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

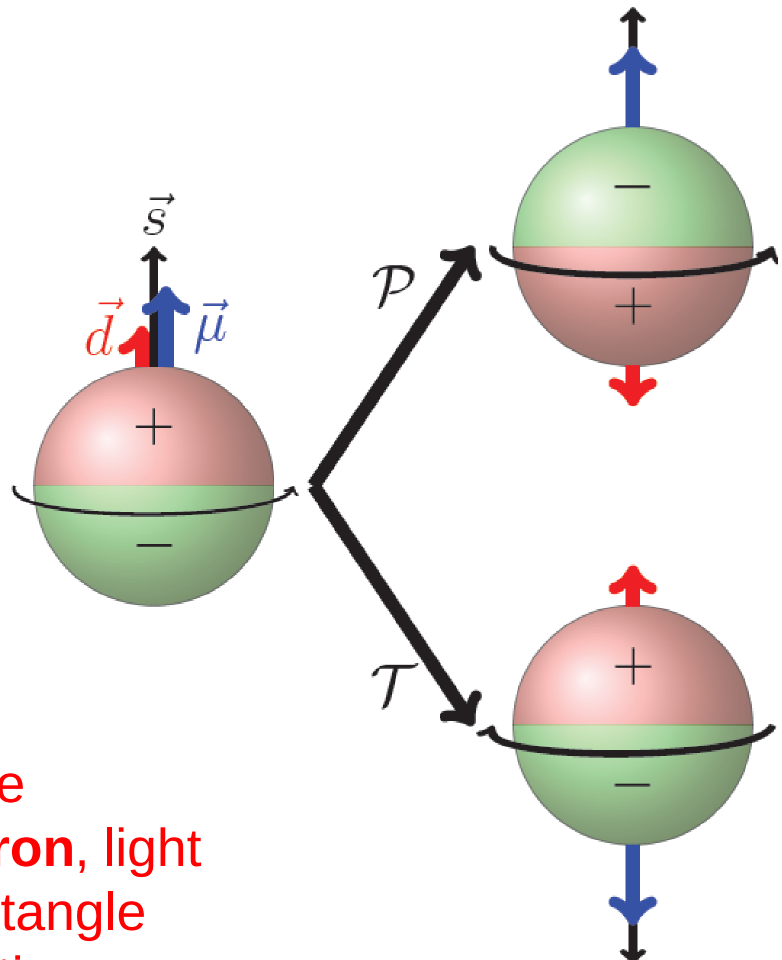
# Electric Dipole Moments

$\vec{d}$: 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:

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

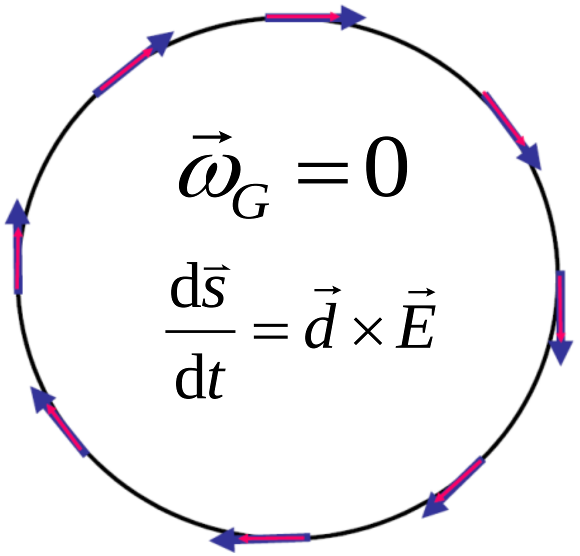
$$\vec{\Omega} = \frac{q}{m}\left\{ G\vec{B} + \left( G - \frac{1}{\gamma^2 - 1} \right)\left(\vec{v} \times \vec{E}\right) + \frac{\eta}{2}\left(\vec{E} + \vec{v} \times \vec{B}\right) \right\}.$$

