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Spin Tracking for Final Ring Design

March 13, 2017 | Andreas Lehrach

Forschungszentrum Jülich (IKP-4) & RWTH Aachen University (Ex.Physik IIIb)

on behalf of the JEDI collaboration

(Jülich Electric Dipole Moment Investigations)

Utilized Simulation Programs

COSY Infinity by M. Berz and K. Makino (MSU)

- based on map generation using differential algebra and the subsequent calculation of the spin-orbital motion for an arbitrary particle, including higher-order nonlinearities, normal form analysis, and symplectic tracking

PTC (Polymorphic Tracking Code) by E. Forest (KEK)

- TPSA maps (truncated power series algebra by Taylor expansion)

Bmad by D. Sagan (Cornell)

- PTC tracking and Runge-Kutta integration

Bench marking with “analog computer” Cooler Synchrotron COSY and other simulation codes

Simulation Setup for COSY Infinity

COSY Toolbox

COSY Lattice → **COSY Toolbox**

COSY INFINITY ↔ **COSY Toolbox** ↔ **Armadillo**

COSY Toolbox → **ROOT**

COSY INFINITY

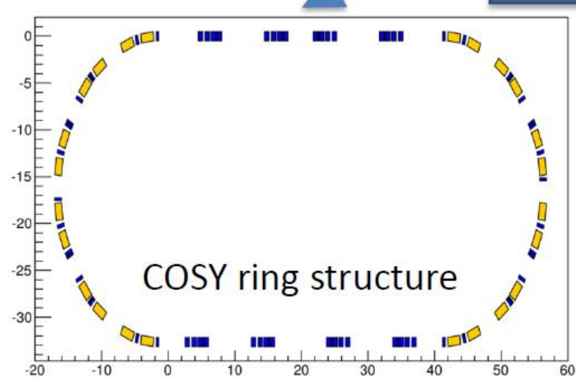
- Calculator:
  - Optical functions
  - Closed orbit
  - Spin tune …
- Tracker:
  - Static maps
  - RF maps (*)

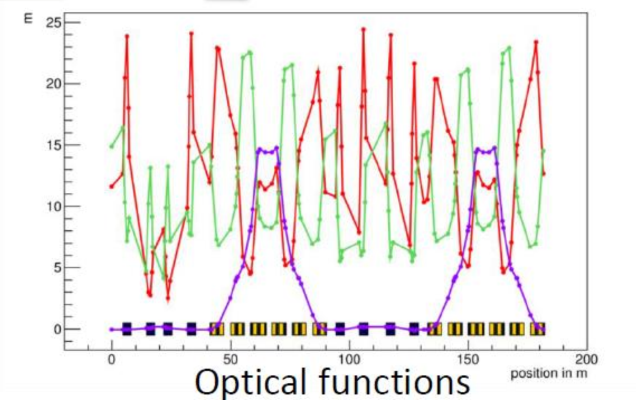
Armadillo

- linear algebra operations
- SVD, pseudo-inverse

ROOT

- plotting
- storage (ROOT files/trees)

