STATUS REPORT ON THE SPIRAL2 FACILITY AT GANIL

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on behalf of the SPIRAL2 collaboration

Abstract

The GANIL SPIRAL2 project is based on the construction of a superconducting ion CW LINAC with two experimental areas named S3 ("Super Separator Spectrometer") and NFS ("Neutron For Science"). This status will report the construction of the facility and the first beam commissioning results.

The perspectives of the SPIRAL2 project, with the future construction of the low energy RIB experimental hall called DESIR and with the construction of a new injector with q/A>1/6 or 1/7, will also be presented.

INTRODUCTION

Officially approved in May 2005, the GANIL SPIRAL2 radioactive ion beam facility (Fig. 1) was launched in July 2005, with the participation of many French laboratories (CEA, CNRS) and international partners. In 2008, the decision was taken to build the SPIRAL2 complex in two phases : a first one including the accelerator, the Neutron-based research area (NFS) and the Super Separator Spectrometer (S3), and a second one including the RIB production process and building, and the low energy RIB experimental hall called DESIR [1,2].

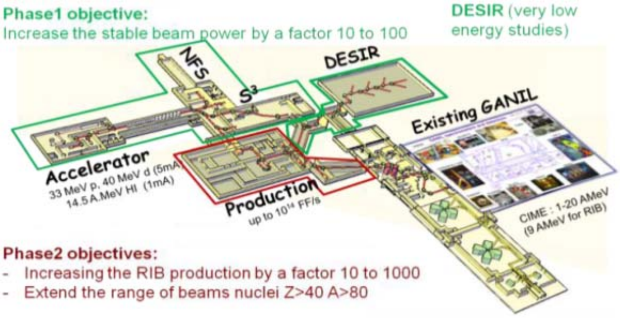

Figure 1: SPIRAL2 project layout, with experimental areas and connexion to the existing GANIL.

In October 2013, due to budget restrictions, the RIB production part was postponed, and DESIR was planned as a continuation of the first phase.

The extension of the SPIRAL2 facility, with the construction of a new injector with q/A>1/6 or even 1/7 heavy ions connected to the LINAC, is also evaluated. This new injector will increase the competiveness of the SPIRAL2 facility by producing higher beam intensity and also heavier ion species.

The SPIRAL2 facility is now built, the accelerator installation, connecting tasks are almost achieved and the beam commissioning have started with very good results with the goal of the first beam for physics (NFS) in 2017 [3,4].

ACCELERATOR-NFS-S3 BUILDING

The construction permit of the accelerator-NFS-S3 building was obtained in October 2010. The construction of the building started in January 2011. After a difficult excavation work (Fig. 2) and geotechnical/geologic studies, the first concrete started in September 2011 (Fig. 3). The building with the conventional utilities was officially received by the end of 2014 (Fig. 4).

Significant key figures of the SPIRAL2 building construction are:

- 14 000 m^3 of concrete poured,
- 2 200 T of steel reinforcement used,
- 450 000 work hours,
- Up to 120 workers on site.

Figure 2: End of excavation work mid 2011.

Figure 3: First concrete in September 2011 and the foundation stone ceremony in October 2011.

Figure 4: Completion of the accelerator building (October 2014). The beam axis is 8 meters underground.

SPIRAL2 LINAC STATUS

Beams Requirements

The layout of the SPIRAL2 LINAC takes into account a wide variety of beams to fulfill the physics requests. It is a high power CW superconducting linac delivering up to 5 mA proton and deuteron beams or 1 mA Q/A > 1/3 ion beams (Table 1). Our major challenges are to handle the large variety of different beams due to their different characteristics (in terms of particle type, beam currents – from a few µA to a few mA - and/or beam energies), a high beam power (200 kW, CW) and to answer correctly to the safety issues, especially with the deuteron beam.

Table 1: Beam Specifications

Particles	**H^+**	**D^+**	**ions**	**option**
Q/A	1	1/2	1/3	1/6
Max I (mA)	5	5	1	1
Max energy (MeV/A)	33	20	15	8.5
Max beam power (kW)	165	200	45	51

Injector

The injector is composed of two specialized ECR ion sources and of a warm RFQ. Both ECR sources and their Low Energy Beam Transport lines (LEBT) have been successfully tested and qualified at an earlier stage [5] in the past years at LPSC Grenoble and IRFU Saclay. The assembly at GANIL of the two ion sources and their respective LEBT started in November 2012 (Fig. 5), while construction of the building continued. They are now fully installed in the SPIRAL2 building (Fig. 6). All the required connections (cables, fluidic networks…) to supply and to control the two ions sources and the LEBT were ready end of year 2014. The first proton beam was extracted on December 19, 2014. The First heavy-ion beam was obtained in July 10, 2015 (230 µA argon 9+).

