THE SPIRAL-2 SUPERCONDUCTING LINAC

R. Ferdinand, GANIL, Caen

Abstract

The SPIRAL-2 driver accelerator is composed of an injector and a superconducting linac. The SC linac is composed of 2 cryomodule families, basically one of low beta, called Cryomodule A, and one of high beta, called Cryomodule B. The low-beta family is composed of 12 single-cavity cryomodules. The high-energy section is composed of 7 cryomodules hosting 2 cavities each. The design goal for the accelerating field of the SPIRAL-2 QWRs is 6.5 MV/m. The linac configuration, the cavities and cryomodule tests and status will be described, as well as collaborations and contracts with the industries.

INTRODUCTION

After a Detailed Design Study phase (Nov. 2002 – Jan. 2005) [1] and following the recommendations of international committees, the French Minister of Research took the decision in May 2005 to construct SPIRAL-2 at the GANIL site. Its construction cost was estimated at 136 M€ (manpower not included).

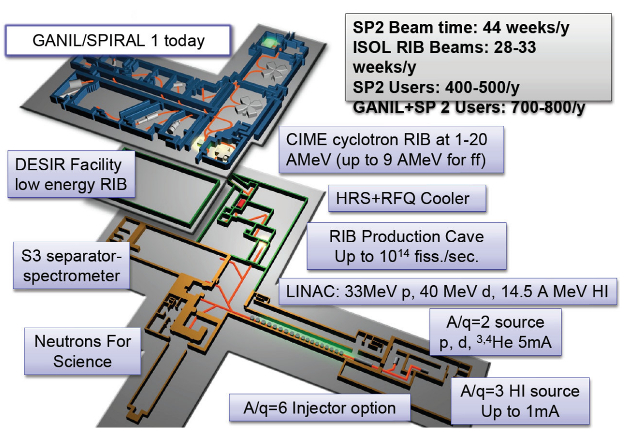


Figure 1: New and existing (in dark blue) facilities at GANIL site. Accelerator and stable beam physics in brown, RIB in green.

The new Spiral 2 project enlarges the range of accelerated ions by production of high-intensity RIBs (radioactive ion beams) of fission fragments using ISOL (isotope separator on line) techniques. Figure 1 shows the new layout. Two experimental halls are dedicated to new experiments with high-intensity stable beams: S^3 ('Super Separator-Spectrometer') and NFS ('Neutrons For Science') with pulsed neutron beams.

The neutron-rich radioactive ion beams will be mainly produced via the fission process induced by fast neutrons in a depleted UC_x target (11g/cm^3 density), with the goal of up to 5.10^{13}–10^{14} fissions/s. This value has been used for all safety and radiation-protection-related calculations. It has to be designed for three 3-month irradiation periods per year. The RIBs will be delivered either at low energy to the DESIR experiment hall dedicated to nuclear physics experiments using low-energy and low-intensity radioactive beams, or sent towards a charge breeder and post-accelerated by the existing GANIL cyclotron (CIME) and analysed through the GANIL complex.

The accelerator driver must deliver deuterons of energy up to 40 MeV with a beam current up to 5 mA and heavy ions with beam currents up to 1 mA. It will be optimised in energy for ions of mass-to-charge ratio A/q=3, resulting in an output energy of about 14 MeV/u. It will also be able to accelerate ions of mass-to-charge ratio A/q=6 for a later upgrade.

The neutrons (with an spectrum peaked at about 14-MeV) are generated by the break-up of the 40-MeV deuterons in a thick carbon target ('converter'). To achieve the high fission rate goal, the final converter will require 200 kW of primary deuteron beam. Initial operation with a carbon converter at 50 kW is foreseen.

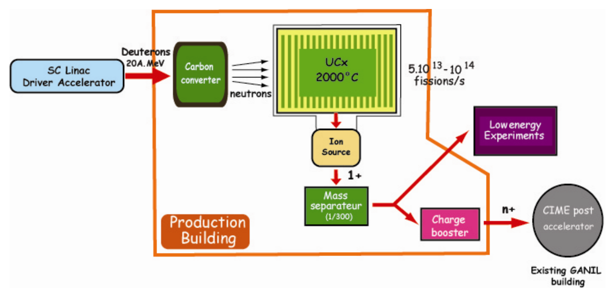


Figure 2: RIB production via the ISOL technique.

