

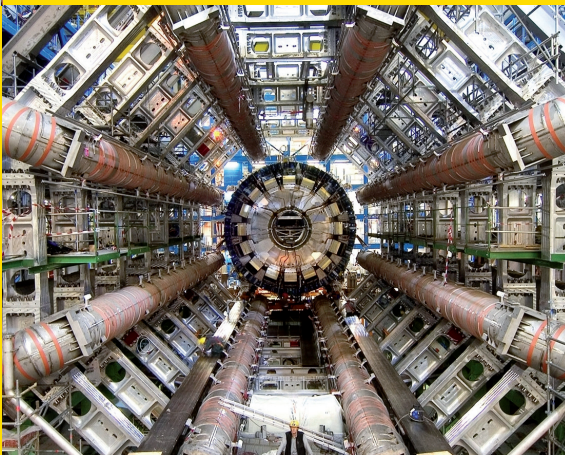
Physical sciences division (DSM)

Laboratory of research into the fundamental
laws of the Universe (Dapnia)

Accelerator, cryogenic and magnetism department

SACM 2004-2006

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Preface

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Technical platforms

The accelerator, cryogenic and magnetism department (SACM)

Dapnia/SACM is developing and realizing particle accelerators, cryogenic systems and superconducting magnets for the scientific programs of Dapnia and more widely of CEA. Dapnia/SACM is mainly involved in large scale projects. These projects are conducted within the Dapnia project organisation and rely on the skills and activities of all the Dapnia groups.

In December 2006, 67 engineers and 51 technicians or administrative staff belongs to the division. SACM welcomes also several Ph. D., visitors and many trainees.

The division is organized in four laboratories:

- Leda (Laboratoire d'études et de développement pour les accélérateurs).
- Lesar (Laboratoire d'études des structures accélératrices et des radiofréquences).
- Leas (Laboratoire d'études des aimants supraconducteurs).
- LCSE (Laboratoire cryogénie et stations d'essais).

A scientific and technical committee, the CSTS, consisting of 16 members including 5 international experts not coming from CEA has a yearly meeting for assessment of on going activities and evaluation of new proposals. The CSTS is assisting the head of SACM in the definition of the strategy in Research and Development. More specifically, the orientations in European programs are reviewed by the CSTS.

In order to reach its goals, SACM runs various installations:

- specialized laboratories for electrical, cryogenic, mechanical, radiofrequency tests, materials characterization, chemical treatment of surfaces for accelerating structures;
- large cryogenic test facilities at 4 K and 2 K for superconducting samples up to 20 kA, for superconducting electromagnets, for superconducting RF cavities and their power couplers, with the attached acquisition, and analysis tools;
- a liquefaction systems station for the production of liquid helium and three refrigeration stations associated to test facilities.

During the last three years, SACM had a strong contribution to the Large Hadron Collider LHC accelerator and detector construction at Cern. These years have seen several successes with the delivery of

the 360 cold masses of the main ring quadrupoles, the test on surface of the CMS solenoid, the full assembly and test in the cavern of the Atlas toroid. Following these large projects the existing skills in cryogenic and magnetism have been reengaged. Two new magnets have been launched: the Neurospin Iseult, MRI solenoid and the R3B Glad spectrometer, which are real scientific and technical challenges.

SACM has kept at a very high level its involvement in the development of superconducting cavities both with the International Tesla collaboration and within the 6th European PCRD. A very high accelerating field value has been obtained in November 2006 taking advantage from the new electro polishing bench. Also the SACM has consolidated its knowledge in protons ECR sources which delivers currently 100 mA dc. Significant progress has also been obtained in RFQ construction and in the accelerator assembly for Iphi.

In the three coming years efforts will be focused on the achievement of the Iphi injector, the commissioning of the Sophi positron source, the construction of the Spiral-2 injector, the production of the Ifmif-Eveda prototype equipments, assembly and test of the Spiral-2 cryomodels and R&D actions in the frame of the 7th PCRD. All these activities require large conventional facilities; the gathering of the teams on the Saclay site will be completed together with the construction of a new clean room and associated chemical process. It will result in an up-to-date accelerator R&D platform at Saclay.

In the cryomagnetism area, the test of the W7X coils will end up in 2009 and technological extensions are expected for the Iter program. The R3B Glad spectrometer will be assembled and the magnetic mapping will validate its use for nuclear physics. Development program for the MRI Neurospin Iseult will pass the critical phases in view of obtaining its challenging performances in field, stability and homogeneity.

From now to 2010 and in its complementary areas of cryomagnetism and accelerators, the SACM Division will live rich hours at the level of the scientific ambitions of the CEA Saclay and of its surrounding communities.

Antoine Daël, chef du SACM



LEDA

The **Laboratoire d'études et de développements pour les accélérateurs** (Leda) represents SACM's competencies in the area of designing and building systems for the production, transport and acceleration of particle and light ion beams.

As of December 2006, Leda is staffed by 14 engineers, 7 technicians and 2 doctoral students. More specifically, Leda includes:

- ▶ A team of experts in the field of beam dynamics applied to linear and circular accelerators, including collective effects such as space charge or wake fields, and in electromagnetic calculations applied to electrostatic, magnetic and radiofrequency systems.
- ▶ A team of experimental researchers specialized in the operation of sources and injectors, and in the measurement of beam parameters involved in developing and using diagnostics.
- ▶ A vacuum and ultra high-vacuum laboratory focused on accelerator vacuum calculations and the techniques of heat treatment and desorption measurement.
- ▶ A technical team experienced with the installation, mechanical assembly and cooling of accelerators.

The laboratory's achievements in recent years include starting construction of the deuteron accelerator Spiral 2, following the success of the preliminary project, and of Califes, an electron injector for the CTF3 project at Cern. Another milestone has been the gradual implementation of a demonstrator of the feasibility of Iphi, a high-intensity proton injector, and in particular of its radiofrequency quadrupole.

Leda is looking towards the future through its involvement in the construction of high-intensity linear accelerators for nuclear energy (Ifmif), and by exploring the theory and techniques of new-generation particle accelerators, such as e+e- linear colliders and neutrino factories.

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LESAR

The **Laboratoire d'études des structures accélératrices et des radiofréquences** (Lesar) is in charge of developing the radiofrequency (RF) structures necessary for accelerating particle beams. A significant portion of the laboratory's work focuses on superconducting cavities, used for various types of accelerators (ions, electrons, protons), and aims to continuously improve their performance and stabilise their operation.

The specific skills of the 19 engineers and 11 technicians who comprise Lesar can be divided into two themes:

- ▶ Studies of accelerating structures, from design with RF simulation software until prototype testing. This activity includes the tuning of cavities and other RF components, design of RF electronics and control, and prototype tests using beams. Over the course of 2006, all the test cryostats for superconducting cavities – notably Cryholab, for testing in an accelerator-like environment – were brought together and upgraded, along with the ancillary cryogenic equipment, in a new zone known as SupraTech-Cryo/HF.
- ▶ The behaviour of superconducting cavities in response to surface treatments, as well as measurements on superconducting materials. The laboratory is equipped with advanced facilities to carry out its research: a chemistry laboratory, a cleanroom (class 100) with a high-pressure rinsing system, and a physical vapour deposition (PVD) bench.

The laboratory's key achievements over the last three years:

- ▶ Participation to build, test and install the first cryomodule of Soleil, a french synchrotron radiation facility.
- ▶ Cryomodule study for the Spiral2 accelerator, with tests on a quarter-wave cavity prototype.
- ▶ Development of a frequency tuning system which includes piezoelectric rods optimized to compensate for radiation pressure forces.
- ▶ Development of an electropolishing bench for single-cell cavities.
- ▶ Installation of a pulsed 1-MW radiofrequency source operating at 700 MHz.
- ▶ Design and development of a high-frequency antenna for use with a 7-T MRI machine.
- ▶ Development of a cleanroom baking procedure for superconducting cavities which enhances performance at high accelerating gradients.

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LEAS

The **Laboratoire d'études des aimants supraconducteurs** (Leas) offers its expertise in magnetic field area to Dapnia physicists and is staffed by 10 technicians and 19 engineers as of December 2006. The laboratory's teams are responsible for the design and control of superconducting magnets for experimental facilities, especially large magnets or those with high magnetic fields.

In designing superconducting magnets, Leas applies its expertise to the domains of coil geometry optimisation, conductor design, mechanical, electromagnetic and thermal calculations, and magnetic protection in the event of quench. In addition to the design of magnets, Leas also has the capacity to manage large projects, to develop magnets and integrate them into cryostats, and to provide follow-up for industrial achievements. Magnet control is handled jointly with the Laboratoire cryogénie et station d'essais (LCSE); measurements include analyses of tests at ambient and cryogenic temperatures, e.g. analyses of quench and magnetic measurements.

A major milestone in recent years has been the completion of development activities for the LHC (Large Hadron Collider) accelerator at Cern, with important contributions in Saclay, at Cern and amongst European industry groups: integration and cavern tests of the toroid Atlas, assembly and conclusive surface tests of the solenoid CMS, and completion of industrial cold mass assembly for the machine's main quadrupoles. Activities related to coil tests for the stellarator W7-X are ongoing and new projects are underway: the dipole for the R3B spectrometer and the solenoid for the Iseult imaging system.

To remain competitive, Leas has defined several areas for further development. For that it maintains and enhances its design tools (namely its computing tools) and supports a programme of R&D aimed at achieving high magnetic fields. This R&D is focused on using niobium-tin, and on using superconductors at high critical temperatures. These activities enable Leas to maintain or establish numerous contacts with other laboratories in Europe and elsewhere throughout the world, not to mention the other laboratories of SACM, Dapnia and the CEA.

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LCSE

The mission of the **Laboratoire cryogénie et station d'essais** (LCSE) is the control of cryogenics for superconducting magnets, accelerating cavities, physics detectors (cryogenic target systems, calorimeters), and the production and distribution of liquid helium as well as the distribution of liquid nitrogen.

This control is applied to designing, building and operating cryogenic installations of various sizes and types. The liquids used are boiling or supercritical helium, superfluid helium, liquid nitrogen, liquid argon and liquid hydrogen. The cooling machines range from cryogenerators to refrigerators with turbines, and include cooling circuits using circulators or thermosiphon.

Design, construction, integration and adjustment are focused on cryostats and the associated cryodistribution. The traditional users are elementary particle physicists and nuclear physicists who work with accelerators (Cern, GSI, Hera, TJNAF, Ganil). The other users belong to the medical community (NeuroSpin, a cerebral imaging project), the fusion community (Iter) or the laboratory's testing and characterisation stations.

These testing stations comprise a very complete set of 15 core facilities for determining mechanical, thermal and electric properties of various materials (insulators, composites, metal alloys and superconductors) at cryogenic temperatures and in a magnetic field. They are also used to test magnets and cavities as well as their components.

The laboratory's expertise continues to develop thanks to R&D projects, in areas such as the two-phase flow of helium, thermal hydraulics of thermosiphons, and heat transfer in superfluid helium and porous materials.

As of December 2006, the laboratory is staffed by 13 engineers, 15 technicians and 2 doctoral students.

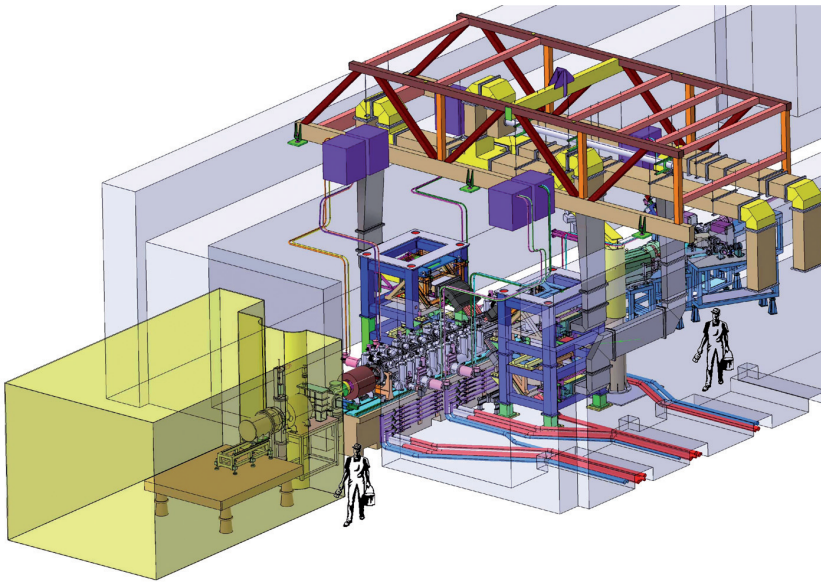
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High-intensity
ion linear accelerators

High-intensity proton injector (Iphi)

A high-intensity proton accelerator is an intense source of secondary beams: neutrons, muons, neutrinos, radioactive nuclei, etc. Their characteristics open new fields of study and application, 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 Institut national de physique nucléaire et de physique des particules (IN2P3) of the CNRS, and Cern.



3D representation of the Iphi accelerator, from the Silhi source at the bottom left to the beam stopper at the upper right, via radiofrequency accelerating cavities and the beam diagnostics line. The grey components represent the concrete biological protection system.

Iphi is a proton injector prototype which accelerates a continuous 100-mA beam at energies up to 3 MeV. It consists primarily of a proton source and its low-energy beam transport system (95 keV), an RFQ (radiofrequency quadrupole) accelerating cavity with an energy up to 3 MeV, and a diagnostics line designed for extremely precise measurements of all the essential characteristics of the beam as it leaves the RFQ. In parallel, a prototype of the DTL (drift tube linac) cavity – the most suitable for accelerating the beam once it leaves the RFQ – was successfully developed and tested at Cern in 2002.

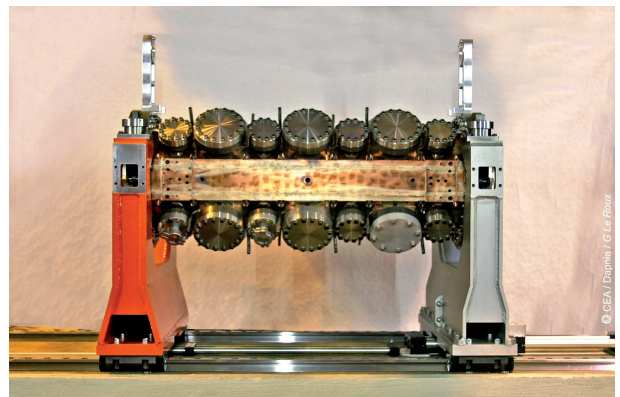
Building the RFQ accelerating cavity

The RFQ accelerating cavity is the heart of this accelerator. When this type of cavity resonator is excited by a wave of radiofrequency (352 MHz for Iphi), it collects the continuous beam from the source with practically no loss and accelerates it while at the same time focusing it. The downside to these exceptional qualities is that the cavity is very difficult to implement. Building RFQ components is a technological challenge.

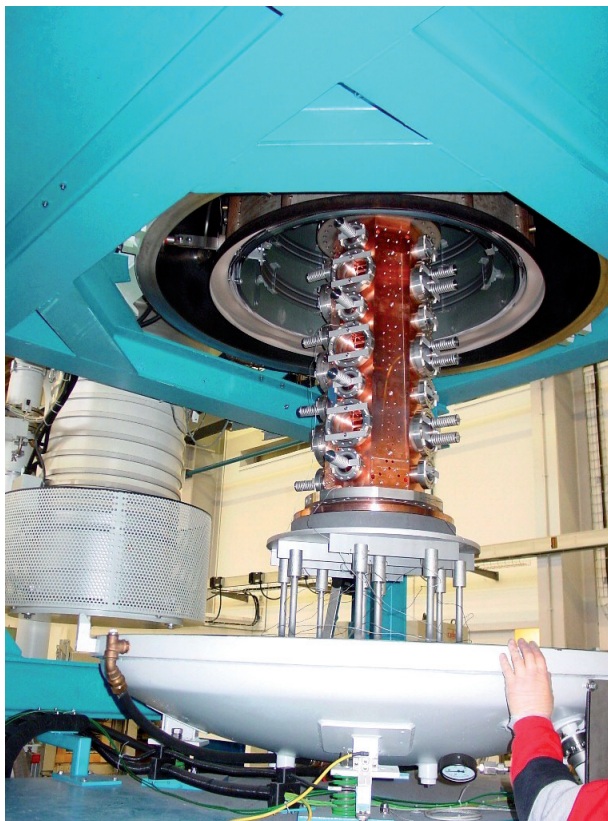
The cavity is composed of six sections, each about one metre long. Each unique section is machined in four

parts known as electrodes. The modulated profile of these electrodes requires a precision of ± 20 micrometres. Longitudinal cooling channels are drilled along one metre; they must be positioned with a precision of ± 0.2 mm.

The material selected is an ultra-pure, oxygen-free copper, hot forged in three dimensions then stabilized by a thermal cycle. After the roughing phase, each electrode undergoes a new thermal cycle in a vacuum



View of the 1st section of the radiofrequency quadrupole accelerator installed on its support structure.



View of the 2nd section of the radiofrequency quadrupole entering the brazing oven at Cern.

at 600 °C, aimed at relieving the mechanical stress caused by the milling tool. As a result of these treatments, the material is extremely ductile and thus very difficult to machine. Following the final machining stage, the four electrodes are assembled by an initial brazing at 800 °C in a vacuum oven. A second brazing stage assembles all the appendages necessary for operation.

After construction of a functional validation prototype, production of the sections began in 2004 and will be completed in 2007. Mécachrome is in charge of the machining, and assembly is being carried out by the Cern brazing shop.

Radiofrequency tuning of the RFQ

To accelerate the beam nominally, RFQ radiofrequency must also be adjusted with a very high degree of precision. This involves inserting into the cavity 96 copper cylinders called pistons, the measurements of which must be adjusted individually to comply with the electric field law calculations. Under no circumstances can this tuning be performed in an empirical manner. A fullscale aluminium mockup of the cavity was constructed to study and develop tuning procedures. In 2006, these procedures were validated on the mockup, which was successfully adjusted with the required precision. In 2007, these procedures will be applied to the copper cavity following assembly and alignment of the six sections on their base.

Installation at the Saclay site

The installation of Iphi at the Saclay site, in the halls formally occupied by the Saturne accelerator, began in 2003 with the assembly of the proton source and the biological protection system; installation will be completed in 2007. Testing of the cooling system and the RF power generator is scheduled to begin during the first quarter of 2007. Critical activities in 2007 will include the brazing of the RFQ sections carried out at Cern, as well as the assembly and radiofrequency tuning of the cavity.

The Saclay tests will involve three phases lasting around one year. A period of eight months will be spent on commissioning and ramp-up to Iphi's nominal performance levels. The next two to three months will be dedicated to reliability tests at reduced intensity levels as part of the European programme Eurotrans. During a third period, the chopper system developed at Cern for rapid beam chopping will be installed and tested. Following these tests, planned for 2007-2008, part of Iphi will be disassembled, transferred to Cern and eventually integrated into the injector for Linac 4/SPL (Superconducting Proton Linac).



Overall view of the diagnostics line during assembly. From left to right: A triplet of quadrupoles, a dipole for guiding particles based on their energy, and two quadrupoles at the end of the line.

Ifmif accelerator complex

In 2006, the Iter project was officially launched and France was selected as the location for this experimental controlled fusion reactor, to be built at the CEA's Cadarache site. Iter is part of a vast research and development programme aimed at constructing and operating an electric generating unit by 2050. An intermediary step is planned with the construction and testing of the demonstrator known as Demo by 2040. Fusion reactors use energy from neutrons produced by fusion reactions. The neutron flux planned for Demo will be so intense that each atom in the reactor's structural materials will undergo several displacements during its lifetime. Such neutron flux seems incompatible with currently used materials, in terms of mechanical resistance. It is therefore crucial to develop, test and validate new alloys capable of resisting such flux while maintaining the necessary properties. This is the goal of the International Fusion Materials Irradiation Facility (Ifmif), currently in the planning stages.

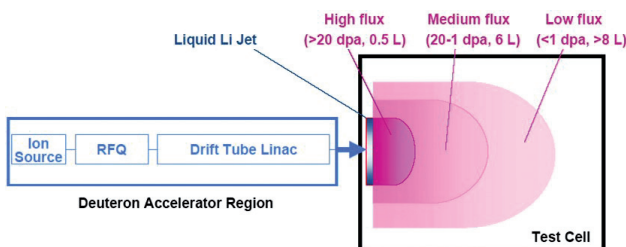


Diagram of the Ifmif station designed for irradiation testing of materials.

The Ifmif project is aimed at building an enormous testing station in which an intense beam of deuterons would interact with a lithium target in order to produce a 14-MeV neutron flux capable of provoking more than 20 displacements per atom and per year in a 0.5-litre sample. The intense deuteron beam this entails (250 mA of D^+ at 40 MeV) would be produced by two linear accelerators working in parallel. This type of accelerator has never been built.

A prototype phase known as Eveda (Engineering Validation and Engineering Design Activity) must be completed prior to the construction of Ifmif. During this phase, an accelerator – with a 125-mA source of deuterons, a RFQ (radiofrequency quadrupole) accelerating cavity, a drift tube linac (DTL) and a beam stopper – will be built, assembled and tested.

Eveda responsibilities will be shared by Europe and Japan, as defined in 2006 during negotiations on a so-called "broader approach" to Iter. The Ifmif-Eveda programme will take place over six years. Accelerator subsystems will be built jointly by Italy, Spain and France. The system will be assembled and tested in Japan at the Rokkasho site.

In France, Dapnia and SACM teams are in charge of coordinating the accelerator group, which involves an international team at the Saclay site. They will also oversee the construction of several subsystems, in particular the injector and the DTL.

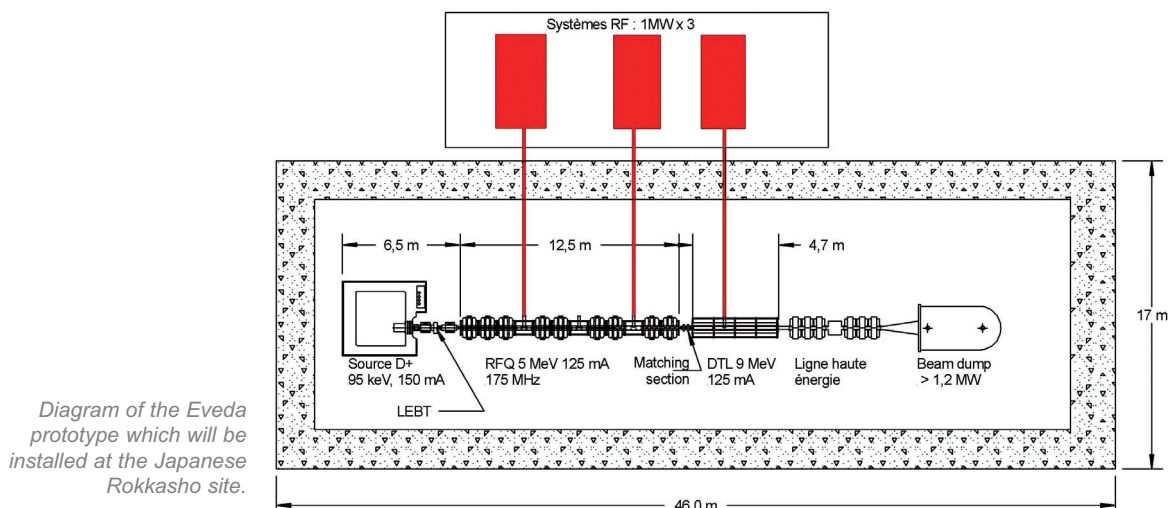


Diagram of the Eveda prototype which will be installed at the Japanese Rokkasho site.

