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BEAM COMMISSIONING SPIRAL2

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Abstract

SPIRAL2 is a superconducting linear accelerator which is part of the GANIL accelerator complex in Caen, France. Whole injector, RFQ and diagnostics were validated between 2012 and 2018 and on July 8th 2019 the authorization to operate SPIRAL2 facility was obtained. Since then, in two 6-month periods, the MEBT line and linac have been commissioned with proton and helium beams. This article presents the results obtained and the comparison with the simulations. Optimization of the platform source voltage to avoid synchrotron oscillation in the RFQ is also presented.

INTRODUCTION

The SPIRAL2 accelerator is made up of a 5 mA p-d ion source, a 1 mA heavy ions source ($A/Q \leq 3$), a CW RFQ and the superconducting linac with 26 cavities divided into two sections: a first low energy section (β=0.07) with 12 cryomodules each containing one cavity and a second high energy section (β=0.12) with 7 cryomodules each containing two cavities [1]. This high power CW superconducting linac designed to accelerate beams up to 200 kW (D^+) is able to produce beams with a wide range of intensity (from few µA to 5 mA), as well as energies from 0.75 MeV/u to 33 MeV/u (see Table 1) [2].

Table 1: Beam Specifications

Particles	H^+	D^+	Ions	Option
A/Q	1	2	3	7
I< (mA)	5	5	1	1
E< (MeV/A)	33	20	15	7
Power< (kW)	165	200	45	49

The commissioning of the source, LEBT and RFQ was successfully done with several particles from both ion sources using a diagnostic-plate [3, 4] from late 2015 to 2018. The MEBT line commissioning started after the authorisation for operation on July 2019 and the linac beam tuning started after the internal authorisation obtained on October 28th the same year. During the next two 6-months operation, the MEBT line has been commissioned with H^+ and $^4He^{2+}$ and the linac tuning has been carried out with proton beam up to 16 kW beam power.

Comparison between measurements and simulations for the emittances, beam profiles and single bunch selector in the MEBT line are shown. A phase variation measurement and the optimization of the source high-voltages are explained. Finally a short description of the 16 kW achievement, 10% of the nominal proton beam power in the linac, is recorded.

INJECTOR STATUS

The proton/deuteron source produce up to 6 mA proton beam and 10 mA deuteron beam at the RFQ input, with high stability but a lifetime of 1000 h due to degradation of the boron nitride disk located inside the source. In the case of the ion source phoenix V2, An upgrade was carried out during the year 2020 with the aim of doubling the intensity. [5, 6]. Phoenix V3 has been validated during 2020 commissioning period with 4 mA of He beam at the source output.

MEBT LINE

In 2019 the MEBT line was validated with a 5 mA H^+ beam and in 2020 with a $^4He^{2+}$ beam.

Figure 1 shows the MEBT line composed of 10 quadrupoles, a slit system to clean the beam halo [7], 3 beam profilers, 3 rebuncher cavities, 1 H-V emittance meter, the single bunch selector with its beam dump, 1 phase pick-up (PC21), the ACCT/DCCT measuring the linac input beam intensity [8] and a Faraday cup.

The emittance and beam profile measurements are described below.

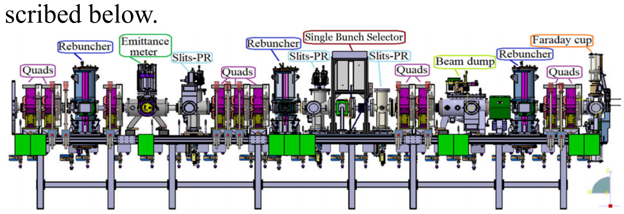

Figure 1: SPIRAL2 MEBT line layout.

Emittances and Beam Profiles

The MEBT transverse emittances are in agreement with the expected ones for H^+ and $^4He^{2+}$ beams as is shown in Fig. 2 for the proton beam. Table 2 gives the measured and the TraceWin [9, 10], simulated values for a 5 mA H^+ beam and a 0.5 mA $^4He^{2+}$ beam.

