FORSCHUNGSZENTRUM JÜLICH

Rogowski coils as beam position monitors

Helmut Soltner and Fabian Trinkel, March 13th 2017
Kick off meeting at CERN

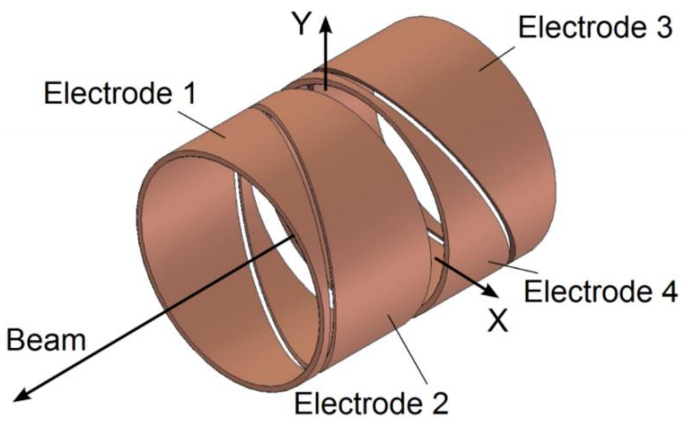
Outline

- Cylindrical and toroidal BPMs – Rogowski coils
- Test stand for BPMs
- Analytical description of BPMs
- Integration of BPMs with COSY and new findings
- Future developments

Beam Position Monitor (BPM)

BPM measures transverse beam positon (x_0, y_0)

Conventional method:

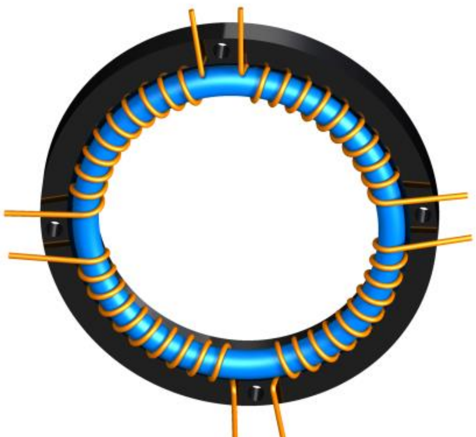


Length ≈ 20 cm

Easy to manufacture

Accuracy of the existing COSY BPM system ≈ 0.1 mm
Not enough for an EDM measurement

New development:

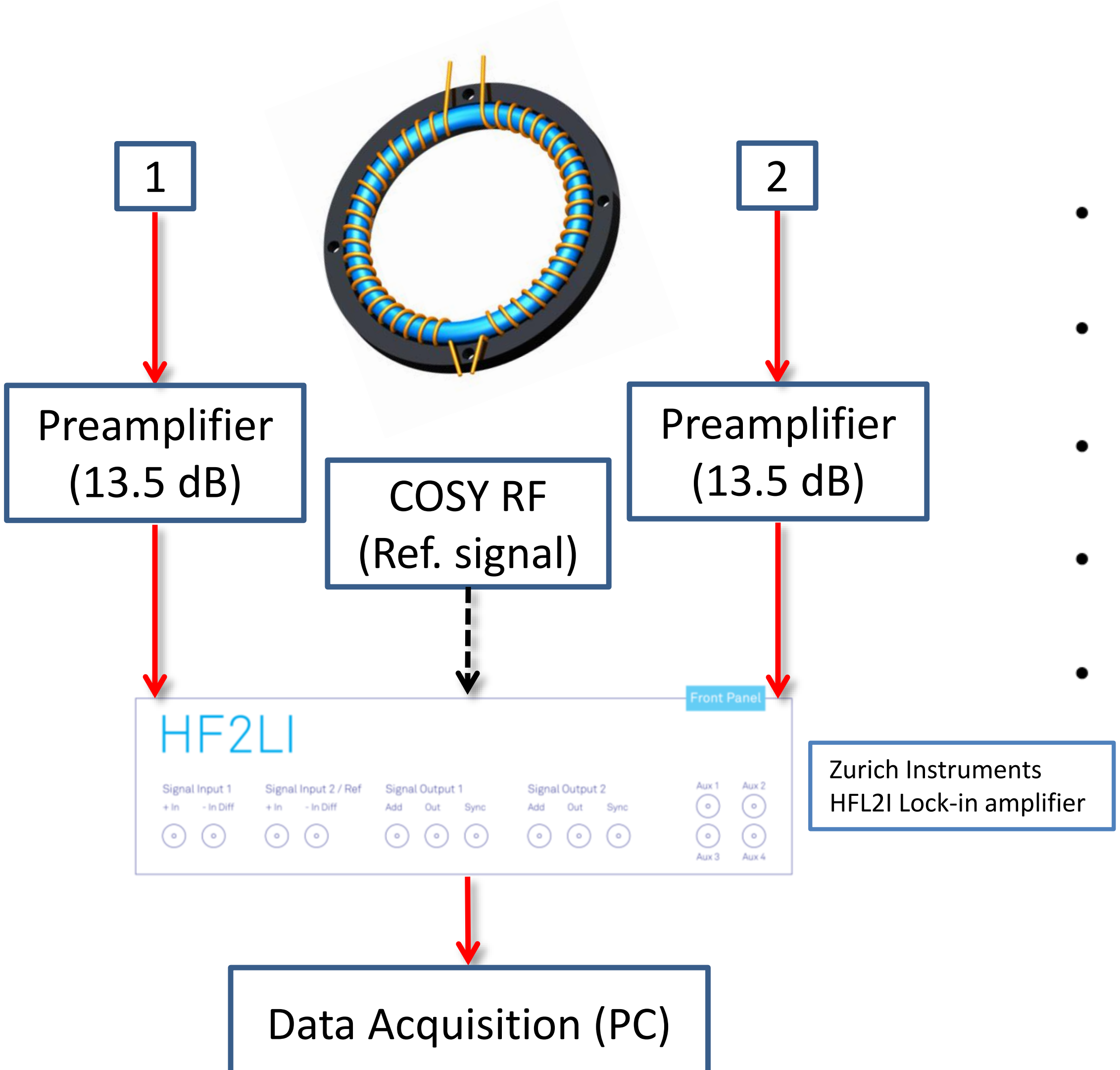


Length ≈ 1 cm

Excellent response to RF signal

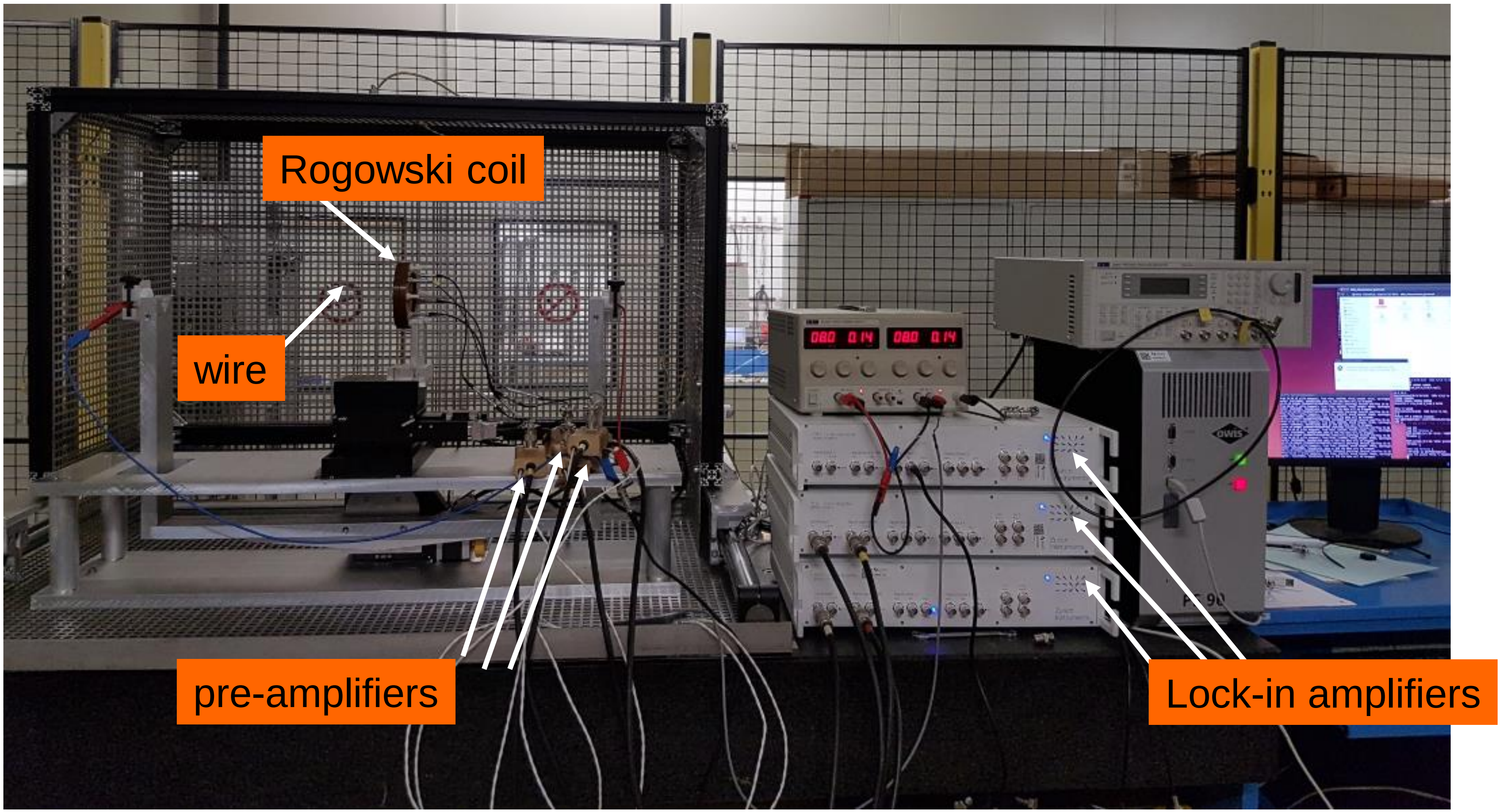
More precise position measurement with Rogowski BPM system and a first step to a SQUID-based BPM development

Data acquisition



- Bunched deuterons
- $N_{particles} = 10^{10}$
- Energy: $E = 970\ \mathrm{MeV/c}$
- Sampling rate: 4.45 ms
- Each interval consists of 1000 data points

Test stand for development of BPMs

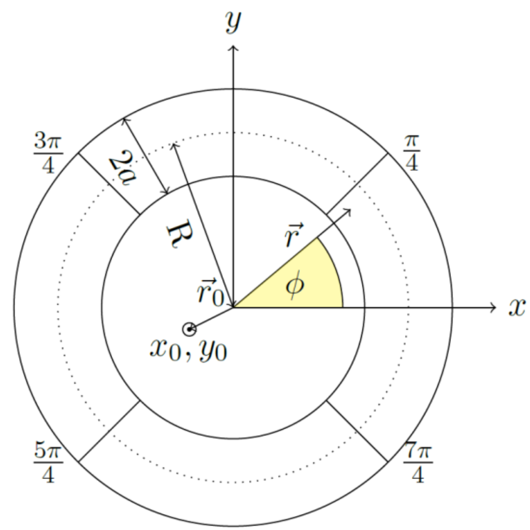


Calculation of flux through Rogowski coil

Vector potential A_z of a rotationally symmetric particle beam

$$\vec{A}(\vec{r}) = \frac{\mu_0}{4\pi} \cdot \int \frac{\vec{j}(\vec{r}\,')}{|\vec{r} - \vec{r}\,'|} d\vec{r}\,'$$

$$A_z(\rho,\varphi) = \frac{\mu_0}{2\pi} \cdot \int_{R^2} j(\vec{r}\,') \cdot \ln(|\vec{r} - \vec{r}\,'|) \cdot d\vec{r}\,'$$

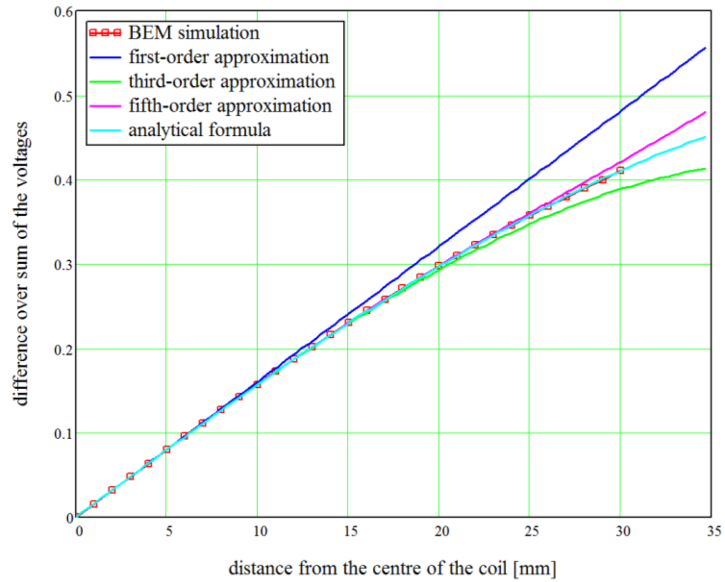


R = 40 mm
a = 5.075 mm
N = 365

Difference voltage over sum voltage

$$\frac{\Phi_\Delta}{\Phi_\Sigma} = -\frac{a}{R} \cdot \frac{\displaystyle\sum_{m=0}^{\infty} \frac{(-1)^m \cdot \sum_{k=0}^{m} \binom{2m+1}{2k} \cdot (\frac{x}{R})^{2m+1-2k} \cdot (\frac{y}{R})^{2k} \cdot (-1)^k}{(2m+1)^2} \cdot A(m, a/R)}{\pi^2 \cdot (1 - \sqrt{1-(a/R)^2})}$$

Linear model



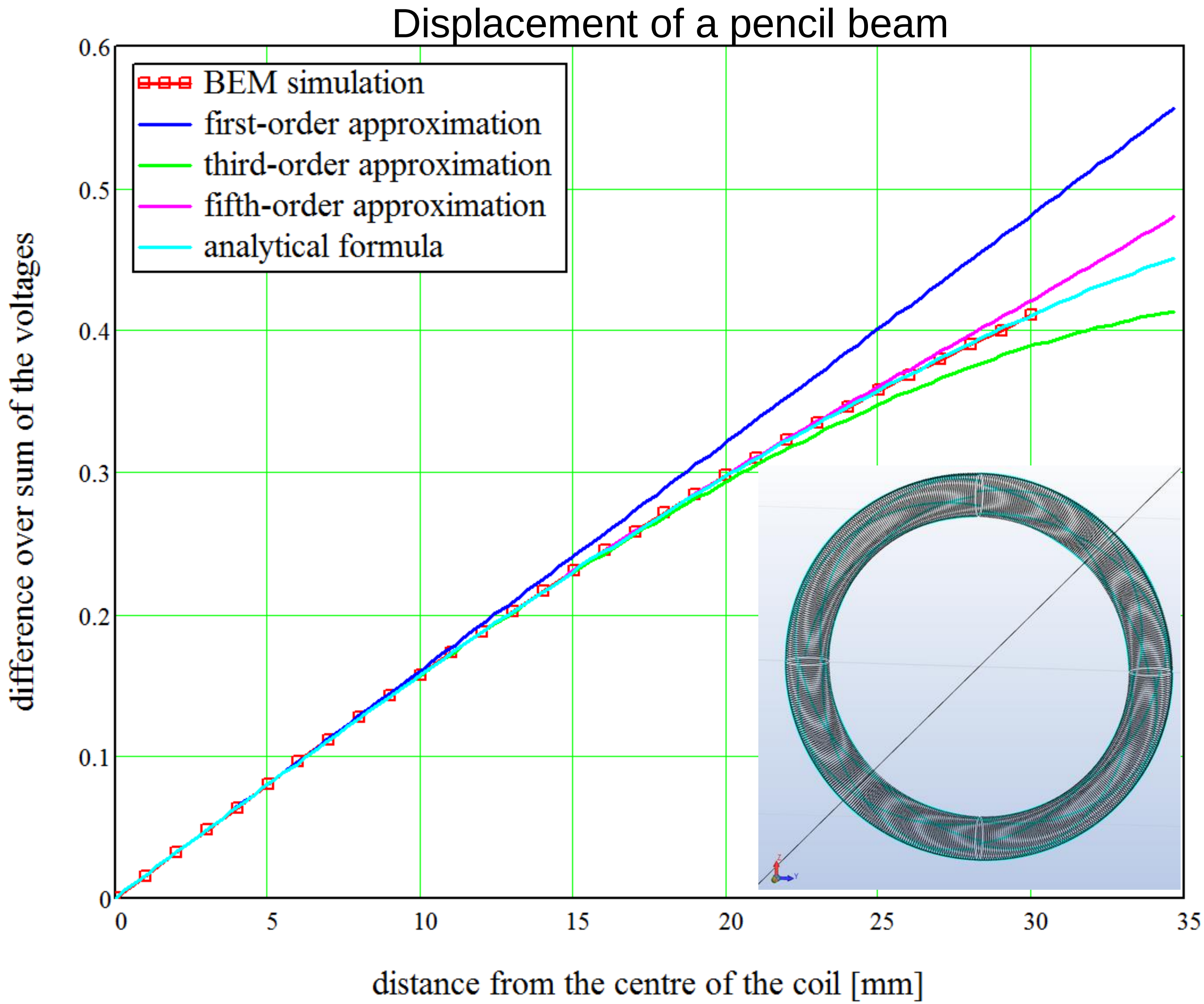
$$U_{\text{ind},1/1} = \frac{d\mathrm{I}_0}{dt}\mathrm{N}\mu_0\left[R - \sqrt{R^2 - a^2}\right]$$

