Electric Dipole Moment Measurements at Storage Rings (JEDI project at COSY/Juelich)

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Tbilisi, Georgia, August 2018

Outline

- Symmetries
- Electric Dipole Moments (EDMs)
- EDM Measurements at Storage Rings
  (JEDI project at COSY/Juelich)

Symmetries

Symmetries

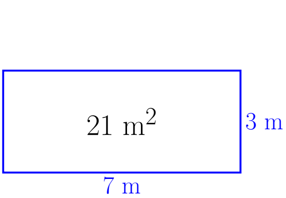
Symmetry: System does **not** change under certain transformations:
rotation, mirror image, translation, ...

Esthetic Reasons

Practical Reasons

A farmer has a fence of 20 m at his disposal.
Task: Build a rectangular enclosure with the largest area.

Solution: The rectangular enclosure with the largest area has also the highest symmetry: **square**

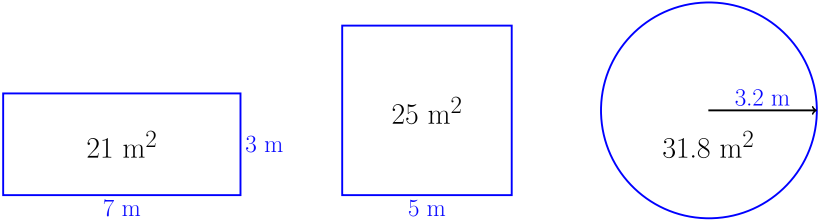


Practical Reasons

A farmer has a fence of 20 m at his disposal.
Task: Build a rectangular enclosure with the largest area.

Solution: The rectangular enclosure with the largest area has also the highest symmetry: **square**

If one drops the constraint of a rectangular shape, one finds even a solution with a larger area and even higher symmetry: **circle**



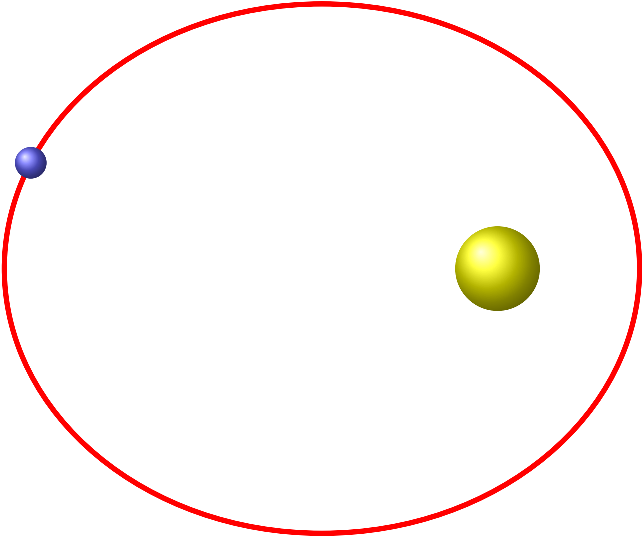
Fundamental Symmetry Transformations in Physics

- **Parity** $\mathcal{P}$ (or a point reflection at the origin)
- **Time Reversal** $\mathcal{T}$ (flip direction of time)
- **Charge Conjugation** $\mathcal{C}$ (Exchange particles with antiparticles)

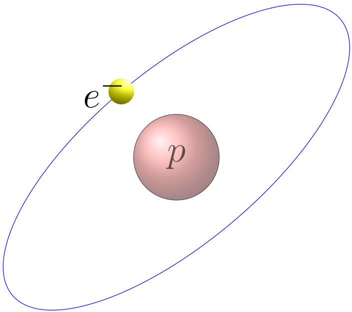
Parity $\mathcal{P}$

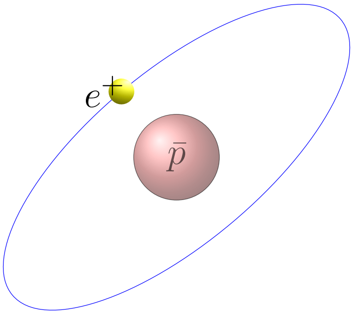
Parity $\mathcal{P}$

Time Reversal $\mathcal{T}$



Charge Conjugation $\mathcal{C}$: Matter–Anti-matter





matter:
exists naturally on earth

anti-matter:
created in laboratory

$\Rightarrow$ huge asymmetry between amount of matter and anti-matter

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For a long time, people believed that physical laws are invariant unter these transformations

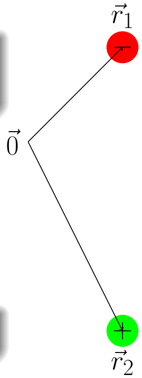
Today we know that all these three symmetries are violated.