The matching optimization between LEBT and RFQ allowed 33% emittances reduction for protons in comparison with the values obtained in 2018 on the D-plate commissioning [11].

As can be seen in Fig. 3, the beam profile measurements are also in agreement with the simulations for the 0.25 mA proton beam used for linac tuning.

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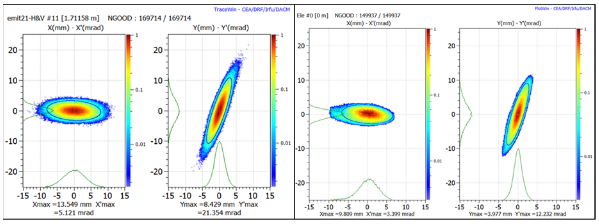

Figure 2: Simulation (left) and measurement (right) of a 5 mA proton beam.

Table 2: MEBT Simulated and Measured Emittances

MEBT	5 mA H^+ sim/meas	0.5 mA $^4He^{2+}$ sim/meas
$\varepsilon_{xx',rms}$ (π.mm.mrad)	0.23/0.23	0.09/0.12
$\beta_{xx'}$ (mm/ π.mrad)	3.65/3.66	2.59/2.45
$\alpha_{xx'}$	-0.16/-0.17	0.16/0.17
$\varepsilon_{yy',rms}$ (π.mm.mrad)	0.25/0.25	0.08/0.09
$\beta_{yy'}$ (mm/ π.mrad)	1.44/0.41	0.52/0.57
$\alpha_{yy'}$	-0.43/-0.41	-1.46/-1.49

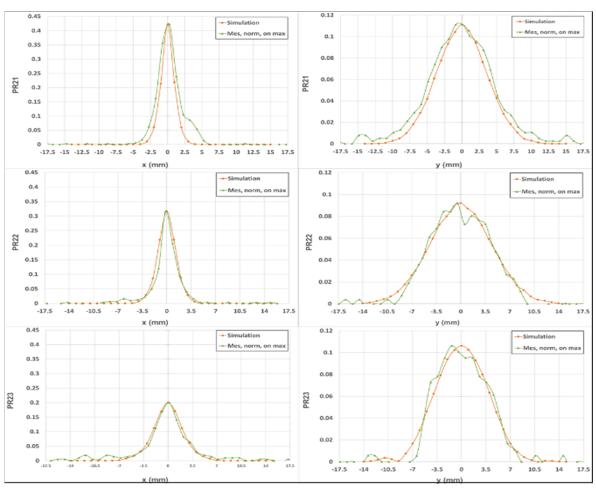

Figure 3: Beam profile simulations (orange) and measurements (green) of a 0.25 mA proton beam.

MEBT Rebuncher Tunings

The rebuncher tunings were carried out measuring the phase on the pick-up (PC21) at the end of the MEBT line as a function of the phase of each rebuncher. The objective was to find the phase in rebuncher mode for each of them.

The 360° phase measurements of the rebunchers were compared with the simulation using 3D field maps. Figure 4 shows the agreement between phase measurement and simulation for rebuncher 3.

Single Bunch Selector

The single bunch selector is required for physics in the Neutron for Science (NFS) experimental area (neutron time of flight measurement) but also to limit the beam power accelerated by the linac. This system allows to select one bunch over 100 to 10000, while the discarding the others [12]. Separation, injection and transport have been validates at 5 mA, 1 mA and 0.2 mA for pulsed and CW H^+ beams and 1.2 mA $^4He^{2+}$ beams.

