Mitglied der Helmholtz-Gemeinschaft

Challenges in optics requirement and control of Storage Rings for Precision Measurement of EDM

February 6, 2015 | Andreas Lehrach

RWTH Aachen University & Forschungszentrum Jülich

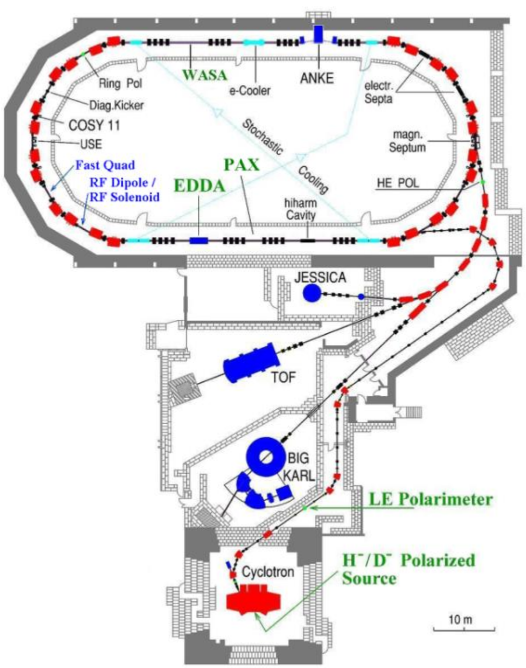
on behalf of the JEDI collaboration

(Jülich Electric Dipole Moment Investigations)

Accelerator Physics at FZ Jülich

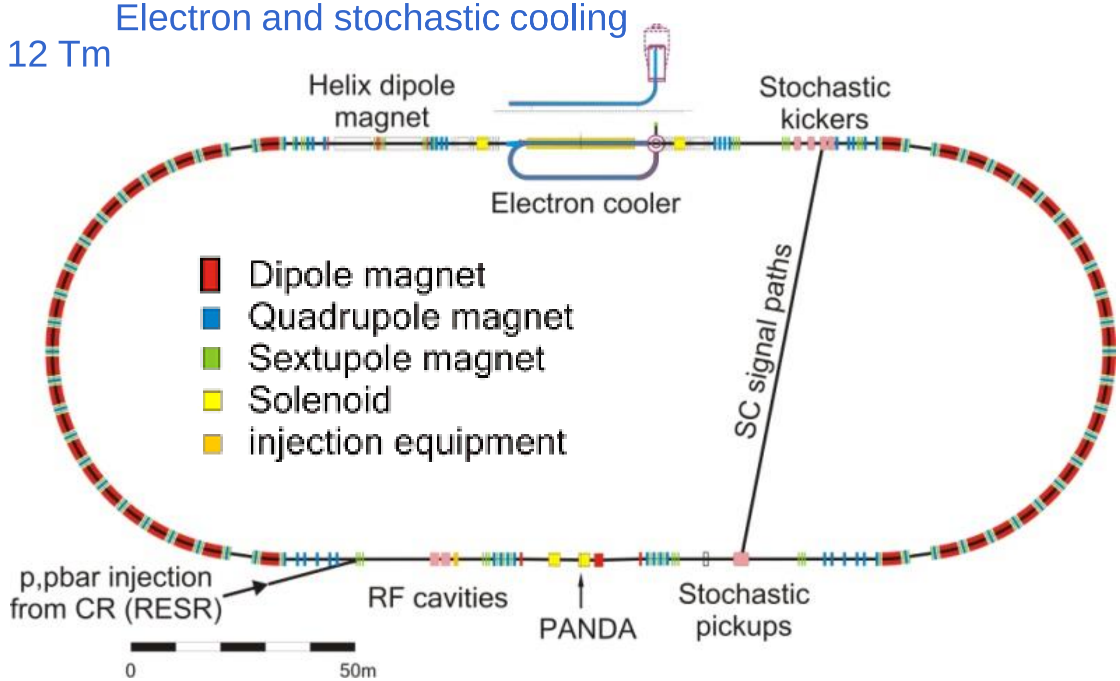
Cooler Synchrotron COSY

Circumference: 183 m, magnetic rigidity 12 Tm
Polarized proton and deuteron beams
Electron and stochastic cooling



High-Energy Storage Ring HESR at FAIR

Circumference: 576 m, magnetic rigidity 50 Tm
Antiproton and ion beams
Electron and stochastic cooling



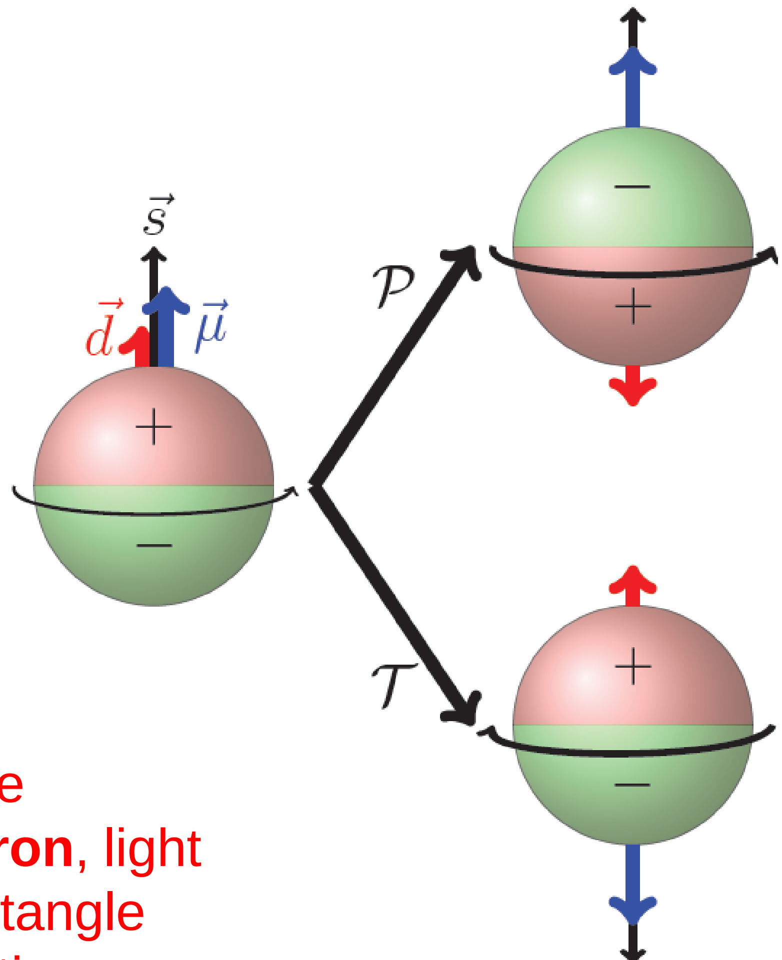
Cooperation with Universities:

COSY Association of Networking Universities (CANU)
COSY F&E program
Jülich-Aachen Research Alliance (JARA-FAME)
Accelerator physics lectures at Aachen and Bonn
Student summer school with Univ. of Bonn, Gießen and Bochum
Bachelor/Master and PhD theses in accelerator physics

Electric Dipole Moments

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

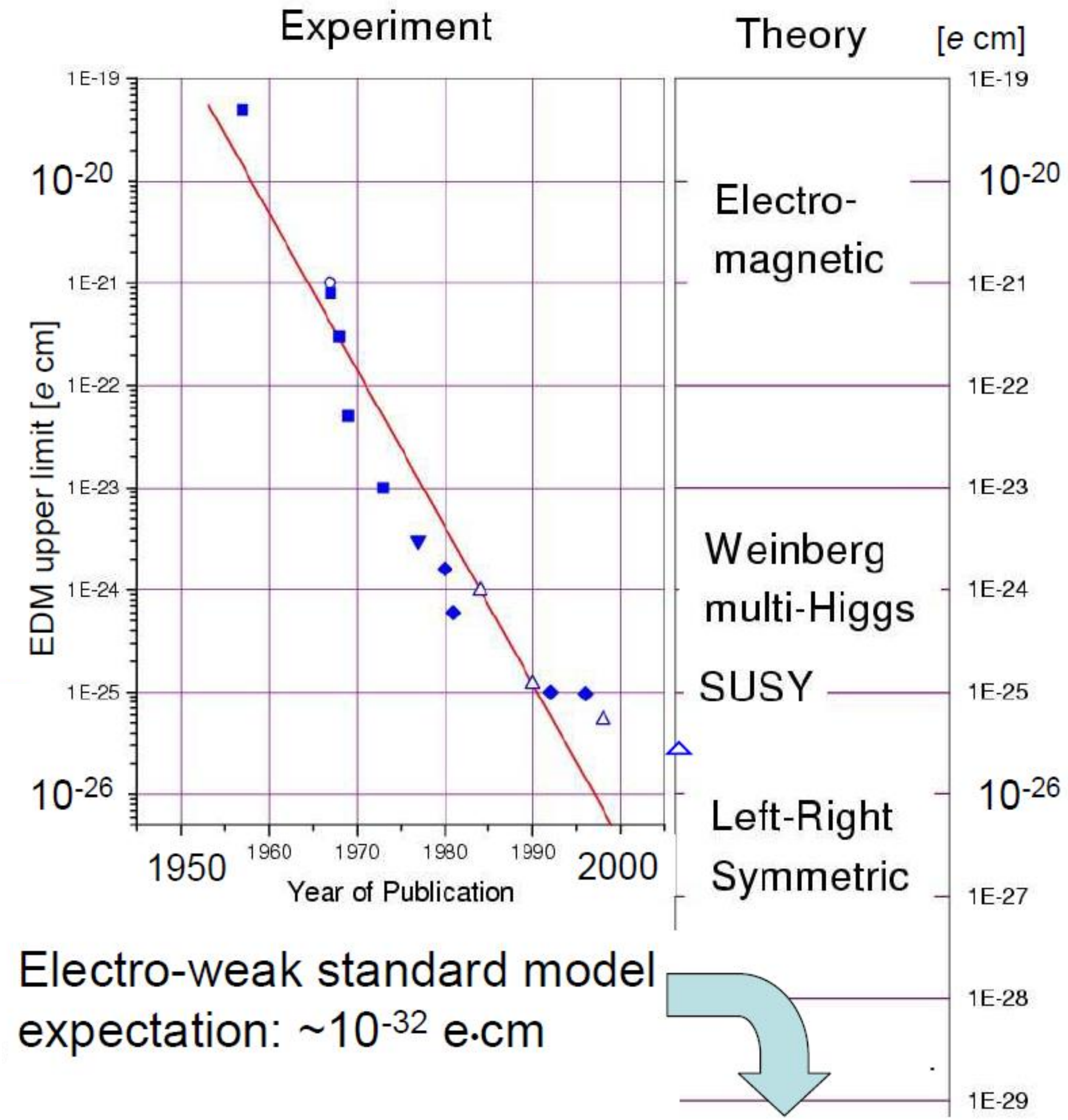
$$
\begin{array}{rrcl}
 & H & = & -\mu\vec{\sigma}\cdot\vec{B}-d\vec{\sigma}\cdot\vec{E} \\
\mathcal{T}: & H & = & -\mu\vec{\sigma}\cdot\vec{B}+d\vec{\sigma}\cdot\vec{E} \\
\mathcal{P}: & H & = & -\mu\vec{\sigma}\cdot\vec{B}+d\vec{\sigma}\cdot\vec{E}
\end{array}
$$