The driver [2-3] will accelerate many particles in CW in a wild range of energies. It consists of high-performance ECR sources, a RFQ and a superconducting linac. The driver must provide all energies from 2 MeV/u to the maximum design values.

The next paragraphs will focus on the SC linac description and its construction in a close interaction between the laboratory partners and the industry.

SPIRAL-2 CONSTRUCTION

Innovating technologies needed for the construction of this new generation of SC linac accelerators imposes a challenging strategy to be developed between the laboratories and the industry.

In the SPIRAL-2 project a development cycle was adopted: construction and test of prototypes, establishment of detailed specifications and series construction of the components. In the different stages of the project a close relationship was needed between the academic and industrial partners. In parallel, the main goal of the project was to stay inside the limits of the allocated budget without scarifying the foreseen performances.

For most of the accelerator parts, the associated laboratories are responsible for their procurement, under GANIL's supervision. GANIL has the responsibility to organise the call for tenders, submission analysis and final contracts with the industry. The project teams have the intellectual ownership of the design, and are then responsible for it.

INDUSTRY'S INVOLVEMENT IN ACCELERATOR BUSINESS

Why not consider that commercial companies may participate more intensively into the design phase of an accelerator project? Obviously there are few commercial companies able to design and build a dedicated accelerator or accelerator parts for a new challenging project which aims to push the performances at the cutting edge of the technology. The commercial companies in the technology domain usually maintain only a small development team in the accelerator field. It could hardly be otherwise, since any other strategy would have to offer a reasonable return on investment expectation. In fact, the design and construction of accelerators components is usually one activity aside from the mainstream for the industry, but it could become a technological "showcase" and a source of intellectual progress for small and medium-sized firms. Such companies have to depend on the other more lucrative activities to survive. A critical size with an adapted organization, and a wide range of projects plus financial backing is needed to survive.

This can be different if there is a reasonable guarantee of future series production, as in the dedicated cyclotron business (isotope production or medical applications) or in the series production of SC cavities for electrons and ions accelerators [4].

One aspect which becomes critical for the industry is also the long delays between the initial design ideas and the formal decision to proceed to the construction of components. This difficulty is enhanced by time needed for the international collaborations to reach a partner agreement in order to launch the prototyping and series fabrication phases. It is difficult for the private companies to take the risk and to maintain a development team accompanying the negotiation and preliminary phases of the projects. Generally, we have a targeted need, with technical risks sometimes being inevitable. This is not exactly the case in medical accelerator business where the same accelerator can be duplicated with some expectation of profits.

INDUSTRIAL ASPECTS FOR SPIRAL-2

Technology transfer requires from the accelerator staff a range of expertise that we did not had at the beginning of the project. Such expertise has to cover such varied domains as quality assurance, legal issues, finances and intellectual property rights.

Industrial Collaborations

Industrial collaborations do exist within the project at a different level and it is becoming important for the project team to improve and develop these aspects. In the last years, the French laboratories playing a major role in this field (CEA and CNRS institutions) have largely improved their infrastructure equipments, becoming de facto the R&D developers. At the same time the fabrications of almost all the components have completely been stopped in the laboratories and progressively ordered to the industry. Considering this present situation the sharing of know-how and the associated transfer of technology is becoming more evident in Europe today.

The French CNRS and CEA institutions have a superb tool for the SC cavities, the SupraTech test stands in Orsay and Saclay. It is a technological platform for R&D in superconducting and cryogenic systems activities. This tool may one day be an important component of the strategy for the partnership with private companies. Today, it is actively used for SPIRAL-2, and the teams acquire a know-how that will one day be shared to the industry.

Concerning the Spiral 2 project in Europe, an important group of industries contribute to the fabrication of prototypes and serial components. Moreover, the interaction between the R&D developed in the laboratories and their industrial know-how has allowed to introduce a large number of improvements needed to achieve the specifications of many innovative devices. Related to the SC cavities and associated components, these companies (i.e. ACCEL, ZANON, SDMS-resuming activities on aspects left vacant by CERCA, ACS, CRYODIFF, etc) have contributed to the success of the prototyping phase and have in charge the construction of the main series components.

Within the Project

One of the more important aspects of the collaboration with industry is to set up the switch from prototyping to series productions phases. The goals are to respects the specifications, costs and schedules with a minimum of nonconformities.

Planning

The interaction between laboratories and industry is a very complex task, mostly from the schedule point of view. The responsibility for fabrication is shared between different partners, and schedules have to fit together. The commercial and contractual aspects add more rigidity to this complicated task, but it introduces milestones which appears finally as a positive aspects contributing to a good compromise.