(1.6 mV for our parameters)

$$U_{\text{ind},1/2} = \frac{d\mathrm{I}_0}{dt}\frac{\mathrm{N}}{2}\mu_0\left[R - \sqrt{R^2 - a^2}\right]\left(1 - \frac{2}{\pi\sqrt{R^2 - a^2}}x_0\right)$$

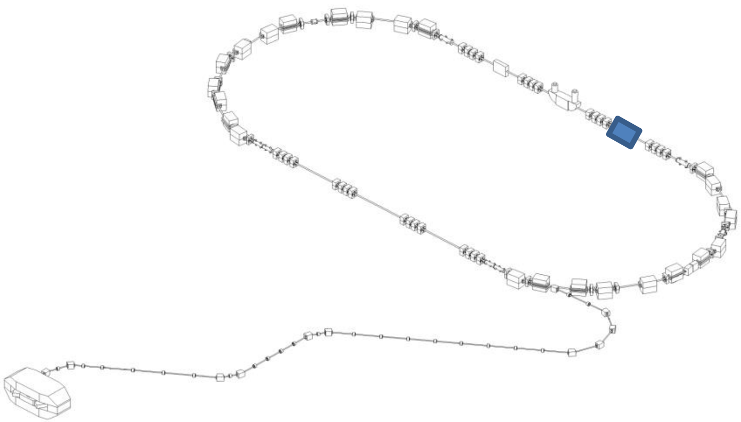
$$\frac{\Delta U_{1/2}}{U_{1/1}} = \frac{2}{\pi\sqrt{R^2 - a^2}}x_0$$

