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Beam and Spin Dynamics for Storage Ring Based EDM Search

May 6, 2015 | Andreas Lehrach

RWTH Aachen University & Forschungszentrum Jülich

on behalf of the JEDI collaboration

(Jülich Electric Dipole Moment Investigations)

Outline

Introduction

Motivation for EDM measurements

Principle and methods

Beam and Spin Dynamics

Measurements:

- spin tune
- spin coherence time

Simulations:

- benchmarking
- investigation of systematic limits

Achievements & Goals

Electric Dipole Moments

$\vec{d}$: EDM

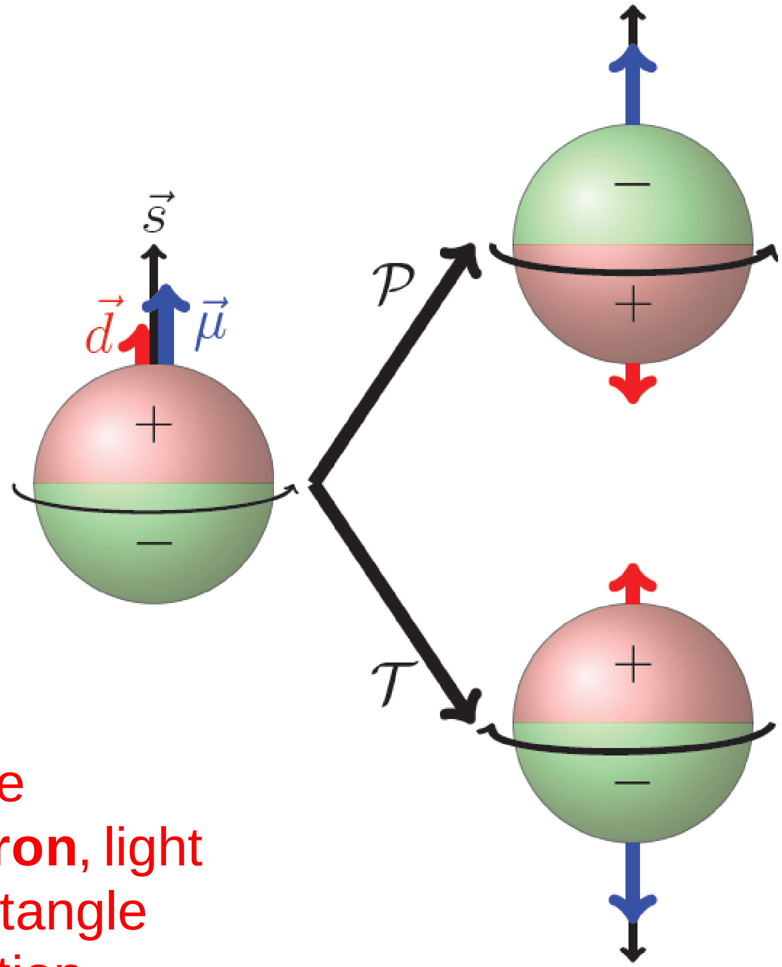
$\vec{\mu}$: magnetic moment

both || to spin

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

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

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



It is important to measure neutron **and proton and deuteron**, light nuclei EDMs in order to disentangle various sources of CP violation.

EDMs are candidates to solve mystery of matter-antimatter asymmetry

EDMs – Ongoing / Planned Searches

- Neutrons ~200
  - @ILL
  - @ILL,@PNPI
  - @PSI
  - @FRM-2
  - @RCNP,@TRIUMF
  - @SNS
  - @J-PARC

- Molecules ~50
  - YbF@Imperial
  - PbO@Yale
  - ThO@Harvard
  - HfF+@JILA
  - WC@UMich
  - PbF@Oklahoma

Rough estimate of numbers of researchers, in total ~500 (with some overlap)

- Atoms ~100
  - Hg@UWash
  - Xe@Princeton
  - Xe@TokyoTech
  - Xe@TUM
  - Xe@Mainz
  - Cs@Penn
  - Cs@Texas
  - Fr@RCNP/CYRIC
  - Rn@TRIUMF
  - Ra@ANL
  - Ra@KVI
  - Yb@Kyoto

- Ions-Muons ~200
  - @BNL
  - @FZJ
  - @FNAL
  - @JPARC

NEW

- Solids ~10
  - GGG@Indiana
  - ferroelectrics@Yale

P. Harris, K. Kirch … A huge worldwide effort

Spin Precession with EDM

Equation for spin motion of relativistic particles in storage rings

for $\vec{\beta}\cdot\vec{B}=\vec{\beta}\cdot\vec{E}=0$.

The spin precession relative to the momentum direction is given by:

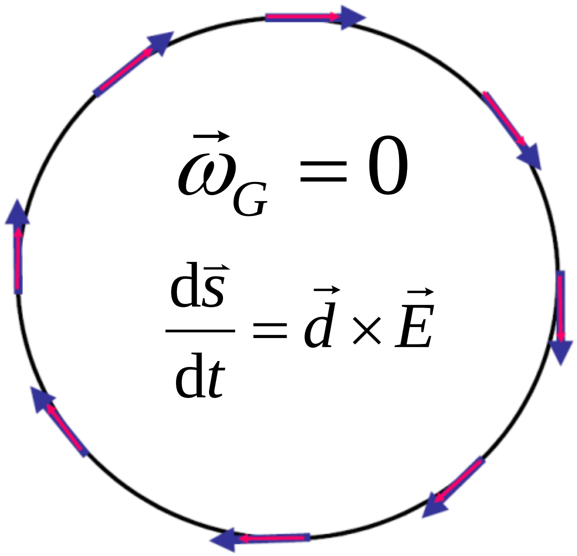
$$\frac{d\vec{S}}{dt}=\vec{\Omega}\times\vec{S}$$

