OPTIMISATION OF THE LINEAR–CUT BEAM POSITION MONITORS BASED ON FINITE ELEMENT METHODS

P. Kowina, W. Kaufmann, J. Schölles, GSI, Darmstadt, Germany

Abstract

This contribution presents investigations of the Beam Position Monitors (BPMs) for the FAIR project. In the simulations, performed using CST Studio Suite 2006B, the linear-cut BPMs based on a metal coated ceramics were considered as the only solution that meets the required mechanical stability of $\sim 50\mu m$ under cryogenic conditions. The most important BPM features like displacement sensitivity or linearity of position determination were compared for different BPM geometries. In these geometries, based on elliptically shaped ceramic pipe, the vertical and horizontal electrode pairs were either mounted subsequently in series or were spirally shaped and combined alternatively within one unit. It is shown that optimised BPM design with the serial mounted electrodes and separating ring inserted in between the adjacent electrodes has a very high sensitivity and shows much better linearity of the position determination than the design based on spiral–shaped electrodes.

INTRODUCTION

The BPMs that are presented here will be used in superconducting heavy ion synchrotron SIS100 — the main synchrotron in the FAIR accelerator complex [1]. All 84 BPMs will be installed in the cryostats of the quadrupole doublets and will be mechanically fixed to the quadrupole chambers [1, 2]. The cryogenic operation requires a special BPM design that considers e.g. the matching of the thermal contraction of the materials used. For the foreseen bunch frequencies of 0.5 MHz $< f_b <$ 2.7 MHz and bunch lengths ranging from few meters up to several hundreds meters the designed BPM should show a good response in the frequency range from ~ 0.1 MHz to 100 MHz. For such frequencies and bunches much longer than the BPM length a linear–cut BPM is preferred. Its high linearity of the position determination is advantageous for beams that are transversally large and have a complex charge distribution. In order to reach the desired position accuracy of 100 μm [3], the mechanical stability should be in the order of 50 μm. Only the design based on a metal coated Al_2O_3 ceramics gives the required mechanical stability in the cryogenic environment. The aperture of the BPM should be elliptic — matched to the aperture of the proceeding quadrupole chamber to prevents a beam–to–ground impedance jumps. Available total detector length of 400 mm (flange–to–flange) allows to equip each BPM with electrodes for both, horizontal and vertical beam position measurement. The foreseen dynamic range of signal amplitude of over 120 dB [4] requires special electronics [5] and a very careful BPM design. Particularly, the relative

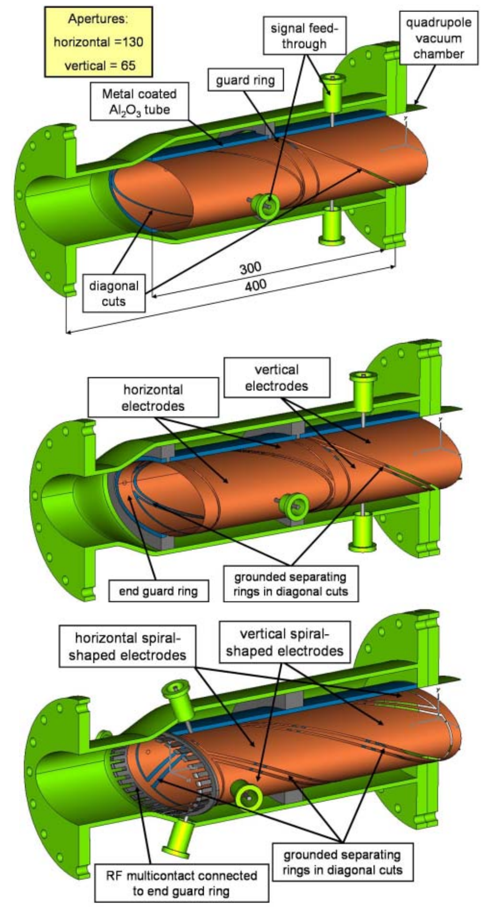

Figure 1: Models of the BPMs compared in the simulations, see description in text.

distances between electrodes, guard rings and chamber elements have to be large enough to prevent discharges, that may appear for the most intense beams, for which the expected peak voltage of BPM signals reaches 1.8 kV [4].

