THE SPIRAL 2 PROJECT: CONSTRUCTION PROGRESS AND RECENT DEVELOPMENTS ON THE SC LINAC DRIVER

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Abstract

The construction of the new Spiral 2 facility has started in Caen (France) at the National Heavy Ions Accelerator Center (GANIL). The SPIRAL 2 project is based on a multi-beam Superconducting Linac Driver delivering 5 mA deuterons up to 40 MeV and 1 mA heavy ions up to 14.5 MeV/u. Different Radioactive Isotope Beams (RIB) production methods are foreseen: 1) by fission process (up to 10^{14}fissions/s, induced in an UCx target by fast neutrons from a C converter bombarded by deuterons), 2) by fusion-evaporation residues or transfer products, using p, D, 3,4He and heavy ions beams in different targets. The high intensity beams delivered by the Superconducting LINAC Driver, will also open new perspectives for super-heavy and very-heavy nuclei synthesis and spectroscopy. In addition to fundamental research in nuclear physics, the SPIRAL 2 facility will be also a high performance multidisciplinary tool for many other areas of science and technology: nuclear energy, material sciences, atomic physics and biology.

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 in Caen, France. On the 1st of July 2005, the construction phase of SPIRAL2 was launched within a consortium formed by CNRS, CEA and the region of Basse-Normandie in collaboration with French, European and international institutions.

The importance of the availability of Radioactive Ion Beams (RIB) has been often underlined in the last years. NuPECC (Nuclear Physics European Collaboration Committee) and ESFRI (European Strategy Forum on Research Infrastructures) established roadmaps and recommendations for the next generation of facilities in Europe. FAIR in GSI laboratory in Darmstadt (Germany) and Spiral 2 in GANIL laboratory are among the selected projects. Both projects are complementary and are based on two different RIB production methods: FAIR is based on In-Flight Fragmentation techniques, while Spiral 2 uses the Isotope Separation on Line (ISOL) techniques.

The GANIL facility (Caen, France) is one of the major RNB and stable-ion facilities for nuclear physics, astrophysics and interdisciplinary research in Europe. Since the first beams delivered in 1983 the performances of the GANIL accelerator complex, was constantly improved with respect to the beam intensity, energy and available detection systems. Almost since the beginning of the experimental program, the facility delivered RIB produced "in-flight" at fragment separators. The new facilities related to the Spiral 2 project enlarge the range of accelerated ions by production of high intensity RIB of fission fragments. The new buildings: Driver Accelerator, RIB Production, and two new Experimental Halls, are illustrated in Fig. 1. A new experimental hall dedicated to high intensity stable beams and neutron experiments (AEL) and a hall for low energy RIB experiments.

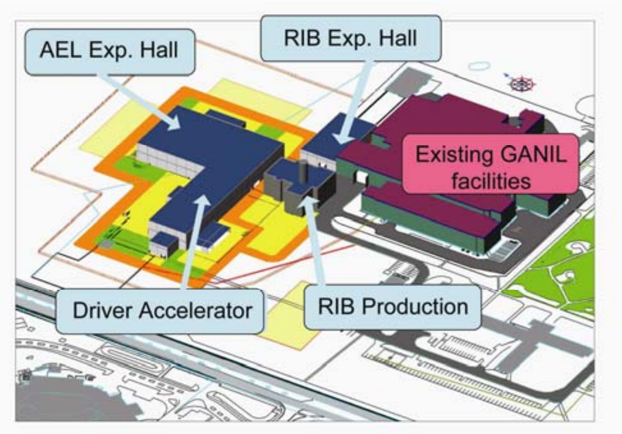

Figure 1 : Spiral 2 new buildings (blue) and existing facilities at the GANIL site

The Spiral 2 project proposes three different methods of production of radioactive beams [2] [3]:

1) fission of Uranium Carbide (UCx) target with a high neutron flux produced by a deuteron beam impinging on a Carbon converter,
2) direct interaction of deuterons in a UCx target,
3) interaction of heavy ion beam with different targets

The radioactive atoms are then ionized and extracted from a target/ion-source system, and finally sent to either a low energy experimental hall, or driven towards a charge breeder and post-accelerated by the existing CIME cyclotron (Fig. 2)

The radioactive neutron rich beams will be mainly produced via the fission process induced by fast neutrons in a depleted UCx target (11g/cm^3 density), with the aim of 5.10^{13}-10^{14} fissions/s. For efficient diffusion and effusion of the radioactive atoms, the UCx target must be heated at temperatures above 2000°C.