$$\vec{\Omega}=\frac{q}{m}\left\{\underbrace{G\vec{B}+\left(G-\frac{1}{\gamma^2-1}\right)\left(\vec{v}\times\vec{E}\right)}_{\text{Magnetic Dipole Moment}}+\underbrace{\frac{\eta}{2}\left(\vec{E}+\vec{v}\times\vec{B}\right)}_{\text{Electric Dipole Moment}}\right\}.$$

$$G=\frac{g-2}{2},\ \vec{\mu}=2(G+1)\frac{q}{2m}\vec{S},\text{ and }\vec{d}=\eta\frac{q}{2m}\vec{S}.$$

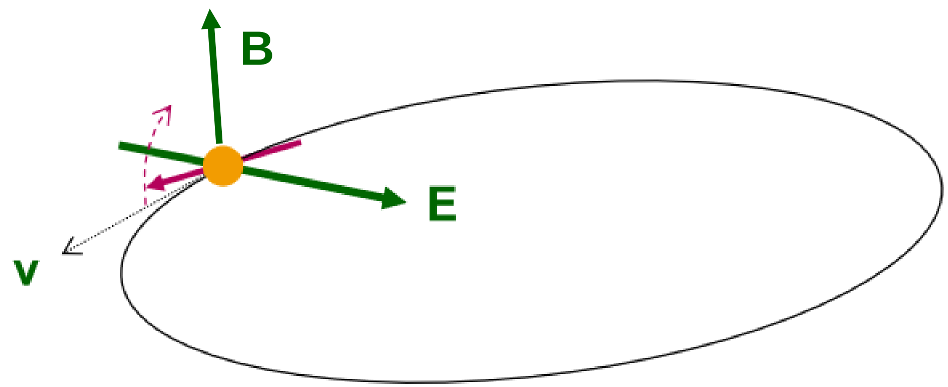
Search for Electric Dipole Moments

Approach: EDM search in time development of spin in a storage ring:



$$\vec{\omega}_G = 0$$

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{d} \times \vec{E}$$



"Freeze" horizontal spin precession; watch for development of a vertical component !

A *magic* storage ring for protons (electrostatic), deuterons, and helium-3

particle	p (GeV/c)	E (MV/m)	B (T)
proton	**0.701**	**16.789**	**0.000**
deuteron	**1.000**	**-3.983**	**0.160**
^{3}He	**1.285**	**17.158**	**-0.051**

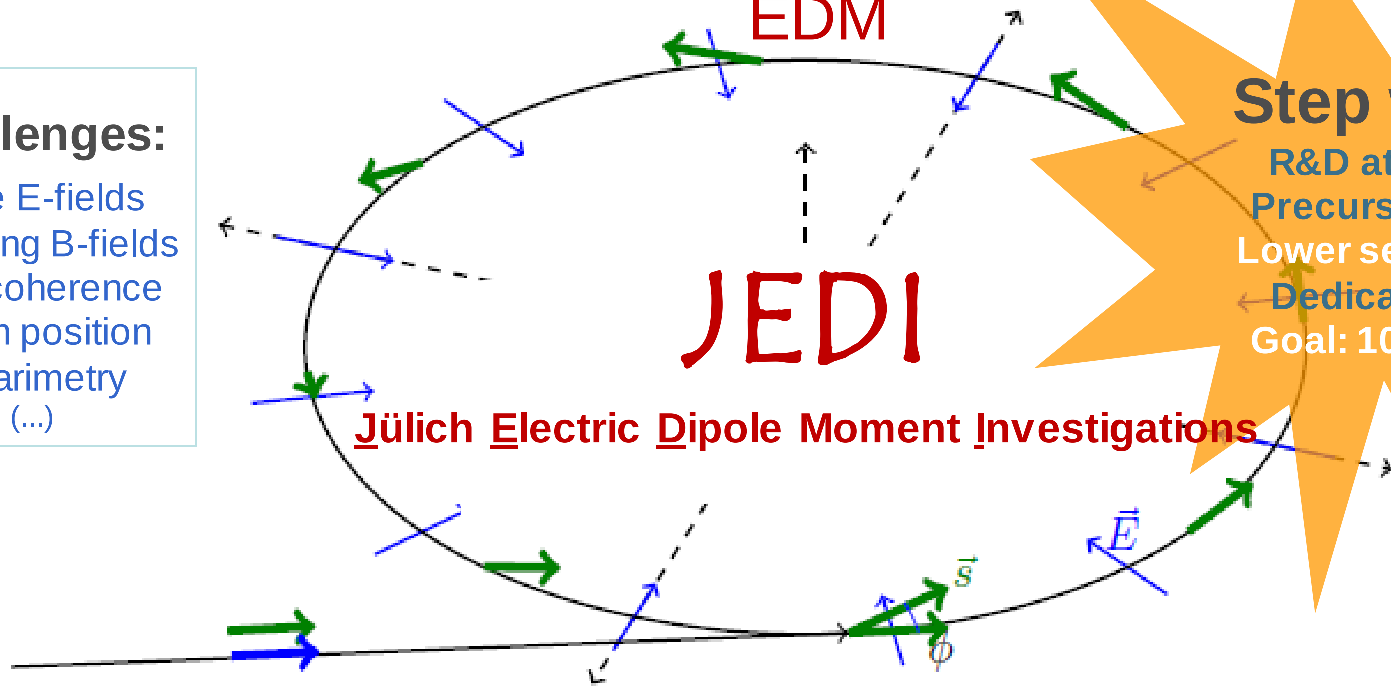
One machine with r ~ 30 m

Storage Ring EDM Project

… measure for development of vertical polarization

⇔

EDM



JEDI

Jülich Electric Dipole Moment Investigations

Challenges:

