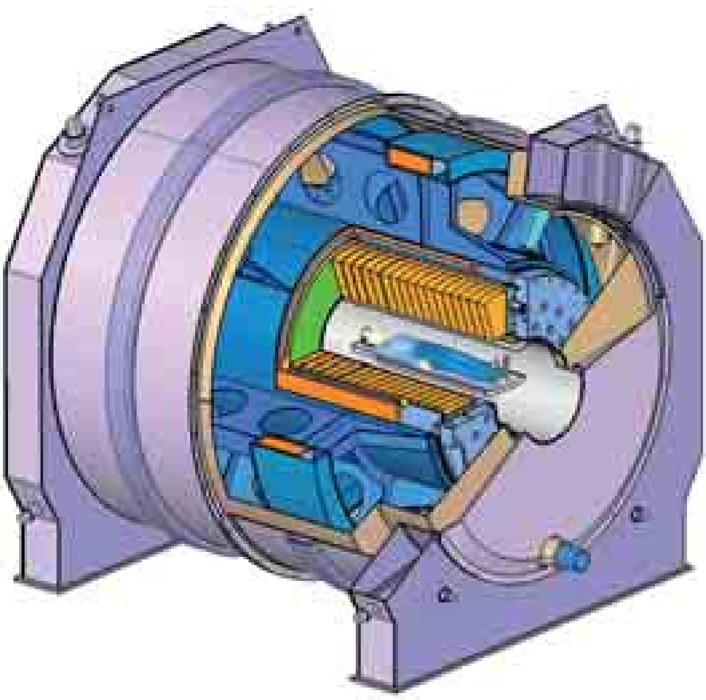
The ISEULT high magnetic field imager for the NEUROSPIN platform

Magnetic resonance imaging (MRI) is a diagnostic and research tool used in the neurosciences. In 2012, the NEUROSPIN centre will take delivery of an 11.75 teslas magnetic resonance imager (MRI) with a 90 cm diameter opening capable of scanning the patient's entire body. The use of this magnet in molecular imaging, together with new pharmaceutical contrast agents, will enable a deeper understanding of the brain by improving the images by a factor of ten. The development of ISEULT is part of a larger Franco-German project being carried out in collaboration with major industrial companies active in the field, including Guerbet, Siemens Medical Solutions and Alstom.

The challenges for the ISEULT magnet

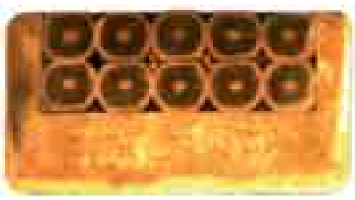
The design of the ISEULT magnet includes a number of characteristics that set it apart from conventional MRI magnets. There are five main technological problems to be overcome before such a magnet can be manufactured:

- A high intensity 11.75 T magnetic field.
- A large usable volume of several liters compared with other imaging systems already installed at the NEUROSPIN site which generate a field of 17 T but in a volume that is one hundred times smaller.
- Temporal stability, with variations in the magnetic field of less than 10^{-9} T over a period of ten minutes.
- A magnetic field that is homogeneous to within 5.10^{-7} T throughout the volume of interest corresponding to the brain of the patient.
- Containment of the magnetic field inside the experiment room.



Cross-section of the ISEULT 11.7 T magnet. The superconducting windings are shown in orange, the structure held at 1.8 K in blue, and the cryostat in grey.

The coil consists of several thousand kilometers of niobium-titanium superconducting wire wound in double pancake coils and carrying a current of 1483 A with a stability of 0.05 ppm / hour. This superconductor is maintained at a very low temperature of 1.8 K by means of 5000 liters of superfluid helium isolated from the exterior by series of insulating enclosures. A development program including a number of prototypes and special test stations will be required in order to understand and overcome these problems.



Superconducting cable (9.2 mm x 4.9 mm) for the main coil in a trough. Ten strands of composite NbTi-Cu wire inserted in a copper trough and coated with solder.

Completion of the development phase

A series of small specialized prototypes were manufactured between the end of 2009 and the start of 2012, and tests were carried out on model coils in order to demonstrate the principles of assembly and to verify the capability of the conductor to operate under the nominal magnetic field and associated forces. One of the prototypes, identified as R1, consisted of an assembly of six double pancake coils. Each double pancake coils consisted of eleven turns of the final ISEULT conductor and used the same components and assembly procedures as the final magnet. After winding, the six double pancake coils were assembled into a mechanical support structure consisting of stainless steel flanges, and an axial force of 240 tonnes was applied via twelve aluminum tie rods. The R1 prototype was then inserted into the 8 T magnet in the SEHT test station in order to apply a maximum field of 12 T to the conductor.

The initial cooling and testing of the R1 prototype was successfully completed in late December 2011 and early January 2012. By ramping up the current in both SEHT and R1, the conductor was subjected to an azimuthal stress reaching 225 MPa, well above the maximum nominal stress of 170 MPa expected in ISEULT. Additional tests at 4.2 K showed that the conductor could reach 96 % of the theoretical critical current, equivalent to a variation of 0.1 K from the theoretical critical temperature. This result compares well with the temperature margin of 1 K assumed during the dimensioning of the ISEULT magnet. In conjunction with the application of an axial stress of almost 110 MPa, these tests have demonstrated the ability of the conductor to withstand the mechanical stresses that they will be subjected to in ISEULT with a margin of almost 20 % while under the magnetic field conditions representative of those of ISEULT.

These excellent results completed the final qualification phase of the components and manufacturing procedures for the manufacture of the ISEULT coils. The way was now clear for Alstom to begin manufacture of the 170 production double pancake coils on February 1, 2012.

The R1 prototype: Stack of six prototype pancake coils, with an inner radius of 185 mm and an outer radius of 240 mm, mounted in a mechanical support structure in order to study the mechanical characteristics of the ISEULT conductor when subjected to a high magnetic field (12 T).

The 11.7 T magnet is currently being manufactured

The 190 km of conductor needed for the windings was manufactured in the USA by Luvata Waterbury Inc. between 2010 and 2012. The final double pancake coils are currently being manufactured by Alstom in Belfort. At the end of December 2012, more than 125 units had been completed out of a total of 170. The active shielding coils were also ready to be wound at that time. The remaining components of the magnet had been ordered and were either in manufacture or had been delivered.

The cryogenic system has been designed to cool the magnet continuously, 24 hours a day and 365 days a year. It has already been installed in the NEUROSPIN basement. The heart of the system is a helium refrigerator supplied by Air Liquide at the end of 2010. The acceptance tests showed that its performance was better than planned.

Winding one of the production double pancake coils.

The DC power system consists of two power converters. The first of these brings the magnet up to the nominal current of 1483 A at 40 V, and the second then provides continuous power to the magnet at the nominal current in stabilized mode. These two power units will be delivered to NEUROSPIN in the middle of 2013.

Radio frequency antenna array

A magnetic resonance image is formed by processing the relaxation signal from a previously excited atomic nucleus, usually hydrogen. An antenna is used to excite the nuclei with electromagnetic radiation, and to receive the relaxation signal. The operating frequency increases in proportion to the static magnetic field, from 128 MHz at 3 T to 500 MHz at 11.7 T. At frequencies up to 128 MHz, a single antenna is used to provide a sufficiently uniform excitation. At higher frequencies, the interaction between the transmitted wave and the material of the body results in strongly heterogeneous excitation, and an antenna array is needed.

Antennas developed by SACM for operation at 7 T. From left to right: Eight and twelve channel antennas, together with their Singular Value Decomposition (SVD) interface.

A preliminary eight channel 7 T antenna array has been built by SACM. The parallel transmission methodology used to achieve a uniform excitation will be finalized at the NEUROSPIN center using a phantom, an object with dielectric properties similar to those of a human head. Parallel transmission seeks to achieve a uniform excitation in two ways. The amplitude and phase of the signal fed to each element in the antenna array may be adjusted while maintaining identical pulse timings to all elements in order to generate a uniform radio frequency electromagnetic field across the region of interest. Unfortunately, this method is not effective across the entire brain region. Another degree of freedom in the time domain is required with individually shaped pulses being fed to each channel and transmitted simultaneously with the gradients of the magnetic field. During excitation, these gradients allow movement within the Fourier space, a dual of the image space, in order to cover a range of spatial frequencies and avoid the destructive interference that leads to artifacts. The flip angle become homogeneous when using this second method.

In order to obtain the first images of the human brain at 7 T in 2010, the eight channel antenna was certified by the Bureau Veritas to be in compliance with the IEC 60601-1 standard relating to medical electrical equipment. The experiment was conducted with authorization from the French Agency for the Safety of Health Products (AFSSAPS), now renamed the National Agency for the Safety of Medicines and Health Products (ANSM), under a protocol entitled, 'Assessment of the value of magnetic resonance imaging and spectroscopy at 7 teslas in the study of brain structure and function'. This work was also approved by the Committee for Personal Protection (CPP). A twelve channel antenna array is has been built and is currently under test with the aim of doubling the receive sensitivity. A patented signal distribution system is used to drive the array with just eight transmitters. The measured increase in sensitivity should lead to a marked improvement in the image resolution compared with a 3 T scanner. The 11.7 T antenna for the ISEULT project has already been built to the same design. It will be commissioned and tested on site as soon as the magnet is delivered.

