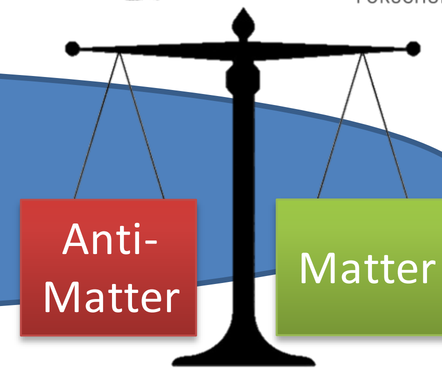
# Measurement of Electric Dipole Moments at COSY in Jülich

March 7, 2016 | Fabian Hinder for the JEDI Collaboration

Second Matter & Technology Student Retreat – KIT – Karlsruhe

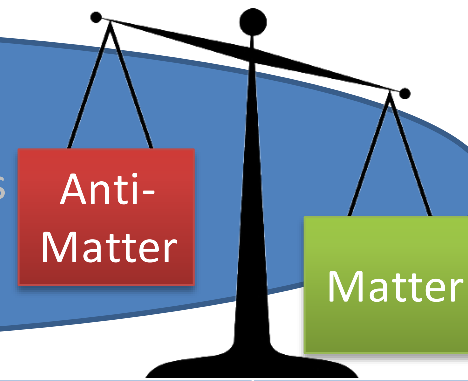
# Baryogenesis

<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

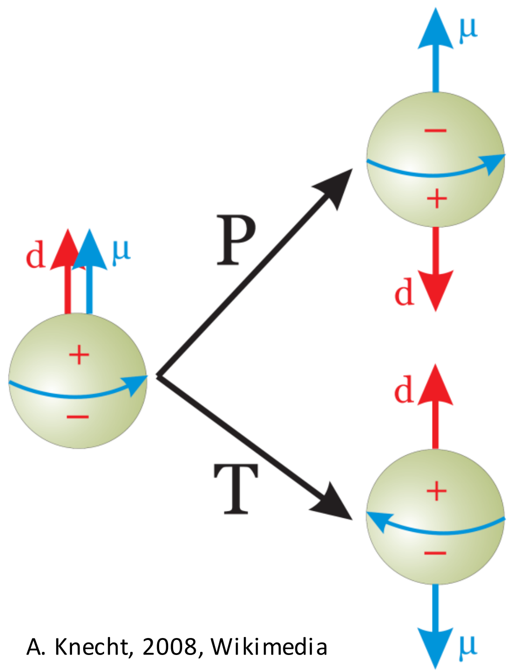
Annihilation

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

<u>Today</u>

Matter

# Electric Dipole Moments (EDMs) as CP Violating Source




A. Knecht, 2008, Wikimedia

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

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

- EDM: $\vec{d} = \underbrace{\sum_i \vec{r_i} q_i}_{\text{classical}} \rightarrow \underbrace{\mathrm{d} \cdot \vec{s}}_{\text{quanten mechanics}}$

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

- Permanent EDMs of light hadrons are $\mathcal{T}$- & $\mathcal{P}$-violating
  - $\mathcal{CPT}$ theorem ⇒ $\mathcal{CP}$ violation
- Search for new $\mathcal{CP}$ violation by measuring EDMs of charged particles in storage rings

# Measure EDMs in Storage Rings

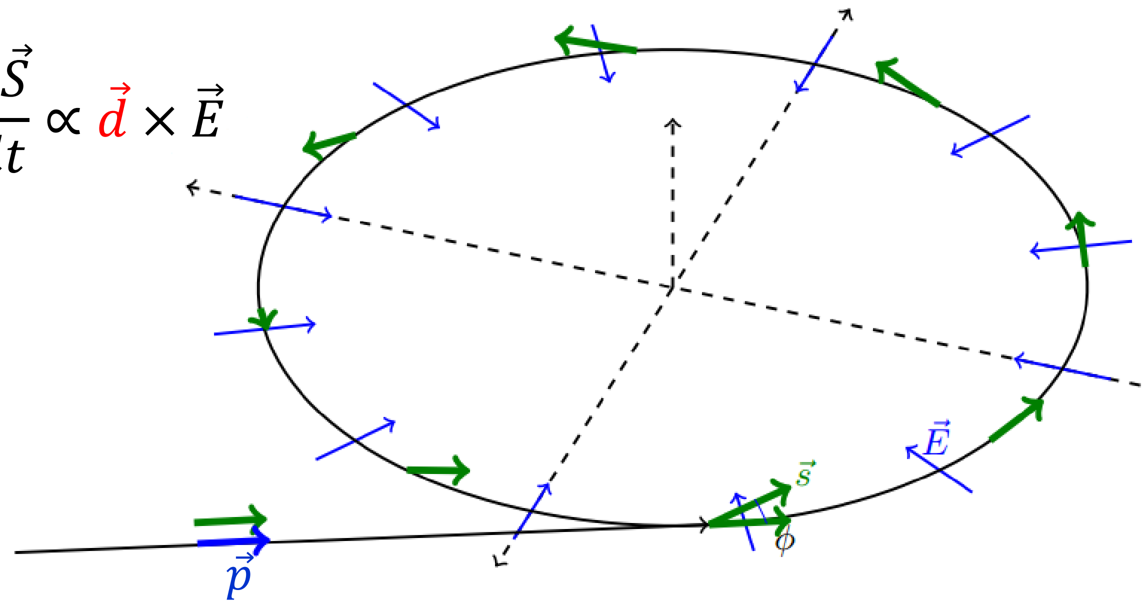
All EDM experiments:

- Interaction of field $\vec{E}$ and EDM $\vec{d}$

→ Spin rotates

- Charged particles: Lorentz force
- Accelerator as trap for charged particles

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




Generic Idea:
(Frozen Spin method)

1. Inject polarized particles with spin parallel to momentum
2. Apply radial electric field to particle in storage ring
3. Due to EDM $\vec{d}$ spin rotates out of horizontal plane
4. Measure build-up of vertical polarization $\phi \propto \vec{d}$

# Spin Motion in Storage Rings

*Thomas-BMT-Equation:*

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

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

$$\vec{\Omega}_{EDM} = \frac{q\eta}{2m}\left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{\mathrm{B}} - \frac{\gamma}{\gamma + 1}\vec{\beta}\left(\vec{\beta} \cdot \frac{\vec{E}}{c}\right)\right)$$

