Electric Dipole Moment Measurements at Storage Rings

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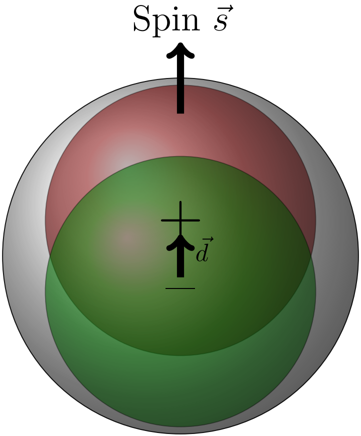
for the JEDI collaboration

Spin 2016, Urbana Champaign 2016

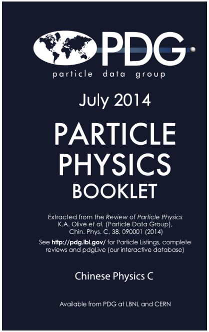
Outline

- Introduction & Motivation
  What are EDMs?, What do we know about EDMs?
  Why are EDMs interesting?
- Experimental Methods
  How to measure charged particle EDMs?
- Recent Achievements
  How do manipulate and measure a polarization with high precision!

Electric Dipole Moments (EDM)



- separation of positive and negative charge
- fundamental property of particles
  (like magnetic moment, mass, charge)
- existence of EDM only possible via violation of time reversal $\mathcal{T}$ and parity $\mathcal{P}$ symmetry



p

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 1.00727646681 \pm 0.00000000009$ u

Mass $m = 938.272046 \pm 0.000021$ MeV [a]

$|m_p - m_{\overline{p}}|/m_p < 7 \times 10^{-10}$, CL = 90% [b]

$|\frac{q_{\overline{p}}}{m_{\overline{p}}}|/(\frac{q_p}{m_p}) = 0.99999999991 \pm 0.00000000009$

$|q_p + q_{\overline{p}}|/e < 7 \times 10^{-10}$, CL = 90% [b]

$|q_p + q_e|/e < 1 \times 10^{-21}$ [c]

Magnetic moment $\mu = 2.792847356 \pm 0.000000023\ \mu_N$

$(\mu_p + \mu_{\overline{p}})\ /\ \mu_p = (0 \pm 5) \times 10^{-6}$

Electric dipole moment $d < 0.54 \times 10^{-23}\ e\,$cm

Electric polarizability $\alpha = (11.2 \pm 0.4) \times 10^{-4}$ fm^3

Magnetic polarizability $\beta = (2.5 \pm 0.4) \times 10^{-4}$ fm^3 (S = 1.2)

Charge radius, μp Lamb shift $= 0.84087 \pm 0.00039$ fm [d]

Charge radius, $e p$ CODATA value $= 0.8775 \pm 0.0051$ fm [d]

Magnetic radius $= 0.777 \pm 0.016$ fm

Mean life $\tau > 2.1 \times 10^{29}$ years, CL = 90% [e] ($p \to$ invisible mode)

Mean life $\tau > 10^{31}$ to 10^{33} years [e] (mode dependent)

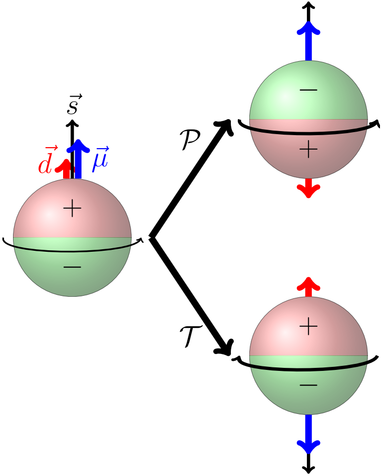
$\mathcal{T}$ and $\mathcal{P}$ violation of EDM

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

$$H = -\mu\frac{\vec{s}}{s}\cdot\vec{B} - d\frac{\vec{s}}{s}\cdot\vec{E}$$

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

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



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

$\mathcal{CP}-$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

Matter-Antimatter Asymmetry

Excess of matter in the universe:

