Electric Dipole Moment Measurements at Storage Rings

J. Pretz
RWTH Aachen & FZ Jülich

UW Seattle, Nov. 2016

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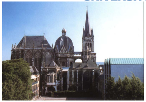
- RWTH (Rheinisch-Westfälische Technische Hochschule)
- founded in 1870
- 42 000 students (total population 250 000)
- largest technical university in Germany



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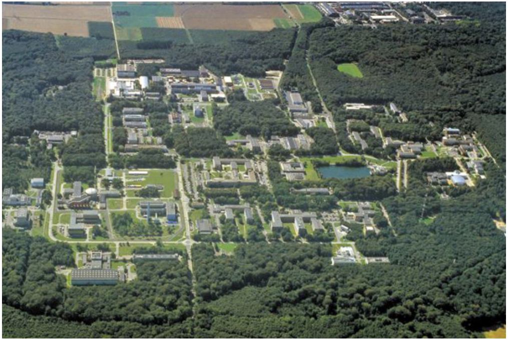
octogone: tallest building (30m) north of the Alpes for two hundred years

JÜLICH FORSCHUNGSZENTRUM



- one of the largest interdisciplinary research centers in Europe
- 6000 staff members (2000 scientists)

- “Forschungszentrum Jülich works on key technologies for the grand challenges facing society in the fields of information and the brain as well as energy and environment.”

Outline

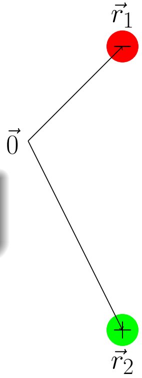
- Introduction & Motivation
  What are EDMs?, What do we know about EDMs?
  Why are EDMs interesting?
- Experimental Methods
  How to measure charged particle EDMs?
- Recent Achievements
  How do manipulate and measure a polarization with high precision!

What are EDMs?

Electric Dipoles

Classical definition:

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



Order of magnitude

	atomic physics	hadron physics
charges	e	
$\vert\vec{r}_1 - \vec{r}_2\vert$	1 Å= 10^{-8}cm	
EDM		
naive expectation	$10^{-8} e \cdot \mathrm{cm}$	
observed	water molecule	
	$2 \cdot 10^{-8} e\cdot$ cm	

Order of magnitude

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charges	e	e
$\lvert\vec{r}_1 - \vec{r}_2\rvert$	1 Å= 10^{-8}cm	$1\mathrm{fm} = 10^{-13}$cm
EDM		
naive expectation	$10^{-8} e \cdot \mathrm{cm}$	$10^{-13} e \cdot \mathrm{cm}$
observed	water molecule	neutron
	$2 \cdot 10^{-8} e \cdot$ cm	$< 3 \cdot 10^{-26} e \cdot$ cm

Operator $\vec{d} = q\vec{r}$

is odd under parity transformation ($\vec{r} \to -\vec{r}$):

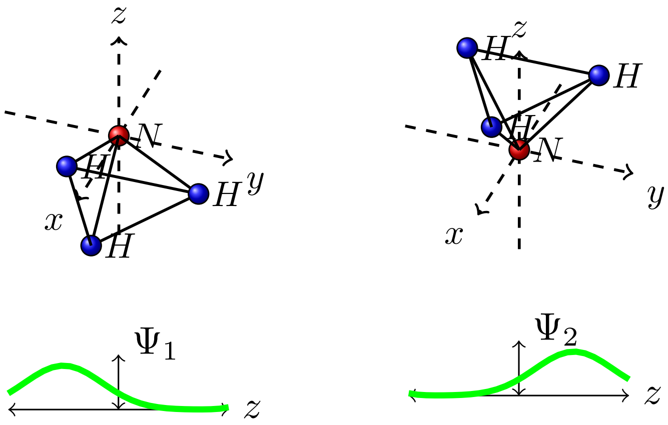
$$\mathcal{P}^{-1}\vec{d}\mathcal{P} = -\vec{d}$$

Consequences:
In a state $|a\rangle$ of given parity the expectation value is 0:

$$\left\langle a|\vec{d}|a\right\rangle = -\left\langle a|\vec{d}|a\right\rangle = 0$$

but if $|a\rangle = \alpha|P = +\rangle + \beta|P = -\rangle$
in general $\left\langle a|\vec{d}|a\right\rangle \neq 0 \Rightarrow$ i.e. molecules

EDM of molecules



ground state: mixture of

$$\Psi_s = \frac{1}{\sqrt{2}} (\Psi_1 + \Psi_2) , \quad P = +$$

$$\Psi_a = \frac{1}{\sqrt{2}} (\Psi_1 - \Psi_2) , \quad P = -$$

EDMs & symmetry breaking

Molecules can have large EDM because of degenerated ground states with different parity

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Elementary particles (including hadrons) have a definite parity and cannot posses an EDM
$P|\text{had}>= \pm 1|\text{had}>$

EDMs & symmetry breaking

Molecules can have large EDM because of degenerated ground states with different parity

Elementary particles (including hadrons) have a definite parity and cannot posses an EDM
$P|\text{had}>= \pm 1|\text{had}>$

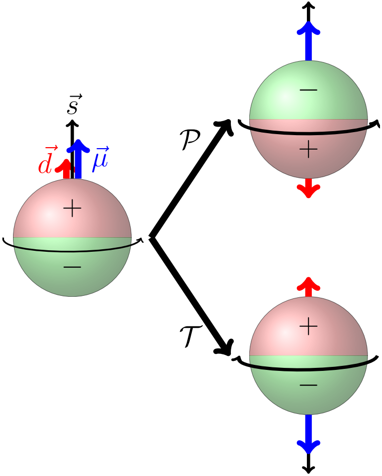
unless

$\mathcal{P}$ and time reversal $\mathcal{T}$ invariance are violated!

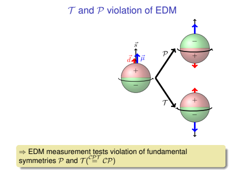
$\mathcal{T}$ and $\mathcal{P}$ violation of EDM

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

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



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

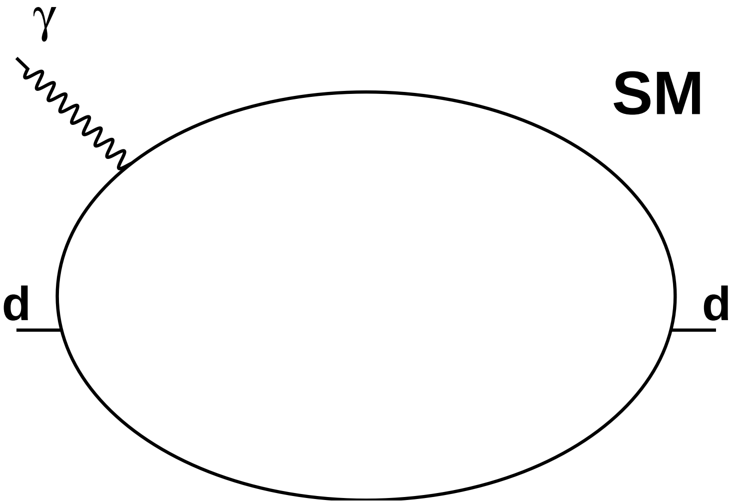


Note: EDM has to be parallel to spin.

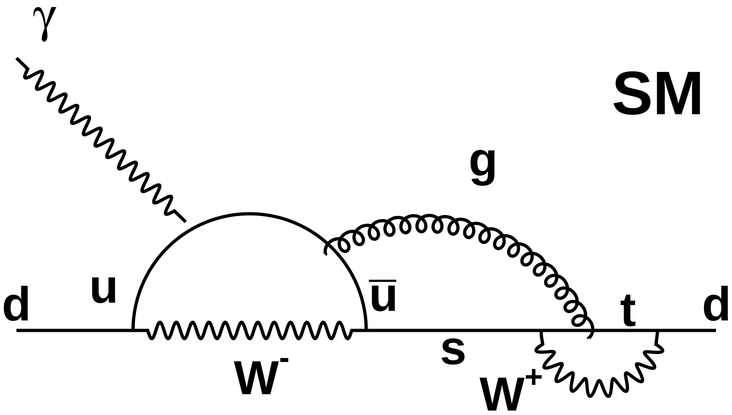
$\mathcal{CP}-$Violation and connection to EDMs

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

EDM in SM and SUSY



EDM in SM and SUSY



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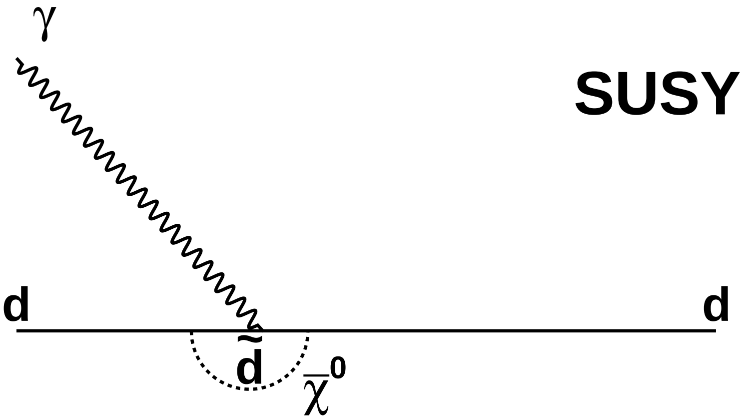


Connection to Cosmology: Matter-Antimatter Asymmetry

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

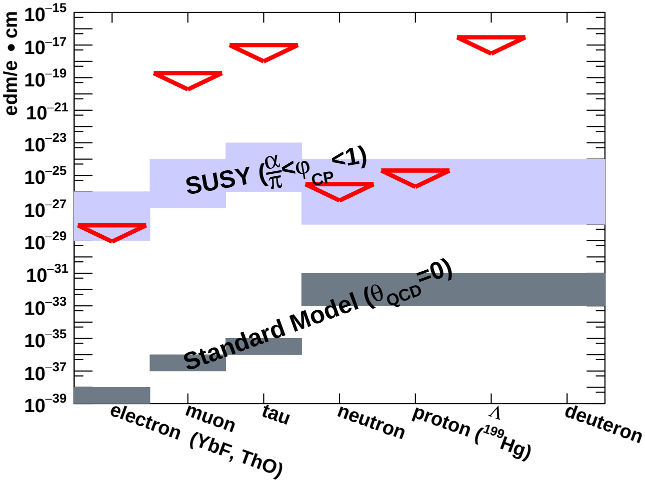
⇒ New $\mathcal{CP}$ violating sources beyond SM needed to explain this discrepancy

They could show up in EDMs of elementary particles

* SCM: Standard Cosmological Model

What do we know about EDMs?

