Development of Closed Orbit Diagnostics toward EDM Measurements at COSY in Jülich

March 17, 2016 | Fabian Hinder[1, 2] for the JEDI collaboration
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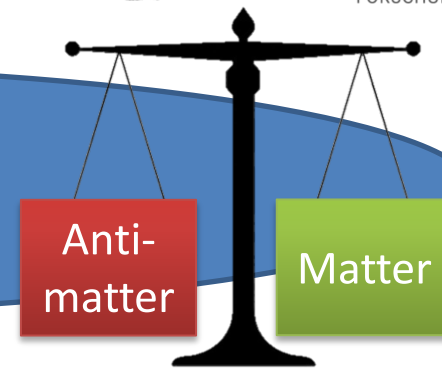
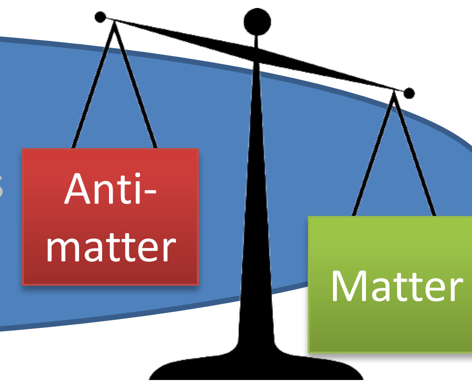
Baryogenesis

<u>Big Bang</u>
Symmetry between
matter & antimatter



<u>Early Universe</u>
Three Sakharov conditions:
1. Baryon number violating interactions
2. Non thermal equilibrium
3. **Violation of $\mathcal{C}$, $\mathcal{CP}$ symmetry**



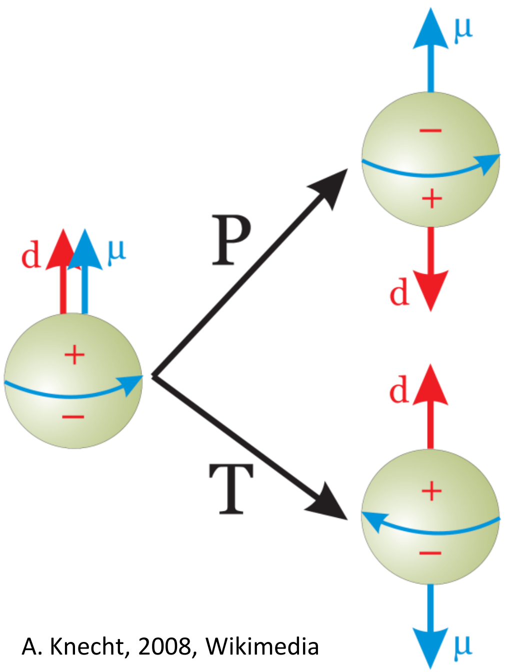
via: Strong $\mathcal{CP}$ violation (SM)
Electroweak $\mathcal{CP}$ violation (SM)
Beyond SM physics

<u>Today</u>

	Measurement (WMAP 2003)	Standard Model Expectation
$(\eta_B - \eta_{\bar{B}})/\eta_\gamma$	$(6.14 \pm 0.25) \cdot 10^{-10}$	10^{-18}

Matter

Electric Dipole Moments (EDMs) as CP Violating Source



A. Knecht, 2008, Wikimedia

$$\vec{\mu} = g \cdot \frac{e}{2m} \vec{s}$$

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

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

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

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

- Permanent EDMs of light hadrons are $\mathcal{T}$-violating
  - $\mathcal{CPT}$ theorem ⇒ $\mathcal{CP}$ violation

- Search for new $\mathcal{CP}$ violation by measuring EDMs of charged particles in storage rings

- SM: $d \approx 10^{-31} ecm$

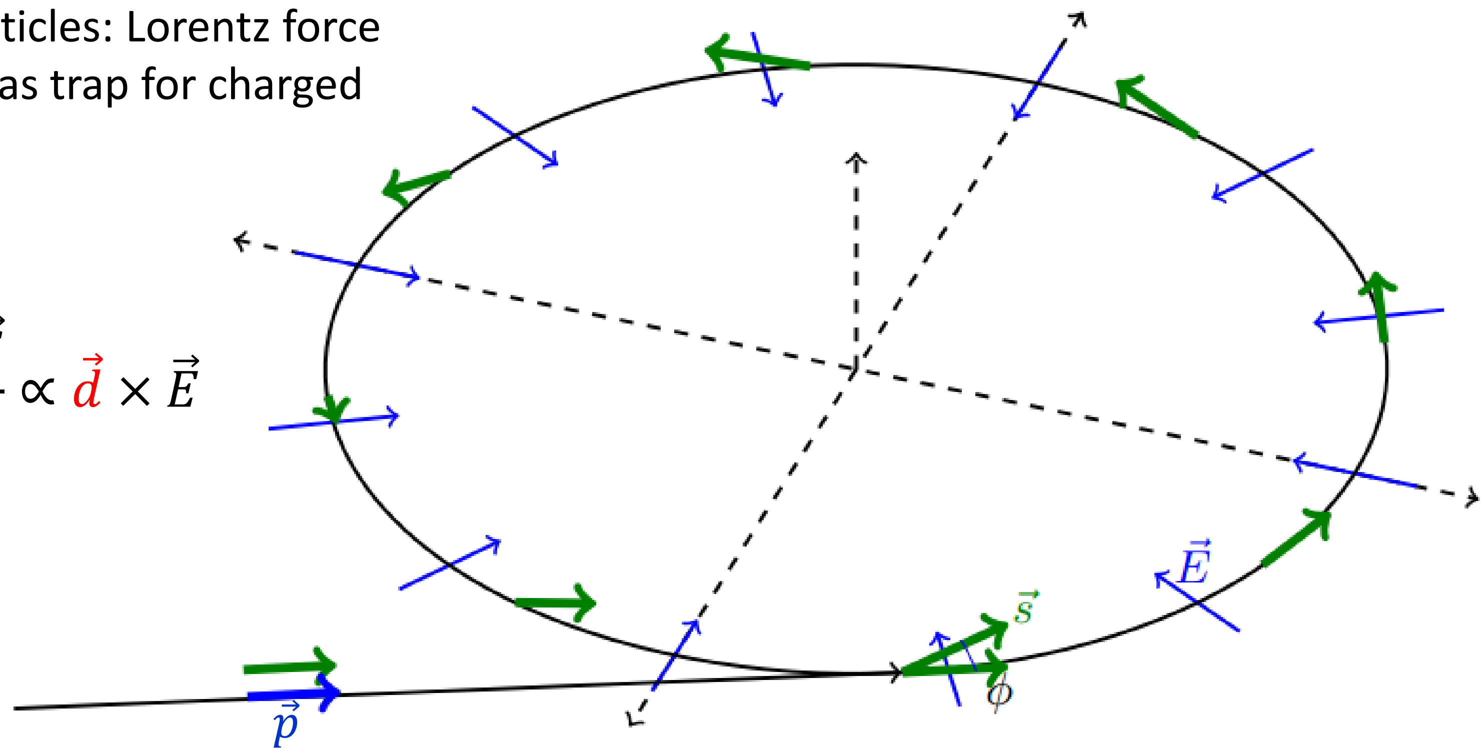
Measure EDMs in Storage Rings

(Frozen Spin Method)

All EDM experiments:

- Particle in trap
- Interaction of field $\vec{E}$ and EDM $\vec{d}$
  → Spin rotates
- Charged particles: Lorentz force
- Accelerator as trap for charged particles

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



Spin Motion in Storage Rings

Thomas-BMT-Equation:

$$\frac{d\vec{S}}{dt} = \vec{S} \times \vec{\Omega}_{MDM} + \vec{S} \times \vec{\Omega}_{EDM}$$

$$\vec{\Omega}_{MDM} = \frac{q}{m\gamma}\left(\gamma G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right)$$

$$\vec{\Omega}_{EDM} = \frac{q\eta}{2m}\left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B}\right)$$

$$\vec{\mu} = 2(G+1)\frac{q}{2m}\vec{S}$$

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

	G
Proton	1.792847357
Deuteron	-0.142561769

Spin Motion in Storage Rings
(Pure Electric Ring)

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Pure electric ring:

- “Freeze” spin ⇒ $\vec{\Omega}_{MDM} = 0$
- Only possible for Protons (G>0)

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Spin Motion in Storage Rings

(Combined Ring $\vec{E}$ & $\vec{B}$)

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(Pure Magnetic Ring)

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Pure magnetic ring:
- Frozen spin not possible ($\nu_s = \gamma G$)