The neutrons (about 14 MeV) are generated by the break-up of 40MeV deuterons in a thick Carbon target (Converter). For such a high fission rate, the final converter should sustain 200kW. Initial operation with a

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Carbon converter at 50 KW is presently considered. The converter study takes benefit of recent development and collaborations with INFN-LNL and BNPI-Novosibirsk laboratories.

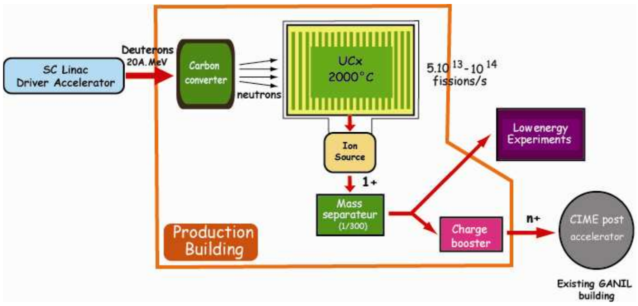


Figure 2 : RIB Production technique in Spiral 2

Different types of Ion Sources (single charge state) are presently been studied :

- ECR for gaseous elements.
- FEBIAD (Forced Electron Beam Ion Arc Discharge).
- Surface Ionization Source.
- Laser Ion Source.

The RIB intensities in the mass range from A=60 to A=140 will be of the order of 10^6 to 10^{11} particles/s (pps) surpassing by one or two order of magnitude any existing facilities in the world. For example, the intensities should reach 10^9 pps for ^{132}Sn and 10^{10} pps for ^{92}Kr. A direct irradiation of the UCx target with beams of deuterons, ^{3,4}He, ^{6,7}Li, or ^{12}C can be used for higher excitation energy that could increase a higher production rate for specific nuclei.

Target - Ion Source Production Module

Two RIB production systems, using the high energy primary beams from the driver accelerator are presently considered [4] :

- A "Red" Production cave where the C converter, the UCx target and associate Ion Source are located.
- A "Yellow" Production cave for lower intensity and less critical production systems.

The first Target-Ion Source (TIS) system under development is based on the fusion-evaporation reaction type, and is being designed in the IN2P3/CENBG laboratory. The main technical challenge concerns the thermal design of the target, which has to withstand very high power densities (several 100µA beams).

The high power TIS production module has been totally redesigned, taking into account the numerous constraints given by the radiological environment and the safety and contamination handling rules. The production module will be a totally remote-operated system, which will be disconnected, transported into the hot cell for maintenance and TIS replacement, and reconnected by a robot and manipulator system Fig.3.

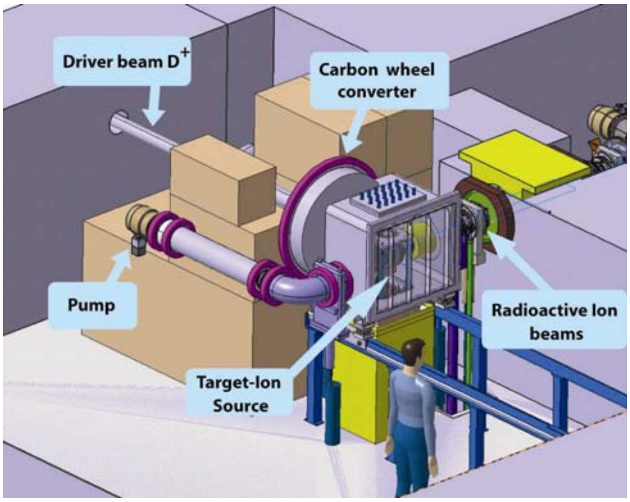


Figure 3: Spiral 2 UCx production module

Radioactive Beam transport lines

A preliminary implementation scheme of the RIB transport lines is proposed in Fig. 4, and the detailed study has still to be started in close collaboration with the building technical design team.

The single charged beam (1+) line, going from the ion sources towards the identification stations, the low-energy experimental area DESIR or the charge booster (ECR ion source 1+ to n+) will include both electrostatic and magnetic components. The mechanical design of the lines is based on the use of independent modules that will be extracted with remotely operated tools from inaccessible places like the production caves, around the charge booster, and in any zone where radioactivity and/or contamination will become important.