Magnetic Moment — Electric Dipole Moment

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

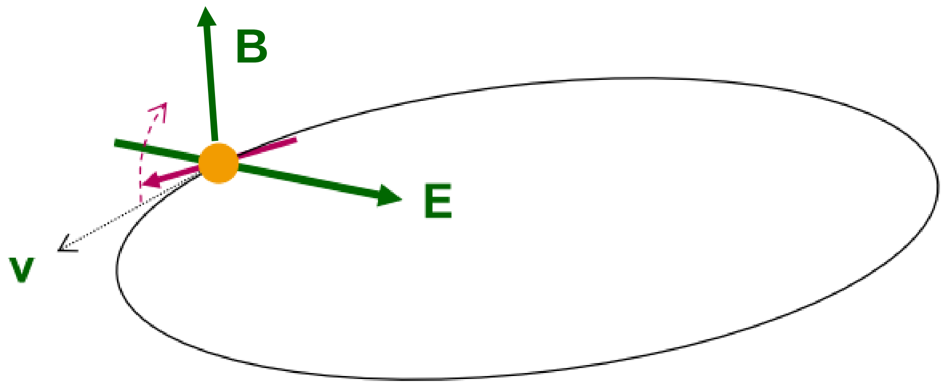
# Search for Electric Dipole Moments

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

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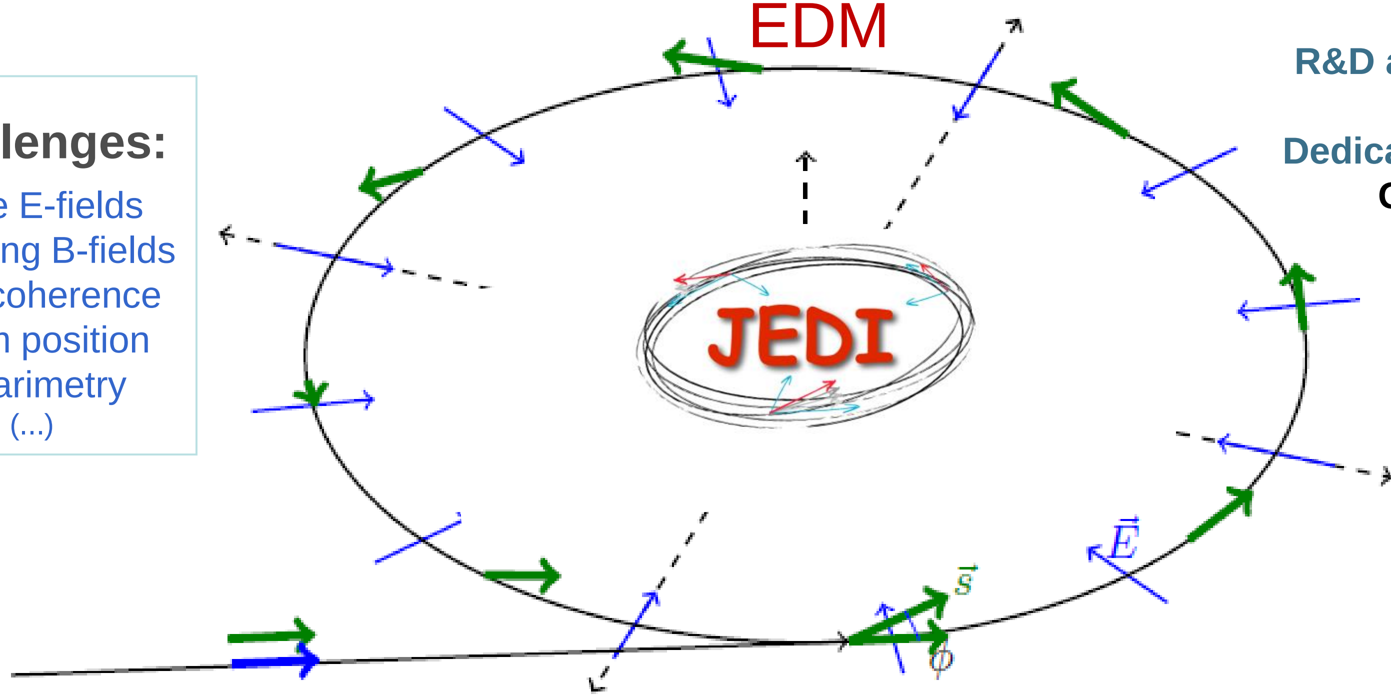
… measure for buildup of vertical polarization

⇔

EDM




**Challenges:**

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

**Step wise:**

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

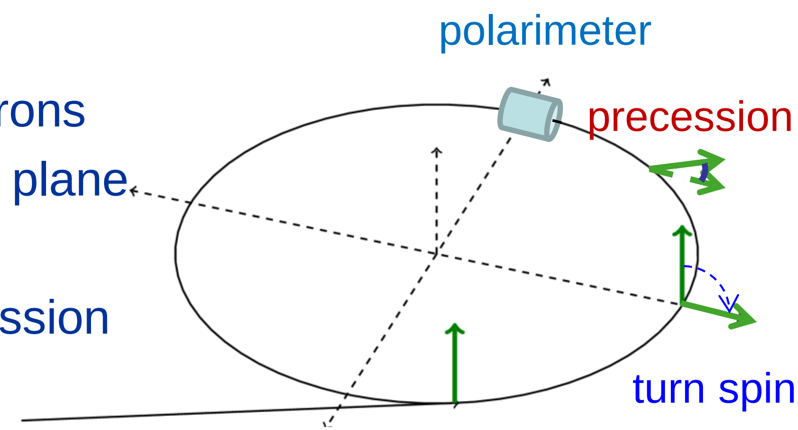
**Dedicated SR (after PoF-3)**
**Goal: $10^{-29}$ e·cm**