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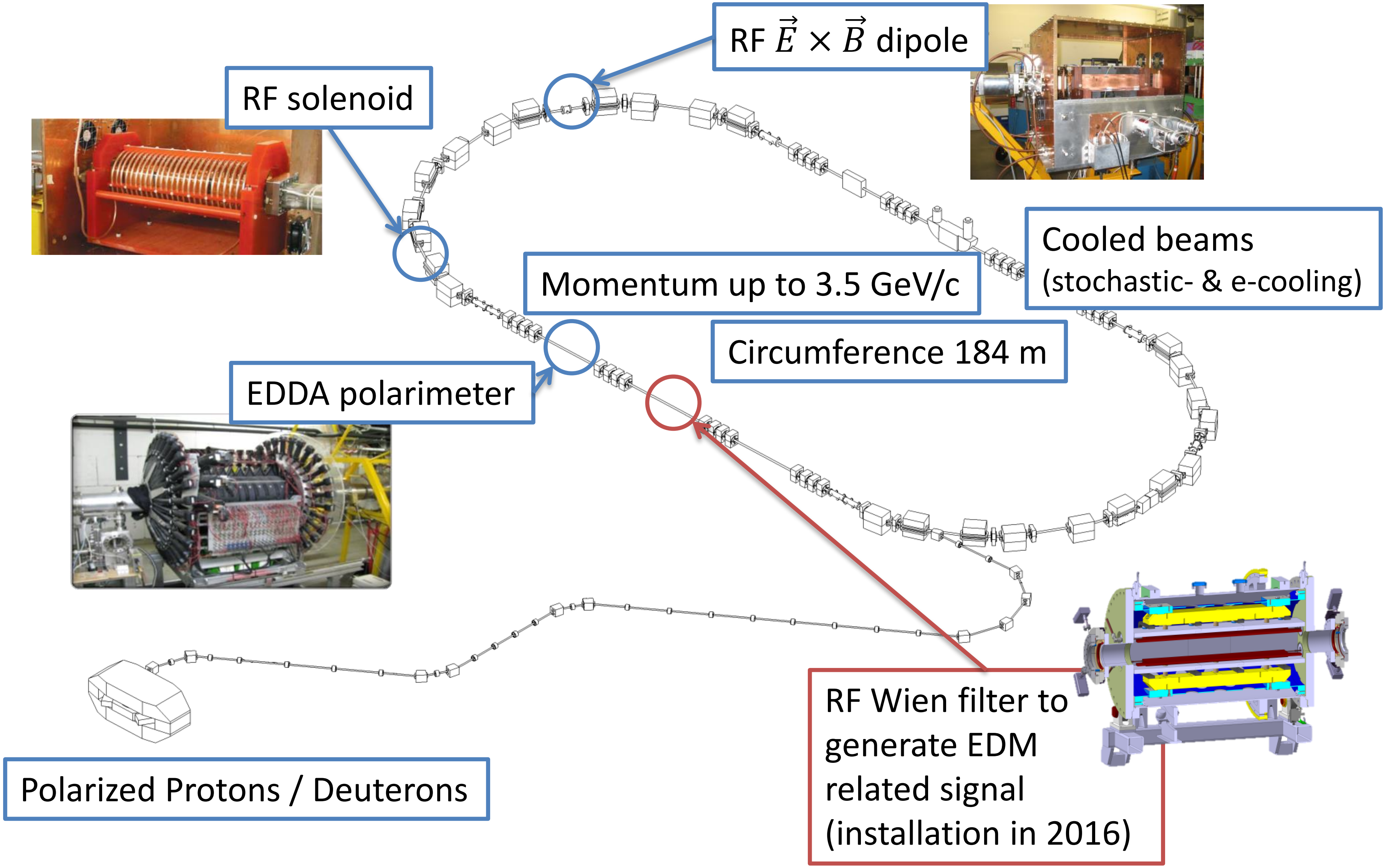
New method proposed to measure EDMs at COSY Jülich

Cooler Synchrotron COSY in Jülich



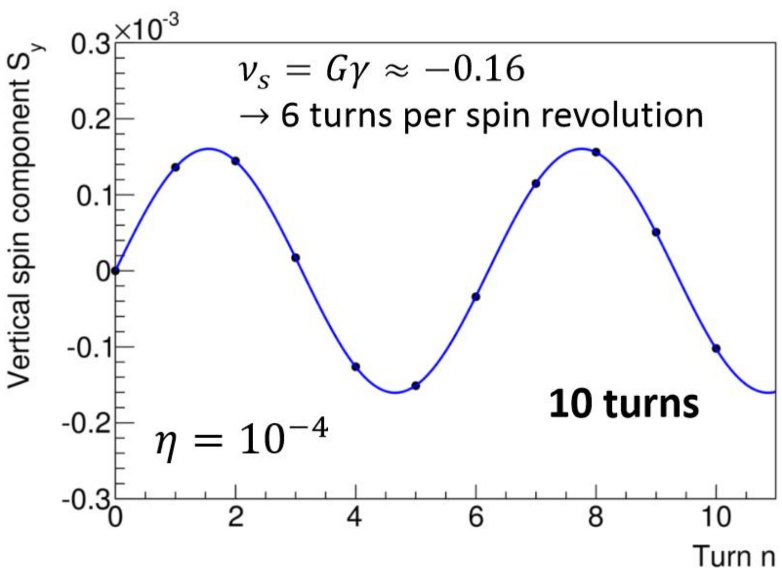
Resonant Wien Filter Method*

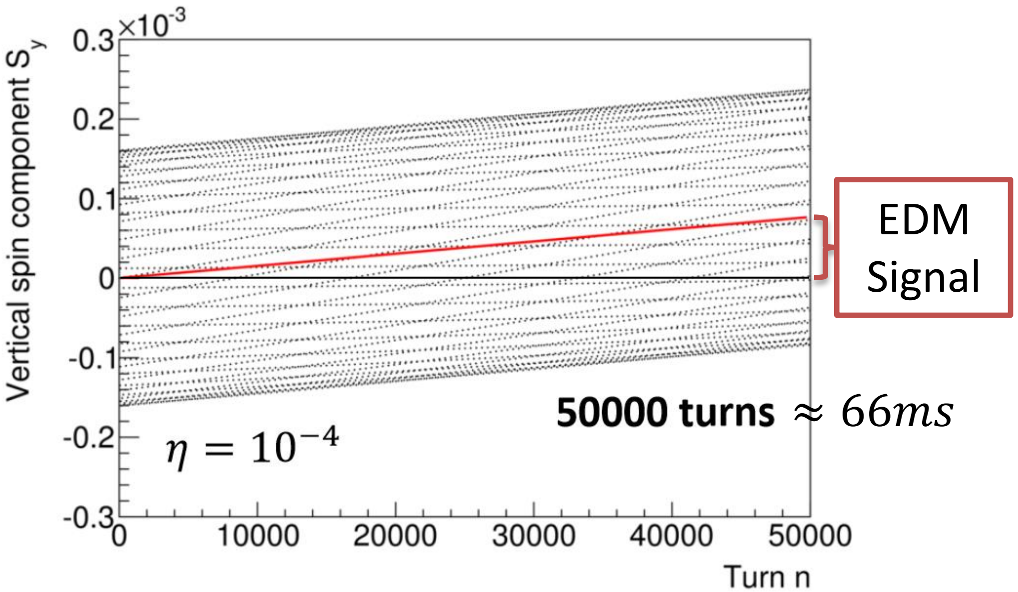
(Idea of First Direct Deuteron EDM Measurement)

- EDMs introduce vertical component of an horizontal polarized beam
- RF device used to accumulate this signal
- Device in Wien filter configuration to cancel beam perturbation
- Measure vertical polarization build-up (S_y per particle turn n) in $t_{meas} \approx 1000s$

$$\vec{\Omega}_{MDM} = \frac{q}{m\gamma}\gamma G\vec{B}$$

$$\vec{\Omega}_{EDM} = \frac{q\eta}{2m}\vec{\beta} \times \vec{B}$$





*W. M. Morse, Y. F. Orlov and Y. K. Semertzidis, Phys. Rev. ST Accel. Beams 16, 114001 (2013)

Courtesy: Marcel Rosenthal (m.rosenthal@fz-juelich.de)

