ENERGY AND LONGITUDINAL BUNCH MEASUREMENTS AT THE SPIRAL2 RFQ EXIT

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Abstract

A new step of the SPIRAL2 commissioning started in December 2015 with the acceleration of a first proton beam at the RFQ exit. A test bench, with all the different diagnostics which will be used on the SPIRAL2 accelerator, was installed directly after the first rebuncher of the MEBT line in order to qualify beams but also to test and make reliable the diagnostic monitors.

In 2016, different ion beams are qualified by the diagnostic test bench. This paper describes the results of the energy measurements done by a Time of Flight monitor and the longitudinal measurements using a fast faraday cup.

INTRODUCTION

The SPIRAL2 driver is designed to accelerate and deliver proton beams, deuteron and ion beams with q/A=1/3 to NFS (Neutron for Science) and S3 (Super Separator Spectrometer) experimental rooms. Table 1 shows the main beam characteristics.

Table 1: Beam Specifications

Beam	P	D+	Ions (1/3)
Max. Intensity	5 mA	5mA	1 mA
Max. Energy	33 MeV	20 MeV/A	14.5 MeV/A
Max. Power	165 kW	200 kW	43.5 kW

Currently, an Intermediate Test Bench is installed in the MEBT line. The commissioning is in progress in the accelerator part composed by 2 sources (a proton/deuteron source and an ion source with a q/A=1/3), the LEBT lines, a chopper, a RFQ, a rebuncher as shown in the figure 1.

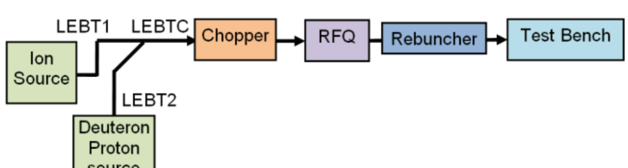

Figure 1: Injector diagram.

A first proton beam was accelerated through the RFQ in December 2015. In the first semester of 2016, the commissioning was done with proton and helium beams in pulse and CW mode, up to the nominal beam intensities. In parallel, the installation of the accelerator process continues.

INTERMEDIATE TEST BENCH

The "Intermediate Test Bench" or "Diagnostic Plate" was built to test all the different diagnostics which will be used on the SPIRAL2 Accelerator.

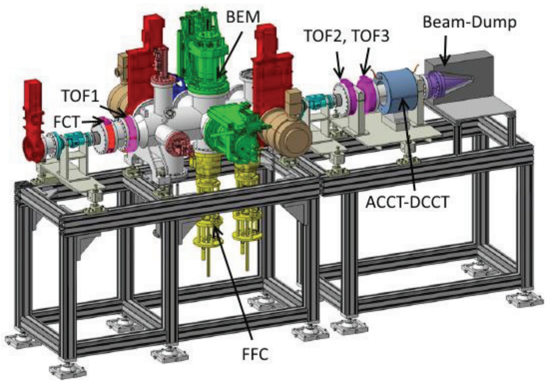

Figure 2: View of the intermediate test bench.

The Test Bench is installed after 3 quadrupoles and the first-rebuncher of the MEBT in order to validate the RFQ, the diagnostics by measuring the following beam characteristics (Figure 2):

- Intensity with ACCT, DCCT transformers and Faraday Cup (FC)
- Transverse Profiles with Multiwires beam profile monitors (SEM) and Ionization Gas monitor
- Transverse emittance with an Allison Scanner Emittancemeter (H an V)
- Phases and Energy with the Time of Flight (TOF) monitor
- Longitudinal profile with a Fast Faraday Cup (FFC) and a Beam Extension Monitor (BEM)
- Beam Position, Phase and Ellipticity with 2 Beam Position Monitors (BPM)

BEAM ENERGY PRINCIPLE

The beam energy is measured by using 3 electrodes pick-up (TOF1, TOF2 and TOF3). The energy is calculated, with a Time of flight method [1].

A dedicated electronic measures, using an I/Q demodulation method, the In-phase component I(t) and the Quadrature component Q(t) of the first harmonic [2]. An EPICS Interface, connected to the TOF electronic device by a Modbus-TCP communication, calculates the phases and the amplitudes from these components [3]. From the difference phases, the energy is determined.

