JÜLICH
FORSCHUNGSZENTRUM

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SPIN 2014

The 21st International Spin Physics Symposium

Storage Ring Based EDM Search

Achievements and Goals

October 20, 2014 | Andreas Lehrach

RWTH Aachen University & Forschungszentrum Jülich

on behalf of the JEDI collaboration

(Jülich Electric Dipole Moment Investigations)

JEDI

Outline

Introduction

Motivation for EDM measurements

EDM Measurements in Storage Rings

Principle and methods

Achievements:

- very precise spin tune measurement
- long spin coherence time (SCT)

R&D work for dedicated storage rings

Summary / Outlook

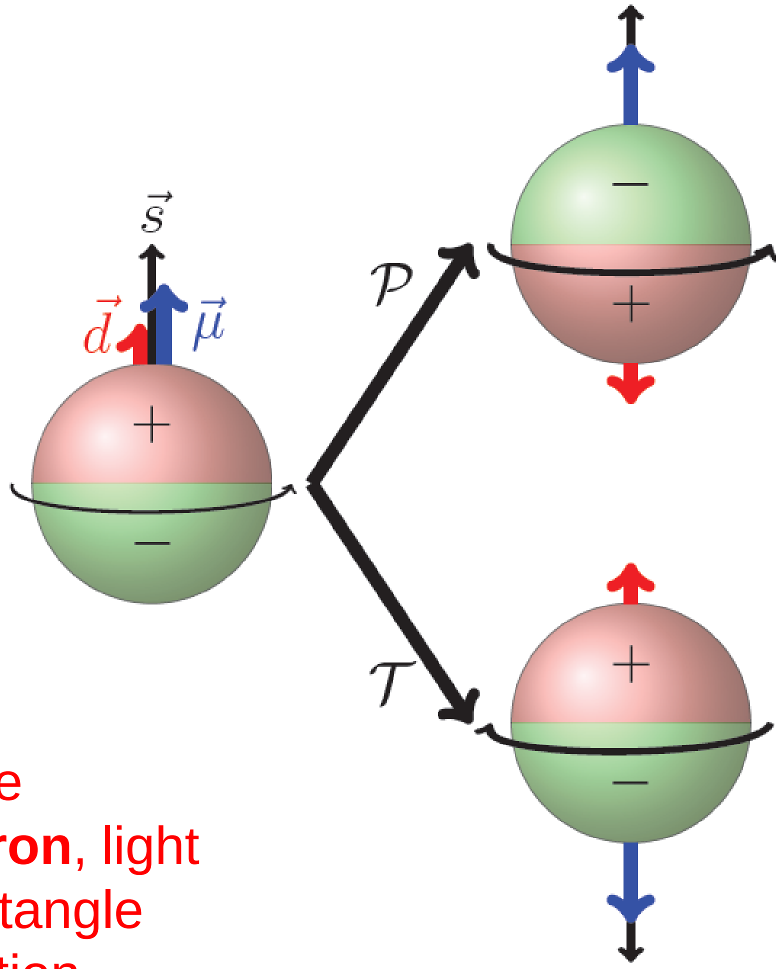
Electric Dipole Moments

$\vec{d}$: 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

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:

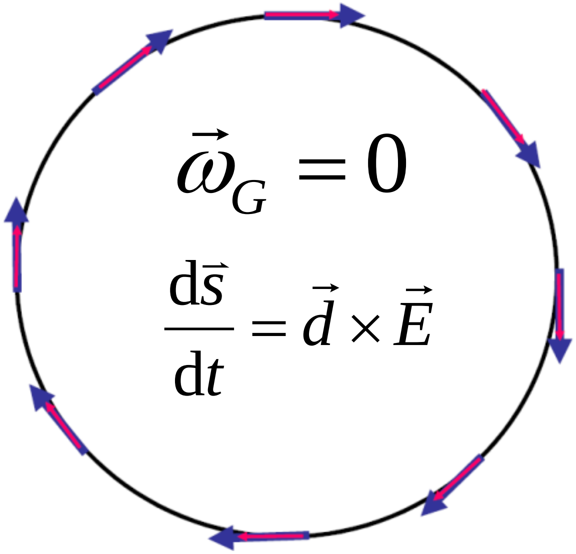
$$\frac{d\vec{S}}{dt}=\vec{\Omega}\times\vec{S}$$

