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STUDY AND CHARACTERIZATION OF SPIRAL2 BPMs

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Abstract

The SPIRAL2 facility currently under commissioning at GANIL in France will deliver high-intensity up to 5mA 20MeV/n light and heavy-ion beams. SPIRAL2 beams are accelerated by a Radio Frequency Quadrupole (RFQ) and a LINAC composed of 26 superconducting cavities. A tuning of the SPIRAL2 LINAC relies mainly on Pick-up Beam Profile Monitors (BPM). 20 BPMs are mounted inside the warm sections between superconducting cavities. They serve to measure a beam transverse position to center the beam, a phase to tune cavities and an ellipticity to adjust beam optics along the LINAC. The phase and ellipticity measurements require high acquisition accuracy of the BPM signals.

This paper deals with an analytical study and CST code simulations of the BPM performed in order to determine correction coefficients for the ellipticity measurements. The results of calculations were compared to experimental ones obtained with two BPMs located on a "diagnostic plate" after the RFQ and a BPM located in the MEBT. Finally, the BPM acquisition chain was carefully characterized to identify its uncertainties and to ensure that it meets initial specifications.

INTRODUCTION

SPIRAL2 LINAC [1] is composed of 19 cryomodules that contains accelerating cavities. Warm sections are installed between cryomodules. These sections contain two quadrupoles and a pick-up type BPM inside the first quadrupole of each warm section.

SPIRAL2 BPM are designed to monitor beam position, phase and ellipticity with the following specifications: (Table 1)

Table 1: BPM Specifications

Parameter	Resolution	Range
Position	+/- 150µm	+/-20 mm
Phase	+/-0.5 deg.	+/-180 deg.
Ellipticity	+/-20 % or +/- 1.2 mm^2	

The BPM probes are composed of 4 squared electrodes (Fig. 1) connected with 23 meters long cables to the BPM acquisition electronics. The electronic modules were constructed by the Electronics Division of "Bhabha Atomic Research Centre" (BARC) in the framework of collaboration with the SPIRAL2 project. The French laboratory IPN Orsay and GANIL are in charge of the global BPM installation and commissioning [2].

The BPM electronics process the signal at two frequencies: the accelerating frequency 88MHz and its harmonic 176MHz. The beam position, ellipticity phase and bunch length are calculated from the 4 BPM signals [3].

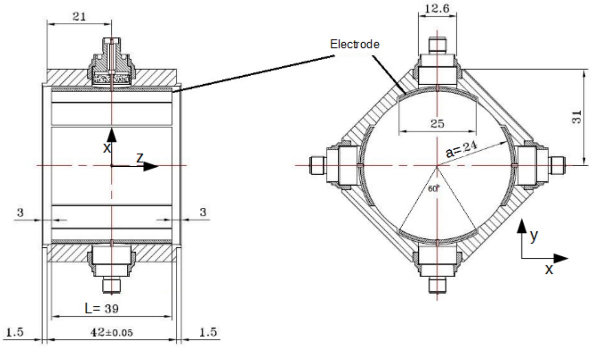

Figure 1: SPIRAL2 BPM Mechanics.

The tuning of the SPIRAL2 LINAC will be performed in two steps. In the first one, the beam will be centered using the BPM position measurements and the phase of each cavity will be tuned using the beam phases measured by BPM. In the second step, the beam will be matched along the LINAC using ellipticity and position measurements from BPM.

The proton beam velocity will increase along the LINAC from β=0.04 to about β=0.26. Position and ellipticity sensitivities depend on the beam velocity and the processed frequency. This dependence should be taken into account in order to obtain the absolute values of the measured parameters.

