OPTIMISATION OF ”SHOE-BOX TYPE” BEAM POSITION MONITORS USING THE FINITE ELEMENT METHODS

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Abstract

The enhancements of the sensitivity and linearity of the position determination are the main goals in the optimisation of the Beam Position Monitors (BPMs) for ion synchrotrons. High position sensitivity can be achieved by the reduction of the coupling capacities and the plate-to-plate cross talks. For instance, the insertion of an additional guard ring into the gap between the active plates increases the sensitivity even by a factor two due to reduction of the cross talk. High linearity is typical for the shoe-box type BPM, however, it might be strongly influenced by discontinuities or/and imperfections of the components which are spoiling the fields homogeneity in the BPM volume. This requires a very careful design, especially in the regions close to the edges of the active plates. The BPM response has been investigated in the frequency range from $0-200$ MHz. It is shown that the transversal transfer impedance is frequency dependent; however, in the range up to 50 MHz (typical for the BPM applications) it varies only in the order of a few percent. The displayed simulations are performed using CST Microwave Studio.

INTRODUCTION

Motivation for the investigation described in the present work were the optimisations of the BPM's construction for the HICAT synchrotron dedicated for the cancer therapy [1]. The synchrotron will be operated with the maximal bunch frequency of 6.74 MHz (at the maximal extraction energy). The ^{12}C and ^{16}O ions will be accelerated up to $50-400$ MeV/u.

The investigations presented in this contribution are based on existing constructions of the shoe-box type pick-ups used at Heavy Ion Synchrotron (SIS) and Experimental Storage Ring (ESR) at GSI. The schematic views of the SIS– and ESR–BPMs are shown in Fig. 1.

The typical bunch frequency of SIS and ESR is in the range from 800 kHz up to 5 MHz at the maximal energy of about 1 GeV/u depending on the charge state of the ions.

The ESR BPM construction differs from the SIS one, since only in the ESR pick-ups the additional ground ring in the diagonal cut has been used, see Fig. 1. This separating ring is supposed to reduce the cross talks between the two close laying signal plates. Both setups are equipped with guard rings, however, the width of the guard rings and the width of the cuts between plates and guard rings for SIS- and ESR-like construction are different.

The main objective of the studies was to investigate how the presence of the certain pick-up's components (like guard rings, separating ring etc.) and their geometrical dimensions influence on the pick-up sensitivity and linearity of the beam position determination.

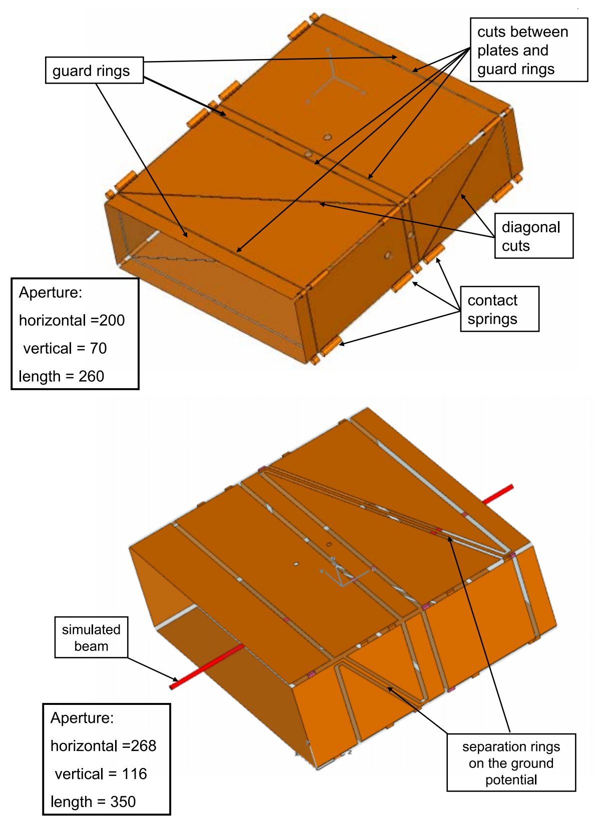

Figure 1: Schematic view of the SIS (top) and ESR (bottom) BPMs— here shown without chassis.

As the simulation tool ”CST Microwave Studio” (CST-MW) version 5 has been used. All simulations were performed using the transient solver.

The bandwidth of 0–100 MHz, typical BPM preamplifiers [2], allows to observe up to the 20 harmonics of the bunch frequency. Since it is interesting, how a BPM behaves in frequency range slightly exceeding this limit the frequency regarded in the simulations was chosen to be in the range of 0-200 MHz.

In the present contribution by ”horizontal plates” or ”horizontal contact” etc. we understand those pick-up components, which are used for the measurements in the horizontal direction. Analogous nomenclature is used for the ”vertical” components.

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PLATE–TO–PLATE CROSS TALK

The cross talk between the plates of the BPM influence negatively the amplitude of the output signals. The larger the coupling the smaller is the difference of the output signals for a given beam displacement.