Huge E-fields
Shielding B-fields
Spin coherence
Beam position
Polarimetry
(…)

Step wise:

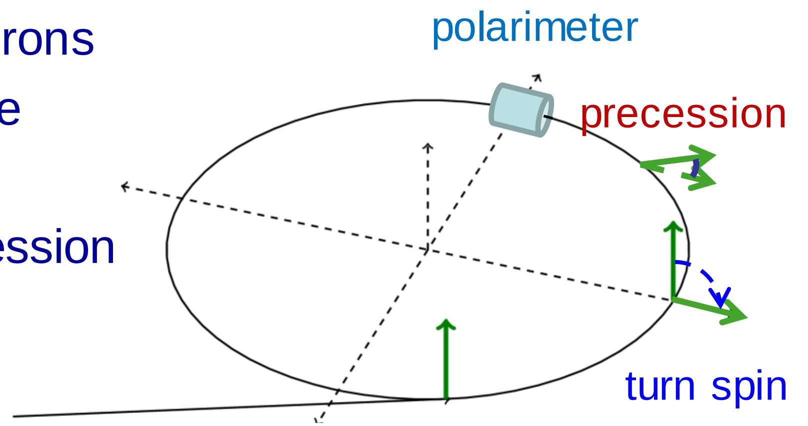
R&D at COSY
Precursor Expt.
Lower sensitivity
Dedicated SR
Goal: 10^{-29} e·cm

JARA Jülich Aachen Research Alliance

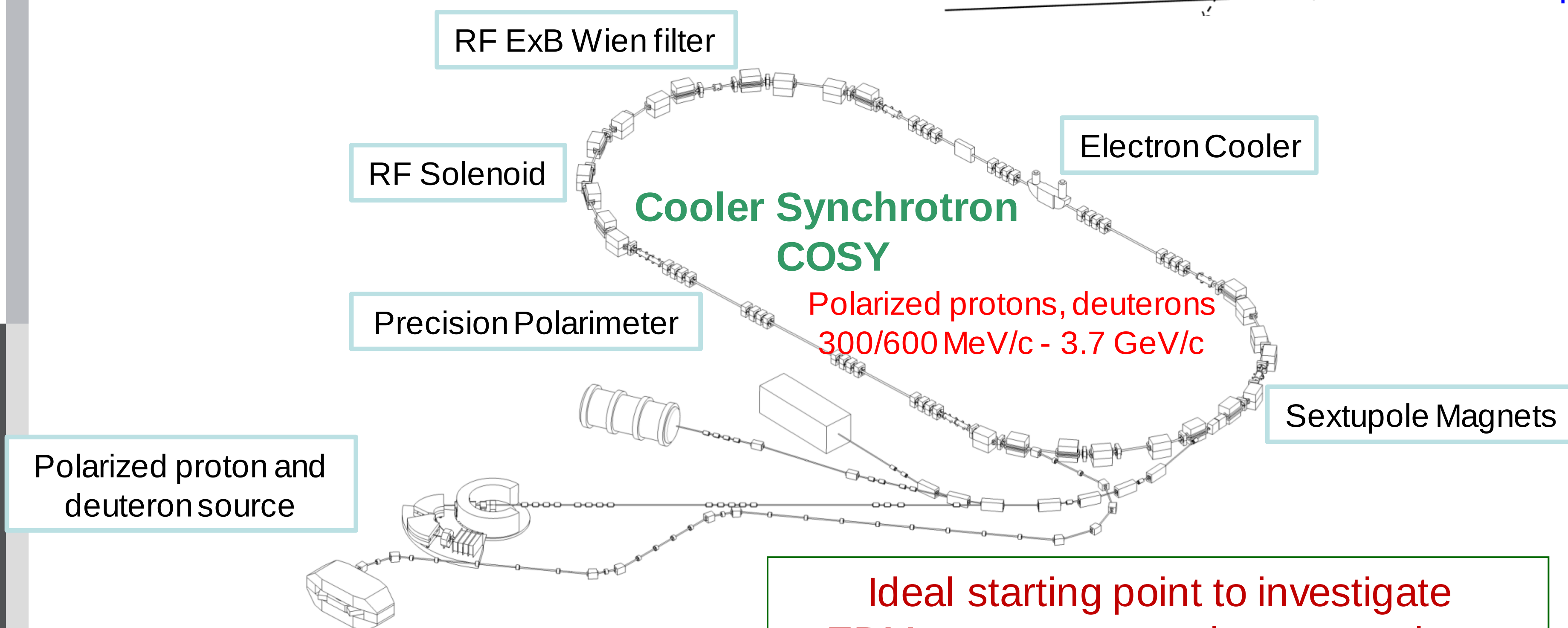
> 100 members
(Aachen, Bonn, Dubna, Ferrara, Cornell, Jülich, Krakow, Michigan, St. Petersburg, Minsk, Novosibirsk, Stockholm, Tbilisi, . . .)
12 PhD students from JARA-FAME (**F**orces **a**nd **M**atter **E**xperiments)
http://collaborations.fz-juelich.de/ikp/jedi/

