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RESULTS OF SPIRAL2 BEAM POSITION MONITORS ON THE TEST BENCH OF THE RFQ

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Abstract

SPIRAL2 project is based on a multi-beam superconducting LINAC designed to accelerate 5 mA deuteron beams up to 40 MeV, proton beams up to 33 MeV and 1 mA light and heavy ions (Q/A = 1/3) up to 14.5 MeV/A. The accurate tuning of the LINAC is essential for the operation of SPIRAL2 and requires measurement of the beam transverse position, the phase of the beam with respect to the radiofrequency voltage, the ellipticity of the beam and the beam energy with the help of Beam Position Monitor (BPM) system. The commissioning of the RFQ gave us the opportunity to install two BPM sensors, associated with their electronics, mounted on a test bench. The test bench is a D-plate fully equipped with a complete set of beam diagnostic equipment in order to characterize as completely as possible the beam delivered by the RFQ and to gain experience with the behaviour of these diagnostics under beam operation. This paper addresses the measurements carried with the two BPMs on the Dplate: energy, transverse position and ellipticity under 750 keV proton beam operation.

GENERAL DESCRIPTION OF SPIRAL2

SPIRAL2 facility is being installed in Caen, France. It includes a multi-beam driver accelerator (5mA/40Mev deuterons, 5mA/14.5MeV/A heavy ions). The injector is constituted by an ECR ion source (Q/A= 1/3), an ECR deuteron/proton source, a low energy beam line (LEBT) followed by a room temperature RFQ which accelerates beam up to an energy of 0,75MeV/u. A medium energy line (MEBT) transfers the beam to the superconducting Linac.

The Linac is composed of 19 cryomodules: 12 contain one β= 0.07 cavity and 7 contain two β = 0.12 cavities. The cavities operate at F_{acc} = 88.0525MHz.

Main beams accelerated by the superconducting Linac are mentioned in table 1.

Table 1: SPIRAL2 Main Beams Parameters

Particle	Current(mA)	Energy(MeV/u)
Proton	0.15-5	2 -33
Deuteron	0.15-5	2 -20
Q/A = 1/3	0.15-1	2 -14.5
Q/A = 1/6	0.15-1	2 -8

SPIRAL2 nominal mode of operation is planned to be C.W. mode. The considerations on commissioning and tuning periods of the LINAC lead to a pulsed mode operation in order to minimize the mean power of the beam. The shortest duration of a macro-pulse will be 100 µs. The repetition period varies from 1ms to 1s. The intermediate configurations have to be taken in account in order to reach the C.W. operation. The step to increase or decrease either the macro pulse duration or the repetition rate will be 1µs.

SPIRAL2 BEAM POSITION MONITORS

A doublet of magnetic quadrupoles is placed between the cryomodules for the horizontal and vertical transverse focusing of the beam. Beam Position Monitors (BPMs), of the electrostatic type, is inserted in the vacuum pipe located inside the quadrupoles of the LINAC.

20 BPMs are installed along the SPIRAL2 linac. They enable the measurement of Beam transverse position, phase and transverse beam ellipticity as defined in [1]. The combination of the measured phases of two adjacent BPMs enables the measurement of Beam energy.

SPIRAL2 BPM [1] is composed of 4 capacitive sensors. Each BPM was characterized on a dedicated test bench based on a coaxial transmission line. The characterization delivers BPM electrical centre coordinates, position and ellipticity sensitivities and offsets at β≈1 [2].

Each BPM sensor feeds an electronic module through 23 meters long coaxial cables. The 20 BPM electronics modules are located in four VME 64x crates. Each module contains an analog and a digital board. The design of the analog module of the card is based on the scheme of auto-gain equalization using offset tone having frequency slightly offset from the RF reference [3]. The electronic module works either at F=88.0525 MHz or at 2*F=176.1050 MHz to deliver the required information.

Two prototypes of the BPM readout electronics module were qualified in IPN leading to several upgrades in order to meet specifications. Series of 22 electronic modules is presently under qualification at IPN.

THE SPIRAL2 INTERMEDIATE TEST BENCH (SP2-ITB)

An "Intermediate Tests Bench" (ITB) has been assembled as part of the injector commissioning plan [4]. The ITB is positioned after the focusing quadrupole following the first re-buncher of the M.E.B.T. Two other focusing quadrupoles are placed between the re-buncher, and the RFQ. A beam stopper able to withstand nearly the full power of the beam terminates the ITB which includes 18 beam diagnostics identical to the SPIRAL2 driver ones. The aim of the ITB is to fully characterize the properties of the beam accelerated by the RFQ and also to study the behaviour of these diagnostics. Figure 1 shows the ITB.

