COMMISSIONING OF SPIRAL2 CW RFQ AND LINAC

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Abstract

The SPIRAL2 88 MHz CW RFQ is designed to accelerate light and heavy ions with A/Q from 1 to 3 at 0.73 MeV/A. The nominal beam intensities are up to 5 mA CW for both proton and deuteron beams and up to 1 mA CW for heavier ions. The design foresees almost 100% transmission for all ions at nominal beam current and emittance. Beam commissioning of the RFQ and linac cool down started already. The specifications have been achieved within the measurement precision for the different ions accelerated yet. This paper describes the beam commissioning strategy, the measurement results in both transverse and longitudinal planes and the successfully first cryogenic tests of the linac.

INTRODUCTION

GANIL is significantly extending its facility with the new SPIRAL2 project based on a multi-beam Superconducting CW linac driver [1, 2].

The layout of the SPIRAL2 driver 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 ion beams for Q/A > 1/3 (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 energy), 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
A/Q	1	2	3	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

PROJECT STATUS

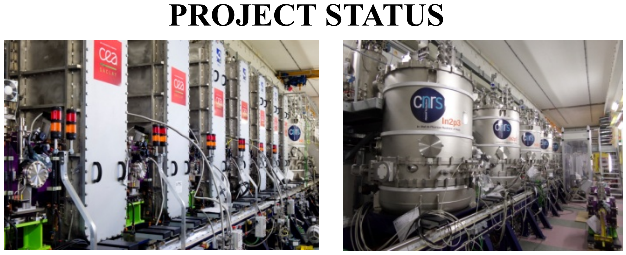

Figure 1: Cryomodules in the linac tunnel.

All superconducting cryomodules are installed (Fig. 1). HEBT installation is ongoing. Cryogenic valves boxes manufacturing defects resulted in more than a year delay for the repairs. Small isolation vacuum leaks are still observed on several valve boxes and cryomodules when cold, therefore a new dynamic pumping system has been designed and installed.

BEAM COMMISSIONING

Reference particles were selected related to an increasing stress for the RFQ cavity (increasing vane voltage). We started with the proton beam (A/Q=1). This validated the light ion source, its LEBT and the RFQ at 50 kV vane voltage. The second beam, $^4He^{2+}$ beam, up to 2mA (A/Q=2), is chosen to mimic the future deuteron beam and validate the RFQ vane voltage at 80kV. It also allowed us to start validating the heavy ion source performances. The third beam is chosen to demonstrate the ultimate performances of the injector: 1 mA, CW, A/Q=3 ion beam. For this, the $^{18}O^{6+}$ ion beam is chosen as the more convenient to produce up to 1 mA. The RFQ has to work at its maximum vane voltage of 113.6 kV. The 5-mA deuteron beam or RF injection in the cryomodules requires the final authorization from the French nuclear safety authorities. We are still waiting for this, and ready to proceed. All the other A/Q particle tunings will be extrapolated from these reference beams.

The heavy ion source was damaged during the installation work, making it at the moment impossible to measure other particle beams before the linac injection.

INJECTOR RESULTS

ECR Source Results

Up to 11 mA H^+ beam current can be extracted from the light ion source (70% proton fraction). The permanent magnet positions in the ion source have been adapted online in order to optimize and stabilize the tuning performances and repeatability of the ion source. Argon, helium and oxygen beams have been extracted from the heavy ion source..

Especially with the heavy ion source, the LEBT emittance may show some strong filamentations. Fortunately, three pairs of H and V slits are located in the common LEBT to define the emittances. We usually optimize the line transport with the transverse emittances to get the highest beam current on the final LEBT Faraday cup, then cut the halo (few % of the total intensity) to get a 100% transmission through the RFQ.

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

Emittances have been measured both in CW and pulsed mode operation, to measure and optimize the neutralization time. For example, the characteristics of a 5.8 mA proton beam are stabilised after about 400 µs with a residual pressure of 10^{-6} mbar (uncorrected value).

Table 2: Measured Performances 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 RF Conditioning

TOUTATIS [3] simulation with the measured voltage law [4,5] *AND* the manufacturing errors showed that the expected transmission up to the MEBT faraday cup is 100% for proton, 99.97% for $^4He^{2+}$ and 99.77% for $^{18}O^{6+}$.

The cavity voltage measurement was calibrated using an X-ray energy measurement technique. See [5] for the details of the voltage law in operation.

