FEM SIMULATIONS – A POWERFUL TOOL FOR BPM DESIGN

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Abstract

This contribution focuses on extensive simulations based on Finite Element Methods (FEM) which were successfully applied for the design of several Beam Position Monitor (BPM) types. These simulations allow not only to reduce the time required for BPM prototyping but open up new possibilities for the determination of characteristic BPM features like signal strength, position sensitivity etc. Since a precise visualization of the signal propagation along the BPM structure is possible, effects like field inhomogeneities or cross-talks between adjacent electrodes can be controlled. Moreover, modern simulation programs enable to define a charge distribution moving at non relativistic velocities, which has an impact on the electromagnetic field propagation. It is shown that for slow ion beams the frequency spectrum of the BPM signal depends on the beam position. Simulation methods are discussed in the context of different BPM realizations applied in hadron accelerators. All simulations described in this paper were performed using CST Suite ® [1].

LINEAR-CUT BPM

Proton and ion synchrotrons are usually operated at the bunching frequency f_{rf} in the order of few MHz. In these accelerators bunches typically have a length of a several meters. For such beam parameters linear-cut BPMs are preferred due to its excellent linearity of the position determination and the independence of the measurements in the orthogonal directions [3]. Moreover, the full transversal coverage by the electrodes allows precise position measurements even for the beams with transversal large and complex charge distribution. An example of such a BPM, sometimes called "shoe-box" due to its cuboid shape, is shown in Fig. 1. Also other geometrical realizations, having e.g. elliptic cross section, show the same electromagnetic properties, see [4] and references therein.

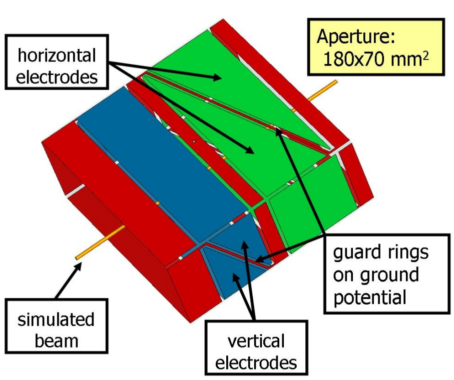

Figure 1: An example of the linear-cut BPM [2].

The most important BPM parameter is its *position sensitivity*, defined as an response of the BPM on the beam displacement [3].

Assuming the bunches much longer than the BPM itself, the electric field propagation in the BPM can be well approximated with TEM wave traveling on a wire. The eventual influence of effects caused by non-relativistic beams is minor and can be neglected. Based on this assumption the BPM position sensitivity can be experimentally determined using so called stretched wire method, see e.g. [5]. In this method the amplitude changes of the signals induced in the electrodes are measured as a response on the changing wire position.

Similarly, position sensitivity can be obtained by means of FEM-based simulations that allow optimization of the BPM design entering in the time consuming prototyping phase. Since simulations enable three dimensional field visualization, the field inhomogeneities or distortions effecting BPM linearity caused by e.g. structure discontinuities can be found and eliminated.

The optimizations performed for linear-cut BPMs with rectangular as well as elliptic cross sections and different electrode arrangements are described in Refs. [2, 4, 6]. It was investigated how the presence of different BPM components like e.g. guard ring influence the position sensitivity and linearity of the position determination. In order to investigate the influence of the whole environment on the position readout, the complete BPM was modeled together with the surrounding vacuum chamber [7]. All components were defined with realistic material permittivity and conductivity. The volume was divided in 3-dimensional hexahedral meshes with typically 10^6 to 10^7 cells – depending on the model complexity. The number of meshes is mainly blown-up by small curved parts or elements oriented diagonally with respect to the main coordinates. The beam was simulated as a traveling wave on a wire using the CST Time Domain Solver and thus reproducing the stretched wire method. An excitation was defined as a Gaussian shaped pulse with length of 5 μs corresponding to the bandwidth of 200 MHz. The position sensitivity was calculated from S-parameters expressed in frequency domain as described in [2]. The goals in optimization of the BPM design were: i) enlarged position sensitivity, ii) linearity of the position determination, ii) reduction of the offset between electrical and geometrical center of the BPM and iv) independence of measurements with respect to the orthogonal directions.