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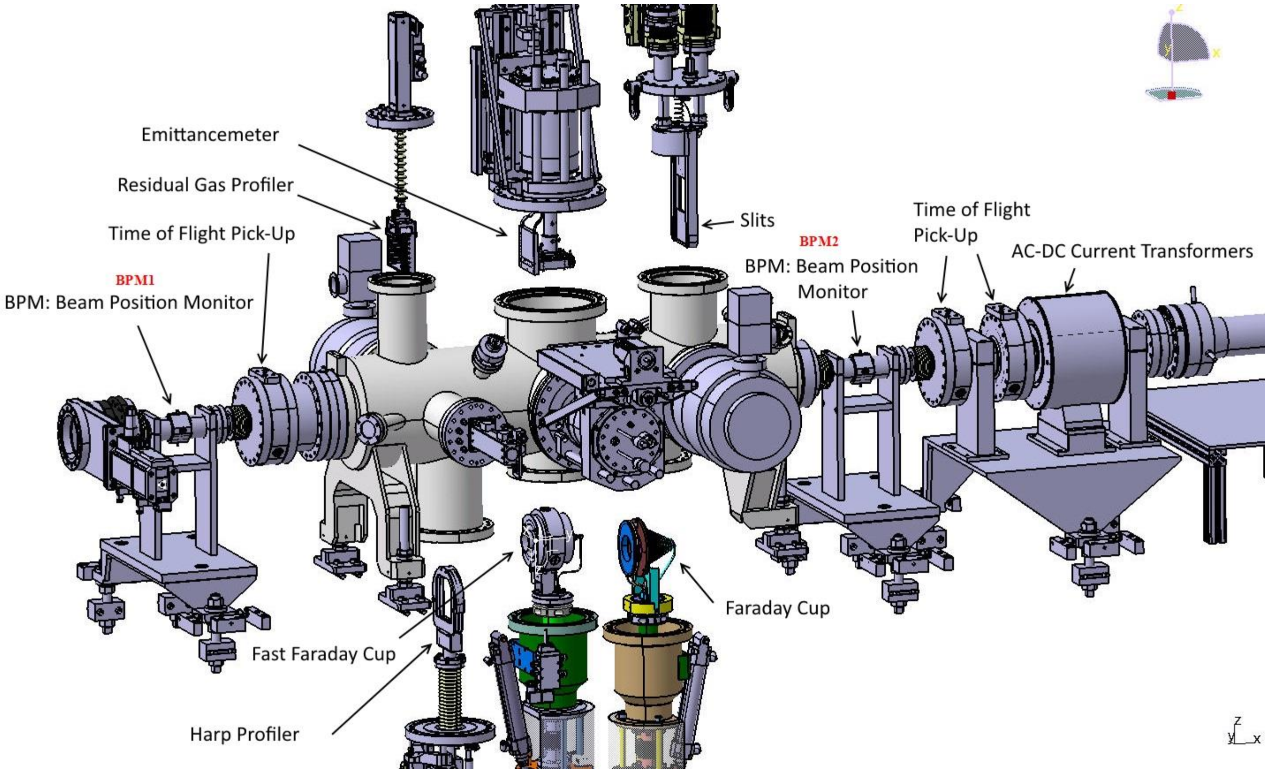

Figure 1: View of the SPIRAL2 Intermediate Test Bunch (SP2-ITB) equipped with a full set of beam diagnostics

All kinds of measurements may be carried: beam intensity, transverse beam position, profiles and emittance, phase and longitudinal emittance with a beam energy equal to 750keV/A.

Control command operation gathers the measurements performed by all these diagnostics almost on real time (every 200ms).

BPM MEASUREMENTS ON SP2-ITB

BPM1, at the left in Fig. 1, was mounted in 2015, BPM2 was mounted in 2017. Operations with the BPM1 took place in 2016; their results were reported in [1]. Operations with both BPMs took place in fall 2017 and April 2018. The following information should be mentioned:

- Nominal relative beam velocity β_{nom}=0.03949.
- Distance between the 2 BPM: D=1,692m.
- Proton beam used.
- A movable slit system is located ahead BPM2 at the right of Fig. 1. It includes four slits: two in the X axis and two in the Y axis. Each slit can move in a ±5mm range.
  • The movable slit system induces a rectangular shape of the XY cut of the beam seen by BPM2. The centre coordinates and the lengths are controlled: for example, if the two slits on the X axis are respectively positioned at -4mm and 2mm and if the two slits positioned on the Y axis are respectively positioned at 0mm and 4mm, then the XY cut of the beam out of the movable slits system is a rectangle centred at (-1mm;2mm) with lengths equal to 6mm and 4mm respectively on the X and Y axes.
- Mean Current measured by the Faraday Cup is 1.2mA.
- Current measured at the beam dump at the end of the SP2-ITB varies from 40µA corresponding to a beam aperture of 2mm by 2mm and to 1mA corresponding to a beam aperture of 10mm*10mm.