Quality assurance

From the beginning of the project we had to face problems and errors that good quality assurance should have solved. Most of the companies cite IS0 9001 accreditation for their quality assurance as a means of gaining marketing advantage.

From the project management side, we unintentionally minimised the time and resources to include such quality assurance requirements in the calls for tenders. The second error was to underestimate the cost of such strong requirement on the series production. The budget was established using the prototype cost, with the idea that the series production would show a significant cost saving. In fact, quality assurance is a major objective when you build an accelerator, mainly for the series fabrication, and its associated cost must not be neglected.

In many SC components for the project, the companies had also to solve the delicate objectives of big industrial boilers objects with tight tolerances. They gradually improved and finally succeeded.

Future

Technology transfer might be more obvious later on, when the project may need to repair or build a few more elements in the coming years. At that time all responsibility will have been transferred from the labs to GANIL. At that stage the contractors are likely to have to explain how the objects were built!

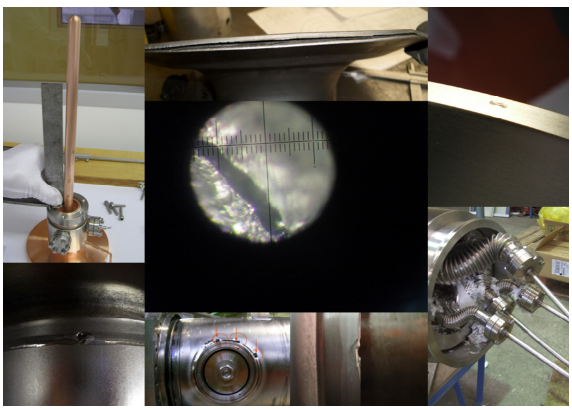


Figure 3: Illustration of some of the difficulties the project has had to face during the prototyping phase.

THE ACCELERATOR SUB-SYSTEM

The Injector

The injector, dedicated to protons, deuterons and ions of A/q=3, is mainly composed of two ECR ion sources with their associated low-energy beam transport (LEBT) lines, a warm RFQ and the medium-energy (MEBT) line connected to the LINAC.

The 2.45-GHz ECR source for deuterons is a "simplified" SILHI-like source (100 mA CW, 95 kV), initially developed by the CEA/DAPNIA laboratory for the IPHI project. It will also produce protons (5 mA) and H_2^+ (β=0.0067). The ECR source for SPIRAL-2 is now under construction. It is a pure CEA-Saclay design, elements being separately bought and assembled.

The objective for SPIRAL-2 is also to produce a large diversity of heavy ions with intensities up to 1mA: noble gases like Ar^{12+}, and metallic ions like Cr, Ni and Ca are required. The LPSC laboratory in Grenoble is in charge of the tests of the PHOENIX V2 source with the objectives of the project. In parallel, a new ECR source design has recently been proposed by the LPSC: the so- called "A-Phoenix" source [5]. It is a hybrid ECRIS with high-temperature superconducting (HTS) coils (3T axial magnetic field) and a permanent-magnet design (2T hexapolar field). With a 28-GHz frequency, the goal is to approach 1-mA intensity for an Ar^{12+} ion beam. The components of the source are now assembled and the first beams have been extracted.

Developed by the CEA/DAPNIA team, the RFQ is a 4-vane, 5-metre warm copper cavity, ensuring acceleration up to 0.75 MeV/u (β=0.04). A 1-metre segment was built during the APD phase as a prototype. The former ACCEL Instrument Company, now named RI Gmbh, won the call for tender and started the construction phase. The first metre is expected during the last quarter of 2009.

The Superconducting Linac

The superconducting linac is composed of cryomodules of type A developed by CEA-Saclay, and cryomodules of type B developed by IPN-Orsay. Both types of cavities will be equipped with the same power coupler specified for a maximum power of 20 kW, which is being developed in a third laboratory, LPSC-Grenoble.

General development programs are quite similar for both cryomodules: a first qualification cryomodule was designed by the lab teams, assembled and tested before the series production could begin. These qualification cryomodules must reach the specifications for the LINAC and will be installed on the final machine. All the components of the series (cavities and cryomodules) are then manufactured industrially. Chemical treatments, HPR rinsing in a clean room, assembly, and RF tests of the cavities in vertical cryostat and RF power tests of the cryomodules are done in the respective labs. A study was made in 2006 to evaluate the use of an industrial company to proceed with the assembly and test of the series production, and the idea was finally abandoned.

