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FINAL RESULTS OF THE SPIRAL2 INJECTOR COMMISSIONING

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Abstract

The SPIRAL2 injector, made up of a 5 mA p-d ion source, a 1 mA heavy ion source (up to A/Q = 3) and a CW 0.75 MeV/u RFQ, has been commissioned in parallel with the superconducting linac installation. This commissioning is successfully completed now and the Diagnostic plate (D-plate) used to characterize the injector beams is removed. This paper presents the results obtained with the reference particles (H^+, $^4He^{2+}$, $^{18}O^{6+}$ and $^{40}Ar^{14+}$) and a comparison with the simulations. The connexion to the SC linac and the future linac beam commissioning is briefly described.

INTRODUCTION

The layout of the SPIRAL2 accelerator takes into account a wide variety of beams to fulfil the physics requests [1]. It is a high power CW superconducting linac delivering up to 5 mA proton or deuteron beams or 1 mA ion beams with A/Q ≤ 3. Our first challenge is to handle a large variety of beams with different characteristics: beam currents ranging from few µA to several mA, beam energies from 0.75 to 20 MeV/u, beam powers up to 200 kW, pulsed mode or CW. Another challenge is to handle the safety issues, especially with the deuteron beam.

The first commissioning phase has concerned the injector made up of the two ion sources, the LEBT lines (Fig.1) and the RFQ.

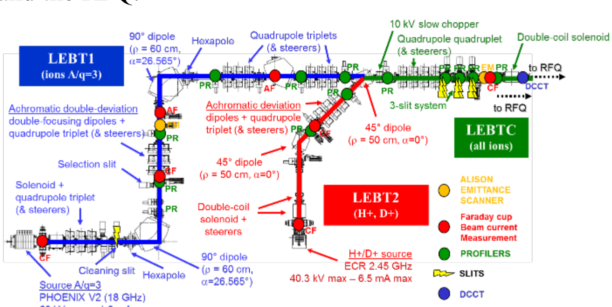

Figure 1: LEBT lines.

Three beams: p, He and O have been selected for measurement in order to best describe the injector performances.

For the 5 mA proton beam the RFQ vane voltage is only 50 kV. It is the easiest to produce (low RF power in the RFQ cavity) but the most difficult to transport in the LEBT due to the space charge forces.

$^4He^{2+}$ was selected to mimic the future deuteron beam without neutron production due to the d-d reactions. It also allowed to test the heavy ion ECR source and LEBT1. For this A/Q = 2 beam the nominal RFQ vane voltage is 80 kV.

The ultimate injector performances are for an A/Q = 3 beam up to 1 mA. The $^{18}O^{6+}$ has been selected but the source delivered only up to 0.8 mA CW. For this A/Q = 3 beam the RFQ vane voltage is 114 kV (1.65 Kilpatrick).

RFQ PERFORMANCES

Stable operation of the RFQ at high vane voltage was not easy to achieve [2] but recent improvements of the LLRF and cavity conditioning procedure lead to an availability above 95% at 114 kV. We now observe about 1 spark every 4 hours with sometime up to 4 min to recover 114 kV, the spark rate is expected to decrease with time.

DIAGNOSTICS

Three quadrupoles, one rebuncher and a D-Plate (Fig. 2) were installed behind the RFQ to tune the beam transport in both transverse and longitudinal planes and to measure its characteristics. It allowed to measure:

- Intensities with Faraday cups, ACCT and DCCT,
- Transverse profiles with classical multi-wire profilers and ionization gas monitor (MIGR),
- H and V transverse emittances with Allison type scanners,
- Energies with a Time of Flight (TOF) monitor,
- Phases with the TOF and the 2 BPMs,
- Longitudinal profiles with a Fast Faraday Cup (FFC), and a Beam Extension Monitor (BEM),
- Beam position and ellipticity ($\sigma_x^2 - \sigma_y^2$) with the BPMs.

The diagnostics performances are given in [3, 4, 5, 6].