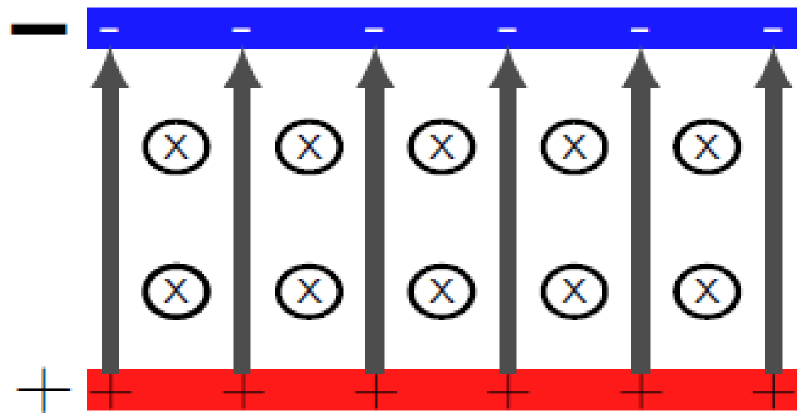




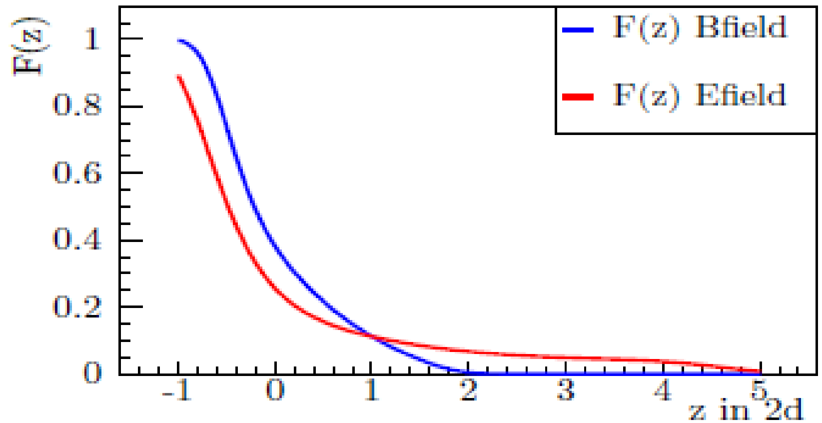
Courtesy: Marcel *Rosenthal*

Extension of COSY Tool Box

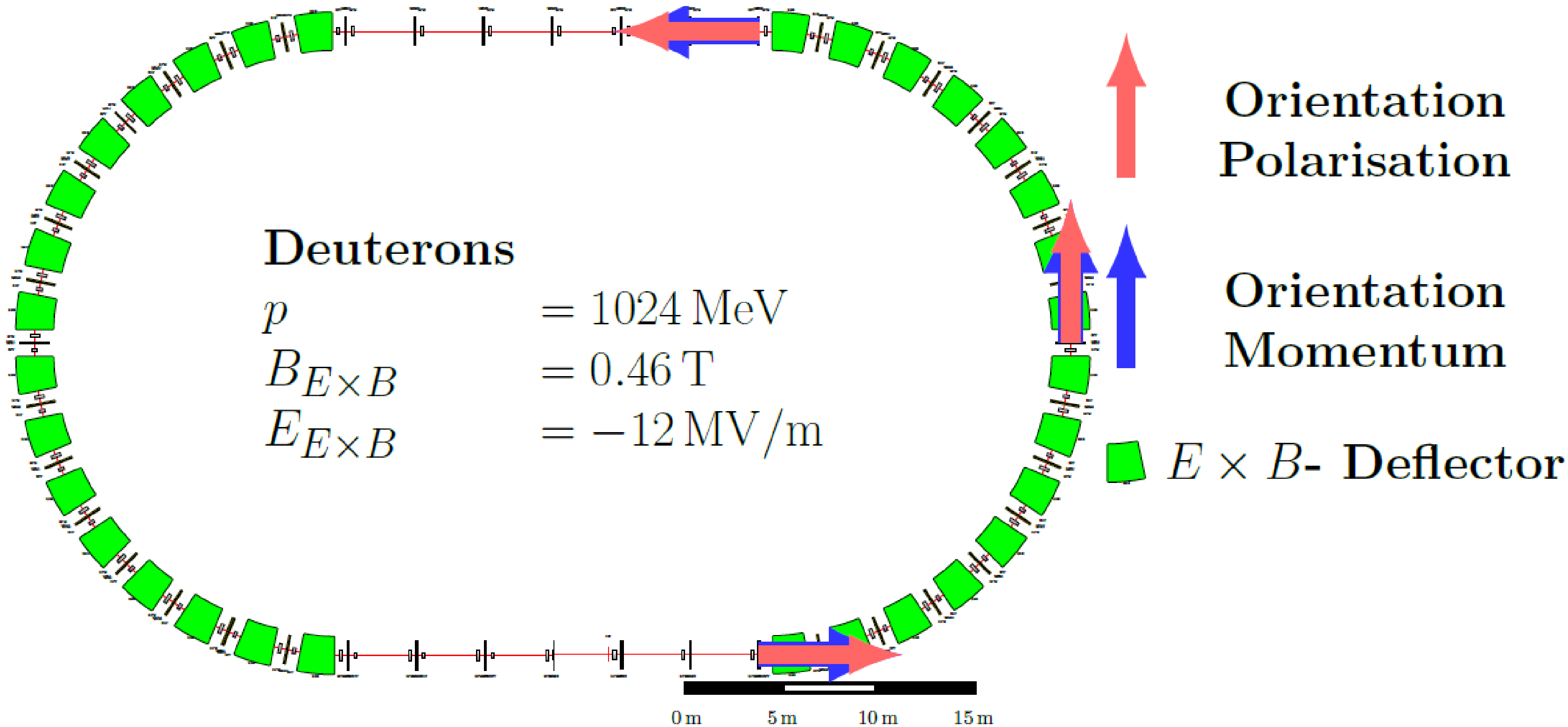
New Elements



Fringe Fields

