NUMERICAL CALCULATIONS FOR THE FAIR PROTON LINAC BPMS

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Abstract

Fourteen Beam Position Monitors (BPMs) will be installed along the FAIR Proton Linac. These monitors will be used to determine the beam position, the relative beam current and the mean beam energy by time of flight (TOF). A capacitive button type pickup was chosen for its easy mechanical realization and for the short insertion length which is important for the four BPMs locations of the inter-tank sections between the CH-cavities. Depending on the location, the BPM design has to be optimized, taking into account an energy range from 3 MeV to 70 MeV, limited space for installation and a 30 mm or 50 mm beam pipe aperture. This paper reports wake field numerical simulations performed by the code CST PARTICLE STUDIO to design and characterize the BPMs. Response time of monitors are presented and results of calculations for various pickup-geometries are discussed taking into account different beam velocities.

INTRODUCTION

The FAIR Project [1] (Facility for Antiprotons and Ions Research), built at GSI Darmstadt, requires a Proton Linac [2] which has to provide the primary proton beam for the production of antiprotons. This Linac will operate at a frequency of 325 MHz. It will deliver a 70 MeV beam at a current limit of 70 mA with a repetition rate of 4 Hz for injection into the SIS 18. The main beam parameters are listed in Tab. 1.

Table 1: FAIR Proton Linac Parameters

Parameter	Value
Final energy	70 MeV
Pulse current	70 mA
Protons per pulse	7.10^{12}
Macro pulse length	30 to 100 µs
Repetition rate	4 Hz
Trans. beam emittance	4.2 µm (tot. norm.)
RF-frequency	325.224 MHz

The fourteen Beam Position Monitors (BPMs) will be installed along the Linac as shown Fig. 1.

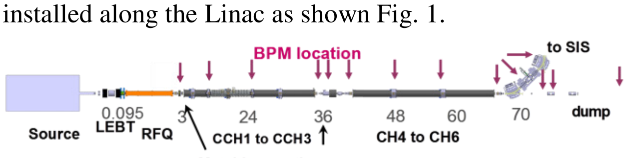

Figure 1: Distribution of Beam Position Monitors along the Linac.

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At nine locations the vacuum chamber aperture is 30 mm. Due to the different requirements, monitors installed in the transfer section, the dump and between the two dipoles will have a vacuum chamber aperture of 50 mm.

The same type of button electrode is foreseen along the Linac with an energy varying from 3 MeV to 70 MeV and a change of vacuum chamber geometry.

The main measurement is to determine the beam displacement, with a spatial resolution of 0.1 mm averaged on a macro pulse of 36 µs duration, by calculating the ratio of the difference over sum voltage between two opposite buttons. The sum signal from a BPM can be also used as a relative measurement for the beam current. An important application at a proton Linac comprising of novel CH-cavities is the determination of the beam energy after each DTL tank which can be calculated via the time of flight determination of a bunch between two BPMs. For this time measurement, an accuracy of 8.5 ps has to be achieved corresponding to a phase resolution of 1°.

The main parameters are summarized in Tab 2.

Table 2: FAIR Proton Linac BPM Parameters

Parameter	Value
Beam pipe diameter	30 mm intertank section, 50 mm transfer lines
Length	50 mm
Beam energy	From 3 MeV to 70 MeV
Bunch frequency	325.225 MHz
Beam pulse length	36 µs nominal
Bunch length	150 ps typical
Average current	35 mA nominal, max 70 mA
Position resolution (RMS)	100 µm averaged on a macro pulse of 36 µs
Operation range	± 5 mm
Phase resolution	1° averaged on a macro pulse of 36 µs

LAYOUT

Beam dynamics requirements and compactness of the beamline require that some BPMs (at four locations) will be an integral part of the inter-tank section between the CH cavities [2]. In this context and after having performed some preliminary simulations [3], a capacitive button type BPM with buttons of 14 mm diameter was chosen for its easy mechanical realization and short

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insertion length to fit into the inter-tank sections of the CH-cavities.