Details of the cavity and cryomodule design were described in [6,7].

Cryomodules A - β=0.07

Each type A cryomodule includes one single superconducting QWR cavity, designed at β=0.07 [8].

At present, one cavity prototype and a 'qualifying' cavity have been tested in vertical cryostat. While the prototype reached the specifications, the qualifying cavity performance was not as good as expected. The maximum accelerating field, 11 MV/m, was much higher that needed, but the Q_0 value was a factor 10 below the acceptable value, about 2×10^8 (see Figure 4). Fortunately small gradients are required at the beginning of the LINAC, and the beam losses can be kept below the 10-W limit ($E_{acc} < 4.5$ MV/m).

This is a typical situation describing a faulty prototyping procedure. To solve this problem two new prototypes have been ordered to two different companies.

The tests of the 2 cavities will allow us to understand if the problem arises from the design, from the niobium used or from the manufacturing company. The 2 manufacturers will also allow us to speed up the process while having confidence in the cavity design. The remaining series of cavities of this order will then be manufactured by one or both companies. We recently received the first one from ZANON. Measurements will soon be made.

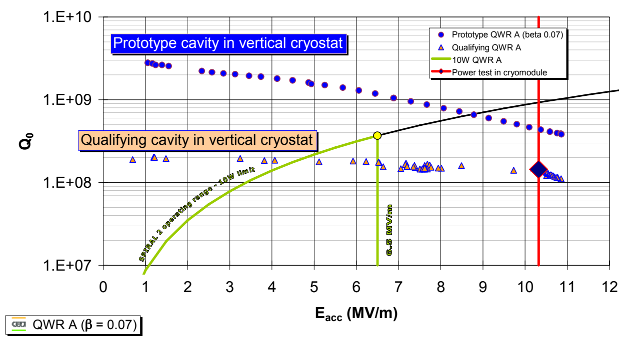


Figure 4: Prototype and qualifying QWR type A cavity in a vertical cryostat.

The qualifying cryomodule was tested with the qualifying cavity. It is an assembly of parts ordered from different company. The cool-down is reasonably fast, in about 24 h down to 100K, then 1 h to 4K. The measured static consumption is about 7 W, while the expected value is 4 W. The valve box, cryogenic lines and cryomodule dissipate about 25 W @ 4K, slightly more than expected. RF was injected, and an accelerating field of 10.3 MV/m could be reached (blue diamond point in Figure 4).

The call for tenders for the series of cryostats is ongoing.

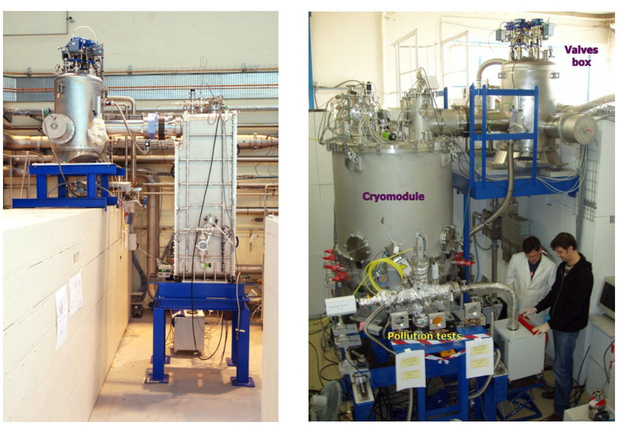


Figure 5: One the 12 type A cryomodules and one of the 7 type B cryomodules.

TYPE B CRYOMODULES - β=0.12

Resonators

At present time, one prototype, 2 pre-series cavities and four of the series of cavities have been tested.

The former ACCEL Company (now RI Gmbh) is manufacturing the series of cavities. Five of the series are being fabricated at present. The ACCEL Company has made improvements to the mechanical manufacture since the first was made.

The first series of cavities show good electro-magnetic qualities and all have very similar performance (see Figure 6). This is a very good sign of the company's mastery of the manufacturing procedures, and the IPN-Orsay team's cleaning and assembly procedures. The results are very homogeneous, despite the many human errors observed during the process.