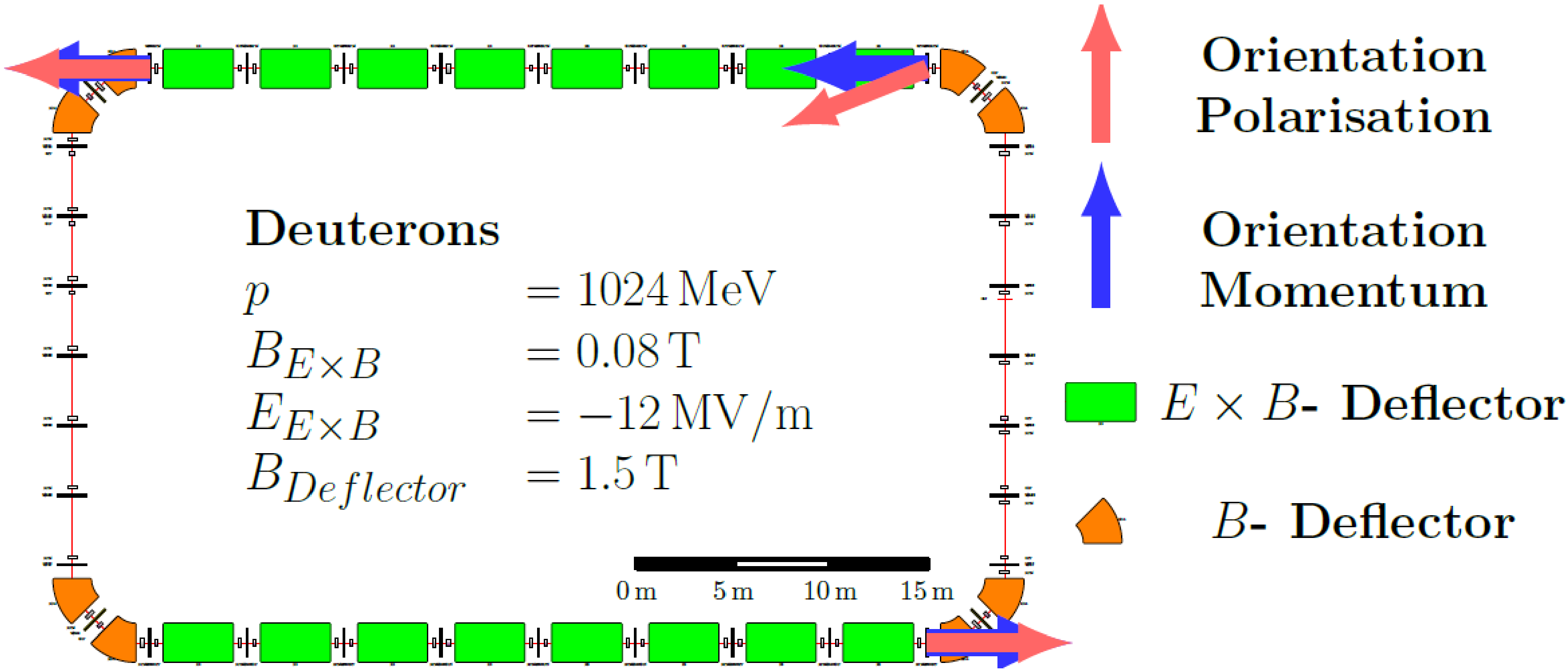


Frozen Spin Ring



$$\frac{d\vec{s}_{MDM}}{dt} = -\frac{q}{m}\left\{a\vec{B}+\left(\frac{1}{\gamma^2-1}-a\right)\vec{\beta}\times\vec{E}\right\}\times\vec{s} \stackrel{!}{=} 0$$