Figure 5: start of the assembly of equipments at GANIL/SPIRAL2. Left: first quadrupole installed, right: beginning of the assembly of the mechanical frame.

The 4 vanes RFQ is a cooper cavity working at 88.0525 MHz, consisting of 5 sections of 1 meter long each.

The installation started in May 2014 with first of all the implementation and fixing of the mechanical frame, and then the assembly of the 5 sections (Fig. 7). The RFQ was fully assembled in Sept 2014.

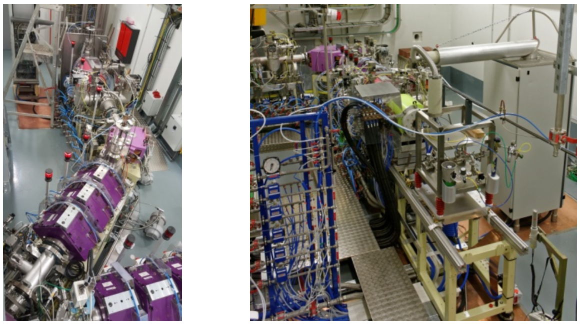

Figure 6: sources and LEBT at GANIL/SPIRAL2. Left: light ion source (H$^+$, D$^+$), right: heavy ions (Q/A>1/3).

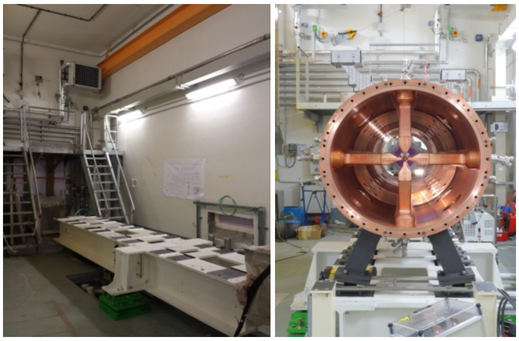

Figure 7: Left: mechanical frame, right: 2 RFQ sections.

The voltage law tuning [6,7] was ended in March 2015 (Fig. 8). Final measured voltage errors are smaller than 2.1% for the quadrupole component, 0.5% and 1.1% for the dipole S and T components respectively. Toutatis simulation with the resulting voltage law *AND* the manufacturing errors showed that the expected transmission is still 100% and above 99.7% of accelerated particles.

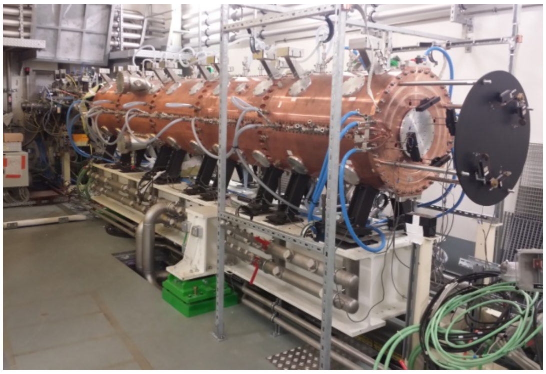

Figure 8: RFQ during the bead pull measurements.

The cavity RF conditioning started on November 15th, 2015 with only three out of four RF amplifiers. The conditioning in CW mode up to the maximal possible accelerating field level (85 kV for 110 kW within the cavity) went smoothly. The cavity voltage measurement was calibrated using an X-ray energy measurement technique. The 16 pick-ups located along the 5m long RFQ allow controlling the voltage law in operation, making a comparison with the last beadpull measurements. The relative errors are less than ±0.2% as the vane voltage is varied from 20 kV to 80 kV (Fig. 9).

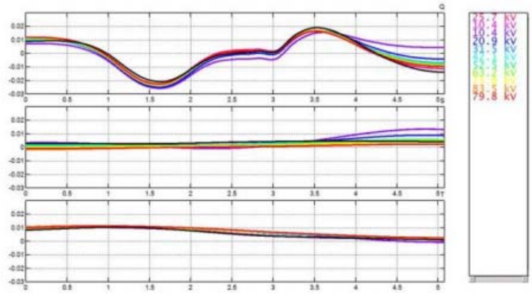

Figure 9: Voltage error versus accelerating voltage.