BEAM ENERGY MEASUREMENTS

Beam and TOF Features

The beam features were the following (table 2):

- Proton Intensity: from few 10µA to 5mA
- Helium $^{4}He^{2+}$ Intensity: few 10 µA to 1 mA
- Slow Chopper duty cycle: From 1/10000 to 1/1
- Chopper Frequency: 1Hz to 5 Hz

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Table 2: TOF Features

Features	Values
Frequency (MHz)	88.0525
Period (ns)	11.36
Energy E (MeV/A)	0.73
Velocity β=v/c	0.04
Length between 2 bunches Lacc (cm)	13.6
Length between TOF1-TOF2 (m)	1.616
Length between TOF2-TOF (cm)	13
Bunch number between TOF1-TOF3	12
Electrode diameter (mm)	80

Electronic Initialization

Before measuring the energy, the electronic device can be initialized to increase the accuracy. Without signals, an offset subtraction allows to decrease the offset level of the 3 modules from -70 dBm to -110 dBm. The cable lengths between the electrodes and the system were adjusted very precisely. However, a test signal can be sent on the 3 electrodes with the same delay, a phase compensation between pick-ups allows to correct few tenths of degree. The type of accelerated particles is automatically retrieved from the data base of the control system.

Proton Energy Measurements

The beam energy is firstly measured with the RFQ "on" and the rebuncher "off" with different beam intensities. VRFQ = 50 kV, I crest = 3.9 mA

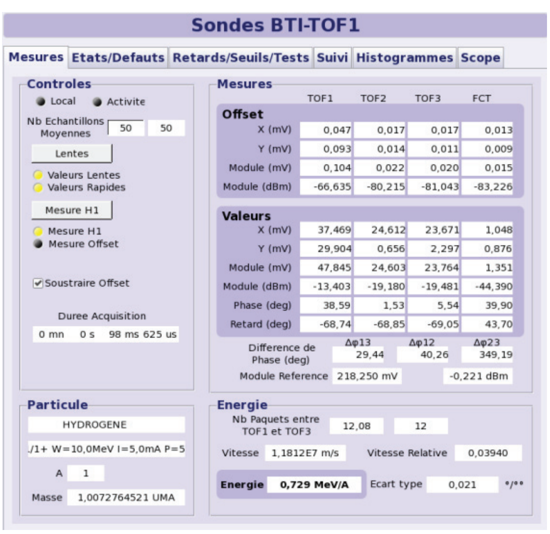

Figure 3: TOF values with rebuncher "off".

The table "Valeurs" in the page "mesures" of the graphical Interface (figure 3) indicates the X and Y signal components of the 3 electrodes, the FCT (Fast Current Transformer) and the modules and phases.

The bunch number, the energy E13 and this standard deviation are displayed in the "Energie" frame.

Separately, in order to verify the value, the energy is also calculated between each electrode on an excel spreadsheet. The 3 values are very similar around 729.32 MeV.

Helium Energy Measurements

VRFQ = 80 kV, I crest = 1.1 mA,

The 3 energy values are shown in table 3.

Table 3: Energy Measurements

Energy (keV)	Rebuncher off	Rebuncher on V = 75 kV, φ = -67,9°
E 12 (TOF1-TOF2)	727.95	727.28
E 13 (TOF1-TOF3)	727.96	727.28
E 23 (TOF2-TOF3)	728.07	727.30

The rebuncher is started at 75kV and its phase is tuned at -67.9° to find the same TOF phases with the rebuncher off. The rebuncher phase is after shifted on 360° (fig. 4).

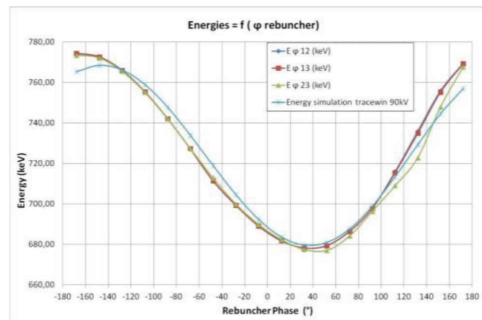

Figure 4: Energy in function of the rebuncher phase.