The future

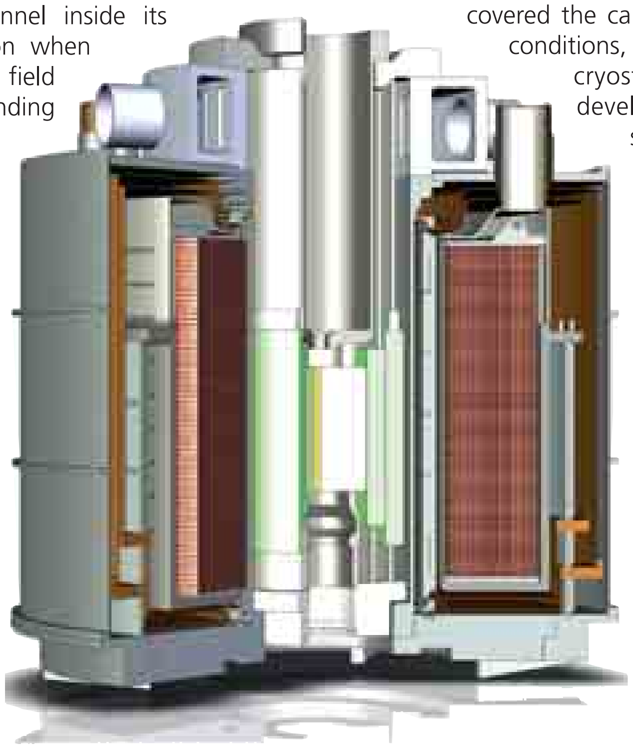
The magnet will be assembled at Alstom following delivery of the cryostat components. Delivery of the magnet to Saclay is due at the end of 2013. Once delivered to NEUROSPIN, the magnet will be connected to the cryogenic and electrical systems prior to a full set of qualification tests at 1.8 K and the ramp-up to the nominal magnetic field. The first images obtained at 11.7 T using the radio frequency antenna developed at SACM are expected to be produced during the course of 2014.

Examples of images, free from artifacts and contrast losses, obtained at 7 T using parallel transmission and the eight channel antenna.

The superconducting coil for the hybrid magnet at the LNCMI

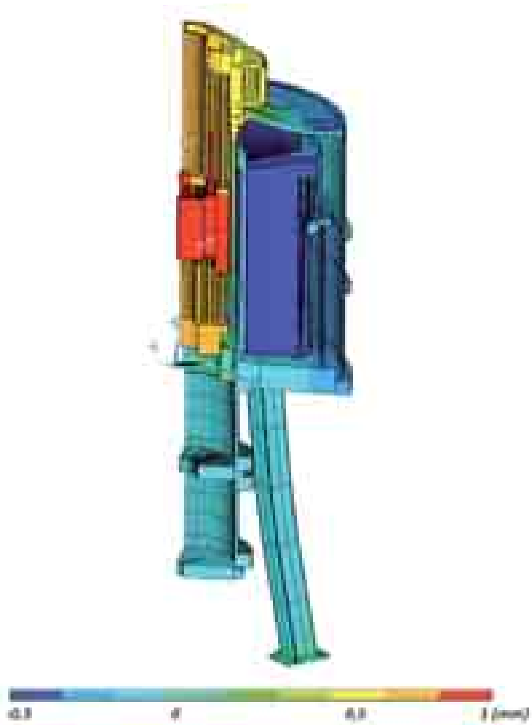
The National High Magnetic Fields Laboratory (LNCMI) in Grenoble is building a hybrid magnet capable of generating 43 teslas in a diameter of 34 mm by combining resistive magnets and a superconducting magnet. In the end of 2010, following preliminary feasibility studies, the CNRS and CEA signed a collaboration agreement putting SACM in charge of design studies and monitoring of construction of the 8.5-Tesla superconducting electromagnet. The hybrid magnet will comprise a concentric assembly of resistive magnets that will generate 34.5 teslas (Bitter coils and polyhelix coils) in the center of the superconducting solenoid to be created.

The solenoid superconducting magnet is designed with a superfluid helium channel inside its conductor, to prevent transition when there is a variation in the central field of 1 Tesla per second, corresponding to the increase and decrease of the current in the resistive magnets. This solenoid, having an internal diameter of one meter, shall be able to withstand very high levels of mechanical and electrical stress in the event that the magnetic field of the central resistive magnets is accidentally lost. In this case, the magnet will be temporarily be subject to a mechanical pulse equal to 3 times its mass (75 tonnes) and the eddy current screen will be supporting 100 times its mass (370 tonnes). These mechanical stresses and the voltages caused by the eddy currents will make it impossible to prevent the superconductor's transition in the unlikely event of this extreme accident situation. We have calculated the components so as to prevent a destruction of the cryostat and to mechanically reinforce the superconducting magnet.



The designs performed over the course of 2011–2012 covered the calculation of transient accident conditions, the design of the coil and the cryostat, and the design and development of cryomechanical support systems. These supports are very elaborate and robust enough to absorb temporary impacts while maintaining the permanent heat supply level (0.3 W) needed to keep the magnet at 1.8 K. A patent is currently being obtained for their design, which is highly innovative in terms of shape and quality of insulation with respect to their mechanical strength.

Cross-section of the hybrid magnet for the LNCMI. In green: the resistive magnets. In brown: the superconducting magnet that will be arranged in double pancake coils.



Mechanical vibration analysis of the structure of the hybrid magnet (in blue: the superconducting solenoid; in red: the resistive magnets). Vertical movements amplified by 200 at t =7 ms after the incident. Calculations performed on a quarter of the structure using the ANSYS code based on a model initially studied by the LNCMI in 2004, then adapted and rewritten for the configuration of the current magnet by the SIS in 2012. Although the elements were all securely held in the structure, the calculations predict millimeter shifts resulting from structural deformations.

Testing of superconducting magnets for the KATRIN experiment

The KATRIN experiment (Karlsruhe tritium neutrino) is an experiment performed in order measure the mass of neutrino with sub-eV accuracy, by examining the spectrum of the electrons β emitted by the beta radiation of the tritium. The tritium source is made up of an assembly of superconducting solenoids M_1-M_2-M_3 which guide the electrons toward the spectrometer. These superconducting magnets will be powered in a series in the final experiment. The magnets have been individually manufactured and tested by Bruker. Their initial protection system was passive and based on cold diodes. However, this principle was recognized as limited for low-voltage quenches in particular, during which the magnets were not sufficiently protected. A new active protection system, using an external discharge resistor and a detection system was jointly developed by IRFU and KIT (Karlsruhe Institut für technologie).

The vertical station of building 198 of CEA Saclay, with a depth of 8 m, was used to test the magnets in pairs in a liquid helium bath at 4.2 K. In order to decrease the quantity of helium required for cooling, polystyrene foam was placed along the length of the magnet cryostats. The electrical circuit, discharge resistor and contactors and detection and acquisition system are a result of modifications to the Seht testing station.

Cold tests of the magnets in the vertical cryostat were used to check that the detection and protection systems were operating properly. First, the magnets were tested at their nominal current (314 A), both individually and in pairs. This made it possible to validate operation in a series, for large magnetic forces caused between the magnets in particular, equal to 20 tonnes.

Quench caused, with discharge of helium.

Installation of a magnet pair in the cryostat of the vertical testing station.

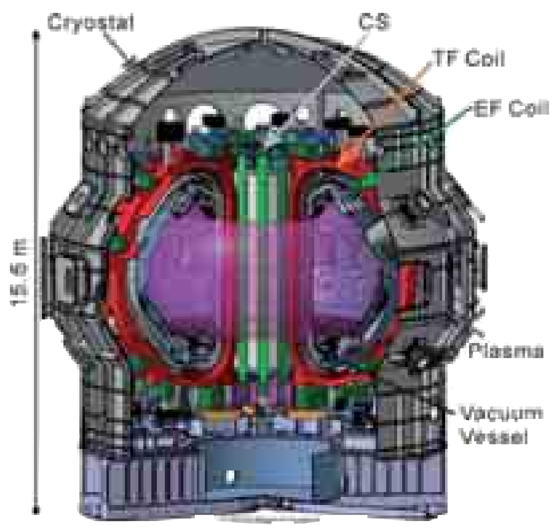
Quenches were then caused by the heaters placed on the solenoids. Detection limits—for voltage and duration—were adjusted to prevent any inadvertent detection not resulting from a true transition. The test results are perfectly consistent with the simulations carried out; they show that the magnets are sufficiently protected in their serial configuration by the new safety system.

Less than one year passed the signature of the collaboration agreement and the submission of the final report for the KIT tests.

Cryogenics

Test station for the toroidal coils of the Tokamak JT-60SA

As part of the agreement between Europe (F4E, Fusion For Energy) and Japan (JAEA, Japan Atomic Energy Agency) for a broader approach to controlled fusion using magnetic containment, Europe is in charge of updating the Tokamak JT-60, located in Naka, Japan, including the design, creation and testing of 18 new superconducting toroidal magnets used for the magnetic containment of plasma. SACM is in charge of construction of the cold testing station for these 18 superconducting magnets. Testing of the first magnet is expected to take place in May 2014.



