Development of Beam Position Monitors for Storage Rings

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Precision experiments

COSY storage ring: polarized proton/deuteron beams

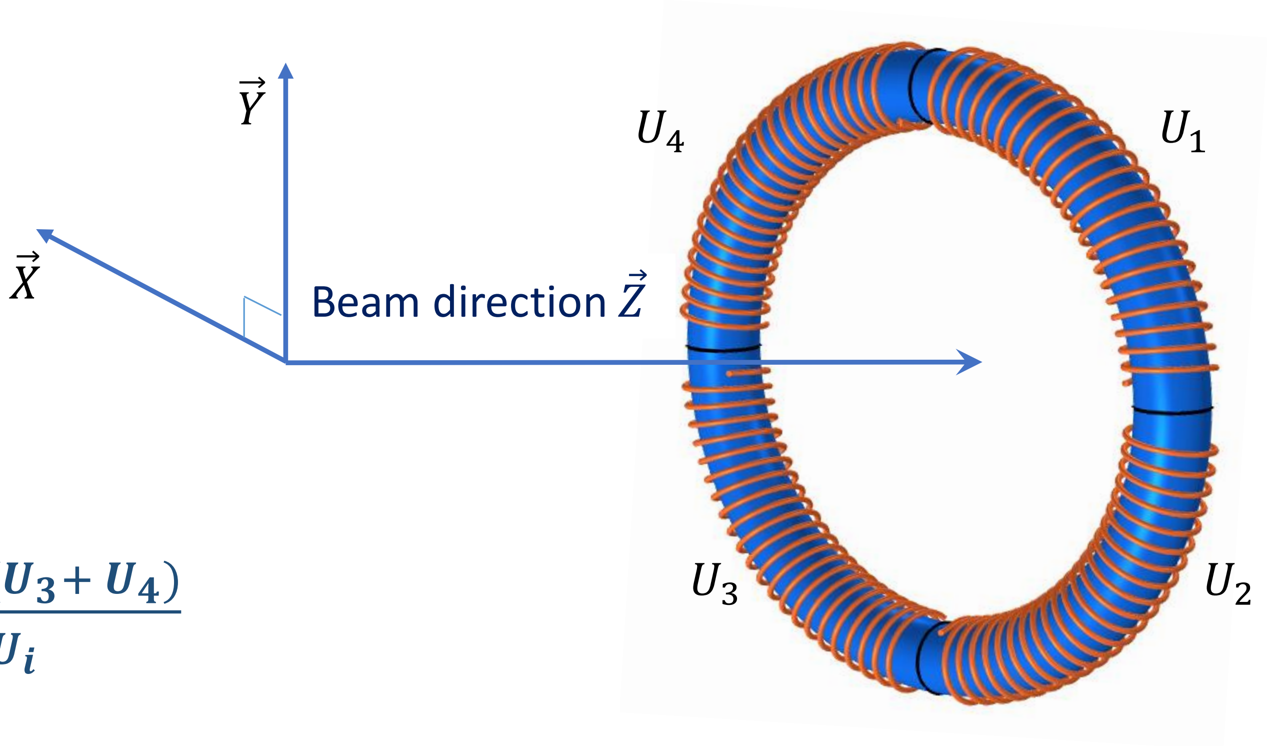
The search for electric dipole moment

Knowing beam positions is mandatory

Working principle

Rogowski based coil

Current signal induces voltage signal

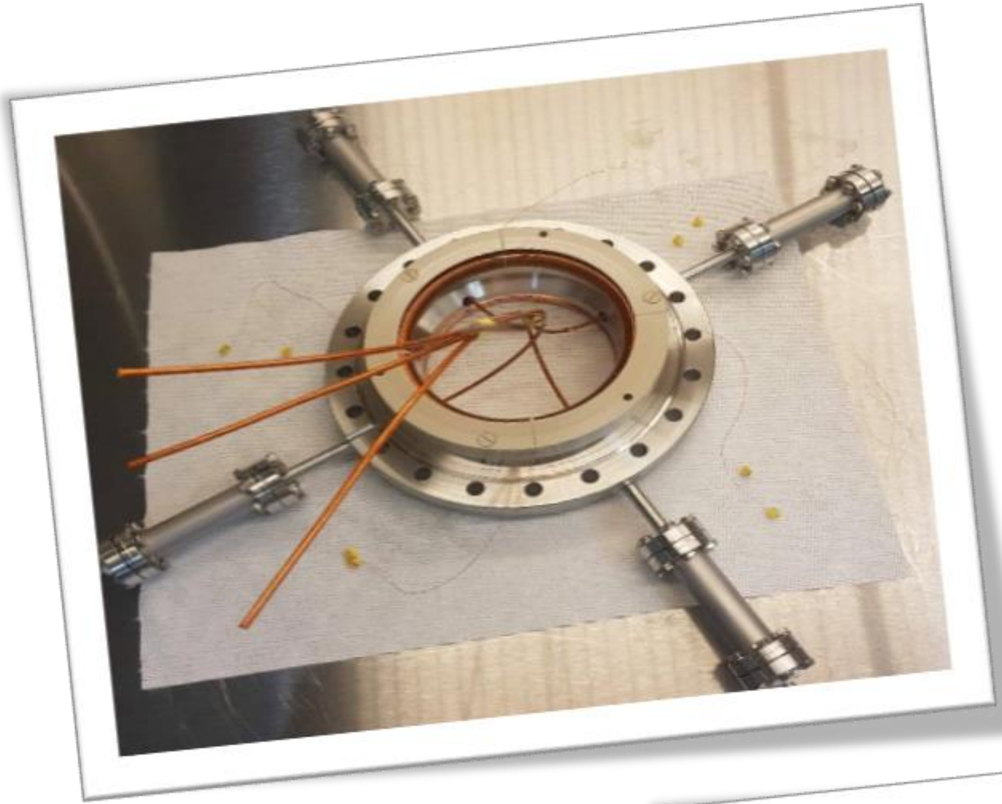


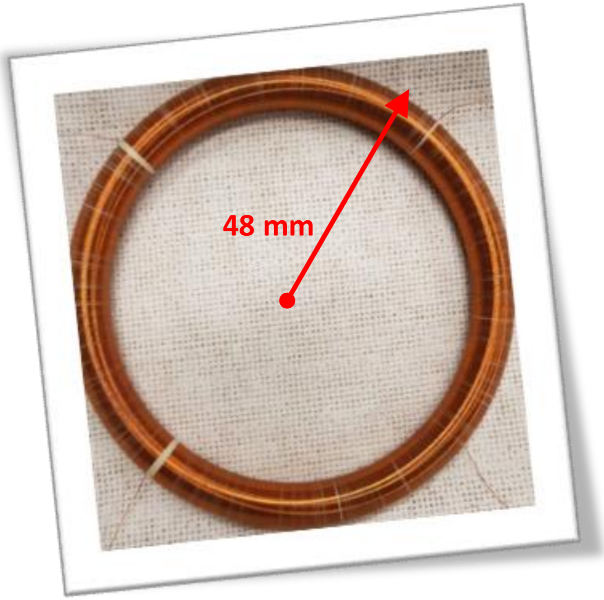
$$Horizontal\ ratio = \frac{\Delta U_{hor}}{\sum_{i=1}^{4} U_i} = \frac{(U_1 + U_2) - (U_3 + U_4)}{\sum_{i=1}^{4} U_i}$$