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

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

| | G |
|---|---|
| Proton | 1.792847357 |
| Deuteron | -0.142561769 |

# Spin Motion in Storage Rings
## (Pure Electric Ring)

*Thomas-BMT-Equation:*

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Pure electric ring:

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

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| Proton | 1.792847357 |
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# Spin Motion in Storage Rings
## (Combined Ring $\vec{E}$ & $\vec{B}$)

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

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Combined ring ($\vec{E}$ & $\vec{B}$):
- Frozen spin possible for Protons and Deuterons

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# Spin Motion in Storage Rings
## (Pure Magnetic Ring)

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

Pure electric ring:

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

Combined ring ($\vec{E}$ & $\vec{B}$):

- Frozen spin possible for Protons and Deuterons

Pure magnetic ring:

- Frozen spin not possible ($\nu_s = \gamma G$)

| | G |
|---|---|
| Proton | 1.792847357 |
| Deuteron | -0.142561769 |

# Spin Motion in Storage Rings (Pure Magnetic Ring)

*Thomas-BMT-Equation:*

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

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

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Combined ring ($\vec{E}$ & $\vec{B}$):

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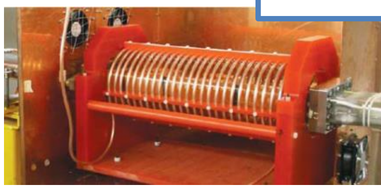
New method proposed to measure EDMs at COSY Jülich

# Cooler Synchrotron COSY in Jülich

RF $\vec{E} \times \vec{B}$ dipole

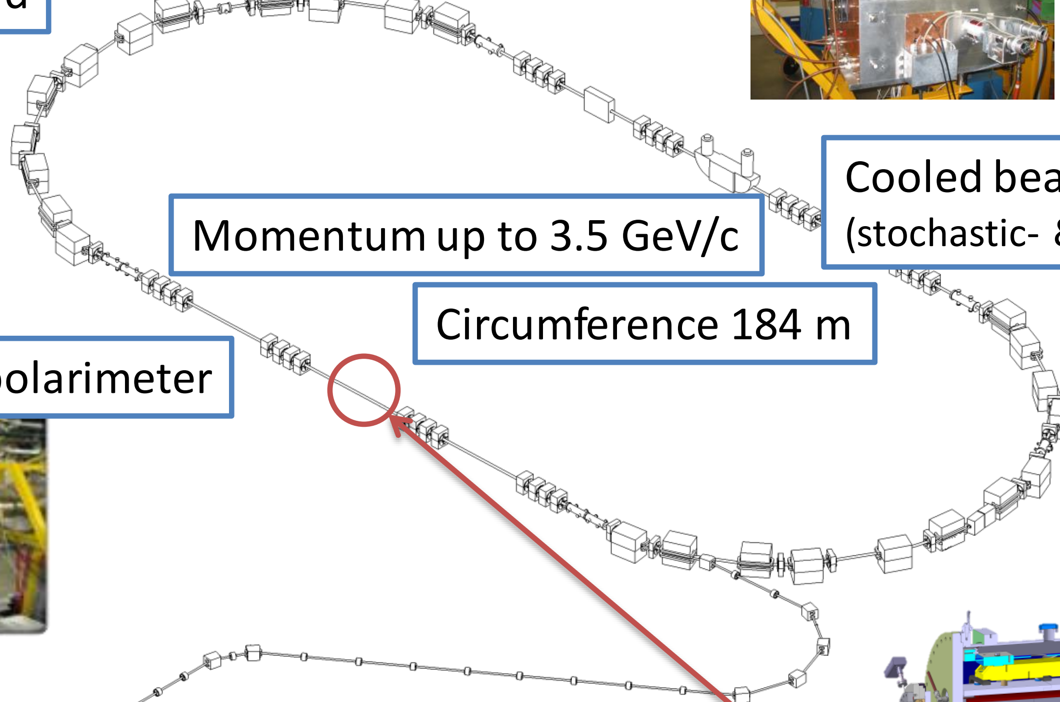
RF solenoid



Cooled beams
(stochastic- & e-cooling)

Momentum up to 3.5 GeV/c

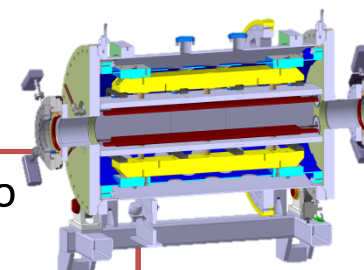
Circumference 184 m



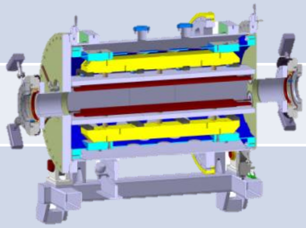
EDDA polarimeter

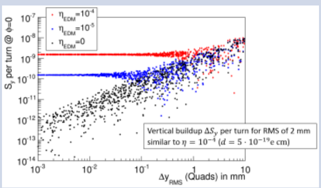
Polarized Protons / Deuterons

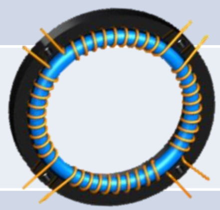
RF Wien filter to generate EDM related signal (installation in 2016)

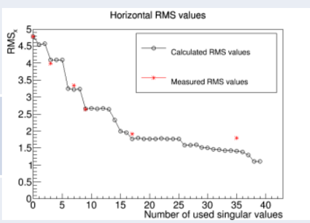


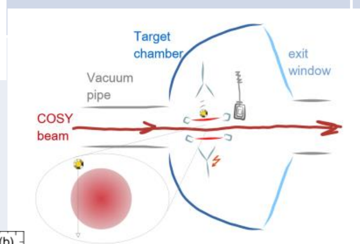
# PhD Theses within JEDI

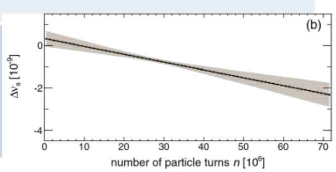







| Topic | Student |
|---|---|
| RF ExB dipole | Sebastian Mey[1,2] |
| RF stripline Wien filter | Jamal Slim[3] |
| Spin tracking (Simulations) | Marcel Rosenthal[1,2]<br>Stanislav Chekmenev[2]<br>Artem Saleev[1] |
| Beam Position Monitors | Fabian Trinkel[1,2]<br>Fabian Hinder[1,2] |
| Orbit correction | Fabian Hinder[1,2] |
| Polarimetry | Fabian Müller[1,2]<br>Nils Hempelmann[1,2]<br>Paul Maanen[2] |
| Spin tune measurement (Data Analysis) | Dennis Eversmann[2] |