Up to now, various technical difficulties do not allow us to condition the RFQ cavity at its ultimate performance (CW, 113 kV). They reside in RF amplifier reliability and performances, difficulties with the LLRF, and a long response time of the cooling circuit used to tune the cavity resonance frequency. The behavior of the cavity itself is good up to now since we have reached the nominal voltage in pulsed mode with a 20% DC.

On December 3, 2015 the 88.0525 MHz RFQ cavity was ready for beam, and the first proton beam was successfully accelerated. The theoretical 100% transmission was obtained after a few hours.

SC LINAC

Eighteen of the nineteen superconducting cryomodules are installed (Fig. 10). The last cryomodule is currently under maintenance (small helium leak).

Warm sections including two quadrupole magnets and a BPM are located between the cryomodules. The first five warm sections also include a longitudinal bunch extension monitor (BEM).

All the valve-boxes needed to be repaired. It was a very long process to manage that delayed the installation by one year.

Figure 10: Cryomodules in the LINAC tunnel.

In July 2016 all the conditions were gathered to allow the first cool down of the SC LINAC. The tests consisted of cooling down three cavities in two different types of cryomodules (one high and one low β). This stage allowed us to test a major part of the cryogenic installation (cryoplant, cryodistribution) as well as the preliminary version of the PLCs and C/C. The cryomodules were selected at both ends of the helium distribution lines (CMA1 and CMB7) in order to validate the whole cryogenic line at once. Due to an instrumentation failure in the first valve box, the tests were done with CMA3 and CMB7. It was the very first time that liquid helium flowed in the cryogenic lines in the LINAC tunnel. Both cryomodules were regulated at 4K after about 20 hours of cool-down (Fig. 11).

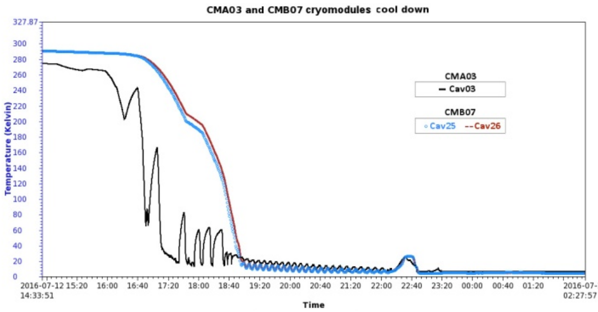

Figure 11: Very first cool down of LINAC cryomodules.

High Energy Beam Transport Lines (HEBT)

The High Energy Beam Transport lines are divided in three beam lines:

- A line up to the Beam Dump,
- A line to transport the beam in NFS cave,
- A line to transport the beam in S3 cave.

The installation of the HEBT equipments has started (Fig. 12) and will be completed beginning of 2017.

Figure 12: HEBT lines.

FIRST BEAM COMMISSIONING RESULTS

Sources Results

Both sources perform in GANIL as in their respective development labs. Up to 11 mA can be extracted from the light ion source (70% proton fraction). Argon, helium and oxygen have been extracted from the heavy ion source.

Figure 13 shows rms normalized emittances equal to 0.5 and 0.7 π.mm.mrad, larger than the expected 0.4 π.mm.mrad. These values measured for an A/Q = 2 helium beam are mainly due to the fact that the line is optimized for the A/Q = 3 beams. Whatever, three pairs of H and V slits are located in the common LEBT to define the emittances. We usually tune the line and optimize the transverse emittances to get the highest beam current on the final LEBT Faraday cup, then cut the halo (a few % of the total intensity) to get a 100% transmission through the RFQ.

The performances measured at the end of the LEBTc are given in Table 2.

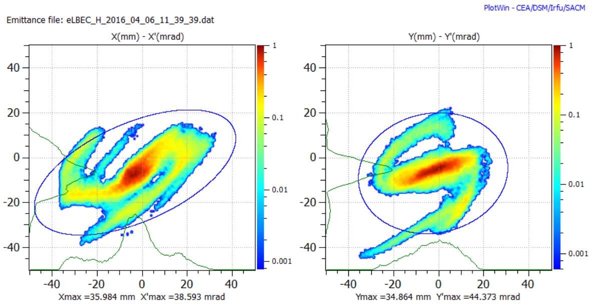

Figure 13: LEBTc emittance measurement for a 1.35 mA He beam, open slits, before hexapole tuning optimization.

