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Institut de recherche sur les lois fondamentales de l'Univers

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DACM 2016-2020 Department of Accelerators, Cryogenics and Magnetism

DACM
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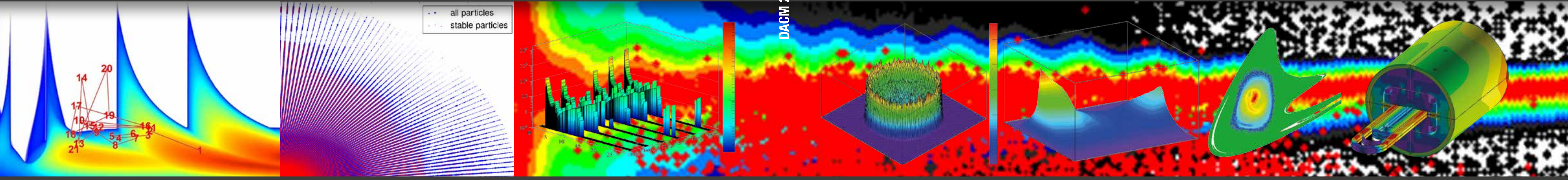


DACM
and LABS

DACM **2016-2020**

Department of Accelerators, Cryogenics, and Magnetism

The DACM is one of the departments of the Institute of Research on the Fundamental Laws of the Universe (IRFU) of the CEA's Fundamental Research Division.

The DACM's mission is to develop and build particle accelerators, ion sources, accelerating cavities, cryogenic systems, and superconducting magnets for the scientific programs at IRFU and the CEA. It features extensive equipment and systems for assembly, integration, and testing, including magnet winding and assembly rooms, vast clean rooms for accelerator systems, small-scale test stations for materials characterization, and large-scale workstations capable of testing complete assemblies (coils, superconducting cavities, and injectors).

The DACM develops large-scale projects in collaboration with other departments within the Institute and numerous national, European, and international partners. It also develops the corresponding test facilities and relies on significant R&D in these developments to prepare the future of our technologies and provide the instruments required for making progress in fundamental and applied research.

This R&D is organized around the department's themes (new accelerator concepts, new materials for cavities, continuous wave cryomodules, efficient radio frequency sources, innovative cryogenic cooling solutions, high field magnets, etc.) and allows us to welcome young PhD students and post-doctoral researchers. The DACM participates in university training in our fields through courses taught by the department's engineers and technicians.

Finally, an important mission of the department is technology transfer to industry, which is evaluated by the number of patents published, licenses transferred, and collaborations with industry.

The DACM plays a major role in building the high-tech instruments required for the Institute's research projects, such as SPIRAL2, FAIR, SARAF, FCC, and others.

The department's unique skills and knowledge are applied to related fields such as energy (in materials studies for thermonuclear fusion via the IFMIF projects and qualification of the coils for the Japanese tokamak JT-60SA), life sciences (with the Iseult ultra-high-field magnetic resonance imager for Neurospin), light sources (SOLEIL and XFEL) and neutron sources (ESS).

The department has completed many projects in the last five years: the first elements of the CEA's contribution to the FAIR, ESS and SARAF accelerators have been delivered and include a complete proton injector, RFQ, cryomodules, and a medium-energy beam transfer line; the medical imaging magnet of the Iseult project has reached its nominal field; and prototype magnets using Nb_3Sn and HTS superconducting conductors have established world records. All JT-60 SA toroidal coils have been qualified in the test station hosted at DACM, and the 103 XFEL cryomodules assembled at DACM have been delivered.

The next few years will see the commissioning of the ESS and SARAF accelerators, as well as the start of the realization of the new material irradiation source for fusion, DONES. The DACM will also participate in the French effort for the US PIP2 project located at Fermilab, by supplying about ten low-beta cryomodules. In the field of cryomagnetism, the DACM will increase its efforts to develop new high-field magnets in Nb_3Sn and HTS, necessary for future particle physics colliders and European high magnetic field laboratories. It is also involved in all major European programs focused on the development of accelerators and superconducting magnets (I.FAST, HITTRIplus, ISABEL, SuperEMFL, etc.) and the associated technological platforms and infrastructures (EquipEx PACIFICS, FASUM).

DACM's Organizational Structure

The DACM consists of five major technological laboratories dedicated to the five main themes that characterize our activities, as summarized in the presentation of each laboratory:

- LCSE Cryogenics Laboratory and Test Stations.
- LÉAS Laboratory for Superconducting Magnet Research.
- LÉDA Accelerator Design and Development Laboratory.
- LIDC2 Laboratory for the integration and development of cavities and cryomodules.
- LISAH Accelerator and Hyperfrequency Systems Engineering Laboratory.

The management team (DIR) represents the sixth "laboratory" and includes the laboratories' shared staff and resources, mainly related to occupational safety, quality monitoring, environment, infrastructure management, store management, supervision of operating schedules, and coordination of three secretarial offices.

The five technological laboratories are located throughout more than 12 buildings, featuring assembly areas, test platforms, work rooms, meeting rooms and other offices. As of late 2020, 91 engineers and 38 permanent technicians and administrative staff members as well as 34 temporary employees (fixed-term contracts, post-docs, trainees) worked on our programs.

In order to carry out the numerous projects in which the DACM is involved, the five laboratories and the department's project teams are structured according to the principles of matrix management, so that multidisciplinary project teams can be organized to create synergy in the search for solutions, while implementing appropriate technological choices. To monitor the department's activities, the 12 members of the Research Unit Committee meet twice a year to examine questions raised by staff about department organization, resources, and activities.

To guide the choice of programs and desirable developments for the future of our activities, the department's Scientific and Technical Committee (with eight elected members and eight appointed members) met four times a year. Committee members assessed the relevance of proposed thesis topics, the themes and sums allocated to internal R&D supported by the department's budget, internship proposals, and collective responses to requests from external scientific organizations (HCERES, P2IO, Université Paris-Saclay, etc.). In addition, each year at external Scientific and Technical Committee meetings, the Committee holds discussions regarding current and future programs and projects with experts from outside the CEA.

CRYOGENICS LABORATORY AND TEST STATIONS (LCSE)

The task of LCSE is to master cryogenics technology applied to superconducting magnets, accelerating cavities, physics detectors (cryogenic target systems, calorimeters), and the production and distribution of liquid helium.

For its own developments, and to meet project needs for development and testing, the laboratory designs, builds, and operates several test and characterization stations to determine the mechanical, thermal (see figure), and electrical properties of complete cryogenic subassemblies (such as magnets within cryostats, cryomodules, ...), or their basic components (coil cold mass, RF cavities, instrumentation). These stations of various types and sizes use low-temperature refrigeration systems, such as refrigerators or cryogenerators, using the following fluids: helium I and II, nitrogen, argon, neon, or hydrogen.

More specific R&D activities are being carried out on the study and improvement of low-temperature heat transfer systems (helium II in porous media, PHP (pulsating heat pipes) with different gases at cryogenic temperatures), on two-phase flows (thermosiphon with helium I or nitrogen), on the thermohydraulics during magnet "quench", and on the development of cryogenic targets in liquid or solid hydrogen.

At the end of 2020, laboratory staff consisted of 16 engineers, two doctoral students, and six technicians.

LABORATORY FOR SUPERCONDUCTING MAGNET RESEARCH (LEAS)

In December 2020, the Laboratory for Superconducting Magnet Research (LEAS) consisted of six technicians, 20 engineers, four doctoral students, and two work-study students. The laboratory's mission is to ensure the implementation of superconducting materials as required by the department's various projects, and more broadly to meet the needs of IRFU physicists for magnetic fields.

LEAS applies its expertise to the optimization of coil geometry, conductor design, mechanical, electromagnetic, and thermal calculations, magnetic protection in the event of a fault, and the final measurements required to validate proper operation.

In addition, LEAS has the capacity to manage large projects, to develop magnets and integrate them into cryostats, and to monitor industrial development of components and mass-manufactured magnets. Magnets are inspected jointly with the LCSE (Cryogenics Laboratory and Test Stations).

The laboratory's projects rely primarily on NbTi and Nb_3Sn conductors and high-temperature superconductors of the family ReBCo. NbTi is mostly used for large magnets (MRI Iseult) or for mass-produced industrial magnets (SARAF solenoids, Super FRS dipoles). Nb_3Sn and ReBCo are used to develop magnets of more than 12 T, thus meeting the demand for very high magnetic fields from laboratories such as the LNCMI (French National High Magnetic Field Laboratory) in Grenoble, or in view of the FCC (Future Circular Collider) in partnership with CERN.

ACCELERATOR DESIGN AND DEVELOPMENT LABORATORY (LEDA)

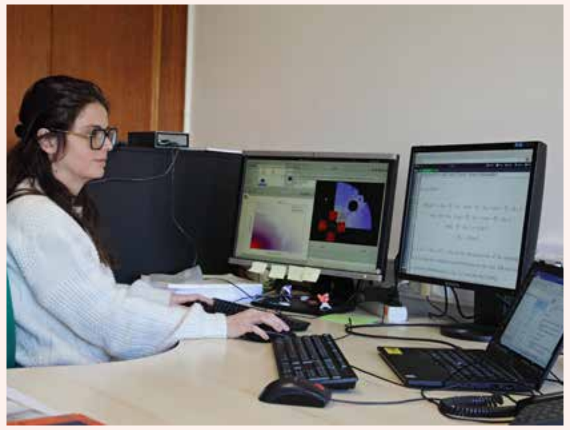
The Accelerator Design and Development Laboratory oversees the design, construction, testing, and operation of devices and tools used to produce, transport, accelerate, measure, and simulate charged particle beams.

As of December 31, 2020, LEDA employed 23 engineers, six technicians, one PhD student and one engineering intern working on the design, construction, assembly, commissioning, testing, and the optimization and/or simulation of:

- High-intensity light ion sources.
- Beam diagnostics and beam intercepting devices such as beam dumps or targets.
- Low- or medium-energy beam-transport lines, including the design and monitoring of warm magnet construction.
- Radiofrequency quadrupole (RFQ) accelerating structures.
- Accelerators or colliders for nuclear physics and high-energy physics.

The LEDA teams are also working on dimensioning and defining vacuum systems, testing and baking devices under vacuum, validating the vacuum tightness of beam lines, on designing, assembling, operating and maintaining water-cooling systems, and on R&D for laser-plasma accelerators.

Between 2016 and 2020, LEDA also maintained and developed the Ion Sources Test Bench (BETSI); the Diagnostics, Vacuum, and Assembly Laboratory (DIVA); and a set of beam dynamics codes commercialized worldwide.



CAVITY AND CRYOMODULE INTEGRATION AND DEVELOPMENT LABORATORY (LIDC2)

LIDC2 focuses on improving the performance of superconducting accelerating cavities and cryomodule integration. LIDC2 has expertise in superconducting cavity integration that has led to the laboratory's involvement in multiple international accelerator projects, such as ESS, IFMIF, or SARAF, requiring the production of numerous cryomodules. To carry out these projects, LIDC2 relies on its substantial facilities: 3000 m² of assembly halls, including 300 m² of clean rooms (ISO7, ISO5, and ISO4), chemical treatment stations aimed at improving the efficiency of cavities (cleanliness, surface states), and a set of technical support laboratories (vacuum, electrical engineering, material characterization). The laboratory provides expertise in designing and developing cryomodules with assembly requirements that are compatible with the chosen production strategy, which is always validated via a prototyping phase. A second important capacity is the laboratory's participation in R&D required to develop superconducting accelerating cavities. Several complementary avenues of inquiry are being explored: cavity chemistry (vertical electropolishing, high-pressure rinsing), characterization (analysis of surface defects, local magnetometry, characterization of materials), and multi-layers, with very promising results in terms of increasing cavity performance.

ACCELERATOR AND HYPERFREQUENCY SYSTEMS ENGINEERING LABORATORY (LISAH)

The Accelerator and Hyperfrequency Systems Engineering Laboratory encompasses DACM's expertise in the design, construction, and qualification of high-frequency accelerator components and their implementation through the use of appropriate instrumentation. As of late 2020, the staff consisted of 16 engineers and three technicians.

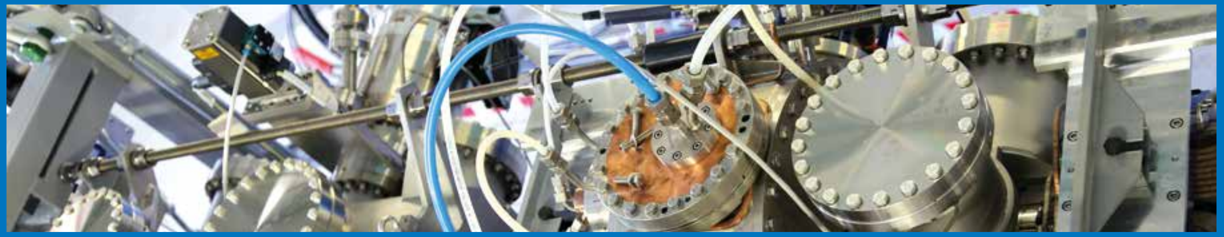
Laboratory activities primarily involve the development of radiofrequency structures for particle accelerators used in physics research (radiofrequency quadrupoles, superconducting cavities, fundamental and higher-order harmonics suppression power couplers), as well as the associated qualification tools, including RF power sources and instrumentation electronics. The laboratory also manages certain shared DACM infrastructures, such as SupraTech-CryoHF RF test platforms for testing cavities in vertical cryostats and cryomodules for ESS and SARAF, as well as the 352 MHz platform providing RF for the IPHI quadrupole. These activities also cover applications in other fields, like antennas for high-field magnetic resonance imaging or for the detection of axions in particle physics.

To carry out its core missions, LISAH benefits from internal expertise within IRFU in the fields of material sciences, process engineering, mechanical design and construction, and quality assurance. The laboratory also contributes to other IRFU projects, either by taking charge of an entire work package, or by providing technical consultancy services.

ACTIVITIES and PROGRAMS

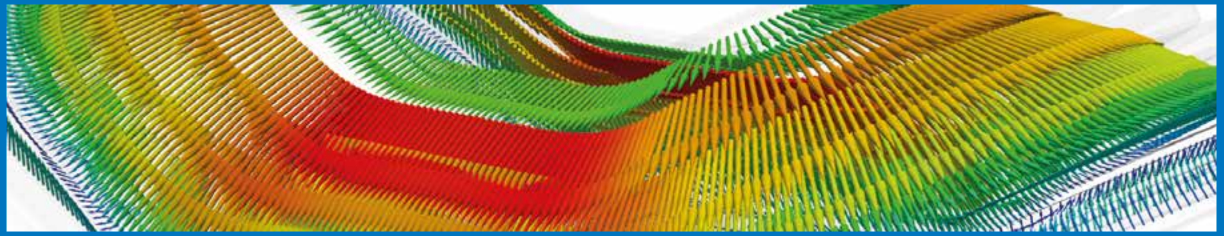
DACM 2016-2020

• Accelerators

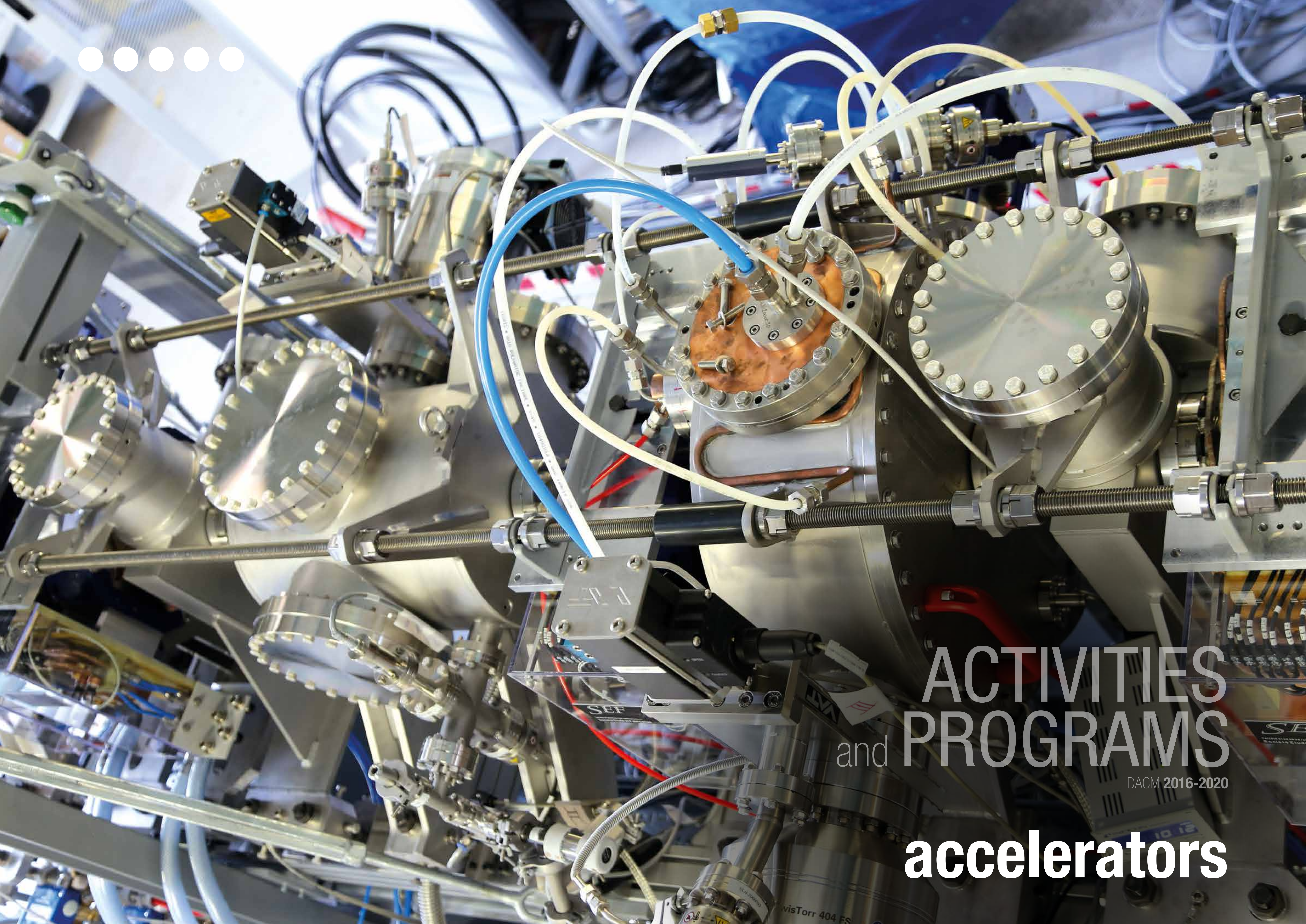


• Cryogenics

• Magnetism



• R&D and technological developments



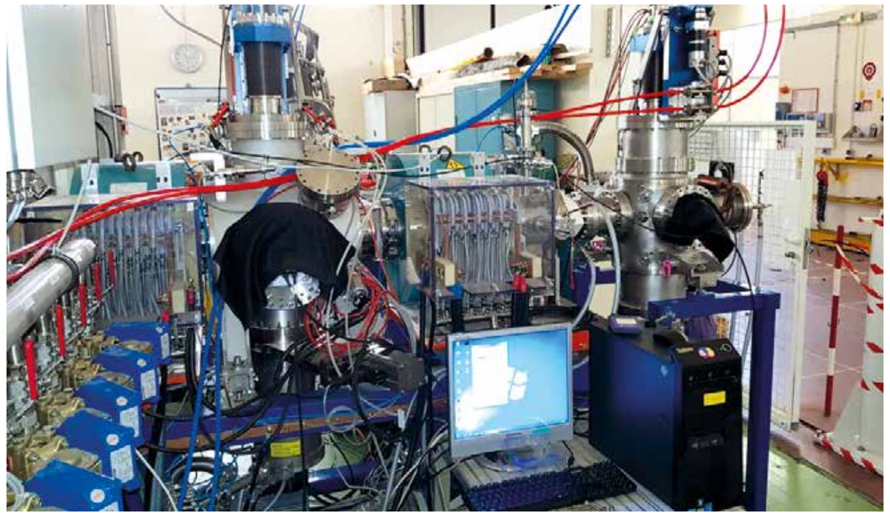
ACTIVITIES and PROGRAMS

DACM **2016-2020**

accelerators

COMMISSIONING OF THE PROTON LINAC INJECTOR OF THE FAIR PROJECT AT SACLAY

The proton linac injector of the FAIR project, which had been in the commissioning phase at Saclay since the end of 2017, was delivered to and installed at GSI (Darmstadt, Germany) in 2020. The objective is to characterize the proton beam in terms of purity, current, and emittance, both in the injector and at the exit.



The very compact low energy beam line of the FAIR injector in phase 3 commissioning in 2020. The beam goes from left to right. The line is equipped with two Allison emittance scanners (the one shown on the left was developed by IPHC, the one on the right by LEDA).

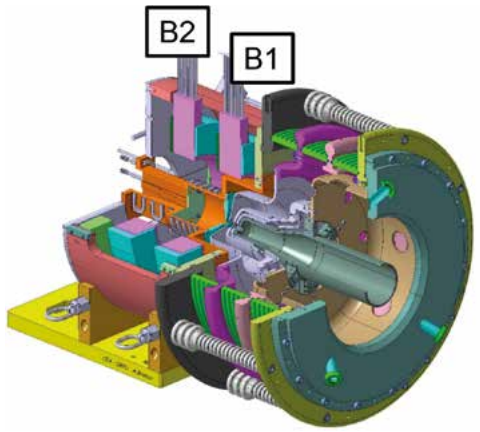
The injector of the FAIR (Facility for Antiproton and Ion Research) project is intended to produce a proton beam that will be injected into the next acceleration stage, an RFQ (Radio-Frequency Quadrupolar cavity) of the "Ladder RFQ" type currently under construction at the University of Frankfort. The injector consists of an ECR (Electron Cyclotron Resonance) type ion source, followed by an LEBT (Low Energy Beam Transport) equipped with two solenoids to ensure the correct focusing of the beam.

BEAM TUNING

A series of diagnostics were used to characterize the beam in three locations: 1) at the exit of the source accelerator tube, 2) on the LEBT between the two solenoids, 3) at the LEBT exit, around the injection focal point into the RFQ. Beam purity was analyzed with a Wien filter (H^+, H_2^+, H_3^+, heavy ions). The total current extracted was measured using an ACCT (AC Current Transformer) and at the end of the line with a second ACCT on the beam stop. Finally, beam emittance was measured using an Allison-type scanner.

The first beams were extracted from the source in mid-2016, starting with plasma electrodes with extraction diameters of 3 mm and 6 mm. This was done in order to begin with a low power beam and debug the whole line. The results obtained with 6 mm were already promising, with **60 mA of total current extracted** and measured at the source output at **a nominal energy of 95 keV**, while the extraction system had been optimized and produced for a beam of 120-130 mA.

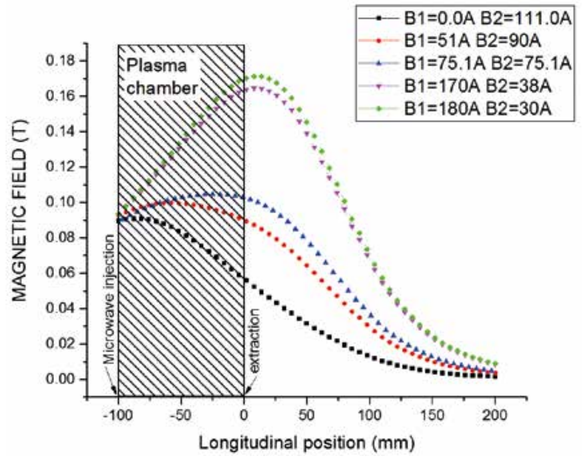
Unlike previous injector commissionings at DACM (IPHI, IFMIF, SPIRAL2), this one followed an innovative procedure consisting of characterizing the beam as a function of the axial profile of the magnetic field in the plasma chamber while maintaining the cyclotron electron resonance zone at the region where the RF wave is injected into the plasma chamber. This is done by varying the current in the two coils: B1 (near extraction) and B2 (near RF injection).



Cross-section of the FAIR ion source. Coils B1 and B2 make it possible to modify the profile of the magnetic field within the plasma chamber.

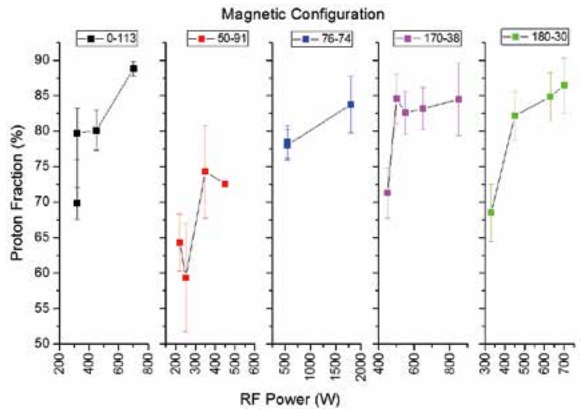
Commissioning of the ECR ion source of the high intensity proton injector of the Facility for Antiproton and Ion Research (FAIR), O. Tuske, N. Chauvin, O. Delferriere, J. Fils, and Y. Gauthier. Review of Scientific Instruments 89, 052303 (2018).

Collaboration Contract for the construction of the international Facility for Antiproton and Ion Research in Europe (FAIR) for the proton Linac.



Profile of the magnetic field as a function of the pair of values B1, B2. The magnetic field 875 Gauss of the resonance zone is the same for each of the configurations.

The various beam settings (gas quantity, RF power, impedance adapter, accelerating voltage in the first gap between intermediate electrode and plasma) made it possible to produce **beams of 40 to 65 mA**. Analysis of beam purity using the Wien filter revealed **a proton proportion of over 80%** in the majority of the magnetic configurations studied, with almost no H_3^+. Emittance measurements showed normalized rms values **varying between 0.27 and 0.46 π.mm.mrad**, primarily according to extracted current, due to space charge.



Proton fraction measured according to the injected HF power, for different magnetic configurations.

This study demonstrated that it is possible to obtain a high intensity beam of 60 mA with a proton proportion of 80% with just one coil close to the RF injection. In addition, this setting generates the beam pulse with the shortest rise time.

At the end of 2017, the soure was equipped in its final configuration with a plasma electrode with an extraction diameter of 9 mm. In 2019, the complete line, including a non-powered beam chopper as well as the RFQ input cone, was operational. Within two years, the project team was able to carry out all the experimental measurements to qualify the injector and ensure the beam conditions for injection into the RFQ.

After qualifying the source by measuring emittance and proportions at the exit of the accelerator tube, measurements were carried out between the two solenoids and in the vicinity of the RFQ injection cone in order to determine the coordinates of the focal point that would deliver the best transmission through the cone. The current was measured at three locations: at the source exit using ACCT1, at the output of the second solenoid using ACCT2, and, finally, on the beam stop.

END OF COMMISSIONING AT SACLAY

Since 2009, when collaboration between IRFU and GSI began, the DACM and DIS agents involved in developing the injector of the FAIR project have demonstrated their ability to design, build, and operate a high intensity proton injector according to the requested specifications. Despite a difficult context concerning the delivery of electrical power supplies, the command and control system, and problems in the production of components such as the RFQ injection cone, the team was able to bounce back and bring the injector to an excellent level of performance in terms of extracted current and emittance. The injector was able to produce a proton current of 120 mA at the end of the line after passing through the RFQ cone, with a normalized emittance of 0.24 π.mm.mrad, compatible with an injection into the future RFQ. The injector was sent to GSI in October 2020.

	MEASURED	PROJECT SPECIFICATIONS
Extraction voltage	95 kV	95 kV +/- 0.1keV
Proton fraction	88%	>80%
Total extracted current:	140 mA	70 mA
Proton current BD	120 mA	
RF power:	1100 W	
H2 gas flow	2.4 sccm	
SOL1:	160 A	
SOL2:	175 A	
Emittance RMS:	0.24 π.mm.mrad.norm	<0.33 π.mm.mrad.norm

Nominal setting values.

SPIRAL2

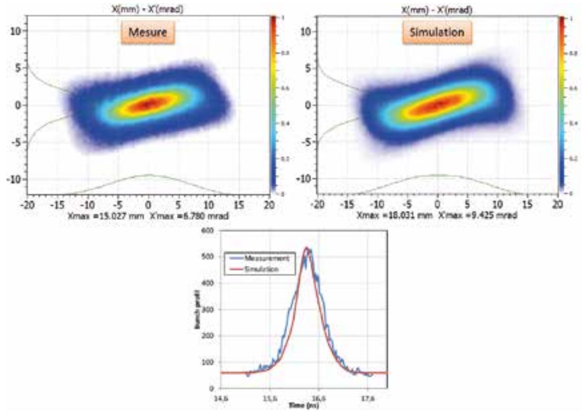
Since 2004, DACM has been a major actor in the SPIRAL2 project, playing a leading role in the preliminary project phase and through to delivery, installation, and commissioning of the injector, RFQ, and low-beta cryomodules at GANIL. Prior to this, the equipment was designed, developed, and tested at DACM at Saclay. Since 2015, DACM has been coordinating the activities related to all work packages provided by IRFU, including those provided by DIS, such as the Low Level RF system, the command and control system, and instrumentation bays. The DACM also brings significant expertise to the field of beam dynamics and beam commissioning, in which it participates. The transfer of responsibility for all systems was effective as of year end 2020.

THE LINEAR ACCELERATOR

The linear accelerator of the SPIRAL2 (Système de Production d'Ions RAdioactifs en Ligne de 2e génération/ Second-generation system for on-line production) of accelerated radioactive ions project at GANIL (Grand Accélérateur National d'Ions Lourds/ Large-scale Heavy-Ion Accelerator) in Caen, begins with the ion sources that deliver light ion beams, protons and deuterons, or heavy ions with Q/A > 1/3, to the LEBTs (Low Energy Beam Transport). These match the beam to inject it into the RFQ (Radio Frequency Quadrupole cavity), which focuses, bunches, and accelerates the continuous beam the longitudinal plane at an energy of 0.75 MeV/A. Then, the MEBT (Medium Energy Beam Transport) adapts the beam in the six dimensions to inject it into the superconducting Linac comprising type A and type B cryomodules, which accelerate it to the final energy of 33 MeV for protons.

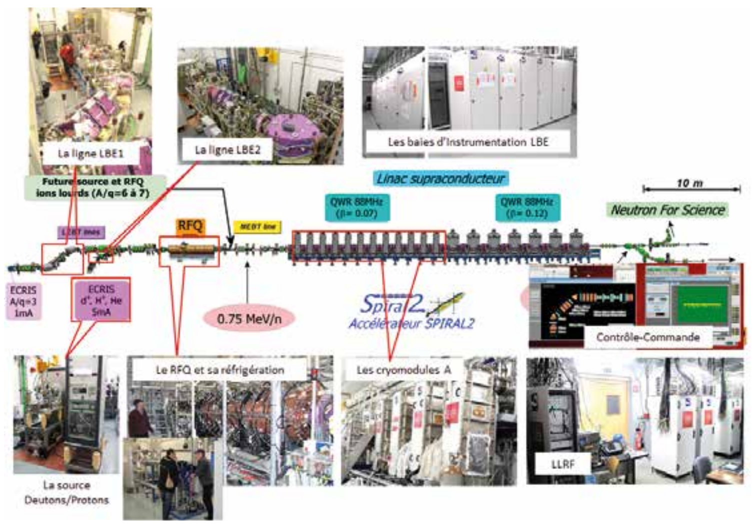
BEAM COMMISSIONING AND DEVELOPING A NUMERICAL MODEL OF THE ACCELERATOR

From the commissioning phase to routine use, the accelerator can only be operated alongside a numerical model that must represent the accelerator as faithfully as possible. This digital avatar is initially built as a predictive tool used to design the accelerator, then to guide its commissioning; in turn, this process calibrates the model, rendering it more accurate and more like the actual machine.



Measurements of the beam's horizontal emittance and longitudinal profile performed at the RFQ exit, compared to simulations.

As expected, commissioning of the accelerator beam was based on its theoretical model. Drawing on experience in injector commissioning and its simulation codes, DACM relied on experimental measurements to continuously improve the theoretical model of the machine, as well as the associated simulation tools. Beam measurements at several key accelerator positions made it possible to validate these developments and achieve excellent results in terms of beam profiles, beam losses, and beam transmission. As a result, the entire Linac, from source to target, is now almost completely tuned by simply displaying the theoretical settings, which results in major time savings, given the multitude of beams and adjustment ranges required by this type of machine. Emittance measurements at the MEBT input or of RFQ transmission as a function of voltage illustrate this excellent match between measurements and simulations.



Layout of the SPIRAL2 linear accelerator with photos of equipment/work packages provided by DACM and DIS.

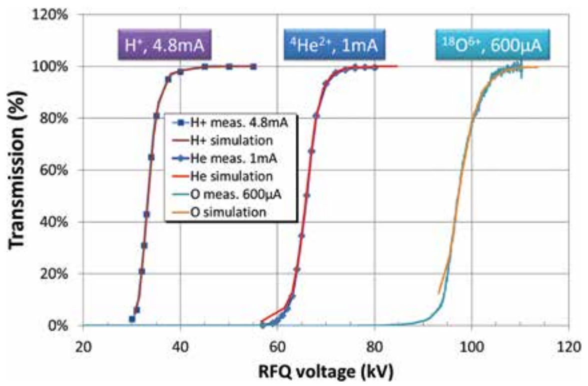
- Final Results of the Spiral2 Injector Commissioning, R. Ferdinand, M. Di Giacomo, H. Franberg, J-M. Lagniel, G. Normand, A. Savalle, D. Uriot, IPAC2019.
- SPIRAL2 Injector Commissioning, R. Ferdinand, M. Di Giacomo Marco, H. Franberg, O. Kamalou, J-M. Lagniel, G. Normand, A. Savalle, F. Varenne, D. Uriot, LINAC2018.

GANIL.

COMMISSIONING OF THE RFQ

The RFQ is an essential structure in the first stages of an ion linear accelerator. It performs beam bunching and pre-acceleration with simultaneous beam focusing in order to counter space charge, which is colossal at low energy. IRFU was in charge of studies, design, construction, assembly, and commissioning of the SPIRAL2 RFQ at GANIL.

The cavity was ramped up to full field on November 15, 2015, preparing the way for acceleration of the first proton beam to its nominal energy of 0.75 MeV (for a voltage of 50 kV) on December 3, 2015 at 9:00am. At the end of 2016, the first ion beam q/A = 1/3 (0.6 mA of 18, 6+ oxygen) passed through the RFQ set at its nominal operating voltage (113 kV). Beam and RF commissioning continued in 2017 until reaching operation at continuous 200-kW RF power and beam power of 3.5 kW



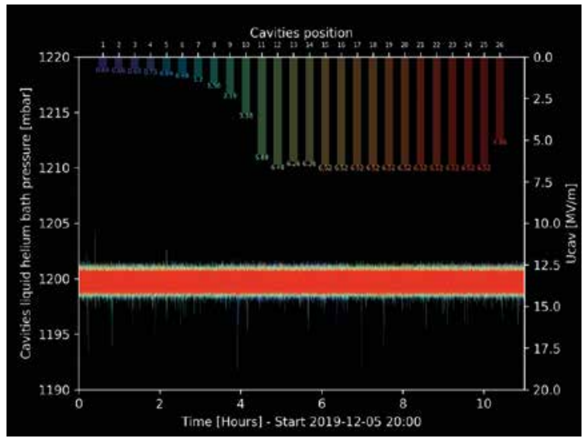
Comparison between measurements and numerical simulations of beam transmission curves for different reference ions as a function of the voltage applied to the RFQ vanes.

Measurements of output beam characteristics carried out during a measurement campaign on the ITB (Intermediate Test Bench), temporarily installed at the exit of the RFQ, were compared to the results obtained by numerical simulations. The concurrence made it possible to validate the design of the RFQ cavity, as well as the complex voltage adjustment procedures implemented by the DACM and DIS teams. It also provides further experimental proof of the accuracy and predictive capability of the simulation codes developed at DACM and used at GANIL.

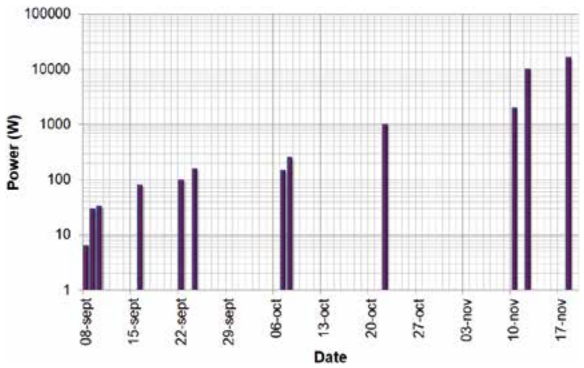
COMMISSIONING OF LOW-BETA CRYOMODULES

The SPIRAL2 superconducting Linac consists of two families of cryomodules, type A and type B. IRFU delivered the 12 type A cryomodules, each incorporating a low beta cavity ($\beta = 0.07$) used to accelerate the particles at a speed equal to 7% the speed of light. IPNO (Institut de Physique Nucléaire d'Orsay/Institute of Nuclear Physics of Orsay) produced the seven type B cryomodules, each incorporating two high beta cavities ($\beta = 0.12$) used to accelerate particles up to 12 % the speed of light.

Following authorization to commission SPIRAL2 issued by the Nuclear Safety Authority on July 8, 2019, many crucial steps were successfully achieved that same year. In July, a first RF injection was performed in a cold cavity, at a temperature of 4 Kelvin. This first ramp-up of the field in a superconducting cavity carried out at GANIL made it possible to validate installation procedures and verify the absence of internal pollution in the cavities. In September, complete qualification of the Linac's 26 accelerating cavities was finalized. The measurements obtained conform to expectations. This step also allowed for validation of the cryogenic performance of the entire accelerator. On October 28, the first proton beam was injected into the Linac and at the end of November a proton beam of about 100 µA with a duty cycle of 1/1000 was accelerated to its nominal energy of 33 MeV. In September 2020, the nominal current of 5 mA was reached, and, finally, in November, the Linac delivered a 16 kW proton beam, which represents 10% of the machine's maximum proton power and marks a major project milestone.



Tuning of the fields in type A & B cavities for a proton beam. The lower curve illustrates the cryogenic stability obtained, which is in accordance with the expectations (+/- 2 mBar).



The gradual increase in the proton beam power of SPIRAL2 in 2020.

SARAF: AN ACCELERATOR FOR NEUTRON PRODUCTION

More than an accelerator, the SARAF-LINAC project embodies the CEA's commitment to delivering a particle beam to its Israeli counterpart. Working from beam specifications alone (deuterons/protons, 40 MeV, 5 mA, pulsed to cw), the department is responsible for defining and manufacturing the accelerator, as well as for installation and commissioning in Israel. Nearly all of DACM's expertise and facilities are mobilized for this purpose.

INTRODUCTION

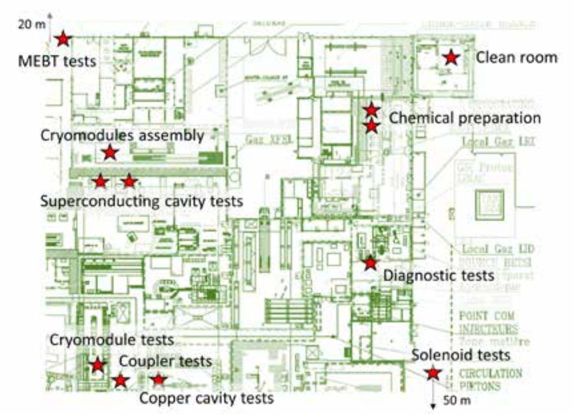
IAEC (Israel Atomic Energy Commission) decided to replace its research reactor for neutron production at SNRC (Soreq Nuclear Research Center), with a proton/deuteron accelerator called SARAF (Soreq Applied Research Accelerator Facility). The first phase was carried out by a private company, which delivered a particle source, a low-energy beam line, a Radio-Frequency Quadrupole (RFQ), and a superconducting prototype module. In 2015, IAEC decided to contract CEA for delivery of the full linac, which will allow to increase the 5 mA beam energy from 1.3 MeV per nucleon to 35 MeV for protons or 40 MeV for deuterons.

During the pre-project phase (2013-2014), a system preliminary design report identified critical components that would require a prototyping phase:
- the copper-coated RF cavities (rebunchers) that keep the beam bunched in the Medium Energy Beam Transport (MEBT) line;
- two types of RF superconducting quarter-wavelength cavities (low- and high-beta) that increase beam energy;
- the 20 kW couplers that support transmission of RF power into superconducting cavities;
- the superconducting solenoids that control the transverse beam size and position.

In 2015, the project's first year, technical specifications were developed for these critical components based on preliminary design studies.

In early 2016, detailed design studies for these critical components began, as well as preliminary design studies for higher-level subsystems like:
- the MEBT line, hosting the rebunchers and quadrupoles, whose main function is to match the beam from the RFQ exit to the superconducting linac;
- and the superconducting linac, comprising four cryomodules hosting the superconducting cavities and solenoids whose main function is to accelerate the beam to its final energy.

In late 2020, the MEBT was being integrated at SNRC, the first superconducting cavities and solenoids had been qualified and were ready for integration into the clean room. The vacuum vessel of the first cryomodule was ready to be equipped with the superconducting components. The project is planned to terminate in 2023.



Implantation of 12 SARAF stations in the Synergium (DACM's experimental platform).