Exploded view of the magnetic system of the Tokamak JT-60SA. In red, the toroidal coils.

The manufacturing of 9 toroidal coils has been assigned to France's CEA; the other 9 will be manufactured by Italy's national agency for energy efficiency, ENEA. The CEA institutes involved in the testing of the coils are the Institute of Nanosciences and Cryogenics (INAC) in Grenoble, the Institute of Research on Magnetic Fusion (IRFM) in Cadarache and the Institute of Research on Fundamental Laws of the Universe (IRFU) in Saclay.

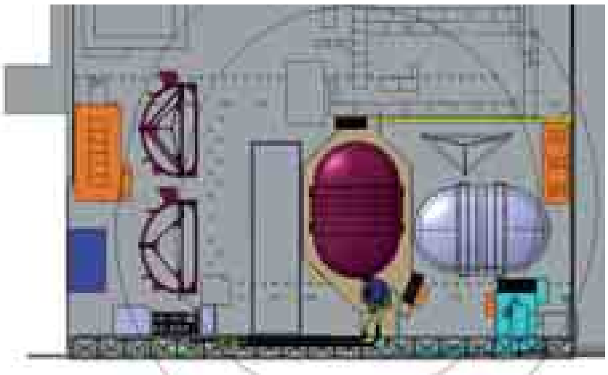
The cold test station team in front of the cryostat.

The project can be broken down into two main phases:

- the development phase consisting in the design, construction and validation of the testing station using a prototype demonstration magnet;
- the operation phase consisting in the performance of validation tests for the 18 toroidal magnets.

The cryogenic tests of the first coils of each manufacturer (2 manufacturers of 9 coils each) will be identical to the serial tests, with the exception that they will include a quench caused by an increase in the operating temperature. These two first tests will be important for:

- checking that the two coils satisfy the technical specifications, analyzing their behavior in nominal testing conditions and controlling their temperature margin, which will define the temperature margin of the serial coils;
- controlling the proper operation of coil potential measurements and acquiring information for the operation of the future machine.



Global description of the test station. On the left: the instrumentation racks in orange, the control room in blue, electrical supply of 26,000 A in gray and the coil supports for the cryogenic tests in violet. On the right: the cryostat in violet with its valve box in blue and helium refrigerator in cyan.

A cryostat measuring 7 m by 10 m will accommodate and test one magnet at a time. In parallel, other magnets will be prepared. The magnets will be tested at helium flowrates of 2 g/s per conductor, with an inlet pressure of 5 bar and a nominal current of 25.7 kA. The test temperature will be incremented up to the limit of quench conditions (from 5 K to 7.5 K).

Large cooling systems

The use of large superconducting magnets on the customer's premises as in the case of Iseult in the Neurospin laboratory or at the testing stations as in the case of JT-60SA in building 126 of CEA Saclay, and accelerating structures with superconducting cavities, on testing stations such as Supratech or on the Linear IFMIF Prototype Accelerator (LIPAc) at Rokkasho in Japan, require cryogenic systems to be installed, absorbing the powers developed at low temperatures in these pieces of equipment (static losses of cryostats and dynamic losses in radio frequency or with a variable magnetic field). These systems rely on industrial helium refrigerators (which have been until this time provided by Air Liquide), adapted and inserted into a cryodistribution architecture satisfying the specific needs of each project (temperature, flowrate, pressure, power to be extracted, etc.).

Following the design and implementation some years ago of the cryogenics in the 2 accelerator cryomodules of the SOLEIL ring, running on saturated liquid helium at 4.45 K, the latest cooling systems of this type that have been installed or will soon be installed are as follows:

- the equipment needed for superfluid helium cryogenics pressurized to 1.8 K for the Iseult magnet in the rooms and basements of the Neurospin laboratory;
- the cryogenic plant of the LIPAc associated with the cryomodule with 8 superconducting cavities at a radio frequency working at 4.45 K; SACM is responsible for the design of this supply and monitoring of its installation in Japan.

Picture of the Air Liquide refrigerator installed in the basements of Neurospin with the storage of 5000 liters of liquid helium in the background.

Both of these 2 projects required the adaptation of the machine's operating mode (magnet and accelerator), gas and liquid storage, the valve panels controlling the return of the fluid to ambient temperature, the valve boxes or cryogenic satellite, the helium pumping systems and the transfer lines providing cooling and continuous and reliable supply of helium to the superconducting elements. The refrigerators selected for these 2 applications develop, respectively, equivalent powers of 200 W and 300 W at 4.4 K for Iseult (already installed) and for LIPAc (in request for proposal).

In the Iseult project, only the refrigerator and the cycle compressors (145 kW installed) have been requested of the manufacturer (Air Liquide Advanced Technologies). All other equipment was been designed and is being manufactured by SACM. In the IFMIF project, very far from our base of operations, the manufacturer who will supply the refrigerator (AL-AT or Linde Kryotechnik) will also have to construct and install the other equipment of the cryogenic station (175 kW installed) based on a design and specifications developed at Saclay.

For these different projects, we draw from the large amount of feedback and know-how of the teams working on our testing stations using these types type of cooling or liquefaction systems (4 machines are currently in service at SACM).

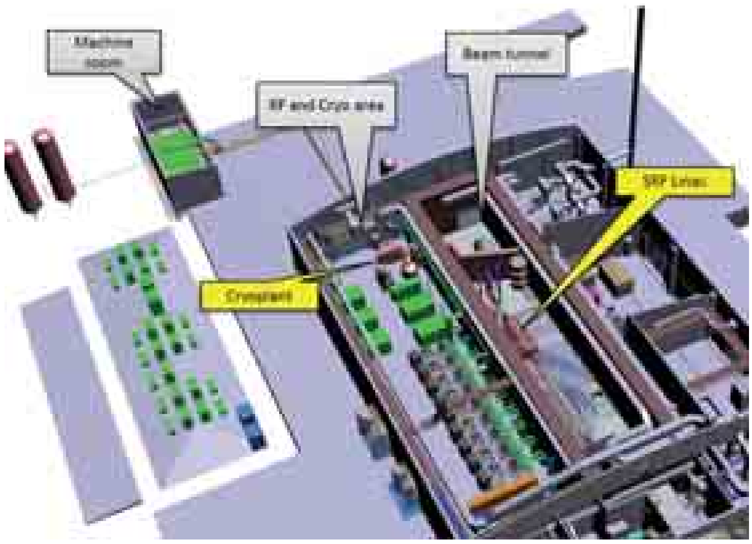
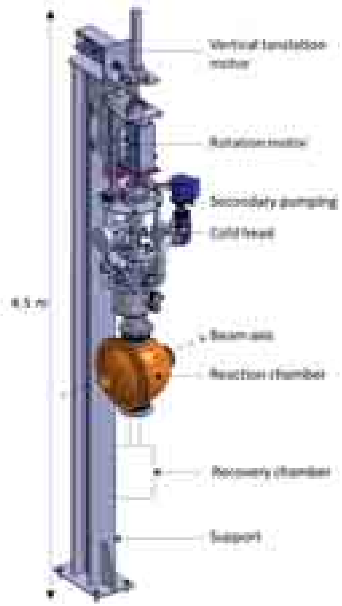


Diagram of the cryogenic plant installed in the IFMIF-LIPAc building in Japan.

The CHyMENE solid hydrogen target for SPIRAL2

Within the framework of the SPIRAL2 project, SACM is in charge of developing a cryogenic system that will provide a thin solid target of pure hydrogen, without a container and suitable for experiments using low-energy ion beams. It will be installed at the GANIL facility in 2016 for the Nuclear Physics Department's research program in the area of exotic nuclei.

The target appears in the form of a quasi-solid hydrogen ribbon (10 mm wide, 50 µm thick), which flows continuously using an extrusion technique in a vacuum inside a reaction chamber in front of the ion beam. This target is developed in collaboration with the the Pelin laboratory, which supplies the extruder, the IPN in Orsay, which is responsible for the extrusion nozzle and IRFU, which is in charge of the overall design of the mechanical and cryogenic system. This assembly comprises a cryostat in a vacuum, providing for vertical movement of 100 mm and a 100° rotation of the target, so as to give 90° analysis angles, with respect to the beam. The cryostat is made up of a cold head providing the power needed (15 W at 11 K) to solidify the hydrogen in the lower part of the extruder.