BEAM MODELIZATION

Let's consider a beam traveling through the BPM along the beam axis. The beam intensity can be expanded in a Fourier series [4].

$$I_b(t) = \langle I_b \rangle \left[1 + 2 \sum_{n=1}^{\infty} A_n cos(n\omega_0 t + \phi_n) \right]$$

With:

- I_b the beam intensity
- $\langle I_b \rangle$ the average beam intensity
- A_n the Fourier component amplitude
- ω_0 the fundamental pulsation
- ϕ_n the Fourier component phase

A wall current density i_w induced by the beam is calculated by solving the Laplace equation [5]:

$$i_w = \frac{A_n \langle I_b \rangle}{\sqrt{2}\pi a} \left[\frac{I_0(gr_0)}{I_0(ga)} + 2 \sum_{m=0}^{\infty} \frac{I_m(gr_0)}{I_m(ga)} cos(m(\varphi - \varphi_0)) \right]$$

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With:

- λ the wave length
- γ the Lorentz factor
- $g = \frac{2\pi}{\gamma\lambda}$
- I_m the modified Bessel function of the first kind

The current density is integrated through the electrode angular width and the transversal beam RMS size σ_x and σ_y.

$$I_w = \int_{-\frac{\phi_0}{2}}^{\frac{\phi_0}{2}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{1}{\sigma_x\sqrt{2\pi}} \frac{1}{\sigma_y\sqrt{2\pi}} i_w e^{\frac{-x^2}{2\sigma_x^2}} e^{\frac{-y^2}{2\sigma_y^2}} dx dy d\varphi$$

With:

- σ_x the rms bunch width on x axis
- σ_y the rms bunch width on y axis
- ϕ_0 the electrode angular width

POSITION MEASUREMENT

As proposed by R. Shafer [4] the BPM position sensitivity K can be expressed as :

$$\left(\frac{R}{L}\right)_{dB} = \left(\frac{I_{WR}}{I_{WL}}\right)_{dB} = \frac{160}{\ln(10)}(1+G)\frac{sin(\frac{\phi_0}{2})}{\phi_0}\frac{x}{a} + O(x^2)$$

$$G = 0.139\left(\frac{\omega a\sqrt{1-\beta^2}}{\beta c}\right)^2 - 0.0145\left(\frac{\omega a\sqrt{1-\beta^2}}{\beta c}\right)^3$$

These equations applied to the position calculations of the SPIRAL2 BPM :

$$X = K\frac{I_{wR} - I_{wL}}{I_{wR} + I_{wL} + I_{wU} + I_{wD}}$$

Gives the following sensitivity:

$$K = \frac{\phi_0 a}{2sin(\frac{\phi_0}{2})(1+G)}$$

With :

- a the BPM radius
- ω the pulsation processed (h1 or h2)
- IwR the signal intensity on the right electrode
- IwL the signal intensity on the left electrode
- IwU the signal intensity on the up electrode
- IwD the signal intensity on the down electrode

The position sensitivities Kh1 and Kh2 calculated along the LINAC at 88MHz and 176MHz, respectively are the following (Table 2):

Table 2: SPIRAL2 BPM Position Sensitivity

beta	Kh1(mm)	Kh2(mm)
0.04	21.8	16.5
0.08	24.2	21.9
0.12	24.7	23.5
0.26	25.0	24.8

ELLIPTICITY MEASUREMENT

The ellipticity E is equal to the difference between the transversal beam RMS size σ_x square and σ_y square.

$$E = \sigma_x^2 - \sigma_y^2$$

The ellipticity is calculated from the wall current equation of the second order, integrated over the electrode width and then integrated over the beam width.

$$I_{wR} = A\phi_0\left[\frac{I_0(gr)}{I_0(ga)} + \frac{4}{\phi_0}\left(\frac{I_1(gr)}{I_1(ga)}\left[sin(1\frac{\phi_0}{2})cos(1\theta)\right] + \frac{1}{2}\frac{I_2(gr)}{I_2(ga)}\left[sin(2\frac{\phi_0}{2})cos(2\theta)\right]\right)\right]$$

$$E = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{1}{\sigma_x\sqrt{2\pi}}\frac{1}{\sigma_y\sqrt{2\pi}}\frac{(I_{wR}+I_{wL})-(I_{wU}+I_{wD})}{I_{wR}+I_{wL}+|I_{wU}+I_{wD}}(x,y,X_0,Y_0)e^{\frac{-x^2}{2\sigma_x^2}}e^{\frac{-y^2}{2\sigma_y^2}} dx dy$$

The resulting equation is:

$$(\sigma_x^2 - \sigma_y^2) = (1-G_E)S\frac{(I_{wR}+I_{wL})-(I_{wU}+I_{wD})}{I_{wR}+I_{wL}+I_{wU}+I_{wD}} - (X_0^2 - Y_0^2)$$