In the CST-MW simulations the BPM without separating ring (SIS-like) was compared to the BPM with the ring (ESR-like). In the last case the width of the ring and the distance from the ring to the plate edges was chosen to be 1 mm. The port impedances were defined to be 50 Ω what reproduces later measurements performed with the network analyser. The coupling for the horizontal (left-right), vertical (up-down) plates and for the mixed pairs like: left-up etc. has been investigated.

The frequency dependences of the S–parameters calculated for the horizontal plates of the BPM with and without separating ring are presented in Fig. 2.

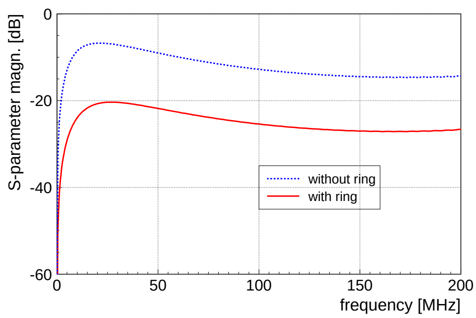

Figure 2: S-parameters for the coupling from one of the horizontal plates to the other obtained in the calculations for the BPMs with and without separating ring.

As indicated in Fig. 2 the coupling for the BPM without separating ring is ~ -8 dB. It means, that about one third of the signal from the one of the plates of the same pair is seen on the other one. In consequence the measured difference of the output signals is strongly suppressed and deteriorates drastically the position sensitivity of the pick-up.

The insertion of the separating ring in the diagonal cut between the plates (see Fig. 1) allows to noticeably reduce the coupling to ~ -20 dB.

The cross talk between orthogonal plates (i.e. right-up etc.) is very weak, in the order of -40 dB due to the guard ring.

Similar results one obtains in measurements for the SIS and ESR BPMs (for ones without and with the separating ring, respectively), performed using a network analyser. In the frequency range up to 100 MHz the absolute values of the plates coupling obtained in the measurements are, with an accuracy better than 1 dB, in line with the results of the simulations.

POSITION SENSITIVITY

The *position sensitivity* is the dependency of the difference between the plate signals (normalised to the sum of the signals) as a function of the beam position in the pick-up. In the following section results of the simulations and measurements of the position sensitivity for the SIS pick-up will be presented.

The ion beam was simulated as a cylinder of a Perfect Electric Conductor (PEC) with the diameter of 1.5 mm and length 10 cm longer than overall dimension of the pick-up. The impedances of the output ports were defined to be 1 MΩ. This corresponds directly to measurements using a setup [3], where the real SIS BPMs were tested using a copper wire mounted precisely parallel to the nominal beam axis. To reproduce the bunched ion beam the wire was connected to a sine wave generator with the frequency of 1 MHz.

In the CST-MW simulations the position sensitivities of the BPMs were extracted from the S-parameters expressed in frequency domain. The output voltages normalised to their sum ($\frac{\Delta U}{\Sigma U}$) were calculated out of the S-parameter values at the frequency of 1MHz applying the following equation:

$$\frac{S_{right \leftarrow in} - S_{left \leftarrow in}}{S_{right \leftarrow in} + S_{left \leftarrow in}} = \frac{\frac{U_{right}}{U_{in}} - \frac{U_{left}}{U_{in}}}{\frac{U_{right}}{U_{in}} + \frac{U_{left}}{U_{in}}} = \frac{\Delta U_{hor}}{\Sigma U_{hor}}, \quad (1)$$

where the S-parameters are given by the output/input voltage ratio [4].

The position of the simulated beam was changed in steps of 20 mm in the horizontal direction within the three planes for the three different and fixed vertical positions, i.e. in the centre of the pick-up high, +20 mm above and -20 mm below the centre plane. For each beam position a full set of the S-parameters was analysed for both horizontal and vertical plate pairs. The results are presented in Fig. 3.

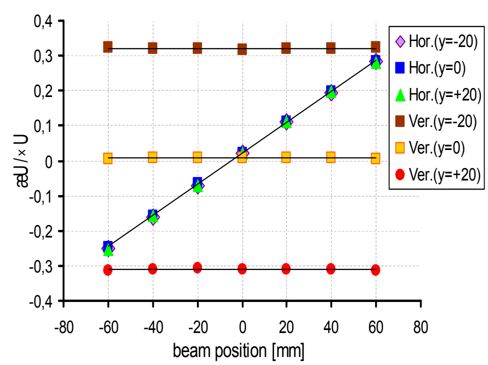

Figure 3: Position sensitivity extracted for the SIS pick-ups for the horizontal beam position shift.

The data points for the position calculation done using the horizontal plates are located on the same diagonal line independently from the vertical beam position (at least for the vertical beam shift of $y \pm 20$ mm). Also in case of the vertical position determination the observed effect is insensitive on the horizontal beam displacement — the data points are located on the three lines parallel to the x-axis where each of these lines directly corresponds to the given y-position. Therefore, the position determination in the horizontal and vertical direction can be treated as independent.