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

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

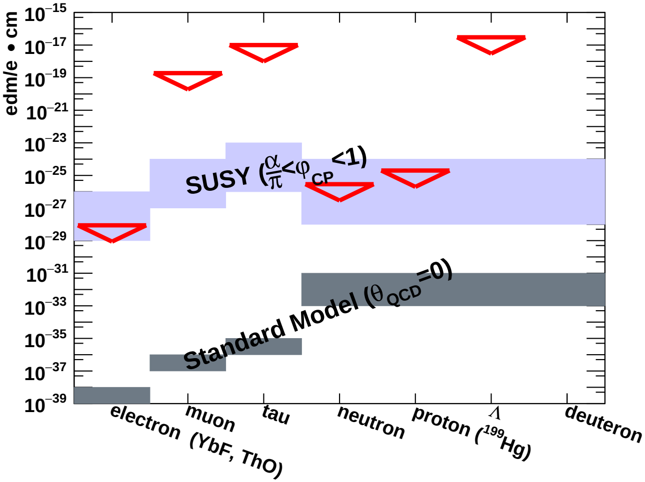
$\Rightarrow$ New $\mathcal{CP}$ violating sources beyond SM needed to explain this discrepancy

They could show up in EDMs of elementary particles

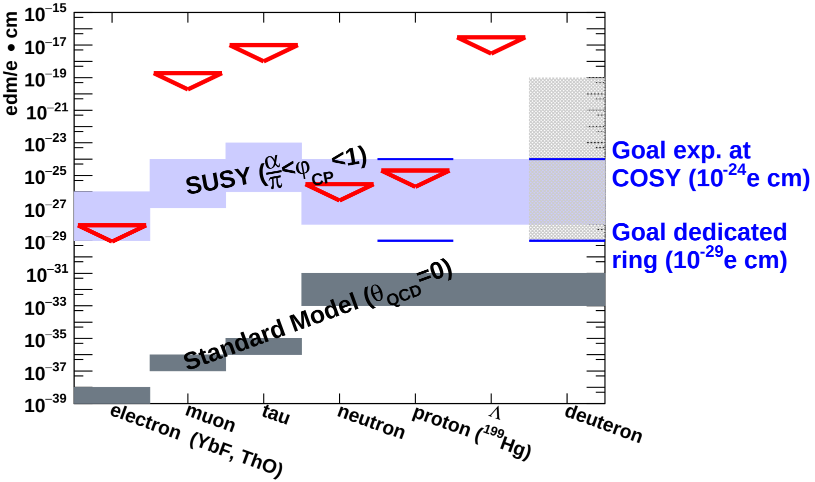
* SCM: Standard Cosmological Model

What do we know about EDMs?

EDM: Current Upper Limits



EDM: Current Upper Limits



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

Why Charged Particle EDMs?

- no direct measurements for charged hadrons exist
- potentially higher sensitivity (compared to neutrons):
  - longer life time,
  - more stored protons/deuterons
- complementary to neutron EDM:
  $d_d \stackrel{?}{=} d_p + d_n \Rightarrow$ access to θ_{QCD}

EDM of one particle alone not sufficient to identify $\mathcal{CP}-$violating source

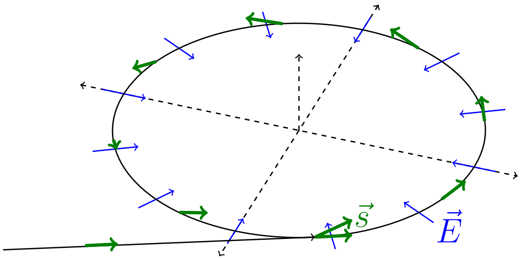
How to measure charged particle EDMs?

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:

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

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

Experimental Requirements

- high precision storage ring $\rightarrow$ **systematics** (alignment, stability, field homogeneity)
- high intensity beams ($N = 4 \cdot 10^{10}$ per fill)
- polarized hadron beams ($P = 0.8$)
- long spin coherence time ($\tau = 1000\,\text{s}$),
- large electric fields ($E = 10\,\text{MV/m}$)
- polarimetry (analyzing power $A = 0.6$, acc. $f = 0.005$)

$$\sigma_{\text{stat}} \approx \frac{\hbar}{\sqrt{Nf}\tau PAE} \quad \Rightarrow \sigma_{\text{stat}}(1\text{year}) = 10^{-29}\, e\cdot\text{cm}$$

challenge: get σ_{sys} to the same level

Spin Precession: Thomas-BMT Equation

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

BMT: Bargmann, Michel, Telegdi

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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)

BMT: Bargmann, Michel, Telegdi

Spin Precession: Thomas-BMT Equation

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

	☺	☹
2.) combined ring	works for $p, d, {}^3$He, …	both $\vec{E}$ and $\vec{B}$ required

BMT: Bargmann, Michel, Telegdi

Spin Precession: Thomas-BMT Equation

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

	☺	☹
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**

BMT: Bargmann, Michel, Telegdi

Recent Achievements:

How do manipulate and measure a polarization with high precision!

