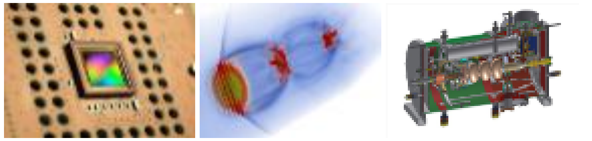
Matter and Technologies



Progress and Plans on Hadron Accelerator Developments at FZJ

Andreas Lehrach,

RWTH Aachen University & FZ Jülich

Subtopic Coordinator ARD ST2

March 9th , 2016

2nd Annual MaT Meeting

KIT, Karlsruhe

Karlsruhe Institute of Technology

HELMHOLTZ ASSOCIATION

Outline

Introduction

Motivation for EDM measurements
Principle and methods

Achievements

Spin tune measurement
Spin coherence time investigation
Preparation for spin tune feedback
Technical developments

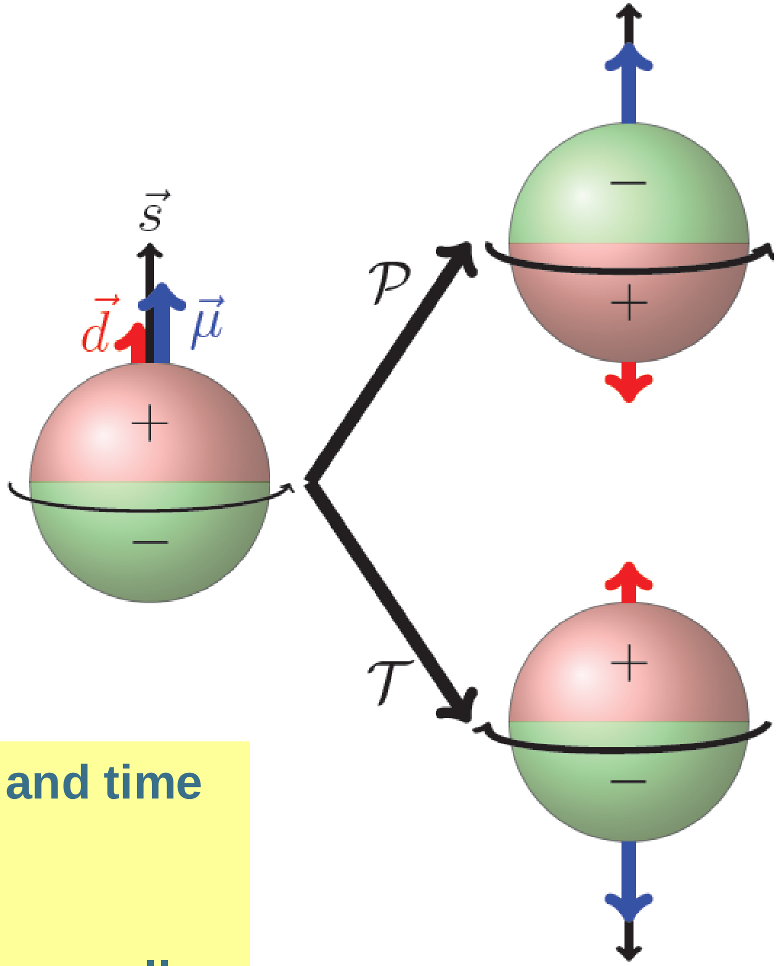
Summary & Outlook

Introduction

Electric Dipole Moments

$\vec{d}$: EDM
$\vec{\mu}$: magnetic moment
both || to spin

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



Permanent EDMs violate parity P and time reversal symmetry T

Assuming CPT to hold, combined symmetry CP violated as well.

EDMs are candidates to solve mystery of matter-antimatter asymmetry

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:

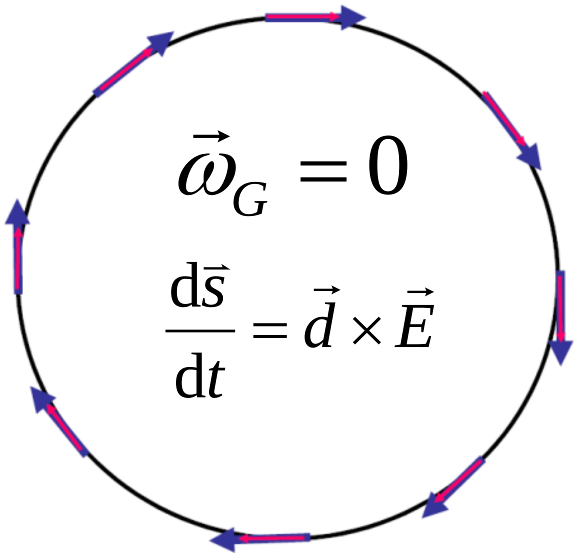
$$\frac{d\vec{S}}{dt}=\vec{\Omega}\times\vec{S}$$

