Development of Beam Position Monitors for Storage Rings

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Precision experiments

COSY storage ring: polarized proton/deuteron beams

The search for electric dipole moment

Knowing beam positions is mandatory
Working principle

Rogowski based coil

Current signal induces voltage signal

\[ \text{Horizontal ratio} = \frac{\Delta U_{\text{hor}}}{\sum_{i=1}^{4} U_i} = \frac{(U_1 + U_2) - (U_3 + U_4)}{\sum_{i=1}^{4} U_i} \]

\[ \text{Vertical ratio} = \frac{\Delta U_{\text{ver}}}{\sum_{i=1}^{4} U_i} = \frac{(U_1 + U_4) - (U_3 + U_2)}{\sum_{i=1}^{4} U_i} \]
BPM construction

- Winding the coil
- Assembling the parts
- Connections for voltage signal

48 mm

10 cm
BPM lab test

- AC current (emulate COSY beam)
- Move the coil by moving the stepping motors
- Measure the coil response

✔ Repeated tests for fixed beam current
✔ Repeated tests for different beam currents
Measured ratios agree with theory

\[ \frac{\Delta U_{\text{hor}}}{\sum_{i=1}^{4} u_i} = c_1 x - c_2 (x^3 - 3y^2x) + c_3 (x^5 - 10y^2x^3 + 5y^4x) + \ldots \]

\[ \frac{\Delta U_{\text{ver}}}{\sum_{i=1}^{4} u_i} = c_1 y - c_2 (y^3 - 3x^2y) + c_3 (y^5 - 10x^2y^3 + 5x^4y) + \ldots \]

Credit: F. Trinkel
Theoretical-based model for coil in air

Possible higher sensitivities for complete BPM coil

\[ \chi^2 = \left[ \text{Ratio}_{\text{measured}} - \text{Ratio}_{\text{expected}} \right]^T \cdot [\text{Cov}]^{-1} \cdot \left[ \text{Ratio}_{\text{measured}} - \text{Ratio}_{\text{expected}} \right] \]

Calibration parameters:
- \( C_1 = 0.01914 \ mm^{-1} \)
- Enhancement factor of \( \approx 1.75 \) (wrt a simple coil in air)
  - \( C_2 = 1.4724 \times 10^{-6} \ mm^{-3} \)
  - \( C_3 = 4.7615 \times 10^{-11} \ mm^{-5} \)
  - \( X_{\text{off}} = -0.401 \ mm \)
  - \( Y_{\text{off}} = 0.3195 \ mm \)
Position accuracy for a range of 11 mm

Position accuracy

- Black dots: $< 0.01 \text{mm}$
- Red dots: $X_{\text{error}} \leq 0.05, Y_{\text{error}} \leq 0.02$
- Orange dots: $X_{\text{error}} \leq 0.11, Y_{\text{error}} \leq 0.07$
Installation in COSY

Rogowski BPM
Calibration independent of COSY beam current

![Graph showing voltage ratio versus current (A)]
Bump test

\[
y = 1.1x - 3.4
\]

\[
y = 1.2x + 1.17
\]
Summary

- The Rogowski BPM was successfully constructed and calibrated in the lab
- The Rogowski BPM was successfully installed and operated in COSY
- The compactness of the Rogowski BPM is a good advantage for this type of coils as monitors

Outlook

- Use the coil as a probe for multi-bunches beam
- Study/calibrate the coil at different frequencies
- Use as a BCT/field probe
- Build several such coils.
Theoretical prediction of coil parameters

\[ c_1 = \frac{2}{\pi \sqrt{R^2 - a^2}} \]

\[ = 0.01092 \text{mm}^{-1} \]

\[ c_2 = \frac{R \alpha}{3 \pi (R^2 - a^2)^{\frac{5}{2}} (R - \sqrt{R^2 - a^2})} \]

\[ = 1.0817 \times 10^{-6} \text{mm}^{-3} \]

\[ c_3 = \frac{R \alpha (4R^2 + 3a^2)}{20 \pi (R^2 - a^2)^{\frac{9}{2}} (R - \sqrt{R^2 - a^2})} \]

\[ = 1.9511 \times 10^{-10} \text{mm}^{-5} \]
Elements of covariance matrix

\[ f_1 = \frac{u_3 + u_4 - u_1 - u_2}{\sum_{i=1}^{4} u_i} \quad (\text{Ratio}_x) \]

\[ f_2 = \frac{u_1 + u_4 - u_3 - u_2}{\sum_{i=1}^{4} u_i} \quad (\text{Ratio}_y) \]

\[ \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \quad (\text{Covariance matrix}) \]

\[ c_{11} = \left[ \left( \frac{\partial f_1}{\partial u_1} \cdot \sigma_{u_1} \right)^2 + \left( \frac{\partial f_1}{\partial u_2} \cdot \sigma_{u_2} \right)^2 + \left( \frac{\partial f_1}{\partial u_3} \cdot \sigma_{u_3} \right)^2 + \left( \frac{\partial f_1}{\partial u_4} \cdot \sigma_{u_4} \right)^2 \right]^{0.5} \]
\[ = \frac{2}{(\sum_{i=1}^{4} u_i)^2} \left[ (\sigma_{u_1}^2 + \sigma_{u_2}^2) \cdot (u_3 + u_4)^2 + (\sigma_{u_3}^2 + \sigma_{u_4}^2) \cdot (u_1 + u_2)^2 \right]^{0.5} \]

\[ c_{22} = \left[ \left( \frac{\partial f_2}{\partial u_1} \cdot \sigma_{u_1} \right)^2 + \left( \frac{\partial f_2}{\partial u_2} \cdot \sigma_{u_2} \right)^2 + \left( \frac{\partial f_2}{\partial u_3} \cdot \sigma_{u_3} \right)^2 + \left( \frac{\partial f_2}{\partial u_4} \cdot \sigma_{u_4} \right)^2 \right]^{0.5} \]
\[ = \frac{2}{(\sum_{i=1}^{4} u_i)^2} \left[ (\sigma_{u_1}^2 + \sigma_{u_4}^2) \cdot (u_3 + u_2)^2 + (\sigma_{u_3}^2 + \sigma_{u_2}^2) \cdot (u_1 + u_4)^2 \right]^{0.5} \]

\[ c_{12}, c_{21} \text{ from correlation between } f_1 \& f_2 \]
Measured coil impedance at the range $200KHz - 2.0MHz$