Cooler Synchrotron COSY

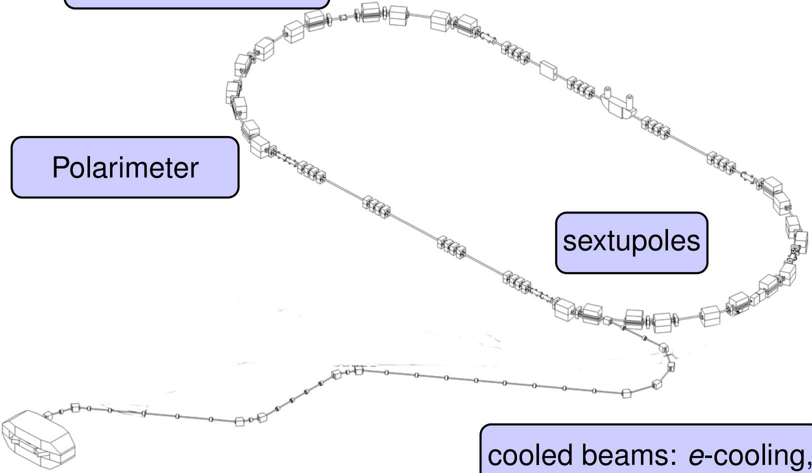
COSY provides (polarized) protons and deuterons with $p = 0.3 - 3.7\text{GeV}/c$

$\Rightarrow$ **Ideal starting point for charged particle EDM searches**

COSY

RF $E \times B$ dipole

RF solenoid



Polarimeter

sextupoles

cooled beams: *e*-cooling,

stochastic cooling

Polarized proton & deuterons

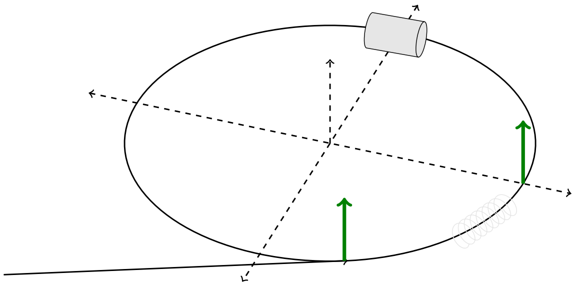
R & D at COSY

- maximize spin coherence time (SCT) (→ E. Stephenson, Tue. 15.20)
- precise measurement of spin precession (spin tune)
- polarization feed back (→ N. Hempelmann, Tue.14.45)
- spin tracking simulation tools, design of dedicated storage ring (→ M. Rosenthal, Tue. 14.30, E. Valetov, Tue. 11.30
- RF- Wien filter design and construction (→ J. Slim, Tue. 14.55)
- tests of electro static deflectors (goal: field strength > 10 MV/m)
- development of high precision beam position monitors
- polarimeter development

More related talks on this conference: R. Talman (Tue. 11.55), B. Lorentz Mon. 14.55), Y. Duteil (Mon. 14.30), W. Hillert (Tue. 12.20)

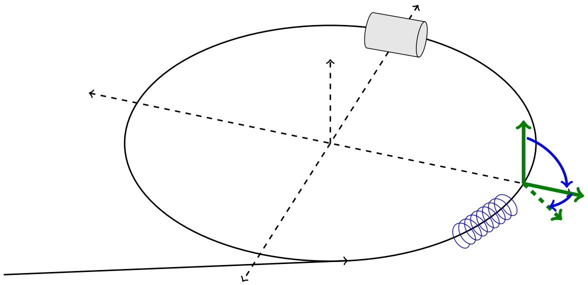
Experimental Setup

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



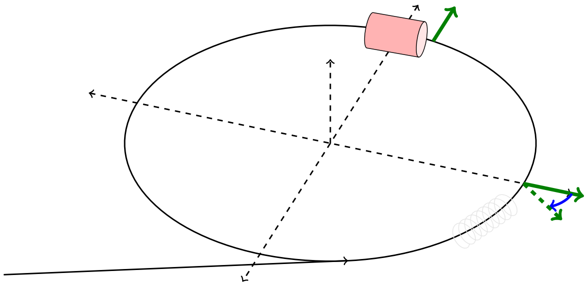
Experimental Setup

- 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

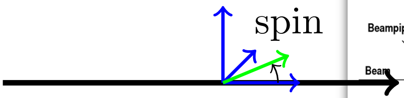
- Inject and accelerate vertically polarized deuterons to $p \approx 1$ GeV/c
- flip polarization with help of solenoid into horizontal plane, precession starts
- Extract beam slowly (in $\approx 100\,$s) on target
- Measure asymmetry and determine spin precession