Spiral 2

The Spiral 2 project aims to produce rare isotope beams at ultra-high intensities, using the best method of production for each radioactive beam. Unstable beams will be produced by means of isotope separation on-line (Isol) via a uranium carbide converter or by direct irradiation of fissile material. The combination of these various techniques will cover broad regions of the nuclear chart far from the valley of stability. In addition to its primary role in fundamental nuclear physics research, Spiral 2 may also serve as a multidisciplinary high-performance tool for scientific areas requiring very intense neutron flux, such as materials science and atomic, solid-state and plasma physics.

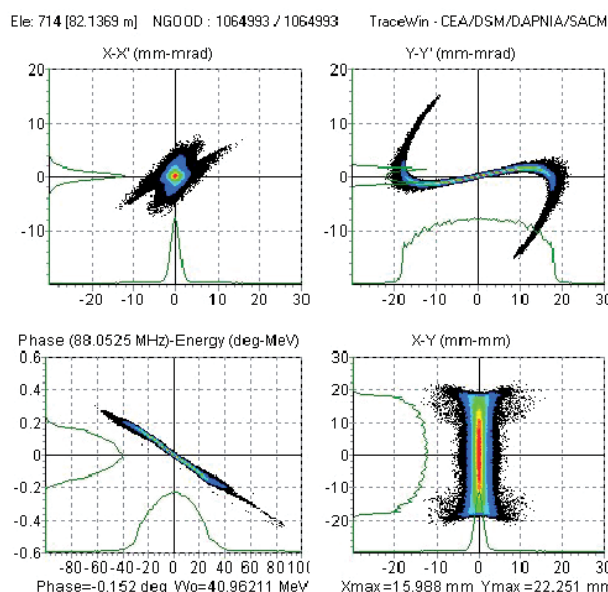
Based on experimental requirements, the specifications for the primary accelerator are as follows:

The primary accelerator must deliver deuterons and protons with beam currents up to 5 mA, and heavy ions with beam currents up to 1 mA. It must be optimized for heavy ions with a charge-to-mass ratio (q/A) of $1/3$.

The machine must offer adaptability for eventually accelerating heavy ions with a q/A of $1/6$.

The energy of each beam must be adjustable from 750 keV/n (kilo-electron volts per nucleon) to 33 MeV/n for protons, 20 MeV/n for deuterons, 14.5 MeV/n for heavy ions with a q/A ratio of $1/3$, and 9 MeV/n for heavy ions with a q/A ratio of $1/6$.

A fast chopper makes it possible to select beam structure (1 bunch out of 100 to 1 bunch out of 10,000).



Simulation of a deuteron beam in the phase space (position, momentum) relative to the uranium carbide target.



Quarter-wave superconducting cavity in its helium vessel.

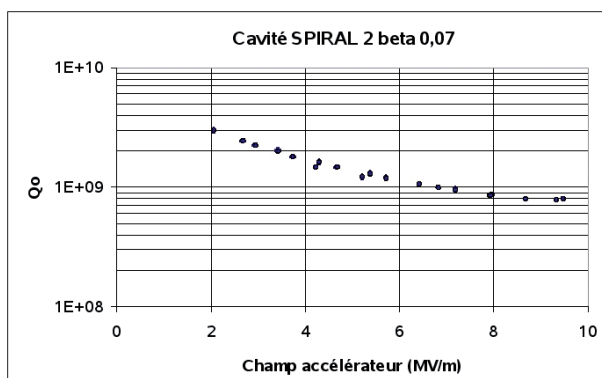
During the general design phase, Ganil consulted with SACM for a feasibility study of the primary accelerator. This led to a detailed design phase (APD) beginning in 2003 and lasting two years. The APD was funded by the CEA, the CNRS and the region of Basse Normandie. A SACM member oversaw project management for this phase. The department was also in charge of:

- Design studies for the machine
- Construction of a prototype of a quarter-wave cavity optimized for accelerating ions at 0.07 times the speed of light in vacuum, which was successfully tested.
- Construction of a deuteron source meeting the accelerator's specifications.

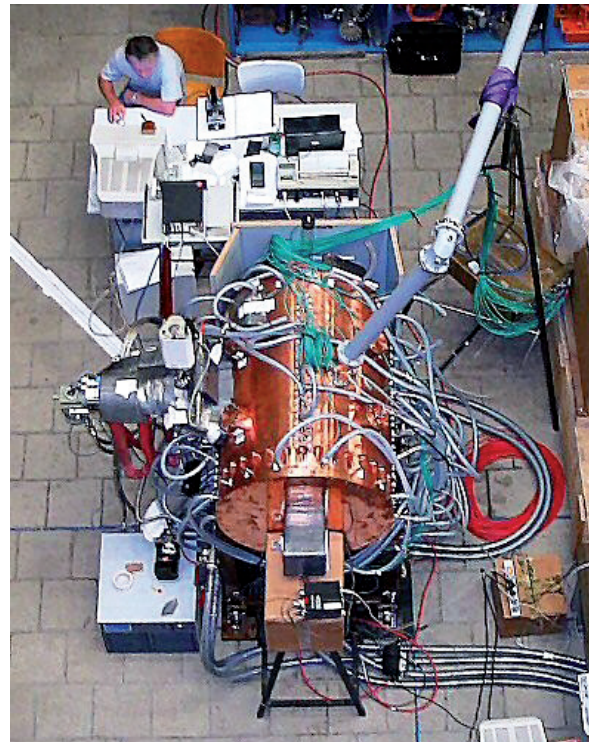
- Design of the RFQ (radiofrequency quadrupole) cavity and construction of a 1-m prototype, which was tested at up to the nominal power of 40 kW.
- Feasibility study on superconducting solenoids.

The design team included members of eight different laboratories, representing the work of 60 people. Their efforts resulted in the definition of a detailed architecture for the primary accelerator as well as initial work on a study of the secondary lines.

Following the design phase, the project entered a transition phase to allow further work on several ongoing actions, such as the validation of the RFQ cooling and vacuum system using new tests, or the cryomodule study for the superconducting cavities, as well as further work on the architecture for the transport of low-energy ions following separation.

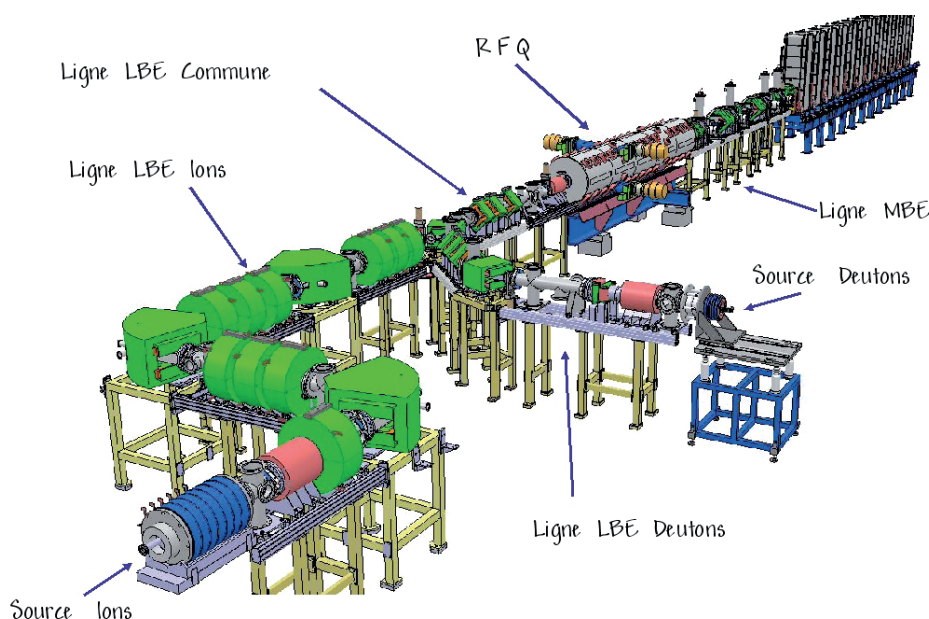


Changes in the quality factor for the quarter-wave superconducting cavity prototype versus the accelerating field.



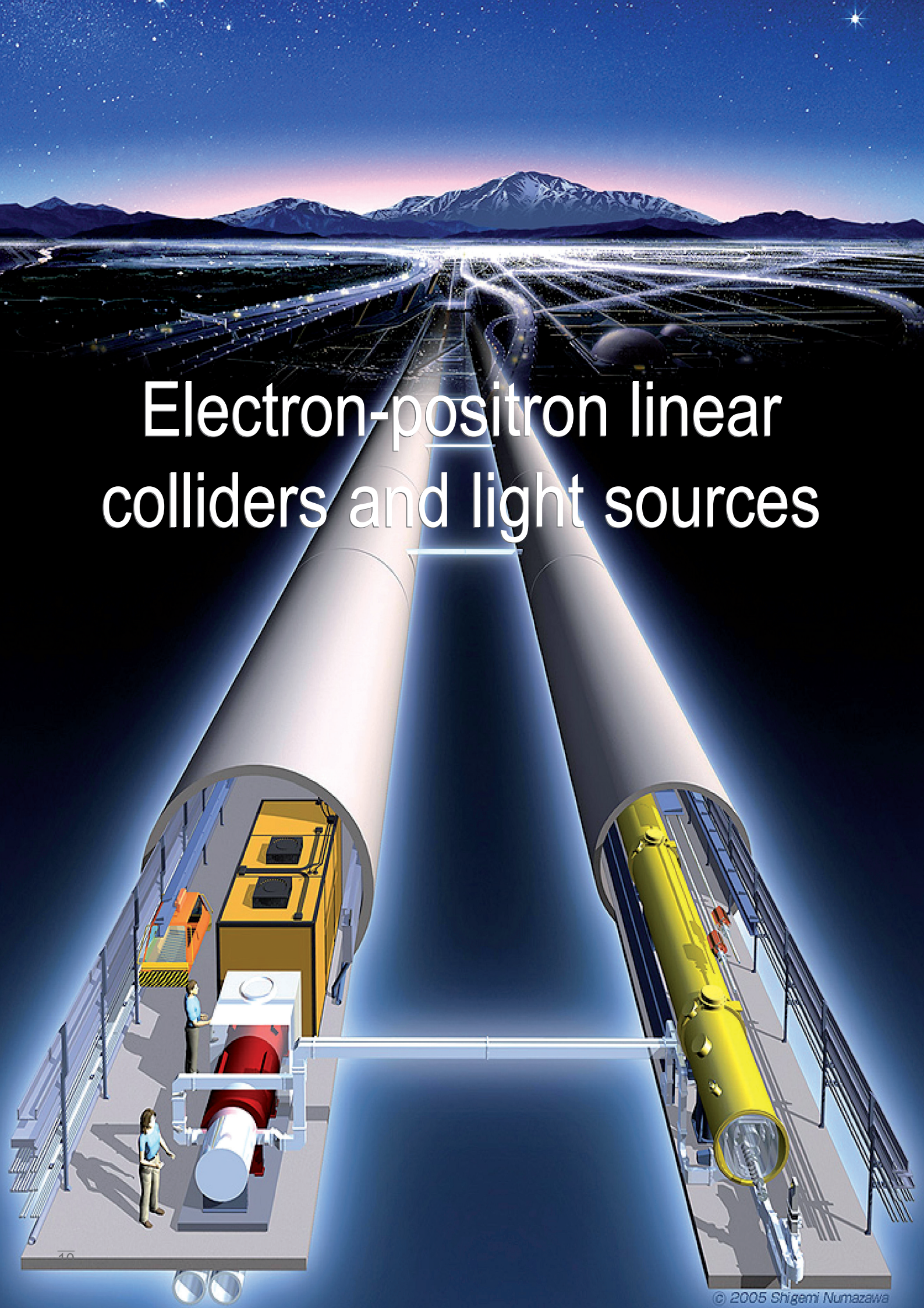
Full-power test of the RFQ accelerating cavity prototype.

In 2005, the project entered the implementation phase. SACM continues its efforts by playing an important role in RFQ construction, and by supplying 12 cryostats, each having a superconducting cavity equipped with its own tuning system and a 5-mA source of protons and deuterons. SACM also acts as the scientific coordinator for the injector project and offers its expertise in the area of beam dynamics.



Architecture of the primary accelerator.
MBE: mean beam energy
LBE: low beam energy
RFQ: radiofrequency quadrupole

Electron-positron linear colliders and light sources



Cryomodules for synchrotron light sources

SACM's work on synchrotron light sources involves the two accelerating cryomodules for Soleil, which has 352-MHz cavities, and the two Super-3HC (third harmonic superconducting passive cavities) cryomodules, whose cavities function at 1.5 GHz. The Soleil cavities, equipped with power couplers, accelerate the beam circulating in the storage ring to compensate for the energy lost at each revolution in the form of synchrotron radiation. The Super-3HC cavities are passive, and it is the electron beam itself that provides them with the electromagnetic energy necessary to eliminate certain beam instabilities, and to lengthen the electron bunches in order to increase beam lifetime. The technology for the two types of cryomodules is based on a radiofrequency structure developed by Alban Mosnier in 1992 for very high current electron sources, B factories, and synchrotron radiation facilities.

Soleil cryomodules

A cryomodule prototype was built in 1999 during the Soleil detailed design phase (APD) in collaboration with Cern. In 2004, changes were implemented by SACM, in collaboration with Soleil and Cern, to make this prototype operational with the Soleil ring: complete disassembly of the cryomodule, cleaning and tests of the superconducting cavities in a vertical cryostat to check that their performance had not been degraded by all the operations carried out during the APD phase, complete reassembly of the cryomodule, and RF validation tests at full power in the Cern bunker.

The tests which took place in early 2005 validated the upgraded cryomodule prototype as being operational with the Soleil ring: reduced static cryogenic consumption (50 W) and enhanced thermal stability of the assembly, very good rejection of the fundamental mode by the dipolar high-order mode couplers, an accelerating field in the cavities ($E_{\text{max}} > 11$ MV/m) and maximum power that is supported by the RF couplers (180 kW in reflection mode). Following these validation tests, the cryomodule was installed at the Soleil ring facility in December 2005. Its cooling at 4 K took place a few months later, in May 2006. In June, the first beam acceleration in the storage ring was performed. During the commissioning phase which followed, the current was rapidly increased to its maximum value of 300 mA, which corresponds to the nominal operating level.

For the second cryomodule, to be identical to the first, Soleil is in charge of project management and the German industry group Accel has been awarded the construction contract, which was signed in October 2005, with a delivery planned for mid-2007. SACM's role is limited to a few specific services and expert studies.



Assembly of HOM (high-order mode) couplers on Soleil cavities in Cern's cleanroom.

Super-3HC cryomodules

Since their 2002 installation on the SLS rings (Swiss Light Source at the Paul Scherrer Institute) and at the Elettra site (near Trieste in Italy), the two cryomodules for Super-3HC have been in regular operation. They have even become a key element in the operation of these facilities, particularly Elettra. Certain maintenance operations are carried out on a regular basis, around every 18 months, to replace the tuning system gearboxes, subject to intense wear at Elettra while they can remain immobile at SLS.

A request for the industrial transfer of this cryomodule has been made by Accel. Likewise, certain facilities have shown interest in this cryomodule and the possibility of installing it on their rings.

ILC collider and XFEL light source, based on superconducting accelerator technology

ILC (International Linear Collider) is a project to build an electron-positron collider for particle physics research that attains energies on the order of a tera-electron volt. The participating laboratories decided to use high-gradient superconducting radiofrequency acceleration (25 MV/m and higher) in 2004, which was developed through the Tesla Collaboration and adjusted on the Flash accelerator (e.g. TTF) at the Desy laboratory (Deutsches elektronen synchrotron) in Germany. This technology has a double objective: 1) to check the performance of the various components and realistically estimate the costs of a collider 30 kilometres in length; and 2) to demonstrate the feasibility of a free-electron laser operating in self-amplifying spontaneous emission mode (Sase) in the ultraviolet range. The second objective has laid the groundwork for XFEL (X-ray Free-Electron Laser), a European project to build a 4th-generation X-ray source.



Artist's rendering of the ILC tunnels:
Klystron gallery on the left, accelerating
cryomodules on the right (courtesy of KEK).

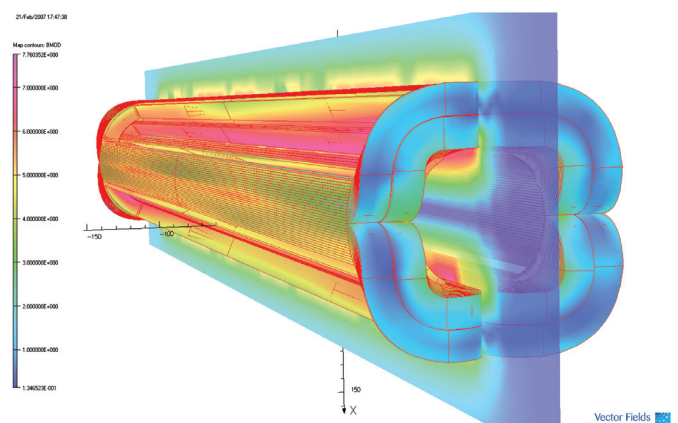
ILC collider

The ILC project is based on linear accelerators with superconducting cavities made of solid niobium with accelerating fields of 31 MV/m or more. Attaining luminosities of $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ requires beam sizes of 6 nm vertically at the collision point and power levels on the order of 11 MW per beam. The collisions involve roughly 3000 bunches per beam-pulse with a radiofrequency (RF) pulse of 1 ms. The RF pulse duration, enabled by superconducting technology, makes it possible to use a fast feedback method (3 MHz) to control the orbit of each bunch at the interaction point,

thereby relieving the alignment and vibration tolerances of the accelerating and focalizing elements.

As part of the international GDE (Global Design Effort) and the European EuroTeV project (Sixth Framework Programme for Research and Development, FP6), we are working on the design of high-energy beam focusing lines and on that of the interaction region. Three research themes are worth noting:

- ▶ Automatic optimisation of the final focus optical system, including local correction at the final doublet of chromatic aberrations.
- ▶ Study of collision stability for a zero-crossing angle in an interaction region including the large-aperture superconducting focusing magnets developed at SACM.
- ▶ Design and magnetic modelling of the solenoid for the LCD (Large Detector Concept) facilities being developed by European particle physics laboratories.

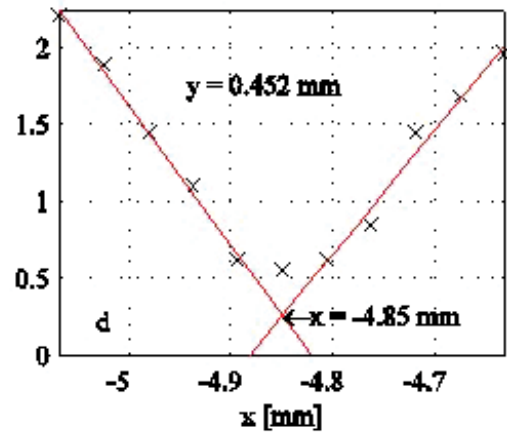


Magnetic model of the final
focus quadrupole.

Flash, a superconducting linear accelerator

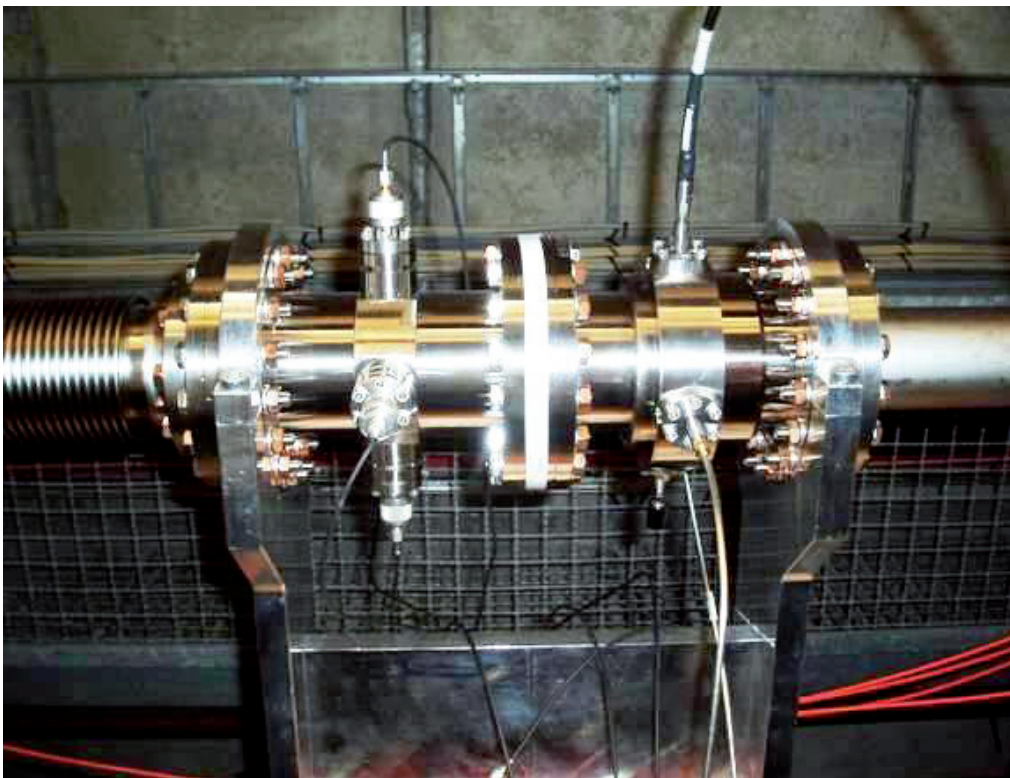
In addition to its 40 high-gradient superconducting accelerator cavities, with total energy on a giga-electron volt scale, the linear electron accelerator Flash enables developing instrumentation and beam diagnostics for the future XFEL and ILC facilities. SACM is involved in the facility's protection system, which uses fast electronics for comparing beam current measurements at various points along the linac. The department also sets up beam position monitors, which use two novel and complementary techniques:

- ▶ Reentry RF cavities adapted to the ultra-clean and cryogenic environment of a Flash cryomodule and targeting micrometric resolution for control of the beam orbit in the quadrupoles.
- ▶ Use of high-order modes (HOM) in the accelerating cavities to improve cavity alignment relative to the beam and to minimise the effect of wake fields.



Beam alignment by minimising the high order mode signal in the first Flash cavity.

SACM also designed a cold RF tuning system for radio-frequency (1.3 GHz) in the accelerating cavities which includes a fast piezoelectric regulation system to compensate for radiation pressure forces. These developments were made possible by the financial support of the Care-SRF (Coordinated accelerator research in Europe – Superconducting radiofrequency technology) programme (FP6).



Position monitor for reentry RF cavities on the Flash beamline.

