# ADVANCES OF THE SPIRAL 2 PROJECT

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for and with the SPIRAL 2 Team

## *Abstract*

The first phase of the SPIRAL 2 project dealing with the high-power superconducting linac and the two experimental areas called Neutron for Science (NFS) and Super Separator Spectrometer (S3) is well advanced. The building and conventional facilities are now ready and the project has entered in a phase during which the linac components are successively installed and commissioned (the first beam was produced in December 2014). After having briefly recalled the project scope and parameters, the constraints linked to the safety rules and the way the installation and commissioning are done will be explained. The next steps which are the DESIR low-energy experimental area and the q/A = 1/7 heavy ion second injector will be also presented.

## SPIRAL 2 STATUS

The agreement giving the start of the SPIRAL 2 project [1] [2] was signed in September 2006 by the French state, Basse-Normandy region, department of Calvados, town of Caen, urban community of Caen-la-Mer, CNRS and CEA. Fig. 1 gives a 3D view of the building; the construction of which started in December 2010. With more than 100 rooms the total surface is 7,200 m$^2$ consisting of 4 floors and 2 basement levels.

Most of the conventional facility equipment and some parts of the accelerator (parts of the ion sources, RFQ cavity, magnets and cryomodule supports…) were installed before the end of the construction of the building (September 2014). Ref. [3] describes the integration of the accelerator processes, construction of the building and process connections.

Fig. 2 gives an overview of the accelerator, beam lines and experimental halls at the -2 level (- 9.50 m underground). The large free space at the north of the two source rooms is reserved for the future installation of a new injector (source and RFQ) able to inject Q/A up to 1/7 heavy ions in the superconducting LINAC. One can also notice that the building has been built in such a way that a LINAC extension at higher energy and/or the installation of new experimental areas are possible.

## *Proton/Deuteron Source and LEBT*

The SPIRAL 2 proton/deuteron source is a 2.45 GHz ECR source which uses permanent magnets, it is designed to produce 5 mA 20 keV proton and 40 keV deuteron beams in CW or pulsed modes.

This source and associated low energy beam transfer line have been constructed by the CEA/IRFU team and successfully tested at Saclay [4]. This work was completed in July 2012. Reliability and stability were improved; emittance was measured and optimized versus space-charge compensation measurements.

The source and beam line have then been dismantled and transported to the GANIL site.