Quasi-Frozen Spin Ring

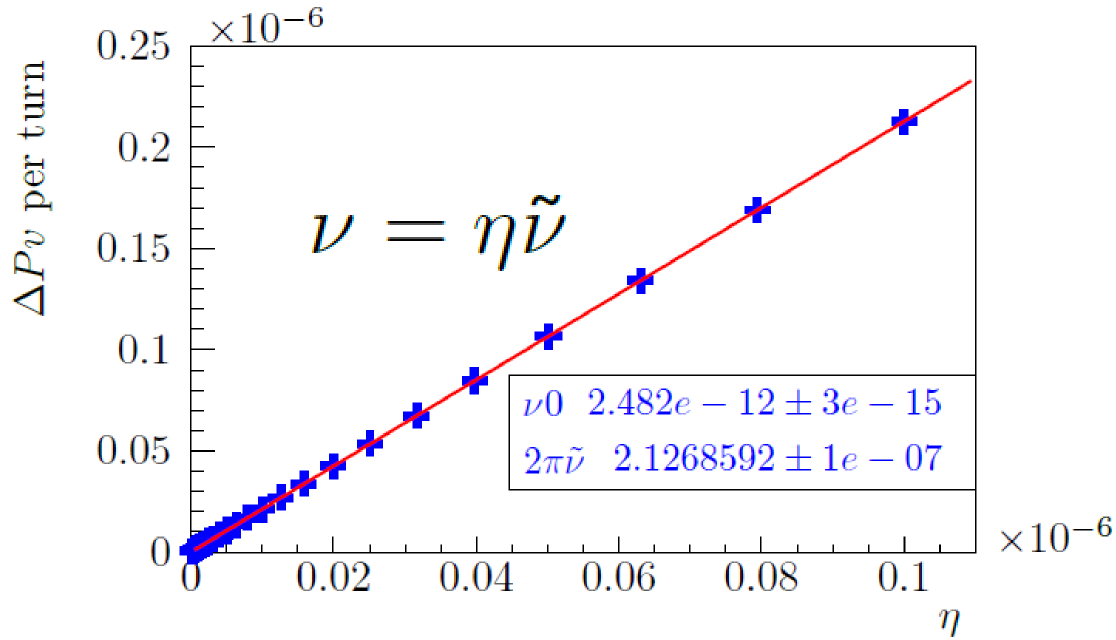


$$\left\langle \frac{d\vec{s}_{MDM}}{dt} \right\rangle = -\left\langle \frac{q}{m} \left\{ a\vec{B} + \left(\frac{1}{\gamma^2 - 1} - a \right) \vec{\beta} \times \vec{E} \right\} \times \vec{s} \right\rangle \stackrel{!}{=} 0$$

Courtesy: Yu.Senichev

EDM Polarization Buildup

- $|d_{edm}| \sim \eta \cdot 5.3 \cdot 10^{-15}$ e cm
- Vertical spin build up per turn:



Lattice	Frozen Spin	Quasi Frozen Spin
$2\pi\tilde{\nu}$	2.13	2.03

Courtesy: A. Skawran

Sensitivity of an EDM Experiment

- The statistical error is controllable for an experiment runtime with roughly 1 year!

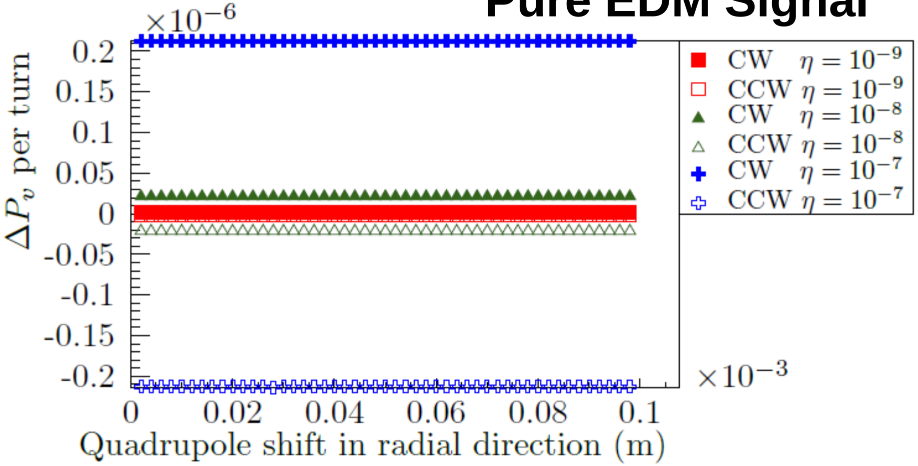
Systematical errors:

- Vertical electric fields
- Transverse magnetic fields
- Longitudinal fields
- Gradient fields
- Gravitation
- …