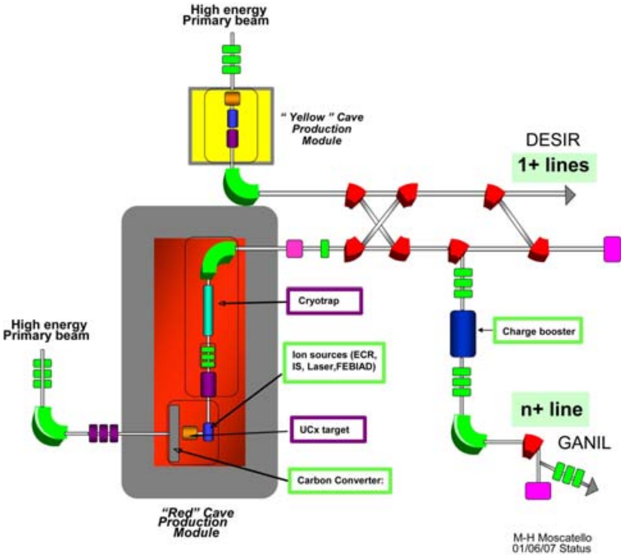


Figure 4: Layout of the RIB production systems and beam transfer lines

The n+ line transports the beam from the charge booster to an existing cyclotron CIME will be constructed with mechanical interfaces allowing the addition of remote-operated valves and bellows in the future, when the RIB intensities reach the nominal values.

The production building, which will host the RIB production caves and the RIB transport lines will be a nuclear type building. The safety requirements imply a double confinement in the whole building that will host the UCx production cave as well as the transport lines for the radioactive beams composed of fission products. The whole vacuum system will be connected to the gas storage system, and a public enquiry will be launched to get the authorization to release gas from the storage facility, after a suitable period of radioactivity decrease.

SPIRAL2 DRIVER ACCELERATOR

Beams to be accelerated

In order to fulfil the physics requirements, the SPIRAL2 driver accelerator must be able to accelerate high-intensity beams of protons, deuterons, ions with $A/q<3$, and optionally ions with $A/q<6$. As indicated in table 1, a maximum beam power of 200kW is required for deuterons in CW mode. In order to transport and accelerate these intense beams with a minimum of losses, many beam dynamics calculations have been performed all along the machine, by using realistic source particle distributions, real 3D magnetic fields, compensation space charge effects in various situations, and also with systematic errors studies. The whole driver accelerator will be controlled using the EPICS software coupled with the TRACEWIN/PARTRAN code in order to implement the notion of a “virtual machine”.

Injector-1

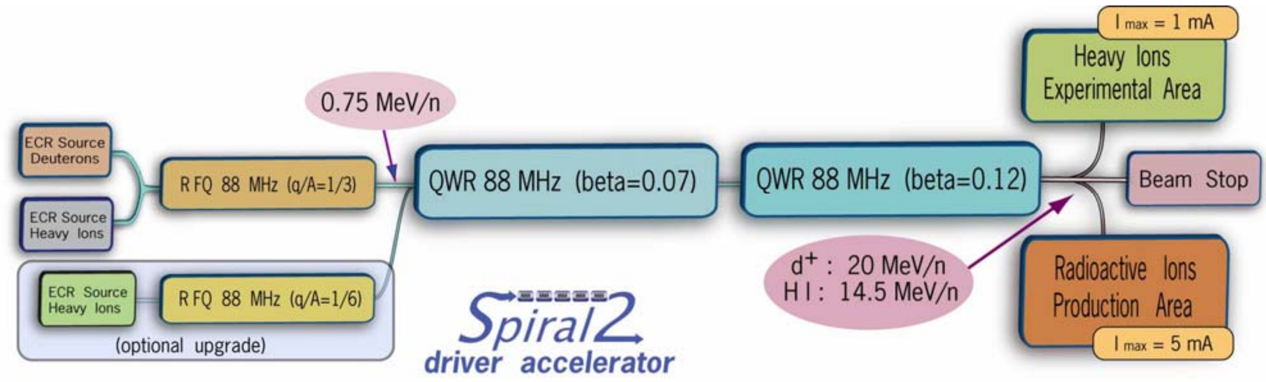
The Injector-1, dedicated to protons, deuterons and ions of $q/A=1/3$, is mainly composed of two ECR ion sources with their associated LEBT lines, a warm RFQ and the MEBT line connected to the LINAC.