Histograms and Standard Deviations

The "histogrammes" sheet shows histograms, standard-deviations of the phase and the energy values.

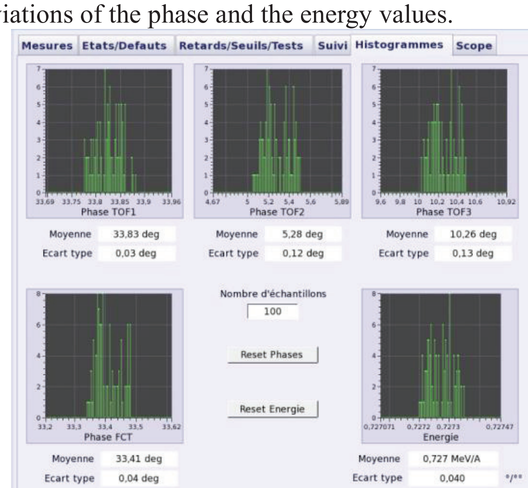

Figure 5: Phases and energy histograms.

The standard deviations give information of the ratio signal/noise. The histogram shapes indicate the nature of noises or disturbances.

A Gaussian histogram, with a low standard deviation like in the figure 5 means a good degree of precision (better than 10^{-4} in energy).

Optimization and Improvements

When the rebuncher is started and when its phase is shifted, the beam is accelerated or decelerated in function of the phase. The bunch numbers change.

$$\varphi 12 = N12 * 360 + (\varphi TOF1 - \varphi TOF2)$$
$$\varphi 13 = N13 * 360 + (\varphi TOF1 - \varphi TOF3)$$

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$$N12 = integer\left(\frac{L12}{Lacc}\right) = Int\left(\frac{L12}{L23} * \frac{360}{\varphi 23}\right)$$

$$N13 = integer\left(\frac{L13}{Lacc}\right) = Int\left(\frac{L13}{L23} * \frac{360}{\varphi 23}\right)$$

L xy: Length between TOFx/TOFy

10 < N12 <11 and 11<N13<12

N12 and (φTOF1-φTOF2), N13 and (φTOF1-φTOF3), don't change exactly at the same moment due to the measurement errors. So when the bunch number changes, φ12 and φ13 can have a jump of 360°.

To resolve this problem, the solution consists to choose E12 or E13 in function of N12 and N13. The bunch number that is farthest from the value change is chosen.

LONGITUDINAL BUNCH MEASUREMENTS

A Fast Faraday Cup (FFC) will be positioned at the end of the MEBT to visualize, characterize the bunch lengths and will be used to tune the 3 rebunchers of the MEBT.

Diagnostic Description

The FFC is a coaxial Faraday Cup with a water-cooled on the outer conductor. The inner conductor (central part) is cooled by conduction via tree ceramic rods. A polarized grid, in front of the coaxial core, is used to shield the cup against the bunch advanced field and to suppress the secondary electrons effects (see fig. 6).

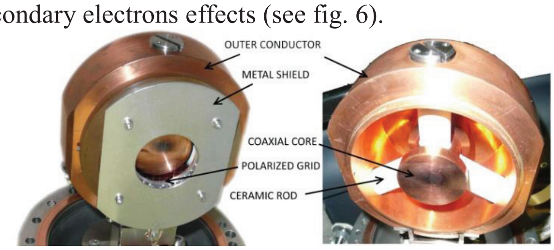

Figure 6: FFC Pictures

The diameter of the central part is 45 mm.

Thermal calculations give the following limits:

The central part limitation: 400 W in continuous beam, 10ms/200ms with a pulse power of 7.5 kW (Pmax)

The grid limitation: 1ms/200ms with a pulse of 7.5 kW.

FFC Bandwidth

The FFC bandwidth is measured with a Vector Network Analyzer, Agilent 8753 ES by reflection (fig 7.).

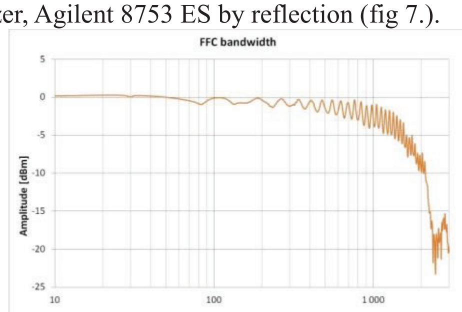

Figure 7: FFC frequency spectrum

The FFC bandwidth at -10 dBm is 2 GHz.

