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SPIRAL2 INJECTOR COMMISSIONING

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Abstract

The SPIRAL2 injector is composed of two ion sources (p/d and heavy ions up to A/Q=3) followed by a 730 keV/u RFQ. Beam commissioning has started in 2014 in parallel with the superconducting linac and HEBT installations. The RFQ beam commissioning started soon after the first RF conditioning done in October 2015. This paper describes the RFQ beam measurements done on the diagnostic plate for the reference particles (H^+, $^4He^{2+}$ and recently $^{18}O^{6+}$) and the difficulties encountered for the RFQ commissioning at the A/Q=3 field level.

INTRODUCTION

The layout of the SPIRAL2 driver takes into account a wide variety of beams to fulfill 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 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

We do not have yet the authorization to accelerate deuteron beams or to inject in the LINAC. A test bench, the Diagnostic-plate (D-plate), is used after the RFQ to validate the RFQ performances, to tests various diagnostics and to measure the beam characteristics for the future Linac injection.

BEAMS FOR COMMISSIONING

Three beams have been selected to demonstrate the injector performances.

The 5 mA proton beam requires only 40 kV on the RFQ vane voltage. It is the easiest to produce, requires little RF in the RFQ cavity but is the most difficult to transport in the LEBT because of space charge forces.

The $^4He^{2+}$ was selected in order to mimic the future deuteron beam. It allows to test the A/Q=3 ECR source and LEBT and requires a little higher RFQ vane voltage (80 kV).

The ultimate injector performances require an A/Q=3 beam up to 1 mA. The $^{18}O^{6+}$ has been selected. The RFQ vane voltage rise to 114 kV (1.65 Kilpatrick). We were not able to achieve stable operation of the RFQ and associated RF system at such set point until recently. 105 kV was easier to achieve and $^{16}O^{6+}$ beam (A/Q=2.67) was used as backup for performance measurement. Recent improvement in the cavity conditioning and LLRF tuning allow a much better cavity operation, leading to an availability of about 75% at nominal voltage (114 kV). The merit of this is that the measurement results for both oxygen beams can be compared, and $^{18}O^{6+}$ can be measured à 105 and 114 kV.

D-PLATE DESCRIPTION

The D-Plate is installed in the Medium Energy Beam Transport Line (MEBT, Fig. 1). It allows to measure:

- Intensity with Faraday cups, ACCT and DCCT
- Transverse profiles with classical multi wire profilers and ionisation gas monitor (MIGR in the text)
- H and V transverse emittance with Allison type scanners
- Energy with a Time of Flight (TOF) monitor
- Phase with the TOF and the 2 BPMs
- 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 the BPMs.

The diagnostics performances are given in [2,3,4]

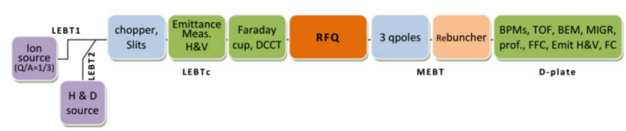

Figure 1: Injector scheme up to Diagnostic Plate.

RFQ RF CONDITIONING

The RFQ RF conditioning improved during the past few months with a better control of the RF chains and better conditioning methods. At first, the RF conditioning was managed in pulse mode with a Duty Cycle (DC) low enough to avoid copper heating. It allows to burn the dusts and spikes. We were quickly able to reach 125 kV (240 kW), 500 µs/100 ms, ending with operation without sparks. The LLRF is then switched in CW mode, integrating a PLL. In both cases (pulsed, CW with PLL), the cavity frequency tuning is manual using the temperature control. In CW mode, the cavity starts to spark at 105 kV, much lower than the level achieved just before in pulse mode. The copper heating in CW mode increases an outgassing inducing sparks at lower voltage. The RF conditioning is greatly improved increasing the copper temperature up to 55°C with RF for few weeks. Coming back to the normal LLRF operation, unfortunately without PLL during the

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power ramp-up, the cavity can now hold the designed voltage (114 kV vane voltage for the A/Q=3 particles) during a few hours, and the reduce 105 kV without sparks. Nevertheless, at design voltage, most of the sparks still create difficulties in the RF chains resulting in long period of beam shut down (30 min to 2 hours). LLRF (Low Level RF) improvement is ongoing, integrating a PLL operation mode. Progresses are expected soon.

RESULTS

Longitudinal Emittances

The longitudinal emittance has been measured (Fig. 2), monitoring the bunch length versus the rebuncher voltage on two different diagnostics: the FFC (σ_{rms}= 320–330 ps) and the BEM (σ_{rms}= 47 ps). The BEM results are equal to the calculated value for our reference beams (Table 2).