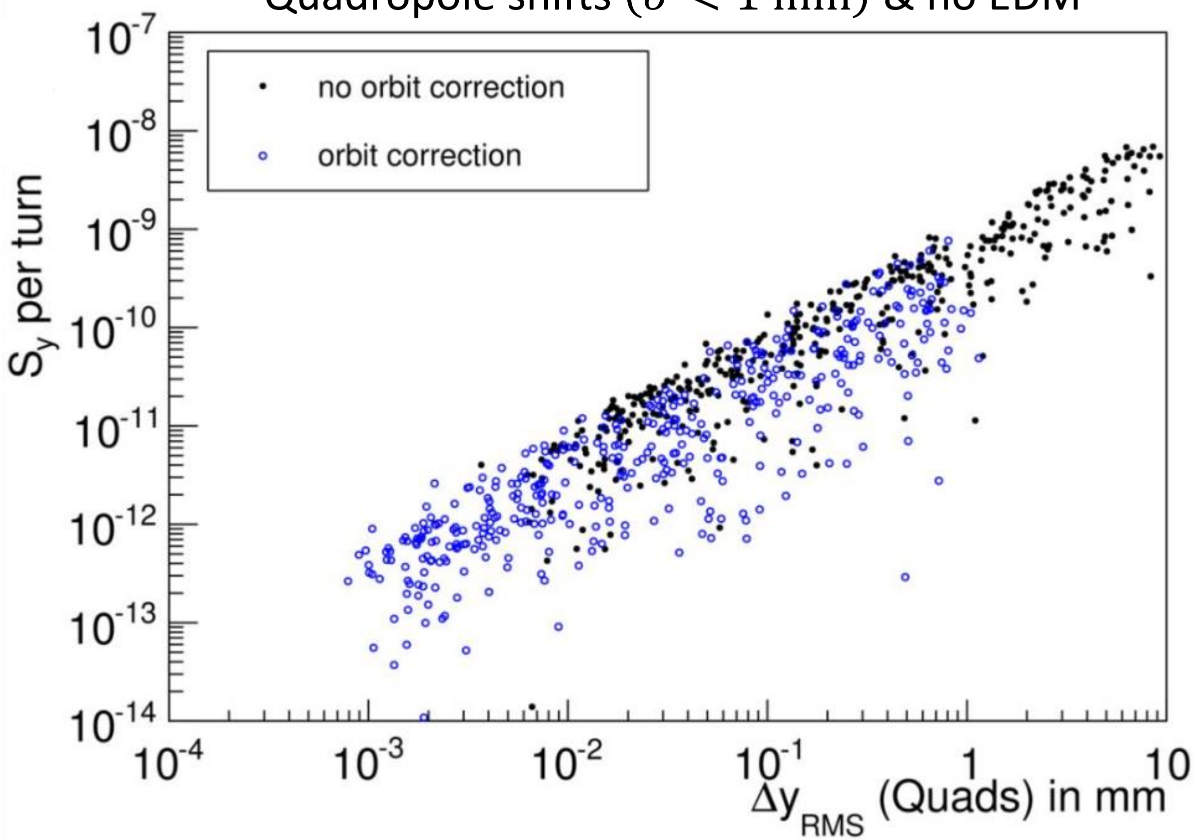
Systematic Effects I

Misaligned magnets lead to

- polarization build up
- orbit distortion

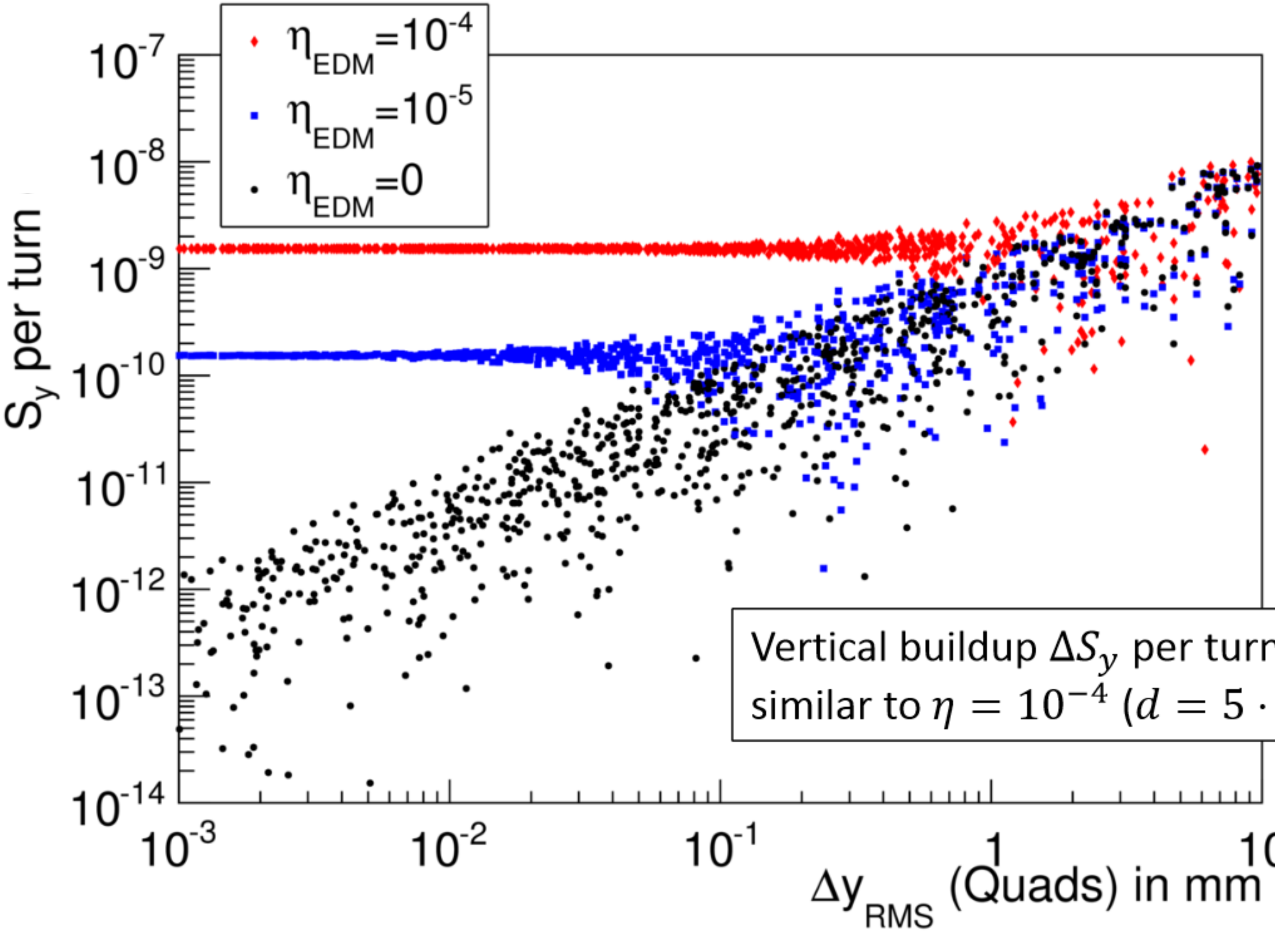
➢ Correct orbit to minimize polarization build up

Quadropole shifts ($\sigma < 1$ mm) & no EDM



Courtesy: Marcel Rosenthal (m.rosenthal@fz-juelich.de)

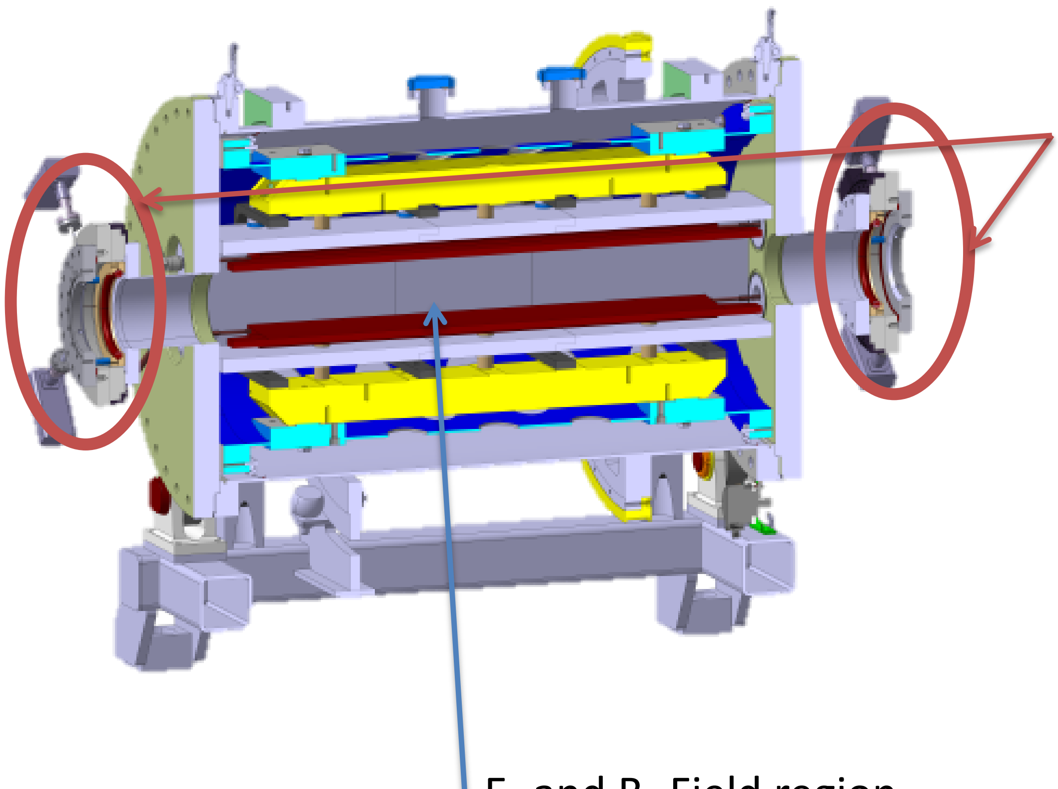
Systematic Effects II



Vertical buildup ΔS_y per turn for RMS of 2 mm similar to $\eta = 10^{-4}$ $(d = 5 \cdot 10^{-19}\text{e cm})$

Courtesy: Marcel Rosenthal (m.rosenthal@fz-juelich.de)