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

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

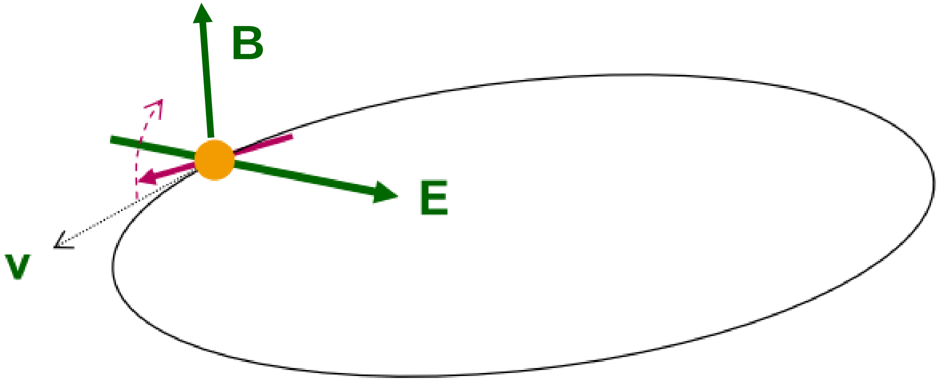
Search for Electric Dipole Moments

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

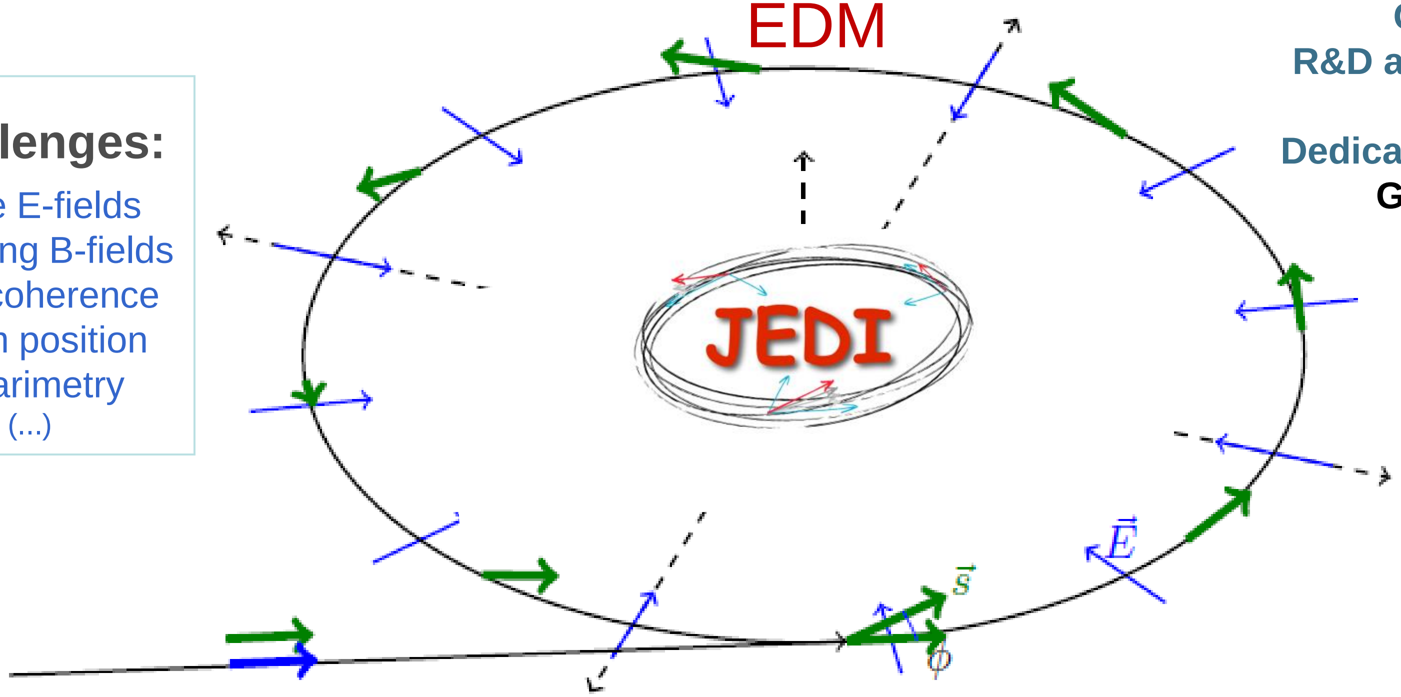
One machine with r ~ 30 m

Storage Ring EDM Project

… measure for buildup of vertical polarization

⇔

EDM



Challenges:

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

Step wise:

COSY (PoF-3)
R&D and Precursor Expt.

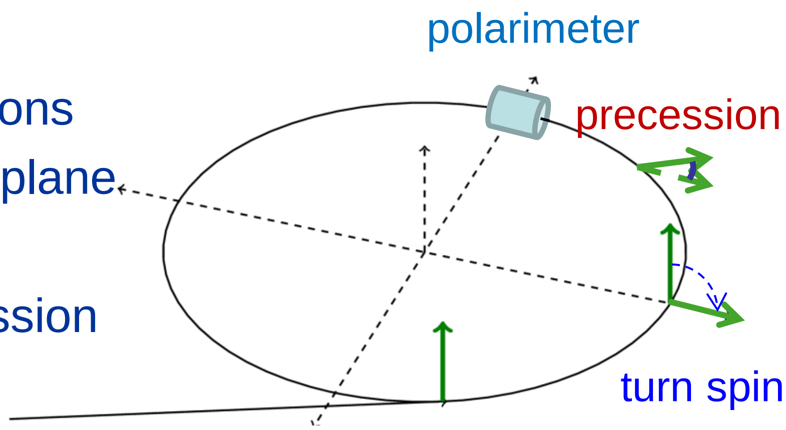
Dedicated SR (after PoF-3)
Goal: 10^{-29} e·cm