[1] IKP, FZ Jülich
[2] III. Phsikalisches Institut B, RWTH Aachen
[3] Institut für Hochfrequenztechnik, RWTH Aachen

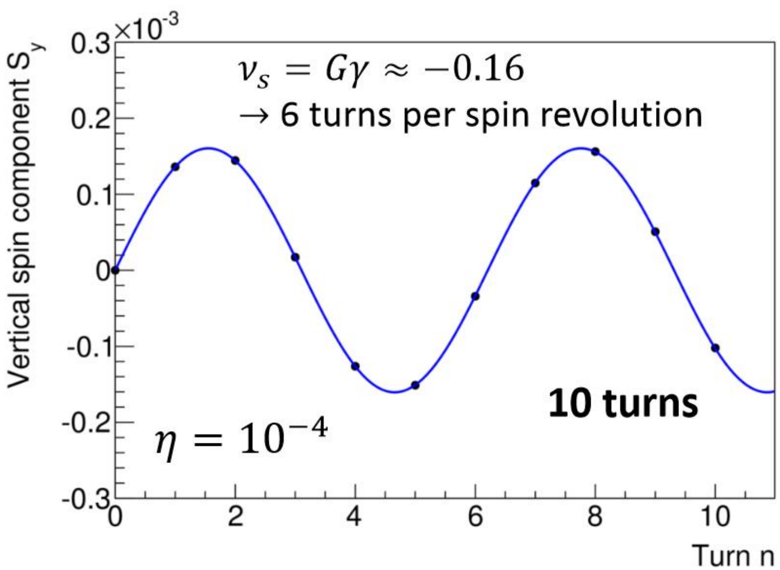
# Resonant Wien Filter Method*

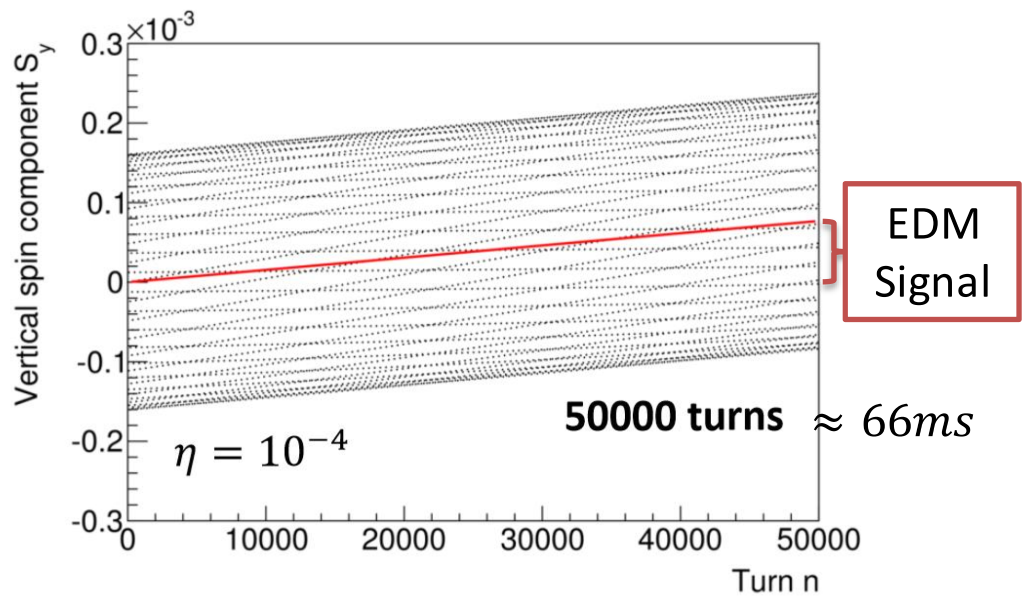
## First direct Deuteron EDM measurement

- 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 $\mathrm{t}_{\mathrm{meas}} \approx 1000s$