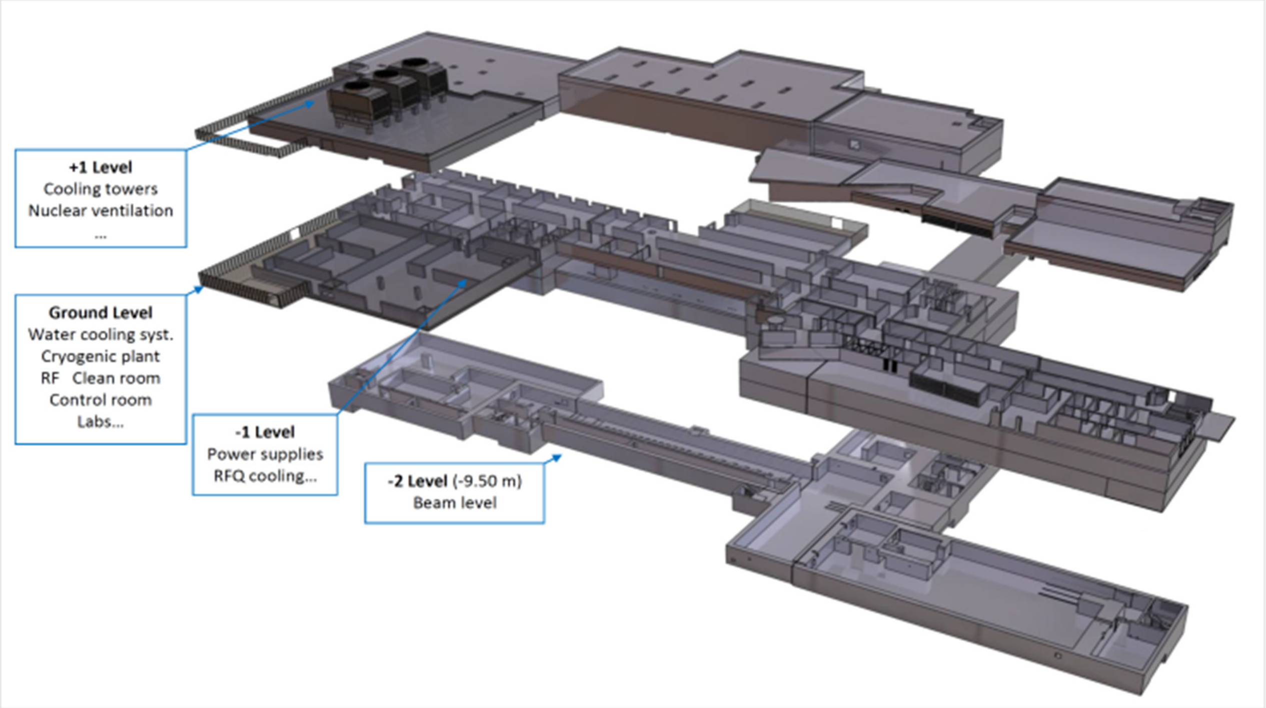

Figure 1: 3D view of the SPIRAL 2 building.

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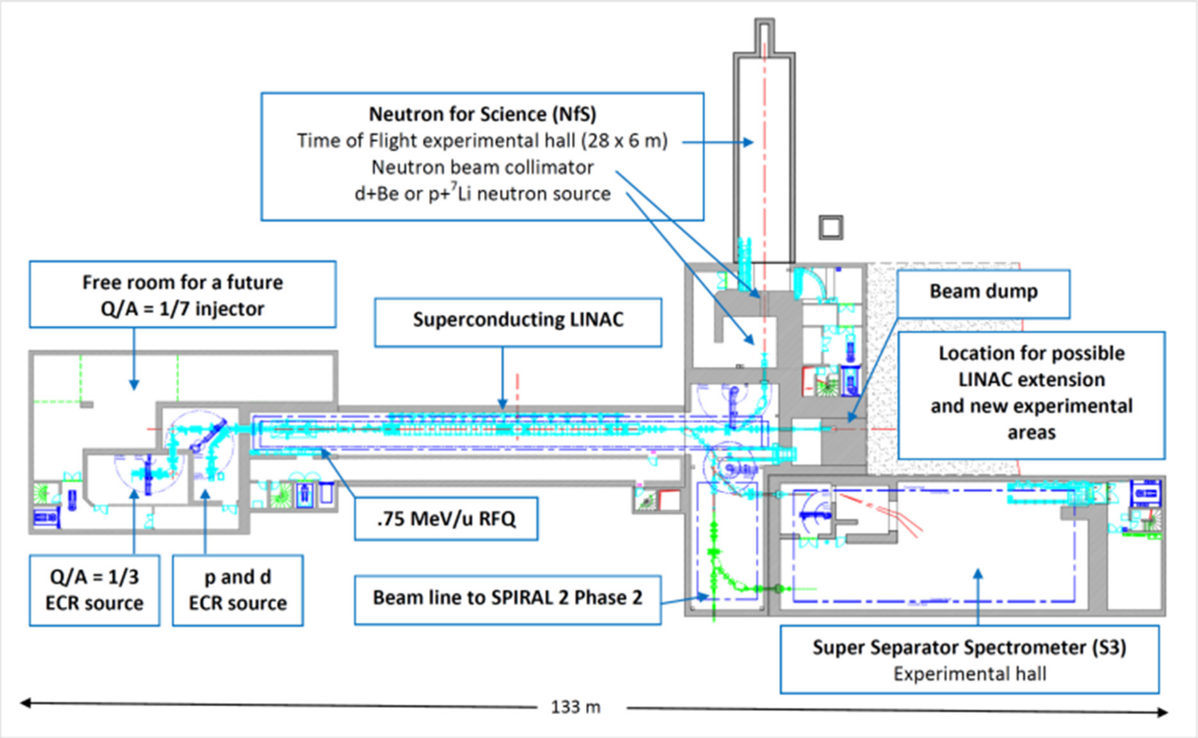

Figure 2: Overview of the accelerator, beam lines and experimental halls at the -2 level.