EDM: Current Upper Limits



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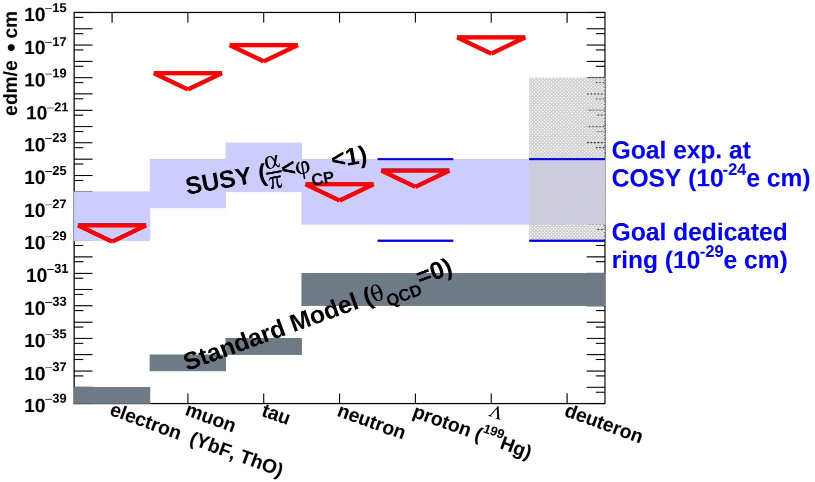
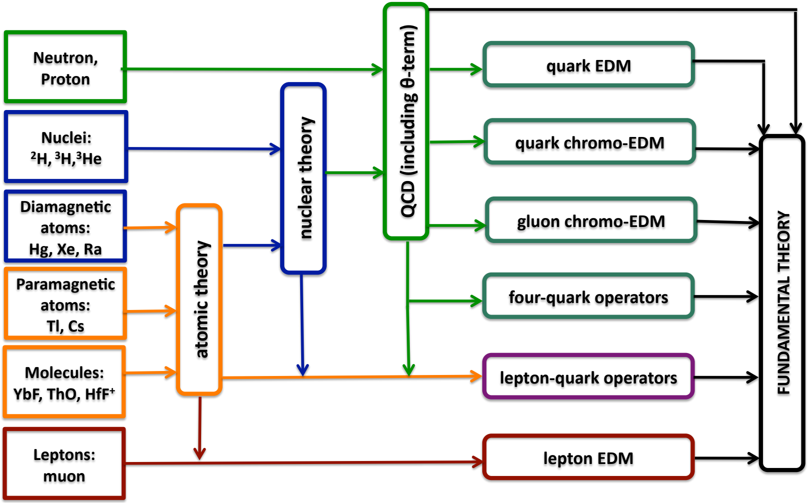


FZ Jülich: EDMs of **charged** hadrons: p, d, ^{3}He

Sources of $\mathcal{CP}$ Violation



J. de Vries

Why Charged Particle EDMs?

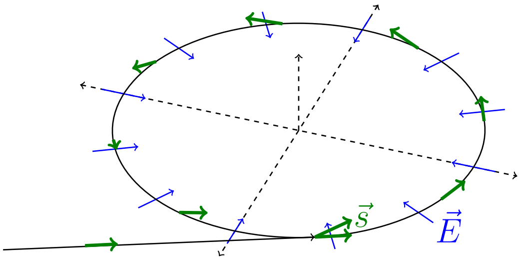
- no direct measurements for charged hadrons exist
- potentially higher sensitivity (compared to neutrons):
  - longer life time,
  - more stored protons/deuterons
- complementary to neutron EDM:
  $d_d \stackrel{?}{=} d_p + d_n \Rightarrow$ access to θ_{QCD}

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:



$$\frac{d\vec{s}}{dt} \propto d\vec{E} \times \vec{s}$$

In general:

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

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

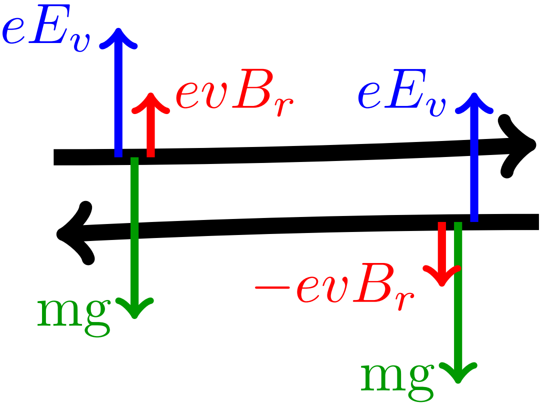
Systematics

Major source:
Radial B field mimics an EDM effect:

- Difficulty: even small radial magnetic field, B_r can mimic EDM effect if :$\mu B_r \approx dE_r$
- Suppose $d = 10^{-29} e\cdot\text{cm}$ in a field of $E_r = 10\text{MV/m}$
- This corresponds to a magnetic field:
$$B_r = \frac{dE_r}{\mu_N} = \frac{10^{-22} e\mathrm{V}}{3.1 \cdot 10^{-8} e\mathrm{V}/\mathrm{T}} \approx 3 \cdot 10^{-17}\mathrm{T}$$

Solution: Use two beams running **clockwise** and **counter clockwise**, separation of the two beams is sensitive to B_r

Systematics



Sensitivity needed: $1.25\,\text{fT}/\sqrt{\text{Hz}}$ for $d = 10^{-29}\,e\,\text{cm}$
(possible with SQUID technology)

Spin Precession: Thomas-BMT Equation

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

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)

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1.) pure electric ring	no $\vec{B}$ field needed, CW/CCW beams simultaneously	works only for particles
2.) combined ring	works for p, d, ^{3}He, ...	both $\vec{E}$ and $\vec{B}$ required

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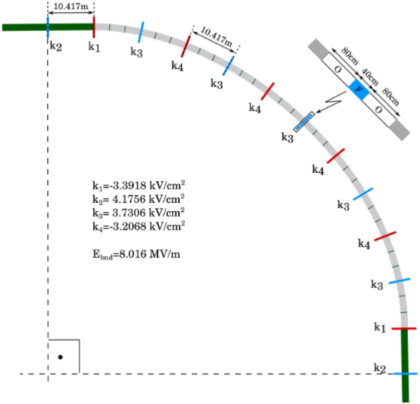
1.) pure electric ring	no $\vec{B}$ field needed, CW/CCW beams simultaneously	works only for particles
2.) combined ring	works for p, d, ^{3}He, ...	both $\vec{E}$ and $\vec{B}$
3.) pure magnetic ring	existing (upgraded) COSY ring can be used, shorter time scale	lower sensitivity, precession due to G,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

BMT: Bargmann, Michel, Telegdi

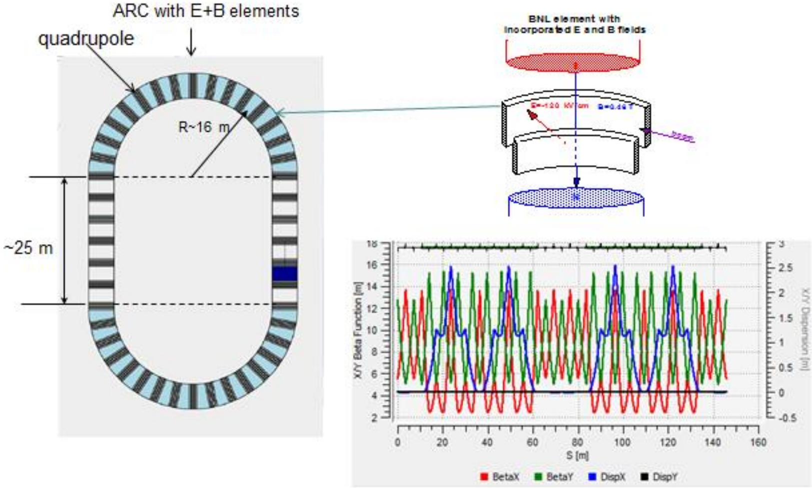
1.) Pure Electric Ring



radius $\approx$ 50 m, $E = 8$MV/m

arXiv:1502.04317, acc. for publication in Rev. Sci. Instrum. (BNL/Korea)

2.) Ring Design with E/B elements



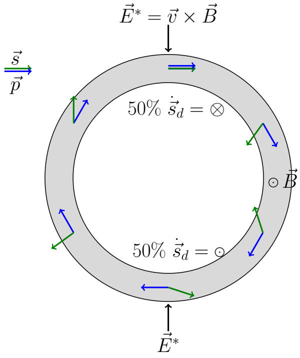
$|\vec{B}| = 0.46$ T, $|\vec{E}| = 12$ MV/m

Y. Senichev (Jülich)

3.) EDM measurement using pure magnetic ring

$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = \frac{-q}{m}\left(G\vec{B} + \frac{m}{es} d\vec{v} \times \vec{B}\right) \times \vec{s}$$

Problem:
Due to precession caused by magnetic moment, 50% of time longitudinal polarization component is || to momentum, 50% of the time it is anti-||.