Experimental Setup at COSY

- Inject and accelerate vertically polarized deuterons
- Spin rotated with RF fields into horizontal plane
- Move beam slowly (in 100 s) on internal target
- Measure asymmetry and determine spin precession



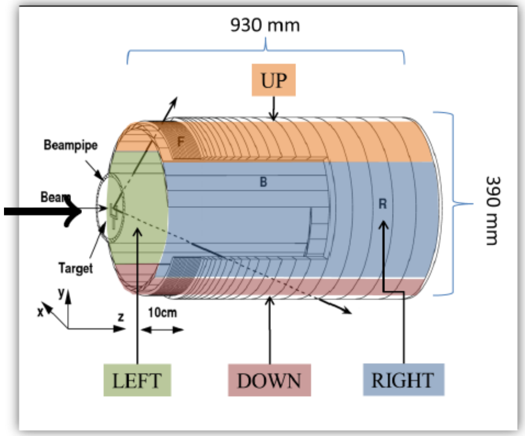
At 970 MeV/c deuterons: $\gamma G \cdot f_{rev} \approx 120$ kHz

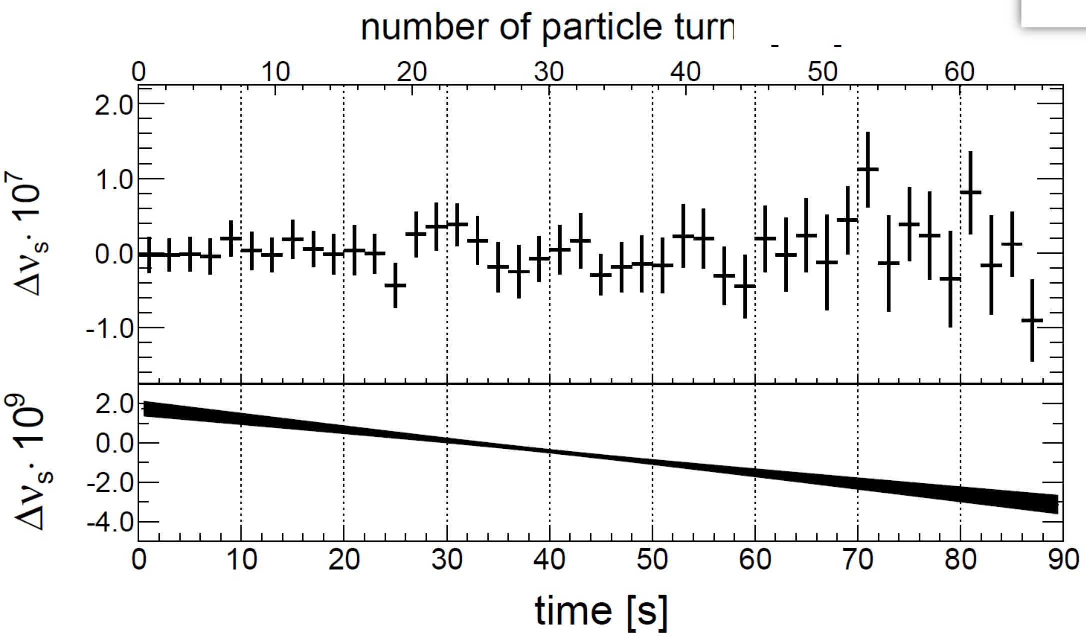


Ideal starting point to investigate
EDM measurements in storage rings

Spin Tune Measurement at COSY

- EDDA Detector to measure asymmetries
- Sophisticated read-out system, which can time stamp individual event arrival times with respect to turn number: Phys. Rev. STAB 17 052803 (2014)
- Map events into first spin oscillation period
- Analyse the spin phase advance throughout the cycle





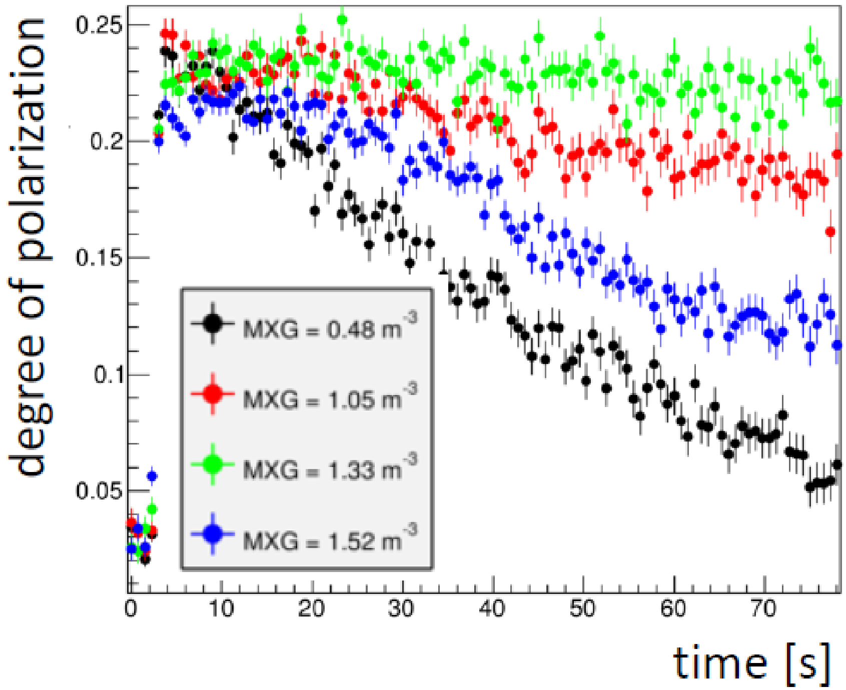
Spin tune ν_s determined to $\approx 10^{-7}$ in 2 s.