Up to now, various technical difficulties did not allow us to use the RFQ cavity at its ultimate performance (CW, 113.6 kV). The RF consumption at nominal voltage is 38kW above the expected value (200kW), and has not been explained so far. LLRF, amplifier and cooling circuit do not allow us to 'lock' the cavity at the right frequency. The data (power meas., beam trans.) are obtained using a loop that follows the frequency of the cavity [5].

Injector Diagnostic Plate

The D-Plate is installed in the Medium Energy Beam Transport Line (MEBT, Fig. 2) in order to validate the RFQ performances, to develop and qualify the diagnostics and to measure the following beam characteristics:

- Intensity with Faraday cups, ACCT and DCCT
- Transverse profiles with classical multi wire profilers and ionisation gas monitor (MIGR)
- H and V transverse emittance with Allison type scanners
- Energy with a Time of Flight (TOF) monitor
- Phase with the TOF and the BPM
- Longitudinal profile with a Fast Faraday Cup (FFC), and a Beam Extension Monitor (BEM)
- Beam position and ellipticity ($\sigma_x^2 - \sigma_y^2$, with σ_x and σ_y the standard deviations of the beam transverse sizes) with the BPM.

The diagnostics performances are given in [6,7,8]

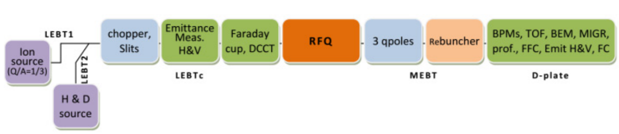

Figure 2: Injector scheme up to Diagnostic Plate.

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 law). By noon the same day, 100% transmission was demonstrated and within a few days, a 5.2 mA CW proton beam was successfully accelerated.

On 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 2). The 100% transmission was obtained with a slight closing of the LEBT slits.

On December 2016 the oxygen beam could be accelerated in the RFQ, but not at the project frequency (see above). Only the beam current transmission could be measured.

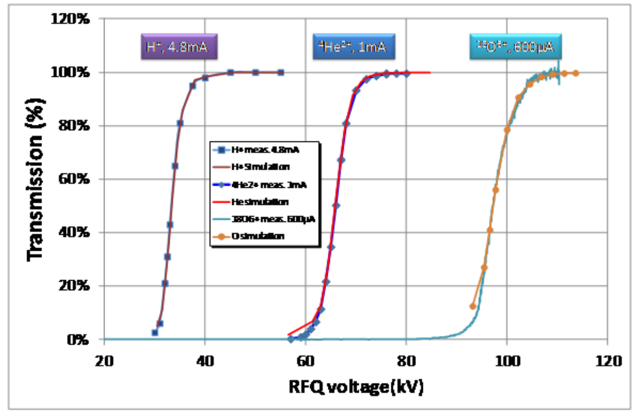

Figure 3: Comparison between measurement and TraceWin/Toutatis simulation (p, He and O beams).

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 (Fig. 3). RFQ output horizontal emittance could be also validated with proton and Helium beam.

The RFQ beam energy is measured using 3 ToF pick up electrodes [8]. 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 below)

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 longitudinal bunch parameters were characterized using two tools: a Fast Faraday Cup (FFC) and a Beam Extension Monitor (BEM). The BEM is composed of a 150 µm tungsten wire interacting with the beam (limited beam power), the measurement is done analyzing the emitted X-rays using µchannel plates coupled with a fast readout anode [8]. The estimated temporal resolution σ = 47 ps corresponds to 1.5° of phase resolution at 88 MHz.

Using the rebuncher, the 3-gradient method has been used to measure a longitudinal emittance of 0.27 π.deg.MeV for the Helium beam (0.19 expected).

The bunch profile measurements done with helium beam current from 0.1 to 1 mA showed very interesting behaviors. The longitudinal bunch shapes are quasi Gaussian at high intensity but have a thin structure at low intensity (Fig. 4). The same behavior is observed with protons (quasi Gaussian shape from 0.5 mA to 5 mA). This behavior was explained through TraceWin simulations (Fig. 5): at low beam current the S-shaped particle distribution in the longitudinal phase-space is not scram-

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bled by the space charge force.

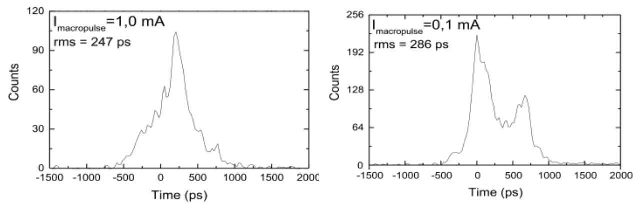

Figure 4: $^4He^{2+}$ longitudinal bunch shape for 1 and 0.1 mA.