Electric Dipole Moments (EDMs)

Electric Dipoles

Classical definition:

$$\vec{d} = \sum_i q_i \vec{r}_i$$

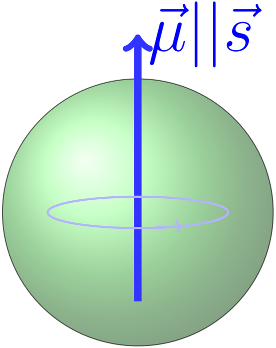


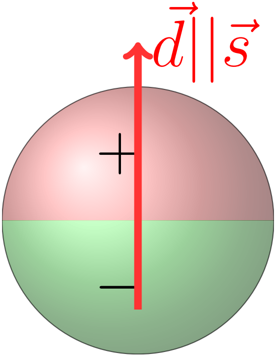
For fundamental particle:

$$\vec{d} = |d|\vec{\hat{s}}$$

EDM must be parallel to **spin** vector $\vec{s}$

Spin, Magnetic and Electric Dipole Moments

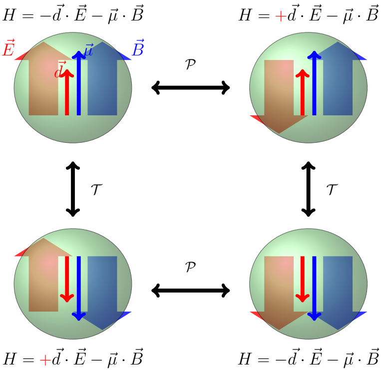




$\mathcal{T}$ and $\mathcal{P}$ violation of EDM

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

$$
\begin{aligned}
& H &=& -\mu\frac{\vec{s}}{s}\cdot\vec{B}-d\frac{\vec{s}}{s}\cdot\vec{E} \\
\mathcal{T}: \quad & H &=& -\mu\frac{\vec{s}}{s}\cdot\vec{B}+d\frac{\vec{s}}{s}\cdot\vec{E} \\
\mathcal{P}: \quad & H &=& -\mu\frac{\vec{s}}{s}\cdot\vec{B}+d\frac{\vec{s}}{s}\cdot\vec{E}
\end{aligned}
$$



$\Rightarrow$ EDM measurement tests violation of fundamental symmetries $\mathcal{P}$ and $\mathcal{T}(\stackrel{\mathcal{CPT}}{=}\mathcal{CP})$

Symmetries in Standard Model

	electro-mag.	weak	strong
$\mathcal{C}$	$\checkmark$	$\lightning$	$\checkmark$
$\mathcal{P}$	$\checkmark$	$\lightning$	$(\checkmark)$
$\mathcal{T} \overset{CPT}{\rightarrow} \mathcal{CP}$	$\checkmark$	$(\lightning)$	$(\checkmark)$

- $\mathcal{C}$ and $\mathcal{P}$ are maximally violated in weak interactions (Lee, Yang, Wu)
- $\mathcal{CP}$ violation discovered in kaon decays (Cronin,Fitch) described by CKM-matrix in Standard Model
- $\mathcal{CP}$ violation allowed in strong interaction but corresponding parameter $\theta_{QCD} \lessapprox 10^{-10}$ (strong $\mathcal{CP}$-problem)

$\mathcal{CP}-$Violation and connection to EDMs

Standard Model	
Weak interaction	
CKM matrix	$\rightarrow$ unobservably small EDMs
Strong interaction	
θ_{QCD}	$\rightarrow$ best limit from neutron EDM
beyond Standard Model	
e.g. SUSY	$\rightarrow$ accessible by EDM measurements

Connection to Cosmology: Matter-Antimatter Asymmetry

Excess of matter in the universe:

	observed	SCM* prediction
$\eta = \dfrac{n_B - n_{\bar{B}}}{n_\gamma}$	$\mathbf{6 \times 10^{-10}}$	$\mathbf{10^{-18}}$