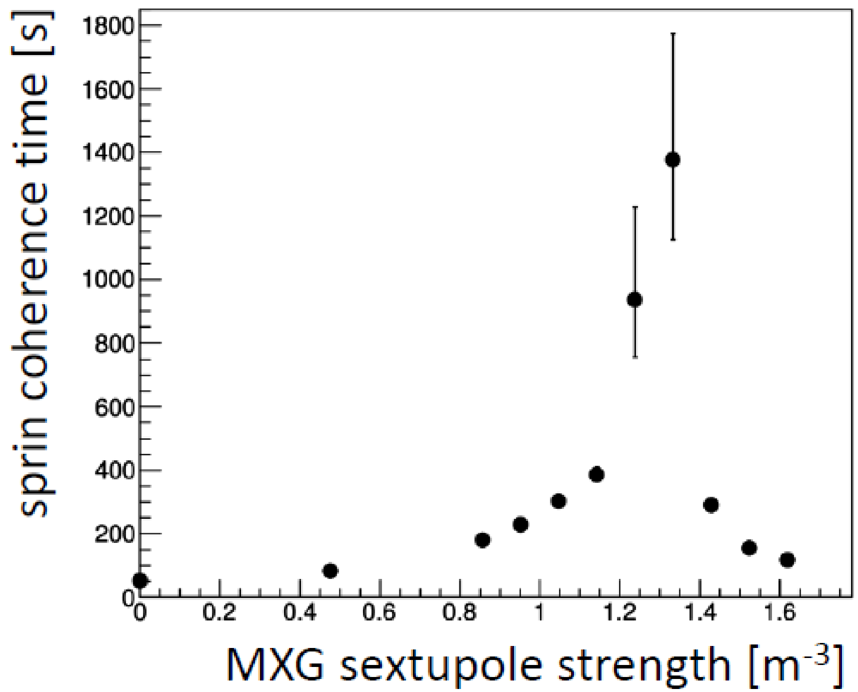
$\bar{\nu}_s$ in cycle at $t \approx 40\ s$ is determined to $\approx 10^{-10}$. (submitted to PRL)

Spin coherence time at COSY

10^9 polarized deuterons at 970 MeV/c, bunched and electron cooled

adjust three arc sextupoles to increase spin coherence time





→ Longest SCT for transverse beam chromaticities close to zero

Poster by Greta *Guidoboni* (UNIFE, Ferrara): ID: 2811 - THPF146
Spin Coherence Time Lengthening of a Polarized Deuteron Beam with Sextupole Fields

Utilized Simulation Programs at Jülich

COSY INFINITY by M. Berz and K. Makino (MSU),

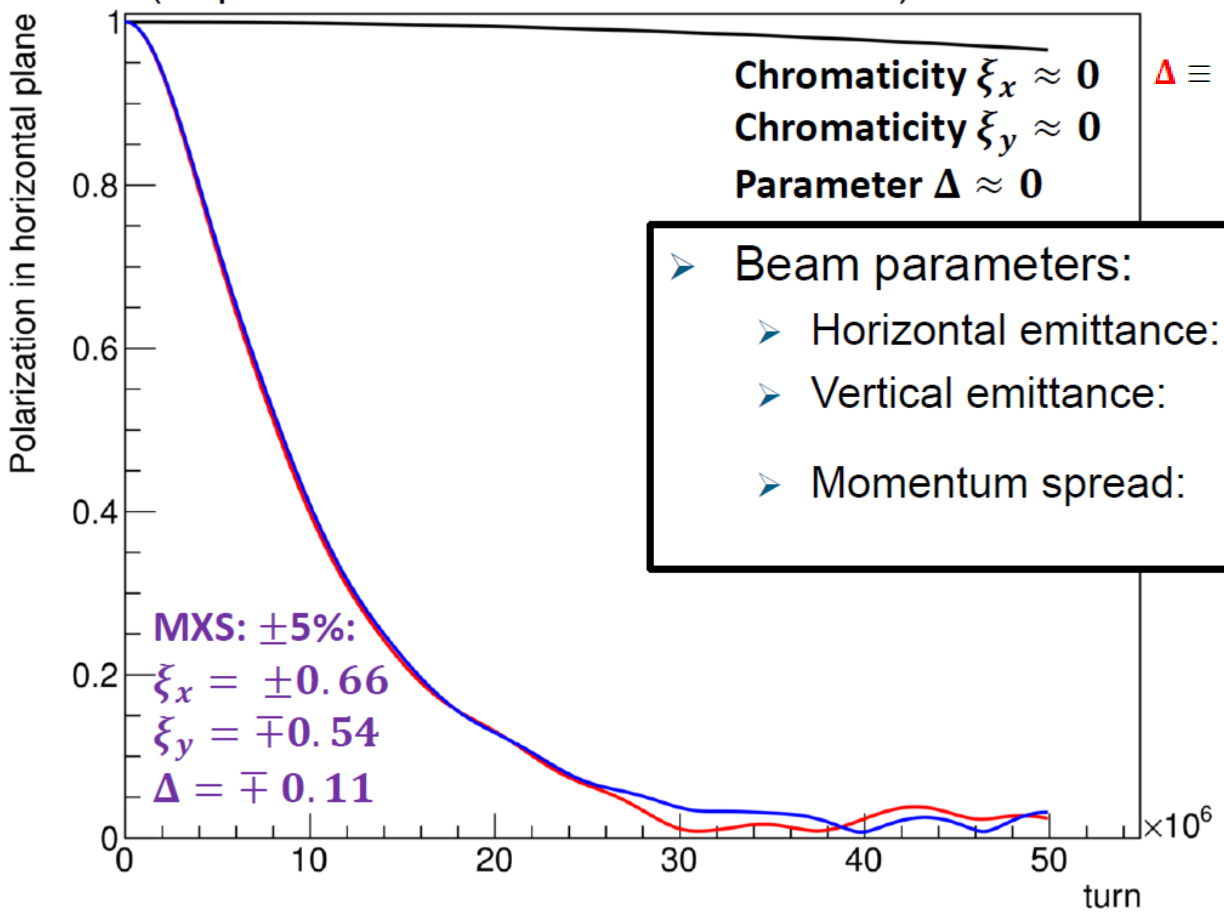
MODE by S. Andrianov, A. Ivanov (StPSU):