Rogowski BPM for RF Wien Filter



Installation of RF Wien Filter between quadrupoles

- Installation of Rogowski Coil BPMs at both ends

➢ Position beam in centre and parallel to Wien Filter

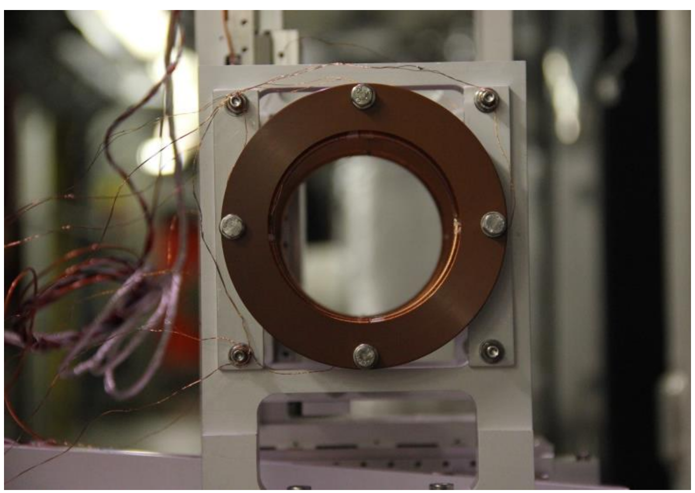
E- and B- Field region

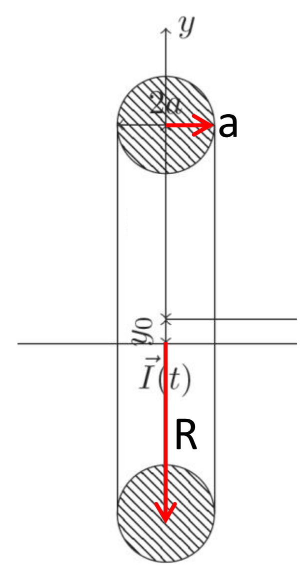
Rogowski Coil

Pickup-Coil to measure the magnetic flux:
Torus with:

- Major radius $R = 40\ mm$
- Minor radius $a = 5\ mm$
- Winding with copper wire $N = 350$ for each segment

- Divided into
  - Four segments
    (BPM in horizontal and vertical plane)



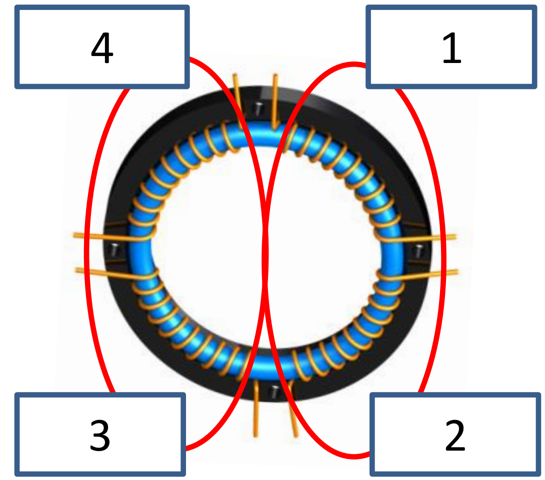


Position Calculation

Induced Voltage: $U_i \propto \dot{I}$

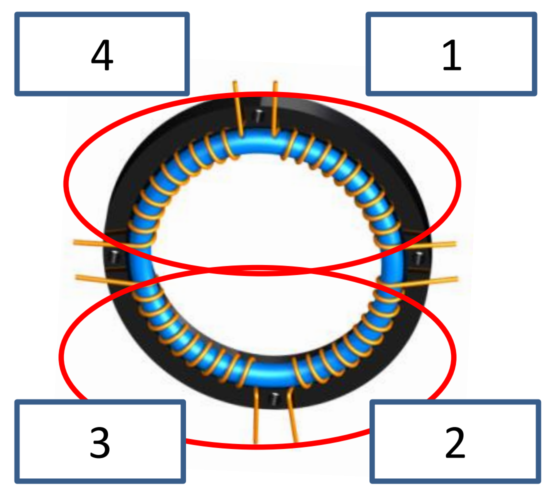
Horizontal:

$$x = \frac{\pi\sqrt{R^2 - a^2}}{2} \frac{(U_1+U_2) - (U_3 + U_4)}{\Sigma U_i}$$

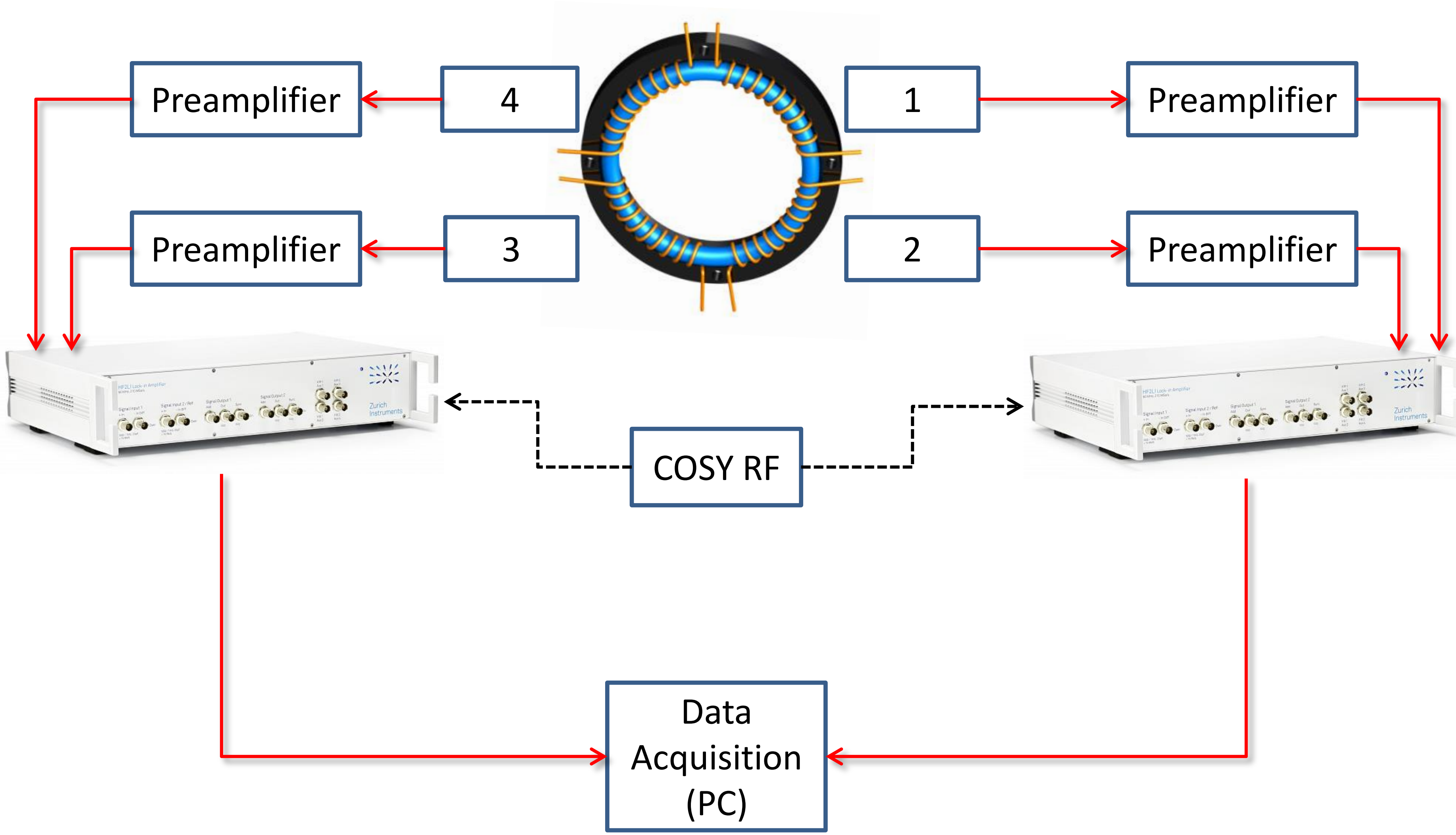


Vertical:

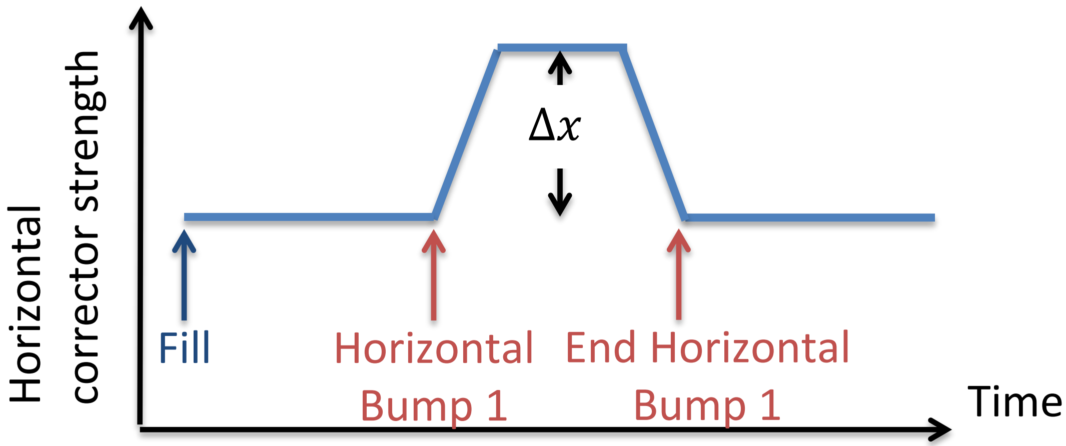
$$y = \frac{\pi\sqrt{R^2 - a^2}}{2} \frac{(U_1+U_4) - (U_2 + U_3)}{\Sigma U_i}$$