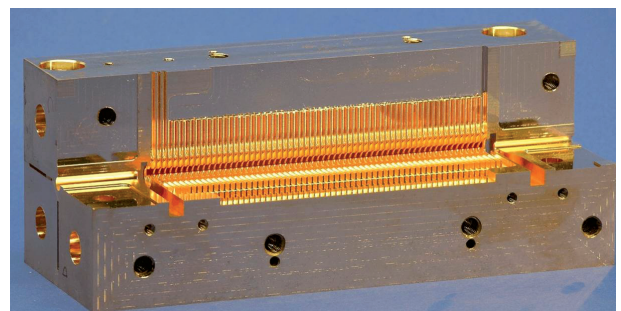
Califes accelerator at the CTF3 facility

Cern, as part of its compact linear collider project (Clic), has initiated a new research and development programme centred on CTF3 (Clic Test Facility 3), which is aimed to validate the concepts allowing to reach energies between 1 to 3 TeV with an accelerator length about 30 km. Technological feasibility is to be demonstrated by 2010, when the first LHC results will lead the physicists to decide what energy range is the most promising for their future works. To achieve this challenging program, Cern sought a large international collaboration including to this date more than 15 laboratories and scientific institutes. Dapnia, in collaboration with the LAL (Linear Accelerator Laboratory from Orsay), is to deliver a linear accelerator known as Califes (Concept d'Accélérateur Linéaire pour Faisceau d'Electrons Sonde) aimed to inject electron bunches into the high gradient accelerating structures (100 MV/m) foreseen for the Clic.

Such a high accelerating gradient prevents the use of superconducting structures and consequently requires an extremely high radiofrequency power (several 100s' of MW peak per structure). Following numerous optimisations, the 12 GHz frequency is now retained. This RF power is obtained from a first electron beam of 150 MeV bunched at 3 GHz whose bunch trains are recombined by 2 rings in order to increase the mean current from 3.5 to 28 Amps and are then decelerated in special structures that provide the 12 GHz RF power to the second beam. The validation of this complex gymnastic is one of the two main objectives of CTF3.

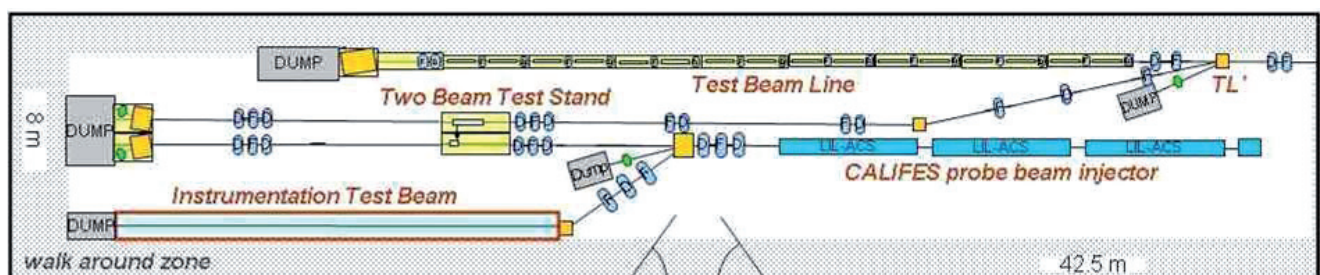
The second objective is to optimise accelerating structure to lower the breakdown rate down to 10^{-6} for a mean field of 100 MV/m during 100 ns. These structures are already under experimentation but up to now without electron beam. The investigation of how the beam is deviated by this structures during breakdown requires to inject electron bunches with accurate characteristics.

In order to meet the required parameters of this 200 MeV probe beam, in terms of emittance, energy spread and bunch-length, the most advanced techniques have been considered: laser triggered photo-injector, velocity bunching, RF pulse compression and power phase shifter. A complete diagnostics set (beam current and position monitor, beam profiler, deflecting cavity, analysis dipole...) has been used in order to check the beam before final use.



High-gradient accelerating structure (courtesy of Cern).

Dapnia has been involved from the beginning of this project, taking into consideration the Cern specifications, proposing a set-up validated by beam dynamics simulations, recovering equipments when available, studying and realizing new equipments and seeking collaboration in Saclay when its expertise was not sufficient (laser pulse processing). Today, the installation phase has started in the new Clex building dedicated to the two beams experimentation. It will be followed by the commissioning in 2008, meanwhile is already explored a continuation of the Dapnia activities within CTF3, like participation to the high gradient accelerating structures developments and specific instrumentation.



Setting up of Califes accelerator in the new Clex building.



Developments for particle accelerators

Developing ion sources

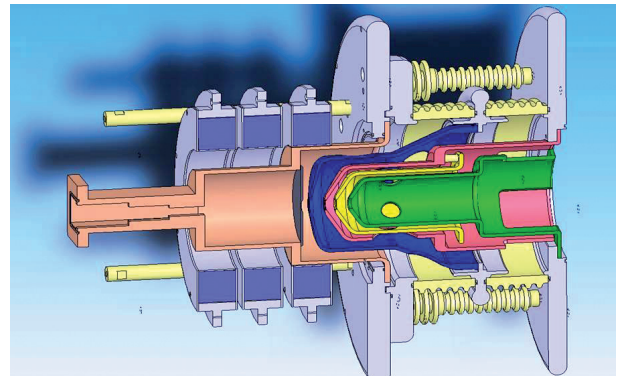
SACM is one of the world's leading laboratories for the intense production of light ions, in demand for tomorrow's high-current accelerators. The beams are generated from ion sources and have energy levels of several dozen keV; they can reach power levels on the order of 10 kW. With the results obtained from the Silhi source, SACM will build deuteron (D^+) sources to equip the Spiral 2 and Ifmif accelerators.

The Silhi source, developed as part of the Iphi project, has demonstrated the efficiency of electron cyclotron resonance (ECR) sources in producing intense proton (H^+) beams. Recent measurements – obtained in collaboration with GSI, the heavy ion research centre in Germany, and the University of Frankfurt – have confirmed the qualities of beams extracted in pulsed mode.

The difficulty of low-energy transport results from variation in space charge compensation along the line. This problem was the subject of an initial study and a thesis at SACM. Further work is necessary to ensure that the beam extracted from the Ifmif source meets the required conditions.

A new source with permanent magnets providing the axial magnetic field was developed for the Spiral 2 project. This source is capable of producing a continuous 5-mA beam of D^+ at 40 keV, while at the same time maintaining reliability, emittance and parameter flexibility. Moreover, a slight modification has made it possible to attain a total intensity of over 100 mA at an energy level of 95 keV, by injecting hydrogen gas in the plasma chamber. Finally, work should begin very soon at SACM on the construction and testing of the final Spiral 2 source.

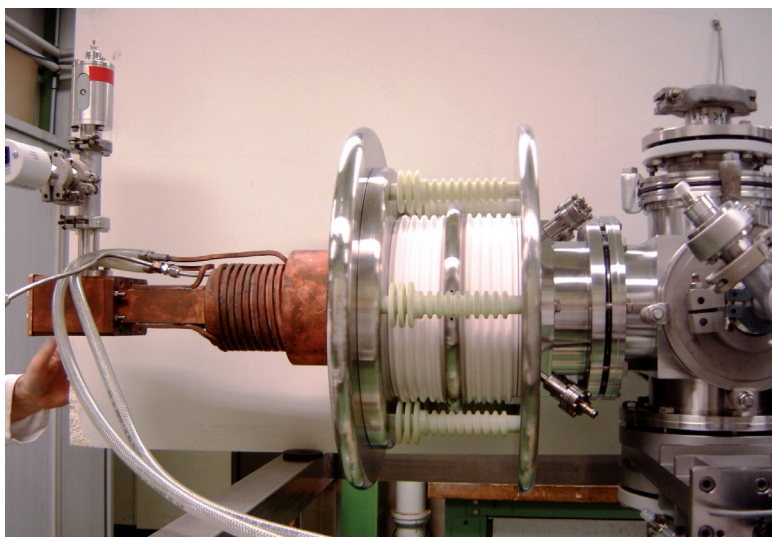
In parallel, the negative ion source (H^-) study continued until December 2005, as part of a European network sponsored by the Fifth Framework Programme for



Cross-section of a permanent magnet source with its system for extracting deuteron beams. From left to right, radiofrequency waveguide, plasma chamber and extraction electrodes.

Research and Development (FP5) which SACM coordinated. For the moment, the results obtained with the ECR source are modest but encouraging: an intensity above 4.5 mA in pulsed mode has been obtained. With a view to boosting performance, theoretical calculations have enabled defining a multipolar magnetic structure, which will be associated with a new plasma chamber.

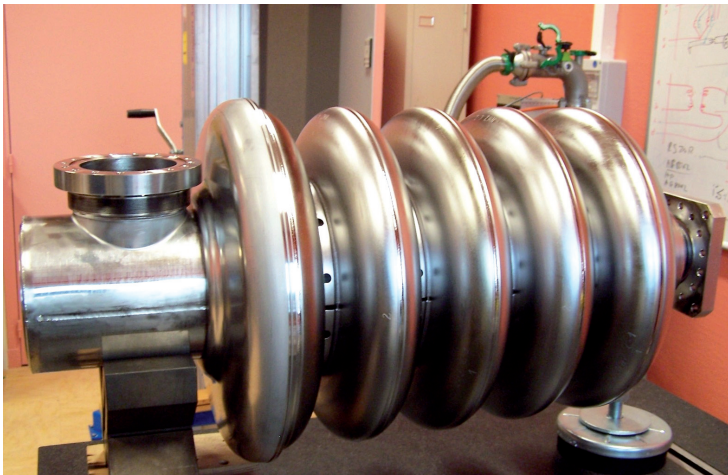
In order to extend and amplify these developments, a study and test bench for ion sources, Betsi, is currently being built. To characterise and optimise futures sources for Spiral 2 and Ifmif, it may be useful to equip these facilities with an instrumented line specifically for the analysis of low-energy beams.



Deuteron source attached to accelerating tube.

Development of superconducting accelerating structures

As part of the European Care (Coordinated accelerator research in Europe) programme, SACM is participating in a project centred on high-intensity pulsed proton injectors (Hippi). Through the research and development necessary for this type of accelerator, ten European institutes are coordinating their efforts to improve the major European installations at Cern in Geneva, the Rutherford Appleton Laboratory in the UK, and the GSI in Darmstadt. The goal is to increase proton and neutrino flux for future physics experiments.



700-MHz superconducting elliptical cavity. This type of cavity, with β equal to 0.5, is particularly well-suited to the energy range 100-200 MeV.

One of the major themes of this programme is the development of superconducting accelerator structures – particularly efficient for accelerating intense beams with a high-duty cycle – which operate in the 100-200 MeV range and attain gradients above 7 MV/m with quality factors on the order of 10^{10} .

SACM, a major player in this programme, is in charge of building and testing prototypes of superconducting cavities, and of developing and conditioning high-power couplers. It will also install and commission a test station with the horizontal cryostat Cryholab and a radiofrequency power source at 704 MHz with peak output of 1 MW.

Superconducting cavities at 704 MHz

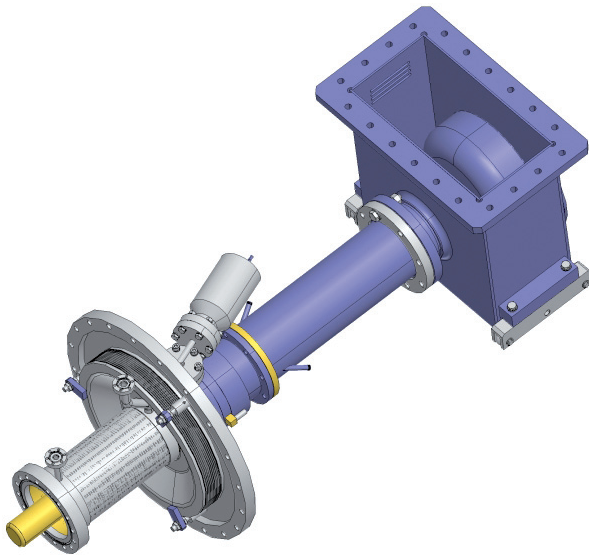
Several types of superconducting cavities exist; the choice depends on the particle to be accelerated and its energy. In the specific case of 100-200 MeV linacs, the proton velocity β is relativistic (comparable to the speed of light) and varies between 0.4 and 0.6. Elliptical cavities where β equals 0.5 are particularly well-suited to this energy range. However, their operation in pulsed mode can be rather complicated due to electromagnetic pressure forces that act on the walls, thereby modifying the frequency of the cavity. The higher the field level, the more pronounced this phenomenon, which can hinder proper beam acceleration.

In order to overcome this limitation, SACM has designed and built an elliptical superconducting cavity at 704 MHz with the capacity to attain high accelerating fields (after optimisation of surface fields and acceleration efficiency); a double stiffening-ring system makes it possible to control frequency variation at the same time.

Developing 704-MHz power couplers

To accelerate the proton beam (several tens of mA) using high fields (10-20 MV/m), each cavity must be supplied with radiofrequency power on the order of several hundred kilowatts. This is the role of power couplers.

SACM is developing a coupler capable of transmitting up to 1 MW to the cavity in pulsed mode, with an average value of 100 kW. A prototype of the alumina window, which separates the ultra-high vacuum of the cavity from the surrounding air while at the same time allowing for high-frequency matching, has been built. It has undergone testing at low-power levels to verify its high-frequency characteristics. Two complete couplers are currently being built.



Pulsed power coupler (1 MW) for superconducting proton linacs. The main components of the coupler are, from right to left in the diagram, the transition between the waveguide and the coaxial, the window, and the cooled connection to the cavity.

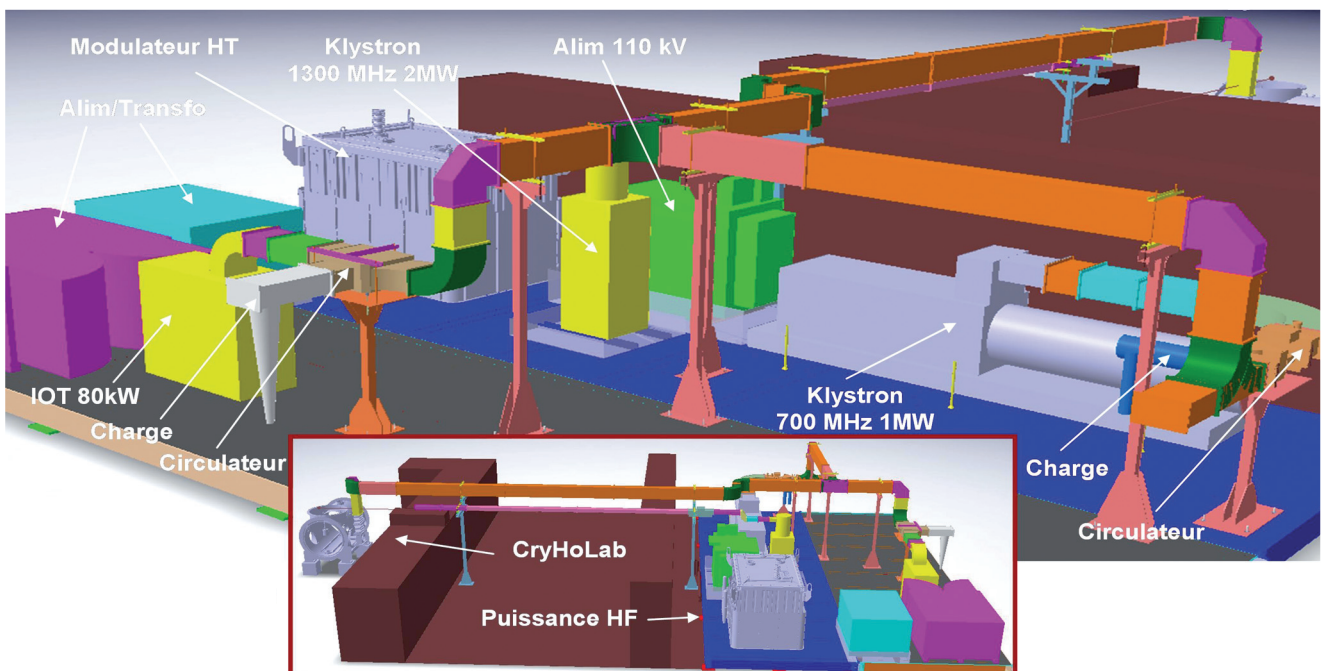


Window of the power coupler (1 MW). The alumina window separates the ultra-high vacuum of the cavity from the surrounding air.

Coupler test bench

In order to test all components, SACM will acquire a high-power test bench at 704 MHz supplying more than 1 MW in pulsed mode. The bench includes a 110-kV power supply, a modulator generating 2-ms pulses at 50 Hz, and of course the klystron which generates the radiofrequency power. The klystron output can be connected via a network of waveguides to a test bench and to Cryoholab, the test cryostat. This allows for studies on power couplers, for their conditioning, and for conducting cavity tests in an environment comparable to that of an accelerator.

SACM's high-frequency high-power installation including benches at 704 MHz and 1300 MHz.



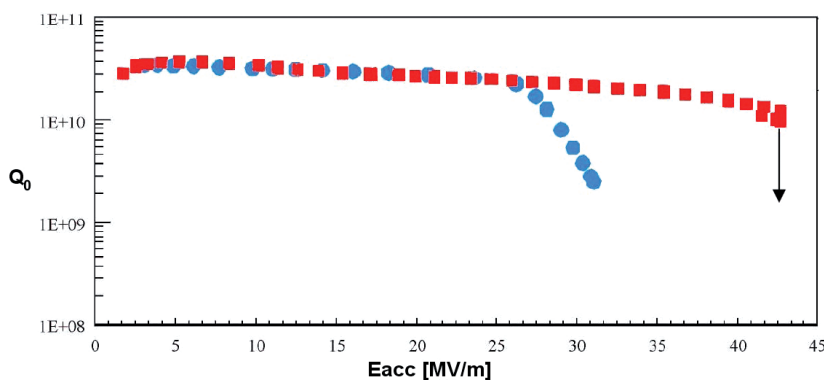
R&D in radiofrequency superconductivity

Reducing the length and thus the cost of the superconducting linear accelerator ILC (International Linear Collider) will require building accelerating structures (nine-cell radiofrequency cavities) one metre in length and capable of reaching acceleration fields of 35 or even 40 MV/m. It is already possible to achieve this with bulk niobium cavities, if they first undergo an electrochemical surface treatment as well as moderate baking at 120 °C for 48 hours. However, the electrochemical results are not sufficiently reliable and reproducible; as for baking, it is not optimized for the industrial production of 20,000 cavities. The R&D on high accelerating gradients at Saclay is aimed at finding solutions to these problems by optimizing electropolishing parameters and developing a more efficient baking process.

Electropolishing study

Initial electrochemical research on niobium samples focused on developing better acid mixtures; at the same time, an effort was made to dilute the acids as much as possible for safety reasons. The studies also examined the solid and gas residues (sulphur and hydrogen respectively) generated during the treatment. The presence of these elements in niobium or at its surface hinders cavity performance. Solutions have been found;

rinsing with alcohol, for example, dissolves the sulphur. During 2006, an electropolishing bench for single-cell cavities was built and commissioned. A first cavity was electropolished in late October 2006 and reached a field of 43 MV/m after baking. Using this electropolishing bench, the new outcomes performed on samples can be validated on the cavities.



Performance data for the first niobium cavity electropolished at SACM. Changes in the cavity quality factor Q based on the accelerating field: before (blue curve) and after (red curve) ultra-high vacuum baking of the cavity at 120 °C for 48 hours.

Horizontal electropolishing system for superconducting niobium cavities.





Infrared lamps for rapid baking.

Improving the baking process

Baking is the final step for reducing quality factor degradation and for obtaining higher accelerating fields.

The treatment consists of maintaining the cavity at an ultra-high vacuum and a temperature of 120 °C for a period of 48 hours. For mass producing the cavities, the baking time is too long and the ultra-high vacuum

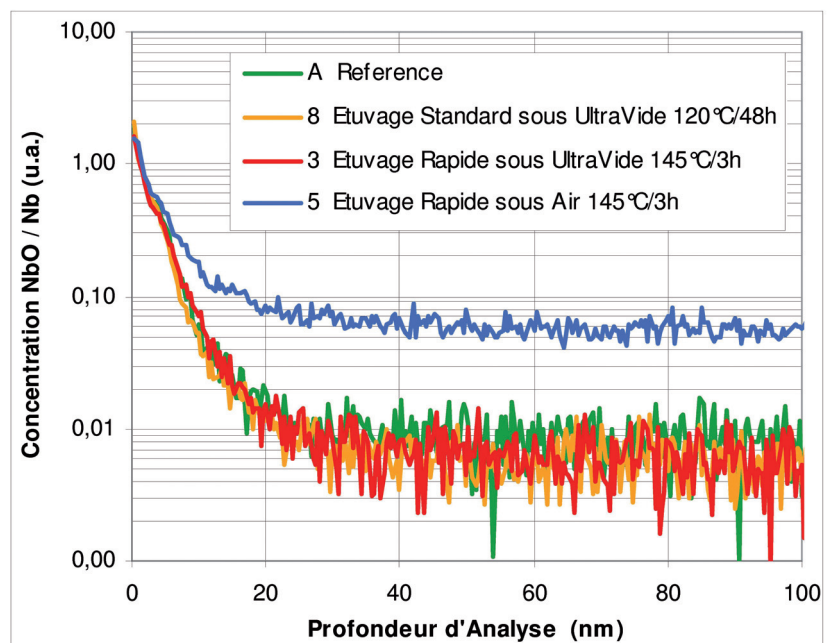
conditioning makes the procedure too complicated. An equivalent baking process was developed with infrared lamps which also uses ultra-high vacuum but takes less time (3 hours at 145 °C).

Researchers are currently studying operating conditions which would allow baking under atmospheric pressure in ambient air or inert gas (argon).

Surface analyses

Baking modifies the characteristics of the superconductor in ways which are not yet fully understood. Since the discovery of this phenomenon, a distribution of interstitial oxygen at the metal-oxide interface has often been proposed as a possible cause. However, the surface analyses conducted by our laboratory using the secondary ion mass spectrometry method (Sims) on niobium samples showed no significant distribution of interstitial oxygen. To explain the physical baking phenomenon, other hypotheses have also been proposed, e.g. vacancy filling at the oxide-metal interface. These new hypotheses will be experimentally checked and ultimately validated in the near future.

Penetration profile of the interstitial oxygen as determined by Sims (secondary ion mass spectrometry). The niobium oxide (Nb_2O_5) film at the surface has a depth of 4 nm.



