SPIRAL2 RFQ BUNCH LENGTHS AND LONGITUDINAL EMITTANCE MEASUREMENTS

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Abstract

The SPIRAL2 beam commissioning has started and the superconducting linac installation is being finalized. The conditioning of the Radio Frequency Quadrupole (RFQ) [1] begun in 2015, and the beam commissioning soon after. Among the beam parameters checked at the RFQ output, the energy, bunch length and longitudinal emittance have been measured for the 3 referenced particles.

INTRODUCTION

GANIL is significantly extending its facility with the new SPIRAL2 project based on a multi-beam Superconducting Constant Wave linac driver [2, 3].

The accelerator commissioning started with the injector qualification on a diagnostic plate (D-Plate) located after the RFQ. We had the objectives to validate the RFQ performances and record beam parameters for various main reference particles: transmission, beam energy, output emittances in the three planes and bunch extension. A great care was taken on the longitudinal plane, as it can lead to linac losses and activations.

EXPERIMENTAL SETUP

Beams Requirements

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

Table 1: Beam specifications (Option is not built yet).

Particles	H$^+$	D$^+$	ions	Ions option
Q/A	1	1/2	1/3	1/6
Max. I (mA)	5	5	1	1

Injector

The injector is composed of two Electron Cyclotron Resonance (ECR) ion sources (for heavy and light ions) and of a normal conducting RFQ connected to the superconducting LINAC. Both ECR sources and their Low Energy Beam Transport lines (LEBT) have been successfully tested and qualified at an earlier stage [4].

On December 03, 2015 the 88.0525 MHz RFQ cavity was ready for beam, and the first pulsed proton beam was successfully accelerated. The theoretical 100 % transmission was obtained after a few hours. Since then, 100 % transmission have been obtained for ^{4}He^{2+} and heavy ion A/Q=3 (^{18}O^{6+}) in both pulse and CW operations.

Injector Diagnostic Plate

The D-Plate is installed in the Medium Energy Beam

transport Line (MEBT) in order to validate the RFQ performances, to develop and qualify diagnostics and to measure the beam characteristics. For the longitudinal plane (Figure 1), it includes:

- Energy with a Time of Flight (ToF) monitor.
- Longitudinal profile and emittance with a Fast Faraday Cup (FFC) and a Beam Extension Monitor (BEM).
- Phase measurement with 2 BPMs, and the 3 electrodes of the ToF monitor

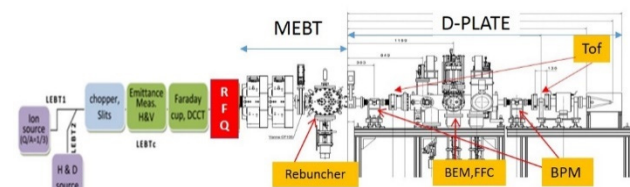The performances of the diagnostics are given in [5, 6, 7].

Figure 1: Injector scheme with the D-PLATE.

The FFC is a Faraday Cup, limited to 400 W beam power. It has a minimum time resolution of σ_{rms}= 330 ps due to bandwidth limitation (2 GHz) [5].

The BEM (Figure 2) is a 150 µm tungsten wire interacting with the beam (involving limited beam power). The bunch shape is measured with the emitted X-rays using µchannel plates coupled with a fast readout anode [6]. The estimated temporal resolution σ = 47 ps corresponds to 1.5° of phase resolution at 88 MHz.
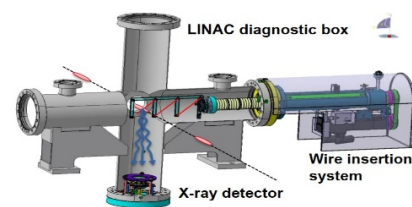

Figure 2 : BEM scheme.

ENERGY AND BUNCH LENGTH

Energy

The RFQ beam energy is measured using 3 ToF pick up electrodes [5]. The beam energy was measured for proton and Helium (pulsed and CW) (Table 2). The other species could not be measured properly due to the installation of a 2nd BPM into the line, which have to be protected with slits. Figure 3 (TraceWin simulations [8]) shows the slit effect on the longitudinal plane due to a correlation introduced by the E_y field in the rebuncher. Due to this effect, the slits induce a phase shift which can be as high as 15°.

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Table 2: RFQ Measured Beam Energy

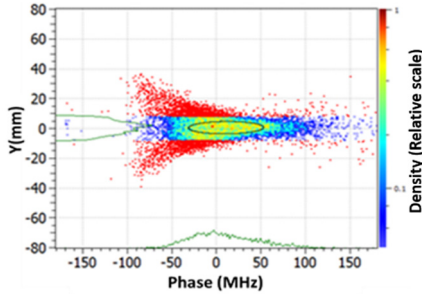| Energy (keV/nucleus)	TraceWin simulation	ToF buncher off	ToF buncher on
Proton	730	729.3	
Helium	727.2	728.1	727.3

Figure 3: Particule losses on the slits in red.

