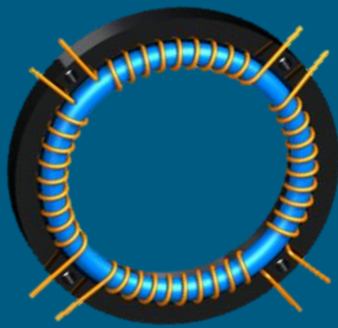
Development of a Rogowski coil as a new Beam Position Monitor (BPM)



Horizontal and Vertical Rogowski BPM

Fabian Trinkel for the JEDI collaboration

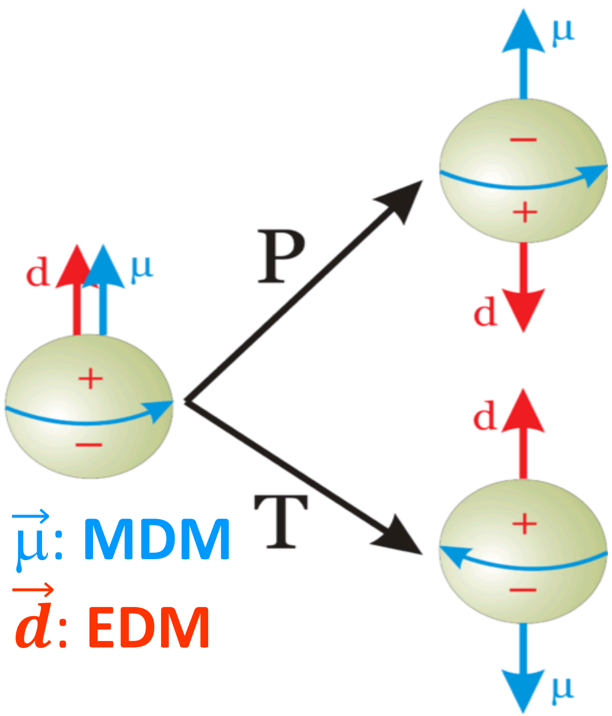
Eucard Workshop Mainz 2015

Content

- Introduction
- Theory for positon determination with a Rogowski coil as BPM
- Technical approach
- First measurements with a Rogowski coil as horizontal BPM
- Summary and outlook

Introduction

Existence of an EDM violates CP-theorem, which is necessary to explain the matter over antimatter dominance in the Universe



$$\mathcal{H} = -\mu \frac{\vec{s}}{s} \cdot \vec{B} - d \frac{\vec{s}}{s} \cdot \vec{E}$$

P: $$\mathcal{H} = -\mu \frac{\vec{s}}{s} \cdot \vec{B} + d \frac{\vec{s}}{s} \cdot \vec{\boldsymbol{E}}$$

T: $$\mathcal{H} = -\mu \frac{\vec{s}}{s} \cdot \vec{B} + d \frac{\vec{s}}{s} \cdot \vec{\boldsymbol{E}}$$

Standard Model EDM prediction: 10^{-32} to 10^{-31} ecm

Aim of Jülich Electric Dipole moment Investigations collaboration:

Measure the EDM of charged hadrons for protons p and deuterons d

EDM measurements in storage rings

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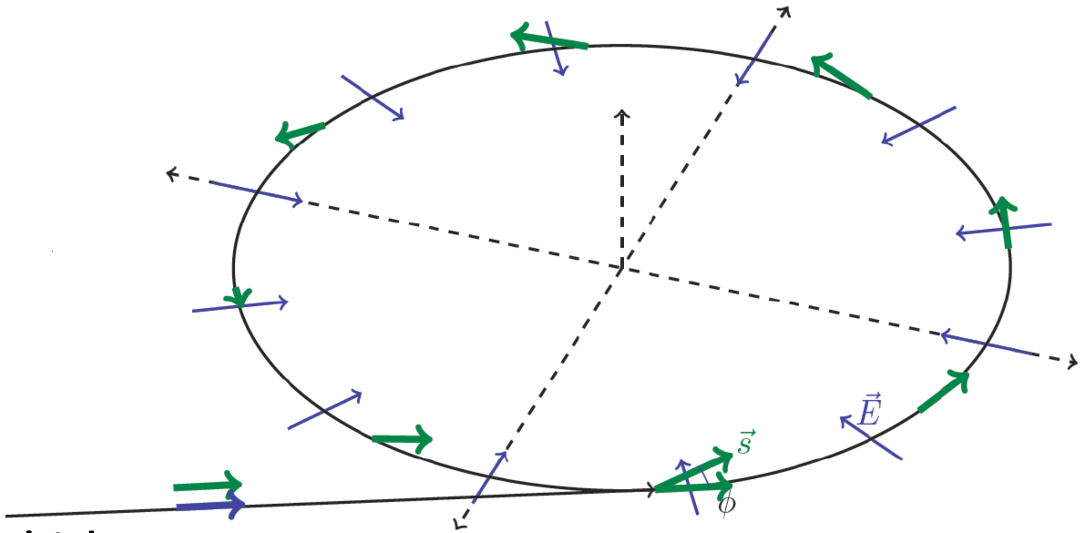


$$\frac{d\vec{S}}{dt} \propto \vec{d} \times \vec{E}$$

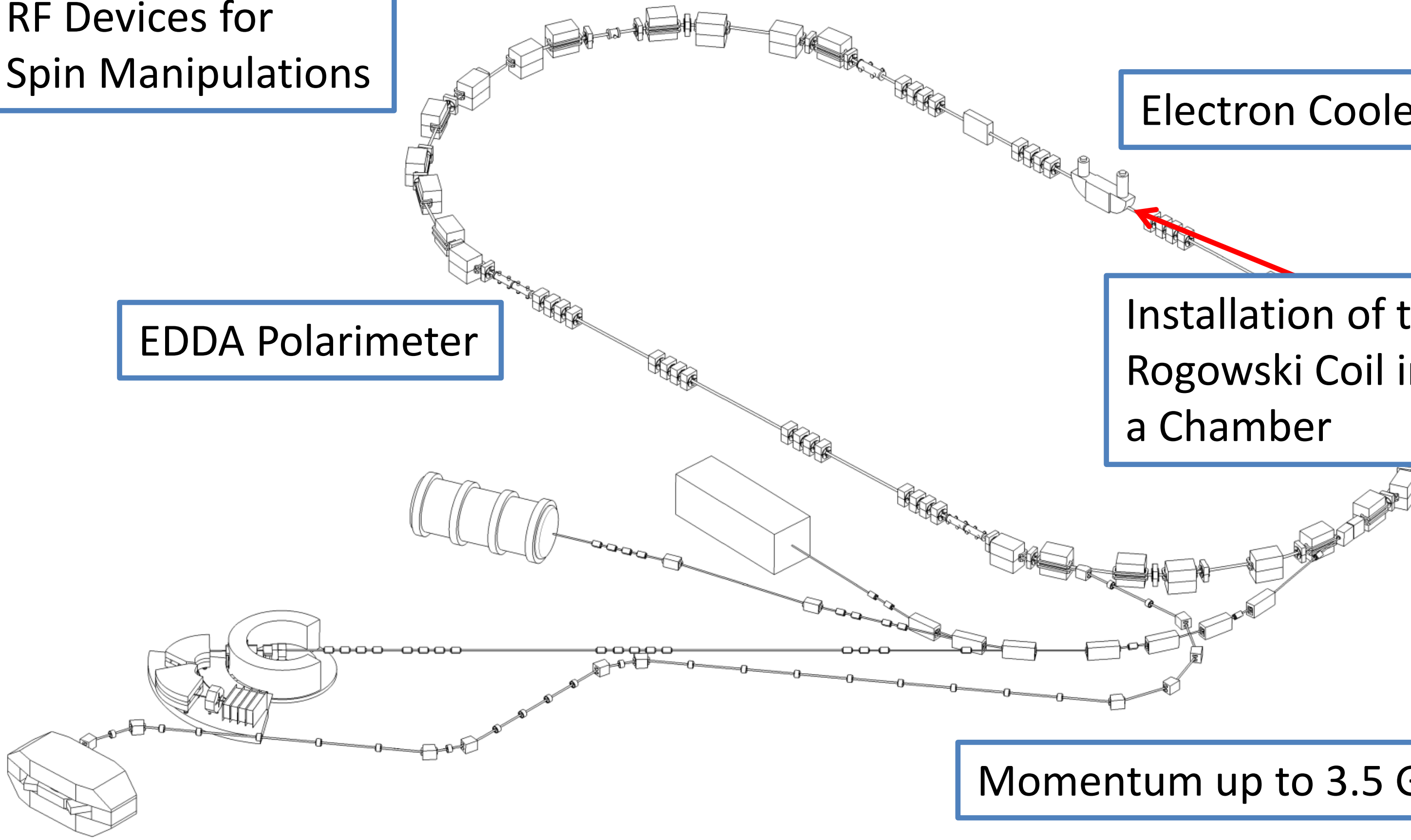
$$\vec{d} = \frac{\eta}{2} \cdot \frac{e}{2mc} \vec{S}$$

General idea:

- Inject polarised particles with spin pointing towards the momentum direction
- “Frozen Spin”-Technique: without EDM spin stays aligned to momentum
- EDM couples to electric bending fields
- EDM leads to a polarization build-up in vertical direction

<u>Challenge:</u>
Control of the Orbit with a very high accuracy to prevent systematic effects

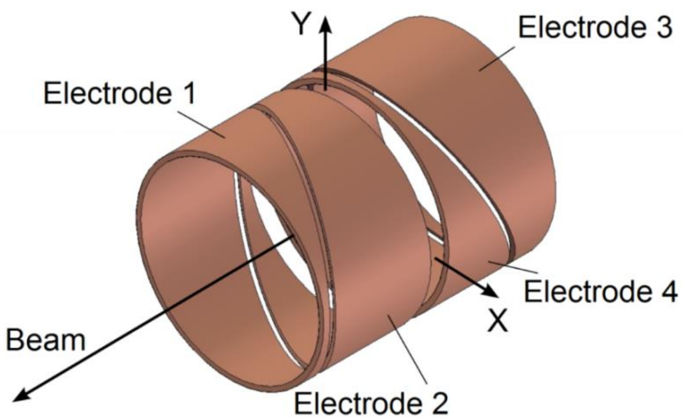
Cooler Synchrotron COSY in Jülich



Beam Position Monitor (BPM)

BPM measures transverse beam positon (x_0, y_0)

Electrostatic BPM (Standard at COSY):

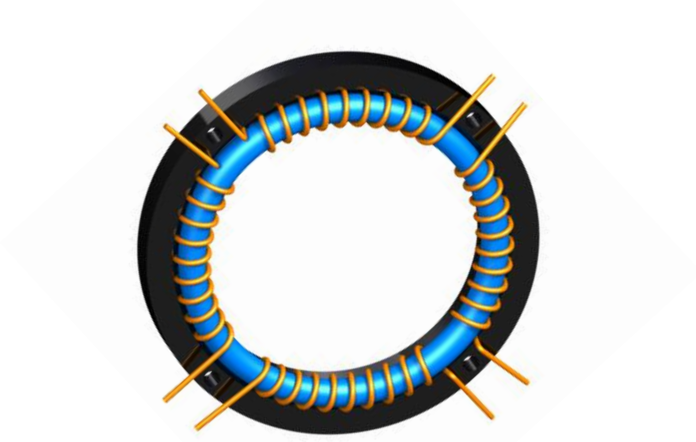


Length ≈ 20 cm

Easy to manufacture

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

Magnetostatic BPM (New Development):