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

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

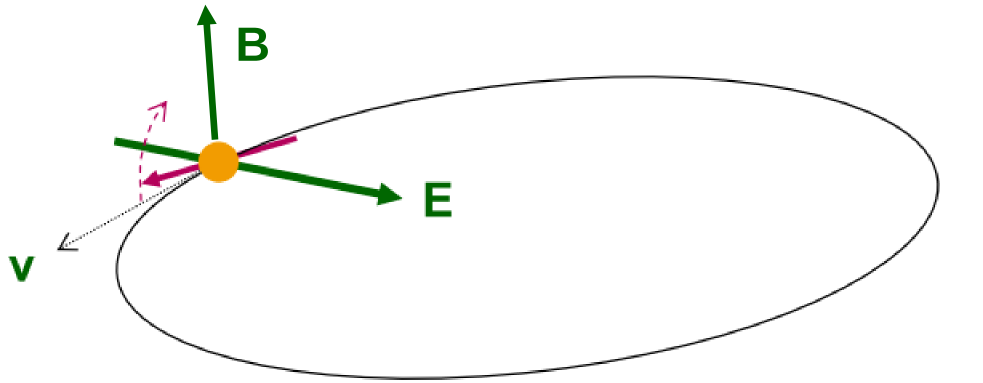
Search for Electric Dipole Moments

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

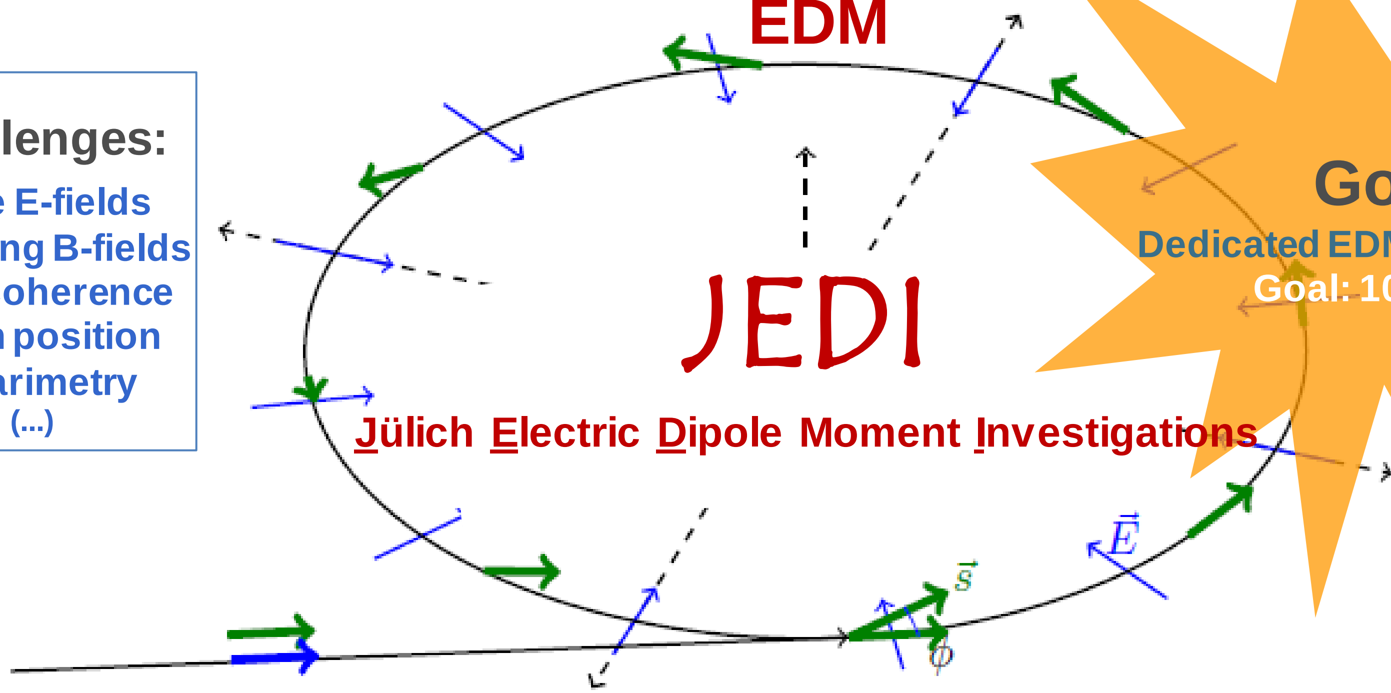
One machine with r ~ 30 m

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
- (…)

Goal:

Dedicated EDM Storage Ring

Goal: 10^{-29} e·cm

JARA Jülich Aachen Research Alliance

~ 100 members

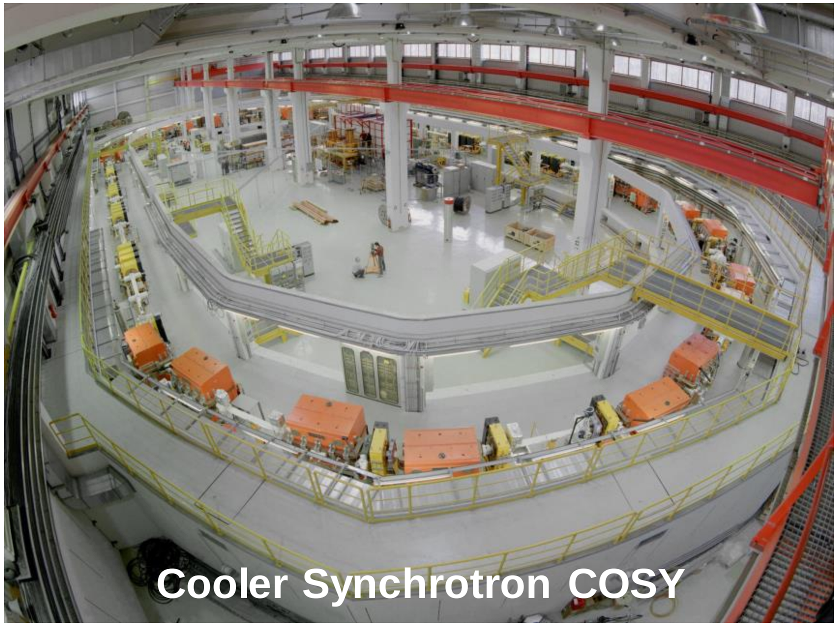
(Aachen, Bonn, Dubna, Ferrara, Cornell, Jülich, Krakow, Michigan, St. Petersburg, Minsk, Novosibirsk, Stockholm, Tbilisi, . . .)

12 PhD students from JARA-FAME (Forces and Matter Experiments)

http://collaborations.fz-juelich.de/ikp/jedi/

Stepwise Approach

Measurements of charged particle EDMs from COSY to a dedicated EDM storage ring



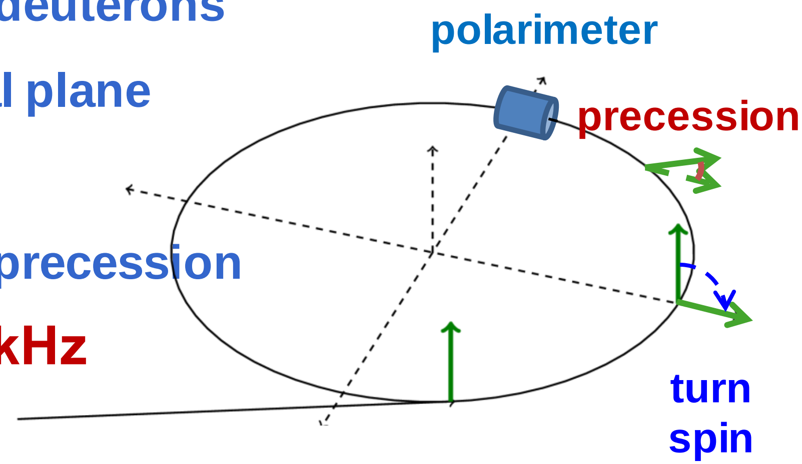
- R&D at COSY
- Precursor experiment for first direct measurement
- Injector for dedicated EDM ring

- CW-CCW beams
- Dedicated ring with high-precision beam diagnostics and polarimetry

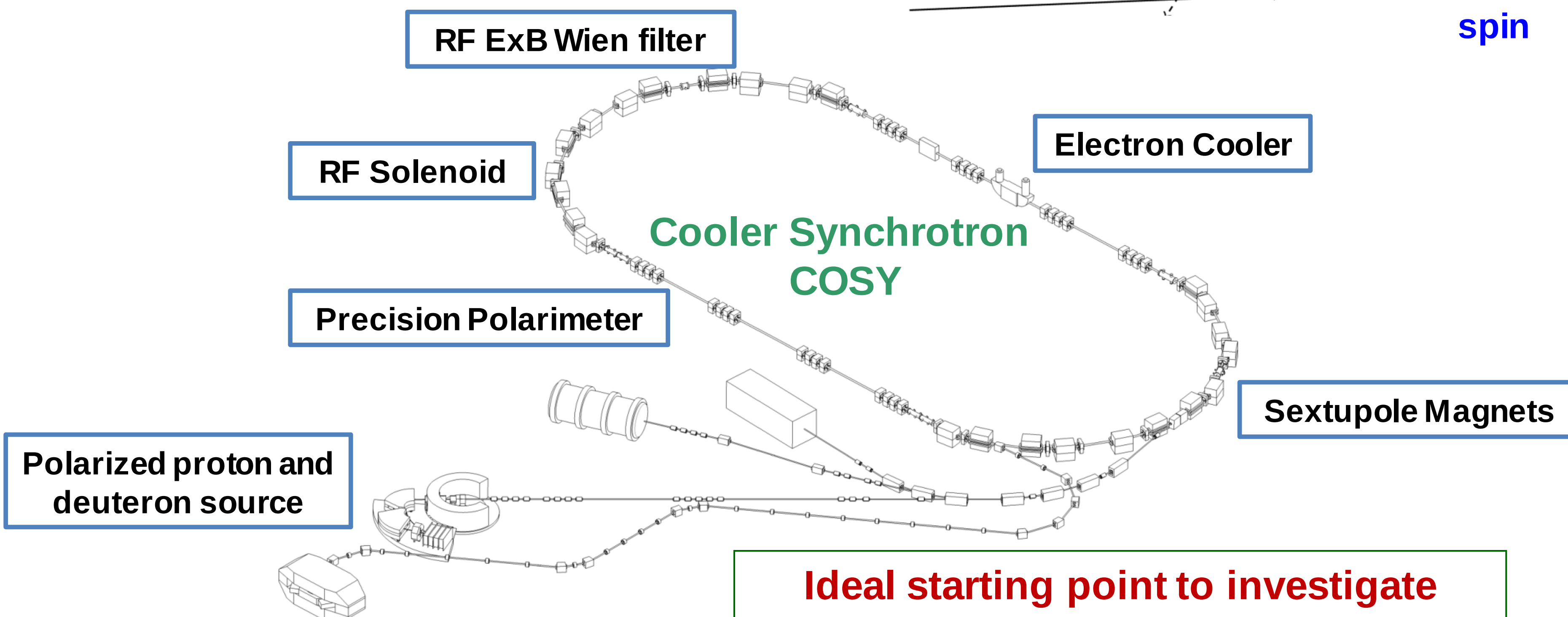
Achievements

Experimental Setup for R&D at COSY

- **Inject and accelerate vertically polarized deuterons**
- **Spin rotated with RF fields into horizontal plane**
- **With noise extraction on internal target**
- **Measure asymmetry and determine spin precession**