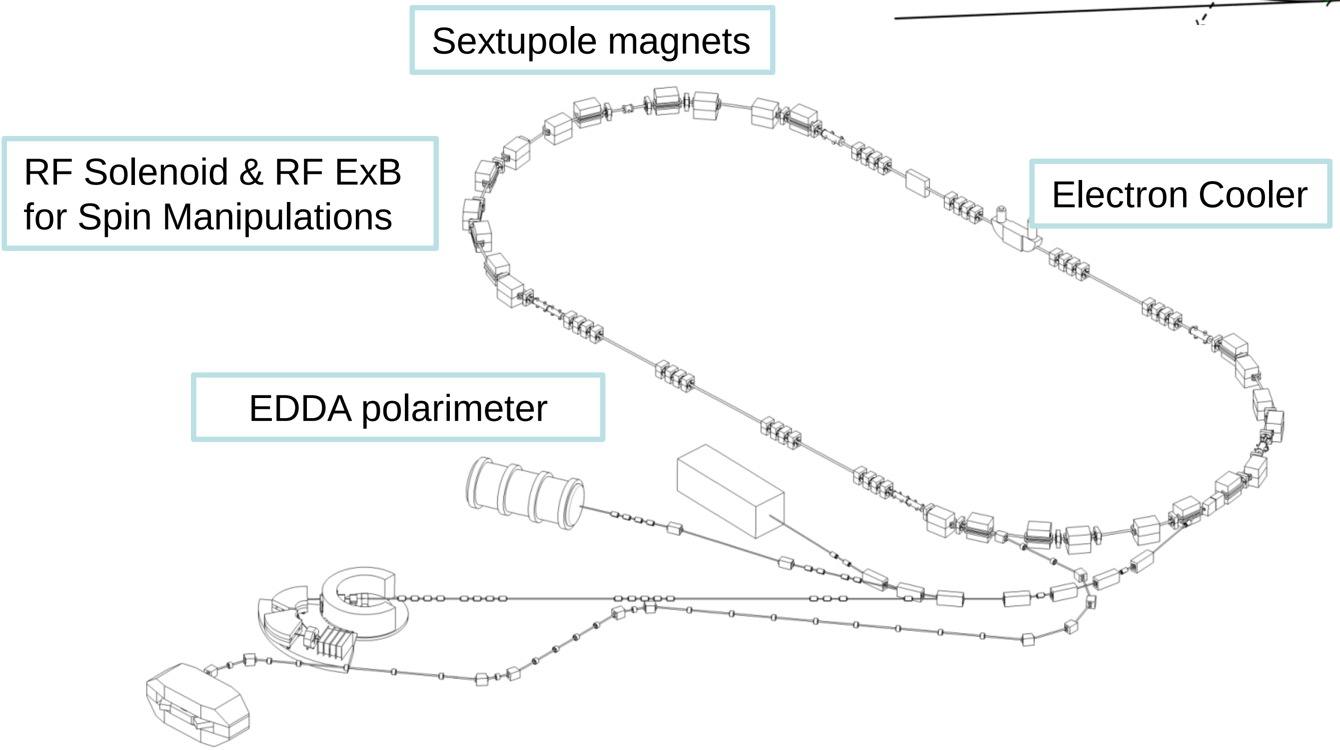
JARA Jülich Aachen Research Alliance

~ 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)

Experimental Setup for R&D at COSY

- Inject and accelerate vertically polarized deuterons
- Flip spin with help of a RF fields into horizontal plane
- Extract beam slowly (in 100 s) on target
- Measure asymmetry and determine spin precession





Spin Tune Measurements

Spin vector precesses with $f_{\text{Spin}} = \nu f_{rev}$ in the horizontal plane

Asymmetry given by:

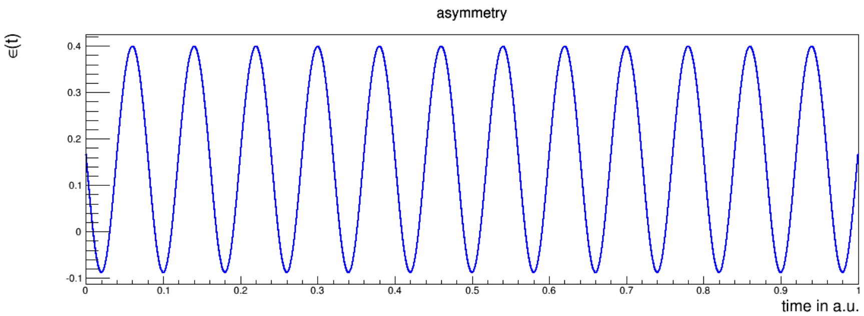
$$\epsilon_V(t) = \frac{N_u - N_d}{N_u + N_d} \approx AP(t)\sin(2\pi\nu f_{rev}t + \phi)$$

What do we expect ?

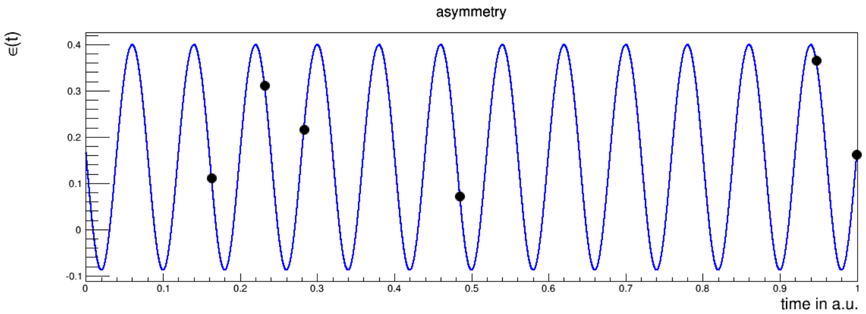
- Deuterons, $p = 0.97\ \mathrm{GeV/c};\ \nu \approx 0.16,\ f_{rev} = 750\ \mathrm{kHz}$
- Spin precession frequency: $\nu \cdot f_{rev} \approx 125\ \mathrm{kHz}$
- Detector rates: $5\ \mathrm{kHz}$
- Only every 25th spin revolution is detected