Length ≈ 1 cm

Excellent response to an RF signal

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

Rogowski Coil

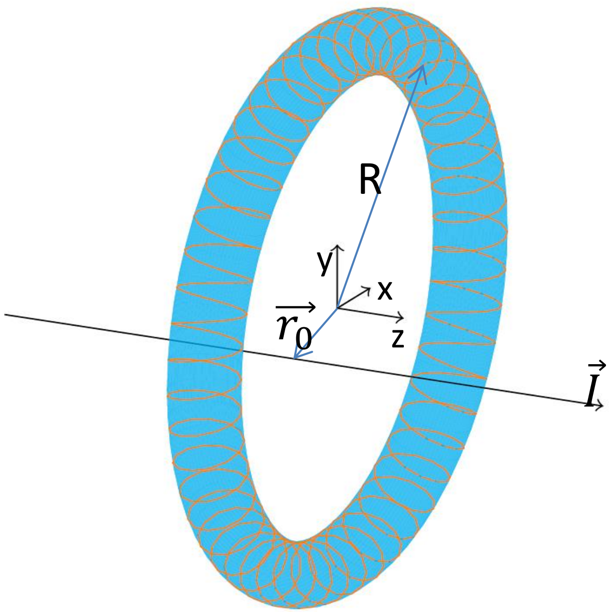
Pickup-Coil to measure the magnetic flux:

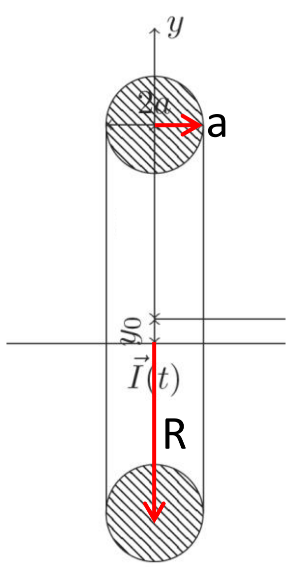
Standard application to measure AC currents

Torus with:

- Major radius $R = 40\ mm$
- Minor radius $a = 5\ mm$
- Winding with copper wire $N = 1400$

- Divided into
    - One segment (BCT)
    - Two segments (BPM in one dimension)
    - Four segments (BPM in two dimensions)





Magnetic Field of Particle Beam

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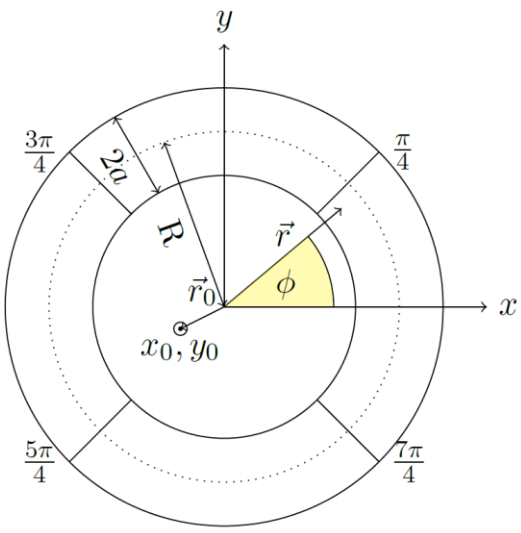


Model:
Pencil-current with constant velocity at position (x_0, y_0)

Particle Beam

Pickup-Coil

Current: $\vec{I} = I_0 \cdot \vec{e_z}$

Position: $\vec{r_0} = \begin{pmatrix} x_0 \\ y_0 \\ 0 \end{pmatrix}$

Position: $\vec{r} = \begin{pmatrix} x \\ y \\ z \end{pmatrix}$

Magnetic Field: $\vec{B} = \frac{\mu_0}{2\pi} \vec{I} \times \frac{\vec{r} - \vec{r_0}}{|\vec{r} - \vec{r_0}|^2}$

Induced Voltage

$$U_{ind} = -\frac{d}{dt}\int \vec{B}\cdot d\vec{A} = -\frac{d}{dt}\iiint B_\varphi drdzRd\varphi$$

Taylor of B_φ to $\mathcal{O}(r_0^2/R^2)$ leads to:

$$U_{ind,1/1} = \frac{dI_0}{dt} N\mu_0 \left[R - \sqrt{R^2 - a^2}\right]$$

Beam Current Transformator †

$$U_{ind,1/2} = \frac{dI_0}{dt}\frac{N}{2}\mu_0 \left[R - \sqrt{R^2 - a^2}\right]\left[1 - \frac{2}{\pi\sqrt{R^2-a^2}}x_0\right]$$

$$U_{ind,1/4} = \frac{dI_0}{dt}\frac{N}{4}\mu_0 \left[R - \sqrt{R^2 - a^2}\right]\left[1 - \frac{2\sqrt{2}}{\pi\sqrt{R^2-a^2}}x_0 - \frac{r_0^2 \sin(2\Psi - 2\varphi)\, a^2}{\pi(R^2-a^2)^{3/2}\cdot(R-\sqrt{R^2-a^2})}\right]$$

† “Mutual inductances comparison in Rogowski coil with circular and rectangular cross-sections and its improvement” http://dx.doi.org/10.1109/ICIEA.2008.4582770

Position Dependency Prediction of a halved Rogowski Coil

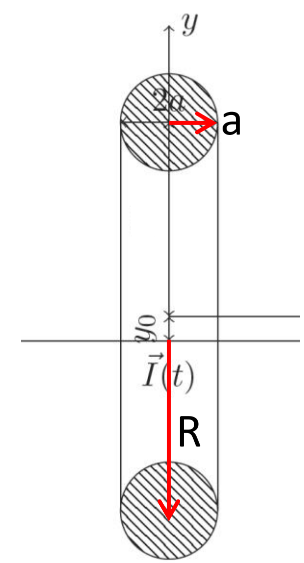
Rogowski coil measures the flux density change
A voltage is induced and the beam position can be determined by:

$$x \propto \frac{U_{Ind,left} - U_{Ind,right}}{U_{Ind,left} + U_{Ind,right}}$$

Theoretical prediction for position dependency of a halved coil as a horizontal BPM should be independent of the vertical beam position and the other way round

Theoretical prediction signal response for a halved coil:

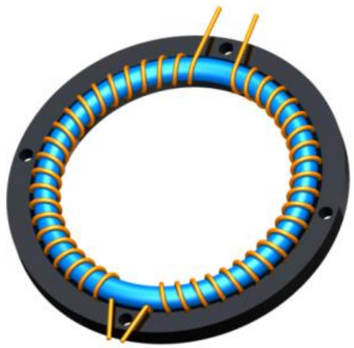
$$\frac{\Delta U_{1/2}}{\Sigma U_{1/2}} = \frac{2}{\pi\sqrt{R^2 - a^2}} x \longrightarrow x = \frac{\pi\sqrt{R^2 - a^2}}{2} \frac{\Delta U_{1/2}}{\Sigma U_{1/2}}$$



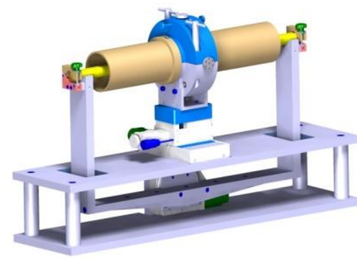
(linear for the x direction) (R radius of the coil, a radius of the toroid)

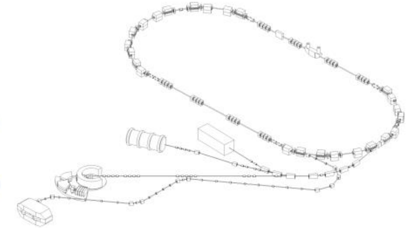
Technical Approach

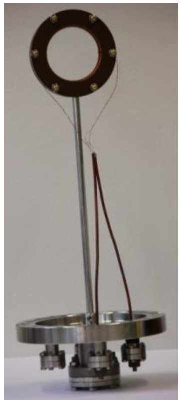
1. Step: Development of a coil with two segments (BPM in one dimension)



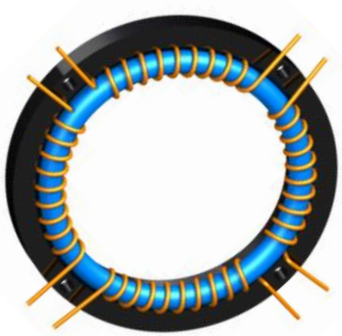
Development of a testbench and measurements with this coil as an horizontal BPM at COSY



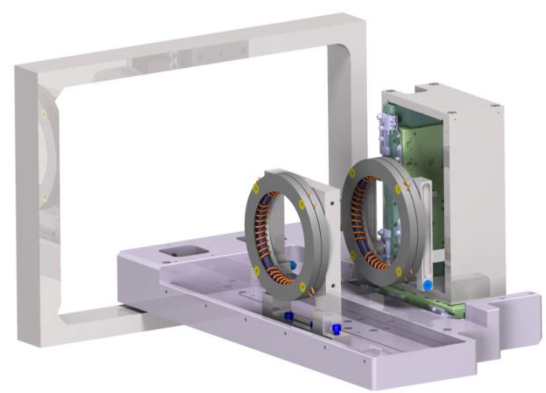




2. Step: Development of a coil with four segments (BPM in horizontal and vertical direction)

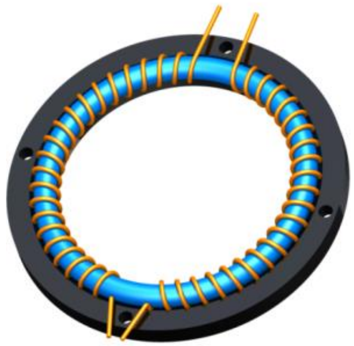


Installation of two Rogowski coils as horizontal and vertical BPMs at COSY

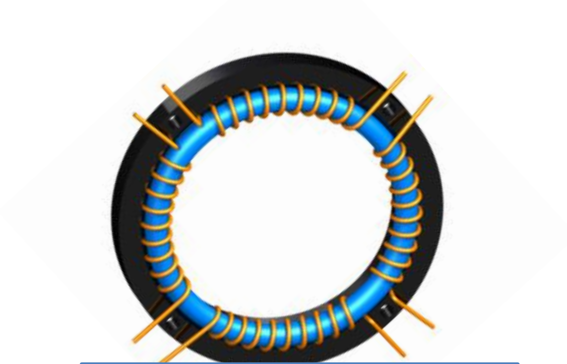


Technical Approach

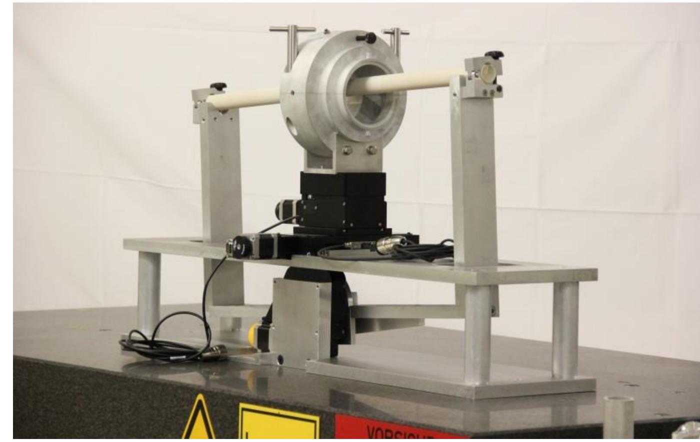
3. Step: Characterise the horizontal Rogowski BPM and the horizontal and vertical Rogowski BPM in the laboratory



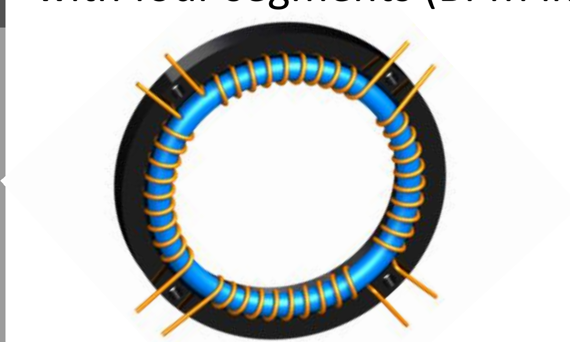
horizontal Rogowski BPM

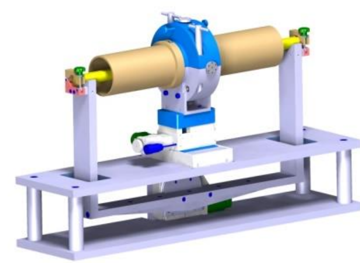


horizontal & vertical Rogowski BPM

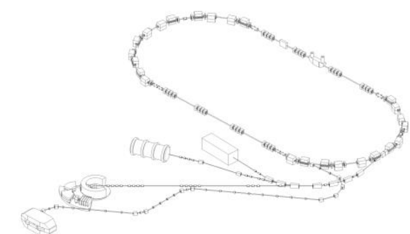


4. Step: Development of a nitrogen or liquid helium cooled coil with four segments (BPM in vertical and horizontal dimension)