E^* field in the particle rest frame tilts spin due to EDM up and down $\Rightarrow$ **no net EDM effect**

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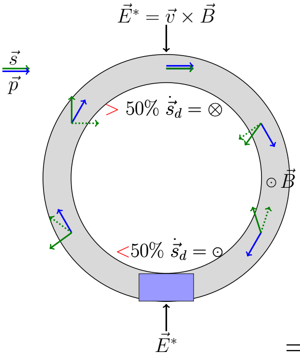
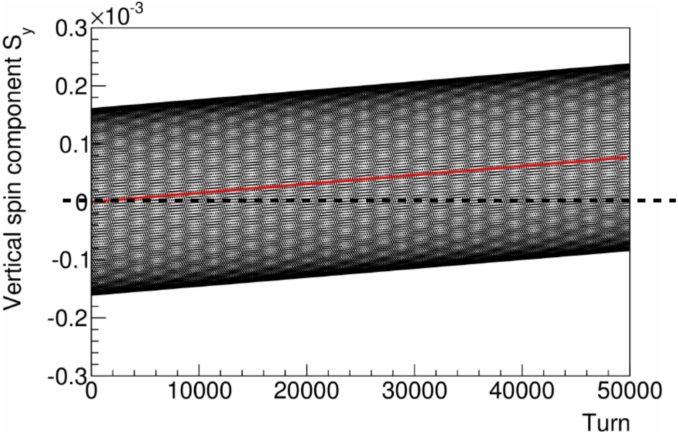


E^* field in the particle rest frame tilts spin due to EDM up and down
$\Rightarrow$ **no net EDM effect**

Use resonant "magic Wien-Filter" in ring ($\vec{E}_W + \vec{v} \times \vec{B}_W = 0$):
$E^*_W = 0 \rightarrow$ part. trajectory is not affected but
$B^*_W \neq 0 \rightarrow$ mag. mom. is influenced

$\Rightarrow$ **net EDM effect can be observed!**

Buildup of vertical Polarisation



for deuterons ($G \approx -0.143, p = 0.97\text{GeV}/c$ ($\beta = 0.459$))

assumed edm: $d = \eta \frac{q\hbar}{2mc} s = 5 \cdot 10^{-19} e{\cdot}\text{cm}$ ($\eta = 10^{-4}$)

50000 turns $\widehat{=}$38ms, ampl. of fast oscillation $\frac{\beta\eta}{2G} \approx 1.6 \cdot 10^{-4}$

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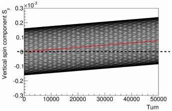

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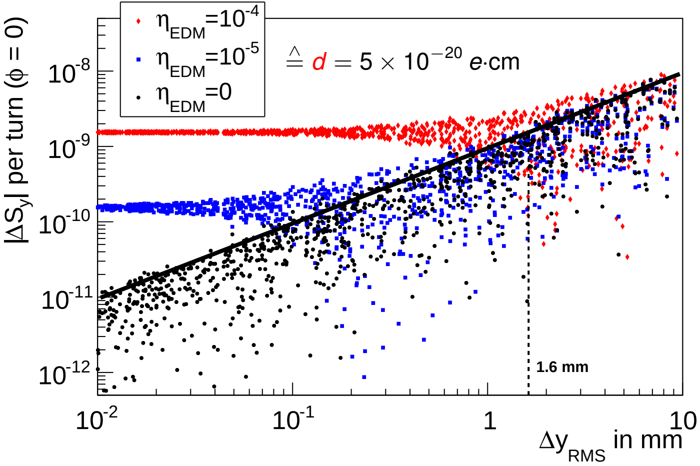
Can be done analytically

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 1μm to 1 mm $\propto \Delta y_{RMS}$,
Use of CW/CCW beams requires only relative measurement of two beams

Recent Achievements:

How do manipulate and measure a polarization with high precision!

Cooler Synchrotron COSY

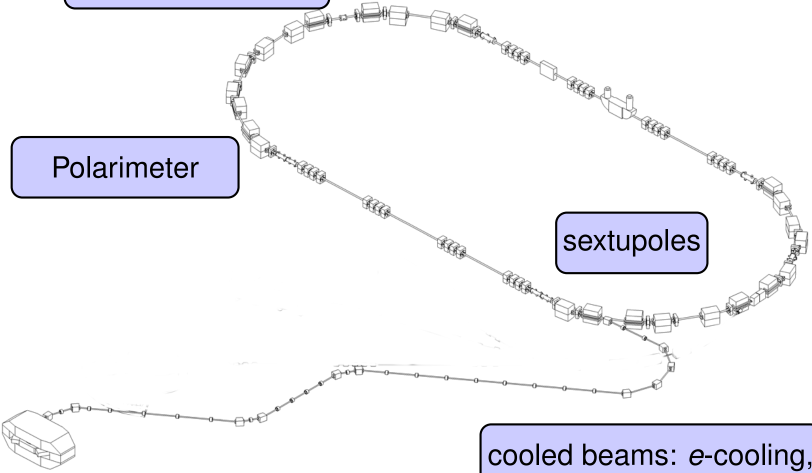
COSY provides (polarized) protons and deuterons with
$p = 0.3 - 3.7\text{GeV}/c$
$\Rightarrow$ **Ideal starting point for charged hadron EDM searches**

COSY

RF $E \times B$ dipole

RF solenoid

Polarimeter



sextupoles

cooled beams: e-cooling,

stochastic cooling

Polarized proton & deuterons

Running Conditions

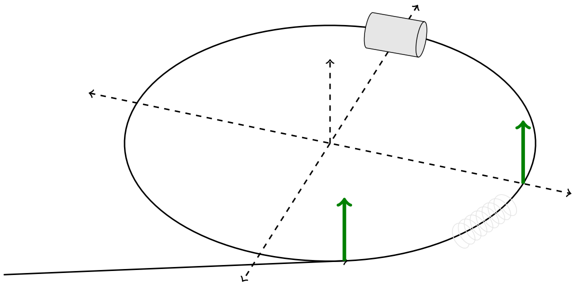
COSY circumference	183 m
deuteron momentum	0.970 GeV/c
$\beta(\gamma)$	0.459 (1.126)
magnetic anomaly G	≈ -0.143
revolution frequency f_{rev}	752543 Hz
cycle length	100-1500 s
nb. of stored particles/cycle	$\approx 10^9$
event rate at $t = 0$	5000 s^{-1}

R & D at COSY

- maximize spin coherence time (SCT)
- precise measurement of spin precession (spin tune)
- polarization feed back
- spin tracking simulation tools, design of dedicated storage ring
- RF- Wien filter design and construction
- tests of electro static deflectors (goal: field strength > 10 MV/m)
- development of high precision beam position monitors
- polarimeter development

Experimental Setup at COSY

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



Experimental Setup at COSY

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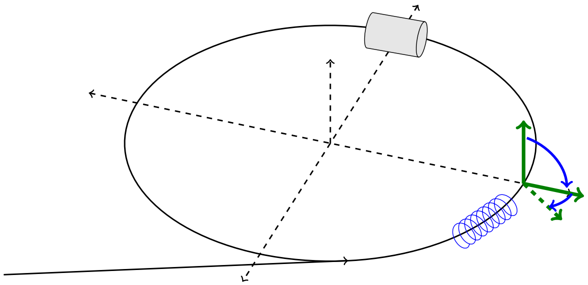
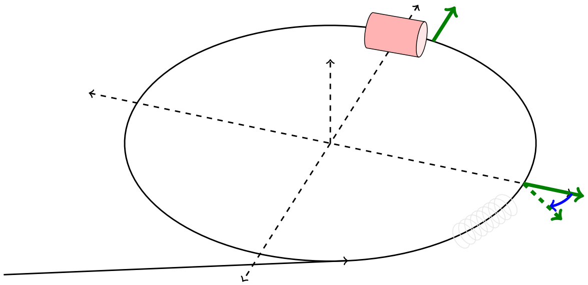
- flip polarization with help of solenoid into horizontal plane, precession starts



Experimental Setup at COSY

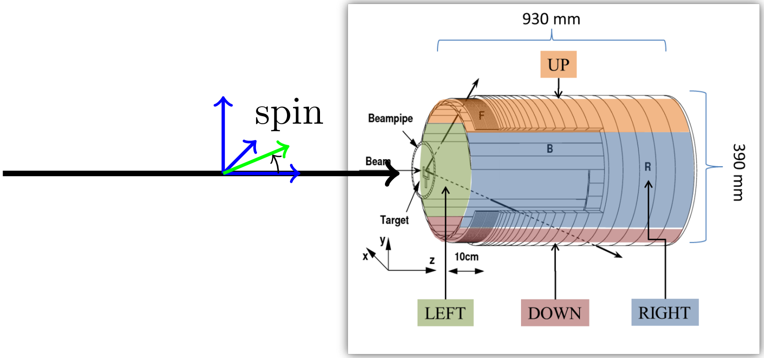
- Inject and accelerate vertically polarized deuterons to $p \approx 1$ GeV/c
- flip polarization with help of solenoid into horizontal plane, precession starts
- Extract beam slowly (in $\approx 100\,$s) on target
- Measure asymmetry and determine spin precession