→ No direct fit is possible

Time stamp events



Example: every 2nd spin precession is detected

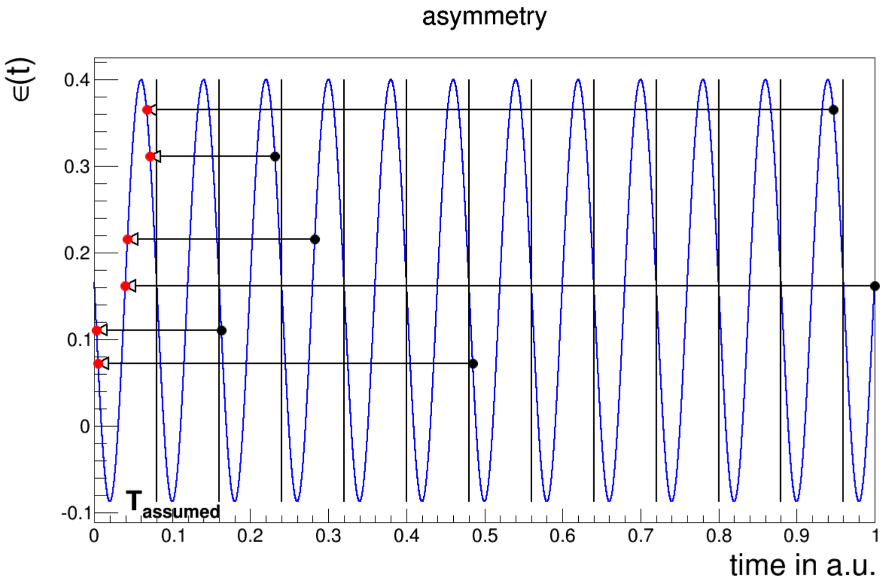


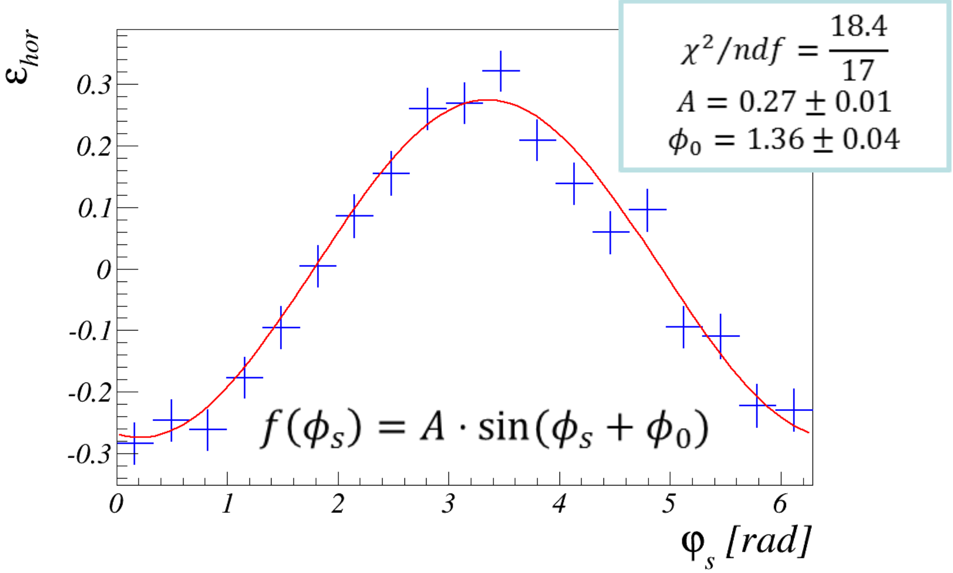
Event Mapping

Mapping the events:

- Assume Spin Tune $\nu_{assumed}$
  - $T_{assumed} = \frac{2\pi}{\nu_{assumed} f_{rev}}$
- Map all events of a macroscopic time interval (2s) in first period:
  - $t' = mod(t, T_{assumed})$
- Fit asymmetry to first period

Extract amplitude $A \propto Polarisation$

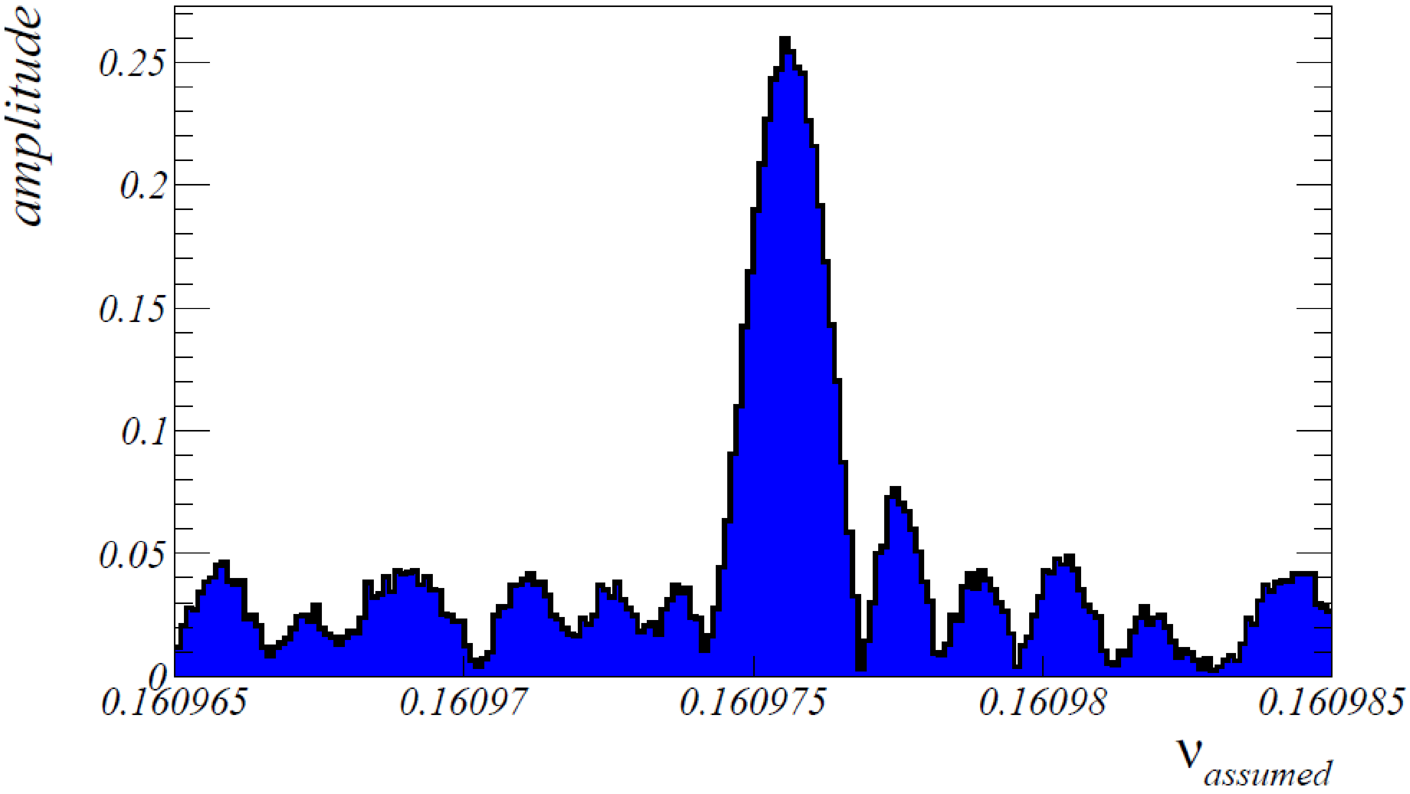




$$\chi^2/ndf = \frac{18.4}{17}$$
$$A = 0.27 \pm 0.01$$
$$\phi_0 = 1.36 \pm 0.04$$