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

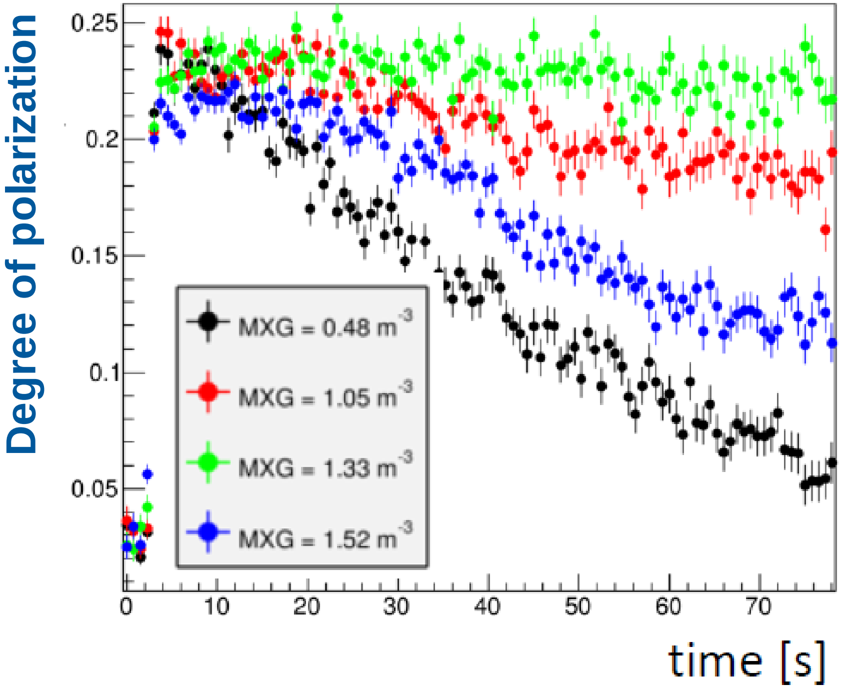


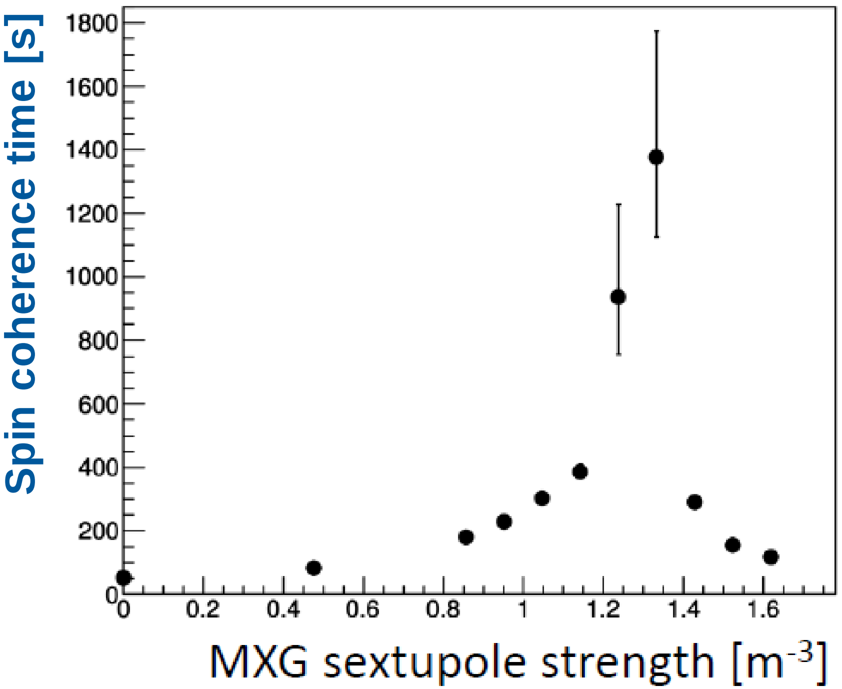
Ideal starting point to investigate EDM measurements in storage rings

Measurement of Spin Coherence Time

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

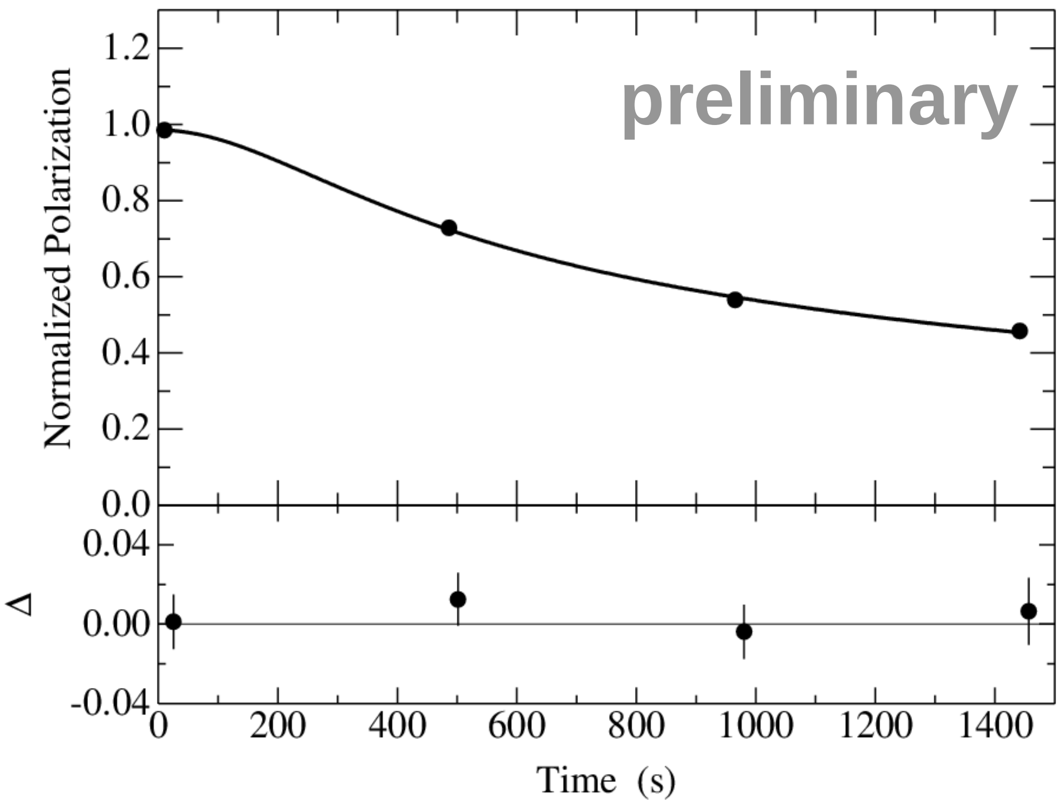
adjust three arc sextupoles to increase spin coherence time





→ Longest SCT for beam chromaticities close to zero at regular betatron tunes ($Q_{x,y}$ = 3.5 – 3.6)

Record In-Plane Polarization Lifetime



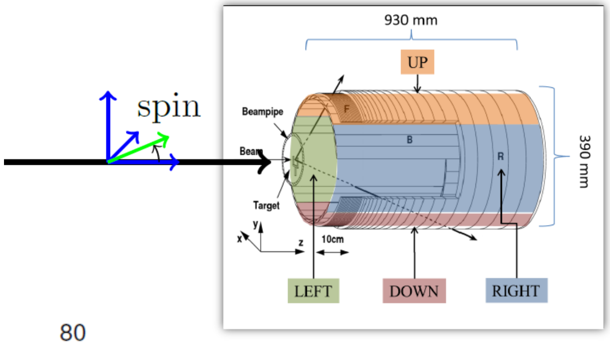
Using a exponential width definition, the lifetime is 2280 ± 336 s.