Two main BPM types were compared: First type considers the geometry shown in Fig. 1 (top and middle) where the vertical and horizontal electrode pairs are mounted subsequently — one pair after the other. The optimisation of this design type, called in this paper *serial BPM* was described precisely in Ref. [4]. It was shown that the improved BPM design with separating ring (Fig. 1 middle) has better linearity of the position determination and higher position sensitivity than the preliminary design shown in Fig. 1 (top). The motivation for further investigations was, that in serial BPM the distance between the point, where the ceramic pipe is fixed to BPM chassis is different for horizontal and vertical signal feed-throughs. Due to this difference, during cooling down from room temperature to liquid helium temperature, the dislocation of the middle pins in the horizontal signal feed–throughs is twice so high as for vertical ones. To equalise this distance for all feed–throughs the geometry shown in Fig. 1 (bottom) and called *spiral–shaped BPM* was proposed. In this geometry the spiral shaped electrodes cover the full BPM length.

METHODS AND RESULTS

For Finite Element Method simulations CST Studio Suite 2006B was used [6]. All BPM components, i.e. ceramic tube, chassis, feed–throughs etc. were defined using materials with realistic permittivity and conductance. The BPM was treated as a semi–coaxial TEM wave guide with the ion beam approximated by a cylinder of a Perfect Electric Conductor (PEC) [4]. For the simulated BPM models the hexahedral mesh grid was used with about 2×10^6 single mesh cells [7]. A broad–band Gauss shaped signal was used as the excitation signal with the rms width of 5 ns, which covers the frequency band from DC–200 MHz. The electrode outputs were defined as the discrete S-parameter ports with characteristic impedance of $1\mathrm{M}\Omega$. Simulations were performed using the Time Domain Solver [7].

The geometrical design of the investigated BPM was optimised regarding the following criteria:

i) The high *displacement sensitivity* is the measure of BPM signal response $\left(\frac{\Delta U}{\Sigma U}\right)$ to the changes in the beam position and is defined in Ref. [4]. The displacement sensitivity of the BPMs was calculated from the S-parameters expressed in the frequency domain [8]. The position of the simulated beam was swept in the horizontal plane in the range ± 50 mm in 10 mm steps. For each beam position the response of the BPM was analysed for both horizontal and vertical planes. The results are presented in Fig. 2. The displacement sensitivity, as given by the slope of curves in Fig. 2 (top), depends strongly on plate–to–plate coupling.

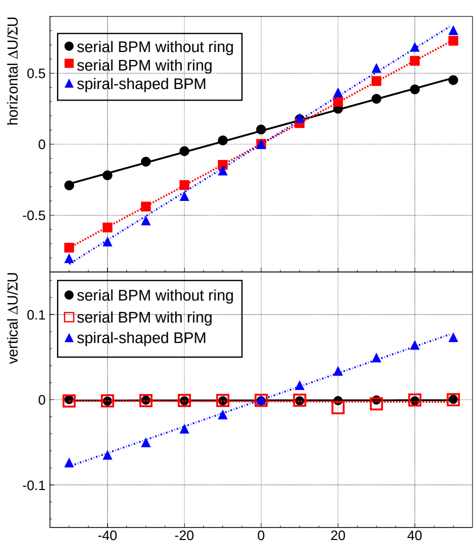

Figure 2: BPM response registered in horizontal (top) and vertical (bottom) plates on the horizontal beam displacement.

