# ANALYSIS OF ASYMMETRY TOLERANCES AND CROSS-COUPLING IN CAVITY BPMS

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*Abstract*

Geometric asymmetries in cavity beam position monitors (CBPM) result in a coupling between the horizontal and vertical signals, which complicates their usage and may affect both the dynamic range and spatial resolution of the system in both directions. Tolerances to several types of geometric asymmetries have been analysed using a 3D electromagnetic field solver (GdfidL). We report on some of the results and discuss the possible impact of the considered geometrical distortions.

## INTRODUCTION

Cavity beam position monitor (CBPM) [1] is a non-destructive electromagnetic pick-up with high position resolution that can reach nanometre level even at sub-nC bunch charge and complements electrostatic button and stripline BPMs in precision beamlines (final focus collider systems, free electron laser undulators). Upon a beam transit, a small part of the energy stored in a bunch of particles is transformed into oscillations of resonant cavity modes, some of which are sensitive to the beam offset. Usually the lowest dipole mode of the cavity with the highest position sensitivity is used for measurements. The power stored in the mode is then coupled out and processed to extract the amplitude and phase and convert them into the position measurement after the charge normalisation.

The best coupling scheme known to date is by slots in the cavity walls aligned to the transverse axes opening into waveguide couplers, Fig. 1. It provides efficient monopole mode suppression by selective coupling, and also separation of the dipole mode polarisations: the horizontal offset is picked up by the vertical couplers, and vice versa. Natural separation is high, several orders of magnitude for narrow slots. However, it is sensitive to the alignment of the coupling slots, and distortions cause some cross-coupling. Below, we present the results of a numerical study of the effect of geometrical misalignments in CBPMs on the cross-coupling and estimate their impact on the corresponding geometrical tolerances.

## ASYMMETRIES UNDER STUDY

A C-band (6.5 GHz) CBPM design was studied using a 3D electromagnetic field solver GdfidL [2], Fig. 1 shows one quarter of the meshed model, so the coupling slots and waveguides are cut in halves. For the purpose of this study, the waveguides end straight into numerical ports as do the ends of the beampipe for the injection of the simulated bunch.

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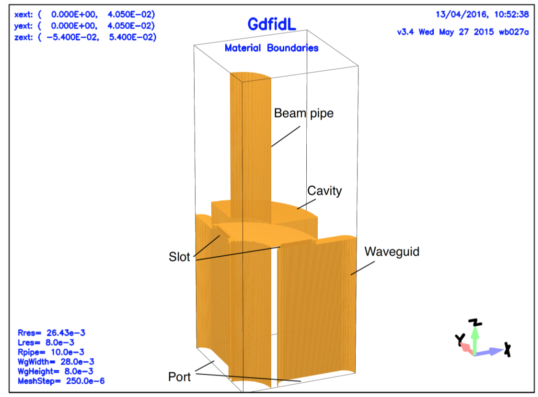


Figure 1: Quarter of position CBPM created in GdfidL.

Figure 2 shows the six types of asymmetries under the study: rotations and offsets of the slots, and cavity and beam pipe ellipticity. The introduced distortions had to be larger than what is expected in real life due to the small but finite mesh size. A bunch of particles was simulated as a line charge with an arbitrary (but a multiple of the mesh size) transverse offset and a Gaussian distribution longitudinally. A finite difference time domain simulation was run with the charge transiting the cavity, and the outputs of the fundamental waveguide mode recorded for the coupler ports.

## SIGNAL ANALYSIS

The signal generated by each cavity mode can be described by a decaying waveform:

$$V(t) = V_0 \cdot e^{-\frac{t}{\tau}} \sin(\omega_0 t), \tag{1}$$

where $V_0$ is the peak voltage, $\omega_0$ angular frequency and $\tau$ decay constant of the mode determined by its coupling, geometry and loading. The output signal in a port is comprised of the sum of all excited modes that couple to the waveguides through the slots, Fig. 3 shows an example output.

In our initial analysis we did not use filtering, so the amplitude was analysed in a window following the decay of some short-lived modes. The signal for each combination of beam offsets in $X$ and $Y$ is then averaged over the window's duration:

$$a_{(X,Y)} = \frac{1}{N}\sum_{n1}^{n2} |V_n|, \tag{2}$$

where $V_n$ is the $n$-th simulated sample within the window. The Fourier transform of the port signals (Fig. 4) taken over the same sample window still shows the presence of other modes, albeit at much lower levels.