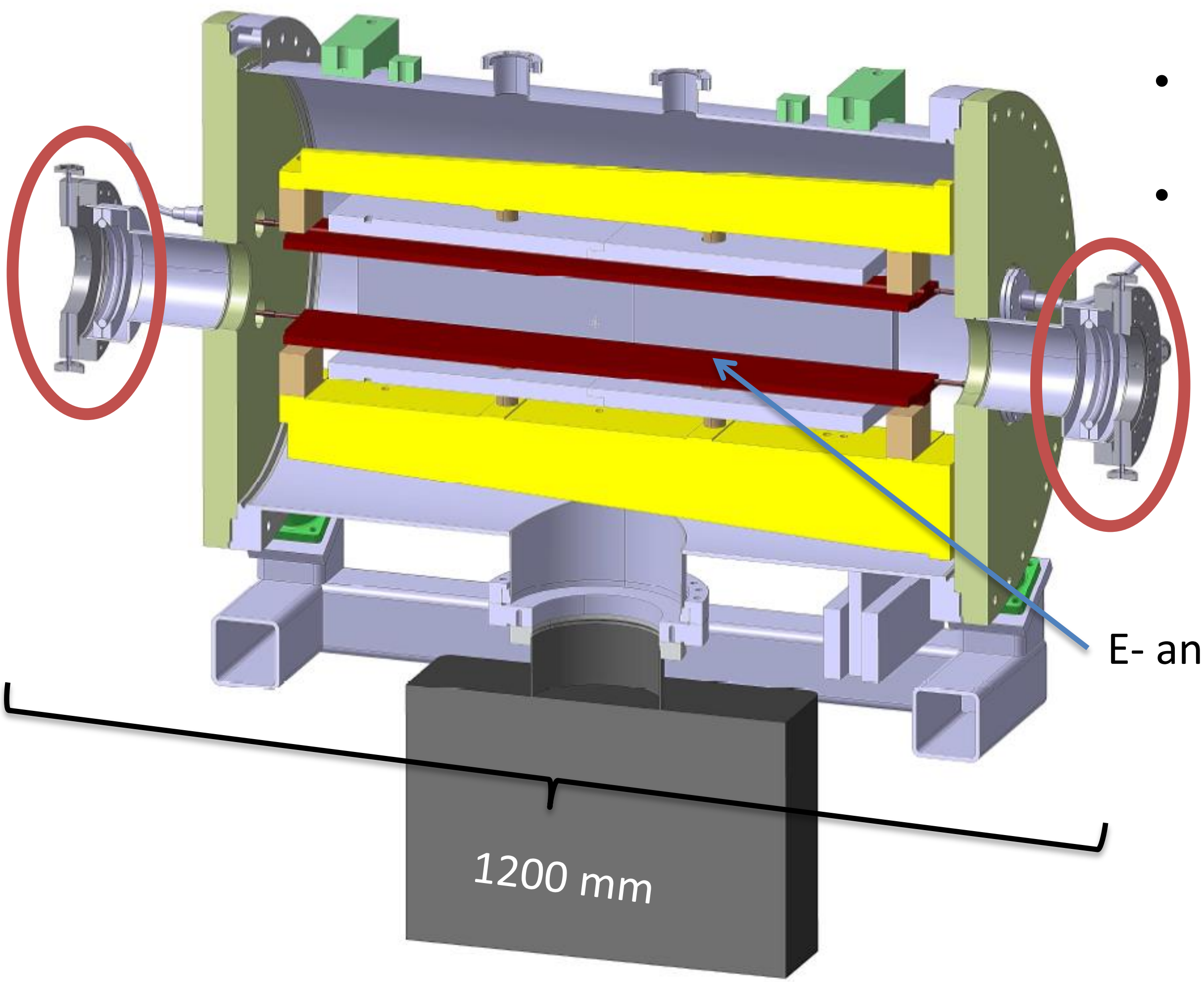


COSY



5. Step: Development of a SQUID-BPM test bench

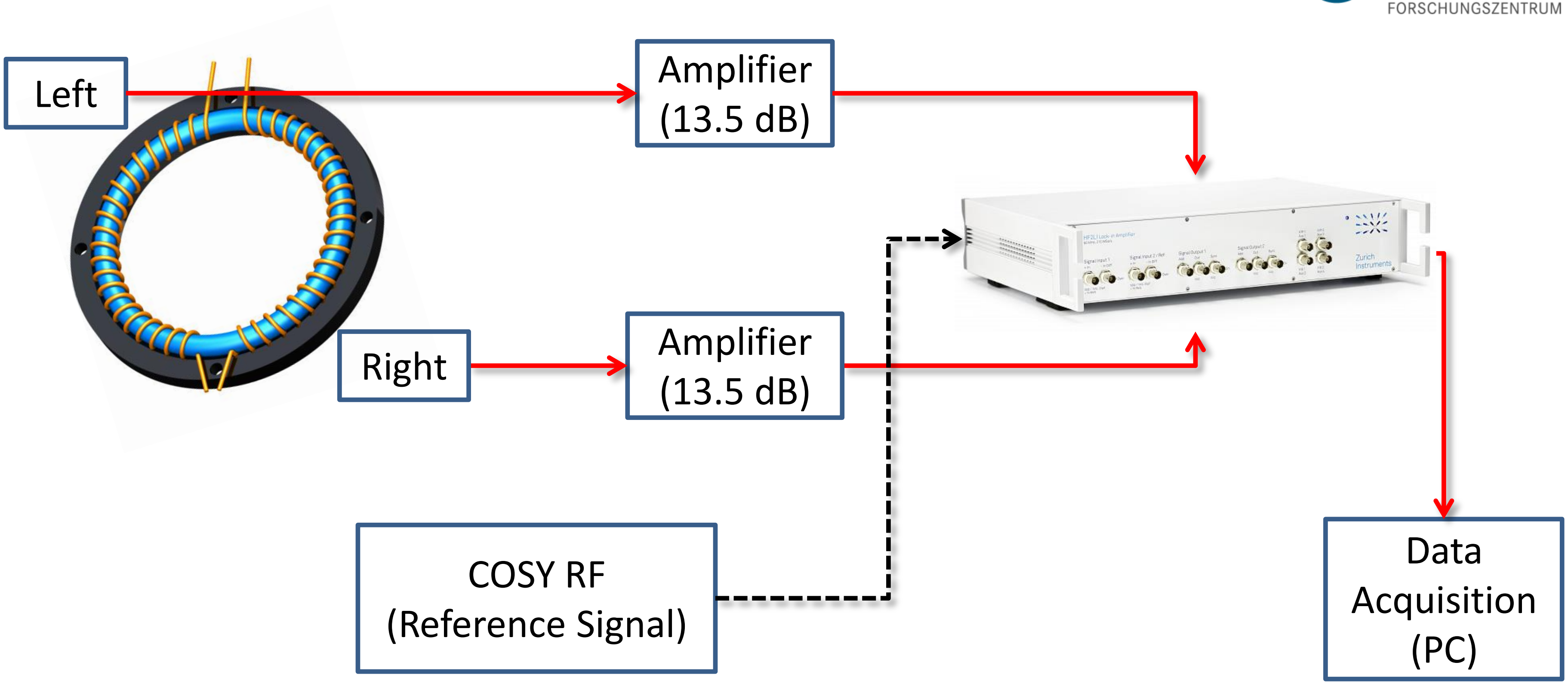
Rogowski BPM for RF Wien Filter



Installation between quadrupoles

- No COSY BPM next to it
- Installation of Rogowski Coil BPMs at both ends
  - Position beam in center and parallel to Wien Filter