Acquisition System

An oscilloscope Agilent DSO9404A with 4 analog channels and bandwidths of 4GHz digitalizes the pulse FFC signal. This oscilloscope was chosen also for its EPICS drivers. A 4 dB attenuator is connected just right after the vacuum feedtrough. The oscilloscope is located at a distance of about 50m in a process room. A high-voltage power supply polarizes the grid in the range of +/- 1500v.

The oscilloscope acquisition is armed on the "Beam synchronization" signal and trigged on the "RF reference" (fig.8). "Beam synchronization" indicates the beam presence depending of the beam modulation done by the chopper, RFQ or sources.

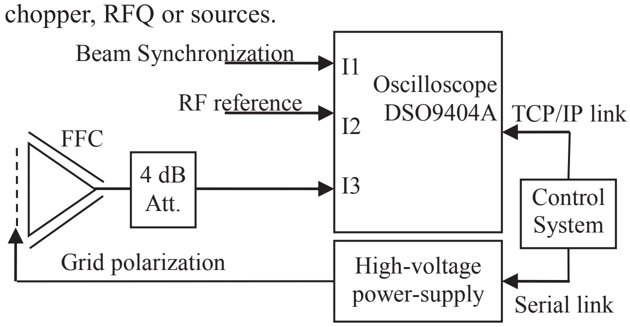

Figure 8: System Scheme

Proton Bunch Measurements

VRFQ = 50 kV, Vrebuncher = 45 kV, I beam = 4 mA

The phase of the rebuncher is tuned to be in the "rebunch mode". The time standard deviation of the beam bunch is calculated with the following formulas.

$$t_p = \frac{\sum_{i=0}^{n} V_{ffc}(t_i) * t_i}{\sum_{i=0}^{n} V_{ffc}(t_i)} \qquad \sigma_t^2 = \frac{\sum_{i=0}^{n} V_{ffc}(t_i) * (t_i - t_m)^2}{\sum_{i=0}^{n} V_{ffc}(t_i)}$$

tp: pulse time position

σt: standard deviation in time

FWHM = 800 ps.

The calculated value from the pulse (fig.9) gives σt = 328 ps while the tracewin simulated value is 220 ps.

The spectral density is determined from the pulse signal by a matlab program.

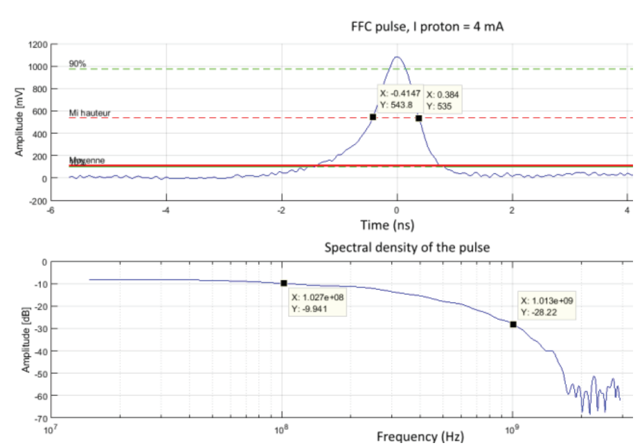

Figure 9: Spectral density of the proton pulse.

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The attenuation between the 100 MHz level and the 1GHz level is equal to 18.3 dB.

Helium Bunch Measurements

VRFQ = 80 kV, I beam = 1.1 mA

The rebuncher phase is tuned and the FFC pulses are acquired for different rebuncher voltages (fig. 10).

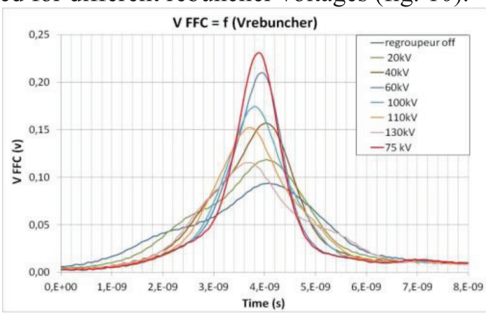

Figure 10: FFC pulse in function of the rebuncher voltage.