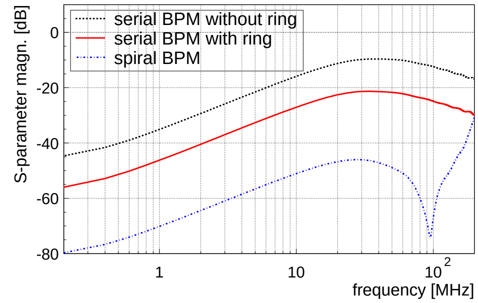

Figure 3: Coupling between two adjacent signal plates obtained in the simulations.

For the ceramic based BPMs large ceramic permittivity ϵ_r=9.6 leads to high coupling capacity that diminishes the difference signal and deteriorates the displacement sensitivity. The methods of investigations of the plate–to–plate coupling are described precisely in Ref. [7]. For the serial BPM the coupling between adjacent plates can be decreased from -9.5 dB to -21 dB by insertion of the separating ring between adjacent plates, see Fig. 3. This increases the displacement sensitivity by a factor of two [4]. In case of the spiral–shaped BPM, the coupling between two plates belonging to the same pair is much weaker than for the serial BPM and is -45 dB. However, it shows a resonant behaviour with a minimum at about 90 MHz [7]. This is the reason for the unhomogenieties in the frequency dependence of the displacement sensitivity for this BPM shown in Fig. 4 (right) and described later on.

ii) *Linearity of the position determination:* The high linearity is typical for the diagonal–cut type BPMs, however, it can be strongly spoiled by unhomogenities of the magnetic and/or electric field caused by e.g. too large distance between subsequent electrodes or by structure discountinities. For the BPM under investigation the maximum deviations from the straight line fit shown in Fig. 2 (top) are smaller than $\pm 2\%$ for the BPM without ring, below $\pm 0.5\%$ for the BPM with ring and $\pm 5\%$ for the spiral–shaped BPM over the whole ± 50 mm displacement range.

iii) The *offset of the electrical centre* of the BPM in respect to its geometrical centre can be reduced from about 13 mm (crossing point with the x-axis of the curve with black circles in Fig. 2 top) to almost zero (curve with the red squares) by an additional massive guard ring installed at the end of the BPM electrodes, see Fig. 1 (middle). It indicates that the geometry of the whole environment (including also the neighbouring guard rings) has to be completely symmetrical for both electrodes belonging to the same electrode pair. This is also valid for the spiral–shaped BPM, where the electrodes have rotation symmetry.

iv) A very careful treatment of the fringe fields is required in order to achieve a maximum *independence of the measurement* in vertical and horizontal directions. Particularly, the length of all guard rings has to be large enough to suppress the fringe fields distortions [9]. For serial BPMs, as it can be seen in Fig. 2 (bottom, circles and squares), the horizontal displacement of the beam has no influence

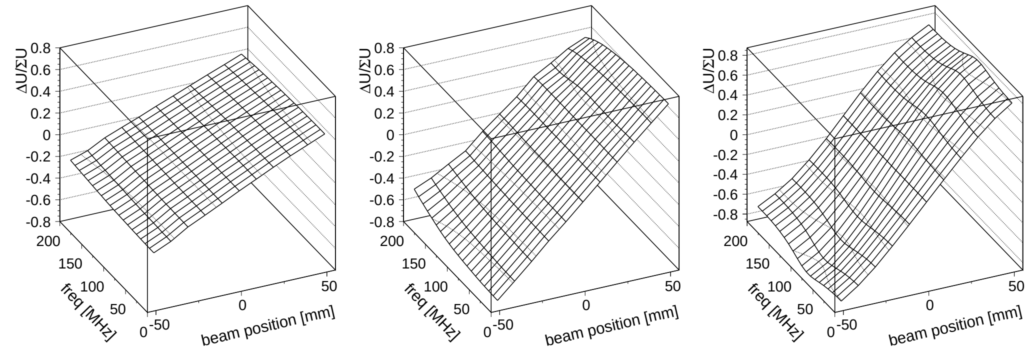

Figure 4: Displacement sensitivity as a function of frequency for the serial BPM without (left) and with (middle) separating ring and for spiral–shaped BPM (right).

on the signal measured in the vertical electrodes. On the contrary, spiral–shaped BPM (triangles) shows a significant horizontal–vertical cross talk due to the increased coupling between the four signal plates. Note that the adjacent plates in the case of the spiral–shaped BPM are the orthogonal plates i.e. electrode pairs: left–top, left–bottom etc.