Deviations from linear model

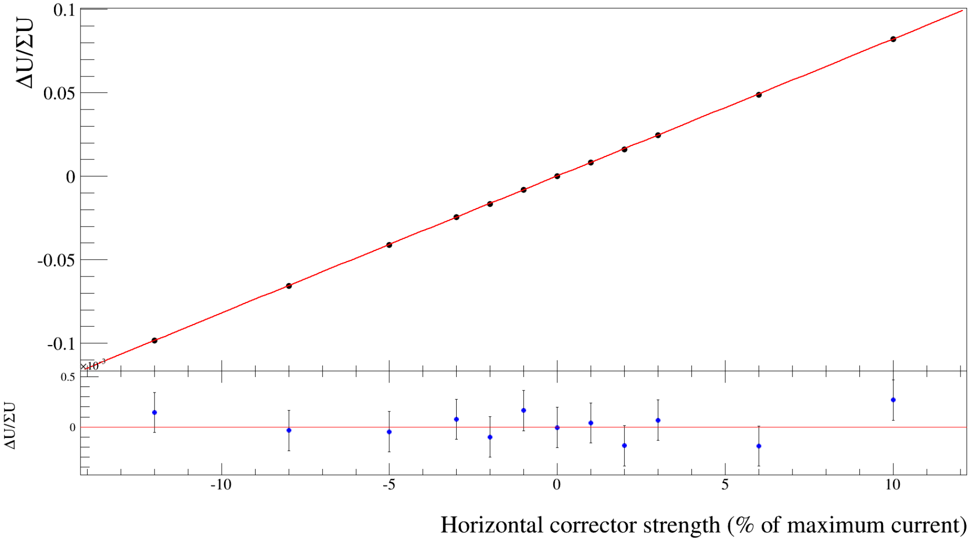


Horizontal Rogowski coil BPM in COSY

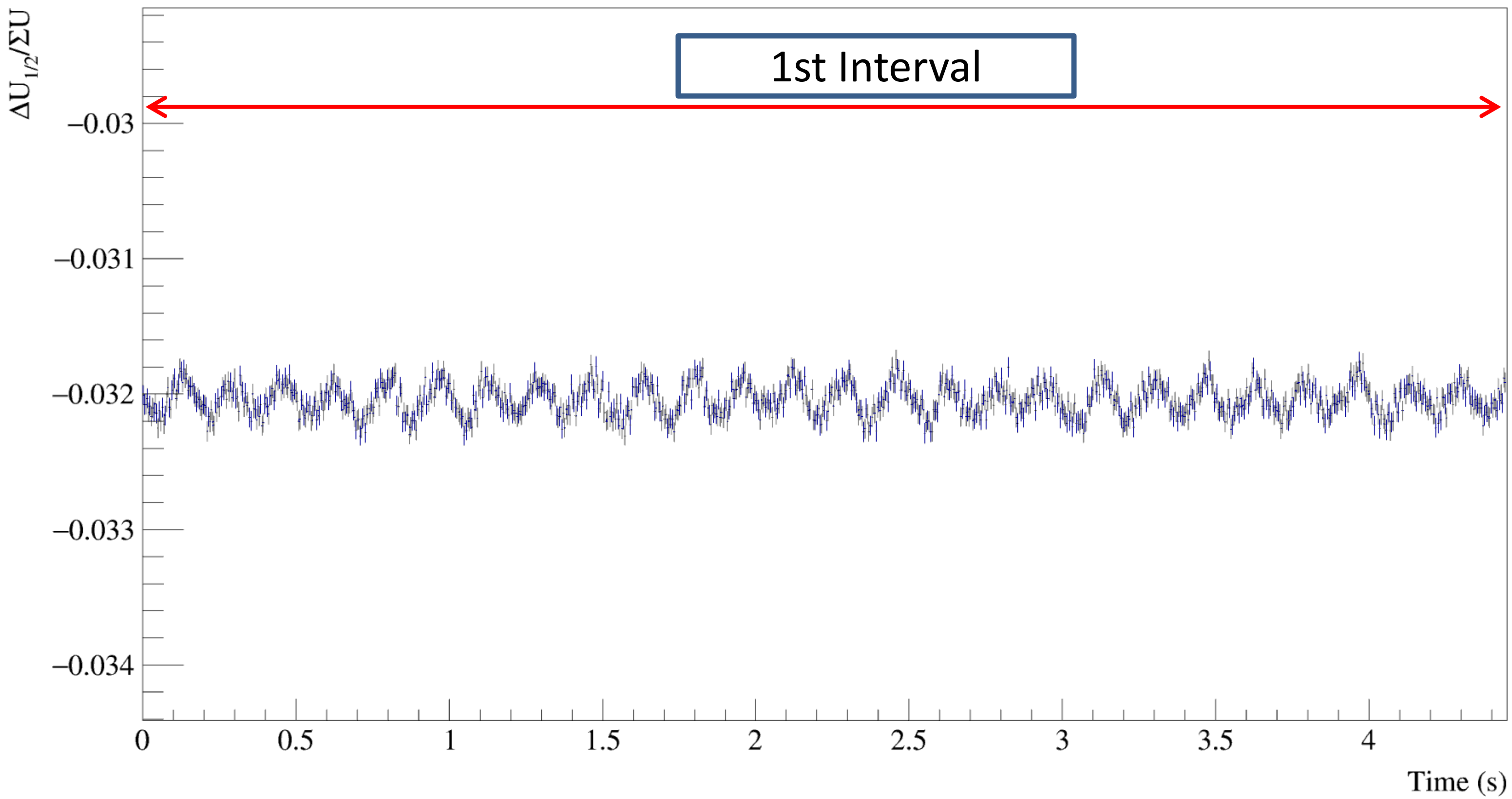
Unidirectional BPM



Result of the horizontal voltage ratio measurement



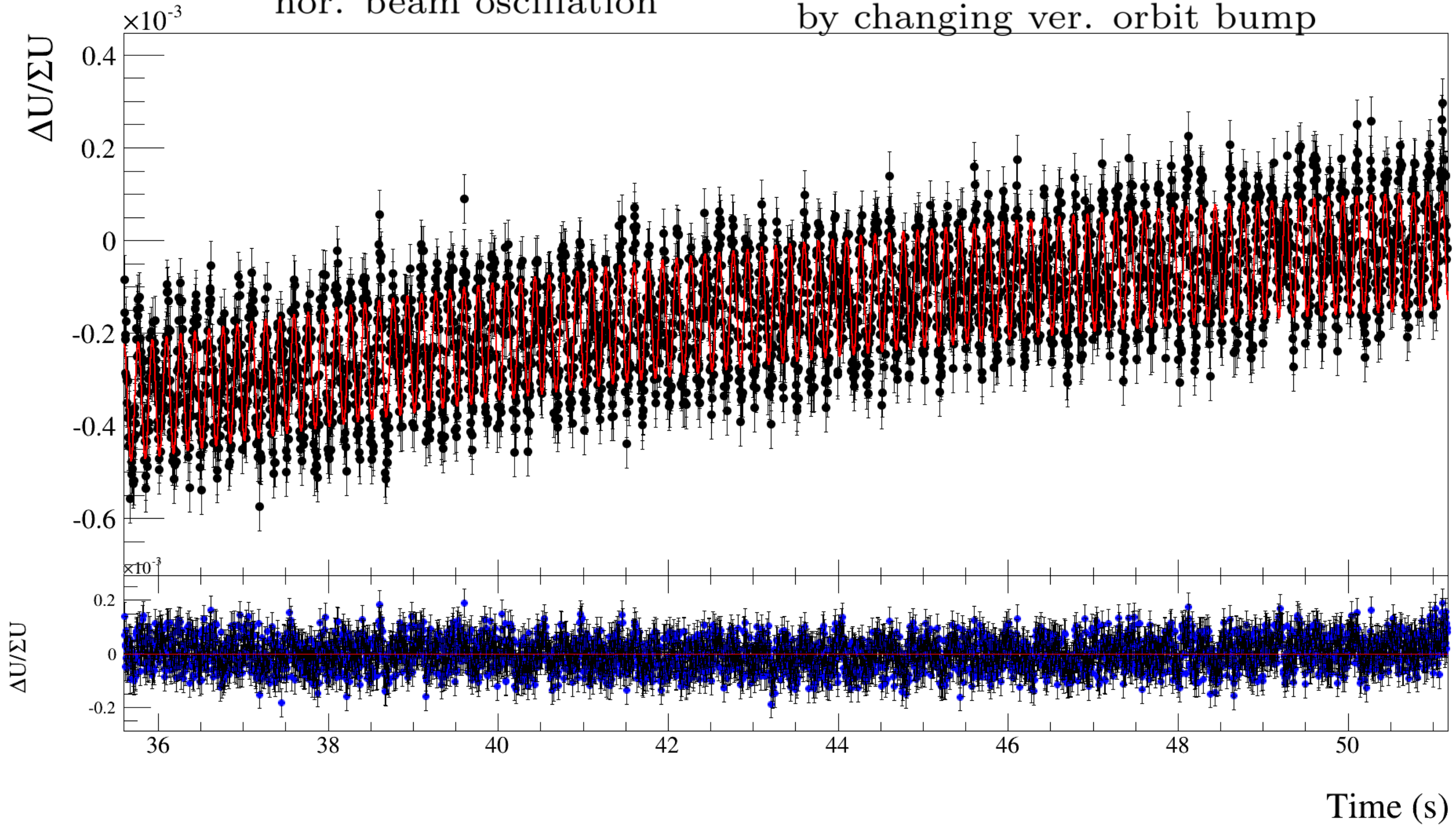
Voltage ratio for horizontal displacement