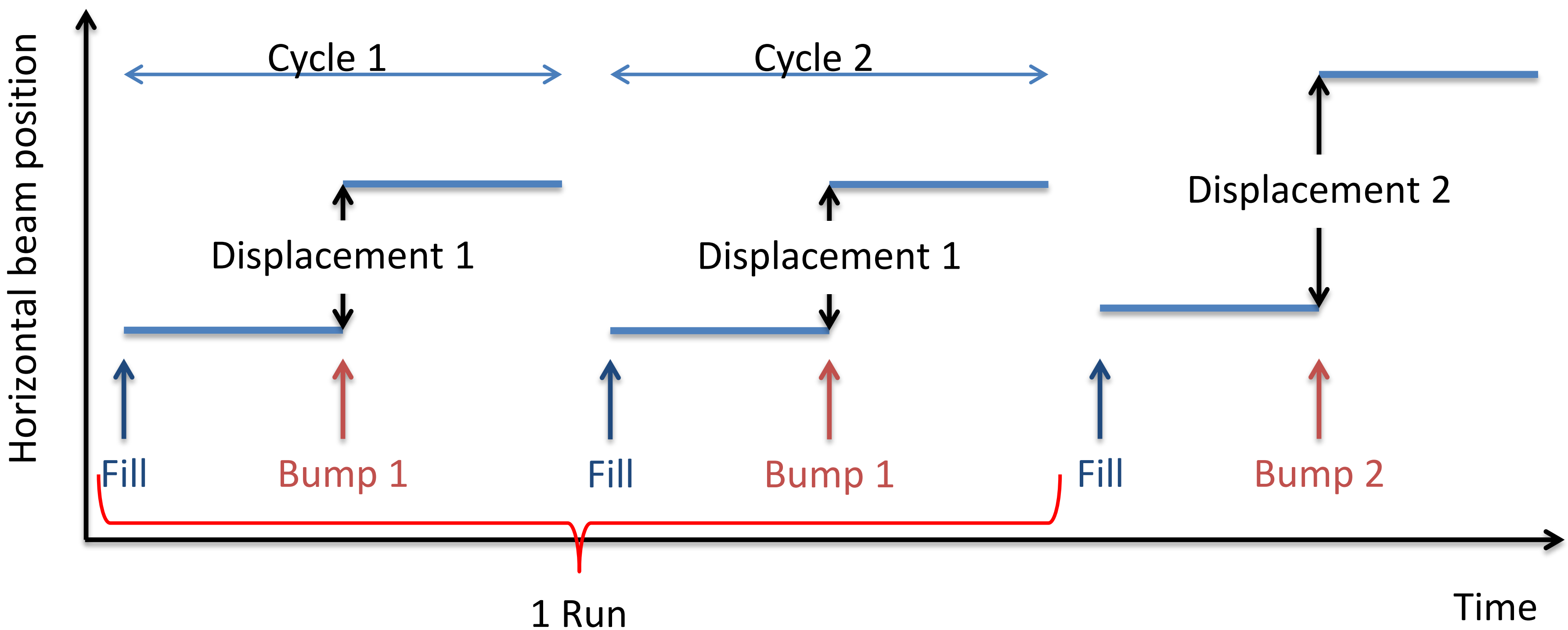
Measurement Setup



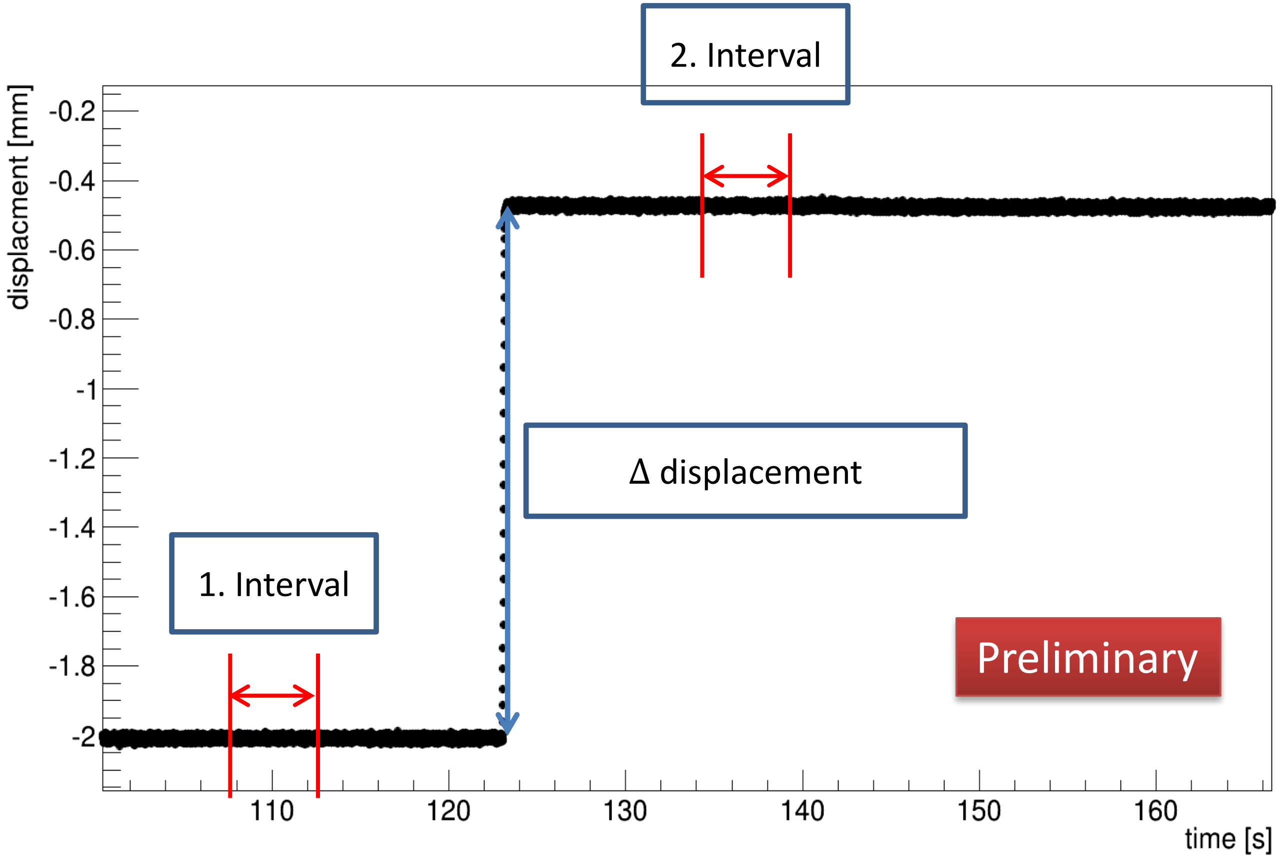
- Unpolarised, bunched deuteron beam (N$\sim 10^9$),
- Momentum 970 MeV/c, revolution frequency 750 kHz
- Horizontal or vertical orbit bump after 33 seconds

Measurement horizontal Displacement

- Measurement of the induced voltages every 4.45 ms for each part of the Rogowski coil
- Create different horizontal orbit bumps with two correctors
- Calculate the displacement as difference of the reference orbit and the orbit bump



Analyse Procedure

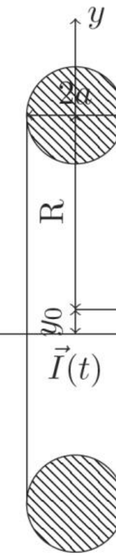


Position determination:

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

Coil Parameters:

R = 40mm
a = 5 mm



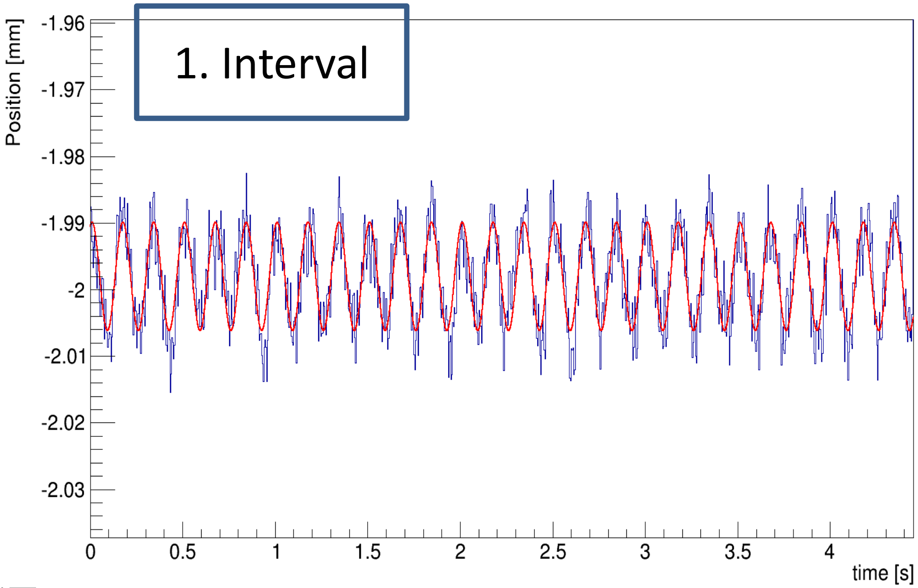
- Define an interval of 1000 data points (4.45s) for the reference orbit (1. Interval) and the orbit bump (2. Interval)
- Calculate the Δdisplacement for each measurement

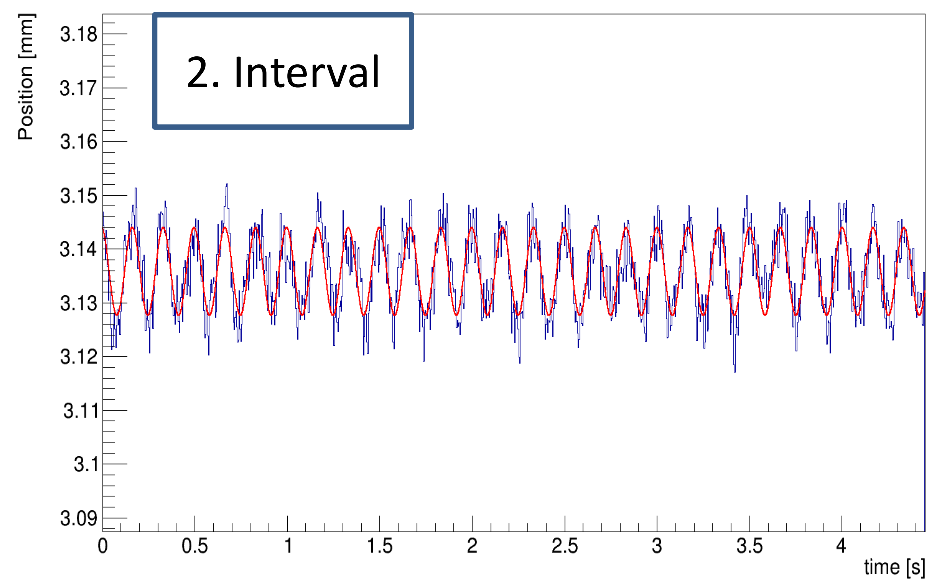
Analyse Procedure

Fit function: $a + A \cdot \sin(2\pi f t + \varphi)$ → Looking for a

$$\sigma_{x,Voltage} = \frac{\pi}{2}\sqrt{R^2 - a^2}\frac{1}{(U_2 + U_1)^2}\sqrt{4{U_1}^2\sigma_U^2 + 4{U_2}^2{\sigma_U}^2} \approx 3\mu m$$

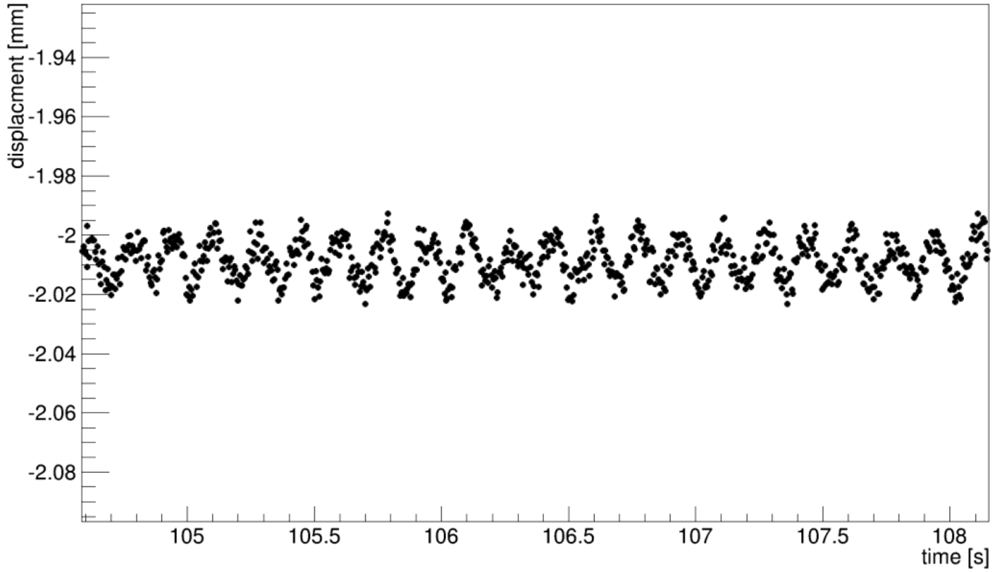
$\sigma_U \approx 0.1\ \mu\text{V}$





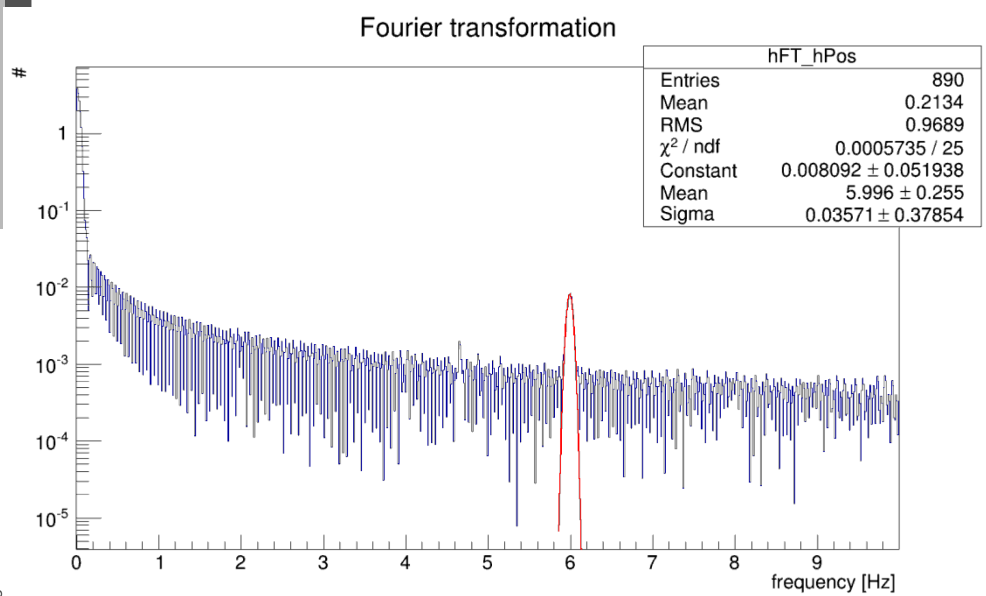
Fit: $\sigma_a \approx 0.1\ \mu m$ (statistical error)

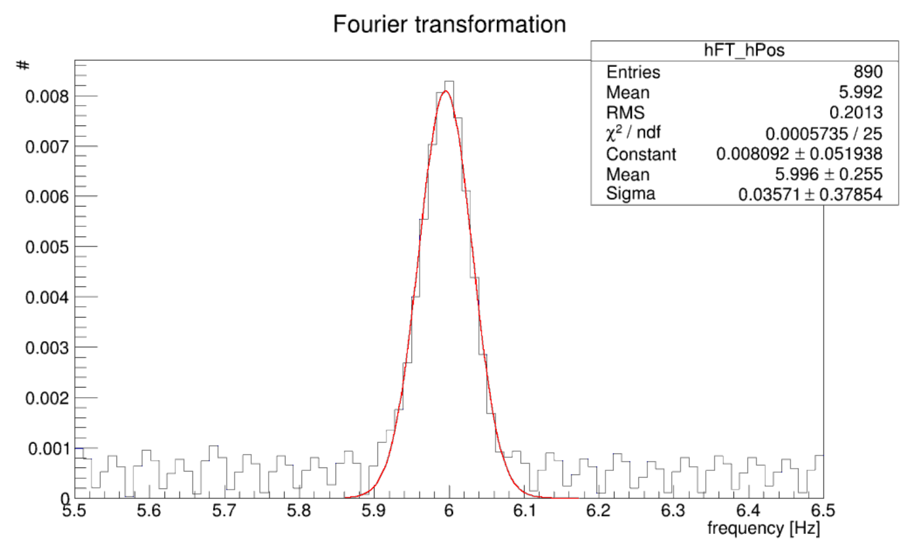
Beam oscillation or mechanical vibrations?