The first SPIRAL 2 beam at GANIL (protons) was produced by this proton/deuteron source on December 19, 2014. Since that time the periods of commissioning are scheduled taking into account the availability of the staff and the installation of the other equipment in the SPIRAL 2 building.

Up to now the goal has been to recover the excellent performances obtained at Saclay and to prepare the RFQ commissioning: proton proportion optimization, alignment and envelope tunings, intensity stability (including high-frequency noise), long run operation (6 mA CW during several nights (up to 14 h) without failure)... To obtain a 6 mA proton beam current at the LEBT end the extraction of 11 mA is required due to the low proton fraction.

The emittance measurement campaigns have been made to verify that H and V emittances of 0.2 π mm mrad rms norm. are still obtained with the 6 mA beam. Both beam intensity and emittance can be adjusted using the 6 H and 6 V pairs of slits installed along the LEBT.

## *Q/A = 1/3 Source and LEBT*

The SPIRAL 2 heavy-ion source is the 18 GHz ECR source PHOENIX V2 which uses three normal conducting coils and a large permanent magnet hexapole. The magnetic field allows an operation at 18 GHz. This source and its LEBT are designed to produce heavy ions with Q/A up to 1/3 with a total extracted beam current up to 15 mA CW at 60 kV. The design allows the installation of a dedicated oven reaching 1,600°C for the production of metallic ion beams [5].

This equipment has been constructed by the CNRS/LPSC Grenoble team and successfully tested since 2010 at Grenoble before dismantling and transport to the GANIL site in June 2014.

In the SPIRAL 2 building (Fig. 3), a first $Ar^{9+}$ beam has been successfully produced at 40 kV on July 2015. It has been analyzed using the first LEBT dipole.

PHOENIX V2 will be used for the SPIRAL 2 linac commissioning with heavy ions and also with $^4He^{2+}$ in order to mimic the deuteron beams before the safety authority authorization.

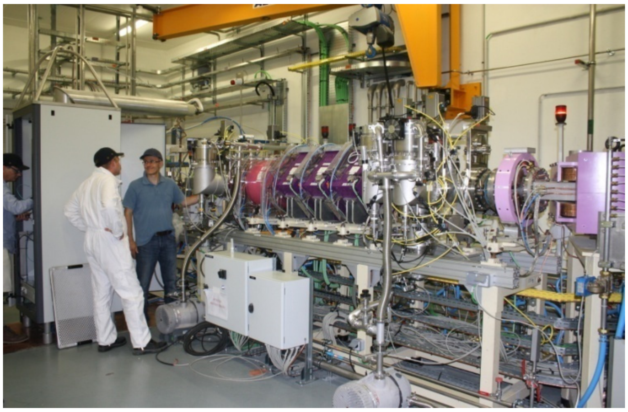

Figure 3: Q/A = 1/3 source and LEBT at GANIL.

## *RFQ and MEBT*

The SPIRAL 2 RFQ cavity [6] has been designed by the CEA/IRFU Saclay team that also managed its realization and installation at GANIL (Fig. 4). The assembly of the five sections was done from September 2014 to November 2015), the vacuum tests done all along this operation have been successful.

Figure 4: SPIRAL 2 RFQ installed in the linac tunnel.

