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

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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 pC
Bunch length, rms	1 ÷ 2 mm

The beam instrumentation within the cryogenic environment needs an extra care to meet ultra-high vacuum, cryogenic and clean room requirements simultaneously. Thus, it is limited mostly to beam orbit monitoring with button BPM pickups due to its simple mechanical design and reliability. For a low energy beam the button-type pickups yield good compromise between amplitude and time responses. In order to optimize the response for precision beam position measurements we used both simple analytical estimations and full 3D simulations using both CST Studio wake-field and ANSYS HFSS TD solvers [2,3]. First prototype of a cold BPM is currently under production as a part of the Half Wave Resonator (HWR) cryomodule for PXIE developing by ANL [4]

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ANALYTICAL CONSIDERATION

A point-like low-beta bunch of charged particles moving inside a hollow metal beam pipe is followed by electromagnetic field with longitudinal extension of about chamber radius. The field on the inner wall of a beam pipe induces a surface wall current which will generate a voltage from pickup electrodes.

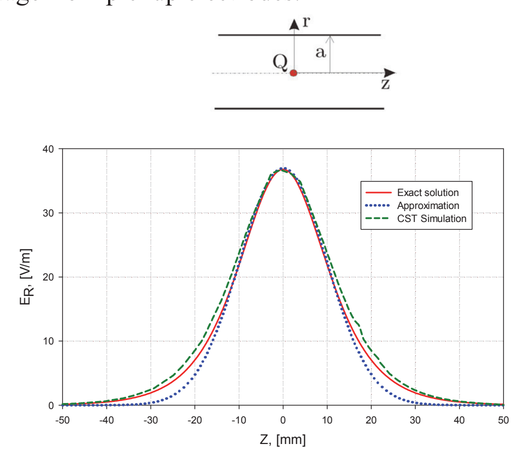

Figure 1: Electrostatic solution for surface electric field produced by 1pC point charge located on the axis within the circle beam pipe of Ø36 mm.

For non-relativistic bunch and vacuum chamber with constant radius we can neglect the relativistic shortening of bunch field. Then an instant electric field distribution for a point charge moving along the pipe axis is the same as for a charge in the rest [5]:

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

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:

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

where $\sigma_E \approx 0.55a$ is the rms width of the field distribution. The example of a surface electric field distribution in the Ø36 mm circle beam pipe is illustrated in Fig. 1 in a comparison with the instant field distribution for the 2 mm rms bunch moving with β=0.15 speed obtained by a numerical simulation with CST Studio. Both, analytical and numerical, results show a good mutual agreement.

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Because of a long tail of field distribution, about a half of the beam pipe radius, the longitudinal dimension of a button pickup has to be order of the $2\sigma_E$ value or larger, otherwise two signals coming from opposite gaps between a button and a beam pipe will cancel each other resulting a reduced output voltage.

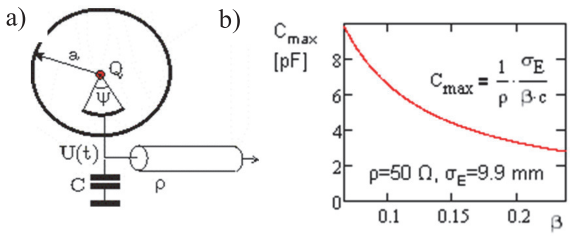

Figure 2: Scheme of a pick-up electrode equivalent circuit (a) and the upper limit of the button electrode capacitance in the beam pipe of Ø36 mm (b).

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

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

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 use for Eq. (3):

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

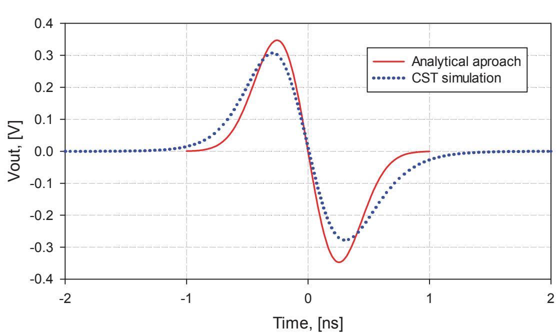

Figure 3: Output signal from a button pickup induced by a single bunch moving with β=0.15 velocity along the axis within circular beam pipe of Ø36 mm.