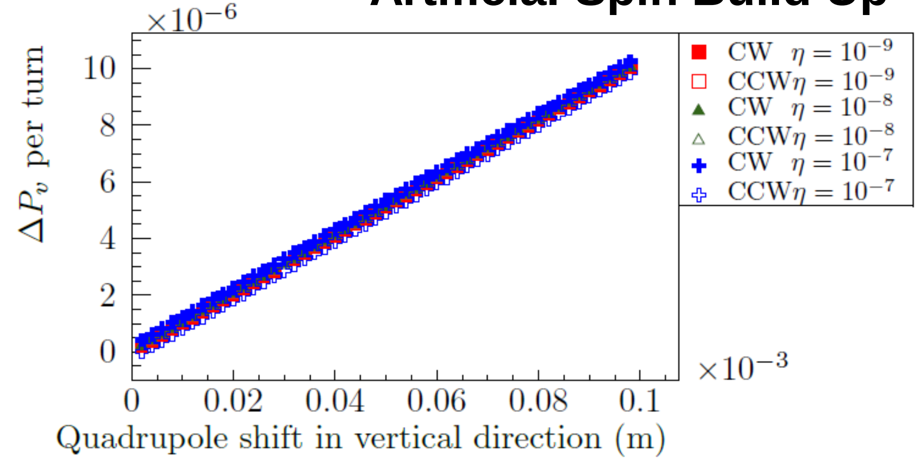
→ Clockwise-counterclockwise beams mandatory cancel systematics and to reach highest sensitivity

