DEVELOPMENT OF A LOW-BETA BUTTON BPM FOR PXIE PROJECT*

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Low-beta Button BPM Design

Abstract

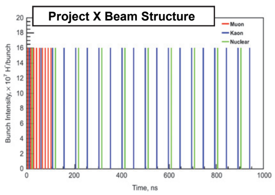
The button Beam Position Monitor (BPM) is under development for a low beta section of the Project X Injector Experiment (PXIE) at Fermilab. The presented paper includes an analytical estimation of the BPM performance as well a direct wake field simulation with CST Particle Studio (on a hexahedral mesh). In addition we present a novel approach of a low beta beam interaction with BPM electrodes realized with ANSYS HFSS Time Domain (TD) solver on unstructured tetrahedral mesh. Both methods show a good agreement of BPM output signals for various beam parameters. Finally we describe the signal processing scheme and the electronics we are going to use

INTRODUCTION

The Project X Injector Experiment (PXIE) is an undergoing project at Fermilab [1]. The PXIE layout includes two low beta superconducting cryomodules capable of accelerating 1 mA average current of H- beam up to 30 MeV. The beam parameters of PXIE superconducting section are listed in the Table 1.

Table 1: Beam parameters at PXIE SC section

Operation Mode	CW
Beam Energy	2.5 ÷ 32 MeV
β	0.07 ÷ 0.26
Average Beam Current	1 mA
Bunch charge	30 pQ
Bunch length, rms	1 ÷ 2 mm
Bunch sequence	10 MHz, 20MHz, 162.5 MHz



For non-relativistic bunch and vacuum chamber with constant radius we can neglect the relativistic shortening of bunch field. Then the instant electric field distribution for a point charge moving along the pipe axis is the same as for a charge in the rest :

$$E_r(r,z) = \frac{q}{4\pi\varepsilon_0}\left(\frac{r}{(r^2+z^2)^{\frac{3}{2}}} + \frac{2}{\pi}\int_0^\infty \frac{K_0(ka)}{I_0(ka)} I_1(kr)\cos(kz)\,k\,dk\right) \quad (1)$$

Here r and z are the transverse and longitudinal coordinates, q is the charge, a is the beam pipe radius and k is the wave-number. The central part of the field distribution on the surface can be fitted by a Gaussian with $\sigma_E \approx 0.55a$ rms width of the field distribution. :

$$E_r(a,z) \approx \frac{q}{3\pi\varepsilon_0 a^2} e^{\left(-\frac{z^2}{2\sigma_E^2}\right)} \quad (2)$$

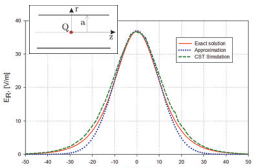


Figure 1. Electrostatic solution for surface electric field produced by 1pC point charge located on the axis within the circle beam pipe of Ø36 mm:

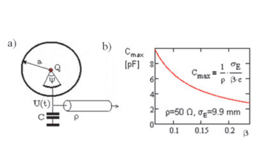


Figure 2. Scheme of a pick-up electrode equivalent circuit (a) and the upper limit of the button electrode capacitance in the beam pipe of Ø36 mm (b).

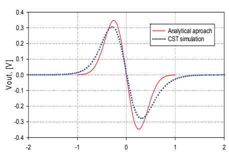


Figure 3. Output signal from a button pickup induced by a single bunch moving with β=0.15 velocity along the axis within circular beam pipe of Ø36 mm

For the estimation of pickup signal amplitude we consider a simple equivalent circuit shown in Figure 2a. The Kirchhoff's current law is:

$$C\frac{dU}{dt} + \frac{U}{\rho} = \frac{\Psi}{2\pi}\left(I(t) - I(t-t_b)\right) \quad (3)$$

where U is an output voltage, $I(t)$ is the beam current distribution on the wall, $t_b = L_p/\beta c$, L_p is the pickup length, C is the button capacitance, ρ is the impedance of coaxial line and Ψ is the button angular width. Evidently, the maximum voltage is achieved with a capacitance approaching to zero. Here we took into account that the current flowing on the wall is repeating the E_r field profile with characteristic time $\tau_E = \sigma_E/\beta c$. It sets an upper limit for the button capacitance $C_{max} < \tau_E/\rho$ (see Fig. 2b) and determines boundaries of DC approximation:

$$U(t) \approx \frac{\tau_\rho}{C}\frac{\Psi}{2\pi} I(t) = \rho\frac{\Psi}{2\pi}\left(I(t) - I(t-t_b)\right) \quad (4)$$

Finally, for the above consideration and using Eq. (2), the BPM output voltage is given by:

$$U(t) \approx \frac{q}{\sqrt{2\pi}}\frac{\rho}{\tau_E}\frac{\Psi}{2\pi}\left(e^{-0.5\left(\frac{t}{\tau_E}\right)^2} - e^{-0.5\left(\frac{t-t_b}{\tau_E}\right)^2}\right) \quad (5)$$

BPM Readout Electronics

The standard BPM readout electronics for PXIE will measure position, intensity, and phase using direct digital down-conversion to measure the amplitude of the 2nd beam harmonic for each electrode. As seen in Figure 5, the 2nd harmonic will produce more signal from the electrode while also minimizing noise pickup at the fundamental. A simplified block diagram is shown in Figure 11. A 2D polynomial fit to the difference over sum in each plane will be used to correct position and intensity for nonlinearities in the button pickup shown here. To study bunch by bunch effects, high bandwidth 20+GS/s scopes will be used to directly sample the button which will provide reasonable signal integration.