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

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

The expected output signal induced by a single bunch (β=0.15) moving along the axis of 36 mm beam pipe is plotted in Fig. 3 for a button pickup with capacitance of few pF and 20mm size. One can see that the analytical approach yields good initial approximation for pickup parameters for further numerical analysis

CST STUDIO SIMULATION

The important part of a button BPM design is a position sensitivity analysis including simulation of a non-linearity in pickup response versus the beam center displacement. A theoretical solution of this problem was first published by R. Shafter in Ref. [6] for a low-beta button-type BPM and 2-dimentional approximation. However, for making a precise map of the beam position through the BPM cross-section suitable for a further correction with read-out electronics, the full 3D simulation using actual BPM geometry is required.

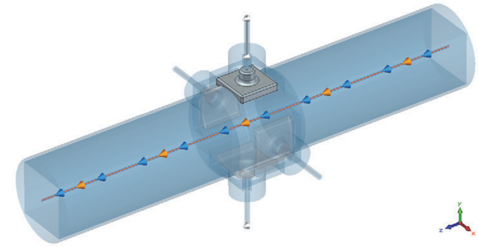

Figure 4: Low-beta button BPM 3D model

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 [4]. 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 and speed up simulations.

We started first with an investigation of output voltages convergence versus mesh size. The calculated BPM signals are shown in Fig. 5 for 4mm rms, β=0.15, 1nC bunch. The CST wake-field solver demonstrates a solid convergence for low frequency part of output signal spectrum and visible differences in high frequencies above 2 GHz.

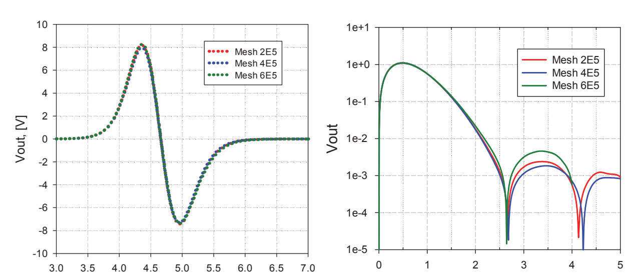

Figure 5: BPM output voltage in time (left) and frequency (right) domains vs. mesh size (CST Studio, 4mm rms, β=0.15, 1nC bunch).

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The longitudinal rms bunch size varies within 1-2 mm range in the superconducting section of PXIE linac. Despite we have neglected the influence of a bunch size in our analytical estimations for low-beta beam we made such simulation with CST. The result is presented in Figure 6. There is only 10% difference in output signal amplitude for 2 mm and 5 mm bunches respectively, but the shorter bunch requires significantly denser mesh and, thus, a longer simulation time. Also the CST wake-field solution becomes unstable for bunch length shorter than 2mm, and, therefore, we decided to use 4mm rms bunch length for the position sensitivity analysis.

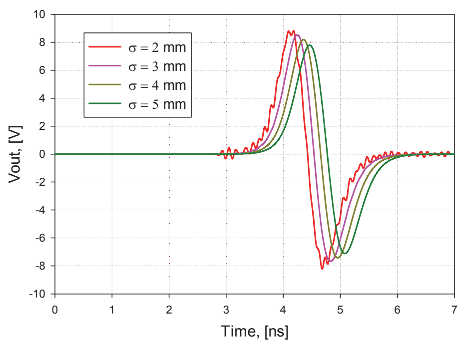

Figure 6: BPM output voltage for different bunch lengths (CST Studio, β=0.15, 1nC bunch).