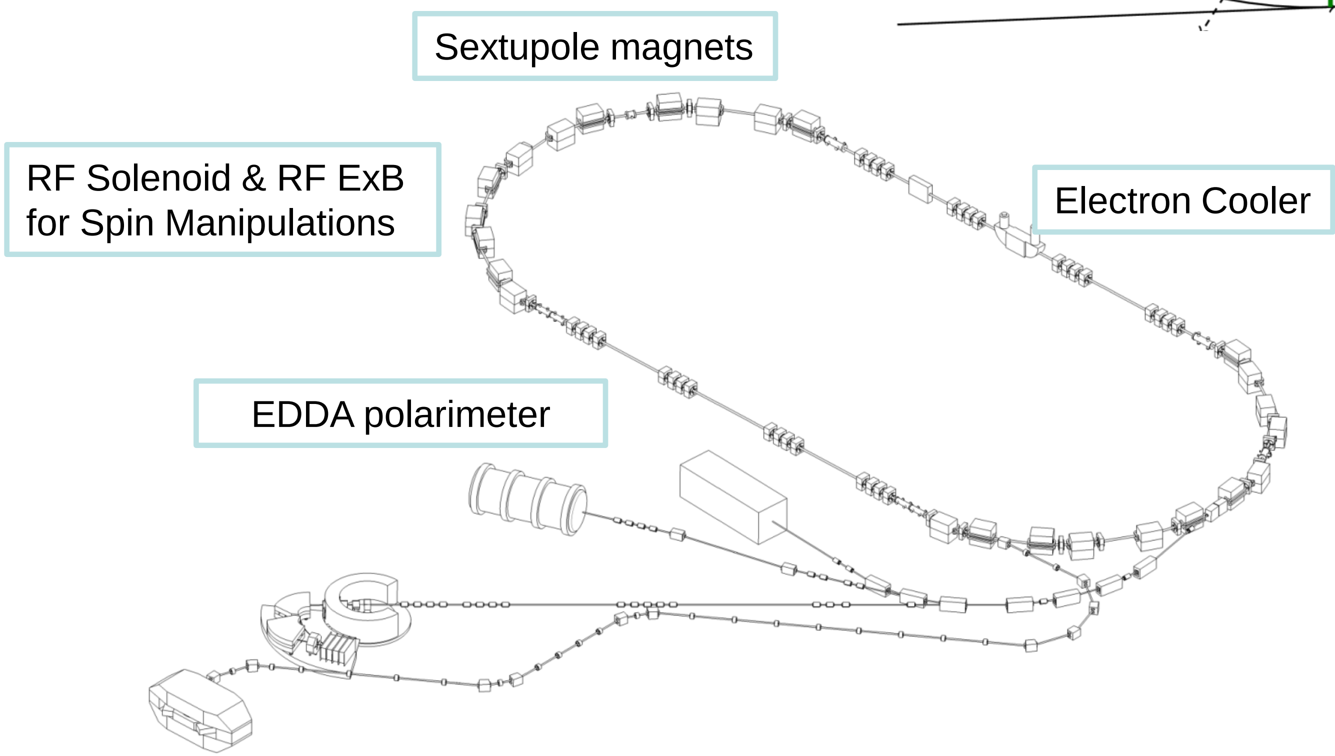
JARA Jülich Aachen Research Alliance

~ 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:

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

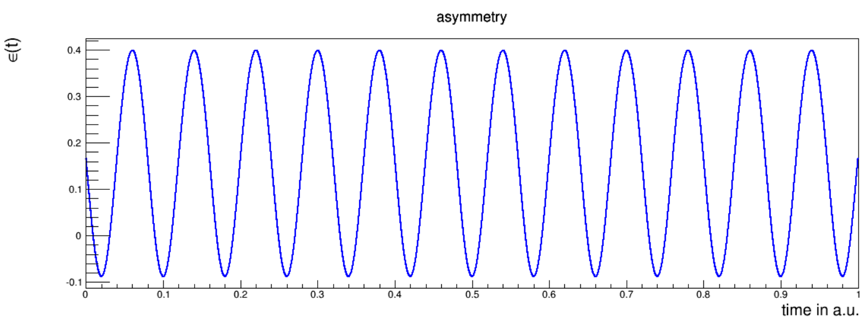
What do we expect ?

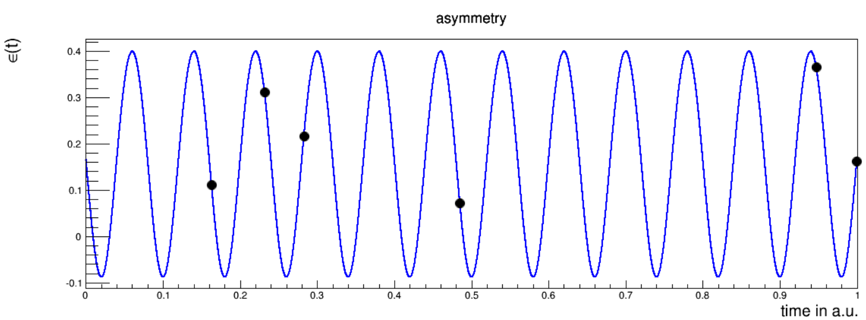
- Deuterons, $p = 0.97\ \text{GeV/c}$; $\nu \approx 0.16$, $f_{rev} = 750\ \text{kHz}$
- Spin precession frequency: $\nu \cdot f_{rev} \approx 125\ \text{kHz}$
- Detector rates: $5\ \text{kHz}$
- Only every 25th spin revolution is detected