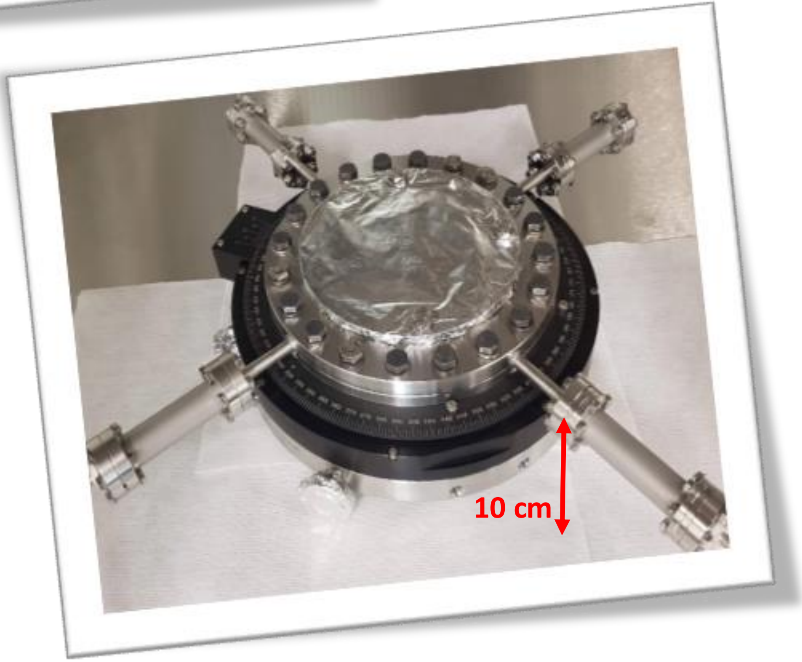
$$Vertical\ ratio = \frac{\Delta U_{ver}}{\sum_{i=1}^{4} U_i} = \frac{(U_1 + U_4) - (U_3 + U_2)}{\sum_{i=1}^{4} U_i}$$