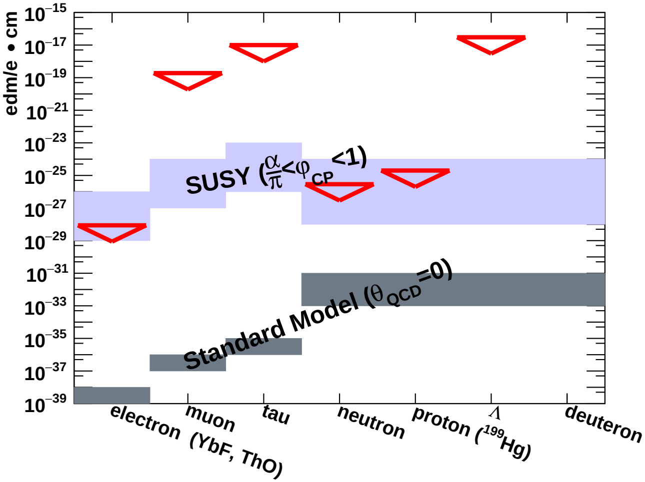
Sakharov (1967): $\mathcal{CP}$ violation needed for baryogenesis

$\Rightarrow$ New $\mathcal{CP}$ violating sources beyond SM needed to explain this discrepancy

They could show up in EDMs of elementary particles

* SCM: Standard Cosmological Model

EDM: Current Upper Limits



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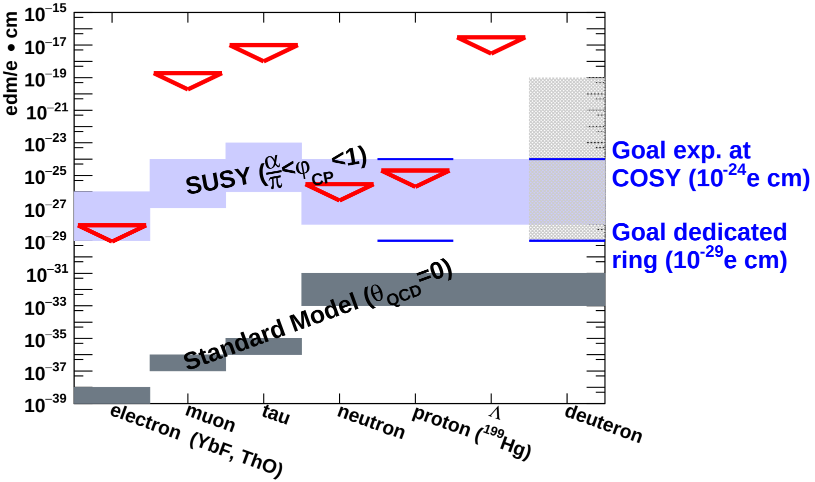
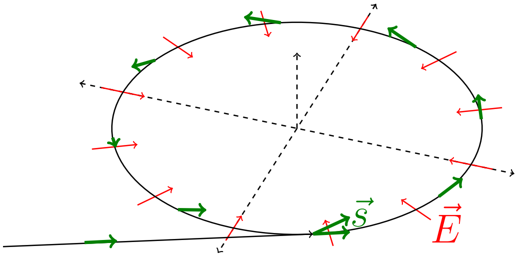


FZ Jülich: EDMs of **charged** hadrons: p, d, ^{3}He

How to measure charged particle EDMs?

Experimental Method: Generic Idea

For **all** EDM experiments (neutron, proton, atoms, . . .):
  Interaction of $\vec{d}$ with electric field $\vec{E}$
For charged particles: apply electric field in a storage ring:



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

In general:

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

build-up of vertical polarization $s_\perp \propto |d|$

Spin Precession: Thomas-BMT Equation

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\Omega} \times \vec{s} = \frac{-q}{m}\left[G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E} + \frac{\eta}{2}(\vec{E} + \vec{v} \times \vec{B})\right] \times \vec{s}$$

$$\vec{d} = \eta \frac{q}{2m}\vec{s}\,, \quad \vec{\mu} = 2(G+1)\frac{q}{2m}\vec{s}$$

BMT: Bargmann, Michel, Telegdi

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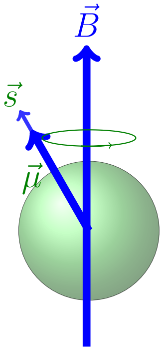