$$f(\phi_s) = A \cdot \sin(\phi_s + \phi_0)$$

Assumed Spin Tune vs. Amplitude



- set $\nu_s = \nu_{max}$ and determine phase in macroscopic time bins of 2s

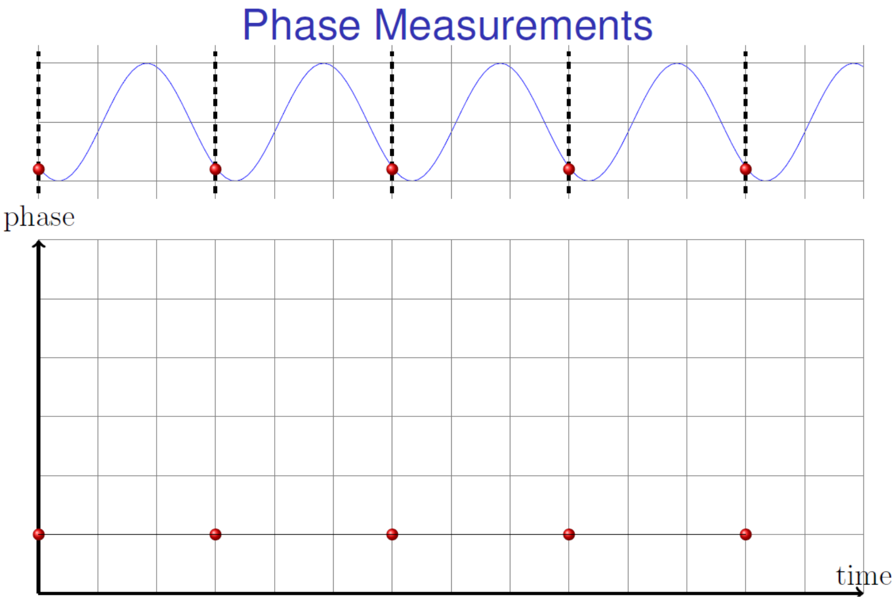
→ ν_{max} correct spin tune in the macroscopic time intervals of 2sec

- $\nu_{max} = 0.160975 \pm 10^{-6}$ → allows for $\sigma_s \approx 10^{-6}$

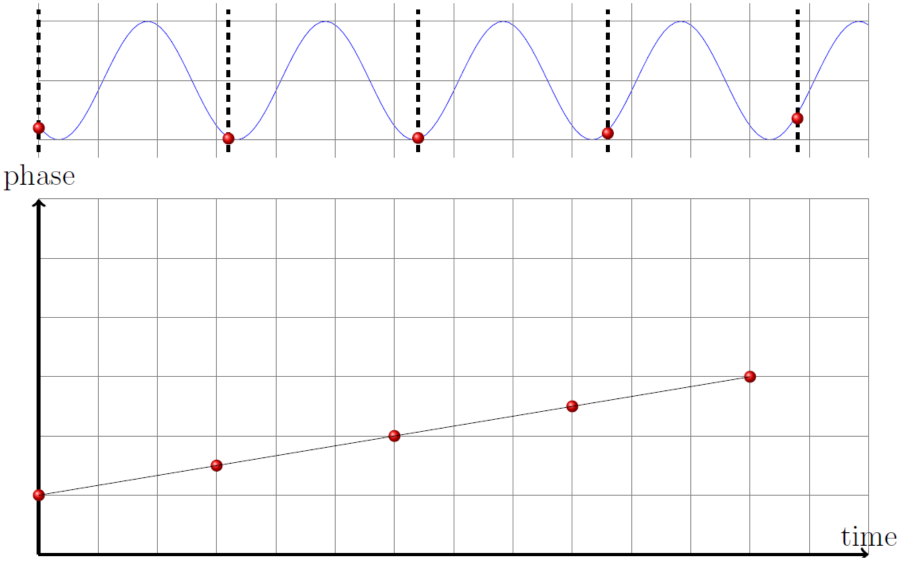
- now fix spin tune and observe phase vs. time