This is a new record for in-plane polarization lifetime, exceeding the Novosibirsk results for electrons by about three orders of magnitude.

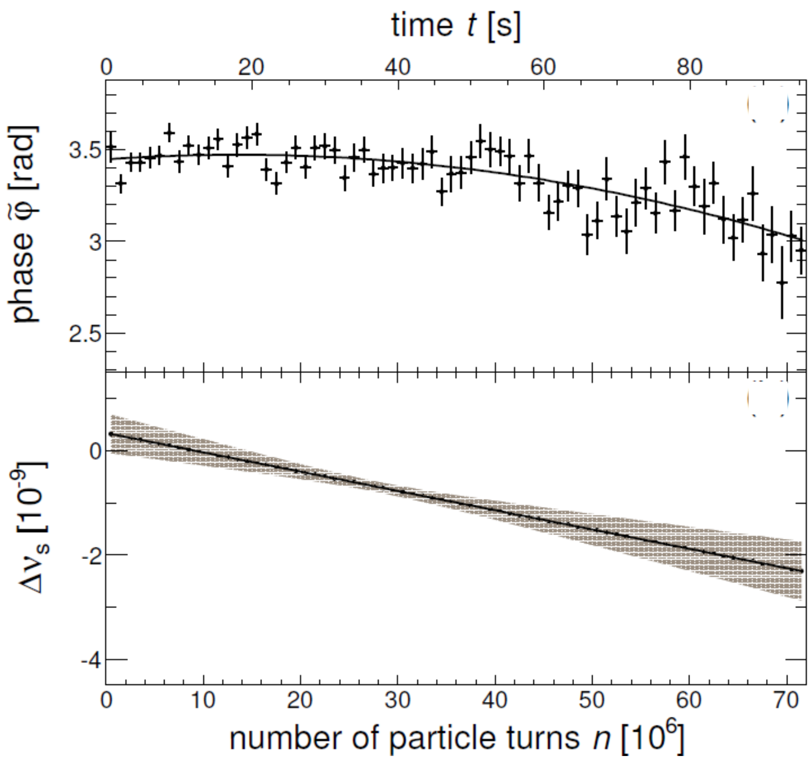
Submitted to Phys. Rev. Let.

High-Precision Spin Tune Measurement

- **EDDA Detector to measure asymmetries**
- **Sophisticated read-out system, which time stamps individual event times with respect to absolute cycle time: Phys. Rev. STAB 17 052803 (2014)**



$$\nu_s(n) = \nu_s{}^{\text{fix}} + \frac{1}{2\pi}\frac{\mathrm{d}\tilde{\varphi}(n)}{\mathrm{d}n}$$
$$= \nu_s{}^{\text{fix}} + \Delta\nu_s(n)$$



Spin tune ν_s determined to roughly 10^{-7} in 2 s
ν_s in 100s cycle at t ≈ 40 s determined to roughly 10^{-10}

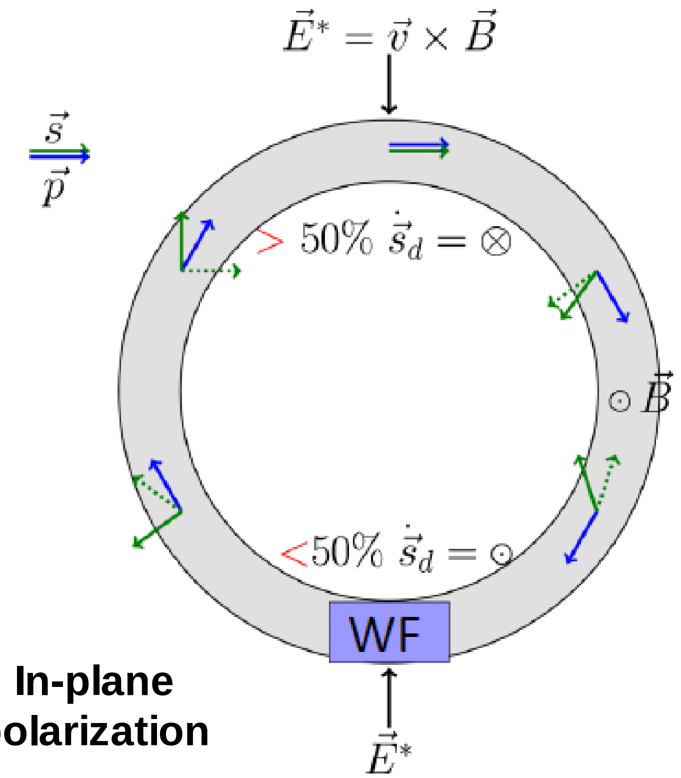
PRL 115, 094801 (2015)

Resonance Method in Magnetic Rings

RF *ExB* dipole in "Wien filter" mode

→ Avoids coherent betatron oscillations

$\boldsymbol{E}^* = \mathbf{0} \Rightarrow \boldsymbol{E_R} = -\beta \times \boldsymbol{B_y}$ „**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**

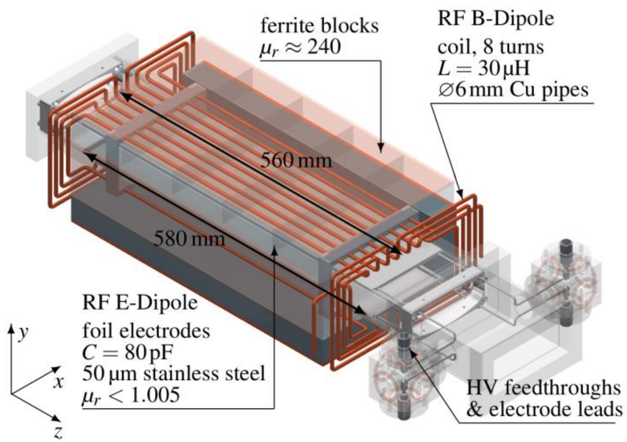
→ continuous buildup of vertical polarization in a horizontally polarized beam.

→ net effect due to EDM

→ Investigation of sensitivity and systematic limitations

RF ExB Wien Filter

Schematic view of RF ExB Wien filter



Measurements

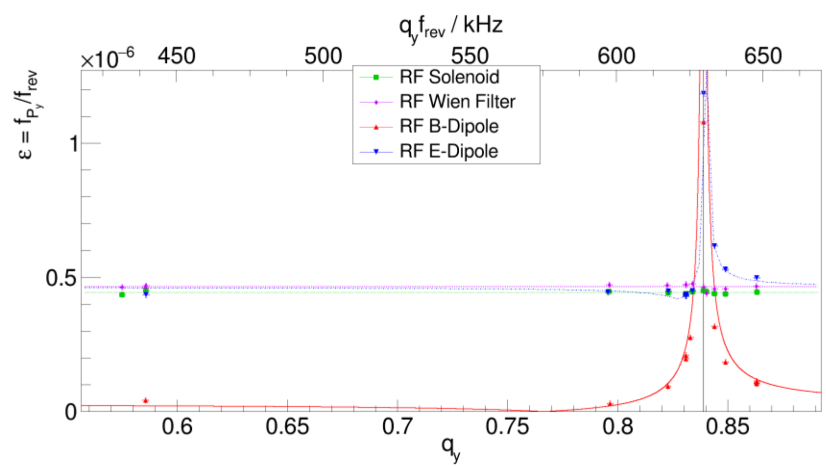
with RF ExB Wien filter and RF Solenoid

- **Spin resonance: $f_s = (1+\gamma G)\, f_{rev} = 630$ kHz**
- **Analyse the spin phase advance throughout the cycle**