The dependence of BPM output signal versus bunch velocity is illustrated in Fig. 7 for the beam beta range of 0.06 to 0.16. The signal amplitude grows almost linearly with low betas, while the signal spectrum is extended from 1GHz to 2.5 GHz.

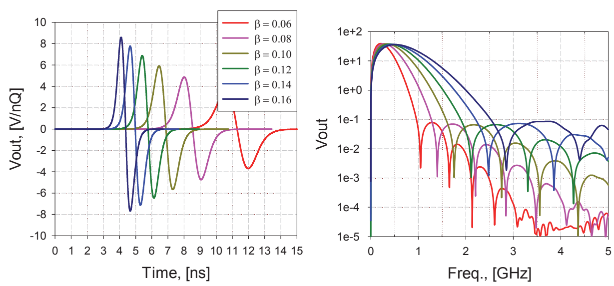

Figure 7: BPM output voltage in time (left) and frequency (right) domains vs. beam velocity (CST Studio, 4mm rms, 1nC bunch).

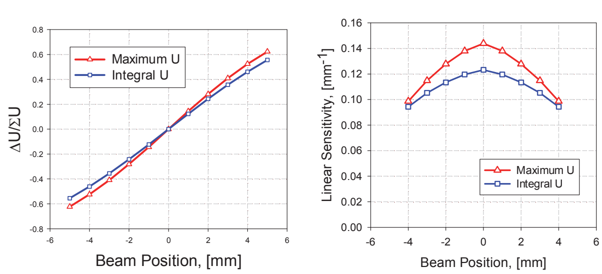

Figure 8: Vertical beam position calculated using 'delta-over-sum' method (left) and linear BPM position sensitivity (right).

Finally the BPM position sensitivity simulations were performed. The positions in vertical direction were calculated from amplitudes of the signals induced in the opposite BPM electrodes using the 'delta over sum' method [7]. We applied two methods for the 'delta over sum' calculation, first is conventional manner using maximum value of the output voltage and second is by integrating voltage over the pulse time. The results are shown in Fig. 8 for both methods. The integral algorithm gives better beam position linearity but its practical realization with modern electronics is still questionable.

ANSYS HFSS 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, which leads to significant increase of a simulation time and a required memory. There is an alternative full-wave 3D Finite Element Time Domain (FETD) method which uses an unstructured conformal mesh [8] with respect to all details of the 3D model geometry. For example, the FETD method was realized at Ace3P T3P solver [9] and demonstrated a fast performance and a good accuracy by developing the curved–button BPM for LHC [10]. 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 [11].

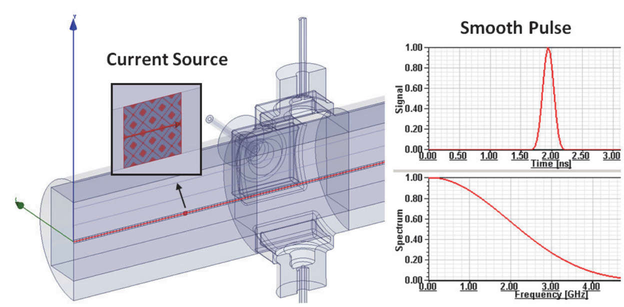

Figure 9: The moving smooth pulse of current approach for a Gaussian bunch emulation at HFSS TD solver.

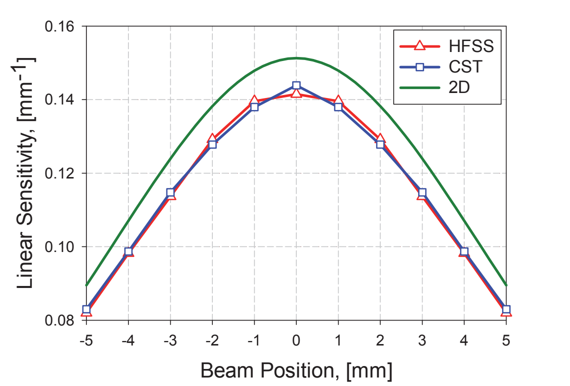

Figure 10: The button BPM position linear sensitivity calculated numerically (HFSS and CST) and analytically (2D) using 2-dimentional approximation.