The low level RF tuning operations of the RFQ, including the voltage law bead-pull measurements and the 40 plunger adjustments ended in March 2015. The voltage errors are smaller than 2.3 % for the quadrupolar component, 0.9% for the dipolar longitudinal component and 1.4% for the dipolar transverse component. With such errors the expected transmission is 99.7 % (TOUTATIS code simulation). In air, at 38°C copper temperature, the resonance frequency is 88.0159 MHz, the quality factor is 13,526 and the total coupling coefficient is 1.021 (177 kW dissipated power expected at maximum voltage).

The first equipment of the Medium Energy Beam Transport line (MEBT, 0.75 MeV/u, between the RFQ and super-conducting linac) and the diagnostic plate are installed. They are ready and waiting for the first RFQ beam qualification. The fast chopper (bunch selector) development is being completed. The pulse generators and the vacuum chamber equipped with the electrodes are ready while the electronics to synchronize the two fast pulses to the 88 MHz beam is still under commissioning at INFN/LNS.

### *Superconducting LINAC*

Table 1 gives the main linac parameters associated to the different ion species, including the ions produced by the future Q/A = 1/7 injector. This table shows the wide range of particles, intensities and energies which has to be managed in addition of the duty cycle range (from CW to single bunch using the fast chopper).

Table 1: SPIRAL 2 linac main beam parameters

| **Particle** | **I max (mA)** | **W (MeV/u)** | **Max beam power (kW)** |
|---|---|---|---|
| Protons | 5 | 2 – 33 | 165 |
| Deuterons | 5 | 2 – 20 | **200** |
| Q/A = 1/3 | 1 | 2 – 14.5 | 45 |
| Q/A = 1/7 | 1 | 2 – 8 | 48 |

The linac is composed of 19 cryomodules [7], 12 with one β = .07 cavity/cryomodule (CEA/IRFU Saclay) and 7 with two β = .12 cavities/cryomodule (CNRS/IPN Orsay). Both cavity types are equipped with RF couplers designed by CNRS/LPSC Grenoble.

Four low-beta and three high-beta are installed in the linac tunnel and connected to their valve box (Fig. 5). The first connections with the room temperature intermediate sections will be done mid September.

Figure 5: Low β (up) and high β (down) cryomodules installed in the linac tunnel (July 2015).

### *RF Systems*

The RFQ cavity uses four 60 kW triode-based amplifiers and the superconducting cavities use individual solid state amplifiers (Fig. 6) able to deliver up to 20 kW. Amplifiers, distribution lines, circulators, LLRF and interlock PLC have been tested independently, installed in the building and interconnected. The commissioning has begun from the RFQ RF system, the RFQ cavity conditioning should begin by the end of October.

### *Cryogenic System*

The cryogenic system (1,300 W equivalent 4.5 K) is installed and under validation. The first production of liquid helium has been done in July. The end of the liquefier tests and the receipt of the cryogenic installation are expected by the end of September.

Figure 6: Solid state 88.0525 MHz amplifiers.

### *HEBT and Beam Dump*

The High Energy Beam Transfer lines drive the linac beam to the beam dump, to the NfS and S3 experimental halls and further on to the SPIRAL 2 Phase 2 production building (see Fig. 2). The HEBT magnet installation is in progress (Fig. 7) and the 200 kW beam dump designed by the CNRS-IPN Lyon team is already built.

Figure 7: HEBT installation in the SPIRAL 2 building.

### *Experimental Areas*

NfS (Neutron for Science, Fig. 8) is the experimental area built to produce high power neutron beams from proton and deuteron beams ([1], see X. Ledoux, "NfS"). NfS plan to be ready for first SPIRAL 2 experiment from September 2016.

S3 (Super Separator Spectrometer), the experimental area built to produce very/super heavy elements ([1], see A. Drouart, "S3"), plan to be operational in 2017.

Both experimental halls are designed to have the possibility to use actinide targets.