- S: BPM sensitivity for relativist beams
- G_E: BPM ellipticity correction coefficient

$$S = \frac{a^2\phi_0}{2sin(\phi_0)} \qquad G_E = \frac{1}{12}\left(\frac{\omega a\sqrt{1-\beta^2}}{\beta c}a\right)^2$$

Table 3: SPIRAL2 BPM Ellipticity Corrected Sensitivity

Beta	Sh1(mm^2)	Sh2(mm^2)
0.04	313	206
0.08	339	313
0.12	344	333
0.26	347	345

The Table 3 shows the evolution of the ellipticity sensitivity at different β.

BEAM TESTS

The injector commissioning was done by using a D-Plates at the exit of the RFQ [6] in 2018. Two BPM monitors were tested with the injector beams.

The beam transverse position X and Y has to be measured by the BPM's with a precision of +/-150µm (Table 1). This requirement imposes a maximum difference of 0.07 dB between the gains of the 4 acquisition chains. The reference ellipticity in the LINAC is evaluated at 6 mm^2, with required resolution of +/-1.2 mm^2. In order to reach this resolution, the gain differences between channels have to be lower than 0.03 dB.

In order to obtain the precision requirements, the electronic modules were calibrated before the beam measurement in collaboration with the BARC designers. The tests were carried out by modifying the beam position and ellipticity. Additional modifications and optimization of the electronic module were performed in the first semester of 2019.

New BPM tests were performed with a BPM installed on the MEBT. The beam ellipticity was changed varying the current of a quadrupole in the MEBT (I Quad in Fig. 2).

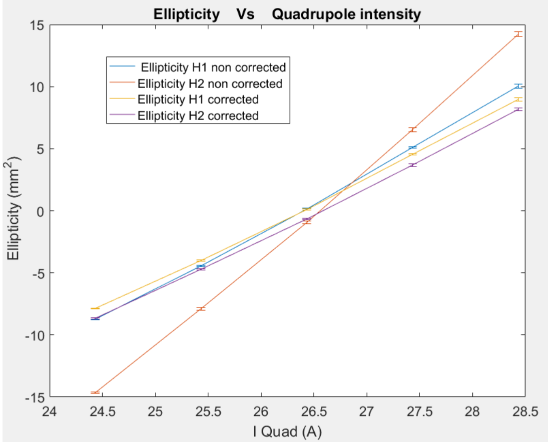

Figure 2: Ellipticity measurement on SPIRAL2 MEBT.

The Figure 2 shows preliminary results in August 2019. The ellipticity correction G_E allows measuring nearly the same ellipticity at 88MHz and at 176MHz. The ellipticity difference between h1 and h2 is mainly due to the slight gain mismatch of the four channels.

BUNCH LENGTH MEASUREMENT

The bunch longitudinal length is another useful parameter for the SPIRAL2 tuning and which can be measured from the h1 and h2 BPM amplitudes.

The bunch is assumed to have a Gaussian shape with a temporal length σ_{tp}. The BPM electrode has a length L and a capacity C. The effect of the SPIRAL2 bunches on the BPM has been simulated with the CST Particle Studio code using the Wakefield solver [7].

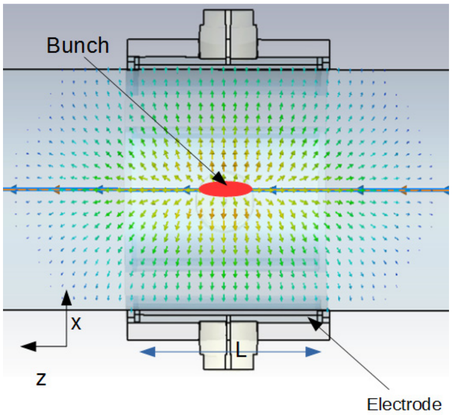

Figure 3: CST code electric field representation at low β with 0.25ns RMS bunch length and 56pQ charge.

The Figure 3 shows the electric field (arrows) induced by a bunch traveling through a BPM at β=0.04. One can notice that the calculated electric field is not radially symmetric. In contrary to a case of a quasi-relativistic beam the expansion of the electric field at low beta is wider than the beam bunch.

