Impact of orbit distortions on EDM measurements

Marcel Rosenthal on behalf of the JEDI collaboration
2015-11-04 | Beam Dynamics meets Diagnostics, Florence, Italy

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Outline

Introduction

- What are Electric Dipole Moments (EDMs)?
- How to measure them in in Storage Rings?
- What is planned for the Cooler Synchrotron COSY in Jülich?

Simulation Framework

- Transfer Maps for time-varying fields
- Benchmarking using spin oscillations in presence of time-varying fields

Studies towards EDM Measurements at COSY

- Polarization signal due to non-vanishing EDM
- Fake signals arising from misalignments

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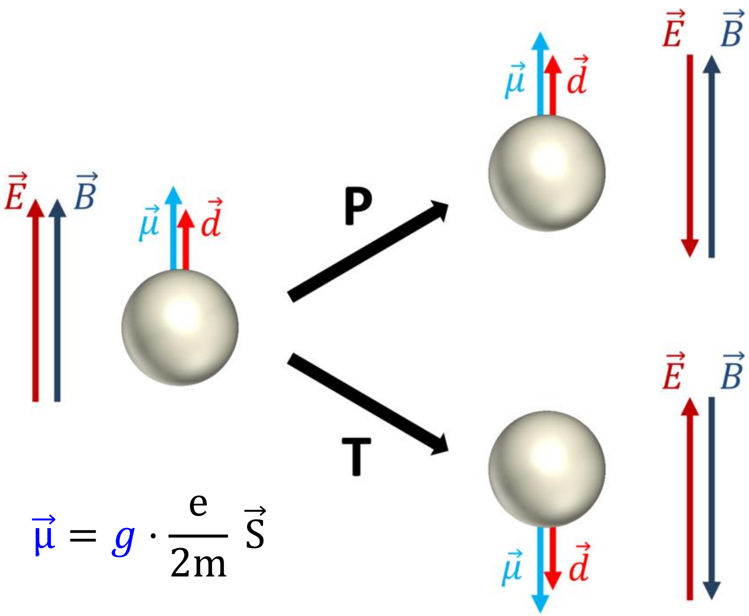
CP-Violating permanent EDMs



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

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

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

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

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

- Electric Dipole Moments:
  - Charge separation (classical picture)
  - Fundamental property
- Permanent EDMs of light hadrons are P- and T-violating
  - CPT-Theorem: CP-Violation
- Known CP-Violation not sufficient to explain Matter-Antimatter-Asymmetry in universe
- Search for new sources of CP-Violation by measuring Electric Dipole Moments of charged hadrons in storage rings

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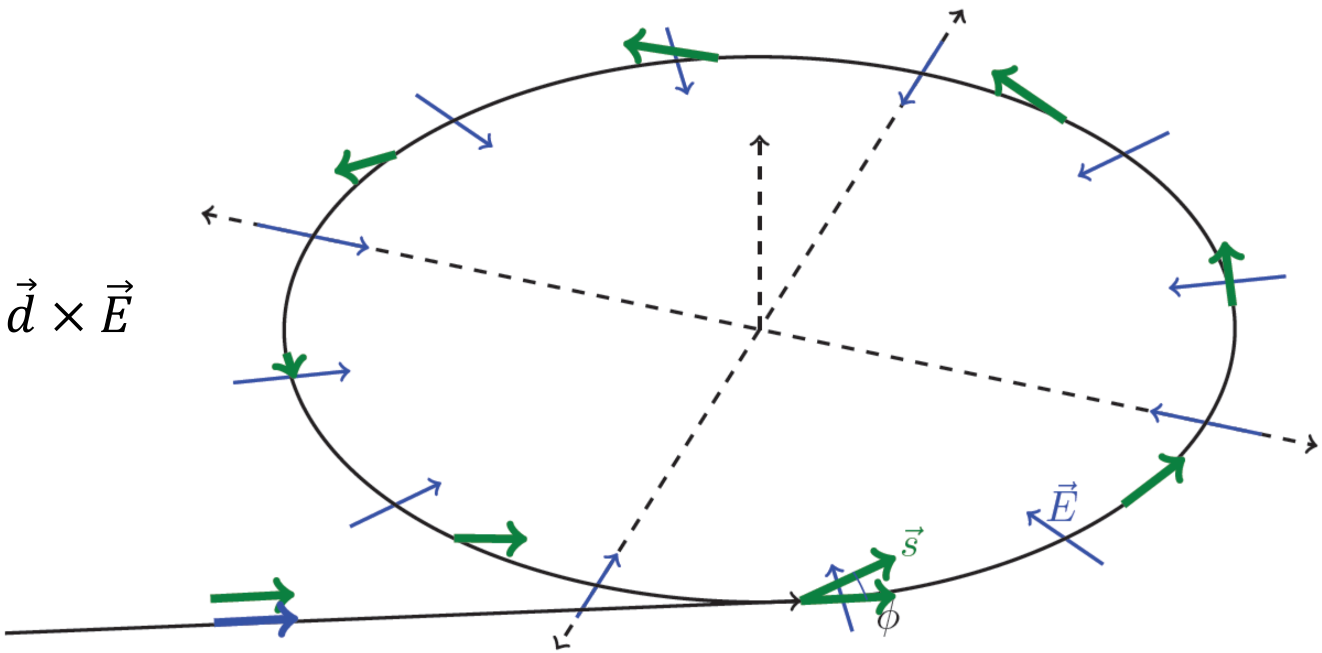
EDM measurements in storage rings

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



- General idea:
  - Inject polarised particles with spin aligned to momentum direction
  - *„Frozen Spin"*-Technique: without EDM spin stays aligned to momentum
  - EDM couples to electric bending fields → slow signal buildup

- All electric ring is concept for a final dedicated machine

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Thomas-BMT-Equation

- Equation of spin motion for relativistic particles in electromagnetic fields:

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

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

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

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

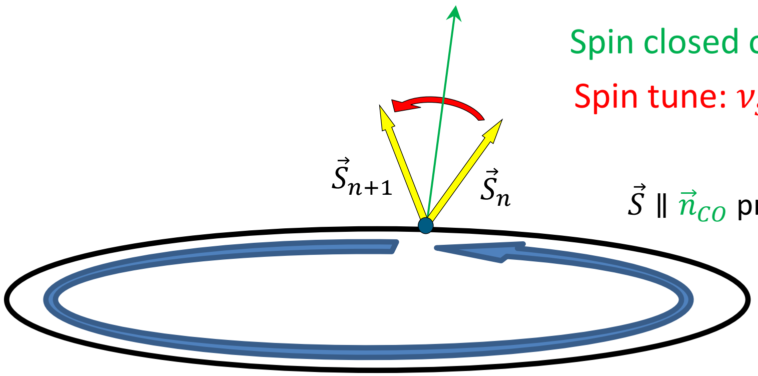
$$\vec{d} = \eta\cdot\frac{e}{2mc}\vec{S}$$

	G
Proton	1.792847357
Deuteron	-0.142561769

- Comparison to equation of motion:

$$\frac{d\vec{p}}{dt} = \vec{\Omega}_{cyc} \times \vec{p}$$

$$\vec{\Omega}_{cyc} = -\frac{q}{\gamma m}\left[\vec{B}_\perp + \frac{\vec{E}\times\vec{\beta}}{\beta^2 c}\right]$$



Spin closed orbit: $\vec{n}_{CO}$

Spin tune: ν_s

$\vec{S} \parallel \vec{n}_{CO}$ preserved

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Pure electric ring

- Comparison of $\vec{\Omega}_{\mathrm{MDM}}$ and $\vec{\Omega}_{\mathrm{cyc}}$ for pure electric bend

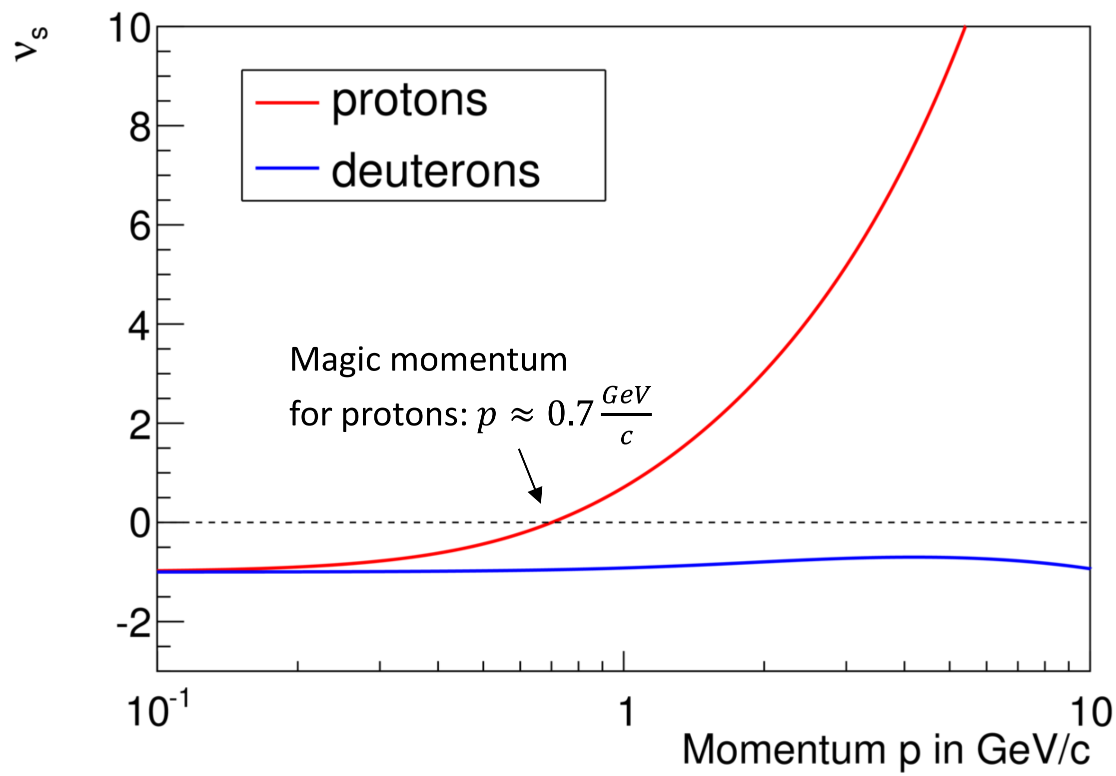
  $\vec{n}_{CO}$: vertical

$$\nu_s = \pm \frac{|\vec{\Omega}_{MDM} - \vec{\Omega}_{cyc}|}{|\vec{\Omega}_{cyc}|} = \pm \frac{G(\gamma^2 - 1) - 1}{\gamma}$$