CW-CCW Measurement

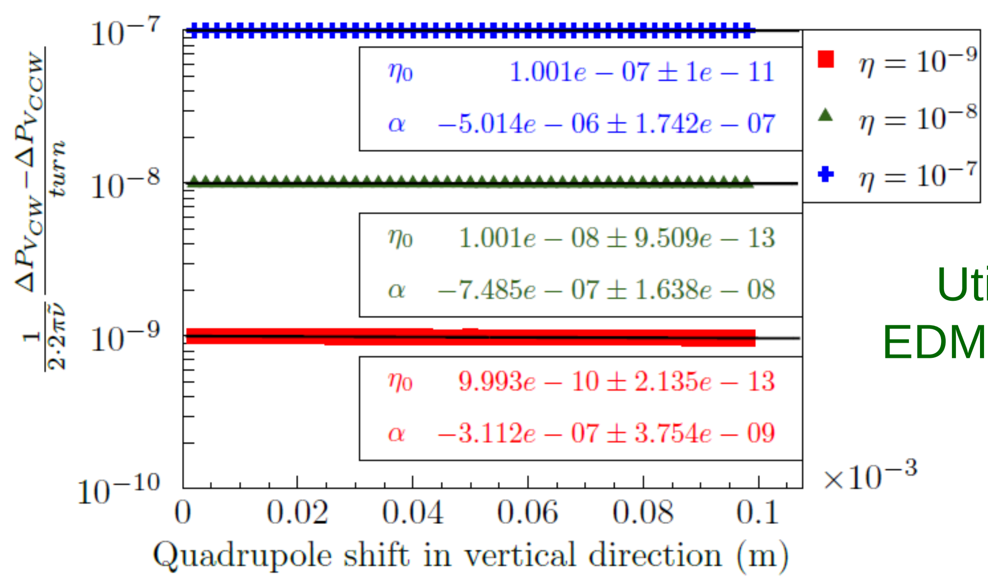
Pure EDM Signal



Artificial Spin Build Up



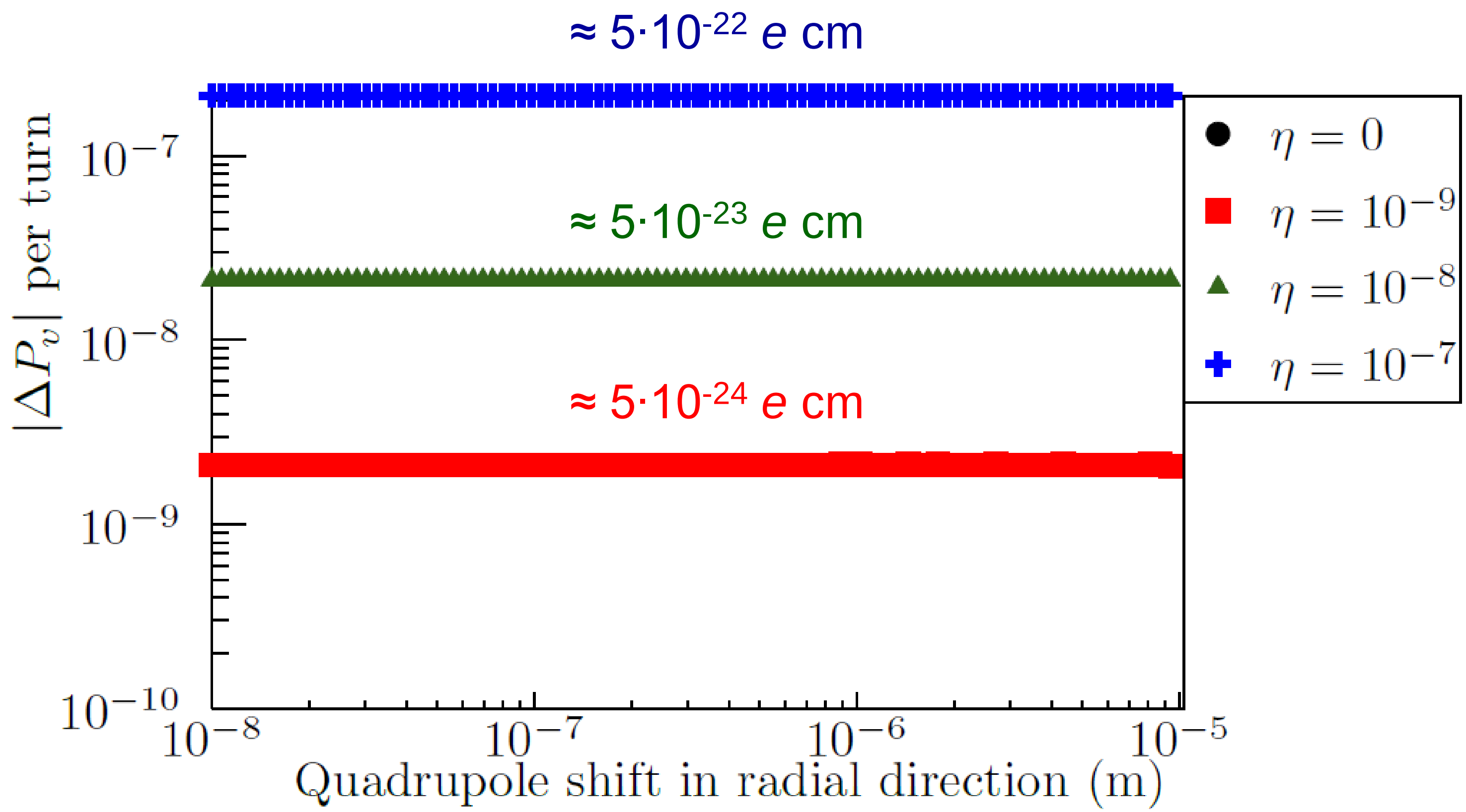
EDM Determination



Utilized magnitude of EDM could be reproduced

Courtesy: A. Skawran

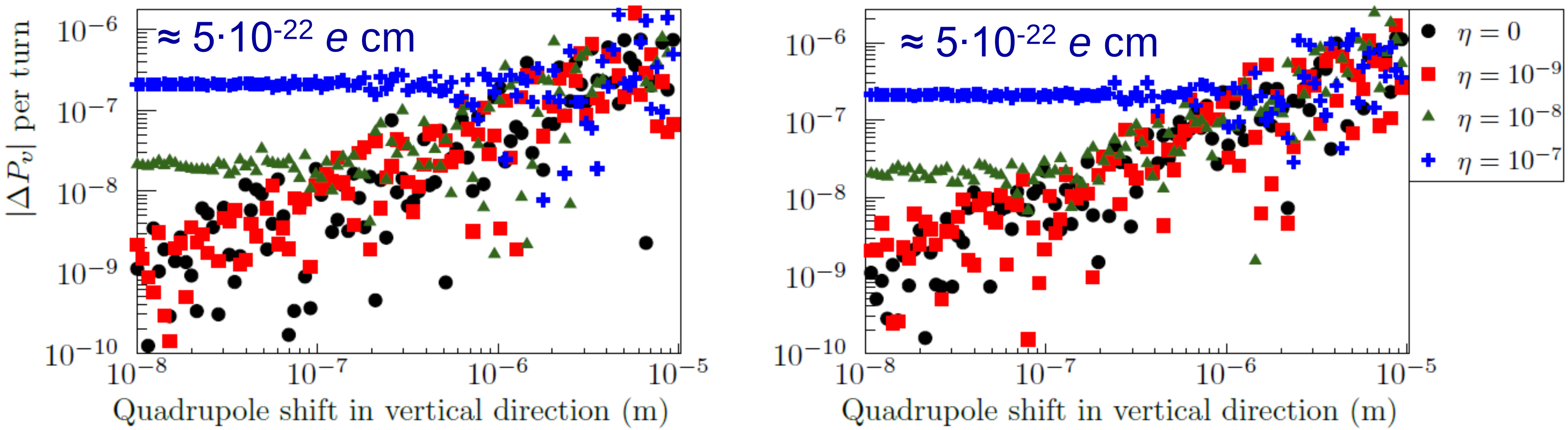
Quadrupole Shift in Radial Direction



Spin perturbation is negligible at this EDM magnitude

Courtesy: A. Skawran

Quadrupole Shift in Vertical Direction



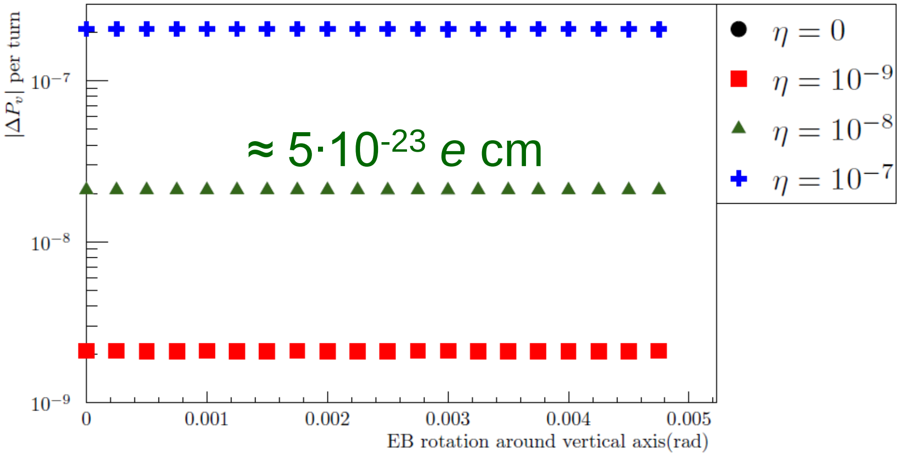
