
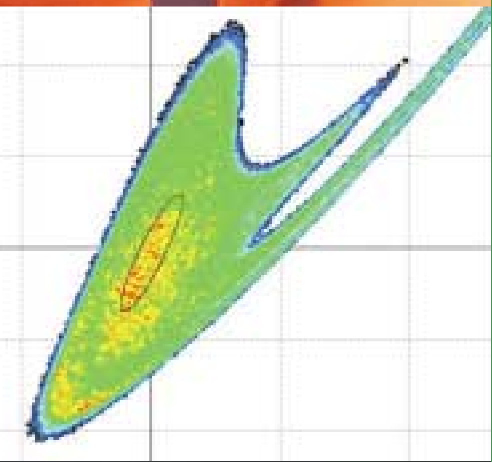

Direction des sciences de la matière

Département d'astrophysique, de physique des particules, de physique nucléaire et de l'instrumentation associée

SACM

Service des accélérateurs, de cryogénie et de magnétisme

2001-2003

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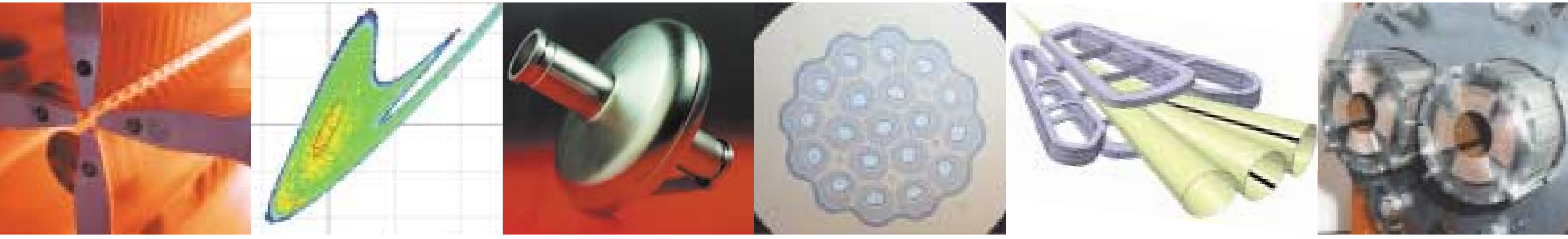
Contents



The SACM

Dapnia/SACM (Service des Accélérateurs, de Cryogénie et de Magnétisme) *covers accelerator and superconducting magnets developments, including the associated technologies.*

In June 2004, 66 engineers and 58 technicians or administrative staff belong to the division. Vitality of SACM also requires the presence of PhD thesis and visitors. The division is organized in four laboratories:

- *LEDA* (Laroratoire d'Etudes et de Développement pour les Accélérateurs)*: general design of accelerator complex, beam dynamics, beam element realization;*
- *LESAR* (Laboratoire d'Etudes des Structures Accélératrices et des Radiofréquences)*: design of superconducting cavities and development of radiofrequencies technology;*
- *LEAS* (Laboratoire d'Etudes des Aimants Supra-conducteurs)*: realization and tests of large scale, high performance – high field or high precision – magnets for accelerators and detectors, and also for MRI magnets;*
- *LCSE* (Laboratoire Cryogénie et Stations d'Essais)*: running and development of test facilities and laboratories, cryogenics R&D, liquid helium production for Dapnia needs and external collaborators.*

Priorities of SACM are driven by the scientific program of Dapnia. A prime mission of the division is also to develop new technologies and instruments to be used by fundamental research including the need of others communities than particle or nuclear physics ones. SACM is supported by the other divisions of Dapnia. It can play a leading role in large scale projects and develop the necessary tools to do so. Technology transfer to industry is a frequent out come of such projects.

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

- *specialized laboratories for electrical, cryogenic, mechanical, RF 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 station for the production of liquid helium and three refrigeration stations associated to test facilities.*

SACM has a strong contribution to the Large Hadron Collider (LHC) accelerator and detectors construction at CERN. During the previous years, the industrial production of the cold masses of the superconducting quadrupoles has started, the first integration of the Atlas toroid magnets has been achieved, and the CMS solenoid modules realization has made a major progress. The division contributes to many accelerator projects, let us mention:

- *the construction of two cryomodules for harmonic cavities for the synchrotron light facilities SLS (Zurich) and ELETTRA (Trieste);*
- *the development of a high intensity proton source which can achieve many scientific objectives;*
- *the technical design study for Spiral 2;*
- *a strong contribution in the CARE integrated activity within the 6th European Community Framework Programme (FP6).*

It should be noted that the personnel of the division and most of its installations are being gathered on the Saclay site.

In the next three years, the priority remains to successfully complete LHC projects. Emphasis will be put on high intensity proton and hadron beams and the division will also strongly contribute to the international effort toward e^+e^- linear colliders. The R&D on Nb_3Sn technology will be pursued. Tests of W7-X coils will continue until 2007 and the division will join the international ITER project when it is launched. A specialized participation to the Neurospin neuro-imaging centre and fourth generation synchrotron light sources will complement this ambitious program. SACM maintains large collaborations with other CEA and CNRS divisions and all large particle and nuclear physics laboratories, and with many industrial companies.

Pascal Debu, head of SACM

LEDA

The ***Laboratoire d'études et de développements pour les accélérateurs*** (LEDA) assembles within the SACM the expertise concerning the design and the realization of particle production, transport and accelerating systems. This includes the physics of charged particle beams through magnetic and radio frequency elements, the realization and operation of sources, injectors and transfer lines for ions or electrons, and the management of accelerator projects.

As of June 2004, the LEDA comprises 16 engineers, 8 technicians and 3 thesis students forming specifically:

- a team of experts in beam physics 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 radio frequency systems;
- a team of experimentalists specialized in the operation of sources and injectors, and in the measurements of beam parameters involving the realization and the use of beam diagnostics;
- an ultra-high vacuum laboratory competent in the accelerator vacuum calculation and in the techniques of thermal treatment and material desorption measurements.

The prominent facts within the last years have been the re-commissioning and the optimization of the high intensity proton and deuteron source Silhi, and the gradual installation of the test facility of a high intensity proton injector, Iphi, in particular of its radio-frequency quadrupole section.

For the future, LEDA is engaged in the exploration of the theoretical and technical basis of the next generation of particle accelerators such as e^+e^- linear colliders, neutrino factories and new generation light sources.

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LESAR

The ***Laboratoire d'études des structures accélératrices et des radiofréquences*** (LESAR) is in charge of the development of the radio frequency (RF) structures and the associated equipments (slow and fast cold tuning system, flange and gasket, couplers for RF power, dampers for high order modes, ...) used for acceleration of particle beams. A broad part of the laboratory is devoted to the development of superconducting cavities, with the aim to improve their performances and to stabilize their operation.

15 engineers and 15 technicians are working in this laboratory, and their various competences are needed for the improvement of the two main topics of the laboratory:

- Studies of accelerating structure from design with RF simulation software to prototypes testing. There are several RF warm and cryogenic test benches in the laboratory. In particular, Cryholab allows testing cavities and their ancillaries in the same configuration as inside an accelerator. This activity also includes tuning of cavities and other RF components, design of electronic and RF control (field stabilization, beam diagnostics, control, interlock), as well as tests with beam of prototypes and structures.
- The behaviour of the superconducting cavities according to the surface treatments (chemistry, water rinsing, heat treatment, oxide layers ...) and various experiments on superconducting materials. Several equipments support this activity: laboratory for the chemical treatments (with electro-polishing facility), a clean room (class 100) equipped with a high pressure rinsing apparatus, a physical vapour deposition (PVD) bench.

Main results for these last 3 years:

- Accelerating gradient of 40 MV/m with a single-cell cavity after a usual chemical treatment and hold a record of 42 MV/m with electropolishing (Saclay-DESY-CERN collaboration).
- Installation and operation of the Super-3HC cryomodules on both PSI (Zurich) and ELETTRA (Trieste) synchrotron radiation facilities.
- Test with the ESRF beam of the cryomodule prototype developed for the Soleil facility.

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LEAS

To meet the needs of the Dapnia physicists in the scope of magnetic fields, the ***Laboratoire d'études des aimants supraconducteurs*** (LEAS) comprises, in June 2004, 19 engineers, 8 technicians, 3 PhD students and one apprentice. The laboratory teams ensure the design and the control of superconducting magnets works integrated into experimental devices, and in particular big size magnets or high magnetic field magnets.

Within the framework of the superconducting magnets design, LEAS exerts its competences in the scope of the coils geometry optimization, design of the superconducting conductor, mechanical, electromagnetic and thermal calculations, and magnets protection in the event of quench. In addition to the magnets design, LEAS is able also to ensure the management of great projects, to deal with the magnets realization and their integration in their cryostat and to ensure the industrial achievements follow-up. Collaboration with the LCSE ensures the magnets control. Measurements cover the tests analyses at ambient and cryogenic temperature with, in particular, quench and magnetic measurements analyses.

These last years were marked by the passage of end of studies to the achievements for the Large Hadron Collider for CERN with an important participation, in Saclay, at CERN and in European industry, to the realization of the Atlas and CMS detectors.

To remain competitive, LEAS has defined several axes of progress. For that it maintains and improves its design tools - calculation tools, in particular - and supports a program of R&D aiming to obtain high magnetic fields. This R&D currently relates to the use of Nb_3Sn and could, in the years to come, relate to the use of new superconducting materials.

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LCSE

The mission of the ***Laboratoire cryogénie et stations d'essais*** (LCSE) is the control of cryogenics for superconductor magnets, accelerating cavities, physics detectors (cryogenics targets, calorimeters) and the production and distribution of liquid helium and distribution of liquid nitrogen.

This control applies in the capacity to conceive, build and operate various installations of very varied size and nature. The fluids implemented are boiling or supercritical helium I, helium II, liquid nitrogen, liquid argon or liquid hydrogen. Cooling machines are cryocoolers, refrigerators with turbines and cooling circuits with circulators or thermosiphon.

The design, realization, integration and development relate the cryostats themselves and their cryodistributions. The principal users are particle accelerators like CERN, GSI, HERA, TJNAF, Ganil or test facilities of the laboratory.

Fifteen test facilities make it possible to determine mechanical, thermal and electrical properties at low temperature and under magnetic field of various materials (insulators, composites, metal alloys and superconductors) and also to test magnets and cavities with their associated components.

The development of the laboratory expertise is ensured by the R&D on the two-phase flow of helium I, fundamental studies on the thermosiphon and thermal transfers in helium II and porous materials.

The manpower of the laboratory in June 2004 is 12 engineers, 20 technicians and 1 PhD student.

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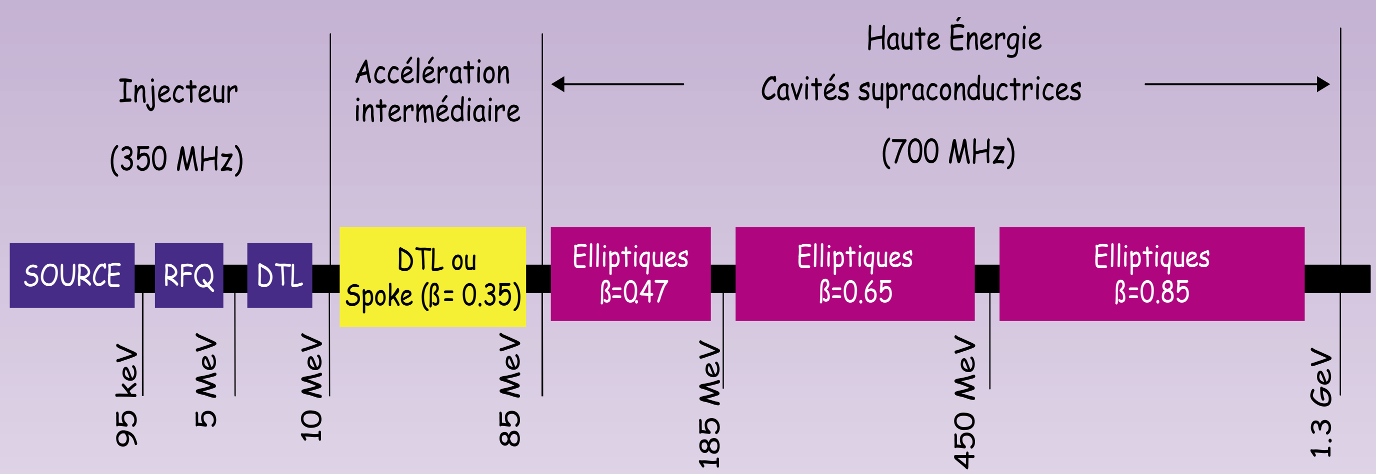
High-intensity ion linear accelerators

High-intensity high-energy linear accelerators, capable of consistently reaching 1 GeV and several tens of milliamps, find numerous applications in nuclear and particle physics, and in condensed matter physics as well. The interaction of a proton beam, accelerated by a Linac of this kind, with a target, enables the production of particles such as radioactive ions, neutrons, neutrinos or muons. These particles then form secondary beams, which may be used for example in the transmutation of nuclear waste or for studying the structure of various materials.

These future generation accelerators will apply technologies that are the subject of ongoing R&D programmes at SACM, such as the Iphi *(Injecteur de protons de haute intensité)* project for the low energy part, and the programme for 700 MHz superconducting accelerator cavities for the high-energy part. Knowledge and experience gained in these two areas have enabled SACM to play an important role in the Spiral 2 project, a complete Linac designed for the study of a large range of exotic nuclei.



The Iphi project

The High Intensity Proton Injector (Iphi) is a prototype of the low energy part of future generation high-current accelerators: a 100-mA proton beam is accelerated to 3 MeV. Its aim is to set up technological, industrial and experimental benchmarks for future Linac designs, and to lend credibility to high intensity proton projects. It does this by confirming our ability to build and then use this kind of installation, and by verifying the validity of the beam dynamics calculations. The performance data of the beam coming from the radio frequency quadrupole (RFQ) are central because they determine the complete Linac structure. Iphi consists of a proton source and low energy beam transport (95 kV), a RFQ accelerator cavity bringing the energy to 3 MeV, and a diagnostic line, designed to measure, as precisely as possible, all the main characteristics of the beam accelerated by the RFQ. A drift tube linac (DTL) prototype, a cavity for accelerating the beam coming from the RFQ, has been developed in parallel. The Iphi project is being carried out jointly between the *Direction des sciences de la matière* (DSM) of the CEA, the *Institut national de physique nucléaire et de physique des particules* (IN2P3) of the CNRS and the European Organisation for Nuclear Research (CERN). Once the trials provisionally set to begin in 2006 at Saclay are over, part of Iphi will be transferred to CERN and eventually incorporated in the Superconducting Proton Linac (SPL) injector.

At the end of 2002, the Silhi proton source was transferred to the Iphi project site. After restart, a few days were enough to extract a beam in excess of 100 mA.

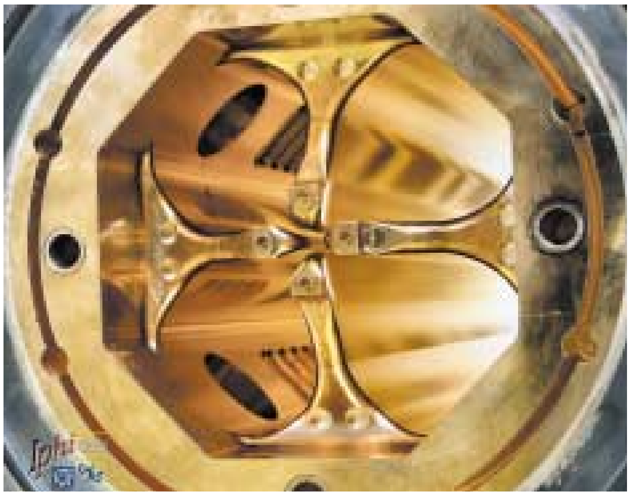
Building the RFQ

A particular feature of this system is the tightness of those of its dimensional tolerances that are linked to high power dissipation. Although its fabrication is very precise, thermal expansion have to be considered. A metal with very high thermal conductivity was needed: copper. Its main disadvantage is its low elastic limit. A metallurgical and a thermomechanical study, as well as a vacuum analysis, have allowed exact determination of the characteristics of copper and the structure of the sections so as to give expansion compensation and satisfy all operating demands.

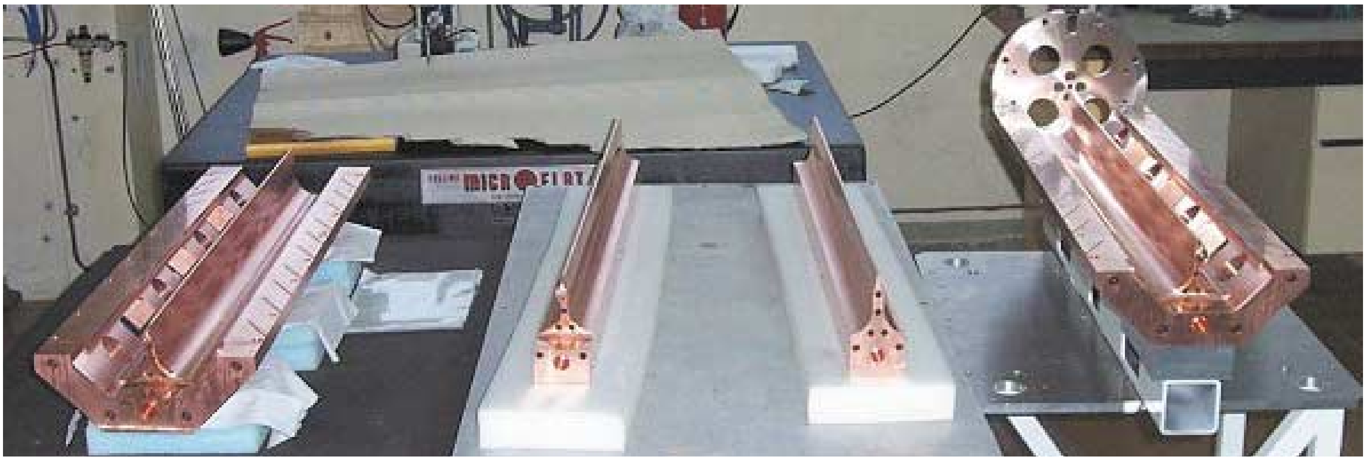
First section prototype of the radio frequency quadrupole for Iphi.

Problems in machining arise mainly from very high variability in the profile of the vanes, the required accuracy, and the need to avoid residual stresses that might cause brazing deformations. This requires rigor in the use of the machine tools, as well as precise checks on them. The flow-process grids and methods of machining have been perfected in the course of several sample tests at the premises of the sub-contractor in question. The brazing study was split into two: on the one hand, assembly of the outer stainless steel flanges such that they do not put out of shape the ends of the vanes; and on the other, assembly of the 4 vanes, also without any ensuing deformation.

A prototype was built and the tolerances were met. It has validated the fabrication flow-process grids, even though brazing repairs have had to be carried out. Machining of the sections is carried out by a private company. They will be brazed at CERN. This financial analysis presupposes that project design and management supervision will be practised by the CEA. Delivery is foreseen for the end of 2005.



One RFQ segment end. The magnetic field turns at this point to pass from one quadrant to another. The very rounded shapes minimise and distribute the RF power deposits.



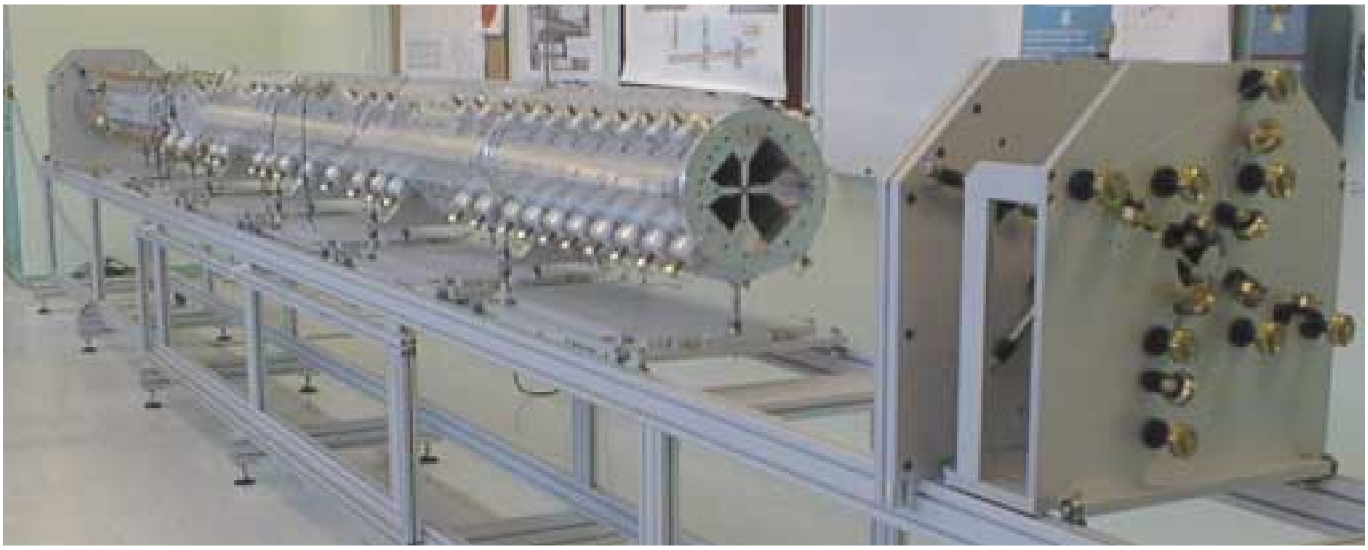
The 4 RFQ vanes are machined before being assembled and brazed. This split into 2 minor vanes (in the centre) and 2 major vanes helps adjustment of the assembly.

Procedure for RFQ radio frequency tuning

A radio frequency (RF) cold model of the RFQ has been built with the aim of verifying the design based on three- dimensional calculations, of evaluating a certain number of features which cannot be easily accessed from these calculations, and finally of demonstrating the effectiveness and precision of the algorithms for RF tuning. This is a modular model: six 1 m sections can make up RFQs of variable length or segmentation that are adjustable using slug tuners, coupling plates of adjustable thickness and dipolar stabilisation rods. The RF field inside the cavity is measured using a bead pulling technique: an automatic bench, guided using LabView©, checks the four-quadrant displacement of a small metal bead and triggers the vector network analyser. Raw data (~8000 samples) are first pre-processed. This deals with phase drift and non-linearity compensation, alignment on a common positional scale, noise reduction, reconstruction of voltages and their signs, as well as of boundary conditions (extreme values, connections). A numeric model then calculates the corrections for line parameters and the dimensions of adjustable components. It is also used to check electric symmetry of the RFQ during construction. We have developed user-friendly software that allows execution sequencing of the 38 processing-blocks presently in existence. A common hub automatically monitors software changes and variations in processing parameters, ensuring operational continuity of the program over the years.