Particle beam dynamics

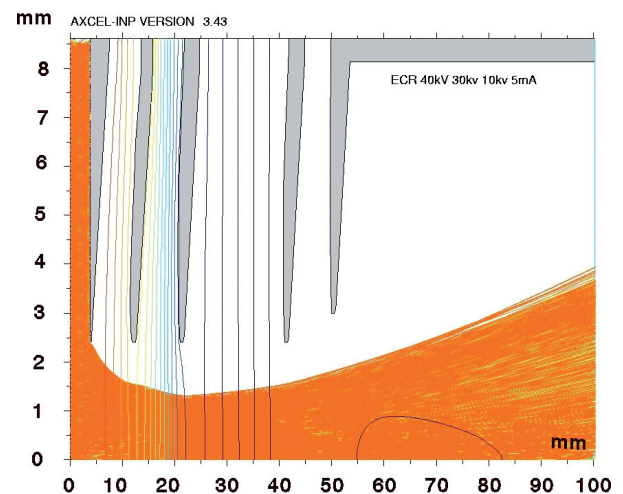
Beam dynamics may be defined as the study of charged particle motion in static or time-dependent electromagnetic fields. These fields may be external or generated by the particle distribution. For electrons, the effective synchrotron radiation must be considered. There are various problems to overcome in accurately modelling beam dynamics; examples at the fundamental level include interaction with the residual gas, interaction with solid interfaces, the dynamics of ion source plasmas, and beam optics in the presence of high-order electromagnetic elements (hexapoles, octupoles). Then there is the challenge of dealing with halo formation and beam losses for the maintenance of future high-power accelerators. One may also cite cost optimisation for accelerator systems. To meet these challenges, analytical models must be developed, as well as computer codes and numerical methods that make the fullest use of IT resources, such as distributed cluster computing.

Beam simulation in electron cyclotron resonance sources

The emergence of several projects over the last 10 years has prompted the CEA and the CNRS to form a partnership around high-current accelerators, focused specifically on developing a low-energy demonstrator: the high-intensity proton injector Iphi. The projects that led to this collaboration include Spiral 2 at Ganil, Ifmif which requires deuteron beams, the Fair project at GSI, and hybrid reactors in need of protons. Other projects – such as SPL at Cern, the proton driver at Fermilab, or spallation sources – require negative hydrogen ions, which are later injected into the compression rings.

All these machines require a powerful and reliable source of ions, which Dapnia/SACM is capable of designing and building.

Modelling the extraction system involves calculating the plasma expansion meniscus, as well as beam generation, via a multi-electrode extraction system.



Axcel code simulation of the extraction of a 5-mA deuteron beam at 40 kV. In grey, cross-sections of the five electrodes; in orange, particle trajectories.

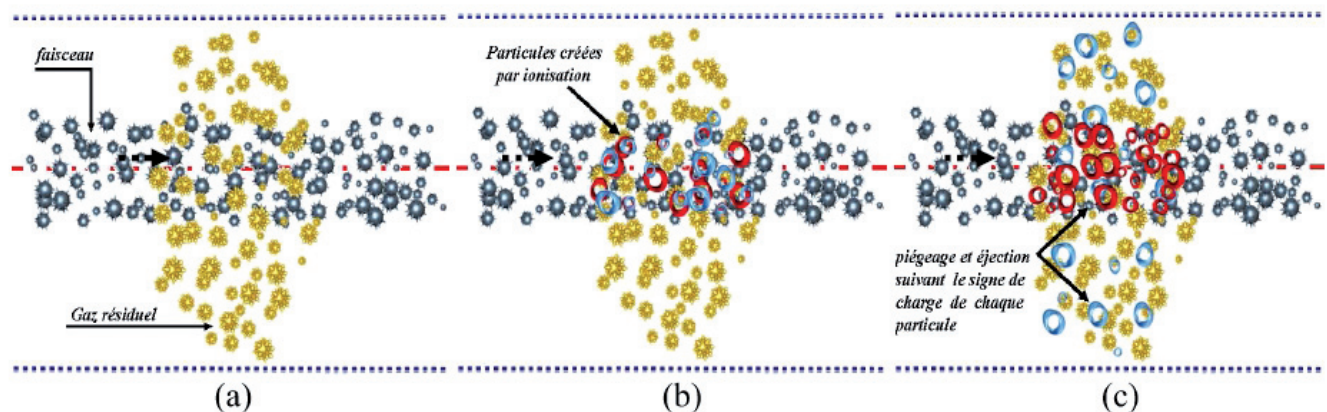


Diagram showing the process of space charge compensation.

Given that the quality of low-energy beams strongly influences accelerator design, it is important to continue work on sources and their extraction systems. A new computer code would provide a better understanding of plasma creation, and of the interaction between the radiofrequency wave and the plasma, which would in turn enable moving beyond certain hypotheses in the design of the machines.

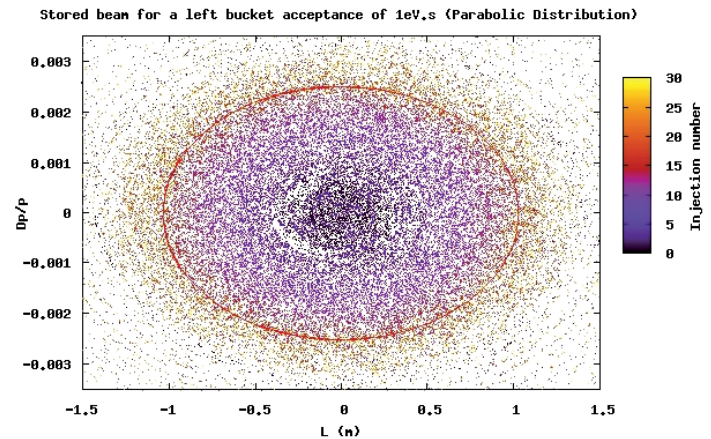
Particle transport in a low-energy line

Beyond the extraction zone, beam transport is simulated in the low-energy line using different codes developed at SACM, specifically for simulating mixed ion beams in the space charge regime or the space charge compensation regime.

Emittance in the low-energy part of an accelerator must be controlled because it plays a critical role in the machine's high-energy operation. In the case of high-current accelerators such as Iphi, after source extraction the beam must be guided so as to limit losses as well as any increase in emittance. The dynamics of these intense beams are dominated by nonlinear effects of the space charge field. The residual gas from the vacuum chamber ionises atoms as the beam passes through, thereby inducing partial space charge compensation. To achieve a more precise simulation and a better fit with experimental measurements on the Silhi source, specific research has been conducted as part of a SACM thesis. This has enhanced understanding of the physical phenomena involved in intense beam dynamics in the space charge compensation regime.

Beta-beam dynamics

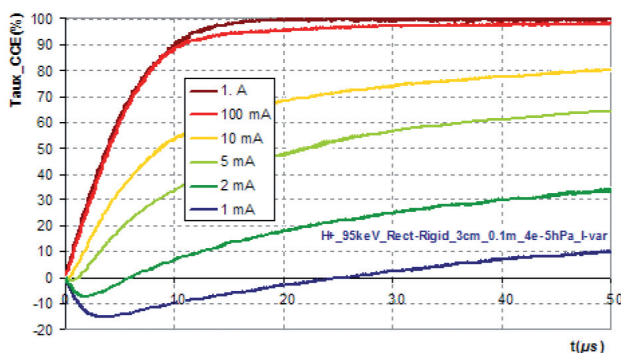
Understanding the properties of neutrinos is one of the current challenges in physics. Until now, physicists have used the sources available to them: neutrinos from space, or from nuclear power plants. Future studies will



Representation in space of the beam's energy-position phases after 30 injections. The most recent injections are in black, the oldest are in yellow. The oldest particles pushed beyond the limit (red ellipse in diagram) are no longer accepted by the machine. These ions must be collected before they collide with the walls of the vacuum chamber

require more intense neutrino beams which are better defined in terms of energy and "flavour". Beta-beams are one of the new sources envisaged for producing neutrino beams.

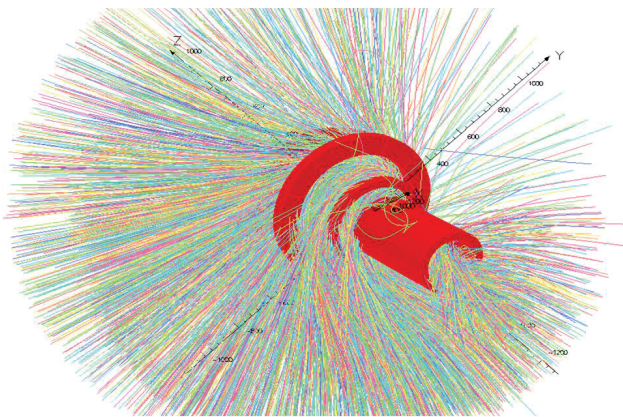
The studies are being conducted as part of the European project Eurisol, in collaboration with several laboratories including the CNRS, Cern and GSI. The aim is to use the beta radioactivity of He^6 and Ne^{18} nuclei as a source of neutrinos. Depending on the species, this produces electron neutrinos or antineutrinos with a known energy spectrum which is relatively narrow. Following acceleration, the radioactive beta nuclei are stored in a ring 7 km in circumference (to be defined by SACM) which includes two long straight sections aligned with the experimental site. During each revolution, a well-defined proportion of stored nuclei decay, emitting neutrinos in their direction of propagation. The decay occurring in one of the straight sections produces a short pulse of neutrinos directed towards the detector. As for the resulting nuclei, Li^6 or F^{18} , they are lost in the ring and constitute an activation source which must be controlled. To obtain the neutrino flux necessary for the experiments, a sufficient number of nuclei must accumulate in the decay ring and their disintegration must be compensated periodically by the injection of new nuclei. These processes also result in losses which must be controlled.



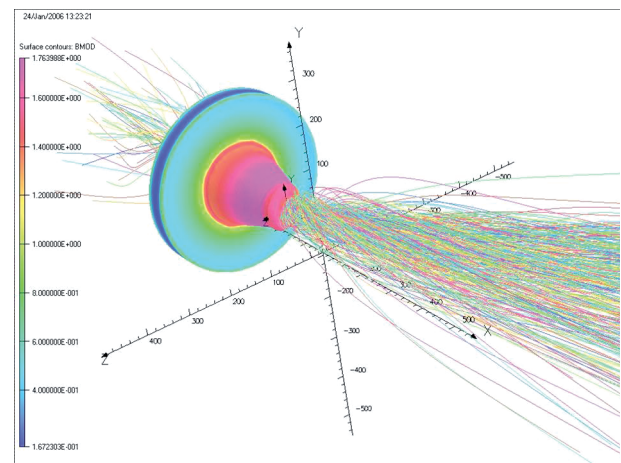
Changes over time in the level of space charge compensation for six different intensities of an H^+ beam.

Developing a source of positrons

As a technological extension of the fundamental antihydrogen R&D carried out by Dapnia's particle physics department (SPP), the Sophi project aims to build a source of high-intensity positrons. Positrons are produced when electrons interact with a tungsten target; they are then collected and guided by a magnetic system. The system's novelty comes from the low energy of the incident electrons, which produces a positron beam with strong dispersion in terms of energy and impulse. The difficulty lies in capturing these positrons and in separating them from the electrons, which are still 1000 times more numerous.



Electron flux after the tungsten target.



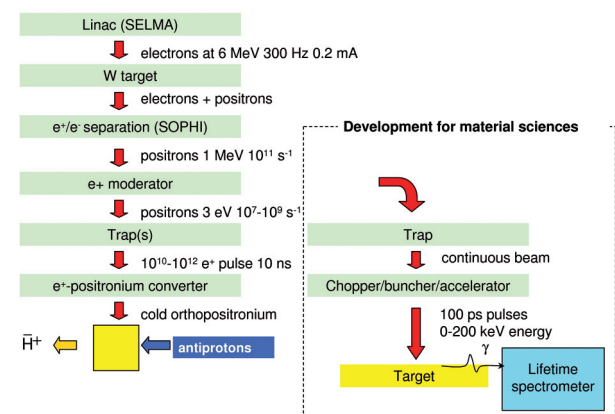
Positron flux after the target.

The ultimate goal of the antihydrogen experiment is to verify the sign and the intensity of 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 construction of the source, based on a concept patented by physicists Patrice Perez and André Rosowsky, was funded by the French National Research Agency in 2005, and completed in 2006 with funding from the Essonne General Council by the acquisition of a miniature electron linac, named Selma, with an energy level of 6 MeV.

In 2006, the design of the capture and magnetic separation system was optimized by integrating the linac's parameters. Implementation and safety studies have been conducted to prepare for installation in Building 126. In October 2007, Sophi and Selma will be installed in the hall previously occupied by the Saturne accelerator. These facilities will be used to demonstrate the feasibility of an intense source of positrons capable of filling the traps for the antihydrogen experiments at Cern.

In parallel, studies have been conducted in collaboration with the Cern-based teams of Professor André Rubbia to identify materials that can generate a high number of positroniums. Positrons are used in materials science as probes to characterise the size of point defects in crystal structures. The new source may ultimately be a replacement solution for sodium-22 sources, which currently supply positrons for materials science applications.



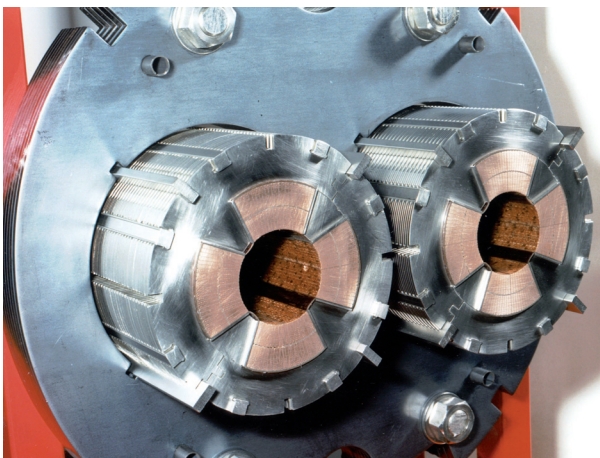
Experimental principles for making antihydrogen and for the materials science applications.



Superconducting electromagnets

Superconducting quadrupole magnets for the LHC

SACM has been commissioned to design the cold masses of the main quadrupole electromagnets of the Large Hadron Collider (LHC) as part of France's exceptional contribution to the construction of the machine. The main technological difficulties arise from the need for high mechanical precision to guarantee the 10^{-4} relative field homogeneity over the three metres of the magnet, with high electromagnetic burst forces of 4 times 110 tons per metre of the magnet. Moreover, the design must be suited to the industrial production of 400 units. After transferring its know-how to the manufacturer, SACM monitored the production of the magnets entrusted to the German company Accel, who delivered the last cold mass to Cern in the autumn of 2006.



The quadrupoles have a dual aperture configuration and are combined in the same magnetic and cryogenic structure. The main characteristics of the magnets are: a length of 3.2 m; an aperture of 56 mm; and a field strength gradient of 223 T/m.

A cold mass is a helium chamber containing three dual aperture magnets, a main quadrupole magnet and two compensating magnets. The main quadrupole magnet has two apertures in which the particles of each beam circulate.

For each of these apertures, four superconductor coils are braced in a stainless steel collar assembly which makes them integral. The major factor affecting the performance of the magnet is the care taken when winding the superconductor cable and collaring the coils. Although the coils are 3m in length and have an average radius of 4cm, the order of magnitude to assess their quality is around twenty microns. This dimension guarantees the quality of the magnetic field which will be used to focus the particle beam and ensures their mechanical stability.

Industrial production monitoring

The production monitoring phase was carried out by an SACM technician present on Accel's premises every other week and by two engineers. The team was organized so as to ensure an uninterrupted presence to enable its members to react quickly to the company's

requests. 4 cold masses were produced per week in the nominal production phase. Consequently, any breaks in the production process were very costly. The cold masses were monitored in the factory at the main production stages: during and after winding and during the collaring of the magnets. The fineness of the hot magnetic measurements made it an essential fault detection tool. The test bench installed in the factory showed its efficiency half way through production when it detected the fact that the permeability of the austenitic steel in the collars was 10% higher than the nominal value. Parasite effects were cancelled out by carefully selecting the position of the magnets in question in the machine, which reduced the lateness and made it possible to use most of these collars, while the supplier restored nominal quality of the steel.

The originality of the quality system put in place

The main tool we used for monitoring production was the non-compliance management system. Its objectives were to be able to react quickly if a fault was detected at each production stage up to the cold acceptance test at Cern, and to have records of the cold masses during the twenty years of operation of the LHC.

The three month period between the manufacture and the testing of a magnet corresponded to the production



The stored quadrupole magnets before assembly in cold masses (photo Accel).



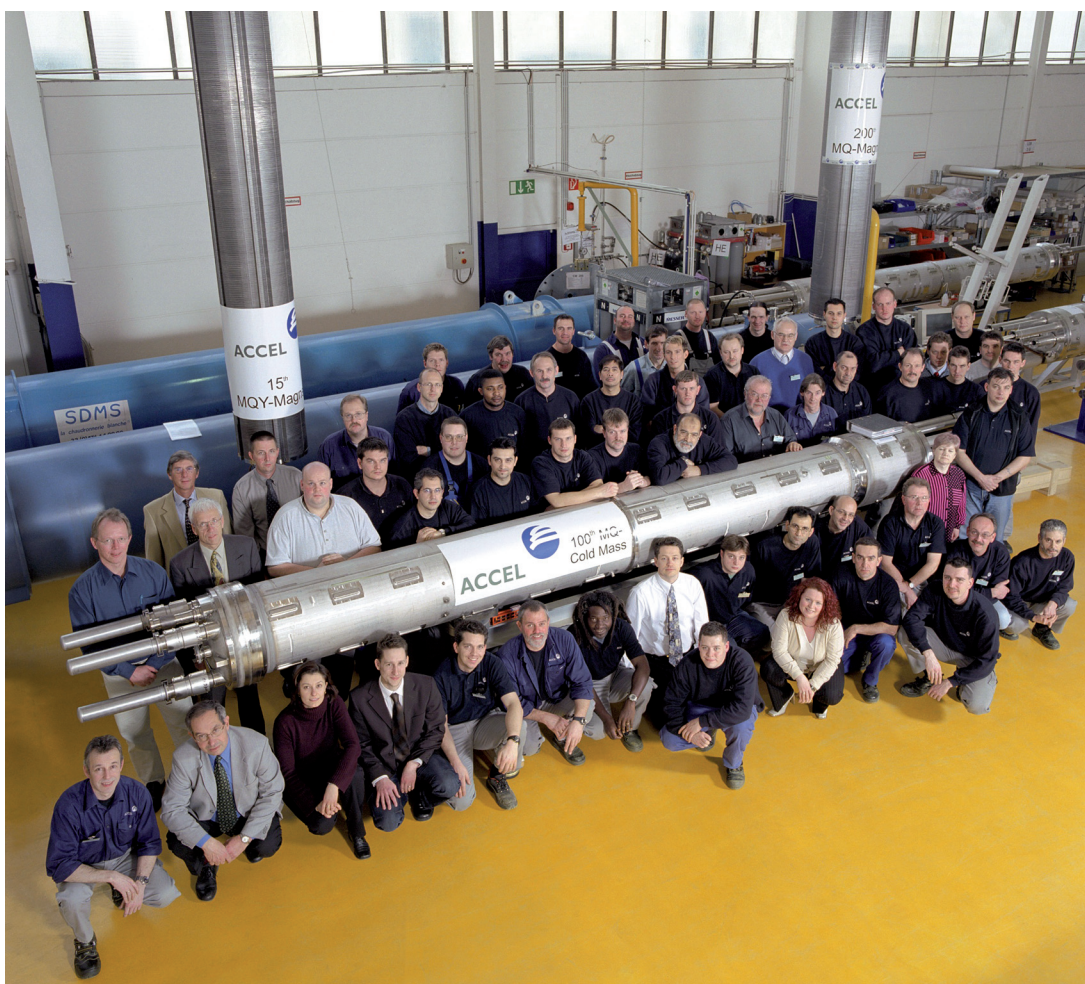
Lowering of the first cold mass into the LHC tunnel on 19 April 2005 (courtesy of Cern).

of forty cold masses. All deviations had to be known and analysed in order to allow the appropriate corrective action to be taken as quickly as possible. To reduce uncertainties, one main quadrupole magnet out of ten was tested separately. This procedure has made it possible to check from July 2002 that the industrial transfer was carried out properly. Out of 400 cold masses, only one magnet was rejected.

Experience feedback from the collaboration

In December 2004, the 100th cold mass off the production line was celebrated. In November 2006, 6 years after the signing of the contract with Accel, production was finished. This was the end of the 10 year period of the collaboration agreement between Cern and CEA. In fact, this agreement formalised a 17-year collaboration which began at the end of the 1980's based on the CEA's expertise, proven during the manufacture of the quadrupoles for the Hera machine. Two prototypes had therefore already been designed, manufactured by SACM then tested in 1994 at Cern.

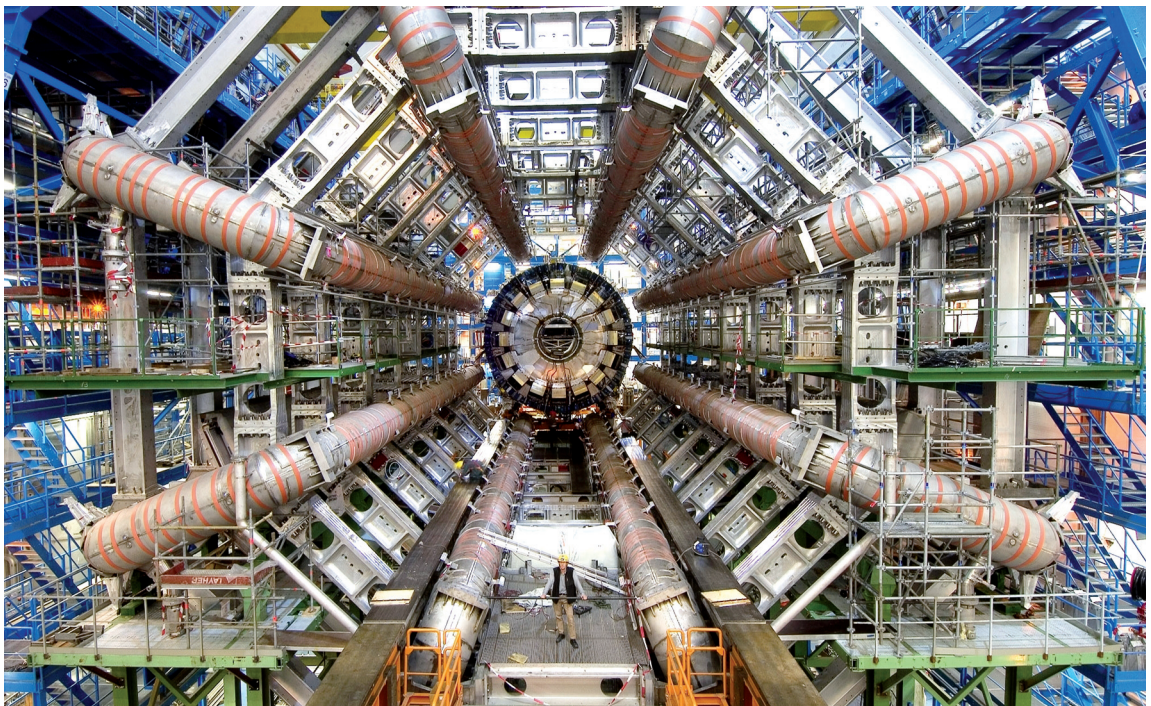
The close collaboration between SACM and Cern was the driving force behind the success of this project. The two laboratories combined their expertise in a spirit of mutual trust, following carefully developed quality control procedures.



100th cold mass off the production line (courtesy of Accel).