PROJECT RESOURCES

The SARAF-LINAC project requires the complete panel of expertise available within DACM laboratories:
- **DIR** is in charge of allocating resources, technical expertise, administrative support, IT, and security, which are essential to carrying out our activities in the best conditions;
- **LEDA** is in charge of project management, system engineering (including beam dynamics), vacuum, beam diagnostics, and the MEBT;
- **LISAH** is in charge of RF cavities and rebunchers;
- **LIDC2** is in charge of cryomodules;
- **LEAS** is in charge of superconducting solenoids;
- **LCSE** is responsible for running tests of superconducting solenoids and the cryogenics for all other tests.

Since the project began, 86 people have been involved, representing a work force of 75 m.y.

It is important to note that the project also involves all DIS laboratories; this department is DACM's inseparable partner in designing and manufacturing accelerators. The project also involves staff from DEDIP, DPhN, GANIL (at project launch), and IRFU management. During the 2015-2020 period, a total of 169 engineers and technicians were assigned to the project (corresponding to 130 m.y), and more than 200 people have been involved in one way or another.

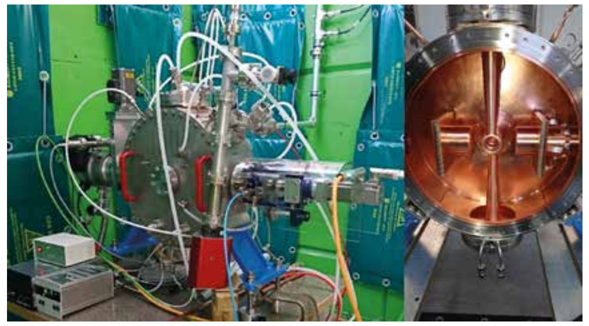
The SARAF-LINAC project greatly benefits from the wealth of DACM infrastructures, including:
- clean rooms (cleaning, high-pressure rinsing, assembly of cold mass elements)
- cryogenic test stands (superconducting cavities and solenoids)
- chemical preparation stands (superconducting cavities)
- RF test bunkers (single cavities or cavities assembled in cryomodules, couplers, Low Level RF)
- large assembly rooms with cranes (MEBT, cryomodules)
- laboratories for preparation and qualification of vacuum performances (DIVA, etc.)
- the mechanical workshop (for last-minute adjustment of components or tooling)
- the electronics and mechanics laboratories where small components can be designed and qualified.

MEDIUM ENERGY BEAM TRANSPORT LINE (MEBT)

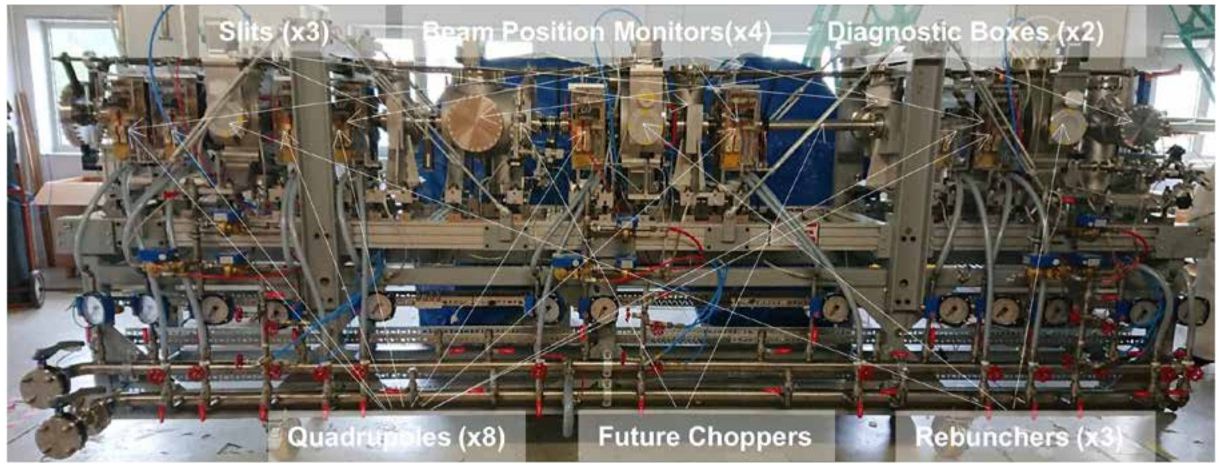
The MEBT serves to measure and clean the beam exiting the RFQ and match it for injection into the superconducting linac. The various components of the MEBT were assembled and tested at Saclay (without beam) in summer 2020. The MEBT has since been delivered and installed at SNRC. It should be tested with beam in 2021.

Rebuncher qualification

The rebunchers were designed at GANIL before returning to Saclay for the manufacturing and testing phases. In 2019-2020, they were qualified in a dedicated bunker at Saclay. After undergoing a bandwidth measurement to ascertain its quality factor, the RF power was injected into the rebuncher to reach 1.15 times the nominal field for several hours. Verification was undertaken to ensure that the RF frequency of the rebuncher can be controlled with the tuner within the required range without temperature drift. The three rebunchers were then assembled in the MEBT.



Test and inside view of rebuncher 1.



MEBT assembled and tested at Saclay in 2020.

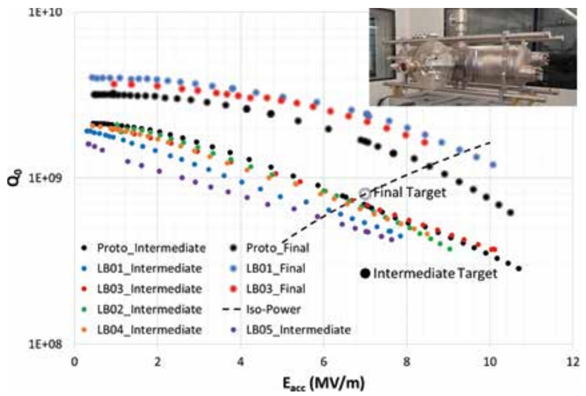
THE SUPERCONDUCTING LINAC

The function of the superconducting linac is to accelerate the beam to the required energy level. It consists of four cryomodules that maintain the 27 accelerating superconducting cavities and the 20 focusing superconducting solenoids in position (~±1 mm) and at cryogenic temperatures (~4 K).

Qualification/preparation of superconducting cavities

Two types of superconducting cavities are used: 14 low-beta cavities in cryomodules 1 and 2, and 15 high-beta cavities in cryomodules 3 and 4. The cavities are manufactured by a private company and their surfaces are prepared by and at CEA. They are qualified first in a vertical cryostat (CV2), then equipped with their high-power coupler in a dedicated cryostat. Once the cavity is cold, the RF power is progressively increased in the cavity; the field in the cavity and its associated intrinsic quality factor can be estimated using measurements of injected, reflected, and transmitted power. The higher the intrinsic quality factor, the less power the cavity consumes. The cavity undergoes two qualification steps:
- an intermediate qualification determines if the initial phases of fabrication were nominal,
- and a final qualification evaluates the cavity's final performance.

As of mid-January 2021, three low-beta cavities were qualified and three were partially qualified. The first six cavities will be completely qualified by the end of February 2021, ready to be assembled in the first cryomodule.



Conditioning and qualification of the first superconducting cavities.

The Saraf-Linac Project 2019 status, N. Pichoff, R. Duperrier, G. Ferrand, B. Gastineau, F. Gougnaud, M. Jacquemet, C. Madec, O. Piquet, T. Plaisant, F. Senée, D. Uriot; D. Berkovits, Y. Luner, A. Perry, E. Reinfeld, IPAC2019, Melbourne, Australia.

Israel Atomic Energy Commission (IAEC), Israel.

Soreq Nuclear Research Center (SNRC) of the Israel Atomic Energy Commission (IAEC), Israel.

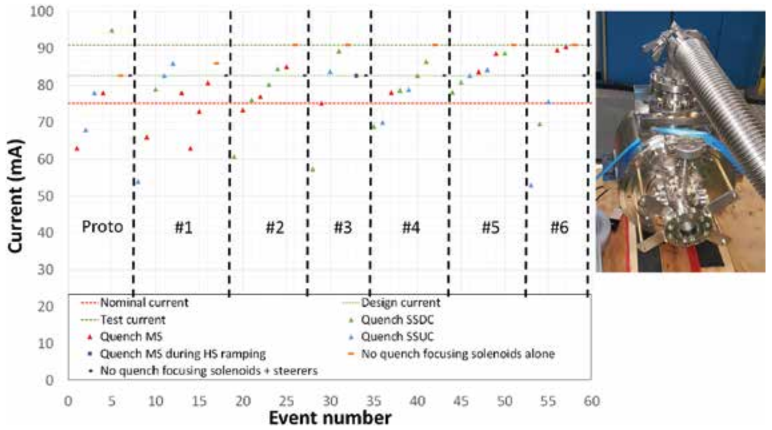
Qualification/conditioning of RF couplers

The 31 RF couplers (including four spares) have been prepared and conditioned up to 20 kW on a dedicated test bench. Two couplers are mounted in series on a specific conditioning box. The RF power enters through one coupler, passes through the box, and propagates through the second coupler to a charge. The position of the charge is changed to produce different configurations of the RF field that represent different phases used for the operation of the couplers.
All couplers are now ready to be assembled on the cavities and integrated into the cryomodules.

Qualification of superconducting solenoids

Superconducting solenoids and their current leads are qualified in a dedicated cryostat. Once the solenoid is cold (4K), the current is progressively increased to 1.2 times the nominal value. The magnetic Lorentz force induced during this conditioning phase moves the magnet wires to more stable positions, producing local warming that can induce a quench (fast transition from superconducting phase to normal conducting phase). The magnet becomes more robust and its current limit increases. This process is called magnet training.

As of mid-January 2021, six solenoids had been completely qualified (at cryogenic temperature) and 11 others had been partially qualified (at room temperature). The first six solenoids are ready to be assembled in the first cryomodule.

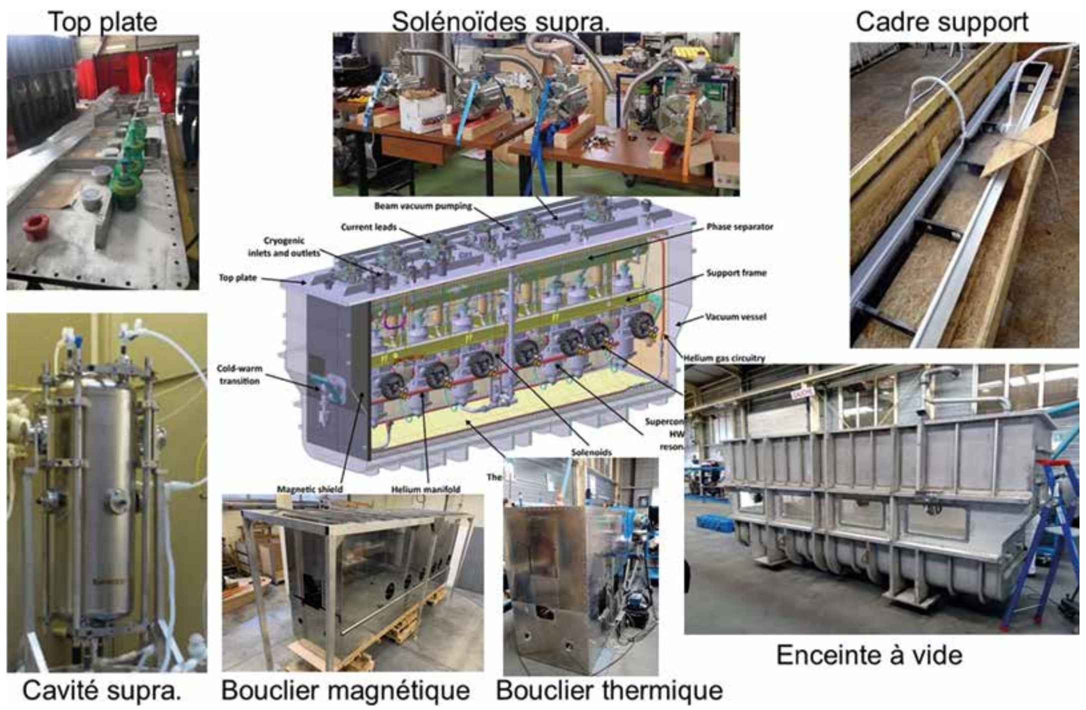


Training and qualifying the first superconducting solenoids.

BEAM DIAGNOSTICS

Beam diagnostics are used to tune the accelerator. Interceptive diagnostics (in contact with beam) require that specific precautions be taken because of the high-power density of the beam, which can exceed 1 MW/cm^2. Non-interceptive diagnostics allow monitoring of the beam during operation.

As of mid-January 2021, beam diagnostics were at different stages of development:
- Some had been delivered: current monitors, beam position monitors, fast Faraday cup.
- Some were being tested: Faraday cup.
- Some were being manufactured: beam profile and loss monitors.



Main components of a cryomodule.

The European approach to the fusion-like neutron source: the IFMIF-DONES project, A. Ibarra *et al.*, Nucl. Fusion 59 (2019) 065002 (21pp), https://doi.org/10.1088/1741-4326/ab0d57.

DRF, Irfu and cited European programs.

1°) In the framework of the WP-ENS of the EUROfusion program: CIEMAT, MPG, LPP-ERM-KMS, RBI, VTT, CEA, KIT, WIGNER-RCP, ENEA, LEI, IPPLM, CCFE
2°) In the framework of DONES Preparatory Phase: 13 collaborators (including CIEMAT, INFN, IFJ PAN, KIT, RBI, SCK.CEN).

DONES

Derived from IFMIF, DONES (Demo Oriented NEutron Source), was developed to test and qualify specific materials to be used in the construction of future fusion reactors. DACM participates in defining the accelerator through beam dynamics studies, as well as in finalizing the design of both the Injector and the SRF-Linac.

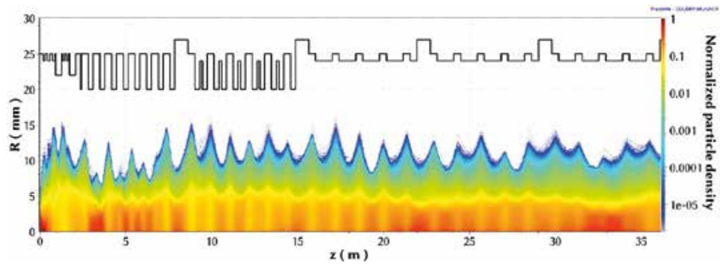
In December 2017, the joint proposal from Spain and Croatia for a construction site located in Granada was accepted. This intensified the design study process of the entire DONES infrastructure, which is being carried out mainly through the European programs EUROfusion/WPENS and DONES Preparatory Phase. Its linear accelerator must deliver a very high-intensity beam, of a level never before achieved, in order to generate neutrons with an energy spectrum and a flux identical to those bombarding the plasma chamber walls of future fusion reactors.

BEAM DYNAMICS

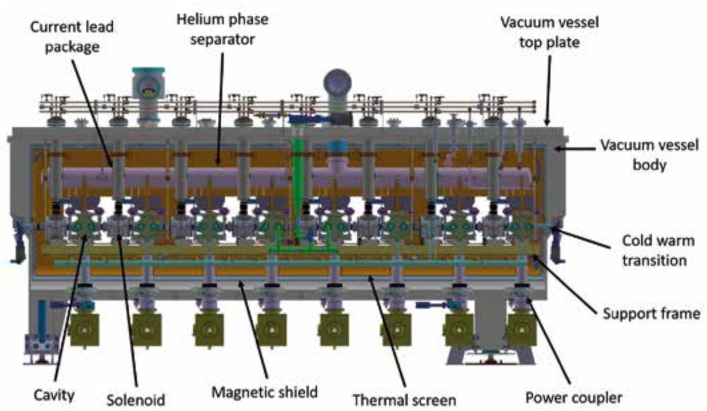
The main evolution of the accelerator with respect to IFMIF lies in the SRF Linac as the room-temperature inter-cryomodule sections must be significantly lengthened in order to meet mechanical installation requirements. Consequently, the accelerator structure has been completely modified to compensate for this focusing deficit. Instead of the four cryomodules present on IFMIF, it was necessary to equip DONES with five cryomodules. The system was optimized to accelerate a D$^+$ beam from 125 mA to 40 MeV while maintaining beam losses of less than 1 W/m. A total of eight solenoids and four accelerator cavities were added in order to obtain, respectively, better transverse focusing and greater longitudinal acceptance by optimizing the synchronous phase law (i.e., configuration of RF phases of the accelerating cavity). This new configuration was validated by an error study that accounted for the misalignment of elements (solenoids, cavities) and fluctuations in power supplies. The results demonstrated that the accelerator meets requirements in terms of sensitivity to error.

SRF LINAC

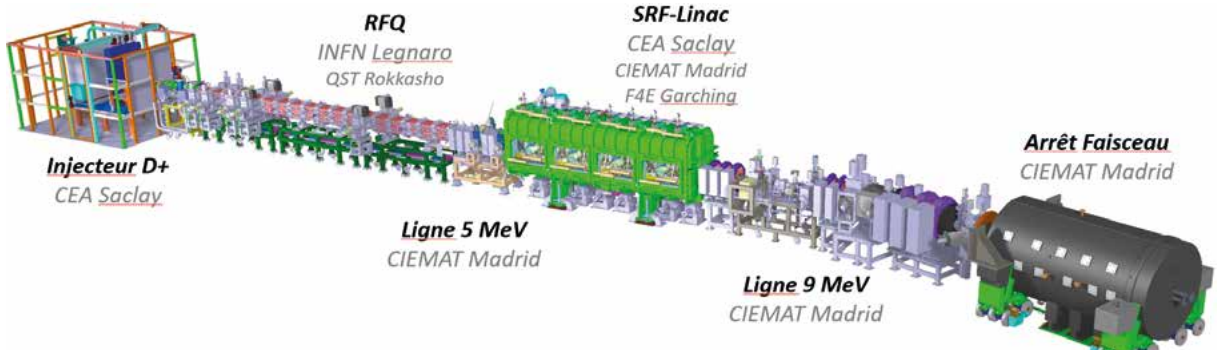
The SRF Linac is made up of five cryomodules: two cryomodules housing half-wave, low-beta, superconducting cavities (identical to those developed for the prototype accelerator LIPAc), and three cryomodules housing high-beta, half-wave cavities, currently in the prototyping phase. The latter were designed to maintain greater mechanical stability during operation and to produce an accelerating field of 4.2 MV/m with a maximum dissipation of 7.4 Watts in order to transfer up to 200 kW of power to the deuteron beam in continuous mode. The DONES cryomodules are similar to those developed for IFMIF, with the addition of cavity strings supported by a titanium frame connected to the top of the vacuum chamber by means of vertical titanium alloy tie rods. However, integration studies revealed the need to re-adapt the diameter of the helium circuit's phase separator and shorten the power couplers for the high-beta cryomodules. The method for inserting the cold mass into the vacuum chamber was also modified: the constraints induced by installation of the rails used for end-loading are incompatible with the available space on DONES, so top-loading, a more conventional method for this type of cryomodule, was selected.



Transverse beam density in medium energy beam line and SRF-Linac.



View of the DONES cryomodule including main components.



Mockup of the LIPAc prototype installed at the Rokkasho site in Japan.

IFMIF/EVEDA

The IFMIF/EVEDA project is a collaboration between Europe and Japan that was initiated within the framework of research on materials that must be capable of withstanding very intense neutron radiation, like that produced by tokamaks (fusion reactors) of the future. IRFU/DACM is heavily involved in the design, construction, installation, and commissioning of the LIPAc accelerator prototype, in particular the Injector, the SRF Linac and the Cryoplant.

Supported by the Broader Approach Agreement signed between Euratom and the Japanese government through an EVEDA (Engineering Design and Engineering Validation Activities) phase of design and prototyping, the IFMIF (International Fusion Materials Irradiation Facility) project is focused on designing and building a dedicated facility for qualifying materials that could potentially be used to line the walls of the plasma chamber for the future DEMO demonstration power plant, the successor to ITER (International Thermonuclear Experimental Reactor). In the initial validation phase, the decision was made to build and install (at the Rokkasho site in Japan), in addition to a 1/3 scale liquid lithium target and instrumented test cells, a prototype accelerator called LIPAc, in order to accelerate deuteron (D^+) beam up to the energy of 9 MeV and a continuous power of 1.1 MW. Until now, no other accelerator in the world has achieved this level of performance.

For historical and strategic reasons, CEA-IRFU is an important contributor to the design and validation of the IFMIF prototype accelerator, in which INFN-Legnaro (Italy), SCK-CEN (Belgium), CIEMAT (Spain) and QST (Japan, formerly JAEA) are also collaborating. Coordination is shared between Europe (F4E, Fusion for Energy) and Japan (QST). The DACM has technical responsibility for the Injector, SRF-Linac and Cryoplant. Supported by other IRFU departments, it is also involved in the installation and commissioning of the prototype accelerator in Japan.

INJECTOR

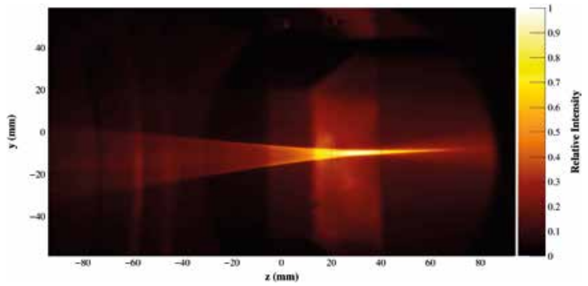
Over the 2017-2019 period, the DACM teams helped optimize operation of the Injector, which consists of an ECR (Electron Cyclotron Resonance) type ion source that produces the desired ion beam; two solenoids that allow the beam to be transported and matched for injection into the following accelerator section, namely the RFQ (Radio Frequency Quadrupole cavity); and finally, diagnostics (intensity, emittance, and species measurements) to characterize the beam. The objective is to produce and transport a deuteron beam of 140 mA at 100 keV with an emittance of less than 0.3 πmm.mrad in order to maximize RFQ transmission. An initial series of experimental campaigns were carried out to qualify the injector operating at low duty cycle (i.e. less than 5%). In this mode, a beam of D^+ of 140 mA was obtained at the end of the line with an emittance between 0.25 and 0.3 πmm.mrad. It has been verified that about 90% of the beam extracted from the source consists of D^+. The position of the electrodes in the source extraction system was then optimized, thereby reducing beam emittance by approximately 10%. Finally, a beam of D^+ was injected at low duty cycle into the RFQ and accelerated with a transmission of 90% leading to 125 mA of D^+ at 5 MeV, which represents a major step for the IFMIF/EVEDA project. Following this achievement, the current goal is to achieve the desired beam characteristics with a continuous beam (i.e. 100% duty cycle). Such performance exceeds the current capabilities of state-of-the-art high-intensity injectors. In order to achieve this ambitious goal, while maintaining emittance that remains within the RFQ acceptance, an experimental program has been established to gradually increase the diameter of the source plasma electrode, which defines the extracted beam. For the time being, a stable 117 mA beam of D^+ at 100% duty cycle has been obtained, which represents a very encouraging result as intensity is increased towards the 140 mA target.

Fish-eye view of the 36-meter-long prototype accelerator installed at the Rokkasho site in Japan (in the 2020 configuration, SRF-Linac is replaced by the extension line).

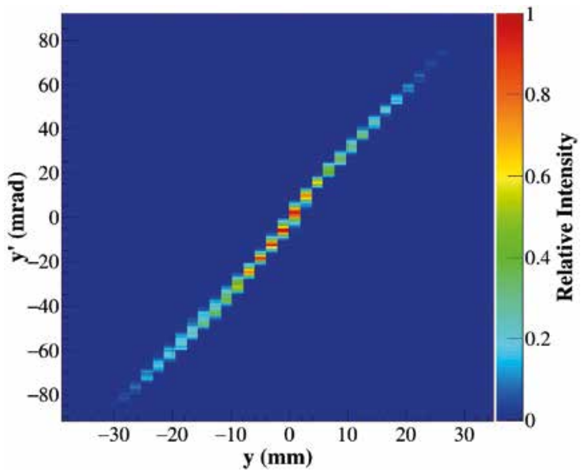
Overview of the IFMIF/EVEDA project, J. Knaster *et al.*, Nuclear Fusion, (2017), 57(10).
Progress Report on LIPAc, M. Sugimoto *et al.*, 29th Linear Accelerator Conference, LINAC2018, Bejing, China.

French contribution in kind to IFMIF/EVEDA.

CIEMAT, INFN, SCK-CEN, coordination by F4E and QST.



Transverse profile of a 100 keV - 120 mA D^+ beam in the low energy line of the LIPAc injector.

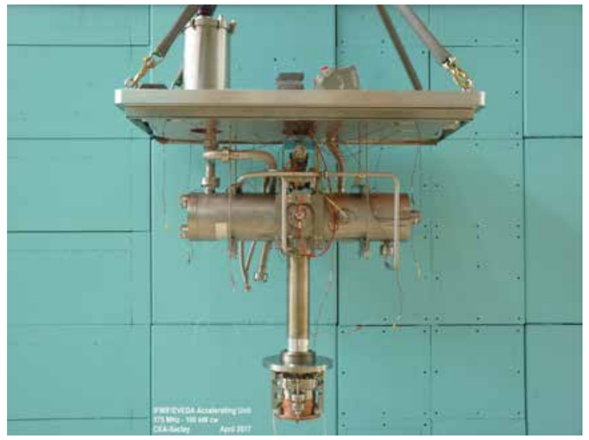


Distribution in the transverse phase space (yy') of a 100 keV - 140 mA D^+ beam with a duty cycle of 3% at the end of the low energy line of the LIPAc injector.

SRF LINAC

During the 2016-2019 period, several activities took place concurrently: components of the SRF-Linac were manufactured and some of them were qualified; assembly and installation operations of the SRF-Linac in Rokkasho were prepared; and the cryoplant dedicated to the operation of the SRF-Linac was delivered and installed at the Rokkasho site. DACM teams managed all contracts for the manufacture of SRF-Linac components, in particular the superconducting cavities, power couplers, and frequency tuning systems, as well as the vacuum chamber, magnetic shielding, thermal screen, support frame for the cavity string, phase separator, and the cryogenic piping, plus a multitude of small parts. They carried out qualification tests on the main components (couplers, cavities) and fully integrated tests of accelerator units in a cryostat called SATHORI, which was designed and built in Saclay specifically for this purpose. These components were shipped to Japan between 2017 and 2020. Concurrent to monitoring the manufacture and qualification of components, the CEA participated in preparing cryomodule assembly at the Rokkasho site. As this operation was subcontracted by F4E, the CEA prepared documents presenting the main sequences of cryomodule assembly and contributed expertise to drafting specifications and technical analysis of bids. The DACM teams participated in technical meetings between F4E and the company RI (Research Instruments) during the design phase and assembly preparation, and in follow-up of the first coupler assemblies with superconducting cavities inside the clean room built by QST specifically for these operations. Although assembly was put on hold in mid-2019 following difficulties encountered by some partners, it should resume in 2021. The SRF-Linac is scheduled to be integrated into the prototype accelerator in 2022.

DACM and IRFU will once again be needed in 2022 for the integration of the SRF linac into the accelerator, as well as the commissioning of the entire accelerator, with beam. DACM's participation in these operations reinforces its technical expertise in the field of low-energy and very high intensity light ion accelerators.



Accelerating unit qualified in 2017 at DACM.

THE EUROPEAN SPALLATION SOURCE (ESS)

ESS is the future European Spallation Source currently under construction in Lund, Sweden. IRFU is contributing to the development of up to 70% of the length of the 360-meter-long accelerating sections through the design, construction, assembly, testing, and delivery of the RFQ and 30 fully equipped medium-beta and high-beta cryomodules.

RFQ in assembly in the ESS tunnel.

ESS will generate neutrons produced by spallation, a nuclear reaction caused by irradiating a tungsten target with an intense, high-energy proton beam which is in turn produced by a superconducting linear accelerator (Linac supra). The ESS source will be pulsed at 14 Hz, with a duty cycle of 4% and a pulse length of 2.86 ms.

The Linac includes, among others, a low-energy section (E ≤ 90 MeV) with an RFQ (Radio Frequency Quadrupole) and a DTL (Drift Tube Linac), and a high-energy section made up of superconducting medium-beta and high-beta elliptical cavities that are designed to gradually accelerate protons up to 2 GeV. IRFU's contribution includes the supply of the RFQ and the 30 medium- and high-beta cryomodules. Each cryomodule is equipped with four elliptical cavities supplied by ESS. In the 2016-2020 period, DACM constructed and delivered the RFQ, tested prototype cryomodules, launched contracts for procurement of series cryomodule parts, and began the industrial assembly phase.

RFQ

The RFQ is an accelerating cavity operating at 352.21 MHz located at the entrance of the ESS accelerator, just after the ion source, and serves to bunch, focus, and accelerate the beam from 75 keV to 3.6 MeV. It comprises five sections of four brazed poles in ultra-pure copper and stainless steel, each measuring about one meter long, machined with a mechanical precision of a few tens of micrometers. It is equipped with 60 slug tuners for adjusting the voltage law required by the beam and cavity resonance of the cavity at 352.21 MHz. Twenty-two RF pick-ups are used to monitor RFQ operation, and two power couplers allow 1 MW of RF power to be transmitted into the RFQ cavity. The RFQ is cooled by a hydraulic system, known as a skid, and the vacuum system is produced and assembled by ESS.
Construction of the sections took more than three years, and the equipment required more than 15 contracts, the first of which was launched in 2015.

After reception at the manufacturer and verification at Saclay to ensure that each section had been completed correctly, in particular the voltage law, using a "beadpull" measurement, the sections of the RFQ were delivered to ESS in August 2019, a few months after the skid. The RF assembly and settings (frequency and voltage law) were strongly impacted by the Covid-19 crisis; however, as of September 2020, the RFQ was almost ready for conditioning, which is scheduled to begin in April 2021.

DEVELOPMENT AND CONDITIONING OF POWER COUPLERS FOR CRYOMODULES

Each cavity is equipped with a power coupler supplied by CEA, i.e. 120 couplers in total. They are composed of three elements:
- a window-antenna which ensures the cavity's vacuum seal and allows coupling of the radiofrequency power into the cavity (1.1 MW peak at 704.42 MHz with a pulse width of 3.6 ms);
- a double wall tube, which allows in particular the thermal transition between the cavity flange at 2 K and the window flange at ambient temperature;
- a doorknob transition, which allows RF transmission of the waveguides into the window.

In order to validate the design and performance of the couplers, ten prototype couplers (six medium-beta and four high-beta couplers) were manufactured and conditioned over the 2016-2018 period. The couplers are conditioned in pairs on a coupling box. This prototyping phase also allowed to improve the coupling box design, to optimize the handling and assembly steps of the couplers in a clean room, to automate the coupler baking (acquisition of an oven to bake at 170° C) and to develop two fully automated conditioning benches. Following this prototyping phase, series production of 120 couplers and 15 coupling boxes began. In December 2020, provisioning of 30 medium-beta couplers was nearly complete and 24 out of the 30 couplers had been conditioned. After conditioning, the couplers are transferred to the company B&S, which assembles them on the cavities, supplied by ESS, in the clean room.

Window-antenna of ESS power coupler.

Coupler conditioning bench.

CRYOMODULE ASSEMBLY

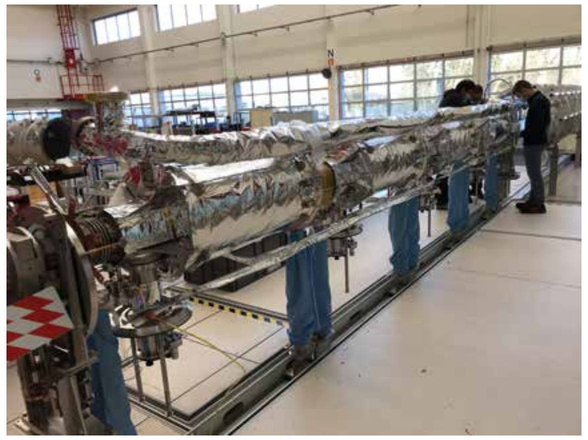
Most calls for bids for component procurements were launched in 2016 and contracts were signed in 2017. The assembly of the 30 series cryomodules at the CEA Saclay site was assigned to a private company, B&S. The 10-member B&S team includes eight technicians. DACM trains the team of technicians and monitors assembly quality.

Assembly activities are divided into eight workstations: two in the clean room (ISO 4 or ISO 5) for power coupler assembly and cavity train and six outside the clean room for the assembly of the components around the train: cryogenic tubes, a thermal shield, spaceframe (cold mass support structure), and vacuum chamber, in order to build the cryomodule. Each station requires multiple assembly, tightness, alignment, and RF measurement checkpoints.

In order to validate the cryomodule design and assembly principles, a medium-beta M-ECCTD prototype (CM00) and a high-beta H-ECCTD prototype (CM30) were built and tested at Saclay in 2018 and 2020 respectively. Test feedback was implemented on cryomodules being assembled.

As of late 2020, two series cryomodules had been fully assembled (CM01 and CM02) with active support from DACM technical teams and training for B&S operators. Starting with CM05, in early 2021, B&S will assemble in complete autonomy and responsibility. Learning gestures, techniques, and logic associated with assembly are acquired gradually, leading to a reduction in assembly time from four months for CM01 to two months for CM07. Handover of assembly activities will allow for monthly shipments of cryomodules to the ESS site in Lund. The nine medium-beta series cryomodules must be shipped to ESS by the end of October 2021, and the 21 high-beta cryomodules by October 2023. In addition, the high-beta prototype will be refurbished as a medium-beta cryomodule to serve as a spare.

Bellow assembly on a cavity in clean room.



Fully-equipped cavity train.

Cold mass ready for insertion inside its vacuum vessel.

Tests at high rf power of the ESS medium beta cryomodule demonstrator,
P. Bosland, C. Arcambal, S. Berry, A. Bouygues, E. Cenni, G. Devanz, T. Hamelin, X. Hanus, O. Piquet, J.P. Poupeau, B. Renard, P. Sahuquet, G. Olivier, J.P. Thermeau, C. Darve, P. Michelato, in Proc. 10th Int. Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, 19-24 May 2019

French in-kind contribution to ESS.

INFN (Italie) and STFC Daresbury (UK).

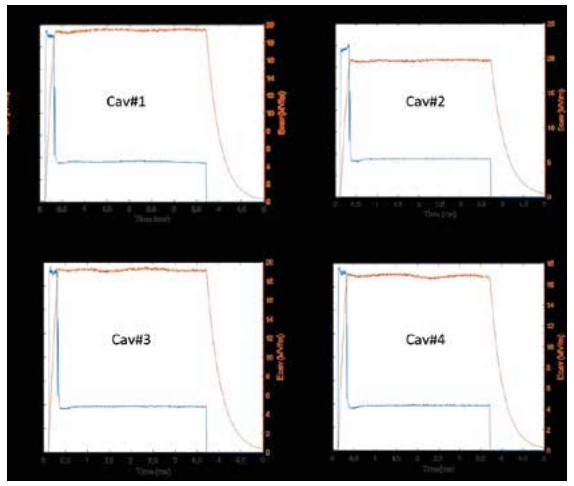
POWER TEST OF THE CRYOMODULES

ESS requirements for cryomodule performance—Pmax = 1.1 MW, Eacc = 16.7 MV/m at 14 Hz and 3.6 ms RF pulse duration—are at the leading edge of current know-how.
Cryomodule power testing serves to evaluate the quality of the cryomodule assembly and verify the accelerating field, cryogenic losses, compensation for frequency shifts by the tuning system, the maximum power transferred by the power coupler, and instrumentation operation. Eight cryomodules will be tested at CEA: the two prototype cryomodules, and each type of the first three series cryomodules. To validate them, all series cryomodules will undergo RF power testing in Lund before being installed on the Linac.

The CM00 prototype cryomodule was tested in late 2018 in the DACM test bunker. All four cavities performed as required. The piezo-equipped tuning system very effectively compensated for the Lorentz forces, thereby stabilizing the accelerating field extremely quickly over the duration of these long RF pulses. These results validated the technology developed and implemented for series cryomodules. Following testing at CEA, the CM00 cryomodule was delivered without incident by dedicated transport to ESS in February 2019. It is now installed in the ESS test bench and is being used to carry out verification tests of the station before it is commissioned for series cryomodules. Cryogenic tests at 2 K were carried out there in 2020, and confirm results previously obtained at CEA. RF power tests will begin in early 2021.

The test of the first series cryomodule CM01 with RF power and at 2 K is the project's second major milestone. All its components are the result of series production and this cryomodule was assembled by the DACM team, who trained the new B&S team at the same time. One year after the successful test of the prototype cryomodule, this CM01 cryomodule has been successfully tested, and all four cavities achieved the performances required by ESS. It was also delivered safely to ESS in February 2020, and acceptance checks revealed no damage. Final acceptance testing will be performed following the CM00 prototype cryomodule test.


CM00 prototype cryomodule in the CEA Saclay test bunker.



RF pulse of the four cavities and couplers during CM01 cryomodule test.


CM01 cryomodule being checked at ESS in Lund.

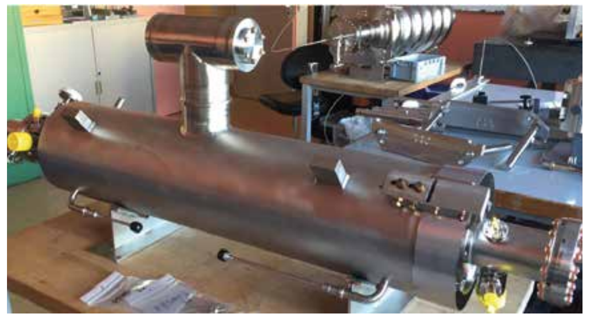
Ile-de-France SESAME 2015 15013104.

IRFU (DACM + DIS), SOLEIL, CNRS/IJClab, Thalès, SigmaPhi.

LUCRECE: A PROTOTYPE CRYOMODULE FOR LUNEX5, A FIFTH GENERATION FEL

LUCRECE (Lunex Cryomodule pour Electrons de Cadence Elevée) has as objective to develop the key RF components for a cryomodule which will be the building block of a 400 MeV superconducting linac for LUNEX5 (Laser à électrons libres Utilisant un accélérateur Nouveau pour l'Exploitation de rayonnement X de 5^{e} génération), a demonstrator for a fifth generation high brilliance light source.

CEA will provide the project with a niobium cavity and its mechanical tuning system; qualify the cavity's performances with a test carried out in a vertical cryostat; and test both the fully equipped cavity with a power coupler (provided by IJClab) and its tuner in a horizontal cryostat using a solid-state power source developed by SOLEIL. The design chosen for this cavity, which will operate in continuous mode, is the same as that used for the LCLS-II (Linac Coherent Light Source) SRF linac, allowing high quality factors up to an accelerating electric field of about 16 MV/m. In order to reach this level of performance, the cavity receives a special heat treatment called nitrogen doping: a small amount of nitrogen is allowed to diffuse in the mass, and the controlled diffusion depth, along with electro polishing allow to tailor the niobium surface properties, enhancing its performance at the required accelerating field. The cavity, shipped by the vendor to CEA in late 2020, will be qualified in vertical cryostat in early 2021, and testing of the fully equipped cavity in horizontal cryostat, with the cavity cooled by superfluid helium at 2K, is planned for 2022.

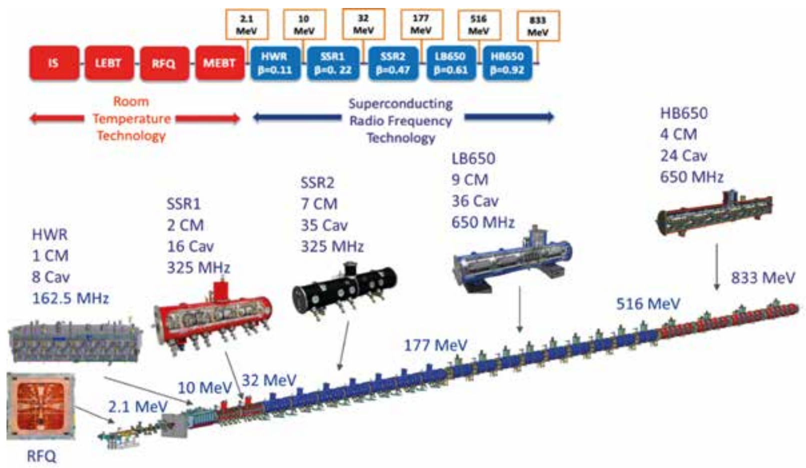

LUCRECE cavity with its He tank.

PIP-II ACCELERATOR PROJECT

The goal of the PIP-II (Proton Improvement Plan II) project is to enhance the capabilities of the Fermilab accelerator complex (USA) to support the delivery of 1.2 Megawatt (MW) beam power to the Long-Baseline Neutrino Facility (LBNF) neutrino production target, and to allow upgrade to multi-MW capability for DUNE (Deep Underground Neutrino Experiment), an international project that includes CEA. The central component of PIP-II is a new 800 MeV superconducting linear accelerator for accelerating H- ions, replacing the existing 400 MeV injector of the Booster Ring.

Downstream the 2.1 MeV hydrogen ion injector already in operation at Fermilab, the linear accelerator comprises five sections of superconducting cryomodules optimized for accelerating H- ion beams up to 833 MeV.