In our model, a four-wire loaded transmission line under load simulates the RFQ. A rigorous mathematical analysis enabled us to establish convertible relationships between infinitesimal perturbations of line parameters and the resulting perturbations of inter-electrode voltages. Tuning adjustments therefore generally consist in a certain number of repetitions of the cycle, where perturbations of voltage are measured and line parameters are corrected. Convergence conditions are also demonstrated mathematically.

Our model was tested successfully in various configurations: 1 segment of 1 m, 1 segment of 2 m, 1 segment of 3 m, 2 segments of 1 m coupled to electrodes of consistent shape, then to electrodes of variable shape, and recently 2 coupled segments of 2 m, where voltage errors of 40% have been brought down to less than 2% in 3 repetitions. Line symmetry errors can be identified to a few parts per thousand. After these tests are successfully completed, the model can be used in RFQ design, for example for RF stability analysis, as well as for thermal deformation sensitivity analysis etc. In effect, it can be used for any kind of cavity.



Modular RFQ model for RF measurements. The six 1 m sections are assembled. The two outer plates (one of them is in the foreground) are there to tension the wire to which the perturbator, a metal cone, is attached. Antennas sited on each side flange map the field resulting from this perturbation.

DTL prototype

The DTL is a RF accelerator structure for ions, both light and heavy, of a design dating back to the 1950s. Nevertheless it remains an up-to-date machine, as shown by its use in a recent accelerator, the Spallation Neutron Source in the United States. This structure, with alternating accelerating gaps and drift tubes (metal tubes protecting the beam from the deceleration phase of the RF wave, and containing the quadrupoles necessary to focus it), is interesting in the case of a high power machine like Iphi because of its reliability and its performance (accelerator efficiency, shunt impedance, etc.). Nevertheless, a DTL suited to proton currents of several tens of milliamps has never been built. The difficulties are linked in particular to the force of the focusing magnets that are usually located in the

The two models of magnetic quadrupoles developed for the DTL. On the left: conventional cobalt iron magnet; on the right: innovative magnet with external water cooling.

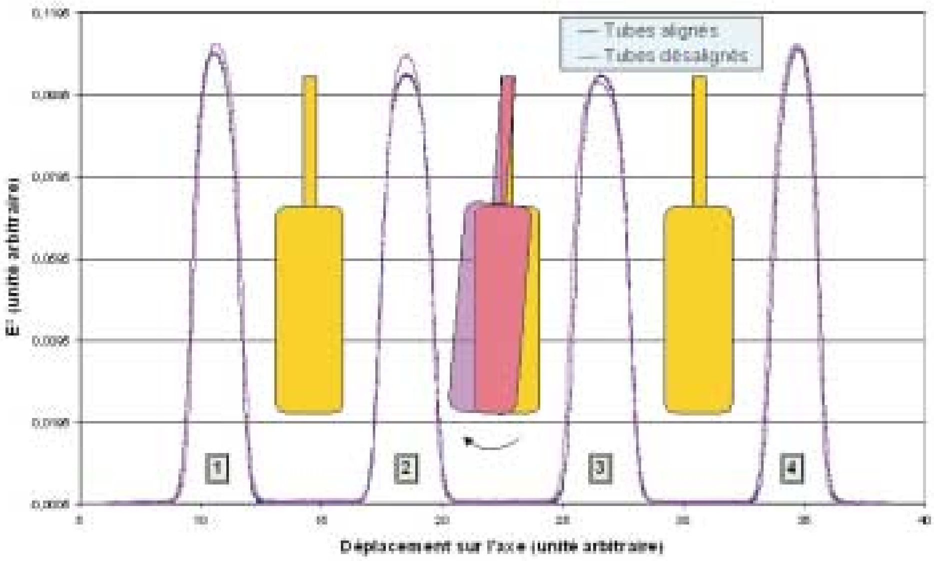
small drift tubes and to the power deposits on the walls of the machine and on the drift tubes.

For this reason a DTL prototype has been designed and built. It represents the initial part of the complete DTL, the most complex part, since it is the most compact. It contains four accelerating gaps and three complete drift tubes, two of which contain a focusing magnet. These latter are of differing designs. The first is conventional, made of cobalt iron and supplied by hollow conductors (which are therefore self-cooling). Nevertheless, given the highly reduced dimensions, this technology is at its limits; a new concept of magnet where the conductors are cooled from outside has been developed. This innovative technology ensures greater thermal and magnetic efficiency.

The drift tubes containing these magnets are made of pure copper and are electron beam welded. Build tolerances are in the order of a hundredth of a millimetre. The outer wall of the prototype is made of stainless steel, coppered on either side using an electrolytic process. The internal copper plating, with a thickness of 50 microns, allows attainment of electric conductivity necessary to obtain good RF characteristics, whereas the external copper plating gives the casing the right thermal properties to dispose of the high power deposits.

This prototype has been tested under real power conditions at CERN. 50 kW were continuously injected into this machine, which has a length of 35 cm and a diameter of 50 cm. Different tests were carried out: cold-model accelerating field testing, and then hot-model, using an X-ray spectroscopy technique; analysis of the thermal behaviour of the cavity; thermal disalignment of the drift tubes caused by thermal effects; influence of the joints and contacts on the quality and vacuum factor etc. These tests have allowed us to check the feasibility of the concepts involved, as much at the level of the mechanics and technology of the accelerator cavity as at that of the focusing magnets, and to identify possible improvements. The target objectives were met: two quadrupolar magnet models have been successfully tested, and a fabrication technology suitable for a high power DTL has been identified, opening up the way to a complete machine.

Internal view of the DTL prototype. Cleanliness and rounded forms are the keywords. The three drift tubes are perfectly aligned and must remain so during operation.



Cold-model analysis of accelerating field during DTL prototype testing. The blue curve corresponds to a measurement when all the drift tubes are aligned. The pink curve indicates the effect of single drift tube disalignment on the accelerating field evolution.

The Spiral 2 project

The aim of the Spiral 2 project is the study of neutron-rich or neutron-deficient nuclei, far removed therefore from the valley of stability, using the isotope separation on-line (ISOL) method, by covering a much greater area of radioactive ions and at intensities far greater than those at present available at the laboratory of the *Grand accélérateur national d'ions lourds*, also known as Ganil, at Caen.

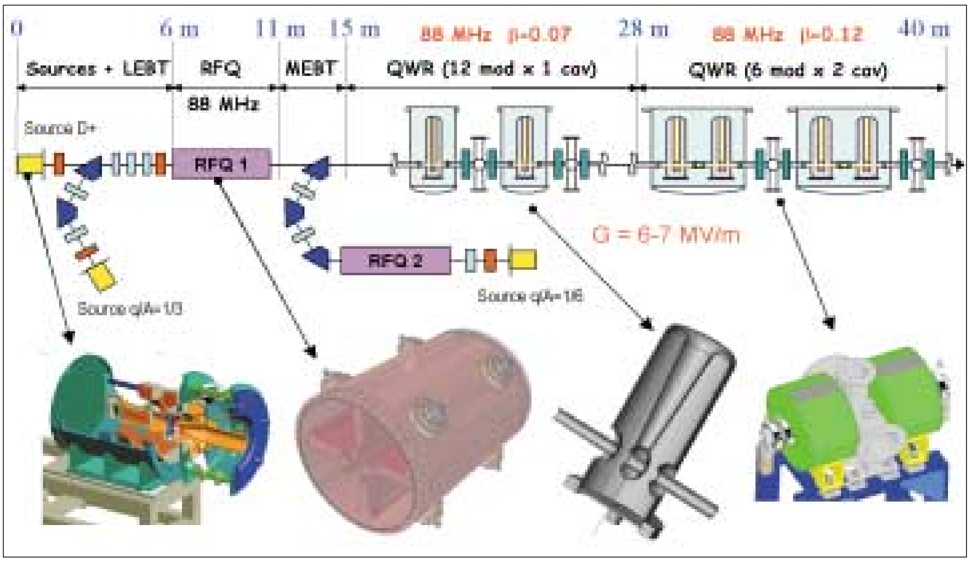
First studies at Ganil on the possibility of producing high-intensity secondary beams, with a view to extending the range of the nuclei produced by the present Spiral facility to medium- mass nuclei, started as early as 2000. The proposed method to produce the radioactive ions relies on fission induced by light particles, either with or without an intermediate target to generate high fluxes of neutrons. In order to compare this method with the alternative photo fission method, a Preliminary Design Study was recommended by the Scientific Council of Ganil and resulted in the "LINAG Phase I" report. The "LINAG" option was finally chosen in Spring 2002 after a series of reviews commissioned by a Committee comprising experts from different major laboratories. Following this recommendation, the DSM and IN2P3 institutes decided to launch a two-year detailed design study which started in November 2002. A collaboration agreement between CEA, CNRS and the *Region Basse-Normandie* were signed in September 2003, with the aim of bringing the scientific objectives up to date, clarifying the chosen technical options and defining the necessary R&D programmes. In addition, the final report must include the results of safety and radiation protection studies, an estimate of construction costs and a construction schedule.

The team is made up of individuals belonging to 8 different laboratories, and this represents the work of 60 full time equivalent people over 2 years. Besides the management of the project (the project leader is member of SACM) the contribution of SACM focuses on the components of the accelerator: their design, development and fabrication needed to validate the technical options.

The chosen method of production relies on fission induced either by fast neutrons from a carbon convertor on a uranium carbide target, or by direct bombardment of the fissile material. In addition, acceleration of heavy ion high-intensity beams will allow to carry out fusion-evaporation experiments. The driver accelerator will produce deuteron beams of 5 to 40 MeV or ion beams of 1 mA at approximately 15 MeV per nucleon, characterised by an electric charge to ion mass number ratio of 1/3, with the option of further increase in mass and energy. The deuteron beam will be converted to intense neutron flux in a carbon convertor that will produce 10^{13} fissions per second in a thick uranium carbide target. After diffusion and ionisation the ion beams will be separated in a separator and can then be reaccelerated in the existing medium energy cyclotron CIME, after being further ionised using an electronic cyclotronic resonance charge breeder.

The following options have been selected:

- The deuteron source design is based on the one of the Silhi source.
- The fabrication technology for the radio frequency quadrupole must be developed and improved so as to reduce its cost.
- After studying various superconducting resonator configurations, the project decided on a compact structure, with a small cryostat system containing one or two quarter-wave cavities, where focusing is carried out by quadrupoles interspersed between the cryostats. In these cavities that have a large internal surface area, the challenge is to obtain electric fields in the order of 40 MV/m, without field emission or quality factor degradation.



Structural outline of the Spiral 2 Linac.
LEBT: Low Energy Beam Transport
RFQ: Radio Frequency Quadrupole
MEBT: Medium Energy Beam Transport
QWR: Quarter-Wave Resonator

Superconducting cavities for a proton Linac

At high energy, protons can be accelerated by elliptical niobium superconducting cavities operating at the temperature of superfluid helium (< 2.17 K). This high energy part of the Linac is made up of several sections, made up of groups with multi-cell cavities of varying geometries, suitable for proton velocity relative to the speed of light (ß = v/c = 0.47, 0.65, 0.85). Over the last three years, we have set up a number of "tools" allowing us to build and test these cavities.

Cavity design, fabrication and testing

The design work and first tests on mono-cells were the subject of a university thesis presented in 2001. Mechanical and electromagnetic 3D calculation codes were used to define the shape of the cavity. The accelerating electric field along the beam axis is optimised, at the same time as limiting the maxima of the electric and magnetic fields on the internal cavity surface. Because these latter are responsible of cavity performance limitations through surface electron emission and heating of the wall leading to loss of niobium superconductivity. These cavities also demand a very good quality factor[1] so as to minimise cryogenic consumption.

Elliptical mono-cell cavity fitted with its helium vessel.

After the work carried out on mono-cell cavities, development continued with the fabrication and testing of a 5-cell cavity (f = 700 MHz, ß = 0.65), working jointly with the IN2P3 *(Institut national de physique nucléaire et de physique des particules)*. In each case, the performance of the cavities built was about 30% superior to that required by the specifications for their incorporation in the Linac.

Five-cell cavity in clean room. Before being tested, the cavity is rinsed with ultra pure water under high pressure (80 bar).

At the moment, R&D is centred around the construction and testing of mono and multi-cell cavities with a value of ß = 0.47 as well as follow-up of technological developments needed.

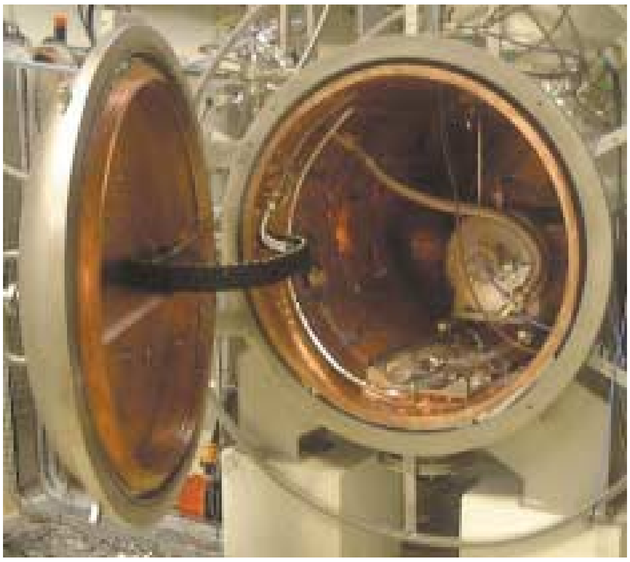
Technological developments

Given the length (1 m) and mass (~100 kg) of one 5-cell cavity, special commissionning tools were needed, in particular handling trolleys, one of which is specially designed for dust-free clean room environments.

So as to fully fit out the cavity, we are developing with IN2P3 a cold tuning system which will allow adjustment of cavity frequency by mechanical deformation, as well as a power coupler and its associated test bench allowing us to inject the radio frequency field into the cavity.

Commissioning Cryholab

Cryholab is a horizontal laboratory cryostat for testing mono and multi-cell superconducting cavities at liquid helium temperature (4.2 K) or superfluid helium temperature (1.8 K), in conditions close to those of an accelerator. A helium tank is welded around the cavity and this latter is sited horizontally



Five-cell cavity in Cryholab.

along with its power coupler and cold tuning system. So that Cryholab can operate alone, a liquefier, supplying the necessary liquid helium, is combined with it.

Cryholab has been designed and built in cooperation with IN2P3 and is partly financed by the *Ile de France* region.

Because of thermal insulation, the cryostat is first cooled to the temperature of liquid nitrogen (77 K): this kind of constraint is also present in accelerators. The cavity cooling process is therefore slow and reduces cavity performance, since niobium hydrides form at around 100 K. To prevent this happening, the cavity must first be annealed to eliminate the hydrogen trapped in the material: this operation is carried out at 800°C in a vacuum oven.

Installation and commissioning of Cryholab took place in 2000 and 2001. First tests on mono-cell cavities took place at the end of 2001 and the beginning of 2002. A 5-cell cavity test was carried out at the beginning of 2003 with an operational helium liquefier. The coupler, which will allow us to continuously inject the 700 MHz radio frequency wave (with a power of 80 kW), or inject it in pulsed mode (1 MW), has been the subject of studies and is under construction.

Cryholab will be used to test other types of superconducting cavities as part of several European programme for development of accelerators.

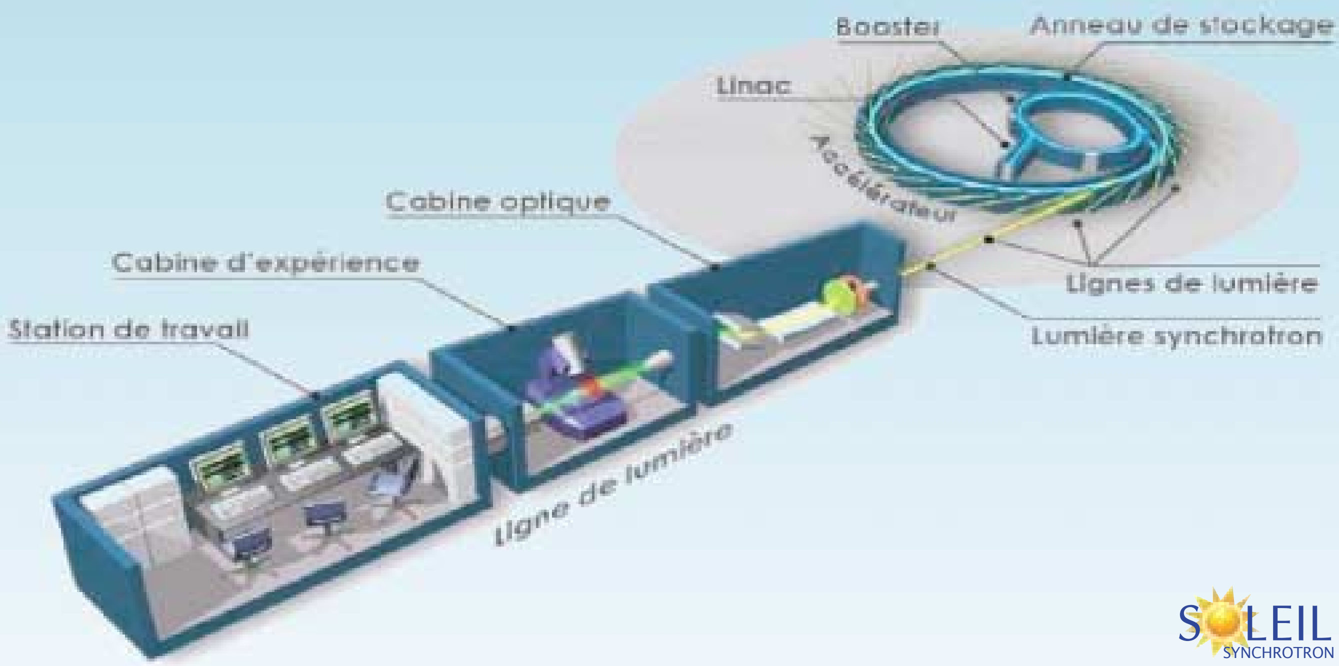
[1]The quality factor is proportional to the ratio of radio frequency energy stored in the cavity to the energy dissipated over a RF period.

Dedicated Cryholab platform for testing superconducting cavities under conditions close to those of an accelerator.

Electron-positron linear colliders and light sources

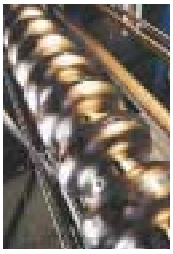
Breakthroughs in particle physics are closely related to the availability of electron beams of ever-increasing energy and luminosity. Electron accelerators are also essential to free electron lasers operating in the ultraviolet and X-ray regions. To supply the high brilliance beams used in solid-state physics, as well as in chemistry and biology, 3rd generation synchrotron radiation machines also operate with very intense electron beams.

The SACM is involved in the TESLA (Tera-electronvolt Energy Superconducting Linear Accelerator) project, a fully superconducting linear e^+e^- collider. Its expertise gained in free electron laser sources, achieving self-amplified spontaneous emission on the TTF (Tesla Test Facility) prototype accelerator, has enabled it to contribute to the Arc-en-ciel (Accelerator-Radiation Complex for Enhanced Coherent Intense Extended Light) proposal, an innovative installation of 4th generation light source. The division is also deeply involved in the design of 3rd generation light sources as a result of its participation in the Soleil *(Source optimisée de lumière d'énergie intermédiaire de Lure)* pre-project, where it developed an original design of superconducting cavity module, which was then used to improve two existing radiation sources.



SOLEIL SYNCHROTRON

The Tesla project and the TTF prototype accelerator



Tesla is an electron-positron linear collider project for particle physics aiming at energies in the teraelectronvolt range. The construction of the TTF prototype at the DESY *(Deutshes elektronen synchrotron)* laboratory in Germany has allowed us to check the performance of the various components and to make a realistic estimate of the costs of such a machine. This installation has also allowed to demonstrate the feasibility of a free electron laser operating in the self-amplified spontaneous emission mode in the ultra violet region.

The Tesla project

After the publication in March 2001 of the Technical Design Report, which described the full project, we are presently working on improving the beam delivery system to the interaction point by designing three sub systems. These are as follows:

- the beam switchyard: a structure similar to that used on synchrotron radiation sources has been adopted to minimise the emittance growth induced by synchrotron radiation;
- the emergency extraction line;
- the collimation system of the final transport line, taking into account the higher order dispersion effects.

The TTF prototype accelerator

In September 2001, by reaching the coherent emission saturation regime, the TTF installation demonstrated the validity of the principle of self-amplified spontaneous emission (SASE) of UV light, of wavelength equal to 98 nm, in a free electron laser.

Moreover, in the course of 2003, two electropolished 9-cell superconducting cavities reached the accelerating gradient of 35 MV/m in extensive operating tests in the horizontal test cryostat, Chechia, supplied by Dapnia in 1999.

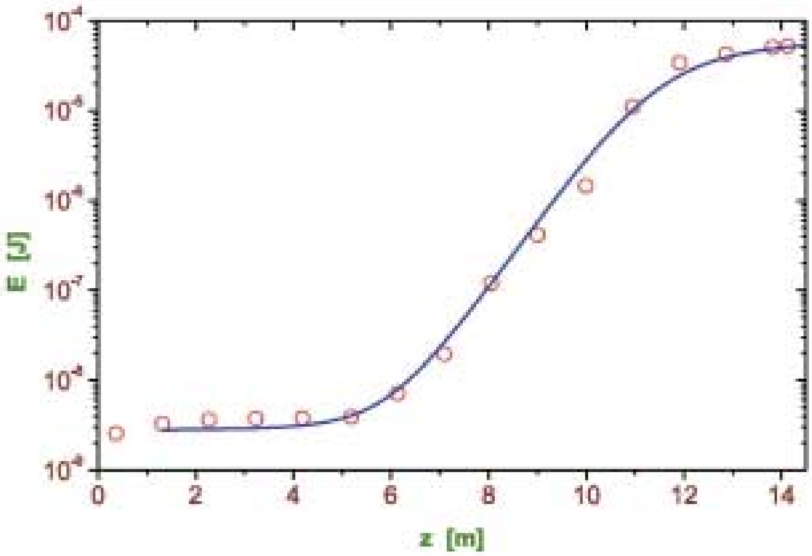
SACM was involved in these results in four ways:

- The proper functioning of the two position monitors allowing alignment of the beam trajectory as it enters the ondulator, a necessary condition for the amplification of the SASE-FEL signal. We also designed a new monitor specially suited to cryogenic environment, which will shortly be tested in a TTF cryomodule, and could be used in Tesla and in the X-FEL free electron X ray laser project.

