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
<table>
<thead>
<tr>
<th>Operation Mode</th>
<th>Beam Energy</th>
<th>( \beta )</th>
<th>Average Beam Current</th>
<th>Bunch charge</th>
<th>Bunch length, rms</th>
</tr>
</thead>
<tbody>
<tr>
<td>CW</td>
<td>2.5 ÷ 32 MeV</td>
<td>0.07 ÷ 0.26</td>
<td>1 mA</td>
<td>30 pC</td>
<td>1 ÷ 2 mm</td>
</tr>
</tbody>
</table>

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 response. 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].

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]:

\[
E_r(r,z) = \frac{q}{4\pi \varepsilon_0} \frac{r}{(r^2 + z^2)^{3/2}} + \frac{2}{\pi} \int_0^\infty \frac{K_0(ka)}{J_0(ka)} I_1(kr) \cos(kz) kd\kappa
\]

(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:

\[
E_r(a,z) \approx \frac{q}{3\pi \varepsilon_0 a^2} a^2 \exp\left(-\frac{z^2}{\sigma^2}ight)
\]

(2)

where \( \sigma \approx 0.55a \) 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 \( \beta = 0.15 \) speed obtained by a numerical simulation with CST Studio. Both, analytical and numerical, results show a good mutual agreement.
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 $2\sigma_r$ 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.

The expected output signal induced by a single bunch ($\beta=0.15$) moving along the axis of 36 mm beam pipe is plotted in Fig. 3 for a button pickup with capacitance of few pF and 20 mm 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-dimensional 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.
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.

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.

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].
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 \( t_{\text{delay}} = L/c \). 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, \( \beta = 0.15 \) 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.

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 \( \approx 300k \) 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 2\(^{nd}\) beam harmonic for each electrode. As seen in Fig. 5, the 2\(^{nd}\) 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.

**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**