(Sign fixed by orientation of $\vec{n}_{co}$)

- Pure electric ring for proton frozen spin

- Combined ring (electric/magnetic) for deuteron frozen spin



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Pure magnetic ring

- Comparison of $\vec{\Omega}_{\mathrm{MDM}}$ and $\vec{\Omega}_{\mathrm{cyc}}$ for pure magnetic bend

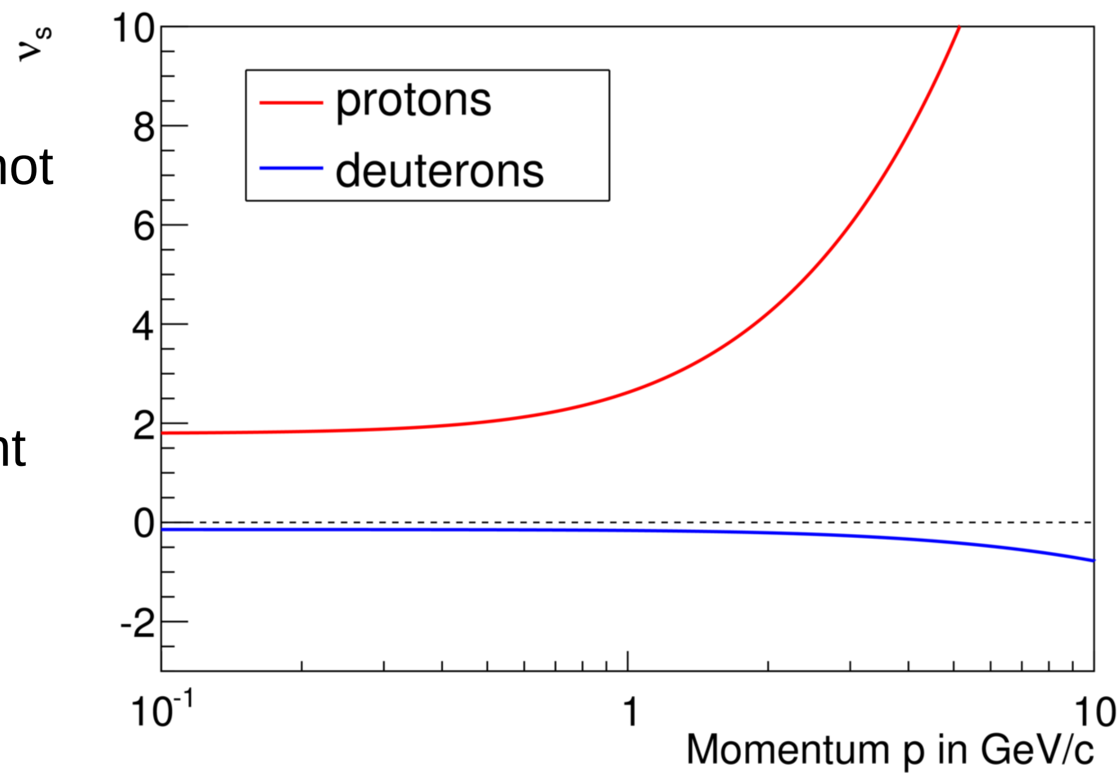
  $\vec{n}_{CO}$: vertical

  $$\nu_s = \pm \frac{|\vec{\Omega}_{MDM} - \vec{\Omega}_{cyc}|}{|\vec{\Omega}_{cyc}|} = \pm G\gamma$$

  (Sign fixed by orientation of $\vec{n}_{co}$)

- Frozen Spin Method not applicable in pure magnetic ring

- Different measurement method proposed



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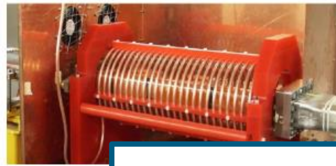
The Cooler Synchrotron COSY

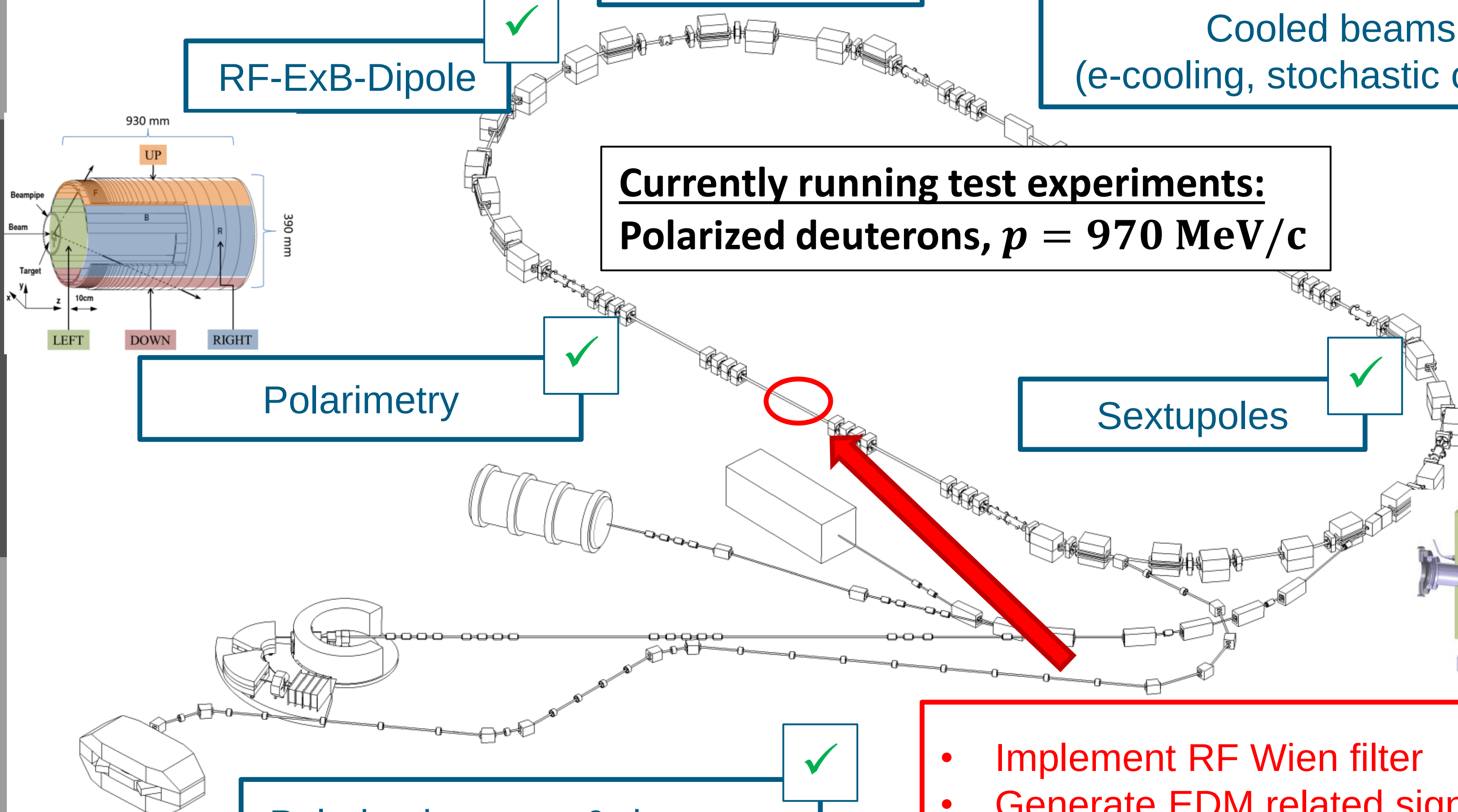


RF Solenoid ✓

RF-ExB-Dipole ✓

Cooled beams
(e-cooling, stochastic cooling) ✓

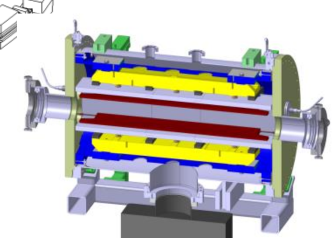
Polarimetry ✓



<u>Currently running test experiments:</u>

Polarized deuterons, $p = 970\ \mathrm{MeV/c}$

Sextupoles ✓



Polarized protons & deuterons ✓

- Implement RF Wien filter
- Generate EDM related signal

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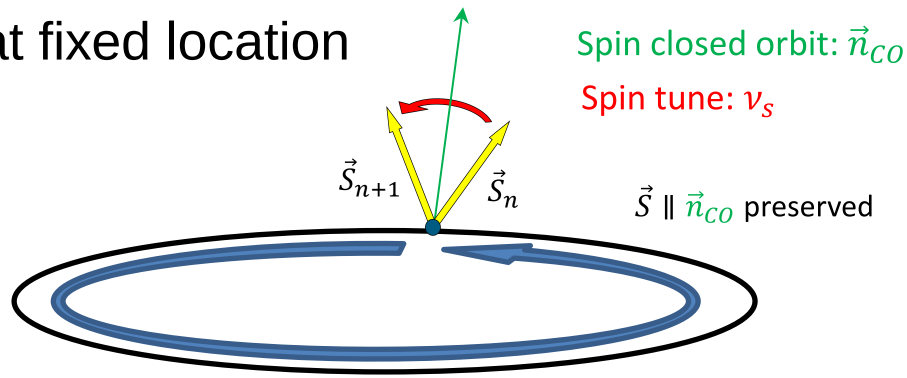
Spin Tune / Spin Closed Orbit