As seen in Fig. 3 the position sensitivity of the simulated BPMs is extremely linear even for the horizontal beam displacements in the range of ± 60 mm. With the fit to the data for the different beam displacement with a linear function:

$$\Delta x = K \frac{\Delta U}{\Sigma U} + \delta x \qquad (2)$$

the *pick-up constant* K and *pick-up offset* δx can be deduced. For the simulated SIS pick-up the values are:

$K_{hor} = 226$ mm $\quad \delta_{hor} = -4.8$ mm
$K_{ver} = 62.7$ mm $\quad \delta_{ver} = +0.39$ mm.

The values obtained in the simulations are 20% larger than the experimental values measured with the test setup [3], since in the simulations the capacities of the feeds-throughs and preamplifiers were not taken into account due to memory and CPU–time limitations.

FREQUENCY DEPENDENCE OF THE POSITION SENSITIVITY

Typically, the position sensitivity is shown at a given frequency (in that particular case 1MHz) which usually corresponds to the bunch frequency of the measured beam. However, due to the bunch structure, higher frequency components enter into the measuring system — if one considers bunches with a Gaussian shape and the bunch frequency of 5 MHz, the frequency spectrum is in order of several tenth of MHz. Therefore the analysis of the frequency dependence of the position sensitivity is of great importance. This can be clearly seen in Fig. 4 (left) where the results of the simulations for the horizontal position determination for the BPM without the separating ring are shown. In this figure the position sensitivity starting at frequency of about 50 MHz shows an extremely nonlinear behaviour.

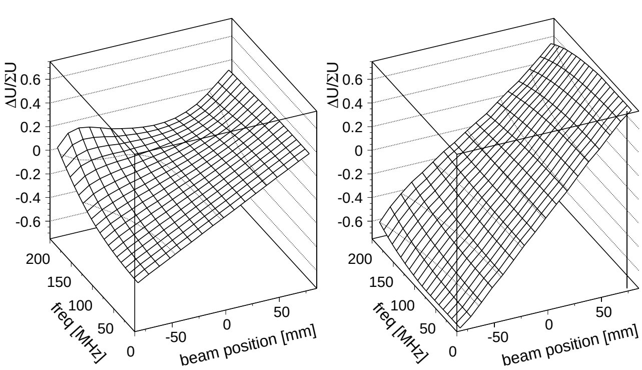

Figure 4: Position sensitivity as a function of the frequency for the horizontal beam displacement obtained in the simulations for the BPM without (left) and with separating ring (right).

The right part of Fig. 4 presents the results of the calculations for the BPM with separating ring. An insertion of the separating ring not only increases the position sensitivity but also makes it much more linear and less frequency dependent.

Projection of the slices perpendicular to the frequency axis taken at a given frequency (for instance 1 MHz) lead to a similar plot as in Fig. 3. By fitting of those slices with a linear function given by the Eq. 2 one can extract both pick-up constant (K) and offset (δ) separately for each frequency point in the investigated frequency range, see Fig. 5.

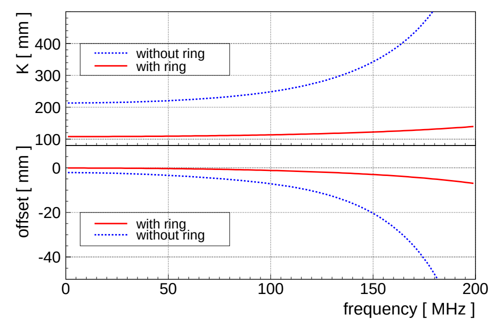

Figure 5: Frequency dependence of the pick-up constant (top) and offset (bottom) for the horizontal beam position determination simulated for the BPMs without and with separating ring.

In the figure it is clearly seen, that the sensitivity of the BPM with separating ring is almost a factor of two larger than for the BPM without the ring [1]. The "BPM constant" K is actually not constant anymore since it varies strongly over the 200 MHz frequency range. For the horizontal position measurement the variation is in the order of 50% for the BPM with separiating ring. The offset in this frequency range drifts from -0.05 mm to -7 mm. In the case of the BPM without the ring the variation of both K and offset is even six times larger. The drop of the BPM sensitivity is caused by the inductive coupling between the plates and the ground which contributes to the coupling impedance strongly at the higher frequencies.

The BPM for the HICAT facility are constructed as a BPM with separating ring since this configuration shows better linearity and much higher position sensitivity than the BPM without the ring. Reducing the bandwidth up to 50 MHz with a low pass filter one can neglect the correction of both pickup constants and offsets since they are constant within an accuracy of 3%.

REFERENCES

[1] H. Eickhoff et al, EPAC'04, July 2004, Lucerne, p. 290.

[2] G. Vismara, BIW'00, Cambridge AIP 564, p. 36.

[3] P. Moritz, GSI-Darmstadt, Private communication.

[4] see e.g. B. C. Wadell, *Transmission Line Design Handbook*, Artech House Boston (1991), ISBN 0-89006-436-9.

[1] The smaller the K in the Eq. 2 the larger is the BPM response ($\frac{\Delta U}{\Sigma U}$) for the same beam shift (Δx).