Spin Phase vs. Time

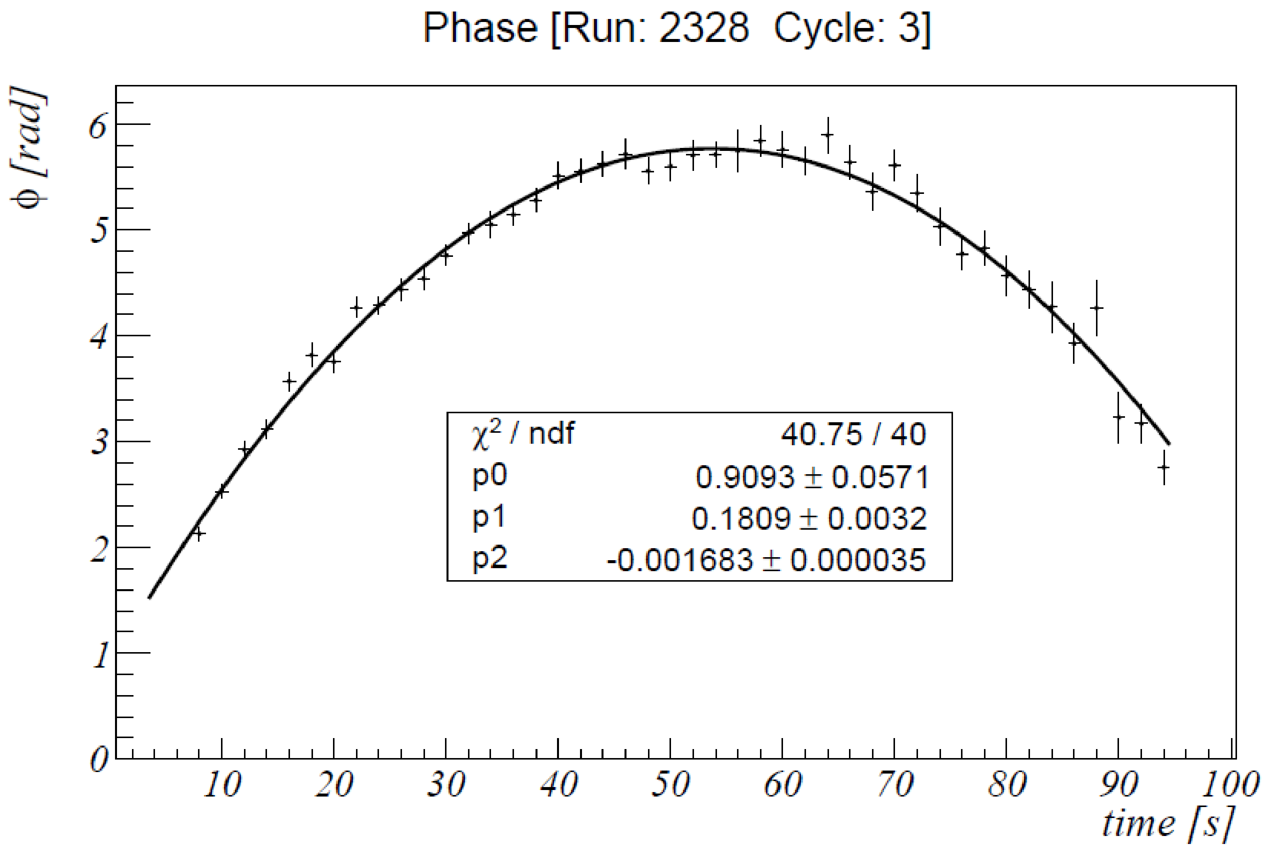
$$\nu_s = \nu_{\text{assumed}}$$


Phase Measurements

$$\nu_s = \nu_{\text{assumed}} + \Delta\nu$$

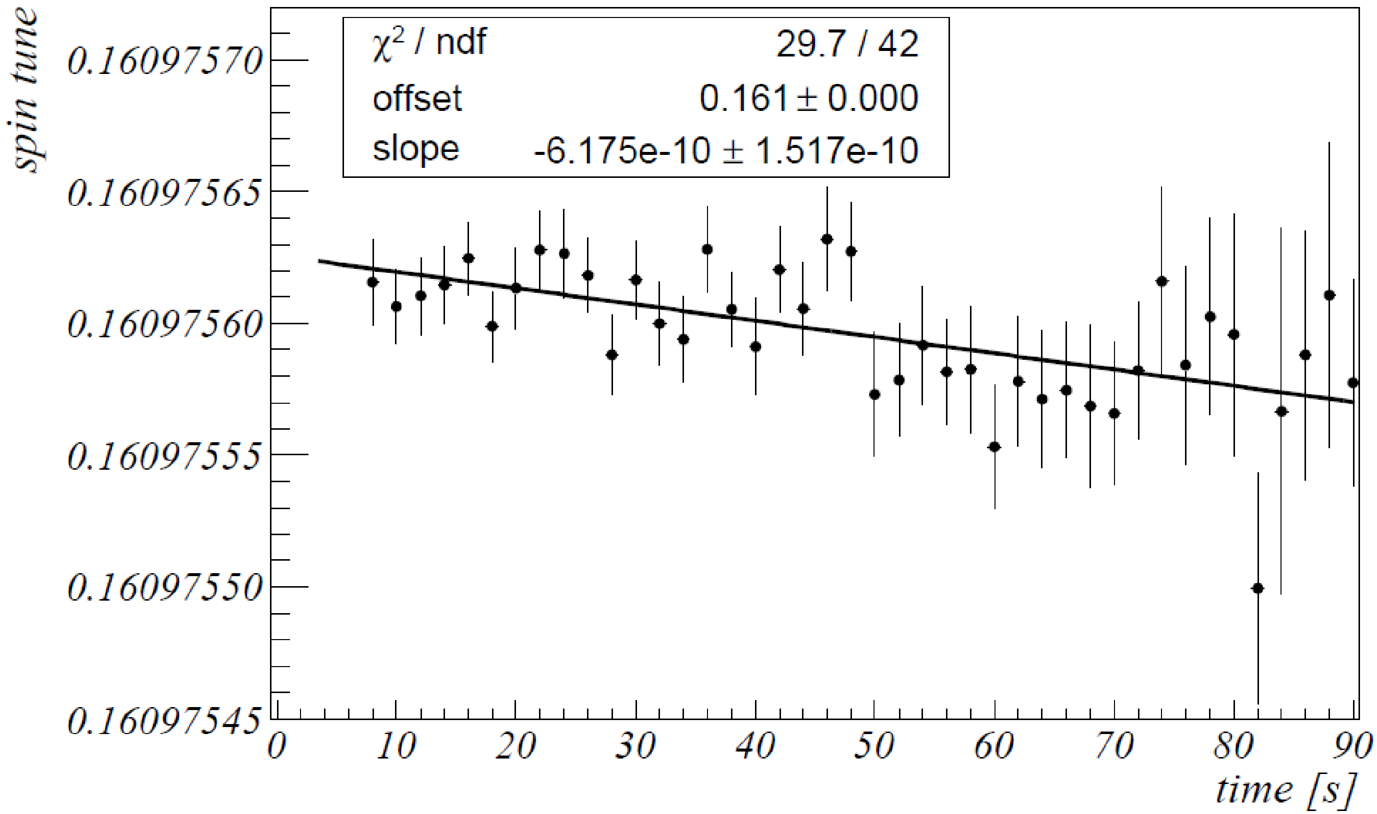


Spin Phase vs. Time



- 1st derivative gives deviation from assumed spin tune

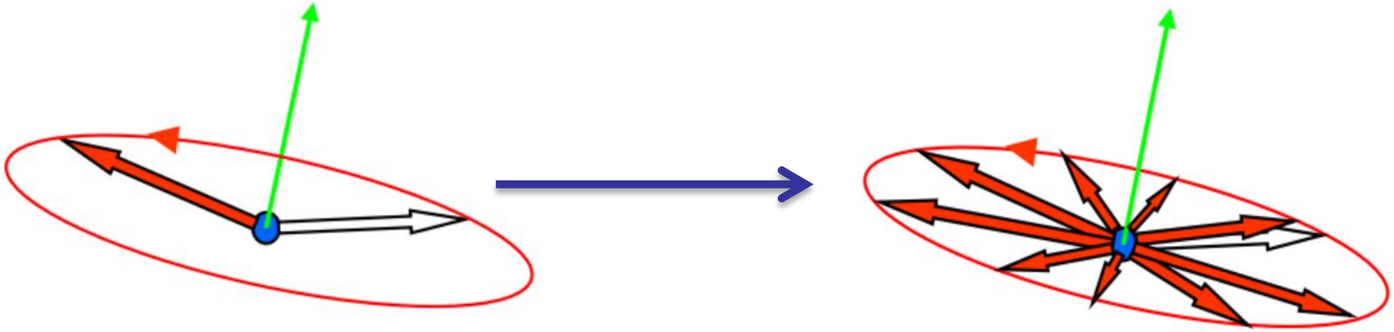
Spin Tune Measurement



- Spin tune ν_s can be determined to 10^{-8} in 2 s
- Average ν_s in cycle (100 s) determined to 10^{-10}
- $\nu_s \approx \gamma G$ varies within one cycle and from cycle to cycle by 10^{-8}