The toroidal magnet for the Atlas detector

Physical detectors like those in the future Large hadron collider (LHC) at Cern require intense magnetic fields that bend the trajectory of the particles in order to measure the quantity of movement. The magnetic system of the Atlas detector in the LHC is made up of several superconducting magnets at the temperature of liquid helium, i.e. -269°C . It comprises a central toroid, two end-cap toroids and a central solenoid. Dapnia was responsible for the design and industrial monitoring of the construction of the toroid within the framework of an agreement signed with Cern in 1997.



Atlas's central toroid in the cavern (courtesy of Cern).

The Atlas experiment

The Atlas experiment is, among other things, composed of a large spectrometer for muons, particles with very high energy levels. This assembly makes it possible to measure the trajectory of muons bent by an intense magnetic field very precisely, thanks to 3 concentric layers of multi-wire chamber detectors. The physicists at Dapnia wanted to achieve this magnetic field without the presence of magnetised iron which would disturb the muons; they therefore devised the concept of the large air-core toroid. Subsequently, the fact that the physicists and engineers at Dapnia were working in very close quarters constituted the ideal conditions for the genesis of this very original design. In this important project, we find at Dapnia's side, the INFN's Laboratorio accettori e superconduttività applicata (Milan) and several teams from Cern. Each contributed to different parts of the magnet. The Atlas muon spectrometer is located in a very large magnetic field which surrounds the whole experiment. To build a magnet capable of producing such a field, Dapnia's research engineers designed a set of eight rectangular superconducting coils 25 m long and 5 m wide, supplied with a current

of 20,500 amperes. The magnetic field produced surrounds the experiment like a torus, and this is why the Atlas giant magnet is described as "toroidal".

The toroidal magnet's eight superconducting coils

Before building the first coils in the toroid, Dapnia first developed the B0 coil, a prototype 1/3 of the full length. This "small" coil, which was the size of a double-decker bus, made it possible to validate the technological options which were to be utilised for the construction of the final magnets in the mechanical, thermal and electric domains. Built in 1999 in Saclay, B0 used the components and assembly procedures planned for the production run, and was successfully tested during 2001 at Cern.

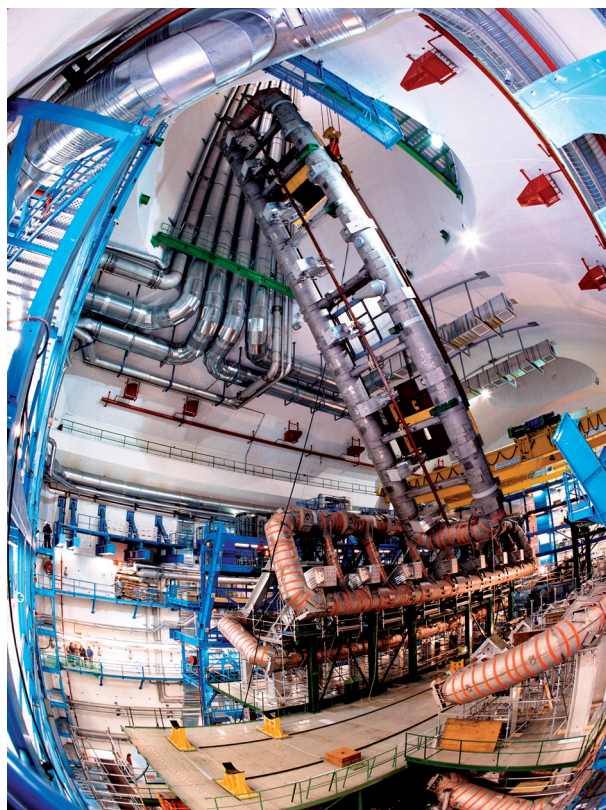
After the tests of the prototype coil B0 in 2000 and 2001, the final coils of the toroidal magnet were built at Cern from components supplied by a number of



Integration of shields at Cern: The multi-layer superinsulation was laid on the left side of the coil in the foreground; in the background the shielding is completed (courtesy of Cern).

European industrial companies. Dapnia carried out the industrial monitoring of the manufacture of most of the components and technical monitoring of their assembly at Cern. Thirty kilometres of superconductor cables were required to make these coils, which are cooled to the temperature of liquid helium. To guarantee the operation of the superconducting magnets, individual tests are carried out on each coil on a surface test station, with higher currents than those planned for normal operation. Thus, on Tuesday 7 September 2004 at 1.42 am, BT1, the first of the central toroid coils withstood the injection of a 22,000 amp current for the first time. BT1 had now become the largest superconducting coil "fit for service" in the world. The eight coils were therefore tested one at a time on the surface with a current of 22,000 amperes, taken underground and then assembled in 2005 in the Atlas cavern 100 m below ground, by means of an aluminium structure. Laid out in the shape of a star to within a few millimetres accuracy, these coils occupy a volume equal to

that of a six-floor building. The structure will have to bear the weight of the 1,400-ton muon detector and withstand extraordinary magnetic forces. On Thursday 29 September 2005, the toroidal magnet broke free from its support cradle. The deformation of the structure after the freeing was predicted by calculations that were so precise that the releasing of the hydraulic cylinders, initially forecast to last five days, was completed after 48 hours, and at the same time complying with the expected geometry to the nearest millimetre.



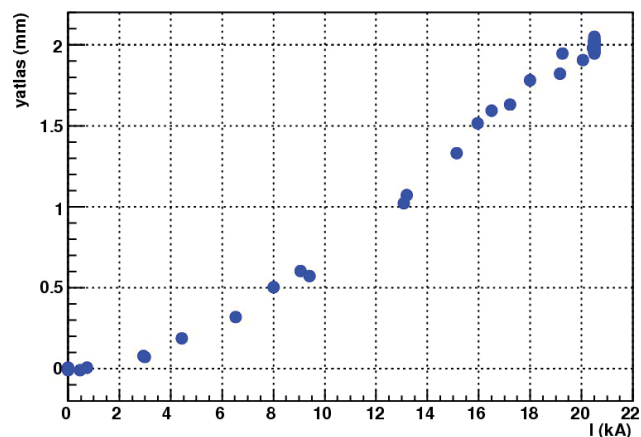
Lowering of the 8th Coil into the Atlas cavern (courtesy of Cern).



The first of eight coils in the central toroid being tested at Cern on the cryogenic test station (courtesy of Cern).

The cryogenic ring

A cryogenic distribution line divided into 8 sections, is positioned on the outer edge of the toroid, longitudinally near to the centre of the magnet. Each section is 6 m long and distributes cryogenic fluids (helium in gas and liquid form) and electric power to the eight coils. The top section is connected to the current lead cryostat. The bottom section comprises a cryogenic valve unit allowing the fluids to be distributed to the eight sections. The three types of section were built in Saclay and then delivered to Cern. The toroid installation and the final welds were completed in March 2006.



Changes in the vertical position of a coil located at the top of the toroid, according to the electric current.



One of the sections of the cryogenic distribution line, before the heat shields are put in place. At the centre of the assembly, we can pick out the helium pipes and the busbars (superconducting links between the current leads and the winding).

Starting up the central toroid

The whole toroid was cooled to -269°C for the first time in June and July 2006, and was then gradually put into operation from September onwards.

A 21,000 amp current was injected into the 8 coils of the Atlas magnet during the night on Thursday 9 November 2006. This was 500 amps more than the current required to produce the planned magnetic field.

All the operating tests were successful and Atlas therefore became the largest superconducting magnet in the world. Once powered up, the magnet stores 1.1 GJ of magnetic energy, equivalent to the energy required to lift the Eiffel tower 10 metres off the ground. While the current was rising, the star shape made up by the coils gradually distorted towards an

oval form, with an amplitude of 2 mm. This amplitude conforms to a large degree to the models used to calculate the mechanical deformation.

Collaboration agreements

It was essential to collaborate with European industry in order to make the toroid. Hence, Dapnia worked with Technicatome in France, ASG-Superconductors in Italy, Leipert and EAS in Germany, Corus and Exotech in Holland, HTS in Switzerland, FCM in Spain, RusAl in Russia and MZOR in Bielorrussia.

Only very close cooperation between Dapnia's different departments (Particle physics department, Department of accelerators, cryogenics and magnetics, Systems engineering department, Department of electronics detectors and information technology) enabled this project to be successful. This success is the result of more than 10 years effort within the framework of a worldwide collaboration. It is a decisive stage in the setting to work of the Atlas detector at Cern, before the production of data which is planned for the end of 2007.

The superconducting solenoid for the CMS detector

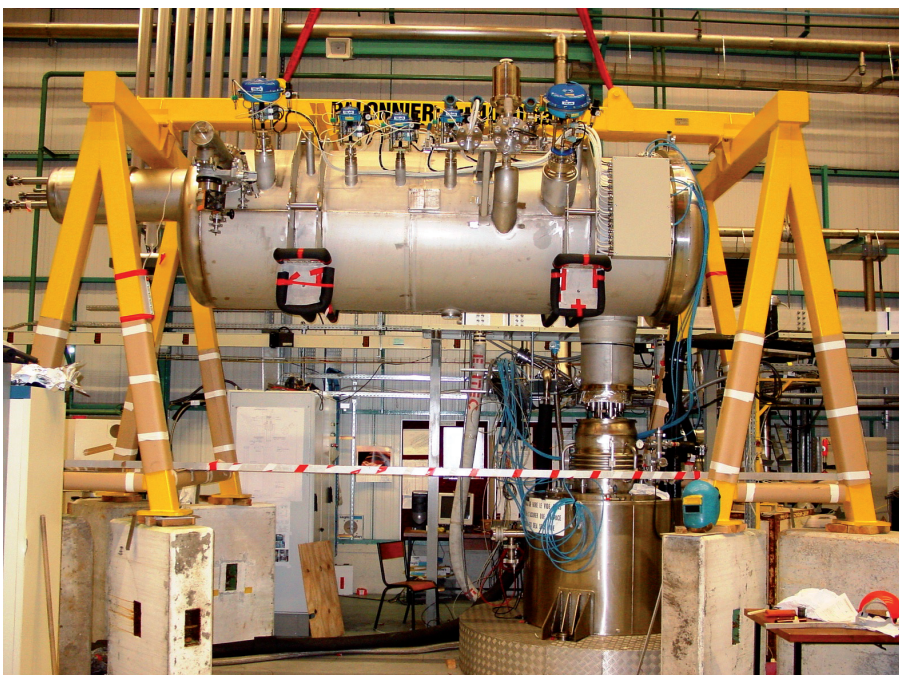
On the basis of a collaboration agreement with Cern that has been in place since 1996, Dapnia is involved in the overall design, production and testing of the superconducting solenoid for the CMS (Compact muons solenoid) experiment that is to be installed at Cern on the LHC (Large hadron collider) collider. Within Dapnia, SACM is acting as a pilot service for the project on the magnetic and thermal design aspects, on the monitoring of the assembly and the surface testing at Cern, assisted by the SIS (systems engineering department) on the mechanical design aspects, the monitoring of industrial production and the instrumentation. Apart from its size and stored magnetic energy, the special features of this solenoid are the conductor which is reinforced by aluminium alloy (a concept put forward by Saclay) and the design of the coil in five modules with four conductor layers each, wound inside a cylinder which serves as a outer mandrel. The years from 2004 to 2006 witnessed the end of the industrial production of the individual components of the solenoid, the end of the tests of the most critical components at low temperatures in Saclay, before their final assembly, the final assembly of the magnet in a hall on the surface at Cern, the installation of certain parts of the detector tested at the same time as the magnet, and the complete cryogenic and magnetic tests of the magnet up to its nominal characteristics.

Qualification of critical components in Saclay

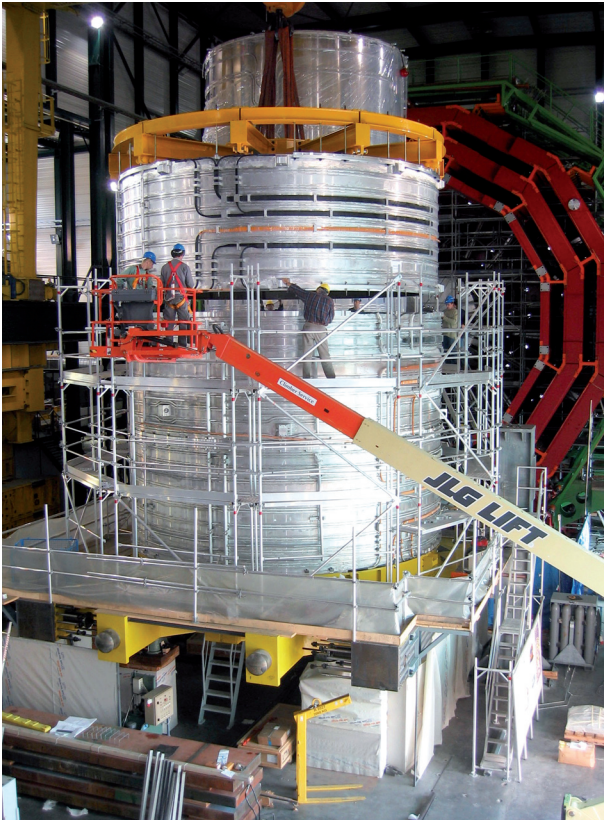
Following the current leads, which were tested in Saclay in cryogenic and electrical conditions that were highly representative of their operation in the magnet, the 8 m deep vertical cryostat was used to test the 30 coil suspension tie rods in the vacuum chamber: 4 vertical tie rods and 8 radial tie rods, approximately 1.9 m long, 16 longitudinal tie rods 5.5 m long, in two equal lengths. All the tie rods were tested in real cryogenic conditions, that is to say with one end at around 20 K and the other at 300 K, at values of up to 110% of their

maximum working load. All the tie rods successfully passed this test without any problem.

The phase separator, an essential component for the operation of the proximity cryogenics in thermosyphon mode was tested, first on its own, then connected to a long loop simulating the magnet's circuit. These tests enabled us firstly to check the operation of the phase separator and secondly to understand the thermo-hydraulic operation of this cooling mode better.



Test of the phase separator at Saclay connected to a cryogenic loop reproducing the operation of the magnet in thermosyphon mode.



Installation of the 3rd module of the coil on the assembly platform at Cern (courtesy of Cern).

Assembly of the cold mass at Cern

Designed at Dapnia, the solenoid assembly scenario materialized in 2001, by the arrival at Cern and the blank testing of the assembly platform, then by the arrival of the 1st module of the coil in February 2004. The five modules which make up the coil assembly were delivered over a period of one year, up to January 2005, and superposed vertically around the internal vacuum chamber also supporting the internal thermal shields. Then, after the external thermal shields were put in

place, the assembly was tilted into the horizontal position and inserted into the external vacuum chamber, positioned in the magnetic yoke in August 2005.

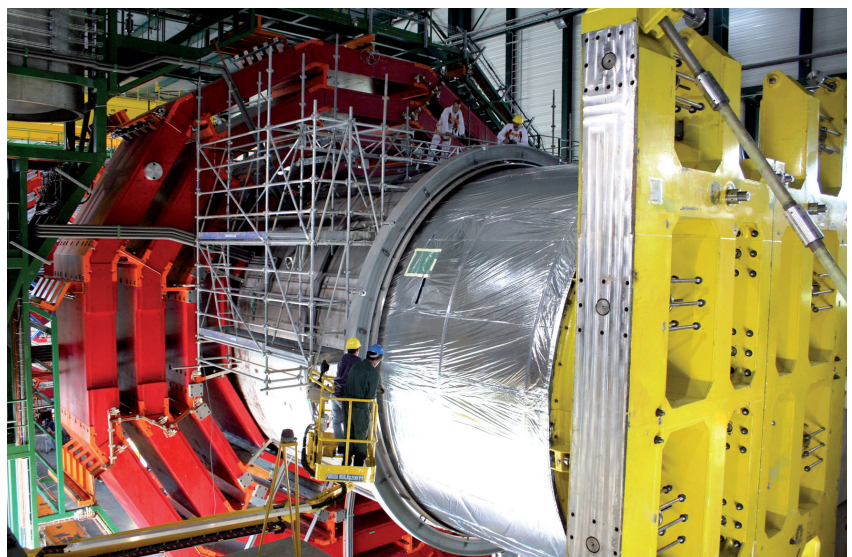
After the installation of the cryogenic chimney, linking the phase separator to the magnet and housing all the measuring cables, the current lead chimney and the end parts of the vacuum chamber were put in place at the end of 2005, thus finalizing the assembly of the magnet.

Surface tests at Cern

When the vacuum chamber was closed, pumping was started and the magnet cooling phase started at the beginning of February 2006. Four weeks later, the magnet was at 4 K, and a few low current tests were possible. It wasn't until the end of July 2006 that all the detectors that had to be tested with the magnetic field were installed in the magnet and the magnetic yoke was closed, and it was only then that the current in the magnet could be increased significantly.

The electrical tests of the magnet took place in two periods.

- End of July 2006 to end of August 2006: gradual increase up to the nominal field, with a systematic check of the operation of the control and safety systems. The nominal field of 4 T at the centre of the magnet (for a current of 19,141 A) was attained on 28 August 2006. During these tests, the magnet behaved perfectly. Only two auxiliary systems (magnetic valve and dc current transformer) gave slight cause for concern.
- October 2006: the magnetic field in the magnet was measured at different field values and the settings were refined for long-term operation.



Insertion of the cold mass into the external vacuum chamber and the magnetic yoke (courtesy of Cern).

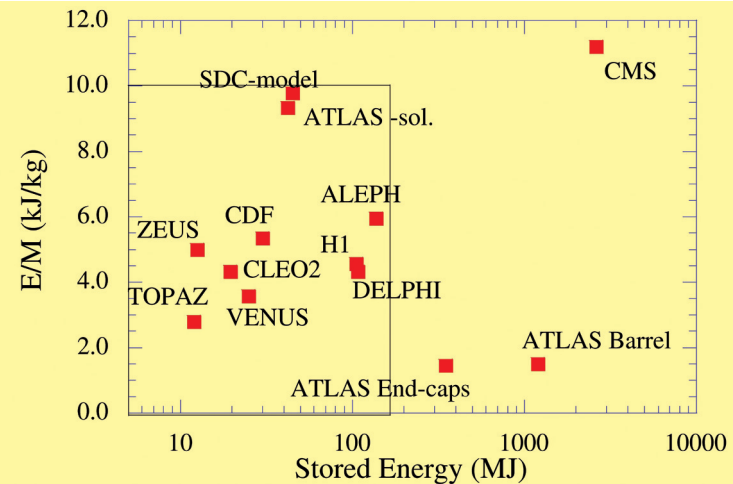


The magnet is ready to be cooled.
The current lead chimney is visible at the top left (courtesy of Cern).

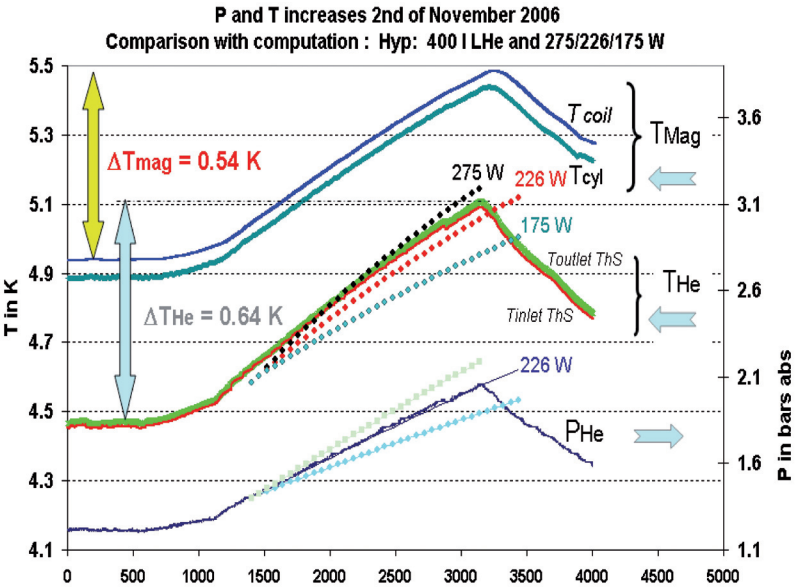
These tests ended with a partial thermal stability test, by raising the temperature of the magnet by pressurizing the cooling system. A rise of 0.5 K in relation to the normal operation temperature had no effect on the magnet. The magnet passed all the planned tests successfully.

During these tests, Saclay's contribution was mainly related to monitoring temperatures, stresses and movements of the cold mass, to the checking of the current leads and the analysis of the protection system, in particular in the event of rapid discharge of the magnet; during all the tests, the magnet never quenched naturally, but the deliberate activation of a fast discharge caused magnet quenching by the effect of the currents induced in the cylinders supporting the winding (quench-back effect).

From the beginning of November 2006, the magnet was heated by circulating a current in the winding. Heating up to ambient temperature was achieved by the end of November. In parallel, the magnetic yoke of the magnet was disassembled and transferred into the cavern. At the end of December 2006, four of the fifteen main assemblies making up the detector had been lowered into the cavern.



Of all the superconducting magnets tested, CMS is the one that has the most total stored energy and the most energy per unit mass of coil.



Raising the temperature of the magnet by pressurizing the helium used for cooling. The changes in temperature also allow heat losses to be estimated.

The Clas solenoid for the DVCS experiment

Within the framework of the collaboration between Dapnia and the Jefferson Laboratory in the United States, SACM designed and made a superconducting solenoid for the Clas detector (Cebaf* large acceptance spectrometer) for the Deep Virtual Compton Scattering distribution studies (DVCS) in collaboration with the Nuclear Physics department and the Systems engineering department. The first series of experiments in DVCS physics started in March 2005 in Newport News in Virginia.



*Tests of the magnet at Saclay in December 2004. The main characteristics of the magnet are:
A field at the centre of 4.65 T in an aperture 230 mm in diameter.
A field external to the vacuum chamber lower than 3 mT from an external diameter of 912 mm.
The nominal current is 650 A and the magnet operates in liquid helium at 4.2 K.*

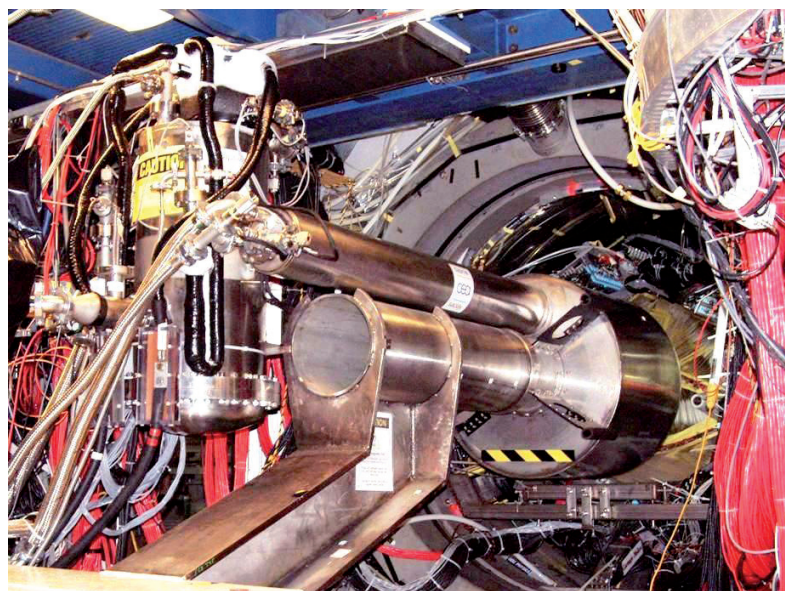
The superconducting magnet operates in the centre of the magnetic field created by the six magnets in the Clas toroid. To limit the interacting forces between the toroid and the solenoid, we used the active shielding technique. A second solenoidal coil placed around the

main coil cancels the field at the periphery of the assembly. The two solenoids had been wound in 2003. They were assembled then integrated into the cryostat during 2004.