BPM construction

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



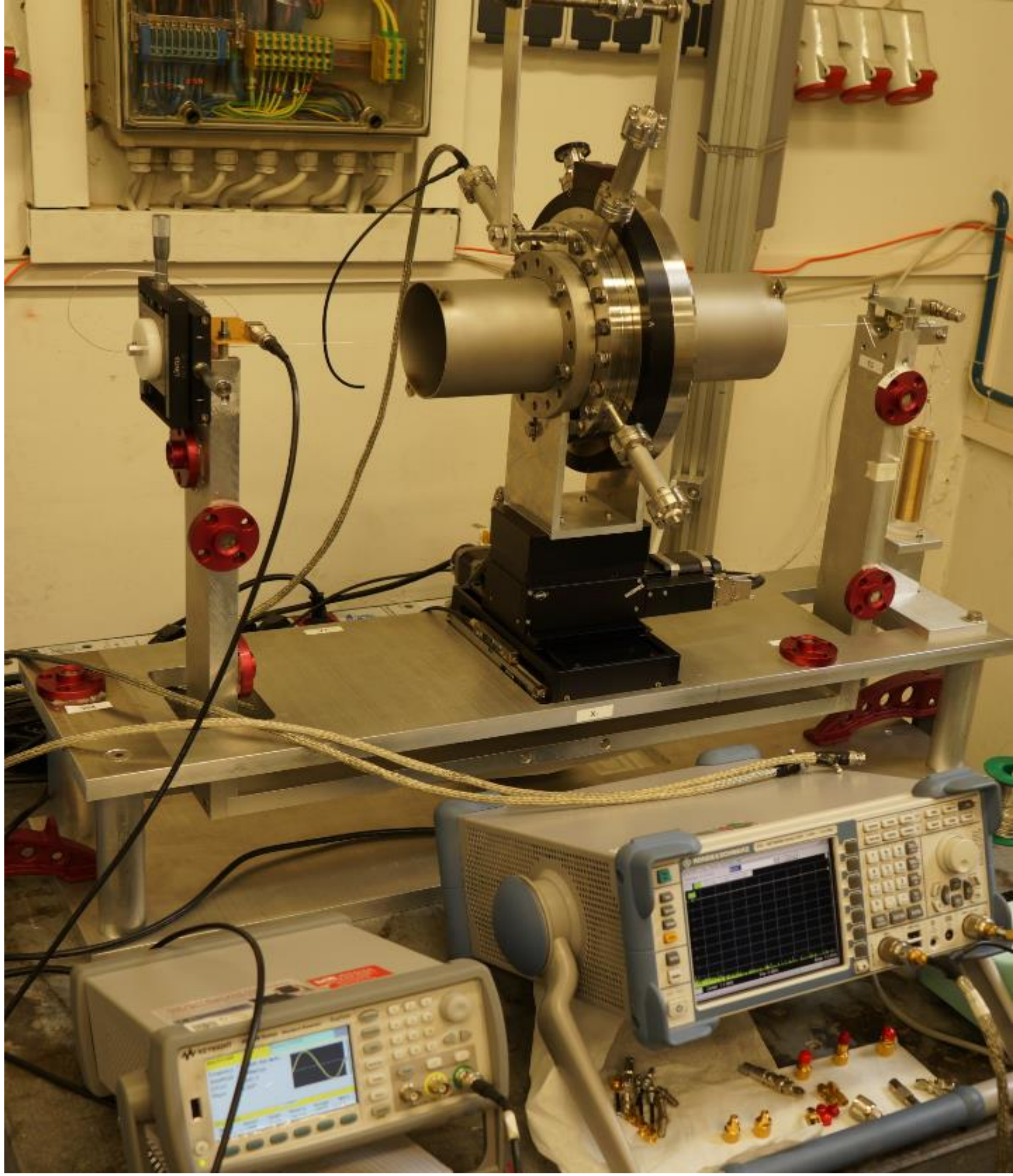




BPM lab test

- ❑ 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



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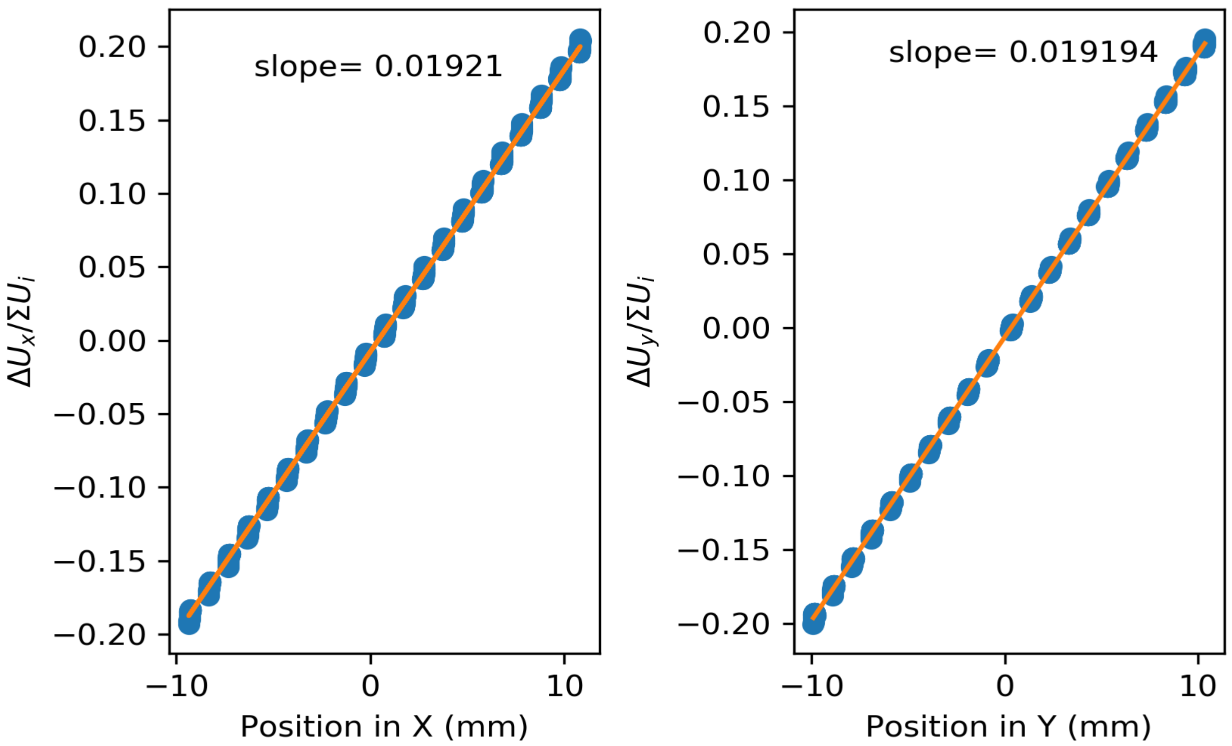
Measured ratios agree with theory



- $\frac{\Delta U_{hor}}{\sum_{i=1}^{4} U_i} = c_1 x - c_2\left(x^3 - 3y^2 x\right) + c_3\left(x^5 - 10y^2 x^3 + 5y^4 x\right) + \ldots$

- $\frac{\Delta U_{ver}}{\sum_{i=1}^{4} U_i} = c_1 y - c_2\left(y^3 - 3x^2 y\right) + c_3\left(y^5 - 10x^2 y^3 + 5x^4 y\right) + \ldots$

Credit: F.Trinkel

Theoretical-based model for coil in air

Possible higher sensitivities for complete BPM coil

$$\chi^2 = \left[Ratio_{measured} - Ratio_{expected}\right]^T * [Cov]^{-1} * \left[Ratio_{measured} - Ratio_{expected}\right]$$

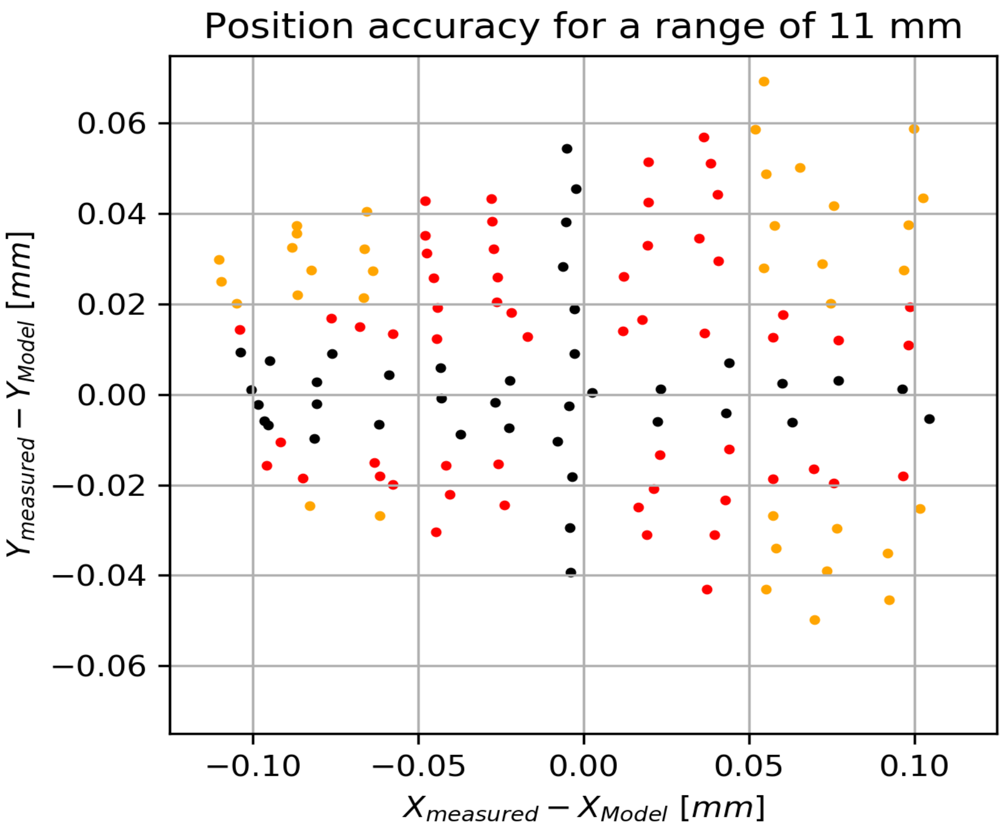
Calibration parameters:

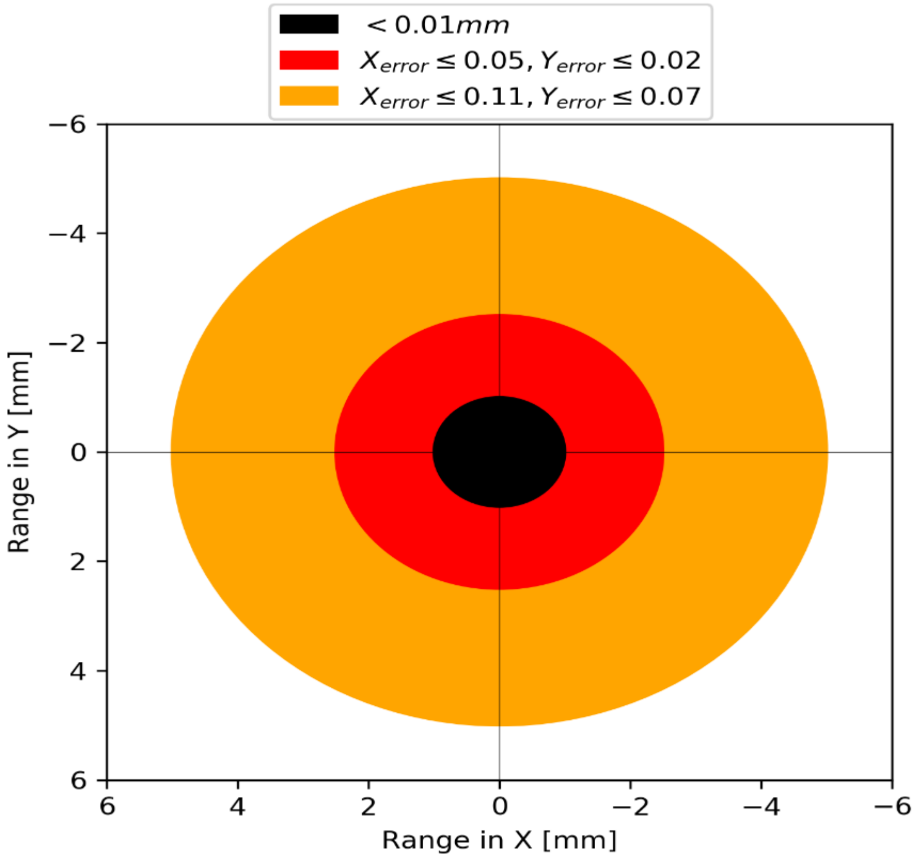
- $C_1 = 0.01914\ mm^{-1}$

Enhancement factor of ≈ 1.75 (wrt a simple coil in air)