- 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
- an MPI version of COSY Infinity is running on the Jülich supercomputer

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

Simulations of SCT (COSY INFINITY)

- Deuterons, $p = 970\ MeV/c$, initially radial polarized (→ precession around vertical axis)



$$\Delta \equiv \left[\alpha_1 + \frac{3}{2\gamma_0^2}\left(\beta_0^2 - \left(\alpha_0 - \frac{1}{\gamma_0^2}\right)\right)\right] = 0$$

- Beam parameters:
  - Horizontal emittance: $\epsilon_x = 5\ \mathrm{mm\ mrad}$
  - Vertical emittance: $\epsilon_y = 5\ \mathrm{mm\ mrad}$
  - Momentum spread: $\left(\frac{\Delta p}{p}\right)_{rms} = 5 \cdot 10^{-4}$

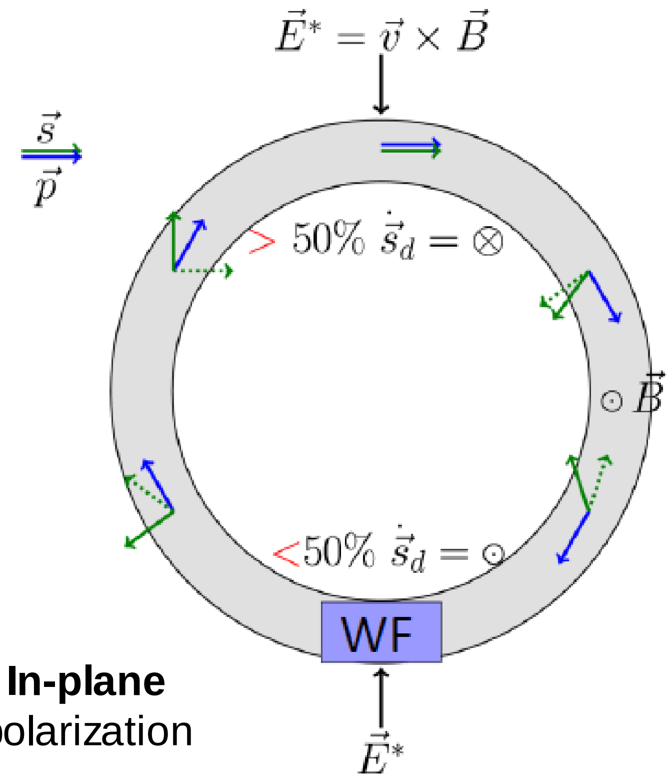
No nearby spin resonances!

Courtesy: Marcel *Rosenthal* (FZJ)

Resonance Method in Magnetic Rings

RF *ExB* dipole in "Wien filter" mode
→ Avoids coherent betatron oscillations

$\boldsymbol{E}^* = \boldsymbol{0} \Rightarrow \boldsymbol{E_R} = -\beta \times \boldsymbol{B_y}$ „**Magic RF Wien Filter**" no Lorentz force
→ **Indirect** EDM effect



In-plane polarization

- Modulation of horizontal spin precession in the RF Wien filter
- EDM's interaction with the motional electric field in the rest of the ring

→ continuous buildup of vertical polarization in a horizontally polarized beam.

→ **net effect due to EDM**

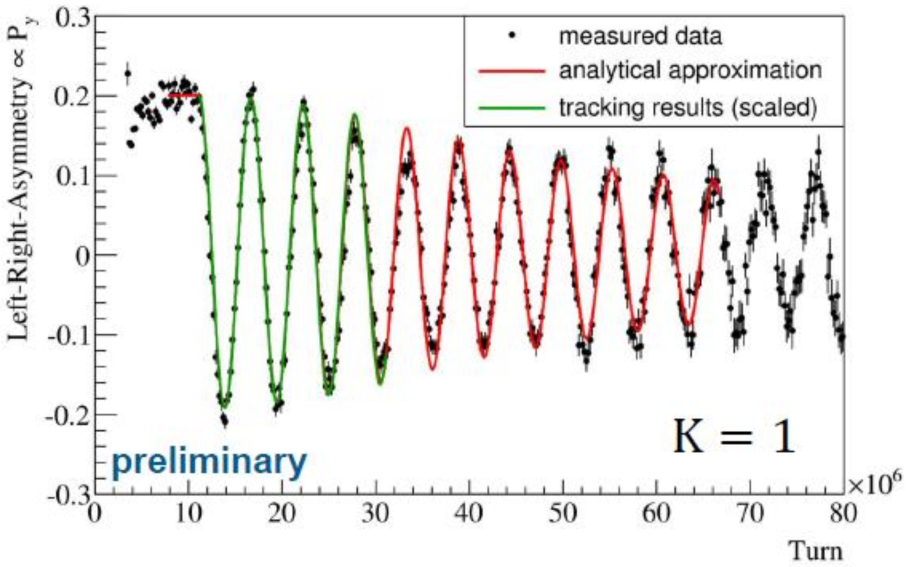
→ Investigation of sensitivity and systematic limitations