→ No direct fit is possible

Time stamp events

Example: every 2nd spin precession is detected



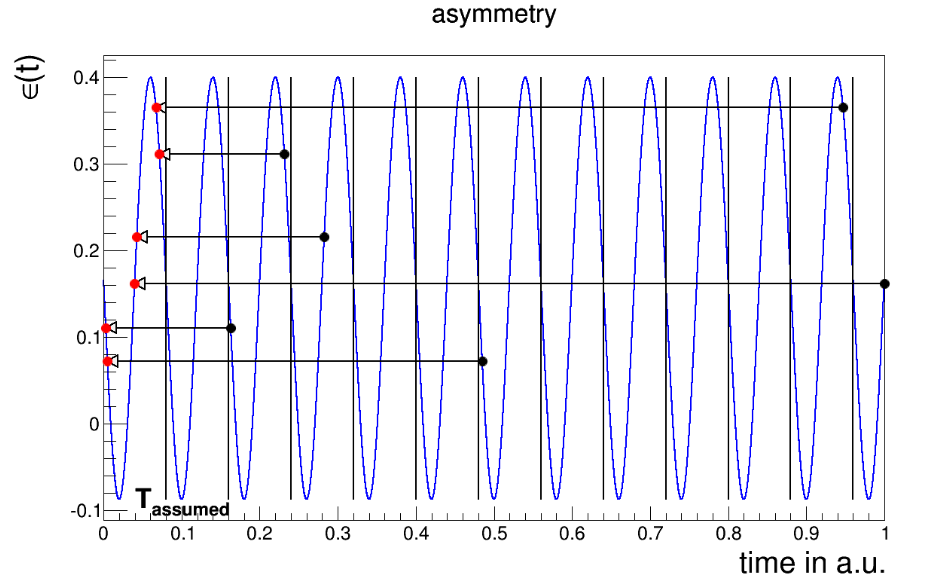



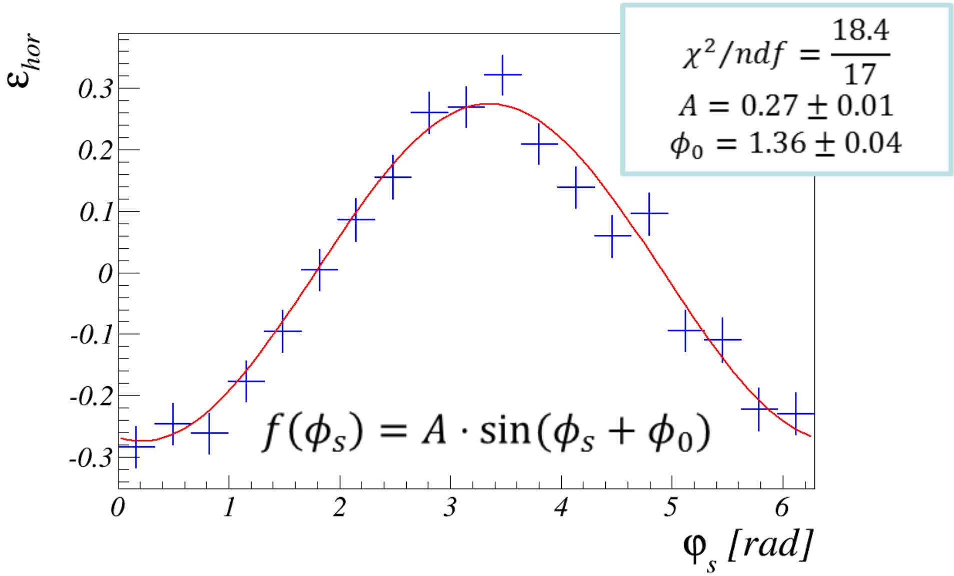
# Event Mapping

Mapping the events:

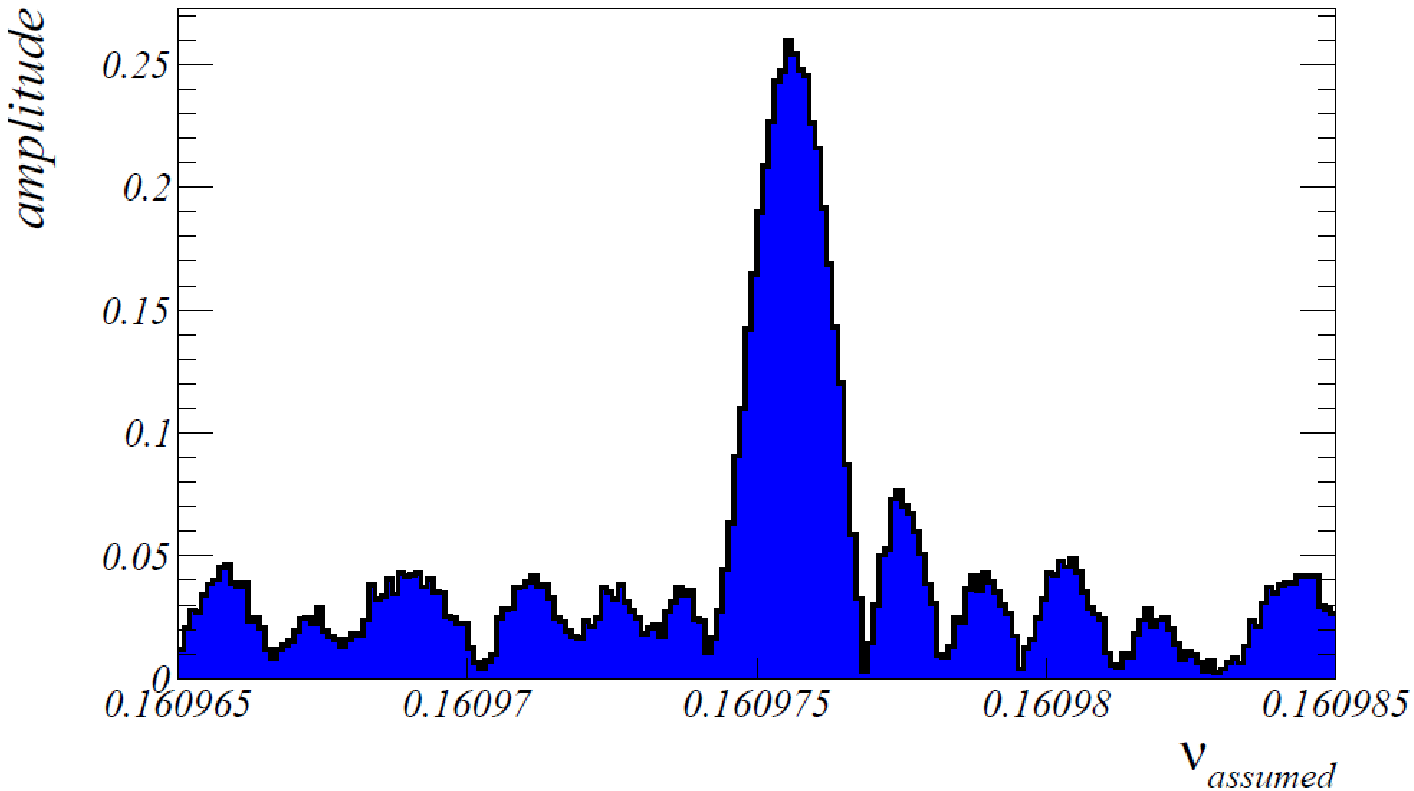
- Assume Spin Tune $\nu_{assumed}$
  - $T_{assumed} = \frac{2\pi}{\nu_{assumed} f_{rev}}$
- Map all events of a macroscopic time interval (2s) in first period:
  - $t' = mod(t, T_{assumed})$
- Fit asymmetry to first period