The cryostat required complex mechanical assembly operations to satisfy the constraints for use at the Clas centre and to enable the magnet to be transported by air and by land. The magnet was custom designed with an external clearance of 10 mm in respect of the detector's diameter. The cryogenic interface is offset 2 m behind the magnet. Finally, the configuration of the site also made it necessary to implement horizontal cryogenics which operate by natural convection with no cooling control mechanism or logic controller.

The completed assembly was tested in Saclay in December 2004. It was sent to the United States in January 2005. We installed the magnet in the Jefferson Laboratory (Jlab) in February 2005, where it passed all the safety and commissioning tests successfully up to the start of the physics experiments on 1st March. The Clas-DVCS magnet has opened up new opportunities for the Clas detector centre. It was quickly adopted by Jlab's scientific community who use it for other experiments in addition to DVCS studies. A second series of DVCS measurements are being programmed for the start of 2008.

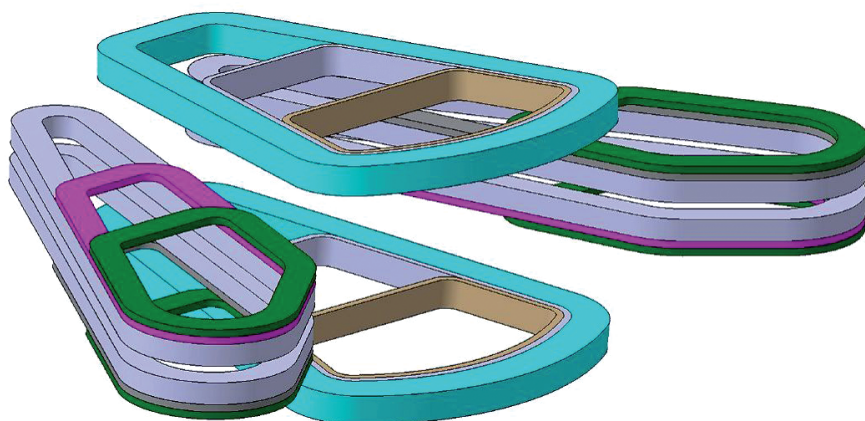
* Cebaf are the Continuous Electron Beam Accelerator Facilities



The magnet at the entrance of the Clas detector in September 2005. On the left, the cryogenic satellite which accommodates the helium distribution and the current leads.

The superconductor dipole R3B - Glad

The European collaboration R3B (Reactions with relativistic radioactive beams of exotic nuclei), including 50 institutes from 19 countries, set up with GSI at Darmstadt in Germany, a programme devoted to the emerging physics of exotic nuclei with relativistic energies. This programme necessitates the construction of experimental installations with improved performance: inverse kinematics reaction, total detection of the products of reaction and resolution. Within the detection assembly, the large acceptance superconductor spectrometer Glad (GSI large acceptance dipole) will play a central role. The preliminary draft was studied within the framework of the 5th European outline programme of research and development (5th PCRD). The decision to finance the construction of the R3B-Glad magnet was made in October 2005, under the 6th PCRD.



The geometry of the 6 double pancake superconducting coils is adapted to the conical acceptance of the beam in order to minimise the fringe field and the stored energy, while providing an intense magnetic deviation field that is sufficiently homogeneous to ensure the required momentum resolution.

Spectrometer specification

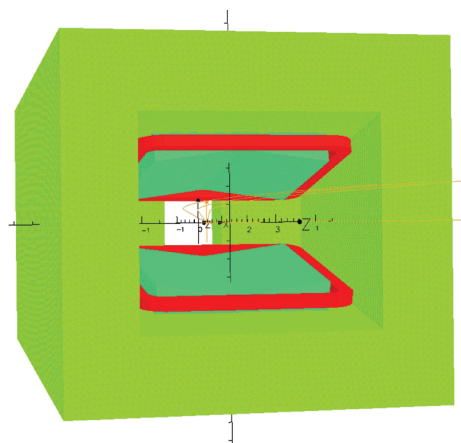
Analysing the particles from reactions between the radioactive ion beam and the secondary target, the Glad dipole magnet had to take account of numerous constraints, including:

- ▶ a field integral of 4.8 T.m making it possible to deflect the high magnetic rigidity heavy ions by 18° (typically 15 T.m for $^{132}\text{Sn}^{50+}$) and protons by up to 40°;
- ▶ a large angle opening, both horizontal and vertical ($\pm 80\text{mrd}$), also giving transparency to neutrons, not deviated by the magnetic field;
- ▶ a large momentum acceptance making it possible to detect protons and heavy relativistic nuclei, up to the energy of 1 GeV per nucleon;
- ▶ a negligible fringe field ($< 20\text{ mT}$), in particular around the target zone located 1 m upstream from the magnet entrance face;
- ▶ a resolution of 10^{-3} with momentum and of 1 mrad with angles reconstructed at the target.

Magnet design

The design study carried out between 2001 and 2003 produced a magnet using an active shielding magnetic configuration with an innovative design, the Tigra trace (Tilted and graded trapezoidal racetracks) or "butterfly" design, a name suggested by the shape of the six superconducting coils that make up the dipole.

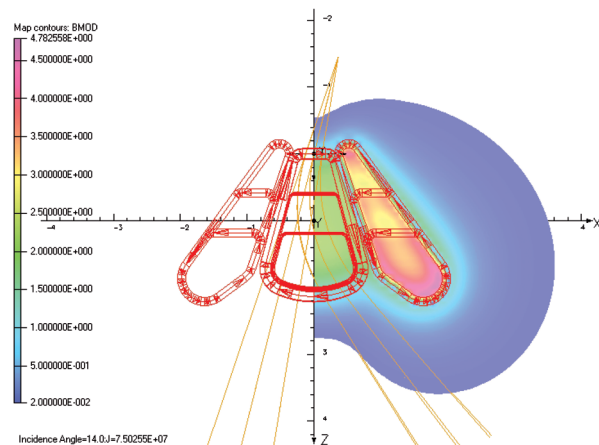
A comparison with a more basic design was requested and done in 2004-2005. However the circular coil solution led to a more complex magnet (10 coils), while iron shielding proved heavy (over 300 tons), costly, and with no decisive advantages as regards the momentum resolution and fringe field required. The new European contract, CNI Dirac Phase 1 (Construction of new infrastructure – Darmstadt ion research and antiproton centre) from the 6th PCRD, which will finance the project from 2006 to 2010, has therefore retained the initial so-called "butterfly" design.



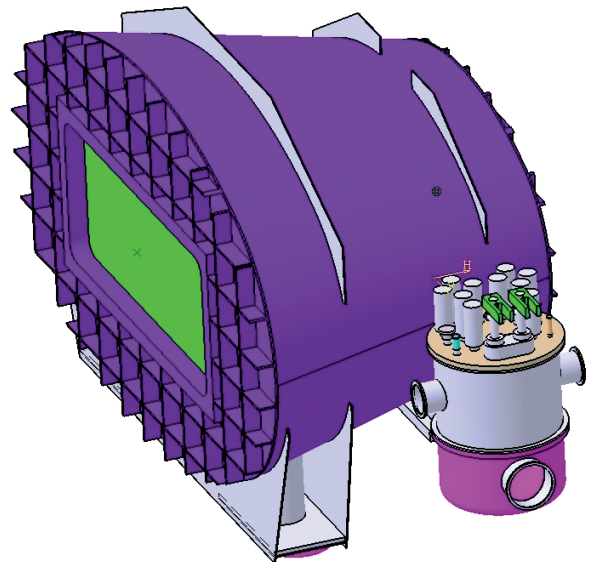
Solution not chosen: super-ferric magnet (superconducting coils in red around the poles drawn to produce a homogeneous field map). In light green: iron shielding.

The plane coils made in the shape of a racetrack are placed closest to the beam so that they adapt better to the required conical acceptance. In order to carry out an active shielding and a principal field homogeneous, they are trapezoidal with a gradually increasing number of turns longitudinally; this ensures a constant magnetic deviation in the useful volume of high field. The stored energy is thus minimized, just like the fringe field in the target zone upstream to the magnet.

In 2006, proposals to meet the technical challenges that are posed by this superconductive magnet, relating in particular to how to withstand the intense magnetic



Magnetic field map (with the fringe field limit at 20 mT). The variation in the number of ampere-turns along the axis of symmetry of the magnet contributes to the creation of a homogeneous vertical dipolar field in the useful volume for the beam analysed. Proton and neutron trajectories are shown in orange.



Elliptical cone-shaped cryostat between two reinforced end plates. The cryogenic satellite (in the foreground) contains the cryo-valves and the electrical current leads.

effort (300 to 400 tons per metre), cooling down to 4.5 K using a liquid helium thermosyphon, and to the magnet safety system and the system of control, were submitted at the technical design review. Finally the 5 tons, the equivalent of 16 km, of niobium-titanium superconducting cable in Rutherford-type were ordered at the end of 2006.

Some figures and special features of the "butterfly" magnet

Rutherford NbTi superconducting cable winding in 28 double pancakes, in the shape of tilted trapezoidal racetracks. Active shielding (with no iron). Fringe field = 20 mT, 0.3 m from the cryostat.

Current density in the coils = 80 A/mm². Field on the conductor < 6.5 T. Current = 3,700 A.

Field integral = 4.8 Tm. Central field = 2.4 T. Stored energy = 24 MJ.

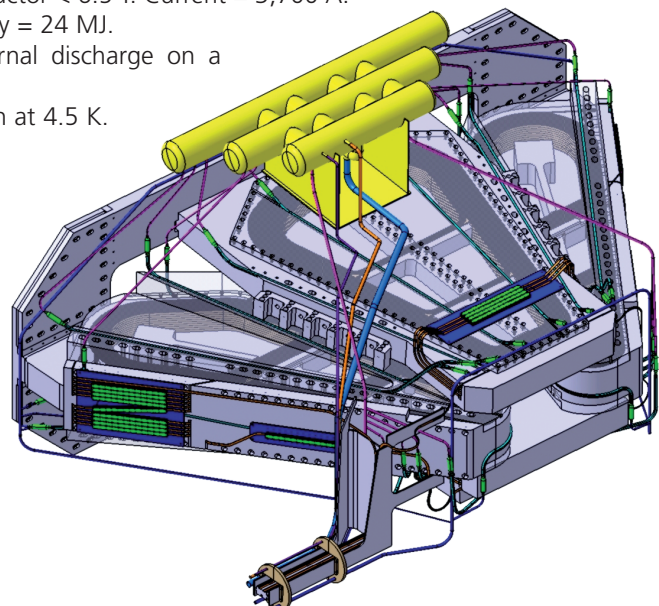
Protection in the event of quenches by means of external discharge on a resistance of 0.25 ohms.

Indirect cooling by means of a liquid helium thermosyphon at 4.5 K.

Magnetic forces = 300 to 400 tons per metre.

Total mass of the magnet with the cryostat = 50 tons.

Overall dimensions: W 3.5 m x H 3.8 m x l 6.6 m.



The magnet's cold mass will comprise the 6 coil casings with their connections and mechanical supports, as well as the indirect cooling tubes and the junctions between the superconducting cables (shown in green). In yellow there is the liquid helium tank at 4.5 K supplying the cooling down thermosyphon.

The solenoid for the Compass experiment

One of the objectives of the Compass experiment, located on the Super proton synchrotron (SPS) at Cern is to study the origin of nucleon spin. This experiment used a target polarised in the 2.5 tesla magnetic field that is produced at the centre of the superconductor magnet Compass. The design and realization of this magnet were fully resumed after a first fabrication did not reach the requested characteristics. Dapnia, through the Nuclear Physics department, the systems engineering department and SACM has played a very important role in taking the project in hand again. Finally, a magnet with the requested parameters has been operational for physics on the CERN experimental areas since the middle of 2006.

After a first unsuccessful tentative for the construction of their superconducting magnet, the Compass collaboration appointed an expert committee to redesign a new magnet able to reach their requests and to follow-up its industrial construction.

SACM was very much involved in this new phase:

- ▶ participation to the expert committee,
- ▶ follow up of the reconstruction of the magnet by industry,
- ▶ realization of the reception tests at Saclay, then at CERN, including in particular two magnetic measurement campaigns to get the requested field homogeneity.

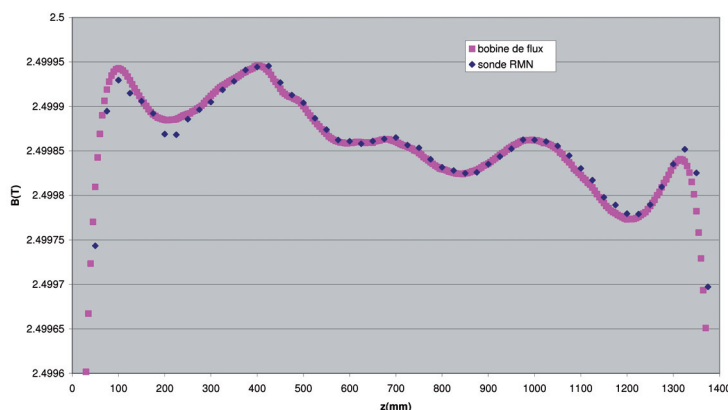
The magnet reached its nominal field without any quench, despite a short which appeared in one of the correction coils. This short makes the operation of the magnet more complex, as this special situation must be taken into account when ramping the main coil.

In collaboration with SIS, SACM performed two magnetic measurement campaigns on the magnet. A first one was done at Saclay at the end of 2005 to characterize the field and to make a first homogenization of the field. Then, beginning of 2006, a second campaign was done at CERN to take into account the magnetic environment, in particular the proximity of the SM1 conventional dipole. By getting independently the magnetic characterization of the main solenoid and of each correction coil, it has been possible to determine a



Installation of the magnet at the SACM magnetic measurements laboratory.

set of correction currents to improve the field homogeneity of the solenoid alone. A homogeneity better than 10^{-4} was obtained in the useful zone (cylinder of 1.3 m in length and 3 cm in diameter), and this value complied with the physicists' requirements.



Magnetic flux density curve along the solenoid axis after compensation.

Tests on the Wendelstein 7-X stellarator coils

The W7-X project is run by the Plasma Physics Institute in Garching (Germany) that is responsible for the manufacture of one of the research machines for the European programme of thermonuclear magnetic confinement fusion. This machine, called stellarator Wendelstein 7-X, has a diameter of the order of 15 metres and a mass of 550 tons and is made up of 70 superconducting magnets designed to confine plasma.

The department of accelerators, cryogenics and magnetism is responsible for the acceptance tests on 70 magnets that are made in Germany, Italy and England, before installing them definitively on the stellarator that was built in Greifswald in Germany.

Main tests

The tests enable the electrical, thermal and hydraulic behaviour of the magnets to be studied at ambient and cryogenic temperatures. To achieve a regular rhythm of 2 tests per month, a test station comprised of two cryostats that can each accommodate two magnets each was designed, made and qualified in Saclay in the 2000's. The tests are programmed over a period of 5 years starting in 2004.



Installation of a non-flat superconducting coil in one of the two cryostats in the W7-X test station.

At the room temperature, four stations are used to carry out the following tests:

- ▶ coil insulation test in relation to the coil unit (10.4 kV),
- ▶ layer to layer insulation test (1,600 V AC, 2 kHz),
- ▶ sensor insulation test in relation to earth (50 V).

At the cryogenic temperature, the two cryostats are used to carry out the following tests:

- ▶ monitoring of the load loss in each magnet circuit,
- ▶ raising the nominal current of the magnet ($\approx 17,600$ A) then monitoring the margin between the nominal operation of the magnet and the critical operation for which the magnet loses its superconducting state,
- ▶ transition of each coil by increasing the temperature (increment of 0.1 K every hour).

Results of magnet tests

Since the beginning of 2004, the 2 cryostats have been operational in the test stations. We have carried out 40 current tests, validated 16 magnets including 11 magnets with flat geometry and 5 magnets with other configurations.

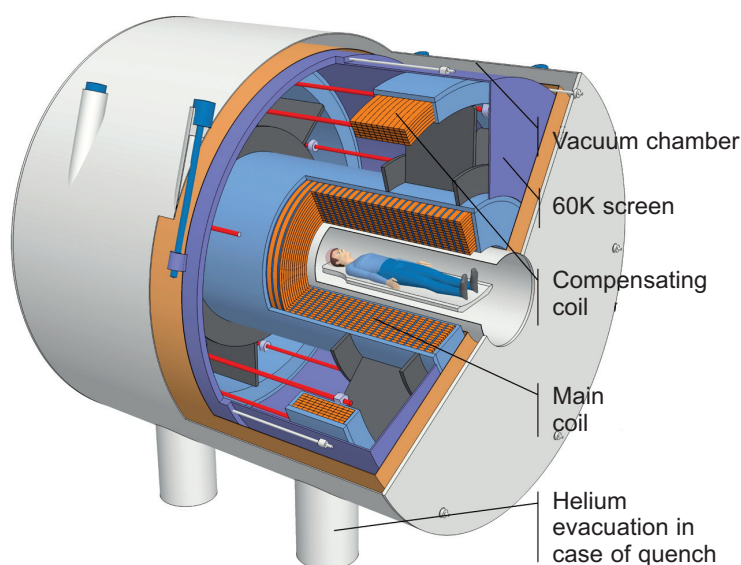
These tests have highlighted the following:

- ▶ leaks on the helium cooling circuits of the coil units of the flat magnets,
- ▶ helium leaks on the electrical junctions of the double layers of some flat magnets,
- ▶ insufficient electrical insulation of some electrical junctions of the double layers of other "non-flat" magnets,
- ▶ magnet quench protection cables not withstanding insulation voltages of 10 kV.

At present, some magnets that had problems have been modified and repaired and must now be tested. The manufacturing process of new magnets incorporates technical modifications which solve the different problems encountered during the tests. The magnet production rate is rising, our current testing speed should enable us to reach 20 magnets per year in the next two years.

The Iseult project for the Neurospin platform

The CEA Life Sciences Division proposed the Neurospin project, which consists of a neuro-imaging and nuclear magnetic resonance (NMR) spectroscopy centre. Aiming to extend the boundaries of cerebral imaging, this technical platform, that was inaugurated on 24 November 2006 at CEA Saclay, is already equipped with two systems producing magnetic fields of 3 T and 7 T for clinical studies on humans. At the end of 2007, a 17 T system, intended for pre-clinical studies on primates and small animals, will also be set to work. Finally, as part of the Franco-German project Iseult, Dapnia is taking part in the production of a 11.75 T magnet for the whole human body which should be installed at Neurospin in 2011. This magnet is an ambitious project which will allow us to push back current technological frontiers.



Longitudinal section of the principle of the Iseult magnet. The magnet will generate a magnetic field with an intensity of 11.75 T at its centre – more than 230,000 times the earth's magnetic field – in a volume of several cubic metres (a useful aperture of 90 cm in diameter allowing the passage of the whole of a patient's body). When it is put in service in 2011 it will be the first of its kind in the world.

The context of the Neurospin project

The magnetic resonance imaging technique (MRI) is a diagnostic and research tool used in the neurosciences. In this context, the Neurospin project's goal is to develop a centre comprising 4 imaging devices: two imagers of 3 T and 7 T (Siemens) for clinical research, a 17 T small opening imager (Bruker) for pre-clinical research and finally an 11.75 T imager with an aperture of 900 mm (Iseult programme). This high-field large aperture imager is not commercially available at the present time and is being researched in collaboration with Siemens. In this context, Dapnia has been approached with a view to developing and manufacturing the 11.75 T whole body superconductor magnet.

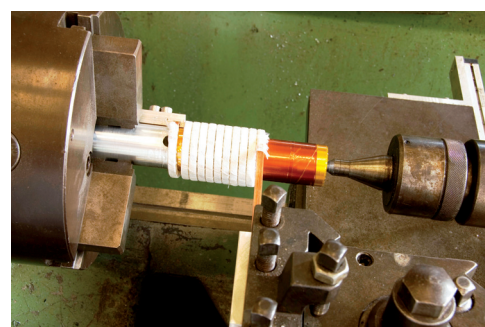
Iseult Collaboration

A collaboration agreement was signed in 2005 between CEA and Siemens for the development of high-field molecular imaging techniques. In this framework, and linked to Franco-German governmental technological innovation initiatives, a programme named Iseult was put in place with Siemens and other industrial and academic partners, such as Alstom and Guerbet in France. The aim of this programme is to develop new

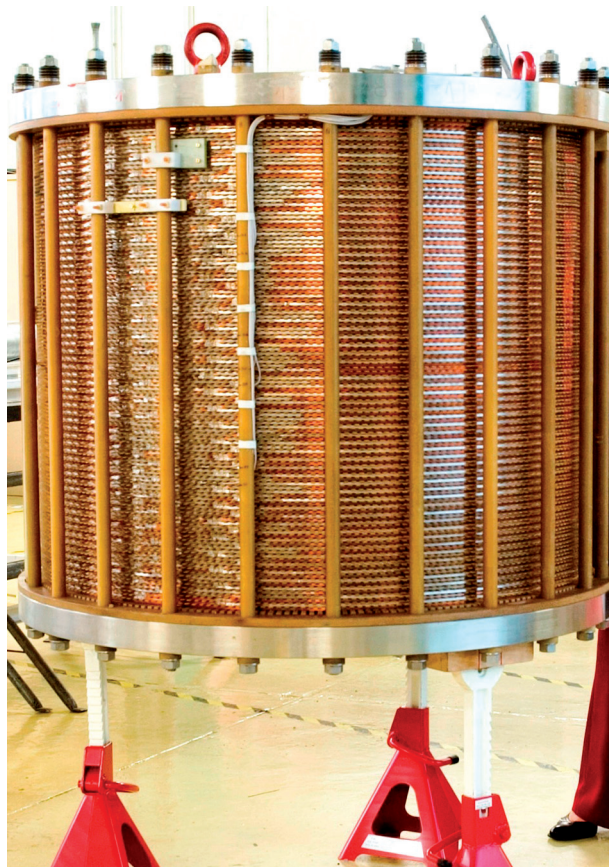
diagnostic tools for neurogenerative diseases, by means of innovative molecular imaging techniques based on the use of magnetic high fields and new pharmaceutical contrast agents.

Special features of the high-field superconductor magnet

Apart from the strong magnetic field in a large volume, we will have to overcome 3 technological obstacles related to the specific requirements of MRI. The first is to obtain a homogeneous magnetic field a few parts per million around the patient's brain, the second is to



Coiling of a conductor for critical current measuring.