- $C_2 = 1.4724 \times 10^{-6}\ mm^{-3}$
- $C_3 = 4.7615 \times 10^{-11}\ mm^{-5}$
- $X_{off} = -0.401\ mm$
- $Y_{off} = 0.3195\ mm$

Position accuracy





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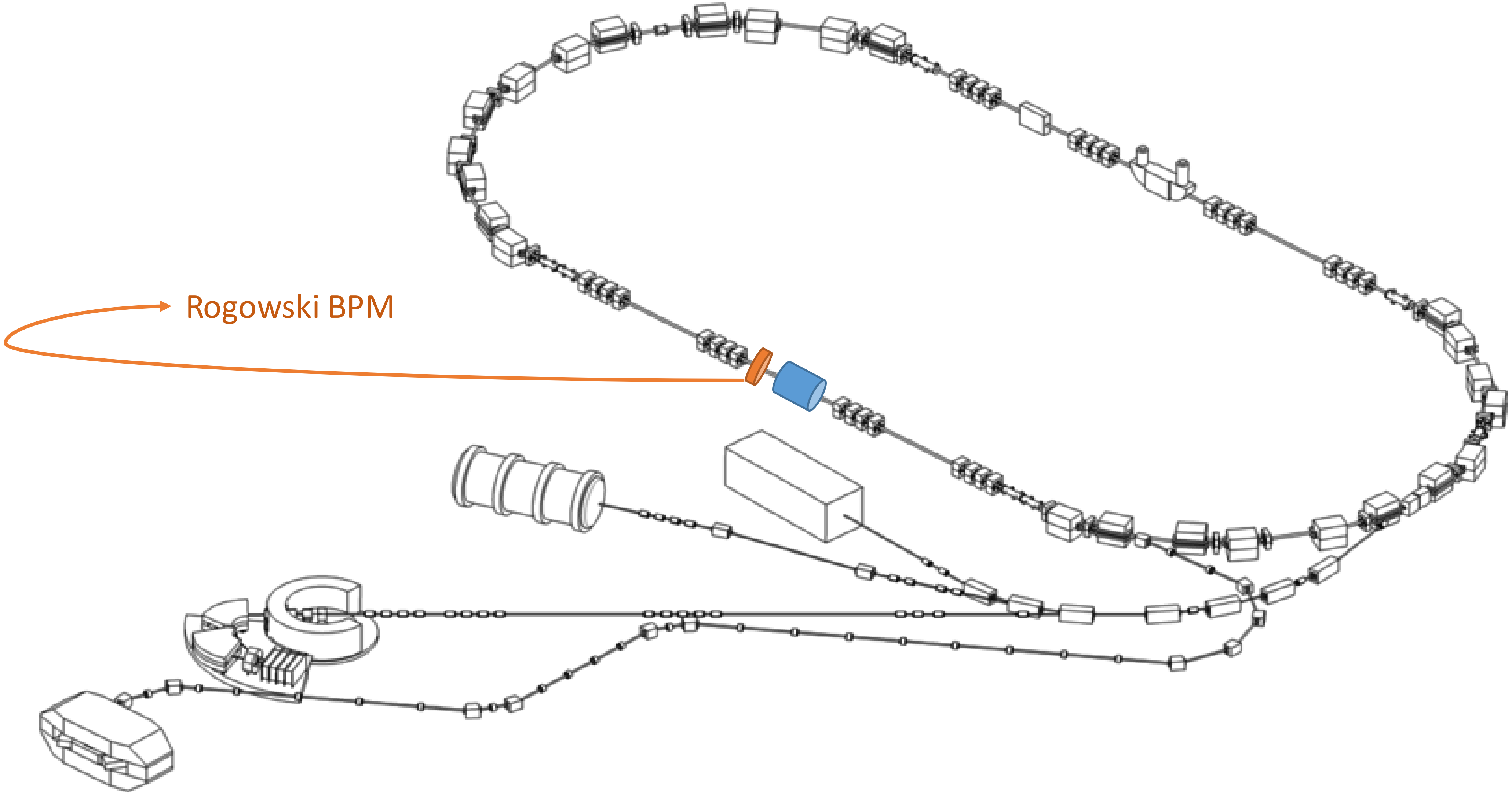
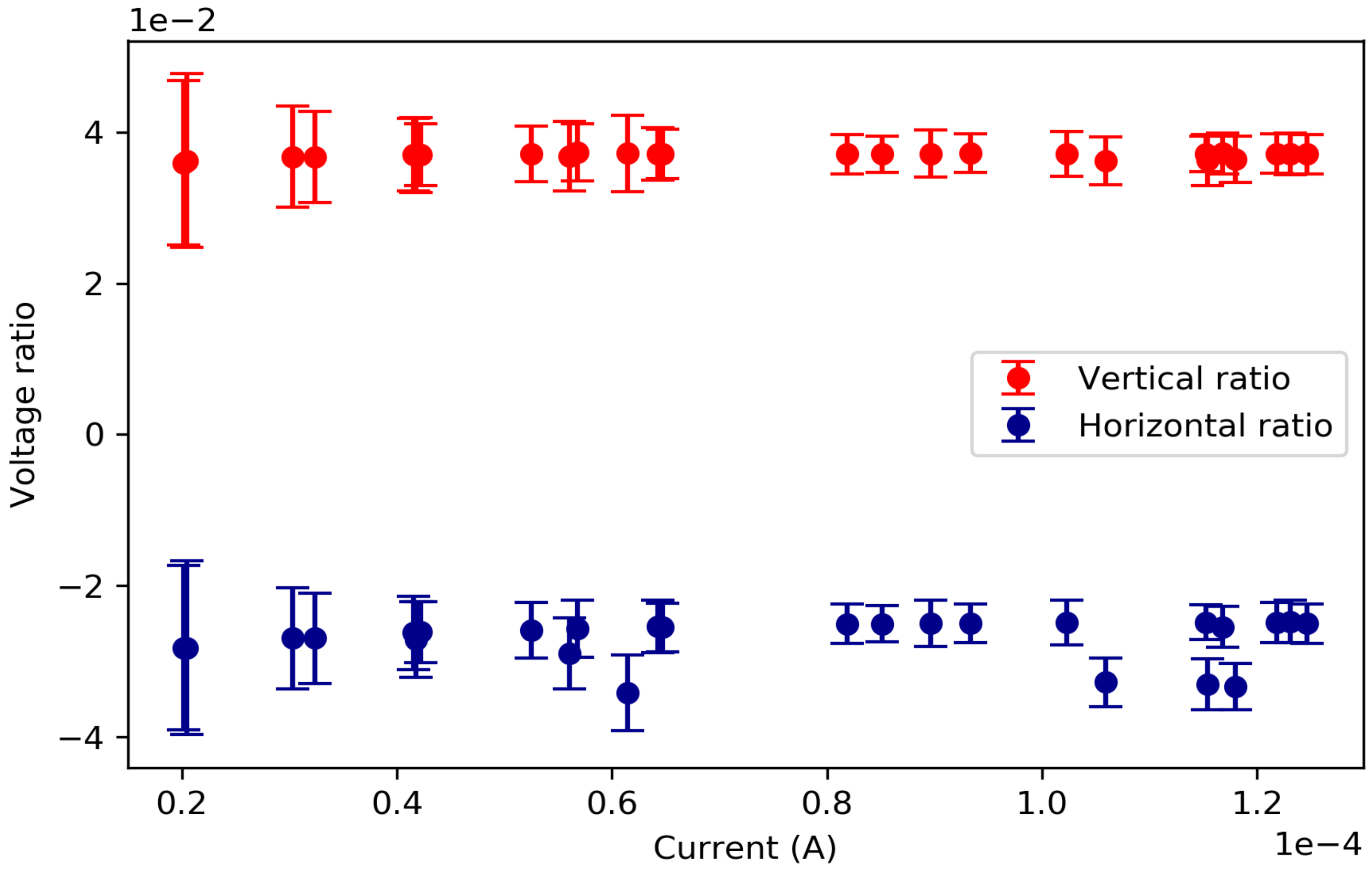
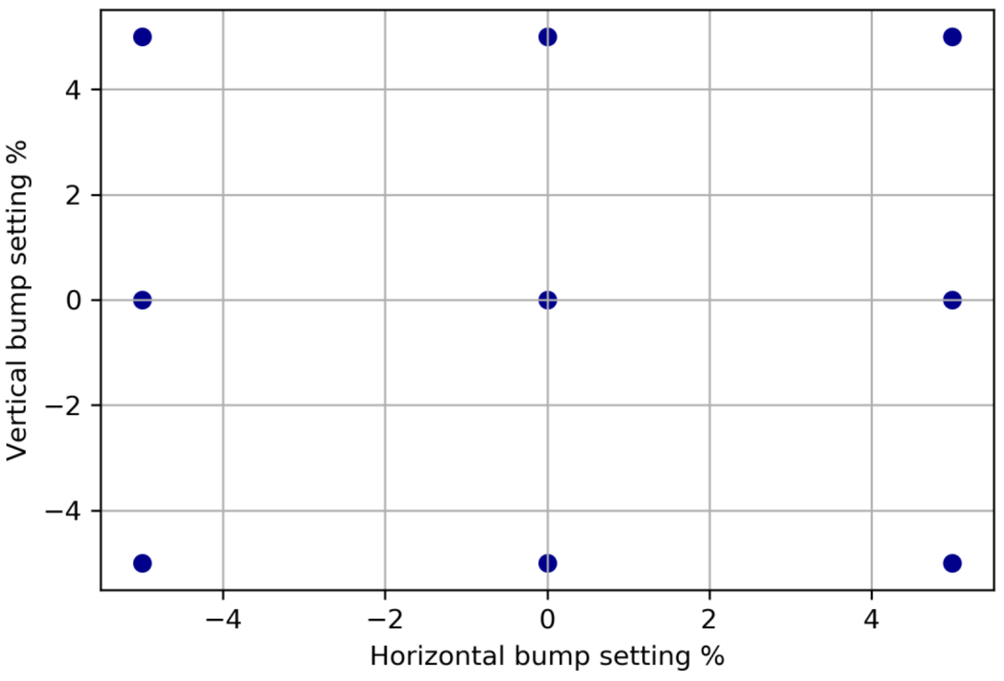
Installation in COSY