The 2.45GHz ECR source for deuterons is a “simplified” SILHI-like source (100mA CW, 95kV), initially developed by the CEA/DAPNIA laboratory for the IPHI project. In 2005, the Saclay source demonstrated its capability to produce a very stable 6.7mA D^+ CW beam with an rms normalised emittance less than 0.1π.mm.mrad [5]. It will also produce protons (5mA) and H_2^+, with a voltage of 20kV for protons and 40kV for D+ and H_2^+ (β=0.0067). The ECR source for SPIRAL2 is now under construction.

The objective for SPIRAL2 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. During the initial DDS phase, an R&D program was conducted to measure the performances of the PHOENIX ECR heavy ion source from the LPSC laboratory (Grenoble), and in particular to measure the transverse emittances obtained for 1mA of O^{6+} at 60kV (0.22 π.mm.mrad rms norm.) In parallel, a new ECR source design has recently been proposed by the LPSC: the so called “A-Phoenix” source [6]. It is a compact 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 plasma tests are being performed presently (Fig. 5).

Table 1: Beam Specifications

beam	p+	D+	ions	ions
Q/A	1	1/2	1/3	1/6
Max. I (mA)	5	5	1	1
Min. output W (Mev/A)	2	2	2	2
Max output W (Mev/A)	33	20	14.5	8.5
CW Max. beam power (KW)	165	200	44	48



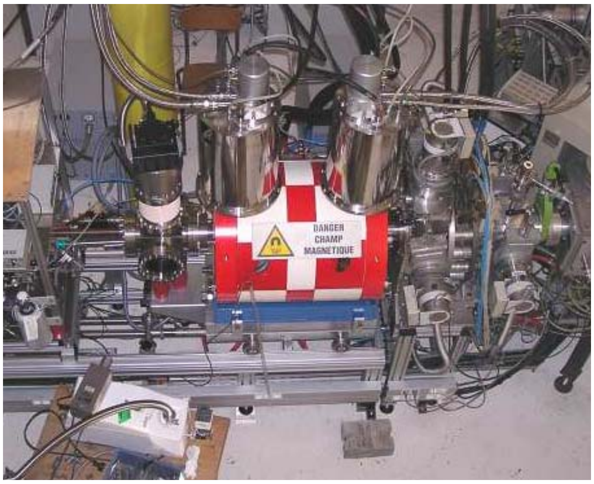


Figure 5 : The new heavy ions ECR source (A-Phoenix) in test at LPSC Grenoble

Both light and heavy-ion ECR sources have their own chromatic transfer line able to separate the species extracted from the source and select the desired purified beam. These lines are connected to a common LEBT which contains a slow chopper, diagnostics and slits to redefine the emittance before connection to the RFQ. The magnetic elements are being manufactured, and their magnetic measurements will start by the end of 2007.

Developed by the CEA/DAPNIA team, the RFQ [7] is a 4-vanes, 5-meter warm copper cavity (88Mhz) performs an adiabatic bunching of the continuous beam, and an acceleration at 0.75Mev/u (β=0.04). It is specially designed to give a transmission of better than 99%. A 1-meter segment prototype was built during the APD phase and tested at Grenoble and Catania in order to check the feasibility. The construction of the RFQ is now starting and will take about two years. The RFQ cavity requires some 150kW and will be driven by four 50kW amplifiers equipped with circulators.

The MEBT line takes care of the beam transmission and matching between the RFQ exit and the LINAC entrance. Its function is also to allow future connection of the injector-2, and to operate a very clean fast chopping of the beam bunches for various AEL experiments. This explains the length of this part (8m) and the necessity to use three rebunchers in order to match the beam longitudinally. Most of the devices are completely designed and will be orded very soon. One exception is the challenging fast chopper and its associated 7.5kW beam stopper, which are under detailed study.