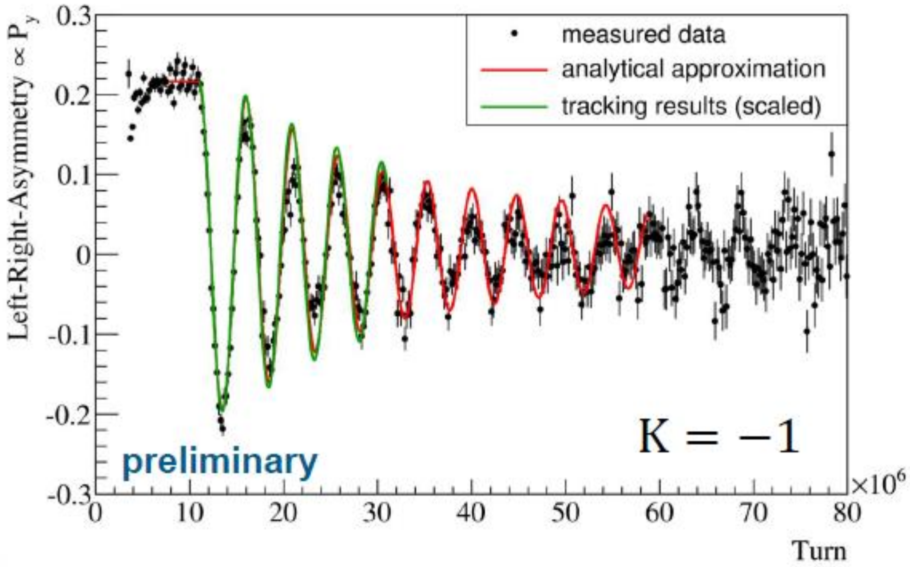
Poster by Sebastian *Mey* (FZJ, Jülich): ID: 2271 - THPF031
Towards an RF Wien-Filter for EDM Experiments at COSY

Benchmarking (COSY INFINITY)

RF spin manipulation elements implemented.
Benchmarking experiment at COSY using driven oscillations induced by the RF solenoid.

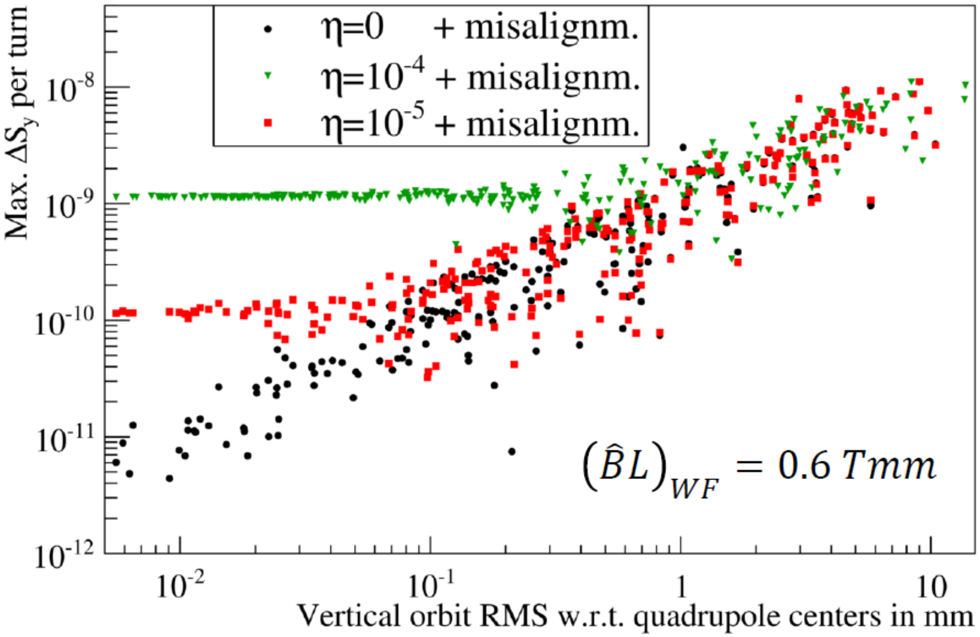
RF field: $B_{sol} = B_0 \cdot cos\,(2\pi \cdot \nu_{sol} \cdot n + \Phi_{sol})$, *resonance condition:* $\nu_{sol} = \gamma G \pm k$





Poster by Marcel *Rosenthal* (FZJ, Jülich; RWTH, Aachen): ID: 2290 - THPF032
Spin Tracking Simulations towards Electric Dipole Moment Measurements at COSY

Simulation of Resonance Method (COSY Infinity)