RF ExB Wien filter Installed in the COSY Ring

Measurement
Resonance strength vs. betatron tune

Spin oscillation frequency [Hz]



Vertical betatron tune

Wien filter condition: Lorentz force is zero

Courtesy: S. Mey

Utilized Simulation Programs for Spin Tracking

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

Bmad: Cornell University

software Toolkit for Charged-Particle and X-Ray Simulations

- wide range of routines for lattice design and tracking
- Runge-Kutta and symplectic (Lie algebraic) integration, interfacing PTC code, Taylor maps to arbitrary order

Collaborators

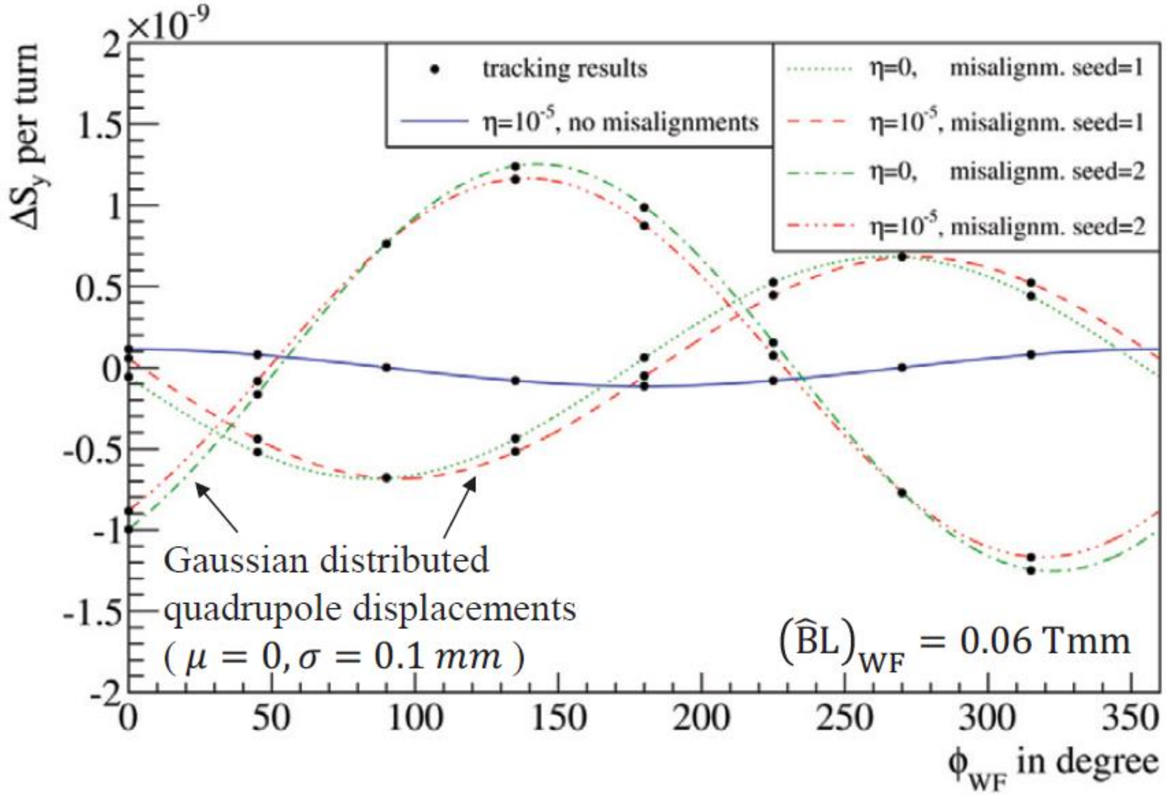
Martin Berz, Kyoko Makino (MSU, USA)

Sergey Adrianov (St. Petersburg State University, Russia)

Jean Marie De Conto (Joseph Fourier University Genoble, France), Maud Baylac (Accelerator Group at LPSC Grenoble, France)

Andrzej Magiera (Institute of Physics, Jagiellonian University, Cracow, Poland)

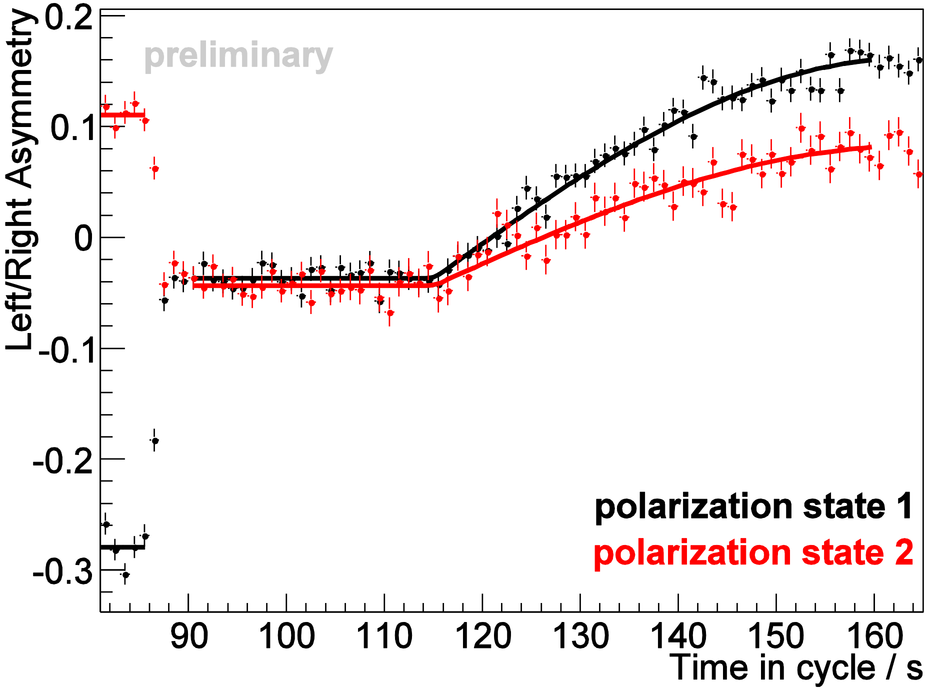
Simulation of Resonance Method (COSY Infinity)

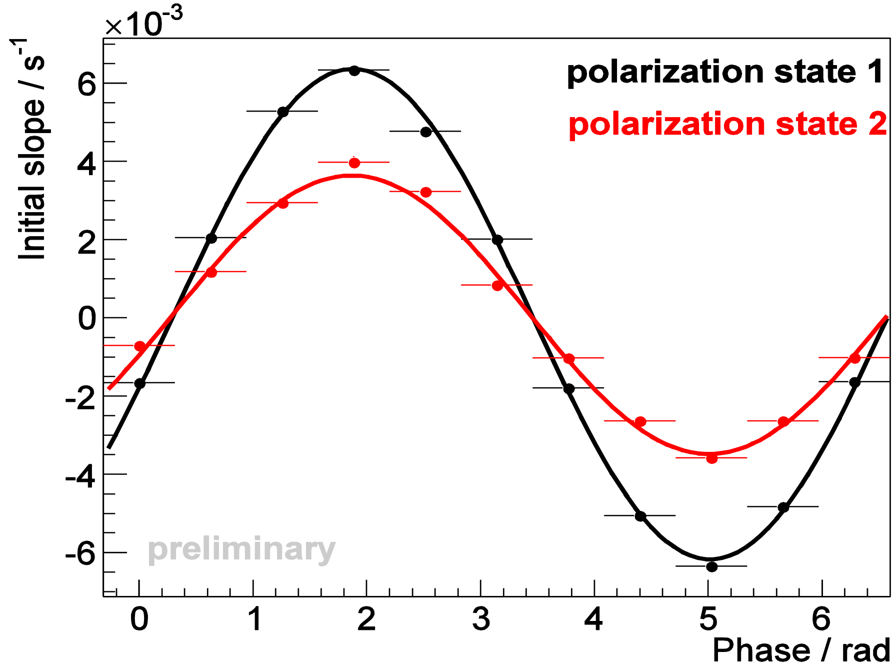


Vertical spin buildup for closed orbit deuterons in an ideal ring, as well as for quadrupole misalignments for two different randomization seeds. The black dots show tracking results, the colored lines are analytical estimates.