Spin Coherence Time (SCT)

- Statistical sensitivity of EDM proportional to SCT
- Spin precession with $f_s = \gamma G\, f_{ref} \approx 125$ kHz
- Momentum spread leads to different precession frequencies

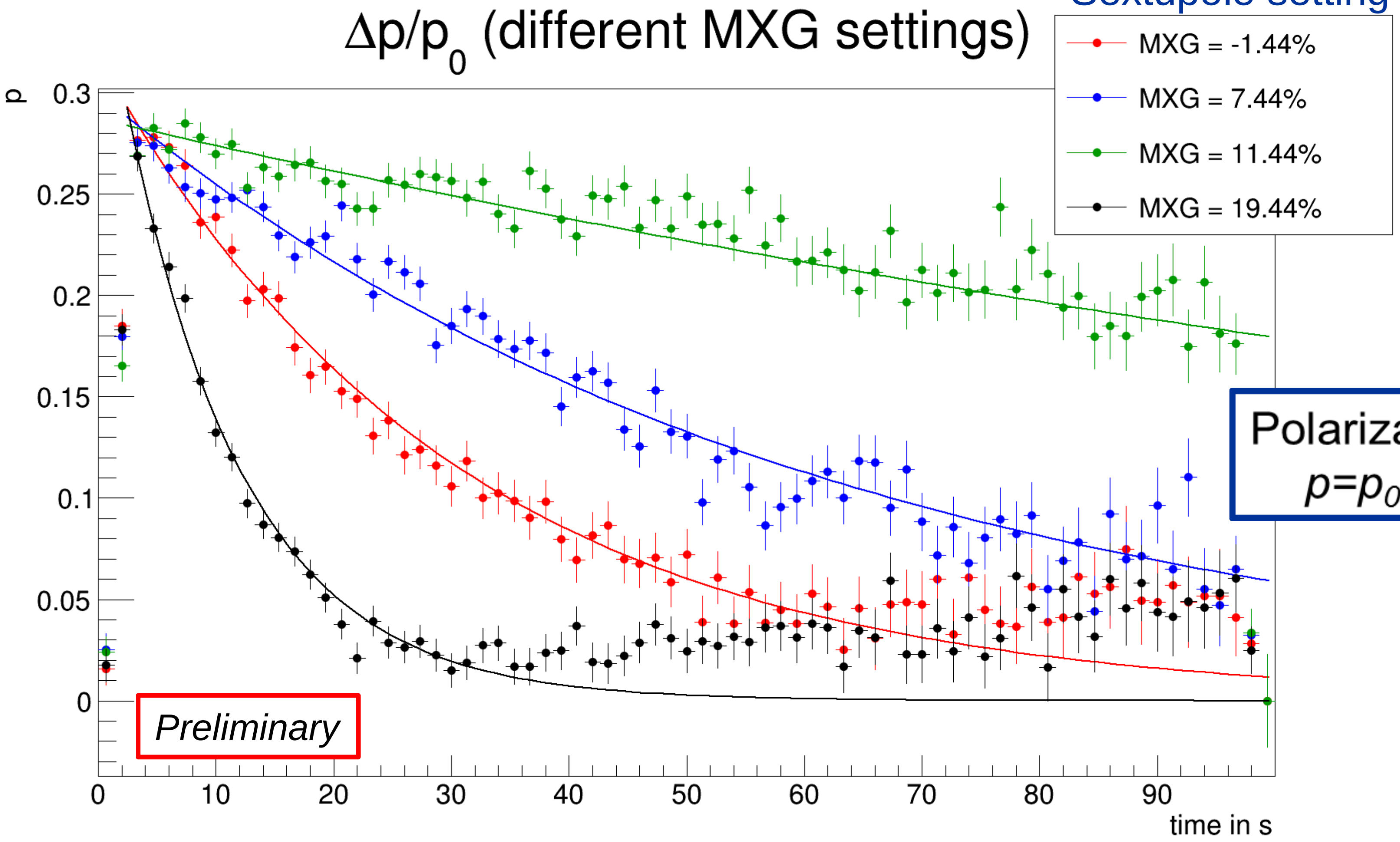


Horizontal Polarization Vanishes !

- Loss of horizontal polarization ↔ spin decoherence

Spin Coherence Time (SCT)

Sextupole setting



Preliminary

Polarization fit:

$p = p_0 e^{-\tau/\tau_{SCT}}$

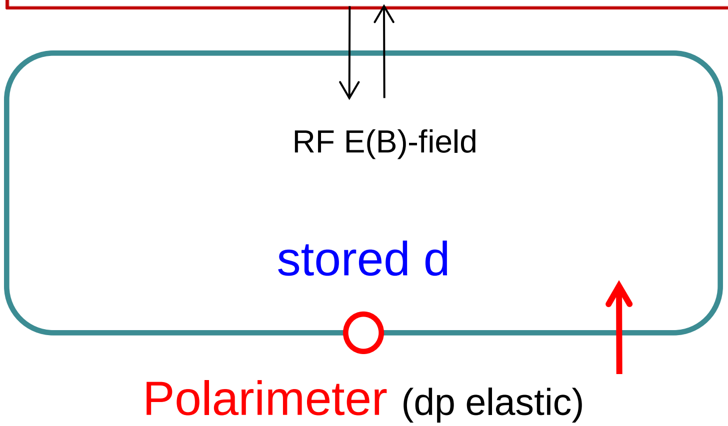
Best Spin Coherence Time: $\tau_{SCT} \approx 400s$

Precursor Experiments:

Resonance Method with „magic“ RF Wien filter

Avoids coherent betatron oscillations of beam.
Radial RF-E and vertical RF-B fields to observe spin rotation due to EDM.
Approach pursued for a first direct measurement at COSY.