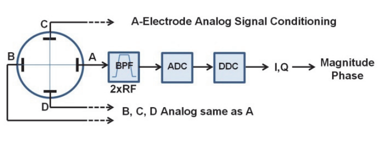
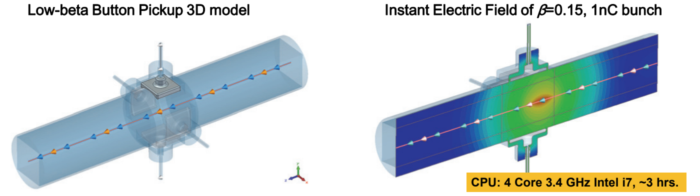


Figure 11. Block diagram for BPM electronics.

CST Particle Studio Simulation

We performed numerical simulations of a button pickup response with CST Studio 2013 wake-field solver on a hexahedral mesh. The 3D BPM mechanical model was developed at ANL in a frame of HWR cryomodule production [2]. The BPM geometry is presented in Figure 4. It consists of four square curved 18 mm buttons hidden in a beam pipe of Ø36 mm. The position of the simulated beam was varied in 1 mm steps within the transverse plane in a range of ±5 mm. We used the perfect magnetic boundary condition in vertical XZ plane in order to lower a mesh size (~500k elements) and speed up simulations.



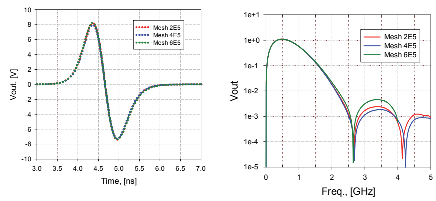


Figure 5. BPM output voltage in time (left) and frequency (right) domains vs. mesh size (4mm rms, β=0.15, 1nC bunch).

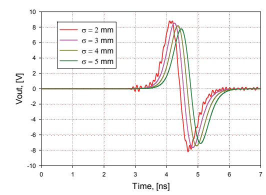


Figure 6. BPM output voltage for different bunch lengths (β=0.15, 1nC bunch).

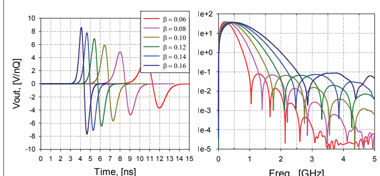


Figure 7. BPM output voltage in time (left) and frequency (right) domains vs. beam velocity (4mm rms bunch).

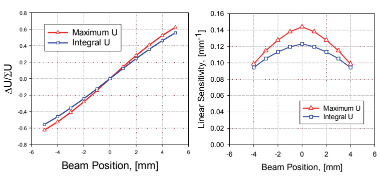
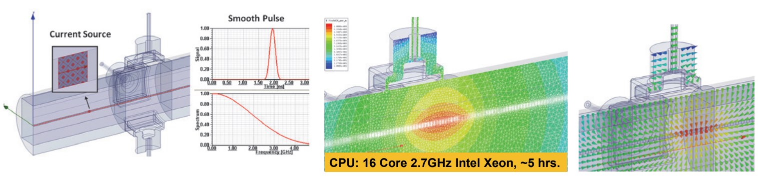


Figure 8. Vertical beam position calculated using 'delta over sum' method (left) and linear BPM position sensitivity (right).

HFSS Transient Simulation

The main drawback of the CST wake-field solver on a hexahedral mesh is its inability of a local mesh refinement or sub-gridding. Therefore, it demands a large mesh size for the description of a complex geometry with tiny details like a narrow coaxial gap. There is an alternative full-wave 3D Finite Element Time Domain (FETD) method which uses an unstructured conformal mesh with respect to all details of the 3D model geometry. Recently ANSYS announced the HFSS Transient module utilizing a finite-element mesh and it led us to consider the HFSS code for the design of low-beta BPM.



The moving smooth pulse of current approach for a Gaussian bunch emulation at HFSS TD solver

Tetrahedral mesh (~300k) with local refinements along the beam trajectory and around pickups

Vector Electric Field of 4mm rms, β=0.15 bunch

Because there is no direct beam excitation source available in the HFSS Transient module, we imitate a Gaussian bunch with the moving smooth pulse of current approach. To this purpose we place a set of current pulses along the beam trajectory with appropriate duration and delays equal to a beam flight time $t_{delay} = L/\beta c$. The amplitude of each current pulse is normalized to the bunch charge.

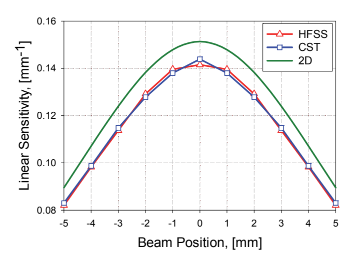


Figure 9. The button BPM position linear sensitivity calculated numerically (HFSS and CST) and analytically (2D) using 2-dimentional approximation.

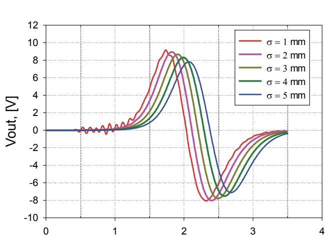


Figure 10. BPM output voltage for different bunch lengths (β=0.15, 1nC bunch).

Conclusion

A button-type BPM for the low-beta section of Project X superconducting linac was designed. The BPM electrical performance was numerically simulated with two independent codes, CST Studio and ANSYS HFSS. Both codes demonstrated excellent mutual agreement and well corresponded with theoretical predictions. Besides, we found that HFSS TD solver is a versatile tool for designing fine aspects of BPM pickups and simulating short bunches

REFERENCES

[1] Project X Reference Design Report, Project X Document 776-v7, FNAL, USA, (2013).

[2] P. Ostroumov, et al., "Development of a Half-Wave Resonator for Project X", WEPPC039, IPAC'12, New Orleans, USA

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