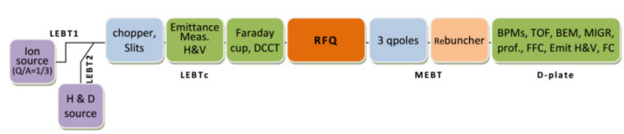

Figure 2: Injector scheme up to Diagnostic plate.

BEAM MEASUREMENTS

Transmission Measurements

The RFQ always work in CW mode from the RF point of view, its design foresees 100% transmission for all particles. This 100% transmission has been measured for 5 mA H^+, 2 mA $^4He^{2+}$ and 0.8 mA $^{18}O^{6+}$ pulsed and CW beams and for a CW 25 µA $^{40}Ca^{14+}$ beam. In Fig. 3 the transmission curves are compared with the TraceWin/Toutatis [7] simulations as a function of vane voltage. The 100% transmission of a CW A/Q = 3 beam at nominal voltage was a major step for the RFQ cavity validation.

Fig. 4 shows that for the A/Q = 3 beam the RFQ transmission rises from 93 to 100% rising the vane voltage from 105 to 114 kV.

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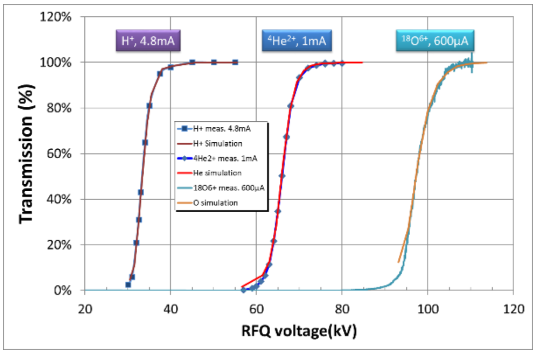

Figure 3: Transmission of the 3 reference particles.

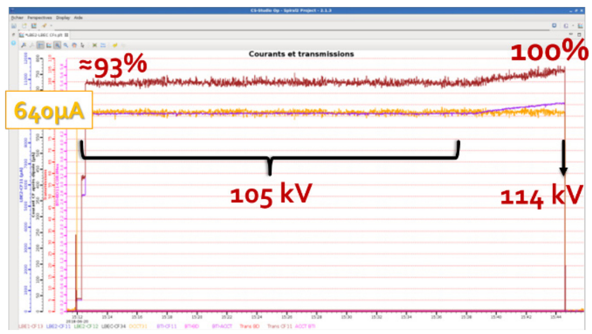

Figure 4: CW operation with 650µA $^{18}O^{6+}$ beam. Beginning with 105 kV and finishing with 114 kV. The red line is the RFQ transmission, orange the beam current before RFQ, violet the beam current after the RFQ.

The solenoid used to match the beam to the RFQ includes two independently powered coils. This allows finding the set point and gives a degree of freedom, avoiding the classical physical coil displacement. The 100% set point is easily found making a scan (Fig. 5).

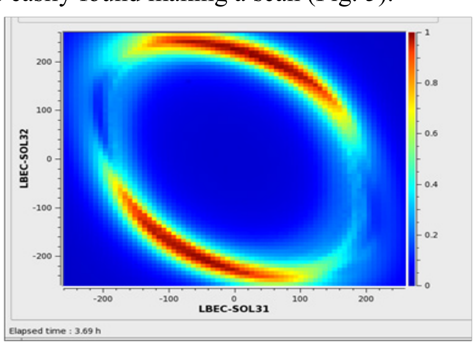

Figure 5: LEBT solenoid scan for the 25µA $^{40}Ar^{14+}$. The 100% transmission is reached in the dark red region.

Transverse Plane Measurements

The nominal RFQ beam characteristics have been achieved for all tested particles ($1 \leq A/Q \leq 3$).

The LEBT1 which is designed to transport the beam from the Phoenix V2 ECR ion source includes hexapoles to take care of the aberrations produced at the source level. The tuning of those magnets have a big impact on the emittance. The transverse emittances can be measured after the selection dipoles (Fig 1) and at the end of the line.