Extract amplitude $A \propto Polarisation$



# Assumed Spin Tune vs. Amplitude




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

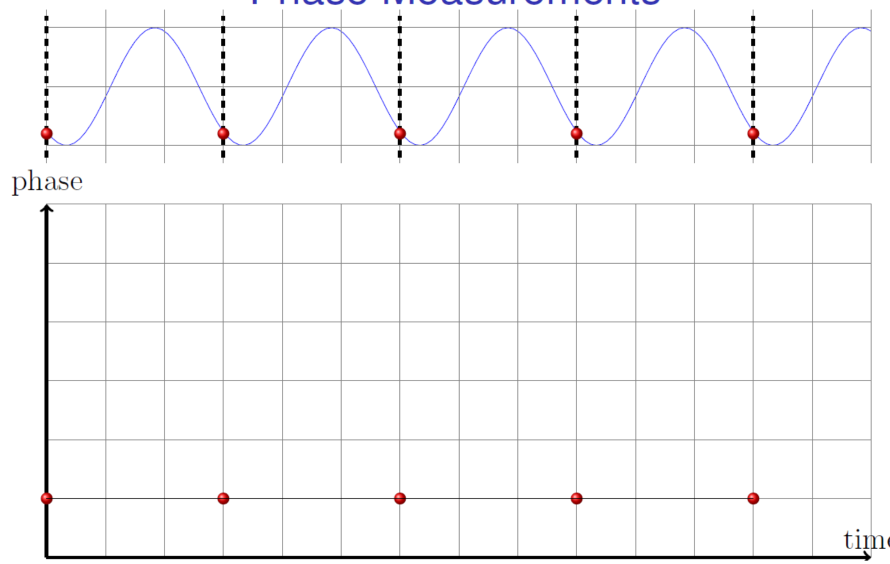
→ $\nu_{max}$ correct spin tune in the macroscopic time intervals of 2sec

- $\nu_{max} = 0.160975 \pm 10^{-6}$ → allows for $\sigma_s \approx 10^{-6}$
- now fix spin tune and observe phase vs. time