- Spin motion on closed orbit at fixed location in static ring:

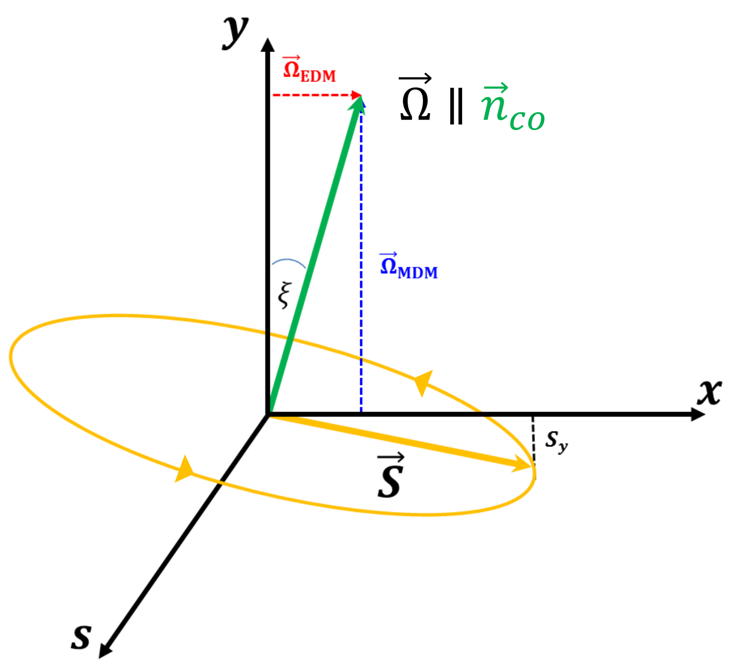


- EDM tilts spin closed orbit:

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

$$\vec{\Omega}_{MDM} = -\frac{q}{\gamma m}\left[(1 + G\gamma)\vec{B}\right]$$

$$\vec{\Omega}_{EDM} = -\frac{q}{m}\frac{\eta}{2}\left[\vec{\beta} \times \vec{B}\right]$$



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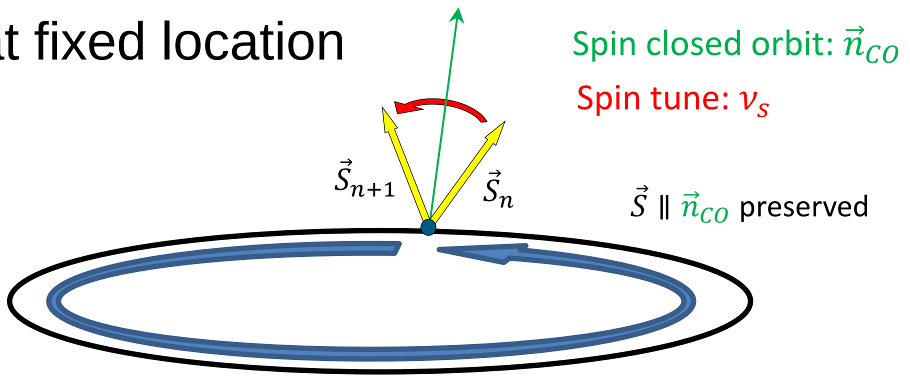
Spin Tune / Spin Closed Orbit II

- Spin motion on closed orbit at fixed location in static ring:



- EDM tilts spin closed orbit:

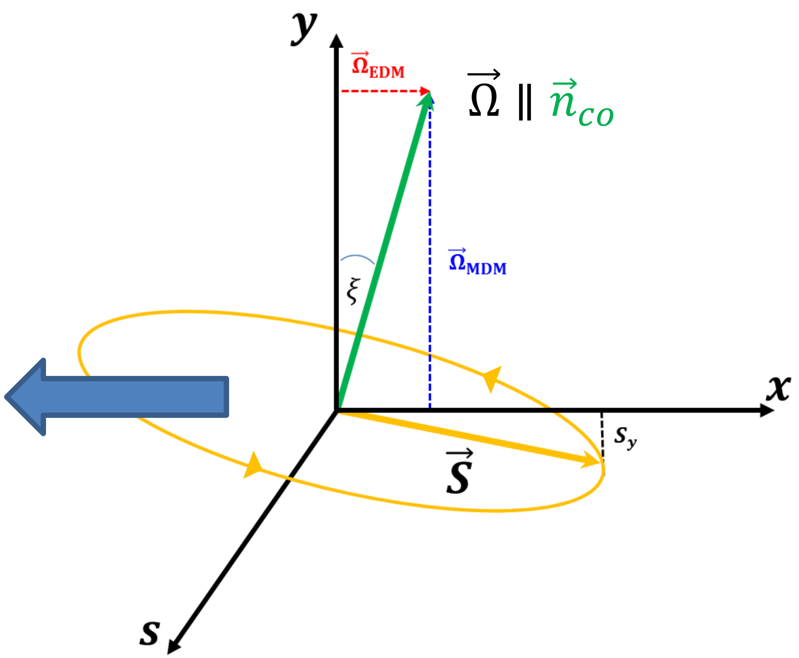
Fast oscillating vertical spin component S_y:

Amplitude: $\mathrm{A} = \sin(\xi) \approx \frac{\eta\beta}{2G}$

Order of magnitude (deuterons, $p \approx \frac{1GeV}{c}$)

$\boldsymbol{\eta = 10^{-4}}$: $\boldsymbol{A \approx 0.15 \cdot 10^{-3}}$

$(\eta = 10^{-4} \leftrightarrow d \approx 10^{-19} e\ cm)$



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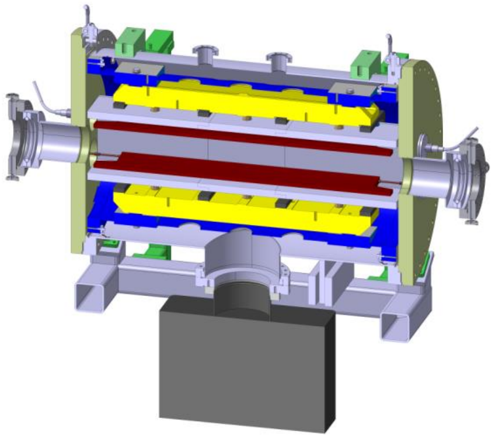
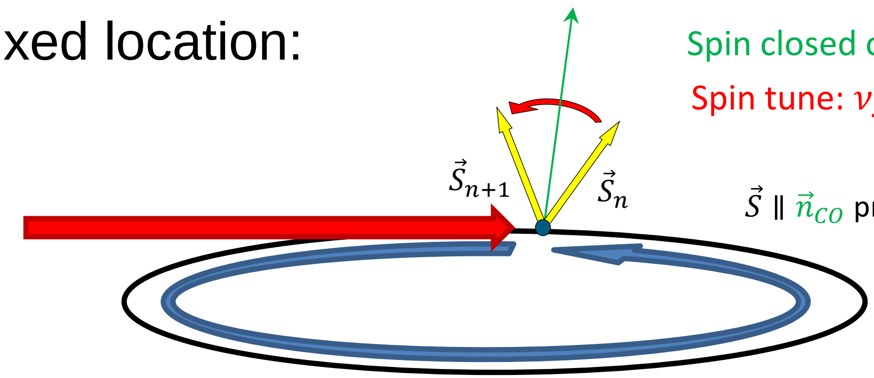
Spin resonance by RF field

- Place RF Wien filter at fixed location:





- Spin motion induced by RF Wien filter (radial E-field / vertical B-field)
  - Fields: $B_{WF} = \hat{B}_{WF} \cdot \cos(\omega_{WF} \cdot t + \phi)$

    $E_{WF} = \hat{E}_{WF} \cdot \cos(\omega_{WF} \cdot t + \phi)$

    $\hat{E}_{WF} = -\beta c \hat{B}_{WF}$
  - Vanishing Lorentz force → no EDM interaction: $\vec{\Omega}_{\mathrm{EDM}} = 0$
    - Spin rotation axis vertical, not parallel to $\vec{n}_{CO}$!
  - Resonant spin interaction: $\omega_{WF} = \omega_{spin} + K \cdot \omega_{rev} = (\nu_s + K) \cdot \omega_{rev},\ K \in \mathbb{Z}$
    - Accumulation of vertical spin signal

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Outline

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Simulation Framework

- Transfer Maps for time-varying fields
- Benchmarking using spin oscillations in presence of time-varying fields

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Framework

COSY Lattice

COSY INFINITY

M. Berz, K. Makino et al.

- Calculator:
  - Optical functions
  - Closed orbit
  - Spin tune
- Tracker:
  - Static maps
  - RF maps