Table 2: Measured Performance at the LEBT End

Particle	Beam current (mA)	Emit X (π.mm.mrad)	Emit Y (π.mm.mrad)
H^+	5.2	0.18	0.2
$^4He^{2+}$	1.35	0.54	0.43
$^{18}O^{6+}$	0.75	0.44	0.41

RFQ Beam Commissioning

On December 3, 2015, the first proton beam was accelerated at 0.73 MeV (200 μA of proton, 200 μs/250 ms, 50 kV vane voltage). By noon the same day, 100% transmission was demonstrated and within a few days, a 5.2 mA CW proton beam was successfully accelerated (Fig. 14).

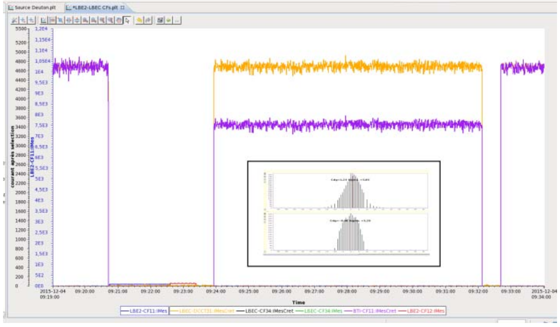

Figure 14: 4.8 mA proton beam current measured before (orange) and after (magenta) the RFQ. The 2 curves superimposed at both ends show the 100% transmission. In the middle, a profiler inserted just after the RFQ intercepts a part of the accelerated beam.

In February 2016, a 1.34 mA, CW $^4He^{2+}$ beam was accelerated with up to 98.5% transmission in spite of an input transverse emittance bigger than expected (see Table 3). The 100% transmission was obtained with a slight closing of the LEBT slits.

Table 3: RFQ Measured Beam Energy

Energy (keV/nucleus)	Toutatis simulation	TOF buncher off	TOF buncher on
Proton	730	729.3	
Helium	727.2	728.1	727.3

The beam transmission as a function of RF vane voltage and the beam characteristics were measured. There is a very good agreement between these measurements and the beam dynamics simulations performed using the TraceWin/Toutatis code. This is illustrated by Fig. 15 for the RFQ transmission and by Fig. 16 for the RFQ output horizontal emittance.

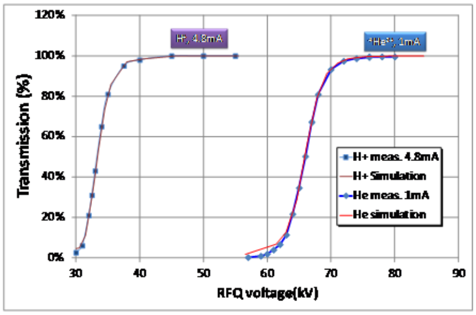

Figure 15: Comparison between measurement and TraceWin/Toutatis simulation (p and He beams).

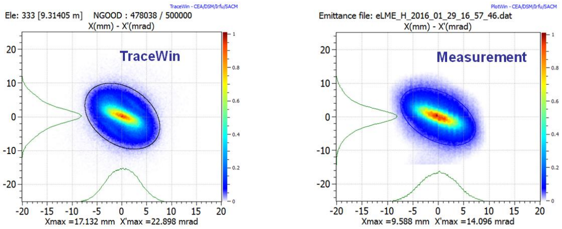

Figure 16: 5 mA proton beam in the Diagnostic-plate.

The RFQ beam energy is measured using 3 ToF pick up electrodes [7]. The proton beam was measured from 10 μA to 5 mA (pulsed and CW), helium beam from 10 μA to 1.5 mA (see Table 3).

The longitudinal bunch parameters were characterized using two tools: a Fast Faraday Cup (FFC) and the Beam Extension Monitor (BEM).

Figure 17 shows again a good agreement between the two measurements and the TraceWin simulations.

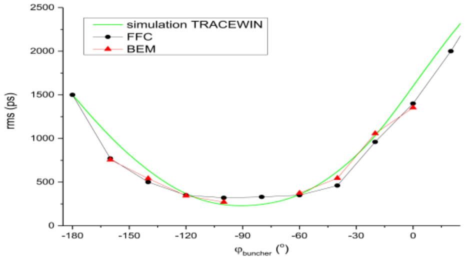

Figure 17: Comparison of the bunch width between FFC, BEM and TraceWin simulations.