The displacement sensitivity is often frequency dependent which is especially harmful for bunches with varying longitudinal structure [4, 8]. For those bunches the frequency spectrum varies in time, which effects the beam position estimation. For the serial BPMs, as it can be seen in Fig. 4 (left and middle) the displacement sensitivity is nearly frequency independent, whereas the spiral–shaped BPM shows strong inhomogeneities already at frequency of about 90 MHz, Fig. 4 (right). Projections of slices per-

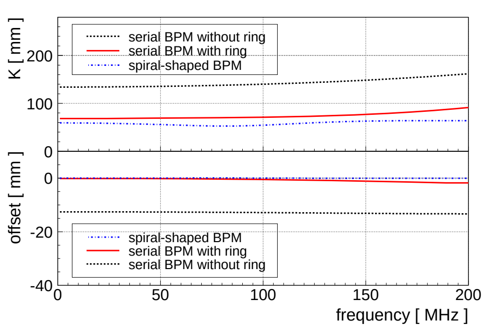

Figure 5: Frequency dependence of *"pickup constant"* K (top) and offset δ of the BPM (bottom) for the horizontal beam displacement.

pendicular to the frequency axis for given frequency (e.g. at typical bunch frequency of 2.5 MHz) lead to the plots in Fig. 2. For each of this slices the *"pickup constant"* K and BPM offset δ can be found [4]. The frequency dependencies of these parameters are shown in Fig. 5. The displacement sensitivity of the BPM with guard ring is a factor of two larger compared to the BPM without ring and is 15% smaller than for the spiral–shaped BPM [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 centre of the serial BPM without separating ring is about 13 mm whereas the offset for the serial BPM with ring and spiral–shaped BPM is consistent with zero in a frequency range up to 100 MHz.

[1]The smaller the value of K the larger is the BPM response $\left(\frac{\Delta U}{\Sigma U}\right)$ for the same beam shift (Δx), see Ref. [8].

CONCLUSIONS AND PERSPECTIVES

Simulations showed that the serial BPM with separating ring provides good linearity and high displacement sensitivity. Hence, the separating ring should be always considered in the BPM design as long as a ceramic solution is used. The BPM design based on spiral-shaped electrodes show strong frequency dependence of the displacement sensitivity. Moreover, for this design type the measurements in vertical and horizontal directions are correlated. Therefore, this PBM design is excluded. Since the serial BPM design does not satisfy all mechanical requests, further field/signal simulations will be performed for alternative BPM geometries [10]. First tests of the mechanical features of ceramics in low temperatures showed that the metal coated ceramics can be used under 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-Suite 2006B.

REFERENCES

[1] FAIR – Baseline Technical Report available on: http://www.gsi.de/fair/reports/techrep_e.html

[2] J. Stadlmann et al., *Proc. EPAC06*, Edinburgh (2006) p.214.

[3] A. Galatis et al., *Proc. EPAC06*, Edinburgh (2006) p.1019.

[4] P. Kowina et al., *Proc. EPAC06*, Edinburgh (2006) p.1022.

[5] J. Schölles et al., *Proc. DIPAC05*, Lyon (2005) p.190.

[6] http://www.cst.com

[7] P.Kowina, *Reports of CARE meeting*, Lüneburg (2006), available on: http://adweb.desy.de/mdi/CARE/Lueneburg/ABI-Lueneburg.htm

[8] P. Kowina et al., *Proc. DIPAC05*, Lyon (2005) p.114.

[9] J. H. Cuperus, NIM **145** (1977) p.233-243.

[10] E. Schulte, *Beam Instrumentation*, CERN-PE-ED001-92, Rev. Nov 1994, p.129 and references therein.