Beam position oscillation with 6 Hz

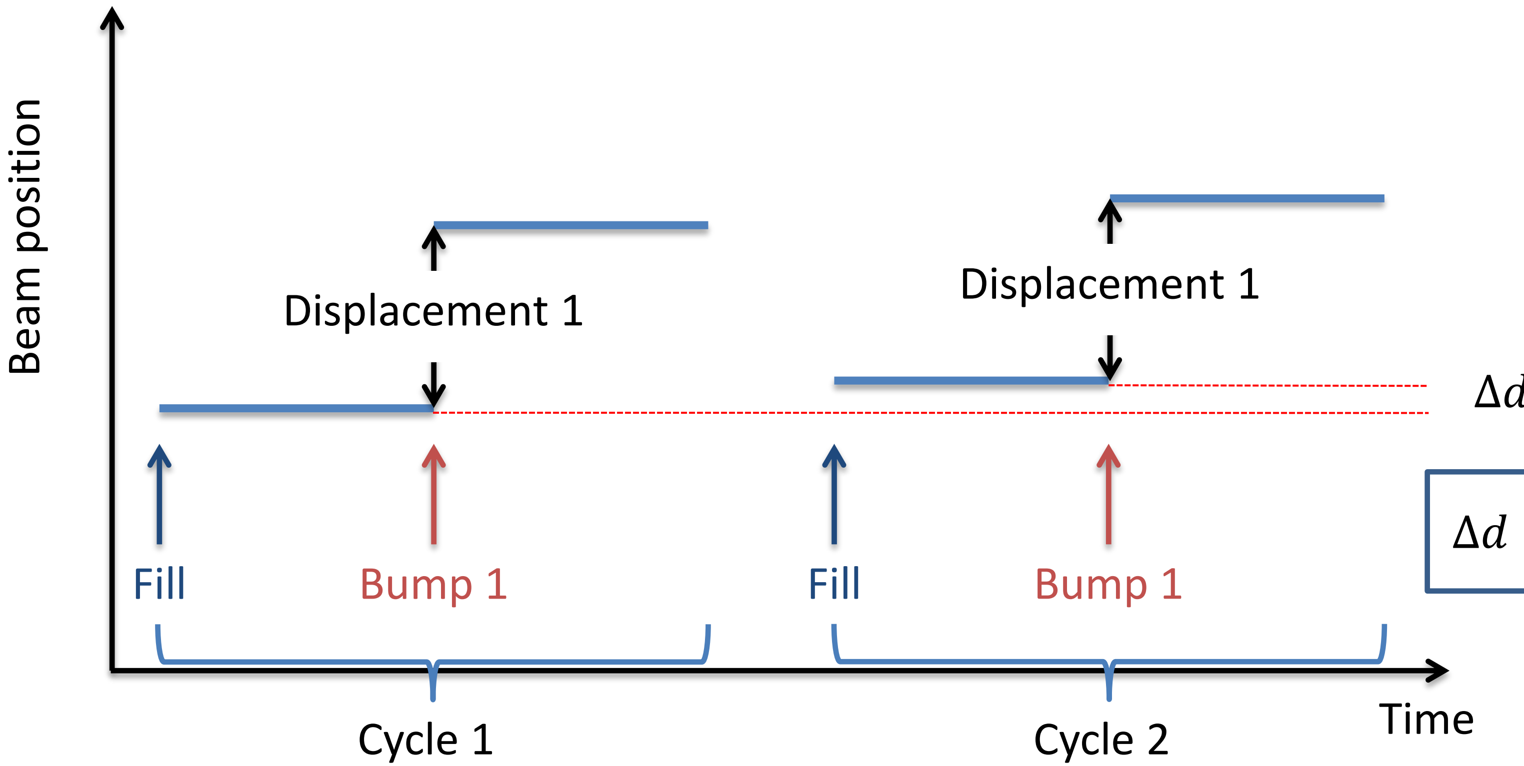
- The source of this oscillation is unknown until now
- With the standard COSY BPM system it is not possible to disentangle the oscillation





Displacement variation from cycle to cycle

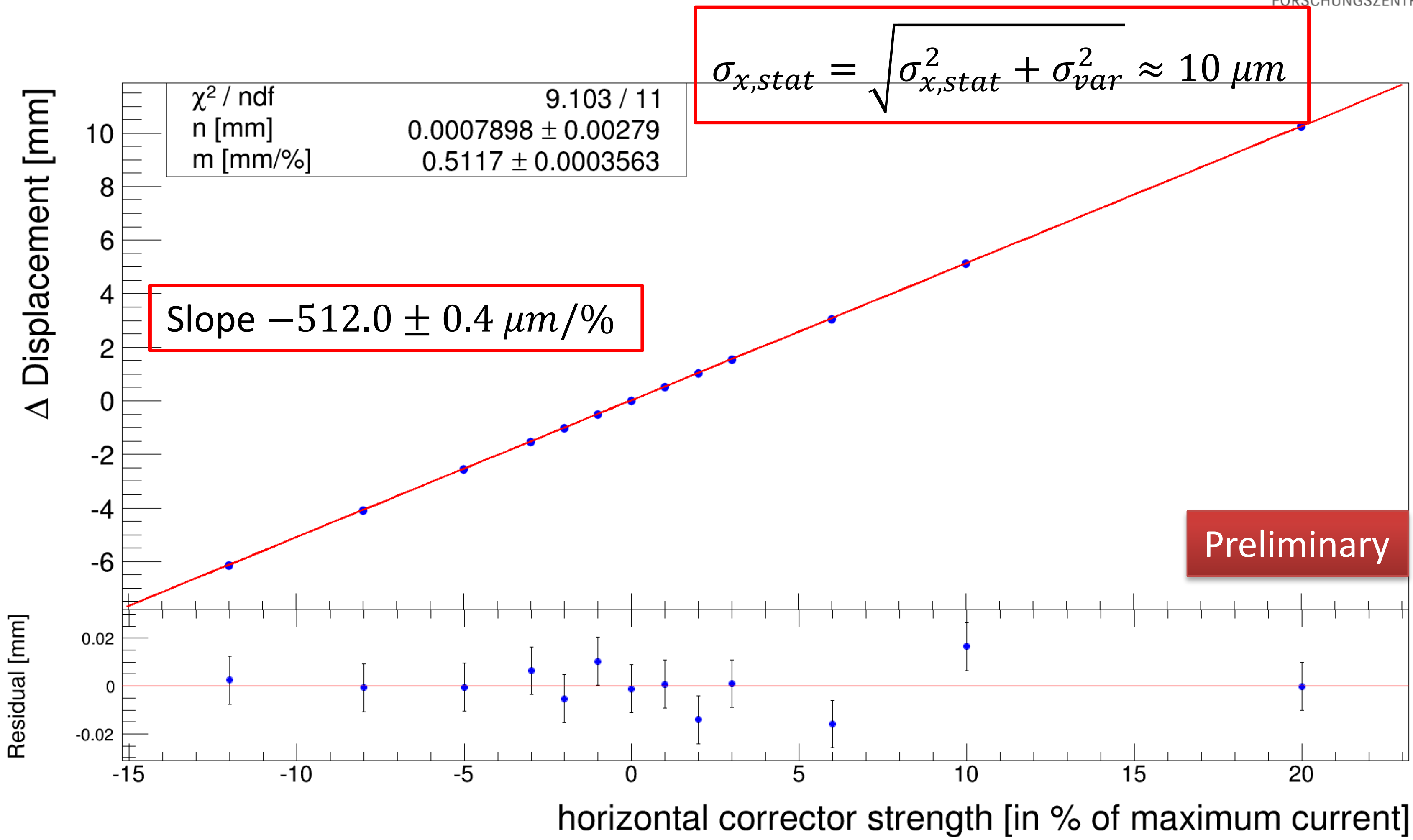
Determine the variation of the displacement from cycle to cycle with constant magnet settings



$$\Delta d = \Delta P_2 - \Delta P_1$$

$$\sigma_{var} = 10\ \mu m$$

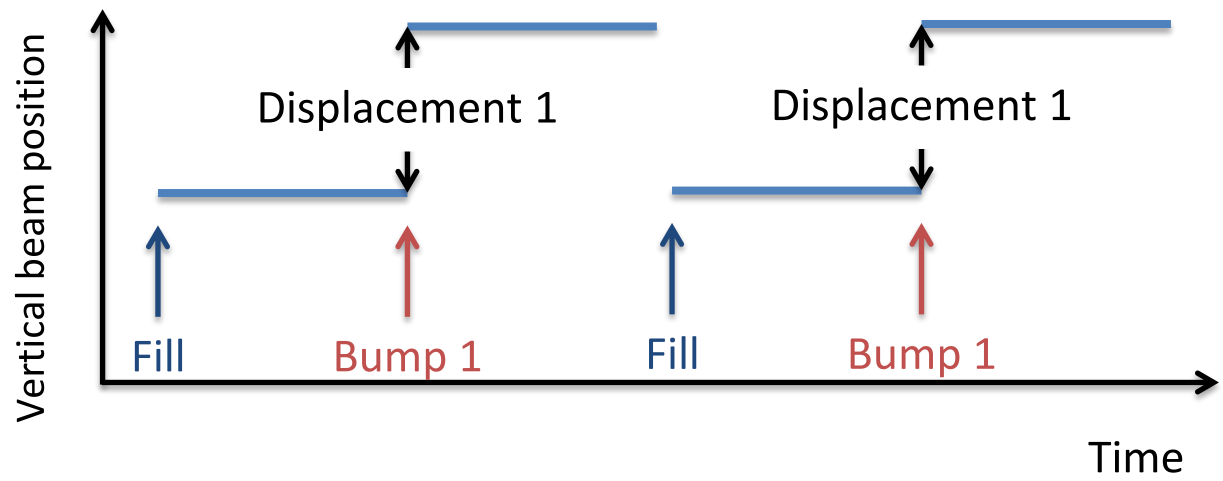
Varying Horizontal Corrector Strength



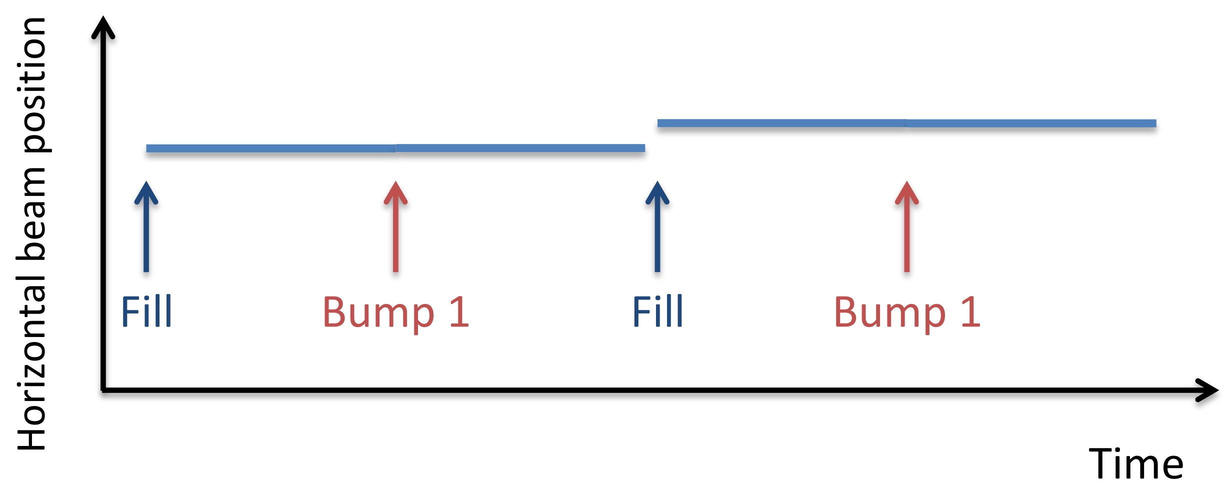
Theoretical expectation is consistent with the horizontal orbit measurmenet at the accelerator