Quasi-Frozen Spin (left) – Frozen Spin (right)

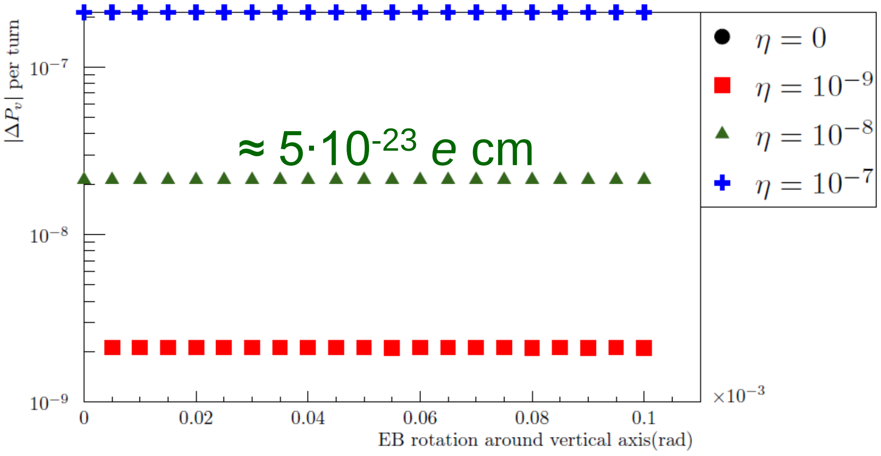
Vertical spin build up for different magnitudes of EDM and Gaussian distributed quadrupole shifts (RMS values) around the vertical axis.
Each simulation has different randomly generated misalignments.

Effect of QFS and FS is roughly the same

Courtesy: A. Skawran

Deflector Rotation around Vertical Axis





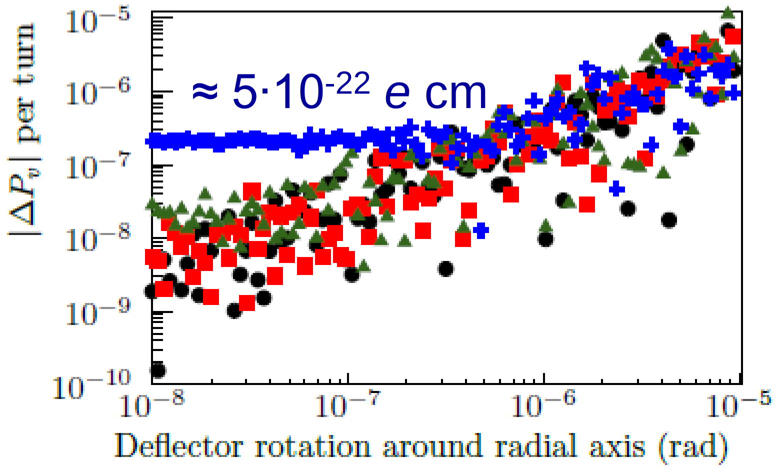
Quasi-Frozen Spin (left) – Frozen Spin (right)