The PIP-II accelerator will be built by an international consortium led by the USA (DOE, Fermilab), including India (DAE), France (CEA, CNRS), UK (STFC) and Italy (INFN]). Commissioning is forecasted for 2027.



CEA contribution is focused on the 'low-beta' LB650 accelerating section comprising nine cryomodules of four β = 0.61 elliptical cavities. It includes design, fabrication, assembly, and qualification of ten cryomodules, namely one pre-production cryomodule prototype and the nine accelerator cryomodules. The cavities, couplers, and tuners of these cryomodules will be provided by Fermilab.

Layout of the linear accelerator PIP-II.

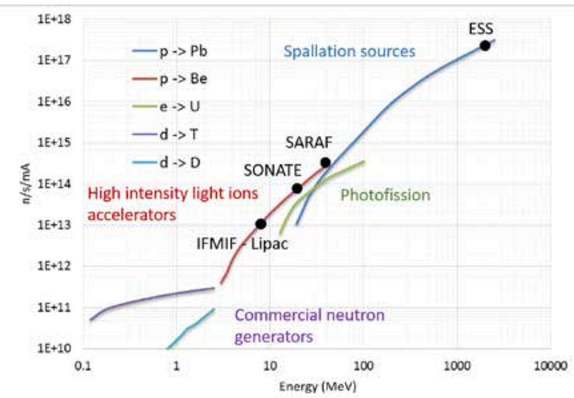
COMPACT NEUTRON SOURCES

Within DRF, a group from IRFU and IRAMIS has been working since 2014 to define a Compact Accelerator-based Neutron Source installation, called SONATE, which will be capable of replacing certain activities performed at the Orphée reactor, which closed in October 2019. This working group identified the Target – Moderator system as the main technological issue that could potentially limit the performance of such a neutron source and began R&D work on this topic at the IPHI accelerator.

THE SONATE PROJECT

Neutrons are an essential tool in the study of the structure of matter at scales between the angstrom and the micrometer, and the study of the dynamics of physics processes at energy ranges between 100 meV and a few neV. They are used in fundamental research in fields such as chemistry, magnetic and superconducting systems, materials science (polymers, liquid crystals, composites, metallurgy), and biology. Neutrons are also used in industry for applications such as neutron imaging of pyrotechnic equipment, fuel cells, and batteries, and for testing radiation-hardened electronic devices.

The development of high-intensity proton or deuteron accelerators at energies between 3 and 40 MeV, and the use of dedicated targets (to generate neutrons) and moderators (to slow neutrons to the energy requested by users) allows for the construction of high-intensity, compact neutron sources and the exploration of applications for science, industry, and society that were hitherto limited to nuclear research reactors. These sources, called compact neutron sources, are a good alternative to nuclear research reactors both in terms of cost and in terms of acceptability by the public at large.



Primary neutron flux per average mA from various accelerator-based neutron sources using various production processes.

Several countries, including China, Japan, and the United States, are already operating neutron sources such as these. The Israeli project SARAF, to which IRFU is contributing, is an example of a compact neutron source under construction. Other countries (Korea, Italy, Spain, Germany) are considering acquiring this kind of source, with budgets ranging from a few tens of thousands to 100,000,000 euros.

Since 2014, IRFU and the Léon Brillouin Laboratory (LLB) at the Saclay Institute of Matter and Radiation (IRAMIS) have been working at the CEA to define the SONATE installation and related R&D. For this installation, studies have shown that a proton accelerator operating at an energy of 20 MeV with a peak current of 60 to 100 mA and a duty cycle of 4% (corresponding to a power on target of the order of 80 kW) would be a reasonable solution in terms of performance, construction planning and construction and operating costs.

The construction of compact neutron sources is the subject of discussions and of joint funding requests among European countries, where similar projects have also emerged. The neutron source SONATE would thus be part of the European landscape in neutron scattering.

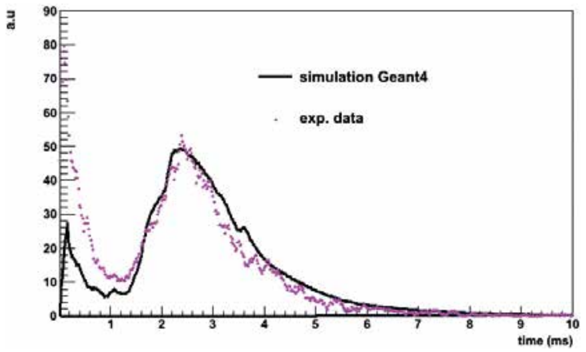
THE IPHI – NEUTRONS PROJECT

The first measurements of neutron production were performed in June and July 2016 in the IPHI accelerator by sending a few Watt beams on a beryllium disk surrounded by a polyethylene moderator. With these tests, the flux, spectrum, and angular distribution of the produced neutrons were measured and compared with numerical simulations.

Development of compact accelerator neutron source, A. Letourneau, A. Marchix, N. H. Tran, N. Chauvin, A. Menelle, F. Ott, and J. Schwindling, EPJ Web of Conferences 146 (2017) 03018.
Neutrons production on the IPHI accelerator for the validation of the design of the compact neutron source SONATE, A. Menelle *et al.*
Performances of neutron scattering spectrometers on a compact neutron source, X. Fabreges *et al.*
Saclay Compact Accelerator-driven Neutron Sources (SCANS), A. Marchix *et al.*, IOP Conf. Series, Journal of Physics: Conf. Series 1046 (2018) 012009.
Validation of Geant4 simulation tool for low energy proton induced reactions, H.N. Tran *et al.*, 2018 J. Phys.: Conf. Ser. 1021 012008.

Île-de-France SESAME 2017 EX023599.

IRFU (DACM + DPhN + DIS + DEDIP) and IRAMIS/LLB.



Comparison of the measured and simulated time-of-flight neutron spectra.

In 2017, supported by a grant from Region Ile-de-France in conjunction with a grant from CEA, R&D began on the construction, at IPHI, of a prototype installation equipped with a target capable of withstanding a beam power of 50 kW, a polyethylene moderator, shielding to limit background noise, and an instrument to perform neutron scattering studies.

The first step consisted of constructing a beryllium target screwed to a cooling support designed for a power of several kilowatts, constructing the moderator-shielding, and setting up diagnostics to monitor the target during data collection.

Between April 2019 and March 2020, five targets were tested using this setup, at a power on the order of 3.5 kW, over a total of 240 hours. One of the targets was tested for more than 100 hours, with the beam power raised to 5.5 kW.

These tests made it possible to confirm consistency between the neutronic simulations and the measurements of the neutron flux; verify the stability of the neutron flux during the tests; study target ageing, particularly the creation of blisters due to proton implantation; validate thermomechanical simulations; and perform the first scattering measurements and neutron images.

In 2020, a new version of the target designed for a beam power of 50 kW was built and installed at IPHI. This target will be tested during the first semester of 2021.

The tests performed thus far have allowed DACM and its collaborators at IRFU and IRAMIS to continue developing their expertise in design, construction, and operation of targets in relation to the compact neutron source SONATE.

The experimental setup installed at IPHI with, on the left, the beamline with its vacuum system and the diagnostics and, on the right, the Target – Moderator system.

THE XFEL PROJECT COMES TO AN END AT CEA

The integration at Saclay of 103 cryomodules for the 17.5 GeV electron accelerator of the Eu-XFEL facility in Hamburg began in September 2012 with the assembly of three pre-series cryomodules and ended on July 27, 2016, with the delivery of the one hundredth and final cryomodule of the production series to DESY, the laboratory in charge of coordinating construction of the superconducting accelerator.

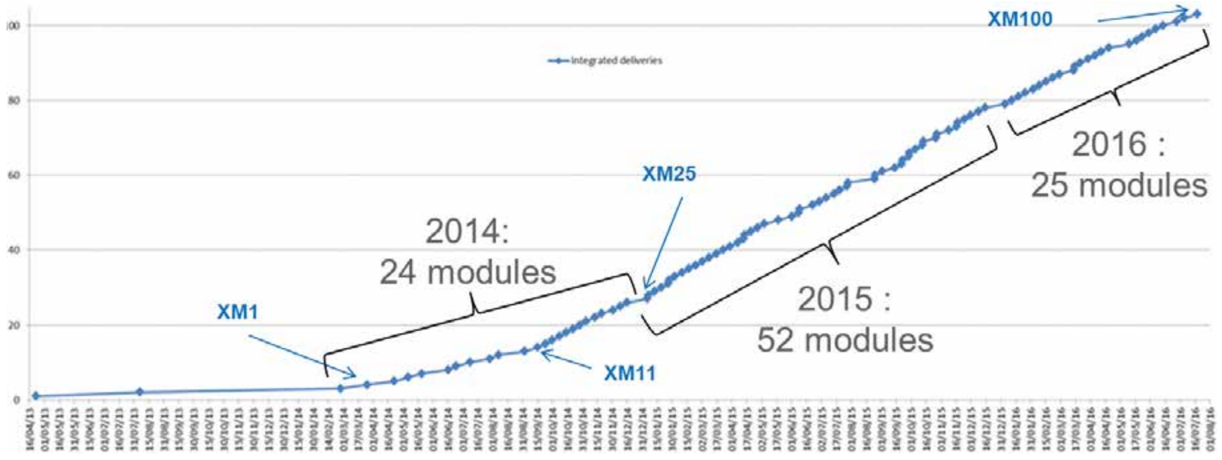
FINAL CRYOMODULE INTEGRATION

As of 2016, 24 cryomodules had been delivered to DESY after integration by the Alsyom company on the technical platform referred to as the "XFEL-Village," under supervision by CEA. In addition, one cryomodule had been partially dismounted and re-assembled by CEA staff to repair a defective component that became evident after its initial delivery in 2015.

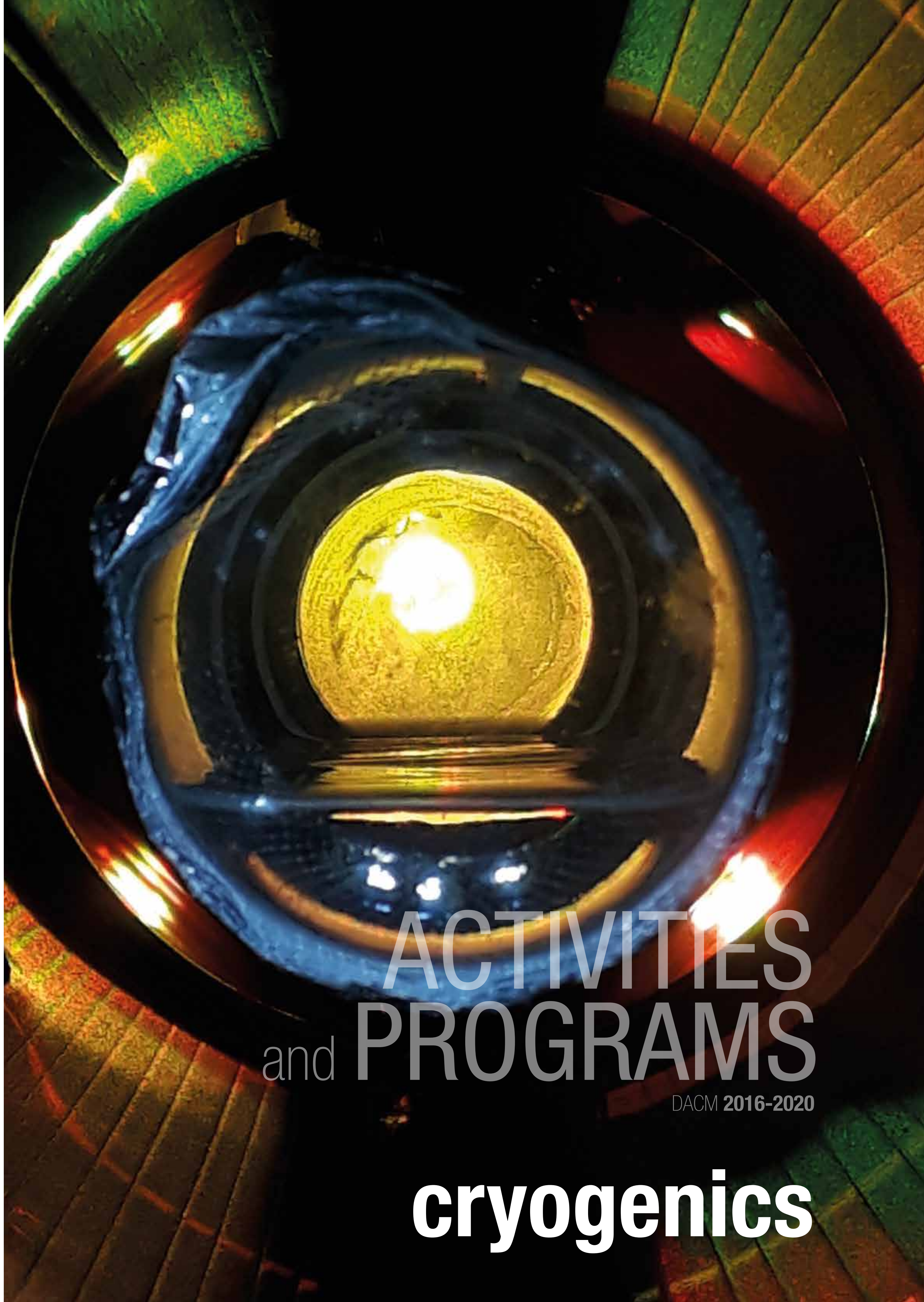
Ninety cryomodules were assembled and delivered to DESY between mid-September 2014 and July 2016, meaning that the CEA reached and even exceeded the assembly throughput of one cryomodule per week, accounting for periods when some components were unavailable.

PERFORMANCE OF CRYOMODULES IN THE ACCELERATOR

The performance goal in terms of accelerating field and cryogenic consumption (Q_0 factor) has also been fulfilled, as the linac energy of 17.6 GeV was reached with 97 cryomodules, instead of the foreseen 101, which corresponds to an average accelerating field of 24.4 MV/m. In stable operation, electron beam energy of 16.5 GeV generates 0.7 Å wavelength photon beams to the photon science users.



Delivery calendar for the 103 XFEL cryomodules.

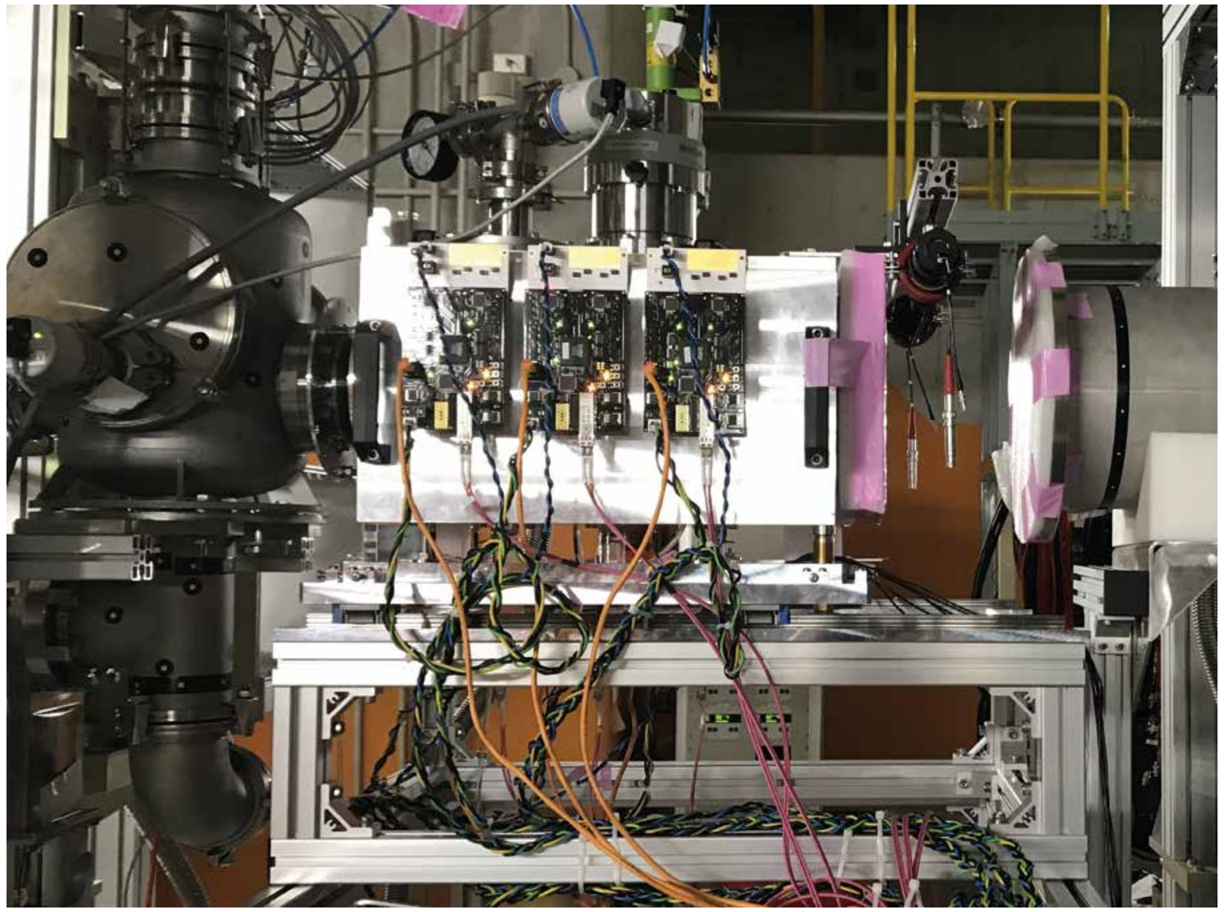


THE LIQUID HYDROGEN TARGETS OF THE MINOS PROJECT

Since 2014, IRFU has contributed to experiments carried out at RIKEN (Institute of Physical and Chemical Research) in the field of nuclear physics as a partner in the MINOS (Magic Numbers Of Stability) Project. The institute provides a hydrogen (or deuterium) cryogenic target system with targets of different thicknesses ranging from 50 to 200 mm.

The three liquid H2 targets operated successfully for more than 120 days during the 2016 and 2017 campaigns. During the 2017 campaign, the experiment required an additional liquid deuterium target. The fluid change took only 5 hours during the corresponding beam shutdown. In the first phase, the liquid hydrogen originally contained in the target was evaporated and evacuated to dedicated storage. In the second phase, the switch to deuterium was made using the gas manifold of the MINOS system. The liquefier and the target remained below 100 K throughout the entire process. In the final phase, the cryostat was cooled to achieve the liquefaction temperature of 23.4 K so that gravity could be used to fill the target with liquid deuterium located more than 800 mm below the liquefier.

During the final experiment of the 2017 campaign, the MINOS cryostat was combined with a new detection system (figure) equipped with a shared vacuum managed by the MINOS system. The target was located a few millimeters from the silicon detectors inside an experimental reaction chamber. The improved quality of the data validated use of this type of detection system with an IRFU liquid target in a constrained environment.



MINOS cryostat combined with a new detection system.

SOLID HYDROGEN TARGET FOR THE CHyMENE PROJECT

Five years ago, within the framework of the nuclear physics programs at IRFU, DACM designed and built the CHyMENE (Thin Hydrogen Target for the Study of Exotic Nuclei) cryogenic system, which enables the production of thin, cryogenic, quasi-solid targets with thicknesses ranging from 20 to 50 µm.

The first task, carried out in 2016, was to demonstrate the continuous production of a 5-mm-wide quasi-solid hydrogen ribbon over 36 hours of operation by monitoring H2 ribbon. This experiment confirms the parameters defined during preliminary tests.The thickness measurement was unfortunately inconclusive. The collimation was too high in front of the source. It induced a loss of energy by α radiation, which lowered the number of hits recorded by the acquisition.

The second task (2018-2020) has validated that the CHyMENE cryostat could produce deuterium ribbon. The multiple parameter adjustments required to produce the deuterium paste (for example 200 bars operating instead of 100 bars for H2) that flows into the nozzle were studied. At the bottom of the extruder, the nozzle assembly was reinforced because of the higher operating pressure.

The third task, carried out during the 2018-2019 period, involved designing a new nozzle to lower the thickness inhomogeneity level down to the 5% specified by physicists with conical detection angles of 100°.
The selected material must combine:

- High thermal conductivity
- Good machinability to achieve tight tolerances
- Good mechanical to limit deformations without additional supporting structures that could obscure the multiple detection angles.

In spring 2019, the CHyMENE team installed the cryostat on a low-energy beam line (1 to 3 MeV) at the IPN Tandem facility in Orsay for the first time, under real operating conditions. To protect the beam vacuum (P< 1.10^{-8} mbar), a conductance break was installed in front of the reaction chamber (P> 1.10^{-4} mbar) equipped with silicon detection.

CHyMENE cryostat on the beam line of IPN in Orsay.

ANR-17-CE31-0005.


Cocotier target environment.

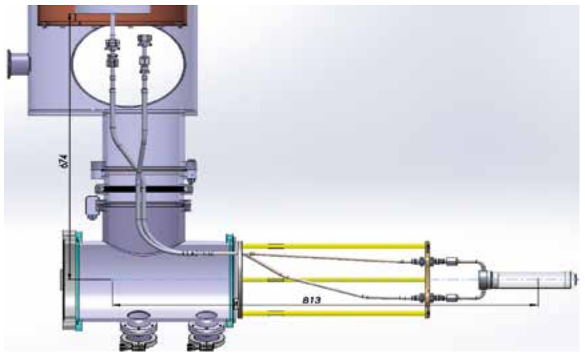
COCOTIER

The Cocotier project, led by the Department of Nuclear Physics, aims to study short-range correlations in exotic nuclei produced by fragmentation with the GSI's FAIR radioactive ion machine. It is part of the international R3B collaboration. To generate these reactions, a proton source is needed and takes the form of hydrogen targets brought to its liquid phase.

The DACM/LCSE modified a hydrogen liquefier previously built for the FRS and Prespec projects, where the targets were located at the bottom of the liquefier in order to adapt it to the new needs of the collaboration. The closed-loop liquefaction system is autonomous and consists of a condenser pot cooled by a Gifford-McMahon type cryocooler. The hydrogen gas is introduced and then liquefied; the liquid flows by gravity to the target, and the less dense, vaporized gas leaving the target returns to the pot where it is re-condensed.

The cryostat (1) is installed upstream of the GLAD (2) magnet and suspended to the frame of the CALIFA (3) calorimeter. The target has the particularity of being at the center of the calorimetric detection with a common vacuum with the Silicium (4) trackers. The cell of the target has a diameter of 42 mm and is made of 180 µm Mylar®. Depending on the desired physics, three target lengths are available: 15, 50, and 100 mm. The target is loaded on its support, much like an explosive shell, so that it can be easily retracted to leave room for a solid target.

This very constrained environment required the development of an off-center target with a center 813 mm from that of the liquefier, with a flow height limited to 674 mm.


Target installation.

The cryostat was installed in January 2020 and the target commissioned in September of the same year. The first experiments were scheduled for March 2021.


Cryostat installation in GSI.

A temperature-controlled cryogen-free cryostat integrated with transceiver-mode superconducting coil for high-resolution magnetic resonance imaging, May 2020, Review of Scientific Instruments 91(5):055106 DOI: 10.1063/1.5143107
All-polymer cryogen-free cryostat for µ-MRI application at clinical field, April 2019 IOP Conference Series Materials Science and Engineering 502:012156 DOI: 10.1088/1757-899X/502/1/012156
Conceptual design of a cryogen-free µMRI device, December 2017 IOP Conference Series Materials Science and Engineering 278(1):01212 DOI: 10.1088/1757-899X/278/1/012122.

SUPRASENSE

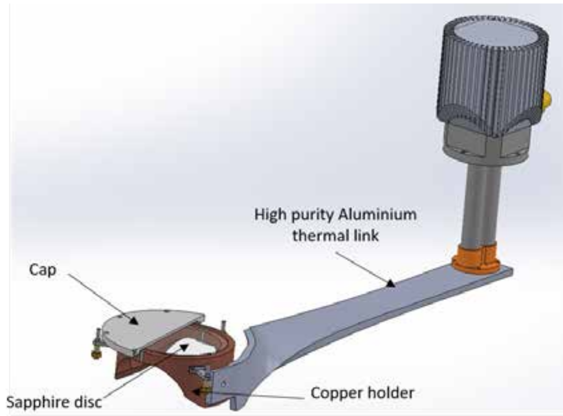
The aim of the SupraSense project, directed by the IR4M laboratory at CNRS, is to develop surface MRI micro-imaging. To achieve high-resolution local images, small coils made of superconducting YbaCuO material are used in place of the conventional copper antennas installed in standard MRI scanners. The LCSE R&D laboratory developed an autonomous cryostat without cryogenic fluids and compatible with a clinical MRI scanner.


Cryostat inserted into the MRI scanner bore.

This cryostat (1) is able to take the resonators to their operational temperature of 60 K. In order to position the coils at the center of the MRI, the cryostat can be inserted into the scanner bore. For this reason, the vacuum chamber is entirely constructed from polymer materials. The cryostat is placed on the MRI bed in place of the patient.

To support user-friendly operation and autonomy compatible with MRI testing, the cryogenic design is based on a pulse tube cryocooler (2) with remote motorization. This kind of cold source does not have moving mechanical parts, which minimizes vibrations that could otherwise degrade image quality. Remote motorization (3) allows the valve motor to be extracted from the scanner's magnetic fringe field. The usable cooled surface is a 150 mm sapphire disc, which can facilitate a network of up to 14 coils. The top side of the disc at 60 K, insulated from the atmosphere by a cap, is placed between 2 and 5 mm from the cryostat's external face at 300 K, thereby reducing the distance between sample surface and coils. The sapphire disc is supported by two complex copper pieces designed to behave with thermal efficiency and to minimize disruptions to the coils and the MRI. The thermal junction between holders and the cold source, situated 750 mm apart, is ensured by conductive links made of high-purity aluminum.

The design has been patented in the United States and Europe. The cryostat was tested on the SHFJ's Philips Achieve 1.5 T scanner in 2018. The signal resolution obtained during the first test using a 12 mm diameter HTC coil was 150 times better than the resolution obtained with a copper antenna of the same diameter.



View of cryogenic parts.

JT-60SA TOROIDAL FIELD COILS

As part of Europe's involvement, led by F4E (Fusion for Energy) to in the construction of the Japanese tokamak JT-60SA, DACM participated in two main activities: cold testing and OIS pre-assembly.

COLD TESTS

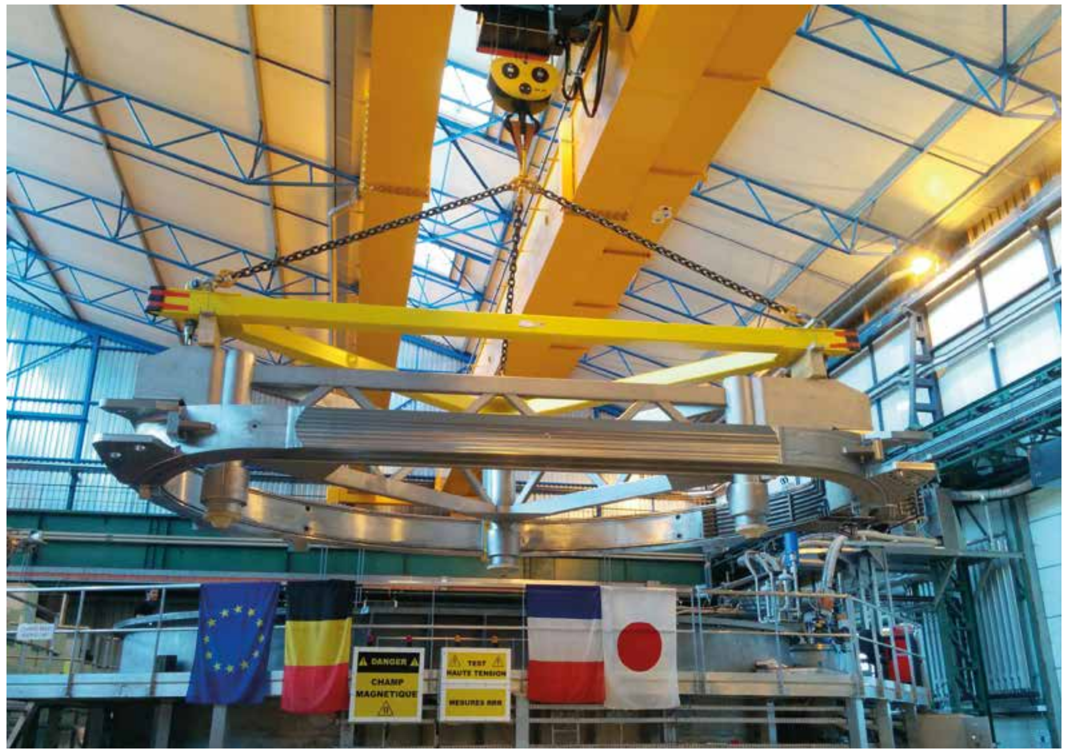
In December 2015, the first Toroidal Field Coil (TFC) of the Japanese JT-60SA tokamak was delivered to Saclay. Between early 2016 and mid-2018, the 18 TFC and two spares were tested at the Saclay Cold Test Facility (CTF).

The main objective of these cold tests was to validate coil performance and mitigate the risks of non-conformities. The most significant tests carried out were:

- Verification of coil ground insulation at 3 kV
- Characterization of pressure drop in the coil during cooling
- Validation of the coil's nominal operation during a one-hour plateau at 25.7 kA with a 5 K supercritical helium flow of 24 g/s
- Measurement of internal and external joint resistance during the nominal current plateau
- Quench initiation, by increasing the inlet coil temperature to 7.5 K, and determination of the experimental quenching temperature.

During the 20 testing campaigns, a few major non-conformities were identified. One of the most critical issues detected concerned ground insulation faults at 3 kV on three coils. Such faults are considered critical because they may induce an electrical short-circuit between coil and ground, severely damaging the coil and the facility or the tokamak. After analysis and examination, all insulation faults on these three coils were identified in the external joints and repaired. A second important issue involved clogging of the coil's hydraulic circuits: some coils had been contaminated with cleaning products used by manufacturing companies. Residue from these products solidified in the coils during cooling and clogged the cooling circuits. A procedure to clean the coils and remove the contaminating residue was implemented during the cooling phase, meaning testing could continue and similar issues could be avoided during tokamak operation.

The tests at 25.7 kA nominal current were all successful and all the coils performed according to their specifications. The joint resistance measured on the 20 coils was between 0.5 nΩ and 1.7 nΩ for a maximal allowable value of 2 nΩ. Quenching temperatures were all between 7.44 K and 7.52 K for a minimal allowable value of 7.3 K.



TF Coil during insertion into the JT-60SA CTF cryostat.

Results of the first JT-60 SA toroidal field coils tests in the cold test facility, November 2017, Fusion Engineering and Design.
Progress of the JT-60 SA Toroidal Field Coils Tests in the Cold Test Facility, April 2018, IEEE Transactions on Applied Superconductivity.

OIS PRE-ASSEMBLY

Following validation by cryogenic tests, eighteen coils were pre-assembled with their OIS (Outer Intercoil Structure) followed-up by IRFU/DIS in the industry.

The OIS is a very slender component weighing about 6 tons that covers the curved part of the toroidal coil. The OIS is then simply attached to the coil. Final assembly is carried out on the tokamak, where all the OIS are linked together to form the toroid exoskeleton. Before assembly, each OIS was individually measured by laser tracker in order to reconstruct its reference planes, which will be used to position it on the coil.

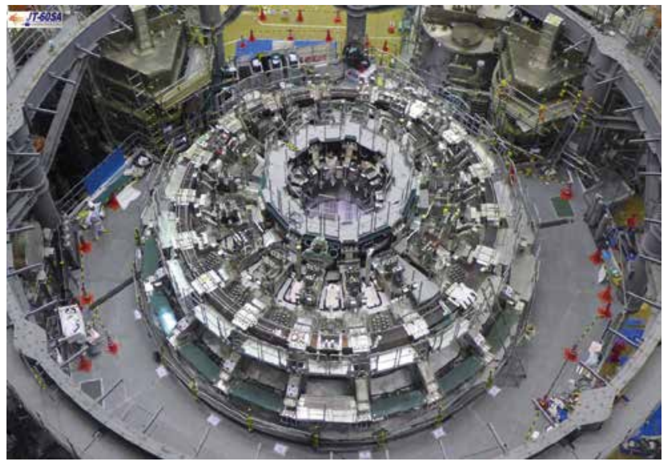
Because of the components' large mass and shape, the decision was made to perform pre-assembly in a vertical position. Tooling and lifting devices were designed and manufactured to safely rotate the coil from a flat delivery position to a vertical assembly position. This tool also allows for reverse rotation of the coil-OIS assembly, which weighs approximately 25 tons. In addition, because the OIS's positioning tolerance in relation to the coil reference planes is only ± 1 millimeter, another specific tool equipped with jacks and sliding plates was developed to guarantee precise movement of the OIS during positioning, which was carried out with continuous laser tracker measurement. Finally, with all operations culminating at a height of nearly five meters, specific scaffolding was built in order to access the work areas on both sides of the coil. Once pre-assembly was complete and the OIS fixed on the coil, the assembly was analyzed with a laser tracker that provided F4E with a file summarizing the location of all survey points on the assembly, which will be reused for final assembly of the tokamak in Japan.

After rotating the assembly back to a horizontal position, the OIS was equipped with its single temperature sensor, the coil's electrical terminals were plated with silver, and the hydraulic circuits were adapted to their final connection configuration on the tokamak. The whole assembly was rigorously vacuum packed and placed in a rigid transport structure weighing around 10 tons to withstand the shipment to Japan.

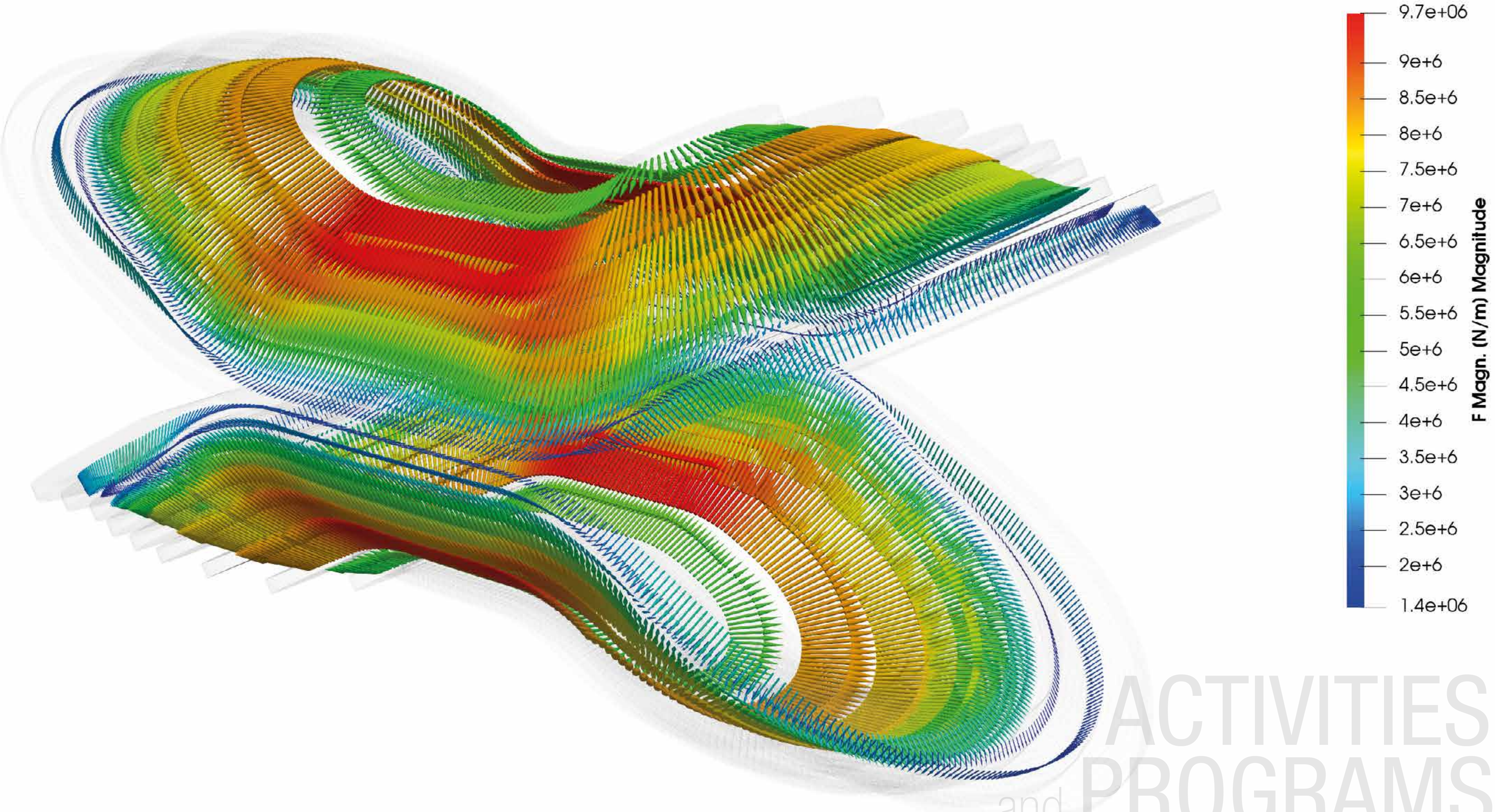
In February 2018, the seventeenth and eighteenth coils were sent to Japan by Antonov Airlines, by dedicated transport, and the last two spare coils were shipped in late 2018. In November 2020, the tokamak reached its 5 K temperature for the first time, thus becoming superconductive and ready for energizing. Its first plasma is expected in February 2021.

OIS on its laser tracker measurement bench.

Coil/OIS assembly on the pre-assembly tool.



Tokamak assembled with the 18 TF coils in Japan.



ACTIVITIES and PROGRAMS

DACM **2016-2020**

magnetism

Development of MQYY: A 90-mm NbTi Double Aperture Quadrupole Magnet for HL-LHC – H. Felice *et al.* [2018].
Mechanical Analysis and Assembly of MQYYM: A 90 mm NbTi Quadrupole Magnet Option for HL-LHC – D. Simon *et al.* [2020].

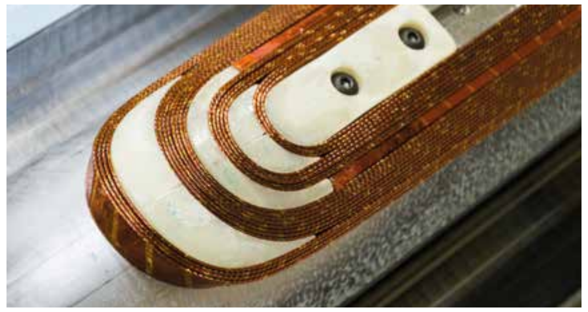
European funding by PCP (H2020) for QUACO.

CERN-CEA collaboration for the MQYYM short model.
CERN-CEA-CIEMAT-NCBJ collaboration for QUACO.

MQYY MAGNET FOR HL-LHC

For the purposes of the HL-LHC project to upgrade the LHC (Large Hadron Collider) in terms of luminosity and to push the LHC's performance even further to increase the potential for discoveries after 2027, new large-aperture superconducting magnets are needed in the interactions section.

The 70-mm aperture MQY quadrupoles are among the LHC magnets that require upgrading. To meet this need, LEAS has been working in collaboration with CERN since 2014 to develop a double aperture NbTi magnet called MQYY. With an aperture of 90 mm, this quadrupole magnet has an operating gradient of 120 T/m at 1.9 K and a magnetic length of 3.67 m. To develop the magnet, the CEA is responsible for designing, manufacturing, and testing a short model with a magnetic length of 1.2 m. At the same time, design and manufacture of two full-scale prototypes was launched with industry partners as part of a Pre-Commercial Procurement (PCP) initiative called QUAdrupole COrrector (QUACO) and funded by the EU. A consortium of European research centers including CERN, CEA, CIEMAT, and NCBJ, is monitoring this project.

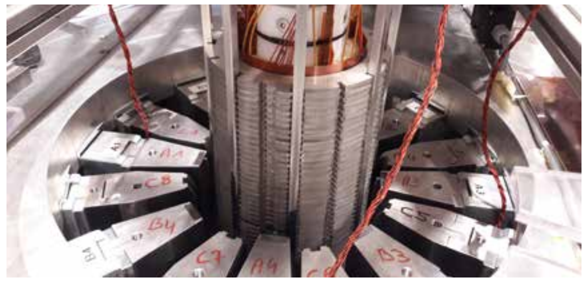


Detail of a coil head during winding.

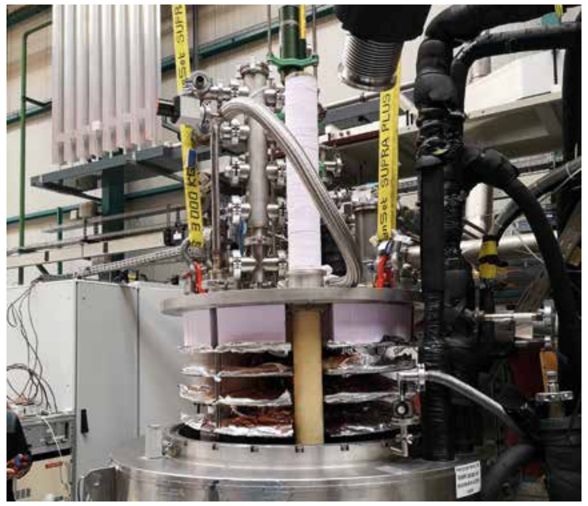
To manufacture the short model, called MQYYM, ten coils were manufactured at CEA beginning in January 2017. These double-layer coils were wound with Rutherford type NbTi cable insulated with three layers of polyamide; the last layer contains an adhesive allowing it to bond the turns together through high-pressure polymerization at 200°C. Once the coils had been made, they were assembled at CERN by LEAS teams. Using a vertical press developed by CERN, the coils were wrapped in a mechanical structure made up of stainless-steel collars. Finally, the magnetic yoke and connection boxes were installed, completing magnet manufacture.