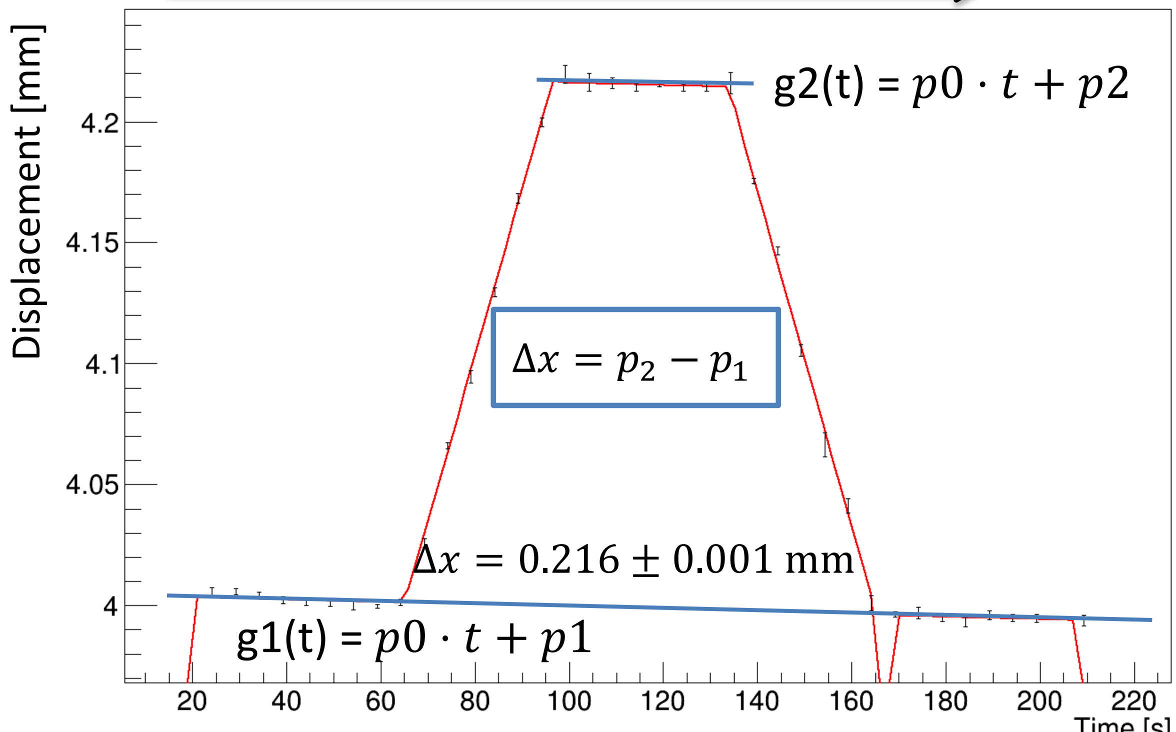


Measurement Setup

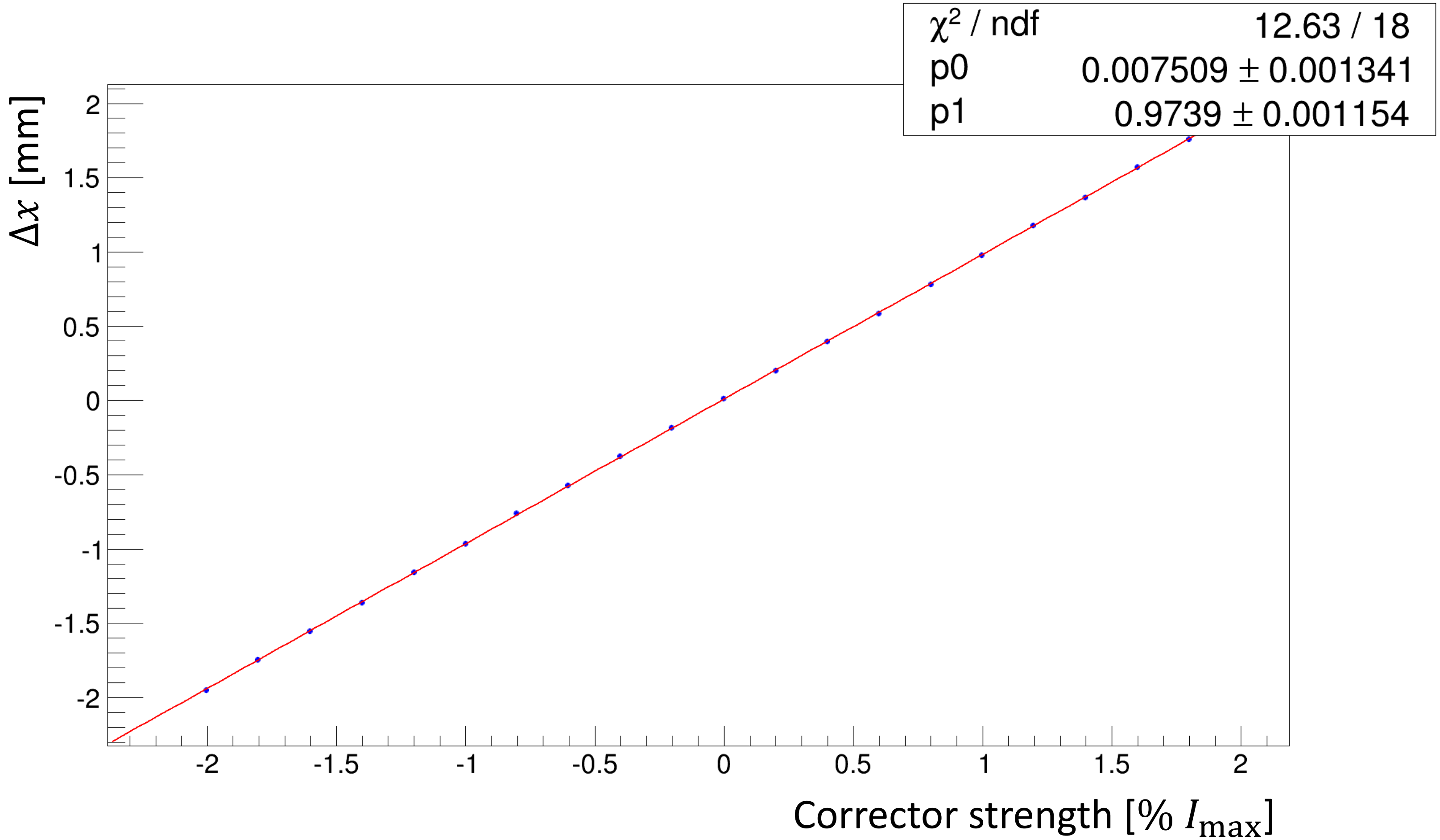


Orbit Bump & Rogowski BPM





Rogowski BPMs Linearity



- Linear over 4 mm
- No "jumps" within this range
- Calibration in Lab
- Installation in new RF Wien filter

Orbit Correction

Beam position at the BPMs — Orbit Response Matrix — Corrector magnet strength

$$\begin{pmatrix} \vec{x} \\ \vec{y} \end{pmatrix} = M_{ORM} \cdot \begin{pmatrix} \overrightarrow{\theta_x} \\ \overrightarrow{\theta_y} \end{pmatrix}$$

$$\Rightarrow \Delta \begin{pmatrix} \overrightarrow{\theta_x} \\ \overrightarrow{\theta_y} \end{pmatrix} = M_{ORM}{}^{-1} \cdot \begin{pmatrix} \vec{x} \\ \vec{y} \end{pmatrix}_{uncorrected}$$

$$M_{ORM} = \begin{pmatrix} M_{xx} & \approx 0 \\ \approx 0 & M_{yy} \end{pmatrix}$$

Determining the Orbit Response Matrix
Two methods:

1. Calculate ORM from optics (β, ϕ, ν, D and η)

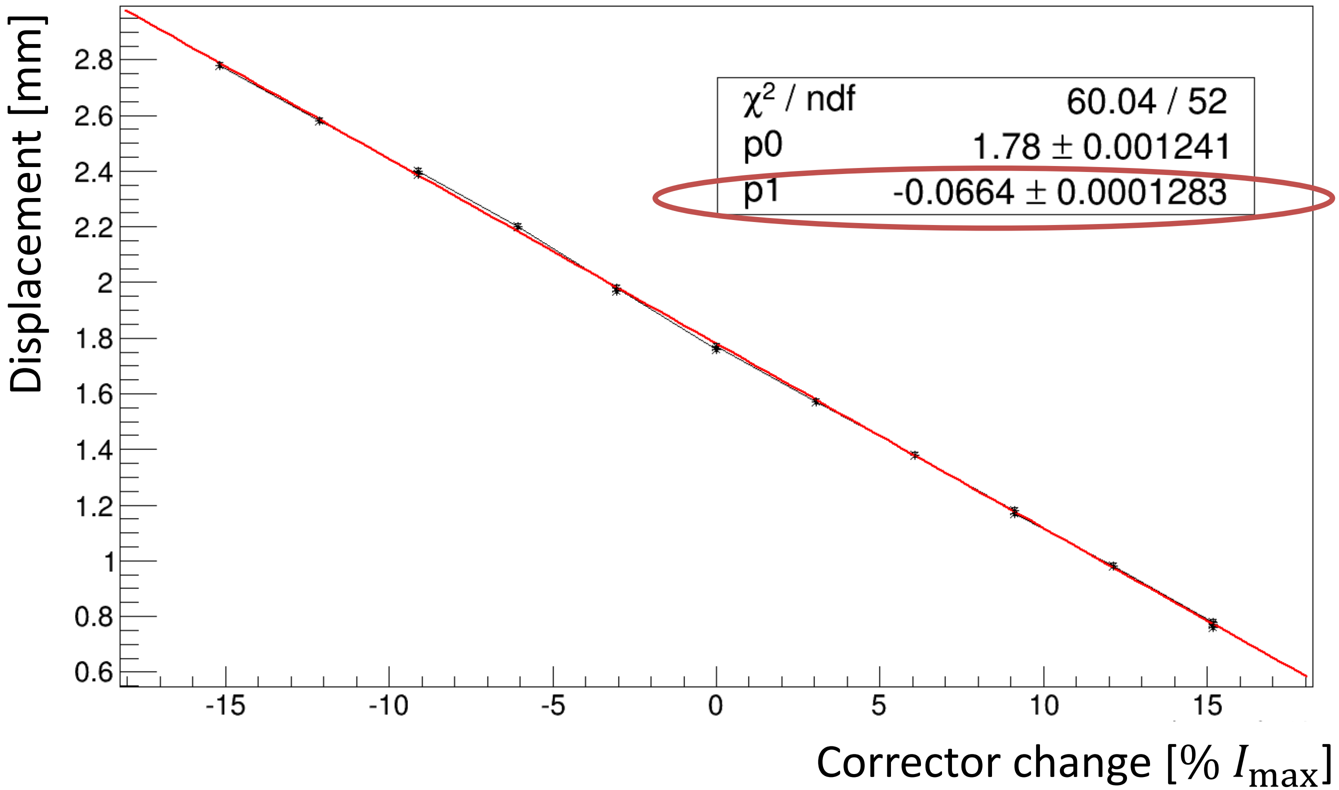
2. Measure ORM model independent

ORM Measurement

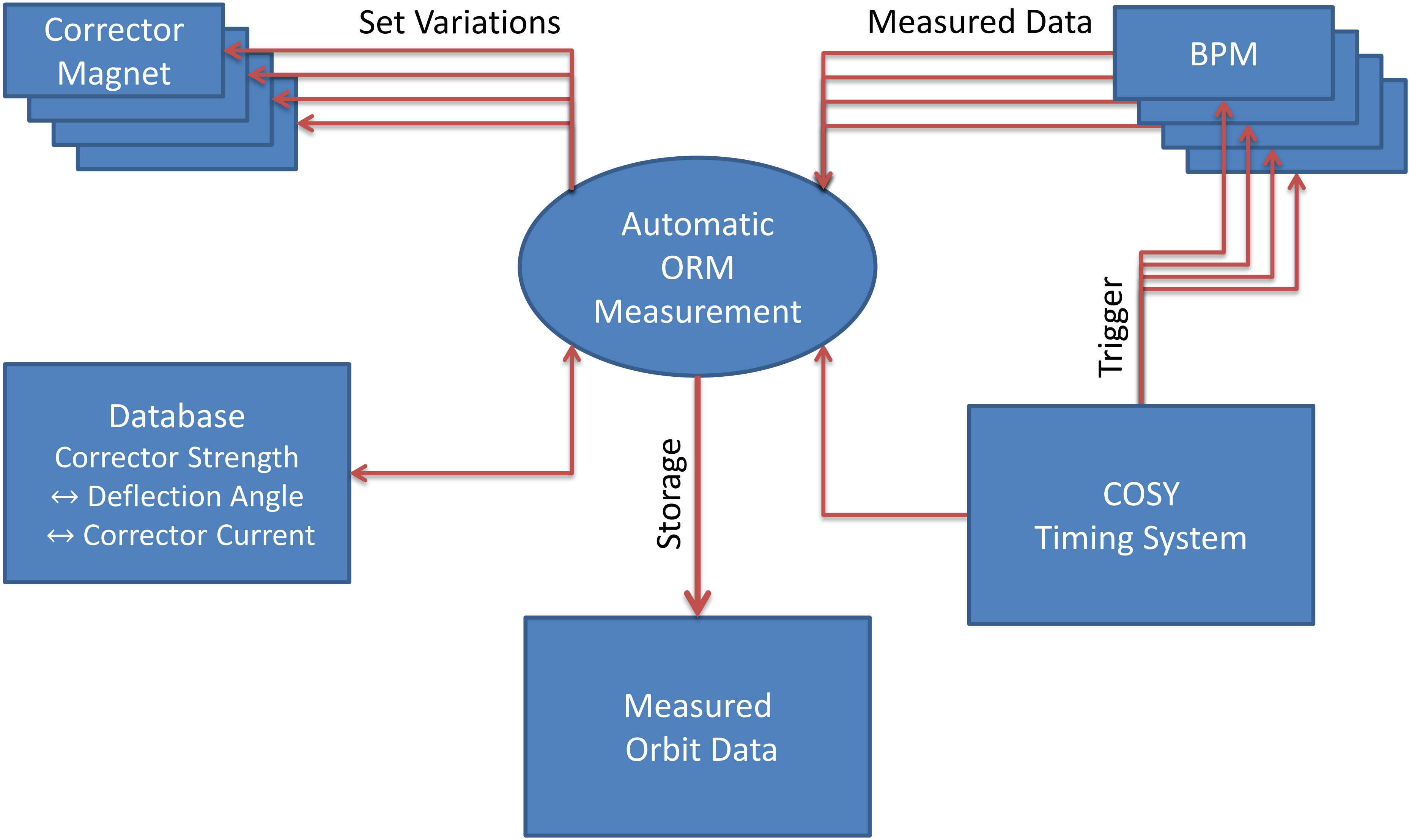
(Model independent)

$$\begin{pmatrix} \vec{x} \\ \vec{y} \end{pmatrix} = M_{ORM} \cdot \begin{pmatrix} \overrightarrow{\theta_x} \\ \overrightarrow{\theta_y} \end{pmatrix}$$

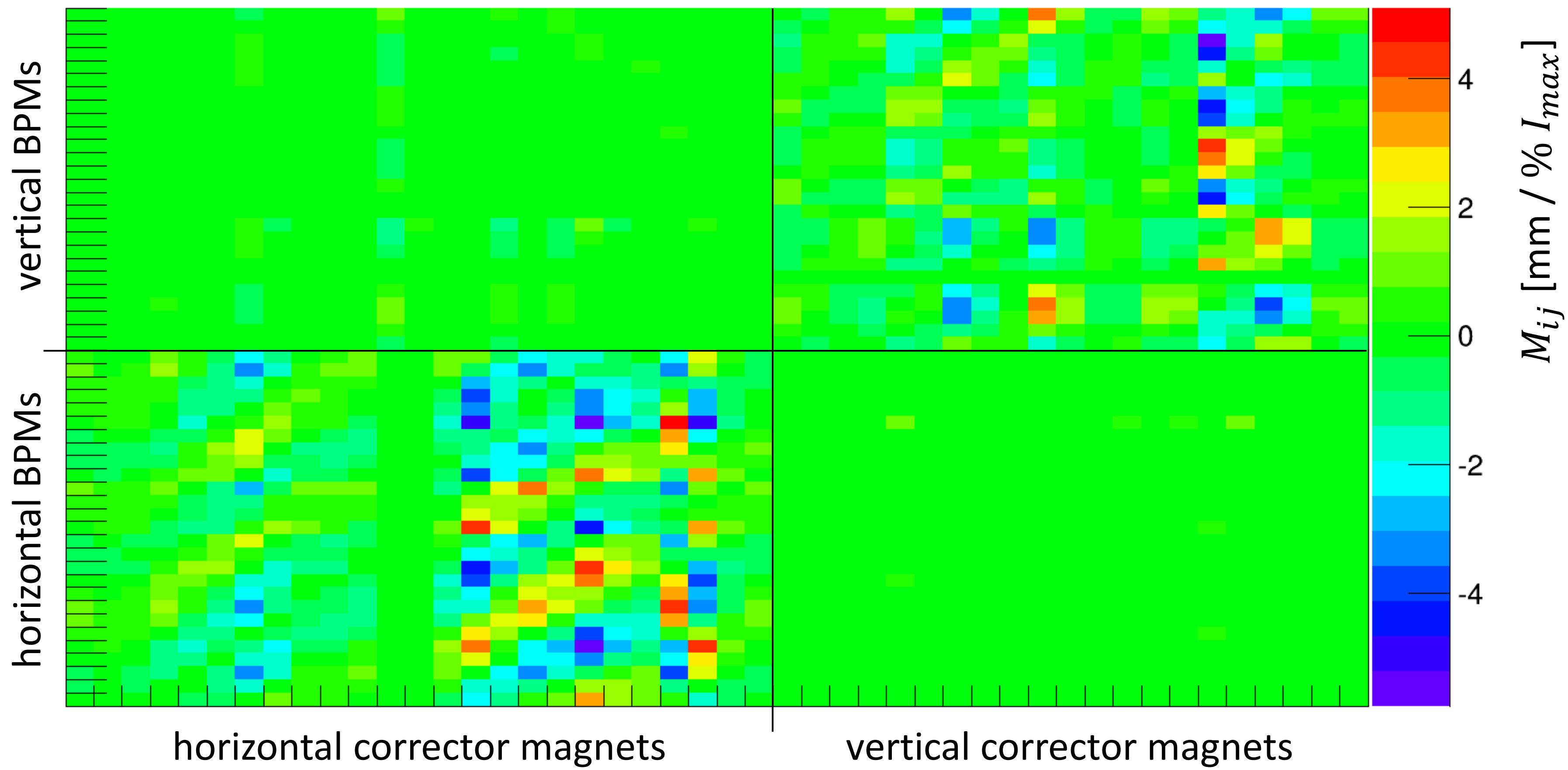
1. Change corrector magnet
2. Measure beam position at all BPMs
3. Repeat 1 and 2
4. Fit linear function for each BPM – corrector combination