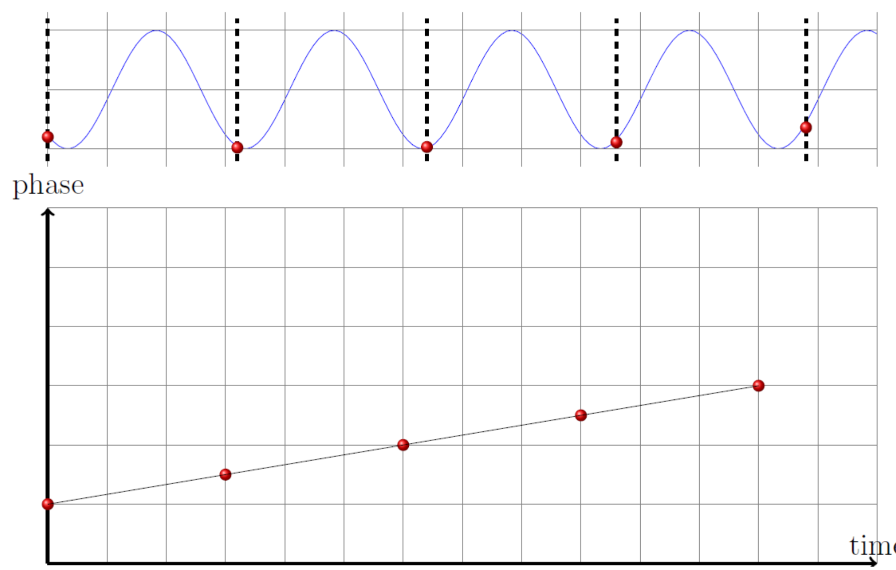
# Spin Phase vs. Time

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

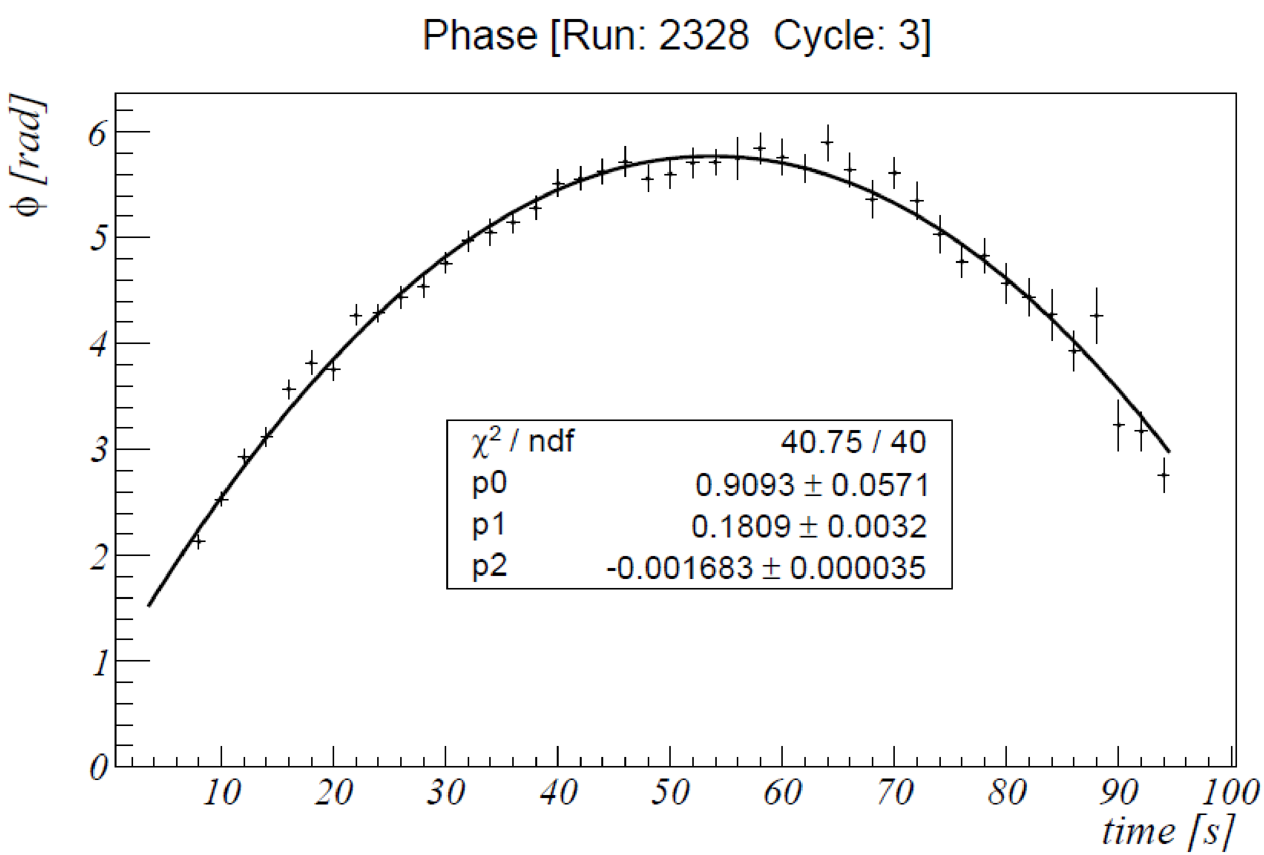
Phase Measurements




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

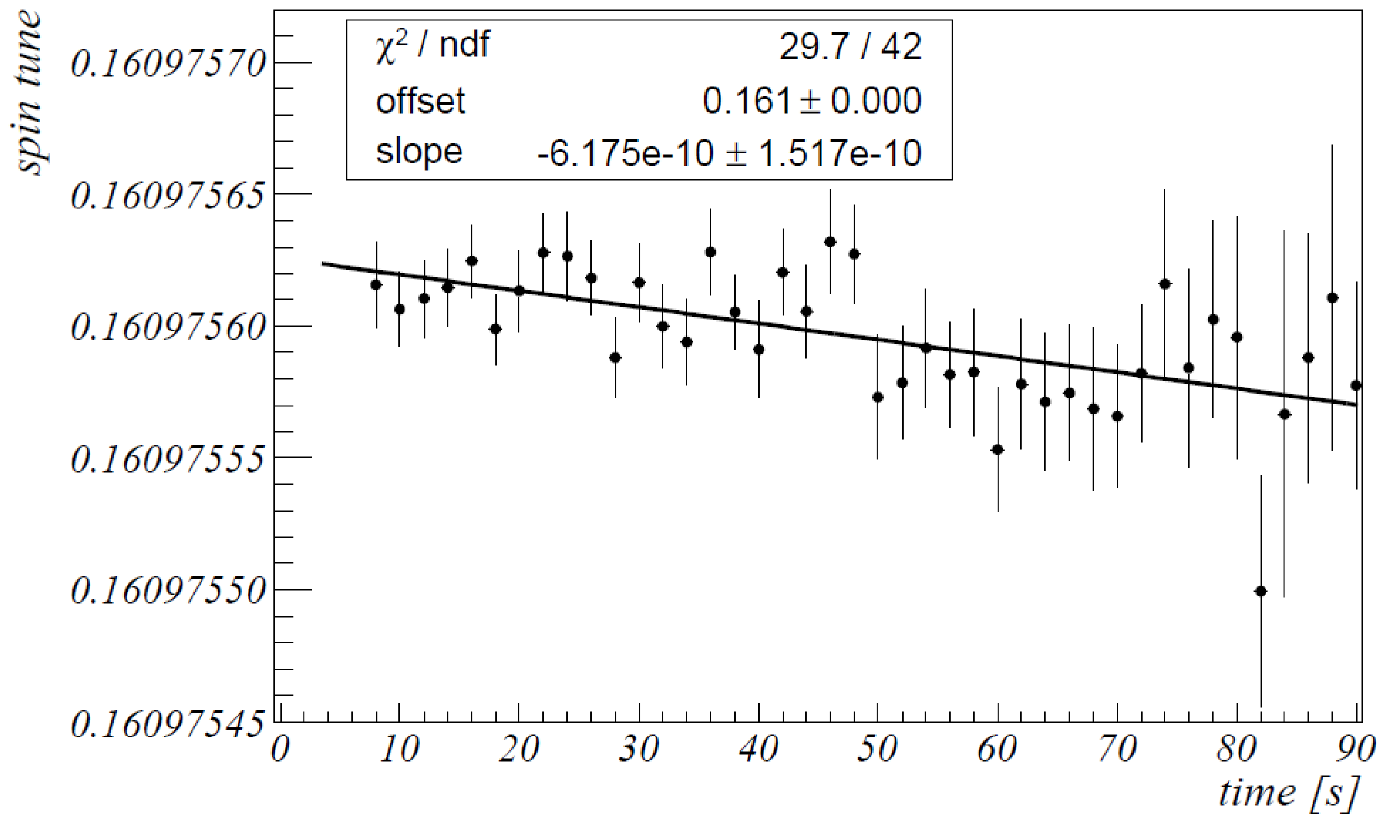