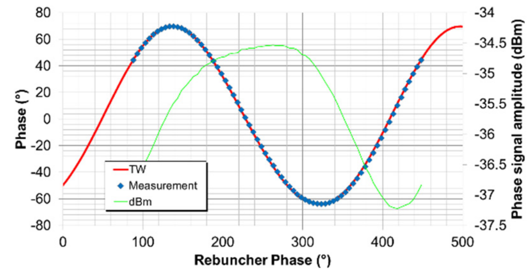

Figure 4: MEBT phase simulation (red line), measurement (blue points) and signal amplitude (green) on the pick-up PC21.

Figure 5 shows the signal on the fast faraday cup for a proton beam, the rejection between 10^{-4} to 10^{-5} was confirmed in NFS experimental room. We expect to confirm this rejection for $^4He^{2+}$ in the next stage of the commissioning.

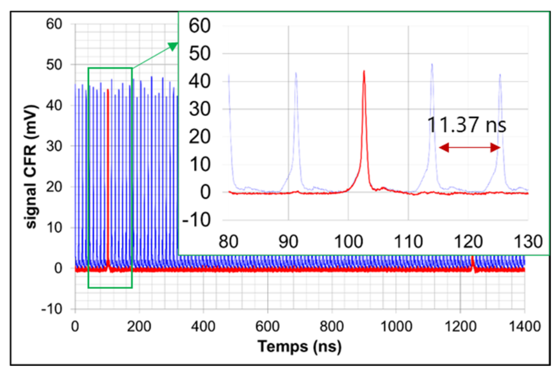

Figure 5: Selected bunch on the fast Faraday cup for a proton beam.

PHASE/ENERGY SHIFT

During the tuning of the rebunchers we detected a variation of the phase measured in PC21 when varying the beam current through the slit system in the LEBT line, and also when varying the RFQ voltage. In the first phase of the study, assuming that this variation was only due to an energy variation in the RFQ, we found that the maximum variation is 1.5%, corresponding to 11.3 keV at the RFQ output.

Simulations performed with TraceWin confirmed that the phase variation at the end of the MEBT line is due to a synchrotron oscillation in the RFQ induced by an input energy error, as shown in Fig. 6.

These large phase shifts on PC21 located far from the RFQ output are reduced when the rebunchers 1 and 2 are in operation. In addition, sending the beam to the linac, we can measure the phase at the first BPM before the first SC linac cavity and control that the energy is right.

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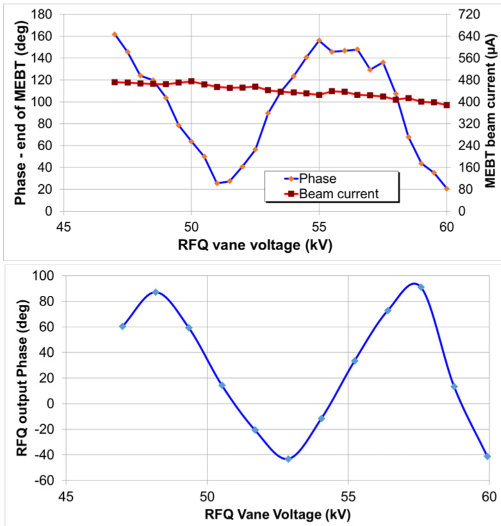

Figure 6: MEBT PC21 phase measurement (top) and Toutatis simulation (bottom) as a function of the RFQ vane voltage.

Platform Voltage Optimization

The ion source platform high-voltages were optimised in order to reduce the fluctuations generated by the synchrotron oscillation. In the case of protons, the minimum fluctuations is obtained at a voltage of 20.07 kV as shown in figure 7. It was reproduced for the helium beam.