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

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




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

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

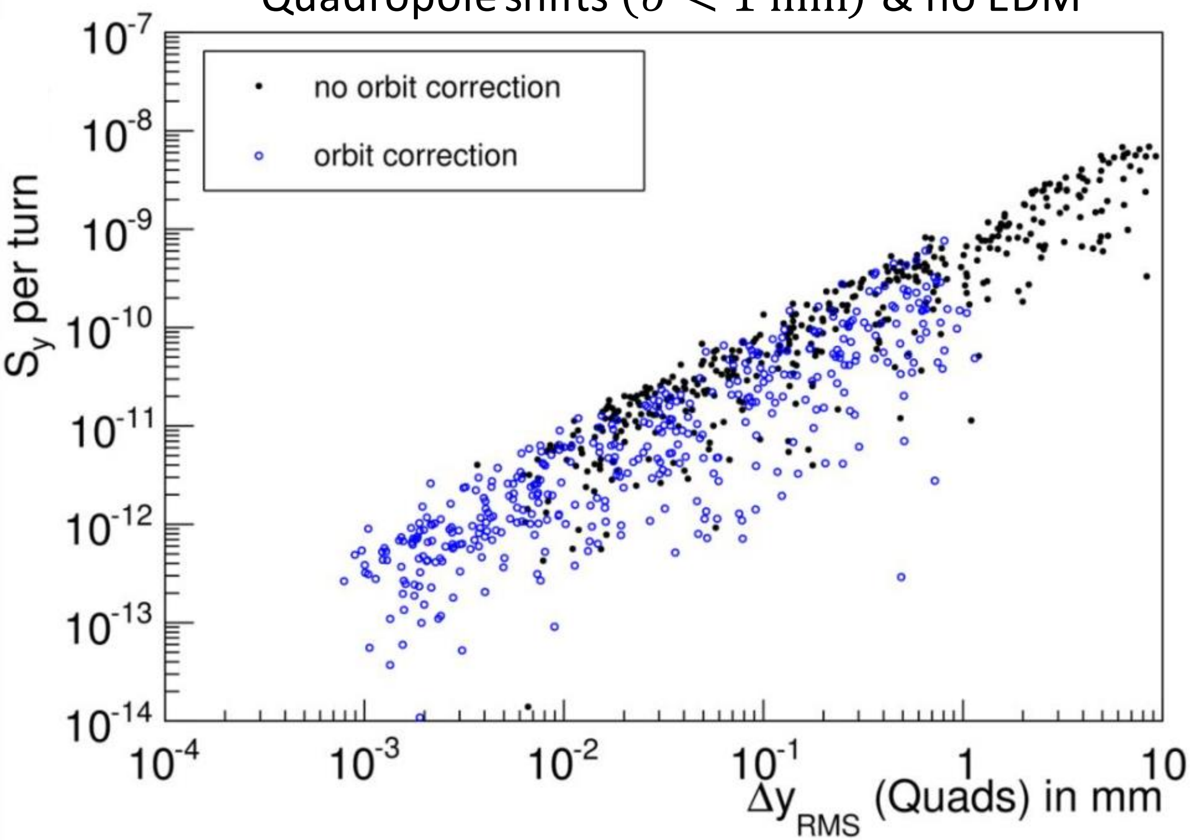
# Systematic Effects I

Misaligned magnets lead to

- polarization build up
- orbit distortion

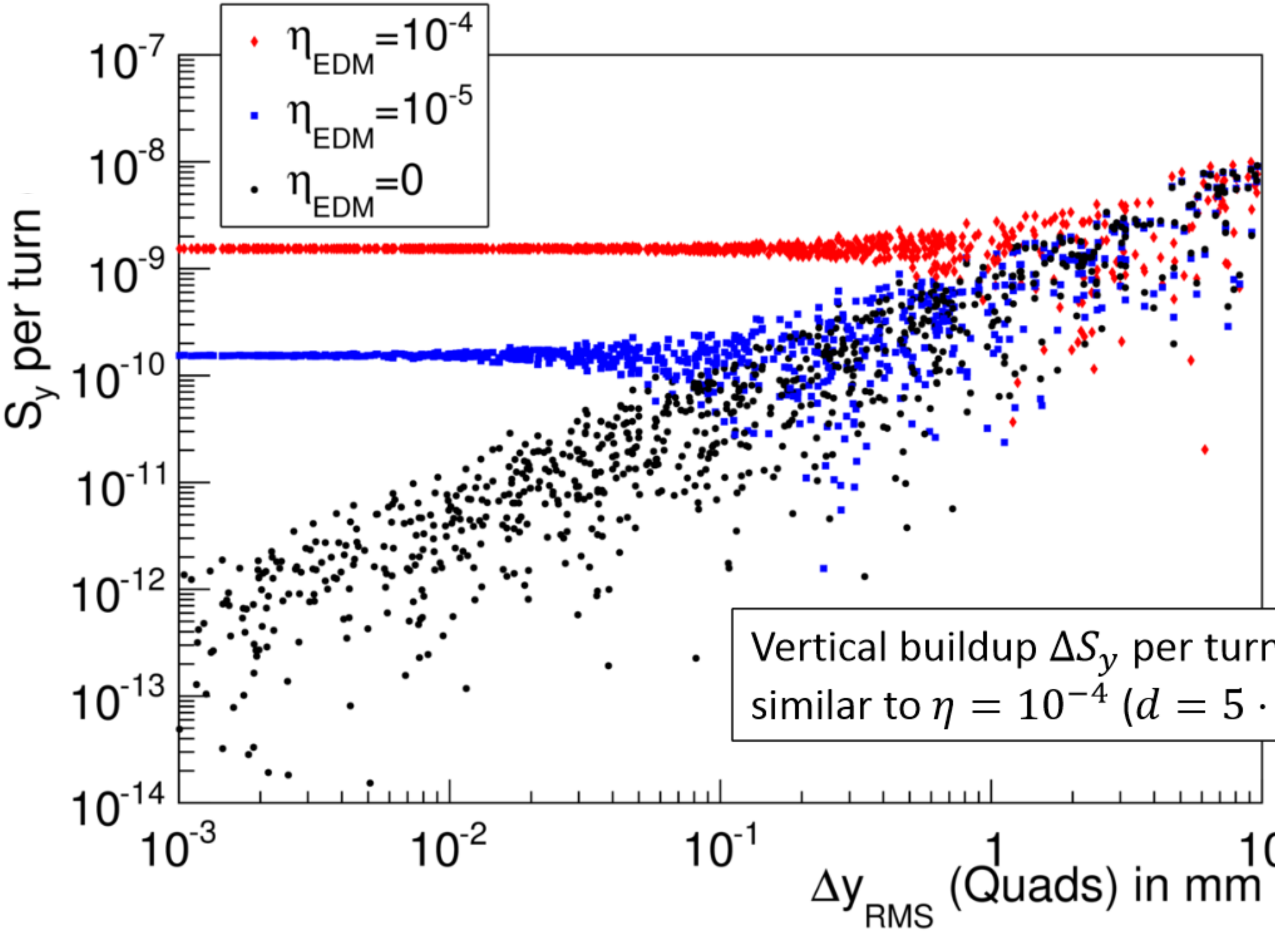
➢ Correct orbit to minimize false polarization build up