Measurement horizontal beam dis-placement in denpendency of a vertical orbit bump

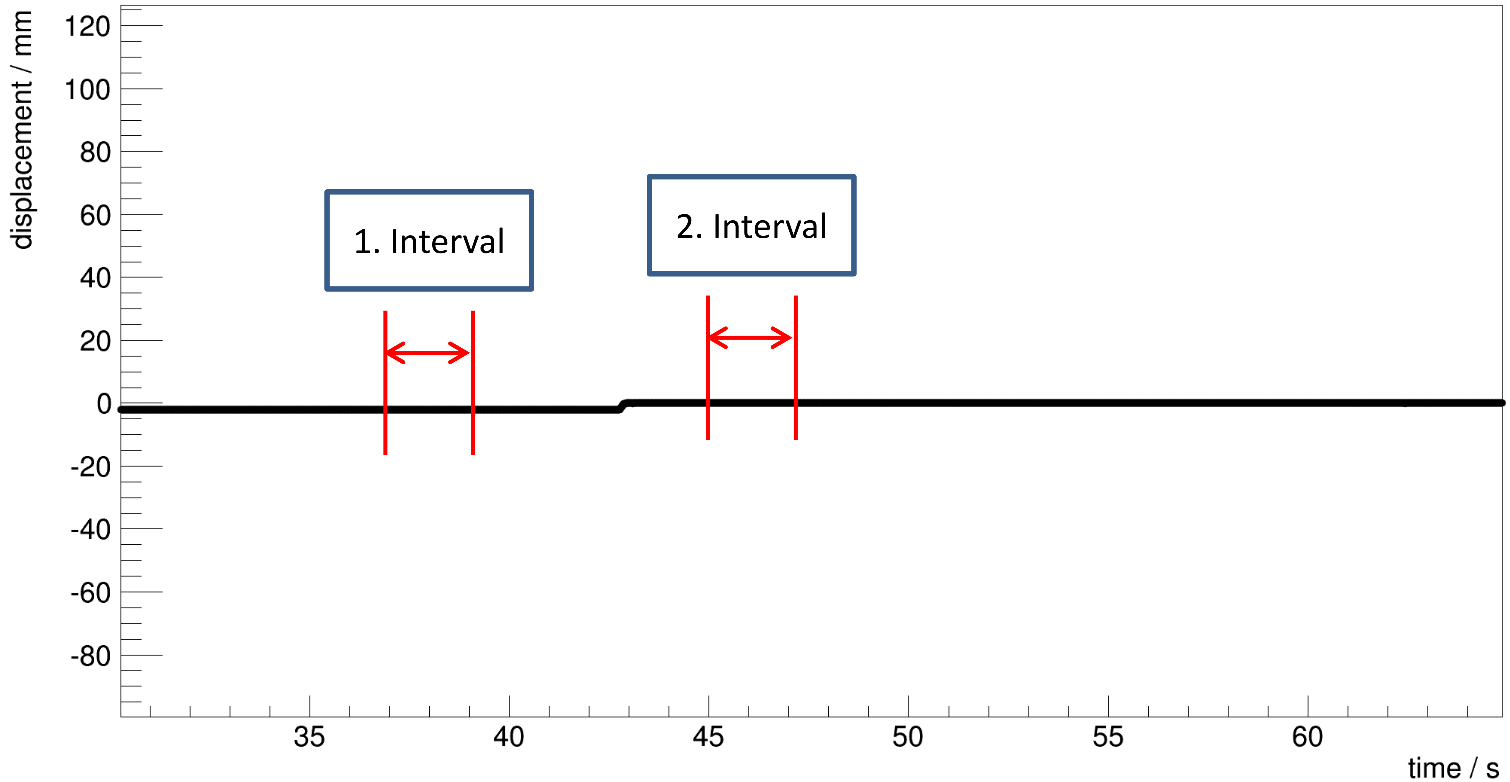
Changing the vertical orbit position with two vertical correctors



Measurement of the horizontal beam position



Horizontal orbit measurement with vertical corrector bump

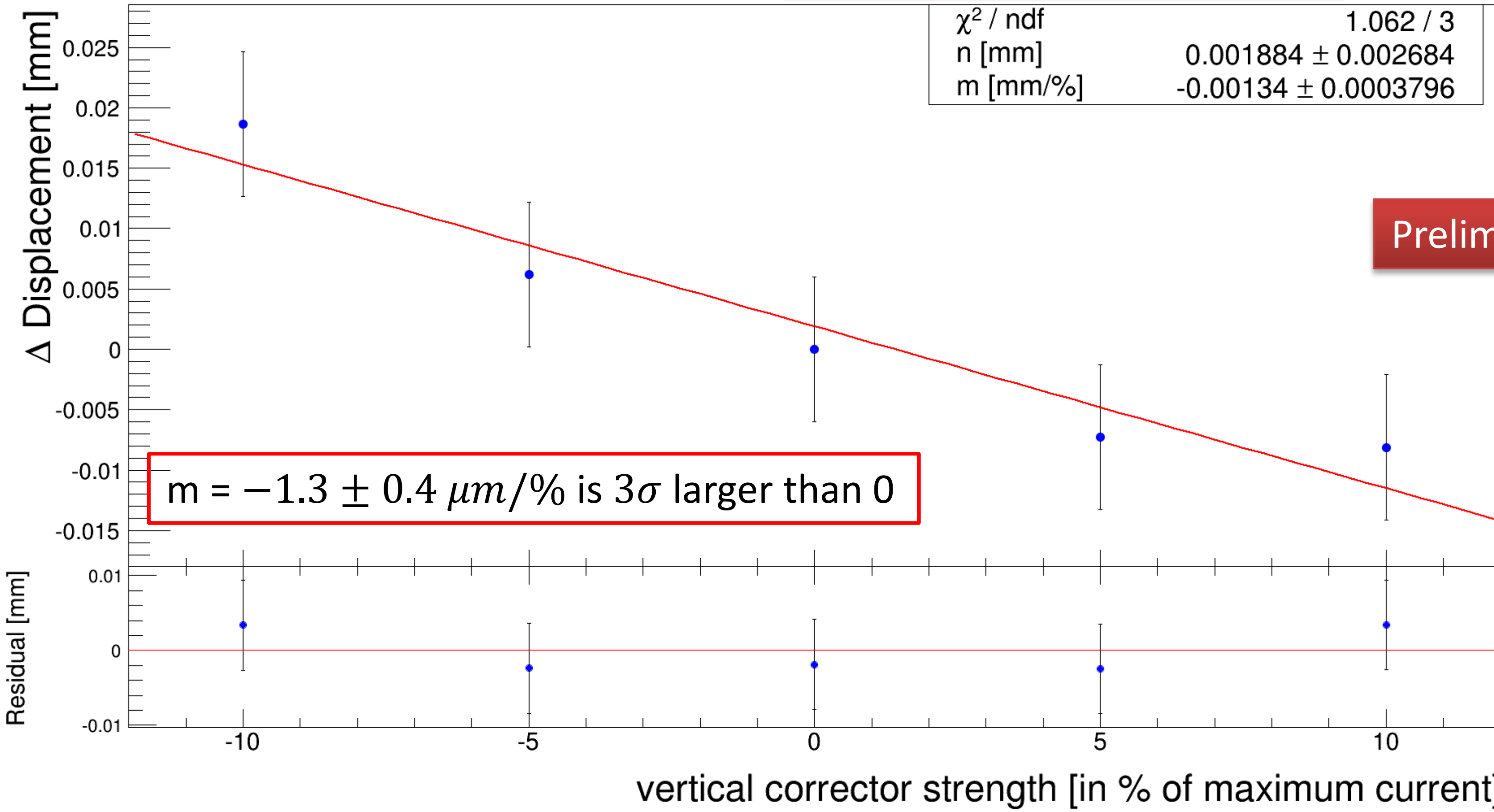


Determine the horizontal $\Delta displacement$ between the intervals for the different verical orbit bumps

The measured horizontal beam position should be independent of the vertical beam poisition

Horizontal orbit measurement with vertical corrector bump

$$\sigma_x = \sqrt{\sigma_{x,stat}^2 + \sigma_{var}^2} \approx 6\ \mu m$$

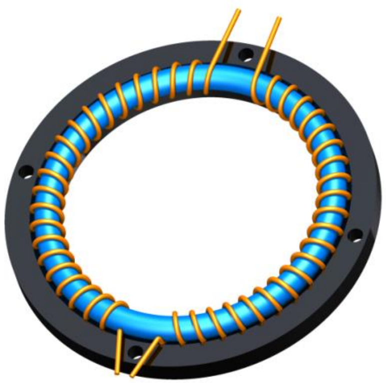


m = $-1.3 \pm 0.4\ \mu m/\%$ is 3σ larger than 0

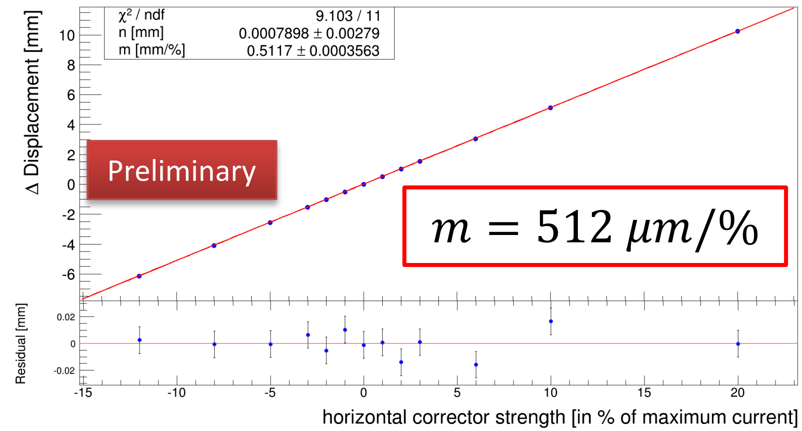
Expectation: no horizontal dependency → small slope, but can be driven from tilts in the magnets or tilt of the coil itself