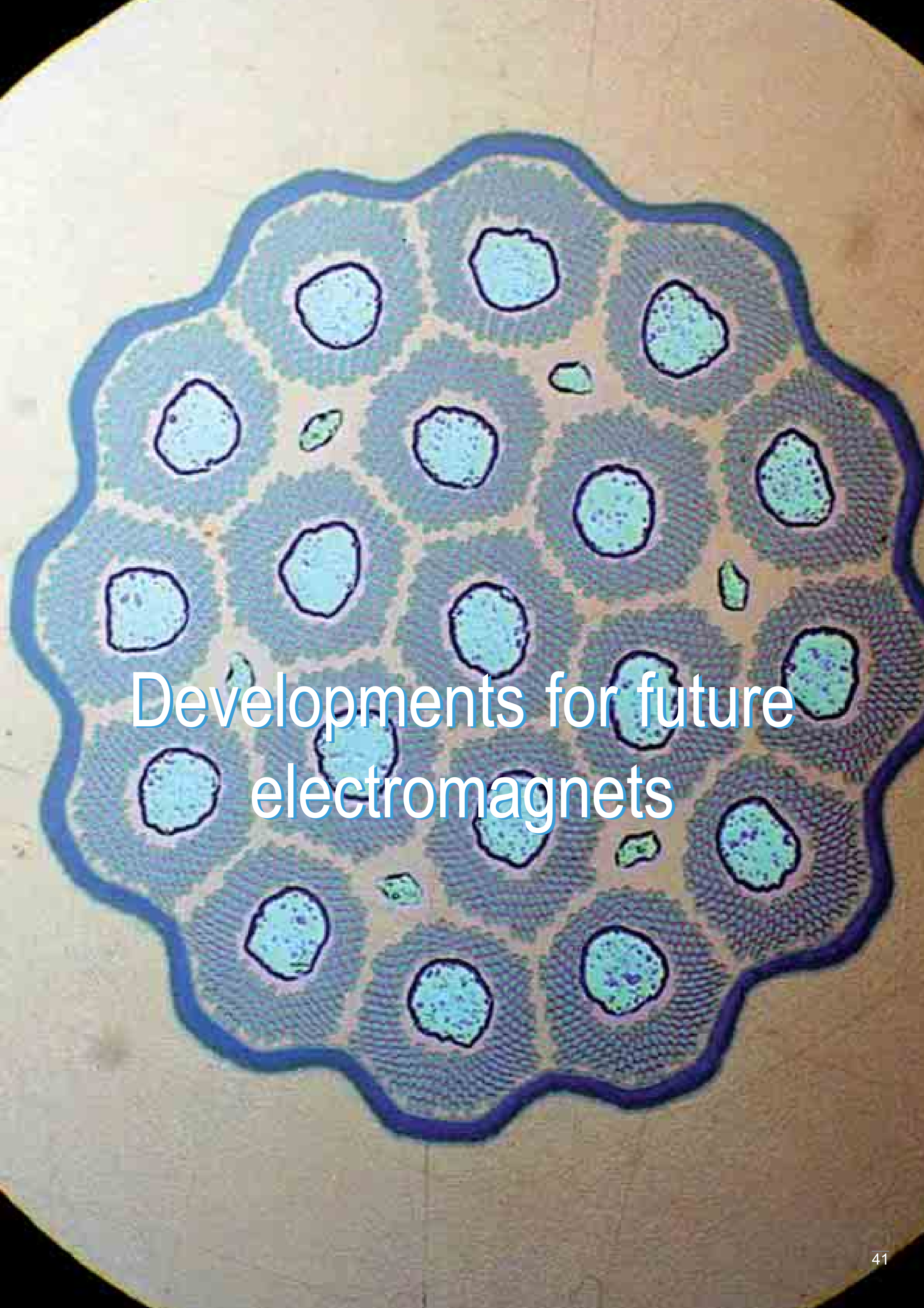


The cryogenic power is transmitted from the source to the extruder by conduction via metals with very high thermal conductivity (10,000 $Wm^{-1}K^{-1}$ at 11 K). In the cryostat, the gaseous hydrogen at an initial pressure of 8 bar is first liquefied in the upper part, then is partially solidified and compressed to 100 bar in the cooled extruder before the solid film is expelled through the nozzle in the center of the reaction chamber. The paste obtained then falls by gravity into a recovery tank where it sublimes. The gas is then pumped and evacuated into a dedicated line. An Instrumentation and Control system controls all equipment, and manages the thermal regulation and safe state of the cryostat.

The liquid hydrogen target for the MINOS project

The Minos (Magic Numbers Off Stability) project aims to analyze, using spectroscopy, the exotic nuclei produced by fragmentation in the new generation radioactive ion machines. The hydrogen target will be installed on the Riken machines in 2013 and GSI/FAIR machines in 2017. SACM is responsible for the development of a cryogenic system producing liquid hydrogen in a Mylar® envelope.

The 120-µm thick Mylar (thermoplastic polymer) allows for a geometry in the shape of a glove finger (150 mm long and 52 mm in diameter), thereby optimizing the analysis angles. The target is created by the assembly of two parts (inlet window and outlet envelope) attached to a stainless steel support. The pressure capacity of this assembly is 6 bar. The cryostat is equipped with a cryogenerator for liquefaction of the gaseous hydrogen at 20.4 K in the condenser associated with the second stage of the cold head (15 W at 20 K). Gravity causes the liquid hydrogen obtained to fall into the target. The cold vapor produced returns to the condenser in a closed circuit. The cryostat is equipped with a cold valve installed on the gas return circuit making it possible to empty the target within just a few minutes. The overpressure created in the target returns the liquid to the condenser and leaves behind only cold vapor. Once the valve is opened, the liquid rapidly fills the target. This operation involving the target in a vacuum environment provides for measurement of the signal-to-noise ratio created by the Mylar envelope. The geometry of the cryostat is designed so as to integrate the target in the center of a TPC (time projection chamber) detection, taking into account the constraints associated with the target's extraction without disassembly of the detection. This equipment is controlled by an Instrumentation and Control system managing the different operation phases and the safe state of the system.



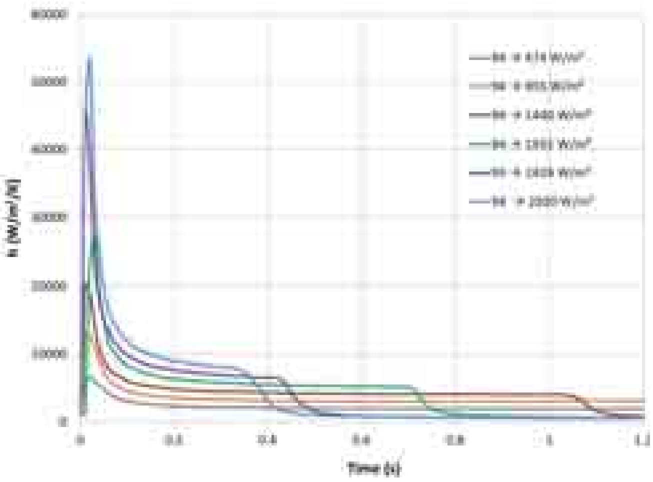
Developments for future electromagnets

R&D on superconducting magnet cooling

In order to optimize the performance of cryomagnetic systems, CEA actively supports R&D efforts involving the cooling of these systems. Research is being led on different topics corresponding to the different types of superconducting magnets. Studies on two-phase helium flows in transient conditions are being led to predict the thermo-hydraulic phenomena occurring during a quench of the superconducting magnets cooled by external flows and operating, for example, by convection. For smaller systems, we are studying the coupling of a circulation loop with cryogenerators so as to create autonomous cooling systems. Finally, studies are also being led to understand the heat transfer in superfluid helium through microchannels representing typical thermal paths in the electrical insulations of accelerator magnets.

Two-phase flow of helium in transient conditions

Certain cooling systems of detector magnets in high-energy physics applications are based on two-phase helium circulation loops. Experimental studies are being led to study the particular case of transient conditions during the cooling of these large magnets. These are crucial, since they cover the scenario in which the magnets transition from the superconducting state to the normal state, dissipating a large amount of heat. The results of the experiments show that heat transfers are improved in the first moments (for about 100 ms) after the power is dissipated. The increase in the heat transfer coefficient along the wall is attributed to a dramatic increase in nucleated boiling, increasing the heat transfer. After this transient state, the transfer coefficient drops significantly for high heat flux densities, leading to the appearance of film boiling, which is catastrophic for cooling. Knowledge concerning these phenomena and their time constants will allow optimizing the cooling of these large magnets.

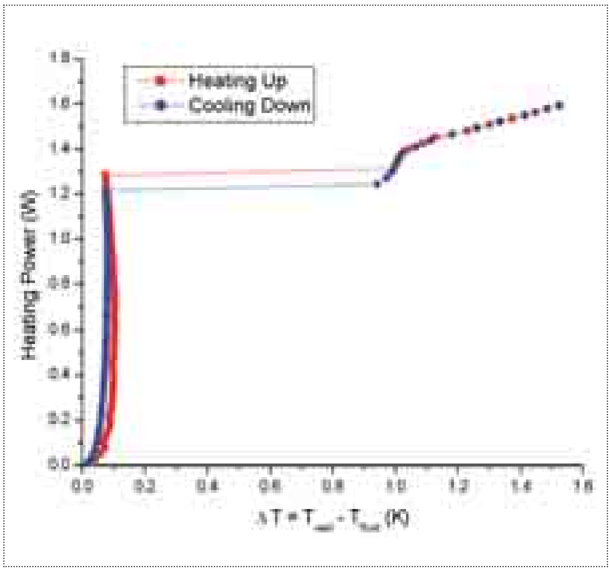


Changes in the wall heat transfer coefficient in the event of a dramatic increase of the heat flux density, from an initial value of 94 W/m² to 2920 W/m².