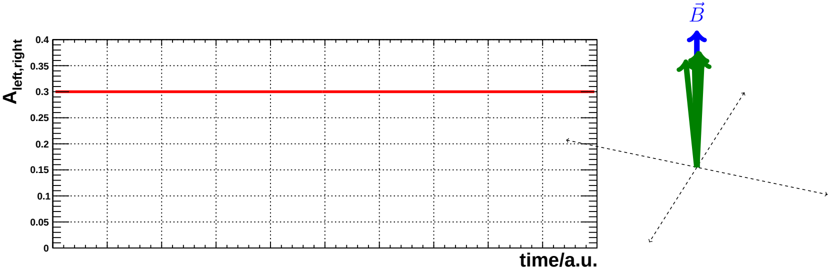
Polarimeter

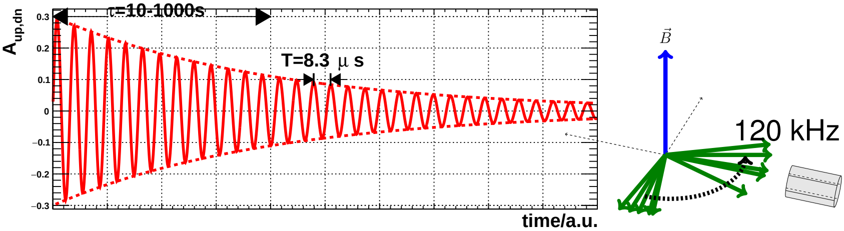
elastic deuteron-carbon scattering,
consists of four scintillator segments: left, right, up, down

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

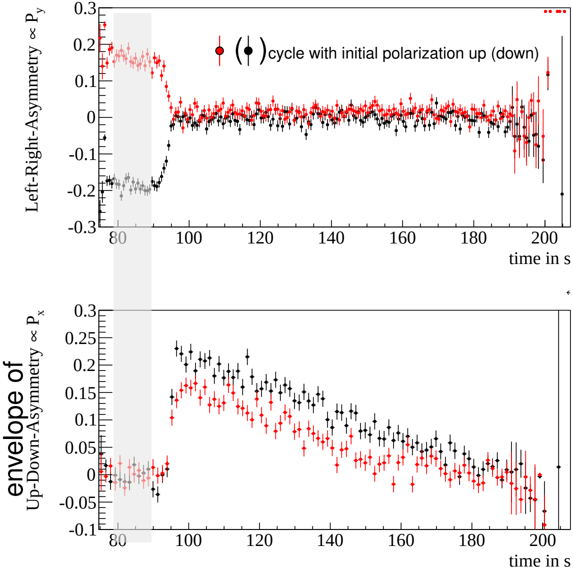


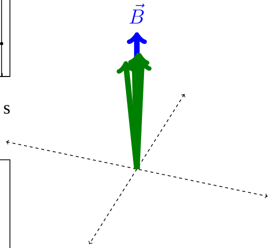
Asymmetries





Polarization Flip

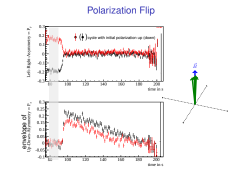




2016-11-01

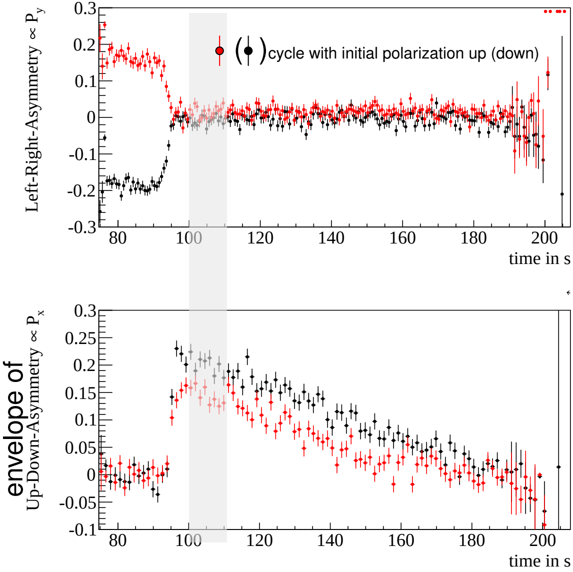
└─Recent Achievements

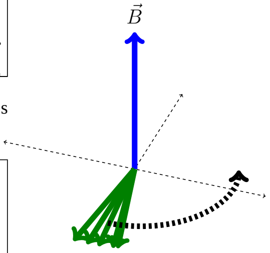
└─Polarization Flip

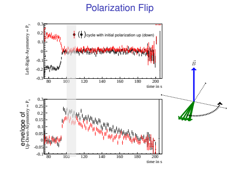


Two cycles are shown!!!

Polarization Flip

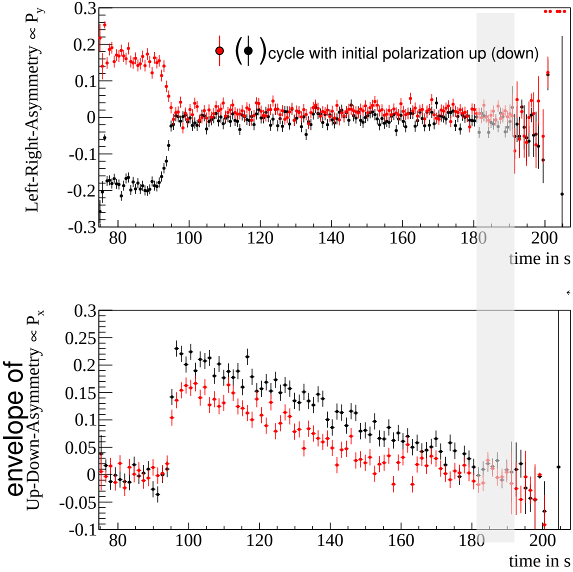


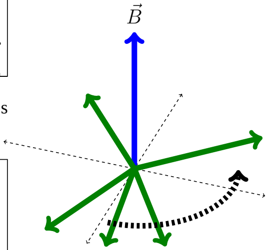


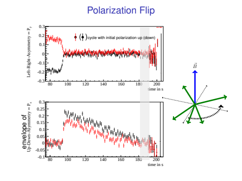


Two cycles are shown!!!

Polarization Flip



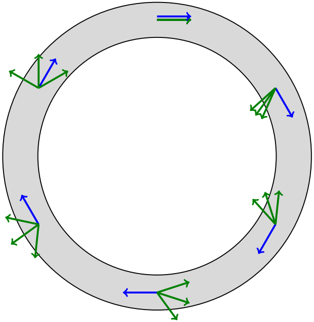


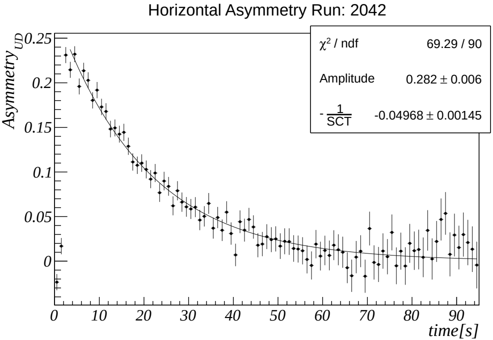


Two cycles are shown!!!

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

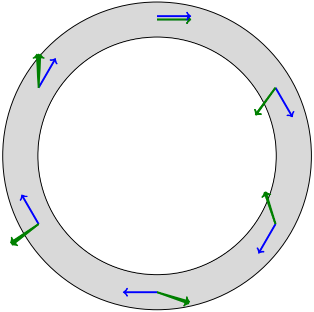
$\Rightarrow$ decoherence after < 1 s

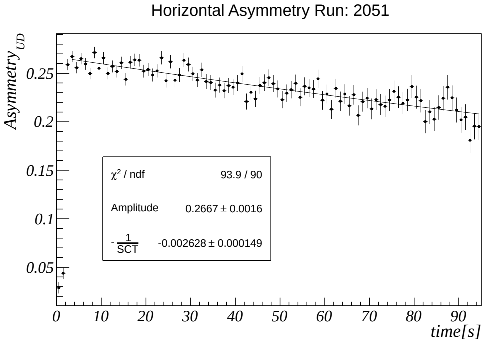
bunched beam eliminates 1st order effects in $\Delta p/p$

$\Rightarrow$ SCT τ = 20 s

Results: Spin Coherence Time (SCT)

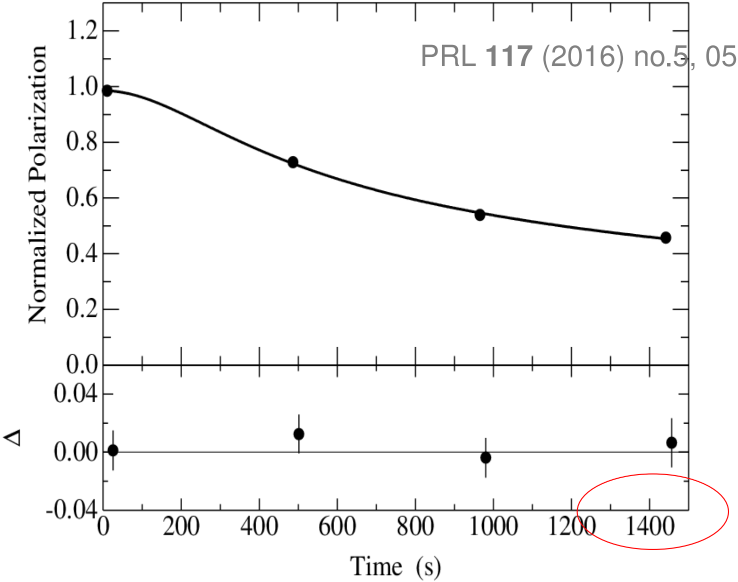
Long Spin Coherence Time





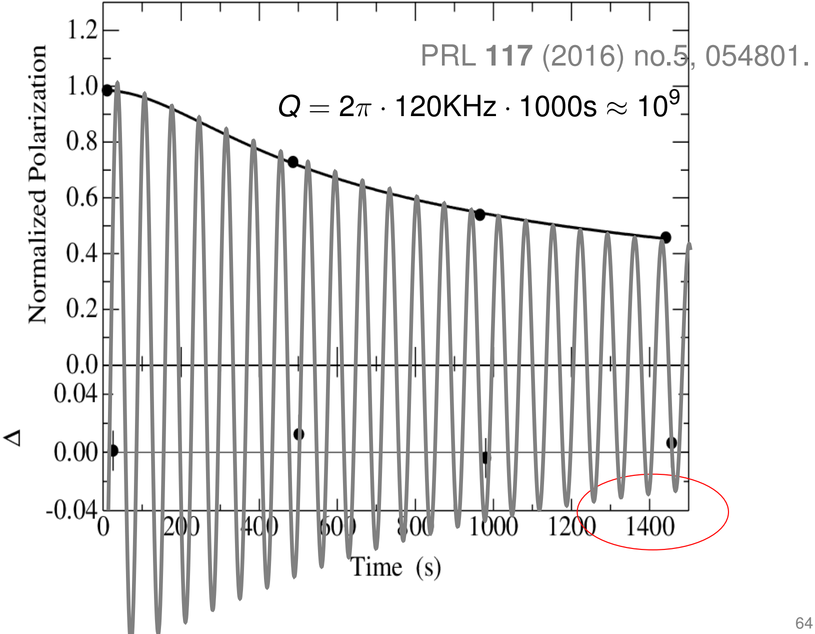
SCT of τ =400 s, after correction with sextupoles (chromaticities $\xi \approx 0$)