BPM Current Dynamic Range

BPM1 measurements on SP2-ITB were run at early 2016, only BPM1 at the left of the image in Fig. 1 was installed and used. Measurements of BPM current dynamic range were run on January 2016 and repeated on June 2016. The following dynamic range were obtained [1]:

- 75 µA - 5.5 mA at F.
- 60 µA – 5.5 mA at 2*F.

BPM Phase Measurements

The phase relative to the accelerating RF signal has been measured simultaneously by the two BPMs and by the three electrostatic P.U. electrodes of the time of flight (TOF) energy measurement system mounted on the SP2-ITB. The BPMs are measuring the phase at F and 2*F whereas the TOF is only measuring it at F. The RFQ phase was swept over 360° with a 10° step over different beam currents. The results show a proper behaviour of the BPM measurement system, either at F or 2*F, and a good agreement with the electrode of the TOF system over the measured beam current dynamic range: Measurements run in February 2016 showed a fluctuation within 1° for medium and high current where as it is less precise for the TOF at low beam currents [1].

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Further measurements run in December 2017 showed less fluctuation for TOF measurements (within 1° as well).

BPM Energy Measurements

Therefore, at a given moment, an estimated n=12 bunches of protons are located between the two BPMs.

Measurement of beam energy at F is performed using the following equation:

$$E_{mes} = E_p * ((1 - \beta_{mes})^{-0,5} - 1). \quad (1)$$

where

$$\beta_{mes} = \mathrm{D} * F_{acc}/\mathbf{c}/(\mathrm{n} + \Delta\varphi/360). \quad (2)$$

where **c** is the light velocity in vacuum, E_p is the proton energy E_p=938,27208MeV/$\mathbf{c}^2$, and Δφ id the difference between the phases measured by the 2 BPM.

At 2*F, equation (3) is used instead of equation (2)

$$\beta_{mes} = \mathrm{D} * F_{acc}/\mathbf{c}/(\mathrm{n} + \Delta\varphi/720). \quad (3)$$

Either at F or 2*F, measured phases at BPM1 and BPM2 mostly vary only by 0.4°, this leads to a very precise measurement of beam energy as shown in Fig. 2.

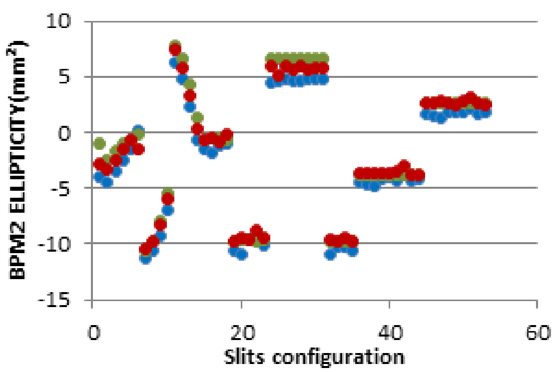

Figure 2: Beam energy measured at 2*F.

The energy measured at F is 727.6keV whether it is measured at 727.1keV with dispersion less than 200eV for both frequencies. These figures are within the precision requested for beam energy measurements ($\Delta E/E<10^{-3}$).

BPM Position Measurements

Measurements in 2016 were run only with BPM1; the position sensitivity was preset to 25.7mm, the BPM position delivered by the readout electronics were corrected based on R.Shafer study [5]. Results showed a good agreement between profiler measurements and BPM1 measurements at F or 2*F [1].

In April 2018, the same corrections were applied for BPM1 and BPM2 position measurements. Over 50 slits configurations were used, the beam position X and Y coordinates changed in the range [-3mm; 2mm]. The beam dump current varied between 40μA and 1mA.

As Profiler was not included in operation, comparison between results of the BPM2 at both frequencies (F and 2*F) is carried: the red dots refer to the corrected measurements at F whether the blue dots refer to the corrected measured at 2*F.

Figures 3 and 4 show a good agreement between position measurements at both frequencies (F and 2*F), hich the good behavior of the readout electronics. Differences were under 50μm for most slits configurations, only configuration leading to a beamdump current of 40μA gives about 1mm difference between the measurements; though, one should notice that at the current, BPM2 sensor output amplitude is about -70dBm at both frequencies.