In January 2020, the CEA received the short model for cold testing in the vertical test facility located in building 198. In March 2021, after several months of preparation, during which the magnet was suspended from the cryostat plate, connected to the current leads, and instrumented, the magnet was cooled to 4.2 K. The current was then ramped up in the coils to create the desired magnetic field. Finally, after only two quenches (the transition from the superconductive state to the resistive state), the magnet reached a current of 4550 A and a gradient of 121 T/m without quench. This current corresponds to the nominal current at 1.9 K and 98 % of the critical current at 4.2 K. These excellent results validate the design and manufacturing procedures proposed by LEAS while awaiting the results of the 1.9 K tests planned for mid-2022.

As for the QuaCo, four companies embarked on the venture in November 2016: Tesla in England, Elytt and Antec in Spain, and Sigmaphi in France. After two design and demonstration phases, Sigmaphi and Elytt were selected in November 2018 for the last phase, during which each company will manufacture one prototype. The two MQYY magnets will be delivered to CEA in June 2021 for cold tests.



Collaring with a vertical press at CERN.



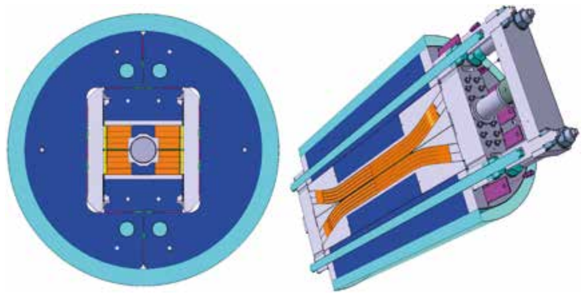
Insertion of the magnet into the vertical test facility in building 198.

Tests of the FRESCA2 100 mm Bore Nb_3Sn Block-Coil Magnet to a Record Field of 14.6 T,
G. Willering, H. Arnestad, M. Bajko, H. Bajas, L. Bortot, L. Bottura, N. Bourcey, M. Duda, P. Ferracin, J. Feuvrier, P. Grosclaude , F. Mangiarotti, D. Martins Araujo, J. C. Perez, C. Petrone, E. Rochepault, G. de Rijk, D. Turi, M. Durante, P. Manil, F. Rondeaux, J.-M. Rifflet,
ASC 2018 – Seattle, October 29 – November 2, 2018.
IEEE Trans. Appl. Supercond., vol. 29, no. August 5, 2019 – n° 4004906.

European program FP7 EuCARD (European Coordination for Accelerator Research and Development), grant agreement n° 227579, then CERN-CEA collaboration contract for superconducting magnets for future accelerators (KE2275/TE).

FRESCA2

FRESCA2 (Facility for the REception of Superconducting CAbles) is a 1.5 m-long dipole designed to generate a central field with a strength of 13 T at 4.2 K in a 100-mm aperture, and homogeneity of about 1 % over 540 mm.



Structure of the dipole FRESCA2 using the key-and-bladder system.

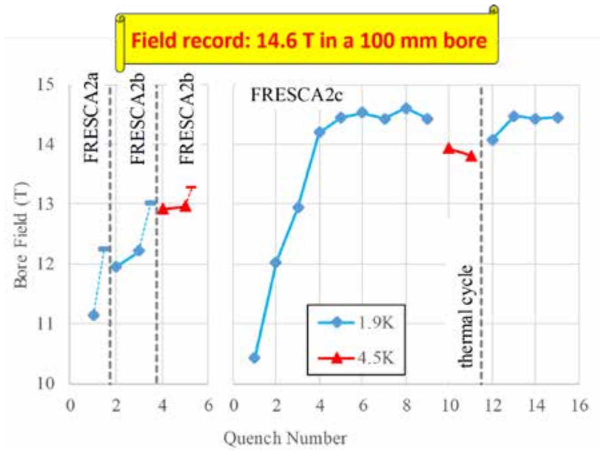
FRESCA2 meets several objectives: the magnet is intended to equip the cable test station at CERN and is part of the R&D program for FCC (Future Circular Colliders). FRESCA2 will provide a background field for testing superconducting cables and magnets using Nb_3Sn and HTc (High critical Temperature) conductors. For example, the HTc dipole developed at IRFU as part of the EuCARD2 program, built with a Roebel conductor made from YBCO tape, will be inserted in FRESCA2 to validate the use of the conductor under high magnetic field (*cf.* chapter on R&D for HTc accelerator magnets).

Design of the magnet and the tooling required to build it, as well as its construction, are the result of close collaboration between teams in two IRFU departments, DACM and DIS, and CERN. A block configuration was chosen for FRESCA2: each pole consists of two "racetrack" coils, each formed by two layers of conductor with the heads tilted to make room for the aperture pipe. The conductor is a Rutherford type Nb_3Sn cable made of 40 strands of 1 mm in diameter. Loading is done using a key-and-bladder system.

After being wound at Saclay, the coils were shipped in their reaction mold to CERN, where they underwent the heat treatment required for the formation of the intermetallic compound with superconducting properties (two weeks at temperatures up to 650°C). Then they were instrumented, impregnated, and assembled into the mechanical structure. In total, seven coils were manufactured and three assemblies were carried out.

The magnet was tested at CERN in the HFM (High Field Magnet) test station. During a first test campaign in February 2017 with the FRESCA2a assembly, the magnet did not exceed 12.2 T because a coil was found to be defective. The coil was replaced and the new FRESCA2b assembly tested in August reached a field strength of 13.3 T. In 2018, a third FRESCA2c assembly was carried out with an increase in mechanical preload for 15 T, and during tests the magnet reached a field strength of 14.6 T at 1.9 K and 12105 A, and 13.9 T at 4.5 K and 11460 A. This maximum field sets a record for accelerator magnets. With stable operation at 14.4 T at 1.9 K, and 13.6 T at 4.5 K, the FRESCA2 magnet was certified for use both in the cable test station and with insert magnets.

Detail of a coil head after winding at Saclay.



Training quenches – (courtesy of G. Willering – CERN).

Final Design of the Superferric Branched Dipoles for the FAIR Super-FRS, A. Madur *et al.*, IEEE Transactions on Applied Superconductivity, vol. 29, no. 5, August 2019.

French contribution to the FAIR project.

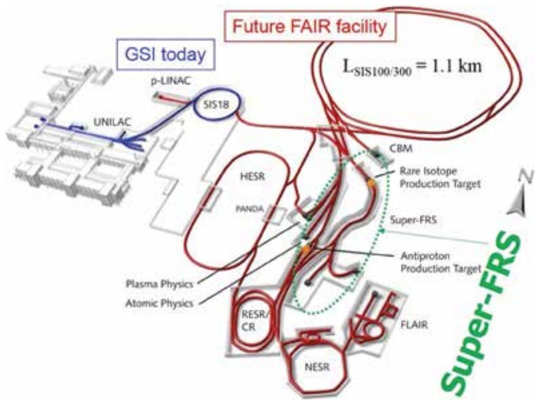
SUPER-FRS DIPOLE FOR FAIR

FAIR (Facility for Antiproton and Ion Research) is an international project aimed at building a new heavy ion particle accelerator in Darmstadt, Germany, to explore and understand the nature of matter and the evolution of the universe.

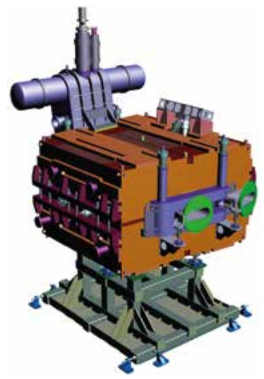
The accelerator will produce intense secondary particle beams of unstable nuclei or antiprotons. The particles will reach energies of up to 1.5 GeV/u with intensities of 10^{12} ions/s. Among the different particle accelerators comprising FAIR is Super-FRS (Superconducting FRagment Separator), an in-flight separator that will generate and spatially separate rare isotopes from all elements to be studied in various experiments installed down its three branches. For this project, and as part of the French contribution to FAIR, DACM is responsible for designing and monitoring the manufacture of 21 standard and three “branched” superferric dipoles, which are necessary to direct the separated particles along each of the separator's three branches. To carry out their function, these dipoles (standard and branched) must have a maximum field of 1.6 T at the center of the aperture, a radius of curvature of 12.5 m for the particle trajectory, a wide aperture in both the horizontal and vertical axes (± 190 mm x ± 70 mm), and a uniform magnetic field integral of ± 3 x 10^{-4} throughout the useful area.

The superferric dipoles include two trapezoidal superconducting coils, and the magnetic field is shaped through a room-temperature iron yoke. The coils are made of NbTi superconducting wire and cooled by a flow of liquid helium at 4.5 K in a 20 x 10 mm² channel, with one channel per coil. The flow is generated using the thermosiphon principle, which is activated through heaters to initiate and control the flow. This active thermosiphon concept has been validated by an R&D experiment carried out in the DACM laboratory. The cold mass at 4.5 K is surrounded by a thermal shield cooled by a helium gas between 50 K and 80 K flowing through copper pipes brazed to the shield. The cold mass and the thermal shield are inside a room-temperature vacuum vessel, around which the iron yoke is installed.

The contract to manufacture the standard dipoles was awarded to Elytt (Spain) in spring 2018, and DACM has been overseeing design and manufacturing activities. The First of Series (FoS) standard dipole was completed in December 2020 and was transported to CERN for cold tests in spring 2021 before being shipped to FAIR. The branched dipoles are also manufactured by Elytt, and the design phase was validated in December 2020. The FoS branched dipole is expected by the end of 2021. As for the standard magnets, DACM is responsible for monitoring the design and manufacturing phases. For each FoS, DACM participates in the cold tests at CERN. Finally, DACM is also involved in the design and manufacture of the dipoles' 24 vacuum chambers, which will be provided by the Budker Institute of Nuclear Physics (BINP, Novosibirsk) as part of the Russian contribution to the FAIR project.



Layout of FAIR facility.



Branched dipole.

First of Series standard dipole on its stand.

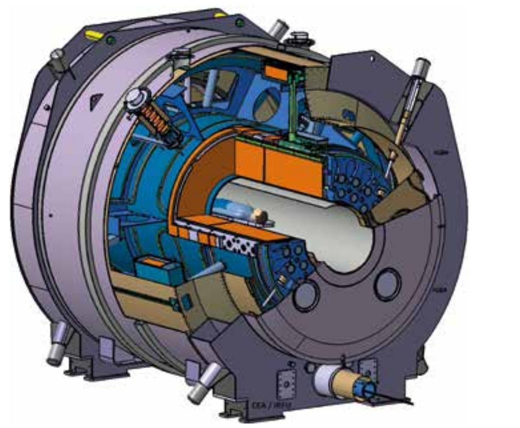
THE 11.72 T ISEULT WHOLE-BODY MRI

The 11.72 T whole-body magnet developed for the ISEULT project was delivered to NeuroSpin in 2017, and reached its nominal magnetic field for the first time in July 2019. This unique tool will push back the boundaries of cerebral imaging. IRFU was responsible of the design, production and commissioning of the magnet, as well as development of all the facilities required for its operation (cryogenic plant, power racks and power supplies, control systems and protection).

THE ISEULT PROJECT

The Magnetic Resonance Imaging (MRI) technique is a diagnostic and research tool for neuroscience. For this purpose, the CEA's NeuroSpin center at Saclay has received a 11.72 T magnet intended for the future ISEULT MRI.

With a central aperture of 900 mm in diameter, allowing the passage of a patient's entire body, this imager, combined with new pharmaceutical contrasting agents, will advance fundamental knowledge of the brain in the cognitive sciences, as well as in the diagnosis of neurodegenerative diseases by improving image resolution by a factor of ten. The ISEULT project is part of a Franco-German collaboration with major manufacturers in the sector: Guerbet, Siemens Medical Solutions, and General Electric (GE).



Cross-section of the 11.72 T magnet. The windings are shown in orange, the cold mass at 1.8 K in blue, and the cryostat in purple.

A UNIQUE MAGNET FOR A UNIQUE MRI

The ISEULT magnet differs from conventional MRI magnets with specifications that reach far beyond the usual performance:

- A magnetic field of 11.72 T, nearly 230,000 times the Earth's magnetic field
- A central aperture of 900 mm that allows images to be taken in a volume of nearly one liter at this magnetic field level; the opening corresponds to those of commercial MRI magnets up to 7 T, compared with very high field MRIs (above 17 T) that offer useful areas of only a few cubic centimeters
- Extremely high temporal stability (the magnetic field must not vary by more than one billionth of one tesla for ten minutes)
- Field homogeneity of 5.10^{-7} T over the study volume represented by the patient's brain
- Containment of the magnetic field within the experiment room (active shielding obtained using two additional coils to create a counter field)
- A highly reliable control and protection system that guarantees the magnet's operation 24 hours a day, 365 days a year.

The magnet is composed of a set of coils made from several thousand kilometers of niobium-titanium superconducting wire energized with a current of 1 483 A. This superconductor is maintained at an extremely low temperature (1.8 K, *i.e.* -271°C) using 5000 liters of superfluid helium protected by a series of insulating external enclosures.

YEARS OF R&D AND MANUFACTURING

Arrival of the magnet at Saclay.

After four years of R&D and prototyping, production was launched on February 1, 2012, by Alstom (since acquired by General Electric). Construction began with the winding of 170 double pancake coils with an external diameter of 2 m. The main coil and the two shielding coils were manufactured at the same time, and the cold mass was finalized in 2015 with the integration of the shielding coils and double pancakes into their supporting structure.

In 2016, the helium vessel was closed and then tilted horizontally. It then took almost one year to complete manufacturing, including mounting the thermal shield, routing all the instrumentation wires, and closing the vacuum chamber. A few days before leaving Belfort, the cryogenic circuits underwent a final helium leak test that validated all the welds carried out in previous months on the circuits and internal enclosures. The 132-ton magnet then began its two-week journey across Europe in a special convoy. After arriving in Strasbourg by road, the magnet was transferred to a boat to reach Corbeil-Essonnes via the Rhine and the English Channel, before going up the Seine. The magnet travelled the final 40 kilometers by road in six hours and was delivered to CEA Saclay and installed in its arch at NeuroSpin in June 2017.

CONNECTING EQUIPMENT AT NEUROSPIN

The cryogenic plant designed to cool the magnet (21 W @ 1.8 K; 0.125 MPa and 610 W @ 55 K) had already been installed in NeuroSpin's basement: the Air Liquide liquefier was delivered in 2010, along with the cryogenic satellite, an essential system that serves as an interface between the liquefier, the power supplies, and the magnet. The entire electrical power system (40 freewheel diodes, the external dump resistor, power contactors, nine stabilized 40 A power supplies for active field correction channels, and a 48 V battery network) was delivered in 2016, before each piece of equipment was individually tested. The magnet quench detection and control system and the acquisition system, developed specifically by the CEA using high-reliability PLCs, were also put into service. The magnet was then connected to these devices using a sort of “umbilical cord” called a heat pipe (*caloduc* in French), a complex mechanical assembly of nearly 200 parts with a mass of 900 kg and assembled to the nearest millimeter to account for the limitations of components during the cooling phase. The heat pipe ensures a tight connection of the windings, instrumentation, current leads, and cooling circuits between the magnet and all other peripheral equipment. Assembly and testing of the heat pipe took almost 13 months of efforts.

COMMISSIONING PHASE

Magnet cooldown began on November 19, 2018. The magnet reached its nominal temperature of 1.8 K on March 7, 2019; it took 250,000 liters of nitrogen and 18,500 liters of helium to cool the cold mass (105 tons cooled to 1.8 K) and the thermal shields (3.4 tons cooled to 55 K).

After a lengthy verification phase, including leak tests, electrical tests, instrumentation tests, and low-current magnetic measurements, the rise in the magnetic field was carried out in stages. At each stage (1.5 T, 3 T, 7 T, 9 T, 10 T), magnetic measurements and fault tests were carried out to assess the reliability of the protection systems. The emergency stop systems also underwent several tests. The nominal field of 11.72 T was reached for the first time on July 18, 2019, after a ramp-up in current which took 30 hours. After several tests were carried out to validate the temporal stability of the magnetic field, a first series of magnetic measurements was undertaken using a system of NMR (Nuclear Magnetic Resonance) probes to assess homogeneity in the useful area at the nominal field. The current was decreased as a specific discharge procedure was tested. A second energization was carried out a few months later to test the correction system (shimming), which allows the homogeneity of the magnetic field to be adjusted using small iron shims (5 904 pieces with a mass of 27 kg). Fault tests and implementation of the high availability developed to ensure the continued operation of the installation then began. Concurrently, Siemens took over to transform the ISEULT magnet into an operational MRI by installing the gradient coils and MRI control systems. The Faraday cages were assembled and the patient bed installed, thus completing preparation of the arch.

Installation of the magnet in its arch.

View of the heat pipe (umbilical cord connecting the magnet with the cryogenic plant).

The project team, after the first ramp-up in current.

Commissioning completion of the Iseult Whole Body 11.7 T MRI System, L. Quettier *et al.*, IEEE Transactions on Applied Superconductivity, Volume: 30, Issue: 4, 2020.
Manufacturing Completion of the Iseult Whole Body 11.7 T MRI System, L. Quettier *et al.*, IEEE Transactions on Applied Superconductivity, 2018.

NEXT STEP

Beginning in 2021, all the equipment required to take an image will be tested together. The initial objective will be to verify that all the systems can operate at the same time at this specific field level, and that they do not disturb magnet function. Then, interaction between the gradient coils and the magnet will be tested at different field levels, before reproducing the same sequences at 11.72 T. The first images should be obtained at the end of the year using fruit and small animals, before making the first acquisitions on a human volunteer in 2022.

Placement of iron shims to adjust the homogeneity of the magnetic field.

Insertion of Siemens gradient coils.

Positioning of the patient bed.

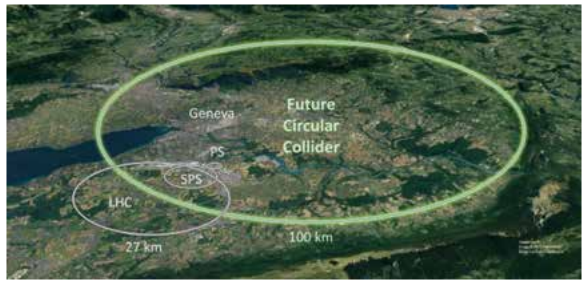
2-D and 3-D Design of the Block-Coil Dipole Option for the Future Circular Collider, M. Segreti *et al.*, in IEEE Transactions on Applied Superconductivity, vol. 29, no. 5, pp. 1-4, August 2019, Art no. 4000404, DOI: 10.1109 / TASC.2019.2892058.
FCC-hh conceptual designs and windability of the Main Quadrupoles, C. Genot *et al.*, IEEE Transactions on Applied Superconductivity, vol. 31, no. March 2, 2021, Art no. 4000107, DOI: 10.1109 / TASC.2020.3045876.

EuroCirCol, H2020 Framework Program, Grant Agreement 654305.
CEA-CERN collaboration: ADDENDUM FCC-GOV-CC-0121/KE3782/TE.

STUDIES FOR FCC SUPERCONDUCTING MAGNETS

In the framework of the EuroCirCol Work Package 5 (WP5), the LEAS team participated in the conceptual study of the high-field magnets needed to guide and focus the beam in the collider, as well as in the development of a cost model for these magnets.

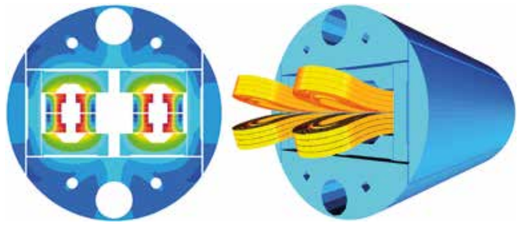
Between June 2015 and May 2019, DACM participated in the design study of the FCC (Future Circular Collider) in the framework of the European program EuroCirCol. The objective of the program was to carry out a feasibility study of a proton collider targeting a collision energy of 100 TeV (an order of magnitude greater than in the current LHC) on a 100 km circumference. A design report was submitted in January 2019, for input to the next update of the European Strategy for Particle Physics.



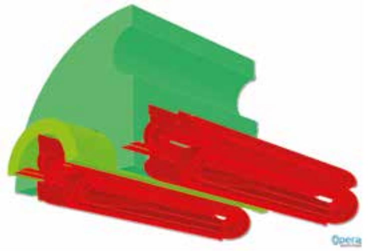
A proposed location for the FCC tunnel (Picture: CERN).

DIPOLES

The beam guiding dipole magnets should produce a magnetic field of the order of 16 T over a 50-mm aperture. Four different configurations were studied as part of EuroCirCol's WP5; LEAS focused on the "blocks" option, carrying out the magnetic and mechanical study – 2D and 3D – of a double-aperture dipole model in Nb_3Sn. Each dipole is made up of four "block" type coils with flared ends. In order to optimize the use of the conductor, and therefore its cost, two different conductors are used in each coil: a high-performance cable in the high-field area and a less efficient cable in the low-field area. The study on high-field dipoles will continue as part of a CERN/CEA collaboration with a study and development program aimed at the creation of a single-aperture demonstrator dipole (F2D2).



2D and 3D design of the double-aperture block-coil dipole.



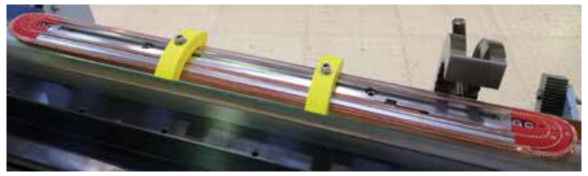
3D electromagnetic model of the FCC-hh quadrupole magnets.

QUADRUPOLES

High-gradient Nb_3Sn lattice quadrupoles were also investigated by closely following the specifications from the optic layout of the machine. After several iterations, a 2D baseline design of the MQ (Main Quadrupole) was selected, then included in the FCC-hh Conceptual Design Report.

COILS

The 3D design of Nb_3Sn coil ends is known to be a critical phase, especially for small apertures (50 mm for FCC-hh lattice magnets). To avoid potential problems, a 3D design was first carried out, taking into account field quality constraints, field margins in critical areas, and mechanical stress. Then, winding trials with Nb_3Sn cables were performed to help with design selection and identify critical geometrical parameters.



Winding trial of one FCC-hh quadrupole magnet coil with a Nb_3Sn cable.

3D Conceptual Design of F2D2, the FCC Block-Coil Short Model Dipole, E. Rochepault *et al.*, IEEE Trans. Appl. Supercond., Vol. 30, no. 4, 2020.
F2D2: A Block-Coil Short Model Dipole Towards FCC, H. Felice, *et al.*, IEEE Trans. Appl. Supercond., Vol. 29, no. 5, 2019.
R2D2, the CEA Graded Nb_3Sn Research Racetrack Dipole Demonstrator Magnet, V. Calvelli *et al.*, submitted to IEEE Trans. Appl. Supercond.

CERN/CEA Collaboration agreement No. KE3782 – FCC-hh magnet studies.

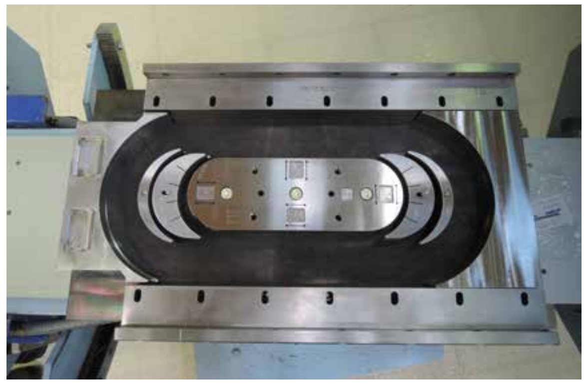
R2D2, THE Nb_3Sn FCC DEMONSTRATOR

Nb_3Sn high-field superconducting magnets (15-16 T) are currently under development within the framework of studies being carried out on future particle accelerators (conceptual study for the FCC [Future Circular Collider], see corresponding chapter).

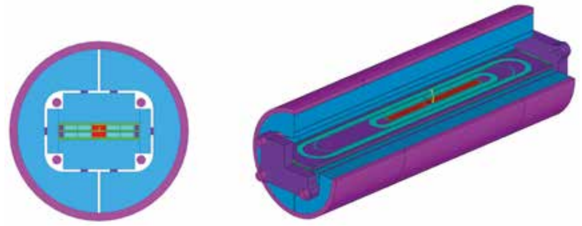
LEAS is specifically responsible for designing and fabricating a dipole demonstrator for the FCC called R2D2 (Research Racetrack Dipole Demonstrator). A joint development plan has been established with CERN within the framework of a CEA/CERN collaboration. The first step consists of fabricating a Nb_3Sn coil, of the SMC (Short Model Coil) type, based on drawings and tooling provided by CERN. This step will demonstrate that LEAS is capable of mastering all steps required to fabricate a Nb_3Sn coil. The coil will be assembled and tested at CERN, and should generate a magnetic field of at least 12 T. Fabrication will start in early 2021.

The second step consists of designing and manufacturing the demonstrator magnet. This magnet will be the first Nb_3Sn magnet composed of two different cables inside the same winding layer ("grading"). This new technology maximizes the current density in the coils, in order to reach high magnetic fields while staying compact. The main goal of the R2D2 magnet is to demonstrate the feasibility of this technology to generate a magnetic field of around 12 T. To achieve this goal, two approaches have been proposed. On one hand, LEAS has developed a method to make the junctions between cables on the coil exteriors. Comparative mock-ups are being developed to validate this method, then implement it in R2D2. An alternative method has been developed in the framework of a collaboration between CEA, CERN, and EPFL-SPC, allowing to make the junctions inside the coils. Moreover, LEAS is developing technologies necessary for the assembly of coils in mechanical structures following the key-and-bladder method used successfully in several model magnets (see chapter on FRESCA2). Conceptual design of the magnet has been finalized, detailed design is ongoing, and fabrication should begin in 2022.

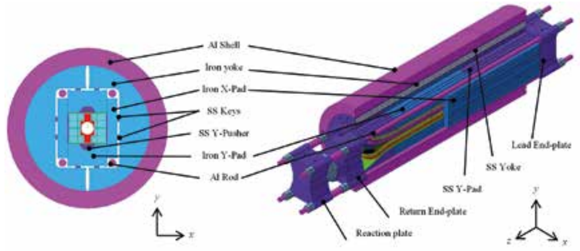
Successive steps will involve fabricating a short model for the FCC, called F2D2 (FCC Flared-ends Dipole Demonstrator). An initial single-aperture conceptual design has been proposed, inspired by the double-aperture design initially proposed by CEA for the FCC dipoles. The use of "grading" technology will generate a magnetic field of 16 T while limiting size. Production will take place in the framework of a new CEA/CERN agreement, after 2023.



Blank assembly of the SMC winding tool.



X-section and isometric views of R2D2.



X-section and isometric views of F2D2.

38 mm diameter cold bore metal-as-insulation HTS insert reached 32.5 T in a background magnetic field generated by resistive magnet, Philippe Fazilleau, T. Lécrevisse *et al.*, Cryogenics 106 (2020), p. 103053.
Construction and Test of a 7 T Metal-as-Insulation HTS Insert Under a 20 T High Background Magnetic Field at 4.2 K, J. Song, X. Chaud, B. Borgnic, F. Debray, P. Fazilleau and T. Lécrevisse, *IEEE Transactions on Applied Superconductivity*, vol. 29, no. 5, pp. 1-5, Aug. 2019.
Metal-as-insulation sub-scale prototype tests under a high background magnetic field, Philippe Fazilleau, T. Lécrevisse *et al.*, Superconductor Science and Technology 31.9 (July 2018), p. 095003.

National Research Agency (ANR-14-CE05-0005).

NOUGAT

NOUGAT (NOUvelle Génération d'Aimants pour la production de Teslas) is a high critical temperature superconducting (HTS) insert magnet, the fruit of a collaboration between CEA and CNRS. On March 26, 2019, it generated a central magnetic field of 32.5 T, setting a new world record in the area of high magnetic fields for a superconducting coil with a useful diameter of 38 mm.

NOUGAT magnet during insertion in the LNCMI test facility.

To achieve high magnetic field magnitudes, resistive magnets are assembled with superconducting magnets (hybrid magnets). Magnets made of resistive coils are extremely costly in terms of energy, limiting experiment time to a few hours. On the other hand, magnets using low critical temperature superconductors (LTS), such as NbTi or Nb_3Sn, remain limited to maximum magnetic fields of around 12 T and 23 T, respectively.

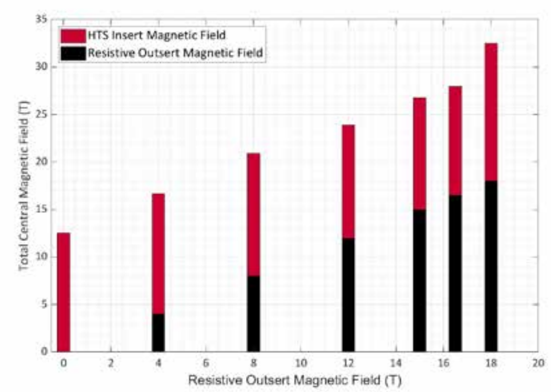
With the addition of HTS winding, the same temperatures can be reached at higher magnetic fields with values of 30 T to 50 T. In this way, it is possible to increase the value of the total magnetic field or even to replace the resistive windings for a lower power requirement (from a few MW, for an installation of resistive coils, to a few tens of kW, for a superconducting magnet). Finally, it allows for significant gains in compactness.

The HTS NOUGAT insert has been designed to produce 10 T in an external magnetic field of 20 T. The external magnetic field was generated by resistive coils at LNCMI and may eventually be generated by a LTS superconducting magnet. The innovation we have validated at such a high field intensity is the use of HTS Metal-as-Insulation (MI) winding, made of double pancakes to avoid the issues encountered with insulated windings in other competing laboratories (NHMFL in US and Tsukuba in Japan). This alternative technique consists of co-winding HTS tape with a metallic tape, without insulation and without impregnation, which provides excellent protection against quench (transition from the superconducting state to the resistive state), thanks to the redistribution of current to the adjacent turns and an additional mechanical reinforcement necessary to withstand large magnetic forces (Lorentz forces).

The HTS Nougat insert test campaign took place at the CNRS/LNCMI test facility in Grenoble. The insert reached twice its nominal operating field of 30 T, of which 12 T were generated by the HTS magnet itself. The insert operated for more than six minutes above this value, at 31 T then 32 T, and eventually set a new world record for an HTS insert of this size with a central magnetic field of 32.5 T, 14.5 T of which were produced by the HTS magnet.

This result demonstrates that HTS MI technology is now stable, and that a magnet generating magnetic fields greater than 30 T with an HTS insert is possible.

The project was funded by the National Research Agency (ANR-14-CE05-0005) and is a collaboration between three French laboratories: the DACM, the LNCMI, and the Néel Institute.



Magnetic field magnitudes during testing of the NOUGAT magnet: in black, the magnetic field generated by the resistive coils; in red, the magnetic field generated by the HTS NOUGAT magnet.

Irfu: 40 %, Europe: 28 %, GSI: 20 % and R3B collaboration: 12 %.

GSI Darmstadt.

GLAD SUPERCONDUCTING SPECTROMETER FOR R³B

The European R³B (Reactions with Relativistic Radioactive Beams of exotic nuclei) collaboration brings together 230 physicists from 63 institutes in 21 countries. The group established a study at the GSI Helmholtz Center for Heavy Ion Research in Darmstadt, Germany, to investigate the emerging physics of exotic nuclei with relativistic energies. The GSI Large Acceptance Dipole (GLAD), a superconducting spectrometer, is an essential component of the R³B detector assembly. IRFU was responsible for the design and construction of the magnet, and its control bays and testing at Saclay, as well as commissioning at GSI of the entire system.

INSTALLATION OF THE SPECTROMETER AT THE GSI SITE

After its delivery in late 2015, GLAD was carefully transferred to air cushions in the Cave-C experimental area at the GSI site. In 2016, it was gradually connected to its various control bays, its dedicated helium refrigerator, and to its power supply. Then numerous compliance tests were performed, which revealed a malfunction on the cold electric busbar supplying current to the magnet. Several test campaigns were carried out to identify the nature of the dysfunction. Ultimately, analyses showed that the busbar was receiving a significant and unidentified heat load of 7 W, unfortunately located in an inaccessible area inside the magnet vacuum chamber. However, the same studies demonstrated that an increase in the mass flow of liquid helium cooling the busbar, approximately double the nominal mass flow, restores functionality, enabling the busbar to reach the magnet's nominal current (i.e., 3584 A.).

MAGNET OPERATION

In late 2018, the magnet reached its nominal current, and even surpassed it: 3590 A. Only one quench (transition from the superconducting state to the resistive state) occurred at 3546 A before the magnet reached its nominal operating current. However, the thermal overload on the busbar led to excessive consumption in liquid helium and the nominal current could only be maintained for a few hours.

For this reason, physics experiments in 2019 were carried out with a current limited to 2400 A. The level of the magnetic field produced, although degraded, was more than sufficient for the first physics experiments.

In early 2020, the liquefier was improved with the addition of liquid nitrogen to its first heat exchangers, which significantly increased its performance. It can now fully compensate for the magnet's overconsumption of helium, which allowed the magnet to reach its nominal current without any quench in March 2020—something which had not yet been achieved following a complete thermal cycling of the magnet— and to operate for 16 hours without any complications.

The GLAD spectrometer is now fully operational for the next experimental campaigns that will start in March 2021.

GLAD magnet installed in the experimental area of Cave-C at GSI.

From Manufacture to Assembly of the 43 T Grenoble Hybrid Magnet - Pierre Pugnat *et al.*
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 30, NO. 4, JUNE 2020
Cryogenic design of the 43 T LNCMI Grenoble hybrid magnet - B. Hervieu *et al.* 25th International Cryogenic Engineering Conference and the International Cryogenic Materials. Conference in 2014, ICEC 25–ICMC 2014.

FR2991809_A1.

Investissements pour l'avenir LaSUP (Large Superconducting User Platform), CNRS, and EU-FP7-Infrastructure-2008-1, EuroMagNET II, Grant agreement number 228043. CEA/CNRS N° C14374.

THE SUPERCONDUCTING MAGNET OF THE LNCMI'S HYBRID STATION

We are reaching the final achievements to be made with this non-standard magnet, which we developed in the framework of a collaboration between CEA/IRFU and CNRS/LNCMI. In 2020, LNCMI (Laboratoire National des Champs Magnétiques Intenses) began integrating the magnet's cryostat. Together we monitored fabrication, as well as receipt of materials.

After a long period of achievements, the LNCMI is about to receive the final elements necessary to assemble the superconducting magnet. The magnet's cryostat and cryogenic satellite were manufactured by the SDMS company. The satellite was delivered in early 2019 and the final cryostat component, the helium vessel, which required a dimensional adjustment, was expected by the end of 2020. The heat pipe that will provide the cryogenic link and the electrical distribution between the magnet and the satellite is nearing completion at Cryodiffusion. At the same time, the LNCMI proceeded, internally, to insert the Rutherford cable into the copper busbar (thermomechanical reinforcement); then Babcock Noell wound and assembled the 37 superconducting double-pancakes in Germany. The coil was delivered to LNCMI in early 2020.


The LNCMI superconducting coil placed on its transport tool.

Tests of the liquefier, satellite, power supply, and the Magnet Safety System have confirmed that these components are functional and meet the required specifications. Field tests at 8.5 T, then at 42 T in hybrid mode, are planned for 2021 and 2022.

WAVE – An innovative magnet devoted to spintronics, T. Robillard *et al.*, Journal of Neutron Research, vol. 22, no. 4, pp. 379-391, 2020.
Realization and commissioning of WAVE Neutrons a Wide Aperture Vector Magnet for Neutron scattering experiments delivered Turn Key, Pasquet *et al.*, Communication at Magnet Technology 25, September 2017.
Development of an Innovative Wide Aperture Vector Magnet: WAVE, IEEE Transactions on Applied Superconductivity, Vol. 26, No. 4, June 2016, C. Berriaud *et al.*

G.Auber. (2012). Cylindrical permanent magnet device with induced magnetic field of predetermined orientation method of manufacture. 1262070

Project supported by the Région Ile-de-France through the NanoK-2014-ML-005.
Project-ANR-16-CE09-0009, Agence Nationale de la Recherche (2016).

WAVE

WAVE (Wide Aperture VEctormagnet) is a magnet dedicated to neutron scattering experiments being carried out at the Laboratoire Léon Brillouin (LLB). LEAS and LCSE provided the preliminary design, which led to a patent in 2012.

The objective of WAVE is to produce a homogeneous dipole magnetic field which can be oriented in all directions, allowing samples crossed by a neutron beam to be analyzed. The first innovative aspect of this design relies on a set of 16 solenoids made of NbTi superconductor (12 for the horizontal component of the magnetic field and two pairs in Helmholtz configuration for the vertical component), thereby maximizing the usable aperture required for the experiments. The second innovative aspect of this design is the selected cooling concept. Thanks to two "thermautonome" cryocoolers studied at DACM, a thermosiphon loop of liquid helium was introduced to cool the coils indirectly at -269°C. This loop was used in tandem with an external tank to collect the helium vaporized during quenches (transition from superconductive to resistive state) of solenoids and to cool them again through the cryocoolers, autonomously, without human intervention.


WAVE magnet.

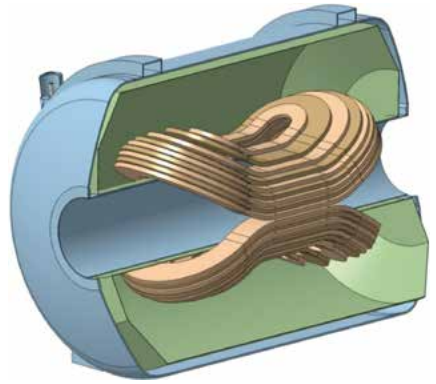
The design was finalized in 2015 by the Sigmaphi Company, which was also in charge of manufacturing. WAVE was delivered to LLB by the end of 2017, after which it successfully passed the cold tests, and the first experiments were able to launch a few months later.

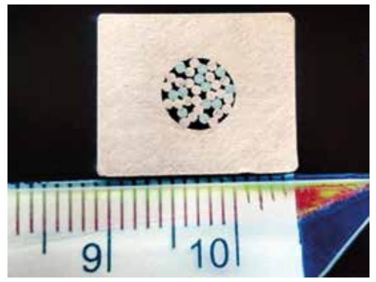
2D and 3D Conceptual Magnetic Design of the MADMAX Dipole, V. Calveli *et al.*,
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, Volume: 30, Issue: 4, Published: JUN 2020.
Conductor Design of the Madmax 9 T Large Dipole Magnet, C. Berriaud *et al.*,
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, Volume: 30, Issue: 4, Published: JUN 2020.

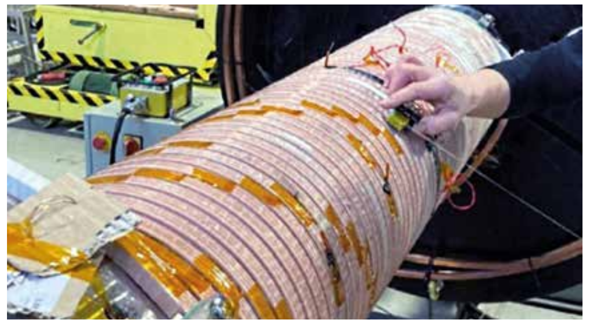
Project funded by the Max Planck Institute as part of an innovation partnership with the CEA.

MADMAX SUPERCONDUCTING MAGNET

In April 2017, the Max Planck Institute (MPI) launched a call for proposals in the context of an innovation partnership to design, certify, and manufacture a superconducting dipole producing a figure of merit of 100 T²m². Equipped with a detector, this magnet could prove the existence of the so called "axion" particle and thus explain dark matter physics. In late 2017, the CEA and the German Noell Bilfinger Company were both selected by MPI to undertake this large-scale project.


Conceptual design of the MADMAX magnet.


"Cable-in-conduit" type conductor sample.


MADMAX prototype coil for quench studies.

In order to achieve the 100 T^2m^2 specification, a magnetic design producing 9 T in a 1.35 m bore has been chosen. This choice makes it possible to use NbTi at 1.8 K for the MADMAX (MAgnetized Disks and Mirror Axion eXperiment) magnet and reduces costs, risks, and delays as compared to a Nb_3Sn solution with a higher field and smaller diameter. Given the exceptionally large dimensions of the magnet and its conductor, a "block" concept has been chosen instead of a "cosine theta" concept. This solution significantly reduces the technological constraints for winding the coils and allows for a more modular assembly. The designed conductor has a 27 mm^2 section composed of NbTi transporting 23 kA at 1.8 K and 10.3 T of peak field. Its section also contains 365 mm^2 of copper needed for protection and mechanics, and 28 mm^2 of void section left for superfluid helium to ensure magnet stability. One of the most critical points of magnet design was how to support the mechanical loads induced by Lorentz forces. In order to maintain an acceptable level of stress in the magnet, each coil is integrated into a stainless-steel casing that support both dipole explosion forces and azimuthal forces accumulation to the mid-plane by arc effect. Finally, the MADMAX magnet is composed of 18 blocks cooled at 1.8 K, capable of producing 100 T^2m^2. The entire magnet is 4 meters in diameter, 6 meters long, and weighs about 200 tons.