# Spin Phase vs. Time




- 1st derivative gives deviation from assumed spin tune

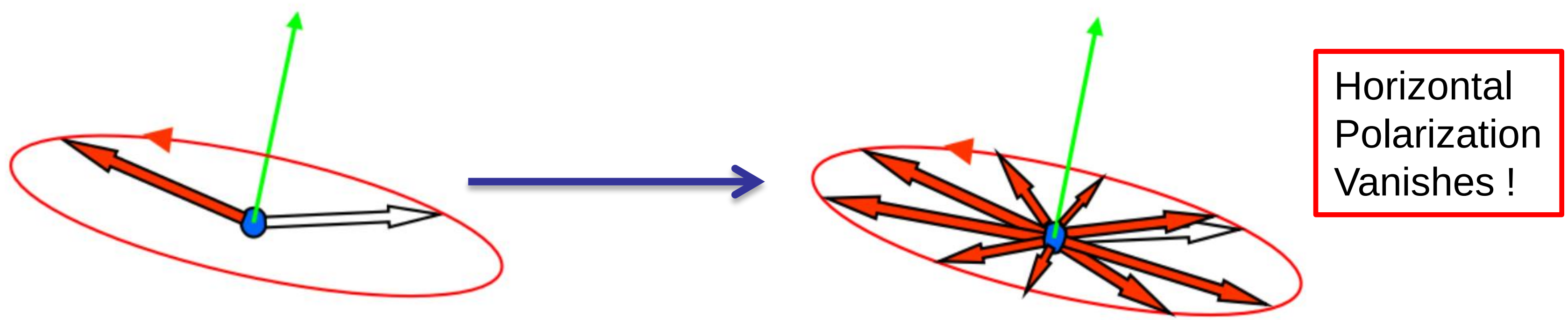
# Spin Tune Measurement




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

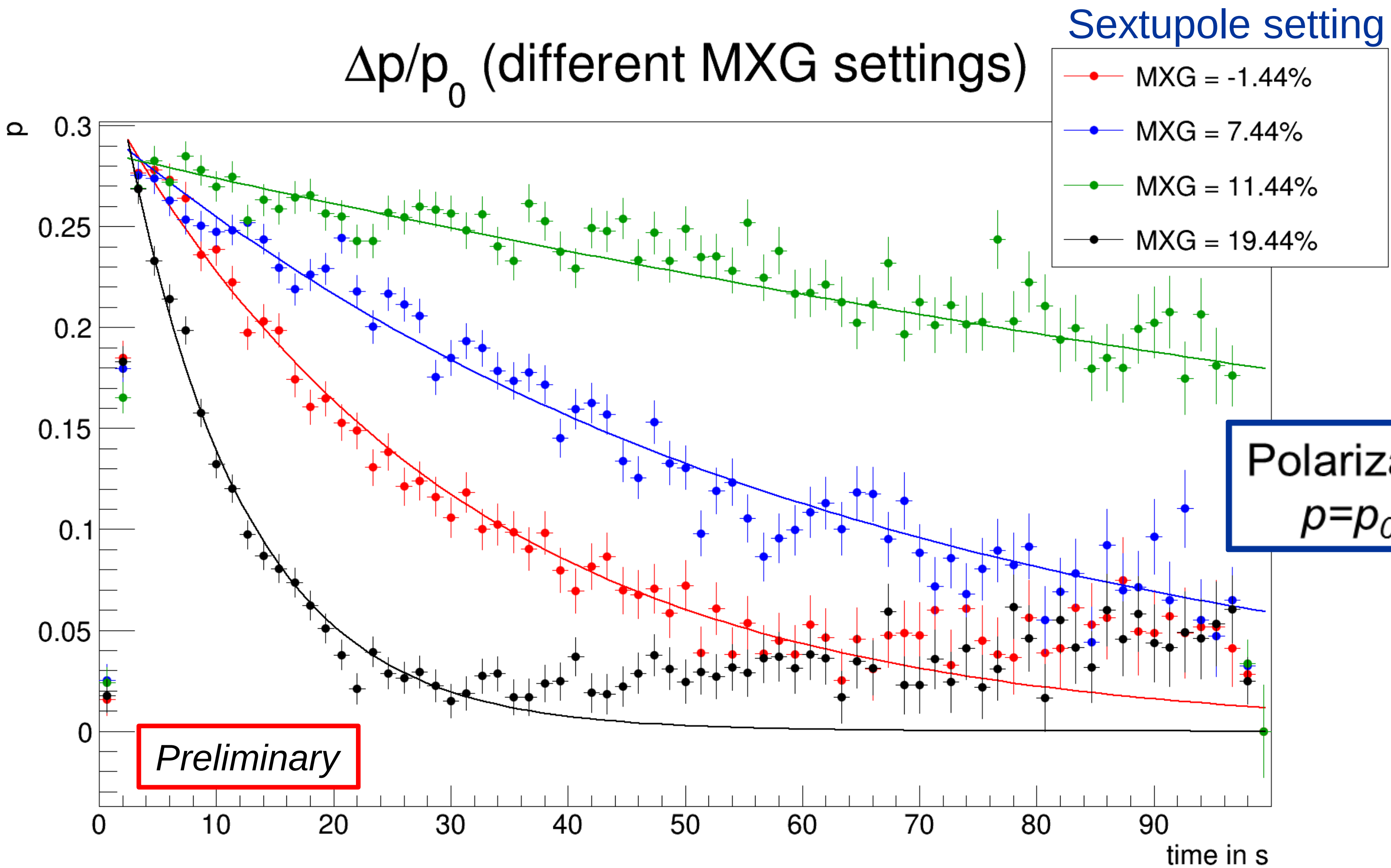
# Spin Coherence Time (SCT)