- The commissioning of a protection system for the TTF machine using fast electronics to compare the beam current measured at different points along the Linac.

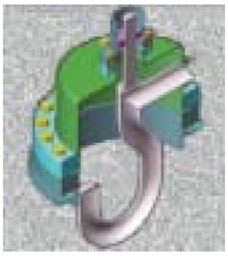
- The development of a method of baking to 110°C as the last stage in the preparation of electropolished superconducting cavities. By reducing the surface resistance, and thereby avoiding general heating of the cavities, this method allows us to increase the accelerating field limit by about 10 MV/m or more, depending on the cavities.

- Beam measurement characterisation of the HOM (high order modes) to validate the damping parameters envisaged by the Tesla project and to improve the beam vs. cavity alignment.

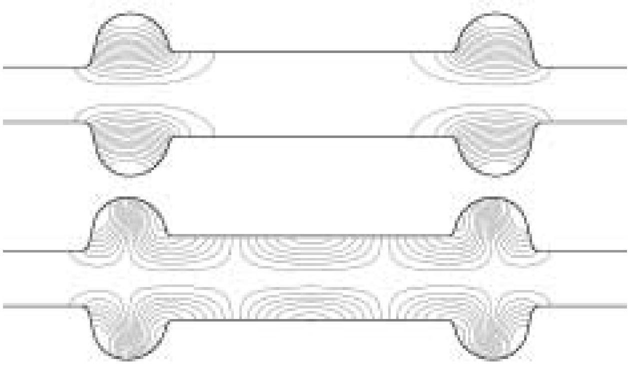


Saturation of the SASE-FEL signal along the TTF ondulator. The interaction between the electron bunch and photons emitted by synchrotron radiation in the ondulator results in the coherent amplification of the luminous emission. This has to happen within a single passage of the beam, since there are no mirrors for very small wavelengths. This application requires a high peak current and good optical quality beam because the interaction between the electron beam and the radiation is relatively weak in the case of UV or X rays.

Superconducting cavities for synchrotron radiation machines: Soleil and Super-3HC cryomodules



To supply high-luminosity light beams, 3rd generation synchrotron radiation machines operate with very intense beams of electrons distributed in packets of very small dimensions. These characteristics can dangerously destabilise the beam. The technology of superconducting cavities is one of the elements that allow bridging of these destabilisation factors and achievement of those beam characteristics needed for high luminosities.



Electric field distribution in the Soleil radio frequency structure for fundamental mode (top drawing) and for HOM mode, the highest order harmonic, (bottom drawing). The couplers, situated at the antinodes of the standing waves vibrating between the two cavities, evacuate the parasite waves to the outside.

The work of SACM in this field is based on a superconducting radio frequency structure (RF) at 4.5 K. We have been able to develop the initial idea behind this within the detailed pre-project of the Soleil project. This “Soleil cavity” is made up of two cells joined by a tube of large diameter. The diameter and length of the tube are calculated in such a way as to trap the fundamental mode within each cell at the same time as allowing higher frequency modes to be extracted. The electron beam, which has a periodic structure, is a probable excitation source for modes of frequency above fundamental one. Superconducting loop couplers placed on the inner tube dampen these higher order modes (HOM). The sitting and geometry of these couplers are optimised by calculation and then by measurements on models. This type of monomode cavity was developed at SACM for two applications:

- The Soleil cryomodule, placed on the storage ring and which compensates for electromagnetic energy lost in the form of synchrotron radiation. Eventually 650 kW will be continuously transferred from an external power RF source to the beam by power couplers.
- The Super-3HC (Third harmonic superconducting passive cavities) cryomodules that suppress beam instabilities using Landau damping, as well as increasing the beam lifetime. In this case, the power source is the electron beam that transfers a small part of its energy to the cavities.

Soleil cryomodules

The prototype cryomodule, which operates at 352 MHz and 4.5 K, has been studied and built by SACM in collaboration with CERN during the first detailed design study phase of the Soleil project. The first power tests took place at CERN in December 1999. After that, an agreement was signed with the European Synchrotron Radiation Facility (ESRF) to carry out a series of beam tests on the storage ring at Grenoble, for both cold and room temperature operation modes. This second mode of operation was not planned at the outset; 2001 was given over to preparing the cryomodule so as to fit it for operation at room temperature without effect for the machine users. During testing carried out in 2002 at the ESRF, the Soleil cryomodule generated peak RF voltage of 3 MV for several hours in a stable fashion with a 200 kW power per cavity, thereby contributing to storage of an 180 mA electron current. This performance is sufficient for the first operational year of Soleil in 2005. The decision has therefore been taken that Soleil will be commissioned with this one cryomodule prototype.

Soleil cavity, ready to be assembled in clean room.

Soleil cryomodule installed on the ESRF storage ring during 2002.

Before being installed on the machine, the cryomodule will be upgraded in the framework of a collaboration between CEA, Soleil and CERN. It will be completely dismantled and have its cavities rinsed. In addition, we will install new dipolar HOM couplers to give better fundamental mode rejection, we will modify the internal helium circuit to improve ring cooling on these couplers, we will add a thermal insulation screen to reduce static cryogenic loss, and we will renew all instrumentation. Mechanical studies were sub-contracted out between May and August 2003, and the dismantling operations began in November 2003. Power testing of the renovated cryomodule is planned for December 2004 at CERN.

A second cryomodule of the same design as the first one and incorporating some additional improvements is being developed. It is expected that it will be installed on the machine in 2006.

Super-3HC cryomodules

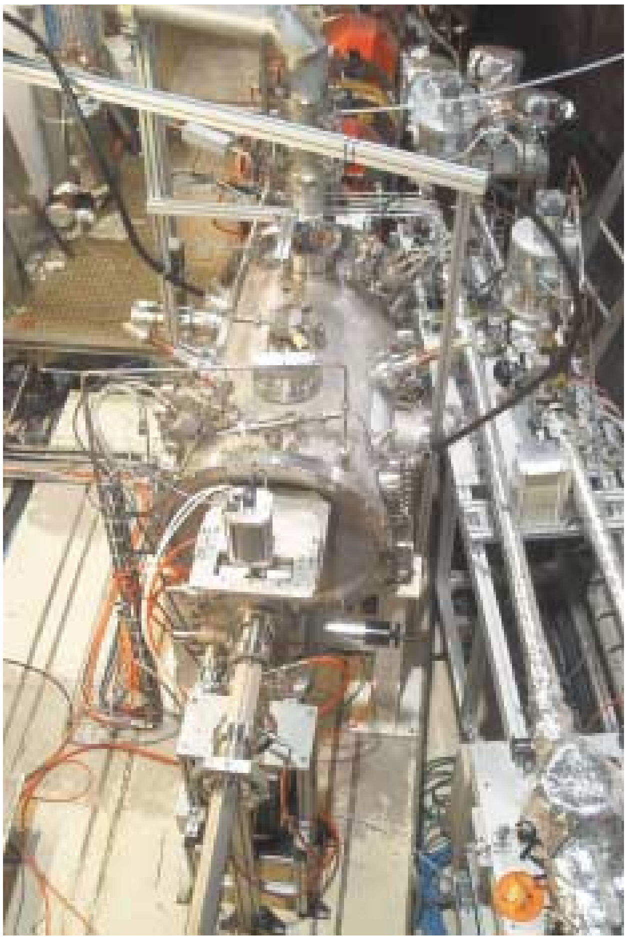
Two harmonic superconducting cavity cryomodules have been developed and built under the aegis of an agreement between CEA, SLS (Swiss Light Source, Paul Scherrer Institut) and ELETTRA (Trieste, Italy). CERN entered this project to undertake fabrication of the two 1.5 GHz copper-niobium cavities. Studies began in 2000. On completion of the construction, assembly and testing phases, the two Super-3HC cryomodules were installed on their respective machines, SLS in June and ELETTRA in August 2002.

Operation of the SLS module has shown its effectiveness on beam stability and life: an increase of a factor of 2.2 has been measured. During 2003 nominal operation of the machine continued with the Super-3HC cavities in action, with no machine stoppages resulting from the cryomodule. Its reliability has therefore been demonstrated.

Assembling the Super-3HC cavities in the clean room of the SACM.

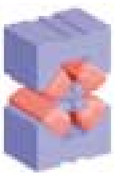
Introduction of the ELETTRA module was delayed by technical problems in the liquefier; initial cooling was carried out at the beginning of January 2003. During periods at room temperature operation, the only mode of operation possible is high-energy operation (2.4 GeV), since at lower energy (2.0 GeV), the beam becomes unstable due to interaction with the Super-3HC cavities. This problem, which had not been anticipated by ELETTRA, is the major failing of the system, in that it prohibits certain modes of operation in the event of liquefier breakdown. On cold operation on the other hand, activation of the superconducting cavities brings important gains in terms of beam stability and life. Thanks to the Super-3HC cavities, for the first time ELETTRA has been able to deliver a 2.0 GeV-320 mA electron beam free from any instabilities. Increase of the beam lifetime by a factor of 3.5 has been demonstrated.

These harmonic superconducting cavities are the first to be installed successfully on synchrotron radiation machines.



Super-3HC cryomodule installed on the ELETTRA storage ring.

The quadrupoles and dipoles of the Soleil synchrotron storage ring



The quadrupolar and dipolar magnets of the Soleil storage ring were studied for the detailed design study of the Soleil project in 1997-1998. There are two types of quadrupole, 128 short quadrupoles and 32 long quadrupoles with the same transverse magnetic section. The renewal of the Soleil detailed design study in 2001 updated the machine parameters, in particular its operating energy to a higher level (2.75 GeV).

The reworking of the Soleil detailed design study allowed to finalise the study of two types of quadrupole. Modelling carried out using the Tosca 3D code gave optimisation of the transverse section and of the end geometry of these magnets by minimising harmonic rates detrimental to the optics, at the same time as holding integral uniformity of field gradient in the useful zone at a level better than $5x10^{-4}$. Only the 45° end chamfer differs from one quadrupole to another so as to reduce the dodecapole and “20-pole” multipolar terms to values below $5x10^{-5}$. The quadrupole prototypes will be measured during 2004 at the Soleil magnetic measurement laboratory at the CEA/Orme des Merisiers site.

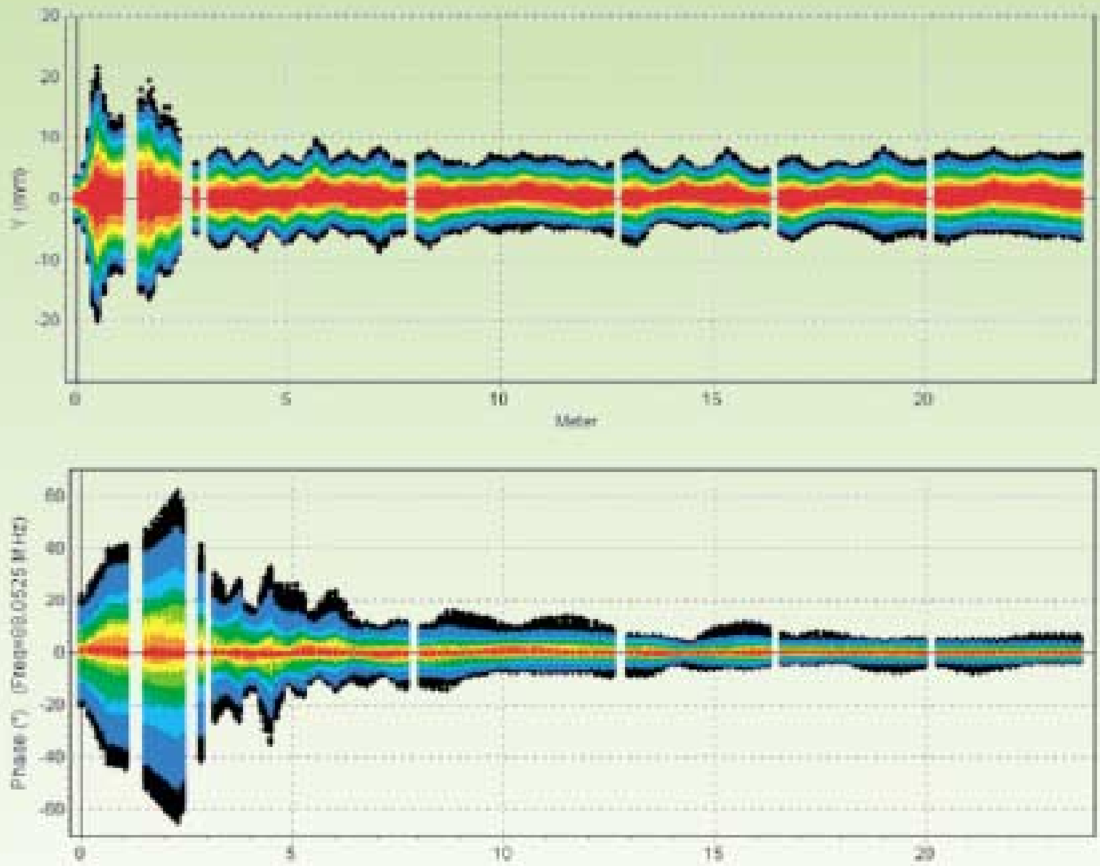
The storage ring dipole operates at a nominal induction of 1.71 T, corresponding to a machine energy of 2.75 GeV. The preliminary version of this dipole was curved with a C-type magnetic circuit. It is now of straight H-type allowing the $5x10^{-4}$ uniformity required of the field integrals to be reached, as well as a magnetic length which is adjusted to the curvilinear length of the iron.

The field uniformity of a dipole prototype measured in the magnetic measurement laboratory conforms to the simulations. Welds along the magnet to hold the plates in position have however caused a 1 mm misalignment of the magnetic lengths between input and output. Analysis of this shortcoming is ongoing.

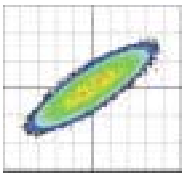
Developments for particle accelerators

Any new project presents challenges of its own and generally needs specific R&D. Conversely, it is often the case that breakthroughs in some one particular R&D can profit to several projects. Several lines of R&D specific to accelerators are pursued at SACM:

- The improvement of analytic models and development of numerical methods for modelling the particle beams dynamics which has to be adjusted to higher and higher requirements for operating parameters (energy, luminosity, reliability, ...).
- The development of ion sources based on plasma generated by electron cyclotron resonance for the production of intense H^+ and H^- ion beams; progress here can result in continuous improvement in intensities and reliability.
- Systematic studies in view of understanding the physical origin of the limits of accelerating field in the superconducting radio frequency cavities, and defining treatment suitable to achieve higher fields. In addition, technological developments allow us to study the construction of complete cryomodules in an accelerator environment, by incorporating superconducting cavities, associated RF components, as well as the supporting instrumentation.



Particle beam dynamics

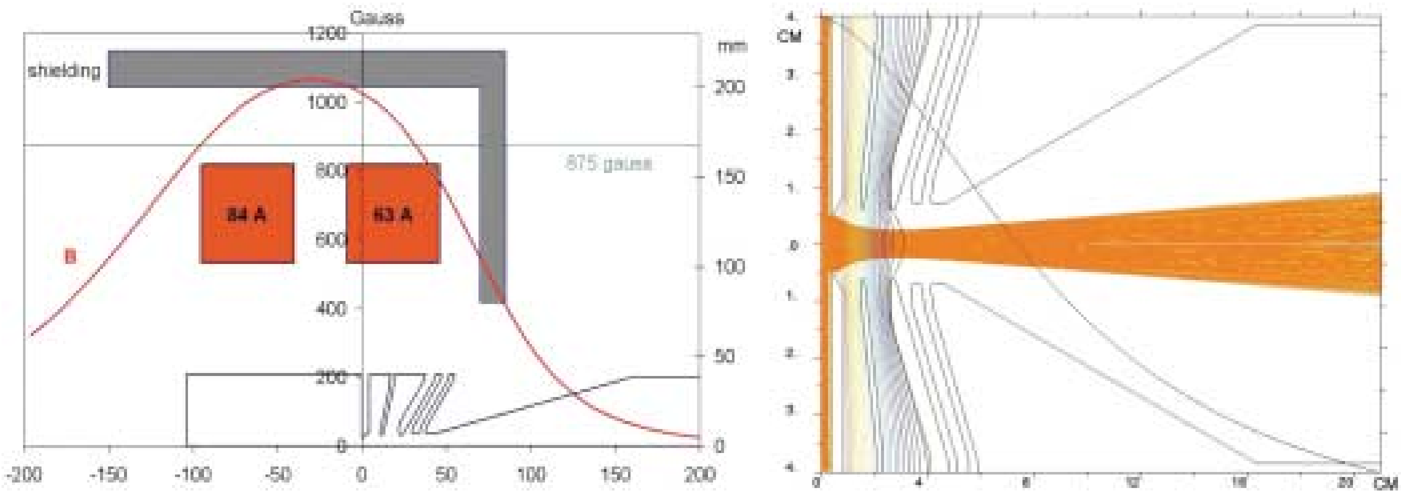


Beam dynamics may be defined as the study of the motion of charged particles in static or time-dependent electromagnetic fields. These fields may be external (curved or focusing magnets) or generated by particle distribution (space charge[1], imaging effect, wake field, beam-beam interaction). For electrons, the effect of synchrotron radiation needs to be considered. There are various challenges facing any attempt to accurately model the beams dynamics that need pointing out. At a fundamental level one may cite the problem of dealing with interaction with the residual gas (diffusion, ionisation, space charge compensation), interaction with solid interfaces (targets, windows, collimators), the dynamics of ion source plasmas, the beam optic in the presence of high- order electromagnetic elements (hexapoles, octupoles, field maps). Then there is also the problem of dealing with halo formation and beam losses for the upkeep of future high power accelerators (less than 1 W/m for beams of several megawatts). At another level one may cite the cost optimisation of accelerator systems. These challenges necessitate development of analytic models, as well as development of numeric methods that make the fullest use of IT resources, such as for example cluster calculation.

Particle transport in a low energy line

The emittance[2] of the low energy part of an accelerator has to be controlled since it is critical for its high-energy operation. In the case of high current accelerators such as Iphi, after source extraction the beam must be guided in such a way so as to limit loss as well as any increase in emittance. The residual gas from the vacuum chamber ionises atoms as the beam passes through, thereby inducing partial space charge compensation. To achieve a more accurate simulation and gain better fit with experimental measurements carried out on the Silhi source, work is at present being undertaken to improve our understanding of the physical phenomena occurring in the dynamics of intense beams in the space charge compensation regime. They are the subjects of a PhD thesis at SACM.

The study of the source extraction system has a number of aspects. First of all, the magnetic configuration of the source, using coils or permanent magnets, must give electronic cyclotronic resonance (ECR), and this leads to optimisation of the magnetic field profile and longitudinal ECR zone adjustment. Modelling of the extraction system is carried out by calculating the plasma expansion meniscus and beam generation via a multi-electrode extraction system. Beyond the extraction zone, beam transport is simulated in the low energy line with different codes developed at the SACM specially for simulating multi-type ion beams in the space charge regime or space charge compensation regime. Here allowance is made for a constant or local compensation factor that is matched against experimental measurements on beam emittance, in the expectation that a more accurate description will ensue.

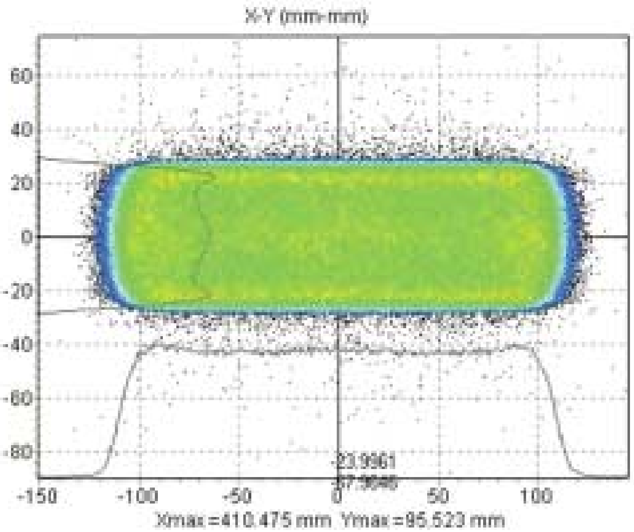


Silhi axial magnetic field and extraction modelling of an H^+ proton beam.

Such electromagnetic modelling, coupled with beam transport for studying low energy beams, is the basis for defining and optimising the Silhi H^+ proton source, and for Silhi simulation using positively charged deuteron (D^+) ions, as well as for defining the extraction system for the D^+ source of the Spiral 2 project.

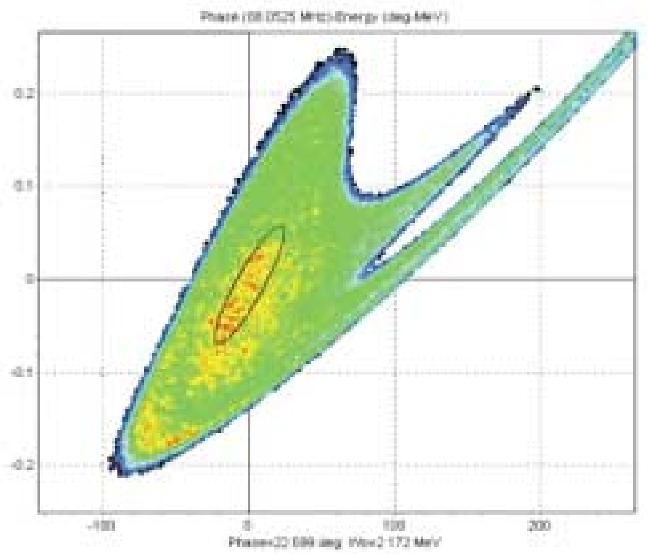
Beam dynamics in high power ion Linacs

Among the laboratories working on linear ion accelerators, SACM has been involved in several projects. For the European Spallation Source (ESS) project, the SACM designed the Linac from the low energy lines as far as ring injection (low energy lines, radio frequency quadrupoles, chopper lines, conventional cavity medium energy part, funnel line[3], superconducting cavity high energy part), then the compression ring, and finally specification of construction tolerances for the Linac (development of a cluster). A similar study has been carried out for the Concert project (multi-user installation). A similar contribution has been made to the International Fusion Materials Irradiation Facility (IFMIF) project. SACM has carried out the design of the radio frequency quadrupoles (RFQs), the drift tube linacs (DTLs), and the high-energy line, with increased density uniformity, and has specified construction tolerances.