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	☺	☹
1.) pure electric ring	no $\vec{B}$ field needed, CW/CCW beams simultaneously	works only for particles with $G > 0$ (e.g. p)
2.) combined ring	works for p, d, ^{3}He, ...	both $\vec{E}$ and $\vec{B}$ required
3.) pure magnetic ring	existing (upgraded) COSY ring can be used, shorter time scale	lower sensitivity, precession due to G, i.e. no **frozen spin**

$$\vec{d} = \eta \frac{q}{2m}\vec{s}\,, \quad \vec{\mu} = 2(G+1)\frac{q}{2m}\vec{s}$$

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Different Options

- Plans for a dedicated ring:
  CPEDM collaboration (CERN,JEDI,Korea, . . .)
- First measurement with existing magnetic ring COSY at FZ Jülich

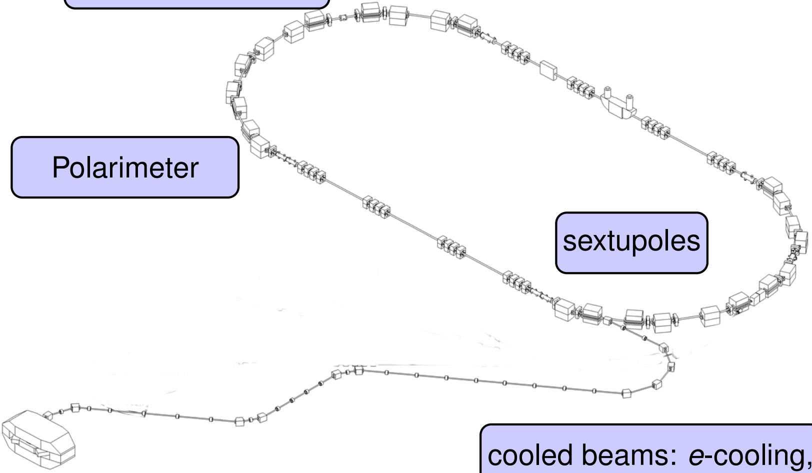
JEDI = **J**ülich **E**lectric **D**ipole Moment

JEDI Project at COSY/Jülich

Cooler Synchrotron COSY

COSY provides (polarized) protons and deuterons with
$p = 0.3 - 3.7\mathrm{GeV}/c$
$\Rightarrow$ **Ideal starting point for charged hadron EDM searches**

COSY



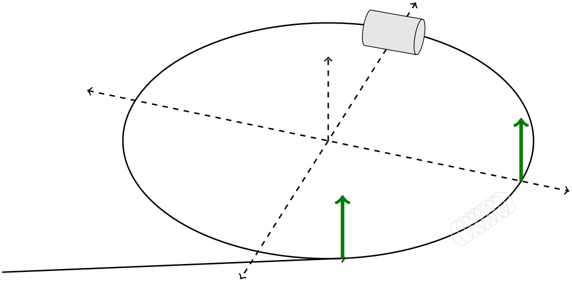
RF $E \times B$ dipole
RF solenoid
Polarimeter
sextupoles
cooled beams: e-cooling, stochastic cooling
Polarized proton & deuterons

Running Conditions

COSY circumference	183 m
deuteron momentum	0.970 GeV/c
$\beta(\gamma)$	0.459 (1.126)
magnetic anomaly G	≈ -0.143
revolution frequency f_{rev}	752543 Hz
cycle length	100-1500 s
nb. of stored particles/cycle	$\approx 10^9$
event rate at $t = 0$	$5000\,\mathrm{s}^{-1}$