Once the magnet design was validated in mid-2019, by both MPI and a committee of external experts, the project entered into a phase of detailed design and R&D, which has concentrated on two possible conductor designs. The first is a Rutherford cable soldered in a copper profile; the second is a "cable-in-conduit " type inserted into the hole of a copper profile. Several samples of both designs have been successfully manufactured and tested. Presently, both concepts are technically viable, but only the second can be industrially manufactured. In conjunction with conductor R&D, a prototype magnet has also been manufactured. This magnet is a solenoid of 2 T designed to have a quench propagation velocity close to that of the MADMAX magnet. In order to test it, the JT-60SA cold test facility has been equipped with a double bath that produced 1.8 K pressurized superfluid helium for the first time in late 2020. Beginning in 2021, quench campaigns will be carried out on this prototype magnet in order to validate the MADMAX magnet's protection computations and safety.

R&D and technological developments

Development of a compact high intensity ion source for light ions at CEA-Saclay, O. Delferrière, R. Gobin, Y. Gauthier, F. Harrault, O. Tuske, 22nd International Workshop on ECR ion Sources (ECRIS), Busan, Korea, 2016, weco02.

Patent FR 2969371 Internal R&D, LEDA finance

DEVELOPMENT OF COMPACT ECR SOURCES: ALISES I, II, & III

Following on from the ALISES I and II sources, the program to produce more compact high-current light ion sources continues with the development and first tests of the ALISES III source.

R&D ALISES CONCEPT

Since 2009, LEDA has undertaken significant research and R&D on ECR (Electron Cyclotron Resonance) high-current light ion sources in its work on ALISES (Advanced Light Ion Source Extraction System) sources. The objective is to obtain a compact source with simple parts to facilitate maintenance and reduce cost. This work draws on expertise acquired since the 1990s in the design and production of SILHI (High Intensity Light Ion Source) ECR sources for accelerators such as IPHI, SPIRAL2, IFMIF, and FAIR.

In a conventional SILHI source, the insulating structure containing the extraction system occupies significant space downstream from the plasma electrode. In ALISES I, a great deal of space was saved on the LEBT (Low Energy Beam Transport) at the source exit by moving the insulating structure upstream. A solenoid can even be implemented at the source exit in order to ensure magnetic resonance with its leakage field (Patent FR 15 56871). In ALISES II, the insulating structure is directly in contact with the copper source body and the extraction electrodes are reduced to simple discs (Patent FR 2969371).

In 2015, the ALISES II source allowed for the regular extraction of a 35 mA hydrogen ion beam with an extraction voltage of 42 kV. A more compact solenoid coil that consumes less current was installed directly around the insulating structure, thereby improving source performance and reducing by half the diameter of the plasma chamber, from 90 mm to 45 mm.

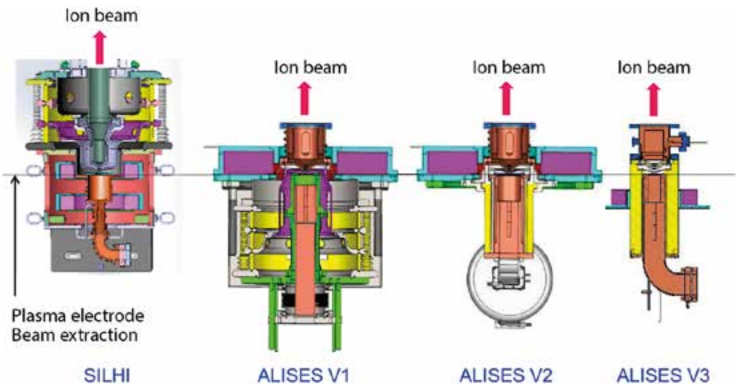
ALISES III

These improvements have all been incorporated into the ALISES III source. Another innovation involved moving the intermediate electrode's HV connector to the rear of the source, in order to avoid the breakdowns often observed on ALISES II. Additionally, the HF elbow is bulk machined, with a monobloc copper assembly comprising the Plasma chamber/Corrugated guide/HF elbow, resulting in an ultra-compact source.

The various advantages of the ALISES III source compared to a SILHI type source are:

- Geometry is considerably simplified and maintenance is easy.
- The distance between the plasma electrode and the first focusing element can be greatly reduced.
- The source is lighter and does not need to be supported, meaning it does not require an HV platform, and is directly connected to the LEBT.
- The ECR magnetic field is generated using a coil powered from ground, thus reducing the electrical power to be supplied to the HV.

The results obtained after the first tests are very encouraging: 45 mA could be produced at 45 kV in pulsed mode with a duty cycle of 25%, a pulse duration of 62.5ms, at a frequency of 4 Hz. The source can also operate in the continuous mode with a current of 36 mA extracted at 50 kV. We will then seek to increase in energy gradually in order to determine its current and voltage limits.



Comparison between geometries of successive generations of ion sources.

Study of space charge compensation in low energy beam lines of high intensity light ion accelerators, F. Gérardin, PhD thesis, Paris-Saclay University, 2018.

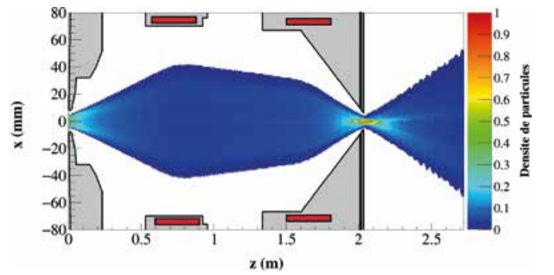
LPSC-Grenoble (France), GSI (Germany), INFN-Legnaro (Italy), LJC-Lab (France), CIEMAT-Madrid, QST (Japan), GANIL (France).

DYNAMICS OF HIGH-INTENSITY PARTICLE BEAMS

Beam dynamics can be defined as the study of the movement of charged particles in electromagnetic fields. The challenges of producing a correct simulation of the dynamics of intense beams require the development of models and specific computer codes. Ultimately, confrontations with experimental data are used to validate and improve the models.

BEAM DYNAMICS IN LOW-ENERGY BEAM TRANSPORT (LEBT) LINES

The dynamics of a high-intensity ion beam in a LEBT is dominated by the space charge field induced by the beam itself. However, this beam also induces ionization of the residual gas present in the vacuum chamber, compensating for the effects of this space charge.
In order to better understand these complex phenomena, self-consistent numerical simulations were carried out with the WARP simulation code. For example, it has been shown that it is necessary to introduce into numerical models several physical reactions that take place in the LEBT, as well as the diagnostic devices that measure the characteristics of the beam by intercepting it. A simulation of this kind was carried out for the LEBT of the IFMIF-LIPAc accelerator with a D^+ beam of 140 mA at 100 keV. The simulations are consistent with measurements of beam emittance at the end of the line.



Transport of a 140 mA D^+ beam at 100 keV in LEBT connected to a diagnostic plate during commissioning of the IFMIF/LIPAC accelerator beam.

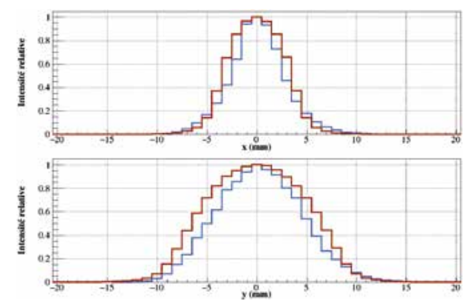
DEVELOPMENT AND DISTRIBUTION OF COMPUTER CODES FOR BEAM TRANSPORT

In the 1990s, a need for very high-power linear accelerators arose in the scientific community. To provide simulation tools capable of precisely calculating the transport of a beam in an accelerator, DACM developed a suite of codes that have been distributed since the 2000s and are now recognized as a standard in the field of high-intensity accelerators. They made it possible to design, for example, the accelerators for the SPIRAL2, linac4, IFMIF, ESS, SARAF, MYRRHA, and IPHI projects. This expert software suite has been distributed since 2009 under CEA license to more than 75 laboratories in 23 countries including CERN, ESS, Fermilab, GSI, RIKEN, RAL, and IJC Lab. A website and a forum for discussions and downloading code have been created: http://irfu.cea.fr/dacm/logiciels/

Map of the geographical distribution of beam dynamics codes developed at DACM.

EXPERIMENTAL ACTIVITIES RELATED TO THE HIGH-INTENSITY BEAM

The beam commissioning phases of high-intensity accelerators are decisive periods for acquiring the experimental data needed to validate numerical simulations and to further our understanding of the physical phenomena at work. For this reason, DACM accelerator physicists are heavily involved in the commissioning of several linear accelerators. For example, a numerical model of cavity tuning was developed and successfully used during the commissioning of the linac for the SPIRAL2 project. During the commissioning of IPHI, measurements of transmission and beam profiles at the output of the RFQ were carried out with a 50 mA beam, demonstrating consistency between simulations and measurements.



Transverse profiles of a 50 mA proton beam at 3 MeV at the exit of IPHI RFQ. The measurements are represented in blue and the simulations in red, in the horizontal (top) and vertical (bottom) planes.

TOWARDS A LASER-PLASMA ACCELERATOR WITH EuPRAXIA

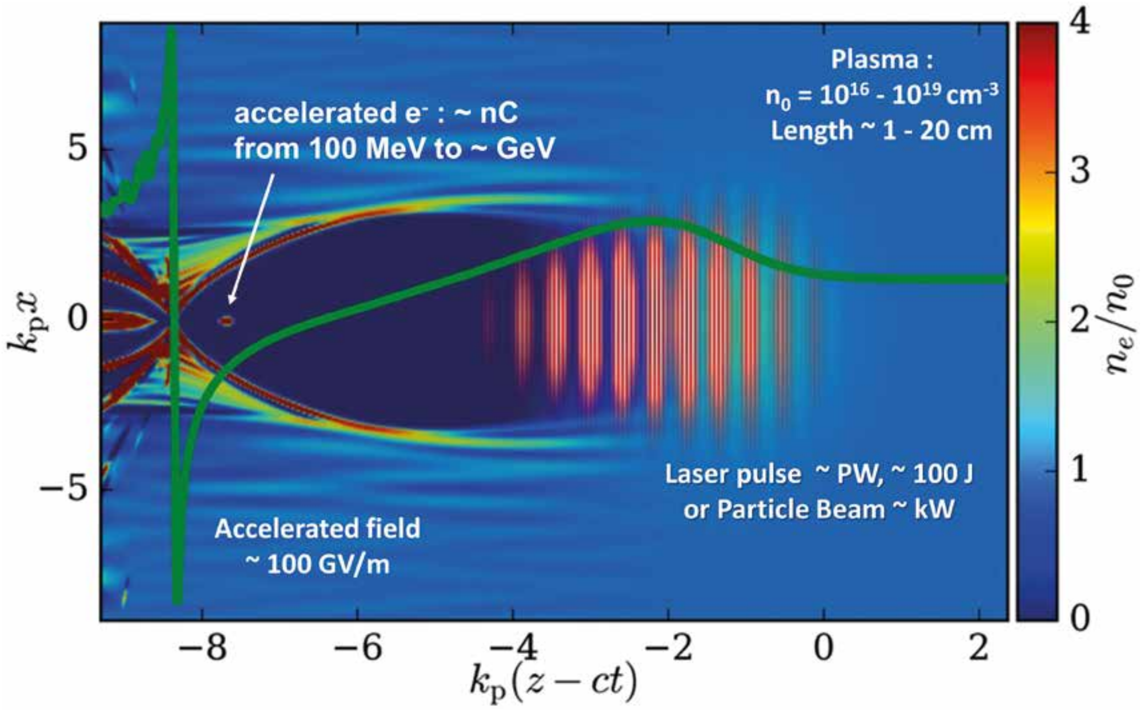
In the last fifteen years, a series of physics experiments around the world have demonstrated the performance of the acceleration of electrons by wake field in a plasma. The EuPRAXIA (European Plasma Research Accelerator with eXcellence In Applications) project has taken another step forward by launching the design phase of a real accelerator based on this new technique. With well-recognized skills in conventional accelerators, DACM has acquired new skills in terms of laser-plasma acceleration, and is now able to make significant contributions to the field, which is located at the crossroads of the two worlds.

THE PRINCIPLE

When passing through a plasma column, a high-power laser or a particle beam leaves in its wake a millimeter-size cavity, with excess electrons behind and on the sides of the cavity. This is known as the mechanism of ponderomotive force. An electron bunch injected into this part of the cavity can be strongly accelerated and focused by the resulting Coulomb forces. Typically, a 1 petawatt laser in a plasma with a density of 10^{16}-10^{19} cm^{-3} can generate an accelerating field of up to 100 GV / m, which is 1000 times greater than the fields produced by conventional radiofrequency techniques. The accelerator size could potentially be reduced by several orders of magnitude.

THE EUPRAXIA CONSORTIUM

The EuPRAXIA consortium includes 16 members, European institutes or universities, and 25 associated partners from across Europe, America and Asia, as well as five private power laser manufacturing companies. EuPRAXIA's objective is to study and build an accelerator based on plasma acceleration techniques capable of supplying on-site communities of users with an electron beam at an energy of 1 to 5 GeV, a charge of 30 pC, emittance and energy dispersion of less than 1mm. mrad and 1%, at a rate of 10-100 Hz, with "industrial" quality reproducibility and reliability. With these characteristics brought together simultaneously, this project aims to achieve a major scientific and technological breakthrough, bringing the acceleration by wake field as a physics experiment, to the accelerator as an installation delivering beam to users.



Beam acceleration by wakefield in a plasma. Image computed in the referential linked to the laser pulse, in reduced coordinates (kp~6.10^4 m^{-1} is the plasma ave number).

Toward a plasma-based accelerator at high beam energy with high beam charge and high beam quality, P.A.P. Nghiem *et al.*, Phys. Rev. Accel. Beams 23, 031301 (2020).

European Union's Horizon 2020 research and innovation program under Grant Agreement No. 653782.

16 European institutes of the EuPRAXIA consortium.

DACM IN PLASMA ACCELERATION PROJECTS

From the first acceleration experiments on the French laser installations UHI-100 and APOLLON, DACM was called upon to carry out the design and magnetic studies of the 50 MeV accelerator plasma beam extraction line, and the transfer line between two plasma acceleration stages, which is an S-shape achromatic line at 300 MeV.
DACM's involvement took on a new level of significance within the EuPRAXIA collaboration, as the department accepted responsibility and co-responsibility for and participated in the work packages "WP2-Physics and simulations," "WP5-Beam transport lines," and "WP15-Diagnostics."

Obtaining a beam that is at once high energy, high charge, and high quality has never yet been demonstrated, neither experimentally nor theoretically. In the face of such major challenges, IRFU's contribution has been decisive. In collaboration with European partners, we applied the approach previously proven in conventional accelerators, which consists of carrying out massive simulations and optimizations in order to obtain the desired beam parameters, and then deduce the necessary laser, plasma, and magnetic components. Following the same approach, error tolerance analyses were performed to identify the most sensitive components that require particular care during implementation. In this way, many acceleration configurations were studied and compared in an effort to select the best options according to the defined objectives.

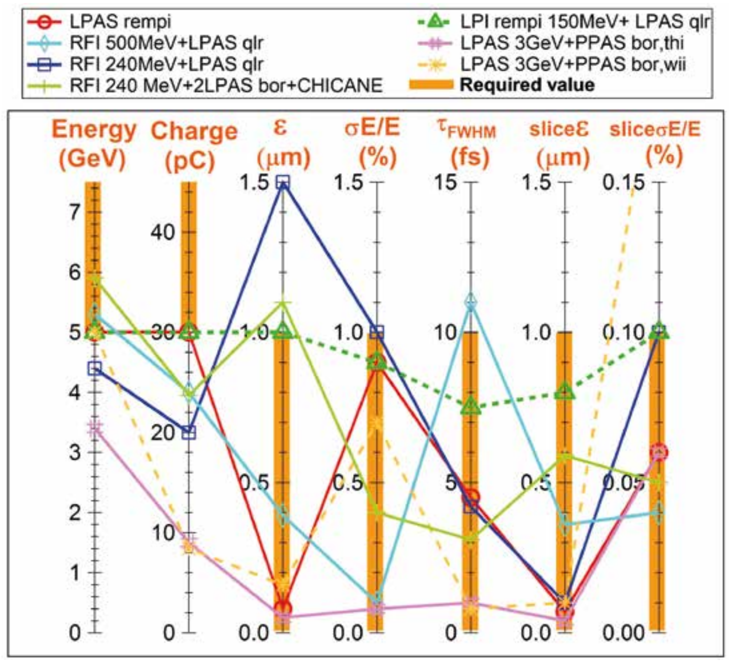
DACM also participated in the process of designing the set of electron diagnostics adapted to wake field accelerated beams, which are much smaller than the conventional variety. A study was carried out for a small aperture, small footprint reentrant cavity BPM (beam position monitor) capable of measuring beam position and charge with a precision of 0.5 μm and a few pC.

The completion of this design study phase marks a decisive step towards developing a real accelerator based on plasma acceleration techniques. In a later step, a yield-performance-risk analysis will be undertaken in order to choose the most robust laser-plasma-linac structure. A more detailed technical study phase will then follow to really begin the manufacturing and installation phase.

CONTRIBUTION TO BEAM PHYSICS

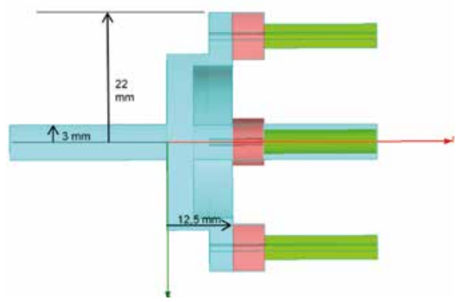
DACM's efforts were particularly focused on the physics of acceleration and transport of the electron beam.
The physical mechanisms acting on the profiles of the accelerating and focusing wake fields were studied in detail, making it possible to guide the fine optimizations carried out by numerical simulations, each lasting more than 10 hours on 2048 computer nodes. In this way, it was demonstrated that with a 30 cm long plasma and a 400 terawatt power laser, a beam can be accelerated from 150 MeV to 5 GeV with, at the exit, an emittance of 1 mm.mrad and an energy dispersion of 1 %.

Drawing on expertise in both laser-plasma acceleration and conventional beam transport lines, DACM studied innovative methods to extract the beam, without degrading it, from a plasma stage, transport it and inject it in a second stage, then transport it to the end user. In this way, we were able, for the first time, to design an entire laser-plasma accelerator, capable of delivering the beam with the desired characteristics to the end user.



Characteristics of the electron beam after acceleration to 5GeV, compared to the objectives (orange bars) for the different acceleration configurations studied for EuPRAXIA.

Holistic consideration of the beam in all six dimensions is particularly crucial in the context of wake field acceleration. The coupling of the different dimensions is indeed noticeable, on the one hand in plasma stages, where acceleration and focusing are intimately mixed, and on the other hand in transport lines, where emittance and energy dispersion are equally significant. Designing a laser-plasma accelerator demands understanding and mastery of this 6D phase space along the entire length of the accelerator.



Design of a beam position monitor for EuPRAXIA.

FUTURE HIGH ENERGY COLLIDERS

We participate in the conceptual design of future circular colliders, able to provide enough statistics to extend physics research beyond the LHC (Large Hadron Collider) at CERN. We study and optimize arc layouts with dipole, quadrupole, and sextupole magnetic components, as well as multipole correctors, in order to provide the required specifications.

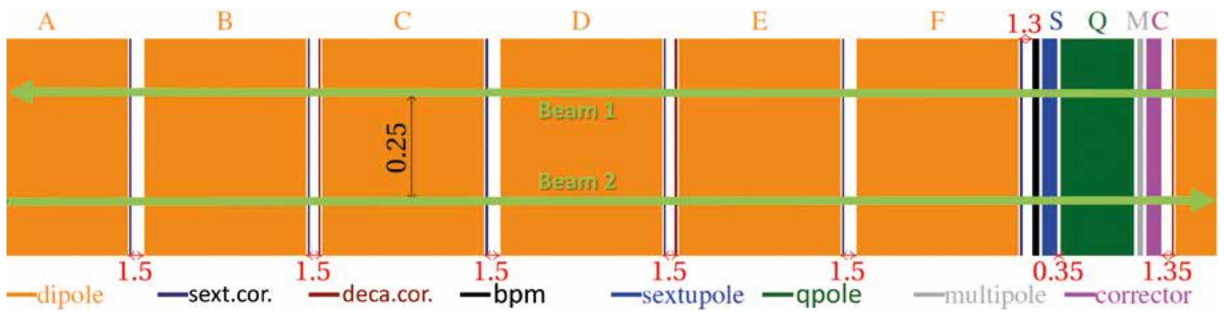
Since the discovery of the Higgs boson at the LHC, the particle physics community has been exploring and proposing the next generation of accelerators to address outstanding questions about the underlying mechanisms and constituent parts of the present universe. One of the possibilities being studied is FCC (Future Circular Collider), a 100-km-long collider at CERN. The hadron version of FCC (FCC-hh) seems to offer the only avenue to reaching energy levels far beyond the range of the LHC in the coming decades, providing direct access to new particles with masses of up to tens of TeV. This requires collision energies of 100 TeV, which can be obtained in hadron colliders with a circumference of 100 km using 16-tesla dipole magnets. The feasibility of such high field magnets with Nb_3Sn cables or HTS (High Temperature Superconductor) inserts is one of the major avenues for R&D research concerning next-generation accelerators.

Studies for the FCC-hh are underway using the highest field magnets currently being designed. They were finalized using 3D field configurations available for the HL-LHC (High-Luminosity upgrade of the LHC) project, and their results can be verified under real conditions with the present LHC magnetic structure.

FCC-hh

DACM/LEDA is responsible for designing the arcs where the dipoles are installed and their integration into the remaining sections of the accelerator. One of the cost killers of the FCC-hh ring is the maximum dipole field. That is why early in the design phase, the arc cells are being optimized in order to minimize the dipole field, which can be done by maximizing the filling ratio of the dipoles, which in turn minimizes interconnection distances and the lengths of all other magnetic components. In this preliminary phase, optimization is a back-and-forth process of testing different magnet designs and their introduction into the arc layouts for verification. The objective is to reach targeted optical performances while satisfying constraints imposed by tunnel excavation, vacuum quality, impedance, and collimation conditions. Other magnetic elements including quadrupoles, skew quadrupoles, sextupoles, and octupoles are also being optimized, together with their volume. Finally, correction schemes (linear and nonlinear) are being studied in order to define magnet tolerances. All studies are being carried out with particle tracking simulations, which are very demanding in terms of computing power, especially tolerance studies, which require heavy statistics. We are exploring the possibility of predicting the stability region for particle motion using machine-learning techniques in order to reduce computing time.

Several magnet designs remain to be tested in this phase, which only uses hard-edge magnetic field profiles. It is expected, however, that superconducting magnets with high field and large aperture will feature a noticeable 3D fringe field structure, which will have a significant impact on particle optics. This must be taken into account, and we are able to do so within the framework of the HL-LHC project.



Layout of the FCC-hh Half Arc cell showing the complete magnetic structure including the main components as well as the correctors. Distances in meters.

FCC-hh: The Hadron Collider. Eur. Phys. J. Spec. Top. 228, 755-1107 (2019), T. Pugnat PhD thesis and A. Abada *et al.* https://doi.org/10.1140/epjst/e2019-900087-0.

The European Circular Energy-Frontier Collider Study (EuroCirCol) project has received funding from the European Union's Horizon 2020 research and innovation program under grant No 654305.

CERN, CNRS, TU-Darmstadt, MOX-Politecnico di Milano.

HL-LHC

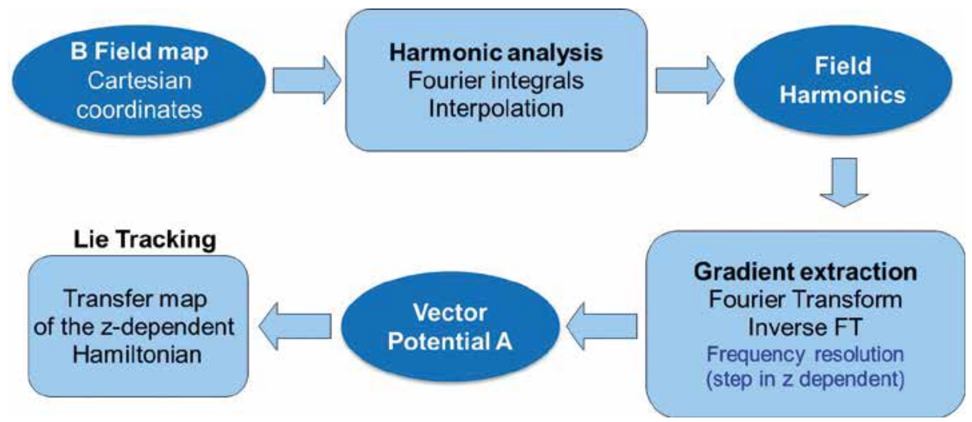
The HL-LHC project will be the first project to use magnets based on Nb_3Sn technology. The objective of the HL-LHC project is to define and study a hardware configuration and a set of beam parameters that will upgrade the LHC to reach 10 times more integrated luminosity than it has in its first 10 years of operation, without saturating the detectors. To this end, DACM/LEDA is performing beam dynamics studies to evaluate the impact of multipole errors and, in particular, of magnet fringe fields on dynamic apertures and other beam characteristics. The inclusion of these effects requires a detailed and realistic model of the central area and extremities (fringe) of the magnetic fields. An accurate description of these fields can be obtained by various finite element field codes, in the form of three-dimensional field data modeled on a grid. Based on these field maps and using Fourier analysis, it is possible to compute the vector potential required to compute the transfer maps using Lie Algebra techniques. We have integrated the new non-linear transfer map into the CERN's SixTrack code, which is used to perform tracking simulations of the LHC and of the future circular colliders. For the first time, it was possible to calculate the impact of the expected 3D field of the HL-LHC's final focus quadrupole on beam observables, such as the detuning amplitude and the dynamic aperture.

It is important to be able to verify these theoretical results under real conditions. This can be done in an accelerator like the LHC, where dedicated machine studies can be planned to test optics and magnet settings using beam-based measurements.

LHC

DACM/LEDA has focused its LHC studies on the impact of the superconducting magnet field quality on the beam. Basically, turn-by-turn Beam Position Monitor (BPM) data are used to reconstruct optics parameters and consequently the linear and non-linear field in circular machines. For the last five years, we have participated in machine development studies aimed at quantifying non-linear magnetic fields in the LHC machine. Analysis of BPM data made it possible to highlight discrepancies between computed and actual measured corrector strengths. We are investigating the possibility of explaining such differences using 3D field description of the magnetic quadrupoles. In parallel, we are exploring the possibility of defining a new beam-based observable which could help to quantify and localize non-linear field imperfections in LHC. To this end, the dependence of the measured beta-beating on the particle amplitude in the presence of non-linear field components has been analytically derived for the first time.

We are studying a possible machine configuration that enhances this beta-beating for a future LHC run proposal.



Procedure used to derive the new non-linear transfer map, using computed or measured 3D magnetic field of a quadrupole.

D2.6: Beam simulation code development, global coherence "Start to End Model of the 100 MeV MYRRHA linac"
D2.4: Beam diagnostic development "Some Crucial beam instrumentation to operate the MYRRHA injector in a reliable way and generating no false interlock during beam operation".

European Atomic Energy Community (EURATOM) H2020 Programme under grant agreement n°662186.

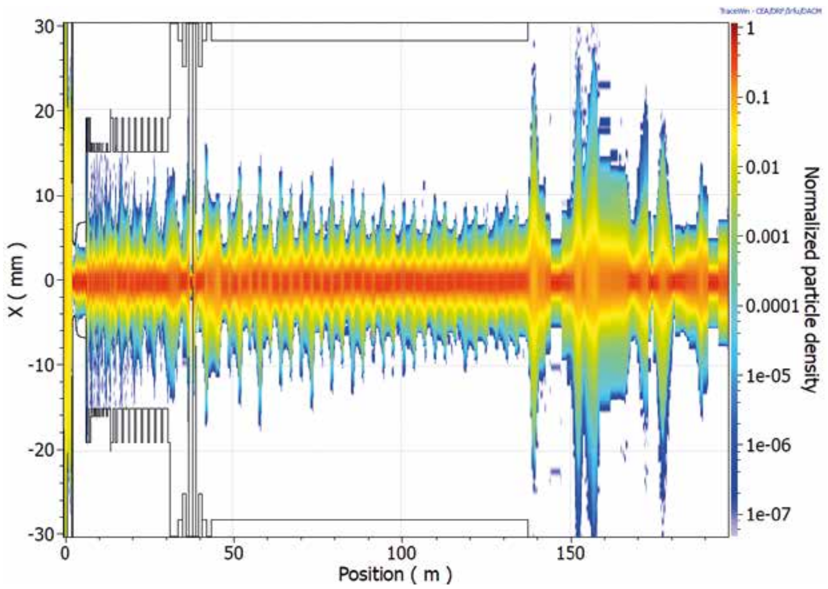
SCK-CEN/IPNO/LPSC/IPHC.

ACCELERATOR DRIVEN SYSTEMS (ADS)

DACM contributes to the European projects MYRRHA and MYRTE by working on high-intensity ADS-type linacs through beam simulations and diagnostic studies.

ADS (Accelerator Driven System) is a conceptual, fourth-generation nuclear reactor in which a subcritical core is driven by a high-intensity proton accelerator. These systems exhibit unprecedented safety and efficiency, in particular with regards to the incineration by transmutation of slow-decaying nuclear waste.

DACM is involved in various European programs dedicated to development of and R&D on high-intensity ADS proton accelerators. As part of MYRRHA (Multi-purpose hybrid Research Reactor for High-tech Applications), a demonstrator project located in Belgium, we contributed to the design and definition of the linear accelerator. Since 2015, within the European MYRTE (MYRRHA Research and Transmutation Endeavor) program, DACM has been coordinating the working group dedicated to studying the optics of the MINERVA accelerator demonstrator, limited to 100 MeV.



Density of the particle beam from the source to the target of the MINERVA accelerator (horizontal projection), obtained by a massive simulation with 5.10^7 particles.

OPTIMIZATIONS AND NUMERICAL SIMULATIONS

The main challenge with this type of accelerator is controlling beam losses, and these losses are due to particles that are ejected from the longitudinal stability space. Numerical simulation methods have been developed to optimize and simulate longitudinal acceptance more realistically. More direct and efficient radio frequency (RF) tuning procedures for accelerating cavities have been deduced.
Massive simulations with 5.10^7 particles from source to target were carried out in order to validate MINERVA's architecture, including new improved RF simulations and accounting for random machine faults.
Operating this type of accelerator requires the parallel operation of a digital model that is as representative of the machine as possible. In 2019, DACM produced a new code that allows direct bilateral dialogue between the control-command system of the real machine and its digital avatar.

4D EMITTANCE METER

DACM developed and produced an innovative 4-dimensional emittance meter diagnostic, which uses a camera to measure the beam impacting a scintillator after having passing through a "pepper pot" (a screen with holes). The entire assembly is equipped with motorized movements in horizontal and vertical. After numerical processing, the images obtained will provide a view of the particle beam's six transverse phase spaces, whereas a conventional Allison scanner emittance meter can only measure one. Progress has been made possible by tests carried out on injectors from other projects currently under development, and a thesis on the subject was supervised by DACM teams.

3D view of the 4D emittance meter.

Geometrical Behavior of Nb_3Sn Rutherford Cables During Heat Treatment, M. Durante *et al.*, IEEE Transactions on Applied Superconductivity, vol. 26, no. 4, pp. 1-5, June 2016, Art no. 4802705, doi: 10.1109/TASC.2016.2530166.
Dimensional Changes of Nb_3Sn Rutherford Cables During Heat treatment, E. Rochepault *et al.*, IEEE Transactions on Applied Superconductivity, vol. 26, no. 4, June 2016, Art no. 4802605. M. Abdel Hafiz, E. Rochepault *et al.*, ASC2020.

CERN/CEA No. KE3586 WP4 - High Field Magnet Materials and Technology. DACM (CEA Paris-Saclay)/LMT (ENS Paris-Saclay).

Nb_3Sn DEVELOPMENTS

To improve the current performance of the LHC (Large Hadron Collider) like in the HL-LHC project and develop future particle accelerators, high magnetic fields are required. To this end, Nb_3Sn-based superconducting electromagnets are being developed.

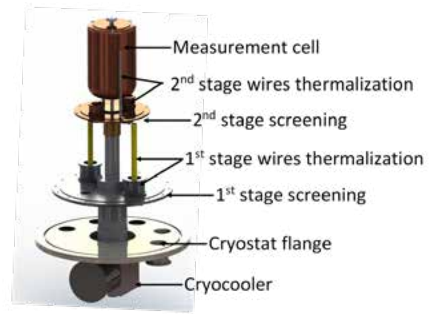
The LEAS is responsible for the design and fabrication of a dipole demonstrator (see chapter on R2D2) in the framework of the Future Circular Collider (FCC) project, the future CERN accelerator (see chapter on the FCC conceptual study). The NbTi alloy currently used in the LHC is limited in practice to magnetic fields of the order of 8 to 10 T. To produce higher magnetic fields, the Nb_3Sn inter-metallic compound must be used. Future accelerator projects require significant developments to aim for the highest fields Nb_3Sn-based magnets can attain, on the order of 15 to 16 T.

The conductors, initially composed of Nb and Sn, must undergo a heat treatment at 650°C in order to form the Nb_3Sn compound through diffusions and phase changes. Unfortunately, the resulting Nb_3Sn is fragile and its superconducting properties are greatly dependent on mechanical stress. To facilitate fabrication, the electromagnet coils are wound before the heat treatment is carried out. Additionally, the thermal and mechanical properties of the conductor have not been fully mastered: better characterization would allow for performance optimization that would push the current limits of Nb_3Sn-based magnets. Various experiments have been designed to quantify these properties within the framework of a collaboration agreement between CEA and CERN.

A first empirical experiment was carried out and consisted of measuring length variations on reduced coils before and after heat treatment. The observed contractions, on the order of several mm/m, were consistent with values obtained on 7 m-long series coils manufactured at CERN for HL-LHC. This type of test will facilitate estimation of variations in length prior to coil series production, thanks to coils using a reduced amount of conductor.

A second, more fundamental, experiment is ongoing. It is based on an innovative method of high-temperature image correlation. A LEAS PhD student (thesis begun in 2019) is developing this experiment and has set it up at the LMT laboratory of ENS Paris-Saclay, as part of a collaboration between the two institutes. The image correlation method offers the advantages of an in situ measurement, in three dimensions, at several scales, and can be adapted to different types of samples. This experiment has already enabled the first observation of width changes in a Nb_3Sn cable as a function of temperature.

A third experiment consists of measuring the thermal conductivity of Nb_3Sn-based conductor samples at cryogenic temperatures. A new Mectix test station, cooled via a cryogenerator, has been designed, built, and commissioned. There, samples can be maintained at variable temperatures between 4 K and 50 K, and their thermal conductivity measured in three directions. Testing on two types of conductors used for HL-LHC will begin in 2021.



Coil in its reaction mold after exiting the oven.

Left: Experimental set-up for high-temperature image correlation. Center: sample holder. Right: Nb_3Sn covered with a speckle.

R&D: HIGH CRITICAL TEMPERATURE SUPERCONDUCTOR (HTS) MATERIALS

DACM's R&D on HTS focuses on several topics that address the problems of coil operation under intense magnetic fields: screening currents, protection against quench, mechanics of the new windings, and cooling.

Image of the HTS pancake used to measure the temporal decay of screening currents.

The first characteristic of HTS materials is, as their name indicates, the ability to operate at much higher temperatures than low-temperature materials (LTS) (up to 93 K for TRBaCuO), but under weak magnetic fields. Their second characteristic, more relevant for our applications, is their capacity to carry very high current at low temperatures (4-10 K), well below their critical temperature, under intense magnetic fields. This induces new constraints that we are studying, and for which we try to provide solutions.

SCREENING CURRENTS AND MAGNETIZATION

The current density distribution within the tapes of an HTS magnet is not uniform and is established according to a phenomenon called "screening currents" with problematic consequences in the magnetic field generated: reduction in amplitude (magnetization), spatial distortion (degradation of homogeneity), and loss of temporal stability.

A PhD thesis has highlighted this phenomenon experimentally by measuring the temporal decay of the magnetic field and thus of the screening currents generated within an HTS pancake coil. Two approaches to reducing the consequences of this phenomenon were then studied: "overshoot" current loading and vortex shaking. Both techniques have shown promising effectiveness in reducing screening currents.

Finally, several numerical codes have been developed to model the phenomenon in axisymmetric 2D (Matlab, GetDP) and 3D (CAST3M).

PROTECTION AGAINST QUENCH

Protection against quench (transition from the superconducting state to the resistive state) of magnets made of HTS materials is more difficult to ensure than for LTS materials because of the propagation velocities of the quenched zones, which are 10 to 100 times lower than in an LTS magnet: this generates very low resistive voltages that are difficult for the detection system to measure.

For better protection against quench, the MI (Metal-as-Insulation) winding technique has been studied and implemented at DACM. It consists of using metallic tape made of stainless steel in place of classical polyimide insulation. A number of experiments on prototypes made of several pancakes and tests on the NOUGAT HTS magnet (see chapter on NOUGAT) have demonstrated the quality of this very effective protection: the magnet is self-protected by redistribution of the currents between turns around the quenched zone, thereby reducing the detection and protection system.

In order to study and understand the phenomenon of current redistribution in MI windings during transient regimes, a PEEC (Partial Element Equivalent Circuit) code has been developed to model a single pancake.
Improvements of the code for a complete magnet (solenoid made of several pancakes or multipole magnet) are currently the subject of a PhD thesis, which also includes experimental measurements of the contact resistance between turns as a function of the compressive force applied between several tapes.

MECHANICS OF MI WINDINGS

The magnetic forces (Lorentz forces) in a magnet increase as the square of the magnetic field magnitude. The associated mechanical stresses can therefore be very high under strong magnetic field.
In addition, MI windings are not impregnated, rendering study of their mechanics particular, in that the turns of an MI winding must remain in contact, a sine qua non condition for the quench self-protection to be effective via the redistribution of current between turns.

Quasi 3-D Model for Numerical Computations of Screening Currents in ReBCO Coils, P. Fazilleau and G. Dilasser, IEEE Transactions on Applied Superconductivity, vol. 30, no. 6, pp. 1-9, Sept. 2020.

Investigation on Two Techniques for the Reduction of Screening Current-Induced Field Effect in REBCO HTS Coils, G. Dilasser, P. Fazilleau, and P. Tixador, IEEE Transactions on Applied Superconductivity 28.4 (June 2018), pp. 15.

Metal-as-insulation variant of no-insulation HTS winding technique: pancake tests under high background magnetic field and high current at 4.2 K, T Lécrevisse, P. Fazilleau *et al.*, Superconductor Science and Technology 31.5 (Apr. 2018), p. 055008.

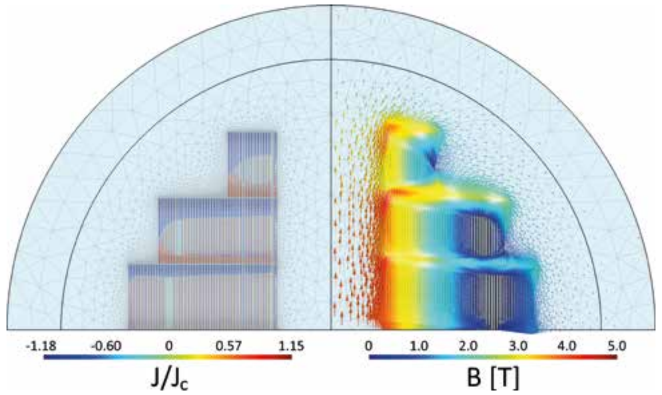
Experimental Measurement and Numerical Simulation of the Screening Current-Induced Field Decay in a Small ReBCO Coil, G. Dilasser, P. Fazilleau, and P. Tixador, IEEE Transactions on Applied Superconductivity 27.4 (June 2017).

Novel analytical formulas of the stresses and displacements within an MI winding, without insulation and without impregnation, were completed in the first part of a PhD thesis underway. Experimental measurements of displacements by Digital Image Correlation (DIC) at cryogenic temperatures (77 K, then 4 K) are being carried out in a second part on a single pancake energized and under external magnetic field in order to deduce the mechanical stresses and to validate the analytical formulas.