Few discrepancies with the simulations are observed. They mostly come from the uncertainty on the source output emittance and space charge compensation factor. The emittances measured in the LEBT1, LEBTc and behind the RFQ (MEBT) are compared with the simulation in Fig. 6. While some differences can be observed for the LEBT emittances the MEBT ones match perfectly. The agreements for the A/Q = 3 beam at 114 kV (Fig. 6) and the 5 mA proton beam with space charge (Fig. 7) confirm the high quality of the RFQ. We expected to improve the comparison in the LEBT with a transport back of the emittance measurement to the source meniscus but the losses on the slits and in the dipoles prevent such a transport back.

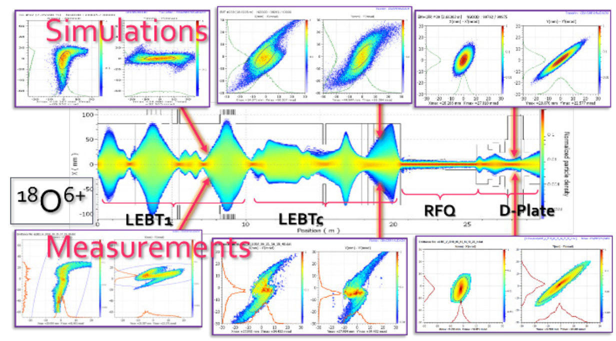

Figure 6: Comparison between simulations and measurements for the transverse emittance of the $^{18}0^{6+}$ beam in the LEBT and MEBT lines (650µA).

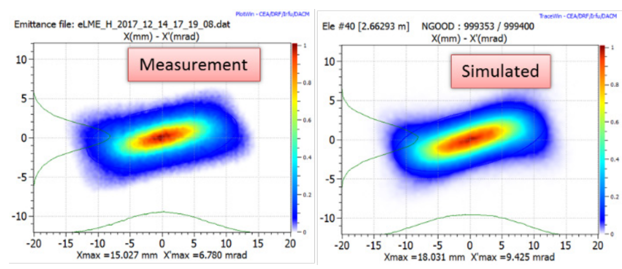

Figure 7: Phase space distribution in the MEBT, comparison for the 5 mA H^+ beam.

The MEBT transverse emittances are in agreement for all the tested particles (ε, α, β). Table 1 gives the measured and the simulated values for various particles.

Table 1: MEBT emittances measured and simulated, ε unit in π.mm.mrad, β unit in mm/π.mrad

MEBT	H^+	$^4He^{2+}$	$^{18}O^{6+}$	$^{40}Ar^{14+}$
$\varepsilon_{xx'}$ / $\varepsilon_{yy'}$	0.34 / 0.38	0.34 / 0.42	0.40 / 0.58	0.19 / 0.29
simulation	0.34 / 0.41	0.40 / 0.41	0.40 / 0.41	0.19 / 0.29
$\beta_{xx'}$ / $\beta_{yy'}$	2.0 / 4.0	1.79 / 3.5	0.6 / 4.0	3.9 / 1.8
simulation	2.0 / 7.1	1.82 / 3.3	0.7 / 3.5	4.4 / 1.3
$\alpha_{xx'}$ / $\alpha_{yy'}$	-0.0 / -2.2	-2.5 / -1.7	-0.5 / -3.3	-0.2 / -0.3
simulation	-0.0 / -3.5	-2.4 / -1.6	-0.6 / -3.0	-0.1 / -0.2
I beam	5 mA	1.6 mA	650 µA	25 µA

A pencil beam can be defined in the LEBTc using the 6-slit system which allows to define an emittance. The 5 mA proton beam was reduced to 150 µA and 0.06 π.mm.mrad at the RFQ input. In this case the emittance growth (x3) between the LEBT and MEBT measurements is not explained by the simulation. The emittance growth can be

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limited but not fully suppressed tuning the last focusing elements before the RFQ, today we don't understand why.