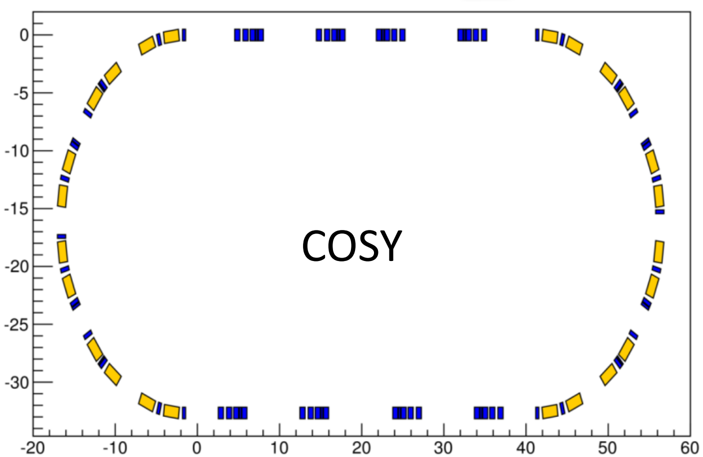
COSY Toolbox

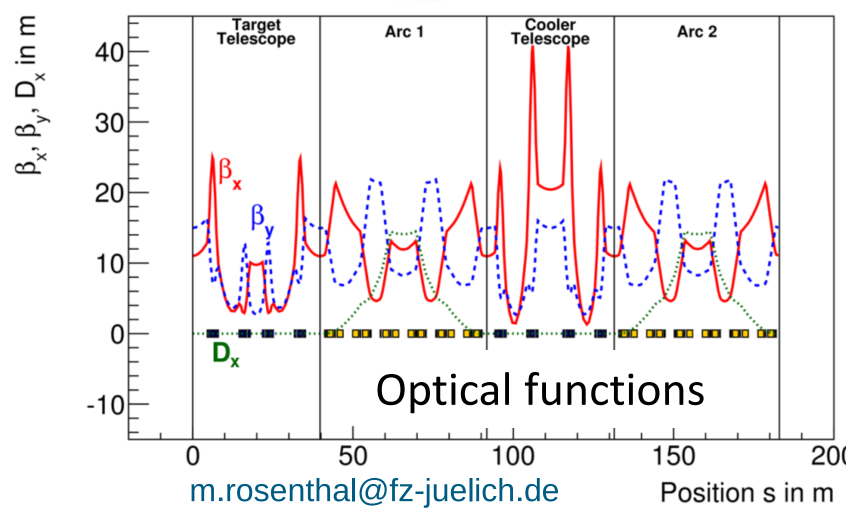
Armadillo

- linear algebra operations
- SVD, pseudo-inverse for orbit correction

ROOT

- plotting
- storage (ROOT files/trees)





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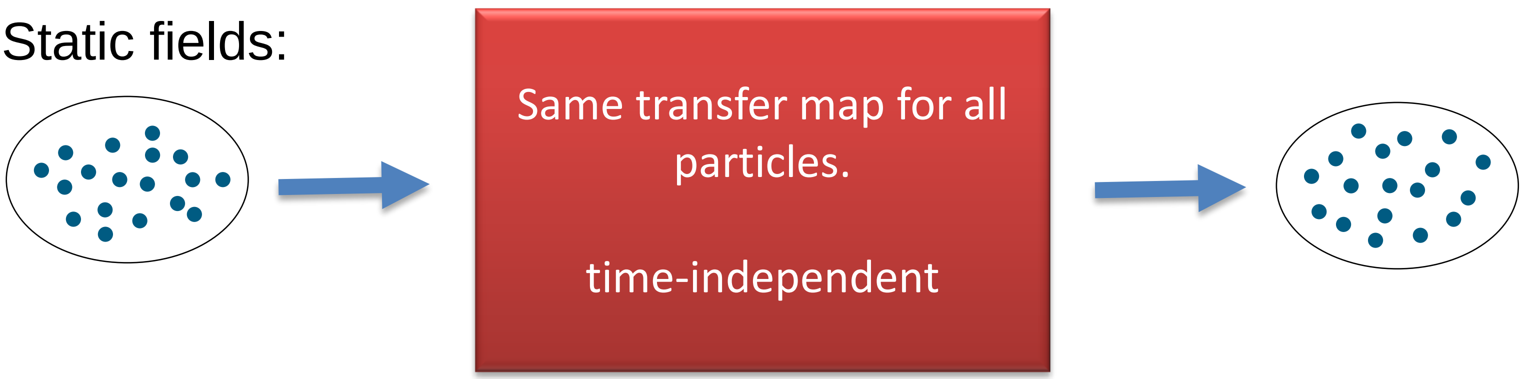
Simulations

- Long-term tracking required:
  - Transfer maps allow for fast tracking and study of the optical system
- Solutions for equations of motion to arbitrary order:

$$\vec{z}_f = \mathcal{M}(\vec{z}_i), \quad \vec{S}_f = \mathcal{A}(\vec{z}_i) \cdot \vec{S}_i$$

- Relate phase space and spin coordinates before and after element
- Static fields:



- In case of time-varying fields, same map can not be reused in subsequent turns

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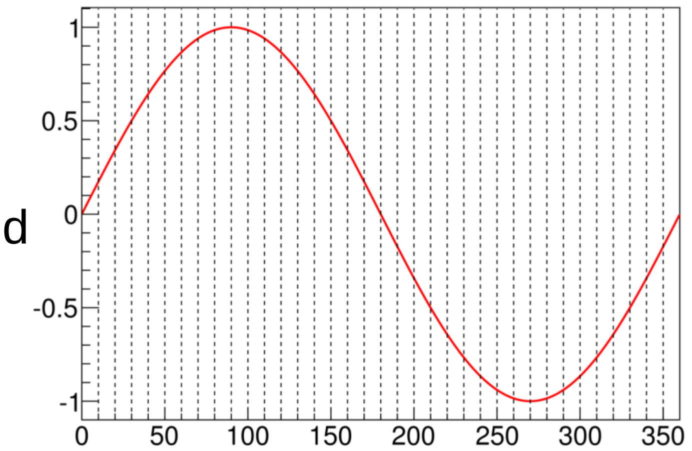
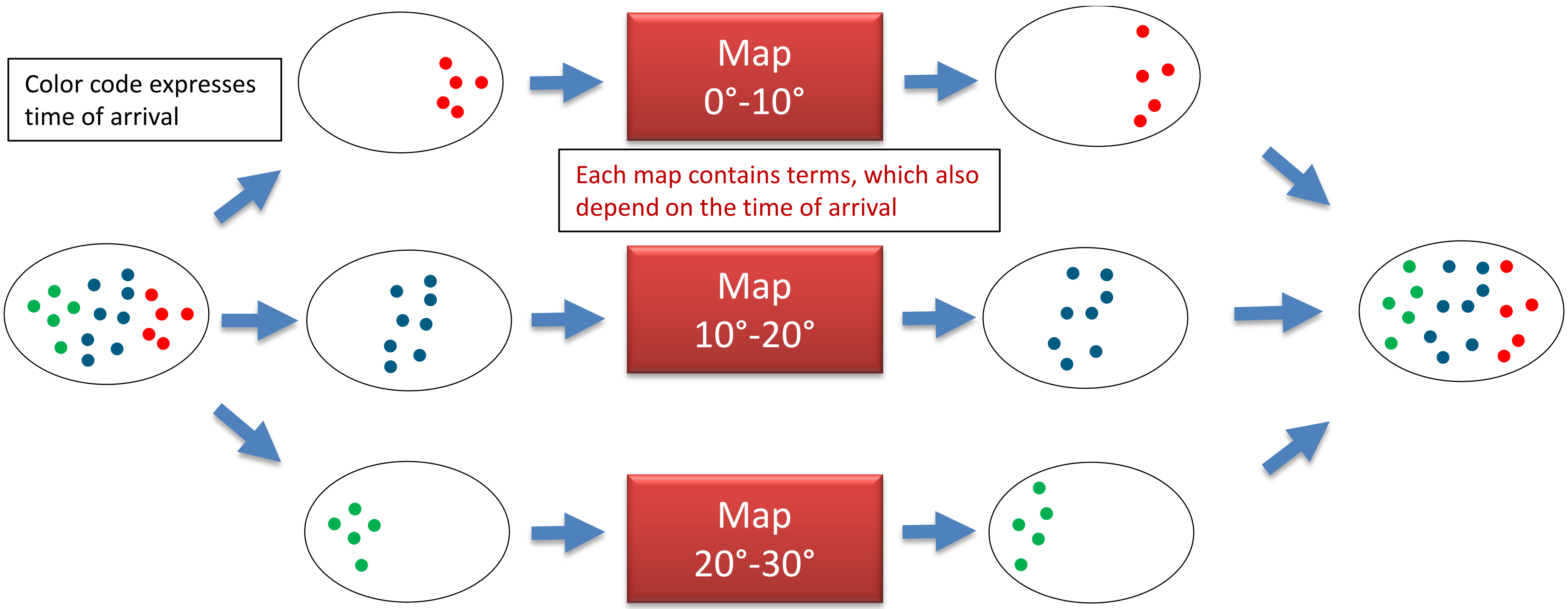
Transfer Maps for RF fields

- Radiofrequency fields:
  - Split element into 36 maps covering the 360° phase interval of the time-varying field