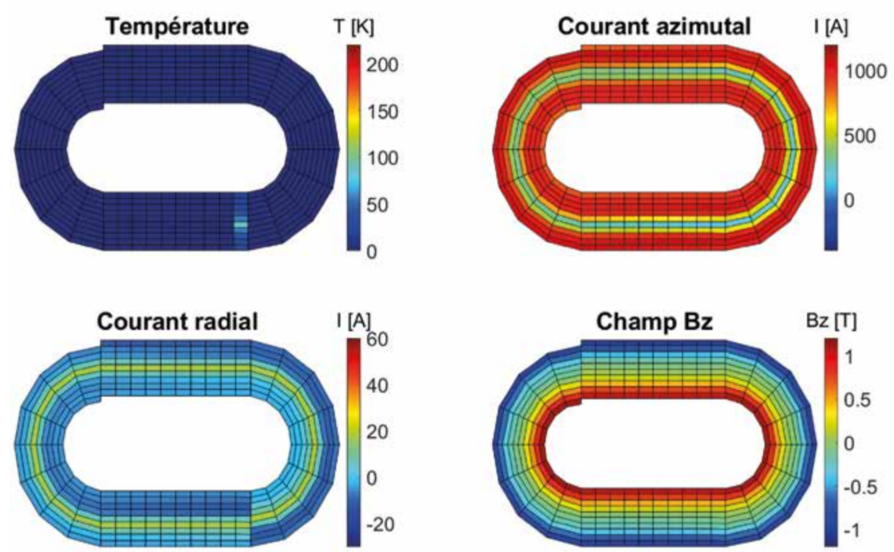
COOLING UNDER AN INTENSE MAGNETIC FIELD

Tests carried out on the NOUGAT magnet have shown cooling problems under intense magnetic field, which have already been highlighted by other laboratories. This phenomenon is due to magneto-gravity volume forces and is being studied in the framework of a PhD thesis in order to determine the underlying physical mechanisms.

The cost of helium also limits the development of experiments using superconductors. With internal funding, the HTS R&D and Cryo R&D are jointly developing and producing a 10 T HTS magnet with MI winding and cooled by Pulse Heat Pipe (PHP) conductive links combined with a cryo-generator (cf. Cryo R&D page).



Example of screening currents in the EuCARD magnet being calculated with GetDP software. On the left, the non-uniform distribution of the current density in the turns of the coils. On the right, the magnetic field generated by this distribution.



Example of calculation using PEEC software in a MI racetrack coil during a quench: temperature, current sharing between turns, and magnetic field.

HIGH CRITICAL TEMPERATURE SUPERCONDUCTOR R&D FOR ACCELERATOR MAGNETS

Between 2016 and 2020, two High critical Temperature Superconductor (HTS) R&D magnets, the EuCARD HTS Insert and the EuCARD2 HTS dipole, underwent production and testing.

The **EuCARD HTS Insert** is a block-type dipole made from a stack of YBCO superconducting tapes, designed to produce a central field of 5 T at 4.2 K (magnet alone or in the 13 T background field of FRESCA2). Design began in 2008 within the framework of the European EuCARD program and is ongoing within the framework of a CERN/CEA collaboration focused on the development of high-field magnets for particle accelerators.

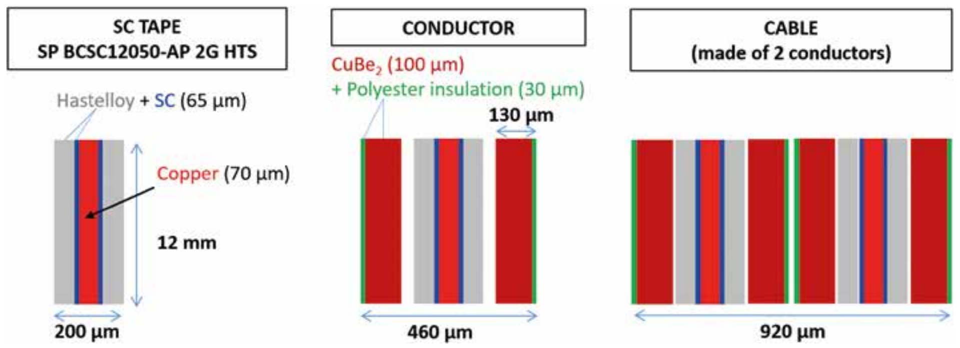
The magnet consists of three flat “racetrack” coils, with one long coil in the center and two shorter coils on the exterior. Each coil is made of two layers of tapes. The transition from one layer to the other is made in the center of the coils, on one side of the straight section, using special shims at the coil's extremities that guide the tapes into the correct position without adding stress.

The superconductor is a 12-mm-wide tape produced by the American company SuperPower and consists of two YBCO tapes welded around a copper stabilizer. Two reacted CuBe2 tapes, insulated on the outer surface with a polyester film, stabilize each superconducting tape. Two such conductors are wound in parallel in order to increase the cable's current capacity and to decrease total magnet inductance, thus simplifying magnet protection.

All components, tools, and production process plans were validated using stainless steel tapes with the same dimensions as the superconducting tapes. The superconducting coils were then manufactured between April and June 2016. The magnet was assembled in its screwed mechanical structure in November 2016. Standalone tests were performed in Saclay between June and September 2017.

The tests were carried out in DACM's Séjos cryostat. The magnet was suspended from the cryostat plate in the center of a 1660 mm tall metal tank and connected to the 5 kA current leads. Magnet performance was first verified at 77 K, a temperature at which expected cable performance can be verified while limiting the energy stored in the magnet and reducing the risks in the event of quench. Tests were carried out first within nitrogen gas, so as not to over-stabilize the magnet, then in a liquid nitrogen bath. Magnet performances were verified at the nominal current of 295 A, then up to 320 A.

Insertion of the EuCARD HTS magnet in Séjos cryostat.



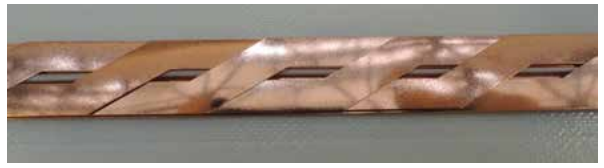
EuCARD insert cable configuration.

Realization and First Test Results of the EuCARD 5.4-T REBCO Dipole Magnet, M. Durante *et al.*, in IEEE Transactions on Applied Superconductivity, vol. 28, no. 3, pp. 1-5, April 2018, Art no. 4203805, doi: 10.1109/TASC.2018.2796063.
Manufacturing of the EuCARD2 Roebel-Based Cos-Theta Coils at CEA Saclay, M. Durante *et al.*, in IEEE Transactions on Applied Superconductivity, vol. 30, no. 4, pp. 1-5, June 2020, Art no. 4602505, doi: 10.1109/TASC.2020.2978788.

FP7 Project EuCARD, Grant Agreement 227579, WP7.
FP7 Project EuCARD2, Grant Agreement 312453, WP10.

KE2275/TE, WP5 between CEA and CERN on research and development for future LHC superconducting magnets.

EuCARD HTS superconducting coils; left: central coil; right: top coil.



SuperOx cable with insulated copper wire in the center.

The magnet was then cooled to a temperature close to that of liquid helium. At this temperature, the nominal current necessary to produce a central field of 5 T is 2800 A. The current of the magnet was gradually increased to 2500 A, in cold helium gas: a magnetic induction of 4.3 T was measured by Hall probes placed in the center of the magnet. Finally, the magnet was tested in a liquid helium bath up to the nominal current of 2800 A, then up to 3200 A: a record field of 5.37 T was measured in the center of the magnet.

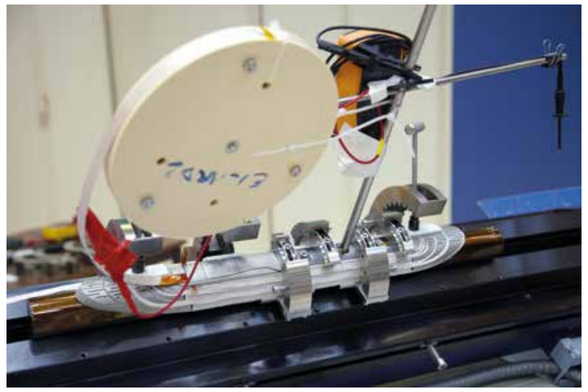
The **EuCARD2 HTS Dipole** is a cosθ-type dipole, made from a YBCO Roebel cable, intended to produce a central field of 5 T when the magnet alone receives power in its magnetic circuit, and of 2.6 T when inserted into the 13 T background field of the FRESCA2 magnet.

EuCARD2 cosθ dipole in its yoke, during preparation for transport to CERN.

All of the steps from design to manufacturing—winding, impregnation, and coil assembly—were carried out by DACM/LEAS with the support of the DIS/LCAP design office, while tests are planned at CERN. These activities were begun within the framework of the European EuCARD2 program and are ongoing within the framework of the CERN/CEA collaboration on the development of high-field magnets for particle accelerators.

The Roebel conductor consists of 15 YBCO HTS superconducting tapes cut in an S-shape and assembled so as to transpose them continuously along the cable. The cable is insulated with a fiberglass sleeve and completed, after winding, by resin vacuum impregnation. The superconducting cable was produced by the SuperOx company. Tape width in the straight parts of the cable is only 5 mm for a cable width of 12 mm, which leaves a space in the center of the cable that limits the mechanical strength of the winding. Insulated copper wire wrapped with a fiberglass sheath was inserted in the center of each length of cable to fill this hole and to load the resin during impregnation. Copper wire could also be used during magnet tests to cancel the inductive effects from the signal of each coil.

The process for coil manufacturing and assembly was validated between 2015 and 2018 with two test coils made with a stainless steel cable, and on several dummy assemblies. Three superconducting coils were then wound and impregnated between March 2019 and July 2020. Two of the coils were assembled in dipole configuration in the mechanical structure in November 2020. The magnet was then inserted into its magnetic circuit and sent to CERN, where it is being prepared for the first test campaign, scheduled for February 2021. The magnet will then return to Saclay, where the mechanical structure will be modified to make it compatible with insertion into the FRESCA2 magnet, before a second and final test campaign.



EuCARD2 cosθ winding.

L'étude et réalisation d'un aimant supraconducteur haut champ (3 + 2 T) en MgB_2 refroidi par conduction, J. Avronsart, Thèse de doctorat de l'Université Paris-Saclay, Saclay, le 9 octobre 2019.
Measurements on Critical Current and Bending Strain Tolerance for Ex Situ MgB_2 Wires and Tapes Under High Field up to 8 T, J. Avronsart, C. Berriaud and al., IEEE Trans. On, App. Supercond., Vol. 28, No. 3, April 2018: 6200305.

SUPERCONDUCTING MgB_2 MAGNET

The scarcity of helium, used to cool superconducting magnets, is pushing manufacturers to use superconductors other than NbTi for magnets immerged in liquid helium baths. Among the most efficient high-temperature superconductors, MgB_2 (Tc = 39 K), discovered in 2001, can be cooled by solid conduction. This material is already available in substantial lengths and at a competitive price that, in some cases, can compete with NbTi.

In this context, a thesis was begun in late 2016 concerning the difficulties of handling MgB_2 conductors. This material has a mechanical strength much lower than that of NbTi. In addition, field performance is limited to about 5 T, especially if the objective is to operate at higher temperatures than that of costly liquid helium.

The work of this thesis consisted of designing and manufacturing a significant prototype for a MgB_2 magnet weighing 50 kg and generating a central field of 2 T in an external field of 3 T. The magnet was cooled by solid conduction with only one cryocooler. The nominal performance was reached: 5 T at 10 K with 200 A.

Superconducting magnet manufactured in the framework of a thesis about the use of MgB_2.

Field Emission Studies on ESS Elliptical Prototype Cavities at CEA Saclay,
Cenni E, Baudrier M, Devanz G, Maurice L, Piquet O, Roudier D., International Conference on RF Superconductivity (19th), JACOW Publishing, Geneva, Switzerland; 2019 p. 1147–51. http://accelconf.web.cern.ch/AccelConf/srf2019/doi/JACoW-SRF2019-THP097.html

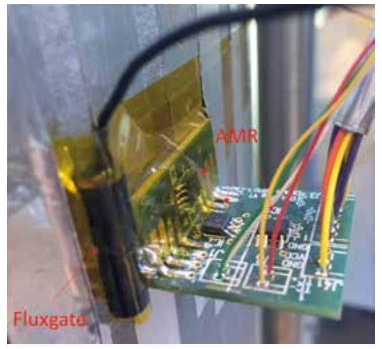
KEK in the framework of TYL-FJPPL ("Toshiko Yuasa" France Japan Particle Physics Laboratory).

DIAGNOSTICS FOR SUPERCONDUCTING CAVITIES

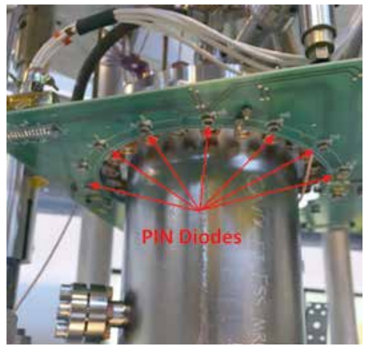
In order for superconducting cavities to achieve high performances, their material behavior and environment must be controlled during operation. In our laboratory, we are currently designing a suite of detectors that will focus on superconducting cavity diagnostics during testing in a liquid helium bath.

On the one hand, the magnetic field, even if lower than Earth's magnetic field, increases Joule losses; therefore it is important to precisely control and measure this field. We are currently developing detectors capable of measuring the magnetic field around the cavity at cryogenic temperature using the AMR (Anisotropic Magnetoresistance) of a ferromagnetic material at their core. These detectors are resistant to cryogenic temperatures, and are much cheaper than the current standard for these kinds of measurements (Fluxgate), which should make it possible to systematically equip cavity cryostats and cryomodules.

On the other hand, field emission is one of the main reasons for the degradation of the quality factor in superconducting cavities. Its presence can limit the ultimate performances of superconducting cavities and hence of the whole cryomodule. The presence of dust particles on the cavity surface is a common source of contamination leading to field emission during cavity operation. Hence, it is essential to better understand what causes this phenomenon and how it evolves from preparation of the cavities in the clean room, through assembly in the cryomodule, and up to final testing and operation on the machine. We are currently developing a suite of tools to address this issue, one of them being arrays of PIN diodes (Fig. 2) capable of detecting gamma rays produced by field-emitted electrons hitting the cavity surface (bremsstrahlung).



Magnetic sensors affixed to a cavity.



PIN diodes array placed around a cavity beam tube.

Optimization of Vertical Electro-Polishing Process: Experiments with Updated Cathode on Single-Cell Cavity and Performance Achieved in Vertical Test. Proceedings of 9th International Particle Accelerator Conference (IPAC'18), Eozénou, F., *et al.* (2018).

KEK (French-Japan TYL/FJPPL Particle Physics Laboratory).

R&D SUPERCONDUCTING CAVITIES

At DACM, R&D activities centered on superconducting cavities aim to improve surface preparation methods, such as electropolishing, and make clean room assembly procedures more reliable by automatizing them.

SURFACE PREPARATION

In addition to the traditional treatment using chemical etching, electropolishing in vertical position has been developed for elliptical niobium cavities. New devices have been installed to measure the thickness of the cavity in real time and to control the temperature using external jets and a cooling box. Since 2017, in collaboration with the Japanese KEK laboratory, rotating cathodes have been developed and implemented to ensure uniform polishing in the cells and better hydrogen evacuation. As a result, promising accelerating gradients have been obtained on single cells of different sizes and geometries: 41 MV / m on single cells at 1.3 GHz, β = 1, of the ILC (International Linear Collider) type, or 27 MV / m before thermal annealing on single cells at 704 MHz, β = 0.86.

An ultra-fast camera for quantitative analysis of the displacement of the gas bubbles completes the set-up, used to observe the interior of the cells during treatment. We plan to use it to study unwanted localized attacks during chemical etching. Previously, we demonstrated that the NOx gases and the geometry of the surface are responsible for the non-uniformities obtained on samples.

CLEAN ROOM ASSEMBLY

Experience feedback from the XFEL (X-ray Free Electron Laser) project confirmed that there is a strong correlation between the field emission limitations of cavities and the uncontrolled incidents that occurred during the assembly phases in a clean room, and the steps involving pumping and returning to atmospheric pressure, which tend to displace dust particles. To remedy this, the collaboration between DACM/LIDC2 and IRFU DIS/LEIGE has developed procedures employing autonomous and automated pumping units according to a meticulous and precise protocol. A software license and knowledge transfer are in progress with a French manufacturer.

It proved necessary to continue automatizing the assembly steps, particularly one of the long and arduous manual operations: cleaning single parts or complex assemblies, such as cavities or couplers, with a blow-off gun delivering bursts of ionized nitrogen. We have made a careful inventory of the individual gestures that go into such cleaning procedures, so that they may be performed by a robotic arm. During an early phase of the project and in collaboration with CEA Tech, we developed a demonstrator using a prototype of iSybot's Syb3 robot. Proof of concept was then demonstrated on a cavity within the framework of the ESS project, and a 6-axis commercial cobot, or manipulator arm, robot, is now under acquisition. The technique has been improved with the use of more suitable ionizing cartridges and improved blowing sequences.

The solutions developed will be applicable to all other DACM projects.

Visualization cavity allowing the observation of fluid dynamics during electrochemical and chemical treatments.

Operator teaching the collaborative robot the location of the cavity flange to be cleaned.

Optimization of tailored multilayer superconductors for RF application and protection against premature vortex penetration, Antoine, C. Z., *et al.* (2019), Superconductor Science and Technology 32(8).

This research theme is funded by two European projects (ARIES and ENSAR2), 1 Equipex, 1 P2IO project (CATTISA), regional (SESAME Axe SRF), and internal resources including a transverse CEA program).

SRF R&D: FUNCTIONALIZATION OF SURFACES AND NEW COOLING TECHNIQUES

Bulk niobium accelerator cavity technology, which is stable today, is based on a material optimized for heat transfer to stabilize cavity operation. By functionalizing the surfaces and developing innovative cooling methods, we can improve the functioning of RF cavities from both a superconducting and a cryogenic point of view, while also supporting other properties such as the secondary emission coefficient of the extreme surface.

ALD, SURFACE TREATMENTS, ANNEALING

Atomic Layer Deposition (ALD) is a thin film synthesis technique based on self-limiting surface chemical reactions. It facilitates the deposit of films with uniform thickness and composition on structures with complex geometries. ALD is used in many applications (e.g., batteries, catalysis, photovoltaics, etc.). The LIDC2 lab focuses on oxide and nitride deposits for superconducting RF cavities, anti-corrosion coatings, and detectors. For superconducting cavities, we have been able to develop a multilayer approach that combines ALD and vacuum heat treatment, which both improves surface superconducting properties and reduces the secondary electronic emission coefficient. We are also developing multilayer superconducting/insulating deposits that would greatly increase cavity performance.

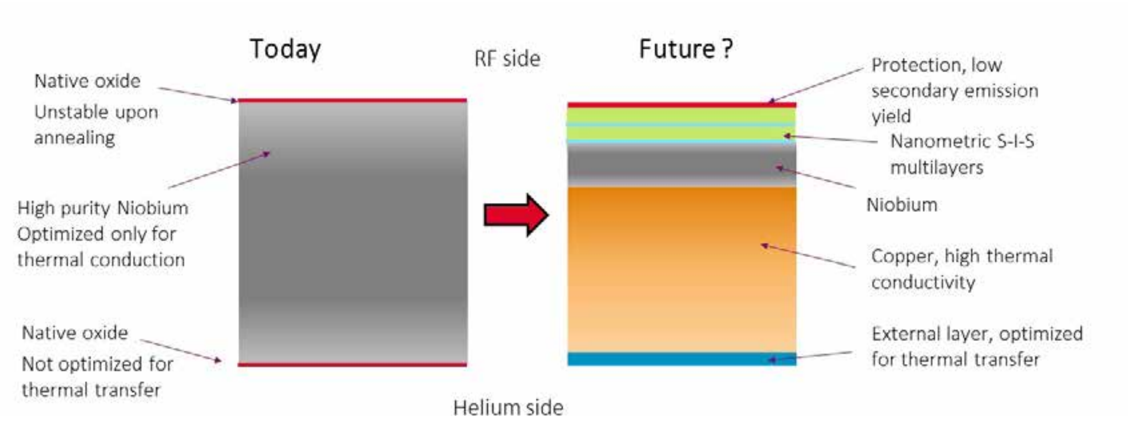
S-I-S MULTILAYERS

Before acquiring deposition techniques, the CEA had begun characterizing SIS (Superconductor-Insulator-Superconductor) structures, in particular a series of Nb (500 nm) / MgO (10 nm) / NbN (25 to 200 nm) layers deposited on sapphire using magnetron sputtering (collaboration Grenoble INP).

We have shown that not only do these structures delay the penetration of vortices into the niobium layer, thereby making it possible to operate at a higher accelerating field, but they are also insensitive to the presence of the numerous defects in films deposited by magnetron sputtering.

NEW COOLING TECHNIQUES

The use of higher critical temperature superconductors in this form reduces the quality requirements for the material, which is favorable to large-scale productions, but also opens the possibility for operating at higher temperatures with new cooling schemes that consume less helium. Our approach is based on a synergy between 3D printing of metal alloys and the deposition of thin superconducting films to optimize cooling and the thermal links between the cavity and the cold source. The superfluid helium currently in use could be replaced by less expensive technologies using normal helium and other cooling techniques such as cryogenerators and oscillating heat pipes. Ultimately, the goal is to demonstrate that a cavity manufactured by 3D printing, with a deposition of superconducting films and cooled by a cryogenerator, has RF performance similar to those obtained by standard methods.



Surface functionalization to enhance cavity performance.

Point Contact Tunneling Spectroscopy apparatus for large scale mapping of the surface superconducting properties, N.R. Groll, M.J. Pellin, J.F. Zasadzinksi, and T. Proslier. Review of Scientific instrument 86, 095111 (2015).

CRYOGENIC DIAGNOSTICS FOR SUPERCONDUCTING RF

DACM is equipped with several characterization tools to investigate the superconducting properties of materials used in devices such as superconducting RF cavities. Two of these set-ups, tunnel microscopy and local magnetometry, are the result of original developments and deliver performances unavailable anywhere else. These support resources ensure efficient R&D on new superconducting materials and structures for SRF (Superconducting Radio Frequency) applications but can also support projects in need of extensive diagnostics.

TUNNEL MICROSCOPY

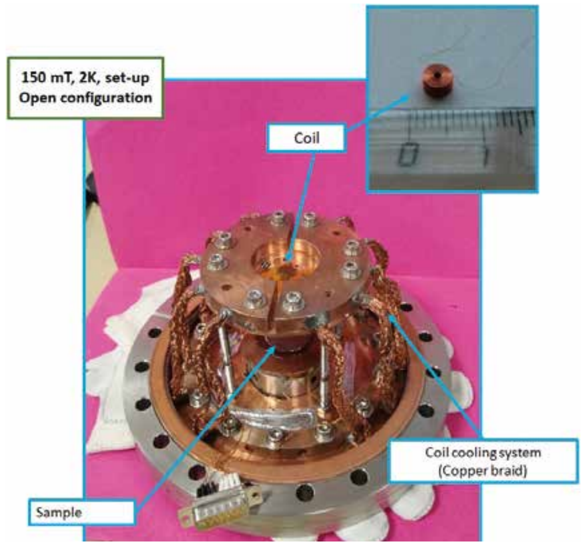
The tunnel spectroscopy apparatus can map the superconducting surface properties of samples and their dependence on temperature and DC (Direct Current) magnetic fields through the local measurement of the density of states. The lateral size of the maps can extend up to 1 x 1 mm², the temperature can be adjusted between 1.4 and 300K, and the magnetic field perpendicular to the sample can be varied from 0 to 6 T. From these measurements, we can infer some of the fundamental quantities related to the superconductor (*i.e.*, its superconducting gapΔ, its critical temperature T_C, and its quasiparticle inelastic scattering coefficient Γ) and correlate them with the performance of the superconducting devices. Several themes are being explored: superconducting RF cavities, quantum bits, and exotic superconducting compounds.

Tunnel microscope in its Faraday cage.

LOCAL MAGNETOMETRY

Unlike conventional magnetometry where samples are immersed in a uniform field, local magnetometry allows measurements to be taken of a sample's first transition fields without being affected by edge or geometry effects. It is particularly suitable for testing how surface treatments or very thin films repel vortices from entering the samples. The particularities of the system developed at Saclay are the field reached (> 220 mT) and the temperature range (1.8 K-40 K), which allows for the exploration of operating conditions within accelerator cavities.

In addition to the original methods described above, the laboratory is equipped with standard transport measurement methods (resistivity) to measure transition temperature and residual resistance ratio.



Local magnetometry set-up.

Développement et réalisation d'un klystron à haut-rendement de type kladistron, Mollard, A., Doctoral dissertation, Université Paris-Saclay (ComUE), 2017.
Klystron efficiency optimization based on a genetic algorithm, Hamel, P., Plouin, J., Marchand, C., & Peauger, F., in 2019 International Vacuum Electronics Conference (IVEC), pp. 1-2, IEEE, 2019.

EUCARD², ARIES. PSI, Uppsala University, Thales MIS.

HIGH-EFFICIENCY HIGH-POWER SOURCES OPERATING AT HIGH FREQUENCIES

The next generation of particle accelerators will require increasingly powerful radio-frequency sources. The energy efficiency of these sources will become a critical issue when considering the operating budget of such facilities. DACM is involved in two European research programs, EUCARD² and ARIES, which aim to increase the energy efficiency of klystrons, which could be used as radio-frequency sources in such particle accelerators.

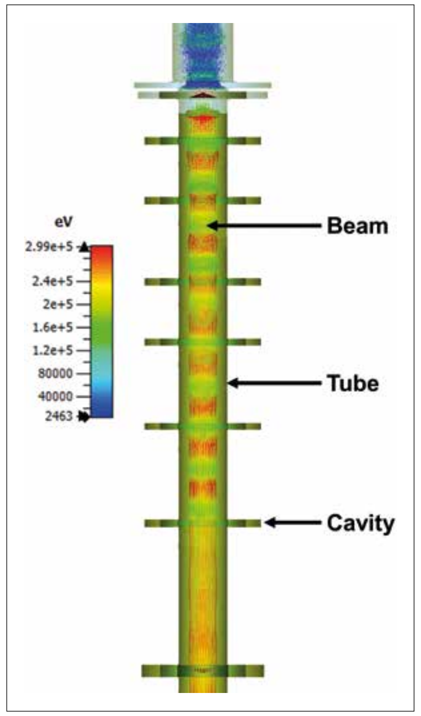
EUCARD²

In the framework of the EUCARD² project and in collaboration with Thales, the interaction line of an existing 5-GHz klystron has been modified to improve its efficiency. A larger number of low coupling cavities were used, allowing a smooth progression of the bunch formation. This method, called adiabatic, can be compared to the beam acceleration in an RFQ (Radio Frequency Quadrupole). This new interaction line has been machined and brazed, the final "kladistron" (adiabatic klystron) has been assembled, and we have measured its performances. The interaction efficiency measured remained lower than expected. Post-mortem measurements and new simulations showed that this lower efficiency was probably due to the difficulty of accurate cavity tuning. Moreover, we realized that the risk of high power gain was inherent in this method and could lead to spurious oscillations in the klystron.

ARIES

In the course of this project, a continuation of the EUCARD² project, a design for a klystron operating at 12 GHz and providing 20 MW was proposed. With performances like these, this klystron could operate on linear colliders such as CLIC or X-Ray Free-Electron Lasers such as CompactLight. The initial objective was to increase by about 10% the efficiency of existing on-the-shelf klystrons, which have efficiency of about 50%-55%. A simulation of our best design demonstrated that it is possible to extract about 65%. Most of our efforts have been concentrated on the bunching process of the electron beam. The adiabatic method used on the EUCARD² prototype was combined with a so-called core oscillation method to extend the core of the electron bunch in order to achieve a more homogenous space charge distribution within the bunch. To maximize the benefits of combining both methods, a genetic algorithm was used. Finally, we paid special attention to output cavity performances, which are highly correlated to the tube's overall performance.

5-GHz klystron (Eucard²) prototype. Interaction line (bottom), collector (top).



Particle in Cell simulation of the klystron design to visualize the beam energy along the tube.

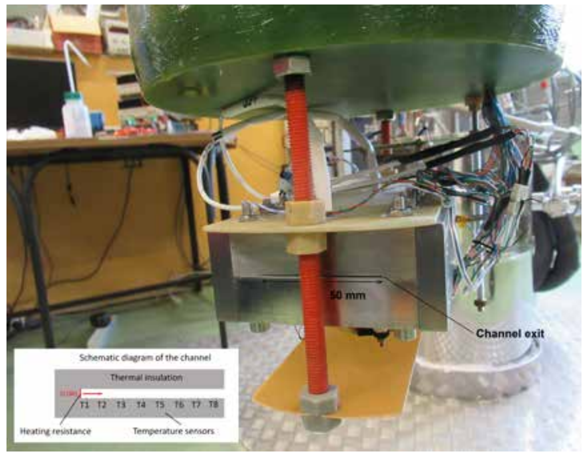
Transient Conjugate Heat Transfer Numerical Simulation in Superfluid Helium, A. Vitrano *et al.*,
IOP Conference Series: Materials Science and Engineering 755, 012068, jun, 2020. doi = {10.1088/1757-899x/755/1/012068}.

STUDY OF HEAT AND MASS TRANSFER IN SUPERFLUID HELIUM IN CONFINED GEOMETRY

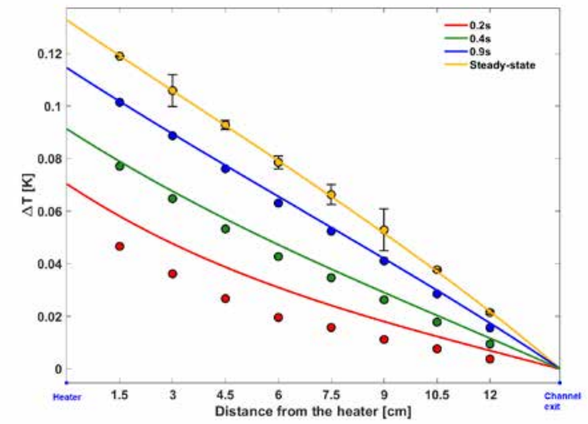
This research is part of general studies on the thermohydraulic behavior of accelerator magnets in the case of transient events like quench (transition from the superconducting state to the resistive state). It is focused on the specific case of CERN magnets cooled by superfluid helium.

The main idea is to investigate the transient heat and mass transfer in superfluid helium in the most characteristic dimensions within the superconducting coil. The space between the non-magnetic steel collars surrounding the coil, which are around 200 µm, is one such characteristic dimension. The main goal of this study is twofold: to comprehend the physical phenomena involved, especially the phase changes due to the large release of heat; and to feed numerical models currently under development. A dedicated experimental set-up has been designed to create a channel with a rectangular and modifiable cross-section. The channel opens on one side to a controlled-temperature superfluid helium bath, and on the other side it is closed by a heater. Eight sensors, installed flush with the wall, and within the wall of the channel, directly measure the temperature of the fluid without disturbing the flow. All the channels are 140 mm long and 50 mm wide. Three thicknesses have been tested—1 mm, 500 µm, and 200 µm—in pressurized superfluid helium in different orientations with respect to gravity.

We report a typical result for the 1-mm thick channel oriented horizontally at a temperature of 1.81 K for a heat pulse of 22 kW/m². This heat flux density does not cause any phase change. The experimental data are compared to the results obtained by numerical simulation, taking into consideration the conservation equations for the superfluid helium with the OpenFOAM® toolbox. This model is based on a simplified version of so-called "two-fluid" equations with an enthalpy-based energy equation and the Sato's law for the equivalent thermal conductivity. The comparison is displayed in terms of temperature increase for each sensor (*i.e.*, as a function of the distance from the heater). In steady-state, the model matches the data extremely well. In transient mode, the computations give acceptable results, even if the numerical code underestimates the temperature increase in the helium. This is probably because the equivalent thermal conductivity data was derived in steady-state conditions. The conclusion is that the experimental and numerical models are sufficiently accurate to constitute solid tools to study the phase changes in confined channels. Experimental and numerical studies at higher heat flux density, creating phase change, are underway.



The 1-mm channel oriented horizontally and installed in the superfluid helium cryostat insert. This picture shows the exit of the channel. The temperature sensors are located at the bottom of the channel.

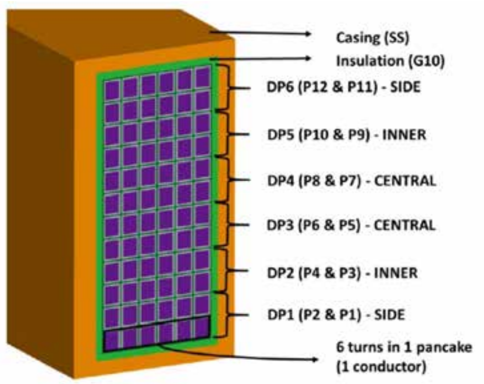


Temperature difference distribution at different times after the heat pulse within the channel (1 mm x 50 mm x 140 mm) at 1.81 K and for a dissipation of 22 kW/m². The measurements are represented by colored circles and the simulation by solid lines.

Quench tests analysis of the first JT-60SA Toroidal Field coils, Huang, Y; Maksoud, WA; Genini, L; Ciazynski, D; Decool, P; Torre, A; FUSION ENGINEERING AND DESIGN; Volume: 124 Pages: 147-152 ; Published: NOV 2017.

THERMOHYDRAULIC BEHAVIOR OF QUENCH PROPAGATION IN JT-60SA TF COILS

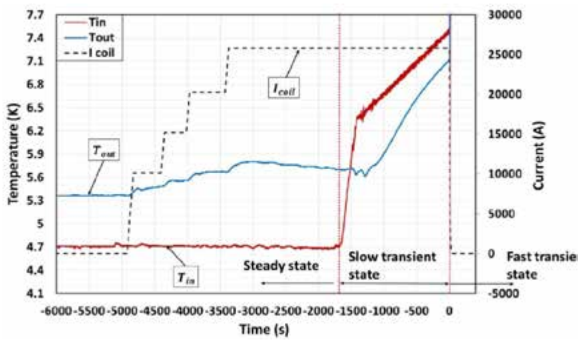
From 2016 to 2018, while validation tests were being performed on the 18 JT-60SA toroidal field coils, in-depth experimental and numerical studies were carried out on the thermohydraulic of quench (transition from the superconducting state to the resistive state) in these magnets.



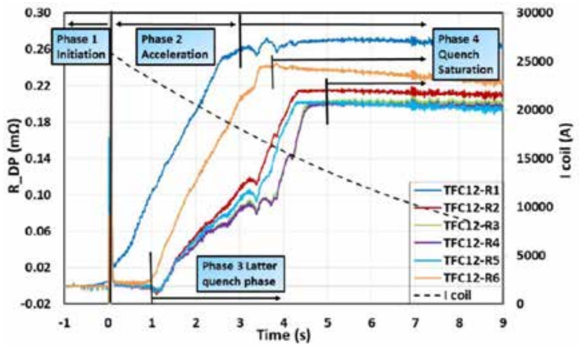
Cross section of a JT-60SA TF coil.

The coils are wound with a Cable-In-Conduit Conductor (CICC) and cooled by forced flow of supercritical helium at 5 K. They are made of six 113-meter-long double pancakes with six turns, each separated by 1 mm of fiberglass insulation; the entire device is impregnated with epoxy resin and inserted into a stainless-steel casing. The experimental protocol used for the quench studies was as follows:

- Cool the coil at 5 K with a helium mass flow rate of 24 g/s in the winding, and 10 g/s in the casing
- Energize the coil at 25.7 kA
- Achieve steady state
- Linearly increase the inlet temperature of the coil from 5 K to its quench temperature of about 7.5 K
- As soon as quench is detected, quickly (60s) discharge the current on an external dump resistor.



Evolution of current and temperature during a quench experiment.



Evolution of the resistance in the six double pancakes during a quench.

Analysis of the 18 completed tests identified the main physical phenomenon that drives quench propagation dynamics. The first phase is the initiation phase, during which quench starts at one precise location in the coil. Experiments demonstrated that this precise location is the result of competition between the coil's thermal and magnetic behaviors. Indeed, the coil's magnetic field map should impose a systematic quench initiation in the central pancakes, where the peak field region is located. However, as the casing transfers heat to the winding, it induces a slightly higher fluid temperature in the lateral pancakes; thus, quench initiation occurs more frequently there. Once quench is initiated, both experiments and computations showed that it enters an acceleration phase due to the thermohydraulic "quench-back" effect. Locally deposited high Joule power induces an increase in pressure and powerful dissipation of the helium inside the conductor. This flow preheats the non-quenched zone of the conductor through friction and induces an acceleration of quench velocity. During this acceleration phase in the first quenched pancake, nearly simultaneous quench initiation was empirically observed about one or two seconds later in all the other pancakes. This phenomenon was induced by the reverse flow of hot helium from the first quenched pancake. Once exhausted, this helium returns by forced flow to the other pancakes, thus quenching them all simultaneously.

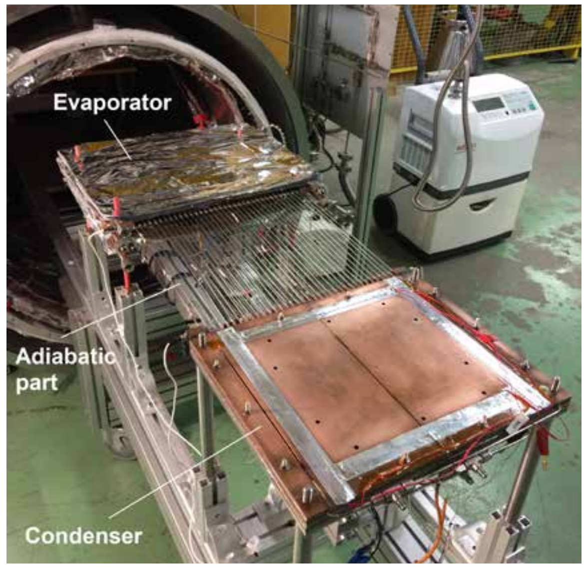
Thermal Study of a one-meter long Neon Cryogenic Pulsating Heat Pipe, M. Barba *et al.*, IOP Conference Series: Materials Science and Engineering 502, 012152, 2019. DOI: 10.1088/1757-899X/502/1/012152.

LONG HORIZONTAL CRYOGENIC PULSATING HEAT PIPE

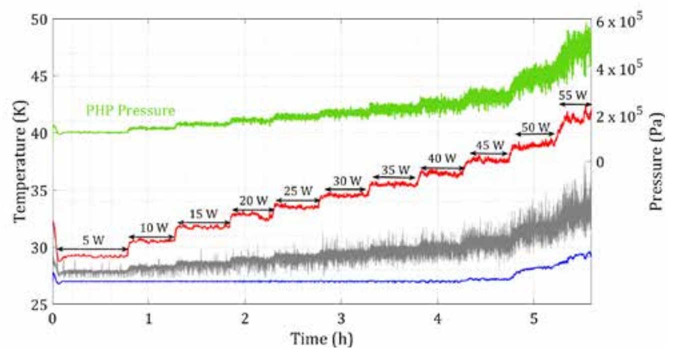
With the rarefaction of helium and the improvement of cryocooling technology (i.e., using a cryocooler as the primary cold source) we foresee that cryocooling will have enhanced enabling capabilities for a broad spectrum of new applications in fields such as medicine, physics, space, electronics, engines, and quantum technology over the next ten years

The main barrier to the development of cryocooling is the thermal weakness of the link between the cold source (cryocooler) and the cryogenic system. In industry and research today, a conductive solid material is most commonly used as a thermal link for its reliability and passivity. The main drawbacks to this are low thermal performance and weight. Solid material conductive links have a high response time and require a large cross-sectional area, and therefore high weight, to transport heat. For the moment, one technical solution, the much more efficient and lighter Pulsating Heat Pipe (PHP), stands out as a potential replacement for conductive links. This heat pipe is composed of a single capillary tube wound between the condenser and the evaporator. The fluid inside, close to saturation, transports a large amount of heat due to the combined effects of phase change and advection. This heat pipe has been proven in other fields, and examples are abundant in fields that require efficient cooling. The system has been attracting attention in cryogenics for about ten years and a number of academic studies have recently been produced. However, by no means have we fully capitalized on this research, which could enable the development of a cooling system embedded within a cryo-magnetic device.

We have developed and tested a 1-m-long PHP in a horizontal position to investigate its working conditions and evaluate its capabilities to replace classical thermal links over a long distance. Our 1-m-long horizontal PHP (Figure 1) made of 36 stainless steel parallel tubes has an internal diameter of 1.5 mm. It is composed of a condenser, on which the cryocooler is thermally anchored, an adiabatic section, and an evaporator on which the cryogenic system to be cooled is attached. Tests have included nitrogen, neon, and argon as working fluid, and figure 2 presents a typical result for neon, with the temperature difference between the evaporator and the condenser expressed as a function of the heat load deposited on the evaporator. During the tests, temperature in the condenser was maintained at 27 K while the heat load was increased gradually in the evaporator. The PHP was able to transfer a heat load of 50 W from the evaporator to the condenser with an equivalent thermal conductivity of 70 kW/m/K. This latter value should be compared with the thermal conductivity of copper at the same temperature (2.29 kW/m/K for standard copper). Moreover, the tests have demonstrated that at 50 W, the PHP can maintain the same thermal performance for more than nine hours.



The 1-meter-long Pulsating Heat Pipe before insertion into the testing cryostat.