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

History of Neutron EDM Limits



- **Smith, Purcell, Ramsey**
  PR 108, 120 (1957)
- **RAL-Sussex-ILL**
  ($d_n < 2.9 \times 10^{-26}$ *e*·cm)
  PRL 97,131801 (2006)

More than
50 years of effort

Adopted from K. Kirch

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

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:

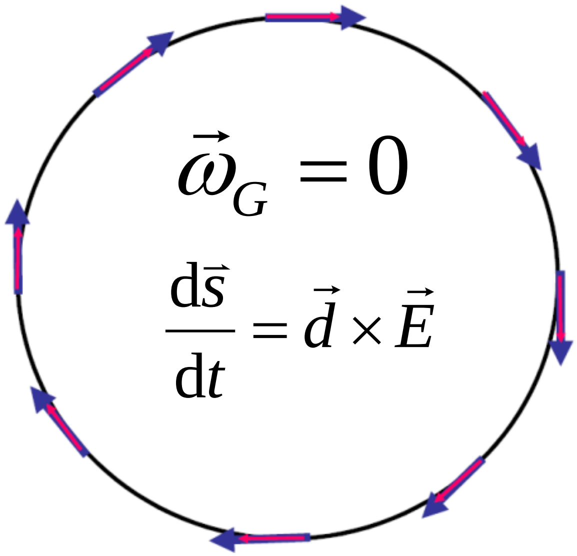
$$\frac{d\vec{S}}{dt}=\vec{\Omega}\times\vec{S}$$

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

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

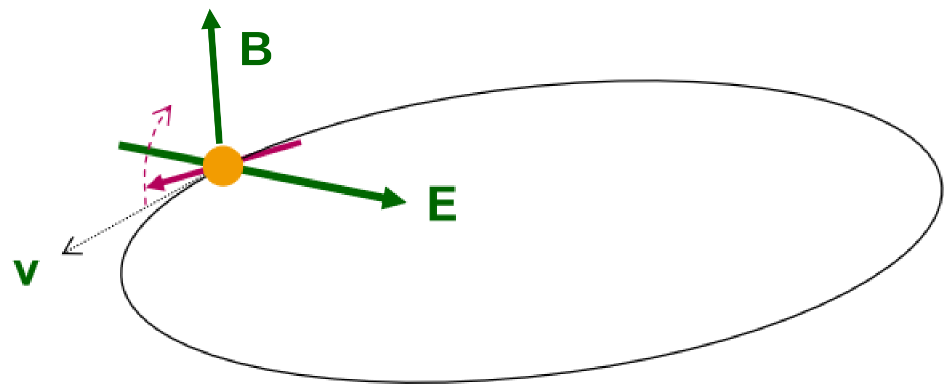
Search for Electric Dipole Moments

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**

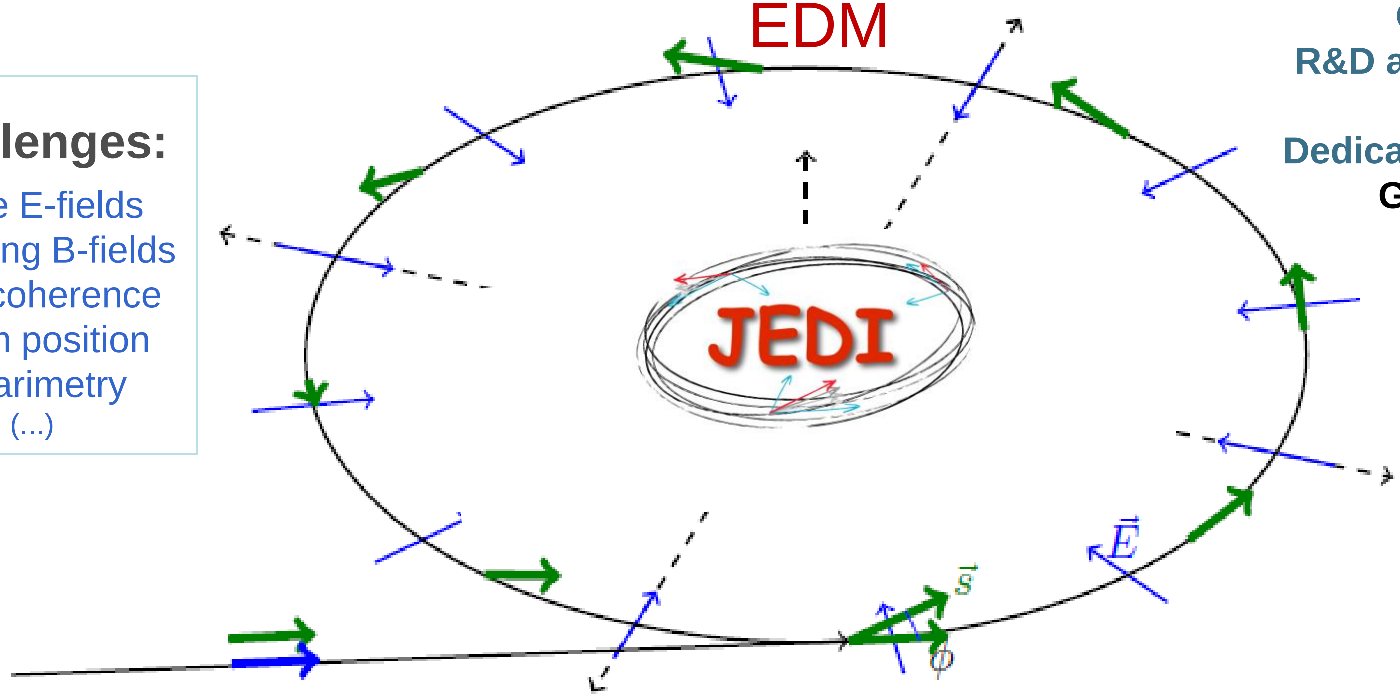
One machine with r ~ 30 m

Storage Ring EDM Project

… measure for buildup of vertical polarization

⇔

EDM



Step wise:

