NUMERICAL CALCULATIONS OF POSITION SENSITIVITY FOR LINEAR-CUT BEAM POSITION MONITORS

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Abstract

In the present contribution results of a simulation of linear-cut Beam Position Monitors (BPMs) based on a design using a metal coated ceramics are compared for two different geometries. The investigated BPMs will be used in the FAIR facility. The simulations were performed using CST Microwave Studio. The main goals of the design optimization were pick-up sensitivity and linearity of the position determination. High position sensitivity can be achieved by reduction of plate-to-plate cross talk caused by coupling capacities. In case of ceramic based BPMs insertion of an additional guard ring into the gap between the active plates leads to an increased sensitivity by about a factor of two.

INTRODUCTION

The BPMs described here, will be a part of the beam diagnostics instrumentation of the superconducting heavy ion synchrotron SIS100 in the accelerator complex FAIR [1]. The extensive simulation programme is focused on the comparison of different geometries of linear-cut Beam Position Monitors (BPMs) for two design types: i) based on metal electrodes and ii) based on metal coated Al_2O_3 ceramics. A construction based on the metal electrodes benefits from its simplicity. In contrast, the advantage of a ceramic solution is a compact construction allowing easy positioning and good mechanical stability in the cryogenic environment.

The accuracy of the beam position determination is a convolution of the mechanical adjustment of the BPM, displacement sensitivity (defined later on) and overall resolution of the readout (including e.g. amplification noise, digitalization resolution, etc.) [2]. In order to reach the desired accuracy of $100\ \mu$m, the mechanical stability has to be about $50\ \mu$m.

Because the simulation programme is still in progress, the present paper presents the results for the BPM with metal coated ceramics.

The SIS100 parameters are tuned for the two design beams; namely for 4×10^{13} protons at 29 GeV and 5×10^{11} U^{28+} ions with energy of 1.5 GeV/u. In the extreme case (i.e. for the intense proton beam) one expects 4×10^{13} charges accumulated in a single bunch of 25 ns length [3]. Assuming a beam in a bunch of parabolic density distribution circulating in the synchrotron ring with the velocity of light and investigated BPM geometry of 125 mm long signal plates with plate–to–ground capacity of 45 pF, the expected peak voltage reaches 1.8 kV [4]. In this case a real problem becomes preamplifier protection. At the other extreme, a fairly weak beam of 10^8 charges per cycle with 100 ns long bunches will be provided as pilot beam or in low intensity operation mode. For such a beam a peak voltage of about 1.1 mV is expected. This is barely sufficient to obtain a detectable difference signal, even if high impedance preamplifiers are mounted directly on the signal feed-through.

The huge dynamic range of over 120 dB does not require only special electronics [5], but also a very careful BPM design. In particular the relative distances between electrodes, guard rings and chamber elements have to be large enough to prevent discharges.

All BPMs will be installed in the same cryostats as the quadrupole doublets [3, 6]. In the arcs the BPMs will be located directly behind the horizontally focusing (second in doublet) quadrupol. In this position the horizontal β-function reaches its maximum. On the contrary, in the straight sections the BPMs will be installed in the middle of the quadrupol doublet at the maximum of the vertical β-function. All BPMs will be equipped with electrodes for both horizontal and vertical beam position measurement.

84 BPM stations are distributed around the 1084 m circumference of SIS100. For almost all operation modes the average phase advance of the betatron oscillations between subsequent BPMs will be smaller than 90^{o} (i.e. more than four BMPs per unit of betatron tune). As stated in Ref. [7] the number of BPMs and their locations are just sufficient for on-line feedback of the closed orbit.

A smooth passage of the beam vacuum chamber apertures between subsequent elements in the lattice prevents a beam–to–ground impedance jump, which is crucial for beam stability. Therefore, the aperture of the BPM will be identical to the aperture of the proceeding quadrupol chamber, see Fig. 1 (top). The only known elliptic and ceramics pickups were those installed more than 50 years ago in the CERN PS facility [8]. The vertical and horizontal plates in those monitors were combined due to the limited space available. In consequence, they present some nonlinearities due to a position-dependent sum signal.

Due to the relatively large bunch length (in comparison to the length of the BPM) and the bunch frequency in the order of a few MHz, the linear cut type BPMs are preferred. The high linearity of the position determination, typical for this BPM style, is advantageous for beams that are transversally large and have a complex charge distribution.