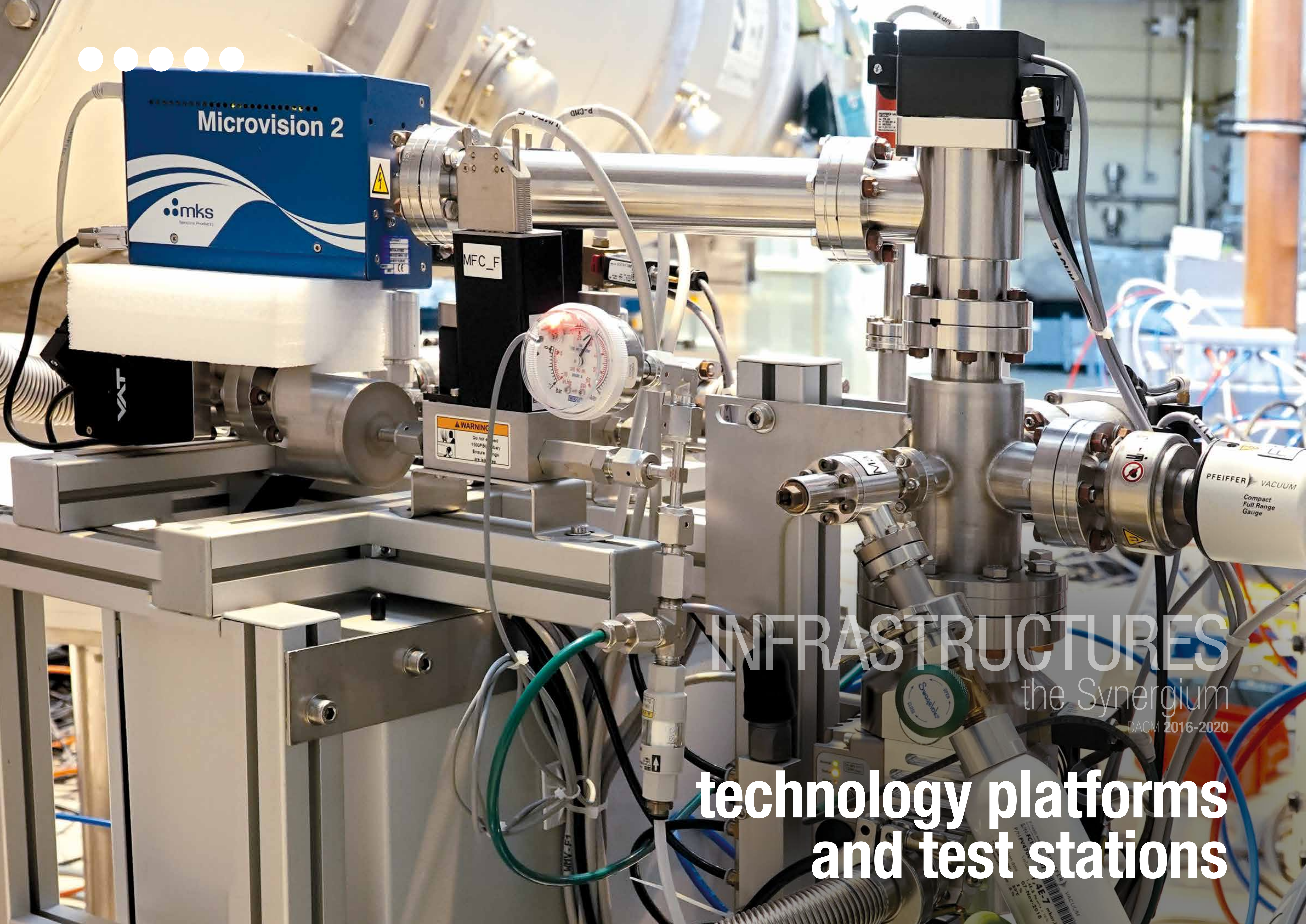


Evolution of the PHP pressure (—) and of the temperatures of the evaporator (—), of the condenser (—) and of the adiabatic part (—) during a test with an increasing heat load at the evaporator from 5 to 55 W.

INFRASTRUCTURES
the Synergium
DACM **2016-2020**

• Technology platforms and test stations

• Laboratories and workshops



INFRASTRUCTURES

the Synergium

DACM **2016-2020**

technology platforms and test stations

The High Intensity Proton Injector (IPHI)

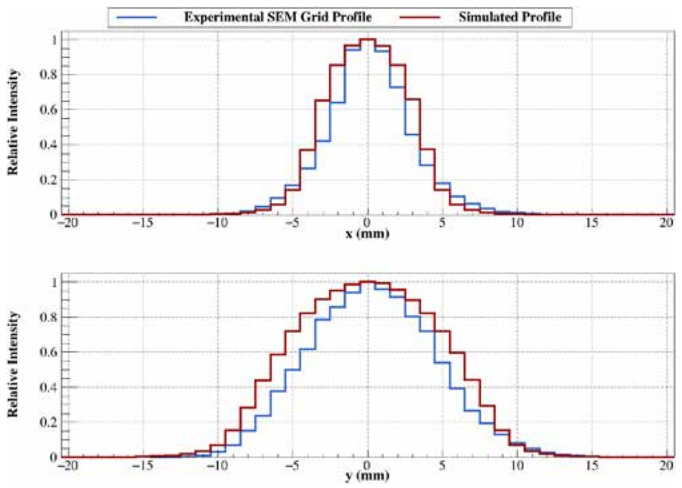
The High Intensity Proton Injector (IPHI) is used to develop and test diagnostics and perform beam dynamics studies. This accelerator can also be used as a neutron source. Its main component is an RFQ (Radio Frequency Quadrupole) capable of accelerating a proton beam from the energy of 100 keV to 3 MeV. The RFQ beam commissioning was achieved in two main phases.

Phase one consisted of accelerating the beam at low duty cycle (5%) in order to characterize it at the exit of the RFQ using diagnostics such as secondary ionization profilers. The 50 mA peak intensity beam profiles were measured and then compared to beam dynamics simulations, which take into account the entire accelerator up to the profilers. A quite satisfactory consistency was observed between measurements and simulations.

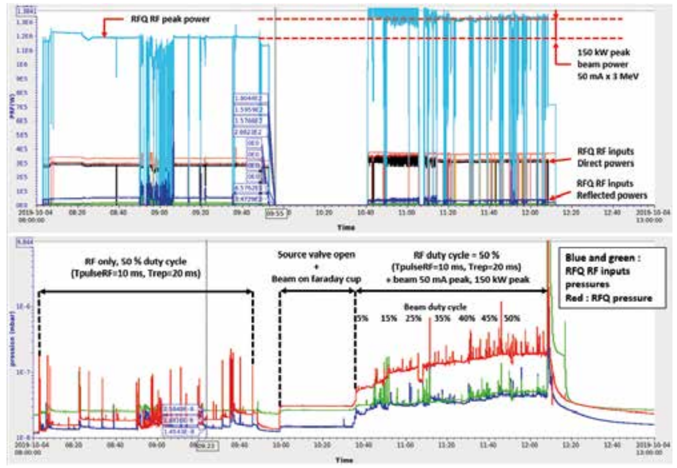
Phase two aimed at increasing the RFQ duty cycle to offer stable operation of the beam at a higher power. The beam intensity was set to 50 mA and the duty cycle was gradually increased. Two weeks of conditioning were necessary to move from the duty cycle of 5% to 50% in a stabilized manner, by minimizing the number of breakdowns. Radiofrequency power was set to around 1300 kW. This conditioning was carried out first without beam, then with beam. The beam was transported to a cooled beam dump. The temperatures measured at four points of this beam dump confirmed, by calculation, the power of the beam actually transported to the dump. During these experiments, a beam power of 80 kW was reached. The objective was to be able to routinely deliver a stable beam of 50 kW.

The IPHI proton beam was also used for experiments in the ARIES program, including those carried out in October 2018 dedicated to testing an instrumentation used for measuring beam positions, a BPM designed by the ESS Bilbao consortium for the ESS (European Spallation Source) neutron source installed in Lund, Sweden. These tests revealed improvements to be made on the BPM system that must be implemented before final manufacture of all electronic units begins, in order to improve their performance.

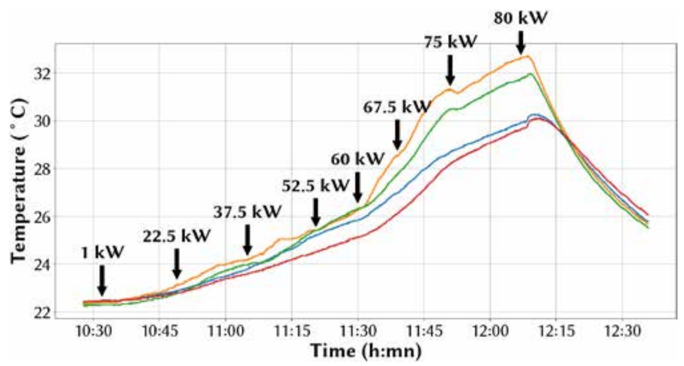
During the 2019-2020 period, an R&D program focused on irradiation tests of beryllium targets for the production of neutrons, part of a design study for a compact neutron source for the French SONATE project. Five targets were tested for a total duration of approximately 250 hours. Two targets successfully operated for approximately 100 hours each, with a total beam power of around 3.5 kW. One of the targets has been tested up to the power of 5.5 kW.



Measured (blue) and simulated (red) beam profiles in the horizontal (or x-plane, top) and vertical (or y-plane, bottom) planes.



First IPHI duty cycle increase, from 5 to 50%, for a 50 mA peak intensity and 150 kW peak power.



Temperatures recorded on the IPHI beam dump during an experiment to increase beam power.

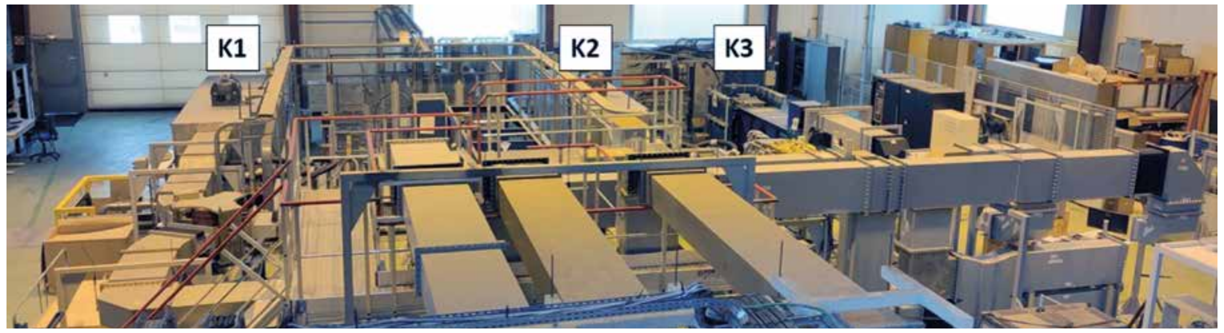
352 MHz radiofrequency platform

The 352 MHz Radio Frequency (RF) platform can generate and deliver RF power at a frequency of 352 MHz for operations, power tests, and RF conditioning of accelerator structures. It is equipped with:

- Two continuous klystrons (TH2089B Thales) (K1 and K2), each capable of delivering 1.3 MW of power.
- A pulsed klystron (TH2179A Thales) (K3) with a peak power of 3 MW, capable of delivering 240 kW of average RF power, with a pulse durations between 10 and 3600 µs, and a frequency repetition of between 1 and 50 Hz.

During the 2016-2020 period, the 352 MHz RF platform enabled:

- Coupler conditioning tests for ESS Spoke cavities.
- Power tests of the couplers for the ESS RFQ (Radio Frequency Quadrupole).
- Power tests of RF windows for the ESS DTL (Drift Tube Linac).
- Conditioning of the RFQ (of the IPHI (High Intensity Proton Injector) up to the duty cycle of 50 %.
- The operation of IPHI up to the duty cycle of 30 %.



352 MHz platform with its 3 klystrons.

Assembly hall 124 North

The XFEL village, where 101 cryomodules had been assembled as of 2016, was refurbished in 2017 to accommodate the assembly of two prototypes and 30 serial cryomodules for the ESS project. Four assembly stations are integrated, following the assembly of accelerator cavities in the clean room.

The cavities are aligned and assembled on a rail, allowing transfer from the clean room to hall 124N. The rail ensures and maintains the precise alignment between the elements, as well as the connection between them, without restriction, to prevent any leakage from the beam vacuum. In the hall, a series of stations are used to equip the cavity train with its cold tuning systems, instrumentation, helium circuitry, and magnetic shielding. The cavity train are then transferred to a second rail for insertion into the vacuum chamber. The cryomodule is then equipped with its external interfaces, ready for testing and/or transport to ESS.

During 2017-2018, the Medium Beta Cryomodule Prototype (MECCTD) was assembled and tested, thereby validating the tools, workstations, procedures, and test station. In 2019, a high-beta cryomodule prototype and a medium-beta series cryomodule were assembled. At the same time, the CEA hosted and trained the B&S company, a subcontractor selected to carry out series assembly. During 2020, operator training continued on the first two series of medium-beta cryomodules. The B&S team will assemble 27 cryomodules at the rate of one cryomodule per month.

A medium-beta cavity train exiting clean room to hall 124 North.

SupraTech-Cryo/HF

New 704 MHz Thales klystron.

The Supratech Cryo/Hyper-Frequency (SCHF) test platform plays a central role in the development and validation of key subunits of superconducting particle accelerators at DACM.

Ongoing adaptation of SCHF infrastructures to project needs has greatly contributed to IRFU's successful participation in international accelerator projects including IFMIF, ESS, and SARAF. This platform will soon be used for the PIP-II project. R&D activity on superconducting accelerating cavities also benefits from this platform for use in internal programs and international collaborations. It provides support for the detailed analysis and the improvement of processes and surface treatments.

During the 2016-2020 period, many objectives were achieved. This is evidenced by the performance validation of the following accelerator subassemblies:

- The cavities of the IFMIF- EVEDA cryomodule, in Vertical Cryostat (VC).
- The IFMIF cavity equipped with its Power Coupler (PC) in a Horizontal Cryostat (HC).
- “Medium Beta” (MB) and “High Beta” (HB) ESS cavities manufactured by IRFU in VC.
- The two ESS prototype cryomodules, MB and HB, as well as the first cryomodule of the MB series.
- ESS MB and HB couplers: prototypes, pre-series, and part of the series.
- The prototype “Low Beta” (LB) cavity at SARAF in VC then in HC with its power coupler.
- The first LB SARAF series cavity.

This increased scientific activity was accompanied by a strong activity of implantation and upgrading of equipment and infrastructure. A list of the main improvements made to SCHF between 2016 to 2020 for the benefit of the projects is presented below:

- RF conditioning of 120 ESS couplers in conjunction with the cryomodule tests required for the installation of a new 1.5 MW pulsed Thales Klystron, operating at 704 MHz, in addition to the existing CPI klystron. A gray room dedicated to the two coupler test benches was also built and fully equipped.
- Cryomodule tests required the installation of a control/command room and instrumentation cabinets in addition to RF power and cryogenics equipment.
- The HC tests for the IFMIF and SARAF cavities were installed respectively in the CryHolab and “CV1” test areas, which required new arrangements of the casemates and the surrounding area to accommodate the respective cryostats, ECTS and SATHORI, and the installation of new power sources.
- The performance requirements of the cavity tests motivated the implementation of a new removable magnetic shielding adaptable to all inserts in the “CV2” test zone.

In line with IRFU's strategy, SCHF will continue updating its equipment, including:

- Specification of a new cold box with greater helium production capacity.
- Ordering two hermetic pumping units to reduce helium gas needs during pumping of helium baths in cryomodules.
- Upgrading the control/command automation network architecture of the cryogenic system.

ESS cryomodule in its bunker during a high-power RF test at 2 K.

Controlled Atmosphere Zones at DACM

For the DACM, controlling particulate contamination is essential to protecting complete, industrially-produced beam line assemblies with cavity trains and their accessories.

To this end, DACM has two Controlled Atmosphere Zones (CAZ) on the Supratech Cleanroom/Chemistry platform dedicated to cavity and cryomodule assembly activities.
The 124 NORD Clean Room is 190 m² in surface, 112 m² of which are ISO class 4 (class 10).

In 2016, it was the site of 101 12-m cavity train assemblies (eight RF superconducting cavities at 1.3 GHz) for the XFEL (European X-ray Free Electron Laser) project; and the launch of the ESS (European Spallation Source) project, with 32 trains of four 704-Mhz cavities to be assembled.

Between the two projects, modifications were made to adapt all tools to the new dimensions of the ESS cavities, and a new station for assembling couplers on their conditioning boxes was created in the ISO class 5 zone.

In 2018, new autonomous, automated pumping units were installed for vacuum operations with reduced contamination (see chapter on R&D).

The 124 EST Clean Room is 90 m² in surface, 52 m² of which are ISO class 5 (class 100), and includes a high-pressure rinsing installation (0.04 µm final filtration). It is dedicated to R&D activities and the SARAF project, which began development in 2018. A new workstation for coupler conditioning and cavity or coupler assembly has also been implemented.

8 XFEL cavity train during clean room assembly.

4 ESS cavity train exiting clean room prior to its insertion into the external cryostat.

Test facility for the MQYYM quadrupole

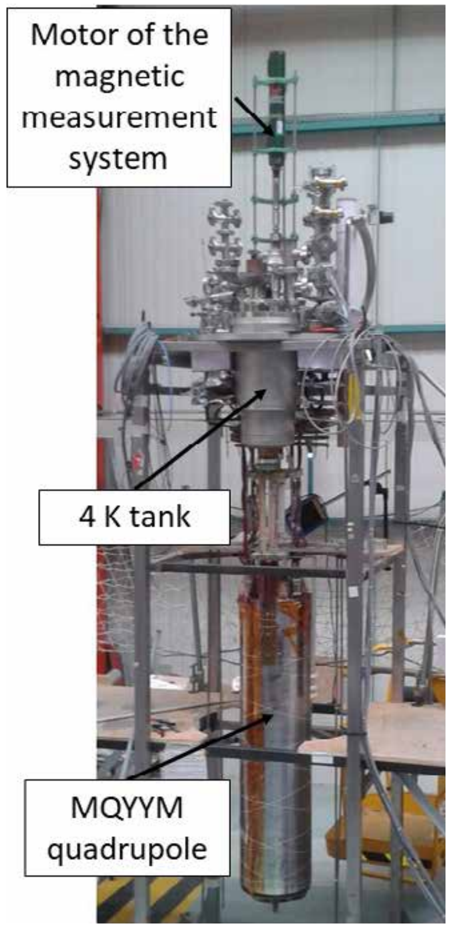
New superconducting magnets are being studied to address the need to increase the luminosity of the LHC (HL-LHC) at CERN. DACM is involved in a collaboration with CERN for the development, design, manufacturing, and cold testing phases of a single-aperture NbTi quadrupole called MQYYM.

DACM is responsible for developing a dedicated test facility to achieve genuine operating conditions for the magnet in order to characterize it (4550 A at 4.2 K / 5925 A at 1.9 K). This station has been developed using existing elements: the three-meter-deep vessel receiving the magnet, the associated cryogenic instrumentation (such as flow or helium pressure regulation valves), the 20 kA power supply, and a magnetic safety/acquisition system for the magnet.

Cryogenic instrumentation has been adapted to temperature requirements, with the installation of a pumping unit with a capacity of 1.1 g/s at 1.9 K. Safety and acquisition systems have also been adapted to the magnet's operating characteristics (inductive coil and acquisition channels). The communication interface and the cryostat monitoring system have been upgraded to fulfill the new requirements of the installation.

In the center of the top plate, an external cryostat motor drives a rotation shaft through a sealed connection. Attached to this shaft is a magnetic measurement probe made up of several coils that rotate in liquid helium at 1.9 K. The centering and guidance on either side of the magnet must allow for a precise rotation frequency of one hertz. The cool down of the magnet, in November 2020, noted a slope of 2 K/h with a maximum temperature gradient of 20 K between the top and the bottom of the magnet. From 95 K to 4.2 K, the magnet consumed 1700 liters of liquid helium. Without current in the magnet, the heat input to the cryostat consumes 15 l/h at a constant level. The consumption of the two resistive current leads (20 years old), measured during test operation, is 4 W/kA. This high load requires a significant helium mass flow to maintain the voltage at the terminals of these current leads at a value lower than 20 mV.

The selected cryogenic option involves operating in liquid helium cooled, at saturation, to 1.9 K, with a pressure of 23 mbars. The cryostat consists of a new support plate on which the 1.5-ton magnet is suspended for immersion in the liquid helium tank. The cryostat is equipped with an internal heat exchanger in liquid nitrogen, allowing the temperature of the magnet to drop to 95 K.



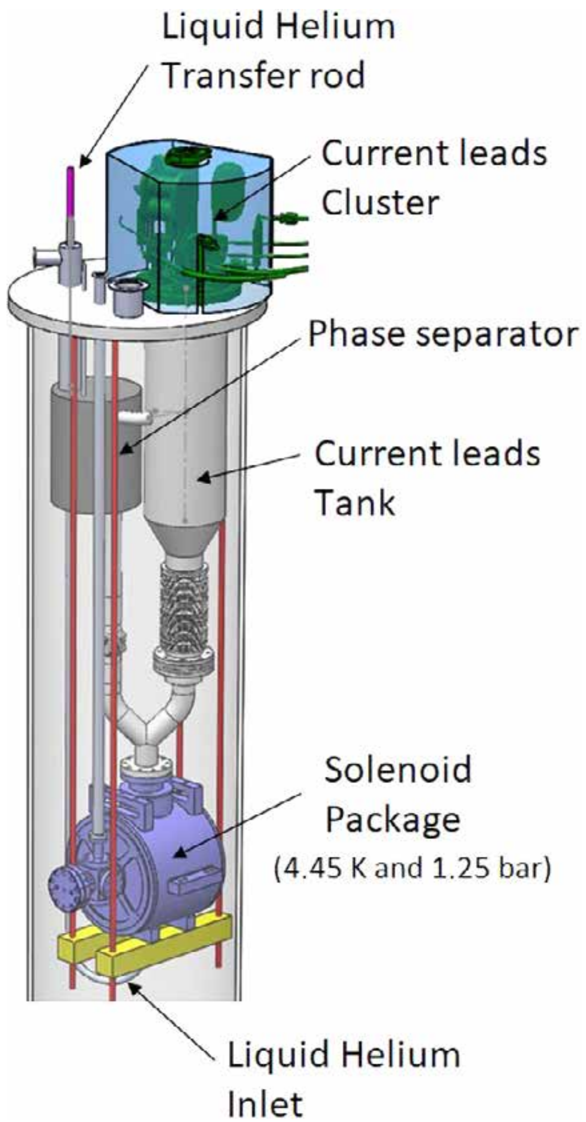
Test insert for the MQYYM quadrupole.

During this campaign, one of the busbars quenched at 1400 A, which brought magnet characterization to a halt. The initial results obtained on the mechanical and magnetic aspects are in accordance with the simulations carried out. The next campaign, scheduled for spring 2021, will be limited to tests at 4.2 K with two new busbars without a "4 K" tank nor a tight feedthrough. In summer 2022, the magnet will be tested at 1.9 K pressurized to 1 bar in the new STAARQ (Station Test Aimant Accélérateur Quadripôle) facility, currently under development.

The SARAF Solenoid test bench

As part of the SARAF superconducting accelerator that CEA has committed to deliver to Soreq in Israel, a cryogenic test bench has been developed to test the Solenoid Packages under operating conditions within the accelerator.

The 20.1-m-long superconducting Linac of SARAF (Soreq Applied Research Accelerator Facility) is composed of four cryomodules, each housing a given succession of accelerator cavities and solenoid packages. There are a total of 20 identical Superconducting Solenoid Packages. Each is composed of a solenoid, which acts as a lens to focus the beam; an instrumentation to measure the position of the beam; and two steering magnets to center this position on the theoretical axis, both horizontally and vertically. The solenoid is connected to two shield coils located at its extremities, to minimize the magnetic field leakage. The maximum magnetic field is 5.8 T. Each Solenoid Package is 34 cm long, including end bellows and flanges. The magnets are powered by a cluster composed of six current leads made of brass, in which gaseous helium circulates.



The SARAF solenoid test bench.

A specific cryogenic test bench was built to validate 23 Solenoid Packages (20 for the accelerator, plus one prototype and two spares) and their current supply clusters. Each magnet, made of NbTi superconducting wires, is tested one by one at a temperature of 4.45 K and a pressure of 1.25 bar in liquid helium. Four temperature sensors record the thermal evolution of the test bench. The pressure of the helium bath is regulated using automatic valves, and several mass flow meters are placed at the outlet of each current lead and at the exit of the cryostat to optimize helium consumption. The maximum currents supplied by three generators to the solenoid coil and to the correcting magnets are respectively 91 and 25 A. In addition, a National Instrument data acquisition system records the electrical behavior of 32 voltage taps using LabVIEW software. The magnetic field is also recorded with eight 3D Hall-Effect sensors, six inside the beam tube along the axis, and two outside the helium tank near the corrective magnets, to monitor residual magnetic fields.

Compliance tests are carried out to verify that each magnet is capable of producing a magnetic field greater than the recommendations. For these magnets, the movements of superconducting wires during the first increases in current induce premature quenches. Several successive ramp-ups must be carried out before the nominal current can be safely reached. On the other hand, the steering magnets can reach their nominal current from the first power-up. Finally, multiple configurations combining different solenoid fields and steerer fields were tested in order to guarantee safe operation on the accelerator.

Cryogenic Test Stations

DACM is equipped with several cryogenic stations designed for the characterization of materials and fluid flows.

MECTIX - MEASUREMENT OF THE THERMAL CONDUCTIVITY OF INSULATORS AND CONDUCTORS

This station, which has been greatly improved and automated in recent years, has a cryogenerator-cooled variable temperature measurement cell for carrying out thermal conductivity measurements using either the differential or the integral method on samples of around 10 cm in length in a temperature range from 4.2 K to 300 K. Various components used in the composition of accelerator magnets have been characterized here as part of two collaborations with CERN (CMA+ and contract KE2736/TE/HL-LHC).

Measuring cell at the MectiX test station.

THERMAUTONOME

This station is a closed circulation loop with recondensation by means of a cryogenerator for characterizing single-phase and two-phase flows by measuring pressure drops and wall temperature increase along a 30-cm vertical test section. Cryogenerator: 1.5 W at 4.2 K. Fluid pressure: from a few mbars to 3 bars. Temperature: from 3 K to 30 K. Max power in the loop: 20 W. The WAVE (Wide Angle VEctor magnet) cooling system was studied and validated on this station, with the support of the program Area of Major Interest in Astrophysics and Conditions of the Appearance of Life Domaine (DIM ACAV, Île de France).

PANAMA – SPECIFIC HEAT CAPACITY MEASUREMENT

This new test station, equipped with a variable temperature measurement cell cooled by a pulse-tube cryogenerator, is used to measure the specific heat capacity of solid materials in a temperature range of 4 K to 300 K. It accepts samples with a maximum volume of approximately 30 cm^3 for a mass between 10 g and 300 g. Different "reference" materials are being characterized to validate the test station. The project is funded by Labex P2iO (Physics of Two Infinities and Origins Labex) at Université Paris-Saclay.

Measuring cell at the Panama test station.

THERMOSIPHON

This station is an open circulation loop with a reservoir for characterizing single-phase and two-phase flows by measuring mass flow rates and qualities, pressure drop, and wall temperature increase along the wall of a 1.2 m vertical test section and a 0.4 m horizontal test section. A mass flow rate of liquid helium from 0 to 22 g/s can be measured and for gaseous helium up to 8 g/s. The same characteristics for liquid nitrogen are 0 to 40 g/s and for gaseous nitrogen up to 40 g/s. Power dissipation in the loop is on the order of 1 kW. Recently, the super-ferric dipole cooling system of the Super-FRS project for FAIR (Facility for Antiproton and Ion Research, Germany) was studied and validated here.

DOUBLE BATH

This station is a cryostat using the Claudet double bath principle for carrying out thermal studies on static pressurized superfluid helium up to a power of 10 W. At 1.8 K its useful volume has a diameter of 250 mm and a height of 300 mm. As part of EASITrain (European Advanced Superconductivity Innovation and Training) and in collaboration with CERN, studies on heat transfer in confined environments are underway.

DiVA and LIDO Laboratories

The DiVA and LIDO laboratories provide test stands for the characterization of DACM accelerator components with respect to vacuum and assembly.

The DiVA (Diagnostics, Vacuum and Assembly) laboratory, which extends over an area of 170 m^2 with a regulated temperature of 21 ± 3°C, supports DACM's R&D and projects with respect to vacuum, diagnostics, and assembly. The lab is equipped with the following test benches and equipment:

- Outgassing test stand: Composed of a NW200CF chamber (250 mm high, in accordance with the NF ISO 21360-1 standard) for the characterization of materials or components under vacuum and their treatment/cleaning using the throughput method. With a bake-out temperature of up to 300 °C and equipped with a residual gas analysis, outgassing flow can be measured from 10^{-4} to some 10^{-10} hPa.l.s^{-1}.
- Vacuum furnace: With an effective internal volume of 200 x 200 x 200 mm the furnace can be heated up to 1100 °C under vacuum at about 10^{-5} mbar for thermal treatments and brazing processes.
- Vacuum chambers: With bake-out temperatures of 130 and 300 °C., this is instrumented with gauges, a residual gas analyzer, and thermocouples, and is equipped with various turbomolecular, ionic, and getter type pumps, which can reach pressures as low as 10^{-11} hPa. For leak, bake-out, and outgassing tests on all types of components and pumps, up to NW300CF.
- BPM (Beam Position Monitor) bench: for characterizing sensitivity and linearity, and determining the electrical center in relation to the mechanical center.
- Assembly marbles, including one non-magnetic marble and one large marble.

During the 2016-2020 period, DiVA laboratory equipment was used extensively for DACM's accelerator projects, on both warm parts, such as sources, RFQs and the medium energy lines, and on cold parts, such as cavities and cryomodules. Including:

- ESS: Multiple leak, hydraulic, and assembly tests of the RFQ and related components such as couplers, tuners, pick up, etc.
- IPHI/SILHI: Mounting and testing of chambers and diagnostics such as the Wien filter, Scanning Electron Microscopy (SEM) grids, and Ionization Profile Monitor (IPM).
- SARAF: BPM tuning and leak tests, desorption measurements of a solenoid, a Faraday Cup, and ACCT.
- SONATE: Assembly and vacuum tests of targets.
- R&D: ALISES III (Advanced Light Ion Source and Extraction System 3) proton source assembly, beginning of heat treatment for R&D cold cavities, tests of EMIT4D (4-Dimensional Emittance Meter), and material desorption measurements.
- LIDO: Measurements of the plasma temperature and electron density in an ECR (Electron Cyclotron Resonance) source without particle extraction.
- External: Outgassing measurements of samples for industry.

The LIDO (Laboratoire D'intégration des Diagnostics Optiques) laboratory is a windowless room that can receive Class 4 lasers (power less than 500 mW). The BEEP (Banc d'Essai et d'Etude du Plasma) experiment is currently installed there to characterize the plasma of an ECR source using Thomson's laser-plasma interaction by diffusion. Measurements of the electronic temperature and density of an ECR source without particle extraction have been performed in the LIDO by the Institut de Combustion, Aérothermique, Réactivité et Environnement (ICARE) laboratory based in Orléans.

The DIVA lab with, from left to right, a vacuum chamber, the outgassing test stand, marbles, the BPM bench, and the vacuum furnace.

From left to right, the Faraday Cup of the SARAF project, the vacuum furnace, and outgassing measurement results.

Insulation Laboratory

The insulation laboratory provides technical support and makes its equipment available for projects: a winding machine (max Φ 400 mm x L 600 mm), ovens and furnaces, a chemistry lab with extraction hoods and ultrasound tanks, a room certified for use in potentially explosive atmospheres (ATEX), and equipment for room-temperature characterizations (tensiometer, rheometer, pycnometer). Among other things, the laboratory has participated in: winding, impregnation of prototypes or characterization samples, preparation of superconducting cables prior to characterization by the dissolving of aluminum or copper, use of resins and chemicals, and cleaning of parts.

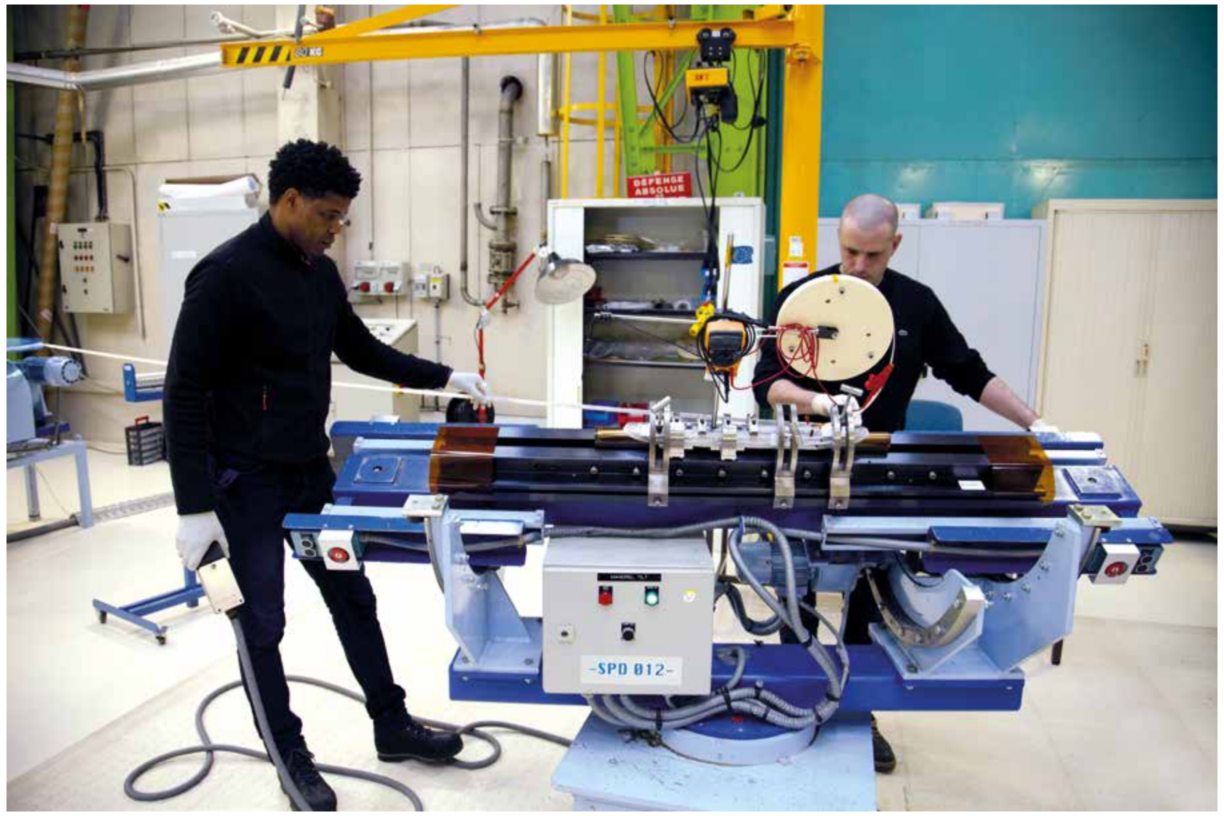
The insulation laboratory.

Superconducting magnet workshop

The workshop carries out the manufacturing of superconducting magnets with coils of limited dimensions (3.2-m long) in NbTi, Nb_3Sn, or HTS (High Temperature Superconductor) materials. It is equipped with multiple apparatuses including:

- Different winding machines equipped with brakes to control the mechanical tension of the conductor, including one with a double axis of rotation.
- A high-temperature (up to 800°C) furnace for heat treatment of Nb_3Sn coils (1.5-m long) under vacuum or neutral gas flow
- A 1500-ton hydraulic press equipped with a heating system for the polymerization under compression of polyimide-insulated coils.
- A vacuum impregnation bench for Nb_3Sn and HTS coils
- Geometric and electrical measuring and monitoring instruments for coils.

In 2018, the workshop was also equipped with a coil assembly system based on the so-called "key-and-bladder" technique as well as with a small magnet model for system validation.



Superconducting magnet workshop.

Mechanical workshop

The mission of the mechanical workshop is:

- To answer specific and urgent work requests when unexpected modifications or rework are required.
- To utilize the mechanical knowledge of its staff to provide technical assistance to various departmental projects (JT-60SA, MADMAX, SARAF, ISEULT, XFEL, IFMI, ESS, etc.), as well as to participate in the production of prototypes for various R&D activities.

To this end, it is equipped with a set of conventional machine tools, including: horizontal lathes, milling machines, drills, a plane-grinding machine, a band saw, and a guillotine shear. The workshop also operates a raw materials store for emergency repairs and work. Manufacturing of fibrous or powdery materials can be managed in a dedicated area of the workshop and is carried out while protecting personnel and machines from the dangers inherent in this type of manufacturing.

Mechanical workshop.

Mechanical test laboratory

The mechanical test laboratory can perform measurements under traction, compression, flexion, shear, and slippage at 300 K and 77 K (liquid nitrogen), and 4.2 K (liquid helium) cryogenic temperatures to determine mechanical characteristics (modulus of elasticity, elastic limit, breaking load, rupture elongation, ductility, and sliding coefficient) of metals and composites (synthetic composites or highly anisotropic compounds such as superconductors) as well as the behavior of complete assemblies compatible with the size of the test bench.

The laboratory has:

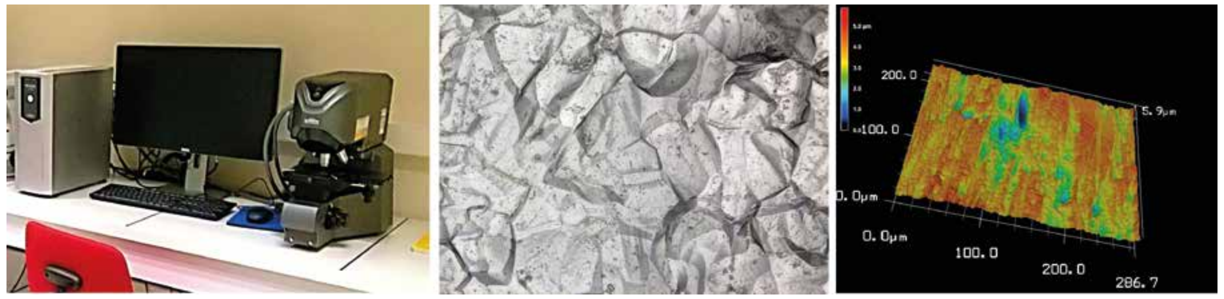
- A hydraulic press with a compression capacity of 1600 kN.
- An Instron electromechanical machine with a traction and compression force of 300 kN.
- An Instron electromechanical machine with a traction and compression force of 150 kN.

Force transfer system (welded ball and sliding tube) on the Nb_3Sn strand.

The latter can be fitted with two cryostats for tests at cryogenic temperatures: one with a traction and flexion capacity of 45 kN, and the other with a traction capacity of 80 kN and a compression capacity of 150 kN.

The largest campaign during the 2016-2020 period focused on characterizations of Nb_3Sn strands via a new test protocol based on an original force transfer system on the strand via a welded ball and a sliding tube.

LABCAS



From left to right: confocal microscope from the PANAMA platform, laser interferential image, and 3D reconstitution of a measured surface.

The Surface Characterization Laboratory (LABCAS) is a platform accessible to everyone in the department and equipped for sample preparation (cutting, resin mounting in a fume hood, mechanical polishing) and immediate observation of samples (optical microscope and camera-equipped binoculars). For more in-depth observations, these samples can be studied on the PANAMA platform, shared by the accelerator laboratories at Paris-Saclay University, where equipment for carrying out more advanced techniques can be found: SIMS, interference microscope, and Scanning Electron Microscopy (SEM).

Onsite, we also have additional characterization resources, including micro-hardness testers, mobile and fixed endoscopes, and a resin deposition system for surface replication.

Some of the LABCAS equipment: in the foreground, vacuum oven, then endoscope, and in the background, optical microscope and binocular magnifier, and micro-hardness measurement.

ALD laboratory

The Atomic Layer Deposition (ALD) laboratory has a research bench dedicated to optimizing conditions for the growth of thin films on samples, and is in the process of implementing a development bench that will serve to deposit films on macroscopic objects. Applications range from the fields of accelerators and detectors to nuclear power and Qbits.

The ALD technique is a synthesis method based on self-limiting and sequential surface chemical reactions between chemical products in vapor form, called precursors. ALD enables layer-by-layer atomic growth and exceptional conformality, both in terms of composition and thickness, on objects with complex geometries and large surface areas. This deposition technique, developed in the 1970s, is time consuming (between 1 Å and 1 nm per min) and is therefore reserved for the synthesis of films ≤ ~ 1 µm.