SCT: Longer Cycles



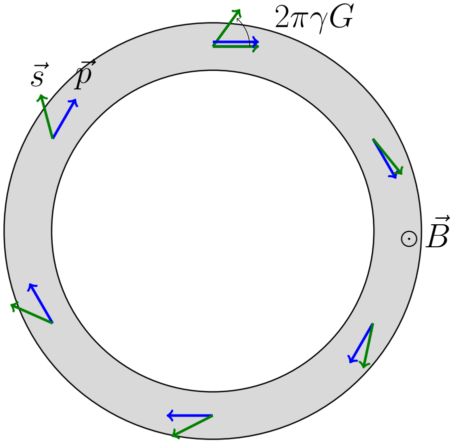
PRL **117** (2016) no.5, 054801.

SCT: Longer Cycles



Spin Tune ν_s

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

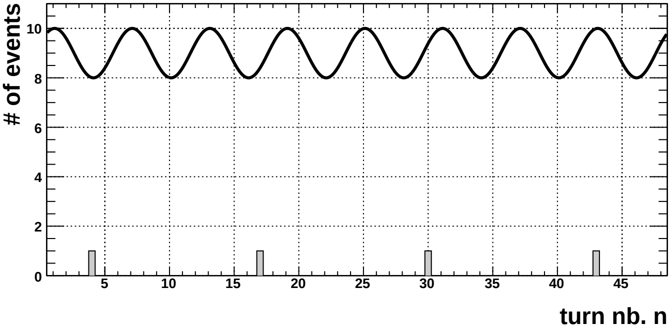


deuterons: $p_d = 1$ GeV/c ($\gamma = 1.13$), $G = -0.14256177(72)$

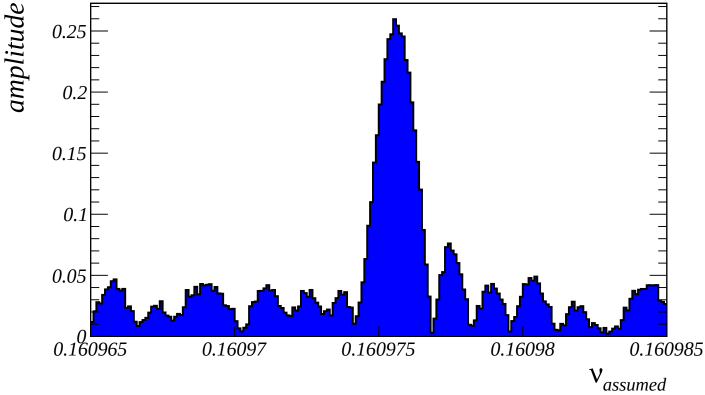
$\Rightarrow \nu_s = \gamma G \approx -0.161$

Spin Tune ν_s measurement

- Problem: detector rate $\approx$ 5 kHz, $f_{spin} = 120$kHz
  $\Rightarrow$ only 1 hit every 25th period
- not possible to use usual χ^2-fit
- try different algorithms,
  mapping, **Fourier analysis**, Maximum Likelihood

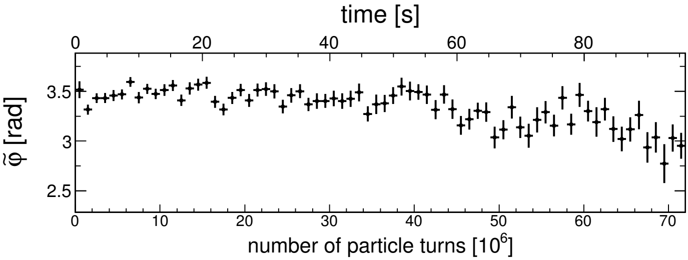


Fourier spectrum for 10^6 turns

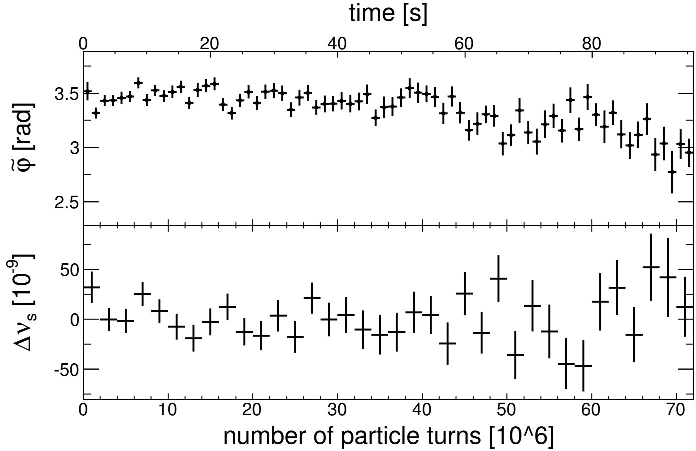


- fix ν_s at maximum and look at phase vs. turn number
  phase is determined for turn intervals of 10^6 turns (≈ 1.3 s)

Results spin tune

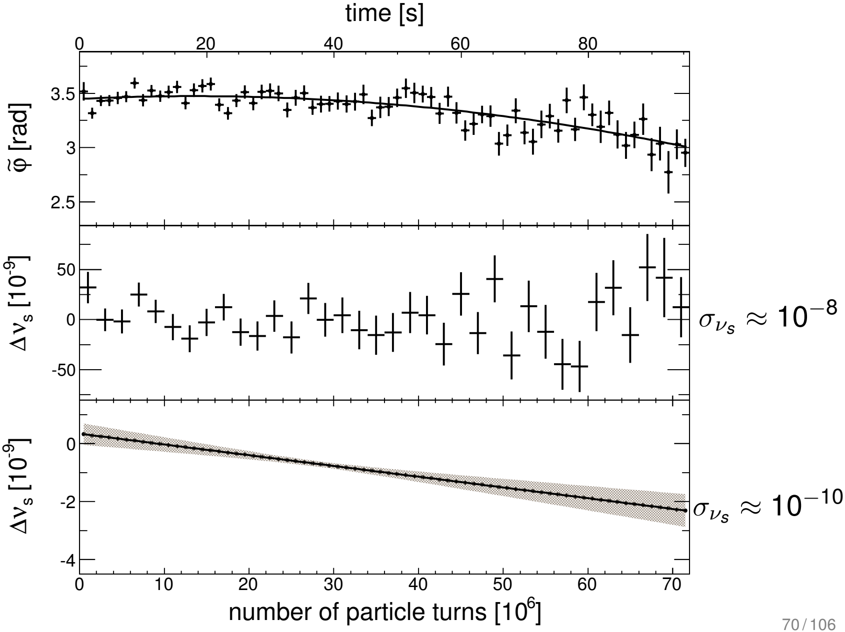


Results spin tune



$\sigma_{\nu_s} \approx 10^{-8}$

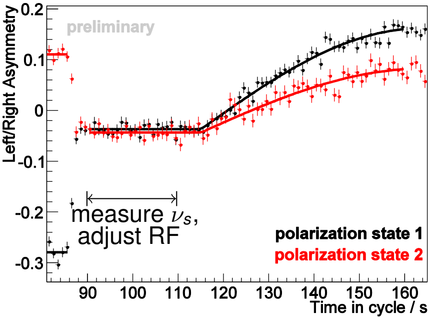
Results spin tune



Spin Tune Measurement

- relative precision 10^{-9} in one cycle of $\approx 100\,s$
- Compare to muon $g-2$: $\sigma_{\nu_s}/\nu_s \approx 10^{-6}$ per year
  main difference: measurement duration 600μs compared to 100 s
- spin rotation due to electric dipole moment:
  $\nu_s = \frac{vm\gamma d}{es} = 5 \cdot 10^{-11}$ for $d = 10^{-24} e\,\text{cm}$
  (in addition rotations due to G and imperfections)
- 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
  needed for final ring (frozen spin) and
  Wien filter method in magnetic ring

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

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

Spare

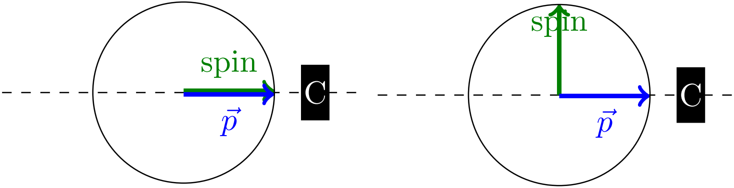
Asymmetry Measurements

- Detector signal $N^{up,dn} \propto (1 \pm P\,A\,\sin(\gamma G \omega_{rev} t))$