Here we concentrate on the aspect of cross-talk between adjacent BPM electrodes that decreases the difference of

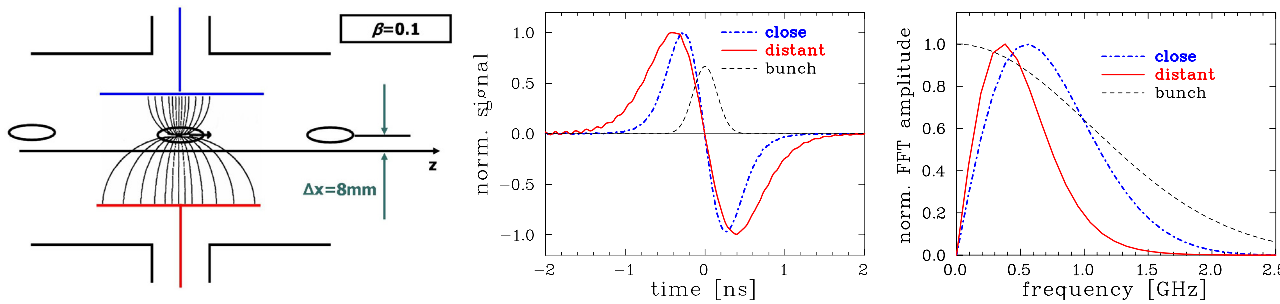

Figure 2: The charge distribution of the bunch moving with $\beta = 0.1$ for 8 mm displaced beam (left). Corresponding signals induced in BPM electrodes (middle) and their frequency spectra (right), for further parameters see text.

signal amplitudes and, in consequence, diminishes BPM position sensitivity. The cross-talk can be measured as response through BPM using network analyzer connected to both electrodes. The result are frequency dependent S21 parameters. Similar cross-talk determination was performed by means of FEM simulations for the geometry shown in Fig. 1 and two different realizations: based on metal coated ceramic or using metal plates. The results are summarized in Table 1.

Table 1: Cross-talk for Geometry from Fig. 1 and Realizations Based on Ceramics and Metal Plates

	ceramics	**metal plates**
no guard ring, 2 mm gap	-8.1 dB	-10.8 dB
with guard ring	-20.8 dB	-22.5 dB

The advantage of the ceramics based solution is its high mechanical stability and relatively easy positioning even of the very complex geometries that consist many elements [4]. The ceramic plates are coated from the inner side with thin metal sheet (typical thickness 50 μm). The shape of electrodes, guard rings etc. is formed by cutting out the fragments of metallization. However, a disadvantage of such solution is the significantly larger (compared to metal plates) coupling capacitance between adjacent electrodes caused by a large relative permittivity of ceramics $\epsilon_r = 9.6$. The better separation could be achieved by increasing the spacing between electrodes. However, for the investigated geometry this distance can not be extended much beyond 2 mm without significant distortion of the electric field in the gap neighborhood. The insertion of the separating ring in the gap between adjacent electrodes, see Fig. 1 improves electrodes separation by more than 10 dB,see Table 1 resulting in an increase of the position sensitivity by factor of two. The maximal reduction of cross-talk would be possible for a geometry based on metal plates equipped with separating ring but is hard due to complicated mechanical alignment of many separate BPM parts. In addition, simulations showed that such a small change in the geometry makes the position sensitivity less frequency dependent [2]. Similar results were obtained for the BPM with elliptic cross section [6].

LOW β EFFECTS FOR BUTTON BPM

In contrast to the assumptions in the previous section for bunch length comparable to the BPM length an influence of the effects due to non relativistic beams on the signal registered in the electrodes becomes more significant. An example for such an accelerator is FAIR proton linac presently under design at GSI [8, 9]. Its accelerating cavities will be driven with a frequency of 325 MHz. In this accelerator BPMs will be installed in several locations over 30 meters of the p-Linac. The beam energy varies along the p-Linac from 3 MeV to 70 MeV corresponding to a beam velocity $0.1 \leq \beta \leq 0.37$. A button type BPM geometry was chosen due to its compact mechanical realization and short insertion length to fit into the short inter-tank sections of the CH-cavities [8]. An additional problem that has to be faced is the rf–power leakage from accelerating cavities, that is especially disturbing in the inter–tank sections, where some BPMs are supposed to be installed. This may require analysis of the beam position on higher rf harmonics.

The position sensitivity of the BPM for non relativistic beams was theoretically investigated by R. Shafer in [10]. The author showed that the BPM sensitivity depends on its geometry, beam energy end frequency on which beam position is analyzed. However, this 2-dimensional formula can not be directly applied to the 3-dimensional BPM geometry, especially for button type BPMs.

The numerical simulations for low β beams were performed by means of CST PARTICLE STUDIO® [1] using the wake-field solver. As a source of excitation a pencil like beam was defined with a Gaussian-shaped longitudinal charge distribution that moves with $0.1 \leq \beta \leq 0.3$. The length of bunches was $\sigma = 150$ ps at a bunch frequency of 325 MHz. The simulated BPM model consists of four planar buttons of Ø 14.4 mm mounted within a beam pipe of Ø 30 mm. The position of the simulated beam was varied in 2 mm steps within the transverse plane in a range of ± 10 mm. The positions in vertical and horizontal direction were calculated from amplitudes of the signals induced in the opposite BPM electrodes using the 'delta over sum'-method (see Ref. [2]).

