Abstract

In the present contribution results of a simulation of linear-cut Beam Position Monitors (BPMs) based on a design using metal coated ceramics are compared for two different geometries. The investigated BPMs will be used in the SIS100 synchrotron at the FAIR facility. The simulations were performed using CST Suite 2006. The main goals of the design optimisation were pick-up sensitivity and linearity of the position determination. The effects often observed in BPMs, like resonances or cross-talks, are discussed together with methods of their reduction. In the last part the questions concerning mechanical challenges in the BPM design are addressed and partially answered.

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1 Introduction to the Fair Facility

The Facility for Antiproton and Ion Research (FAIR), presently under design at GSI, will enable production of intense beams for the full spectrum of ion — starting from antiprotons up to the radioactive beams of uranium ions. The ions will be accelerated up to the maximal energies of 35 GeV or 45 GeV per nucleon depending on the ion type and charge state. The variety of different injectors, synchrotrons and storage rings, see Fig. 1, allows to cover almost all operational modes like slow extraction of the high charge state ions, pulse extraction of the beams with extremely high intensities or storing of the antiprotons (or ions) e.g. for on–beam experiments, see Ref. [1]. The Beam Position Monitors (BPMs) presented in this contribution will be a part of the beam instrumentation of the superconducting heavy ion synchrotron SIS100. The SIS100 has circumference of 1084 m and is one of the two main synchrotrons in the FAIR accelerator complex. It consists superconducting, fast ramped (4 T/s) magnets with a maximal magnetic flux of 2.1 T. The SIS100 parameters are calculated for two design beams: \(4 \times 10^{13}\) protons at energy of 29 GeV and \(5 \times 10^{11}\) U\(^{28}\) ions with an energy of 1.5 GeV/u. The features of SIS100 require a special design of BPMs that considers, for instance, operation of the device at liquid helium temperature.

![Figure 1: FAIR facility. The present GSI facility, depicted with blue colour, will be used as an injector for the future accelerators and beam lines marked with red colour and being presently under design.](image)

1.1 Positioning of BPMs in the SIS100 lattice

All 84 BPMs will be installed in the cryostats of the quadrupole doublets [1, 2]. In the arcs the BPMs will be located directly behind the horizontally focusing (second in doublet) quadrupole, see Fig. 2 (top). In this position the horizontal \(\beta\)-function reaches its maximum. On the contrary, in the straight sections the
BPMs will be installed in the middle of the quadrupole doublet at the maximum of the vertical $\beta$-function, Fig. 2 (bottom). For almost all operation modes the average phase advance of the betatron oscillations between subsequent BPMs will be smaller than 90°. As it is stated in Ref. [3], this is sufficient for the unambiguous closed orbit correction feedback system.

Figure 2: Positioning of the BPMs in the SIS100 lattice.

2 Parameters of SIS100 BPMs

For the foreseen bunch frequencies of $0.5 \, \text{MHz} < f_b < 2.7 \, \text{MHz}$ and aspired bunch lengths the designed BPM should show a good response in the frequency range from $\sim 0.1 \, \text{MHz}$ to 100 MHz. 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.

All BPM components have to be suitable for vacuum pressure better than $10^{-11}$ mbar. Two design types were taken into account: i) design based on metal electrodes and ii) design based on metal coated Al$_2$O$_3$ ceramics. A construction with 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. In order to reach the desired position accuracy of 100 $\mu$m [4], the mechanical stability has to be about 50 $\mu$m. It seems that this can be achieved only with a BPM design based on a metal coated Al$_2$O$_3$ ceramics (type ii)).
A smooth passage of the beam pipe aperture 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 is identical to the aperture of the proceeding quadrupole chamber.

The preliminary design of the SIS100 BPM is shown in Fig. 3. The elliptic ceramic pipe is coated on the inner side with 30 $\mu$m of PtAg metal layer. In this metal coating the electrode shapes are formed by cutting out grooves. Available total detector length of 400 mm (flange–to–flange) allows to equip of all BPMs with electrodes for both, horizontal and vertical beam position measurement.

2.1 Dynamic of the signal amplitude

For the minimal current of the beam that is expected in the SIS100 in low intensity operation mode $10^8$ charges per cycle will be spread over 100 ns long bunches. Assuming a beam of bunches with parabolic density distribution circulating in the synchrotron ring with the velocity of light and investigated BPM geometry with 125 mm long signal plates with plate–to–ground capacity of 45 pF, the expected peak voltage will be as low as 1.1 mV [5]. This is barely sufficient to obtain a detectable difference signal, even with high impedance preamplifiers directly mounted on the signal feed-through. At the other extremum (i.e. for the intense proton beam) $4 \times 10^{13}$ charges will be compressed into a single 25 ns long bunch [1]. For such beams, the maximal expected amplitude reaches 1.8 kV. In this case the preamplifier protection becomes necessary. The huge dynamic range of over 120 dB requires not only a special electronics [6], 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.