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

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

Challenges:

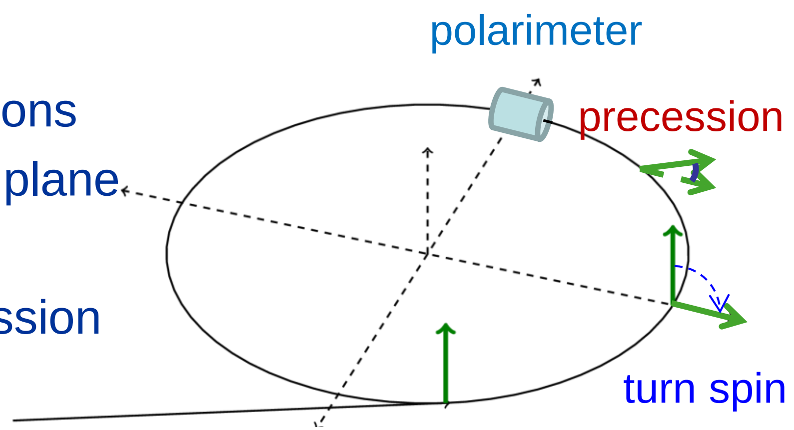
Huge E-fields
Shielding B-fields
Spin coherence
Beam position
Polarimetry
(...)

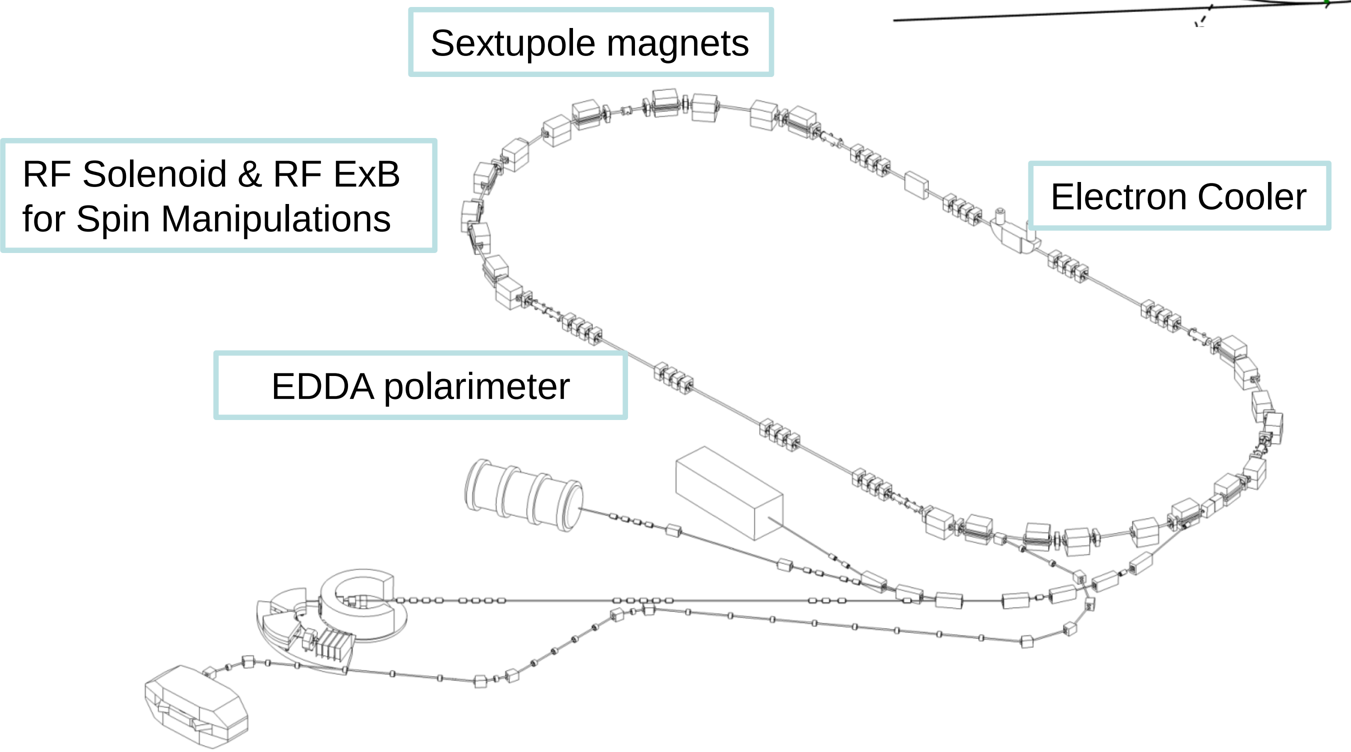
JARA Jülich Aachen Research Alliance

~ 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:

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

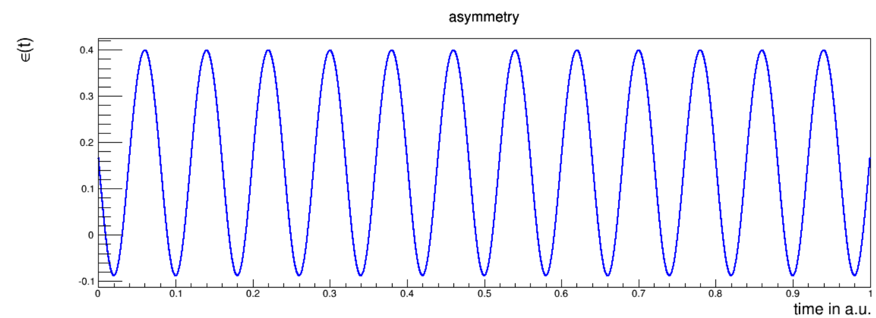
What do we expect ?