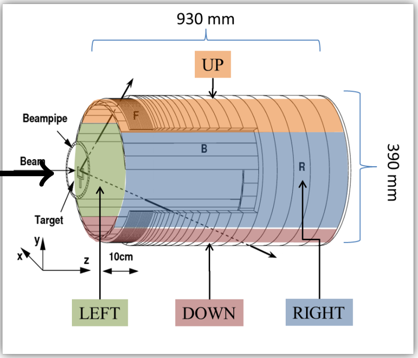


Polarimeter

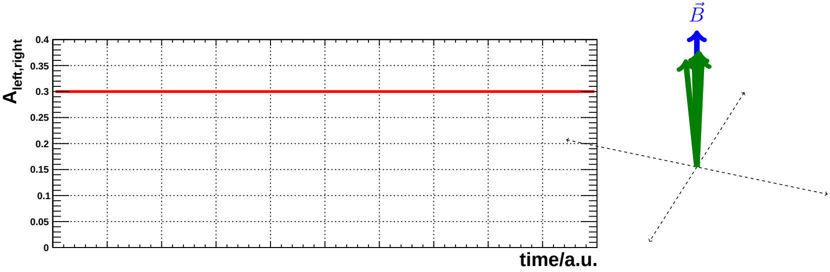
elastic deuteron-carbon scattering,
consists of four scintillator segments: left, right, up, down

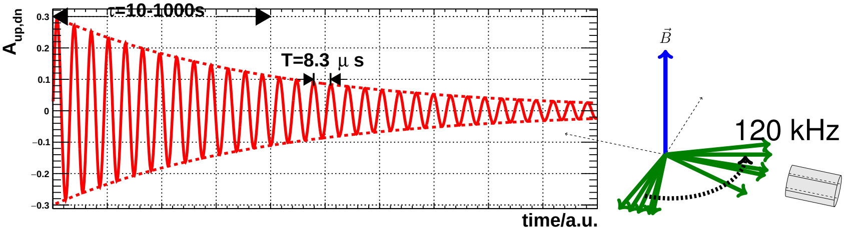
asymmetry $A_{up,down} \propto$ horizontal polarization $\rightarrow \nu_s = \gamma G$
asymmetry $A_{left,right} \propto$ vertical polarization $\rightarrow d$