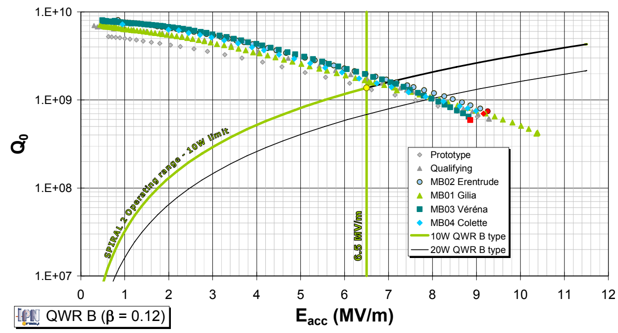


Figure 6: Q_0 curve of the first type B cavities.

The cavity cold tuning is performed using superconducting plungers inserted on the top of the cavity inside the magnetic volume [9].

Cryostat

A first qualifying cryomodule was manufactured and tested with success early in 2008. The serial production contract for the 6 remaining integrated cryomodules was won by the French SDMS company.

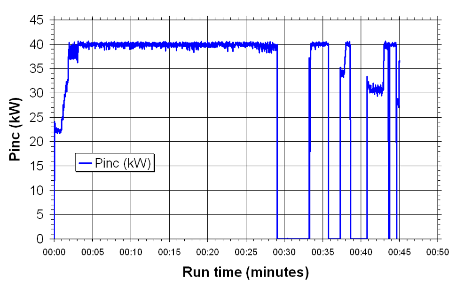
The specified main performances were achieved, i.e. E_{acc} = 6.5 MV/m with a dissipated power < 10 W @ 6.5 MV/m, without magnetic shielding. The static dissipation was 13 W, with 11 W specified, with possibilities for improvement. Good results were obtained with the power coupler, the 10-kW solid-state amplifiers [10], microphonics and the cold tuning system mentioned above. Very interesting pollution tests were performed to validate the surrounding warm sections of the cryomodules [11] and the possible use of interceptive diagnostics close to the cavities. The low-field multipacting problem was solved with the use of the power coupler. See details in [12].

Couplers

The RF couplers have to provide 12 kW of CW power to the cavities at 88.05 MHz for the design goal of an accelerating field of 6.5 MV/m [13]. They are designed by LPSC-Grenoble.

The coupler has a fixed coaxial antenna with a disc-shape ceramic insulator. The coupling is fixed, and the RF system will have to handle some reflected power. The couplers stand upright at the bottom of each cavity. Simulations taking into account the variation of the conductivity of the copper coating with temperature estimate that around 1W of power is deposited on the base of the cavities.

Coupler prototypes have been tested (head-to-head) up to 40 kW CW, with excellent results Transport of the qualification couplers showed some weakness and the design was slightly improved accordingly ((with a hollow antenna).



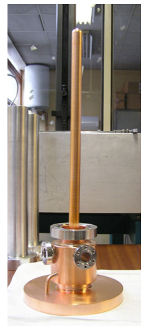


Figure 7: Coupler commissioning

The tender for the series of couplers was won by the SCT Company in France. The tests of the first series coupler are under way, together with the optimization of the ceramic window coating (about 1nm).

Superconducting Linac RF Amplifiers

As the SPIRAL-2 frequency (88 MHz) is in the radio FM domain, the project has chosen solid-state technology (3 – 20 kW) [14]. 360 kW of RF amplifiers, designed and manufactured by commercial companies will be installed.

This domain is the most obvious for technology transfer, especially at this frequency. More and more labs around the world have replaced, or plan to replace, existing electron-tube amplifiers with solid-state ones. The Soleil synchrotron has been the first new machine to choose solid-state technology from the beginning (352 MHz). One 35-kW amplifier and four 190-kW amplifiers are presently running, developed and assembled by the SOLEIL laboratory [15].

For SPIRAL-2 we chose to let the companies do the design, and two first power RF amplifiers for the linac (10kW and 20kW) were designed and manufactured by DBelectronica in Italy. Both prototypes (10 and 20kW) equipped with an external circulator has been successfully tested in GANIL, and are presently used for the cryomodule tests in Orsay and Saclay laboratories.

CONCLUSION

The successful test of the superconducting accelerating structures has proven the concept of the SPIRAL-2 linac. All the tests performed on the elements demonstrate that industry is capable of delivering superconducting accelerator structures ready for testing.

Installation in the linac tunnel is expected to take place in March 2011. First beams are envisaged in 2012.

ACKNOWLEDGEMENT

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