The bunch length is optimized at 75 kV and the pulse time values at this voltage are:

FWHM: 1,05 ns

σt calculated from the pulse = 443 ps

σt simulated with tracewin = 280 ps

BEM and FFC comparison

A Bunch Extension Monitor (BEM) is installed at the same location than the FFC. The BEM principle consists to insert a wire inside the beam and collect the X-rays on a microchannel plate. An integrating electronic device allows to reconstruct the bunch shape [4].

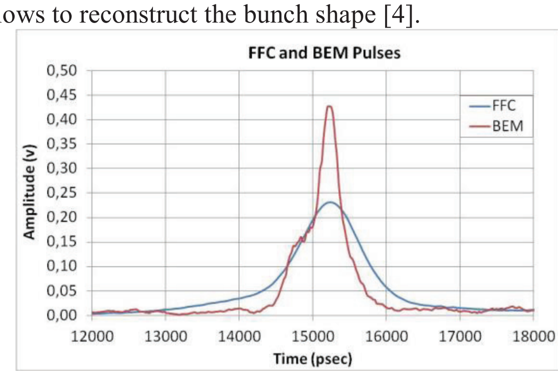

Figure 11: FFC and BEM pulses.

The BEM amplitude is normalised to have the same pulse area than the FFC one. The FFC pulse shape is larger than the BEM pulse (fig. 11).

At 75kV, the rebuncher phase is rotated over 360°, the pulse width is shown in function of this phase (fig. 13).

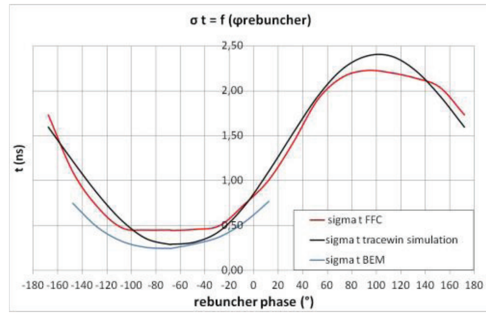

Figure 13: σt $_{FFC}$ in function of the rebuncher phase

The FFC curve shows a time resolution limitation. The minimum σt value is equal to 440 ps. In comparison, the BEM length goes down to 244 ps with a tracewin simulated σt = 280 ps. Following these measurements, the pulse enlargement due to the FFC limited bandwidth and cable distortion is estimated between 120 to 160 ps.

FFC Grid Polarization Influence

The voltage applied to the grid modifies the shape of the FFC pulse. A negative voltage repels the electrons of the secondary emission on the cup, in contrary to a positive voltage which collects these electrons (fig.14).

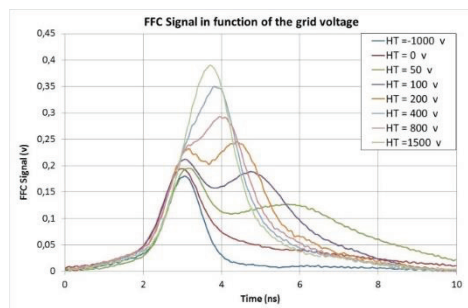

Figure 14: FFC signal in function of the grid voltage.

A low positive voltage generates a slow exit of the electrons. The second pic, produced by the secondary electrons, appears with a time delay from 1 to 3 ns. To minimize the width, the grid voltage is tuned at -1000 v.

CONCLUSION

The SPIRAL2 RFQ injector commissioning is started since the beginning of 2016 with proton and helium beams. It will soon continue with heavier ion beams.

As shown, the results of the energy and bunch length monitors are encouraging. Their functioning responds to the needs and will allow the characterization of the various injector beams.

TOF monitor studies will be done to compare signal amplitude with simulations, to measure the ratio signal/noise in function of the beam intensity and to compare the measurements with the calculated accuracy.

A signal processing of the Fast Faraday Cup should minimize the signal enlargement caused by the limited bandwidth of the Faraday cup.

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