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




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

# Systematic Effects II

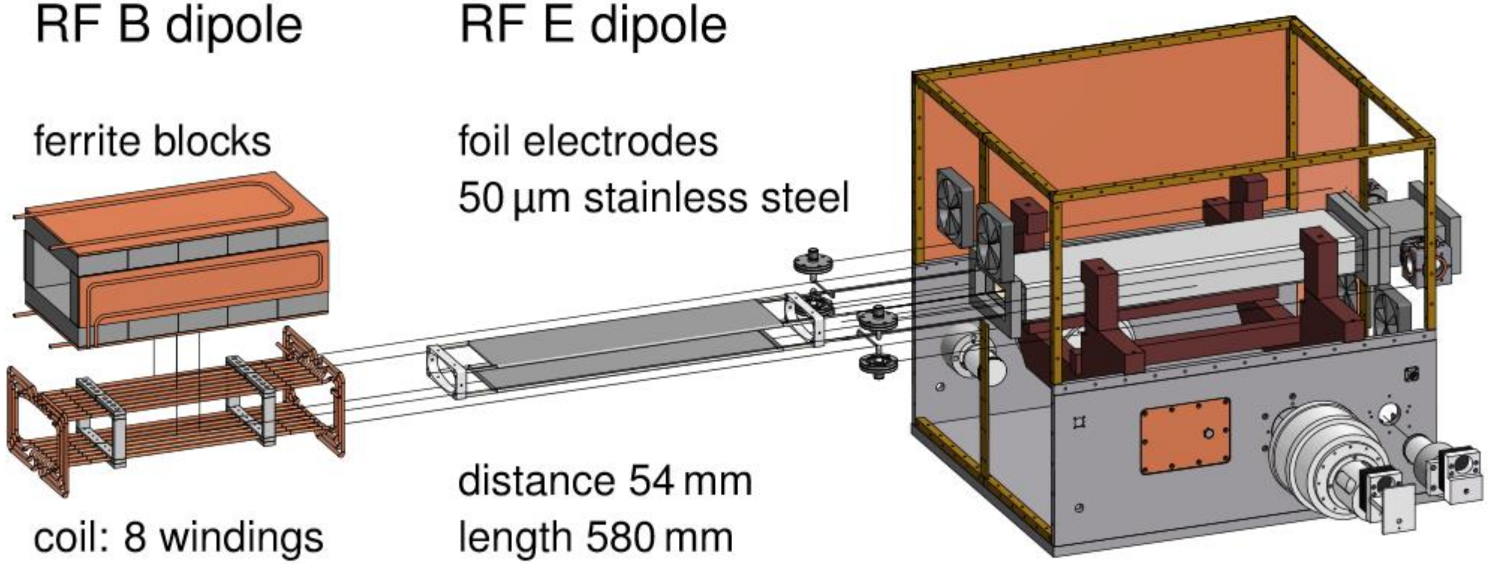


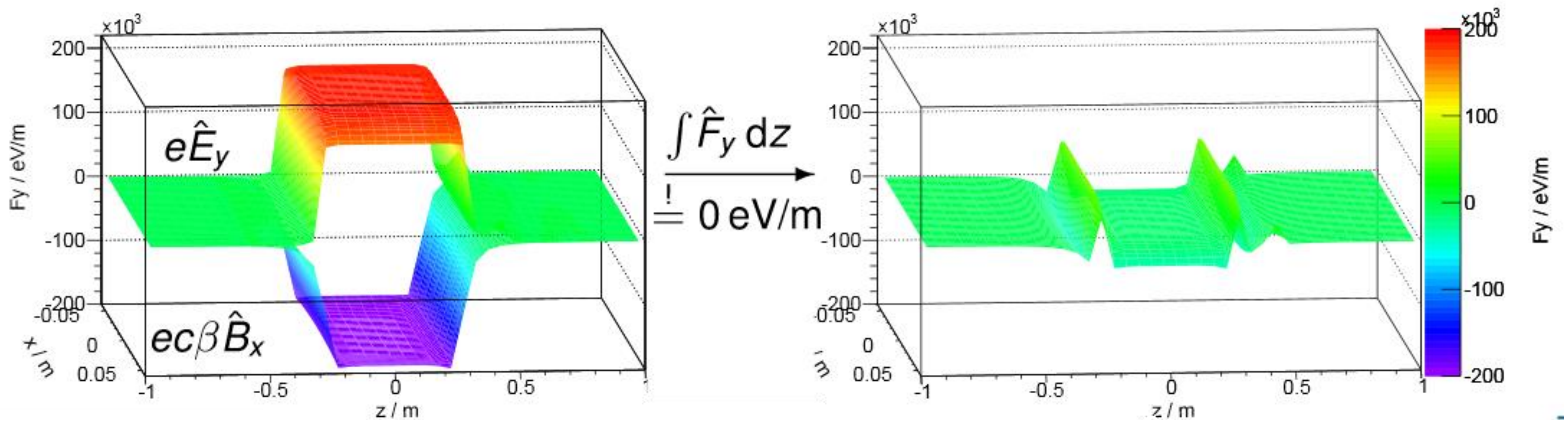

Vertical buildup $\Delta S_y$ per turn for RMS of 2 mm similar to $\eta = 10^{-4}$ $(d = 5 \cdot 10^{-19} \text{e cm})$

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

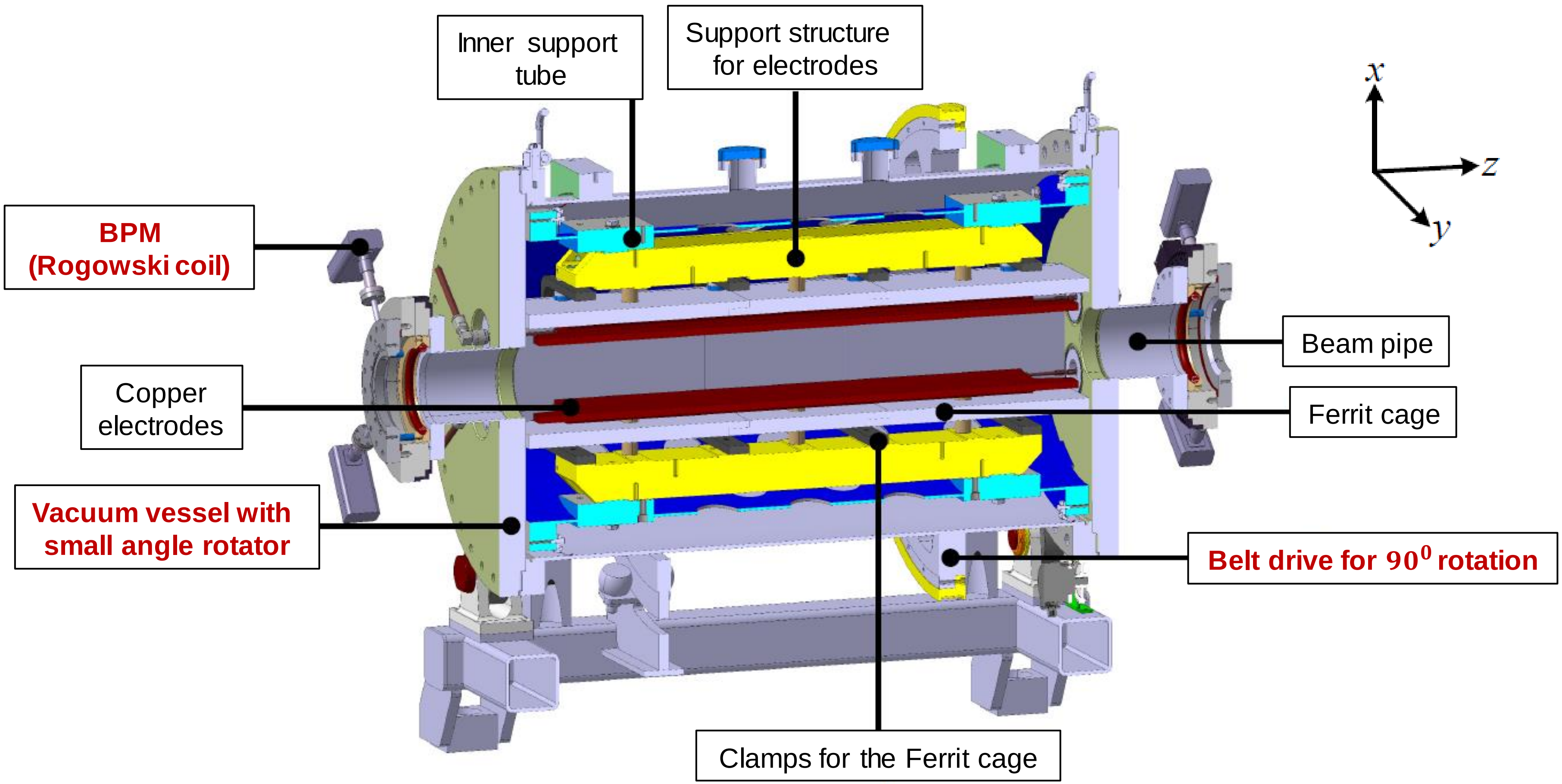
# RF ExB Dipole in Wien Filter Configuration