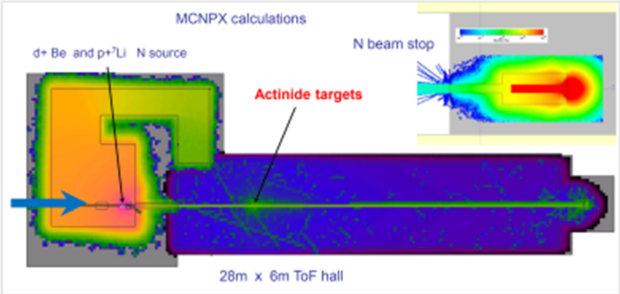

Figure 8: Neutron for Science (NfS) experimental area.

## CHALLENGES

The issues arising when building and operating SPIRAL 2 type facilities are first of all the ones faced in any (accelerator based or not) project: construction of an efficient multi-competency project team, management of the collaborations, performance / cost / schedule / risk optimization... In addition, this new generation of RIB facilities induces at least two new important challenges.

### *Challenge Induced by the Safety Rules*

SPIRAL 2 has been designed to produce high radioactive ion beam intensities and high neutron fluxes and, in addition, to allow the use of actinides targets. The challenges induced by the safety rules are then much more important than for the previous generations of RIB production facilities.

For SPIRAL 2, in addition to the classical "ALARA rule", the safety main objectives are to have an impact on the public lower than 10 µSv/y during normal operation and lower than 10 µSv/accident with a total release lower than 1 mSv/accident for accidental situations (electricity failure, fire, earthquake, plane crash...). These values have a severe impact on the schedule, cost, commissioning and operation of the facility ([1], see C. Brouillard and M. Wentzler, "Safety aspects").

A first example is the resistance requirements against earthquakes which forbid the use of light and cost saving industrial building structures. 15,000 m$^3$ of concrete and 2,200 T of iron (up to 400 kg/m$^3$) have been used for the SPIRAL 2 building (see Fig. 9). The equipment (magnets, cryomodules, helium tanks, cranes...) are also concerned since they must not damage the confinement barriers and shielding in case of earthquakes.

A second example is the obligation to build an expensive and constraining nuclear ventilation system to confine and monitor the activated gases and control their releases using very-high-efficiency filters. Three zones with a pressure gradient have been defined; all the cables and beam pipe wall traversals between two zones must be closed to minimize the air leaks.

The advances done with the French Nuclear Safety Authority are good but it must be pointed out that the safety constraints have been and still are a concern. The SPIRAL 2 experience could benefit to other projects.

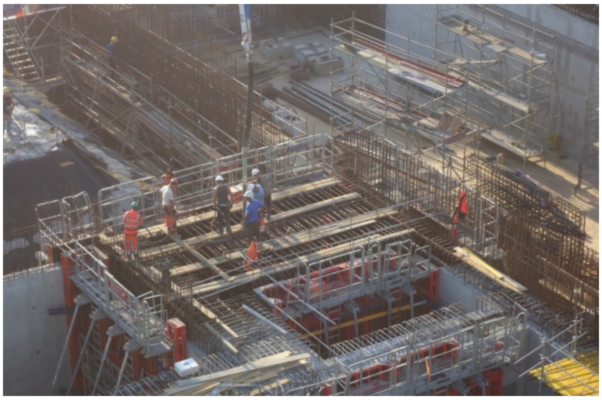

Figure 9: Iron mesh of the SPIRAL 2 building.

### *Commissioning and Tunings for Operation*

For the commissioning and tunings for operation, SPIRAL 2 has issues shared with other high-power accelerators facilities (e.g. spallation neutron sources):

- The use of superconducting cavities forbids or strongly limits the use of interceptive diagnostics to minimize their pollution. Beam Position Monitors will be used for linac cavity tunings but they have a degraded accuracy below 150 µA and they work with bunched beams although the beam is bunched only when the cavities are tuned.
- Beam loss control is an issue to avoid damages (100 W enough to drill a vacuum chamber) and structure activation (the 1W/m limit).