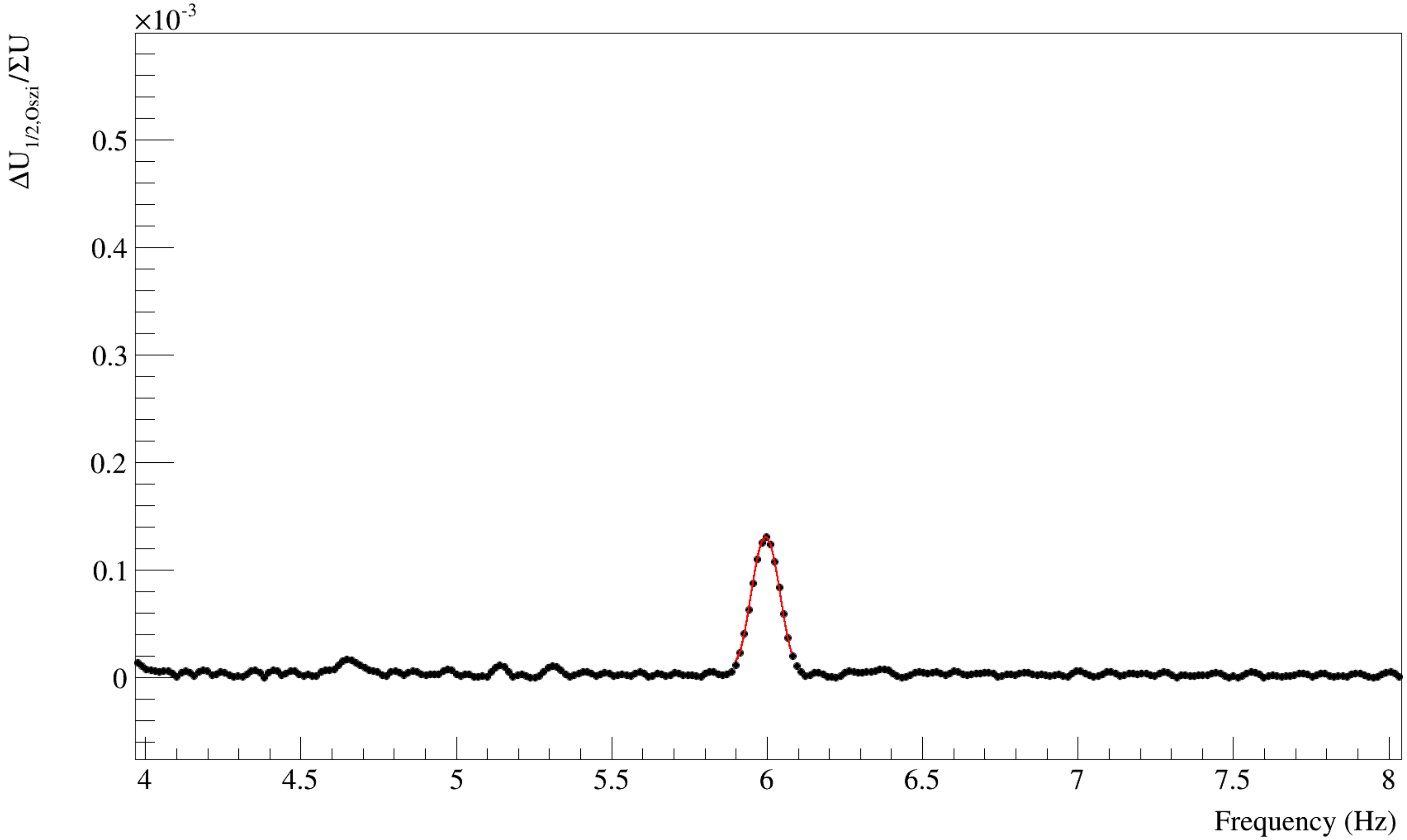
Observation of sinusoidal disturbance

Result of the voltage ratio measurement during vertical movement

$$\frac{\Delta U}{\Sigma U}(t) = \underbrace{\frac{\Delta U_{1/2,\sin}}{\Sigma U}\sin\left(2\pi f t + \varphi\right)}_{\text{hor. beam oscillation}} + \underbrace{b\left(t - t_0\right)^2}_{\text{hor. displacement caused by changing ver. orbit bump}}$$



Analysis of the oscillating signal

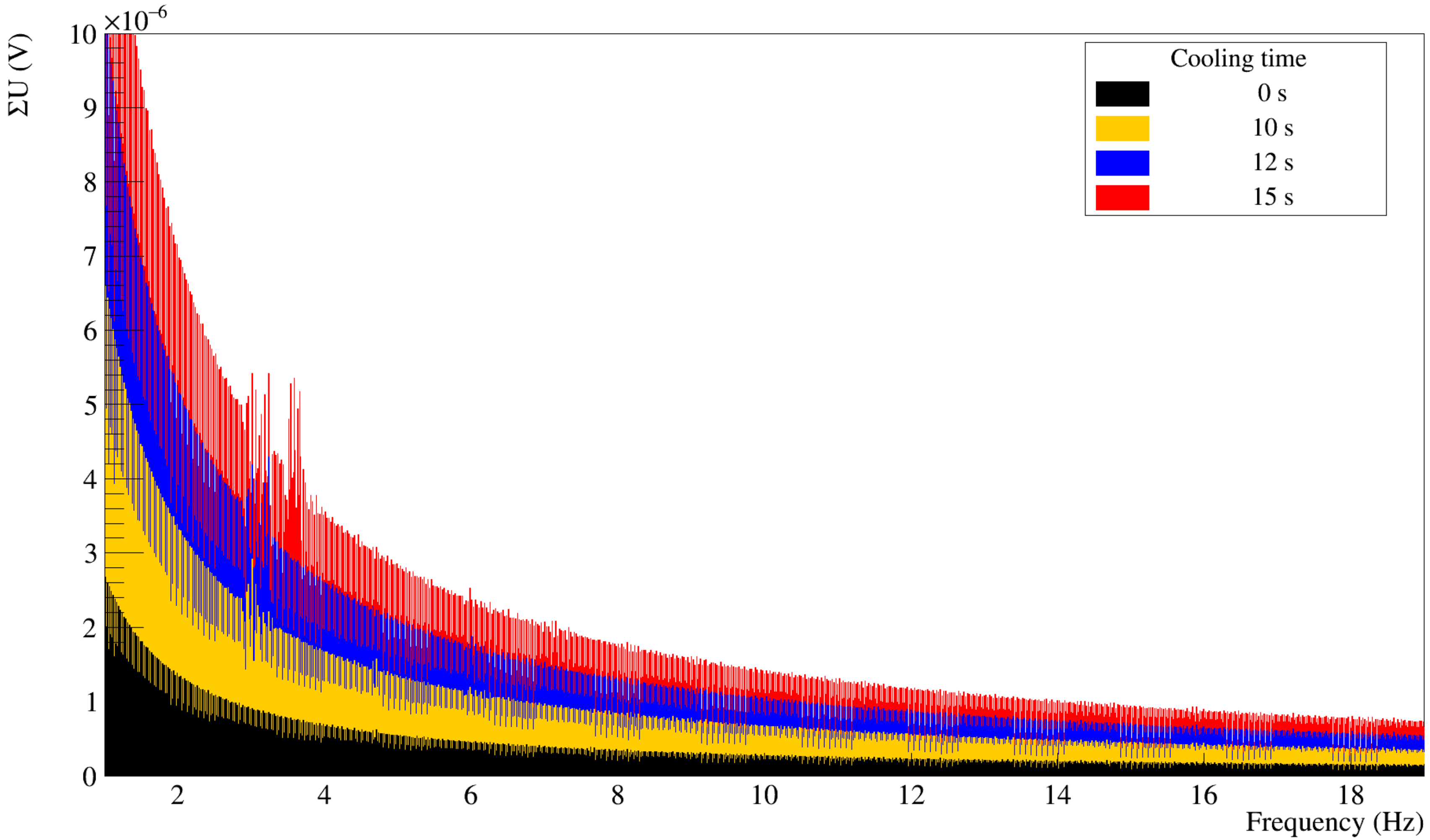


Possible causes for occurrence of 6 Hz oscillation:

- Vibration of the setup with this frequency

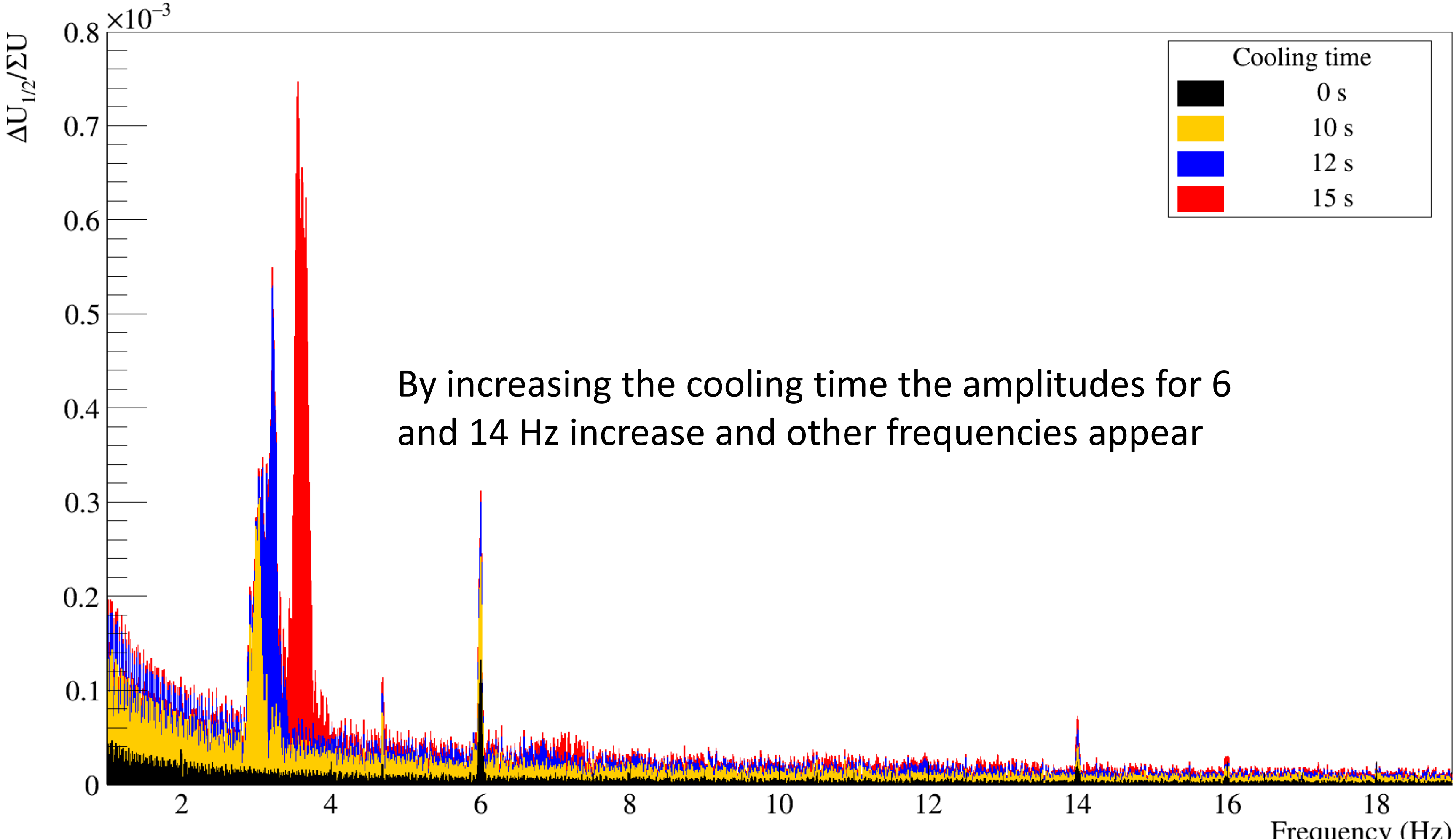
- Periodic excursions of the beam

Fourier spectra of sum voltage



No 6 Hz disturbance in sum spectrum – beam current is constant

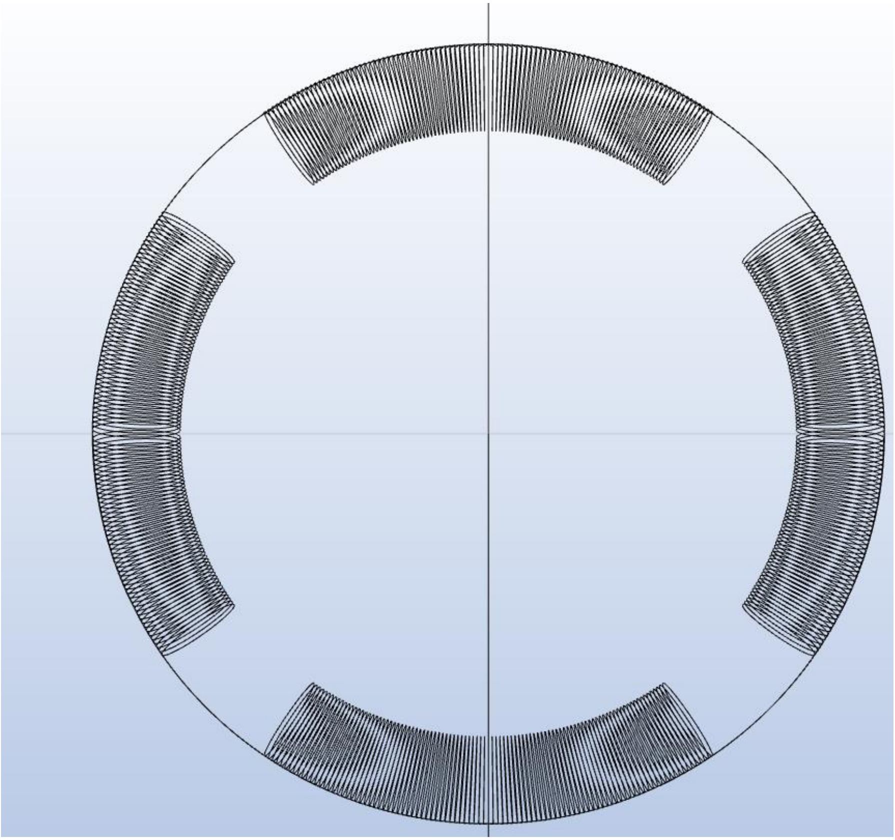
Fourier spectra of difference voltage
Different electron cooling durations

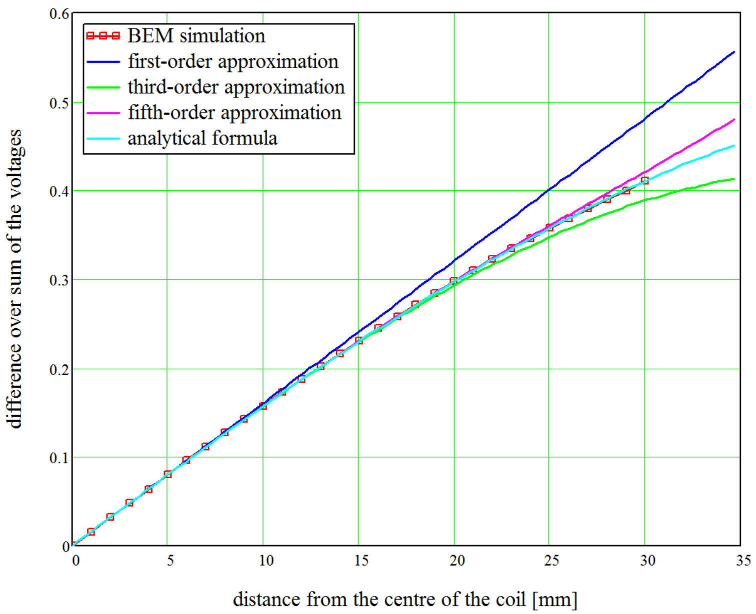


The source of the oscillation is due to the electron cooler and not the Rogowski coil setup

Development #1:
Linearization by omission of coil turns

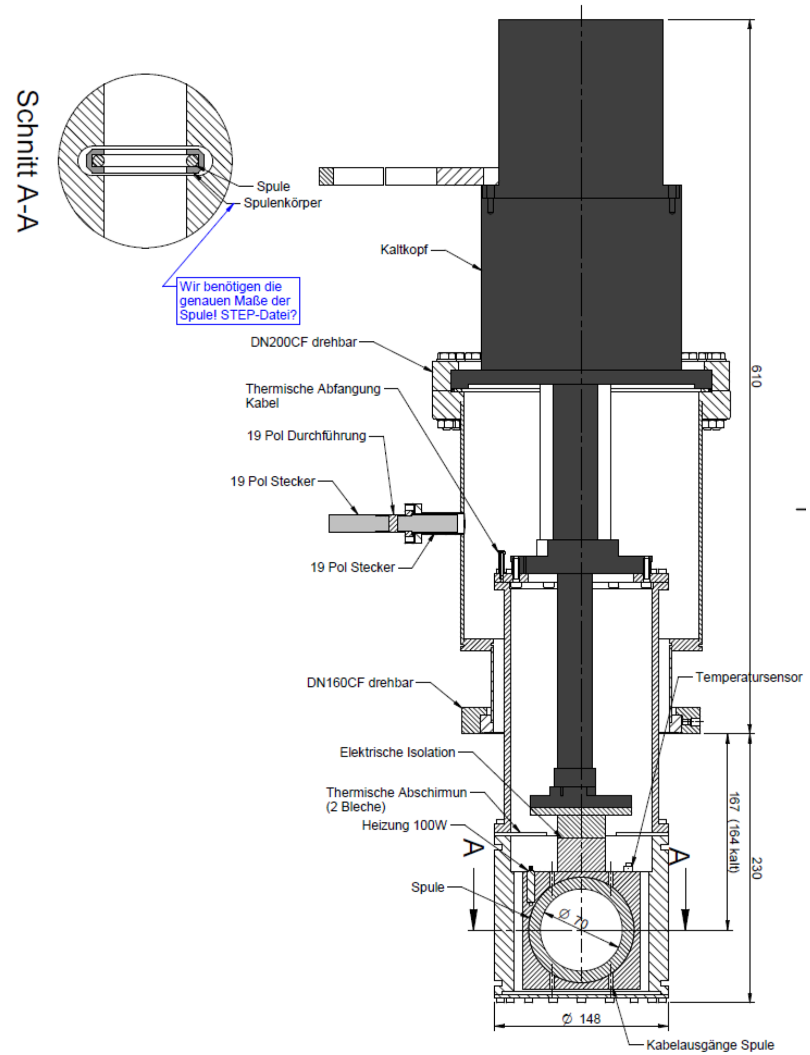
- Third-order terms are cancelled, if coil turns around 45 degree positions are omitted