Courtesy: Sebastian Mey (s.mey@fz-juelich.de)



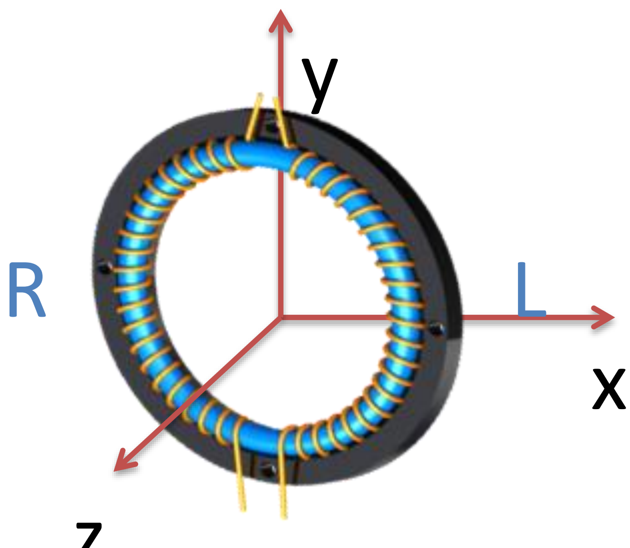
# Stripline Wien Filter

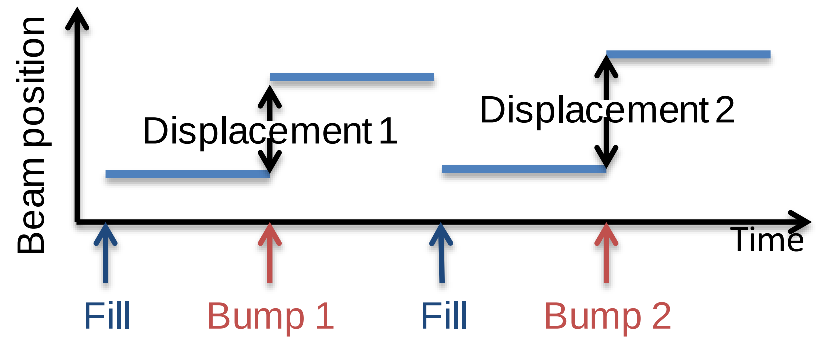



Courtesy: Jamal Slim (slim@ihf.rwth-aachen.de)