This device is composed of 4 electrodes called "buttons" mounted by welding on the vacuum pipe. Those feedthroughs consist of a central conductor with a button electrode and a SMA-type connector with a characteristic impedance of 50 Ω. The field on the inner wall of a beam pipe induces a surface wall current which will generate a voltage on the pickup electrodes.

A first prototype and mechanical design, inserted in the inter-tank section, shown in Fig. 2 is in fabrication state [4]. The housing will be in stainless steel 316LN to avoid magnetic problems. Commercial 14 mm pickups, fabricated by Kyocera, were chosen (Fig. 3).

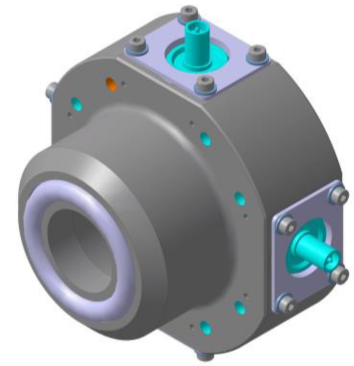

Figure 2: Design of the button BPM installed in the CH-inter-tank section.

Figure 3: Kyocera button – diameter 14 mm.

ELECTROMAGNETIC SIMULATIONS

To improve and extend calculations of the signal response of the monitors, new numerical simulations were performed using a geometrically simplification of the 14 mm Kyocera buttons and different beam properties. The code CST PARTICLE STUDIO with the wake-field solver [5] on a hexahedral mesh is used where the excitation source is defined by a Gaussian-shaped longitudinal charge distribution.

To use the same type of electrode on all BPMs along the linac, BPMs simulations with two beam pipes are shown Fig. 4. The amplitude on a button for a BPM with an aperture of 50 mm will be half of a BPM with an aperture of 30 mm. In the pre-amplifier design, those results will be taken into account.

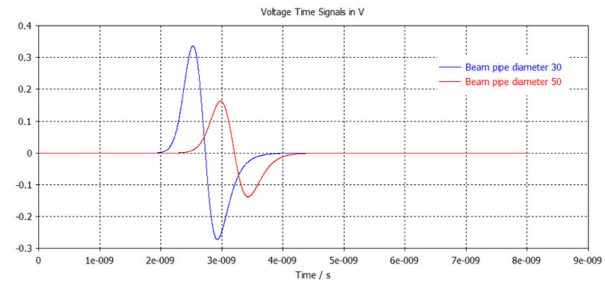

Figure 4: BPM output voltage for two different apertures used on the linac (bunch length 150 ps, β=0.37, 35 mA).

The time and frequency responses of the pick-up were obtained at different beam velocities, namely 0.08, 0.27 and 0.37, while the longitudinal RMS bunch size varies within 60-650 ps range. The results show that the signal amplitude reduces with the length of bunch as shown in Fig. 5. There is a factor 10 between 60 ps and 650 ps. The case, with a long bunch length at β = 0.37 will give the lowest signal amplitude. Those simulations show that for the electronics, a large dynamic range will be necessary.

At low energy with β = 0.08, for bunches shorter than 100 ps, the solution becomes instable. Higher order modes have to be considered which requires denser mesh and, therefore, a longer simulation time.

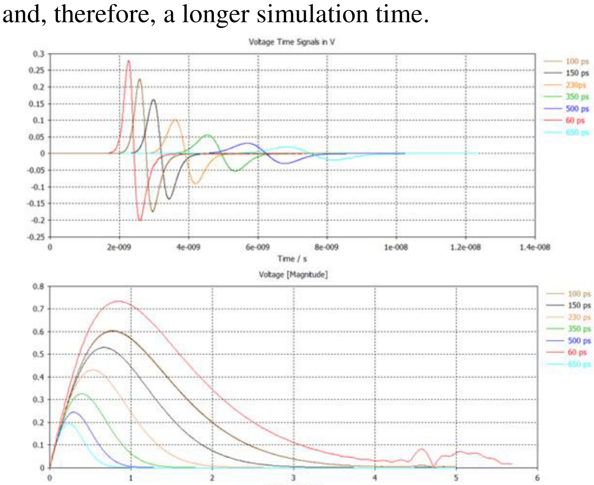

Figure 5: BPM output voltage for different bunch lengths beam pipe = 50 mm, β=0.37, 35 mA.