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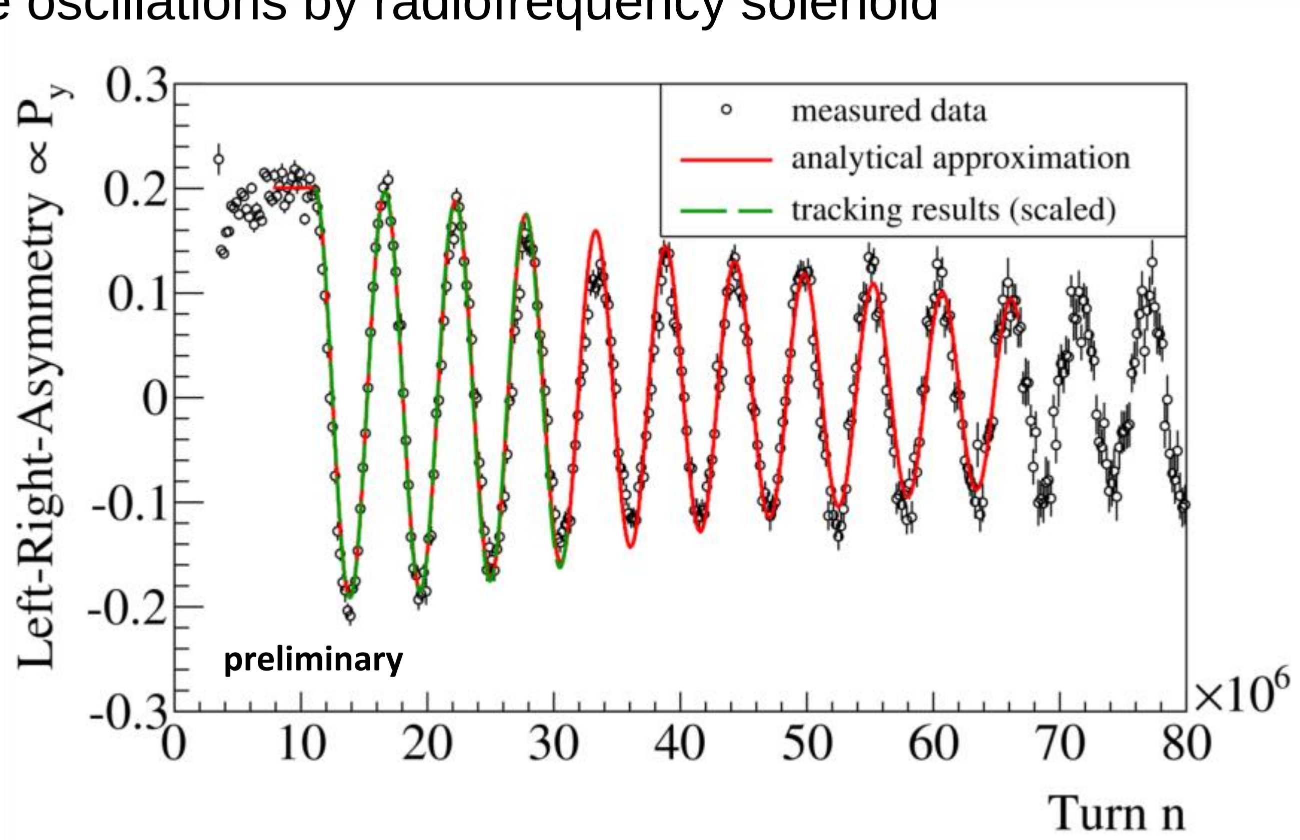
Benchmarking

- Use initially vertical polarized deuteron beam
- Excite oscillations by radiofrequency solenoid



- Data reproducible using map methods

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Outline

Studies towards EDM Measurements at COSY

- Polarization signal due to non-vanishing EDM
- Fake signals arising from misalignments

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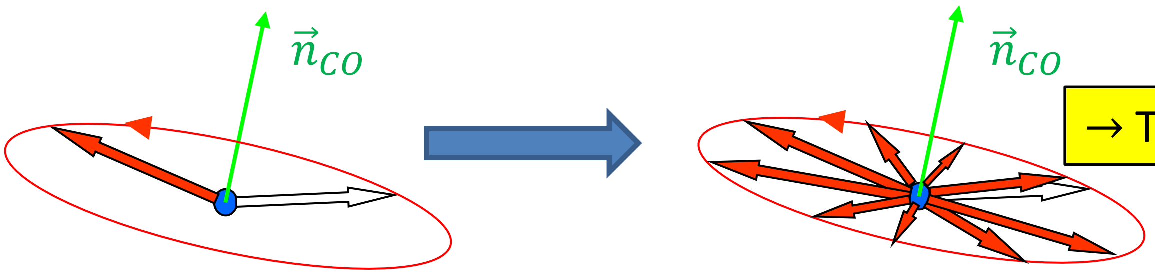
Proposed measurement setup

- EDM experiment:
  - Vector polarized deuteron beam
  - Momentum: 970 MeV/c
  - Applied cooling to reduce emittances and momentum spread
- Initial polarization perpendicular to spin closed orbit
  - Long spin coherence time required



→ Tomorrow, 3:30 pm: V. Hejny

- Measure buildup of a vertical polarization related to EDM

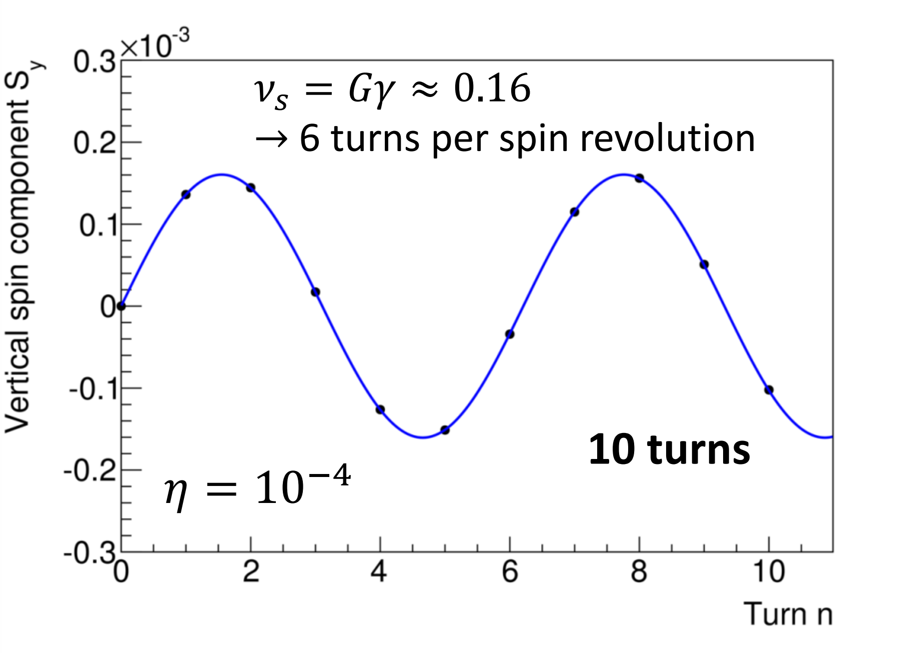
Without Wien filter	With Wien filter
Fast oscillation of S_y: $\eta = 10^{-4}$: $\boldsymbol{A \approx 0.15 \cdot 10^{-3}}$	Additionally, slow accumulation of S_y $\eta = 10^{-4}, \hat{B}_{WF} = 0.1\ mT, l_{WF} = 0.8$ m: $\boldsymbol{\partial S_y / \partial n \approx 0.15 \cdot 10^{-8}}$

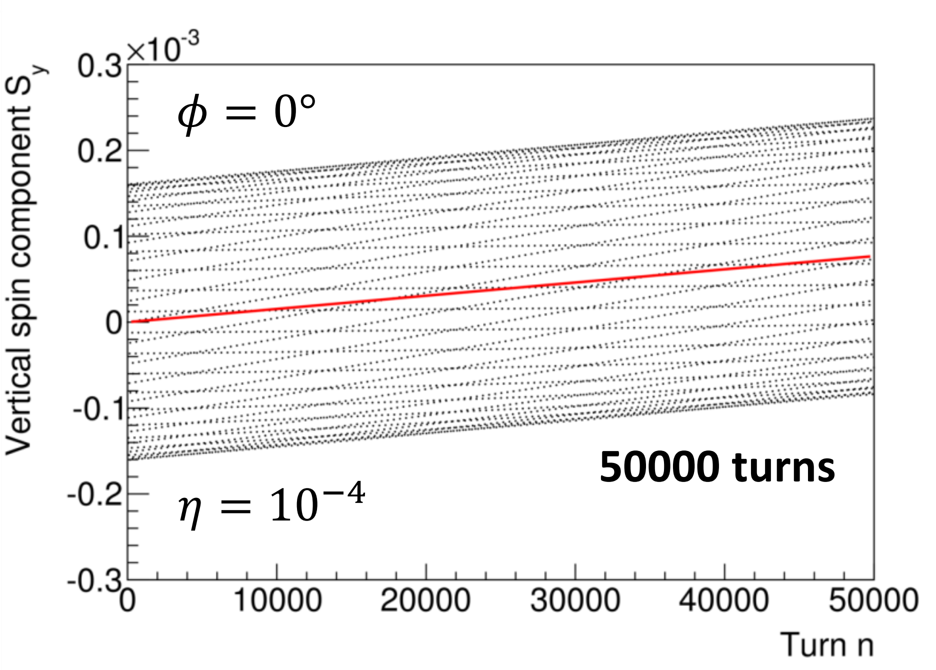
Polarization buildup induced by EDM

- Investigate spin motion on closed orbit
- Radiofrequency fields of the Wien filter:

$$B_{WF} = \hat{B}_{WF} \cdot \cos(\omega_{WF} \cdot t + \phi)$$
$$E_{WF} = \hat{E}_{WF} \cdot \cos(\omega_{WF} \cdot t + \phi)$$