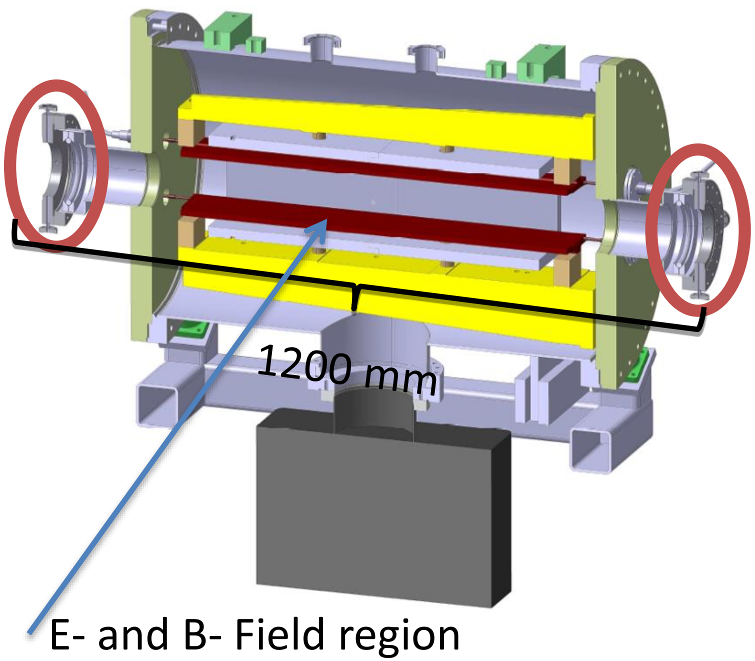
Development #2: Rogowski coil at low temperature: SQUID integration

- Cryostat for the Rogowski coil to test the setup at low temperatures in the laboratory
- SQUID-based Rogowski coil BPM to measure the position of clockwise
- Installation at COSY



Summary and outlook

- Theory of Rogowski coil BPM well understood
- Good agreement with the prediction and the measurement
- New finding about beam oscillation induced by electron cooler
- Further developments: Cryogenics and optimization of winding structure, application on both sides of rf Wien filter



Thank you for your attention.

Position determination and sensitivities

$$\frac{\Delta U_x}{\Sigma U} = \frac{(U_{1,mod} - U_{2,mod})}{U_{1,mod} + U_{2,mod}} = c_1 x_0 - c_3 \left(x_0^3 - 3y_0^2 x_0\right) + c_4 \left(x_0^5 - 10 y_0^2 x_0^3 + 5 y_0^4 x_0\right)$$

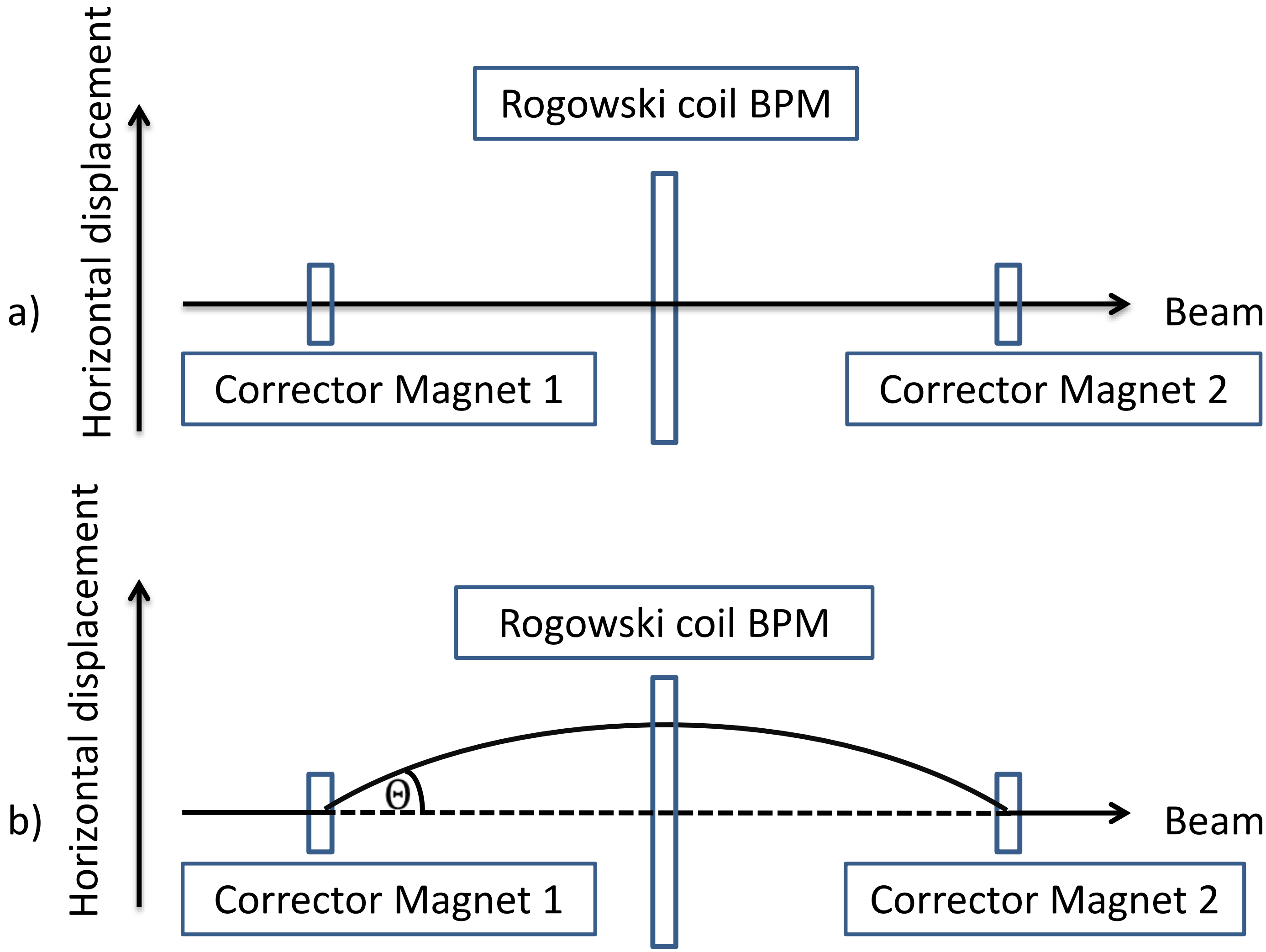
Coil parameters for sensitivities: $a = 5.075\ \mathrm{mm}$ $R = 40\ \mathrm{mm}$

$$c_1 = \frac{2}{\pi\sqrt{R^2 - a^2}} \approx 0.01604 \frac{1}{\mathrm{mm}}$$

$$c_3 = \frac{a^2 R}{3\pi(R^2 - a^2)^{5/2}(R - \sqrt{R^2 - a^2})} \approx 3.4353 \cdot 10^{-6} \frac{1}{\mathrm{mm}^3}$$