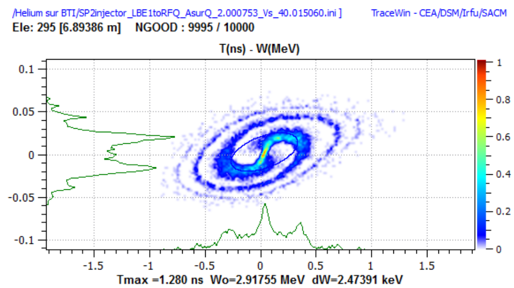

Figure 5: TraceWin simulation of a 0.15mA He beam at the BEM location (see green projection on x-axis).

LINAC First Cool Down

In July 2016 all the conditions were gathered to allow a partial 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 testing cryodistribution, behavior of cryoplant when connected to the LINAC cryo lines, as well as the preliminary version of cryo PLCs and Local Control system [9-11]. However, thermal acoustic oscillations (TAO) in the main liquid helium phase separator prevented the validation of the cryoplant and the cavities pressure/level control. The TAO problem was solved in March 2017, allowing a second cool down with three cryomodules (4 cavities). This time, the objective was to validate the helium pressure stability requirements of ± 3mbar.

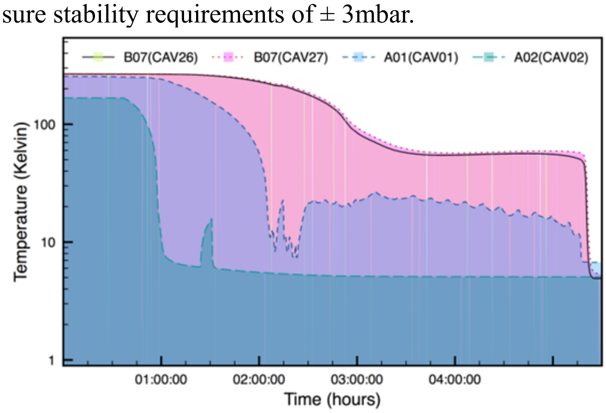

Figure 6: Cool down of the 4 cavities.

Once the cryomodules were cold (cavity at 4K and LHe level stabilized, fig. 6), several successive measurements showed that the thermalization required 5 days for a CMA and 6 days for the CMB. Once stabilized, the following static cryogenic consumptions at 4K were measured (Table 4).

Table 4: Cryomodules LHe Consumption

Static @4K	***CMA01***	***CMA02***	***CMB07***
Saclay/Orsay meas.	5.73 W	3.98 W	19 W
GANIL meas.	4.95 W	2.99 W	12.33 W

The gain observed in the static helium consumption is due to a lower copper shielding temperature (less radiation losses, 60K vs 80K). No degradation during transport from Paris area to GANIL and installation was recorded.

The pressure stability could be optimized within ± 3 mBar for the 3 cryomodules cooled together (fig. 7). The dynamic RF losses were successfully simulated on pressure stability with the CMA heaters (adding 24W per cryomodule, well above the expected RF consumption). Steps of 4W had no impact on pressure stability.

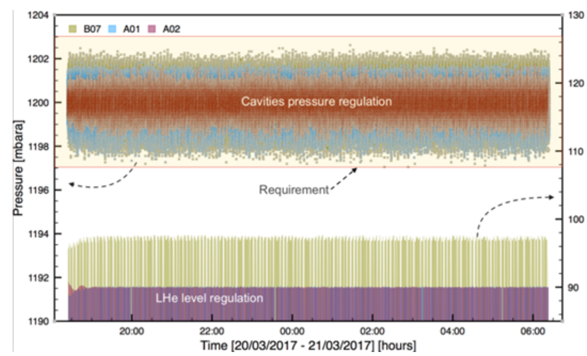

Figure 7: Pressure and liquid helium regulation for 3 cryomodules A01, A02, B07.

The next stage aims to validate several cavities with RF. This is programmed to begin as soon as we obtain the safety authorities authorization. Upon system's performance approval, the whole LINAC will be cooled down and all cavities shall be commissioned at nominal RF gradient.

CONCLUSION

We are facing exciting days, with the first accelerated beams in the injector, and a great 100% transmission through the RFQ. The preliminary results are very similar to the expected theoretical ones, illustrating the good design of the machine, and giving us confidence for the next phases. We are working to solve the technical difficulties in order to validate the A/Q=3 beam at the RFQ exit (Source and RF), hopefully before the end of 2017.

We are still waiting for the safety authority authorisation to allow us to inject RF in the cryomodules.

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