NUMERICAL COMPARATIVE STUDY OF BPM DESIGNS FOR THE HESR AT FAIR

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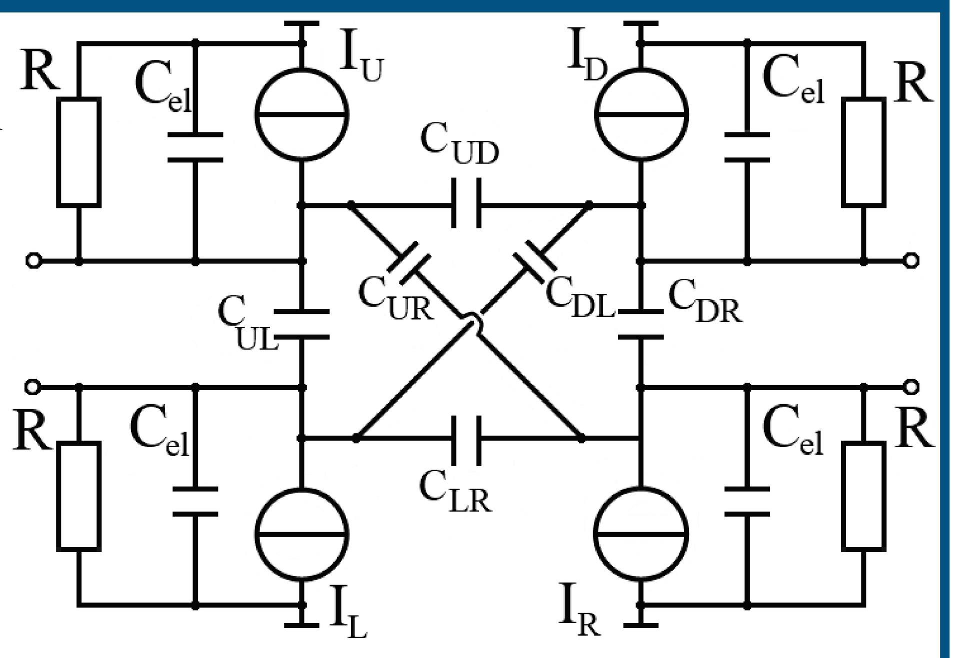
Capacitive Pickups

- Beam induced image currents on capacitive electrodes can be modelled by current sources.

$$I_{img}(t) \propto \frac{d}{dt} I_{beam}(t)$$

- For $f_{Beam} >> f_{cutoff}$:
  - Voltage at resistor ∝ beam shape
- Γ scales the voltage according to beam position
- Analysis tools:
  - COMSOL Multiphyics
  - LTspice



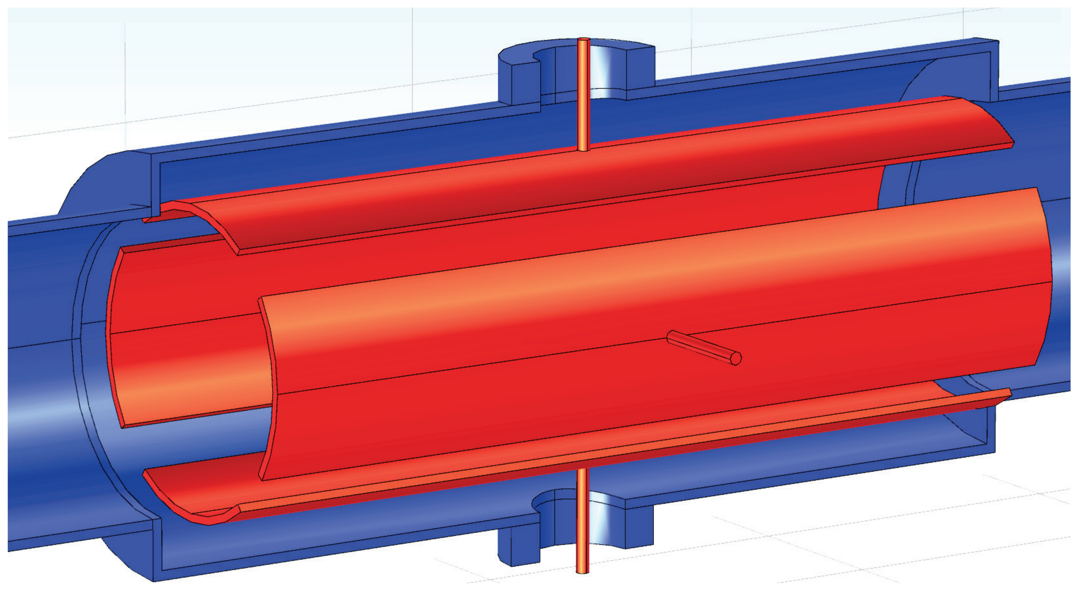
Equivalent Circuit of a capacitive pickup with four electrodes. Each electrode is capacitively coupled to one another and to GND.