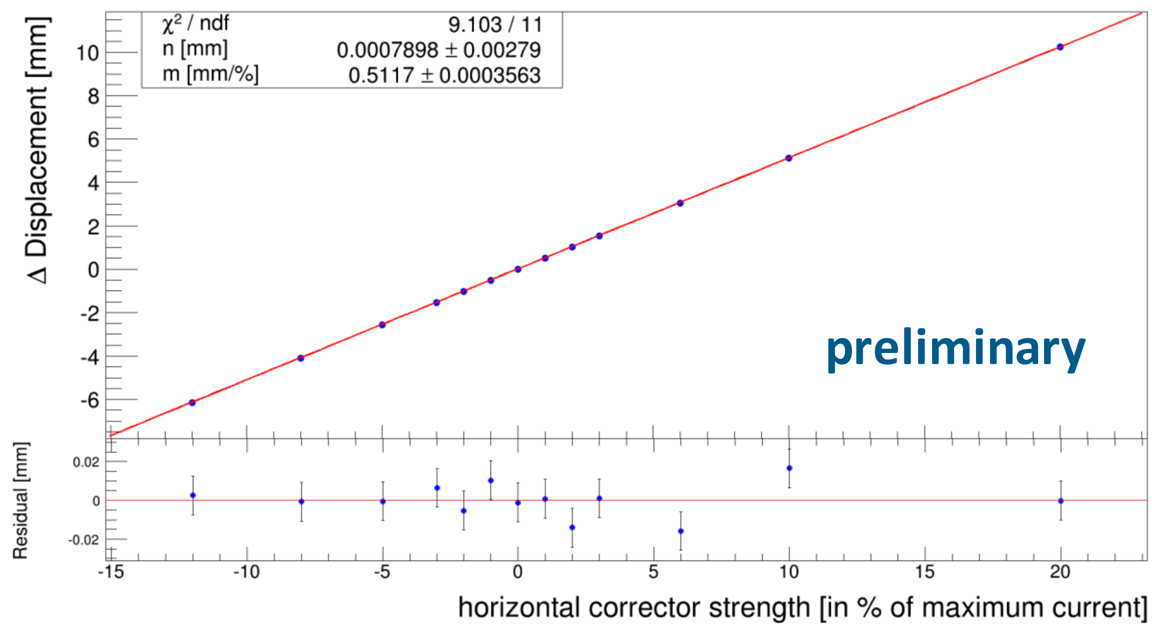
# Beam Position Monitors

1. Change beam position once per fill
2. Measure displacement




$$\frac{U_L - U_R}{U_L + U_R} = \frac{2}{\pi\sqrt{R^2 - a^2}} x_0$$



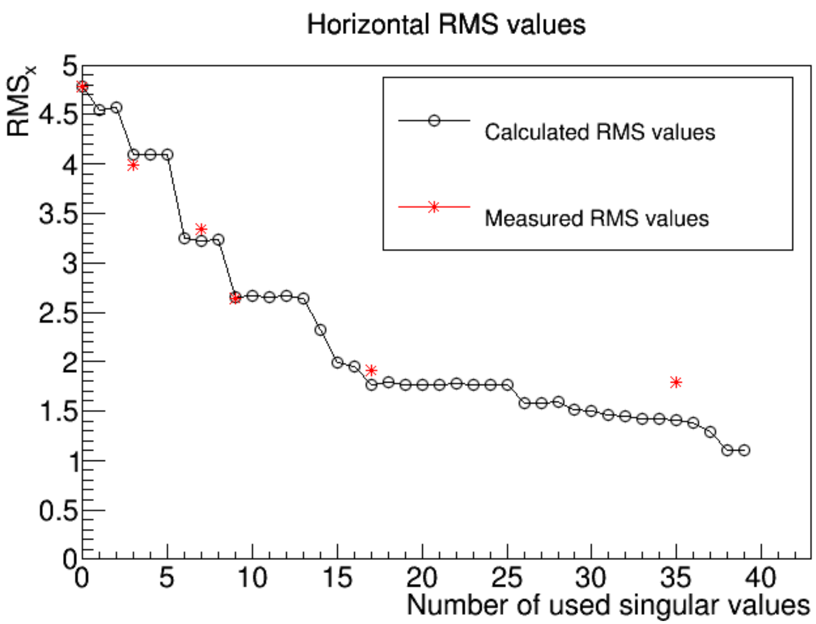

Courtesy: Fabian Trinkel (f.trinkel@fz-juelich.de)

# Orbit Correction

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

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

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




Development of new software tools

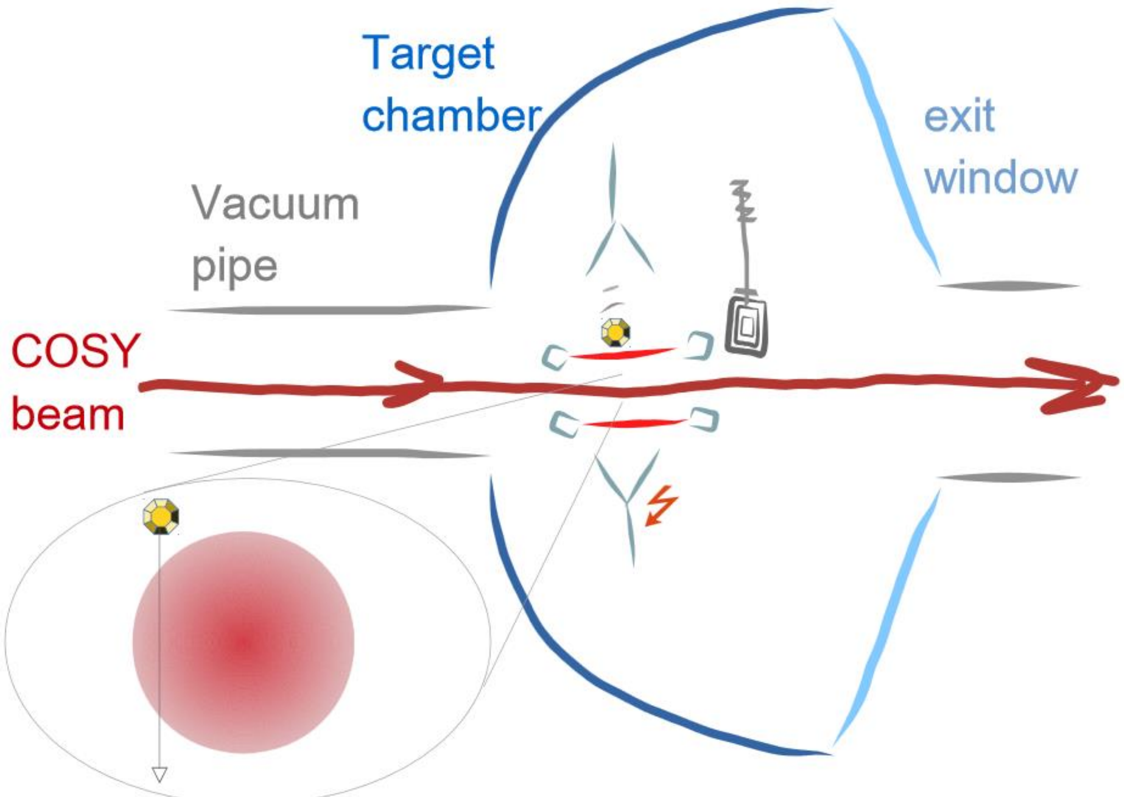
Measurement of ORM automated:

1. Vary corrector magnets
2. Measure beam response
3. Calculate $M_{ORM}$ & $M_{ORM}{}^{-1}$
4. Correct Orbit

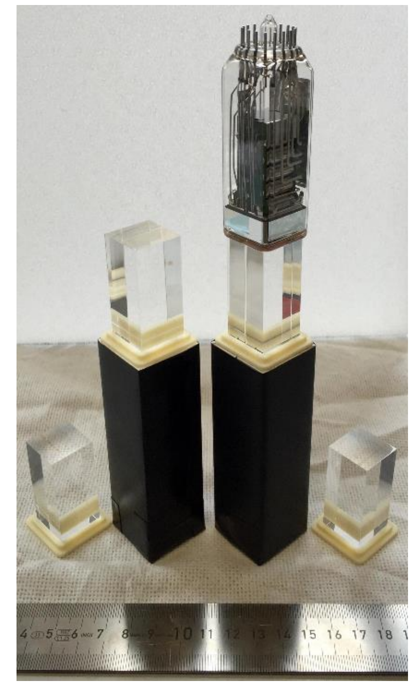
- Time gain: $10h \rightarrow 0.5h$

# Polarimeter

# JuDiT Jülich Ballistic Diamond Pellet Target




Detector design with LYSO crystals



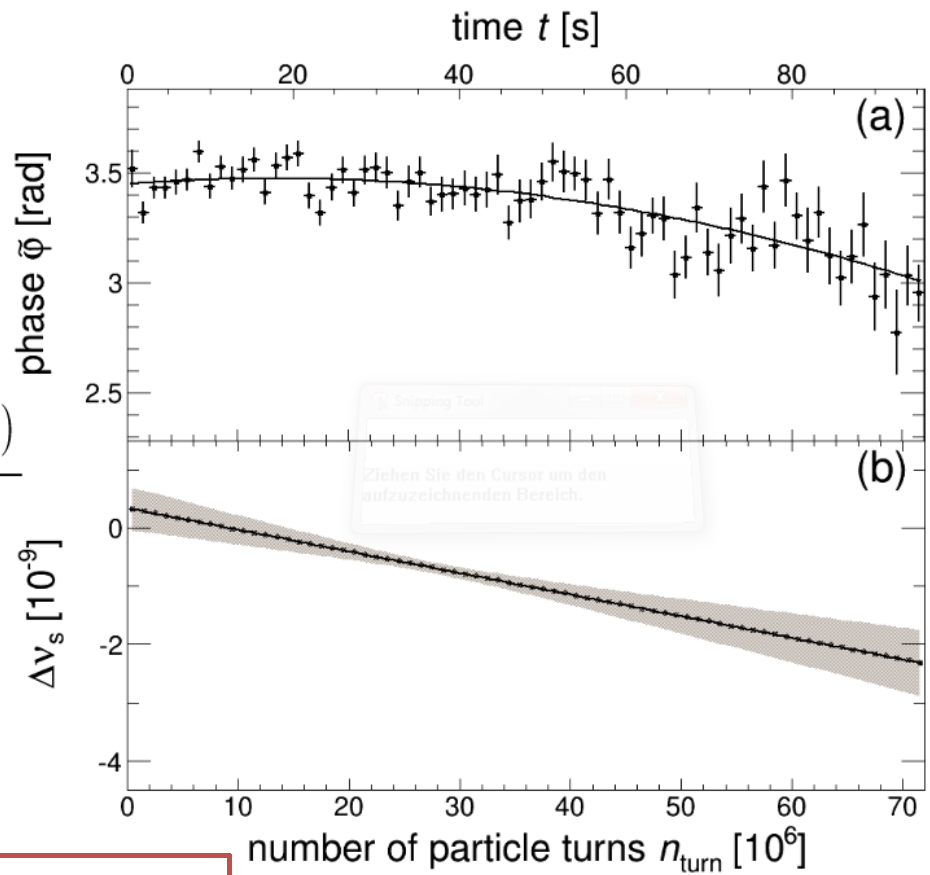
Courtesy: Fabian Müller (fa.mueller@fz-juelich.de)

# Spin Tune Determination

Spin tune interpolation for a whole cycle:

$$\nu_s(n_{turn}) = \frac{\Omega_{MDM}(n_{turn})}{\Omega_{cyc}} = \nu_S^{fix} + \frac{1}{2\pi}\frac{\partial\tilde{\varphi}_{\nu_S^{fix}}(n_{turn})}{\partial n_{turn}}$$

High precision spin tune determination $\sigma_{\nu_s} \approx 10^{-10}$




Applications:

1. Lock RF device to spin precession frequency
2. Measure vertical build-up

Courtesy: Dennis Eversmann (dennis.eversmann@rwth-aachen.de)

# Spin Tune Determination

PRL **115,** 094801 (2015) PHYSICAL REVIEW LETTERS week ending 28 AUGUST 2015

**New Method for a Continuous Determination of the Spin Tune in Storage Rings and Implications for Precision Experiments**

D. Eversmann,[1] V. Hejny,[2] F. Hinder,[1,2] A. Kacharava,[2] J. Pretz,[1,3] F. Rathmann,[2,*] M. Rosenthal,[1,2] F. Trinkel,[1,2] S. Andrianov,[4] W. Augustyniak,[5] Z. Bagdasarian,[6,2] M. Bai,[2,3] W. Bernreuther,[7,3] S. Bertelli,[8] M. Berz,[9] J. Bsaisou,[10,2] S. Chekmenev,[1] D. Chiladze,[6,2] G. Ciullo,[8] M. Contalbrigo,[8] J. de Vries,[10,2] S. Dymov,[2,11] R. Engels,[2] F. M. Esser,[12] O. Felden,[2] M. Gaisser,[13] R. Gebel,[2] H. Glückler,[12] F. Goldenbaum,[2] K. Grigoryev,[1] D. Grzonka,[2] G. Guidoboni,[8] C. Hanhart,[10,2] D. Heberling,[14,3] N. Hempelmann,[1] J. Hetzel,[2] R. Hipple,[9] D. Hölscher,[14] A. Ivanov,[4] V. Kamerdzhiev,[2] B. Kamys,[15] I. Keshelashvili,[2] A. Khoukaz,[16] I. Koop,[17] H.-J. Krause,[18] S. Krewald,[2] A. Kulikov,[11] A. Lehrach,[2,3] P. Lenisa,[8] N. Lomidze,[6] B. Lorentz,[2] P. Maanen,[1] G. Macharashvili,[6,11] A. Magiera,[15] R. Maier,[2,3] K. Makino,[9] B. Mariański,[5] D. Mchedlishvili,[6,2] Ulf-G. Meißner,[10,2,3,19] S. Mey,[1,2] A. Nass,[2] G. Natour,[12,3] N. Nikolaev,[20] M. Nioradze,[6] A. Nogga,[10,2] K. Nowakowski,[15] A. Pesce,[8] D. Prasuhn,[2] J. Ritman,[2,3] Z. Rudy,[15] A. Saleev,[2] Y. Semertzidis,[13] Y. Senichev,[2] V. Shmakova,[11] A. Silenko,[21,22] J. Slim,[14] H. Soltner,[12] A. Stahl,[1,3] R. Stassen,[2] M. Statera,[8] E. Stephenson,[23] H. Stockhorst,[2] H. Straatmann,[12] H. Ströher,[2,3] M. Tabidze,[6] R. Talman,[24] P. Thörngren Engblom,[25,8] A. Trzciński,[5] Yu. Uzikov,[11] Yu. Valdau,[19,26] E. Valetov,[9] A. Vassiliev,[26] C. Weidemann,[8] C. Wilkin,[27] A. Wirzba,[10,2] A. Wrońska,[15] P. Wüstner,[12] M. Zakrzewska,[15] P. Zupański,[5] and D. Zyuzin[2]

(JEDI collaboration)



Mitglied der Helmholtz-Gemeinschaft

# Summary

- First direct Electric Dipole Moment measurement of Deuterons planned at COSY in Jülich
- PhD theses involved:
  - Hardware developments
  - Simulations
  - Software Development
  - Measurements & Data Analysis