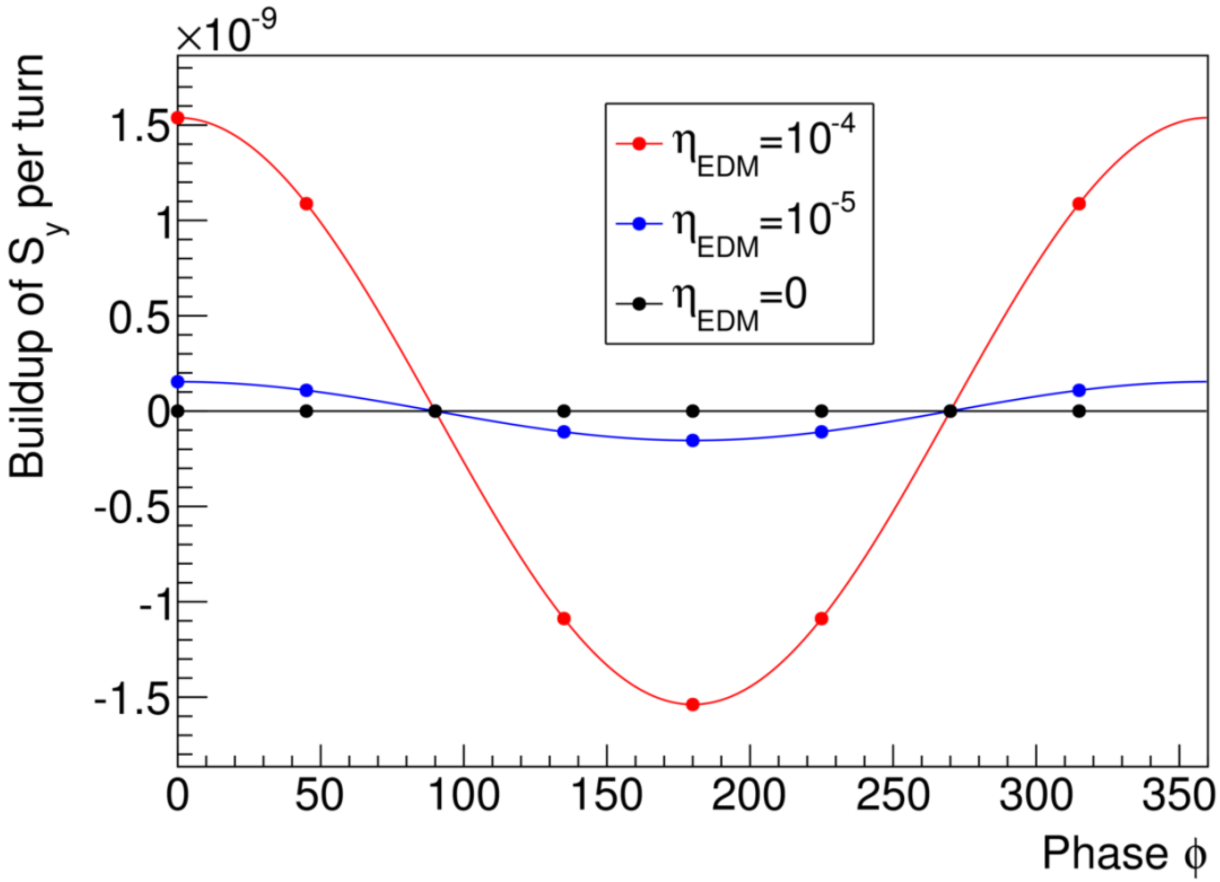
$$\hat{B}_{WF} = 0.1\ \mathrm{mT} \qquad \hat{E}_{WF} = -\beta c \hat{B}_{WF}$$





Phase relation (EDM)

- Phase relation between spin and Wien filter field is important
  - $\phi = 0 \Leftrightarrow$ fields are maximal, when spin is longitudinal at Wien filter location



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Misalignments

- Radial magnetic fields also lead to tilt of spin closed orbit
- Important sources:
  - Vertically shifted quadrupole magnets
  - Rolled dipole magnets

- Examine connection between orbit RMS and vertical spin signal

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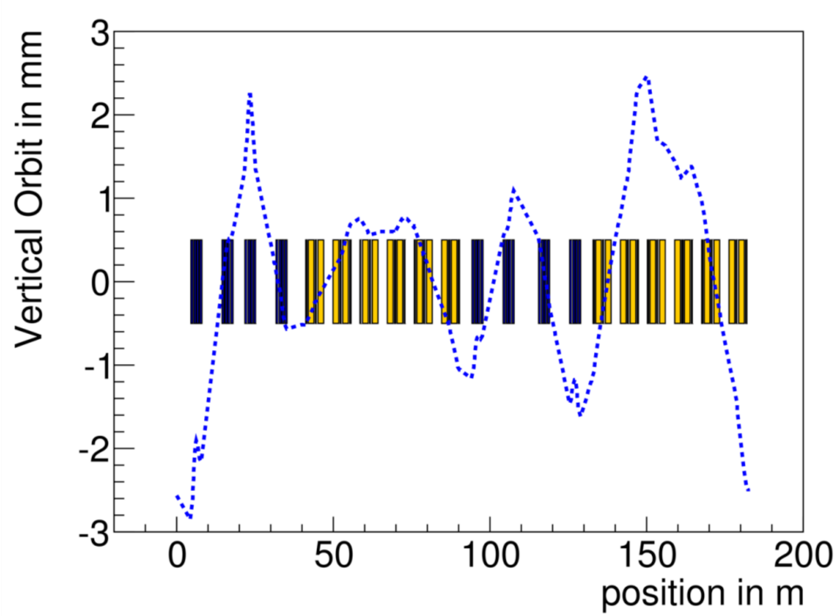
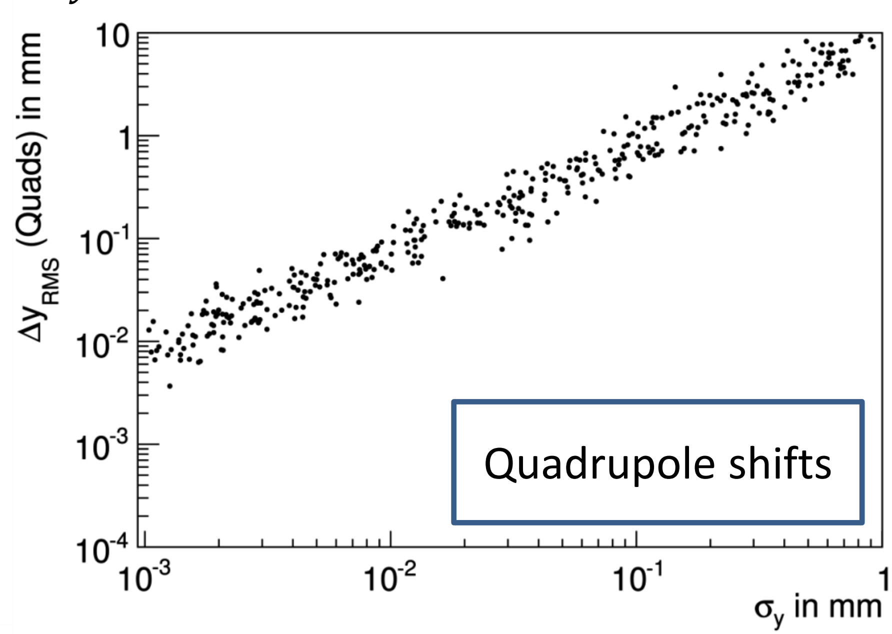
Misalignments II

- Radial magnetic fields also lead to tilt of spin closed orbit
- Important sources:
  - Vertically shifted quadrupole magnets
  - Rolled dipole magnets

- 1. Dice random shifts of quadrupoles in vertical direction
  - Gaussian distributed ($\mu = 0, \sigma = \sigma_y$)

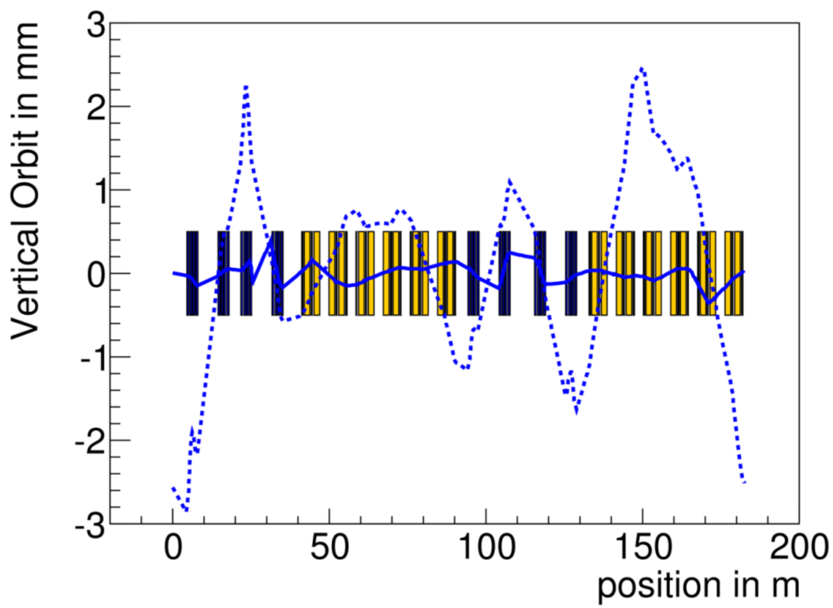


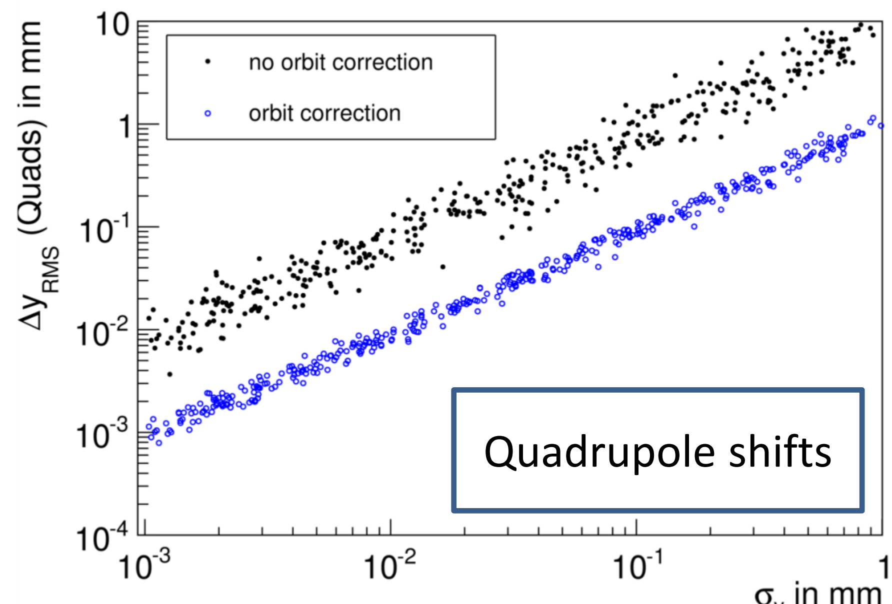


Misalignments III

- Radial magnetic fields also lead to tilt of spin closed orbit
- Important sources:
  - Vertically shifted quadrupole magnets
  - Rolled dipole magnets