Bunch Length

The bunch profiles were measured from 0.1 to 5 mA for all particles [7]. The comparison between 0.1 and 1 mA (here with He beam) showed very interesting behaviors. The longitudinal bunch shapes are quasi Gaussian at high intensity but have a fine structure at low intensity (Figure 4, green projections). The same behavior is observed with all particles. The TraceWin simulations give the explanation: at low beam current the S-shape particle distribution in the longitudinal phase-space is not scrambled by space-charge forces.
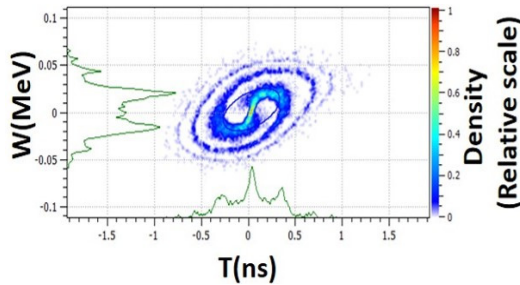

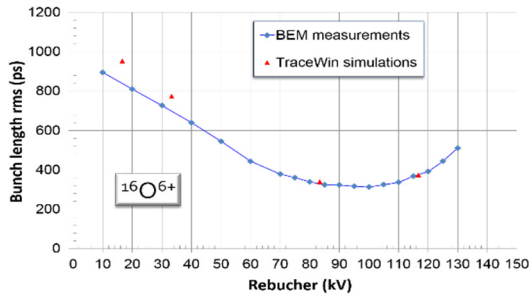Figure 4: Tracewin simulation of a 0.15 mA He beam at the BEM location [7].

Figure 5: Comparison of the bunch width between BEM and TraceWin simulations.

Figure 5 shows the good agreement between the BEM measurements and the TraceWin simulations at different value of the rebuncher voltage for $^{16}O^{6+}$. The FFC was too much limited by its bandwidth to be used.

MC4: Hadron Accelerators

A17 High Intensity Accelerators

Table 3 and Figure 6 show that longitudinal bunch profile and length measurement are close to the simulations for proton at 5 mA.
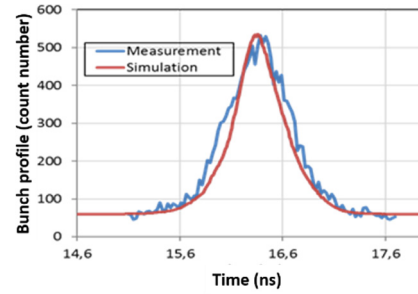

Figure 6: Bunch length measured (BEM) and associated simulation for a 5 mA proton beam.

Table 3: Bunch Length for Proton 5 mA

H+ 5 mA	σz (ps)
Simulation	288.9
Measurement	297.1

LONGITUDINAL EMITTANCE

Measurement Procedure

A voltage scan of the rebuncher and the corresponding bunch length measurement has been used to determine the longitudinal emittance (Figure 7).
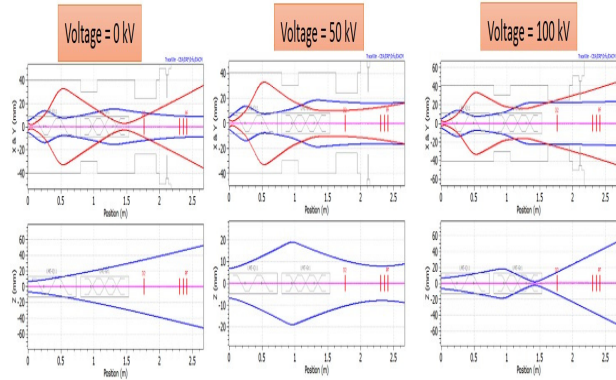

Figure 7: Simulations. Transverse envelopes between RFQ output and BEM (up) and bunch length (down) for different rebuncher voltages.

Emittance Measurement (First Order):

From the bunch length measurement z at different rebuncher voltage, and the T11 formula (Eq.1), the Figure 8 (up) can be created. A polynomial curve can be fitted from which the emittance is extracted using Eq. 2 and 3.

$$T_{11} = 1 - \frac{2\pi L q f V}{mc^3(\beta\gamma)^3} \quad (1)$$

With L the distance between rebuncher and BEM, V the rebuncher voltage, f = 88.0525 MHz, q the charge, m the mass and β and γ the usual velocity parameters of the ion.

$$Y = \langle z^2 \rangle_i X^2 + \frac{2L}{\gamma^2}\langle zz' \rangle_i X + \frac{L^2}{\gamma^4}\langle z'^2 \rangle_i \quad (2)$$

$$\epsilon_{zz'} = \sqrt{\langle z^2 \rangle \langle z'^2 \rangle - \langle zz' \rangle^2} \quad (3)$$