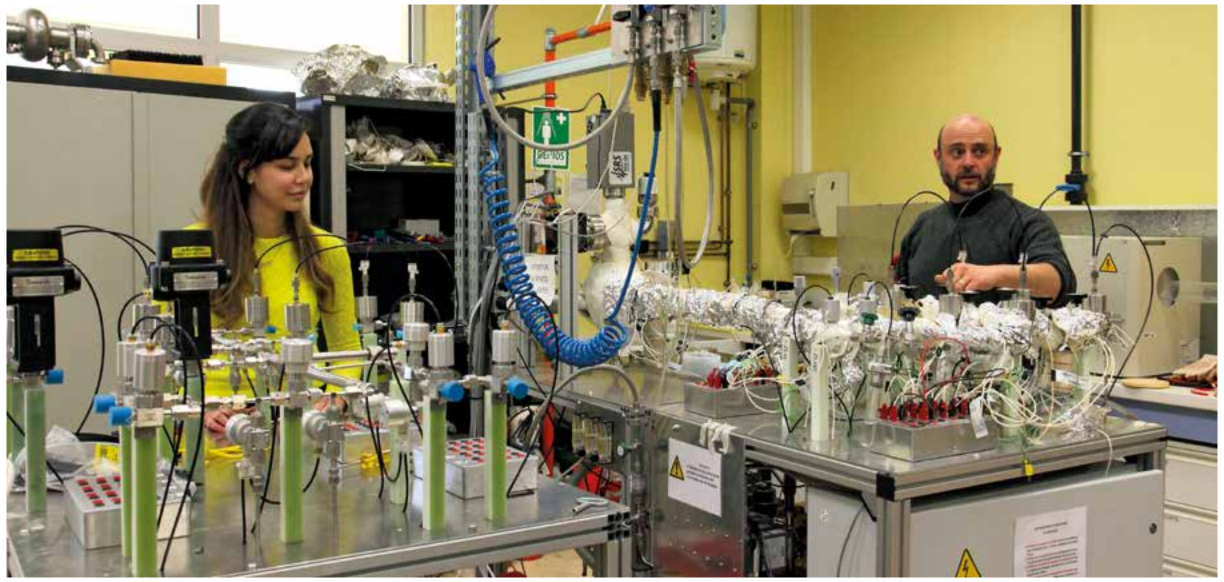
The ALD laboratory was created in 2017 thanks to European, regional, and internal funding. It includes two reactors.

A research reactor dedicated to the optimization of thin-film growth conditions and the study of new precursors/chemistries on samples. This reactor includes:
- A reactor/deposition chamber, 50 cm long and 5 cm in diameter, with an adjustable temperature of 30 to 500°C.
- Seven precursor distribution lines: three lines for solid precursors, which can be heated up to 200°C; two lines for gaseous precursors; and two for liquid precursors.
- One residual gas analyzer that enables in situ gas composition measurements.
- One quartz microbalance used to measure the growth rate of film in situ.

An applications-oriented deposition reactor designed to accommodate macroscopic objects. This reactor, which is under construction, is dedicated to scaling up processes once growth conditions have been optimized on samples. This ALD reactor consists of:
- One vacuum furnace that can reach 900°C and can accommodate large structures sensitive to air exposure at high temperature.
- Nine precursor distribution lines: five solid precursor lines, including one very high temperature line (500°C); two gaseous precursor lines; and two liquid precursor lines.
- One residual gas analyzer.

The ALD laboratory is also equipped with:
- A glove box under inert atmosphere (N_2) for handling air-sensitive chemical compounds.
- A bench to measure film resistivity at room temperature.
- A tubularannealing furnace that can reach up to 1100 °C under a controlled atmosphere (Ar, N_2, O_2, Air, N_2-H_2).
- A binocular magnifying glass.
- An extractor hood.
- A bench under filtered laminar flow for manipulating objects sensitive to dust.

We are pursuing several research themes: the synthesis of thin superconducting films for applications related to particle accelerators and quantum bits, and the deposition of anticorrosion or passivation layers for applications in the nuclear and detector fields.
We have expertise in growing nitride and oxide alloys using ALD. It is also possible to synthesize other alloys and metals such as tungsten (W) and molybdenum (Mo).



ALD laboratory.

the
SUPPORT SERVICES
DACM 2016-2020

the
SUPPORT SERVICES
DACM 2016-2020

IT/secretariat

quality, safety and the environment

The DACM IT unit

The Information Technology (IT) unit provides DACM teams with all necessary hardware and services, and infrastructure for computing, and scientific and technical communication.

To carry out its research activities, DACM staff (research engineers, doctoral students, post-docs, and technicians) has access to scientific and office IT resources, both fixed and mobile. In 2020, this translated to 603 devices, including self-service equipment, in addition to connected devices for experiments and installation security. The IT team ensures a regular supply of equipment and its commissioning, while providing daily support to users onsite and those working remotely. The outbreak of the Covid virus in early 2020 required the application of new measures concerning equipment distribution to comply with distancing regulations, and with the need to supply laptops to staff members who were teleworking.

Working in close collaboration with the Electronics, Detectors and Computing Division (DEDIP) of the CEA, the IT unit manages DACM's various IT resources and secures these tools using the best means possible. To this end, the unit relies on the CEA's NIG608 charter to inform DACM staff of the rules governing best IT practices in order to guarantee the integrity and safety of the network and workstations.

DACM participates in several international collaborations. In order to facilitate communication abroad, the IT unit manages four videoconferencing rooms that enable the department to participate in these collaborations and exchange information with major international research institutes with speed and precision, and in a modern way. For internal communication, five interactive screens located in the DACM facilities keep staff informed in real time of news, highlights, and the arrival of newcomers.

Regarding services, the IT unit has long advocated a zero-paper policy and has initiated a systematic shift to paperless internal administrative documents (e.g., individual presence sheets) and imposes the use of electronic signatures. This greatly facilitates teleworking and the electronic transmission of documents within the department.

Secretariats

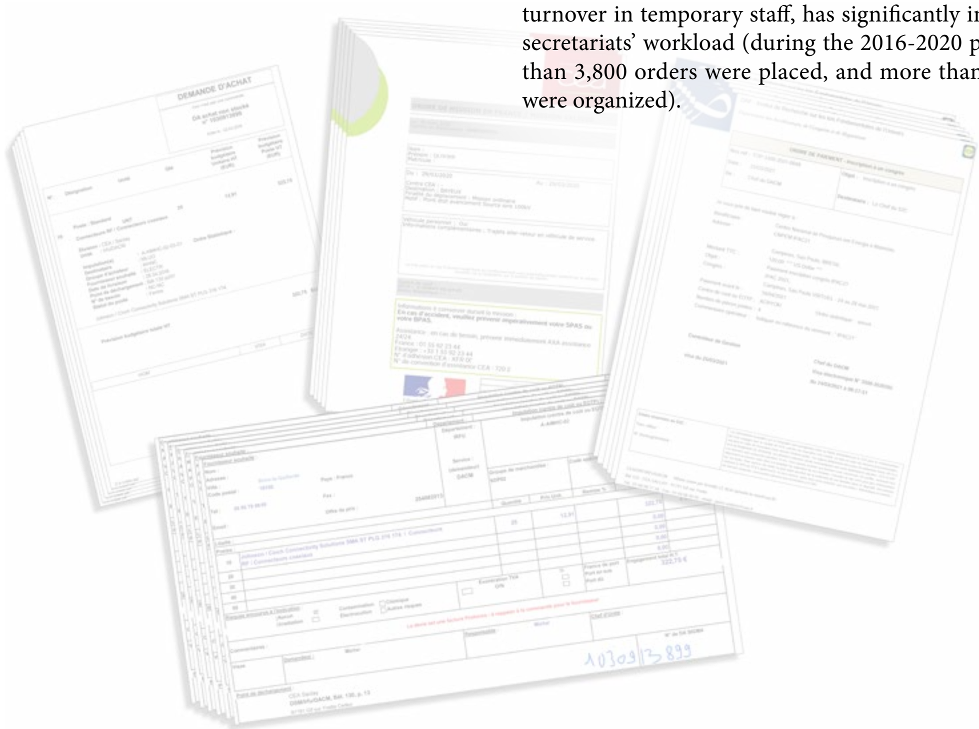
DACM's administrative team consists of three secretariats and one project assistant located in different parts of the facility. It supports the activities of department management and its staff regarding projects, orders, and missions.

The management secretariat, in charge of running DACM and directly involved in the activities of the department head, manages all general administrative tasks as well as the personnel files for DACM's permanent staff (124, in 2020). This office also orders office equipment and stationery supplies.

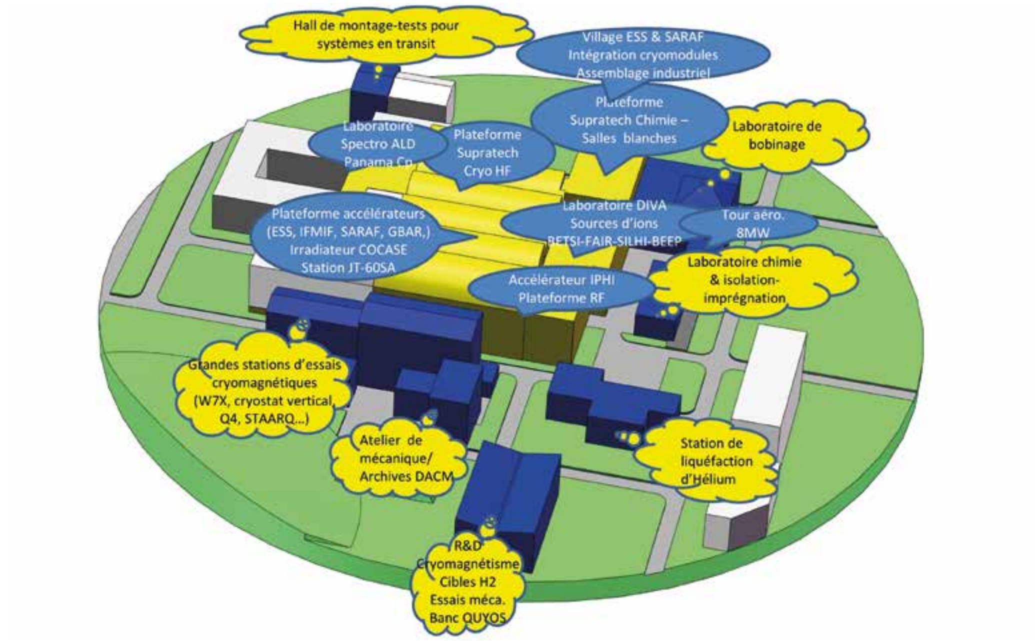
Two other technical secretariats, located nearest to the research teams, oversee laboratory activities and projects. The secretariat for cryomagnetism provides operational support for projects in the LCSE and LEAS laboratories. It also monitors temporary staff (staff on fixed-term contracts, doctoral students, interns, apprentices, and other collaborators). The secretariat for accelerators assists in the operational activities and projects of the LEDA, LISAH, and LIDC2 laboratories. Project support consists of preparing and formatting documents as well as filing paper and digital copies of those documents. The secretariats also provide assistance with conference organization and project development meetings onsite at Saclay.

In addition to overseeing the specific needs of each laboratory, the three secretariats also perform more general tasks such as handling mail, online SAP, Pacha and central store orders, visitor applications, on-call duties, and directory updates for laboratory personnel listings. Other important aspects that require working closely with staff concern the management of conference and congress registrations, the management of missions and their completion, as well as the reimbursement of expenses.

The increasing number of projects and staff, and a higher turnover in temporary staff, has significantly increased the secretariats' workload (during the 2016-2020 period, more than 3,800 orders were placed, and more than 2,700 trips were organized).



Prevention of occupational and environmental risks



DACM facilities 82 (in yellow) and 218 (in blue).

The very nature of DACM's activities exposes it staff and premises to all possible sources of danger: physical risks, chemical risks, electrical risks, fire risks, biological risks, human risks, environmental hazards, etc. To control these risks, the safety/environment team follows the prevention and protection measures recommended by the CEA. Particular effort is made to comply with labor, public health, and environmental regulations. Some activities require authorization from the Nuclear Safety Authority (ASN), the Regional and Interdepartmental Directorate for the Environment and Energy (DRIEE), and the French Senior Defense and Security Official (HFDS).

OVERVIEW

The DACM's two safety perimeters, facilities 82 and 218 at the Saclay site, cover an area of 50,000 m² in 24 buildings or similar technical areas. All activities are ISO 14001 certified and include five batches of facilities classified on environment protection grounds (ICPE). The DACM has an average workforce of 170 permanent and non-permanent employees. It can also accommodate a team of 15 to 30 people from industrial partners, depending on the project. DACM staff also work outside the 218 perimeter on projects including ISEULT (NeuroSpin), SPIRAL2 (GANIL), IFMIF (Japan), ESS (Sweden), and SARAF (Israel).

ORGANIZATION

The safety/environment team consists of an incumbent and deputy facility manager, a facility safety engineer and an assistant, and several safety coordinators. The facility safety engineer also performs the roles of environment officer, waste officer, and radioactive source manager. Because of the number of activities onsite, there are also 44 operations managers (incumbents and deputies) who are able to relieve the security team for certain missions. Safety management is carried out in conjunction with the site support teams: the local safety training team, radiation protection officers, occupational physicians, technical services, and the quality safety, and environment unit.

The many areas requiring coordination and the Land Use Plan (POS) are managed in collaboration with the managers, project leaders, and laboratory managers concerned. In addition, all new handling operations and experiment requests require prior authorization by the facility manager, at a minimum, which, depending on the case, may entail further instructions from the Local Safety Commission (CLS).

FACILITY 82

Facility 82 encompasses the LCSE and LEAS laboratories and the activities of the cryomagnetic test stations and the insulation/impregnation, winding, integration laboratories, and the mechanical workshop. The helium liquefaction station produces and manages an average of 150,000 liters of helium per year.

FACILITY 218

Created in 2005 after the SATURNE proton synchrotron basic nuclear facility 48 was decommissioned, facility 218 includes the experimental areas of the LEDA, LIDC2, and LISAH laboratories dedicated to developing and testing particle accelerator systems. The platform has major technical infrastructure: radiofrequency power sources (352 MHz and 704 MHz klystrons that can deliver 1.2 MW of RF power), ISO 4 and ISO 5 clean rooms, helium liquefaction at 4.2 K, 4 MW power supplies, an 8 MW thermal cooling tower, and highly toxic acid surface treatments (e.g. a mixture of hydrofluoric and sulfuric acid), among other things.

HIGHLIGHTS AND RESULTS

In terms of risk management, the highlights of the 2016-2020 period include:

- Neutron production experiments on the IPHI accelerator.
- Implementation of the prototyping and industrial production phases for the 30 ESS cryomodules.
- Development of test stations for SARAF cryomodule components.
- Start-up and reception at GANIL of the SPIRAL2 accelerator, previously tested at DACM.
- Creation of the Spectro / ALD laboratory – Panama/Cp.
- Testing and shipment to Japan of the 18 supra JT-60SA coils, including mechanical integration of the OIS.
- Evacuation of 1000 tons of "historic" nuclear waste to Andra (DES/EXOTI project).

DACM remains among the CEA/Saclay departments submitting the most requests for operating licenses from the CEA/Saclay CLS.

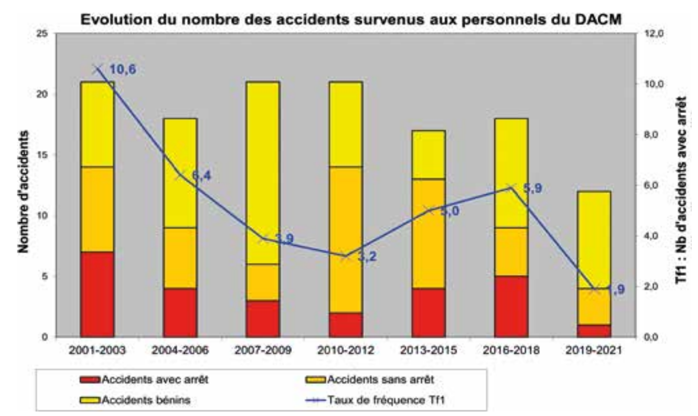
The significant volume of activity in terms of risk prevention is due to the ongoing development of halls and test stations to accommodate the many projects that are often in transit before being commissioned with external partners (CV1 & CV2, Cryholab, XFEL, SPIRAL 2, IPHI, IFMIF, GBar, COCASE, JT-60SA, ESS, SARAF, DES / EXOTI, etc.). For the past 15 years, this has resulted in many large-scale projects with significant concurrent activities that must be analyzed in order to control the associated risks.
In this demanding context, the safety results of the DACM are satisfactory in terms of accident frequency and severity, both for CEA personnel and staff from outside companies. The objectives of improving CEA's safety policy have been achieved over the period 2016-2020.

In the coming years, the main objectives are to:

- Promote DACM heritage.
- Improve safety results and maintain performance in terms of prevention.
- Optimize operation of the Synergium, a multi-project technological platform.
- Ensure the success of new and on-going IRFU projects (ESS, SARAF, IPHI-Neutrons, SATELIT, MADMAX, STAARQ, PIP II, etc.).

	TOTAL DACM 2016-2020
Safety cases CLS, ASN, ICPE, etc.	45
Safety visits	28
Safety exercises	7
Audits and inspections	17
Prevention plans and safety protocols	202
Fire permit	306
New arrivals welcomed	168
Employees in safety training	200
Operations & land use plan meetings	126
Shooting authorization	206

Volume of activity.



Safety results for CEA personnel.

Quality

Quality at DACM is based on the Quality Plan, which outlines procedures to be implemented, and the Electronic Document Management System, used to organize the management and storage of documents.

The quality unit is made up of two quality engineers who can rely on the help of other engineers or technicians according to project needs. Staff ensure that the quality system is deployed and supervise its application throughout the project. Particular attention is given to ensuring compliance and consistency with all of IRFU's quality measures.

The Quality Plan defines the quality objectives of the project as well as the organization and procedures put in place to achieve them. These plans share a common foundation, which is complemented by specific provisions adapted to the context of each project. They establish the quality management rules for all phases of the project, from design to manufacture, including the integration of equipment. To implement Quality Plans, they are defined as procedures (e.g., procedures for managing non-conformities, procedures for identifying components, etc.).The quality engineers organize meetings to inform teams about the quality approach and present them with monitoring tools. They also develop standardized documents for non-conformities, requests for modifications, minutes of meetings, technical reports, technical specifications, etc.

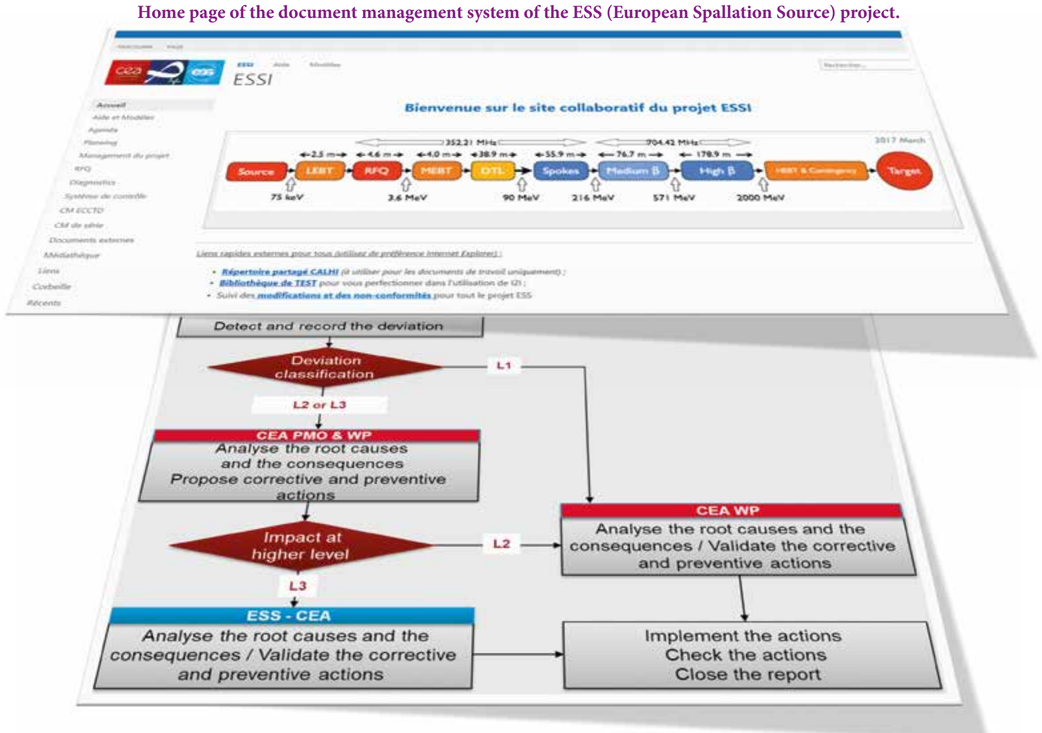
During the production and assembly phases, quality technicians and engineers ensure quality monitoring. They take part in the quality control of components and in the inspection of assemblies.

Quality staff is called upon to manage nonconformity reports and requests for changes. These documents are completed with information provided by project team members. The quality staff checks the documentation in close collaboration with technical experts, and ensures, when equipment is delivered, that the documentation provided to partners or customers is complete and consistent.

In recent years, several departmental projects have employed an Electronic Document Management System (EDMS) to ensure the long-term storage of documents. These EDMSs use the i2i platform chosen by CEA. EDMSs allow different versions of a document to be saved and optimize searches within and consultation of documents. Quality engineers were asked to design and deploy the system, as well as to train the teams in their use. On a daily basis, team members assisted by quality engineers, use the EDMSs to classify and number documents, which facilitates subsequent consultation during previously defined validation procedures. The electronic signature circuit after validation is also directly implemented in EDMS.

At the departmental level, there is an EDMS (https://ged-extra-sacm.cea.fr) available to the laboratories for archiving their documents. It is accessible to all department staff.

Home page of the document management system of the ESS (European Spallation Source) project.



Non-conformance management organization chart.

DISSEMINATING KNOWLEDGE

DACM **2016-2020**

Education

DACM staff regularly teach their fields of expertise in French and international schools, primarily at the Masters level.

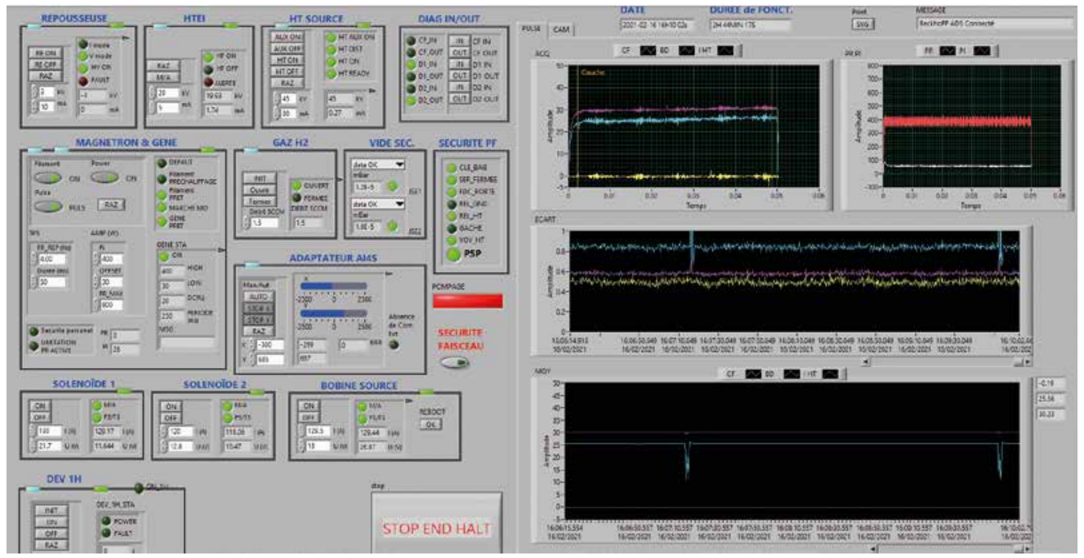
Accelerator physics and its associated technologies and methods are disciplines taught at Masters level (or the equivalent). This instruction is usually given jointly with particle physics or laser and plasma physics. Over the past five years, a dozen DACM researchers have completed roughly 630 hours of teaching (courses and tutorials) in the following areas:
- Electromagnetism
- Beam dynamics
- Microwave
- Superconductivity
- Cryogenics
- Project management

In addition, the experimental infrastructures of DACM, particularly those of the SYNERGIUM were used to provide nearly 200 hours of practical work in Master 2 on topics such as magnetometry, or the creation, transport, and characterization of low-energy protons carried out on the line known as BETSI (Study and Test Bench for Ion Sources). All teaching activities were primarily carried out for the following training courses:
- Master 2 NPAC (Nuclei, Particles, Astroparticles and Cosmology), Paris-Saclay University.
- Master 2 GI-PLATO (Plasmas Lasers Accelerators Tokamaks.
- Large Facilities), Paris-Saclay University.
- Master 2 coordinator of studies in the field of health, Paris-Saclay University.
- Master 1 and 2 in physics, Gustave Eiffel University.
- *"Licence professionnelle"*, Institute of Technology (IUT) of Orsay, Paris-Saclay University.

Scientific and technical recognition in a scientist's field of expertise can be achieved through the invitation to teach their discipline in thematic or summer schools. Several members of DACM regularly participate as teachers in French and international schools such as: the CERN Accelerator School, the European Advanced Superconductivity Innovation and Training (EASITrain) Summer School of Cryogenics, the European Society for Applied Superconductivity (ESAS) Train Summer School on Applied Superconductivity, the Accelerator School of the National Institute of Nuclear and Particle Physics (IN2P3), the Myrrha Research and Transmutation Endeavour (MYRTE) Accelerator School, and the thematic schools of the Association Française du Froid (AFF).

The following table summarizes the number of teaching hours provided by DACM members from 2016 to 2020. It should be noted that involvement in teaching has increased significantly during recent years.

TEACHING TYPE	NUMBER OF HOURS
Lectures and practical work (University/engineers school)	630
Practical Work	201
Thematic schools	54
MOOC (Massive Open Online Courses)	3



Screenshot of practical work in Master 2 on the BETSI line.

Communication

Products designed with communication, educational, and appealing objectives.

Communication at DACM relies on several components: a well-defined strategy, resources such as motivated staff, and a series of onsite locations open to visitors, as well as products and media designed and manufactured ad hoc.

PRINCIPLES AND STRATEGY

Despite its peripheral position, communication is inseparable from the DACM's core activities in science and technology. Beyond the pleasure of communicating the department's work to a large audience, the communication team also has the role of highlighting successful results, thereby justifying the human and financial resources invested in current projects and facilitating the procurement of these same resources for future projects.

With this in mind, discussions were conducted within DACM's communication team, and in conjunction with those of IRFU and Paris-Saclay University, with a view to optimizing the effectiveness of communication activities. This required identifying the different segments within the public that we address and defining the type of message that meets their expectations. Five categories were identified: the general public, young people, students, experts, and VIPs. We will endeavor to adapt our messaging according to the situation, placing more emphasis as needed on scientific explanations or on the societal utility of our work, the large scale of our equipment, and regional and international collaborations, as well as interactions with other research themes.

STAFF RESOURCES AND VISITING POINTS

Although managed by a few designated officials, outreach relies on the many enthusiastic department staff who spare no effort to welcome, explain, and present onsite, as well as in schools and establishments dedicated to spreading scientific knowledge. In addition to these regular activities, we participate to exhibitions and conferences organized on special occasions by the scientific, educational, and cultural organizations in the region.

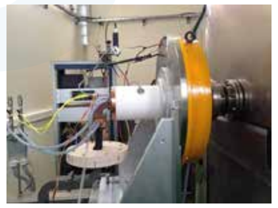
We have identified 13 points of interest likely to welcome visitors within the Synergium, our 25,000 m^2 technological platform: nine experimental areas hosting work on current projects and four specially designed outreach points. Specific circuits between these different points have been established, according to the type of audience and the time allocated. The influx of visitors is significant, around 500 per year.

PRODUCTS AND MEDIA

Over time, many products and media have been designed and produced to serve as effective, educational, and appealing material. These include posters and panels, 3D-printed models, leaflets and manuals, seminars for the general public, and films, including one in 3D virtual reality and one with 3D stereoscopic images. The use of such a variety of media has only been possible with the help of other departments such as DEDIP, DIS, and the IRFU communication team. External contributors, such as media professionals, were also called upon. These collaborations are to be strengthened in order to further improve the quality of the products produced and to assist scientists who have ideas to propose for outreach.

Selection of highlights

FEBRUARY 05, 2016



Innovation in the field of high intensity light ion ECR sources: ALISES II

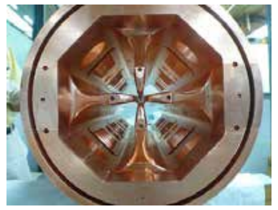
Since the 1990s, IRFU has designed, produced, and operated high-current ECR (Electron Cyclotron Resonance) light ion sources for various projects including IPHI, SPIRAL2, IFMIF, and FAIR. These sources produce intense ion beams with dynamics that require the shortest possible low-energy transmission lines (LBE), which are difficult to achieve due to the size of the sources. The ALISES II source offers an answer to this problem: a compact, high-intensity light ion source, it was developed in 2011 and has undergone continual improvement ever since. It is innovative for its "single-piece" structure, meaning electrical insulation is integrated into the source body itself.

APRIL 20, 2016

Commissioning of the injector of the IFMIF prototype accelerator in Rokkasho (Japan)

The injector of the IFMIF / EVEDA (Engineering Validation and Engineering Design Activities) project was inaugurated on April 21 in the presence of CEA General Administrator Daniel Verwaerde at the Rokkasho site in Japan. Designed and produced by IRFU teams, the injector consists of an ion source, a transmission line, and diagnostic systems. After being tested at Saclay in 2012, all the components were transferred to Rokkasho at the end of 2013 for integration into the accelerator. Between 2014 and 2016, the French and Japanese teams carried out numerous tests, first with protons and then with deuterons in order to verify the injector's capacity to deliver a beam of deuterium ions with an intensity of 114 mA and an emittance of 0.26 pi.mm.mrad. The beam size and divergence currently hold the world record!

MAY 18, 2016



First beam at 75 mA: the end of the tunnel is in sight for IPHI

For the first time, on April 11, the IPHI project demonstrated the feasibility of a proton injector accelerating a beam up to 3 MeV and targeting a direct current of 100 mA. Ultimately, the project will serve as a technological benchmark for the low-energy field of high-current accelerators. The IPHI injector is a demonstrator of the low-energy part of a high-current accelerator. As such, the prototype will provide technological references for the technical choices made regarding future accelerators. This project is being carried out in collaboration with CEA, IN2P3, and CERN.

MAY 24, 2016

JT-60SA: Annie on her way to Japan

Produced in Belfort by General Electric under the supervision of CEA / IRFM, the first toroidal field coil for the superconducting tokamak JT-60SA left Saclay for Naka on May 17 after undergoing a series of cryogenic tests carried by IRFU teams, who also installed the external support system. The coil was nicknamed “Annie.”

NOVEMBER 16, 2016

François Hollande inaugurates the new Spiral2 particle accelerator at Ganil, November 3, 2016

On November 3, 2016, the French president, Francois Hollande, inaugurated the Spiral2 particle accelerator ("2nd generation on-line accelerated radioactive ion production system) at Ganil, thus providing France with one of the five most important nuclear physics research infrastructures in the world. The project, led by the CNRS and the CEA, has received support from the French State, the city of Caen, the Caen-la-mer conurbation, the French department of Calvados, the region of Normandy, and the European Union. IRFU has been a major contributor since 2004.

MAY 12, 2017

Linac 4: a new injector for CERN

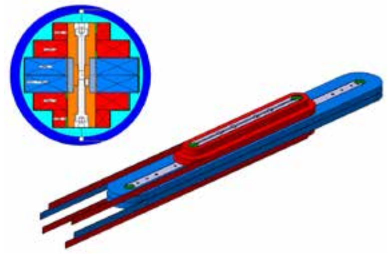
On May 12, 2017, CERN inaugurated a brand new linear accelerator, the Linac 4. Designed with contributions from French agencies CEA/IRFU and CNRS, the machine is the most recently built since the Large Hadron Collider (LHC). When it enters service in 2020, it will become the new first link in the CERN accelerator chain. It will provide proton beams for many experiments and enable the LHC to reach higher luminosity.

JULY 12, 2017

The ISEULT magnet is placed in its arch

On July 6, 2017, in the presence of Daniel Verwaerde, General Administrator of CEA; André Syrota, Advisor to the General Administrator; Claire Corot, Research and Innovation Director at Guerbet; Serge Ripart, Imaging Director at Siemens Healthcare France; and Gilles Bloch, President of the University of Paris-Saclay, the giant, 132-ton magnet designed for the ISEULT project officially integrated the NeuroSpin research infrastructure of the CEA center in Paris-Saclay (Essonne). ISEULT will produce a magnetic field of 11.75 teslas, nearly 230,000 times the Earth's magnetic field, and is the core component of the world's most powerful MRI (Magnetic Resonance Imaging) scanner developed for imaging the human brain.

JULY 27, 2017



A center field record achieved with 4.52 teslas in a high critical temperature dipole magnet

The DACM and DIS teams achieved a record magnetic field of 4.52 teslas at the center of a prototype dipole wound with a superconducting material at high critical temperature during tests in a liquid helium bath. This is 1 tesla more than the last known record set by the same type of dipole.

SEPTEMBER 01, 2017

September 1, 2017: inauguration and launch of the European XFEL project, a new generation of free electron laser

After eight years of construction and testing, XFEL, the European Free Electron Laser, officially began operating in Hamburg (Germany). Eleven countries contributed to constructing the infrastructure for a total budget of € 1.2 billion. In France, IRFU and IN2P3 have played a leading role in the design and construction of the linear electron accelerator necessary to produce a light source in the X-ray range, intended for use by European scientists in physics, biology, and materials sciences.

JANUARY 31, 2018

Nuclear fusion: French superconducting coils ready for the JT-60SA tokamak

Following validation of the latest toroidal field superconducting coils, CEA's involvement in the construction of the Japanese tokamak JT-60SA, designed to study nuclear fusion, is nearing completion. Ten of the twenty coils were manufactured by GE Power in Belfort, under CEA supervision. The coils, weighing nearly 16 tons each, will fly to Naka in mid-February to join the others and integrate the structure of the tokamak. These components are part of the project known as Extended Approach to ITER (International Thermonuclear Experimental Reactor), an international, nuclear fusion, civilian research reactor project currently under construction in Cadarache (Bouches-du-Rhône).

MARCH 28, 2018

SupraSense: a non-magnetic cryogenic device for surface micro-MRI

As part of the SupraSense research program, the IRFU-DACM Cryogenics and Test Stations Laboratory has developed an autonomous and non-magnetic cryostat which meets the need of clinical MRI installations for bringing resonators to their operating temperature of 60 K. This cryostat, with a structure mainly composed of polymers, is also innovative because it is cooled without cryogenic fluid.

DECEMBER 21, 2018

The first ESS accelerator demonstration cryomodule successfully passes the RF power test under ESS conditions!

After more than five years of development, including six months of integration to transform 12,000 spare parts into a complete cryomodule, CEA-IRFU validated the first measurements of this complex system at the nominal ESS accelerator field of 17 MeV / m in the four superconducting accelerating cavities that comprise it.

This key event took the project one step closer to producing the 30 cryomodules that France must deliver to this ESS research infrastructure, a future neutron source in Sweden that will be operational in 2023. This serial integration began in January 2019 under the supervision of IRFU, with the contribution of the company B&S France, and should be completed in 2022.

APRIL 16, 2019

World record: Nougat magnet operated at 32.5 teslas

Nougat, the high critical temperature superconducting insert (SHT), the result of a CEA-CNRS collaboration, has reached a central magnetic field of 32.5 teslas, setting a new world record in the field of high fields for a superconducting coil with a useful diameter of 38 mm. During the test campaign at the CNRS / LNCMI laboratory in Grenoble, the insert reached twice its nominal operating point of 30 teslas and operated for more than six minutes above this value, rising to a central magnetic field of 32.5 teslas, of which 14.5 were produced by the single superconducting magnet. Its innovative "Metal-as-Insulation" winding technology, developed by the IRFU team at CEA, solves the challenge of reconciling operating stability and protection in the event of quench (transition to the resistive state).

JULY 7, 2019

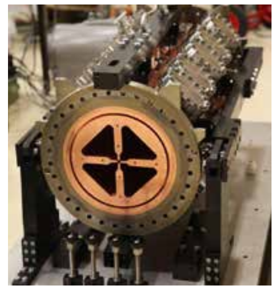
11.7 teslas: a magnetic field world record for an MRI magnet intended for use with the human body

The magnet developed for the ISEULT project, installed at Neurospin (CEA Paris Saclay), reached its nominal field of 11.7 teslas on July 18, 2019. This represents a world record for a whole body MRI magnet intended for use with the human body, capping off years of cutting-edge R&D in the field of superconducting magnets. Over the next few months, the equipment necessary to produce brain images will be installed around the magnet as well as within its central tunnel, effectively transforming it into a human MRI scanner capable of probing the brain to advance basic research and knowledge of the cognitive sciences, and the diagnosis of neurodegenerative diseases.

AUGUST 27, 2019

France delivers essential accelerator equipment to the ESS collaboration

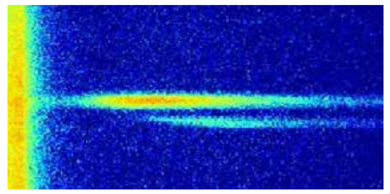
On August 27, 2019, the first accelerator structure, dubbed RFQ (radiofrequency quadrupoles), was delivered by France to the ESS (European Spallation Source) collaboration in Lund, Sweden, as part of its in-kind contributions to the new-generation European neutron source. This RFQ was designed, developed, and manufactured within IRFU by CEA, a French partner.



OCTOBER 10, 2019

First neutron scattering measurements on the "IPHI - Neutrons" source

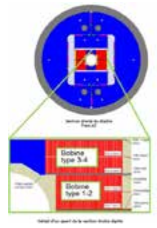
Thermal neutron scattering is a technique employed by nearly 8,000 users in Europe for the study of condensed matter and materials science. This technique entered something of a golden age in the 2000s, with the provision of nearly 35,000 instrument days for users. However, the European neutronics landscape is undergoing radical change as ageing research reactors are gradually decommissioned. A major facility, the European Spallation Source, is under construction in Sweden, but is not sufficient to replace the entire infrastructure represented by the current facilities.



OCTOBER 14, 2019

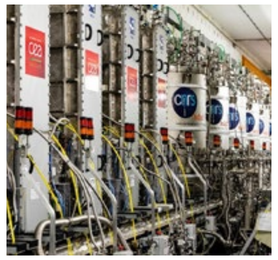
The FRESCA2 project ends on a high note with a record magnetic field of 14.6 teslas and 1.9 Kelvin

After winding, the seventh and last coil of FRESCA2 left Saclay in June 2019 in its reaction mold, bringing to an end IRFU's involvement with this project, which began in 2009 in collaboration with CERN. This type 3-4 coil is a spare coil, which, after reaction, instrumentation, and impregnation at CERN, will join the type 1-2 coils on CERN's shelves.



FEBRUARY 17, 2020

The successful commissioning of Spiral2 at the end of 2019

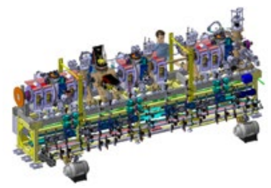


Following the authorization to commission Spiral2 issued by the Nuclear Safety Authority (ASN) on July 8, 2019, many crucial steps were successfully carried out at the end of 2019, notably the acceleration of an initial proton beam to 33 MeV, the nominal energy provided by the linear accelerator of Spiral2 (Linac), and a first test experiment in the experimental room Neutron For Science (NFS).
These initial results in 2019 were very promising and continued in 2020, in particular with increased performance for the Linac and an increase in beam power (10% of the maximum expected power). Test experiments in NFS were also carried out.

JULY 15, 2020

End of the qualification phase of the proton Linac injector of the FAIR project in Saclay

The proton injector of the FAIR proton Linac, which must be installed at the GSI in 2020, has been in the commissioning phase at Saclay since the end of 2017. The objective was to characterize the proton beam, which will be injected into the following acceleration stage, a "Ladder-RFQ" currently under construction at the University of Frankfort. The injector was able to produce a beam with a total intensity of 140 mA with 120 mA of protons transported to the end of the low-energy line. The beam emittance measured after the entry cone of the RFQ is superior to the required specifications, with a normalized value of 0.24 ft.mm.mrad Norm. This means that specifications have been respected and the IRFU has reached its objective. The injector is now in the dismantling phase, after which it will be sent to GSI.



SEPTEMBER 02, 2020

SARAF: delivery of the medium-energy line, MEBT, to SOREQ-Israel

On October 28, 2014, CEA signed a contract with the Israeli Soreq Research Center (SNRC) for IRFU teams to contract an accelerator named SARAF (Soreq Applied Research Accelerator Facility). This agreement included preliminary and detailed study phases carried out over a period of 18 months (2015 and 2016) leading to a six-year project that includes construction, testing, and on-site installation. The aim is to build a superconducting linear accelerator capable of providing beams of protons and deuterons of varying energy between 5 and 40 MeV with an intensity ultimately reaching 5 mA.

SEPTEMBER 25, 2020

IRFU delivers the first serial cryomodule to the ESS collaboration

A year and a half after delivering the prototype cryomodule (CM00) to ESS, IRFU teams delivered the first serial medium beta cryomodule (CM01) to the ESS site. Prior to this, the teams validated the cryomodule's RF and cryogenic performance. It will be tested again on the ESS test bench before entering its final position in the accelerator tunnel. This is a first step: beginning next year, ESS will receive an average of one cryomodule per month for three years.

Publications

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