$\boldsymbol{E}^* = \mathbf{0} \Rightarrow \boldsymbol{E}_R = -\beta \times \boldsymbol{B}_y$ „Magic RF Wien Filter“ no Lorentz force
→ **Indirect** EDM effect



In-plane
polarization

Observable:
Accumulation of vertical polarization during spin coherence time

Investigation of sensitivity and systematic limitations

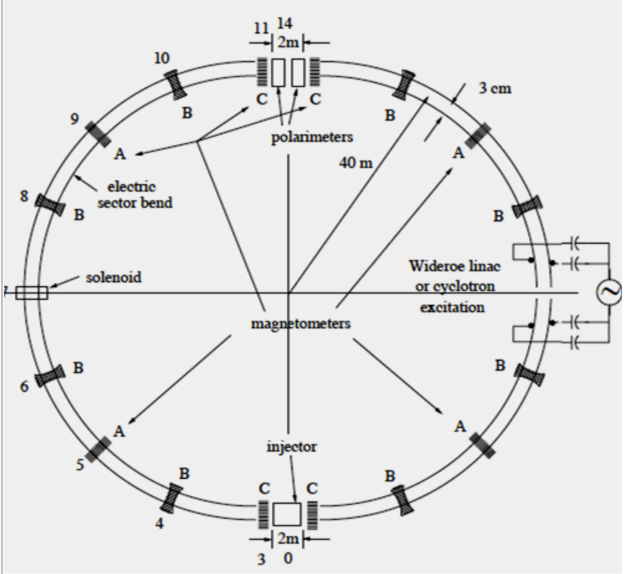
See talk by
A. Saleev, S. Mey and
S. Chekmenev

Storage Ring EDM Project

Options:

All-electric ring (proton, electron): only **E-field**

All-in-one ring (proton, deuteron, ^{3}He): **E- and B-fields**



Challenges:

Huge E-fields

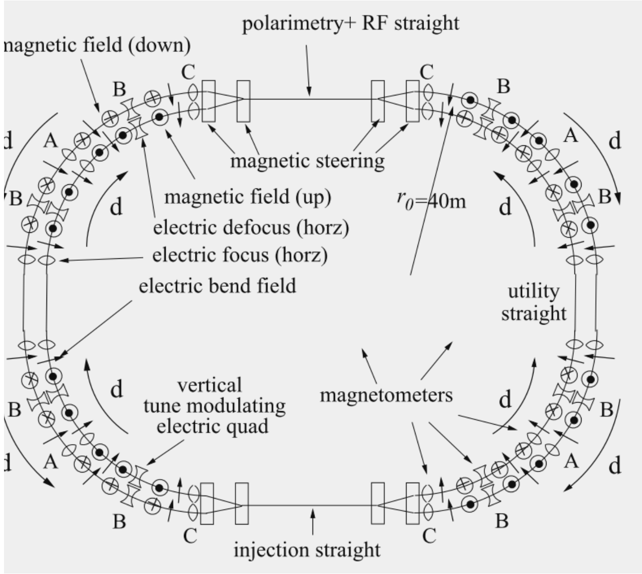
Shielding B-fields

Spin coherence

Beam position

Polarimetry

(...)



srEDM Collaboration - JEDI Collaboration

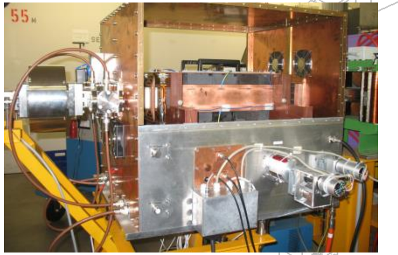
Dedicated precision storage ring

Courtesy R. Talman (Cornell)

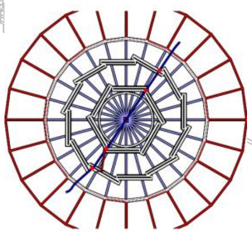
R&D Activities

R&D Activity	Goal	Place / Status
Internal Polarimeter	spin as a function of time Systematic errors < 1 ppm	EDM at COSY
	Full-scale polarimeter	EDM at COSY
Spin Coherence Time	$>10^3$ s	EDM at COSY
Beam Position Monitor	resolution 10 nm,1 Hz BW 64 BPMs, 10^7 s measurement time → 1 pm (stat.) relative position for single and dual beams (CW-CCW)	CW-CCW beams: RHIC IP Single beams: COSY
E/B-field Deflector	17 MV/m 2 cm plate separation, 0.15-0.5T	Jülich
Spin tracking	Symplectic tracking with RF fields and EDM spin kick	Many places

EDM: Prototyping and Spin Physics

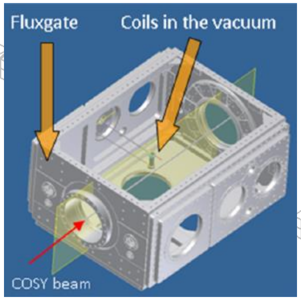


RF ExB Spin Flipper

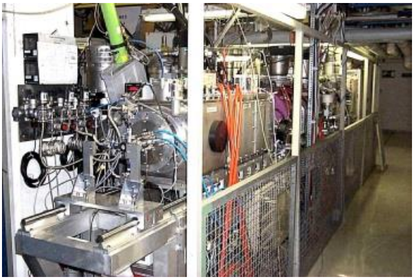


Prototype Polarimeter

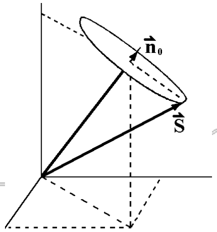
Electrostatic Deflector



SQUID BPM



Polarized Ion source



Beam and Spin Dynamics

Siberian Snake

Utilized Simulation Programs at Jülich

COSY Infinity (MSU) and MODE (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

Summary and Outlook

Achievements:

- Spin tune measurement with precision of 10^{-10} in a single cycle
- Long spin coherence time of roughly 400s
- Several spin tracking codes developed

Goals:

- Continue R&D work at COSY
- Pre-cursor experiment at COSY
- R&D work and design study for dedicated EDM storage ring (CDR end of 2018)

See talks by A. SALEEV, S. MEY and S. CHEKMENEV