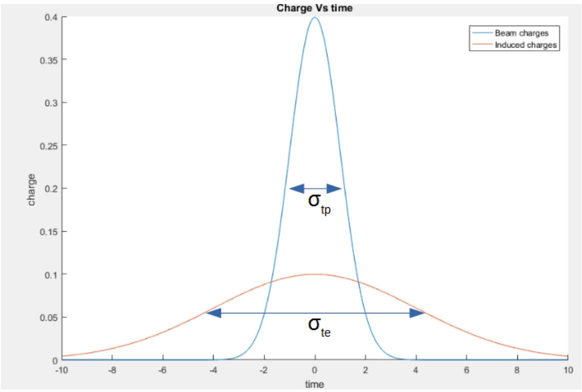

Figure 4: Bunch (beam in blue and induced charge in red) temporal distribution representation.

The RMS width σ_{tp} of the bunch is enlarged by the expansion of the electric field σ_{ta} that gives a global width σ_{te} on the electrode (Fig.4).

The expansion of the electric field in time σ_{ta} is a function of the radius of BPM and β [8].

$$\sigma_{ta} = \frac{a\sqrt{1-\beta^2}}{\sqrt{2}\beta c}$$

This expansion is quadratically added to the bunch length.

$$\sigma_{te} = \sqrt{\sigma_{tp}^2 + \sigma_{ta}^2}$$

The BPM can be used to calculate σ_{te} by measuring the amplitude of the electrode signals at two frequencies.

Let's consider a centered bunched beam of charged particles traveling at β along a BPM with the repetition frequency F_{acc} and the average beam intensity I.

The BPM electrodes have a capacitance C, an angular width of 60° and a length L. The BPM acquisition electronics is considered as a resistance R=50Ω.

The charges Q_{elec} induced by the bunch on the SPIRAL2 electrode can be expressed as:

$$Q_{elec}(t) = -\int_{-\frac{L}{2}}^{\frac{L}{2}} \frac{I}{6\beta c\sqrt{2\pi}\sigma_{te}F_{acc}} e^{-\frac{(t-\frac{z}{\beta c})^2}{2\sigma_{te}^2}} dz$$

The Fourier transform is calculated using formula:

$$\tilde{Q}_{elec}(f) = -sinc(\pi\frac{L}{\beta c}F_{acc})\frac{LI}{6\beta cF_{acc}} e^{-2\pi\sigma_{te}^2F_{acc}^2}$$

The tension U measured by the electronics can be expressed as:

$$\frac{dQ_{elec}}{dt}(t) = C\frac{dU}{dt} + \frac{U}{R}$$

The amplitudes of the vector sum at the fundamental frequency h1 and its second harmonic h2 are the following:

$$h1 = 4\pi F_{acc} sinc(\pi\frac{L}{\beta c}F_{acc})L\frac{I}{6\beta c}e^{-2\pi^2\sigma_t^2(F_{acc})^2}\frac{1}{\sqrt{4\pi^2C^2F_{acc}^2 + \frac{1}{R^2}}}$$

$$h2 = 8\pi F_{acc} sinc(2\pi\frac{L}{\beta c}F_{acc})L\frac{I}{6\beta c}e^{-8\pi^2\sigma_t^2(F_{acc})^2}\frac{1}{\sqrt{16\pi^2C^2F_{acc}^2 + \frac{1}{R^2}}}$$

Then by calculating the ratio between h1 and h2, the induced charge width is:

$$\sigma_{te} = \sqrt{\frac{ln\left(2\frac{h_1}{h_2}\sqrt{\frac{4\pi^2 * C^2 * F_{acc}^2 + \frac{1}{R^2}}{16\pi^2 * C^2 * F_{acc}^2 + \frac{1}{R^2}}}cos(\pi F_{acc}\frac{L}{\beta c})\right)}{6\pi^2 F_{acc}^2}}$$

The bunch length can be calculated by subtracting quadratically the electric field expansion:

$$\sigma_{tp} = \sqrt{\frac{ln\left(2\frac{h_1}{h_2}\sqrt{\frac{4\pi^2 * C^2 * F_{acc}^2 + \frac{1}{R^2}}{16\pi^2 * C^2 * F_{acc}^2 + \frac{1}{R^2}}}cos(\pi F_{acc}\frac{L}{\beta c})\right)}{6\pi^2 F_{acc}^2} - \frac{a^2(1-\beta^2)}{2\beta^2 c^2}}$$

The analytical calculation gives σ_{ta}=1.43ns at β=0.04. For SPIRAL2 BPM's a more precise value of σ_{ta}=1.10 ns at β=0.04 can be calculated using the CST simulation,

BPM signals are calculated using both analytical model with Matlab and numerical model with CST Particles studio.