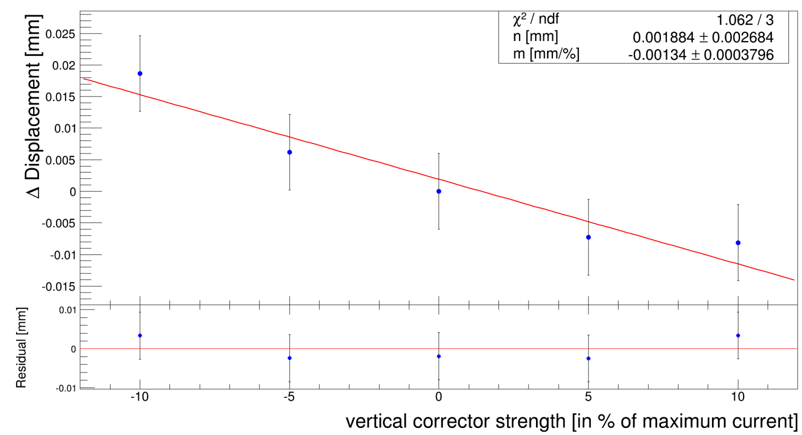
Summary

Installation of a Rogowski Coil as horizontal BPM in COSY



Measurement of the horizontal and vertical beam position dependency

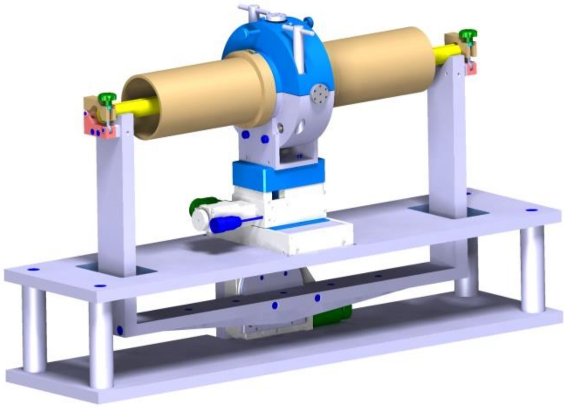


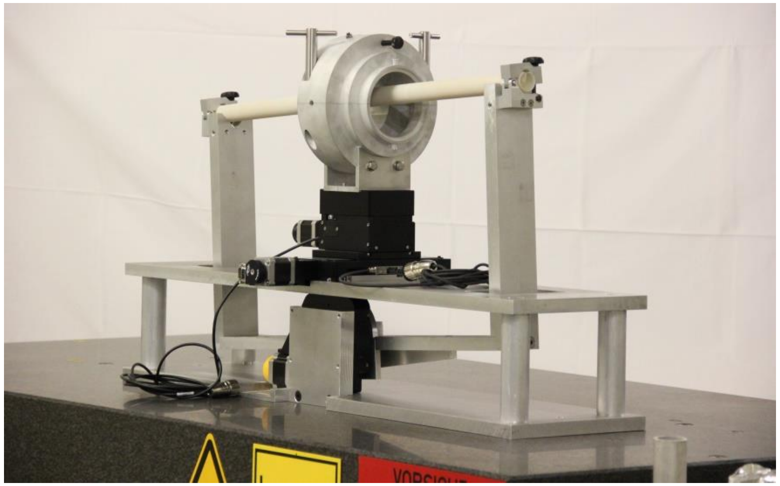


- An uncooled Rogowski coil worked as an horizontal BPM in an accelerator enviroment
- The theoretical predictions for an horizontal BPM have been proven
- The measured sensitivity to the perpendicular axis is at least 400 times smaller and can be regarded as negligible within the confidence intverval

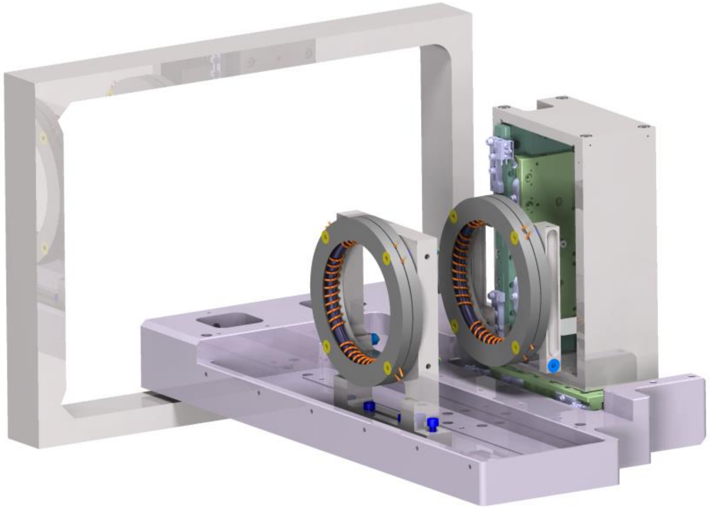
Outlook

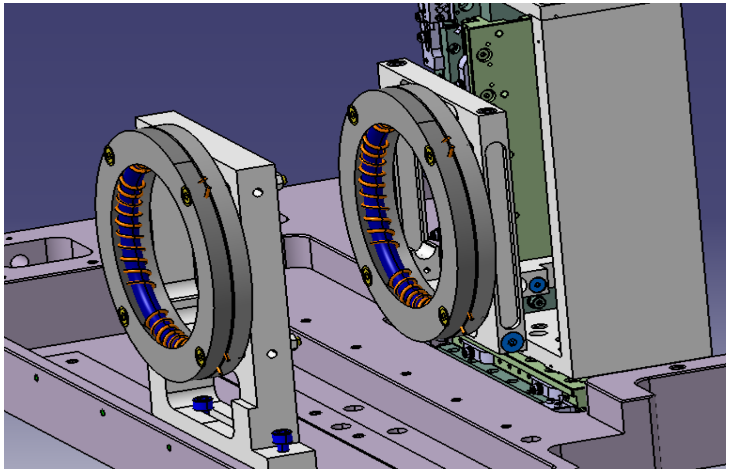
Characterisation of the horizontal and vertical Rogowski BPMs in the laboratory





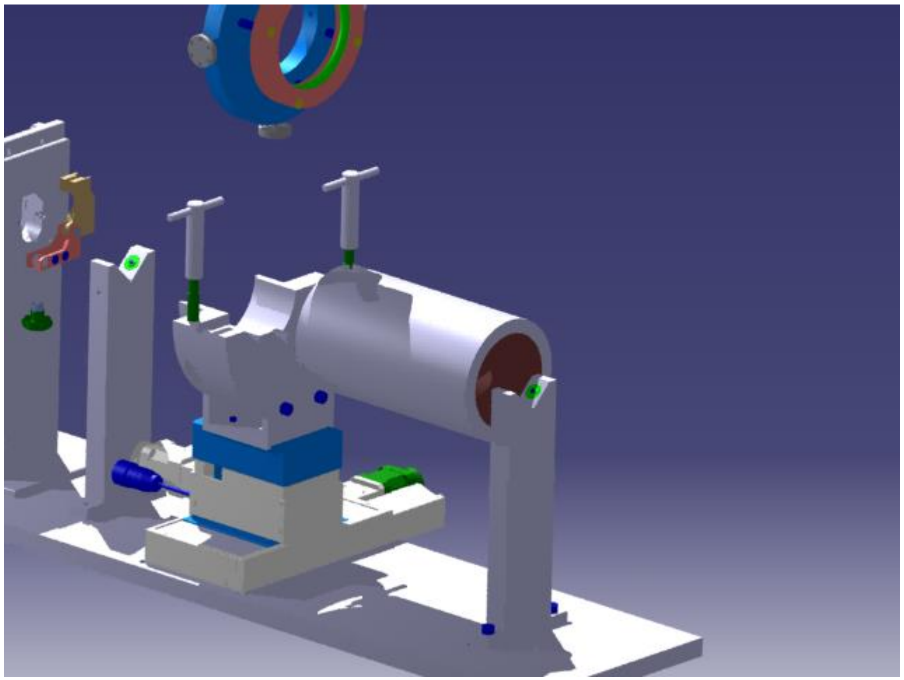
Installation of a moveable Rogowski coil in COSY



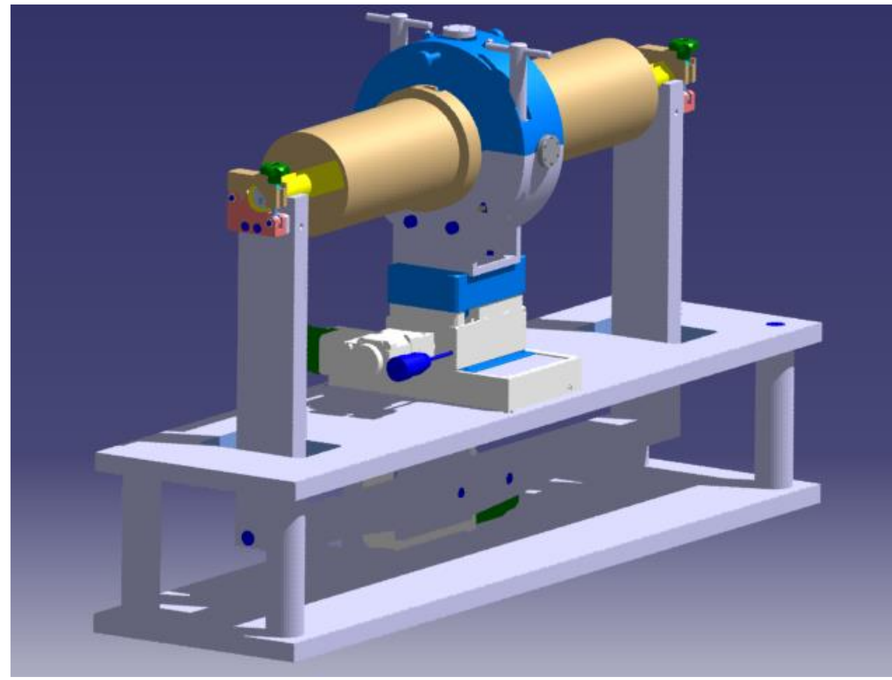


Rogowski Coil Testbench

Installation of the Rogowski coil

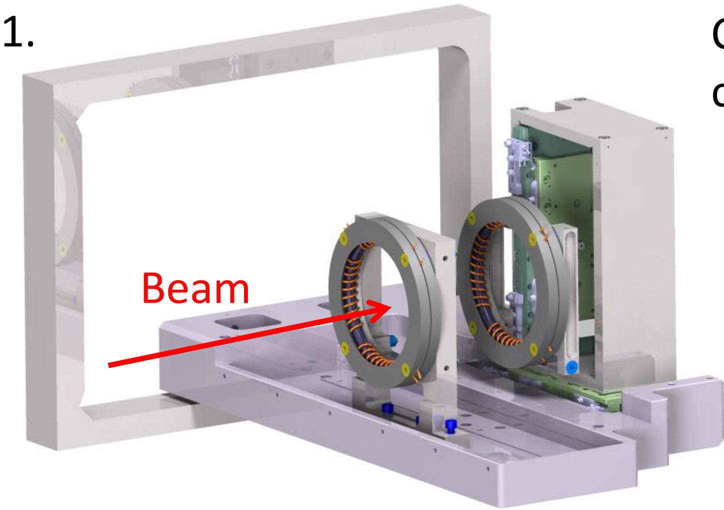


Movement of the Rogowski coil



Null detector

1.



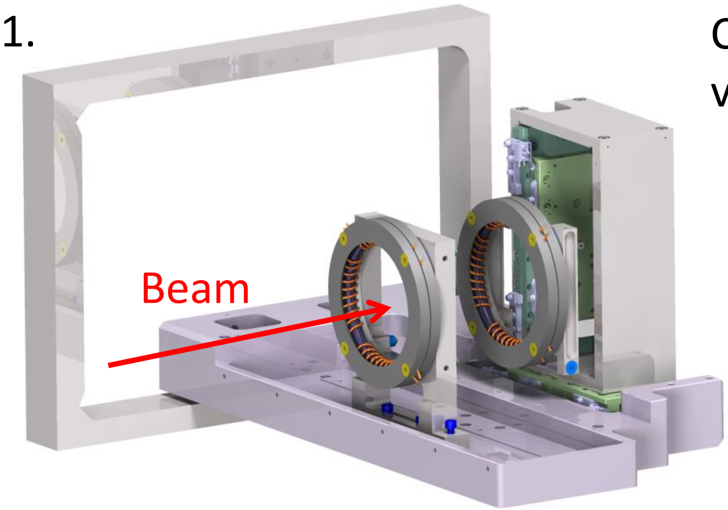
Changing the postion of the coil in horizontal and certical directon until the beam passes central the coil:

$$\frac{\Delta U_{up,dn}}{\Sigma U_{up,dn}} = 0 \quad \text{and} \quad \frac{\Delta U_{left,right}}{\Sigma U_{left,right}} = 0$$

→ Calibration of Referenz Orbit
Highest Sensetivity at Coil Centre

Null detector

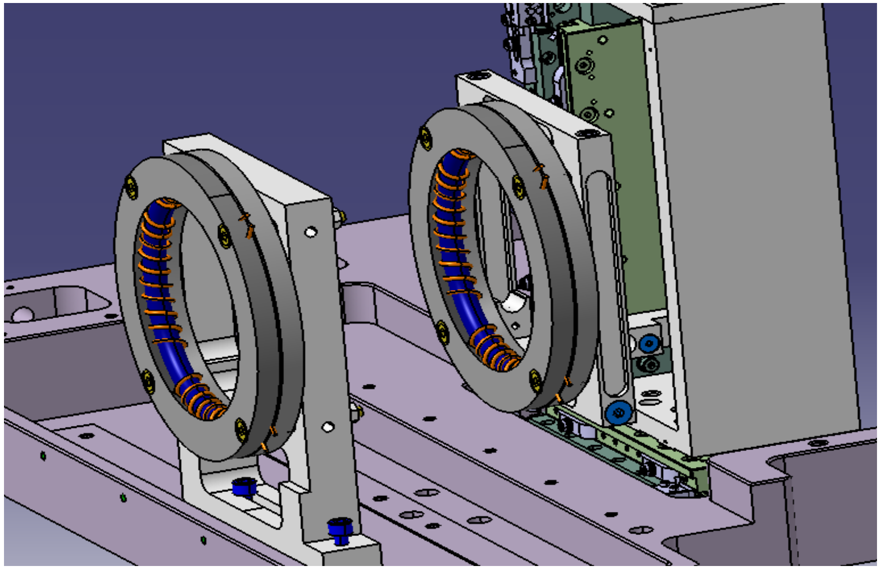
1.