- 2. Calculate Orbit Response Matrix and simulate an orbit correction
  - ~20 correctors and ~30 BPMs per plane





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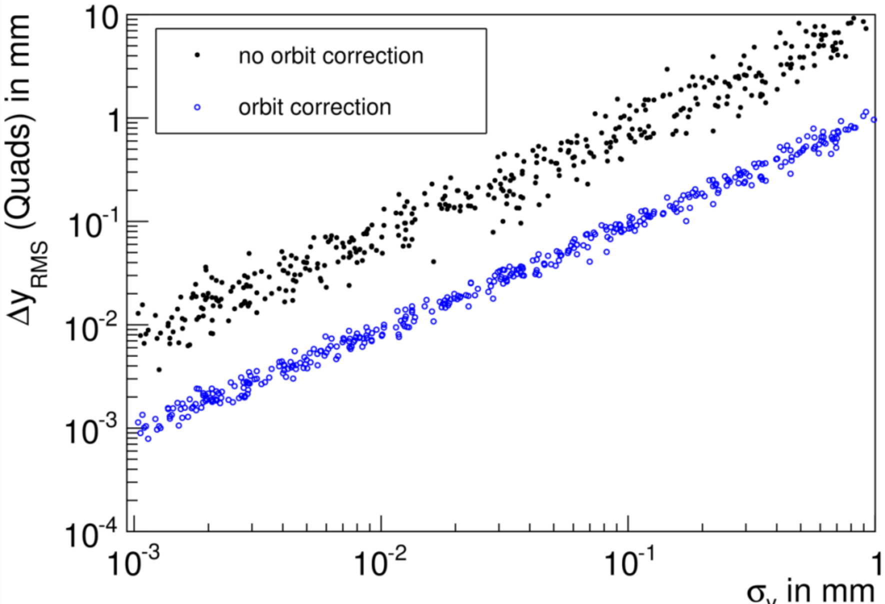
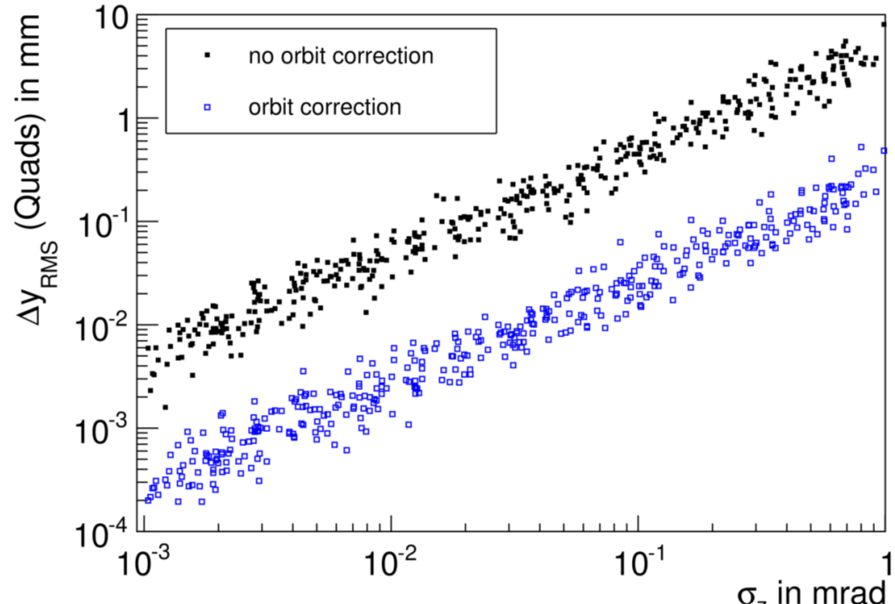
Orbit changes

- Investigate different sets of misalignments separately



Quadrupole shifts



Dipole rolls

- What about the vertical spin accumulation?

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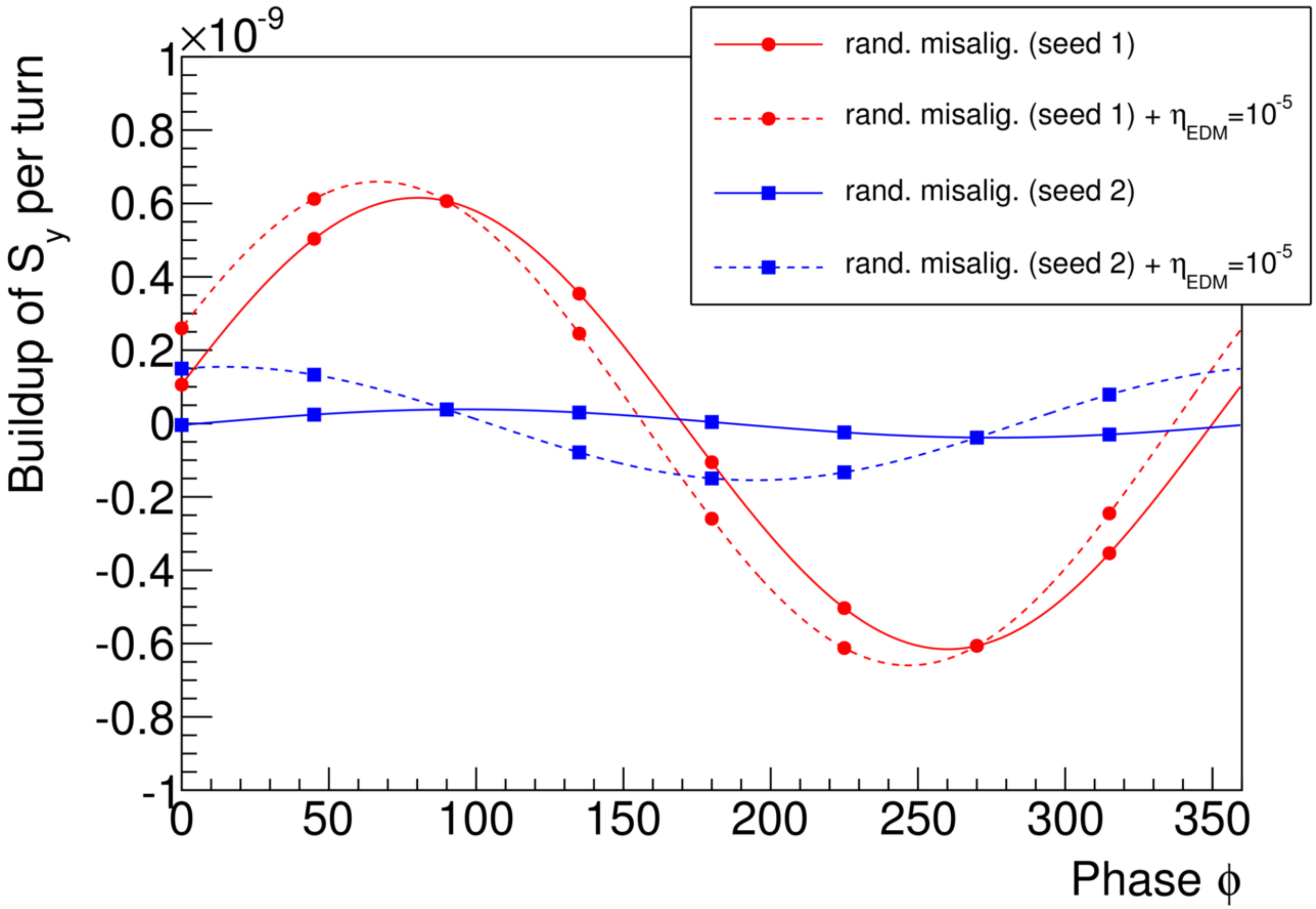
Phase relation (Misalignments)



- Phase relation depends on distributions of misalignments
- Discriminate on $\phi = 0$