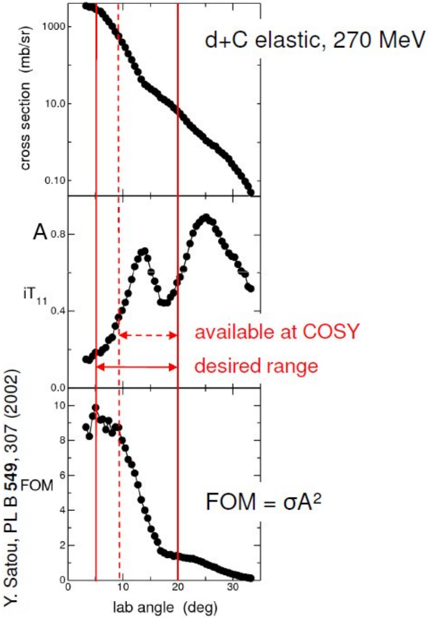
$$A_{up,dn} = \frac{N^{up} - N^{dn}}{N^{up} + N^{dn}} = P\,A\,\sin(\gamma G \omega_{rev} t)$$

A: analyzing power, P : polarization

$A_{up,dn} = 0$ $\qquad$ $A_{up,dn} = PA$



Polarimetry



Cross Section & Analyzing Power for deuterons

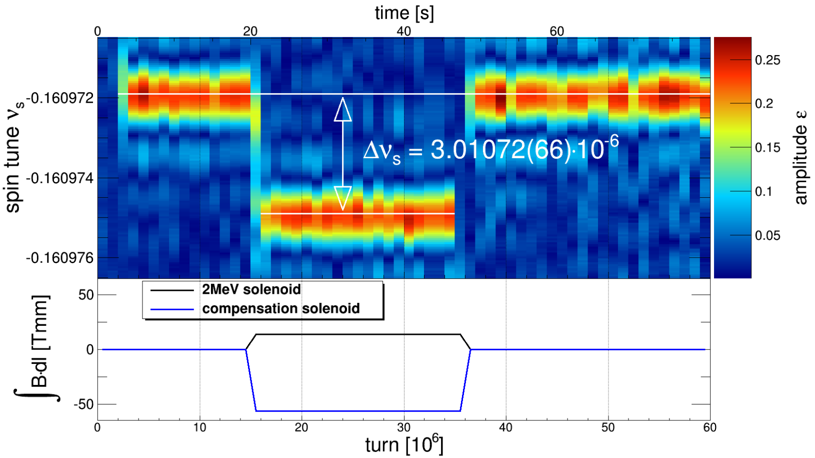
$$N_{up,dn} \propto (1 \pm P\,A\,\sin(\nu_s \omega_{rev} t))$$

$$A_{up,dn} = \frac{N^{up} - N^{dn}}{N^{up} + N^{dn}} = P\,A\,\sin(\nu_s \omega_{rev} t)$$

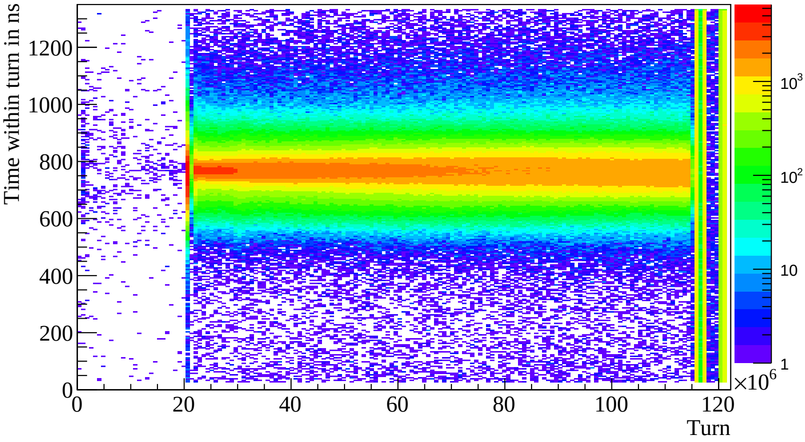
A : analyzing power

P : beam polarization

Spin Tune jumps

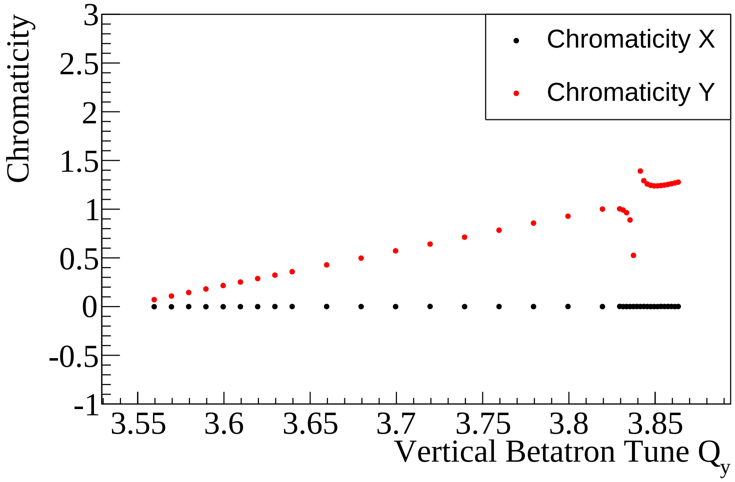


Event Distribution



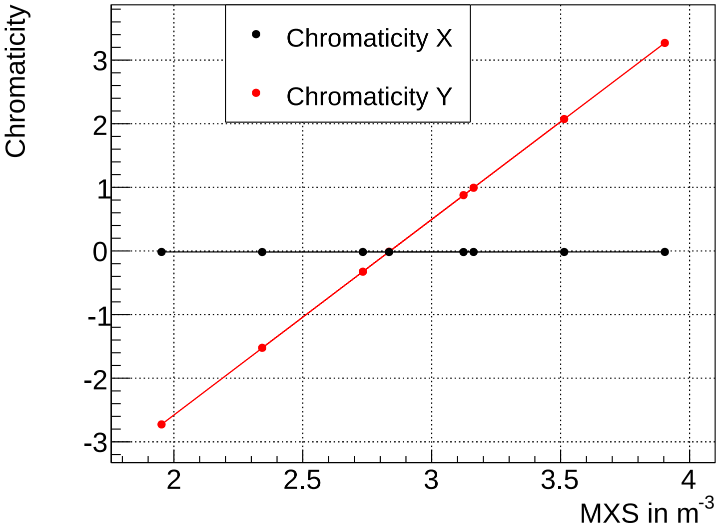
SCT ↔ Chromaticity I

Chromaticities vs. tune giving maximal SCT according to simulation



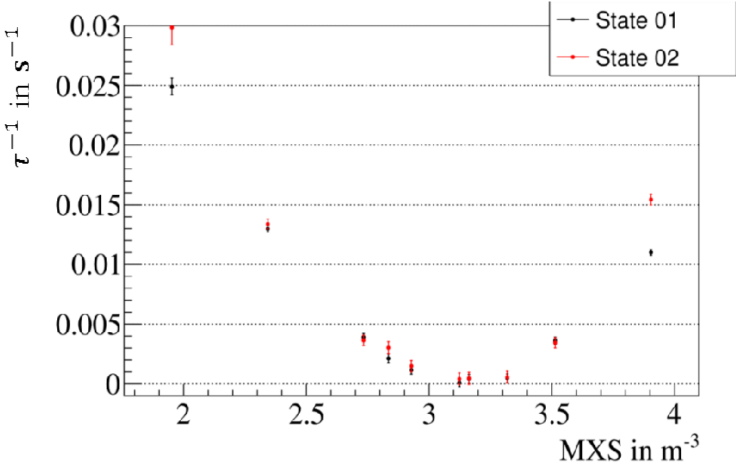
SCT $\leftrightarrow$ Chromaticity II

Chromaticities vs. sextupole setting



SCT ↔ Chromaticity I

SCT vs. sextupole setting



Maximal SCT for predicted sextupole setting

SCT $\leftrightarrow$ chromaticity

chromaticity $\xi = \Delta Q/(\Delta p/p)$

$$\langle\frac{\Delta T}{T_0}\rangle = \langle\frac{\Delta L}{L_0}\rangle - \langle\frac{\Delta\beta}{\beta_0}\rangle$$

$\langle\ldots\rangle$ means time average for one particle

because of bunched beam: $\langle\frac{\Delta T}{T_0}\rangle = 0$

betatron oscillations leads to $\langle\frac{\Delta L}{L_0}\rangle \neq 0$

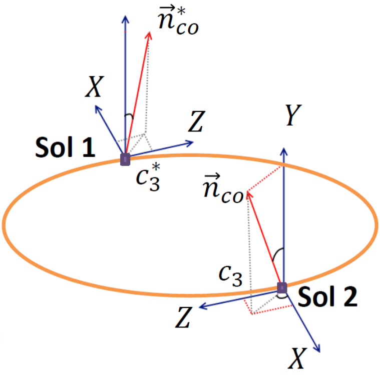
$$\Rightarrow \frac{\Delta\beta}{\beta_0} \neq 0 \Rightarrow \frac{\Delta\nu_s}{\nu_s} \neq 0$$

sextupole settings gives access to

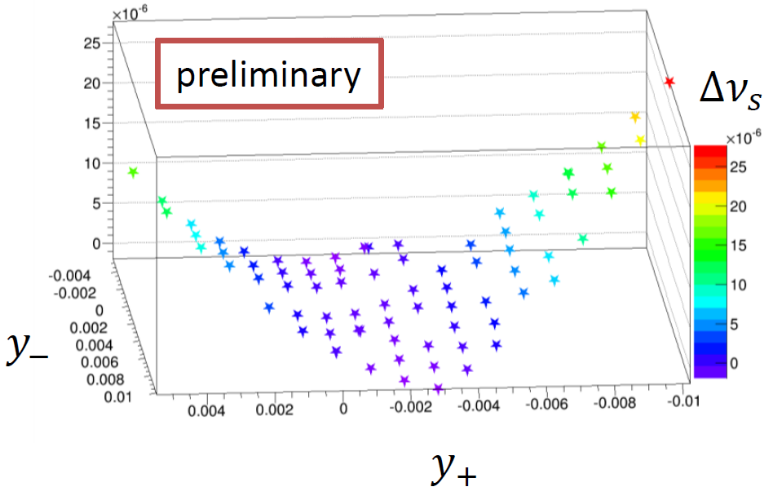
$$\langle\frac{\Delta L}{L_0}_{x,y}\rangle = \frac{\pi}{L_0}\,\epsilon_{x,y}\,\xi_{x,y}$$