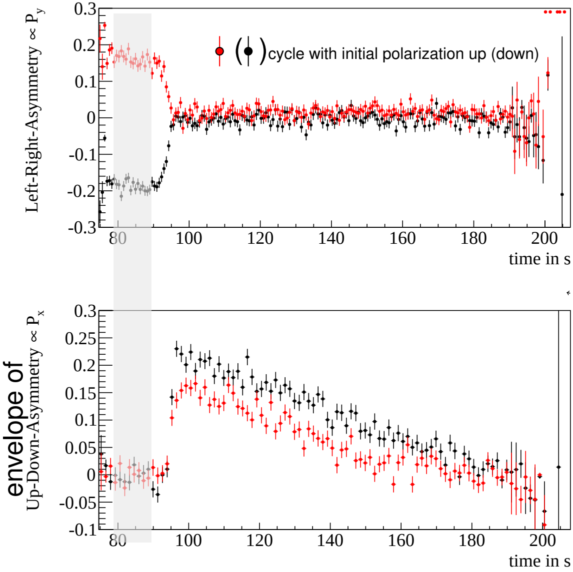


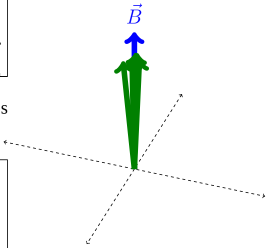
Asymmetries



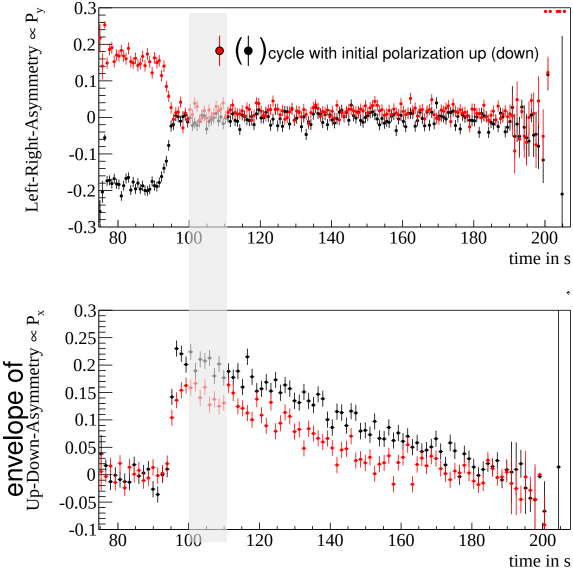


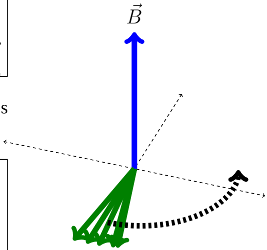
Polarization Flip



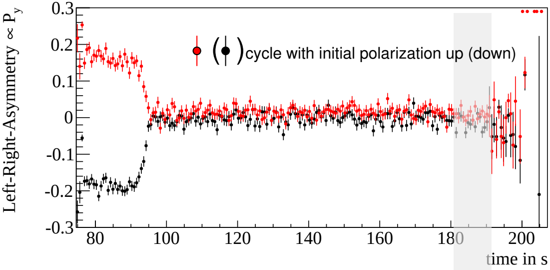


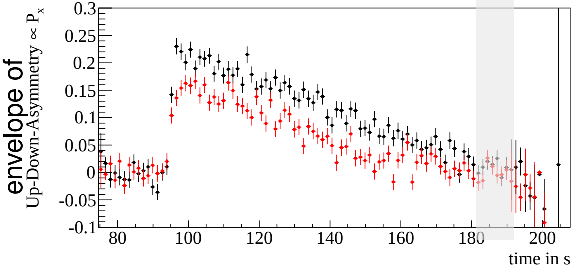
Polarization Flip

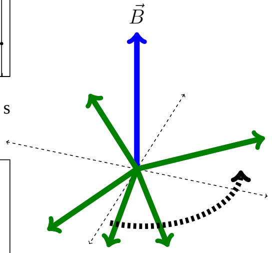




Polarization Flip

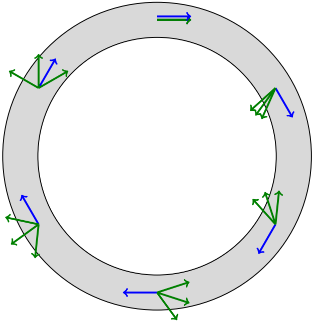


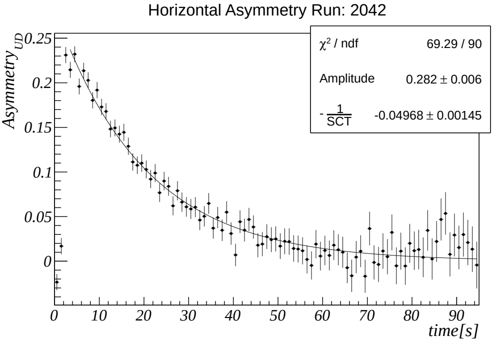




Results: Spin Coherence Time (SCT)

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

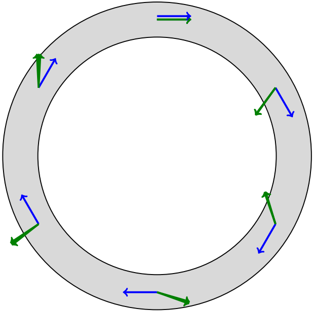
$\Rightarrow$ decoherence after < 1 s

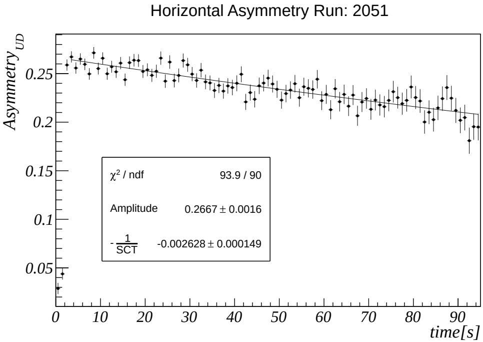
bunched beam eliminates 1st order effects in $\Delta p/p$