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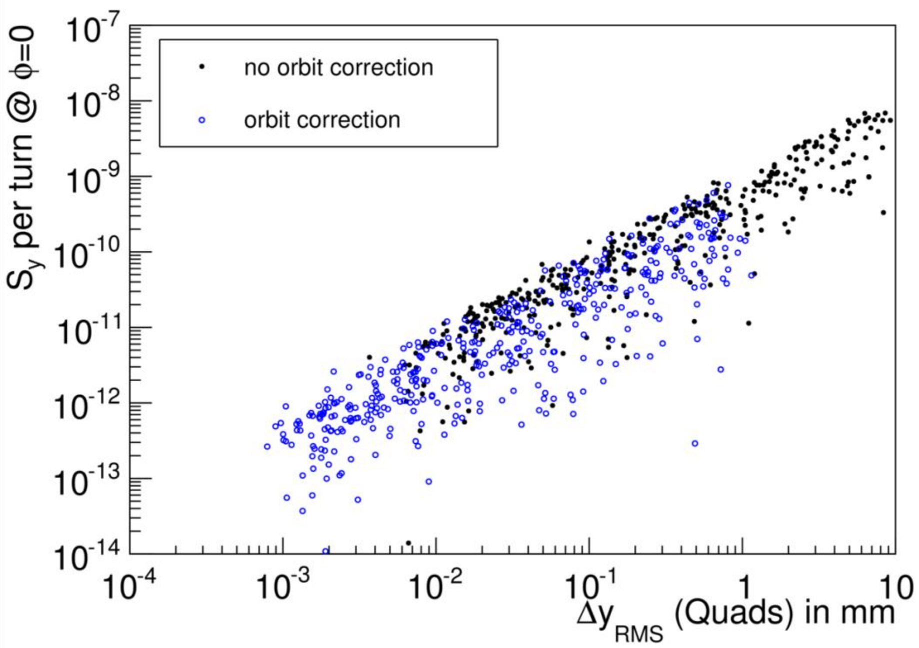
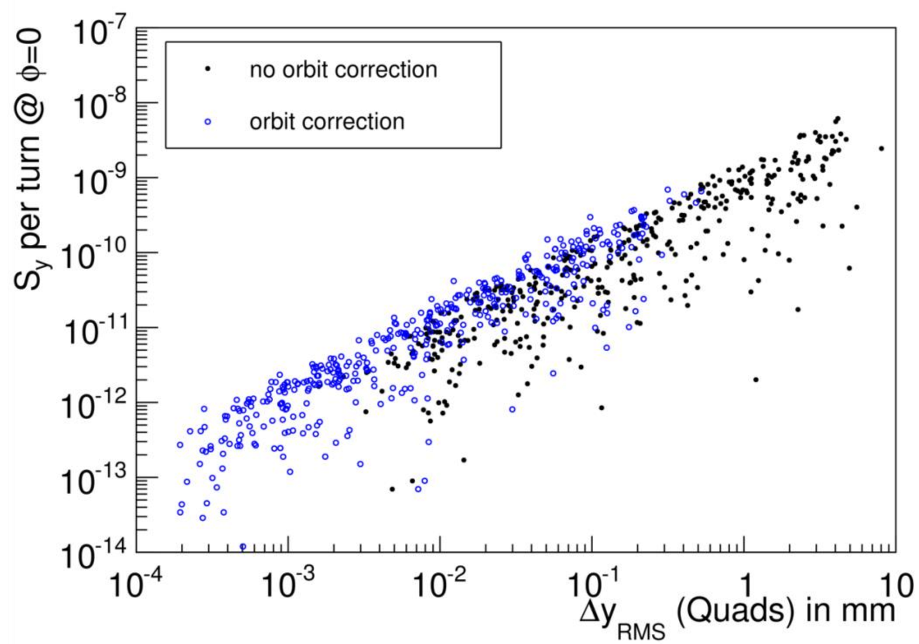
Buildup due to Misalignments

- Induced buildup by misalignments (no EDM)
- Vertical orbit deviations must be minimized to suppress this background





Quadrupole shifts

Dipole rolls

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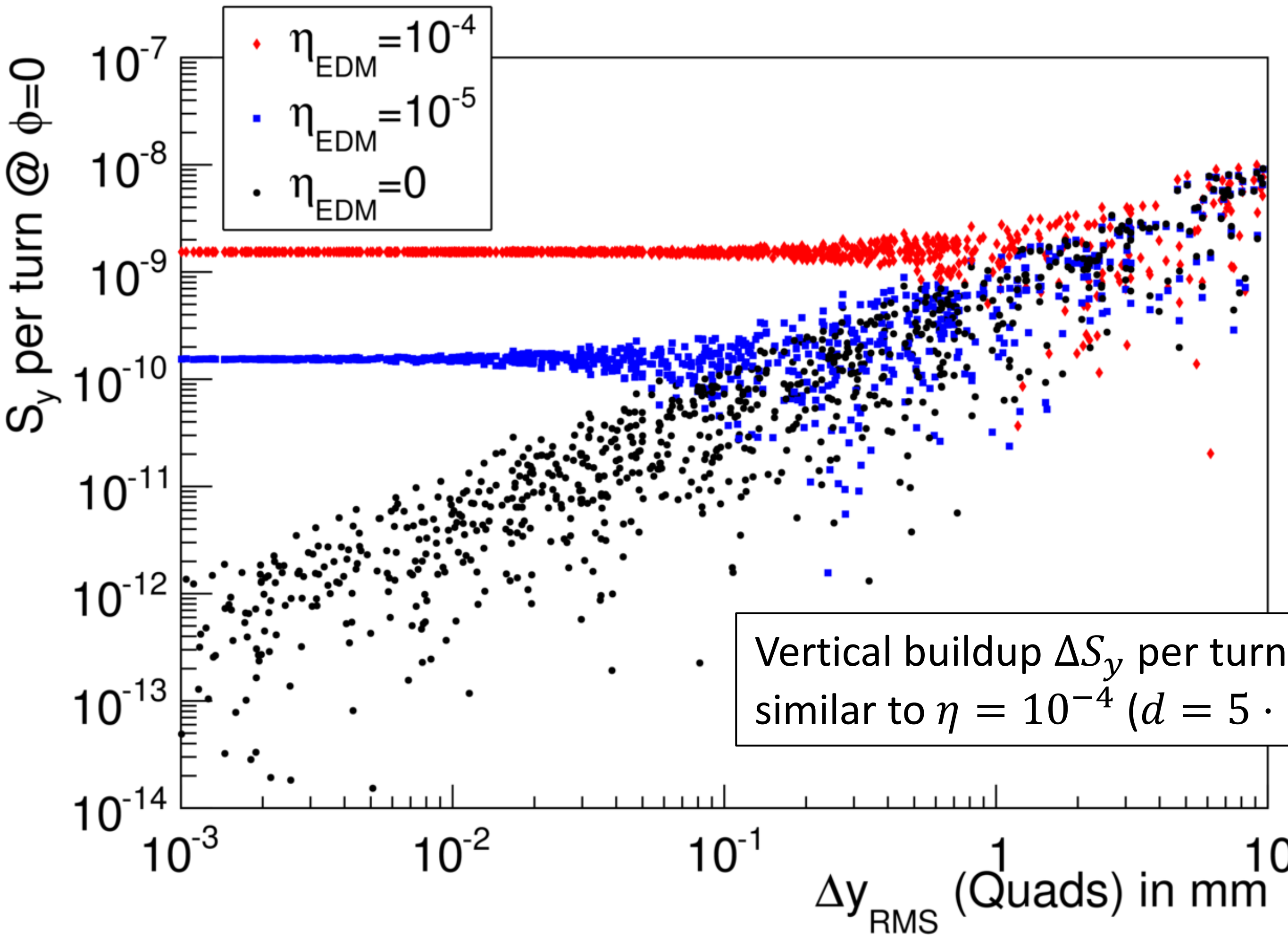
Comparison to EDM signal

- More complete set of misalignments (shifts, tilts, rolls)



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

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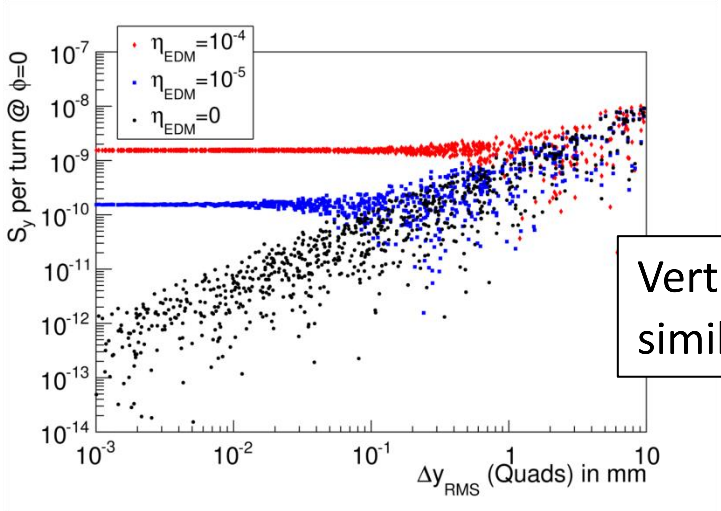
Summary & Outlook

- EDM measurements in storage rings very challenging
- Accelerator ⇔ Experiment
- RF Wien filter method for magnetic ring:
  - Strong background from MDM interactions due to misalignments
  - Good orbit monitoring and control is essential
  - Upgrade of orbit diagnosis system under consideration



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

- **Looking forward to some interesting discussions!**

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Development of new BPMs

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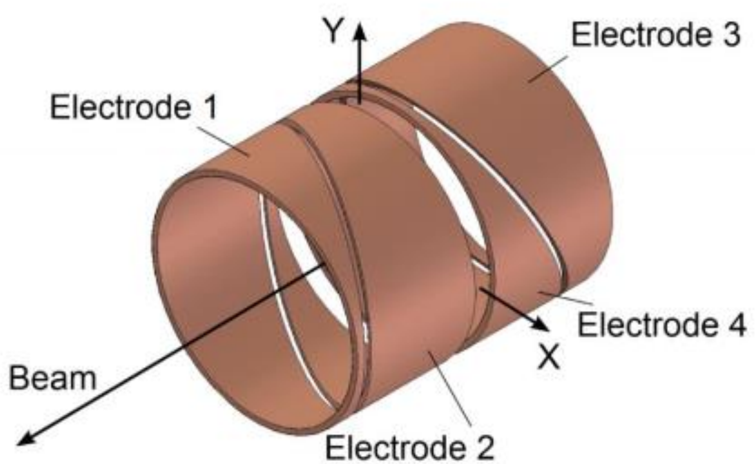
- Upgrade of orbit diagnosis and control required to suppress systematics

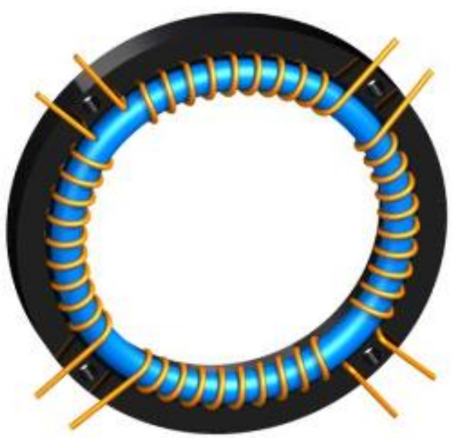
- BPM development on going:

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

Conventional capacitive BPM



New inductive BPM



First step to SQUID-based BPM system