A 5mA pencil beam with a bunch length of σ_{input} = 0.25 ns was assumed in the simulations.

- σ_{tecalc} : Bunch length with the electrical extension calculated from the two-harmonics
- σ_{tp} : Bunch length calculated from σ_{tecalc} subtracted by the electrical extension σ_{ta}

Table 4: Bunch Length Results

Parameter	CST Simulation (ns)	Analytical model (ns)
σ_{input}	0.25	0.25
σ_{ta}	1.10	1.43
σ_{te}	1.13	1.45
σ_{tecalc}	1.27	1.42
σ_{tp}	0.63	X

The Table 4 shows the results using the analytical and numerical methods. The electric field extension is smaller from CST simulation than that obtained using the analytical method. This origin of this difference has to be further studied performing the calculations at different β values.

For the analytical methods, σ_{tp} can't be calculated since it's smaller than the electrical extension.

The numerical result for σ_{tp} shows a difference of 0.38ns with respect to the input bunch length σ_{input}. This difference can be due to different capacitance of the electrodes which was assumed in the calculation to be equal to 10pF.

The electrode capacitance has to be calculated using the CST simulations in order to obtain better results on bunch length measurements.

Measurements on SPIRAL2 D-plate using a BPM and a BEM (Bunch Extension Monitor) [9] were performed in October 2018. The rebuncher phase was scanned from -180° to -60° with a -117° rebunching phase.

The bunch length was measured by the BPM and by the BEM and compared with the TRACEWIN simulations [10].

The electric field extension σ_{ta} used to calculate the bunch length is the one from CST simulations: 1.1ns.

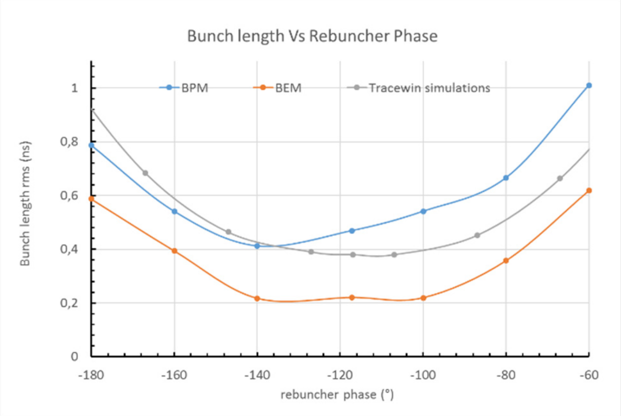

Figure 5: Ellipticity measurement on SPIRAL2 MEBT

The bunch length measurement σ_{tp} is quite close the simulation with maximum deviation 0.2ns of (Fig.5).

The simulation of the bunch length in function of the rebuncher phase is given at the BPM location. Due to the different position along the beam line of the detector the BEM values are not identical to the BPM ones.

These measurements show that bunch length measurement using the h1 and h2 amplitudes from BPM is possible. To improve precision and understand differences between analytical calculation, simulation and measurement, more experimental data should be accumulated at different β.

CONCLUSION

The 20 BPMs are installed in the SPIRAL2 LINAC. BPM additional tests are planned in the MEBT in September this year. Since SPIRAL2 beams are at low beta, correction coefficients have to be considered for the position and ellipticity measurements. Thanks to these coefficients, it was possible to measure the same ellipticity at two frequencies. Simulations and in-beam measurements, indicate that the BPM can be also used to measure the bunch length.

In order to understand in detail, the differences between calculation, simulation and measurements of the bunch length, additional CST simulation are necessary. Different beam positions and velocities will be simulated to understand their influence on induced electric field.

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