Transverse beam distribution on the IFMIF target after density equilibration to minimise thermal gradients.

Within the framework of the Spiral 2 summary pre-project and then of the detailed pre-project as well, the laboratory has played a central role in the design of the Linac and has coordinated the beam dynamics operations for the project. SACM's expertise in RFQ design and modelling has been sought for the RIA project (exotic nuclei source for nuclear physics) as part of a three-month mission to the American National Superconducting Cyclotron Laboratory. This joint effort has also allowed SACM to shine in the first superconducting part of the Linac as a result of its instability studies that have shown the technical solutions chosen (4 cavities per cryostat) to be correct. Beam modelling using an alpha[4] magnet in the ELSA accelerator (CEA-DAM) has allowed us to enhance the range of transport codes at SACM. For the Alice project (heavy ion colliders), SACM is involved in modelling the multicharge ion beam through the RFQ. Finally, adaptation studies for the Iphi RFQ to the needs of the Superconducting Proton Linac (SPL, CERN) for a neutrino factory have also been carried out.

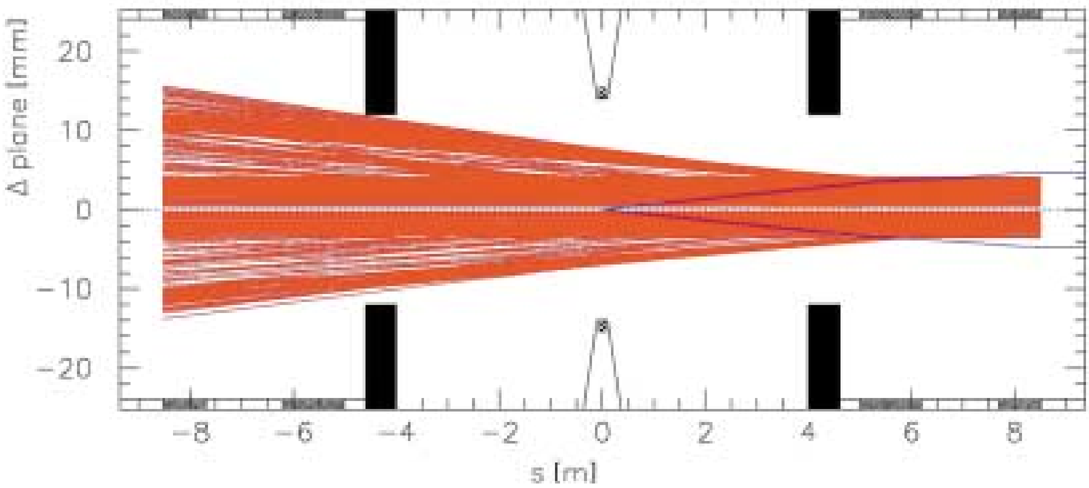


Acceptance in the longitudinal phase space at the entrance to the Spiral 2 superconducting Linac.

Transport in high-energy lines

The final focusing system of the Tesla superconducting linear collider project has been redrawn, incorporating recent progress from SLAC (Stanford Linear Accelerator Center) in optical design for compensation of chromatic aberrations, which, in broadening the beam spread at the point of collision, reduce luminosity. This new line has allowed us, on the other hand, to incorporate the wish of the physicists in charge of the design of the experimental detector to move the final doublet 2 m away from the interaction point.

Beam collimation constraints based on free propagation in the synchrotron radiation interaction region emitted in the final doublet quadrupoles have been recalculated, taking into account, for the first time, energy deviations of the halo particles. This has led to a review of collimation of the energy tails of the beam and to improving the collimation line sited upstream of the focusing system.



Synchrotron radiation beam (red) in the Tesla interaction region. After collimation, it no longer generates e^+e^- pairs (radiation-matter interaction) that might interfere with acquisition.

Hadrontherapy. A 4th generation synchrotron radiation source. Muon collection for a neutrino factory

SACM took part in the technical pre-project (2000-2001) of the Etoile light ion (essentially carbon) hadrontherapy project, which is synchrotron-based (a tripartite agreement between CEA/CNRS/Claude Bernard University - Lyon). At the beginning of 2003 the Claude Bernard University in Lyon asked for surveys of the German Hicat and Italian CNAO projects, which are now being carried out. The aim of these surveys is to provide the necessary technical items to deal with the Etoile contract specifications.

A 4th generation radiation source has been studied by the laboratory. It is based on an electron beam of the gigaelectronvolt range energy, produced by a superconducting linear accelerator; it can deliver stimulated or spontaneous radiation. This perspective of a new source was the subject of an evaluation prompted by the committee of the *Direction des sciences de la matière* of the CEA, and it led to the Arc-en-Ciel project.

The NuFact neutrino factory project aims to produce high flux neutrino beams, adequately collimated, in the direction of large detectors hundreds or thousands of kilometres away, from a high-energy muon storage ring. The SACM is working on the accelerator studies as part of the team of the European Neutrino Group, in particular on the questions of muon collection and acceleration.

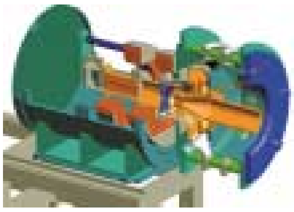
[1]Space charge: A cloud of charged particles generates an electric field, which, depending on the balance between their charge signs and their distribution in space, may lead to a force tending to make the cloud disperse. This force that tends to disperse the particles is the space charge force.

[2]Emittance describes the dimensions of the area occupied in phase space by a particle beam. The smaller the angular divergence, and the smaller the beam, the weaker its emittance.

[3]A funnel line is a device designed to produce a beam by combining two of them together, with the particular aim of doubling the mean current. The particle bunches of the two primary beams are interspersed to form a beam that has double the repetition frequency.

[4]An alpha magnet is a dipolar magnet giving particle separation where the particles have widely varying motions. It bears this name because the trajectories of the particles in the magnet describe the Greek letter alpha.

Ions source developments

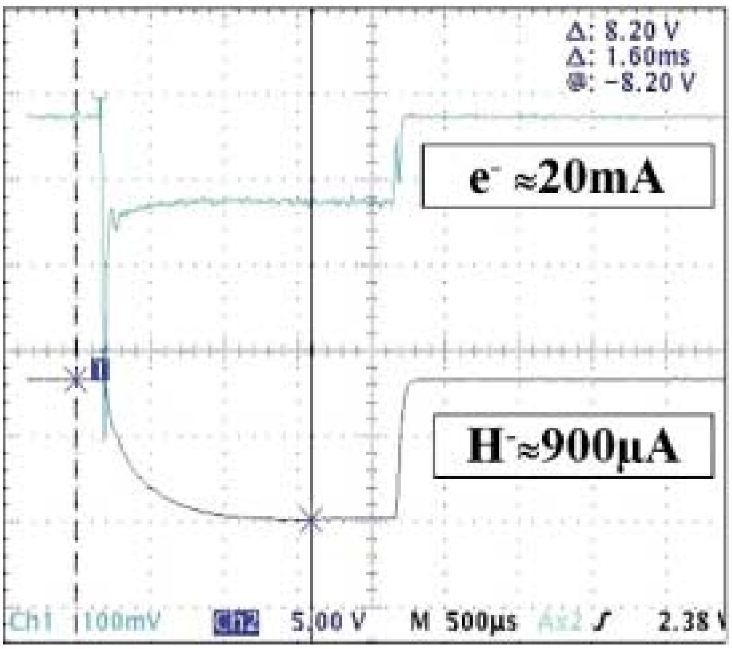


The high-intensity light ion source, Silhi, developed as part of the Iphi project, has demonstrated its efficiency for producing intense proton (H^+) beams with good qualities and a long lifetime. For example, the source operated for 160 hours at 100 mA with a 99.9% availability, thus proving its reliability, which is one of the main objectives of the Iphi project. Encouraged by this performance, we developed two new sources based on the same principle: the plasma is generated by electron cyclotron resonance (ECR) at a 2.45 GHz radio frequency.

For the Spiral 2 project, a source planned for continuous deuteron (D^+) production has been designed at SACM. It is under construction and will be tested in 2004 on the Silhi beam line. Use of permanent magnets allows further increase in reliability and reduction in power consumption, as well as facilitating production. The only drawback is the rigidity inherent in the tuning: the magnets have to be changed or moved to adjust the magnetic configuration. The 5 mA requested Spiral 2 source intensity is rather low and the tuning tolerances are large enough to authorize permanent magnets utilisation. Their advantages therefore speak largely in their favour, in opposition to the Silhi source, for which necessary tuning is very precise. The chosen material is neodymium-iron-boron, which produces a strong magnetic field with a hysteresis cycle sufficient to avoid demagnetisation. The life of these magnets is considerably greater than the source one.

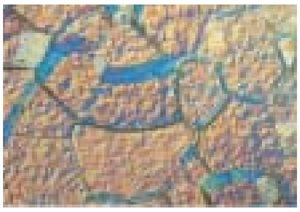
There is a parallel ongoing study of a pulsed negative hydrogen ion (H^-) source. In 2001, spectrometry analysis showed the presence of excited-state hydrogen molecules within the plasma capable of producing H^- ions by dissociative attachment. The first ions were observed at the beginning of 2002. In 2003, after the installation had been moved, the number of H^- ions was greatly increased by separating the plasma chamber into two parts with a stainless steel grid. The role of the grid is to reflect the radio frequency wave, which is not absorbed by the plasma. As a result, it limits electron heating in the area near the extraction hole. The optimisation of the grid potential and the plasma electrode potential, at the same time, allowed to adjust the energy of the particles entering the so-called production zone. Thereby the negative ion intensity increased. The maximum current has reached 900 µA of H^- ions for 20 mA of electrons with a radio frequency power of only 1 kW. The final aim is to produce several tens of mA at 50 or 60 kV with the requested characteristics to inject the beam into the first stage of an accelerator.

Study of the negative ion source is being carried out under the auspices of the European High Performance Negative Ion Sources (HP-NIS) network. Dapnia/SACM is coordinator of this network, where 9 European laboratories are involved. The 4 years programme covers the period from January 2002 to December 2005.



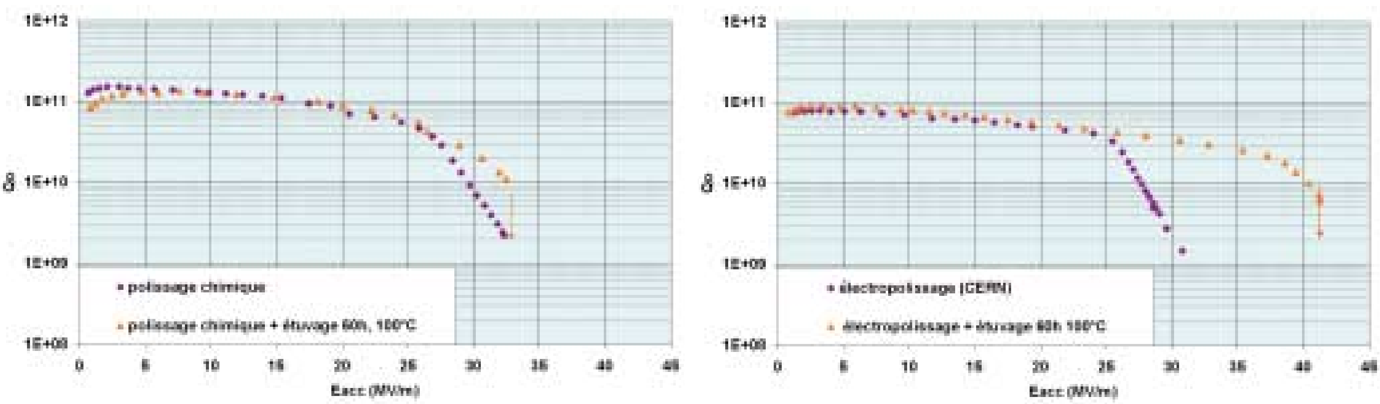
Signal observed on an oscilloscope during 10 kV polarisation of the H^- source to extract the beam. Electrons and negative ions are separated using a dipole magnet.

R&D in radio frequency superconductivity



The R&D involved in superconducting radio frequency cavities aims to understand the physical origins of the limitations of the accelerating electric field of these cavities, and to find ways of dealing with it that will improve their performances. Challenges concern the increase of the accelerating field (E_{acc} > 40 MV/m), allowing reduction in accelerator length, and the increase in the quality factor ($Q_0 > 10^{10}$), i.e. the ratio of stored energy to that dissipated at the walls. This will allow reduction in cryogenic consumption.

Ultimate performance of niobium cavities



Effect of moderate baking on a chemically polished cavity (on the left) and on an electropolished one (on the right).

Over the last years, we have shown baking to be indispensable in getting high accelerating gradients. Baking at 110°C for 60 hours gives reduction of one order of magnitude in surface resistance, and therefore in high field thermal dissipation, without any change in quench position when observed. This result is particularly spectacular in the case of cavities that are not limited by quench before baking. Electropolished cavities, for example, which have not been baked, are presently limited to around 25-30 MV/m. These same cavities reach field strengths above 40 MV/m, limited by a quench, after baking. High field thermal dissipation can therefore be dissociated from the quench phenomenon, which is presently the final limitation.

Present issue: understanding quench

Currents of the order of several 10^9 A/m^2 circulate in the penetration depth of magnetic field; i.e. for niobium, the first 50-100 nanometres of the surface. The limitation is at present quench, a thermal instability generally attributed to some localised defect (of the order of some 10 µm in diameter), which can cause local increase of the magnetic field or temperature, and as a result cause transition from the superconductor to the normal state. It is known that this phenomenon is affected by the final surface treatment and we are currently exploring three possible ways of explaining this:

Chemical surface composition

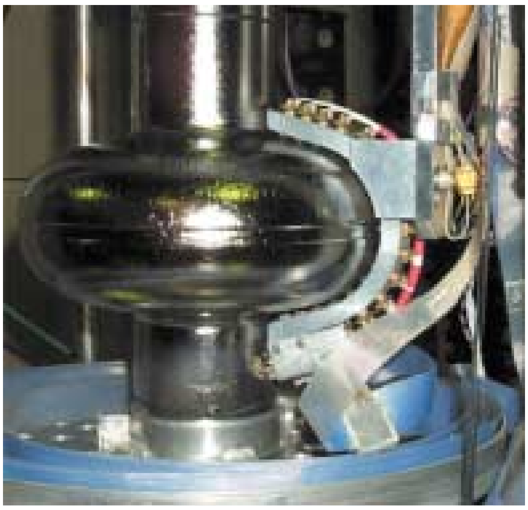
Surface studies carried out on the niobium used in the fabrication of the cavities show that there exists a concentration of impurities at the metal oxide interface, i.e. exactly in that area where thermal dissipation occurs. In particular, during a collaboration carried out jointly with CEA/Drecam, we have been able to measure 200 times more oxygen near the surface than in the bulk of the material. Oxygen is the main impurity in the niobium and may well be involved in the high field thermal dissipation phenomena. It is therefore very important to be able to measure its distribution at the surface with some precision. This study now continues with the start of a PhD thesis carried out jointly with the Max Planck Institute in Stuttgart.

Surface morphology

One of the proposed models involves a local increase in magnetic field on the grain edges resulting from chemical abrasion at the grain boundaries. Until now it has been difficult to assess this effect properly in numeric terms. Thanks to the combination of a temperature map and a replica taken inside the cavity, it has been possible for the first time to make a precise survey of the quench area and to model the local magnetic field increase and its effect on cavity performance. Morphological studies have also shown that the area that is affected by heat from welding displays edges (roughness) which are about 10 times higher than in the rest of the cavity, due to exaggerated grain growth in this area. If these results are confirmed, they might cast doubt on the fabrication method for the cavities, since the current is at its strongest at this area.

Grain boundary studies

Another aspect to radio frequency superconductivity arises from the grain boundaries, which can display “reduced” superconductivity characteristics. An experiment is being carried out to measure the specific resistivity of the niobium grain boundaries. Measurement precision needs improving.



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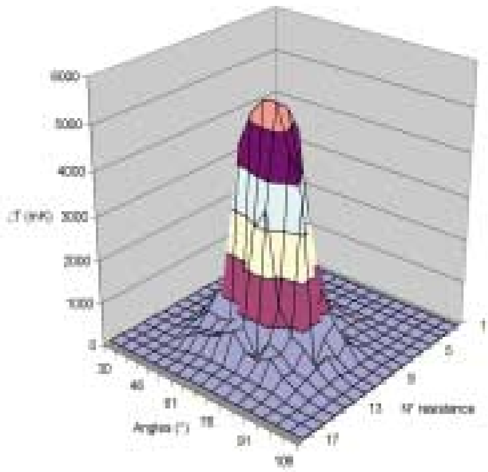

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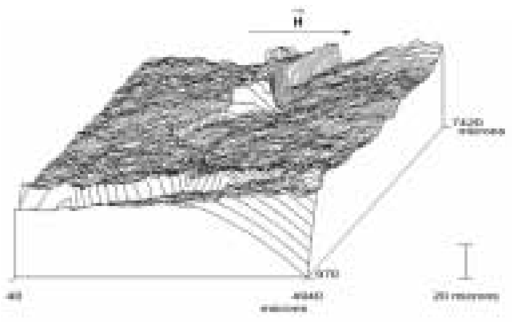

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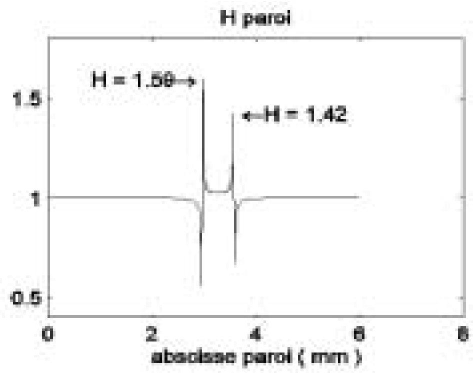


d

The different stages in the morphological study:
a) and b) Quench localisation using temperature sensors.
c) Morphology measurements using replica (inverted profile).
d) Modelling local field increase which results from the observed contour.

Electropolishing or chemical polishing

During a DESY-CERN-Saclay collaboration, a record accelerating field of 42 MV/m has been obtained on a cavity after electropolishing. This method regularly gives fields in the order of 35-40 MV/m, but remains difficult to master. However, a 40 MV/m field has also been exceptionally obtained using the traditional method of chemical polishing. It is therefore important to properly understand the different procedures so that we can adopt the most convenient method. Work is also underway to try to improve the electropolishing parameters.

Instrumentation for particle accelerators

Development of the instrumentation and radio frequency components (RF) covers everything that concerns RF supply, beam measurements (beam position monitor, beam profile monitors…), tuning rings, as well as the design and incorporation of the cavity fittings, such as the couplers that inject the radio frequency wave and the cold tuning systems. At the same time it must make allowance for environmental constraints (i.e. radio frequency, heat and radiation).

RF power supplies

An RF power supply test bench, with continuous feed of 704 MHz and 80 kW, is in the process of being installed at Saclay. It will be used to test the components on the Cryholab test station. The power amplifier is a grid tube IOT (inductive output tube). It is the most powerful at present on the market, and has been specifically developed for use on accelerators. Electrical supply of 40 kV running at 4 A is in place. It also has auxiliary supply for heat and polarisation, as well as for the focuser. A 500 W transistor preamplifier controls IOT input. A safety slide valve (arc detection, focusing error, etc) has been installed but not yet tested. The wave-guide IOT output is connected to a water-cooled coaxial load via an ad hoc jump. The circulator and the short circuit have been received but not yet installed. The sliding short circuit control software has been reworked so it can support Labview©.

The LEP items lent by CERN to test the Iphi radio frequency quadrupole are under installation in the old Saturne hall at Saclay. The 100 kV-40 A supply needed for the two klystrons is being hooked up. The voltage-reducing transformer has been rewound to match the 15 kV system of the Saclay centre.

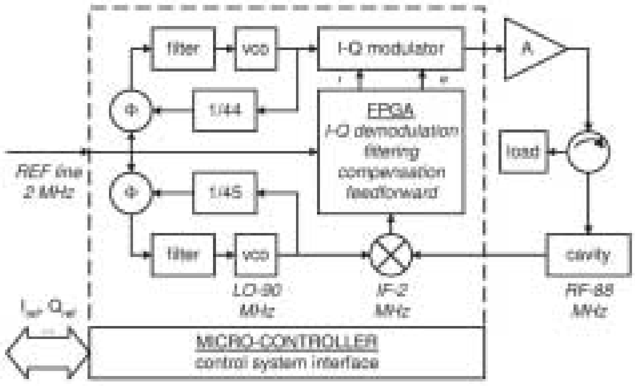
The study of the interface needed for controlling the CERN supply using the Iphi command/control system has been completed.

Low-level radio frequency electronics and beam diagnostics

Low-level electronics use signal processing and control techniques specific to the operation of accelerator sub-assemblies. These are accelerator cavities, the beam position monitor (BPM), machine protection systems, etc.

Installation at Saclay of the 100 kV and 40 A input transformers designed to supply the Iphi klystrons.

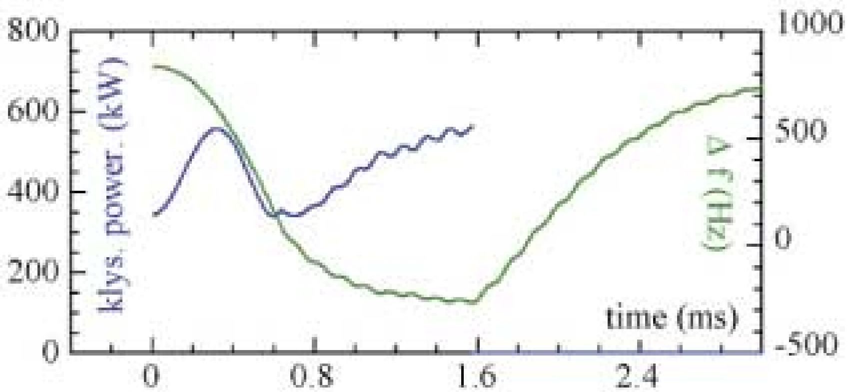
Acceleration of bunches of particles in an RF cavity requires amplitude and RF wave phase feedback. A digitally based system has been studied and proposed for the Soleil and Spiral 2 projects. It can deliver a level of flexibility, integration and reliability greater than that of previous analogical systems and at lower cost. As part of the TTF installation SACM provided high resolution (10 µm) BPMs complete with electronics, fitted on the outside as well as the inside of the cryomodules. The beam diagnostics also include fast electronic current measurement for machine protection against beam losses.