Spin Tune as tool to investigate systematics

$\nu_s = \gamma G +$ imperfections kicks

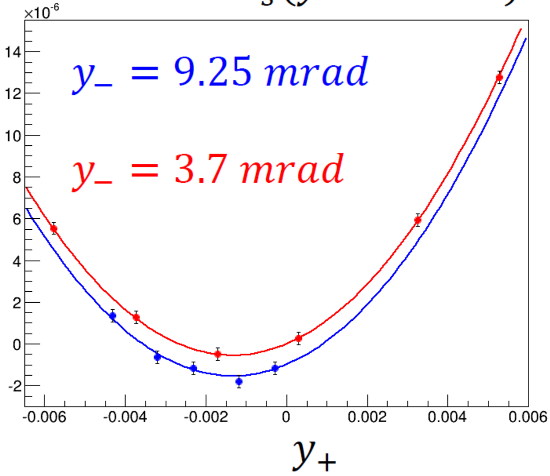


- Create artificial imperfections with solenoids/steerers
- measure spin tune change $\Delta\nu_s$
- expectation $\Delta\nu_s \propto (y_\pm - a_\pm)^2$
  $a_\pm$: kicks due to imperfections,
  $y_\pm$: kicks due to solenoids



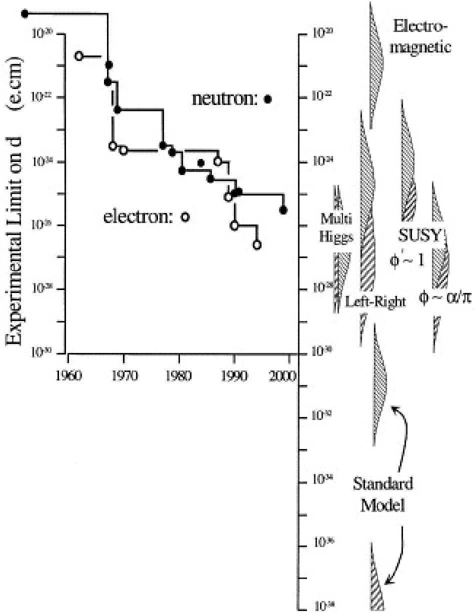
- parabolic behavior expected from simulations
- $y^{\pm} = \frac{\chi_1 \pm \chi_2}{2}$, $\chi_{1,2}$: solenoid strength
  for perfect machine, minimum should be at $y^{+} = 0$

$\Delta\nu_s(y_- = const)$



- parabolic behavior expected from simulations
- $y^{\pm} = \frac{\chi_1 \pm \chi_2}{2}$, $\chi_{1,2}$: solenoid strength
  for perfect machine, minimum should be at $y^+ = 0$

Electron and Neutron EDM



J. M. Pendlebury & E.A. Hinds, NIMA 440(2000) 471

EDM: SUSY Limits

electron:

MSSM: $\varphi \approx 1 \Rightarrow d = 10^{-24} - 10^{-27} e{\cdot}\text{cm}$

$\varphi \approx \alpha/\pi \Rightarrow d = 10^{-26} - 10^{-30} e{\cdot}\text{cm}$

neutron:

MSSM: $d = 10^{-24} e{\cdot}\text{cm} \cdot \sin\phi_{CP} \dfrac{200\text{GeV}}{M_{SUSY}}$

SM EDM values

$$\mu_n = \frac{e}{2m_p} \approx 10^{-14} e\text{cm (CP \& P conserving)}$$

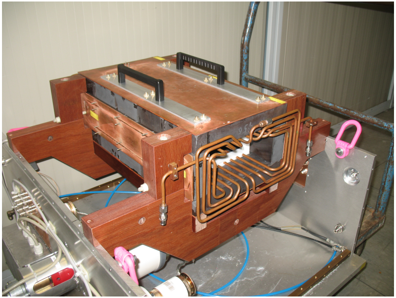
$$d_n = 10^{-14} \times \underbrace{10^{-7}}_{P-violation} \times \underbrace{10^{-3}}_{CP-violation} \times \underbrace{G_F F_\pi}_{\text{no flavor change}} = 10^{-31} e\text{cm}$$

$$\begin{aligned} d_n &= \mathcal{O}(g_w^4 g_s^2) = \mathcal{O}(G_F^2 g_s^2) \quad (3 loop) \\ d_e &= \mathcal{O}(g_w^6 g_s^2) = \mathcal{O}(G_F^3 g_s^2) \quad (4 loop) \end{aligned}$$

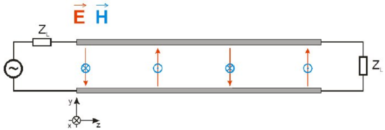
Electrostatic Deflectors

- Electrostatic deflectors from Fermilab ($\pm$125kV at 5 cm $\hat{=}$ 5MV/m)
- large-grain Nb at plate separation of a few cm yields $\approx$ 20MV/m

Wien Filter

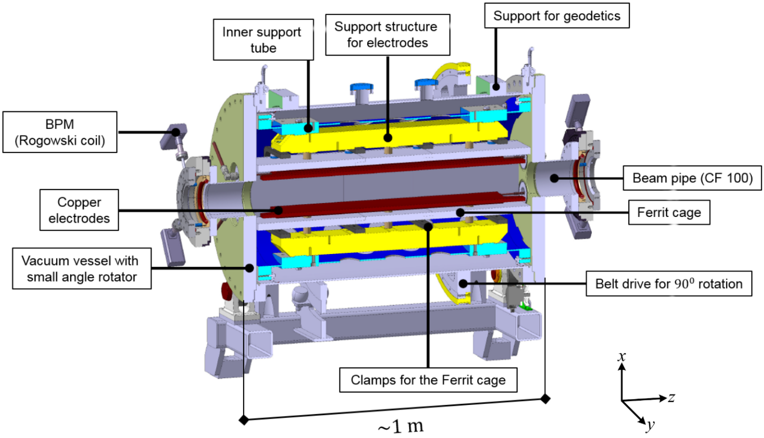


Conventional design
R. Gebel, S. Mey (FZ Jülich)



stripline design
D. Hölscher, J. Slim
(IHF RWTH Aachen)

Wien filter

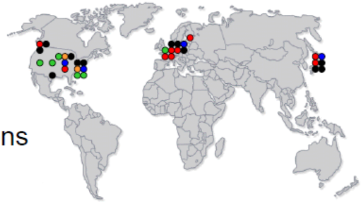


- field: $2.7 \cdot 10^{-2}$Tmm for 1kW input power
- frequency range: 100 kHz-2MHz

EDM Activities Around the World

Rough estimate of numbers of researchers, in total ~500 (with some overlap)

- 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
- 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

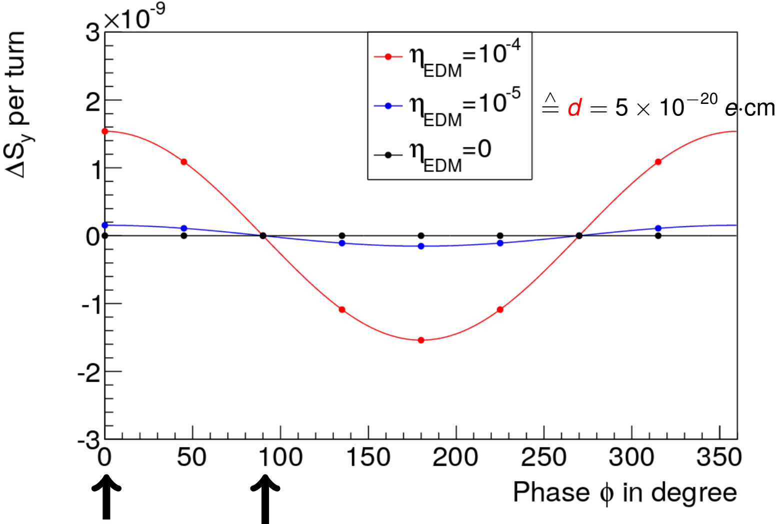
K. Kirch

Systematics

- Splitting of beams: $\delta y = \pm \frac{\beta c R_0 B_r}{E_r Q_y^2} = \pm 1 \cdot 10^{-12}\,\mathrm{m}$
- $Q_y \approx 0.1$: vertical tune
- Modulate $Q_y = Q_y^0 (1 - m\cos(\omega_m t)),\; m \approx 0.1$
- Splitting causes B field of $\approx 0.4 \cdot 10^{-3}\,\mathrm{fT}$
- in one year: 10^4 fills of $1000\,\mathrm{s} \Rightarrow \sigma_B = 0.4 \cdot 10^{-1}\mathrm{fT}$ per fill needed
- Need sensitivity $1.25\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$