3 FEM simulations

As a tool for simulations CST Suite 2006 was used [7]. This software uses the Finite Element Method (FEM). All BPM components, i.e. ceramic tube, chassis, feed–throughs etc. were defined using materials with realistic permittivity and
conductance. All simulations were performed using the Time Domain Solver in the bandwidth of 200 MHz. The usage of the Time Domain Solver was predicted by:

- the simulation duration which — in the contrast to the Frequency Domain Solver — does not depend on number of frequency steps [7].
- the discrete S-parameter port can be defined for the Time Domain Solver only. This is necessary when BPM outputs are defined with an impedance of 1 MΩ.

The hexahedral mesh grid was used being the only possibility when using the Time Domain Solver. For the simulated BPM models the number of single mesh cells ranges from $1 \times 10^6$ to $3 \times 10^6$, depending strongly on the model complexity. The number of mesh cells is blown up mainly by components that are oriented diagonally in respect to the main axis, (like e.g. the separating ring in the diagonal cut). 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 0–200 MHz. The electrode outputs were defined as discrete S-parameter ports with characteristic impedance of 50 Ω for the resonance and cross-talk investigation, and 1 MΩ for the sensitivity determination, respectively.

3.1 Investigation of "low frequency" resonances and reduction of the plate–to–plate cross talk

Elliptic BPM geometry is already too complicated for the clear three dimensional representation of the electric fields. Therefore, the next two topics will be discussed basing on the investigations of the SIS18 BPMs (see Fig. 4 left) and BPMs build for the HIT facility discussed more precisely in Ref. [8].

In the simulations the electrode outputs were defined as discrete S-parameter ports with the characteristic port impedances of 50 Ω. This is equivalent to measurements using two–port Network Analyser. For the capacitive BPM the S11-parameter (reflection) should be consistent with 0 dB over the whole interesting frequency range. Any sharp minimum in S11 spectrum indicates resonant behavior of the BPM for this given frequency. This resonance makes the BPM insensitive for this given frequency. The frequency spectrum of S21–parameter (transmission) is a matter of coupling (plate–to–plate cross–talk) between the electrodes in the tested pair.

3.1.1 "Low frequency" resonances

All structures have characteristic eigen–resonances with the base frequency mainly given by longest geometrical size of the structure. The low frequency resonances are those resonances that appear in the interesting bandwidth — in this case — up to 200 MHz. In the BPM shown in Fig. 4 (left) the RF signal is connected with one of the horizontal plates. As it can be seen on the three dimensional plot of the electric fields in Fig. 4 (right), the signal amplitude on this plate, is one order of magnitude smaller than the amplitude of the resonance which is excited on the opposite BPM side — on the vertical plates. This poor separation between the vertical and horizontal part of BPM is caused by insufficient connection of the middle guard ring with the BPM chassis. It is
made out of 1 mm thick copper wire. Such type of connection does not provide a good ground definition for the higher frequency components of the signal.

Figure 4: SIS18 BPM (1989) (left) and resonant behaviour observed at 295 MHz (right).

The massive middle guard ring connected directly to the BPM chassis, used in the advanced BPM design for the HIT facility (shown in Fig. 5), allows for separation between orthogonal BPM electrodes better than $-40 \text{ dB}$ [8]. This divides the BPM into two separate pieces and in consequence shift the first possible resonance far beyond 400 MHz.

Figure 5: Advanced BPM design for the HIT facility.

3.1.2 Reduction of the plate–to–plate cross–talk

The next problem in the BPMs based on the ceramics is the poor electrical separation between the adjacent signal plates, see Fig.6 (left). This strong plate–to–plate cross–talk is caused by the large ceramic permittivity $\epsilon_r=9.6$ which induces a big coupling capacitance. The larger the coupling the smaller is the difference of the output signals for a given beam displacement. This deteriorates the BPM position sensitivity. In the simulations the cross–talk has been investigated for i) horizontal plates (left-right), ii) vertical plates (top-bottom) and mixed combinations like top-left etc. The separation between the two adjacent horizontal plates for the BPM shown in Fig. 4 (left) is $-8 \text{ dB}$ at the maximum (i.e. at $\sim 20 \text{ MHz}$), and is depicted in Fig. 6 (right) with a dashed line. An insertion of the separating ring in the diagonal cut between the adjacent plates (Fig. 5) increases the plates separation to $-21 \text{ dB}$ indicated by the solid line in Fig. 6 (right).
3.2 Optimization of the position sensitivity