Due to delays concerning the construction of the accelerator building, the whole Injector-1, in the configuration illustrated in the Fig. 6, will be installed at Saclay and tested with beam, before being transported to GANIL. In addition, a specific medium-energy diagnostic plate is under construction at the CNRS-IHC laboratory in Strasbourg, in order to prepare the beam commissioning of the RFQ and of the MEBT during this first phase, and to test various diagnostic devices on line. Associated with a phase length monitor, the first rebuncher will be used to determine the longitudinal emittance of the RFQ.

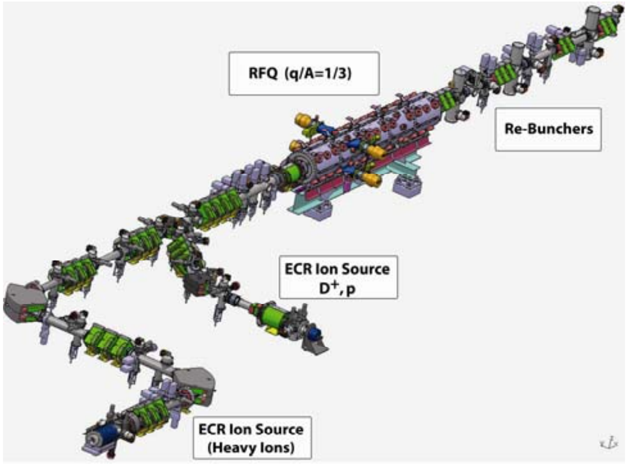


Figure 6: View of the Spiral 2 Injector (phase 1)

Injector-2

The optional Injector-2 will be dedicated to q/A=1/6 heavy ions connected to the LINAC via the MEBT line. This injector is under detailed study in order to prepare enough space in the accelerator building for the future. Although it will give only half the energy compared to Injector-1, there is much interest in having higher beam intensity for very heavy ions. A design study is being conducted in the frame of a MoU with the Argonne laboratory.

Superconducting Linac

The LINAC accelerator is based on superconducting independently-phased resonators. It is composed of 2 families of quarter-wave resonators (QWR) at 88MHz, (Fig. 7) developed respectively by the CEA/DAPNIA and the IN2P3/IPNO teams: 12 resonators with β_0=0.07 (1 cavity /cryomodule), and 16 resonators at β_0=0.12 (2 cavities/cryomodule). The transverse focusing is ensured by means of warm quadrupole doublets located between each cryomodule. Additional dipolar coils are installed into the Q-pole in order to compensate the steering effect of QWR cavities and eventually adjust the optimum beam position. These warm sections include also beam diagnostic boxes implementing different types of sensors (preliminary specifications are: 20 BPM, 10 TOF and 4 phase length measurement devices) and 20 vacuum pumps. The total length of the SC Linac is 30 m.

The maximum operational accelerating gradient of the QWR cavities is $E_{acc}=V_{acc}/\beta\lambda$=6.5MV/m. To acceleration of a deuteron beam of 5 mA at a maximum energy of 40 MeV with minimum losses, leads to an optimization of the operational gradients along the Linac: the β_0.07 cavities between 1.3 and 6.5 MV/m, and the β_0.12 cavities between 5.0 and 6.5 MV/m. The calculated transverse and longitudinal emittance are displayed in the Fig 8. The energy gain along the Linac is displayed in Fig. 9. The beam optics simulations were performed using the TRACEWIN and PARTRAN codes (CEA/DAPNIA). The space charge effects were studied using the 3D-PICNIC routine with 100 000 particles [8]

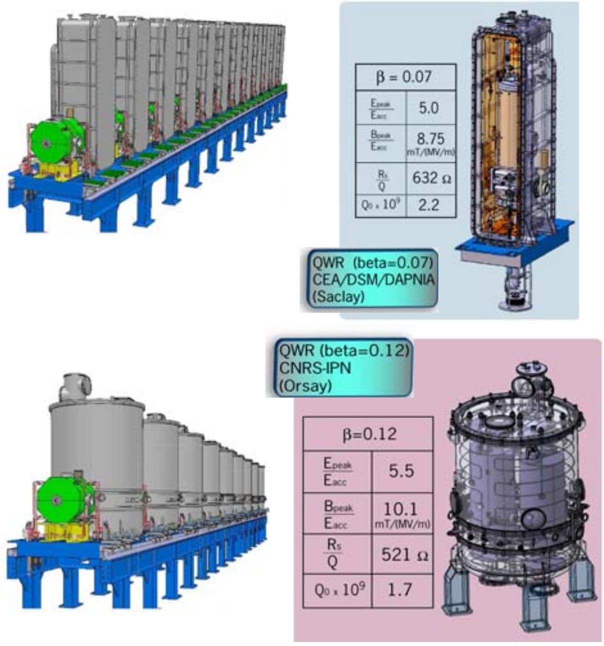


Figure 7: The SPIRAL2 superconducting cryomodules (top: β=0.07, bottom: β=0.12)