Model coil with double pancakes which will create a magnetic field of 8 T in a useful diameter of 600 mm for the Seht test station.

stabilise the field during the examination at a few tens of parts per billion and the third is to confine the field inside the examination room. This is achieved thanks to the 45 tons of main winding of the magnet which must be positioned as precisely as possible around the brain (within a few tenths of a millimetre). The winding is made from several thousand kilometres of niobium titanium superconducting wire wound onto double pancake coils with a current of 1,400 A flowing through it. This superconductor must be kept at a very low temperature (1.8 K above absolute zero, i.e. -271°C) To this end, the coils are immersed in several thousand litres of superfluid helium protected from the exterior by a series of enclosures, like a gigantic thermos flask. The confinement of the magnetic field in the examination room is carried out thanks to a winding which generates a counter field and which cancels out that of the main winding outside the magnet. In a conventional system, several thousand tons of iron shielding would have been required.

The design of the magnet comprises a number of characteristics that sets it apart from conventional MRI magnets. Due to the newness of the solutions proposed, a special development plan has been proposed, the aim of which is to be able to test all the new concepts on prototypes in order to validate the solutions chosen before going on to the construction phase. The main investigation prototypes are as follows:

- ▶ a small model superconducting coil to test the homogenisation principles of the magnetic field from

double pancake blocks with the final design at a scale of 1 in a cryostat to carry out homogeneity and field stability tests.

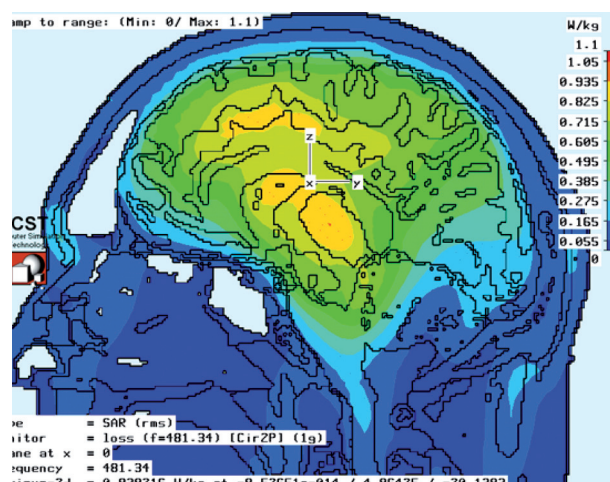
- ▶ a prototype at a smaller scale to study components, manufacturing processes, electromagnetic, thermal and thermohydraulic operating conditions envisaged for the final magnet,
- ▶ a prototype made from an assembly of 16 pancake coils at a scale of 1.

Seht experimental station

The tests of these prototypes necessitate the construction of special cryomagnetic test stations. In particular, the construction of the test station called Seht (eight tesla test station) will also provide an opportunity to assess and validate the developments made in the cryogenics at 1.8 K, the power supply system, the control and monitoring system and the protection of the magnet.

High frequency antennae

An increase in the magnetic field implies an increase in the frequency of the HF signal used for the production of an MRI image. An antenna prototype adjusted to 500 MHz and SAR (Specific absorption rate) measurements have been devised in collaboration with the electronics, detectors and information technology department. In parallel, the SAR induced in the human tissues has been digitally simulated. The main difficulty that has been identified is that of satisfying the requirements for a lower SAR and a lower image contrast artefact due to the physical interaction between the HF wave and the tissues.



Calculated Specific Absorption Ratio (SAR). The RF power deposited on the organic tissue, characterised by the SAR, must be lower than the thresholds laid down in the legislation.

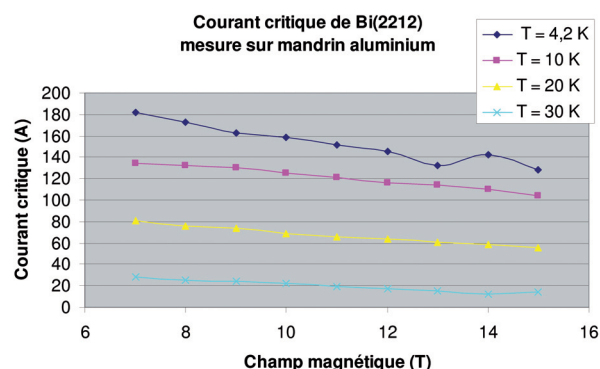
Contribution to the Iter project

Two very important events stood out in the 2004/2006 period as regards the Iter project: the decision taken in June 2005 to build the Iter fusion machine in Cadarache, and the implementation of a "broader-based approach" between Europe and Japan which, in addition to the construction of Iter, is specifically aimed at the construction of two other large items of equipment in the fusion field. The equipment in question is the Japanese tokamak superconductor JT60-SA and the high-intensity accelerator Ifmif, designed to study the effect of radiation on materials that will be used in future fusion reactors. The construction of this accelerator is to be preceded by that of a prototype (Ifmif-Eveda).

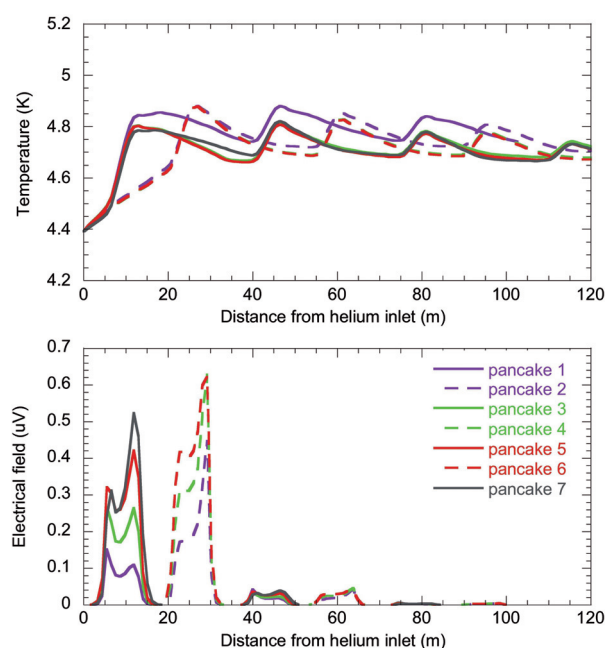
For all these projects, the work is to be performed between the three departments of the Physical Sciences Division involved in fusion: the Department of controlled fusion research (DRFC/Step), the Department of fundamental research into condensed matter (DRFMC/SBT), the Department of astrophysics, particle physics, nuclear physics and related instruments (Dapnia/SACM and SIS), under the auspices of a special coordinating organisation, the three departments coordination committee (CC3D).

Technical activities in 2004-2006 on the Iter project were focussed mainly on preparing bids for calls to tender for the European fusion development agreement (Efda). The SACM was particularly involved in the design of a high-field dipole for a test station for Iter conductors, the construction of a winding model with an innovative resin, thermohydraulic studies on Iter toroidal coils and their cooling systems, studies of the distribution of cryogenic fluids and the characteristics of superconductors at high critical temperatures. Some of these tasks have been completed and other are still in progress.

In parallel with this technical activity, organisational work was undertaken to define the possible participation of SACM in Iter projects (on the basis of a number of tasks proposed by Efda) and JT60-SA. Specifically, SACM has proposed its services in the cold toroidal coil tests.



Measurement of the critical current of a round superconductor strand at high critical temperatures in relation to the magnetic field and the temperature (Efda HTSPER task).



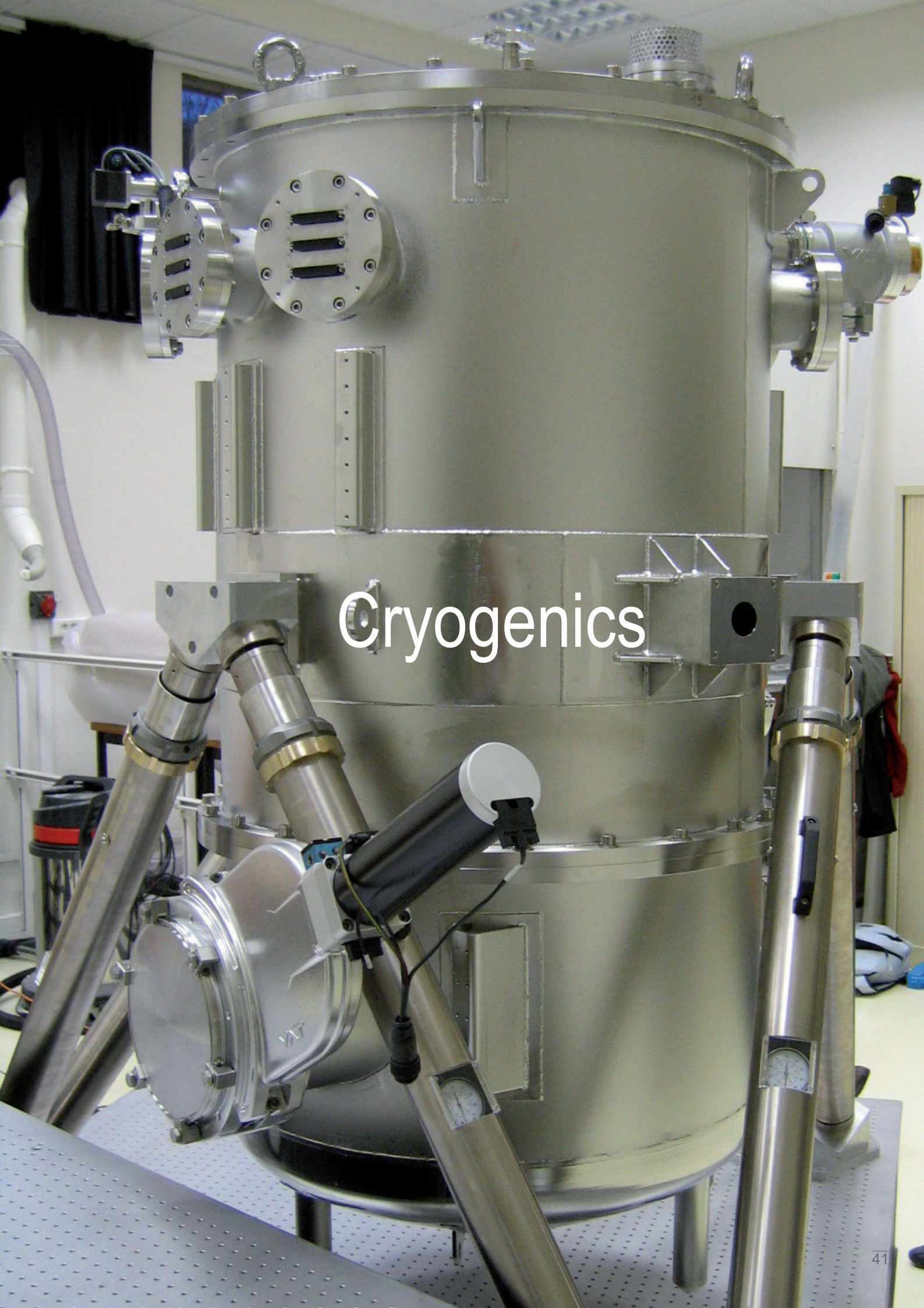
Temperature and electrical field distribution along the 3 innermost turns of pancakes of a toroidal coil at the end of plasma burn (Efda THCOIL task).

The conductors are cables in conduit in Nb₃Sn cooled by supercritical helium.

Electric field is a result of magnetic field, strain and temperature distribution along the conductors. The digital simulations are carried out with the Vincenta code developed by the Efremov Institute in Russia.

In 2006 the groundwork was carried out for the Ifmif-Eveda project, in terms of technical matters on the basis of previous studies and, in respect of the organisational arrangements, with the distribution of tasks between the partners and the setting up of the international team in Saclay. More details regarding the Ifmif accelerators are set out in the description of the high-intensity ion linear accelerators.

Cryogenics



Alternative cryogenics for temperatures above that of liquid helium

It is relatively easy to envisage cooling to the controlled temperature and the extraction of power with helium in gaseous form, but it is more difficult to adjust these two parameters to achieve temperature control to a hundredth of a degree. The first step was taken with the Clas target ten years ago, but it relied upon the condensation of intermediate gases (hydrogen and deuterium) to ensure the required level of stability.

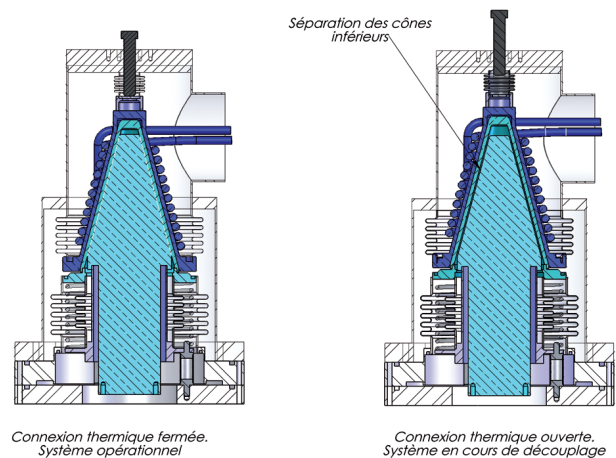
During the tests of superconductors at high critical temperatures, we extended this technique to the temperature range of 5 to 80 kelvins for power of the order of 1 to 10 watts without an intermediate fluid. The technique developed uses 3 levels of exchangers connected in series in order to refine these parameters. The main applications concerned by this process are the Mirim cryostat and the Cétacé test station sample holder.

Within the framework of the nuclear physics project Agata, it is necessary to cool 180 crystals of germanium to the temperature of nitrogen without acoustic vibrations. These crystals are placed in groups of three in 60 cryostats. In addition to the substantial quantities of nitrogen required to absorb the power to be extracted, the vibrations were so loud during the cryostat filling phase that it was necessary to call a halt to the measurements.

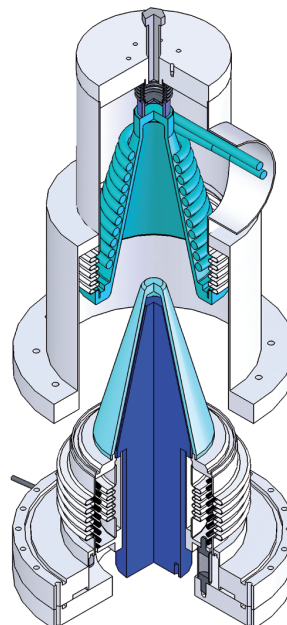
As an alternative solution, we have proposed cooling these crystals with gaseous helium whose fluidic properties should allow continuous silent operation. We studied a solution using a thermosyphon in gaseous helium, between the crystals and an exchanger cooled with liquid nitrogen positioned far enough away so as not to disturb operation. The studies have shown that this system would be viable within the 5 to 15 bar pressure range at a temperature of 77 kelvins with temperature variance of the order of ten kelvins.

The main difficulty with this detector technology is knowing how to dissociate the crystals from the cooling system when cold. Consequently, we have studied a thermal coupling system fitted with a switch which makes it possible to insulate the crystals thermally during this operation.

These 2 cryogenic studies are important, as they open the way for the thermal use of high-critical temperature superconductors over a large range of temperatures with a good level of operating flexibility.



Sectional view of the coupling system studied for Agata. The thermal switch is made up of two cones that fit together and move nearer or further apart as required. When the switch is off, the cones are in contact and the mechanical voids are filled with helium gas. When it is open, the cones are kept a few millimetres apart and a rough vacuum is maintained in the volume between them.



3D view of the coupling system studied for Agata during the uncoupling operation. The navy blue central cone is isolated from the exterior by the thermal switch which provides the radiation protection and the vacuum barrier that are essential to maintain it at 80 kelvins.

The cryostat in the Mirim imager

The JWST (James Webb Space Telescope), future successor of the HST (Hubble Space Telescope) in the year 2013, is being built by Nasa in partnership with Canada and Europe through the ESA (European Space Agency). In this programme, the Astrophysics department is responsible for the construction and testing of the Mirim (Mid infra-red imager) detection instrument which operates in the medium infrared range (5 to 27 μm) to observe the formation and development of galaxies and distant planetary systems.

The SACM studied and established the specifications for the construction of the cryostat for the imager test bench. It is designed to cool the whole instrument, i.e. the opto-mechanical structure and the infrared detector, to a very low temperature (5 to 20 K). The temperatures will be independently controlled with a precision of $\pm 0.1\text{K}$ for the optical structure and $\pm 0.01\text{K}$ for the detector itself in nominal conditions. Cooling and heating stages of around 10 kelvins are necessary to limit the stresses relating to shrinkage and expansion during these phases.

For reasons of stability, it was decided to use liquid helium for cooling; we use the sensible heat of the gas to maintain the desired temperature.

The Mirim assembly will be located inside a thermal shield at 4.2 K directly linked to a 100-litre liquid helium

tank. A second shield at 70 K cooled by circulation of gaseous helium will reduce the radiation required for the first. This assembly is placed in a stainless steel vacuum chamber in order to hold back the heat being transmitted to it by convection and conduction in the air.

Two helium exchanger systems allow the desired temperature of the detector and the opto-mechanical structure to be controlled. The regulation of these temperatures is carried out by controlling the flow of helium in the two systems, and is adjusted more finely by small heating elements located on the heat exchangers. An automatic filling system ensures the level of liquid helium is topped up in the tank, so that the cooling is maintained throughout the test periods



Cryostat mounted on the optical table by means of a hexapod.

The Spaladin hydrogen target

A new liquid hydrogen target will be installed as part of the spallation programme at the GSI research centre near Darmstadt in Germany, which studies the interactions between heavy ions and protons. This target must reduce the parasite interactions both in the target walls and in the target itself to a minimum.

Experiments such as Spaladin choose to accelerate heavy nuclei in the form of ions, and make them interact with hydrogen nuclei to obtain a spallation reaction. The liquid hydrogen is contained in a target that the heavy ion beam strikes. Parasite reaction between the heavy ions and the hydrogen chamber materials – windows – must be limited to the absolute minimum. The physicists have chosen to reduce the thickness of the target and the windows, whilst maintaining an adequate interaction rate.

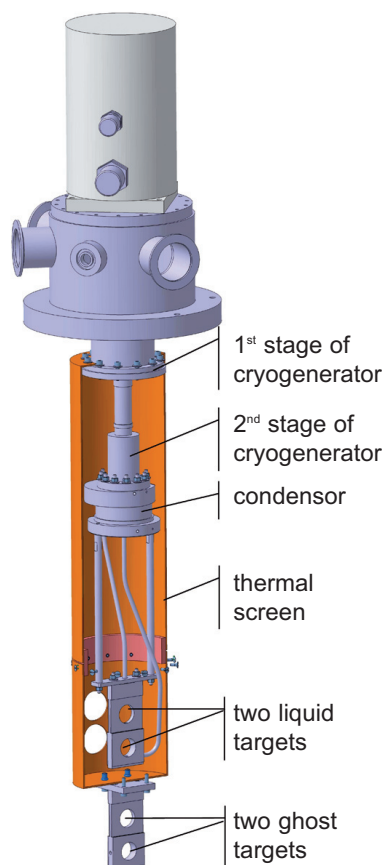
Dapnia's personnel have perfected a new liquid hydrogen target 3 mm in thickness delimited by ultra-thin windows made of aluminised mylar 6 microns in thickness and 25 mm in diameter. The target is in vacuum, and this makes it necessary to work with a very low hydrogen pressure of 150 hPa which corresponds to a temperature of 15.2 K.

The design of the target's filling and draining system is original. The buffer volume that contains the gas is

deformable and this allows this pressure difference to be maintained, whatever the state of the system (initial vacuum, liquefaction, operation, return to atmospheric pressure).

To control the operation of this new target, an electronic and computerised control system is used. It manages the movement of the cryostat so as to move the different targets into the beam's axis: Two "liquid" targets and two "ghost" targets fixed on the lower part of the thermal shield, and an "empty" position. This system also regulates the temperature of the cryogenerator with a stability of 0.01 K. Finally, it manages the alarms and security of the installation in the event of faults (vacuum, hydrogen pressure, loss of temperature regulation or a broken window)

The new target will be used in the next Spaladin experiments that have been accepted by GSI's scientific recommendation committee, and later in the R3B project on the future FAIR machine.



Cross view of the spaladin hydrogen target system.

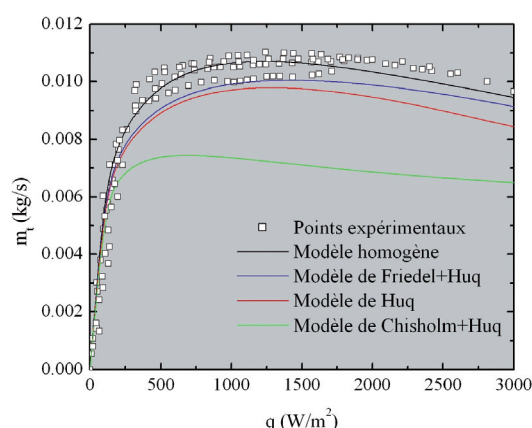


Cryostat for targets, in the background, and hydrogen gas reserves in the foreground.

Two-phase Helium natural circulation flow

This work, which is essentially experimental, is aimed at the study of different parameters in a natural circulation helium loop such as mass flow rates, temperature differences at the wall, pressure variations in the flow, heat transfer coefficients and critical heat fluxes. It is part of the studies of the cooling system of the superconducting magnet in the Compact Muon Solenoid (CMS), the detector that is currently under construction at Cern for the Large Hadron Collider (LHC).

The hydraulic parameters of total mass flow and pressure variation can be modelled using a simple model, the homogeneous model, where the properties such as the density of the two phases are homogenised. The accuracy of the homogeneous model can be explained by the fact that the difference in the physical properties of the two phases is small. The ratio of liquid density to gas density at 4.2 K is only 6, while for water it is 1,000, and that of viscosities is 3. This model has made it possible to validate a numerical simulation predicting the flow rates in the CMS magnet.



Total mass flow rate as a function of the heat flux in a 14 mm diameter tube. The total flow rate is measured by a venturi flowmeter. Different models have been tested and compared to the experimental results: the homogeneous model gives the most accurate results.

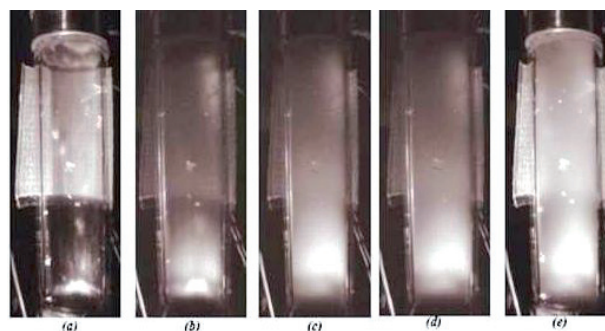
The thermal properties of the flow are also useful for magnet manufacturers, especially the wall heat transfer coefficients. With low heat fluxes, we find a regime dominated by forced convection and, with high heat fluxes, a regime dominated by nucleate boiling. The correlations of different authors have been compared to the experimental results, taking account of the two phenomena, with the help of power laws and weighting coefficients. A correlation developed at the SACM gives greater accuracy and predicts the results to within approximately 15%.