The position sensitivity is the response of the BPM (expressed as the difference of the electrode signals $\Delta U$ normalized to their sum $\Sigma U$) to changes in the beam position and is given by:

$$\Delta x = K \frac{\Delta U}{\Sigma U} + \delta x$$  \hspace{1cm} (1)

The parameter $K$ is usually called pick-up constant. The pick-up offset $\delta x$ 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 semi-coaxial TEM wave guide. The ion beam was approximated by a cylinder of a Perfect Electric Conductor (PEC) with a 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. All four electrode outputs were defined as
S-parameter ports with a characteristic impedance of 1 MΩ. All simulations
were performed using the time domain solver in the bandwidth of 200 MHz.
The simulated beam position was swept in the horizontal plane in the range
±50 mm in 10 mm steps.

The position sensitivity of the BPMs was calculated from the S-parameters
expressed in the frequency domain:

\[
\frac{S_{\text{right-in}} - S_{\text{left-in}}}{S_{\text{right-in}} + S_{\text{left-in}}} = \frac{V_{\text{right}}}{V_{\text{in}}} - \frac{V_{\text{left}}}{V_{\text{in}}} = \frac{\Delta U_{\text{hor}}}{\Sigma U_{\text{hor}}},
\]

where the S-parameters are given by the output/input voltage ratio [9]. For each
beam position the full set of the S-parameters was analyzed for both horizontal
and vertical planes.

Figure 8: Models of the SIS100 BPMs used in the simulations, see description
in text.

In the simulation the two models for SIS100 BPMs shown in Fig. 8 were
compared. Both models are based on the ceramic pipe solution but they differ in
the separating ground rings positioned in the diagonal cut between the adjacent
plates (see Fig. 8 right). Only in the second model an additional massive guard
ring is installed at the end of the signal plates. The geometrical design of the
investigated BPM was optimizes regarding the following criteria:

• Linearity — high linearity is typical for the diagonal–cut type BPMs, how-
ever, it can be strongly spoiled by unhomogenities of the magnetic and/or
electric field caused by e.g. too large distance between subsequent elec-
trodes or by structure discontinuities. For the BPM under investi-
gation the maximum deviations from the straight line fit shown in Fig. 9 are
smaller than ±2% for the BPM without ring, and below ±0.5% for the
BPM with ring, over the whole ±50 mm displacement range.

• The position sensitivity, as given by the slope of the curve in Fig. 9 (left),
is much higher for the BPM with separating ring as compared to the BPM
without ring \(^1\). This is achieved by insertion of the separating ring that
reduces the plate—to—plate cross–talk from -9.5 dB to -21 dB, see Fig. 9
(right).

\(^1\)For the same beam displacement one observe much higher \(\frac{\Delta U}{U}\)
• 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. 9 left) to almost zero (curve with the green triangles) by an additional massive guard ring installed at the end of the BPM electrodes (see Fig. 10). It indicates that the geometry of the whole environment (including also the neighbouring guard rings) has to be completely symmetrical for both electrodes belonging of the same electrode pair.

• 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 move the fringe fields distortions possibly far away from the electrodes. As it can be seen in Fig. 9 (left, blue squares and red triangles) the horizontal displacement of the beam has no influence on the signal measured in the vertical plates.

Figure 9: Left: position sensitivity for the BPM without and with separating ring; Right: Separation between two adjacent signal plates (here horizontal) obtained in the simulations of models with (solid line) and without (dashed line) separating ring.

Figure 10: The massive guard ring installed in SIS100 BPM at the end of the ceramic pipe, see description in text.

3.3 Frequency dependence of position sensitivity

The position sensitivity is often frequency dependent, see e.g. Ref. [8]. This is especially important in the case of bunches that are strongly deformed and/or for the bunches that have inconstant longitudinal structure. For those bunches the frequency spectrum varies in time, which effects the beam position estimation. Therefore, the frequency response of the position sensitivity should be
always investigated for the interesting frequency range. The analysis results are presented in Fig. 11 showing only a moderate frequency dependence even at higher frequencies.

![Diagram](image1)

**Figure 11:** Position sensitivity as a function of frequency for the BPM without (left) and with (right) separating ring.

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, position sensitivity and offset. These dependencies are shown in Fig. 12.