$\Rightarrow$ SCT τ = 20 s

Results: Spin Coherence Time (SCT)

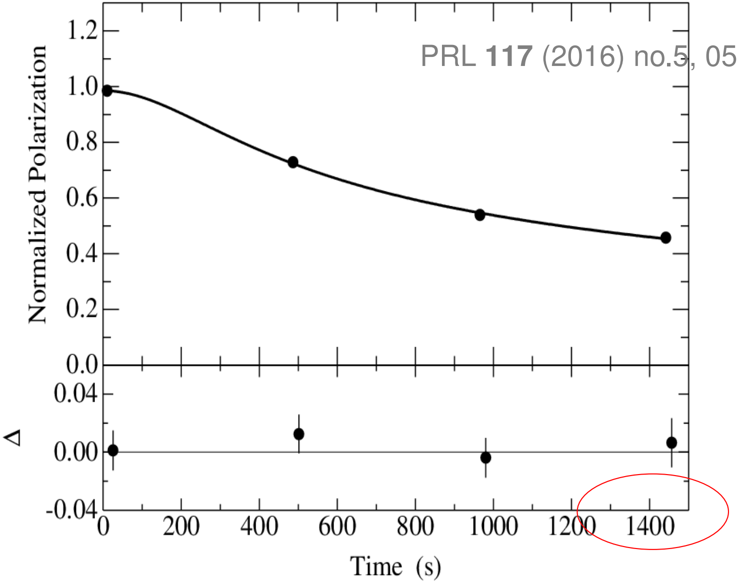
Long Spin Coherence Time





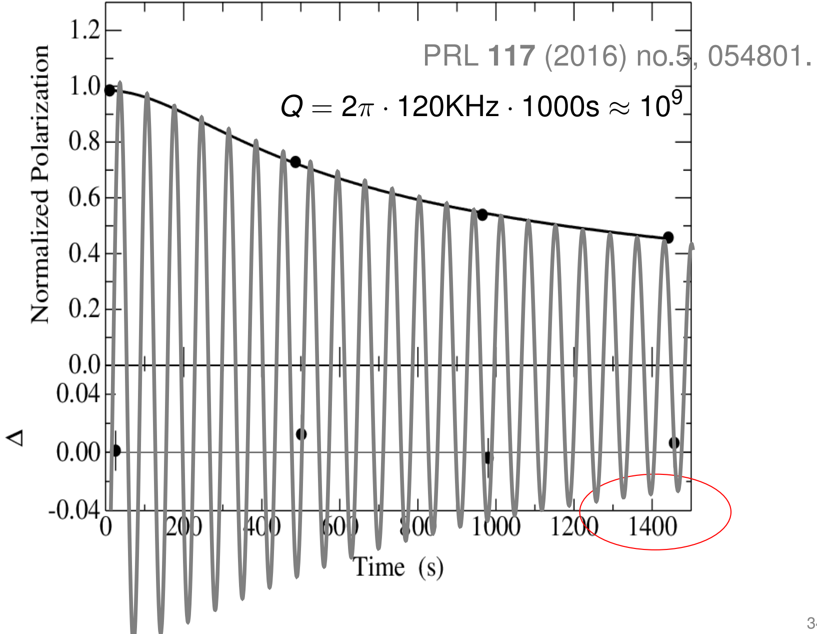
SCT of $\tau = 400\,\mathrm{s}$, after correction with sextupoles (chromaticities $\xi \approx 0$)

SCT: Longer Cycles



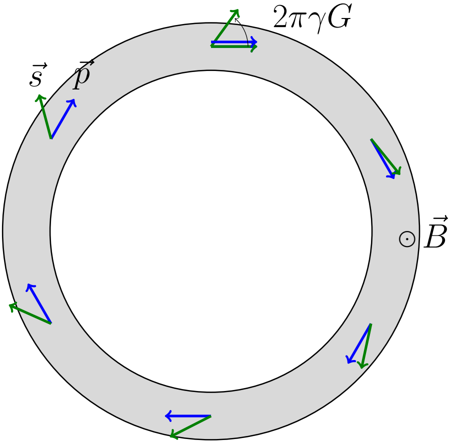
PRL **117** (2016) no.5, 054801.