In a first attempt, multi-particle calculations were performed without errors (alignment errors and component dimensions and fields errors). An increase of the QWR electrode diameter has been adopted: 38 mm for β_0.07 and 44 mm for β_0.12. The expected input emittance at the SC Linac was also limited introducing slits after the RFQ cavity, intercepting 130 W for a D^+ 5 mA beam). With these precautions a theoretical total loss of < 1 W in the SC linac was obtained. The worst case is obtained at low energy operation range. For example: a 2 MeV proton beam and intensity of 5 mA gives a theoretical level of losses < 10 W for all the SC Linac .

HEBT lines and AEL experimental hall

The high energy beam transfer lines (HEBT) are divided into three main parts (Fig. 10):

- HEBT1: A straight beam line with a beam dump is needed for beam commissioning, eventual tuning and beam studies. The maximum power accepted by the beam dump is not precisely defined yet; it will depend on the nuclear safety licensing requirements for handling and maintenance and could range between 50 and 200 KW.
- HEBT2: This transfer line will transport light- and heavy- ion beams towards the two RIB production areas, located in a separate building. (see next section).
- HEBT3: These lines will deliver light and heavy ions to the AEL experimental hall, installed in the same building as the driver accelerator. Three large experimental rooms are presently being studied: a) for neutron experiments where a neutron time-of-flight facility will be installed, b) for high-intensity stable ions experiments where a spectrometer with high mass selectivity will be installed, and c) an inter-disciplinary experimental area for atomic physics and material studies. Several rebunchers are installed in this line in order to reach the bunch length requirements at the target level (<1ns). Various targets will be used, in particular actinides, which necessitate special safety procedures for manipulation.

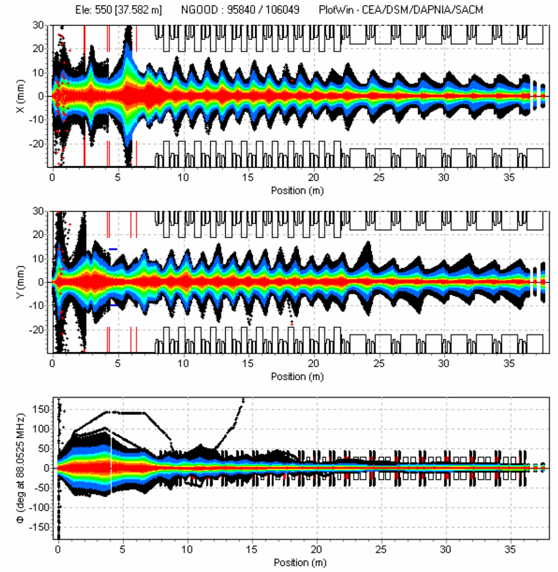


Figure 8 : Transverse and longitudinal emittances in the Spiral 2 Driver Accelerator (d+, 40 MeV, 5 mA)

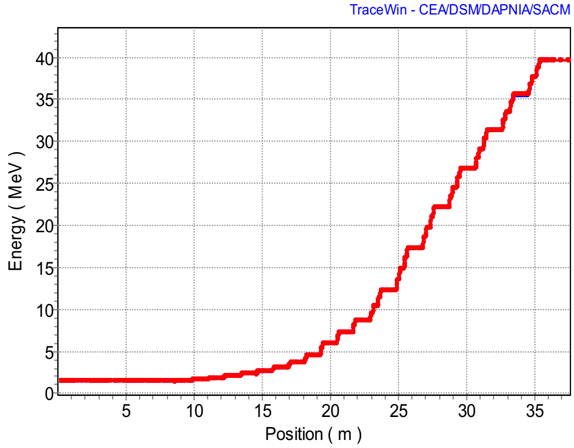


Figure 9 : Energy Gain in the SC Linac (d+, 40 MeV)

PROGRESS ON THE SUPERCONDUCTING LINAC CONSTRUCTION

Two prototypes QWR1 and QWR2 were constructed during the initial R&D phase. Installed in vertical test-cryostats, both resonators reached very high accelerating gradients, between 9 and 11MV/m. [9].