In addition, the situation is complicated by the fact that:

- The tunings must be done for a large range of ions, energies, intensities and duty cycles (see Table 1).
- The beam loss monitors which are usually the key diagnostic to tune such machines have a weak efficiency at low energy.
- The long radial and longitudinal focusing periods imposed by the low frequency double gap cavities is such that the space charge effects (tune depression) are high at 5 mA.
- The limitation of the amount of activated material inventory imposed by the safety rules is such that the use of the beam dump is severely constrained: the authorized maximum beam power per day is 400 W, i.e. only 3 minutes per day to tune a 200 kW beam!

Advances on the SPIRAL 2 commissioning and tunings for operation strategy have been done in 2013 and 2014 by a working group gathering accelerator physicists, safety experts and the engineers in charge of the diagnostics and command/control. The NfS and S3 nuclear physicists in charge of the first experiments have been also consulted to make the choice of the ion species to be used during the commissioning phase ([1], see J-L. Biarrotte, “SPIRAL 2 linac diver commissioning”).

Fig. 10 describes the phasing we plan to use to ramp up the beam power. During the two first phases both intensity and duty cycle must be low to be authorized to lose the whole beam. Diagnostics working well in these conditions are key for the commissioning success.

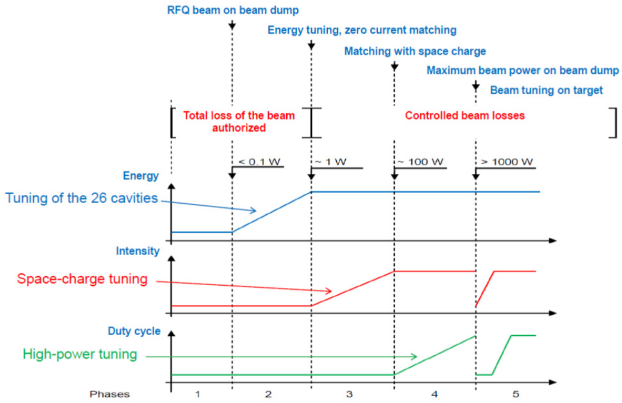

Figure 10: Commissioning / beam tuning strategy.

## SPIRAL 2 1+ PHASE

The totality of the SPIRAL 2 1+ phase budget has been consolidated in June 2015. Fig. 11 gives a schematic view of this SPIRAL 2 extension ([1], see J-C Thomas, “DESIR”), its main components are:

- The DESIR experimental hall for low energy experiments (30 m x 50 m).
- Two beam lines from S3 and SPIRAL 1.
- The RFQ-cooler “SHIRaC” which has proven its ability to obtain 2 π mm mrd emittances with ΔE/E < 1 eV and 50 to 70% transmission for A = 40 to 130.
- A High Resolution Spectrometer (HRS) designed to obtain a M/ΔM > 20,000 resolution at 60 keV.

The detailed studies of the equipment and infrastructures are well advanced and some key pieces of equipment are already available (RFQ-cooler, HRS dipoles…). The first beam is expected in 2021, a date imposed by the safety procedures.

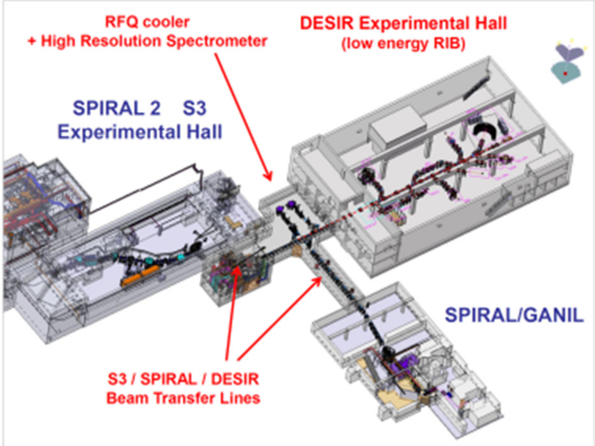

Figure 11: Schematic view of the SPIRAL 2 1+ phase.

## ACKNOWLEDGMENTS

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