$$U_{img}(t) = \frac{l_{BPM}}{\beta c C_{el}} I_{beam}(t)\, \Gamma(r, \theta, bpm)$$

$$\Gamma(\varphi_1, \varphi_2, r, \theta) = \frac{\int_{\varphi_1}^{\varphi_2} \frac{l_{BPM}(\varphi)}{(\vec{r}_{BPM}(\varphi) - \vec{r}_{Beam}(\theta))^2} d\varphi}{\int_0^{2\pi} \frac{l_{BPM}(\varphi)}{(\vec{r}_{BPM}(\varphi) - \vec{r}_{Beam}(\theta))^2} d\varphi}$$

Strip Type BPM

- Symmetric capacitive distribution
  - Unwanted features of diagonal cut BPM are circumvented
- Space restrictions were different
  - higher signal levels, for effectively longer electrodes



Simplified model of the quad strip type BPM. Blue; beam pipe, red; electrodes. Length 270 mm, radius 44.5 mm, angular cover 70° each.

- Higher sensitivity compared to diagonally cut BPM

$$\Gamma(r, \theta) = \frac{\varphi}{2\pi}\left(1 + \frac{4}{\varphi}\sum_{n=1}^{\infty}\frac{1}{n}\left(\frac{r}{b}\right)^n \cos(n\theta)\sin\left(\frac{n\varphi}{2}\right)\right)$$

Equation for influence on right electrode. [3] Electrode dimensions b, φ, beam at r,θ

- Pickup is non-linear, for precise readout outside the of the centre region
  - Lookup table or polynomial response;

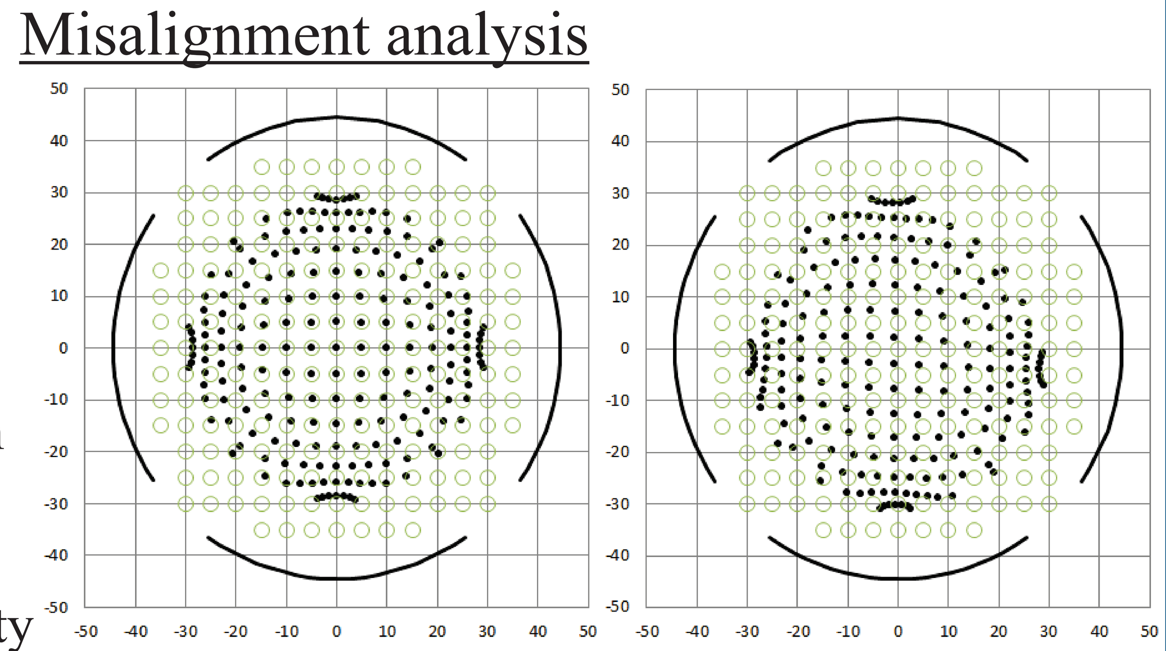
$$X = \sum_{i=0}^{N}\sum_{j=0}^{N} K_{x,ij}\left(\frac{\Delta_x}{\Sigma_x}\right)^i \left(\frac{\Delta_y}{\Sigma_y}\right)^j$$