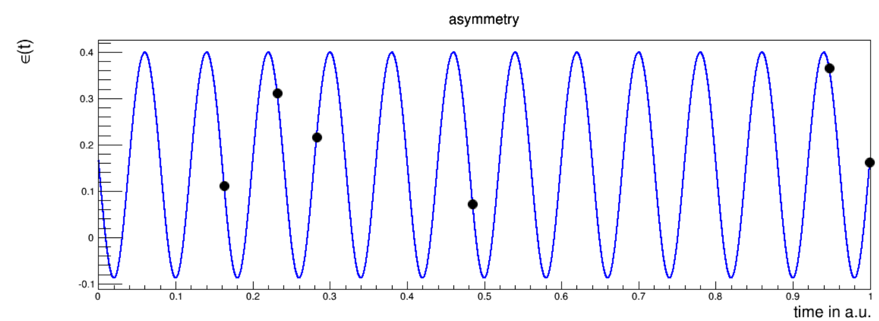
- Deuterons, $p = 0.97\ \text{GeV/c};\ \nu \approx 0.16,\ f_{rev} = 750\ \text{kHz}$
- Spin precession frequency: $\nu \cdot f_{rev} \approx 125\ \text{kHz}$
- Detector rates: $5\ \text{kHz}$
- Only every 25$^{\text{th}}$ spin revolution is detected

→ No direct fit is possible

Time stamp events

Example: every 2$^{\text{nd}}$ spin precession is detected



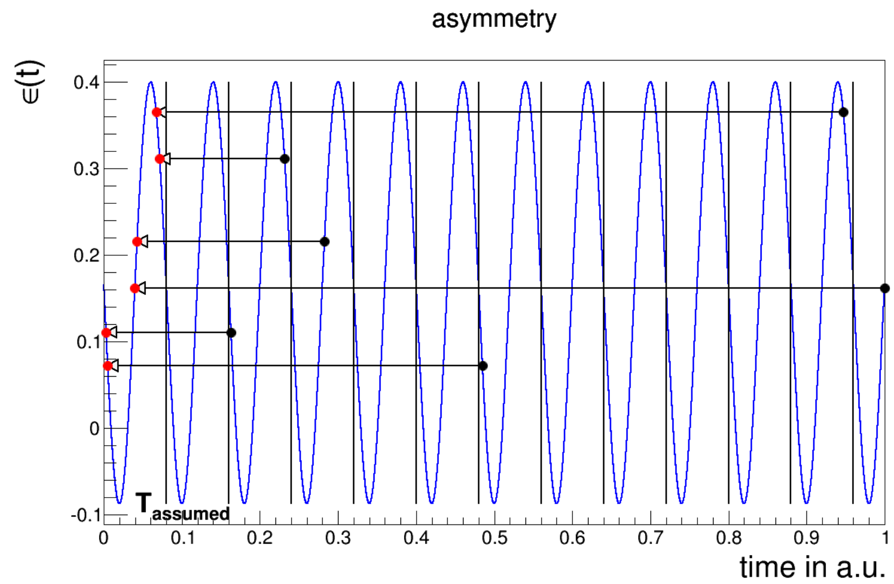


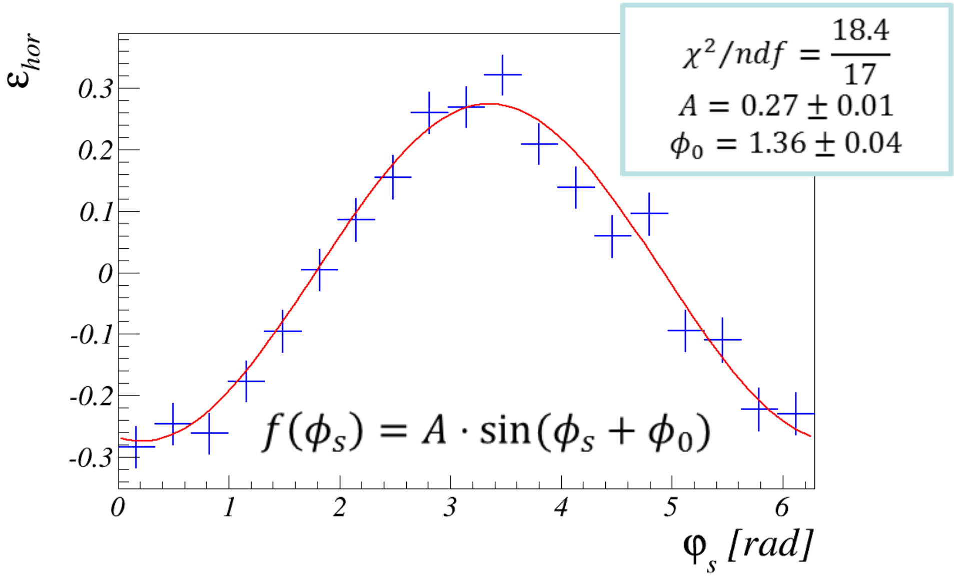
Event Mapping

Mapping the events:

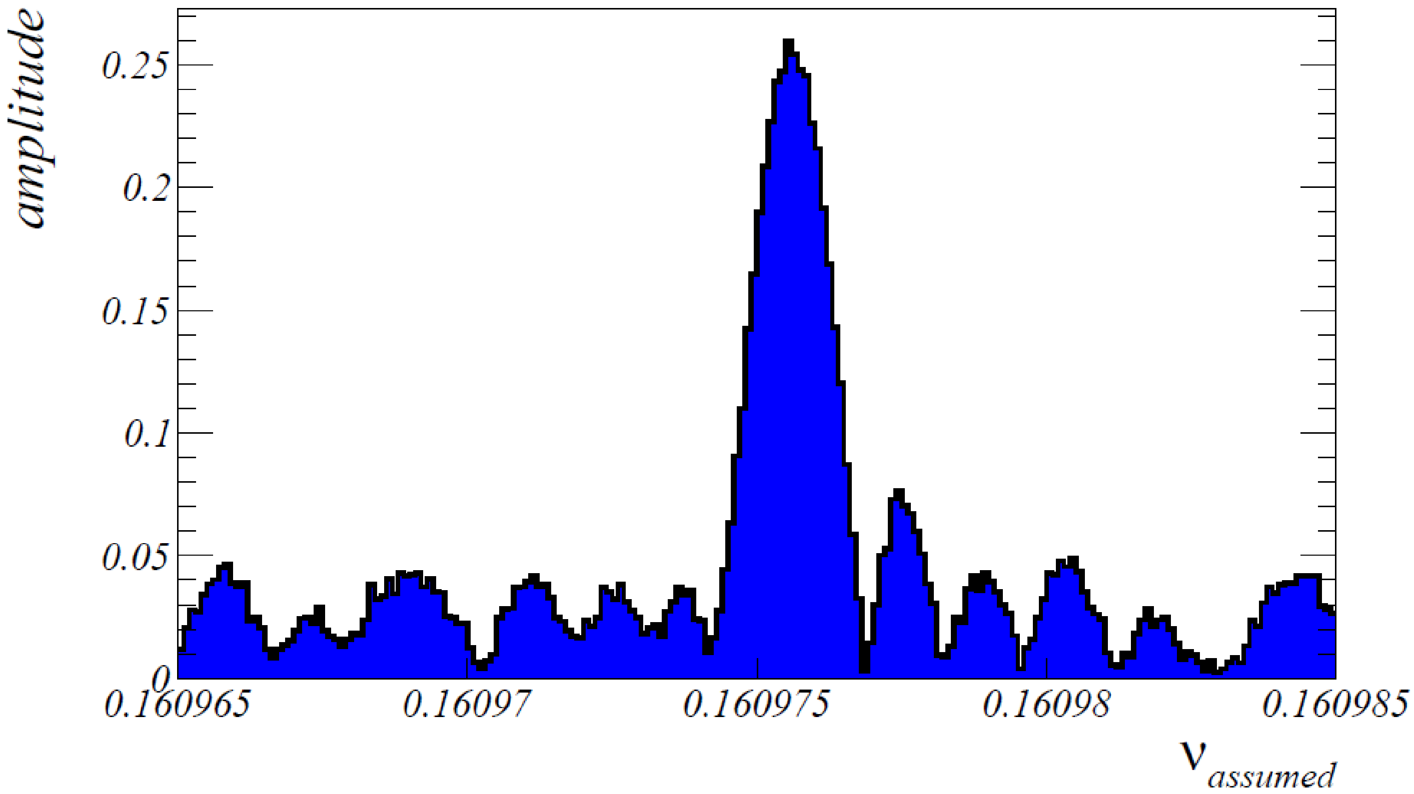
- Assume Spin Tune $\nu_{assumed}$
  - $T_{assumed} = \frac{2\pi}{\nu_{assumed} f_{rev}}$
- Map all events of a macroscopic time interval (2s) in first period:
  - $t' = mod(t, T_{assumed})$
- Fit asymmetry to first period