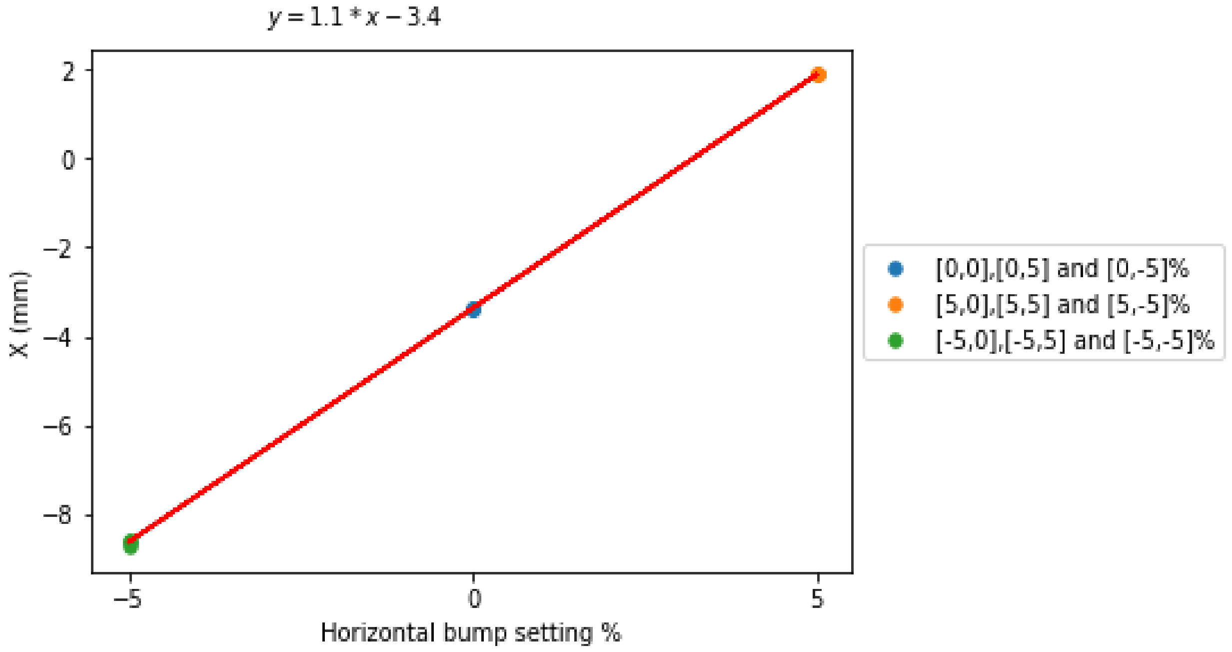
Calibration independent of COSY beam current