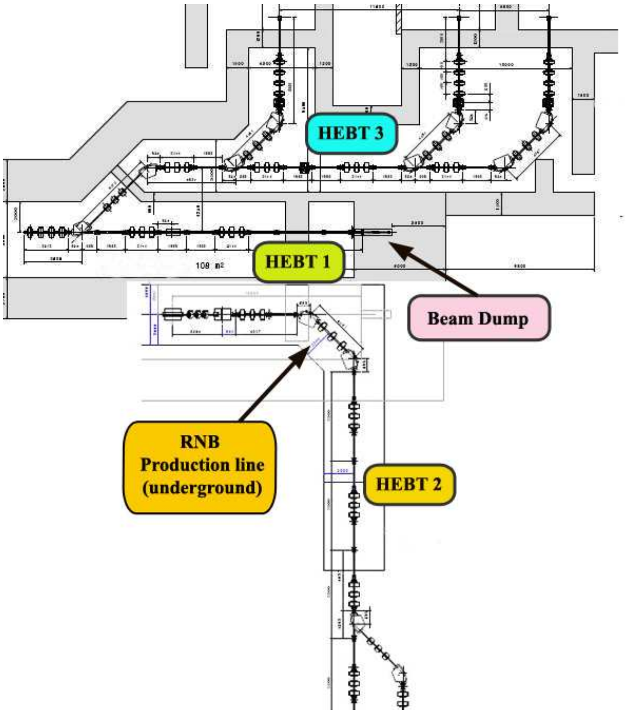


Figure 10: The High Energy beam lines

Three new cavities: 1 QWR 0.07 and 2 QWR 0.12 have been fabricated in the last period, incorporating all the needed ancillary components (helium tank, tuning system anchoring, etc). The first tests with the QWR 0.07 show low Q_O value due to extra losses not yet identified, but confirm excellent performance in peak electric field (11 MV/m). One of the new QWR 0.12 was tested and reached an E_{acc} of 9 MV/m. In the second QWR 0.12 a leakage was observed and the investigations on the causes are under way.

The three best results are presented in the Fig. 11 More details on the results of these measurements are presented in this Workshop [10].

The RF power couplers, developed by IN2P3/LPSC (Grenoble), have to provide 12kW CW power to each cavity. Two coupler prototypes, using either disk or cylinder ceramic window geometries, were also constructed. Both prototypes have reached CW power levels greater than 30kW, giving a good margin for the nominal operation power levels.

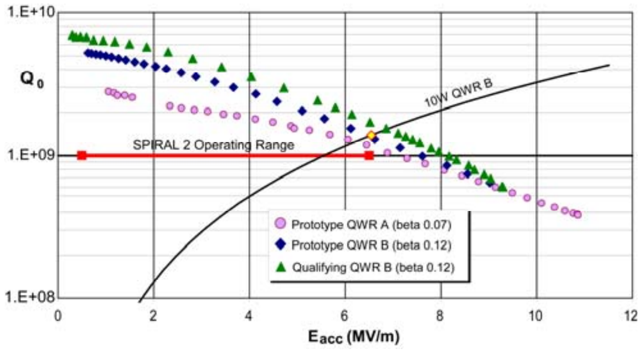


Figure 11: QWR performances of the Spiral 2 prototypes

Five new couplers were recently constructed, three of them will be installed in the two first cryomodules. More details on RF couplers are given in this Workshop [11]

Two cryomodules (one of each beta value) have been designed and constructed and its test will allow the launch of the series units construction. Both cryomodules integrate all the needed components and are completely equipped to be eventually installed in the Driver Accelerator. All the components for the first cryomodules are now available: the β 0.12 Cryomodule is presently assembled and final tests have started, the integration of the β 0.07 Cryomodule components is planned for the end of this year (Fig. 12 a, b). The cryomodules tests include the assessment of two major design aspects: 1) cryogenic operation and static losses measurements, and 2) complete RF tests with a final check at full RF power. This test phase will end in December 2007, in order to launch the cryomodules series production in the period 2008-2009.