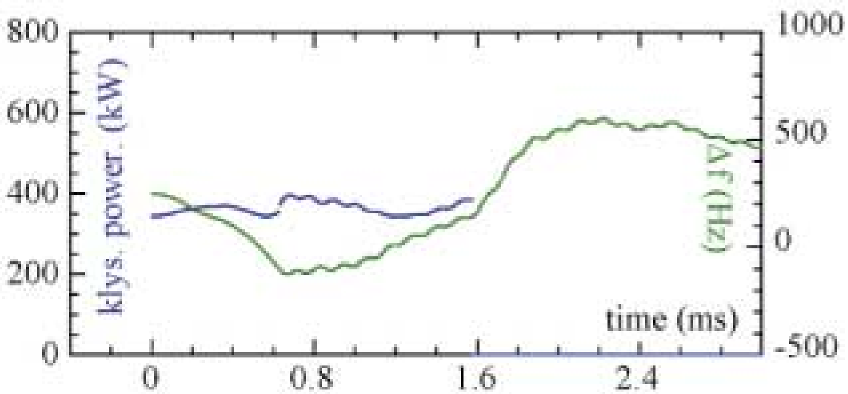
Control of accelerating field: amplitude and phase feedback loops for Spiral 2.

Piezoelectric active compensation of Laplace forces

In pulse mode, superconducting cavities operating at high accelerating gradient undergo mechanical deformation due to Laplace forces, which modifies their resonating frequency. Traditional amplitude and phase feedback needs considerable RF power, since part of the incident power is reflected. A complementary system of piezoelectric bars can counterbalance this effect by applying opposing deformation, but first of all we need to work out the voltage profile that is to be applied over the whole of the RF pulse. In actual fact the linkage between the mechanical characteristics and the variations in radio frequency field result in complex behaviour that must be modelled for each cavity on the basis of their individual experimental data. We have developed this model, as well as a simulation tool to predict the performance and limitations of such a system based on its RF characteristics and the mechanics of its cavities.



a) Without piezoelectric active compensation



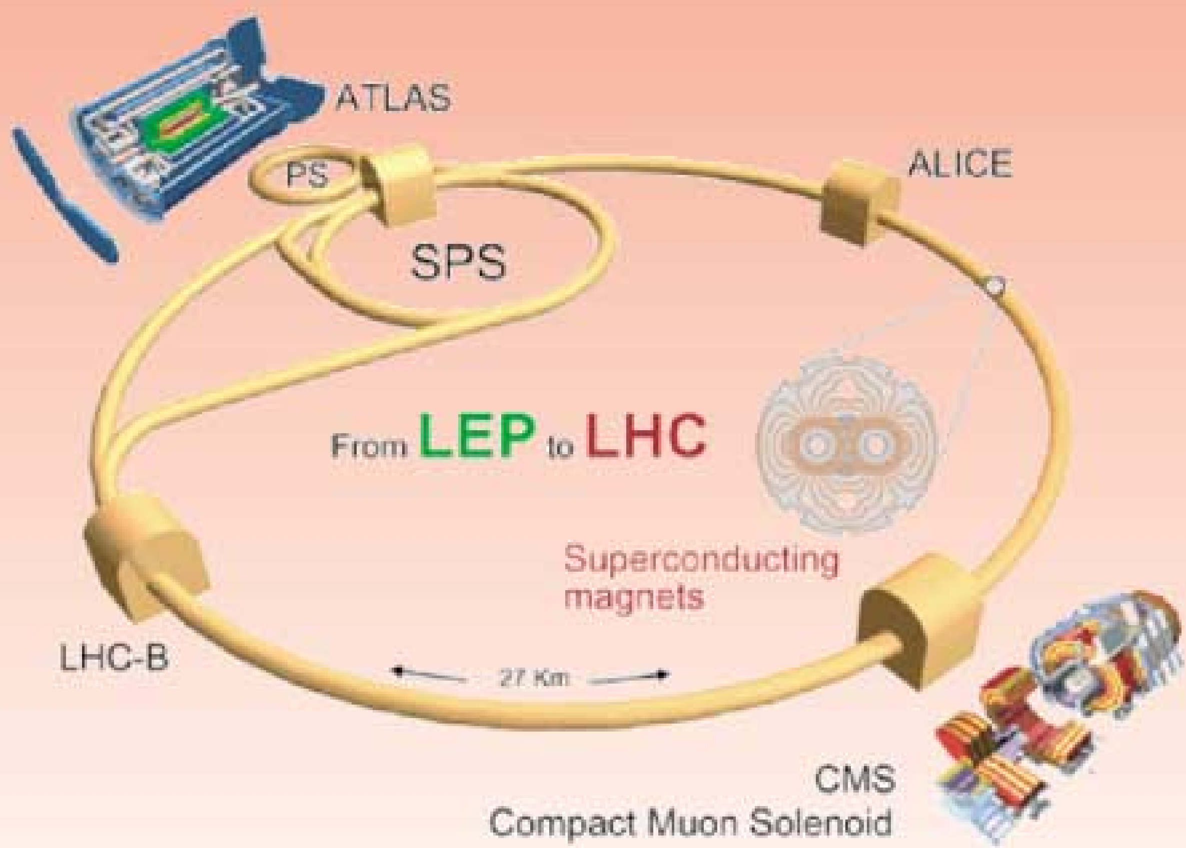
b) With a partial active compensation.

RF power needed and Tesla cavity detuning at 35 MV/m.

Superconducting electromagnets for particle and nuclear physics

The CEA is heavily involved in the research to be carried out for the Large Hadron Collider (LHC), the future particle accelerator of the European Organisation for Nuclear Research (CERN) in Geneva, which will allow collisions between proton beams, where each beam has the energy of 7 teraelectronvolts. Such a high level of energy requires intense magnetic fields and large dimensions, both for the accelerator magnets and those of the detectors. SACM engineers have developed the quadrupole magnets - they are four hundred of them - which are being produced in industry. In collaboration with other laboratories, the division is also taking part in the design and construction of the two large detectors: Atlas (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid), both bigger and more complex than any magnet built up until now.

In close cooperation with the Division of Nuclear Physics of CEA, SACM is participating in the design of cryomagnetic systems for experiments at TJNAF in the United States and GSI in Germany, known as CLAS (CEBAF Large Acceptance Spectrometer) and GLAD (GSI Large Acceptance Dipole) respectively.



The LHC superconducting quadrupoles

As part of the French exceptional contribution to the construction of the Large Hadron Collider (LHC), SACM has seen itself entrusted with the design of the main quadrupole cold masses of the machine. The main technological difficulties arise from the need for great mechanical precision so as to ensure uniformity of the field at the level of 10^{-4} over the three metres of the magnet. The masses need to withstand high electromagnetic bursting forces of 4 times 1100 kN per metre of magnet and be of a design that can serve as the base for industrial production of 400 units. Based on the good results obtained with the three prototypes built at SACM and tested at CERN and at SACM in 2000, SACM carried out technology transfer from 2001 to mid 2003. It is now in charge of manufacture monitoring of the production magnets for which the German company ACCEL has been awarded the contract.

A cold mass is a helium envelope containing three double aperture magnets, a main quadrupole magnet and two corrector magnets. These two corrector magnets are external fittings, but Dapnia has studied their incorporation in the cold mass. Each magnet has two apertures where the particles of each beam circulate.

For each of the quadrupolar apertures, 56 mm in diameter, four superconducting coils are collared together with stainless steel collars thus making one unit out of them. The main aspects of the magnet's performance depend on the care taken during the winding of the superconducting cable and during the collaring together of the coils. Although these coils measure 3 m in length for an average radius of 4 cm, the order of magnitude to which their quality is assessed is about 20 microns. This dimension ensures the magnetic field quality necessary for focusing the particle beam, as well as the coils' mechanical stability. The design principle itself allows us to predict the position of the cables, which are cooled to 1.9 K (-271°C) and supplied by a 13,000 A current. This is in spite of thermal contractions and Lorentz forces that tend to open the apertures and crush the coils. The prototypes have therefore allowed to confirm that the geometry remained mechanically stable in spite of loads equivalent to the weight of a stack of about a hundred cars or so.

Technology transfer to industry

So as to put production on an industrial footing, ACCEL procured additional machine tools, these being somewhat modified when compared to our prototype tools. The most delicate stage was to get consistency of the coils, given these new tools and the change of grade in coil insulating material, which was imposed by CERN. During the period of technology transfer to industry, two SACM technicians, seconded to ACCEL, supervised qualification testing of the tools, explained the operation of the machines used in manufacture, made sure the various procedures drawn up at SACM were applied and made sure also that they were followed by all the production teams. They thus passed on the detailed know how at their disposal.

Storage of the quadrupole magnets before cold mass assembly (by courtesy of ACCEL).

Monitoring industrial production

Manufacture monitoring is carried out at present by an SACM technician at ACCEL every two weeks, the detail analysis being made by SACM engineers.

Production cold mass in front of its pressure test chamber (by courtesy of ACCEL). Before delivery to CERN, ACCEL checks that each cold mass can withstand internal pressure of 26 bar and is helium leak tight up to 10^{-10}mbar.l.s^{-1}.

The cold masses are checked at the company at their main production stages, that is, during and after winding, and during collaring. The accuracy of the magnetic measurements is turning them into an exceptional instrument for fault detection. An automatic test bench has been specially developed based on the acquisition system designed by CERN. It has been installed at the company and detects most measurement errors and system faults.

The originality of the quality system that has been introduced

A quality check system has been introduced from the beginning of the design process for the portfolio of prototype manufacturing drawings, and then for all stages that followed. The main tool for manufacture monitoring is non-conformance management with three objectives: to be able to react rapidly if a fault is detected at any stage of fabrication right up to the cold acceptance tests at CERN; to have available the case histories of cold masses over the twenty years of the LHC's operation; and more generally to engage the company in a quality procedures system.

Knowing that one has three months between manufacture and testing of a magnet, this corresponds to the production of about forty cold masses. Any deviation must be known and analysed so as to take suitable corrective measures at the earliest opportunity. To reduce uncertainty, one magnet out of ten is tested on its own. From July 2002, this procedure has allowed to check that industrial transfer has been properly carried out.

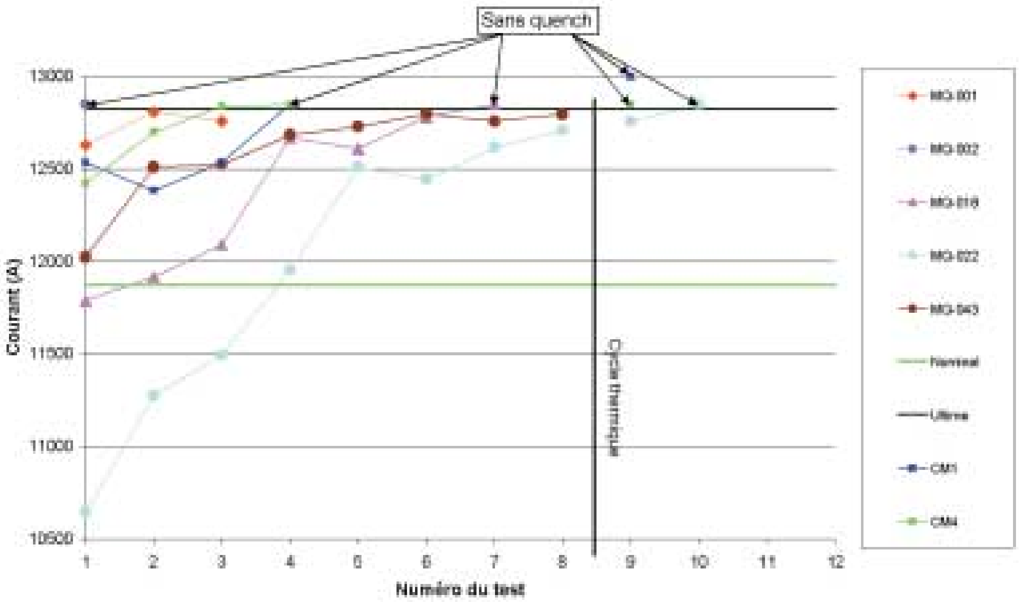
Electric, magnetic and geometric acceptance checks, as well as those on seals and resistance to pressure, are finally carried out on the cold mass before its delivery to CERN and reports are drawn up. So as to make production as fluid as possible, all these tests are carried out by the manufacturer, which checks conformity between the results and the tolerances, as defined by SACM. Any deviation involves a non-conformance report and quarantining of the item during the time it is under analysis by SACM. Delivery to CERN of each cold mass needs SACM's agreement after verification of the validity of all the tests and non-conformances.

Tests at CERN on the production quadrupoles

The first of a production run of about 400 units, the first quadrupole was cooled on its own in July 2002. Though the nominal current is 11,870 A, the magnet experienced its first quench at 12,631 A and its second at 12,808 A, thus reaching a current to match operating values of the LHC machine with a 9 T magnetic field in the dipoles. It must also be pointed out that these quenches did not appear in the magnet, but at the connection point with the test station. The magnet has therefore reached its "ultimate" current without displaying any shortcomings, and as such has improved on the results from the prototypes.

In October 2003 the first cold mass from production was also successfully tested. Since then, five other quadrupoles have been tested, either singly or in a cold mass.

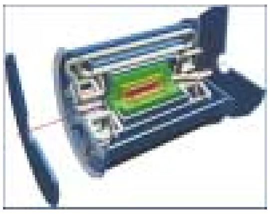
The success of these first tests shows the quality and robust nature of the design produced by Dapnia and makes us confident about the outcome of series manufacture.



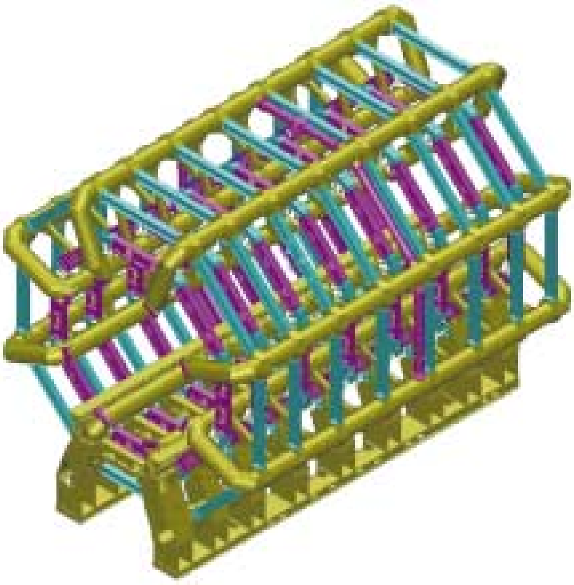
Details of transitions (quenches) in the first production magnets. Each magnet is subjected to a thermal cycle (1.8 K – 300 K – 1.8 K) to check that it is retaining its previous performance.

MQ: single quadrupole magnet
CM: cold mass (main quadrupole magnet + corrector magnets)
Nominal current: 11,870 A
(corresponds to a field gradient of 223 T/m)
"Ultimate" current (the maximum possible current): 12,850 A

The toroid magnet for the Atlas detector



The magnetic system of the Atlas detector for the Large Hadron Collider consists of a central toroid magnet, made up of eight superconducting coils, two end-cap toroid magnets and a central solenoid. Since 1996 Dapnia has been responsible for design and production control of the central toroid on the basis of a cooperation agreement with CERN. After construction and testing of a prototype coil in 2001, the final toroid magnet coils were built at CERN using components supplied by various European firms. From 2000 to 2003, Dapnia carried out the manufacturing monitoring of most of the components and the technical monitoring of their assembly at CERN.

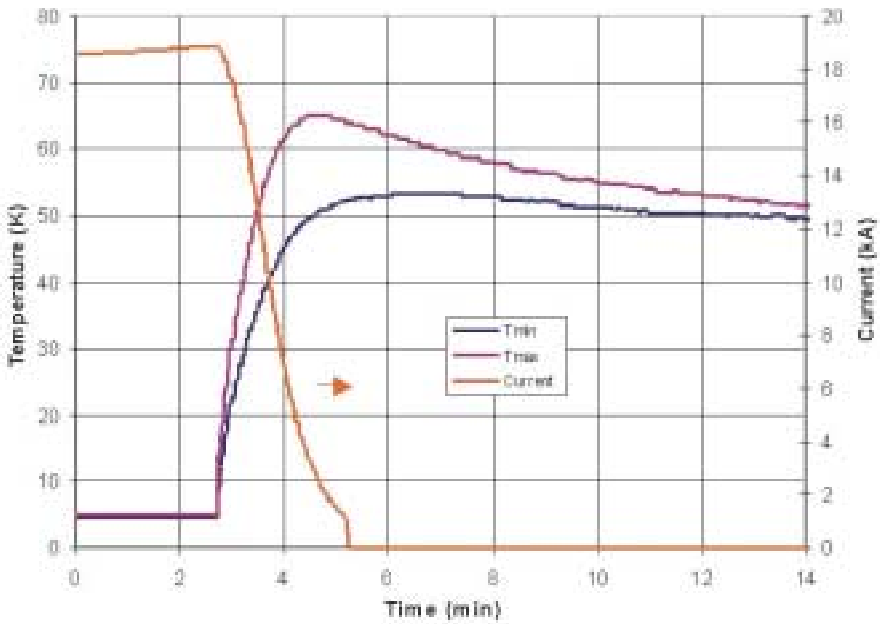


General view of the central toroid: internal diameter = 9.4 m; external diameter = 20.1 m; length = 25.3 m; stored energy = 1080 MJ. In yellow: the eight superconducting coils in their cryostats (8 x 87 tonnes). In fuchsia and turquoise: the warm mechanical structure linking the coils together.

B0 prototype coil testing

Before building the Atlas detector, a 1/3-length prototype of one of the eight coils, the B0 coil, was built in 1999, using as far as possible the components and assembly methods envisaged for the final coil versions. This "small" coil, of the size of a London bus, has confirmed the choices of technological solutions planned for final detector construction, both from a mechanical point of view and from its thermal and electrical aspects.

We cooled this coil twice at CERN during 2001 so as to get as much information as possible from it. It should be remembered that during cooling from 20°C to – 269°C the coil contracts by more than 3 cm whereas the external envelope shows practically no displacement. To simulate the attractive forces between the toroid coils when the 20.5 kA nominal current flows through them, we placed B0 along a block of iron, which acted as a magnetic mirror producing a force of around 5000 kN.



B0 prototype coil testing: increase in temperature due to a rapid discharge from 19 kA onwards.

The current in the coil was raised to the limits of the electrical supply, in other words 24 kA, i.e. 17% in excess of the nominal current. We learned a lot about the stability of the magnet, such as the propagation speeds of a resistive zone and the critical energy for its creation.

The problems encountered during these tests led us to modify the design – that of the conductor output for instance – as regards the final coil versions. Finally we obtained confirmation of the cooling process and the fault procedures, i.e. electric power supply failure, change in helium distribution, etc.

Construction of the toroid magnet cold masses

The central toroid uses 32 conductor unit lengths of 1730 m each. Particular attention has been paid to the line checks at the manufacturers during extrusion of the aluminium matrix surrounding the superconducting cable. The size and profile of the conductor have been measured every 30 cm using two pairs of laser micrometers. Detection of local decohesions on the cable/aluminium interface, due to the presence of large amounts of copper oxide, was measured using Phased Array System (PAS) bias, made up of two ultrasonic transducers.

The conductor (12 mm x 57 mm) is made up of a superconducting cable co-extruded in a high-purity aluminium matrix. Its nominal current is 20.5 kA and maximum field on the conductor is 3.9 T. The wires making up the cable are made of NbTi 50 μm diameter filaments embedded in a copper matrix.

Winding and impregnation of the eight coils was carried out by Ansaldo (Genoa, Italy). So as to retain adequate coil compaction, a stress of 3000 N is applied on the conductor, which is surrounded by its insulation throughout the full winding operation, even when this includes stoppages and start-ups. On account of its large dimensions it is not possible to put the coil in an autoclave for final impregnation. As a result the concept of an expandable chamber has been developed, made of aluminium sheet panels of a thickness of 2.5 mm welded around the coil. Special attention has been paid to the welding to minimise the level of leakage which, based on the experience of the B0 prototype, has to be lower than 10^{-2} mbar.l.s^{-1}. After degassing, the impregnation sequence begins with the injection of epoxy resin. The temperature needed for impregnation is obtained by heating the coil. To do this, a continuous 500 A current is passed through it.

Turn over of a double pancake winding in its cold box during the assembly of the cold mass.

When it comes to incorporating the cold masses, an assembly technique has been developed to allow for the sizeable magnetic forces applied on the conductor. Each winding is inserted in a coil box, a mechanical coil support, and prestressed using bladders working as expanding wedges. These bladders are first of all filled with glass micro balls using a flow of argon gas, and then the residual gas is evacuated and replaced by long pot-life low viscosity epoxy resin, injected at 2 bar. Resin polymerisation is carried out by raising the coil temperature to 70°C by means of a current in the conductor, then by increasing the pressure in the bladders to 125 bar. A final plateau at 125°C is maintained for thirty hours to complete polymerisation. The last of the eight cold masses was assembled at CERN in October 2003.

Incorporating the cold masses in their cryostats

The vacuum vessel of a coil is a racetrack shape tube 1.1 m in diameter and 25 m in length. It is made up of rolled and welded 10 mm stainless steel plates. Dimensional tolerances are less than 5 mm over its full length, which is a technical challenge for this kind of fabrication. At the end of 2003, seven vacuum vessels have been delivered to CERN and the eighth will be delivered in 2004.

The cold mass is supported in the inside of the vacuum sleeve by 8 tie rods and 32 cryogenic stops. The tie rods, made of Extra Low Interstitial

Installing the tie rods in the cold mass.

(ELI) titanium alloy withstand net radial magnetic forces and on bending, allow the 45 mm displacement of the cold mass that results from cooling. After final machining, the tie rods are tested at 4.2 K up to the test load of 250 t. The cryogenic stops are manufactured from glass fibre reinforced composite material tubes. One of the tubes (warm post) links the vacuum vessel to the thermal shield (at 80 K), the other (cold post) links the shield to the cold mass (at 4.5 K). To allow cold mass displacement a sphere covered with a Teflon coating is placed between the two posts; its geometry has been optimised to reduce stress concentrations and possible damage to the coating.