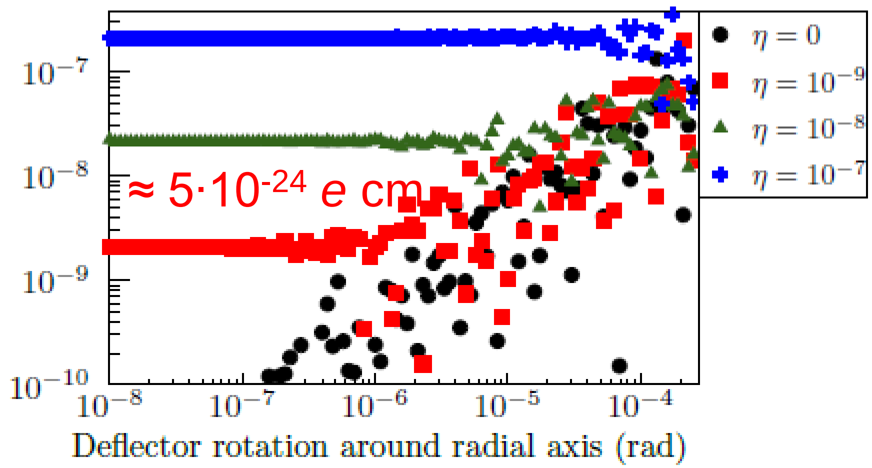
Vertical spin build up for different magnitudes of EDM and Gaussian distributed rotations of ExB deflectors (RMS values) around the vertical axis.
Each simulation has different randomly generated misalignments.

Spin perturbation is negligible at this EDM magnitude

Courtesy: A. Skawran

Deflector Rotation around Radial Axis





Quasi-Frozen Spin (left) – Frozen Spin (right)

Vertical spin build up for different magnitudes of EDM and Gaussian distributed rotations of ExB deflectors (RMS values) around the radial axis.
Each simulation has different randomly generated misalignments.

Artificial spin buildup roughly two orders of magnitude weaker for QS compared to QFS

Courtesy: A. Skawran

Additional Effect for Sideways Spins

$$\frac{d\vec{s}_{MDM}}{dt} =$$
$$\frac{e}{m}\left[\left(a+\frac{1}{\gamma}\right)\begin{pmatrix} -s_y B \\ 0 \\ s_x B \end{pmatrix} - \frac{a\gamma}{\gamma+1}(\beta \cdot B)\begin{pmatrix} -s_y \beta \\ 0 \\ s_x \beta \end{pmatrix}\right]$$

- Frozen Spin: s_x for the reference particle is 0, but particle in phase space will also experience this additional systematic rotation

- Quasi Frozen Spin: the maximum deflection in the horizontal plane $\pi\gamma G$ for the reference particle

Conclusion / Outlook

- Frozen and Quasi Frozen EDM ring lattices investigated
- Even small misalignments influence an EDM measurement
- CW-CCW beams mandatory to efficiently cancel systematic effects
- Estimation for systematic limit (preliminary):

  μrad/μm element misalignment

  → roughly 10^{-23} $e\cdot$cm systematic limit with 10 μm closed orbit

  1 nm relative orbit measurement with CW-CCW beams

  → roughly 10^{-27} $e\cdot$cm systematic limit

- CW-CCW method with not perfectly reversed magnetic fields
- 3D map simulations of curved ExB deflectors

New PhD student will be hired


Thank you!

Deuteron EDM Storage Rings at COSY

„all-in-one" storage ring

Protons: p_p = 0.701 GeV/c
E_R = 16.8 MV/m, B_V = 0 T

Deuterons: p_d = 1.0 GeV/c
E_R = -4.0 MV/m, B_V = 0.16 T

Helium-3: $p_{^3He}$ = 1.285 GeV/c
E_R = 17.0 MV/m, B_V = -0.05 T

„all-in-one" storage ring

Protons: p_d = 0.527 GeV/c
E_R = 16.8 MV/m, B_V = 0.02 T

Deuterons: p_d = 1.0 GeV/c

Helium-3: $p_{^3He}$ = 0.946 GeV/c

Dedicated deuteron storage ring

Deuterons: p_d = 1.0 GeV/c
E_R = -12.0 MV/m, B_V = 0.48 T