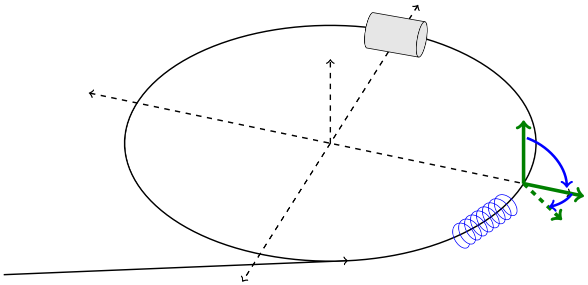
Experimental Setup at COSY

- Inject and accelerate vertically polarized deuterons to $p \approx 1$ GeV/c



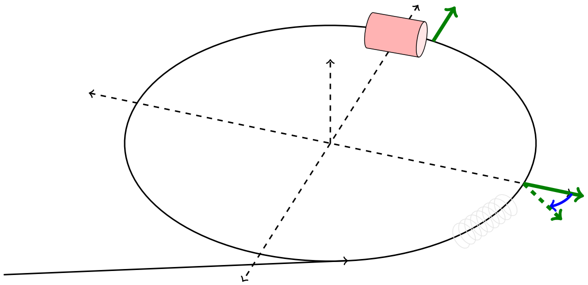
Experimental Setup at COSY

- Inject and accelerate vertically polarized deuterons to $p \approx 1$ GeV/c
- flip polarization with help of solenoid into horizontal plane, precession starts



Experimental Setup at COSY

- Inject and accelerate vertically polarized deuterons to $p \approx 1$ GeV/c
- flip polarization with help of solenoid into horizontal plane, precession starts
- Extract beam slowly (in $\approx 100\,$s) on target
- Measure asymmetry and determine spin precession

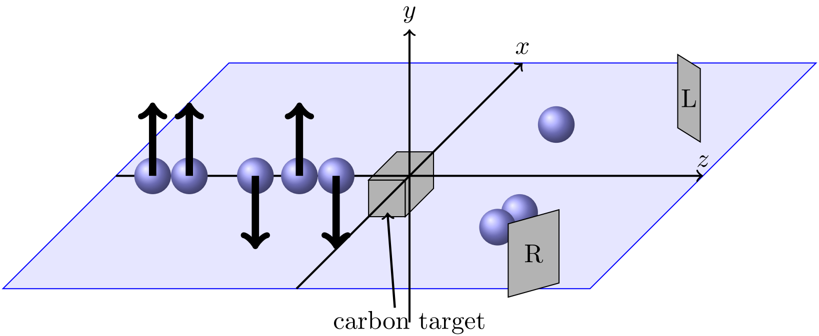


Polarimeter

serves to determine polarisation vector

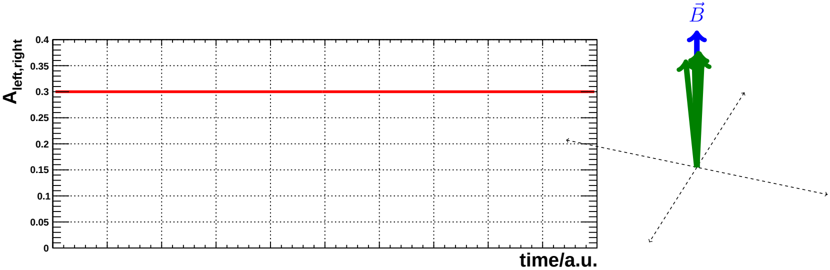
Experimentally: Measure asymmetry of scattered particles: e.g.

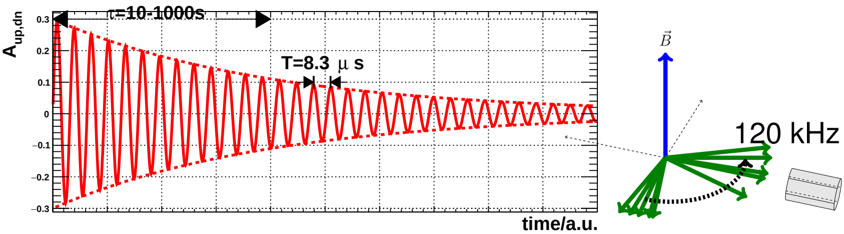
$$P_{\text{vertical}} \propto A_{left,right} = \frac{N_{\text{left}} - N_{\text{right}}}{N_{\text{left}} + N_{\text{right}}} \propto d$$



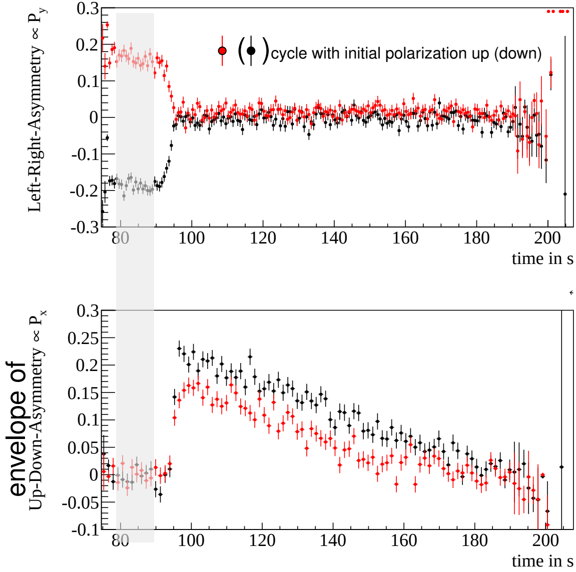
see also talks by I. Keshelashvili, D. Mchedlishvili, F. Müller, D. Shergelachvili, O. Javakhishvili