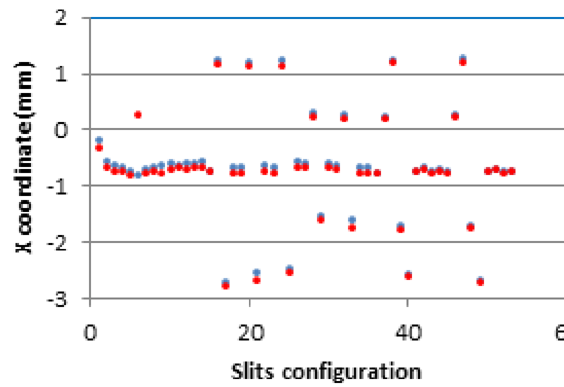

Figure 3: Beam position X coordinate measured by BPM2 vs slits configuration

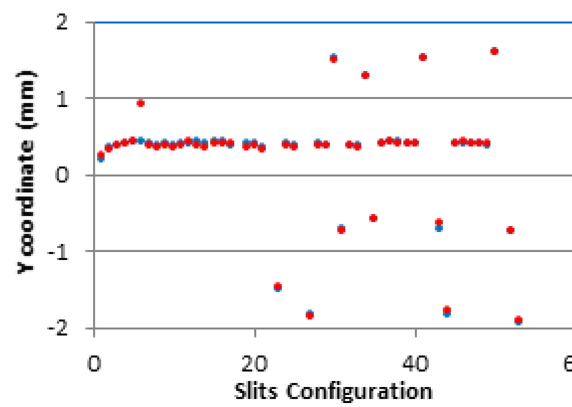

Figure 4: Beam position Y coordinate measured by BPM2 vs slits configuration).

BPM Ellipticity Measurements

BPM ellipticity is defined as $\sigma_x^2 - \sigma_y^2$ where σ_x and σ_y are the standard deviations of the transverse size of the beam [1]. In 2016, the beam transverse shape was modified by changing the current in the quadrupole Q13 located before BPM1. The results showed that BPM1 measurements behave in a similar way to profiler measurements and TraceWin simulations [1]. Precisions asked by specifications were not met due to different reasons, especially the lack of deep investigation of beam ellipticity sensitivity.

In 2016, the ellipticity sensitivity was set to 354mm² which is the ellipticity sensitivity measured during BPM characterization in IPNO [2], it was measured at the BPM electrical centre at β≈1. A deep study of the behaviour of

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ellipticity sensitivity regarding processing harmonic change and low β beam was carried:

- on one side, R.Shafer [5] detailed a method to compute the BPM sensor output level at any processing harmonic for low β beam using modified Bessel functions. Shafer concluded with an approximate polynomial function to calculate beam position sensitivity for low β beam at any processing harmonic.
- On the other side, R.H.Miller [6] detailed for ultra-relativistic beams (β=1) an equation to measure beam ellipticity using BPM sensors output signals.

The method detailed in [5] combined with the equation in [6] were combined to compute BPM ellipticity sensitivity for low β beams at any processing harmonic.

In April 2018, the position sensitivity was again set to 25.7mm and the ellipticity sensitivity was set to 374mm², the beam position and ellipticity given by BPM readout electronics were corrected using the results of the study detailed above. The beam ellipticity was also simulated with TraceWin (TW) at BPM2 location.

The results of the over 50 slits configurations are gathered in Figure 5, the red dots refer to the corrected measurements at F, the blue dots refer to the corrected measured at 2*F and the green dots refer to TW simulation results. The results show a good agreement between BPM measurements at both harmonics and TW simulations. The error is below the 20% threshold recommended in BPM electronics specifications.

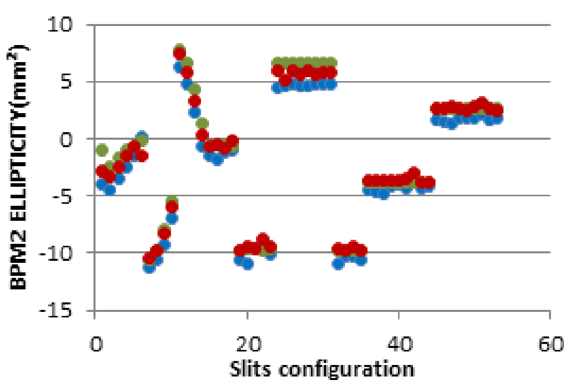

Figure 5 Ellipticity measurements by BPM2 vs Slits configuration

Ellipticity at BPM11 is kept unchanged (55mm² ± 2mm²) no matter the data used (BPM measurements at F and 2*F, TW simulations).

CONCLUSION

Two BPM sensors with their associated electronics for the Linac of SPIRAL 2 have been put on operation on the SP2-ITB on 2018.

Measurements of beam energy are successful and within accelerator specifications ($\Delta E/E<10^{-3}$).

The beam transverse position is measured with 50µm to 100µm precision which is within specifications (less than 150µm).

The phase of the beam with respect to the RF signal is measured with 0.4deg precision which is within specifications (less than 1deg).

Deep investigations were made concerning the ellipticity measurement. The results show a good agreement between TraceWin simulations and BPMs corrected measurement at low β beams and both harmonics. The 20% precision asked by specifications is fulfilled.

ACKNOWLEDGMENTS

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