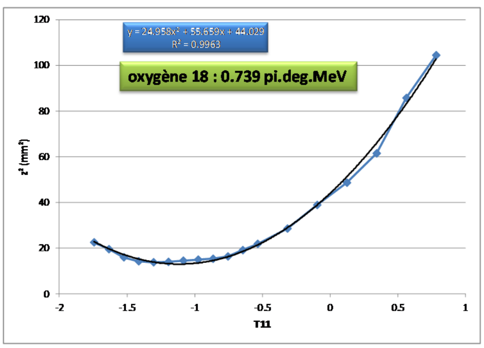

Figure 2: Analyze of Beam Extension Monitor measurements in view of longitudinal emittance calculation.

Table 2: Longitudinal Emittance Measurements

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%

Transverse Emittances

The transverse emittances measured for the reference particles in both planes before and after the RFQ are all within the expected values. More important, the MEBT transport can be remarkably well simulated using the TraceWin code (Fig. 3, 4 and 5). This is unfortunately not the case for the LEBT comparison. We suspect that the solenoid strong focusing into the RFQ cavity generates transverse emittance growth. Variations of the space charge compensation do not allow us to get satisfying simulations.

A 6-slit collimator in the LEBT allows to define the emittance injected in the RFQ. It will be use to generate the pencil beam required for Linac commissioning. Defining an emittance of 0.06 π.mm.mrad with the slits, we were able to measure this value before the LEBT last solenoid, but the measured emittances in the MEBT was ×3 time bigger.

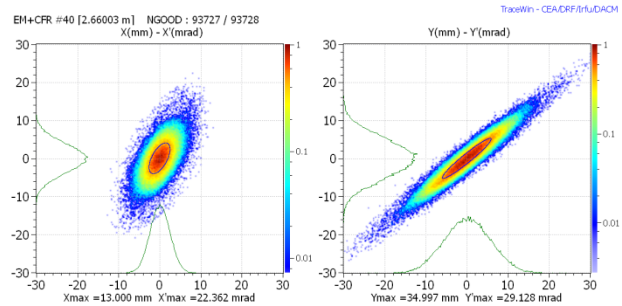

Figure 3: Calculated MEBT emittance – $^{18}O^{6+}$.

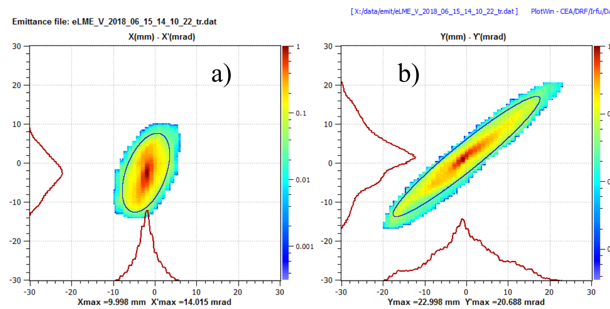

Figure 4: Measured MEBT Emittance – $^{18}O^{6+}$.

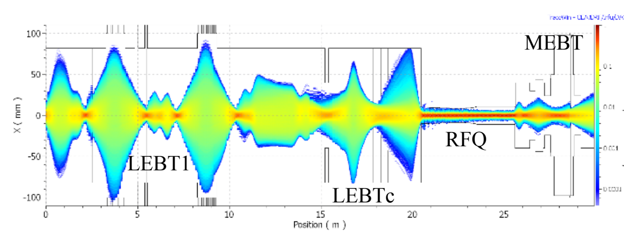

Figure 5: Density plot simulation of the $^{18}O^{6+}$.

RFQ Transmission

The 100% RFQ transmission has been validated for an A/Q=3 beam in CW mode, at the nominal 114 kV (Fig. 6 in CW beam measurement and fig. 7 in pulse mode). The CW $^{18}O^{6+}$ beam was accelerated with success at the reduced voltage of 105 kV with 93% transmission.