Changing the position of the coil in horizontal and vertical direction until the beam passes central the coil:

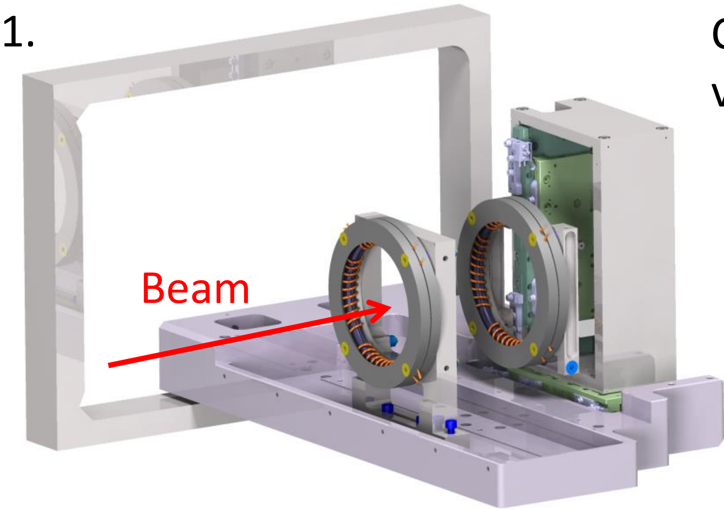
$$\frac{\Delta U_{up,dn}}{\Sigma U_{up,dn}} = 0 \quad \text{and} \quad \frac{\Delta U_{left,right}}{\Sigma U_{left,right}} = 0$$

→ Calibration of referenz orbit
Highest sensitivity at coil centre



Null detector

1.

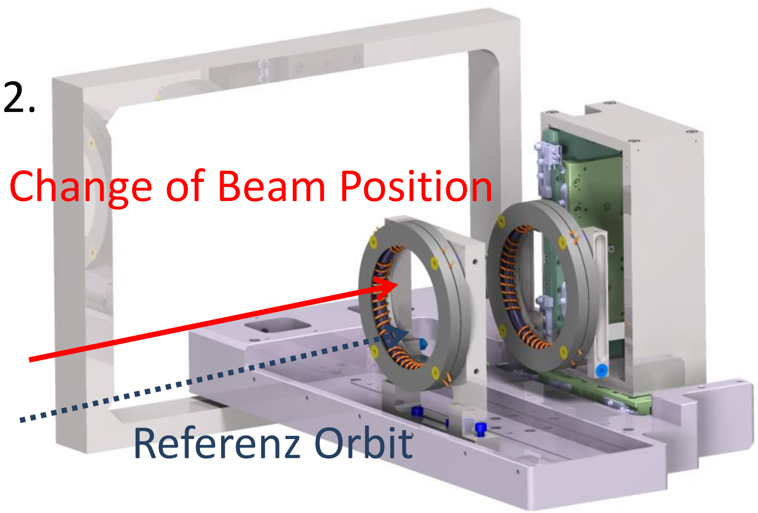


Changing the position of the coil in horizontal and vertical direction until the beam passes central the coil:

$$\frac{\Delta U_{up,dn}}{\Sigma U_{up,dn}} = 0 \quad \text{and} \quad \frac{\Delta U_{left,right}}{\Sigma U_{left,right}} = 0$$

→ Calibration of referenz orbit
Highest sensitivity at coil centre

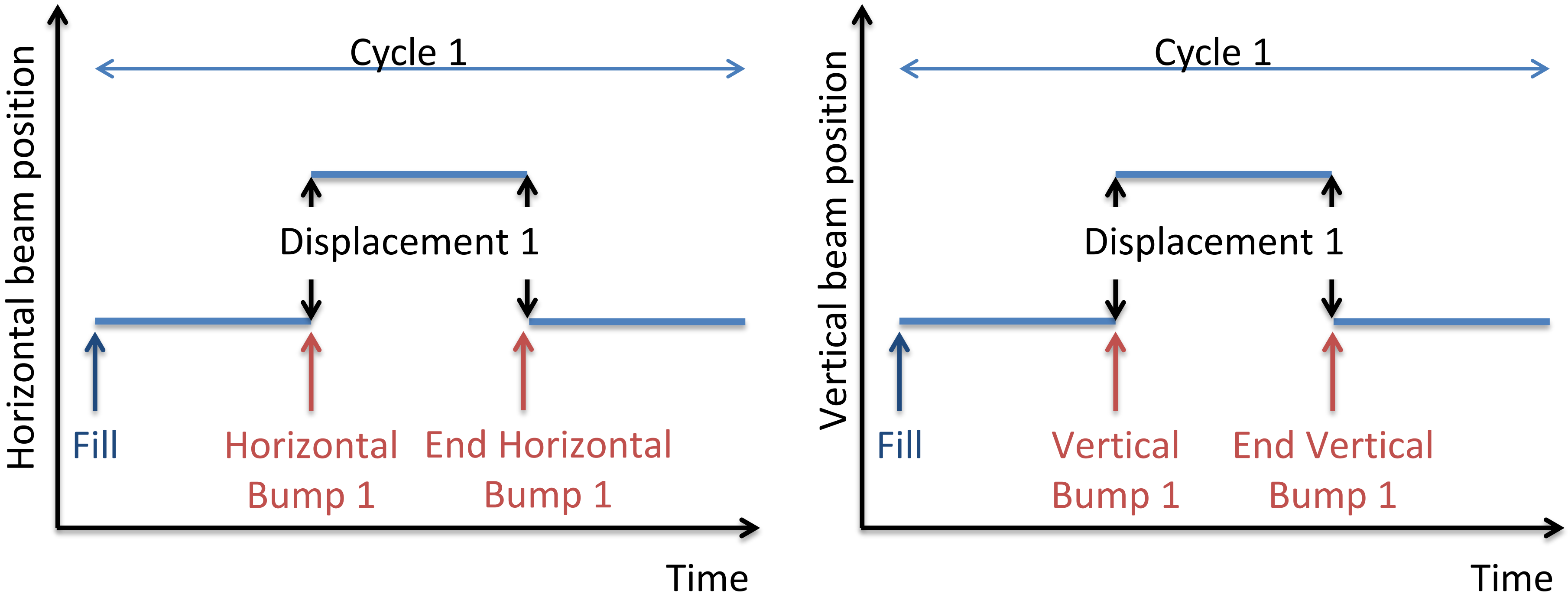
2.



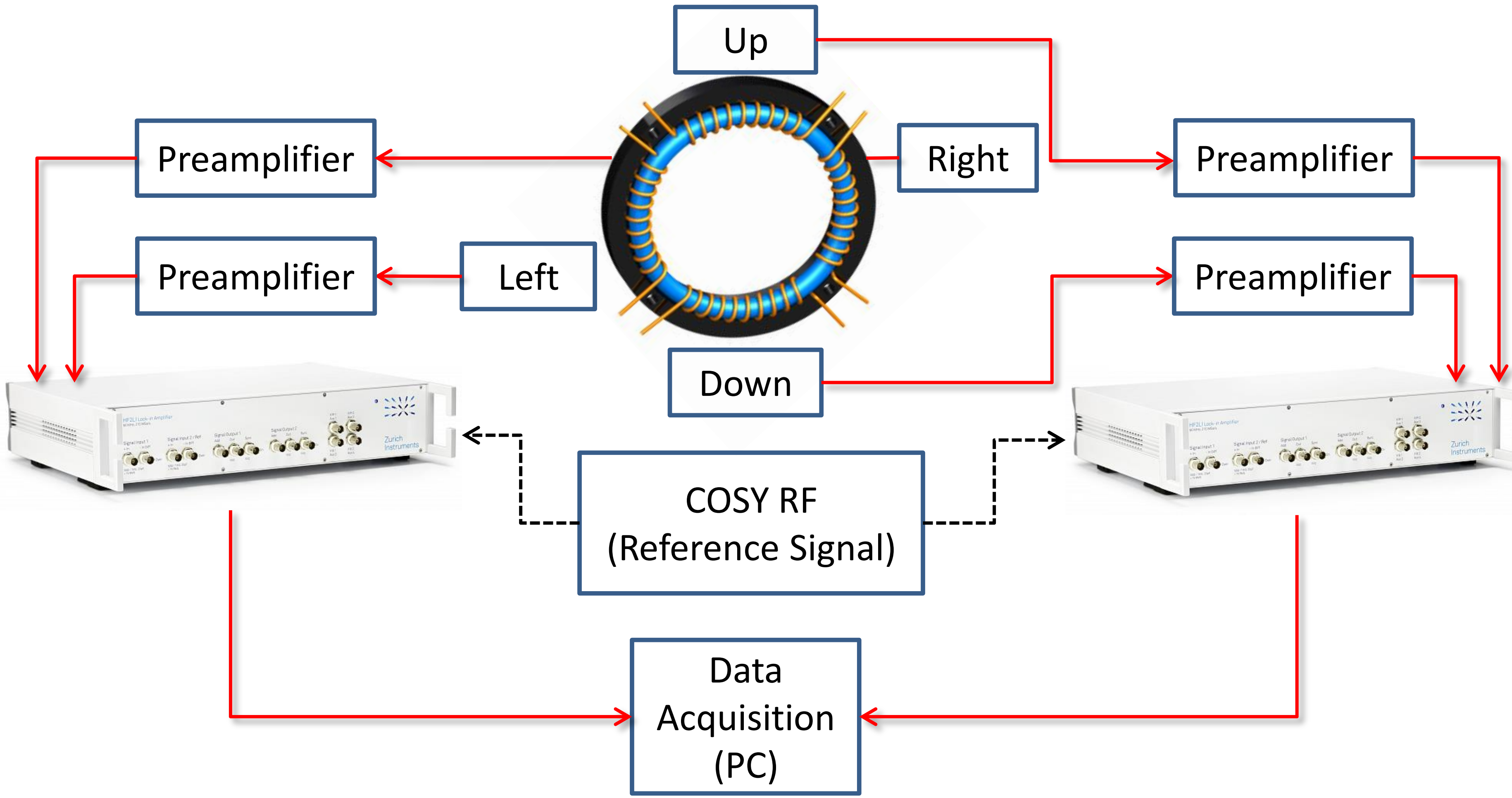
Changing the coil position until:

$$\frac{\Delta U_{up,dn}}{\Sigma U_{up,dn}} = 0 \quad \text{and} \quad \frac{\Delta U_{left,right}}{\Sigma U_{left,right}} = 0$$

→ Measurement of a relative orbit change



Horizontal beam position
Cycle 1
Displacement 1
Fill
Horizontal
Bump 1
End Horizontal
Bump 1
Time
Vertical beam position
Cycle 1
Displacement 1
Fill
Vertical
Bump 1
End Vertical
Bump 1
Time


Up
Right
Left
Down
Preamplifier
Preamplifier
Preamplifier
Preamplifier
COSY RF
(Reference Signal)
Data
Acquisition
(PC)