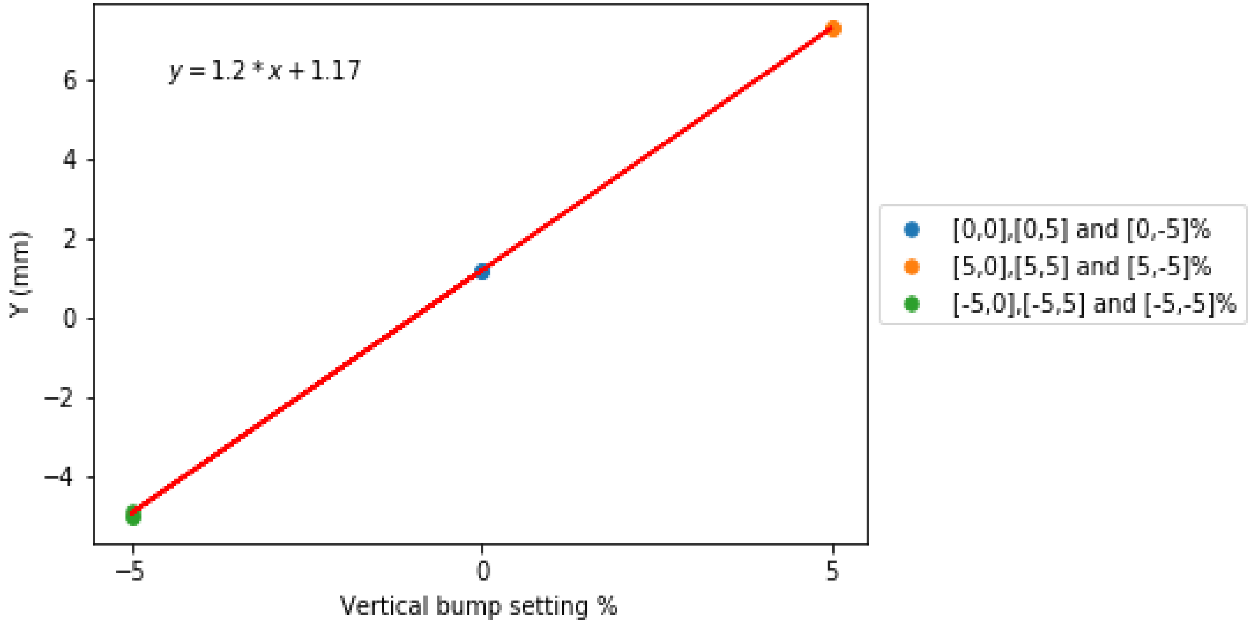
Bump test



Vertical bump setting %
Horizontal bump setting %



$y = 1.1 * x - 3.4$
X (mm)
Horizontal bump setting %
[0,0],[0,5] and [0,-5]%
[5,0],[5,5] and [5,-5]%
[-5,0],[-5,5] and [-5,-5]%



$y = 1.2 * x + 1.17$
Y (mm)
Vertical bump setting %
[0,0],[0,5] and [0,-5]%
[5,0],[5,5] and [5,-5]%
[-5,0],[-5,5] and [-5,-5]%

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

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

  $= 0.01092mm^{-1}$
- $c_2 = \frac{Ra^2}{3\pi\left(R^2-a^2\right)^{\frac{5}{2}}(R-\sqrt{R^2-a^2})}$

  $= 1.0817 \times 10^{-6}mm^{-3}$

- $c_3 = \frac{Ra^2(4R^2+3a^2)}{20\pi\left(R^2-a^2\right)^{\frac{9}{2}}(R-\sqrt{R^2-a^2})}$

  $= 1.9511 \times 10^{-10}mm^{-5}$

Elements of covariance matrix

$$\boldsymbol{f_1} = \frac{\boldsymbol{u_3 + u_4 - u_1 - u_2}}{\boldsymbol{\sum_{i=1}^{4} u_i}} \qquad (\boldsymbol{Ratio_x})$$

$$\boldsymbol{f_2} = \frac{\boldsymbol{u_1 + u_4 - u_3 - u_2}}{\boldsymbol{\sum_{i=1}^{4} u_i}} \qquad (\boldsymbol{Ratio_y})$$

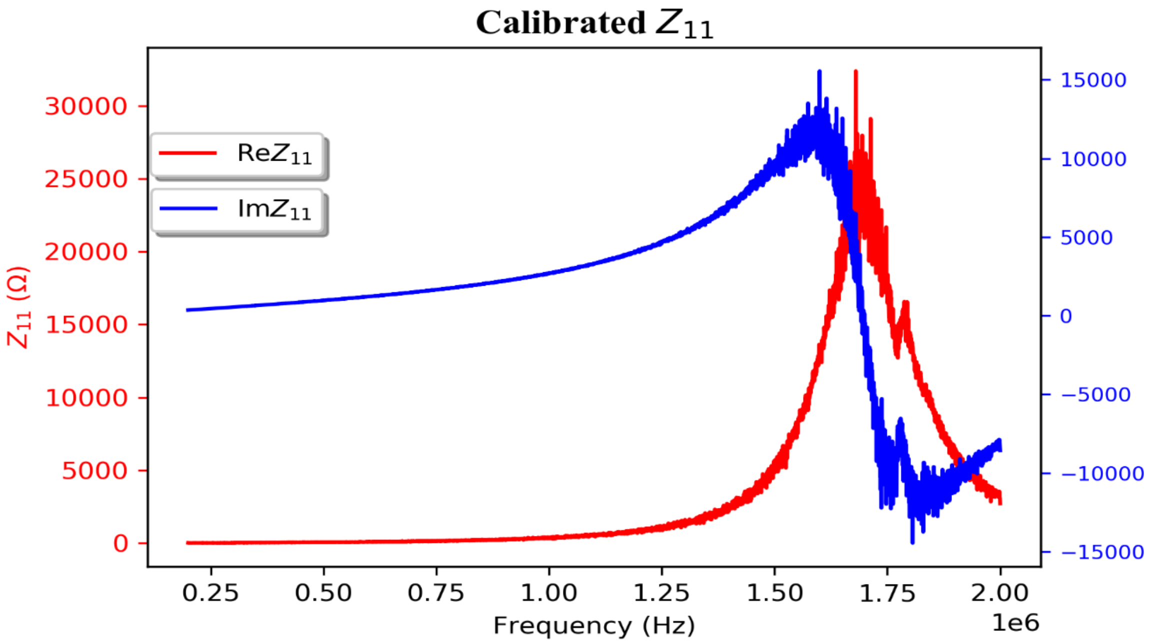
- $\begin{bmatrix} c11 & c12 \\ c21 & c22 \end{bmatrix}$ $\qquad (Covariance\ matrix)$