M. Rosenthal, A. Lehrach
Proceedings at IPAC 2015: THPF032

Spin Tune-Based Feedback System





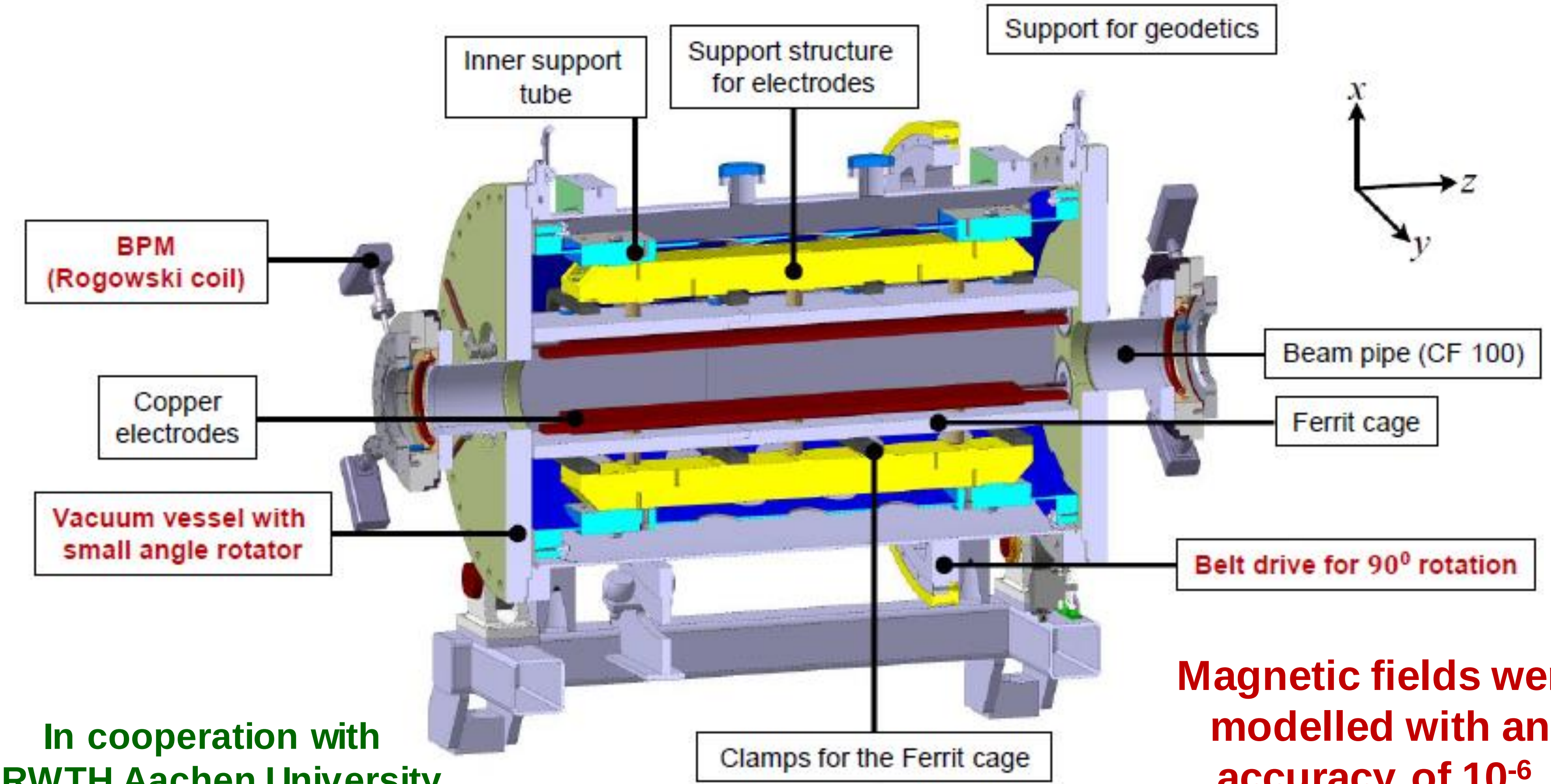
- Polarization rotates in horizontal plane at *t* = 85 s by RF solenoid.
- COSY RF changes in steps of 3.5 mHz according to online spin tune measurement.
- RF solenoid turned back on with low amplitude at *t* = 115 s.
- Polarization rotates back to vertical.

- Initial slope of the polarization build-up as function of the relative phase (online result).

- The difference in amplitude is due to the different degrees of polarization of the two initial states.

Courtesy: V. Hejny

Stripline RF Wien Filter



In cooperation with RWTH Aachen University

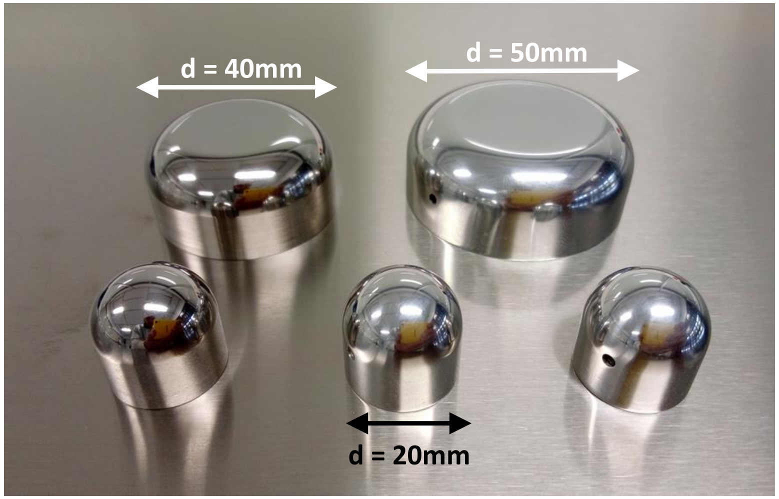
Magnetic fields were modelled with an accuracy of 10^{-6}.

Design model of the RF Wien filter showing the parallel-plates waveguide and the support structure.

Courtesy: A. Nass, J. Slim

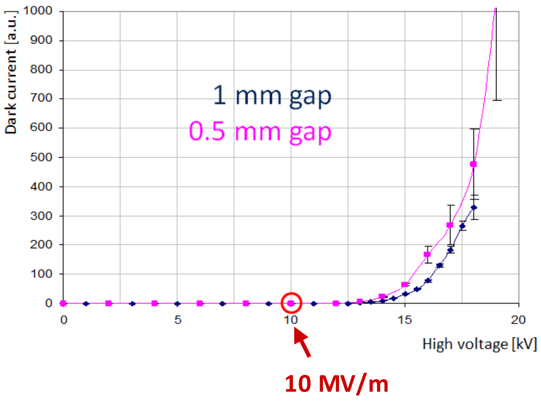
High-Field Electrostatic Deflector Development