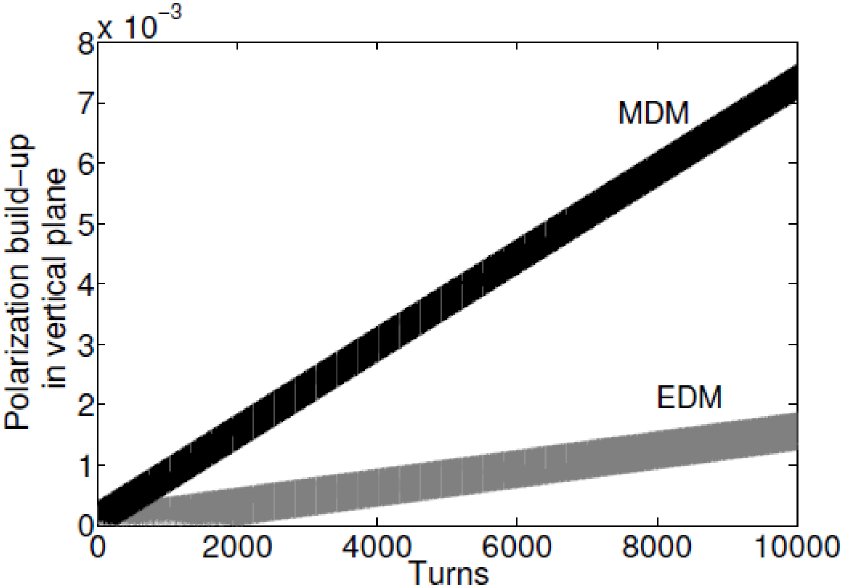


Uncorrected Gaussian distributed misalignments
of the COSY lattice quadrupoles with a standard deviation of 0.1 mm
generate a similar buildup as an EDM of $d = 5 \cdot 10^{-19}$ e cm

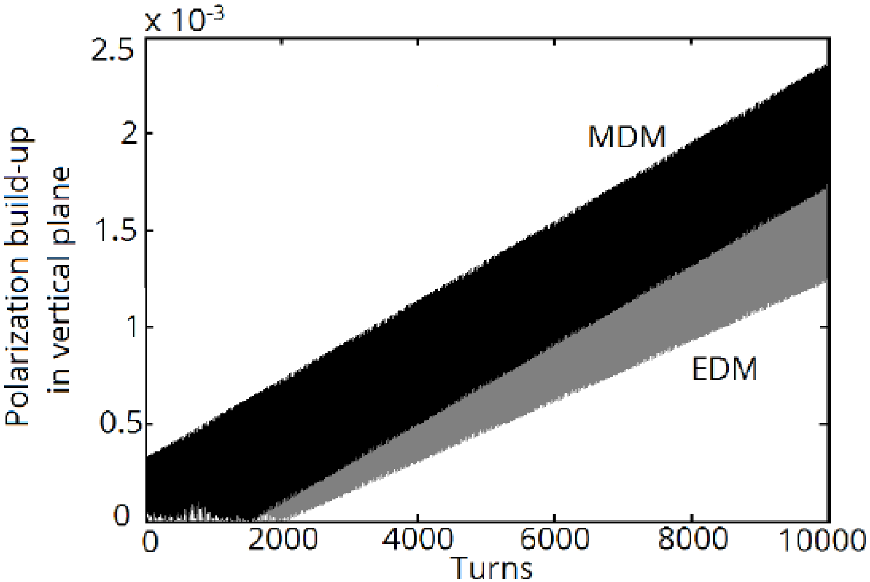
Systematic EDM limit at COSY is in the order of $d = 10^{-19}$ e·cm for a
remaining orbit excitations below the millimeter level,

Poster by Marcel *Rosenthal* (FZJ, Jülich; RWTH, Aachen): ID: 2290 - THPF032
Spin Tracking Simulations towards Electric Dipole Moment Measurements at COSY

Simulation of Resonance Method (MODE)



Black: Misalignments of magnets by 0.1 mm (mrad)
Grey: EDM of $2.6 \cdot 10^{-19}$ e cm



Black: rotation RF Wien filter by of 10^{-4} rad
Grey: EDM of $2.6 \cdot 10^{-19}$ e cm

Error sources:

Magnet misalignments

Wien filter:

- rotation of 10^{-4} rad with respect to invariant spin axis
- relative mismatch between RF Wien filter frequency and the spin resonance frequency of 10^{-5}

→ EDM in the order of $d = 10^{-19}$ e·cm

Courtesy: Stas *Chekmenev* (FZJ)

Simulation Program Development

Aim

- Robust and advanced numerical tracking codes for exploring various systematic effects.
- Sophisticated lattice design tools for EDM storage rings with all electrostatic as well as combined magnetic and electric elements.

Capabilities

- Accurate description of all ring elements including fringe fields.
- Allowing various error inputs for systematics investigation.
- Accurate implementation of RF spin manipulation elements.
- Calculation of orbital and spin motion with a high accuracy for over 10^9 orbital revolutions.
- User friendly graphic interfaces for extracting physical information from tracking data.
  (e.g., orbit, betatron tune, and spin tune from tracking data)

IPAC15 satellite meeting
on Spin Tracking for Precision Measurements
https://indico.cern.ch/event/368912/program

Conclusion

Achievements:

- Spin tune measurement with precision of 10^{-10} in a single cycle
- Long spin coherence time of up to 1000s
- Several spin tracking codes developed and benchmarked
- Investigation of systematic limit for resonance methods

Goals:

- Continue beam and spin dynamics studies at COSY (also with protons)
- First direct EDM measurement at COSY
- R&D work and design study for dedicated EDM storage ring