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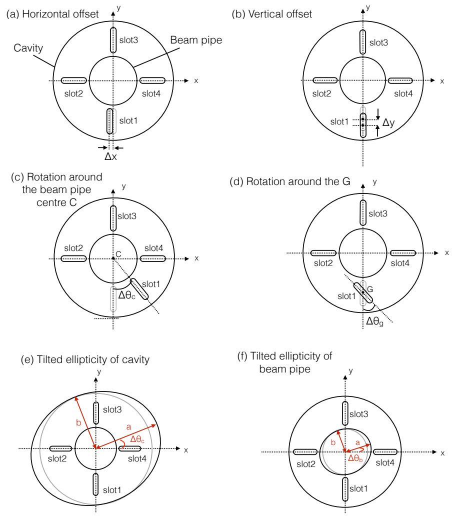


Figure 2: Simulated misalignments: (a) Slot1 offset in $x$ by $\Delta x$. (b) Slot1 offset in $y$ by $\Delta y$. (c) Slot1 rotated around the cavity axis by $\Delta\Theta_c$. (d) Slot1 rotated around its axis by $\Delta\Theta_g$. (e) Elliptical cavity rotated by $\Delta\Theta_c$. (f) Elliptical beam pipe rotated by $\Delta\Theta_b$.

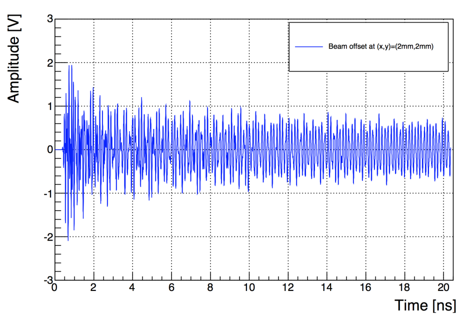


Figure 3: The port signal simulated by GdfidL for the original geometry.

Differences are taken between all average amplitudes in asymmetric simulations $a^{asym}_{(X,Y)}$ and those for the same beam offsets in unperturbed case $a^{orig}_{(X,Y)}$, which are then normalised by $a^{orig}_{(1,1)}$:

$$A^{diff}_{(X,Y)} = \frac{a^{asym}_{(X,Y)} - a^{orig}_{(X,Y)}}{a^{orig}_{(1,1)}}. \tag{3}$$

Figure 5 shows the normalised amplitude $A_{(X,Y)}$ of the signal in Port1 of the original geometry. The normalised difference amplitude ($A^{diff}_{(X,Y)}$) for the case of the horizontal offset is shown in Fig. 6. As expected, cross-coupling is then observed.

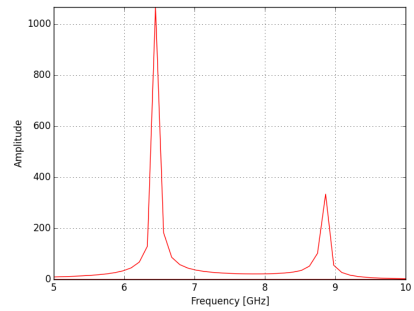


Figure 4: FFT of the port signal. The second peak corresponds to a quadrupole mode.

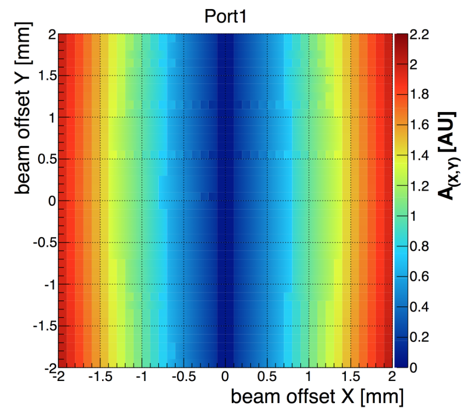


Figure 5: Normalised amplitude in the original geometry.

## CROSS-COUPLING

For the purpose of the analysis of the cross-coupling, we are interested in a single quantity describing the leakage between the $x$ and $y$ signals caused by the introduced misalignment of the geometry. We ran simulations twice: for two values for each misalignment, in order to test the hypothesis of the linear dependency of the leaked amount of signal on the misalignment. The normalised amplitudes of the port signal for the case of a horizontal offset slot are shown again in Fig. 7 (Top) as a series of $x$-scans with the $y$-offset as