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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 idea is illustrated in Fig. 9. The amplitude of each current pulse is normalized to the bunch charge. We repeated the BPM position sensitivity simulations for 4mm rms, β=0.15 bunch charge. Both HFSS and CST solutions are compared in Fig. 10 with analytical 2D approach proposed by R. Shafter in [6]. The numerical results are very similar to each other while the HFSS solution looks more accurate for small beam displacements.

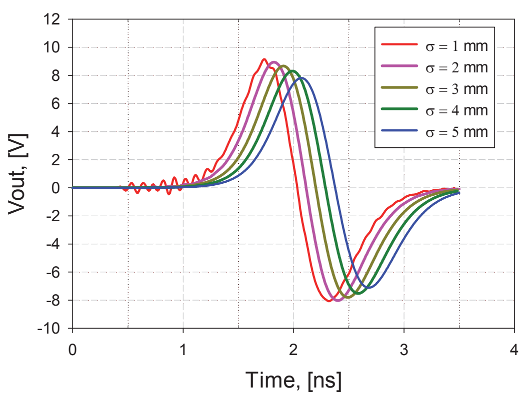

Figure 11: BPM output voltage for different bunch lengths (HFSS Transient, β=0.15, 1nC bunch).

Finally the HFSS capability to simulate BPM response from short bunches was investigated. Thereto we refined a mesh near the axis and ended up with ~300k total tetrahedral mesh elements for 1mm rms bunch length. The results of HFSS simulations are shown in Fig. 11 for bunch lengths up to 1mm rms. We found that it is possible to go beyond the 1mm, which requires just further mesh refinement. It is worth to mention that HFSS TD solver is highly parallelized (almost linear with number of CPUs) and using it on modern workstations can greatly save the simulation time.

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 Fig. 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 12. 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.

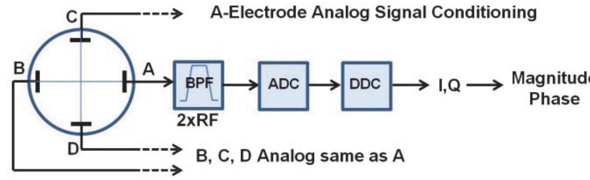

Figure 12: Block diagram for BPM electronics.

SUMMARY

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] http://www.cst.com/
[3] http://www.ansys.com/
[4] P. Ostroumov, et al., "Development of a Half-Wave Resonator for Project X", WEPPC039, IPAC'12, New Orleans, USA
[5] V.Lebedev, "Specifications for PXIE MEBT BPMs", Project X Document 1172-v1, FNAL, USA, (2013)
[6] R. Shafer, "Sensitivity of PUs for low beta beams," Proc. of the BIW 1993, Santa Fe, p.303, (1994)
[7] R. Shafer, Proc. Beam Instr. Workshop BIW 89, Upton, p. 26, (1989)
[8] J-F. Lee, R. Lee, and A.C. Cangellaris, "Time-Domain Finite-Element Methods", IEEE Trans. Antennas Propagat., vol. 45, pp. 430-442, (1997)
[9] Cho Ng, et al, "State of The Art In Finite-Element Electromagnetic Codes for Accelerator Modeling Under Scidac", IPAC'10, Kyoto, Japan, May 23-28, 2010
[10] A.Nosych, "Simulation and correction of CERN BPMs", 8th DITANET Topical Workshop on BPM, CERN 2012
[11] M. Vogel, H. Songoro, "Simulation of Transient Electromagnetic Fields on a Finite-Element Mesh", 2010 Loughborough Antennas & Propagation Conference, UK, (2010)

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