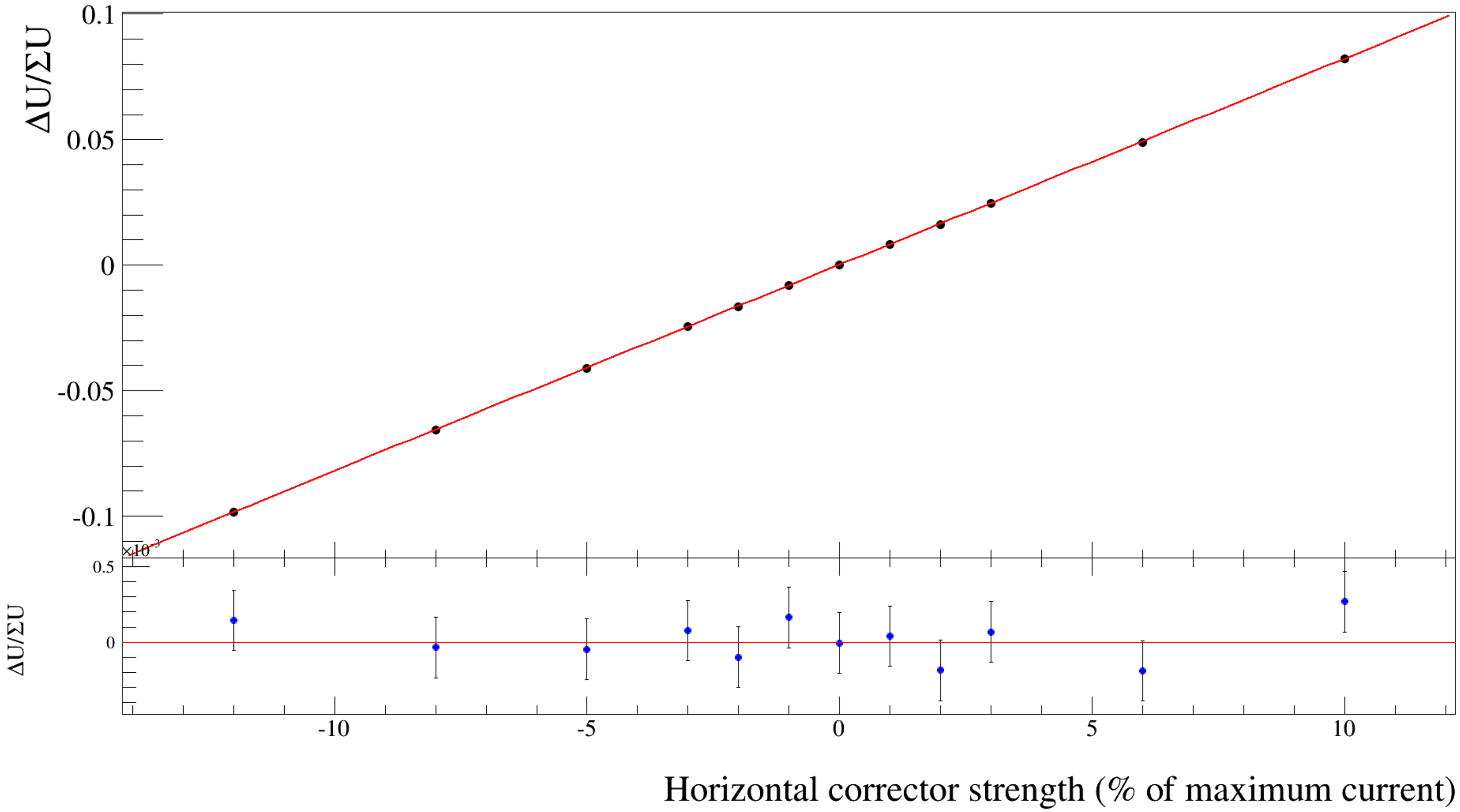
$$c_4 = \frac{a^2 R(4R^2 + 3a^2)}{20\pi(R^2 - a^2)^{9/2}(R - \sqrt{R^2 - a^2})} \approx 1.3451 \cdot 10^{-9} \frac{1}{\mathrm{mm}^5}$$

Local orbit bump



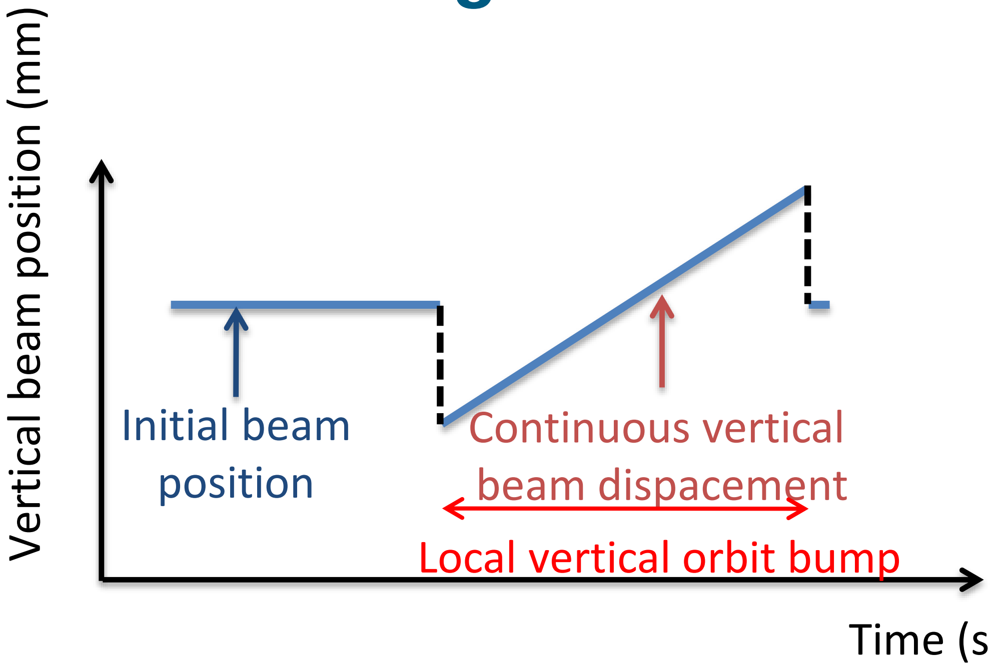
$$x = \text{const} \cdot I_{\text{corrector}}$$

Result of the horizontal voltage ratio measurement



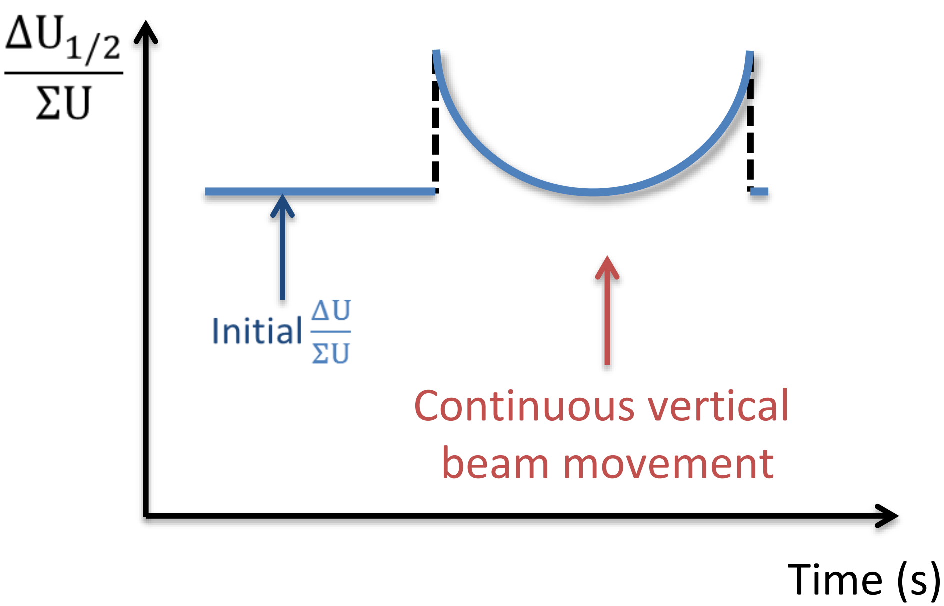
- Only linear term is fitted; the fluctuations from run to run are in the order of $2 \cdot 10^{-4}$
- Higher order terms are smaller than the estimated errors on each measurement
- The uncertainties on the applied corrector magnet current is a systematic effect
- Model and measurement are in good agreement

Vertical voltage ratio measurement



Assumption:

Horizontal orbit stays the same



Model prediction:

$$\frac{\Delta U_{1/2}}{\Sigma U} = \mathrm{const} + \mathrm{const}_2 \cdot y^2$$

Calculate:

$$\frac{\Delta U}{\Sigma U} = \frac{\Delta U_{1/2,\mathrm{movement}}}{\Sigma U} - \frac{\Delta U_{1/2,\mathrm{initial}}}{\Sigma U}$$