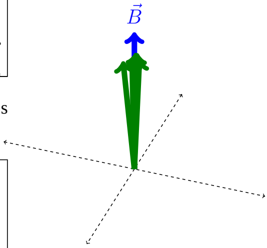
Asymmetries





Polarization Flip





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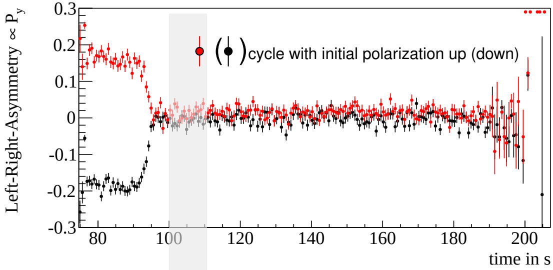

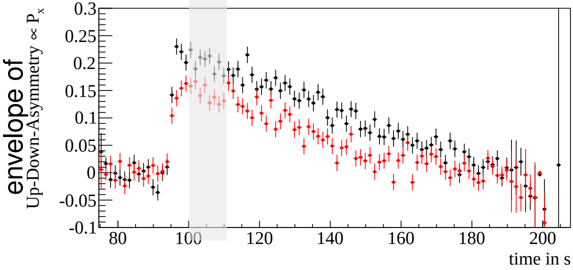

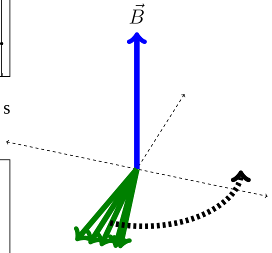

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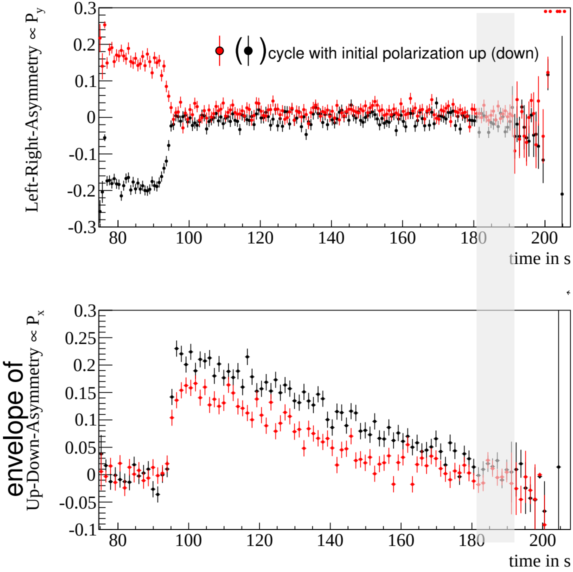
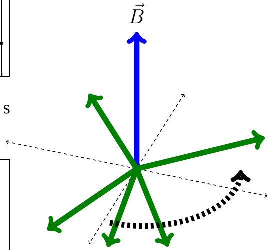
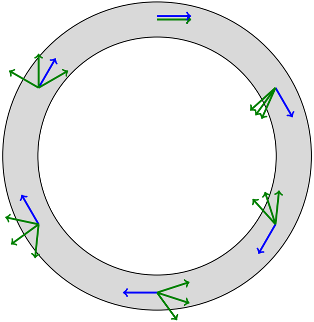
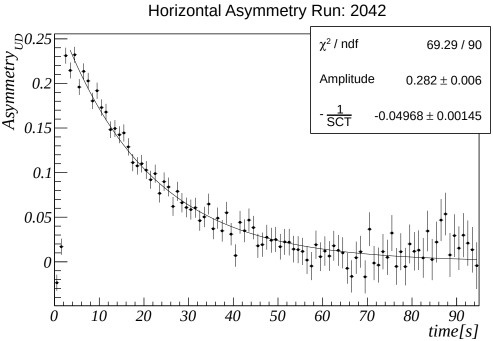