Cooling using a two-phase, autonomous circulation loop

The idea of coupling a natural circulation loop (thermosiphon) with a cryogenerator presents several advantages for the cooling of cryomagnetic systems of medium size and power, operating at low temperatures (10 W to 4.2 K) or at the temperatures of liquid nitrogen (100 W to 77 K). This coupling combines the advantages of a circulation loop and the recondensation of vapors representing a large energy gain (no transport and no loss of cryogenic fluid) and makes this mode of cooling autonomous. It is easy to see interest of such a system placed in the bottom of a tunnel, for example, or for applications using superconductors with high critical temperatures such as power cables or the latest generation electromagnets.

Autonomous convection loop comprising a cryogenerator (top), a condenser (stainless steel pot) and the heat exchanger (a vertical copper tube with a 4 mm diameter and equipped with a heating wire).



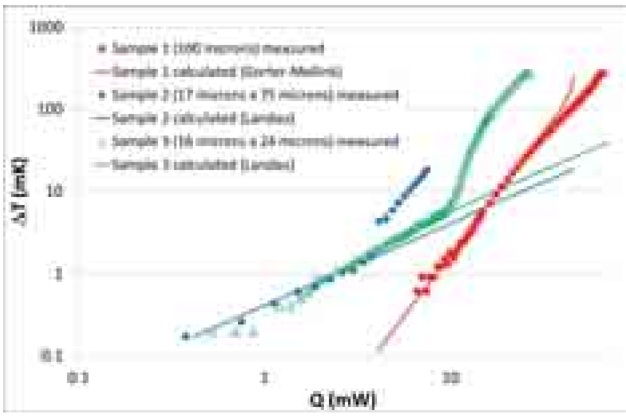
Curve for the boiling of helium with increasing flux (red curve) and decreasing flux (blue curve). The final measurement points (power greater than 1.4 W) were obtained at a pressure greater than the critical pressure of helium ($p_c \approx$ 2.3 bar).

An experimental autonomous loop at helium temperature was developed and instrumented in order to study its cooling capacities. When the power dissipated in the heat exchanger increases, different thermal conditions are encountered in two-phase flows: a natural convection state, a nucleated boiling state, a film boiling state (after a jump in temperature of approximately 1 K), then a supercritical single-phase flow for high heat fluxes. The appearance of this last state is not surprising, since the system operates in a closed loop and not at constant pressure. The cooling capacity of such a system is rather great since the heat transfer coefficient varies from 1 to 10 kW.m^{-2}.K^{-1}.

Heat transfers through microchannels in superfluid helium

For superconducting accelerator magnets cooled by superfluid helium (T < 2.2 K), the electrical insulation of the conductors constitutes the greatest thermal barrier to cooling. The insulation of NbTi magnets is made up of insulation tapes wrapping made of polymer, creating microchannels with typical dimensions of 10 to 100 µm. The thermal phenomena in the superfluid helium at this level of containment must be included in order to optimize the cooling of these magnets. For the analysis of these thermal transfers, microchannels are chemically etched in a Pyrex wafer. A temperature difference, measured with miniature sensors, is created between a superfluid helium volume and the outlet of the channels using a heater. These measurements are compared to the known heat transfer models of the superfluid helium. The Gorter Mellink regime is encountered for channels with large dimensions (100 µm equivalent diameter) and the Landau regime is encountered for smaller dimensions (17 µm x 75 µm and 16 µm x 24 µm). Upcoming studies will focus on dimensions of approximately a micron.

Microchannels (2 mm x 10 µm) dug into a Pyrex wafer. At bottom: helium volume equipped with a heater (wire in pigtail form) and miniature temperature sensors. At top (in green): outlet of channels in the superfluid helium bath.



Temperature deviations in channels of different dimensions. The temperature of the helium bath is 1.9 K.

Developments for future superconducting magnets for the LHC

The LHC (Large Hadron Collider) will achieve its nominal energy of 14 TeV by the end of 2014, and its nominal luminosity of 10^{34} $cm^{-2}s^{-1}$ in 2015. Beginning in 2020, for its operation to remain profitable, the LHC will require a major improvement to significantly increase its luminosity. The configuration of the new machine, called the High Luminosity LHC (HL-LHC), will require, among other things, the replacement of the quadrupole triplets in the interaction zones and the triplets in the insertion zones. In parallel with the studies for the HL-LHC, a second program, called the High Energy LHC (HE-LHC), is underway to explore the possibility of future improvements providing for collision energies ranging from 26 to 33 TeV. The basic idea is to replace all of the magnets in the current machine with magnets having a higher magnetic field, of around 20 T. The only superconducting materials that could provide for the achievement of this highly ambitious objective are Nb_3Sn and superconductors with high critical temperatures.

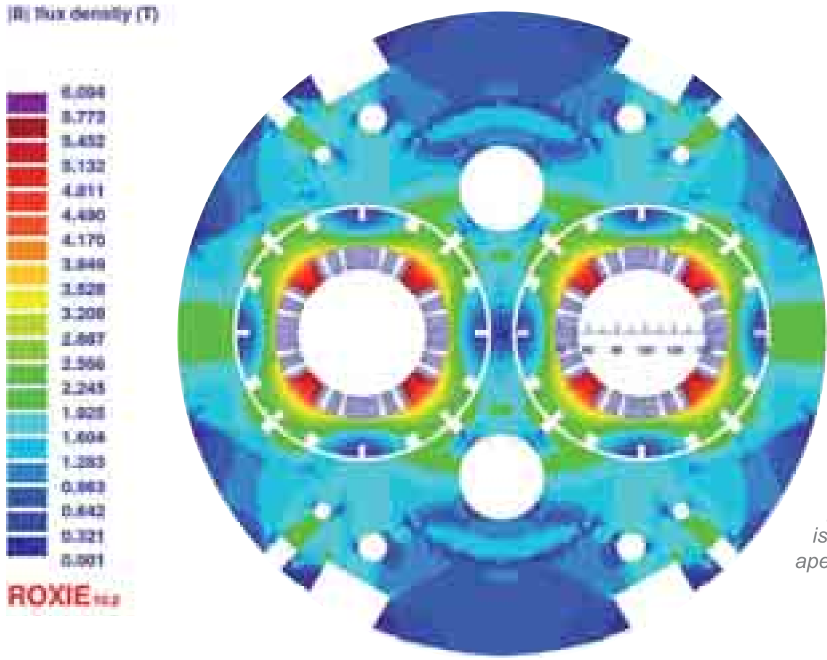
Creation of a coil layer.

In collaboration with CERN, CIEMAT, and RAL (the Rutherford Appleton Laboratory), SACM is in charge of the mechanical validation of the quadrupole design and the construction of four coils for one of the quadrupole models. Each coil is made up two coil layers, manufactured separately and assembled after polymerization by an internal splice. The cables used are the same as those of the LHC arc dipoles; however, new insulation, more permeable to superfluid helium, has been developed to compensate for the higher heat deposits. The coils were delivered to CERN in November 2011. Assembly and collaring was completed at CERN, and the models are currently undergoing testing.

NbTi quadrupole triplets

An increase of the luminosity factor of the interaction zones from 2 to 3 can be obtained by replacing the final focusing quadrupole triplets of the interaction zones with quadrupoles having a large aperture (120 mm, compared to 70 mm for the current triplets), with a maximum field in the conductor of the same level as that of the LHC arc quadrupoles, approximately 7 T, thereby permitting the use of NbTi. The energy stored and the electromagnetic forces involved are, however, much greater due to the larger aperture. It has therefore been deemed necessary to supplement the design studies of the quadrupoles with the development of two validation models.

Photo of the four internal and external coil layers created at the CEA Saclay site.



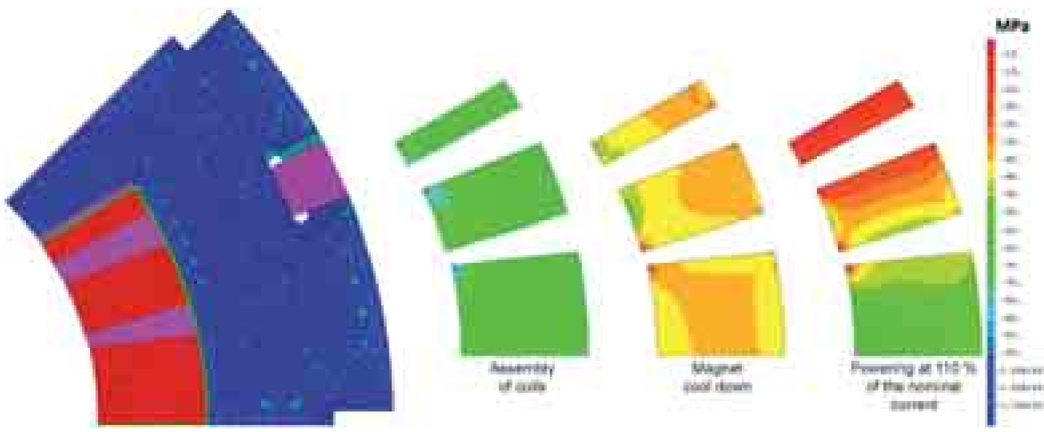
Magnetic design of the quadrupole with a double-aperture of 90 mm, made up of NbTi coils, austenitic steel bracing collars and an iron yoke. The diagram shows the distribution of the magnetic field in the collars and in the yoke when the nominal current is circulating in the two apertures.