Extract amplitude $A \propto Polarisation$





Assumed Spin Tune vs. Amplitude

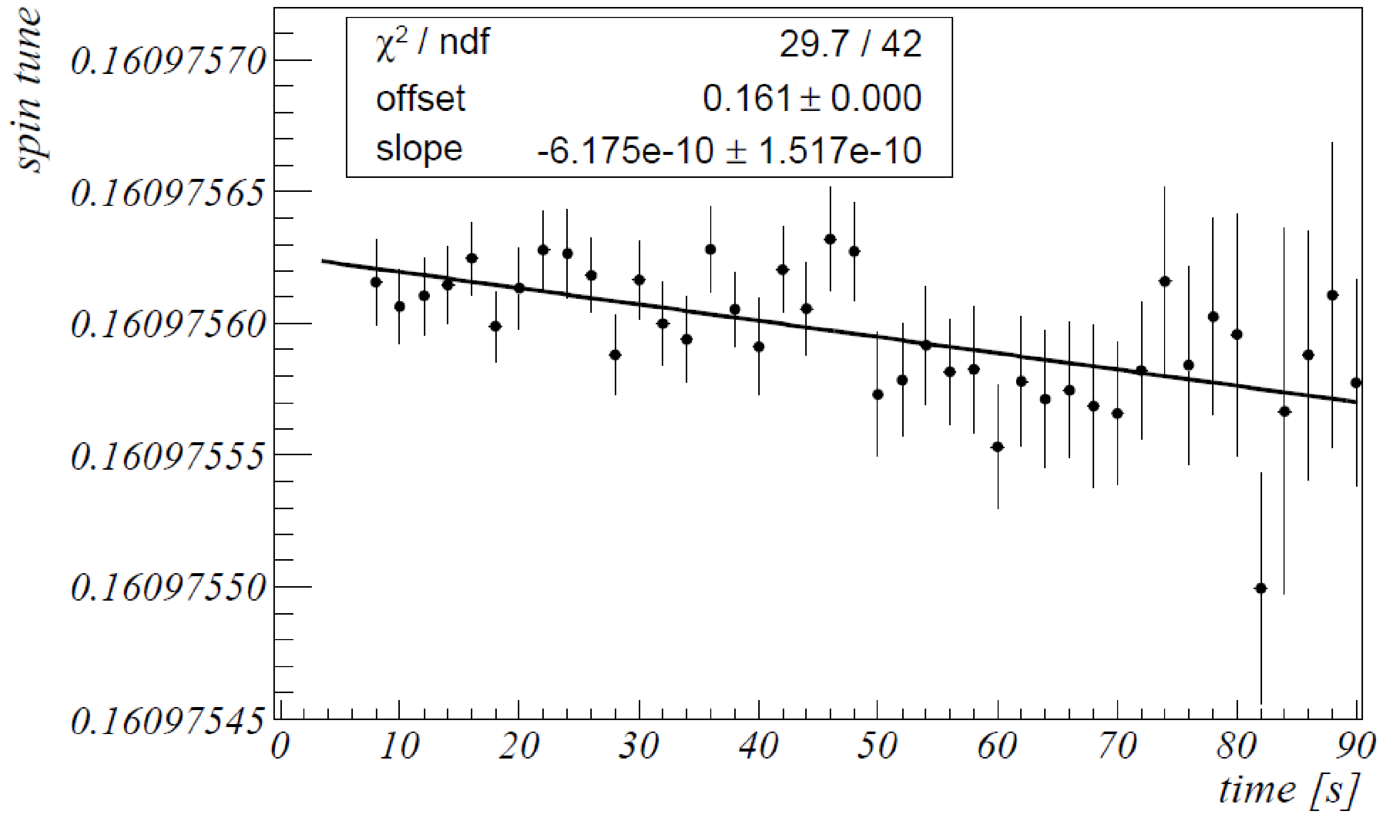


- set $\nu_s = \nu_{max}$ and determine phase in macroscopic time bins of 2s

→ 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

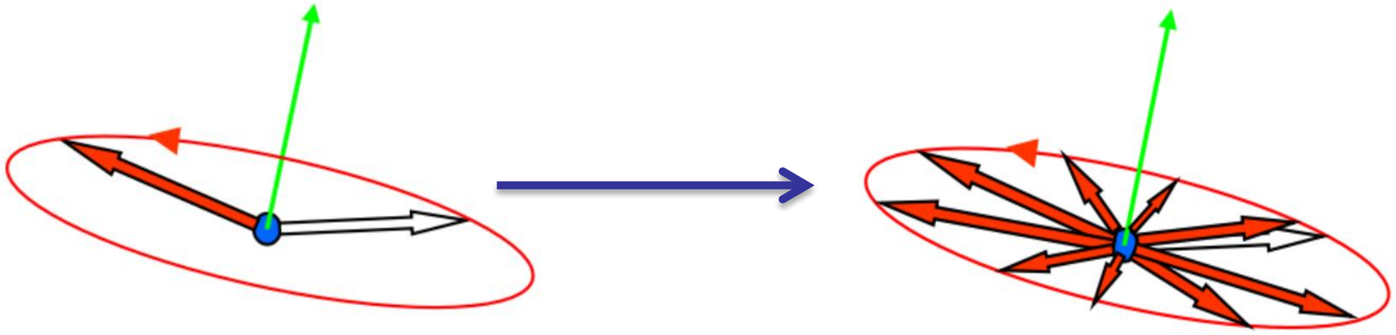
Spin Tune Measurement



- 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)