With the coefficient matrix K and $N = 3$ or greater

- Sensitive to the beam size, due to the non-linearity

Misalignment analysis

- Extensive analysis to proof robust design against misalignments
- Many models with rotation and translation errors
- Result: Any correction scheme for non-linearity correction takes care of misalignments



Projection plots of an ideal and a misaligned BPM. These plots show where the beam would be projected, if the simple linear response is assumed.

References

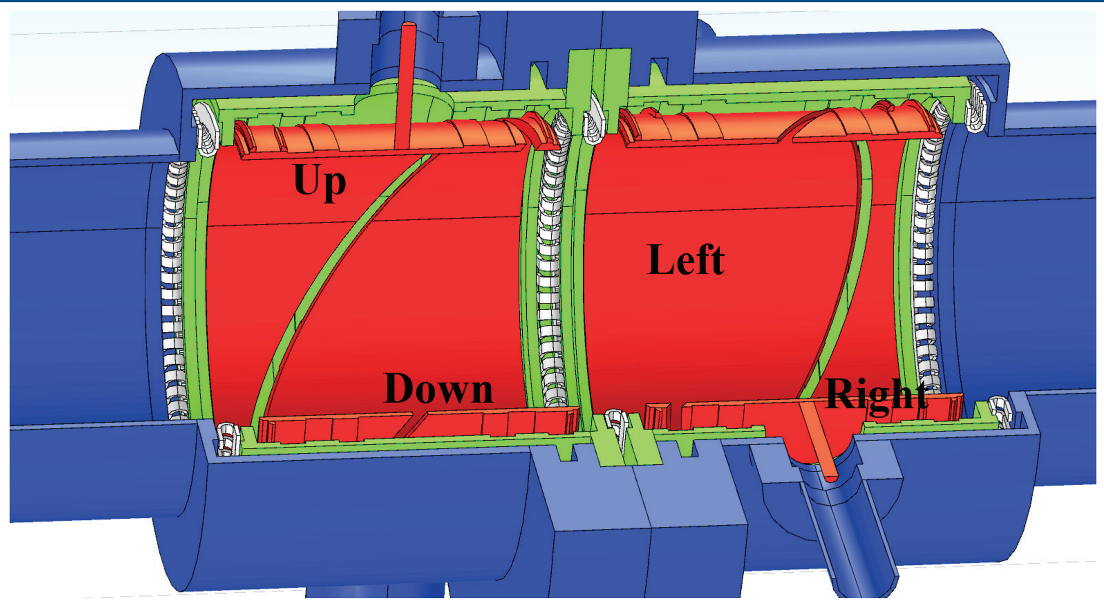
[1] C. Böhme, "Beam Position Monitors for the HESR," Annual Report 2014, FZJ, Germany.