Two-in-one quadrupole with a large aperture

A sub-project of the HL-LHC project, called the Hilumi-LHC, was initiated in 2011. One of its objectives is to improve the magnets in the insertion zones of the LHC. In particular, SACM has been assigned the magnetic and mechanical design of the future quadrupoles of the external triplet, the large-aperture (80 to 100 mm) Q4 quadrupole, which is to replace the current quadrupole having an aperture of only 70 mm. One of the magnetic constraints of the NbTi Q4 quadrupole is a double-aperture, with a spacing of 194 mm, providing for the circulation of two particle beams in opposite directions. The resulting magnetic coupling impacts the quality of the field, especially when the current circulating in the two apertures is different. The currently selected aperture is 90 mm, and the cable is identical to that of the LHC arc quadrupole. Mechanical analyses have provided for validation of the principle for the use of bracing collars for this design, simulating the assembly of the coils, the cooling of the magnet and its operation at 110% of the nominal current.

CEA Saclay and CERN are discussing the possibilities for involvement of SACM in the manufacturing of the future double-aperture Q4 quadrupoles starting in 2013.

On left: mechanical model for validation of the use of the bracing collars for coil assembly. In red: the superconducting cables; in blue: the steel collar. By symmetry, only one octant is modeled. On right: distribution of azimuthal stresses in the coil after assembly of the coils, after cooling of the magnet and during operation of the magnet at 110% of the nominal current.



High-field Nb_3Sn dipole

IRFU R&D activities linked to the use of Nb_3Sn as a superconducting material for high-field magnets will result in the creation of a magnet intended for Fresca 2, the new conductor testing station at the CERN facility. This magnet is a an Nb_3Sn dipole with a length of 1.5 m and an aperture of 100 mm, and capable of providing a field on the axis of 13 T at 4.2 K, with homogeneity of one percent on 700 mm. Design studies for the dipole began in 2009.

Coil head bending test. The heads are tilted down during the winding operation.

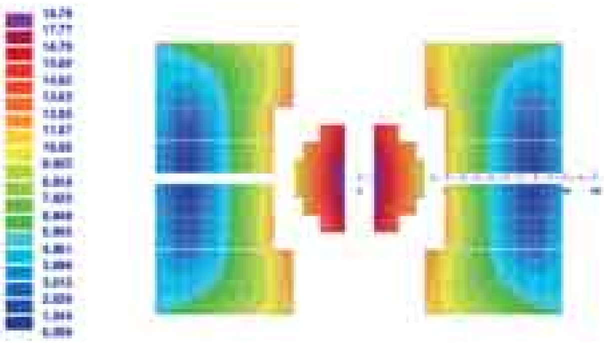
SACM has performed the magnetic and mechanical design studies of the dipole in collaboration with CERN. A block configuration was selected for the coils: each pole is made up of two coils in the shape of a racetrack, each made of two conductor layers with tilted heads providing room for the beam tube. The dipole will be constructed with 1 km of Rutherford type cable made up of 40 strands having a diameter of 1 mm. As part of the partnership with CERN, SACM is responsible for ensuring the supply of superconducting Nb_3Sn strands from two suppliers proposing two different technologies: PIT (powder in tube) and RRP (restacked rod process), thereby requiring duplication of the cable behavior analyses from the point of view of superconducting and mechanics. At this time testing is underway to evaluate the dimensional changes of the cables during the thermal reaction that could result in stresses in the conductor and its deterioration if the structure of the coil and equipment are not properly adapted. Different specific tools have been developed for the testing of the coils to provide selection of the best geometry for the layer jump, to prove the feasibility of the heads in the block configuration and to improve their geometry, then to validate "head-down" coils.

Full-scale model of the dipole insert.

The thermal models of the dipole are now available and calculations in stationary conditions and transient conditions in the helium have been performed to analyze the magnet's behavior during cooling, or during a quench. Digital 2D and 3D models have also been developed to validate the magnet's safety system, made up of 4 heaters distributed over the surfaces of the coils and discharge resistors. The detailed analysis of the coils and the structure of the cold mass is now complete, as is that of the coil, reaction and impregnation tools. The supply of these tools is nearly complete, and we have received the components needed for the construction of a full-scale coil prototype, made of copper, the manufacturing of which should begin in February 2013. The manufacturing of the Nb_3Sn coils is planned for 2013, and the dipole test is to take place in 2014.

High critical temperature superconductor dipole insert

Meeting the induction fields of 20 T is a true challenge attainable only using superconductors with high critical temperatures such as YBaCuO. As part of the European EUCARD program, SACM is responsible for the construction of a dipole insert made of YBaCuO, generating a magnetic field of 6 T at 4.2 K in the 13-T Fresca 2 dipole. The challenges are related to both mechanical aspects, maintaining high forces, and protection aspects, preventing destruction of the magnet in the event of a quench. The magnetic and mechanical designs of this magnet are complete. It will comprise 3 double-layer coils in the shape of a racetrack, assembled around a central iron pole held in place by a stainless steel clamp and a stainless steel external cylinder. The insert components are currently being manufactured. A prototype made up of a single winding layer will soon be built in order to measure the current density transported by the superconducting ribbon as a function of the orientation of the external magnetic field. The insert itself will be wound and assembled during 2013.

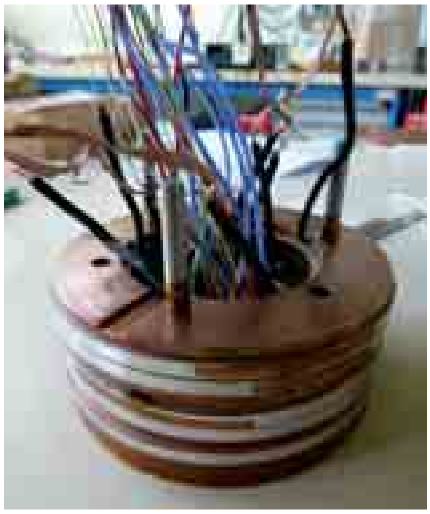


Magnetic field of the insert in the Fresca 2 magnet.

The use of high critical temperature superconductors

Superconducting materials with high critical temperature provide new possibilities: not only is their ability to transport an intense electrical current in the superconducting state preserved at temperatures in excess of 60 K (for certain materials) but, most importantly, they maintain their superconducting properties under an induced field of 30 T providing they are kept at the temperature of liquid helium. Using these materials makes it possible to make superconducting magnets capable of operating between 30 and 40 K, and to make magnets generating magnetic fields of 30 T.

Second-generation superconducting ribbon installed on a Vamas coil ready to be tested.



Double pancake coil made of YBaCuO ready to be assembled on the test probe in the magnetic field.

The SuperSmes project is a collaboration between the laboratories of Grenoble—G2ELab, the Institut Néel and the LNCMI—dedicated to the storage of magnetic energy using superconductors with high critical temperatures. It is part of SACM's R&D on innovative materials.

The goal of this project is to achieve a specific energy density stored in a superconducting coil of 20 kJ/kg, a gain of 45% with respect to the world record at the beginning of the project. It will demonstrate the feasibility of magnetic storage systems. The characterizations of industrial conductors of the YBCO type (yttrium barium copper oxide) have validated the performances of conductors up to 20 T and 30 K and have made it possible to determine the behavior laws for the existing ribbons.

Prototypes of magnets with high specific energy density have been produced, and have attained the goals of the program. With these results, it is possible to envisage the creation of a complete energy storage system, a system that would have applications for electromagnetic launcher or pulse sources with high-power currents. Other identified applications for superconducting materials with a high critical temperature such as the compound YBCO include the production of magnetic fields greater than 20 T for high-field nuclear magnetic resonance and magnetic levitation making it possible to locally eliminate the effect of the earth's gravitational pull.

Solenoid made of YBCO ribbon installed on the test probe and ready to be tested with an induction of 18 T in the testing station at the LNCMI facility in Grenoble.

Use of MgB_2 for dry superconducting magnets

Magnesium diboride (MgB_2) is a known material whose superconducting properties were discovered in 2001. It has a critical temperature of 39 K which ranks in the intermediate temperature superconductors between the low critical temperature superconductors, such as niobium titanium (NbTi) and niobium tin (Nb3Sn), and the high critical temperature superconductors such as cuprates. Its discovery has aroused great interest because its components are cheap and its manufacturing process is similar to that of conventional superconductors. It could therefore eventually replace the conventional NbTi. Only two manufacturers in the world offer this material as tape or wire: Columbus in Italy and Hypertech in the United States.