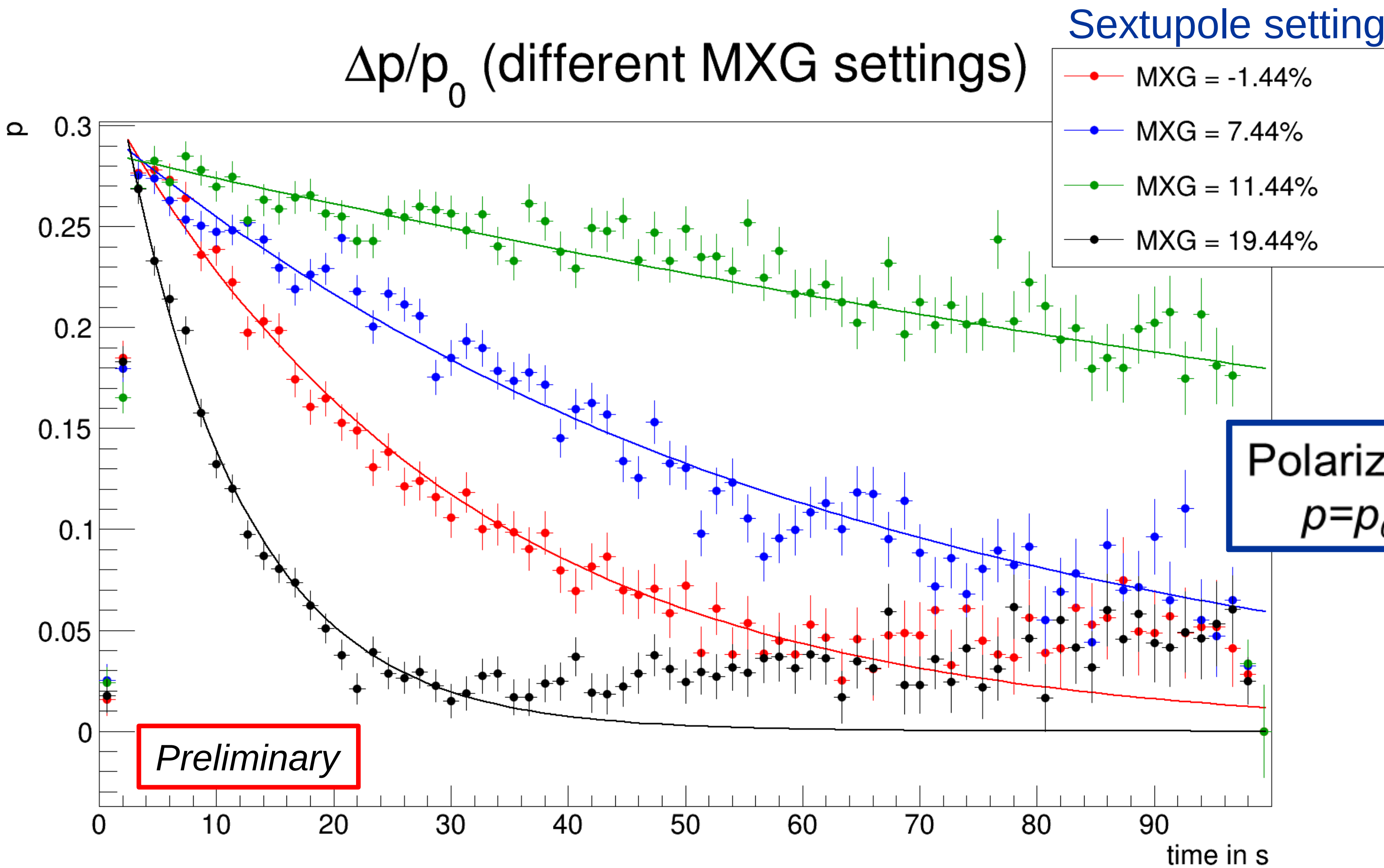
- Statistical sensitivity of EDM proportional to SCT
- Spin precession with $f_s = \gamma G\, f_{ref} \approx 125$ kHz
- Momentum spread leads to different precession frequencies



Horizontal Polarization Vanishes !

- Loss of horizontal polarization ↔ spin decoherence

Spin Coherence Time (SCT)

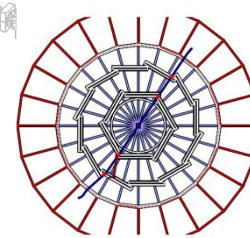


Polarization fit:
$p = p_0 e^{-\tau/\tau_{SCT}}$

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

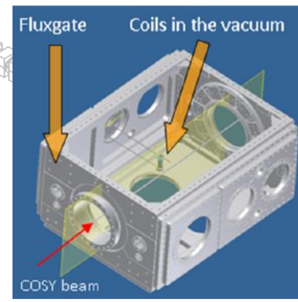
EDM: Prototyping and Spin Physics

RF ExB Spin Flipper

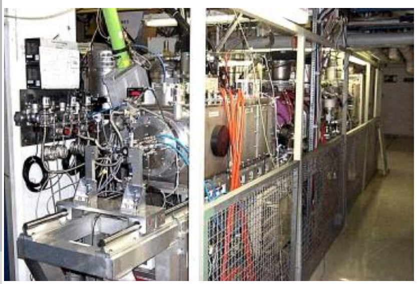


Prototype Polarimeter

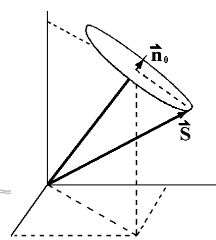
Electrostatic Deflector



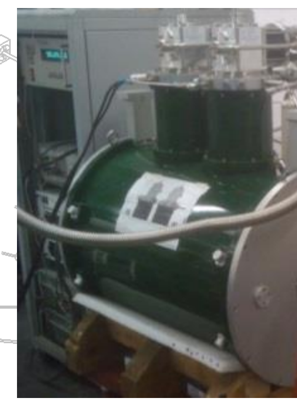
SQUID BPM



Polarized Ion source



Beam and Spin Dynamics



Siberian Snake

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

Optics Requirement and Control

CW/CCW procedure with consecutive beam injections will not perfectly cancel systematic errors:

1. CW/CCW runs are taken at different times (separated by 10^3s)

   → Field stability, ground motion, temperature stability

2. Spatial extent of the beam will be different for CW/CCW

3. Systematic change in E_V when magnetic field is reversed

4. Magnetic field does not reverse perfectly for CW/CCW

Measures:

→ Measure the E-plate alignment and B-fields as a function of time
→ Install active feedback system
→ Measure beam position and profile

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

Trolley Tasks and Goals

- Trolley to measure the E-plate alignment as a function of time, B-fields, and calibrate the pickup electrodes (PE).

- Measuring the E-field plate distance to 10nm (relative alignment)
  Absolute plate alignment with respect to gravity to <1μrad
  → Kerr effect in birefringent crystal and Fabry-Pérot resonator on ESP

- Measuring the magnetic field with NMR and Hall probes

Piezos can be used for nano-positioning the plates.
The plates can be aligned at the $<10^{-7}$ rad level.

Summary and Outlook

Achievements:

- Spin tune measurement with precision of 10^{-10} in a single cycle
- Long spin coherence time of more than 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)