[2] P. Fork, P. Kowina, D. Liakin, "Beam Position Monitors," GSI, Germany.

[3] R. E. Shafer, "Beam Position Monitoring," Los Alamos National Laboratory, Los Alamos

Diagonally Cut BPM

- Chosen design for the HESR [1]
- Beam parameters: $10^8\ \bar{p}$, 3 GeV and 150 m 6σ bunch length
- Analytical and numerical methods yield:
- Voltage of centred beam:
- U_{centre} ~280 µV
- Sensitivity: $S_{x,y}$ = 1.360 %/mm
- Electric centre location: ~0.6 - 0.7 mm in x and y



Simplified Comsol model of the diagonally cut BPM for capacitance determination. Blue; beam pipe, green; grounded housing cylinder, red; electrodes. BPM plane length (e.g. Up + Down) 77mm, radius 44.5 mm.

$$X = \frac{1}{S_x}\frac{U_u - U_d}{U_u + U_d} - X_{off} = \frac{1}{S_x}\frac{\Delta_x}{\Sigma_x} - X_{off}$$

- Asymmetric capacitive distribution causes position dependent offset and tilt of linear response plane.
- Experimental test bench measurements confirm analytical and simulation based results:
  - S_x = 1.318 %/mm, S_y = 1.330 %/mm,
  - Electrical centre offset: x = 0.21 mm, y = 0.94 mm

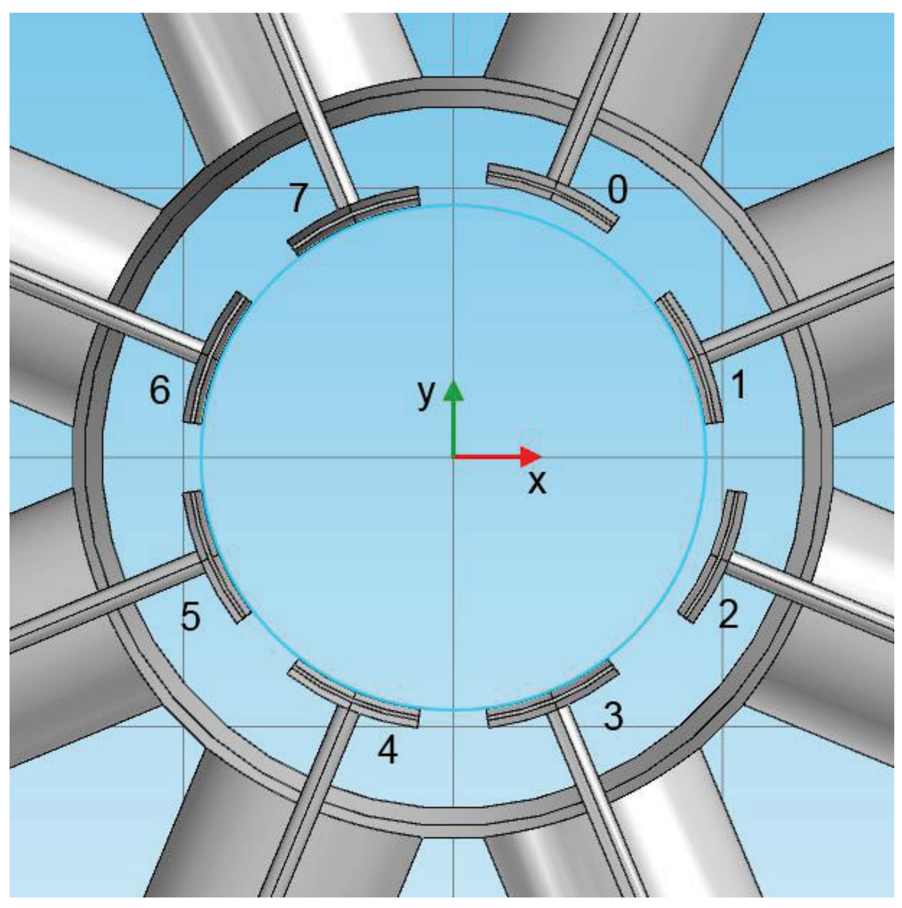
Proposed beam size sensitive pickup

- Coefficient matrices can be obtained for many beam sizes
- Each coefficient can be made a function of beam size:

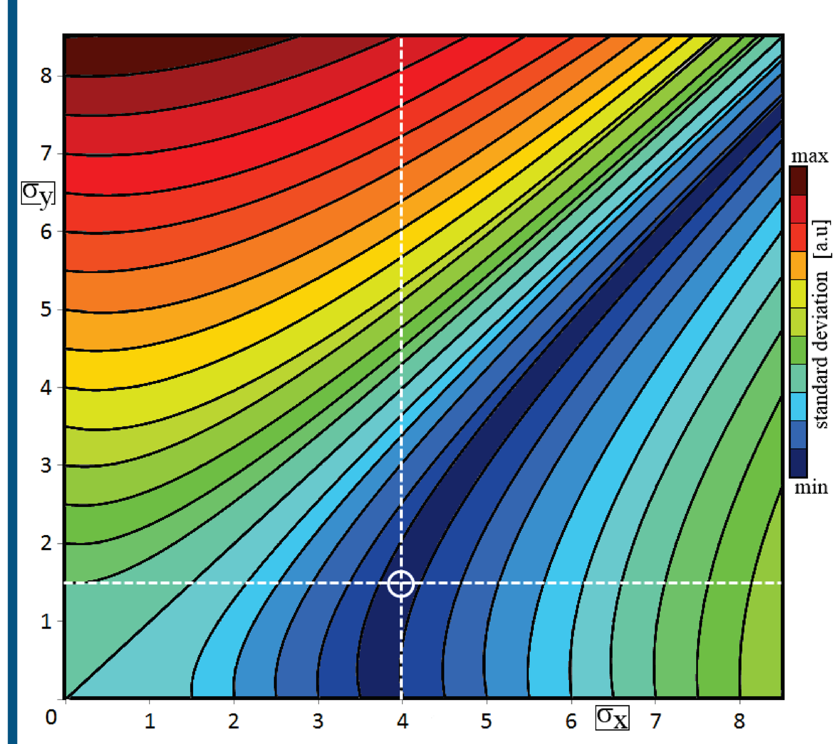
$$X = \sum_{i=0}^{N}\sum_{j=0}^{N}\left(\sum_{l=0}^{M}\sum_{m=0}^{M} G_{x,i,j,l,m}\,\sigma_x{}^l \sigma_y{}^m\right)\left(\frac{\Delta_x}{\Sigma_x}\right)^i\left(\frac{\Delta_y}{\Sigma_y}\right)^j$$

Used N = 8, M = 5

- Choosing $\sigma_x = \sigma_y = 0$, faulty beam positions are obtained, which do not coincide. Instead, they distribute and give a standard deviation. The average value is close to the real beam position
- The actual beam size lies at minimum standard deviation
- Certain elliptical beams are indistinguishable from one another



Conceptual model of a eight strip beam size monitor. Electrode 0 and 2 are shifted straight along the x and y axis. Two electrodes are shifted to obtain multiple electrical centers and thereby different drifts of faulty beam positions.



Colour coded plot of standard deviations of beam positions of various electrode configurations. The isoline plot can be obtained and quantified analytically or by test bench measurements.

$$\sigma_x = \frac{a\sigma_y^2 + b\sigma_y + c^2}{\sigma_y + c}$$

Isoline characterization; a, b as fitting parameters and c is the axis intersect

- If the beta-function is given and two such beam size monitors are installed at locations, where either beam size is bigger, the actual beam size can be calculated (for zero dispersion)
- To eliminate the effects of dispersion, more monitors are needed