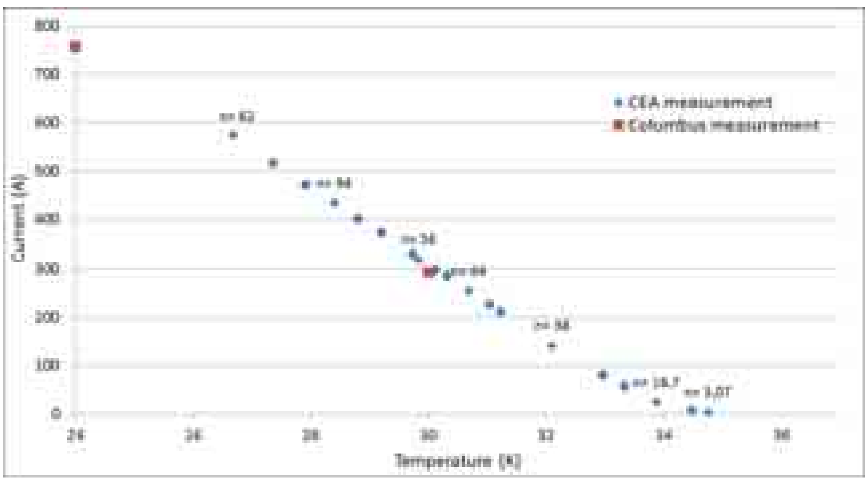
Its present superconducting properties suggest that a MgB_2 magnet could operate at a temperature of the order of 10 K in a magnetic field range up to 4 T. It is then possible to design cryogenics without helium, using only cryocoolers as cold source.

This perspective has led the Department to start a R&D program for developing design and technical tools for building such magnets. Two lines of research are studied: cryogenics specific to this type of application (current leads, electrical insulating thermal contact, etc.), the electromagnet design (characterization of the wire in a magnetic field at different temperatures, protection in case of quench, winding technique, etc.).

This work has begun in late 2011 as part of a thesis in partnership with SigmaPhi. A characterization test facility, without helium, to measure up to 600 A and 3 T the critical current of a MgB_2 tape over a length of one meter on a cylinder of 300 mm diameter at temperatures between 10 K to 40 K has been performed. The first results in self field were obtained in early 2013.

Future goals of SACM are now to wind a test double pancake coil and a solenoid for generating a 1 T in a background field of 3 T. These prototypes will allow to define the operating margins necessary for this type of magnet and to study their protection.

Test facility without helium for measuring the critical current of a MgB_2 tape.



Critical current measurement on a MgB_2 tape from Columbus; n is the index of transition.

Technical platforms

49

Test facilities for superconducting magnets and large size components

W7-X test facility

Trials on current intensity, isolating voltage, mechanical stress, pressure drop and temperature for magnets cooled with supercritical helium forced flow between 4.5 K et 7.6 K.

- 2 cryostats: 5 m useful diameter; 4.1 m useful height.
- 200 W at 4.2 K dedicated refrigerator.
- Data acquisition for cryogenic sensors up to 500 Hz and for voltage measurements up to 20 kHz.

Schema – Horizontal cryogenic station for magnetic tests

Tests of superconducting magnets at temperature between 1.8 K and 4.2 K.

- Horizontal cryostat: 0.6 m useful diameter and 8 m useful length.
- Electrical power supply: 20 kA (10^{-4} stability) under 5 V.
- 160 measuring channels up to 20 kHz.

Vertical test facility

Tests of large scale components at low temperature (in liquid helium or under vacuum).

- Vertical dewar fitted in a pit.
- 0.88 m useful diameter.
- Maximum height under vacuum: 7.9 m with a 7 m thermal shield at 80 K.
- Electrical power supply: 20 kA.

JT-60SA station

Trials on current intensity, isolating voltage, pressure drop and temperature for magnets cooled with supercritical forced helium flow (cold circulator) between 5 K et 7.5 K.

- 1 cryostat oblong: length of 10, width of 6.5 m, useful height of 2 m.
- Dedicated refrigerator: 490 W at 4.2 K + 3.6 g/s from 50 K to 300 K + 1 satellite with a cold pump 30 g/s for a secondary loop.
- Electrical power supply: 25 kA.
- Data acquisition for cryogenic sensors up to 500 Hz and for voltage measurements up to 50 kHz.

Test facilities under magnetic field

Seht – Eight tesla test station

Tests of prototypes or large scale components under magnetic field (8 T).

- Useful diameter: 587 mm at room temperature.

Cétacé – Test cryostat at variable temperature and high magnetic field

Critical current measurements on superconducting samples.

- Maximum current intensity in sample: 2,000 A.
- Maximum magnetic field: 17 T.
- Magnet useful diameter: 64 mm.
- Useful diameter of the sample cryostat: 49 mm.
- Sample temperature : from 1.8 K to 200 K.

Christiane

Critical current measurements on superconducting samples at 4.2 K.

- Maximum current intensity in sample: 3,000 A.
- Maximum magnetic field: 7 T.
- Magnet useful diameter: 90 mm.

SUPRATECH: Platform for technological research on superconducting accelerator cavities

Cryholab – Laboratory horizontal cryostat (property of IRFU-IN2P3)

Tests on superconducting cavities under conditions identical to those in an accelerator.

- RF power coupler: Present: 700 W, Currently in manufacture: 800 kW continuous, up to 1 MW pulsed.
- Pumping system and Hélial 4012 refrigerator: 80 W at 1.8 K and 13 mbar.
- Useable internal dimensions: 1.5 m long by 70 cm in diameter.

Power coupler test benches

The RF components can be tested under both traveling wave and standing wave conditions.

- One 704 MHz test bench capable of pulsed operation at 1.0 MW peak, using 2 ms pulses at a pulse repetition rate of 50 Hz (100 kW mean power).
- One 1300 MHz test bench capable of pulsed operation at 2 MW peak, using 1 ms pulses at a pulse repetition rate of 10 Hz (20 kW mean power).
- One 704 MHz test bench - 80 kW continuous; stable up to 50 kW system.

Chemistry laboratory and clean-room

Chemistry laboratory

- 8 fume hoods for the treatment of samples and cavities, including one closed chemistry cabinet for treating only the internal surface with filtered acids, thereby reducing the risk of contamination.
- Adjacent storage area for acids and solvents.
- Effluent treatment plant for water, acids and vapors.
- 2 ultrasonic degreasing stations (10 l and 120 l).

170 m² clean-room with three ISO class sections 7.5 and 4

Assembly of cavities following high pressure rinsing.

- ISO class 4 clean room: 112 m².
- Washing air-lock for the external cleaning of cavities prior to their entry into the clean-room.
- Ultra-pure and ultra-filtered water loop.
- High pressure rinsing with ultra-filtered pure water.

Additional facilities

- Pure and ultra-pure water treatment plant (4 m³/h).
- Refrigeration unit with a power of 179 kW.
- 370 m² assembly hall with lifting equipment capable of handling loads of up to 20 metric tons.

Vertical cryostats (CV)

Measurements of the accelerator field and over-voltage coefficient of superconducting radio frequency cavities.

- 2 motor pumps: 1 g/s at 13 mbar.
- 1 RF source, 200 W CW, 700 MHz to 1500 MHz.
- 1 RF source, 80 W CW, 4200 MHz to 8600 MHz.

CV1

- Useable diameter: 0.7 m. Height: 2,92 m.
- He depth: 1.9 m at 4.2 K and 1.2 m at 1.7 K.
- Consumption: 1500 l of He per test.

CV2

- Useable diameter: 0.45 m. Height: 1.7 m.
- He depth: 1 m at 4.2 K and 0.6 m at 1.7 K.
- Consumption: 450 l of He per test.

Cold characterization facilities

Measurements in pressurized superfluid helium at 1 atm

- Double bath NED cryostat. Volume at 1.8 K: Diameter 250 mm x Height 300 mm.
- Double bath Th0 cryostat. Volume at 1.8 K: Diameter 200 mm x Height 500 mm.

Residual Resistivity Ratio (RRR) measurements

- RRR measurements on 100 mm x 3.5 mm samples.
- Cryostat: Useable diameter 0.15 m, Height 0.9 m.
- Consumption: 20 l of He per test.

MECTIC – Measurement of the thermal conductivity of insulators and conductors

- Cold head (cryogenerator) used for measurements on samples of around 30 centimeters in size over a temperature range of 3.8 K to 300 K.

Measurement of Kapitza resistance and thermal conductivity

- Thin sample (0.5 mm), up to 80 mm in diameter.
- Temperature range: 1.7 K to 2.1 K.

Thermosiphon loop

Characterization of single phase and two phase flows by measurement of the mass flow rate, volume ratio, pressure drop and wall temperature of a 1.2 m vertical test section and 0.4 m horizontal test section.

- Mass flow rate: Liquid helium 0 to 22 g/s, liquid nitrogen 0 to 40 g/s.
- Mass flow rate: Gaseous helium 8 g/s, gaseous nitrogen 40 g/s.
- Maximum power dissipated in the loop: 500 W.

Thermautonome

Characterization of monophasic flow and two-phase flow on a closed loop equipped with a cold head (cryocooler); measurements of pressure losses and wall temperatures.

- Cryocooler: 1.5 W at 4.2 K.
- Pressure: a few mbar to 3 bar.
- Temperature: from 3 K to 30 K.

Laboratories and workshops

Mechanical testing laboratory

Measurements at 300 K and at cryogenic temperatures 77 K (liquid nitrogen) and 4.2 K (liquid helium): Determination of Young's modulus and breakdown characteristics (stress, strain, etc.) on metal or composite materials. Tests, including slippage and deformation, on mechanical assemblies.

- Hydraulic press with a capacity of 2000 kN in compression.
- Instron electromechanical press with a capacity of 300 kN in both traction and compression.
- Instron electromechanical press with a capacity of 150 kN in both traction and compression, fitted with two cryostats for tests at cryogenic temperatures:
  - Cryostat with a capacity of 60 kN for traction and bending tests.
  - Cryostat with a capacity of 150 kN for compression tests

Impregnation laboratory

Technical support for departmental projects in the insulation and impregnation of superconducting magnets. Impregnation of prototypes and characterization samples, preparation of resins, preparation of conductors prior to characterization by dissolving out aluminum and copper.