Three work areas are used during integration of a cold mass in its cryostat. Work starts with the gluing of the cooling lines, which are made up of two redundant circuits. The tie rods and the cryogenic stops are installed at this stage. The temperature, voltage and stress transducers are then installed, followed by the heat shields and superinsulation. After this operation the cold mass is inserted in the vacuum vessel, which is then closed and welded. Exact geometric checks are carried out throughout the integration operations to prepare for the final positioning of the coils within the cavern.

At the beginning of 2004 two cold masses will be fitted with heat shields and closure of the first vacuum vessel is planned for the beginning of June 2004. The first toroid coil will then be ready for testing.

Cryogenic stop ready for compression and flexion testing. Between the two posts made of composite material - the upper one, which will be linked to the warm vacuum vessel (300 K), and the lower one, to be linked to the cold mass (4.8 K) - the teflonised sphere is visible which will allow displacement resulting from cooling.

Integration of the first shield on the cold mass at CERN. Each shield is made up of 22 separate sections made of four 5 mm thick aluminium panels riveted together. The shield is attached by temporary supports (white cylinders). The final supports will not be installed until the cooling circuits have been welded and tested.

Scale 1 model of the sliding sleeve that will allow electrical and cryogenic hook up between the cryogenic ring and the coil.

Cryogenic ring design

The cryogenic ring is an in kind contribution from CEA/Dapnia to the Atlas project. The years 2002 and 2003 were essentially given over to its design. The role of the cryogenic ring is to distribute the cryogenic fluids and the electric power to the 8 coils. The current is carried to the coils by busbars (superconducting linkages between the electrical leads and the winding) cooled by two-phase helium at 4.8 K and 1.4 bar. The cryogenic ring is divided into eight sectors each 6 m in length, placed between the coils on the external radius of the toroid. Each end of the sector is fitted with a sliding sleeve that will allow electrical and cryogenic hook up to the coil during final toroid assembly. Construction will take place at Saclay in 2004. The first lower sector has to be delivered to CERN in September 2004.

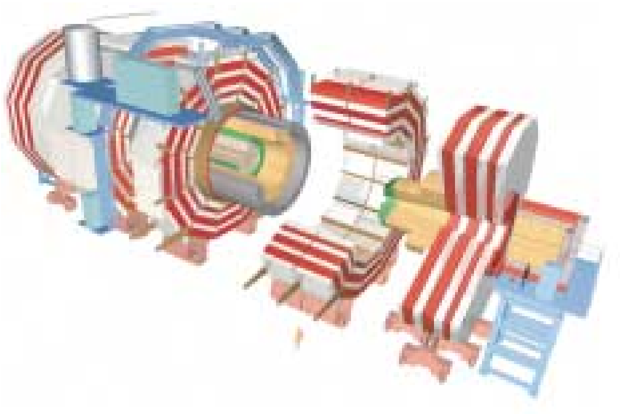
Warm structure and cavern assembly study

The warm structure, the other main item in the toroid assembly, is the mechanical structure that links the coils together. Eight aluminium voussoirs and junction box rings (850 mm x 500 mm section) and spacer rings (600 mm x 400 mm section) carry the weight of the magnet and the muon chambers attached to the vacuum vessels. When current is applied to the coils, a centripetal force of 1200 kN is applied to each cold mass. This force is transmitted to the warm structure by the tie rods. The first segment and junction box prototype has to be ready during February 2004.

The detailed assembly schedule is now defined. Final assembly is to begin in June 2004 and is set to last for over one year.

The CMS detector superconducting solenoid

Since 1996 Dapnia has been responsible for the general design of the solenoid for the CMS experiment of the Large Hadron Collider (LHC) project, as part of a collaboration agreement with CERN. Within Dapnia, SACM acts as the pilot division for the project in regard to the magnetic and thermal design of the magnet, supervision of assembly and surface testing at CERN. It is helped by the SIS *(Service d'ingénierie des systèmes)* as regards the mechanical design and instrumentation aspects, as well as industrial production monitoring. Apart from its size, what is particular to this solenoid are the conductor reinforced by an aluminium alloy and the design of an internal winding in an external cylinder. The years 2001 to 2003 saw the project move from the final study phase to that of component construction and start of assembly. These years allowed SACM to test a certain number of critical components before using them in the magnet.



The superconducting solenoid (in grey) at the centre of the CMS detector.
The magnetic field at the centre of the solenoid is 4 T; solenoid length is 12.5 m with an internal diameter of 6 m. Stored energy is 2.7 GJ. Its mass is 220 tonnes. It is built as five 2.5 m modules.

Cold mass study and construction of its components

Once the general design of the cold mass had been passed in a joint technical review of the project in December 1998, the usual study and construction activities were actioned:

- Detailed drawings finalised.
- Technical specifications drawn up and calls for tender put out via CERN.
- Contractors chosen (with CERN).
- Construction monitoring right up to acceptance.

In effect, SACM is responsible for the technical aspects and is piloting the following sub-assemblies either built by European manufacturers, or built in countries that are taking part in the project. These are sub-assemblies that figured very early on in detailed studies. They are:

- The suspension system, made up of thirty titanium tie rods built in Russia; acceptance was issued in September 2003.
- The proximity cryogenics; construction is ongoing and acceptance is planned for February 2004.

One of the five winding modules under construction at the Ansaldo Superconduttori Company (by courtesy of INFN, Genoa).

- The heat shields built in Italy; the internal shields were installed at CERN in September 2003, the external shields will be installed in the third quarter of 2004.
- The French-built current lead system; it was installed and tested at Saclay in the 3rd quarter of 2003.
- The pumping system awarded to a German company; acceptance is planned for mid 2004.

SACM took part in follow up of the winding. Winding is carried out in Italy by the Ansaldo Superconduttori Company, under the auspices of the INFN *(Instituto Nazionale di Fisica Nucleare)* of

Genoa. At the end of 2003, the five modules making up the winding were 60% completed. SIS is responsible for the internal instrumentation of the magnet diagnostics system and is taking an active part in the magnet control and safety systems.

Specification and qualification of various critical elements

The SACM test stations are used to specify and qualify some of the cold mass elements. The following are worthy of mention in particular:

- Critical current measurement of wires taken out of the conductor at various stages of its manufacture.
- Characterization of the mechanical aspects of the impregnation resin with reference to the surface state of the conductor.
- Cold and room temperature characterization of two types of titanium alloy in the mechanical test laboratory for making the suspension tie rods.
- Refitting a test station for testing all the tie rods under mechanical conditions at 110% of their loading, and under real thermal conditions, once two prototype tie rods have been tested.

Solenoid electric current leads ready to be inserted in the test cryostat for testing.

In addition some specific plant has been refitted or developed:

- A test station for testing electrical connections under magnetic field up to 10 kA; two prototype connections of about 1 m in length displayed a resistance of about 0.9 nW under 2 teslas and 0.6 nΩ under zero field.
- A test station for testing the current leads at their nominal rating (20 kA), with and without cooling.
- A certain number of mock-ups built at Saclay to facilitate final assembly, such as the tie rod introduction mock-up.

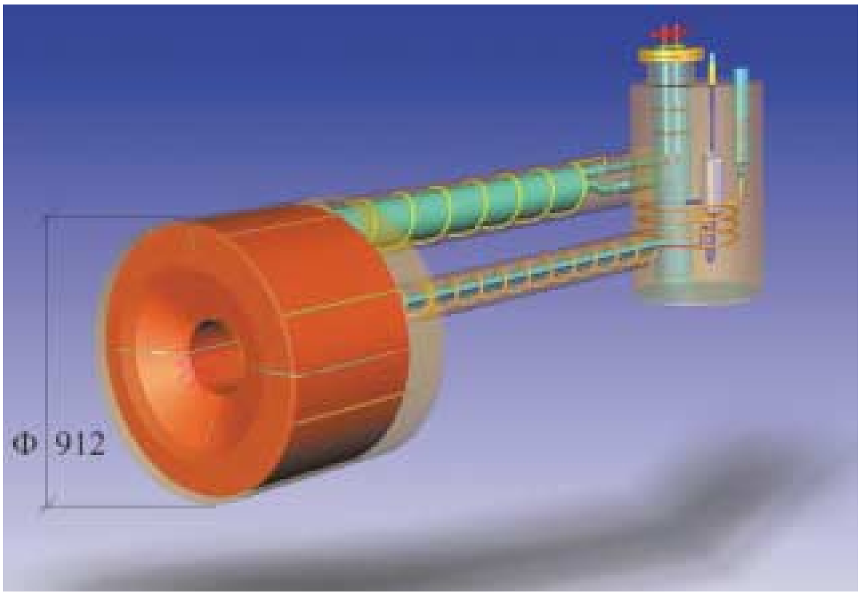
Fitting the cold mass

The solenoid assembly procedure was studied in 2001, and then controlled by an external testing agency. The five solenoid modules will be assembled vertically, to make up the final cold mass. A large platform designed at Dapnia and built in South Korea will be used to support them. The platform will be pivoting so as to swing the coil into its final horizontal position where it will then be held in a cantilever position. The outer vacuum vessel will then be translated horizontally so that the coil can be inserted into it. This platform was successfully tested during the summer of 2002, using the inner vacuum vessel with counterweights to simulate the cold mass.

Testing at CERN of the platform for fitting the cold mass of the CMS solenoid, using the vacuum vessel as load. The platform will be used to assemble and then to swing the solenoid from a vertical to a horizontal position.

The superconducting solenoid for the CLAS DVCS experiment detector

As part of the collaborations with the Thomas Jefferson Laboratory in the United States, Dapnia has undertaken to study and build a superconducting solenoid for the Deeply Virtual Compton Scattering (DVCS) experiment that will take place at Newport News in Virginia during 2004. This magnet will be used in the centre of the toroidal field created by the six CLAS (Cebaf Large Acceptance Spectrometer) detector magnets. The originality of this project is to be found in the addition of a solenoid corrector coil to the main solenoid. This cancels out the interaction forces between the two magnets, with the result that there is considerable reduction in the effects of the magnetic field on its periphery.



Solenoid vacuum vessel (Ø 912mm) at the end of the phase separator (upper manifolds) and of the helium and electric supply pipe (lower manifolds), which are hooked up to the junction box.

The SphN *(Service de physique nucléaire)* is to supervise contract specification for the DVCS experiment, the SACM *(Service des accélérateurs, de cryogénie et de magnétisme)* is the division piloting the building of the system, and the SIS *(Service d'ingénierie des systèmes)* is in charge of mechanical design and monitoring system.

In 2002, studies undertaken jointly between SACM and SPhN resulted in the architecture of this magnet as it is at present. The magnetic field at the centre is 4.5 T in an aperture of 230 mm, the external field at the vacuum vessel is less than 3 10^{-3} T for the diameter of 912 mm, nominal current is 550 A and the magnet operates with liquid helium at 4.2 K. SACM has refined the magnetic studies to the point of simulating the trajectory of the particles that are deflected in the magnetic field. We carried out the heat studies and drew up all the cryogenic installation plans in parallel with the above. SIS began the mechanical, electrotechnical and electronic studies.

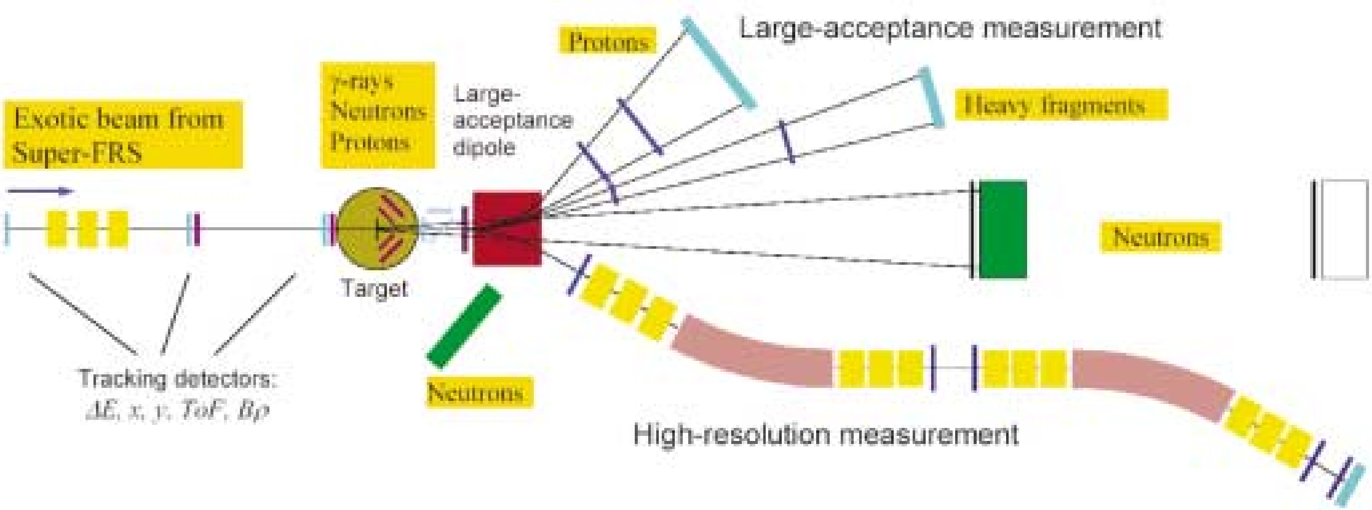
In 2003 SACM carried out winding of the two solenoids, as well as their final assembly and the first warm-model magnetic measurements. SIS built the mandrels, carried out mechanical studies and put out calls for tender for the cryostat vessels and construction of the monitor banks.

Cryostat assembly, 4.2 K testing at Saclay and commissioning of the magnet at Newport News are planned for 2004.

Solenoid being wound at Saclay.

R3B-GLAD superconducting dipole

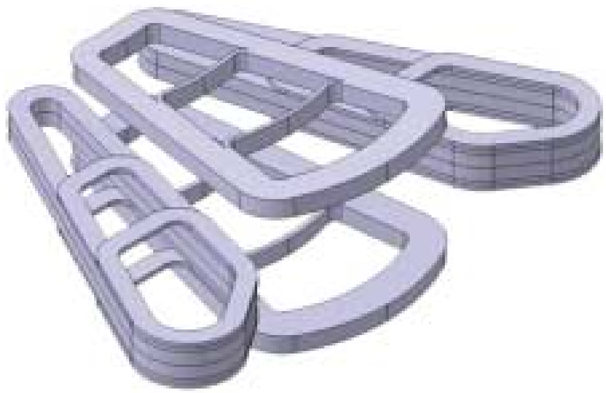
The European R3B (Reactions with Relativistic Radioactive Beams) collaboration sets up a program devoted to the emergent physics of the radioactive heavy ions. Among the existing exotic-nuclear beam facilities in Europe and worldwide, the GSI laboratory *(Gesellschaft für Schwerlonenforschung)* at Darmstad in Germany is the only facility where radioactive-beam experiments at relativistic energies can be performed. During the past decade it was demonstrated that nuclear reactions with high-energy secondary beams are an important tool to explore properties of nuclei far off stability, and that detailed spectroscopic information can be extracted. The energy level required by these relativistic exotic beams (1 GeV per nucleon) needs the construction of experimental facilities with new and improved performances. Within the R3B detector, the large acceptance spectrometer GLAD (GSI Large Acceptance Dipole), designed by Dapnia, achieves, in particular, the total transparency to the large cone of neutrons coming from the target.



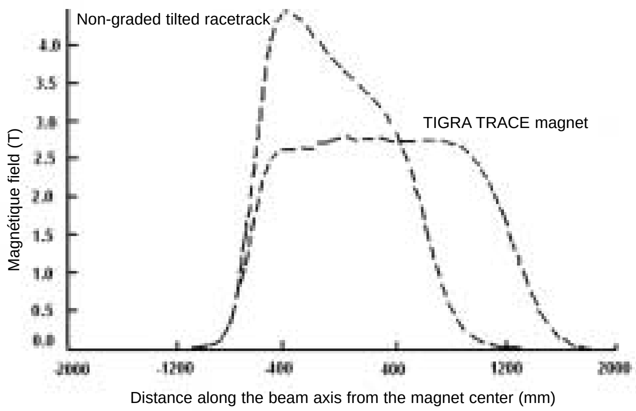
Experimental infrastructure.

Funded by the 5th European Framework Programme for Research and Technological Development (FP5), the design of the large acceptance superconducting spectrometer was carried out between 2001 and 2002. In order to cope with the ambitious experimental requirements, a large acceptance and a high field integral are associated with low fringe fields (< 20 mT at 0.30 m from the magnet entrance), in particular at the target region, where detectors have to be placed. A good separation between downstream trajectories of heavy fragments and protons is also achieved to facilitate momentum analysis.

An innovative magnet design with active shielding consisting of four superconducting coils was developed ("TIGRA TRACE" design: Tilted and Graded Trapezoidal Racetrack coils). The two main race-track coils are vertically tilted - and the side coils horizontally - to minimize the overall volume and stored energy while keeping fringe fields low and matching the required acceptance angle for the particles of interest. The number of turns in the coils is graded in order to achieve a flat profile of the magnetic field (2.7 teslas) in the useful volume and to control the peak field on the superconductor cable (7.5 teslas). The side coils are also graded and optimized to reduce the fringe fields of the iron-



Layout of the four superconducting graded coils. The downstream opening has a width of 1.20 m and a 0.60 m height.

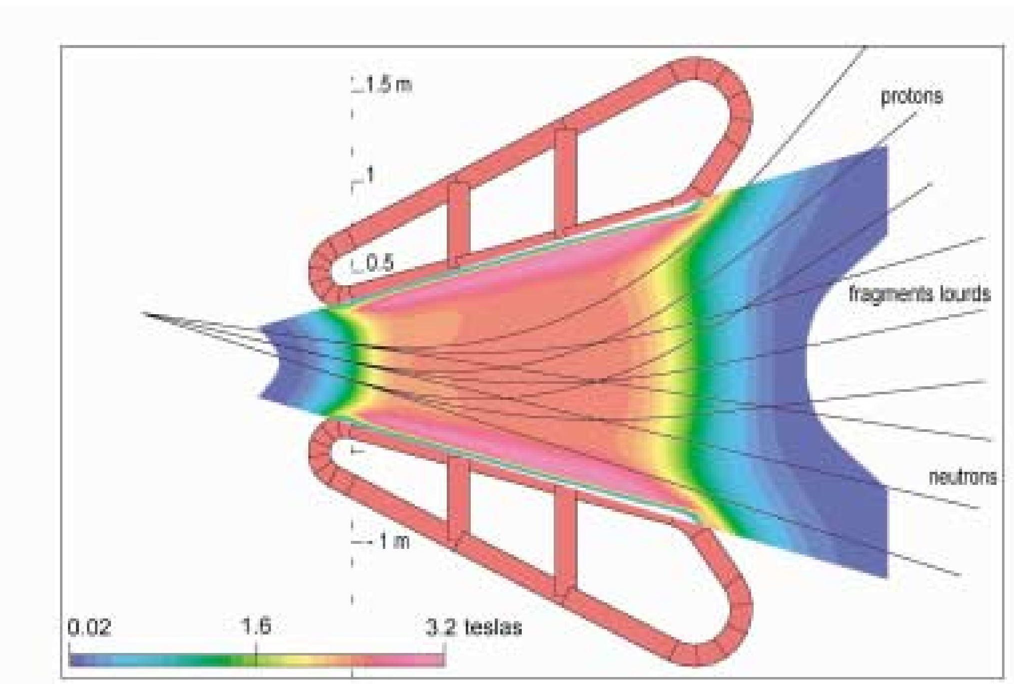


Design comparison. To achieve a flat profile of magnetic field along the beam axis, the coils are graded to compensate their tilt. Then the particles trajectories are well separated.

free dipole, and guarantee a low magnetic field in the target region. The position, the cross-section and the trapezoidal shape of all the coils realize an essentially dipolar field. With a current density of 80 A/mm^2, this new design yields a rather compact magnet, and the magnetic stored energy is minimized (22 MJ). The technology of active shielding has the advantage of linearity between the magnet current and the magnetic field map, combining the advantages of an iron-free superconducting magnet while keeping the fringe fields small.

The protection system uses active quench detection with external dump resistance. The coils are imbedded in an aluminium alloy pre-stressed cold box to cope with forces that reach rather high values (between 3000 and 4000 kN per meter). Helium cryogenic cold mass indirect cooling is performed trough an innovative thermosiphon, the cryostat with its helium phase separator and thermal shield has an outer diameter of about 4 m.

In 2001 the Technical Design Report was examined by an international committee of experts. In 2003 the R3B-GLAD construction project has been prepared for the 6th Framework Programme (FP6), and studies are in progress in order to optimize the final configuration. The Dapnia / SACM is in charge of this magnet project, with the help of SPhN and SIS, and takes part in the R3B collaboration gathering 22 international institutes.