The emittance in the LEBTc may present few tails depending on the source tuning and/or beam current but the emittances produced by the RFQ have no distortion when the matching to the RFQ is optimized (see Fig. 6 and 7). We showed that it is not required to transport the measured LEBTc emittance though the RFQ to have a good definition of the beam at the RFQ exit, a 3σ Gaussian distribution can be used as input beam for the linac.

Longitudinal Plane Measurements

The D-plate allowed measuring various parameters of the longitudinal plane (see [8] for a detailed description).

As explained in [8], the RFQ output energy was accurately measured only for the proton and helium beams using a 3-pick-up TOF device. The measured RFQ output energies were 730.0 keV for the proton and 727.2 keV/u for the helium beams. In both cases, the comparison with the Toutatis code matches within 0.1%.

Bunch length was measured with both a Fast Faraday Cup (FFC) and a Beam Extension Monitor (BEM). The FFC which can handle up to 400 W beams has a resolution of $\sigma_{rms} = 330$ ps. The BEM has a better resolution of $\sigma_{rms} = 47$ ps [3, 5] but is more limited in beam power (35 W).

The longitudinal emittances were computed monitoring the bunch lengths given by the BEM versus the rebuncher voltage (Fig. 8). This first order method which has several limitations discussed in [8] gave good results in our case (emittance value validated using a tracking method).

Table 2 gives the expected and measured longitudinal emittances for the different beams. All those measurements lead to about the same 0.4 π.mm normalized value.

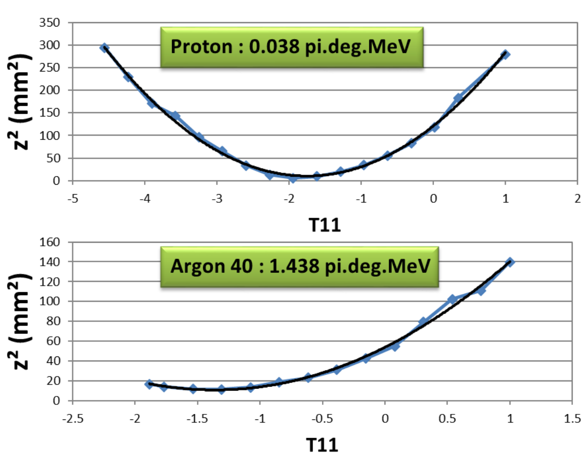

Figure 8: BEM measurements in view of longitudinal emittance calculation for the H^+ and $^{40}Ar^{14+}$ beams.

Table 2: Expected and Measured Longitudinal Emittances

Particle	Expected (π.deg.MeV)	Measured (π.deg.MeV)	difference
Proton	0.034	0.039	+15%
Helium	0.19	0.13	-32%
$^{16}O^{6+}$	0.72	0.64	-11%
$^{18}O^{6+}$	0.78	0.81	+4%
$^{40}Ar^{14+}$	1.85	1.44	-22%

NEXT PHASE

Four cool downs of the superconducting LINAC were carried out for technical validation in parallel to the injector commissioning.

In November 2018, the D-plate was removed and the new components of the MEBT were installed (two additional bunchers, the focusing sections and a bunch selector system with its beam dump). The injector beam line is connected to the cryomodules, ready to start the whole LINAC beam commissioning.

We are now waiting for the authorisation of the French Nuclear Safety Authority to start the RF conditioning of the 19 cryomodules and to begin the beam commissioning. The injection of a first proton beam in the LINAC is expected before the end of 2019.

CONCLUSION

The SPIRAL2 injector - two sources, LEBT lines and RFQ - has been successfully commissioned on the D-plate. CW operation of the RFQ is validated up to nominal voltage. Transmissions, transverse and longitudinal emittances are excellent and match very well the TraceWin simulations for every reference beam (5 mA H^+, 1.6 mA $^4He^{2+}$ and 0.65 mA $^{18}O^{6+}$). $^{40}Ar^{14+}$ beams were studied with intensities down to 25 µA working at the limits of the diagnostics.

The D-plate is now removed and the LINAC commissioning will start as soon as we obtain the authorisation.

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