High Voltage UHV setup in the clean room at RWTH Aachen



Test electrodes from polished stainless steel and aluminum

Simulation and results



Stainless steel

Two small half-spheres (R = 10mm)
17kV at 1mm distance → 17 MV/m

Half-sphere vs. flat surface
12kV at 0.05mm distance → 240 MV/m

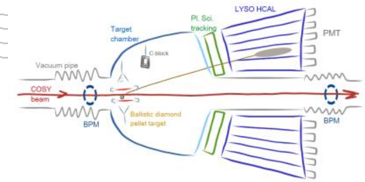
Aluminum

Two small half-spheres (R = 10mm)
3kV at 0.1mm distance → 30 MV/m

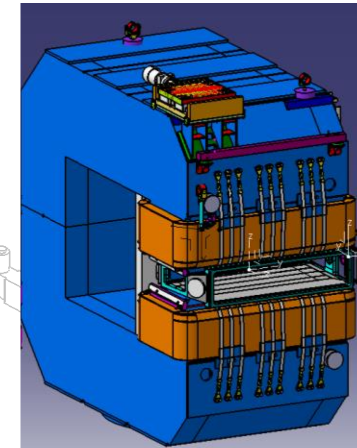
Courtesy: K. Grigoryev

Prototyping

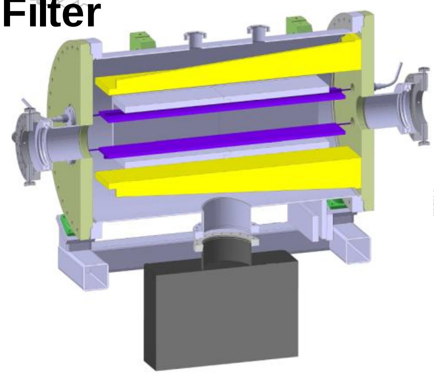
RF ExB Wien Filter



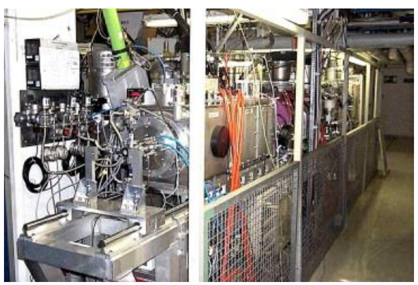
Prototype Polarimeter



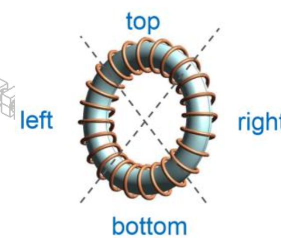
ExB Deflector



RF Stripline Wien Filter



Polarized Ion source



Position Monitor

EDM accelerator and detector component tests

Summary

- Precision Spin Manipulation

Spin tune measurement with precision of 10^{-10}
Spin coherence time of more then 1000s
Spin tune-based feedback system developed
Spin tracking codes developed and partly benchmarked
RF ExB Wien filter build and applied
High-precision stripline Wien filter in preparation

- Deflector Development (Poster session)

High fields reached with scaled models

- Ion Sources (Next talk)

Commissioning of ELENA/CERN source

Outlook

- **Spin tracking: Bench marking experiments**

- **Precursor experiment:**

  Commissioning of high-precision Wien filter

  First direct EDM measurement at COSY

- **Dedicated EDM storage ríng:**

  R&D work and design study

  Development of high-field static E/B deflector

- **Source development:**

  COSY support and participation in ELENA commissioning

  High-intensity polarized light ions for JEDI

Further contributions to this meeting:

A.M. Megia-Macias, Ion Source Integration at the Extreme Low ENergy ring for Antiprotons ELENA at CERN for commissioning

K. Grigoryev, Electrostatic Deflector Development (Poster)

F. Hinder, Measurement of Electric Dipole Moments at COSY Jülich (Student Retreat)

Simulation with COSY Infinity

COSY Toolbox

JÜLICH
FORSCHUNGSZENTRUM

COSY Lattice → **COSY Toolbox**

COSY INFINITY ↔ **COSY Toolbox**

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

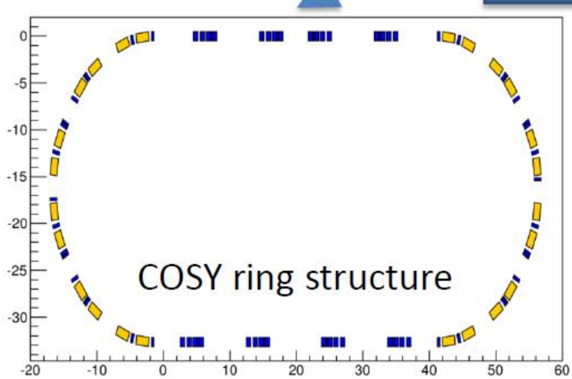
Armadillo ↔ **COSY Toolbox**

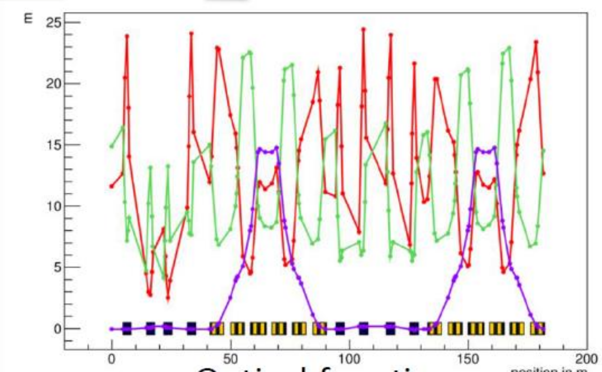
- linear algebra operations
- SVD, pseudo-inverse

COSY Toolbox → **ROOT**

ROOT

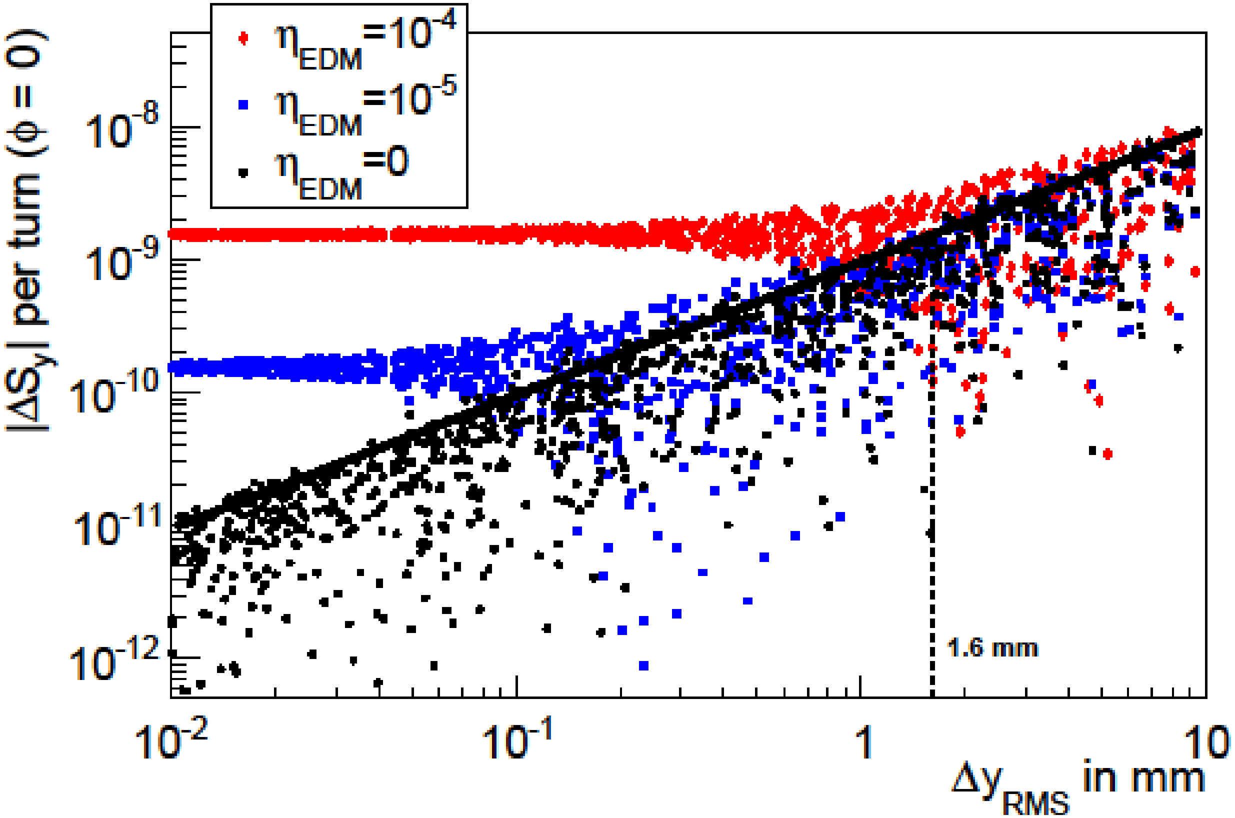
- plotting
- storage (ROOT files/trees)





Optical functions

Systematic Limitations for EDM Measurements



EDM measurement at COSY

Wien filter magnetic field 10^{-4} mT and corresponding electric field
Length of Wien filter 0.8 m

Δy_{RMS} generated by randomized vertical quadrupole shifts assuming Gaussian distributed misalignment errors.