For non relativistic beams the electromagnetic field propagation is faster than the beam itself. Since the electric field distribution has a significant longitudinal component [10] the distribution of the induced charge in the BPM electrodes depends on the relative distance between beam end electrode as shown in Fig. 2 (left): For the closer electrode the longitudinal charge expansion is more narrow than for more distant electrode. It means that signals registered in the closer electrode will have not only higher amplitude but also will be much shorter than that measured on the opposite BPM side, see Fig. 2 (middle). In this figure the signals registered in the electrodes obtained in the simulations for single bunch moving with the velocity of $\beta = 0.1$ are presented. Note that the amplitudes of the both signals Fig. 2 (middle) were normalized to unity for better visualization. The results of Fourier Transformation on these signals are shown in Fig. 2 (right). In the frequency spectrum of the signal registered in the distant electrode high frequency components are strongly suppressed. In consequence, the position calculated form both signals depends strongly on evaluation frequency. The response of the BPM was compared for the first three harmonics of the accelerating frequency, i.e. at 325 MHz, 650 MHz and 975 MHz and for $\beta = 0.1$ and $\beta = 0.3$ are shown in Fig. 3. For $\beta = 0.1$ the position sensitivity, given by the slope of the displayed curves, is significantly higher for the higher frequencies, what is in line with theoretical predictions of Shafer [10] and simulations presented in Ref. [11]. However, it is worth to be emphasize, that the sensitivity at the higher frequencies is larger only close to the BPM center but drops rapidly already for few millimeter beam displacement. For higher beam velocities i.e. for $\beta \geq 0.3$ the electric charge distribution squeezes [10] approaching more TEM wave. Thus the difference between longitudinal expansion of the signals registered in the opposite electrodes become negligible. Therefore, the position sensitivities for $\beta = 0.3$ is almost constant regardless the frequency at which they are analyzed. The effects described above are even stronger in the two dimensional position map. In Fig. 4 each node of grid corresponds to simulated beam position. The reconstructed beam positions show nonlinearities of the position readings. The strength of these distortions grows with the beam displacement typically for button type BPMs [3]. However, for the beam with $\beta = 0.1$, the position maps for first three rf harmon-

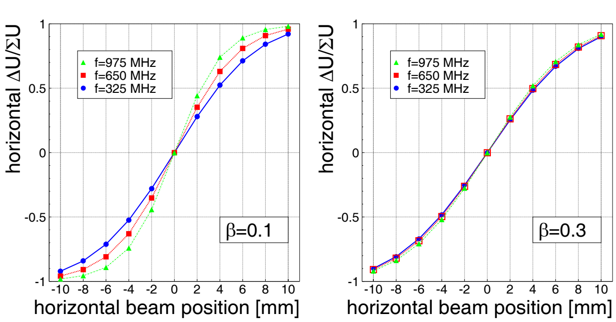

Figure 3: Reconstructed horizontal beam position calculated using 'delta-over-sum' algorithm from signal registered in horizontal buttons for zero vertical beam displacement.

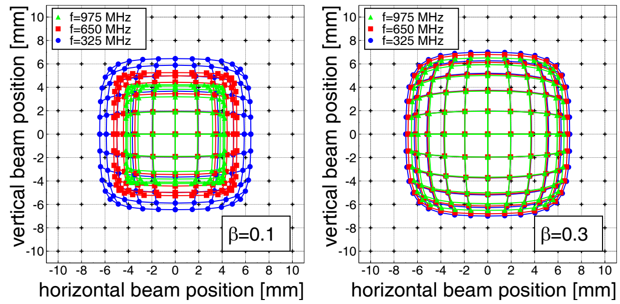

Figure 4: BPM response on variation of transverse beam position for $\beta = 0.1$ (left) and $\beta = 0.3$ (right).

ics significantly diverge from each other. These differences vanish for $\beta \geq 0.3$, Fig. 4 (right). This has to be taken into account when installing BPMs in different locations along the p-Linac: for each location a separate table with correction parameters specific for the given harmonic number and beam velocity have to be prepared. Moreover, BPMs are only usable for limited beam displacement. For this particular case for $\beta = 0,1$ and 3rd harmonics BPM is completely insensitive for the beam displacement larger than ± 5 mm i.e. exceeding $\sim$30 % of BPM aperture. Therefore, it should be kept in mind, that the choice of the rf harmonics is always trade between reduction of the influence of rf–leakage on the BPM signals and reduction of usable BPM aperture.

SUMMARY

The simulations based on finite element methods are very helpful to test different BPM approaches without time consuming prototyping. An 3-dimensional visualization of the field propagation allows to understand complex processes which simplifies optimization of BPM design. Moreover, simulations are successfully used for cases that could not be investigated using a test bench, i.e. for the non relativistic beams.

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