SCT: Longer Cycles



Spin Tune ν_s

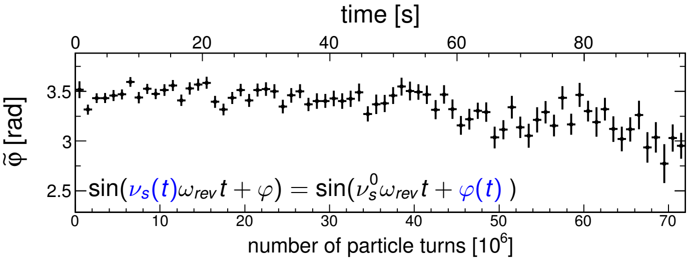
Spin tune: $\nu_s = \gamma G = \dfrac{\text{nb. of spin rotations}}{\text{nb. of particle revolutions}}$



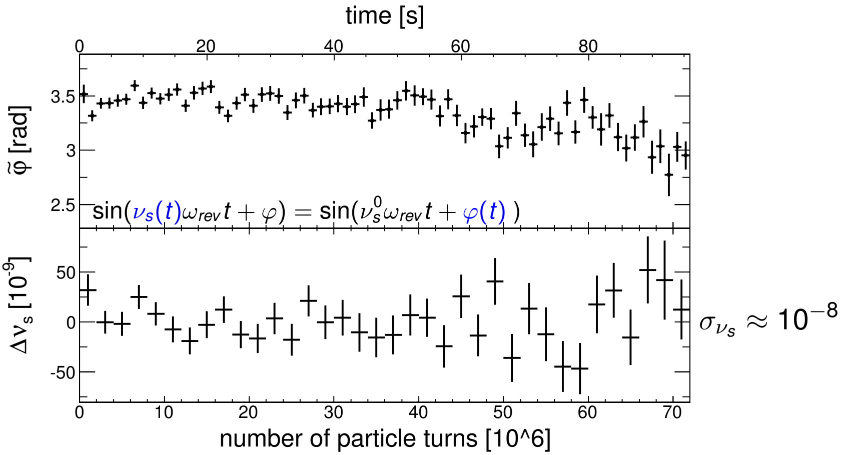
deuterons: $p_d = 1$ GeV/c ($\gamma = 1.13$), $G = -0.14256177(72)$