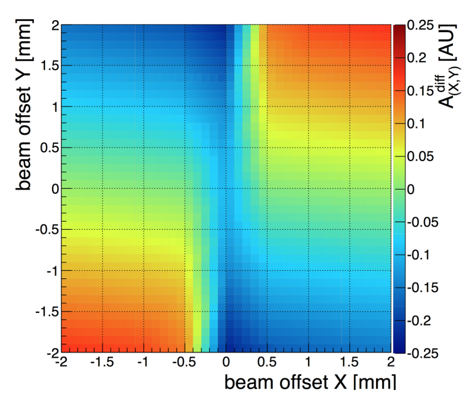


Figure 6: Normalised difference amplitude in case of the horizontal offset of the slot.

a parameter. The V-curve response is clearly shifted from 0 depending on the $y$-position of the beam. The offset is shown in Fig. 7 (Bottom) for two simulated offsets. The cross-coupling is found as the first coefficient of a linear fit, and linearly grows with the amount of perturbation.

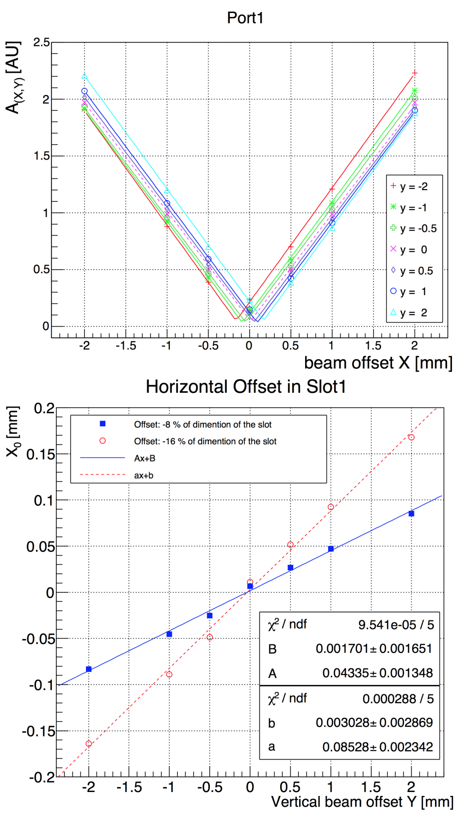


Figure 7: Top: horizontal beam position sensitivities with fixed vertical beam offsets in the Port1. A fitting function $a|x - b| + c$ is applied. Bottom: Cross-couplings in horizontal misalignment in Slot 1. Horizontal offsets in Slot1 are chosen by -8 % and -16 % of dimension of the slot.

Notably, the effect of the vertical offset of Slot 1 in our geometry has a much lesser effect on the cross coupling (in the other pair of slots) than any other perturbations of the slot itself. The total coupling is then a quadrature sum of all measured couplings :

$$C = \sqrt{C^2_{OffX} + C^2_{RotC} + C^2_{RotG} + C^2_{RTC} + C^2_{RTB}}. \quad (4)$$

Finally, a reasonable mechanical tolerance for each misalignment is worked out from the desired total cross-coupling threshold, -40 dB in our case, Table 1.

Table 1: Coupling sensitivities (Sens.) to Misalignments, Tolerances (Tol.) and Couplings (Coup.). Asymmetry cases from (a) to (f) are indicated in Fig. 2.

| Case | Sens. | Tol. | Coup. |
|---|---|---|---|
| (a) | $5.12 \cdot 10^{-1}$ /% | 0.01 % | $3.41 \cdot 10^{-3}$ |
| (c) | $1.68 \cdot 10^{-2}$ /deg | 0.17 deg | $2.88 \cdot 10^{-3}$ |
| (d) | $3.75 \cdot 10^{-2}$ /deg | 0.17 deg | $6.45 \cdot 10^{-3}$ |
| (e) | $1.37 \cdot 10^{-2}$ /deg | 0.17 deg | $2.35 \cdot 10^{-3}$ |
| (f) | $1.09 \cdot 10^{-2}$ /deg | 0.17 deg | $1.88 \cdot 10^{-3}$ |
| Total | | | $8.40 \cdot 10^{-3}$ (-41.5 dB) |

## CONCLUSION

Horizontal and vertical signal cross-couplings have been estimated for several types of geometric asymmetries in CBPMs using a GdfidL. The asymmetry tolerances caused by a combination of several misalignments in CBPMs have been estimated. In the next steps, the signal analysis will be improved to remove unwanted higher order mode contributions.

## REFERENCES

[1] S.Walston *et. al.*, *Nucl. Instr. Meth. A*, Vol 578, pp. 1–22, 2007.

[2] GdfidL, `http://www.gdfidl.de`




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