The available length of the BPM chamber measured between vacuum flanges is 400 mm, which leaves 300 mm length for the active plates including the guard rings. It allows to mount vertical and horizontal plates in series –

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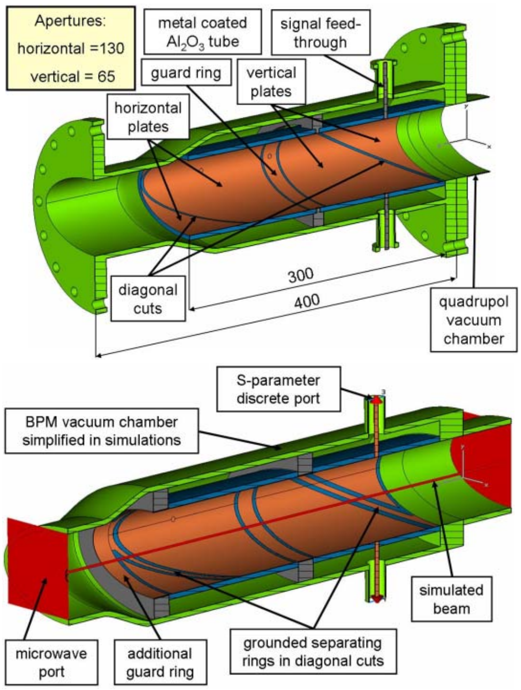

Figure 1: Models of the BPMs used in the simulations, see description in text. Note, the model with the complex BPM chamber (top) was used for of visualization purpose only. In the simulation the BPM chassis was simplified to that shown in (bottom).

one pair after the other. The designed BPM should show a good response in the frequency range from ~ 0.2 MHz to 100 MHz.

SIMULATION RESULTS

As a simulation tool CST Microwave Studio (part of the CST Suite 2006 package) is used. All simulations were performed using the time domain solver in the bandwidth of 200 MHz. In the simulation two models shown in Fig. 1 were compared. Both contain the elliptic ceramic pipe coated on the inner side with 30 μm of PtAg metal sheet. In this metal coating the electrode shapes are formed by cutting out grooves. Both models differ in the separating ground rings positioned in the diagonal cut between the adjacent plates (see Fig. 1 bottom). In addition only in the second model additional massive guard ring at the end of the signal plates is installed.

Displacement Sensitivity

The *displacement sensitivity* is the response of the BPM (expressed as the difference of the electrode signals ΔU normalized to their sum ΣU) to changes in the beam position and is given by:

$$\Delta x = K \frac{\Delta U}{\Sigma U} + \delta x \tag{1}$$

The parameter K is usually called *pick-up constant*. The *pick-up offset* δx represents a misalignment of the electrical center with respect to the geometrical center of the BPM.

In the simulations the BPM with beam inside was treated as a coaxial TEM wave guide. The ion beam was approximated by a cylinder of a Perfect Electric Conductor (PEC) with diameter of 1.5 mm and a length corresponding to the length of the vacuum chamber. The beam was spanned between two wave guide ports defined on both ends. Electrode outputs were defined as S-parameter ports with characteristic impedance of 1 MΩ. The displacement sensitivity of the BPMs was calculated from the S-parameters expressed in the frequency domain [9].

The simulated beam position was swept in the horizontal plane in the range ± 50 mm in 10 mm steps. For each beam position the full set of the S-parameters was analyzed for both horizontal and vertical planes. The results are presented in Fig. 2. Both BPM types show good linearity in

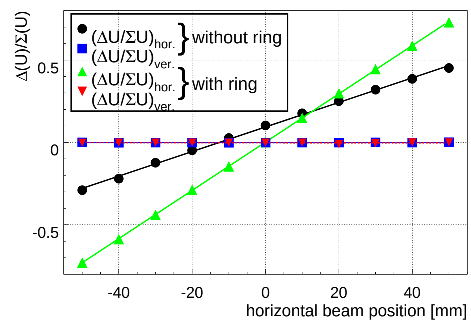

Figure 2: Displacement sensitivity for the BPM without and with separating ring.

position determination. The maximum deviations from the straight line fit are smaller than $\pm 2\%$ for the BPM without ring and below $\pm 0.5\%$ for the BPM with ring over the ± 50 mm displacement range. In addition the horizontal displacement of the beam is not registered by the vertical plates; therefore, the position determinations in both planes can be treated as independent. The offset of the electrical center of a BPM without separating ring is large compared to BPM with ring. It indicates, that a guard ring at the end of the BPM electrodes (see Fig. 1 bottom) is mandatory.