Results: Spin Coherence Time (SCT)

Short Spin Coherence Time





unbunched beam

$\Delta p/p = 10^{-5} \Rightarrow \Delta\gamma/\gamma = 2 \cdot 10^{-6}$, $T_{rev} \approx 10^{-6}$ s

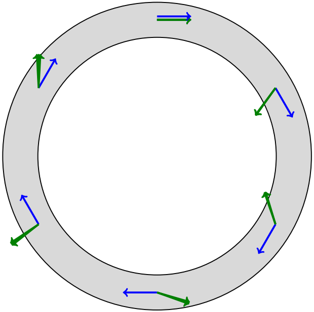
$\Rightarrow$ decoherence after < 1 s

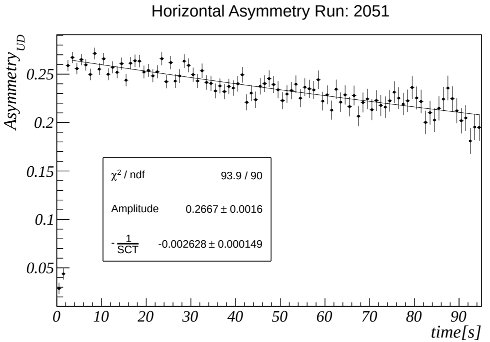
bunched beam eliminates 1st order effects in $\Delta p/p$

$\Rightarrow$ SCT τ = 20 s

Results: Spin Coherence Time (SCT)

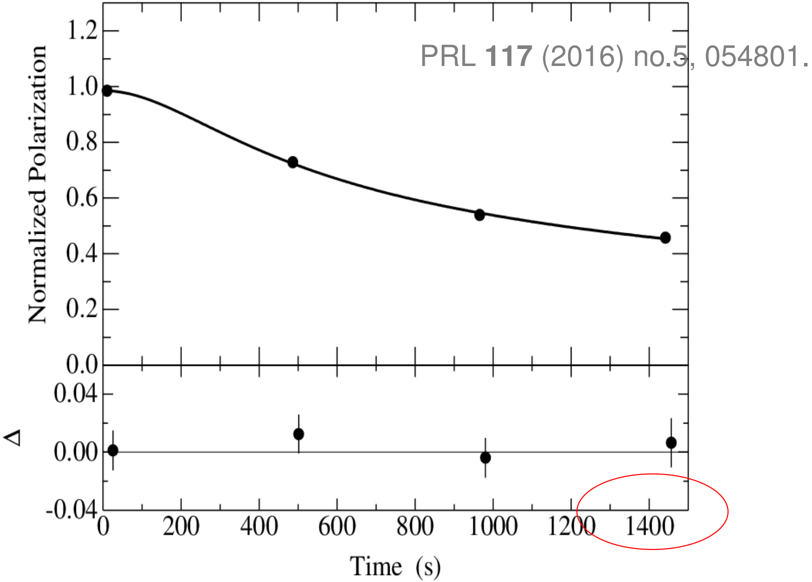
Long Spin Coherence Time





SCT of τ =400 s, after correction with sextupoles (chromaticities $\xi \approx 0$)

SCT: Longer Cycles



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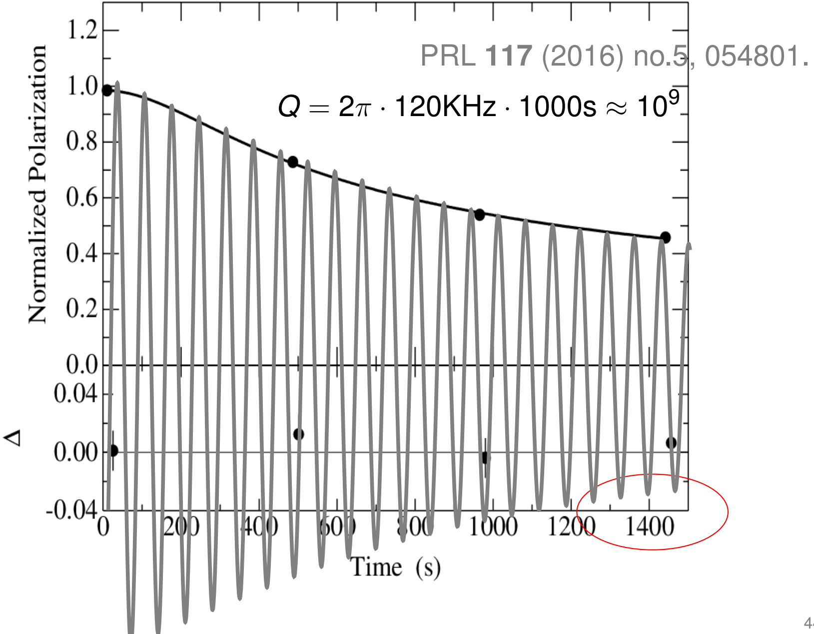