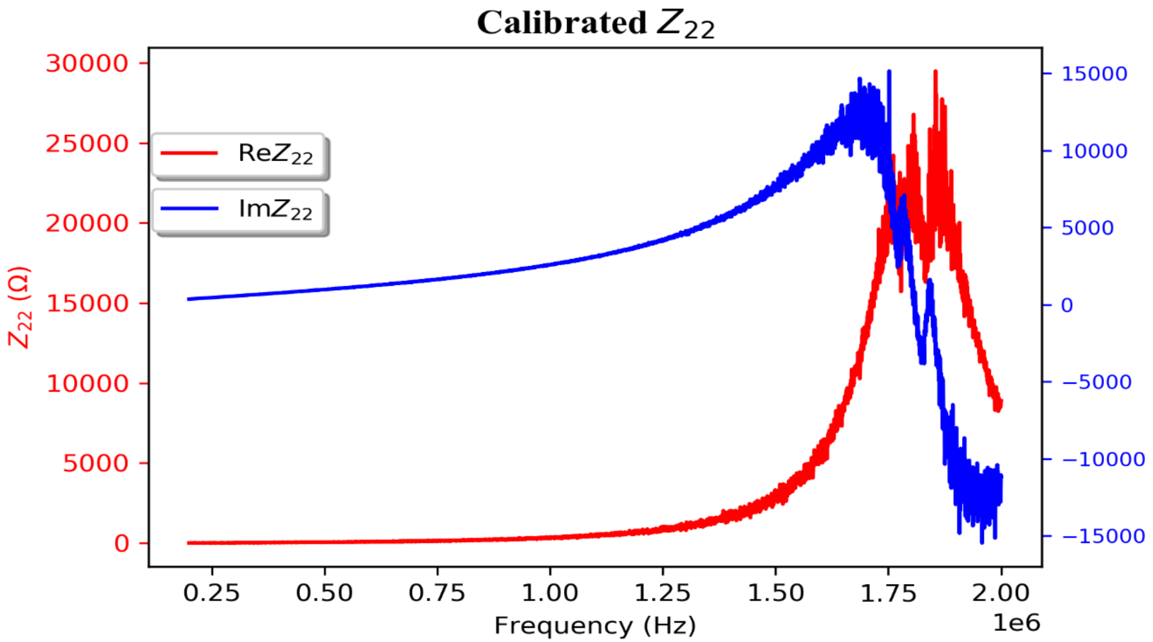
- $$c_{11} = [\left(\frac{\partial f_1}{\partial u_1} * \sigma_{u1}\right)^2 + \left(\frac{\partial f_1}{\partial u_2} * \sigma_{u2}\right)^2 + \left(\frac{\partial f_1}{\partial u_3} * \sigma_{u3}\right)^2 + \left(\frac{\partial f_1}{\partial u_4} * \sigma_{u4}\right)^2]^{0.5}$$
$$= \frac{2}{(\sum_{i=1}^{4} u_i)^2} * [(\sigma_{u1}{}^2 + \sigma_{u2}{}^2) * (u_3 + u_4)^2 + (\sigma_{u3}{}^2 + \sigma_{u4}{}^2) * (u_1 + u_2)^2]^{0.5}$$

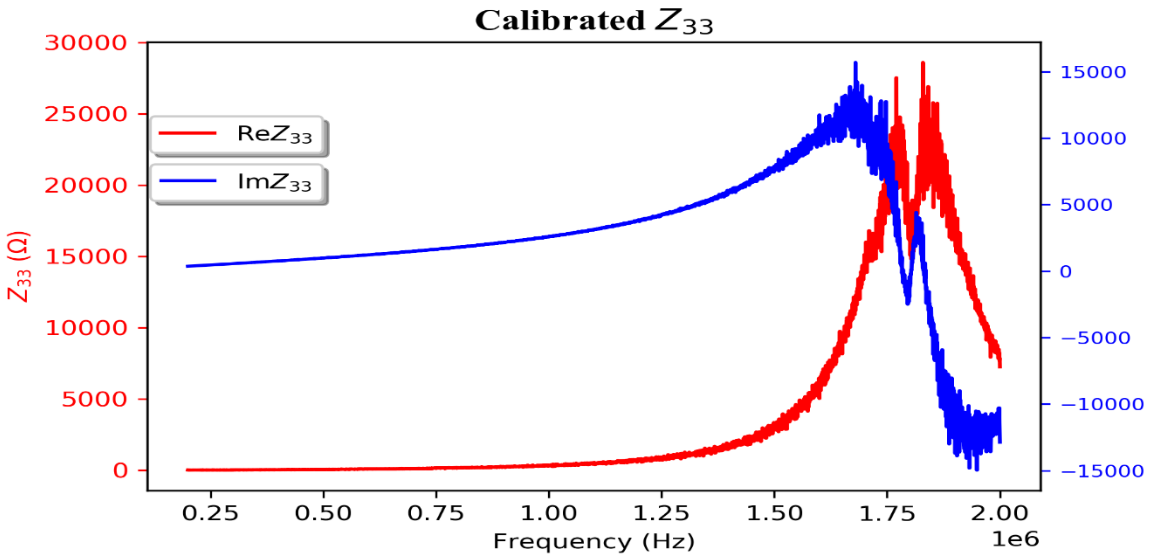
- $$c_{22} = [\left(\frac{\partial f_2}{\partial u_1} * \sigma_{u1}\right)^2 + \left(\frac{\partial f_2}{\partial u_2} * \sigma_{u2}\right)^2 + \left(\frac{\partial f_2}{\partial u_3} * \sigma_{u3}\right)^2 + \left(\frac{\partial f_2}{\partial u_4} * \sigma_{u4}\right)^2]^{0.5}$$
$$= \frac{2}{(\sum_{i=1}^{4} u_i)^2} * [(\sigma_{u1}{}^2 + \sigma_{u4}{}^2) * (u_3 + u_2)^2 + (\sigma_{u3}{}^2 + \sigma_{u2}{}^2) * (u_1 + u_4)^2]^{0.5}$$

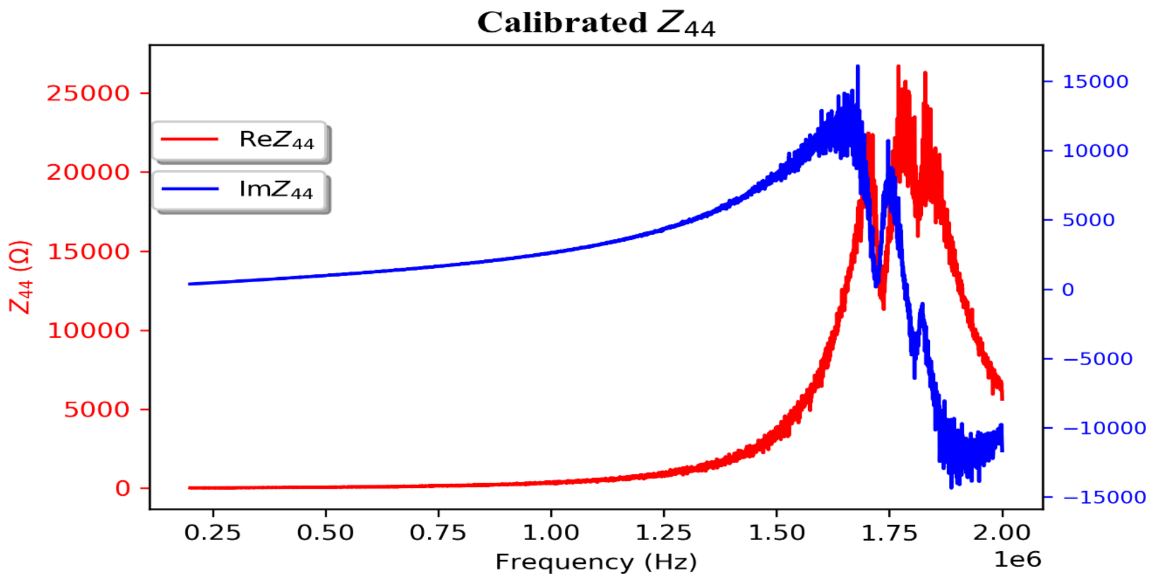
- $c_{12},\ c_{21}\ \ from\ correlation\ between\ f_1\ \&\ f_2$