New Automated ORM Measurement

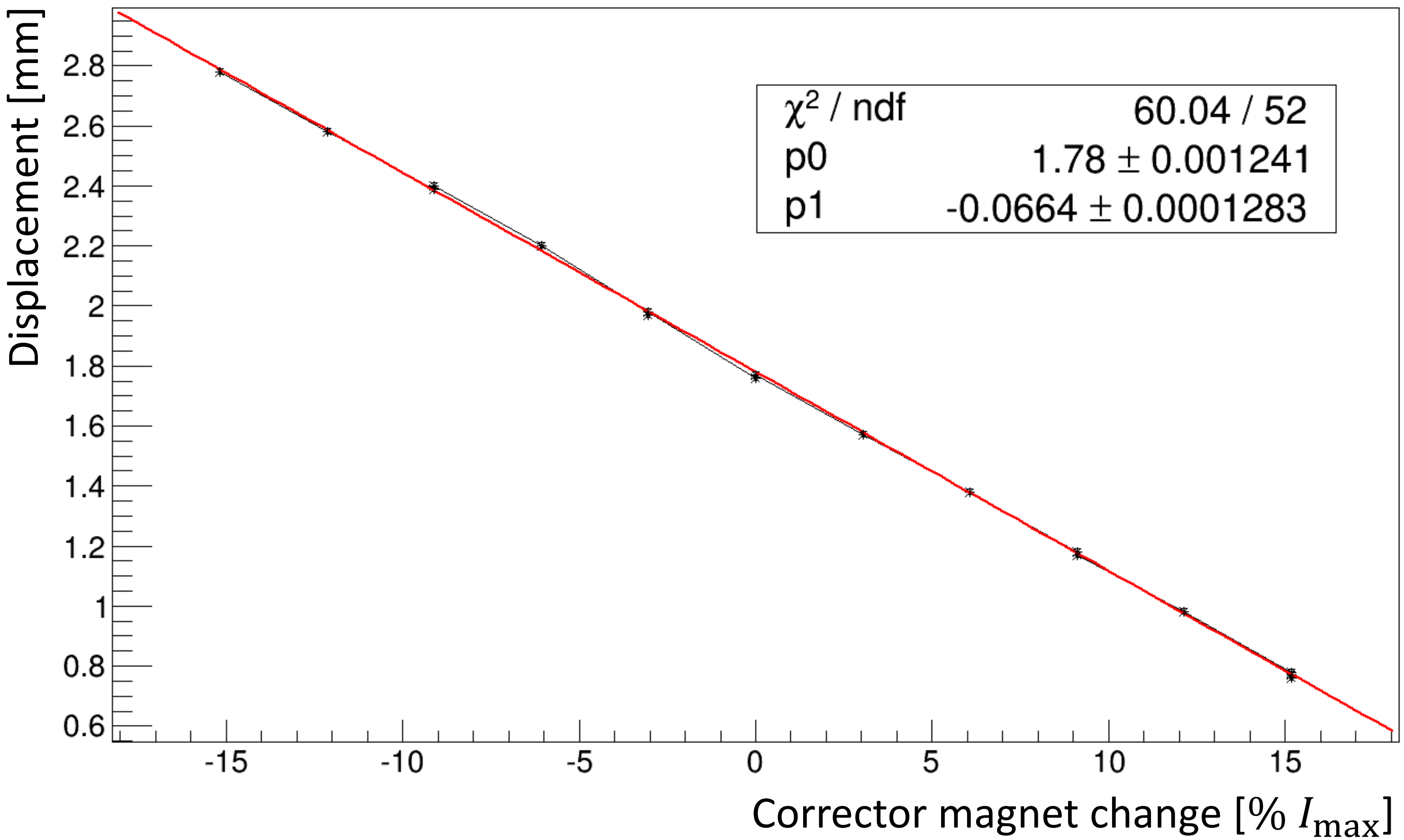


Results I



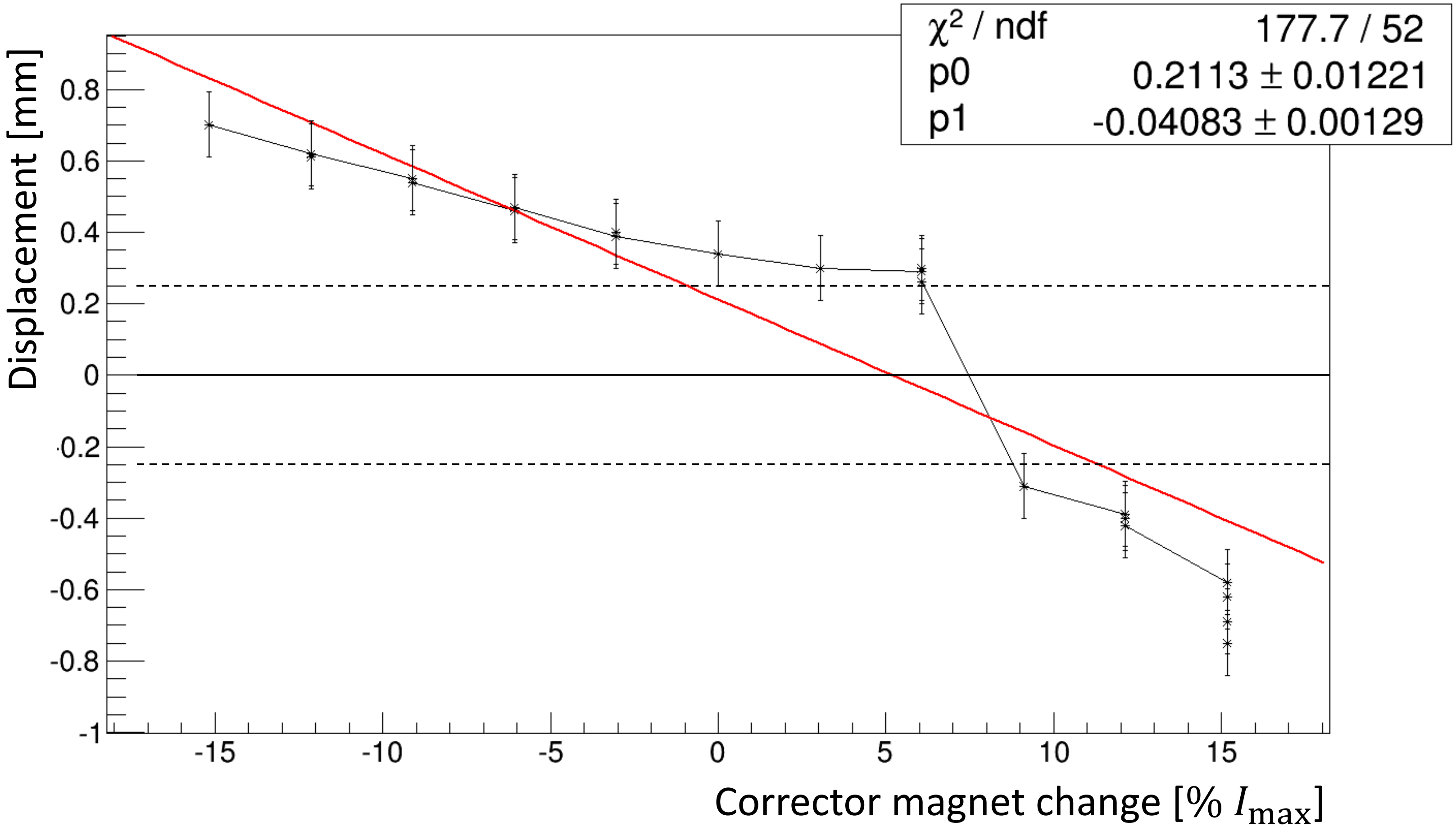
vertical BPMs
horizontal BPMs
horizontal corrector magnets
vertical corrector magnets
4
2
0
-2
-4
M_{ij} [mm / % I_{max}]