Finally, what we know least about is the flow structure, i.e. the geometrical distribution of the two phases in the flow. The cryogenic environment and the decision to be non-intrusive make the creation of a visualisation system difficult. The visualisation system used is

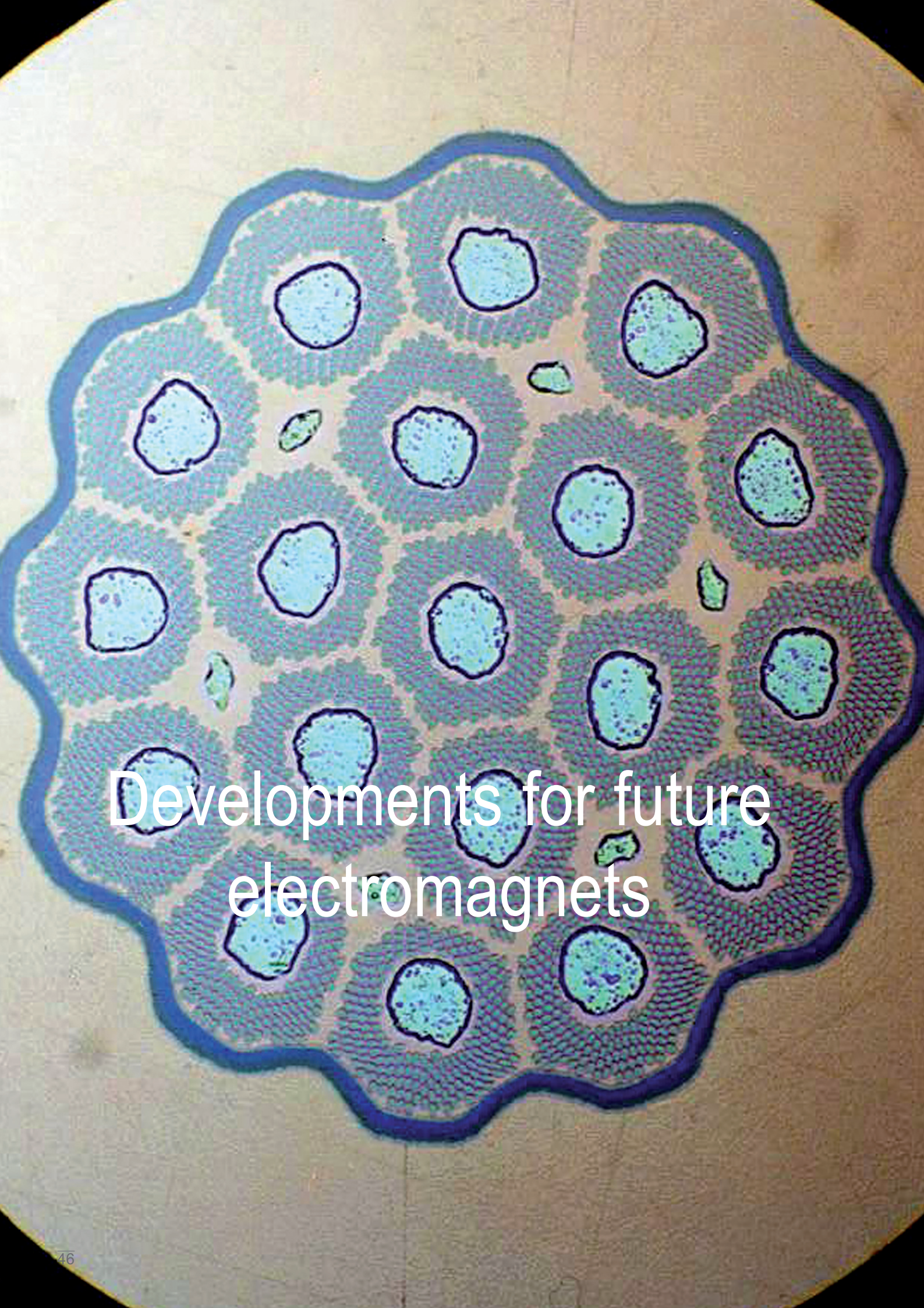
composed of a glass tube stuck onto bellows and a conventional CCD camera. This device has made it possible to provide images of such a flow. The first results are encouraging although problems of blurring have not yet been resolved. The formation of bubbles is clearly visible, but it was difficult to make any conclusions about the flow regime (bubbles, agglomerated bubbles, dispersed air pockets, etc.). Further work is planned to improve the system.



Visualisation device. The glass tube is connected to the study tube by gluing to bellows and metal seals. The CCD camera, with a live view, is maintained at 80 K. The lighting system is composed of external systems (halogen and ordinary bulbs) and an internal optical fibre system.



Visualisation of the flow as function of heat flux. a) 0 W/m², b) 100 W/m², c) 1,000 W/m², d) 2,000 W/m², e) 3,000 W/m².

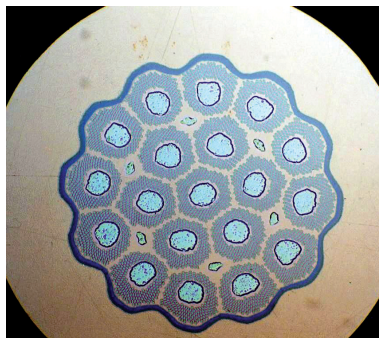
A microscopic image of a biological specimen, possibly a cross-section of a plant or animal tissue. The specimen is roughly circular with a scalloped, irregular border. It is filled with numerous small, light blue, oval-shaped structures, each with a darker blue outline. These structures are arranged in a somewhat regular pattern, separated by a fine, granular, light blue matrix. The entire specimen is set against a light brown, textured background.

Developments for future
electromagnets

Niobium-tin quadrupole model

The objective of the project is to design, build and cold test a niobium-tin (Nb_3Sn) quadrupole magnet prototype based on the design of the quadrupole magnets in the LHC, made of niobium-titanium (NbTi). The critical temperature and critical field of the superconducting compound Nb_3Sn are around double that of NbTi . However, it has some disadvantages. A high temperature thermal treatment is needed to produce it (greater than 600°C) and it is very fragile, with critical parameters sensitive to deformation. It was necessary to rethink the design and manufacture of the coils so as to reduce the risk of damaging the conductor.

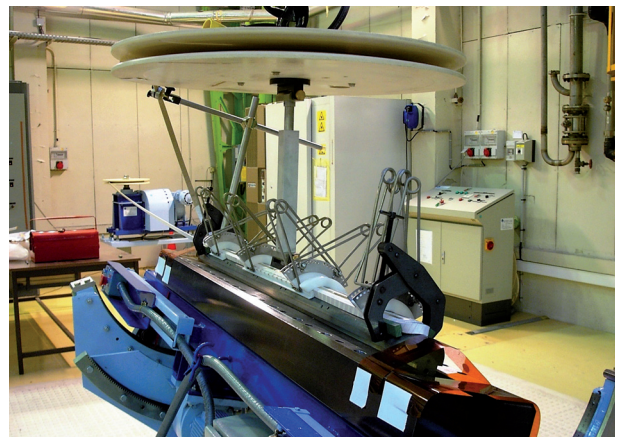
Cross-section of a niobium-tin wire after heat treatment (courtesy of Alstom/MSA).



The coil is made from an unreacted conductor, which contains the precursor of the Nb_3Sn compound, insulated using a fibreglass ribbon. Once the coils are formed, they are subjected to heat treatment at 660°C for 240 hours to allow the formation of the Nb_3Sn compound with the correct stoichiometry. After the heat treatment, the coils are impregnated with epoxy resin under vacuum to ensure mechanical cohesion and allow them to be handled without risk of the conductor being damaged. It takes approximately two months to make a coil.

The manufacture of the Nb_3Sn conductor was carried out under a collaboration agreement with Alstom/MSA which was concluded in March 2004 with the delivery of 5 lengths of 60 m of Nb_3Sn cable, to make 4 coils for the model magnet and one spare coil. 2004 was devoted to validating the winding components and tools thanks to the manufacture of the first test coil. The reaction and impregnation tools were made in the first half of 2005; the tools were validated firstly on the first test coil, and then on a second coil completed in December 2005.

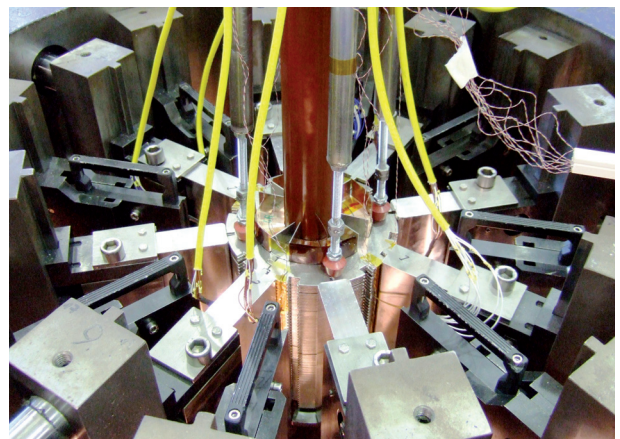
The manufacture of the first certified coil was started in December 2005. Six certified coils were made in 2006 (one more than the number that was originally planned). The electrical and mechanical tests on the coils were carried out at Accel's factory in Germany, using the equipment used for the LHC quadrupoles. Three assembly and bracing tests were carried out on the 200 mm high models, cut out on the right part of the two test poles and representative of the cross-



Winding of a Nb_3Sn pole in building 122 at CEA Saclay.

section of the magnet; these tests validated the mechanical calculation that were the basis for the magnet's design, and the installation procedure of the stress sensors designed to monitor the changes in the coils during the manufacture and the magnet tests.

The assembly of the magnet, the first hot tests and manufacture of the cold mass for the cold tests are planned for the first half of 2007; the cold tests will follow in the second half of 2007.



Bracing test at Accel's factory in Germany.

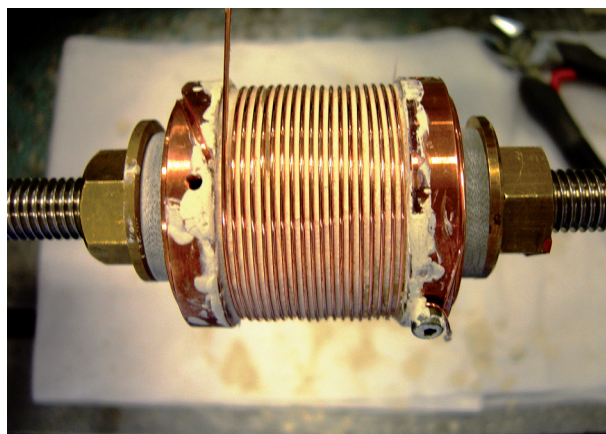
Developing ceramic insulation for superconducting cables

The aim of developing ceramic electrical insulation is to study the implementation of insulation that can withstand the high-temperature heat treatment (600 to 700°C) required for the formation of certain superconductors, in particular those made of niobium-tin (Nb_3Sn). The conductors are covered with fibreglass ribbon coated with precursors which react during the heat cycle, forming the insulation and ensuring the mechanical strength of the coil. In this way, two difficult stages of manufacture are eliminated: the handling of the reacted coil, which is very fragile, to remove it from the reaction mould and insert it into the impregnation mould, and the under vacuum impregnation stage with epoxy resin.

The work performed as part of Alexandre Puigségur's thesis made it possible to define the characteristics of the impregnation solution and showed that the use of this insulation did not affect the properties of the Nb_3Sn strand. A small solenoid was successfully tested under strong external magnetic fields (12 T) in the department's Cétacé test facility and produced a self-field of 3.8 T with a transport current of 740 A.

A second superconductor winding in Nb_3Sn (height 54 mm, external diameter 72 mm) with 400 turns was made, then tested in the Christiane test facility to assess the mechanical resistance of its insulation. Supplied with a current of 590 A, the demonstrator produced an induction of 5.6 T at its centre. By adding the magnetic field of the demonstrator to that generated by the Christiane magnet, we obtained a magnetic induction of 10 T at the centre of the system. No damage was observed in the study range (30 MPa traction, 60 MPa

compression), and the transitions observed were systematically linked to the intrinsic performance of the Nb_3Sn strand used.



Nb₃Sn Wire coil during manufacture.

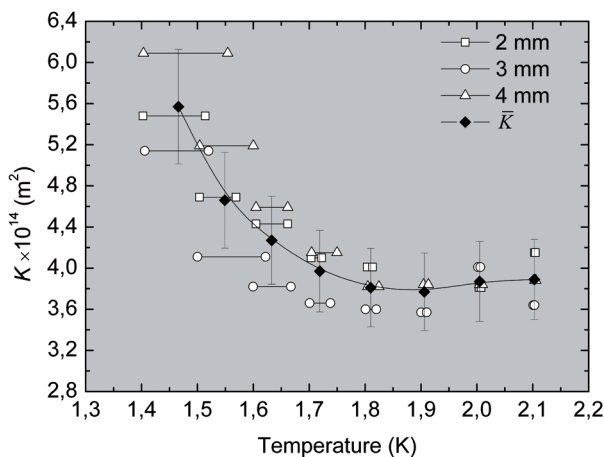
Heat transfer through porous mediums in superfluid helium

It is necessary for manufacturers of superconducting magnets to understand the heat transfer in the windings in order to study thermal stability. For magnets cooled by superfluid helium, such as for example the dipoles and quadrupoles of the LHC, thermal resistance, created by the electrical insulation of the cables, forms the main thermal barrier against cooling. The emergence of Nb_3Sn magnets with a strong magnetic field has led designers to research new insulation systems made from ceramic-based materials. These materials can have a lower porosity than conventional insulation and should reduce the helium cooling accordingly.

An experimental system was developed to study of heat transfer through reference samples. In this type of confined environment, the two regimes of heat transfer in superfluid helium are found: the Landau's regime (regime without superfluid vortex) and the regime of Gorter Mellink (regime with vortex). In Landau's regime the measurements confirmed the law of porous

mediums (Darcy's law) and showed that material permeability can be extracted from it. This permeability, the capacity for a fluid to pass through it, is dependent on the temperature since the "flow" is not isothermal.

This study also demonstrated the concept of tortuosity in superfluid helium: the thermal or dynamic path



depends on the geometry of the porous mediums and not on the thickness. With a high heat flux we found that the Gorter-Mellink regime applies exclusively, where permeability does not play a role but only tortuosity and the heat transfer cross-section. The experimental results showed that the tortuosity varies only by 10% in relation to temperature, which is within the measurement error bar.

Permeability, as a function of the temperature, for different thicknesses of Al_2O_3 materials with an identical porosity of 32%. K is the average value of permeability for the three samples. A 10% deviation of K is presented and compared with the dispersion of the results.

Use of superconductors at high critical temperatures

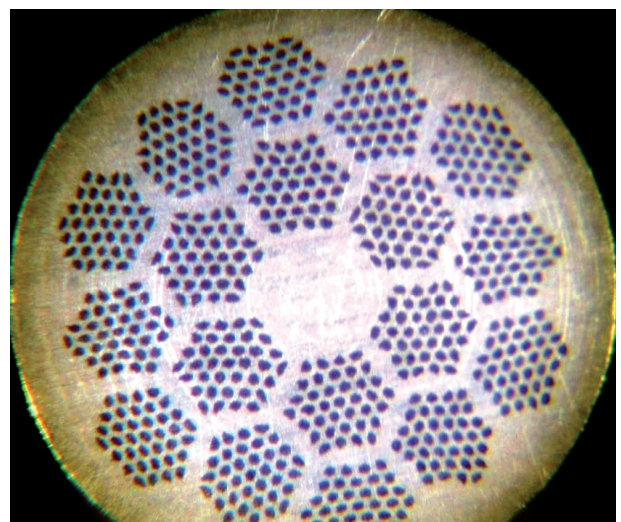
Physicists and engineers have always been intrigued by high transition temperature superconducting materials ever since their discovery in 1986 by Bednorz and Muller. These materials offer new prospects for the SACM. Not only is their ability to transport an intensive electrical current at superconducting state preserved at temperatures in excess of 60K (for certain materials), but most importantly they keep their superconducting properties with an induction of 30T, providing they are kept at the temperature of liquid helium. Thus it becomes possible to make superconducting magnets that function between 30 and 40K or produce magnetic fields of 30T.

In addition to the modernisation of the test facilities, where tests on these new superconductors are conducted, the SACM, with the help of an industrial group, has begun development on the construction of a round strand that can be cabled, and the research of applications requiring the use of magnetic fields higher than 20T.

The developments of conductors are focused on measuring the performance of the existing ribbons, particularly for use in fusion tokamaks. A joint study carried out with the Department of controlled fusion research at Cadarache sets out to qualify Bi2212 superconducting compounds and to study the consequences of their use in the operation of a machine such as the demonstration fusion reactor, Demo.

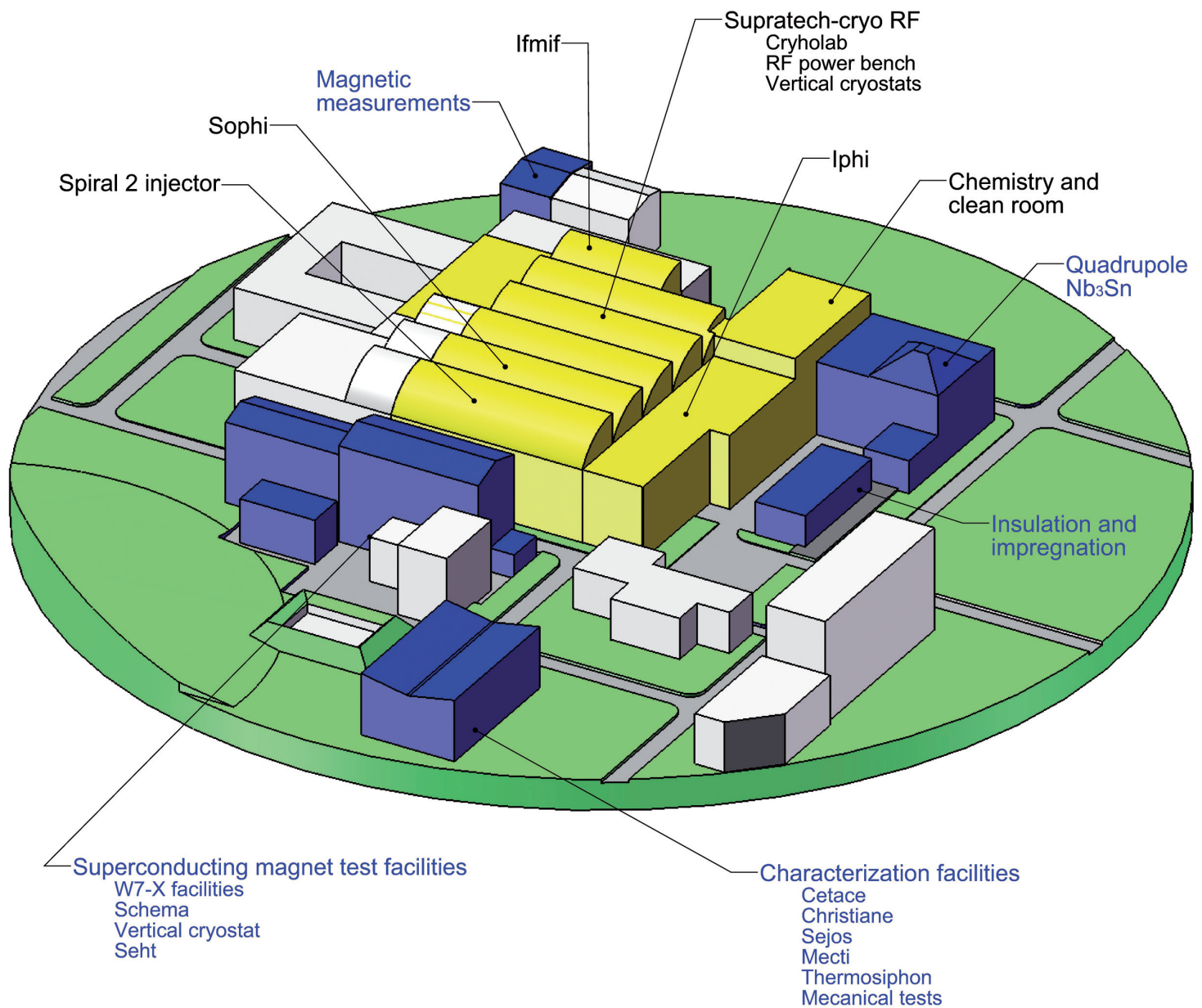
Applications identified as requiring magnetic fields higher than 20T are high field nuclear magnetic resonance (NMR) and magnetic levitation. High field NMR makes it possible to analyse the structure of complex molecules; it is currently thought that 20% of unknown molecular structures could be decrypted with instruments which function at the resonance frequency of a 1GHz proton, corresponding to a magnetic field of 23.5T. Magnetic levitation makes it possible to overcome the earth's gravitational pull in a para-

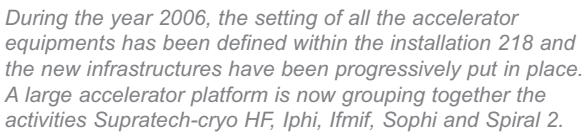
gnetic or diamagnetic environment, and to recreate the conditions of experiments onboard spacecraft. This technique allows us to obtain better crystallographic purity in the development of crystals, to study anomalies in wettability phenomena and changes to self-organisation phenomena in biology or heat exchanges in walls.



Round strand superconductor Bi2212 with 0.8 mm diameter (courtesy of Nexans).

Accelerator and cryomagnetism platforms





Safety and environmental protection

The accelerator, cryogenic and magnetism department of Dapnia integrates into its activities an environmental strategy (ISO 14001) and also risk control procedures implemented by CEA Saclay. The SACM covers two security perimeters on the site (installations No. 82 and No. 218). They cover an area of 32,000 m² with 17 buildings and an average workforce of 140 persons. There are 17 facilities classified for the protection of environment (ICPE). The department's "security environment" team is composed of a Facility Manager, two deputy managers, advised by two facility security engineers and two security officers. In 2006, 11 safety inspections, 4 exercises and 80 safety training course days have been done for SACM. The perimeter of the ISO14001 certified area increases each year. The object is to get the certification for the SACM completely in 2009.

Installation No. 82

Two laboratories of the SACM are included in this installation: the LEAS and the LCSE.

- ▶ 12 buildings
- ▶ 10000 m²
- ▶ 67 workers from CEA (SACM, SIS)
- ▶ 9 ICPE
- ▶ 3 local first-aid teams with 22 volunteers

Activities concern running and development of test facilities and laboratories, cryogenics R&D, liquid helium production (150 m³ per year), prototype mechanical workshop, magnetic measurement, insulation - impregnation and material characterization laboratories.

The transfer and the regrouping of chemical activities (insulation and impregnation) in the same building happen in 2005-2006.

10 persons responsible for buildings (titulars and substitutes) supply the safety team for several actions because of the dispersion of the 12 buildings.



Insulation and impregnation laboratory.

Installation n° 218

That installation has been created in October 2005. The LEDA and LESAR laboratories are included in the installation.

- ▶ 6 buildings
- ▶ 22000 m²
- ▶ 70 workers from CEA (SACM, SENAC, SIS)
- ▶ 8 ICPE
- ▶ 2 local first-aid teams with 17 volunteers

Until the end of 2005, it was the Saturne nuclear installation No. 48. Today it is declassified.

The area of this installation is now strongly rearranged for the implementation of the Cryholab, Iphi, Sophi, Ifmif and Cocase projects.

In September 2006, the chemical laboratory of l'Orme des Merisiers, located near Saclay, has been connected with the installation No. 218. It will join the Saclay site in 2008-2009.



The hall for the installation of Cryholab under fitting-up.

Photographs: CEA credit, if no other mention

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SACM at the end of 2006