Figure 12(a) : The first β 0.07 Cryomodule

Solid-state RF amplifiers will be used, and the two first prototypes of 10 and 20 kW have recently been tested at GANIL [12]. These amplifiers are based on new power transistors for FM applications implemented in water cooled boards, allowing the use of only four 3kW racks for each 10kW cabinet. Power tests on the cryomodules will help to choose the best compromise between the required gain linearity and the working class operating point. An operating efficiency of around 55% is expected.

A new digital low-level RF system is under development and will ensure 10^{-2} and 1° in amplitude and phase stability respectively. The CEA/DAPNIA team in charge of the LLRF is studying a standard card which will be used to control all types of cavities along the accelerator (RFQ, rebunchers and SC LINAC resonators).

Figure 12(b) : The first β 0.12 Cryomodule

SPIRAL 2 CONSTRUCTION MILESTONES

The reference project for the Driver Accelerator was decided by October/November 2006, the RIB production building and its main components must be defined at the end of 2007. Both the detailed study of the buildings and the licensing procedures conducted by the nuclear safety regulation authorities, condition the reference planning and the final steps to reach the foreseen performances. The regulation authorities have recently agreed (July 2007) on a roadmap and an associated planning for the construction and initial operation of the facility. The construction of the SPIRAL 2 buildings (driver accelerator and production areas) at the GANIL site will start in 2009. First commissioning of beams delivered by the Driver Accelerator should take place at the end of 2011 (Fig. 13). Full intensity stable beams should be available for experiments in the 1st Qr. of 2012. Availability of radioactive beams is presently being considered at the end of 2012, with several phases, corresponding to a progressive increase of the power on the production target.

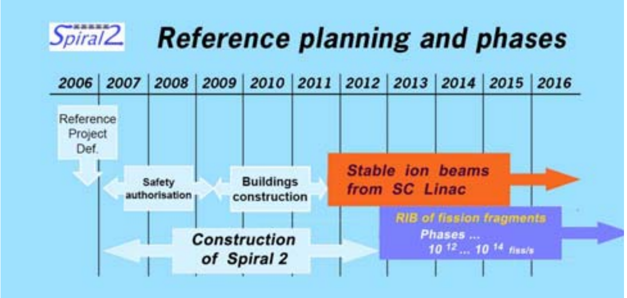


Figure 13 : Spiral 2 planning (October 2007)

ACKNOWLEDGMENTS

Thanks to the SPIRAL 2 project group for their help and specific contributions, in particular: Marcel Jacquemet (Project Leader), Marek Lewitowicz (Scientific Leader), M.H. Moscatello (RIB Leader), J.M. Lagniel (Buildings Leader), R. Ferdinand, P. Bertrand, M. DiGiacomo, C. Van Hille, P. Ausset, J.L. Biarrotte, R. Duperrier, D. Uriot, H. Saugnac, and P. Bosland.

REFERENCES

[1] SPIRAL 2 Project Scientific Objectives and Technical Reports (2005–2006), http://www.ganil.fr/research/developments/spiral2.

- M.H. Moscatello, Proceedings of LINAC04 Lübeck,Germany 2004.
- A. Mosnier, Proceedings of PAC 05, Knoxville (USA) 2005.

[2] M. Lewitowicz, Symposium on Nuclear Physics VI, Tours (France) September 2006, Vol. 891, p. 91, AIP Conférence Proceedings (2007)

[3] M.-G. Saint-Laurent, Acc App 2007, Pocatello, Idaho (USA) July 2007

[4] M.H. Moscatello and P. Bertrand Cyclotron Conference, Catania (Italy), September 2007

[5] R.Gobin et al., Proceedings of LINAC04, Lübeck, Germany 2004.

[6] Th. Thuillier Proceedings of the 12th International Conference on Ion Sources, Jeju, Korea, August 2007.

[7] R Ferdinand et al., Proceedings of EPAC 2006, Edinburgh (UK)

[8] R. Duperrier and D. Uriot, Phys. Rev. Special Topics Acc. and Beams, vol. 9, 044202, 2006.

[9] Devanz et al., 12th SRF Workshop 2005, Cornell University (USA)

[10] G. Olry et al. this Workshop
G. Martinet and D. Longuevergne, this Workshop

[11]Y. Gomez-Martinez et al. this Workshop

[12] M. DiGiacomo et al. this Workshop