Sensitivity and non-linearity response analysis are important parts for a button BPM design. Sensitivity depends on the button diameter, the horizontal and the vertical separations of the buttons, and the distance to the beam.

For the investigation of the position sensitivity and the pickup non-linearity response versus the beam position, the position of the simulated beam (excitation) is moved horizontally and vertically in 1 or 2 mm steps in a range of ± 8 mm. The positions in each directions are calculated from amplitudes of the signals induced in the opposite BPM electrodes using the 'delta-over-sum' method. As depicted in Fig. 6, the operation frequency has more influence at low beta on the sensitivity and linearity.

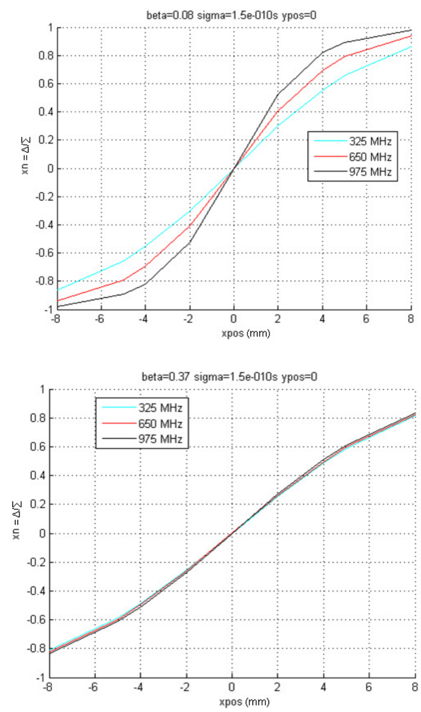

Figure 6: Horizontal beam position calculated using 'delta-over-sum' method at different frequencies with $\beta = 0.08$ and $\beta = 0.37$ for a bunch length = 150 ps. Vacuum aperture: 30 mm, button diameter: 14 mm.

To crosscheck the results of the CST simulations, a comparison with a theoretical estimation of the sensitivity [6] for a low-beta button-type BPM and 2-dimentional approximation is presented in Table 3. The agreement between the simulated and analytical results is reasonable.

Table 3: Comparison of Simulated and Analytical Sensitivities in Units of dB/mm

		Simulation	Theoretical Estimation
E=3 MeV (β=0,08)	325 MHz	2,69	2,67
	650 MHz	3,74	3,71
	975 MHz	5,00	5,05
E=35 MeV (β=0,27)	325 MHz	2,29	2,28
	650 MHz	2,41	2,39
	975 MHz	2,59	2,56
E=70 MeV (β=0,37)	325 MHz	2,27	2,26
	650 MHz	2,33	2,31
	975 MHz	2,42	2,40

To estimate linearity and sensibility, simulations are done with different bunch lengths. For the same pick-up design and the same beta value, the linearity and sensibility are identical compared to the bunch length. These numerical results coincide, as expected, to the results for the analytical investigations in [6] for each individual Fourier component.

To improve the performances of this button BPM, different pickup geometries are simulated.

Figure 7 compare signals with a button height varying from 1 mm to 4 mm and show that signal read by one button decreases with the thickness of the pickup. Button thickness (height) increases the button capacitance in respect to the shield. A modification of the thickness changes also the capacitance and therefore the cut-off frequency. This capacitance is critical and can cause mismatch through the structure.