Activities at COSY

- required for first EDM measurement:
  - maximize spin coherence time (SCT)
  - precise measurement of spin precession (spin tune)
  - polarization feed back
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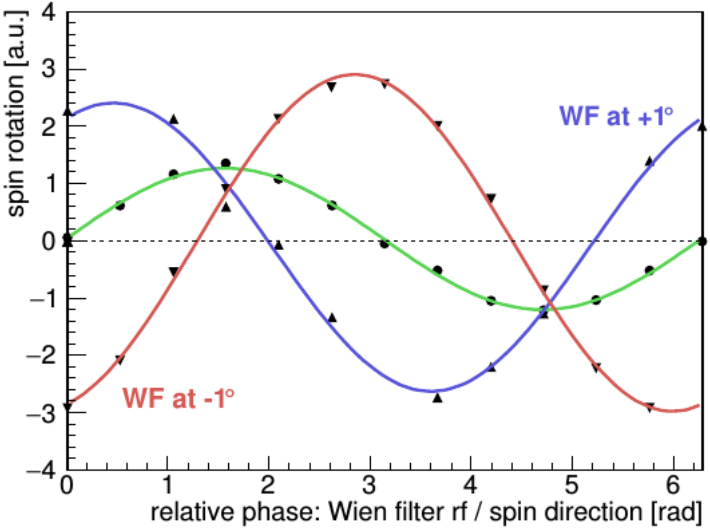
  - polarimeter development
  - development of electro static deflectors

Results from Nov. 2017 Beam Time



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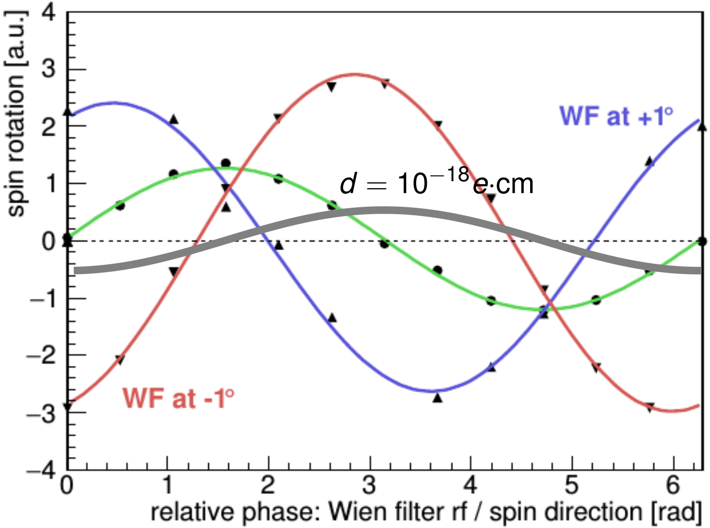

JEDI Collaboration

- **JEDI** = **J**ülich **E**lectric **D**ipole Moment **I**nvestigations
- ≈ 100 members
  (Aachen, Bonn, Daejeon, Dubna, Ferrara, Grenoble, Indiana, Ithaca, Jülich, Krakow, Michigan, Minsk, Novosibirsk, St. Petersburg, Stockholm, Tbilisi, . . .)
- ≈ 10 PhD students

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

Summary

- **EDMs** of elementary particles are of high interest to disentangle various sources of $\mathcal{CP}$ **violation** searched for to explain **matter - antimatter asymmetry** in the Universe
- EDM of **charged** particles can be measured in **storage rings** by observing the influence on the polarisation vector
- First **deuteron EDM** measurement planned at COSY in 2018
- Design of a **new dedicated storage ring** ongoing