Laboratories and workshops

Vacuum and materials laboratory

The Vacuum and Materials Laboratory is responsible for the vacuum design of accelerators, research into the desorption of materials, the development of ultra-vacuum techniques and the mechanics of vacuum systems.

- Ultra-vacuum oven: 1200°C at 10^{-6} Pa.

Winding workshop

The workshop is equipped with four winding machines. Two of them are used to wind solenoid magnets with external diameters of up to 2 m. The other two are dedicated to coils with a vertical rotation axis for realization of accelerator magnets of lengths up to 3 m or pancake coils.

Mechanical workshop

The mechanical workshop provides assistance to SACM in the construction of prototypes, and is able to offer a rapid response to urgent requirements from experiments in the event of unplanned modifications or rework. The workshop is equipped with five lathes, five milling cutters, one flat grinder and a range of other metalworking machines including drills and saws. In 2009, the workshop installed a machining section for composite materials, including a lathe, milling cutter, drill and bandsaw.

Helium refrigerators and liquefiers

Hélial 4012 liquefier - refrigerator
used with CRYHOLAB

- Liquefaction: Around 140 l/h at 4.2 K.
- Refrigeration power: Around 80 W at 1.8 K with a motor pump providing 2 to 4 g/s for 13 to 26 mbar.

CELLO liquefier - refrigerator
used with the JT-60SA test station

- Liquefaction: Around 120 l/h.
- Refrigeration power: Around 400 W at 4.2 K.

Hélial 4003 liquefier - refrigerator
used with the W-7X test station

- Liquefaction: Around 70 l/h.
- Refrigeration power: Around 200 W at 4.2 K.

Hélial 4008 liquefier
in the liquefaction station

- Liquefaction: Around 70 l/h.
- Liquid helium delivered during 2012: 173,000 l.

Water cooling station

STARE – Water cooling station

This cooling station consists of two loops, one primary and one secondary.

- **Primary loop:** This loop is used to cool the test platforms installed in Facility 218 (IPHI, SUPRATECH, IFMIF, SPIRAL 2, and SOPHI). The circulating water is demineralized (10 MΩ.cm) with a total flow rate of up to 600 m^3/h.

This loop is also capable of supplying chilled water at between 9 and 11°C at a rate of 147 m^3/h using a 1200 kW refrigeration compressor.

- **Secondary loop:** This loop cools the water in the primary loop via a 10 MW plate heat exchanger. It is connected to a semi-open forced draft cooling tower capable of extracting 8 MW with a flow rate of 600 m^3/h and a maximum evaporation of 11 m^3/h.

Quality, safety and environment at SACM

The IRFU Accelerator, Cryogenics and Magnetism Department (SACM) complies with CEA Saclay environmental and risk management procedures in all its activities. The SACM covers two security perimeters on the site (installations No. 82 and No. 218). They cover an area of 32,000 m^2 with 18 buildings and an average workforce of 162 persons. These buildings house 6 installations classified for environmental protection (ICPE) and received ISO 14001 certification in 2009.
The department's "security environment" team is composed of a facility manager, two deputy managers, advised by two facility security engineers (ISI) and several safety officers.
Each ISI also acts as an environment contact (IE), waste correspondent, radioactive sources manager and deputy works correspondent. Given the number of activities being carried out in these buildings, together with their extent and dispersion across the site, there are also 32 operating managers and deputies who are able to stand in for the safety team in respect of some of their activities.

Facility 82

This facility includes the SACM LCSE and LEAS laboratories.

- 12 buildings
- 10,000 m^2
- 80 CEA employees
- 3 ICPEs
- 4 local first aid teams (ELPS)

The activities carried out within this facility include the superconducting components cryogenic test stations (samples or complete magnets), insulation-impregnation, winding and magnetic measurement laboratories, and the mechanical workshop. There is also a helium liquefaction and refrigeration station. It delivers an average of 175,000 liters of helium per year to SACM, the CEA, and external clients.

The years 2010–2012 were marked by the performance of tests for the Iseult and R^{3}B-Glad projects.

Cold mass of the Glad magnet for the R^{3}B experiment.

Facility 218

This installation was created in October 2005. Its premises include the LEDA, LIDC2 and LISAH laboratories of SACM.

- 6 buildings
- 22,000 m^2
- 82 CEA employees (SACM, SPhN/LENAC, SIS)
- 3 ICPEs
- 3 local first aid teams

Until the end of 2005, this installation formed the major part of the Basic Nuclear Installation (INB) 48 SATURNE. It is now declassified.

In terms of risk control, the years 2010–2012 were marked by:

- the commissioning of the SUPRATECH platform completed in 2009 by the laboratory of chemistry and the clean room;
- the preparation of the manufacturing phase for the integration of the 103 XFEL cryomodules;
- the performance of tests linked to the SPIRAL2 and IFMIF injectors;
- the downgrading of the authorized ICPE "Chemical Laboratory" of Orme des Merisiers.

Clean room ISO 4.

The rearrangement of the halls in preparation for the several projects carried out within the facility (CRYHOLAB, CV1 and CV2, XFEL, SPIRAL2, IPHI, IFMIF, GBAR, COCASE, JT-60SA, etc.) has resulted in several large-scale worksites involving major activities as follows:

- the construction of the "Village XFel» for the industrial delivery;
- the beginning of works for the installation of the JT-60SA coil testing station;
- a new clean room for the SPIRAL2 and ESS projects;
- renovation and development work in accordance with industrial effluent and stormwater networks;
- work of the basements of the Synergium to remove water seepage and prevent any flood of natural origin or industrial origin;
- the work of thermal insulation of the building 126 through the resources of the Grenelle of the environment (change of 32 000 m^2 of cladding, insulation of terrace and storage facilities);
- the work of rearrangement of the Synergium accesses.

The multiplicity of interferences within the Synergium is managed in short term by meetings of operating managers twice a month and, in longer term, by quarterly meetings on the plan of land with project managers.

Exceptional transportation of the cryostat of the JT-60SA coil test station.

Quality at SACM

The quality at SACM is in the way recommended by the IRFU and more widely by the CEA in the area of quality and risk control. CEA has an operational reference system which adopts the process management to make clearer our operation and monitoring actions.

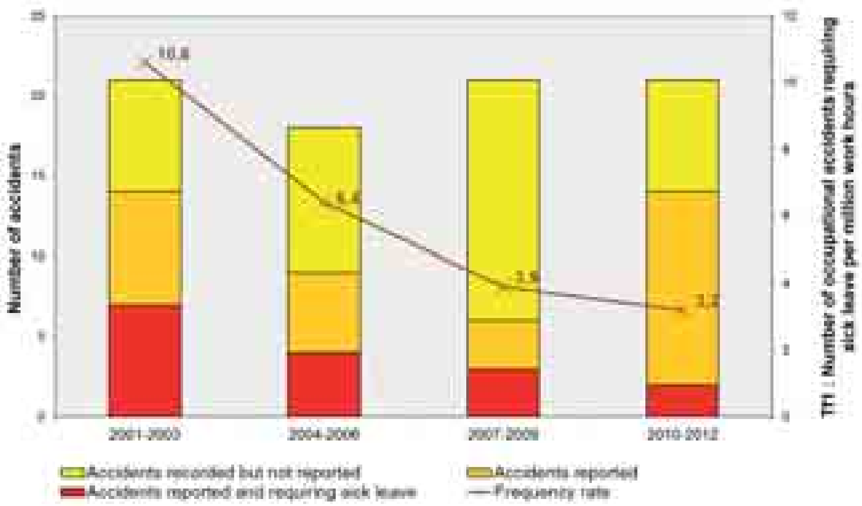
The quality inside projects is managed by two quality correspondents sharing two areas: laboratories LEAS and LCSE on one hand, laboratories LEDA, LISAH and LIDC2, secondly. Reference documents of SACM numerous projects are stored on Irfu network or electronic document management system.
Among these reference documents, there are organization charts, Quality Assurance Plans, Project Management Plans and so on. The quality correspondents can also give advice if requested by the projects.

Action indicators and safety results for the period 2010–2012

	SACM total
Local safety committee safety reports	11
Safety visits	36
Safety drills	17
Audits and inspections	12
Safety plans	105
Fire permits	360
Safety training days	500

SACM is one of the Departments with the largest number of new projects at the design stage (prior to work beginning or during operation) submitted to the Saclay Local Safety Committee in order to obtain authorization from the Director of the Center.

The safety record of SACM has improved continuously since the Department was set up in 2001. In particular, accidents involving personnel have been reduced in both frequency and severity. Even if the total number of accidents, not considering severity, has remained the same, it should be noted that the technical activities of the Department increased greatly in number during this period. In each of the past six years, SACM has surpassed the target set by the CEA as part of the CEA Triennial Safety Improvement Plan of reducing the Tf1 by 5% (by -40% between 2007 and 2009, and by -18% between 2010 and 2012).



Change in number of accidents involving SACM personnel.

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