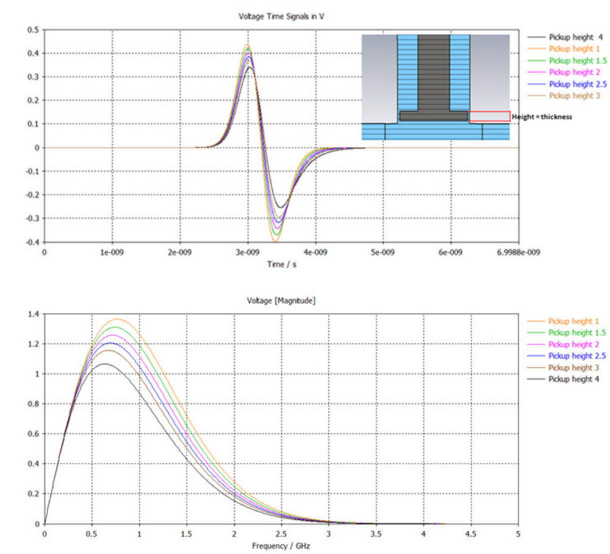

Figure 7: BPM output signals for different height of button given in units of mm. Beam pipe = 30 mm, button diameter: 14 mm β=0.27 for a bunch length = 150 ps, 35 mA.

In the BPM design, gap between the button and inner wall of the BPM housing represents a transmission line. Some resonant modes can be generated, trapped and can deposit power in the button [7]. In general, this power could lead to heating and damages the button and the ceramic insulator or the resonator mode can disturb the beam original beam signal. To minimize the trapped mode impedance; i.e. the transmission line, a thick button (see detail in Fig. 7) and a small gap to the outer housing are preferred with the disadvantage of increasing capacitance and, consequently, lower signal strength.

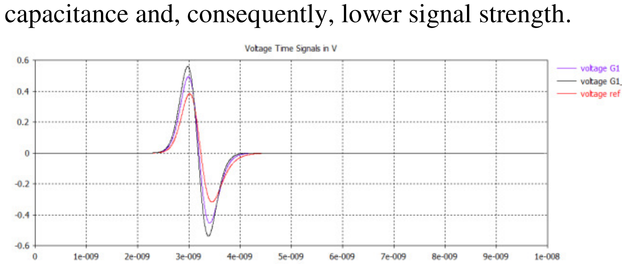

Figure 8: BPM output signals read by one electrode with the gap varying from 0.5 to 1.5 mm. Beam pipe = 30 mm, button diameter: 14 mm, β=0.27 for a bunch length = 150 ps, 35 mA.

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Simulations presented Fig. 8 show the influence of the gap between the button and the inner wall of beam pipe on the signal amplitude read by one electrode. The Kyocera button has a 0.5 mm gap.

The thickness and the gap of button influence the capacitance value. Figure 9 presents some capacitance values calculated for different button geometries.

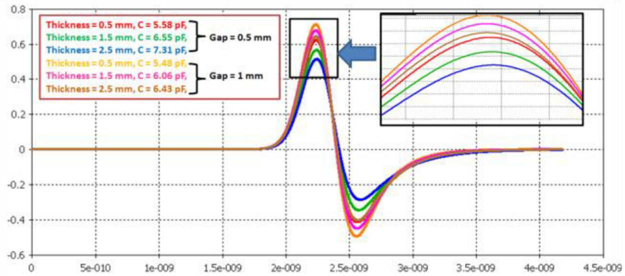

Figure 9: BPM output signals read by one electrode with different button geometries. Beam pipe = 30 mm, button diameter = 14 mm, β=0.37 for a bunch length = 100 ps, 35 mA.

CONCLUSION

Beam Position Monitors are essential devices for the beam-based alignment and diagnostic of the FAIR Proton Linac accelerator.

The BPM electrical performance was numerically simulated with CST Particle Studio. Although the low-energy affects the quality of the measurement, button BPM sensitivity on the beam energy and the frequency results demonstrated good agreement with the theoretical estimation.

A prototype of the BPM with 30 mm aperture is produced at CEA and will be characterized on a test bench with a coaxial wire to verify the results obtained with the simulations.

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