$\Rightarrow \nu_s = \gamma G \approx -0.161$

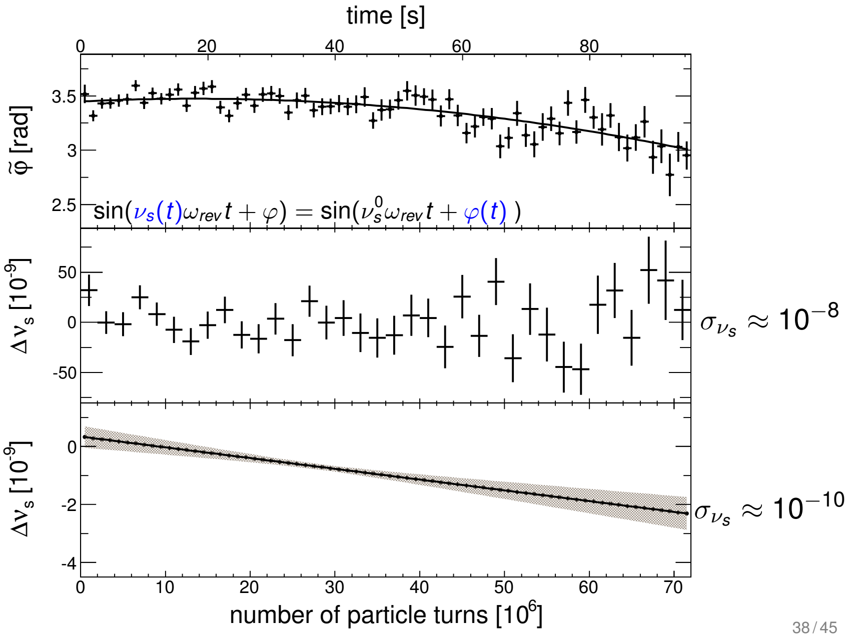
Results spin tune



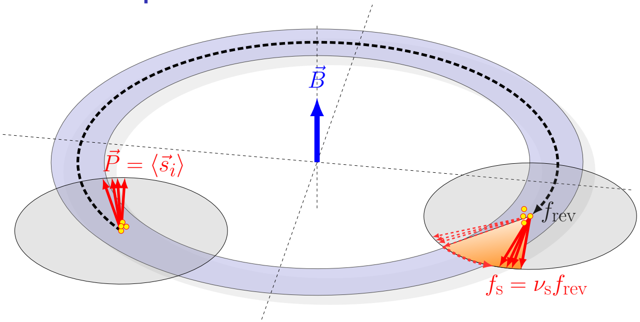
Results spin tune



Results spin tune

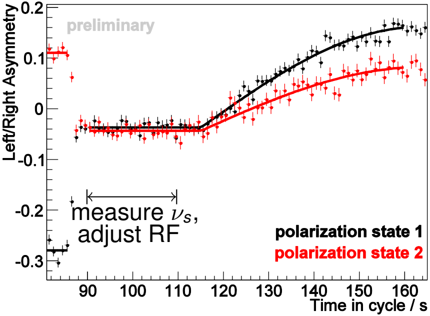


Spin Tune Measurement



- precision 10^{-10} in one cycle of $\approx 100\, s$ (translated to angle, precision is $2 \cdot \pi \cdot 10^{-10} = 0.6\,\text{nrad}$)
- spin tune measurement can now be used as tool to investigate systematic errors
- spin tune measurement allows for feedback system to keep polarization aligned with momentum vector for dedicated ring or at a given phase with respect to radio-frequency Wien filter

Spin Feed back system



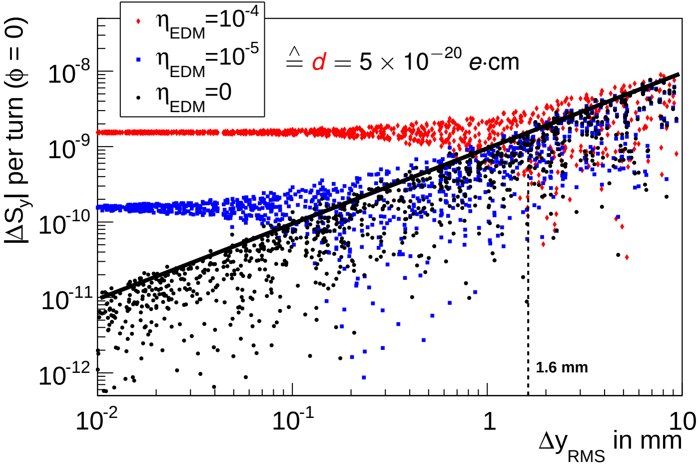
- polarization rotation in horizontal plane at $t = 85$ s
- COSY rf changed during cycle in steps of 3.7 mHz (f_{rev}=750603 Hz) according to online ν_s measurement,

- keeps phase between spin and RF solenoid constant
- solenoid (low amplitude) switched on at $t = 115\ s$
- polarization goes back to vertical direction
- mandatory for **frozen spin** in dedicated ring

Simulations

- EDM signal is build-up of vertical polarization
- radial magnetic fields (B_r) cause the same build-up
- misalignments of quadrupoles create for example unwanted B_r
- $\Rightarrow$ Run simulations to understand systematic effects
- General problem: Track 10^9 particles for 10^9 turns! ($\rightarrow$ use transfer maps of magnet elements (code: COSY Infinity))
- orbit RMS Δy_{RMS} is measure of misalignments

Spin Tracking



Random Misalignments from 1 μm to 1 mm,
Use of CW/CCW beams requires only relative measurement of two beams

JEDI Collaboration

- **JEDI** = Jülich Electric Dipole Moment Investigations
- ≈ 100 members
  (Aachen, Bonn, Daejeon, Dubna, Ferrara, Grenoble, Indiana, Ithaca, Jülich, Krakow, Michigan, Minsk, Novosibirsk, St. Petersburg, Stockholm, Tbilisi, . . .)
- ≈ 10 PhD students
- close collaboration with srEDM collaboration in US/Korea

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

Storage ring steps up search for electric dipole moments

The JEDI collaboration aims to use a storage ring to set the most stringent limits to date on the electric dipole moments of hadrons, describe **Paolo Lenisa**, **Jörg Pretz** and **Hans Ströher**.

Forschungszentrum Jülich

The fact that we and the world around us are made of matter and only

European Research Council

Search for electric dipole moments using stoage rings

PI: H. Ströher, (FZ Jülich),

RWTH Aachen University,

University of Ferrara

Start: Oct, 1st, 2016

Summary & Outlook

- **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**
- Experimentally very challenging because effect is tiny
- First promising results:

spin coherence time:	$\approx 1000\,\text{s}$
spin tune:	10^{-10} in 100 s
feed back system	allows to control spin
simulations	to understand systematics