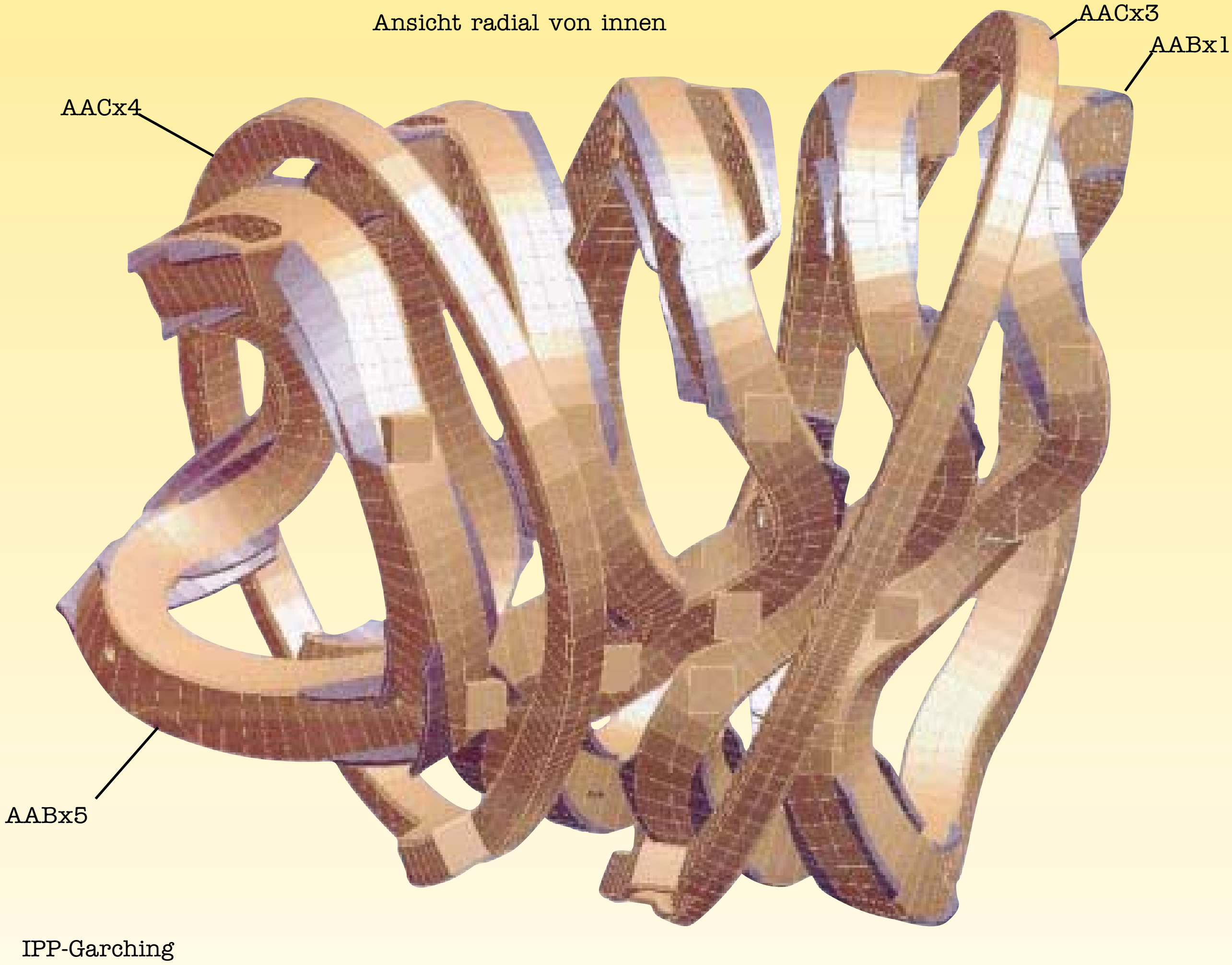
Magnetic field map and sketch of the various trajectories. Upstream and downstream of the coloured area the magnetic field is lower than 20 mT.
The main parameters of the dipole are:
1. A high field integral of about 5 Tm, which gives a bending angle of 18° for 15 Tm beam rigidity; this allows study of exotic nuclei, as 1 GeV/u ^{132}Sn or 500 MeV/u ^{8}He, with a high resolution.
2. A large vertical gap allowing a free cone with an angular range of ± 80 mrad for particles to be detected (including the neutrons).
3. A horizontal acceptance, which allows a maximum bending angle of 40° (protons).

Superconducting electromagnets for other scientific communities

SACM can also develop its cryomagnetic expertise in projects initiated by other scientific communities.

SACM is in charge of acceptance tests on the superconducting coils of the Wendelstein 7-X stellarator, a research machine for thermonuclear fusion by magnetic confinement, conducted by the Institute of Plasma Physics at Garching, in Germany.

As part of the Neurospin project of the *Direction des Sciences du Vivant* of the CEA, SACM has carried out the feasibility study for a wide-bore high-field magnetic system intended to equip this planned neuro-imaging centre using nuclear magnetic resonance.

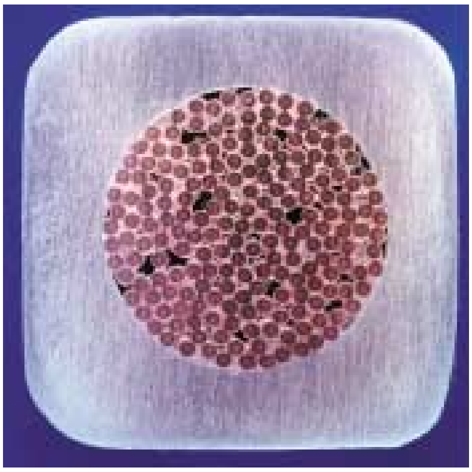


Coil tests for the Wendelstein 7-X stellarator

The W7-X project is lead by the Institute of Plasma Physics at Garching (Germany), which is responsible for building one of these research machines for the European magnetic confinement thermonuclear programme. This machine, called the Wendelstein 7-X stellarator, has a diameter in the order of 15 metres and a mass of 550 tonnes and is made up of 70 superconducting magnets designed for plasma confinement. The SACM is in charge of the acceptance tests of the 70 magnets manufactured in Germany, Italy and England, before their final installation on the stellarator built at Greifswald in Germany. These tests allow to study the electrical, thermal and hydraulic behaviour of each magnet at room and cryogenic temperatures. They are programmed to happen over a 4-year period from 2003 onwards.

Design, construction and qualification of a test station

Even just with regard to the magnetic configuration of the fusion machine, the coils are bound to be of complex geometry. Planar coils have a mass of 3 t and approximate dimensions of 3.5 m x 2.5 m, whereas non-planar coils have a mass of 6 t and dimensions in the order of 2.5 m x 1.5 m. The winding is made up from “cable-in-conduit”, that is to say, the superconducting wires (niobium-titanium and copper composite) are enclosed in a leak-tight aluminium jacket. It is in this jacket that the supercritical helium flows at a pressure of 6 bar and a temperature in the range 4.5 K - 7.6 K. This type of conductor has necessitated some original connecting boxes that include the impenetrable jacket. To obtain the rate of testing needed, a test station including two cryostats, each able to take two magnets, has been designed and built. In July 2000 the first cryostat was delivered, and the first cryogenic tests of this cryostat took place in June 2001.



Section of the cable-in-conduit. The cable is made up of 243 wires of 0.57 mm diameter composed of niobium-titanium and copper. It is inserted in a 16 mm aluminium alloy jacket. Supercritical helium flows through the void between the wires. Operating current is about 17,000 A under 6.2 T.

At room temperature, four stations enable the following main tests to be performed:

- coil-coil box insulation tests (10.4 kV);
- layer/layer insulation test (1600 V ac, 2 kHz);
- transducers/mass insulation test (50 V);
- pressure drop check for each magnet circuit.

At cryogenic temperature, the two cryostats enable the following main tests to be performed:

- pressure drop check for each magnet circuit;
- magnet load increase to nominal current (≈ 17,600A), then checks on the margin between nominal magnet operation and critical operation where the magnet suffers partial loss of its superconductivity;
- transition of each coil by temperature increase.

An electric test bench, validated in January 2003, and a hydraulic test bench, validated in June 2003, have been studied and built, in order to automate different test sequences, as well as to automatically generate reports that can be incorporated in the general test report.

Since electric insulation testing of the magnet has to be carried out at cryogenic temperatures, it has been necessary to develop mass insulation systems with insulating characteristics of 10 kV under vacuum at 4.5 K for the different parts of the installation under load (electrical power leads, hydraulic circuits, electric power inlets etc.). In addition, to connect the magnets to the test station, we have developed some junction boxes. These junction boxes are original because they are reusable, need no welding, are connected directly to the cable-in-conduit and can withstand pressures of 30 bar at 4.5 K.

Magnet cooling is carried out by a 200 W refrigerator rated at 4.2 K directly coupled to a cold box called the “satellite” allowing preparation of the cryogenic fluids for one or other of the cryostats. Helium cooling of different magnet circuits is carried out using supercritical helium at 4.5 K under 6 bar. Investigation of the difference between magnet

Test station cryostats being fitted at Saclay.

operation temperature and transition temperature gives the operating margin of the magnet. This investigation is carried out by raising the helium input temperature by increments of 0.1 K from 4.5 K right up to transition temperature. The installation allows the attainment of temperatures up to 7.6 K.

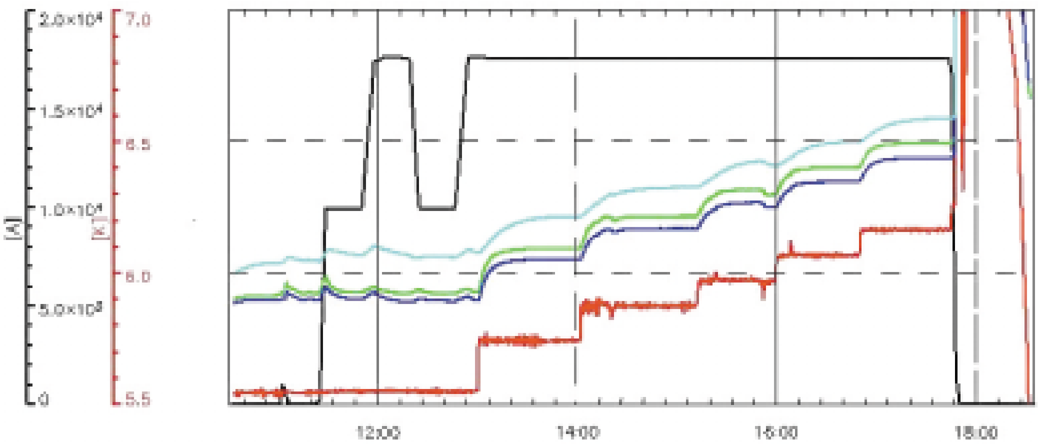
Coil tests

Between September 2001 and May 2003, study of a coil demonstration prototype confirmed the various tests performed at each station. In particular the operating margin test, which was repeated several times, proved to be reproducible and enabled confirmation of magnet stability after several transitions from superconducting to normal state. It also allowed checks of all the systems in the installation, these being control, protection, acquisition and instrumentation.

The first production coil was delivered in June 2003. The first room temperature tests were performed during July 2003. In September, the cryogenic temperature tests were carried out, as well as determination of the magnet margin followed by reheating and final room temperature testing. Power testing at cryogenic temperatures gave evidence of very good magnet stability and an operating margin greater than expected. At the end of October 2003 the coil was ready to be shipped to Germany. All tests that have been carried out are in accordance with the calculated values and this first production magnet can be declared as “passed”.

During the final quarter of 2003, a 6-strong team carried out the room temperature and cryogenic tests on two new magnets inserted together in cryostat no. 2. For 2004, it is planned to test 15 to 20 magnets as they arrive.

Arrival of the production coil at Saclay.



An “operating margin test” of the demonstration coil. The black curve shows the increase in current to its nominal value (14,600 A) with an intermediary plateau at 10,000 A. During this phase, input temperature (in red) is set at its nominal value of 5.55 K. It is then increased by 0.1 K every half hour until coil transition takes place (at 17:48).

The Neurospin project

The *Direction des sciences du vivant* of the CEA proposed the Neurospin project involving the design and construction of a neuroimaging and nuclear magnetic resonance (NMR) spectroscopy centre. Designed to push out the limits of cerebral imaging, this technical platform, to be built within the confines of the CEA Saclay site, will be fitted with four NMR systems. There are two systems producing magnetic fields of 3 T and 11.7 T for clinical studies on humans, and two systems designed for pre-clinical studies on primates and small animals, each of 11.7 T and 17 T respectively. SACM has carried out three studies designed to check feasibility and highlight difficulties in some particularly sensitive sub-components, such as the 11.7 T wide aperture magnet, the magnetic field gradient coils, and the high frequency antennas.

11.7-tesla superconducting magnet

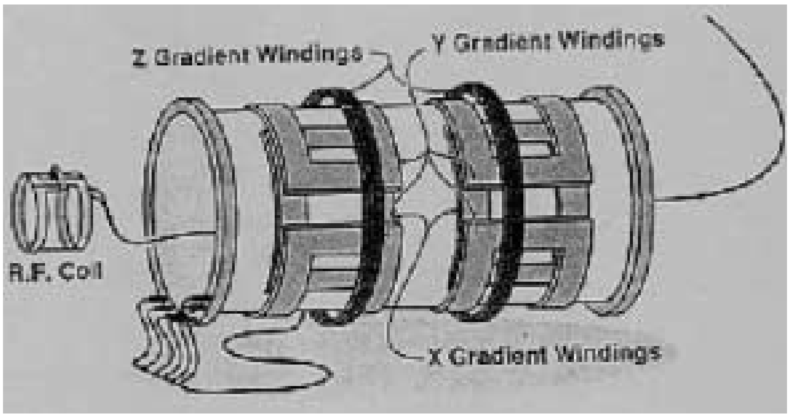
High fields allow us to increase the spatial and temporal resolution of the imagery. A pre-study has shown that it is possible to build a magnet of 11.7 T of 900 mm effective diameter - from niobium-titanium cooled by superfluid helium to 1.8 K – at the same time as meeting field uniformity constraints (0.1 ppm in a 10 cm sphere) and low fringe field constraints ($B < 5.10^{-4}$ T at 5 m radially and 9.6 m axially from magnet centre). The magnetic system obtained has a stored energy of 300 MJ and overall dimensions of 4.1 m in length and 3.2 m in diameter. This study was carried out by the SACM in joint partnership with the SIS.

Magnetic field gradient coils

High fields involve the use of high performance gradient systems, which have high field gradient amplitude and short switching time. Traditional gradient coils used in the NMR magnets are subject to considerable cyclic stressing induced by gradient switching in a high static field; they are therefore fragile and emit high levels of noise. Distribution of the mechanical stresses over a traditional system has been analysed and has allowed us to understand where the noise comes from. Professor Guy Aubert, a scientific advisor at Dapnia, has therefore suggested a new magnet structure whose specific characteristic would be a considerable reduction in the stresses, which should translate into large reductions in noise. This suggestion has been the subject of a patent application. Prototype testing is planned to take place in 2004.

High frequency antennas

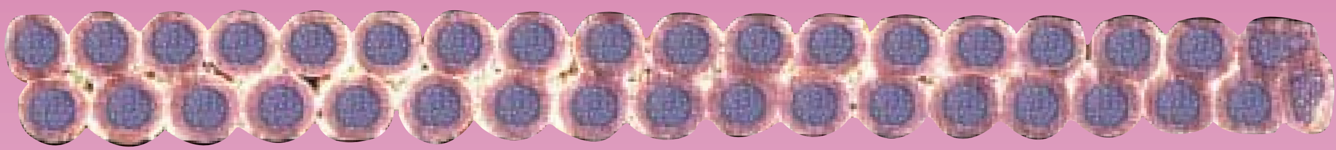
These antennas are used to generate a radio frequency wave (RF) whose magnetic field allows excitation of the nuclei of hydrogen atoms within the sample placed in the cavity, as well as transduction of the very weak radio frequency signal which results from NMR relaxation. SACM has modelled the antennas traditionally used and shown that they could not operate at 500 MHz, the resonating frequency of the protons corresponding to the main field of 11.7 T. A new antenna structure has been suggested by SACM, and a prototype model has been built by the *Service d'électronique, des détecteurs et d'informatique* (SEDI). This prototype is currently under test. Specific absorption rate (SAR) measurements will also be carried out to check that the power generated by the RF pulses in the tissues of the human head remains within acceptable limits.

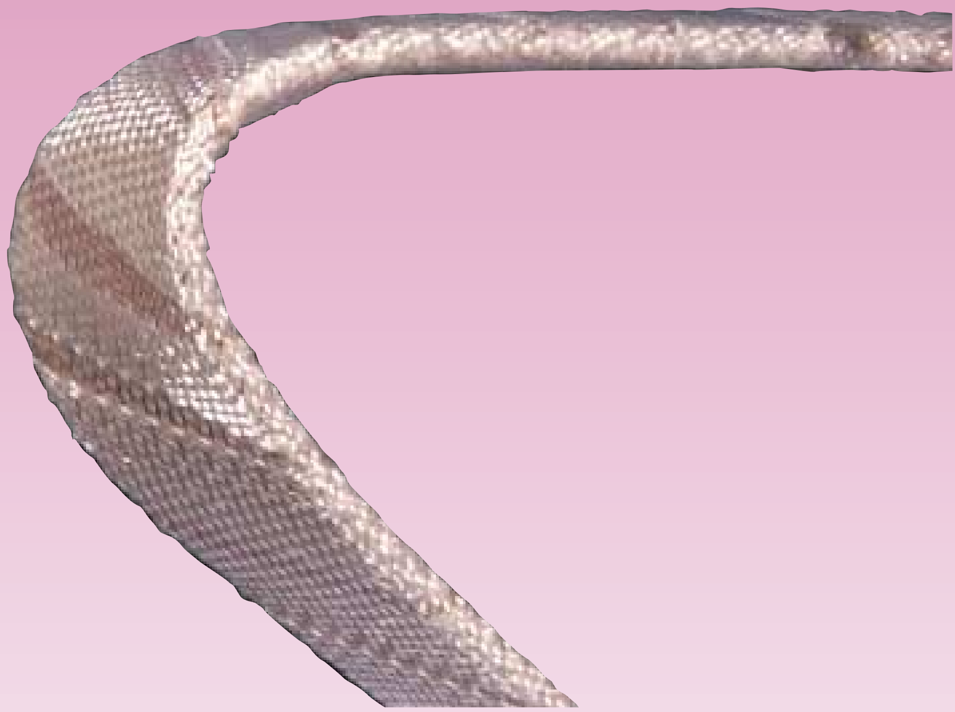


Main solenoid, gradient coils and high frequency antennas layout of an NMR system.

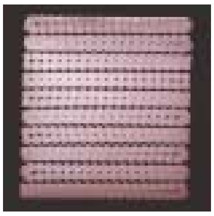
Developments for future électromagnets

The design and construction of high technology cryomagnetic systems are based on R&D activities. At the moment the priority programme is directed at the developments needed for high field magnets (in excess of 12 teslas). Another R&D direction is the hydrodynamics of two-phase helium flows used in particular in systems using thermosiphon cooling.



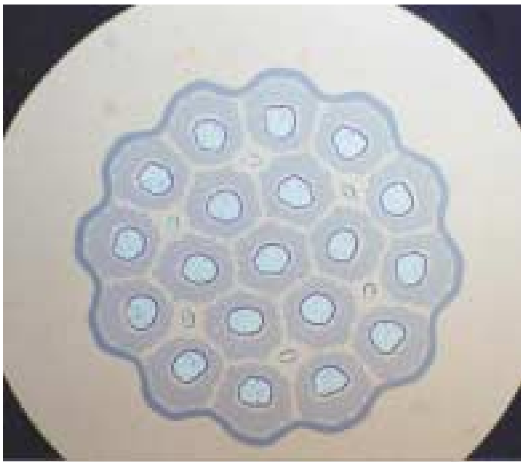


Developments for high magnetic field magnets



At the moment, there is only one superconductor likely to succeed niobium-titanium (NbTi) in the medium term for large-scale applications that need electromagnets using high current densities in high magnetic fields (in excess of 12 teslas). This is the intermetallic compound of niobium-tin (Nb_3Sn). The research and development programme, carried out jointly with CEA and Alstom/MSA, has as objective the acquisition and advancement of Nb_3Sn technology for the management of projects involving new superconducting magnets with very high fields. Three key operations have been carried out in parallel: development of Nb_3Sn wires displaying very high performance characteristics, fabrication of a quadrupole magnet model, and development of ceramic-type electrical insulation.

Development of high-density critical current wires from Nb_3Sn



Nb_3Sn wire developed by Alstom/MSA. The critical current density in the superconductor is 750 A/mm² at 4.2 K and 12 T.

The development is articulated in two phases. The first phase concerned the development of a Nb_3Sn wire meeting the specifications of the ITER model coils so as to allow Alstom/MSA to catch up on ground lost to its competitors, in particular American ones, both in terms of performance and in terms of yield and production costs. This objective was met in 1999 with a wire achieving a critical current density of 750 A/mm² at 4.2 K and 12 T. To remain competitive at world level, Alstom/MSA is now developing, in a second phase, a 2000 A/mm² wire at the same temperature and magnetic field. This second phase is also meant as an intermediate step towards the even more ambitious goal of 1500 A/mm² at 4.2 K and 15 T (corresponding to 3000 A/mm² at 4.2 K and 12 T) set up by the EU-funded CARE/NED Joint Research Activity.

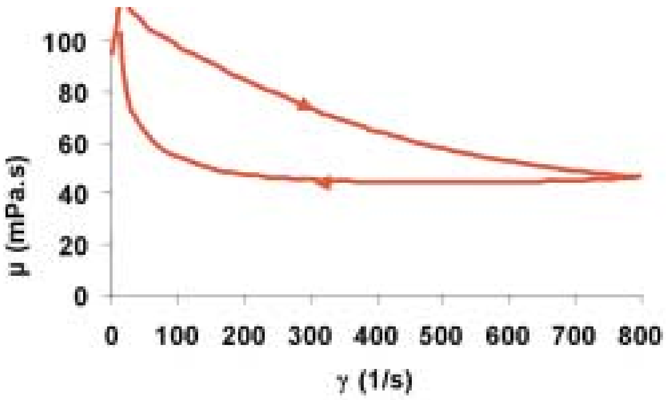
Fabrication of a quadrupole model

The Nb_3Sn compound has a critical temperature and field that are almost double those of NbTi. However, it does have the disadvantages of being brittle and having critical parameters – such as current density - which are sensitive to deformations or stresses. By comparison therefore with NbTi, design and manufacture of the coils have to be completely rethought so as to limit risk of degradation.

Winding tools for manufacture of the quadrupole model at Saclay.

Since 1995, SACM has undertaken the design, construction and cold testing programme of a quadrupole magnet model based on the design of the NbTi quadrupole magnets of the Large Hadron Collider developed by SACM for CERN. The bore is 56 mm and nominal field gradient is 223 T/m for a current of 11,870 A. The model magnet coils will be wound from the phase 1 cable developed by Alstom/MSA.

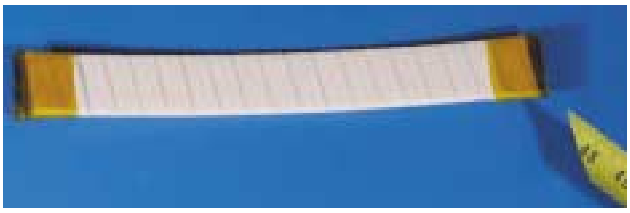
The last three years have been devoted to the finalisation of the design and the procurement of the main components and tools needed for the quadrupole model. All cable lengths have been delivered in February 2004. Winding of the first pole is set to start in August 2004 with cold testing of the magnet foreseen at the end of 2005.



The variation of the viscosity of the solution of precursors, as a function of shear rate, shows off its rheological behaviour. The solution should ensure a good tape impregnation and have a good plasticity.

Developing ceramic insulation

The main objective of the development of ceramic-type insulation is the study and production of an electrical insulation able to withstand the high temperature (600 to 700°C) heat treatment needed to react niobium-tin. The conductors are wrapped in glass fibre tape with a protective coating of precursors that react during the high temperature heat cycle to provide insulation and ensure that the coil has the correct mechanical characteristics. At the same time the niobium-tin compound is formed. In this way, two tricky stages of manufacture are eliminated: handling of the coil after heat treatment to take it out of its mould at a stage when it is very fragile; and then the vacuum impregnation stage using an epoxy resin. This development will unlock one of the doors to the technology of Nb_3Sn compact coil windings by simplifying their scale of manufacture and making it more accessible to industrial processes.