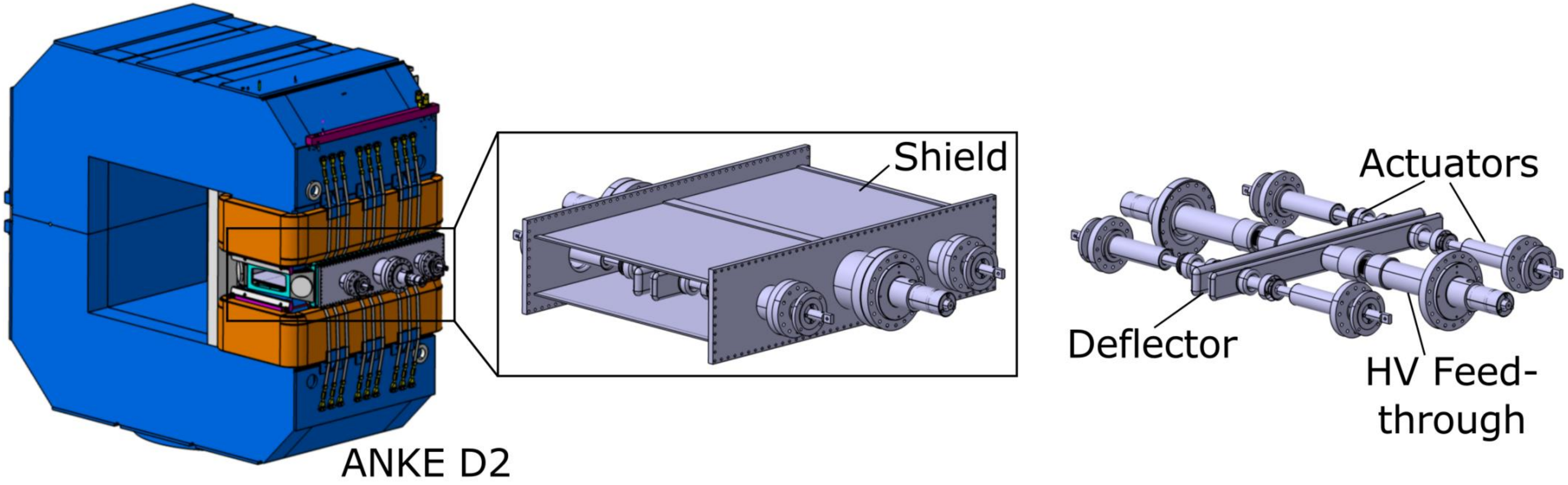
The solid line shows the 90% upper confidence limit for pure misalignments.

The dashed line refers to the location for which the false signal by misalignments is equal to an EDM signal corresponding to $\eta_{EDM} = 10^{-4}$.

This value corresponds to an EDM magnitude of $d_d \approx 5 \cdot 10^{-19}$ *e* cm.

Courtesy: M. Rosenthal

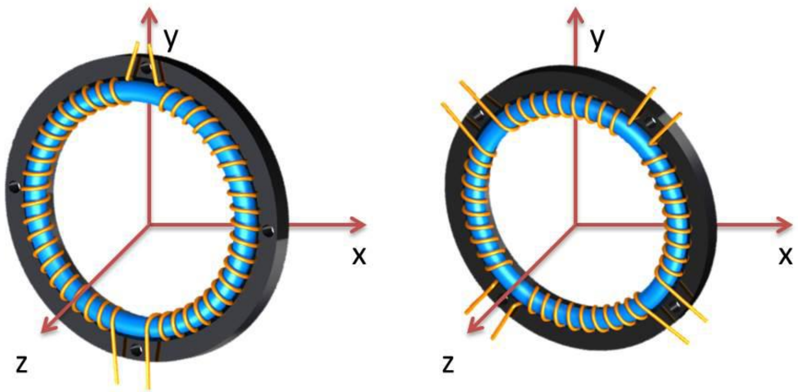
Development of static E/B deflector

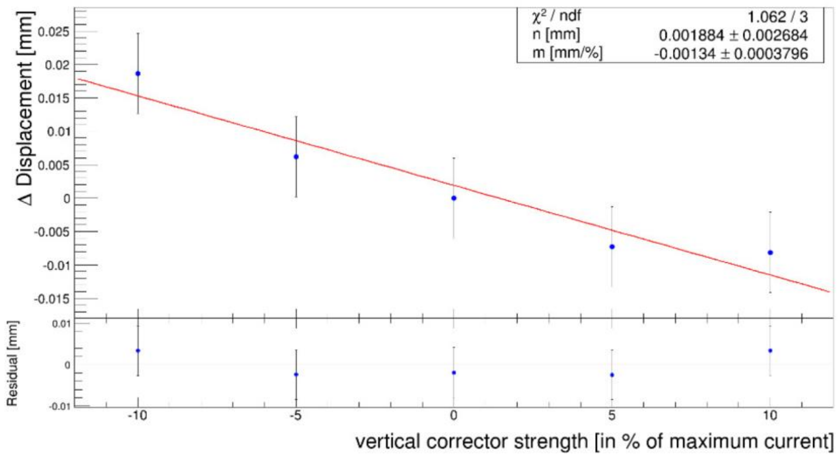


An electrostatic deflector is in development that will be implemented into the ANKE D2 magnet. Materials and coatings have been evaluated that show a high breakdown strength. The first aim of the D2 deflector setup is to study the breakdown behavior. E-field mapping techniques will be developed and applied at the setup. An evaluation of suitable diagnostics is currently carried out. Moreover, different shapes of the deflector will be tested at the D2 deflector setup.

Courtesy: J. Böker

Rogowski Type Beam Position Monitor





Half and quarter winded Rogowski coils in the defined coordinate system. The shown configuration on the left enables a position measurement in *x*-direction. The configuration shown on the right corresponds to a measurement in both directions: *x* and *y*.

Test of the linearity of the BPM response to the corrector magnet excitation, which is proportional to a horizontal beam displacement at the BPM.

Courtesy: F. Hinder, F. Trinkel

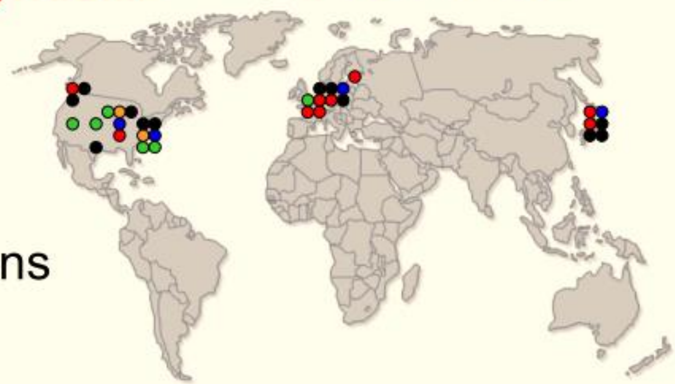
EDMs – Ongoing / Planned

- 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

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

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

Sources of $\mathcal{CP}$ violation