![Diagram](image2)

**Figure 12:** Frequency dependence of “pickup constant” $K$ (top) and offset of the BPM electric centre (bottom) for the horizontal beam displacement.

Position sensitivity and offset for both investigated geometries are almost frequency independent in the relevant frequency range. However, the position sensitivity of the BPM with guard ring is a factor of two larger compared to the BPM without ring. The small reduction of the sensitivity at higher frequencies is caused by inductive cross-talk between signal plates and guard rings that is more pronounced at higher frequencies.

$^2$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 ($\Delta x$).
4 Summary and outlook

Simulations performed using CST Suite 2006 are able to reproduce effect observed in the investigated BPMs. It is shown 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 always be considered in the BPM design as long as a ceramic solution is used. In the future signal/field simulations further geometries, like those described in Ref. [10] will be tested and adopted for the elliptic electrode shape.

5 Mechanical problems – open questions

The operation of SIS100 in cryogenic environment and the demands for good mechanical stability require answers on the following questions:

1 Is the metal coated ceramic suitable for low temperatures (see Fig. 13, detail 1)?

2 How should the ceramic pipe be connected with the BPM chassis (see Fig. 13, detail 2)?

3 How to solve the problems concerning connection and positioning of guard rings in the BPM chassis (see Fig. 13, detail 3)? — This connection should guarantee good electrical contact between the guard rings and the BPM body but, on the other hand, should allow contraction compensation of the ceramic pipe.

4 Which solution for the signal feed through could give a stable enough electrical connection with the coating material of the ceramic pipe, that at the same time, is able to compensate relative displacements of the connected elements (see Fig. 13, detail 4)?

Figure 13: Most challenging detail in the SIS100 design, see description in text.

The first tests of the mechanical features of ceramics at low temperatures and studies based on experiences collected in other institutes allows to prepare preliminary answers on the questions listed above:
ad.1 Two samples of the ceramic–based BPMs shown in Fig. 14 were tested using liquid nitrogen — each sample in 20 thermal cycles. In the last ten cycles the samples were rapidly put into liquid nitrogen to check effects of the thermal shock. The surfaces of the samples were checked for cracks or any other form disintegrations using scanning–electron microscopy. The test samples were:

- CLIC-III BPM: diameter of 50 mm, 2mm wall thickness, coating $5 - 10 \mu m Mo MN, 5 \mu m Ni$ and $\sim 1 \mu m Au$

- GSI-Unilac ring pickup: diameter of 58 mm, 4mm wall thickness, coating metal: $10 - 50 \mu m Mo MN, 1 - 3 \mu m Ni$

In all tests no changes were found neither in the ceramics nor in the metal coating. That indicates that the ceramics can be used under the cryogenic conditions.

Figure 14: Samples use in the cryogenic tests (left) and an example of the surface picture taken using electron microscope (right).

ad.2 The ceramic–metal interconnection was already tested under cryogenic conditions for many element types in hundreds of locations in superconducting Nuclotron synchrotron in Dubna, see Fig. 15. This interconnections remain tight and not destroyed even after several tens of thermal cycles. To solve particularly the problem marked in Fig. 13 with number (2) one can use analogical solution as for the ceramic beam pipe insertion marked in Fig. 15 with arrow. However, first the mechanical stability of this connection have to be tested.

Figure 15: Left: Different examples of the metal–ceramics interconnections used in Nuclotron in Dubna. Middle and right: Ceramic insertion used as an isolator in the superconduction coils in Nuclotron quadrupole.
ad.3 For the good positioning and proper RF connection of the guard rings to the BPM chassis one can use a multi-contact band positioned in the groove formed on the outer side of the guard ring, see Fig. 16. This solution, used already e.g. for CLIC-III BPMs [11], provide good connection for the whole frequency range and leaves enough room for contraction compensation.

![Figure 16: Possible solution for the guard ring positioning in BPM chassis: multi-contact band inserted in the groove formed in the outer part of the guard ring.](image)

ad.4 The question concerning the signal feed–through remains open. There is a number of different possibilities like mini bellows used at DESY [12] or a special membrane connection used at RHIC BPMs, but it is not tested yet if those solutions can be applied in SIS100 BPMs.

5.1 Next steps

Further mechanical tests are foreseen for all crucial BPM components. The samples of feed–through ceramics–metal interconnections etc. will be prepared. All samples will be tested in liquid helium in several tens of thermal cycles. A possible degradation of the sample structure will be investigated in between subsequent thermal cycles. The tests will be performed at GSI in a helium cryostat especially build for this purpose.

References

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