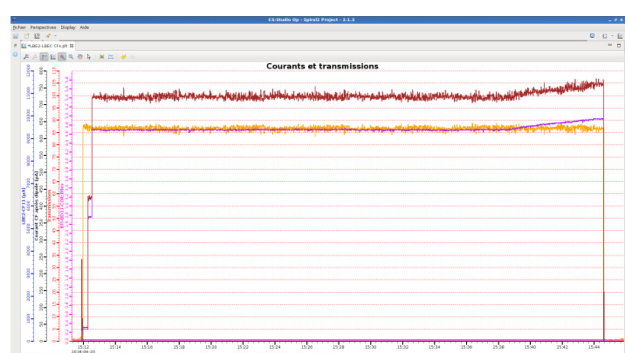

Figure 6: CW operation of the 650µA $^{18}O^{6+}$ beam. At first at reduce 105 kV then at 113 kV. Red is the RFQ transmission, orange the beam current before RFQ, violet beam current after the RFQ.

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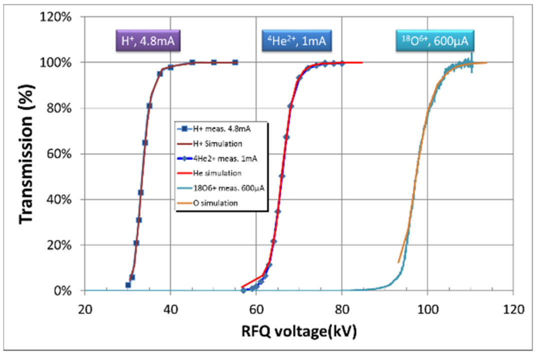

Figure 7: Transmission of the 3 references particles.

Cavity Tuning

The diagnostic plate (D-Plate) serves also as a development platform for the accelerator diagnostics and also presently for the test of the procedure which will be used to tune the SC linac cavities. The rebuncher is used with two longitudinal phase measurements among the 2 BPMs and 3 TOF pick-ups. The tests are done using the well known Signature Matching procedure [5].

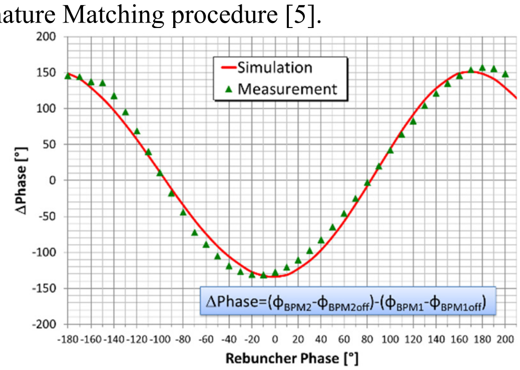

Figure 8: Discrepancy between the phase scan measurements (green dots) and the simulation (red line).

Figure 8 is a typical plot showing the large differences observed between the measurements and the result of the fit done to compute the cavity phase and amplitude tunings. Multiparticles simulations are used to understand the difficulty.

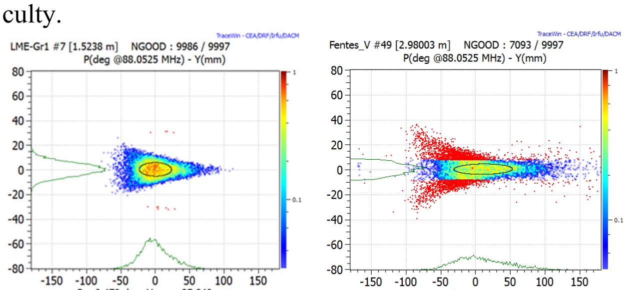

Figure 9: Left, phase – vertical position (ϕ-Y plane) correlation created in the rebuncher. Right, same representation after the MEBT slits. Red particles are lost in the slits.

When the second phase is measured after the MEBT slits, it has been demonstrated that a phase–y plane coupling occurring in the rebuncher induces part of the error. As shown by Fig. 9, the slits located between the 2 BPMs induce a phase shift of more than 10° by cutting dedicated phase in the y-plane.

However, error of several degrees remain using a second phase PU located upstream the slits.

Other Results

Various results were already reported for proton and helium beams [6,7]. They can be resumed as following:

- Ability to extract 11 mA CW from the light ion source resulting in more than 6 mA proton beam at the RFQ entrance and exit.
- Ability to control the beam intensity and radial emittances using the 6 H and 6 V slit system.
- Ability to limit the LEBT emittance growth with pressure increase at the end of the LEBT. Nevertheless, we are not able to have simulations reproducing the observed beams.
- RFQ transmissions are measured to be between 98% to 100% depending on the RFQ injection quality.

CONCLUSION

The great successes of the proton, helium and oxygen beams are promising for the next Linac injection.

Depending on the Nuclear Safety authorization, the D-plate is expected to be removed before the end of the year. Linac RF test should start in April next year and a first beam injection to follow.

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