The assumptions used for this first order method are the following: space-charge is neglected, the rebuncher is considered as a thin lens and there is no emittance variation during transport. The result is given in the Table 4 (First order line).
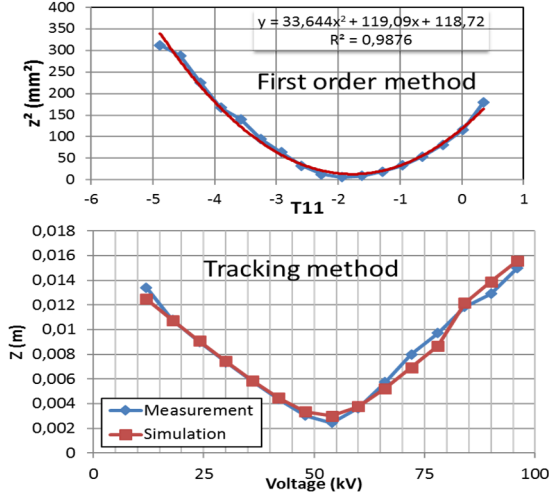

Figure 8: First order and tracking methods for proton (5mA).

Emittance Measurement with Tracking from RFQ Output

To check the previous assumptions, a first tracking simulation has been used including quadrupole field map and measured current vs magnetic field function, 3D rebuncher calculated field map and 3D space-charge (Figure 9).
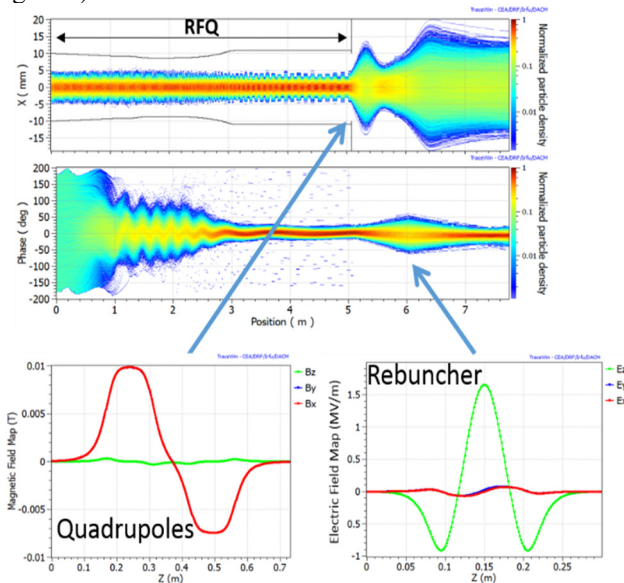

Figure 9: Tracking simulations.

RFQ output longitudinal beam parameters ($\epsilon_{zz'}$, $\alpha_{zz'}$, $\beta_{zz'}$) were adjusted in order to minimize (4), for the n voltage values:

$$\sum_{i=0}^{n} \sigma_{n\ simulated} - \sigma_{n\ measured} \quad (4)$$

Direct Simulation Including RFQ

The longitudinal emittance was also simulated directly using beam transport from the RFQ entrance up to the D-plate ("Simulation" in the Table 4).

Table 4 which gives the results displayed in Figure 8, shows that first order is sufficient to estimate the emittance as a precision better than ~25 % is not expected.

Table 4: Emittance Results with the Three Methods

Proton 5 mA	$\epsilon_{zz'}$ (π.mm.mrad)	$\beta_{zz'}$ (mm/π.mrad)	$\alpha_{zz'}$
First order	0.42	3.34	-3.45
Tracking	0.30	3.51	-3.25
Simulation	0.34	3.72	-3.51

Emittance Results for the Different Species

Comparisons between measurements (First order method) and simulations are given in Table 5 for different species. The reasonable difference can be explained by the measurement errors for different parameters (z, L, V, γ). These longitudinal emittances are close to the expected ones and do not produce losses in the LINAC in simulation. It allows us to validate the RFQ design and our capability to reproduce the beam with simulations.

Table 5: Emittances: Simulations and Measurements

Species	RFQ [kV]	Tracewin [π.deg.MeV]	Measured [π.deg.MeV]	Diff. %
Proton	50	0.034	0.039	15
Helium	80	0.19	0.13	-32
$^{18}O^{6+}$	105	0.73	0.74	1
$^{18}O^{6+}$	113	0.78	0.81	4
$^{40}Ar^{14+}$	113	1.85	1.44	-22

CONCLUSION

The energy, bunch length and longitudinal emittance measured for different species are very similar to the expected results, illustrating the good design of the machine and a satisfactory reproduction of the results by simulation, giving to us confidence for the next phases.

ACKNOWLEDGEMENT

The authors wish to thanks all the GANIL and partner labs for their deep involvement in the SPIRAL2 project.

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