- 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




- Loss of horizontal polarization ↔ spin decoherence

# Spin Coherence Time (SCT)




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

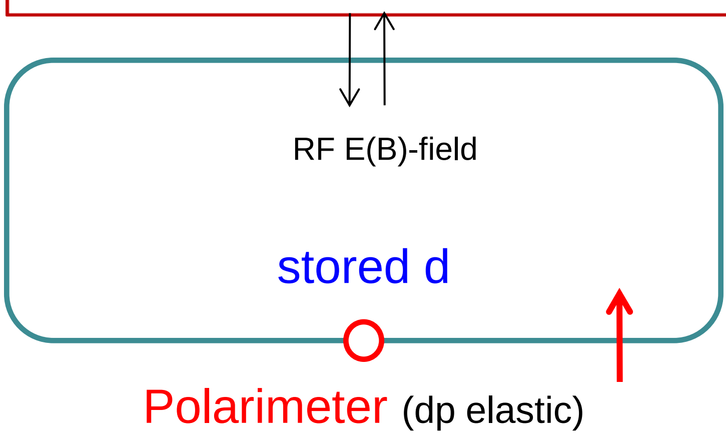
Best Spin Coherence Time: $\tau_{SCT} \approx 400s$

# 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.

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




**In-plane** polarization

**Observable:**
Accumulation of vertical polarization during spin coherence time

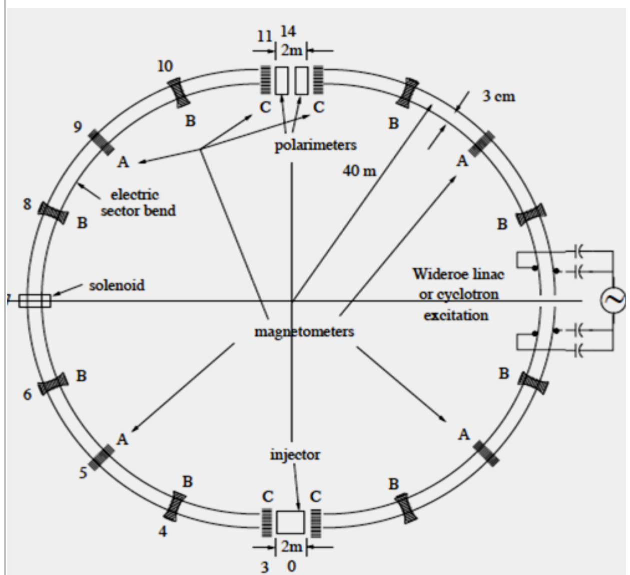
Investigation of sensitivity and systematic limitations

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

# Storage Ring EDM Project

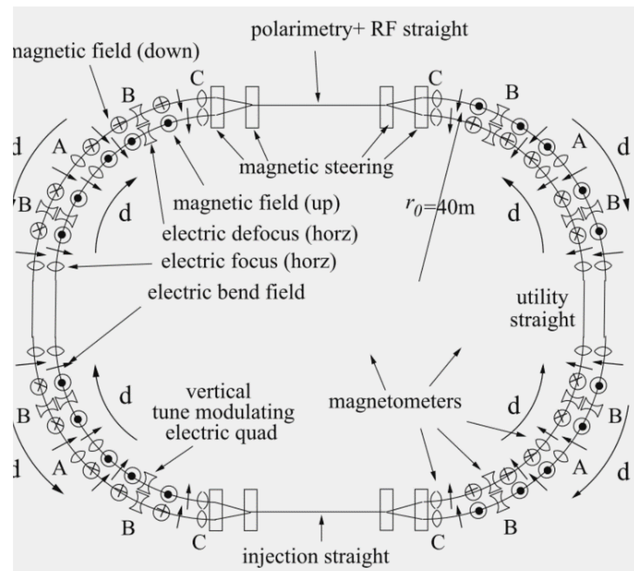
## Options:

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**

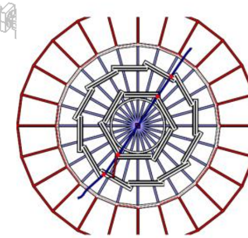
Courtesy R. Talman (Cornell)

# R&D Activities

| R&D Activity | Goal | Place / Status |
|---|---|---|
| Internal Polarimeter | spin as a function of time<br>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<br>64 BPMs, $10^7$ s measurement time<br>→1 pm (stat.) relative position<br>for single and dual beams (CW-CCW) | CW-CCW beams:<br>RHIC IP<br>Single beams:<br>COSY |
| E/B-field Deflector | 17 MV/m 2 cm plate separation,<br>0.15-0.5T | Jülich |
| Spin tracking | Symplectic tracking with RF fields<br>and EDM spin kick | Many places |

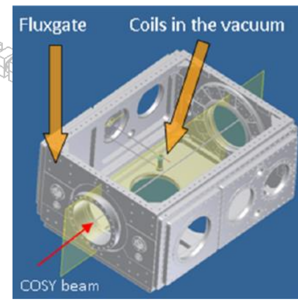
# EDM: Prototyping and Spin Physics

RF ExB Spin Flipper

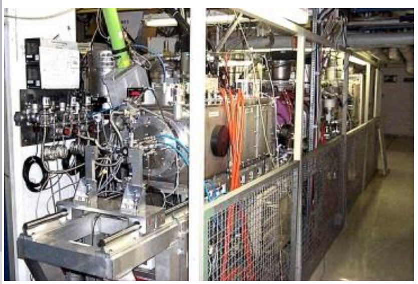


Prototype Polarimeter

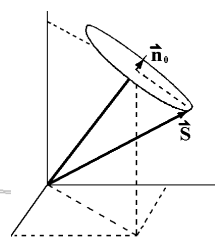
Electrostatic Deflector



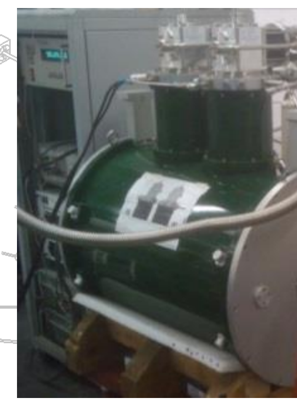

SQUID BPM



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