SPIRAL2 PROJECT PERSPECTIVES

DESIR: The Low Energy RIB Experimental Hall

The experimental setups implemented in the DESIR hall will produce physics using low energy RIBs produced either in the S3 experimental cave or with the GANIL SPIRAL1 facility.

Low energy beam lines will transport the beam from S3 to the DESIR hall and also from SPIRAL1 to DESIR (Fig. 18). A low energy beam transport line will distribute the RIBs up to each experimental setup in the DESIR hall.

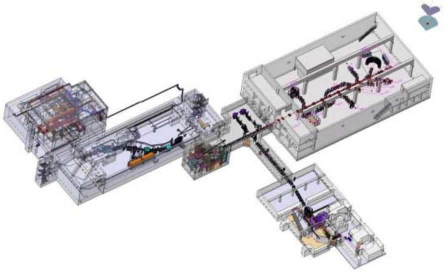

Figure 18: 3D modelization of the DESIR facility.

A High Resolution Spectrometer (HRS), coupled to a RFQ cooler, will be implemented to get the possibility to purify the RIBs before their distribution in the DESIR experimental hall if needed. The two dipoles for the HRS and the connecting beam lines are being installed for the commissioning at CEN laboratory in Bordeaux Gradignan in order to qualify its performance with stable beams. The RFQ cooler, was designed and a first prototype was tested for the SPIRAL 2 phase 2 project [8] and the adaptations for the installation at SPIRAL 2 DESIR is ongoing.

Detailed mechanical studies of the transport beam lines are ongoing with the objective to launch the fabrication in the beginning of next year.

Consultations for the construction of the building will start before the end of this year by the SPIRAL2 project. The objective is to start the building studies in September 2017. In parallel, the regulatory procedure for the construct authorization regarding the building and later on operation of the DESIR facility will be initiated with the French National Safety Authority.

The construction of the building should start end of 2018 and the DESIR facility is expected to be operational beginning 2022.

A/q=6 or 7 Injector

The construction of an injector, with *A/q*=6 or 7 heavy ions connected to the SC LINAC, will extend the possibilities offered at GANIL SPIRAL2 by producing heavier ion beam and/or higher beam intensities.

Table 4 shows the present performances with the SPIRAL2 A/Q=3 ion source and the required specifications for nuclear physics. These new performances will open perspectives for S3 scientific program and will also strengthen the scientific program with DESIR facility.

Table 4: Required Beam Intensities

Ions	**Intensity (puA) [A/Q=3]**	**High Intensity [A/Q=6 or 7]**
^{18}O	216	375
^{19}F	57	50
^{36}Ar	35	40
^{40}Ar	5.8	30
^{36}S	9.2	30
^{40}Ca	6	20
^{48}Ca	2.5	15
^{58}Ni	2.2	10
^{84}Kr	0	20
^{124}Sn	0	10
^{139}Xe	0	10
^{238}U	0	2.5

Space and utilities required for the implementation of this new injector have been taken into account since the construction time of the SPIRAL2 facility.

This injector will be composed of a new generation heavy ions source, a LEBT line, a new RFQ and a MEBT line. They will be connected between the existing A/Q=3 RFQ and the existing SC LINAC (Fig. 19).

Recently, the decision has been taken by CEA and CNRS to launch the studies of this new injector with the help of our partner laboratories. These studies will start beginning of next year with the objective to start the construction from early 2019, once the budget is consolidated.

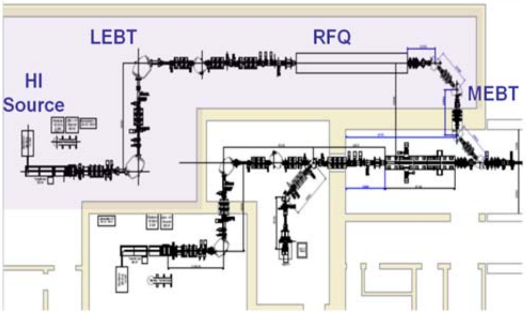

Figure 19: Implementation of the new injector.

CONCLUSION

Construction of the SPIRAL2 LINAC is about to end. The commissioning of the facility with beam has started with the first accelerated beams in the injector, and a great 100% transmission through the RFQ. Next step will be the SC LINAC complete cooling down and RF conditioning in early 2017, and LINAC beam commissioning hopefully by mid 2017.

The future extensions, with the DESIR hall and the new injector, will increase the competiveness of GANIL facility and will open new perspectives for the nuclear physics community.

ACKNOWLEDGMENT

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