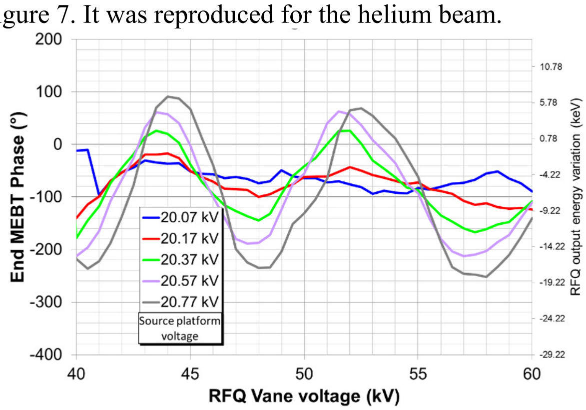

Figure 7: Platform voltage optimization of the p/d source as a function of the RFQ vane voltage.

POWER RAMP-UP

The strategy for the SPIRAL2 linac beam commissioning is divided in five phases. We started with the beam energy, then the intensity and finally the duty cycle. From October 28 to November 15, 2019 started phase 1 tuning at the RFQ energy (rebuncher mode) with a 1 W proton beam. Two weeks later we achieved phase 2, the nominal acceleration at 33 MeV with a 6.4 W pencil beam of 200 µA, 1 ms/s. It allowed us to do the first NFS test experiment on 5th December. Stage 3 was reached on 10th October 2020 with a 4.8 mA proton beam, which includes all the space charge difficulties and a much bigger emittance. The power ramp-up started afterwards. It was a staged approach first at 2 kW, then 10 kW and finally 16 kW. Between each increment, different adjustments were made. The biggest improvement was achieved with the LLRF feedback improvement. But it includes also the MEBT longitudinal matching (rebunchers) and transverse line matching into the linac. We control the losses by monitoring the transmission, beam position, warm section pressure variation and losses measured at the BLMs. Finally, we achieve the 16 kW on 18th October which represent 10% of the maximum proton beam power. The steps of the power ramp-up are shown in Figure 8.

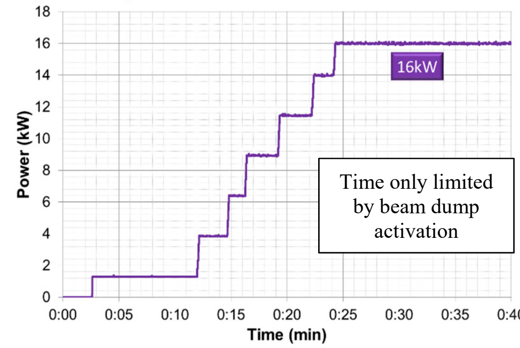

Figure 8: SPIRAL2 power ramp-up on 18th October.

Figure 9 shows the beam loss measurements at 16 kW, the linear extrapolation to CW and the thresholds at 1 W/m of the linac operation. This SPIRAL2 validation at 16 kW, demonstrate the feasibility to work at 165 kW(CW) with proton beam.

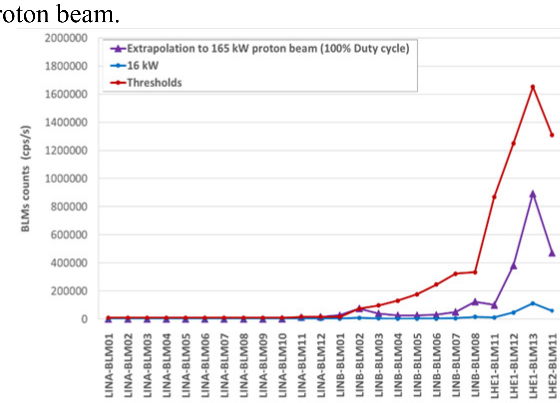

Figure 9: Beam loss measurements at 16 kW (blue), extrapolation to CW (purple) and threshold (1 W/m).

CONCLUSION

The SPIRAL2 MEBT line has been successfully commissioned with both H^+ from the proton/deuteron source and $^4H^{2+}$ from the heavy-ion source Phoenix V3. The nominal operation of the Single Bunch Selector and the ability to precisely match the beams to the SC linac have been also demonstrated. The 2021 objective is to validate the linac with the nominal D^+ beam current, using the MEBT single bunch selector.

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