As already shown in Ref. [9] the displacement sensitivity is often frequency dependent. This is especially harmful for bunches which are strongly deformed and have inconstant longitudinal structure. For those bunches the frequency spectrum varies in time, which effects the beam position estimation. Therefore, analysis of the frequency response of the displacement sensitivity is of great importance. The results of this analysis are presented in Fig. 3 showing a moderate frequency dependence even at higher frequencies. Projections of slices perpendicular to the frequency axis for given frequency (e.g. at typical bunch frequency of 2.5 MHz) lead to the plots in Fig. 2. Least-square fits of a linear function given by Eq. 1 to the data for each frequency value, yield the frequency dependencies of both parameters, displacement sensitivity and offset. These dependencies are shown in Fig.4. Displacement sensitivity and offset for both investigated geometries are almost frequency independent in the relevant frequency range. How-

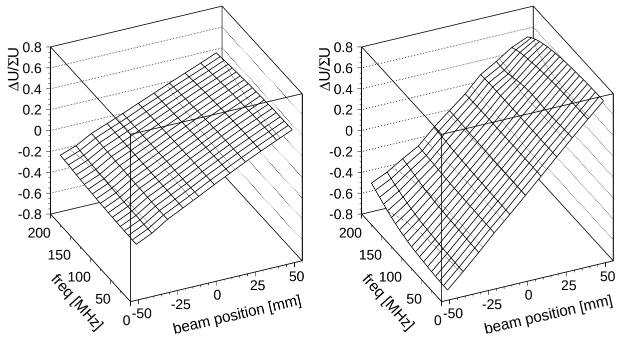

Figure 3: Displacement sensitivity as a function of frequency for the BPM without (left) and with (right) separating ring.

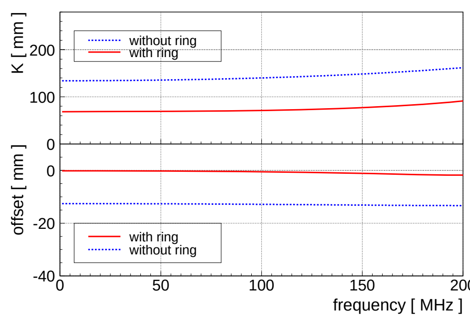

Figure 4: Frequency dependence of *"pickup constant"* K (top) and offset of the BPM electric center (bottom) for the horizontal beam displacement.

ever, the displacement sensitivity of the BPM with guard ring is a factor of two larger compared to the BPM without ring [1]. The moderate drop of the sensitivity is caused by inductive cross talk between adjacent signal plates which is more pronounced at higher frequencies. Moreover, the offset of the electric center of the BPM without separating ring is about 13 mm whereas the offset for the BPM with ring is consistent with zero in a frequency range up to 100 MHz.

Separation of Adjacent Plates

Fig. 5 shows the separation between the two adjacent horizontal plates for the BPM without a separating ring obtained in the simulations is -9,5 dB. This strong coupling is caused by the large ceramic permittivity ϵ_r=9.6 which induces a big coupling capacitance. The poor plate separation diminishes the difference signal and deteriorates the displacement sensitivity. An insertion of the separating ring increases the plates separation to -21 dB. For the description of the simulation method see [9]. Due to the relatively large total length of the PU electrodes, the cross talk between horizontal and vertical plates can lead to low frequency resonances. To avoid this effect an additional massive guard ring has to be installed in the middle of the

[1]The smaller the value of K in the Eq. 1 the larger is the BPM response ($\frac{\Delta U}{\Sigma U}$) for the same beam shift (Δx).

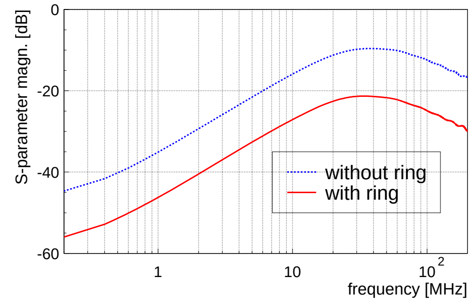

Figure 5: Separation between two adjacent signal plates (here horizontal) obtained in the simulations of models with (solid line) and without (dashed line) separating ring.

BPM. This allows to achieve a separation of the orthogonal plates better than -45 dB.

Similar results were obtained in simulations performed for the HIT BPMs [9] and following measurements with a HIT BPM prototype.

CONCLUSION AND PERSPECTIVES

Simulations showed that a BPM design with separating ring provides good linearity and much better position sensitivity than a BPM without ring. Hence, the separating ring should be always considered in the BPM design as long as a ceramic solution is used.

In future signal/field simulations further geometries, like those described in Ref. [8] and adopted for the elliptic electrode shape, will be tested for both metal and ceramic based constructions.

First tests of the mechanical features of ceramics in low temperatures showed that the ceramics can be used under the cryogenic conditions. However, further tests are needed for the several metal–ceramic interfaces. The cryogenic tests will be performed in parallel to the dynamic thermal simulation using the new thermal solver of CST-Suite2006.

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