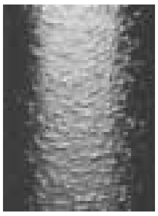


Cable with pre-impregnated tape wrapped before heat treatment (upper photo).
Stack of insulated cables after heat treatment at 660°C (lower photo).

Since January 2001, development has continued as part of research work co-financed by CEA-*Région Languedoc Roussillon* and the *Laboratoire des céramiques et des composants avancés* (CEA, le Ripault) and the *Institut européen des membranes* (CNRS, Montpellier). The main achievements are: optimization of components and of rheological parameters of the solution of precursors, and design and set-up of the impregnation bench for the glass fibre tapes. The first stages of insulation manufacture, that is tape impregnation and wrapping of superconducting cable, have been completed. The first electrical tests have shown that the presence of the insulator during the thermal reaction did not modify the properties of the copper included in the superconducting wires making up the cable. Electrical and mechanical characterizations are ongoing.

Two patents concerning “fabrication procedure for an electrically insulating and mechanically structuring jacket for an electric conductor” have been applied for by the CEA in July 2001 and in May 2003.

Thermohydraulics of helium



Two aspects of research and development are being pursued in the field of thermohydraulics, both oriented towards study of the cooling systems of superconducting magnets. The first aspect, closely connected to the cryogenic system of the magnet of the CMS detector, concerns the study of the two-phase flows – gas and liquid – in a thermosiphon configuration. The second aspect concerns heat transfer to superfluid helium through porous media. In parallel with these developments, thermal measurements of materials at very low temperatures are being carried out so as to meet the needs of internal projects such as Atlas and CMS, or of companies and laboratories from outside.

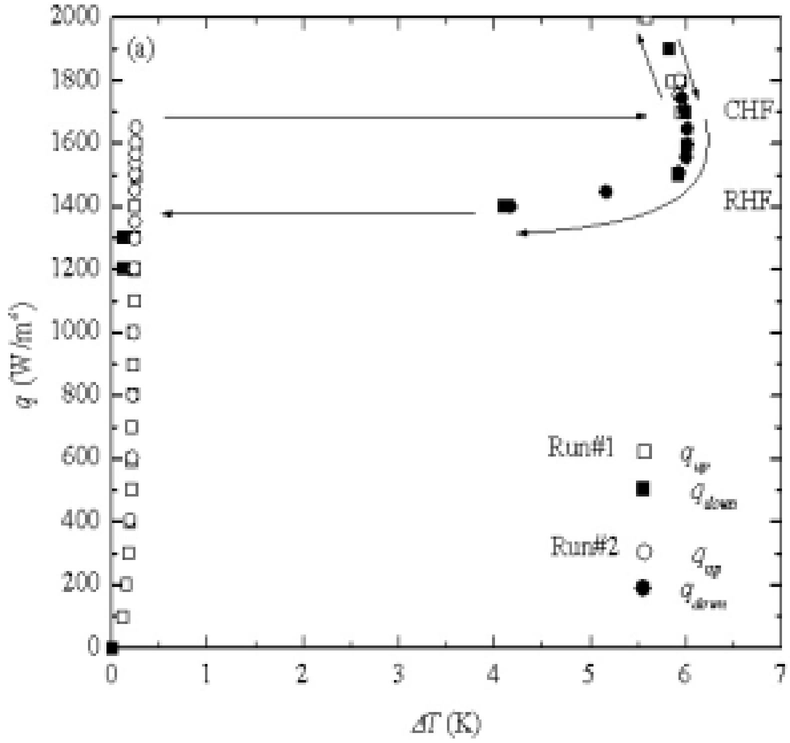
Two-phase helium flows in a thermosiphon configuration

An experimental system made up principally of a phase-separator and a vertical hydraulic pipeline 1.2 m in length and of 14 mm internal diameter, inserted in a U circuit and thus recreating a cooling ring, was designed and qualified in 1999. From 2000 to 2003, heat and mass transfer studies for two-phase flow of helium boiling at 4.2 K allowed us to determine the parameters of the circulating ring, such as the mass flow rates, the temperature differences on the walls, the pressure variations along the flow, the coefficients of heat transfer and critical heat fluxes. Flow rate and pressure variations are correctly predicted by the “homogeneous model”, where a fictional single-phase fluid having averaged characteristics represents the two-phase fluid. Nevertheless some questions remain concerning the evolution of the total mass flow rate as a function of the heat flux. This evolution is similar to that of other two-phase mixtures for small heat flux, where the gravitational pressure gradient dominates the pressure gradient as a result of friction forces. For higher heat flux, that is to say higher proportions of gas, our results do not display the reduction in flow rate expected.

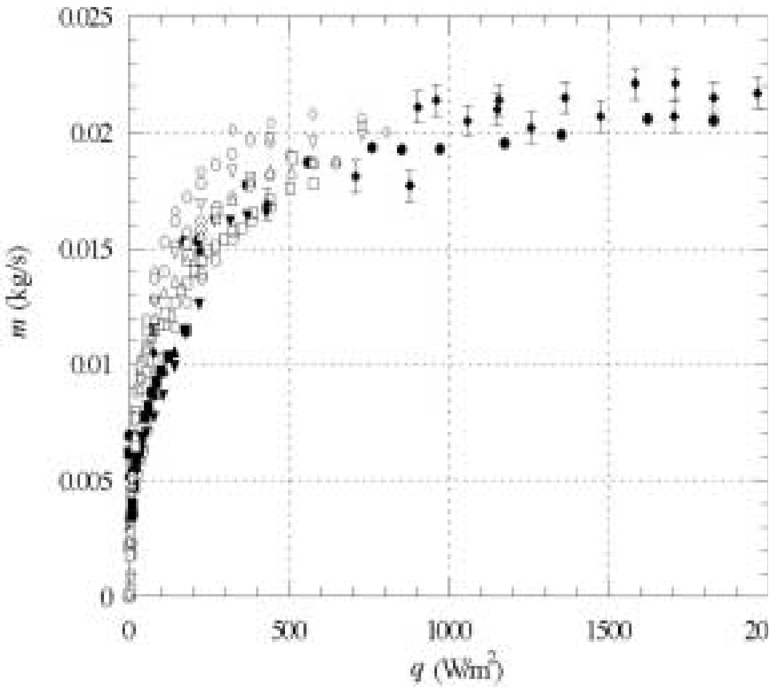
Helium flow loop taken out of its vacuum vessel. The vertical pipe on the right-hand side is equipped with heaters that induce upward flow in this branch, and a correlative downward flow in the left-hand branch of the U. At the top, the pipe empties into the phase separator.

Superfluid helium heat transfer through porous media

For the designers of superconducting magnets, an understanding of heat transfer in the coils is necessary for studies of thermal stability. For magnets cooled by superfluid helium, such as the dipoles and quadrupoles of the LHC, the thermal resistance created by the electrical insulation of the cables forms the main barrier to cooling. With the emergence of high-field Nb_3Sn magnets, the designers are looking for new systems of insulation made up of ceramic materials. These materials can have lower porosity than conventional insulation systems, and as a result this should reduce the cooling efficiency of the superfluid helium. An experimental system has been developed and this allows us to study heat transfer. In such environments consideration must be given to heat transfer at the interface of the solid matrix and the helium, conduction in the solid matrix, and heat transfer in the superfluid helium present in the pores of the media. A first step towards understanding heat transfer is being made using aluminium oxide samples. It will be followed by a second phase, involving studies of the real ceramic insulation.



Temperature difference, ΔT, between the wall of the heated tube and the flowing helium as a function of the heat flux density for a height of 0.3 m. This curve is typical of boiling flow where, with increasing heat flux (q_{up}), it can be found a brutal increase of the ΔT due to a total or partial disappearance of the liquid wetting the wall. This transition corresponds to the change from nucleate boiling to film boiling regime (CHF).



Total mass flow rate of helium in the thermosiphon as a function of the heat flux density along the vertical heated branch. The different symbols indicate tests carried out at different times, but under identical experimental conditions.

Thermal characteristics of low temperature materials

The final aim of these activities is to determine the thermal properties of materials that are used in superconducting magnets. There are two research facilities. One, the “Kapitza” facility, was designed for studying heat transfer at the interface between a solid and superfluid helium. The other is the “Mecti” facility, for measuring thermal conductivity of solid materials at the temperatures of liquid helium and nitrogen. Measurements carried out using the “Kapitza” facility are directed essentially at polymers, such as kapton®, mylar® and apical®, which are used in various cryogenic applications such as the electrical insulation of superconducting coil windings. The “Mecti” facility has allowed us to qualify new impregnation resins and new composite materials formed from a resin-glass microsphere mixture.

SACM equipments

SACM runs outstanding installations necessary for its cryomagnetics and radiofrequency expertise activities:

- large cryogenic test facilities at 4.2 K and 1.8 K for superconducting samples, for superconducting electromagnets, for superconducting radiofrequency cavities and their power couplers, with the dedicated acquisition and analysis tools; the followings are worthy of mention examples: the W7-X test facility, Cétacé, a test facility dedicated to superconducting sample in a magnetic field up to 17 T, and Cryholab, a large horizontal laboratory cryostat, joint property of Dapnia and IN2P3;
- specialized laboratories for electrical, cryogenic, mechanical, radiofrequency tests, material characterization, chemical surface treatments of superconducting accelerating structures; a magnetic measurement laboratory is being set up to provide for needs of several projects;
- several large helium liquefier and refrigerator units.

Test facilities for superconducting magnets and large size components

W-7X test facility

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

- 2 cryostats: 5 m useful diameter; 4.1 m useful height.
- 200 W at 4.2 K dedicated refrigerator.
- Electrical power supply: 25 kA.
- Data acquisition for cryogenic sensors up to 500 Hz and for voltage measurements up to 20 kHz.

Schema - *Station cryogénique horizontale pour essais magnétiques*

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

- Horizontal cryostat: 0.6 m useful diameter and 8 m useful length.
- 25 W at 1.8 K (450 W at 4.2 K) refrigerator.
- Electrical power supply: 20 kA (10^{-4} stability) under 5 V.
- 160 measuring channels up to 20 kHz.

Vertical test facility

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

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

Test facilities under magnetic field

Cétacé – *Cryostat d'essais à température ajustable et champ élevé*

Critical current measurements on superconducting samples.

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

Christiane

Critical current measurements on superconducting samples at 4.2 K.

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

Séjos – *Station d'essais de jonctions supraconductrices*

Tests of electrical joints at 4.2 K.

- Maximum current intensity in sample: 10 kA.
- Maximum magnetic field: 4.7 T.
- Magnet useful diameter: 90 mm.
- Useful diameter of the sample cryostat: 76 mm.
- A superconducting transformer will allow testing conductors at current intensity up to 70 kA.

RMN 530 magnet

Tests under magnetic field of components such as sensors, gauges, etc. at room temperature.

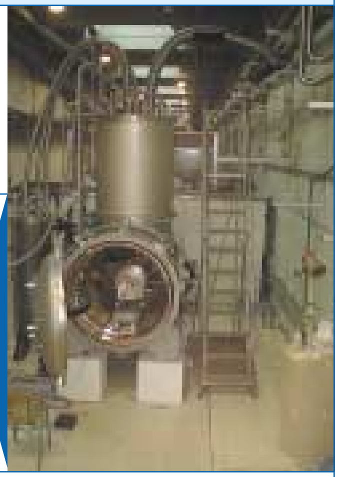
- Maximum magnetic field: 2 T.
- Magnet useful diameter: 510 mm.
- Horizontal axis.

Optimist magnet

Tests under magnetic field of components such as sensors, gauges, etc. at cryogenic temperature.

- Maximum magnetic field: 8.8 T.
- Magnet useful diameter: 150 mm.
- Horizontal axis.

Test facilities for superconducting cavities and associated components



Tests benches for power couplers

Two facilities for radiofrequency power tests: one 1300 MHz test bench with 1.5 MW peak power in pulsed mode, 1 ms pulse with a 10 Hz frequency ;
one 704 MHz-80 kW test bench in continuous mode.
RF components may be tested with stationary or non-stationary waves.

Cryholab – *Cryostat horizontal de laboratoire* (property Dapnia - IN2P3)

Tests of superconducting cavities in the same conditions as in an accelerator.

Radio frequency power supply: now 700 W; foreseen: 80 kW for continuous input; up to 1 MW for pulsed input.
Pumping unit coupled with Helial 4012 refrigerator: 80 W at 1.8 K and 13 mbar.
Useful internal size: 1.5 m length and 70 cm diameter.

Cryostats verticaux CV

Accelerating field and quality factor measurements of superconducting radiofrequency cavities.

2 pumping units: 1 g/s at 13 mbar.
1 RF sources: 200 W cw, 700 MHz at 1500 MHz - 1 RF source: 80 W cw, 4200 MHz at 8600 MHz.

CV1	CV2	CV3
Useful diameter: 0.7 m, height: 2.92 m.	Useful diameter: 0.45 m, height: 1.7 m.	Useful diameter: 0.35 m, height: 1.5 m.
LHe height: 1.9 m at 4.2 K, 1.2 m at 1.7 K.	LHe height: 1 m at 4.2 K, 0.6 m at 1.7 K.	LHe height: 1 m at 4.2 K, 0.6 m at 1.7 K.
Consumption: 1500 l / test.	Consumption: 450 l / test.	Consumption: 400 l / test.

Characterization facilities

Residual resistivity ratio (RRR) measurements

RRR measurement samples: 100 mm x 3.5 mm.
Cryostat: 0.15-m useful diameter, 0.9-m height.
Consumption: 20 l / test.

Mecti - *Mesure de conductivité thermique des isolants*

Cold head allowing measurements on 30-cm long samples in the temperature range from 1.8 K to 60 K with helium and from 80 K to 150 K with nitrogen.

Thermosiphon

Characterization of two-phase flows with measurements of mass-flow, vapour quality, pressure drop and wall temperature along a 1.2-m vertical test section, inserted in a U-shape thermosiphon cooling loop.

Liquid helium mass flow: from 0 to 22 g/s.
Vapour quality: from 0 to 0.25.
Wall heat flux: from 0 to 2.2 kW/m^2.

Helium refrigerators and liquefiers

Liquefier/refrigerator Helial 4012 coupled with Cryholab
Liquefaction capacity: 200 l/h at 4.2 K.
Refrigeration capacity: around 80 W at 1.8 K with a pumping unit of 4 g/s at 13 mbar.

Liquefier/refrigerator Cello coupled with Schema test facility
Liquefaction capacity: 120 l/h.
Refrigeration capacity: around 450 W at 4.2 K

Liquefier/refrigerator Helial 4003 coupled with W-7X test facility
Liquefaction capacity: around 70 l/h.
Refrigeration capacity: around 200 W at 4.2 K.

Liquefier/refrigerator 4008 – liquefaction station
Liquefaction capacity: around 70 l/h.
Refrigeration capacity: around 200 W at 4.2 K.
Liquid helium delivery in 2003 : 176,000 l.

Laboratories and workshops

Mechanical test laboratory

Measurements at 300 K as well as at cryogenic temperatures 77 K (liquid nitrogen) and 4.2 K (liquid helium), of yield properties (stress, strain…) and Young's modulus for metallic and composite materials; tests on mechanical joints (sliding friction, deflection…).

Hydraulic press: compression capacity of 2000 kN.

Electromechanical testing machine INSTRON®: tensile and compression capacity of 300 kN.

Electromechanical testing machine INSTRON®: tensile and compression capacity of 150 kN, equipped with 2 dewars for cryogenic tests:

60-kN capacity dewar for tensile and flexure tests,

150-kN capacity dewar for tensile and compression tests.

Chemical laboratory and clean room

Chemical laboratory

Surface treatments of superconducting accelerating cavities.

8 hoods for sample and cavity treatment, including a closed chemistry facility where only the inner surface of cavities is treated with filtered acids in order to reduce dust contamination.

3 ultrasonic bays (10 l, 60 l, 120 l).

Ultra pure water production facility (3 m^3).

Characterization means (optical microscope, gloss meter, high precision weighing machine).

Class 100 clean room (35 m^2)

High pressure rinsing and assembly of cavities and ancillaries in clean condition.

Laminar flux (class 100).

Ultra pure ultra filtered water loop.

Ultra high vacuum laboratory

The ultra high vacuum laboratory takes charge of the vacuum calculations for accelerators, the research about material desorption and the development in ultra high vacuum techniques and vacuum theory.

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

Vacuum techniques workshop

The workshop makes use of the pumping units and leak detectors required by vacuum insulated dewars, and for the tightness tests of cryogenic vessels, tubes and ducts.

Winding machine workshop

In this workshop two winding machines are available: the first one is convenient for winding solenoid magnets up to 2-m outer diameter, the second one is used for small size coils or for wrapping small length of conductor in view of test characterizations for instance.

Impregnation laboratory

There is provided the technical support for the insulation and impregnation of the superconducting coils designed in the division: impregnations of characterization samples and prototypes, processing of resins, dissolution of aluminium and copper for conductor preparation …

Mechanical workshop

The mechanical workshop is more a prototype workshop than a production workshop. It is available for urging needs of experiments and in case of modification requirements. It makes available : 5 turning lathes, 5 millers, 1 reaming machine, 1 flat surface grinder, and other machines like drilling machines, sawing machines …

General information

Human resources

At the end of 2003, the SACM workforce consists of 138 people.

Breakdown of the SACM personnel according to categories

Budget

Sharing of expenditures for SACM in the year 2003 (k€)

Scientific activities

The scientific results in the period 2001-2003 included 162 publications, 5 PhD theses, 2 patents and 2 prizes.
The publications list is given in the Dapnia website:
http://www-dapnia.cea.fr/Doc/Publications/index.php
8 SACM physicists give lectures in universities or *grandes écoles*.

Scientific and technical committee

A scientific and technical committee, made up by 16 members, meets twice per year.
It assists the SACM head in drawing up the R&D policy of the division;
it gives its advices on the new proposals and takes stock of the activities in progress.
The minutes of the last councils are reported in the website:
http://w10-dapnia.saclay.cea.fr/Sacm/compterendus/index.php

Safety

The general safety rules are given in the CEA booklet *Instructions générales de sécurité du centre d'études de Saclay* which can be consulted in:
http://www-saclay.cea.fr:8000/ise/textes_reglementaires.htm
The specific instructions of the installation 82 are summarized in a memorandum given in the website:
http://w10-dapnia.saclay.cea.fr/Sacm/securite/index1.php

SACM personnel at the end of 2003

ANTOINE	Claire
ARNAUD	Michel
ASPART	Alain
AUCLAIR	Jean-Pierre
BALLESTER	Francisco
BAUDOUY	Bertrand
BEAUVAIS	Pierre-Yves
BEN ISMAIL	Ahmed
BENKHEIRA	Lahcène
BENMEZIANE	Karim
BERNAUDIN	Pierre-Emmanuel
BERRIAUD	Christophe
BERRY	Stéphane
BERTON	Jean-Bernard
BIAGINI	André
BISSIRIEX	Jacques
BOSLAND	Pierre
BOUDIGOU	Yves
BOURDELLE	Gilles
BOUZIAT	Denis
BRASSEUR	Alain
BRAUD	Didier
BREDY	Philippe
CARRE	Stéphane
CAZANOU	Marc
CAZAUX	Sandrine
CHARRIER	Jean-Pierre
CHARRUAU	Georges
CHEL	Stéphane
CHESNY	Philippe
COADOU	Bernard
CONGRETEL	Gerard
COTTEVERTE	Eliane
CURTONI	Aline
DARENNES	Jean-Jacques
DEBU	Pascal
DE-MENEZES	Denis
DECHAMBRE	Thierry
DELFERRIERE	Olivier
DELHEUSY	Mélissa
DENIS	Jean-François
DEREGEL	Jean
DESAILLY	Catherine
DESMONS	Michel
DEVANZ	Guillaume
DEVRED	Arnaud
DOUARIN	Jean-Dominique
DUPERRIER	Romuald
DURANTE	Maria
FAZILLEAU	Philippe
FELICE	Hélène
FERDINAND	Robin
FRANCE	Alain
GAGNE	Michel
GAIFFIER	Jacques
GALLOYER	Jean-Maurice
GASSER	Yves
GASTINEAU	Bernard
GAUTHIER	Yannick
GENIN	Christian
GENINI	Laurent
GHELLER	Jean-Marc
GOBIN	Raphaël-Jean
GODON	Pascal
GOUET	Jacky
HAMDI	Abdallah
HANUS	Xavier
HARRAULT	Francis
HERVIEU	Bertrand
HUMEAU	Michel
JABLONKA	Marcel
JACQUES	Eric
JUSTER	François-Paul
KABBOUCH	Hafid
KIRCHER	François
KULBICKI	Lucien
LANNOU	Hervé
LAZARD	Gerard
LE DORTZ	Patrick
LE-GUEN	Marcel
LEBOEUF	René
LEROY	Pierre-Alain
LEVESY	Bruno
LOTTIN	Jean-Pierre
LOUCANO	Delfin
LUONG	Michel
MAGNE	Christian
MAILLERET	Charles
MANZATO	Michael
MAYRI	Christophe
MEOT	François
MEURIS	Chantal
MICHEL	Frédéric
MONNEREAU	Gilles
MOSNIER	Alban
MOUGEOT	Denis
MOUYON	David
NAPOLY	Olivier
NARDIN	Philippe
NICOLLEAU	Catherine
NOVO	Jorge
PAGET	Florian
PAINCHAULT	Michel
PALANQUE	Serge
PAPARELLA	Rita
PAYET	Jacques
PAYN	Alain
PEROLAT	Alain
PERRIN	Jean-Luc
PES	Chhon
PHILIP	Danielle
PIQUET	Olivier
POITEVIN	Michel
PORCHER	Alain
POUPEAU	Jean-Pierre
PRZYBYLSKI	Alain
PUECH	Anne-Marie
PUIGSEGUR	Alexandre
QUETTIER	Lionel
REGNAUD	Sylvie
REY	Jean-Michel
RIFFLET	Jean-Michel
RONDEAUX	Françoise
ROUDIER	Dominique
SAHUQUET	Patrick
SCHILD	Thierry
SEGRETI	Michel
SIMON	Fabrice
SUEUR	Michel
THOMAS	Denis
TOUET	Joël
TRILLAUD	Frédéric
URIOT	Didier
VACHER	Thierry
VEDRINE	Pierre
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