Measured coil impedance at the range $200KHz - 2.0MHz$



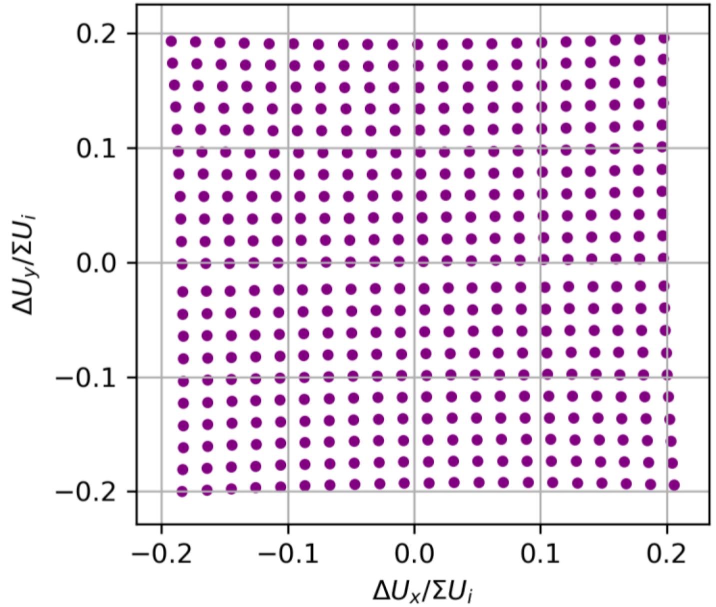




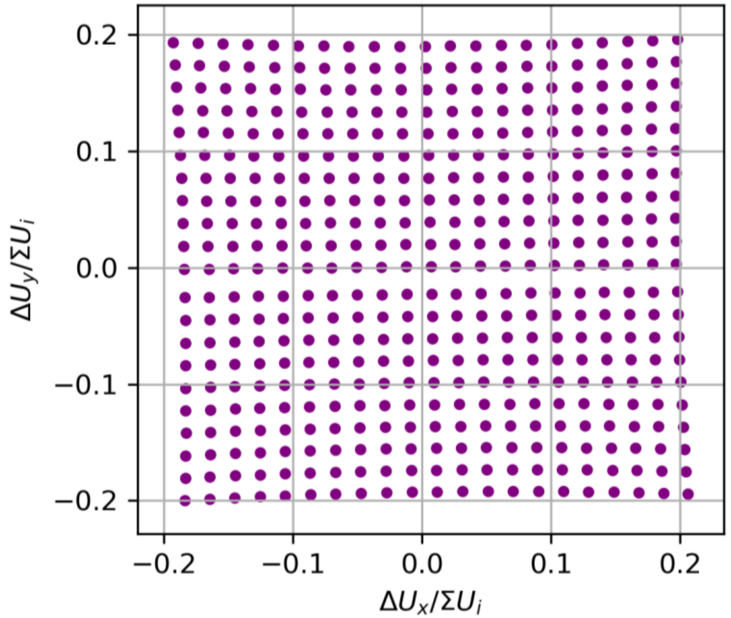


Backup

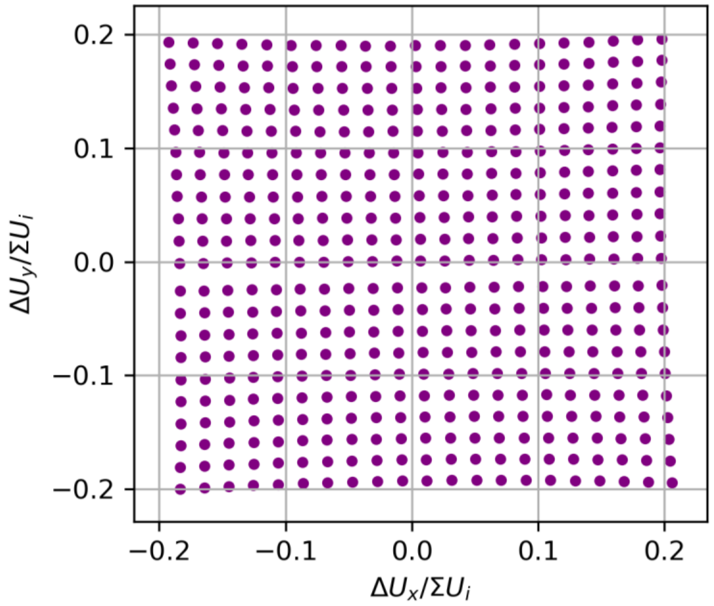
$0.992\ mA \sim 8.16e9\ particles$



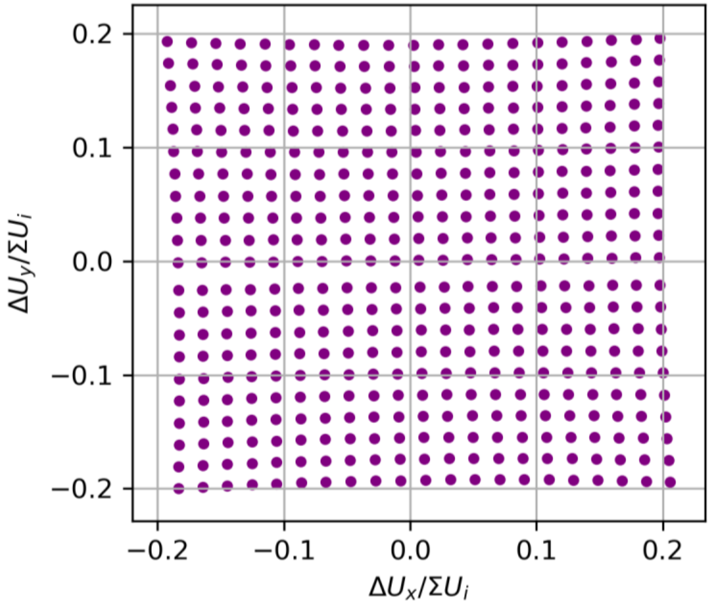
$0.595\ mA \sim 4.89e9\ particles$



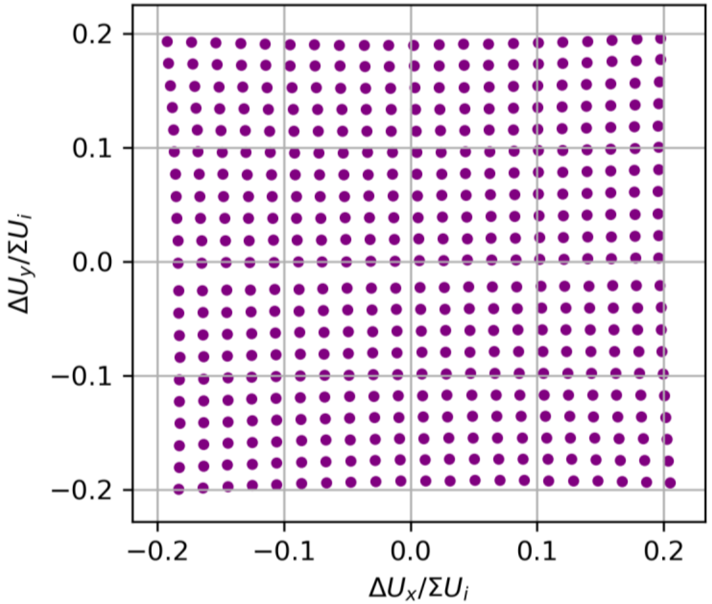
$0.496\ mA \sim 4.08e9\ particles$



$0.298\ mA \sim 2.46e9\ particles$



$0.0992\ mA \sim 8.16e8\ particles$



$0.0595\ mA \sim 4.89e8\ particles$