Results II



Good example of BPM response

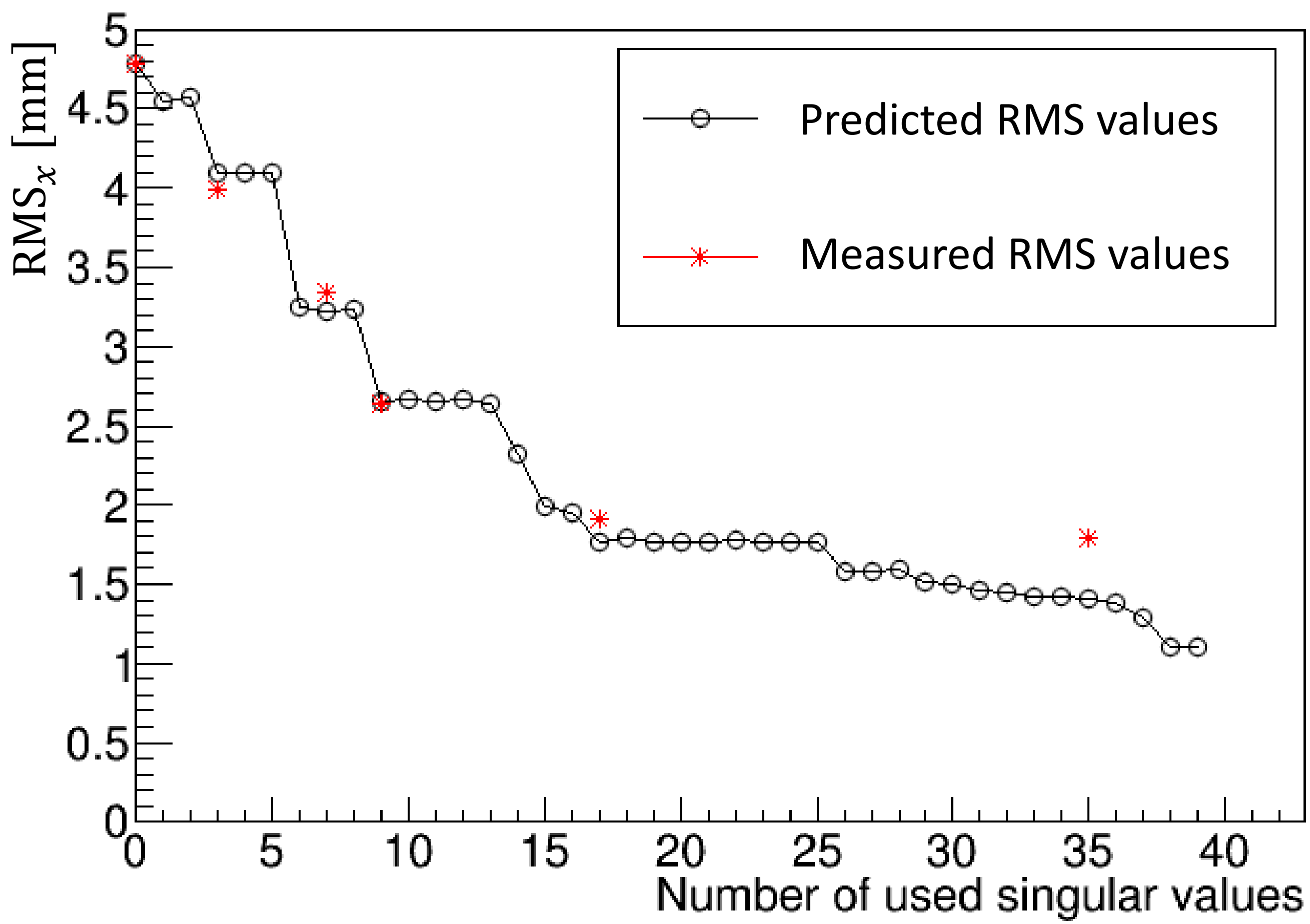
Results III



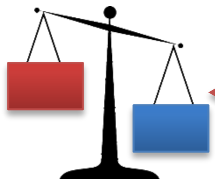
Offset in BPM electronics influences ORM measurement

Orbit Correction

$$\begin{pmatrix}\vec{x}\\ \vec{y}\end{pmatrix} = M_{ORM}\cdot\begin{pmatrix}\overrightarrow{\theta_x}\\ \overrightarrow{\theta_y}\end{pmatrix} \quad\Rightarrow\quad \Delta\begin{pmatrix}\overrightarrow{\theta_x}\\ \overrightarrow{\theta_y}\end{pmatrix} = M_{ORM}{}^{-1}\cdot\begin{pmatrix}\vec{x}\\ \vec{y}\end{pmatrix}_{uncorrected}$$

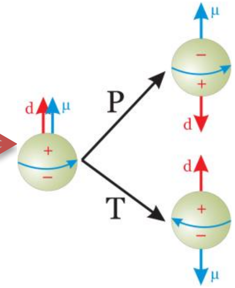


Summary

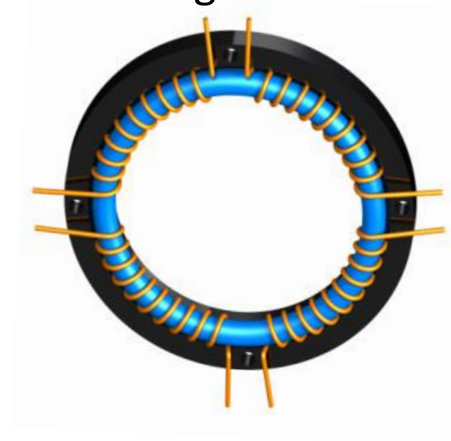


Matter – Antimatter Asymmetry

EDM as CP source



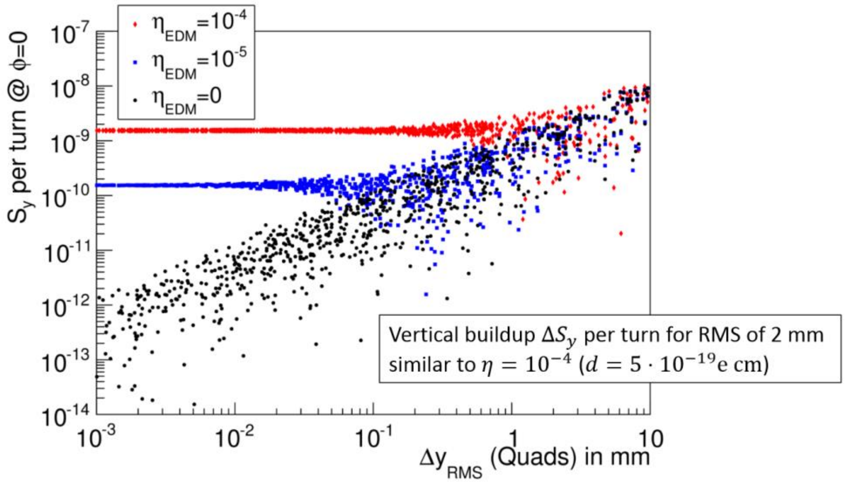
New Rogowski BPM



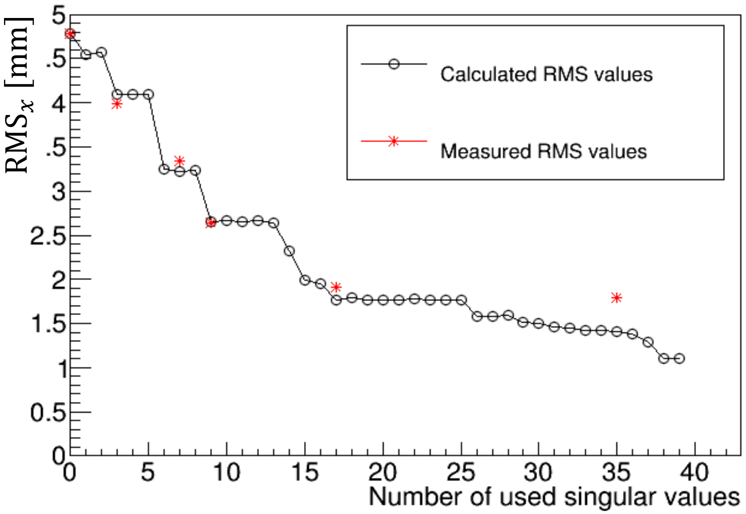
EDM measurement at accelerators

Specially:

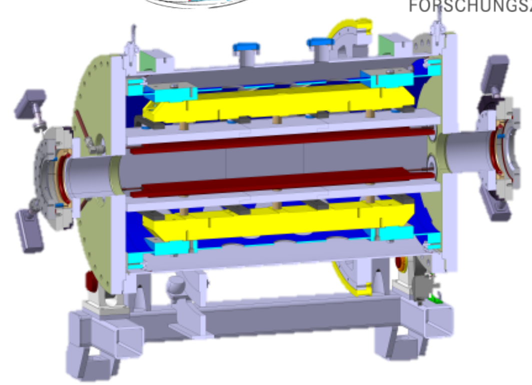
- RF Wien Filter method
- Orbit control necessary



Orbit correction



Outlook



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- In parallel development of orbit control, spin simulations and upgrade of BPM system
- Perform **first direct** EDM measurement for deuterons

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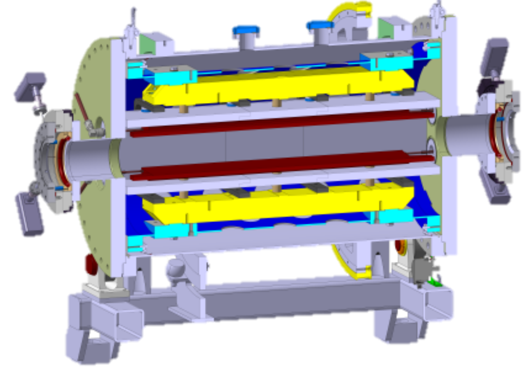

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