D. Kawall

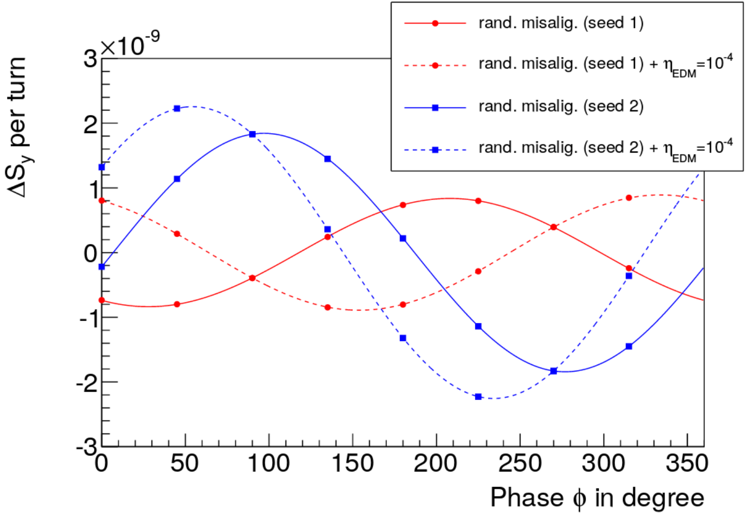
Phase WF - Polarisation



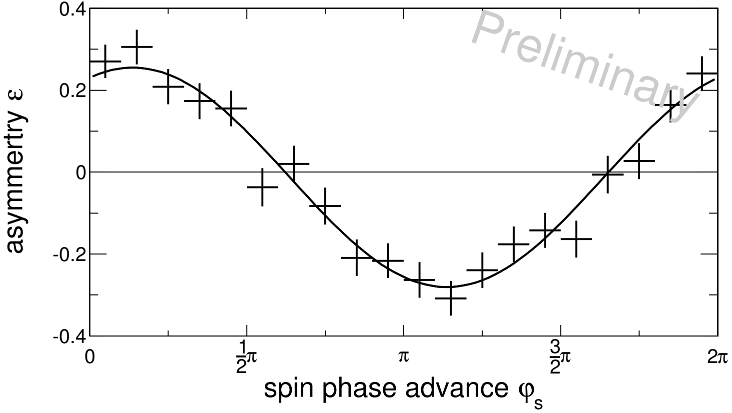
B_y, E_x max von $\vec{s} || \vec{p}$

B_y, E_x max von $\vec{s} \propto \vec{p}$

Systematics

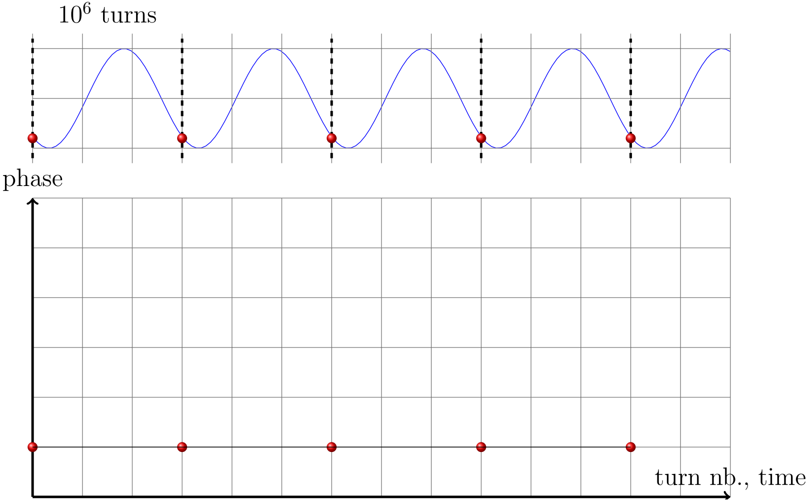


Asymmetry in 1st period



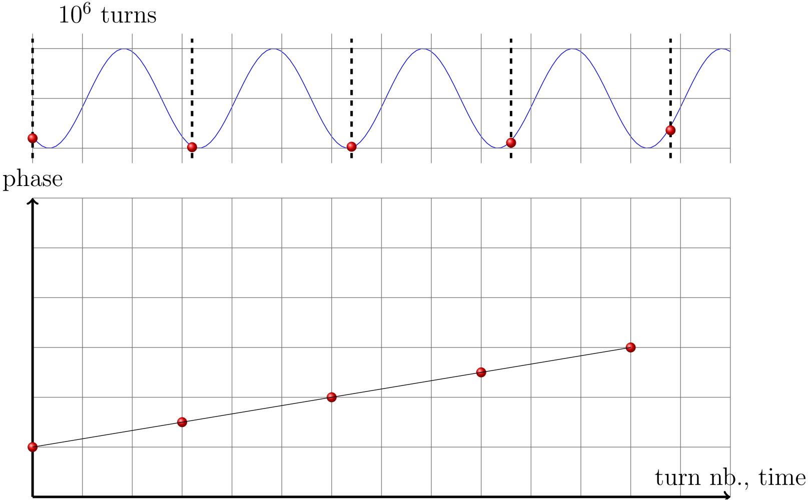
- only works if $T_s = \dfrac{1}{\nu_s f_{rev}}$ is correct.

Phase Measurements



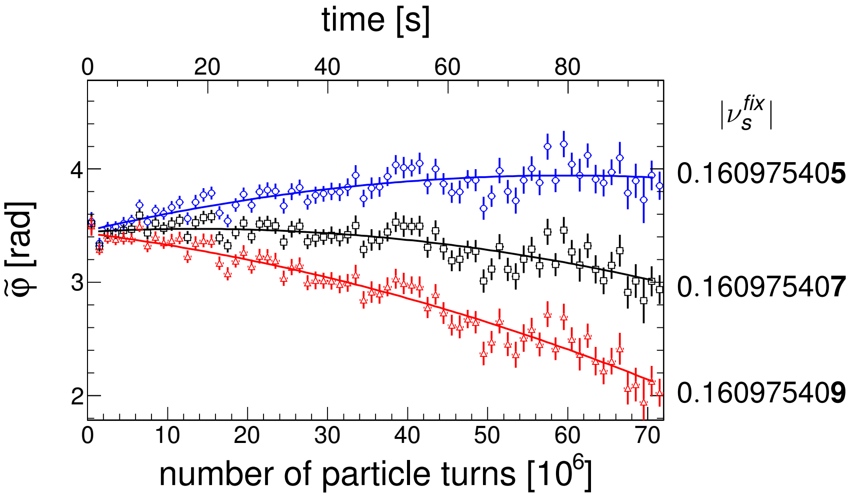
1st derivative gives deviation from assumed spin tune

Phase Measurements



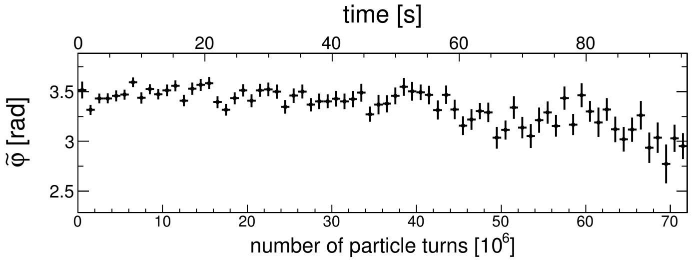
1st derivative gives deviation from assumed spin tune

Phase vs. turn number

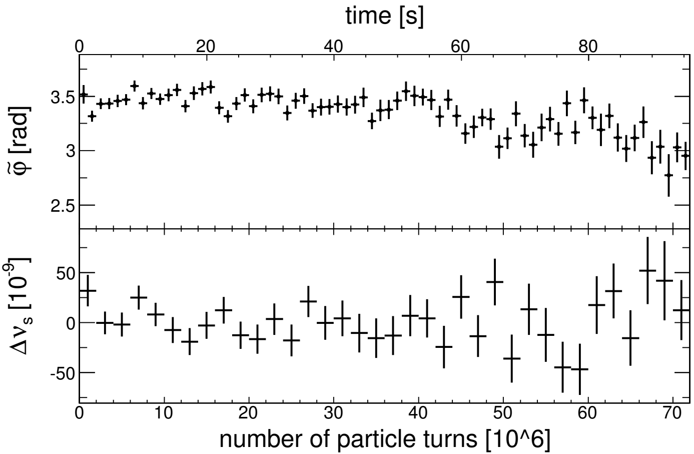


$$\nu_s(n) = \nu_s^0 + \frac{1}{2\pi}\frac{\mathrm{d}\tilde{\varphi}}{\mathrm{d}n}$$

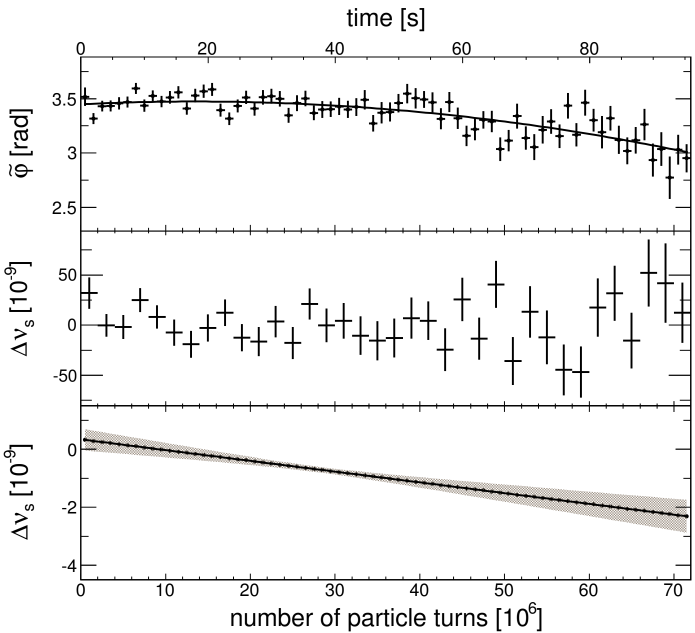
Results: Spin Tune ν_s



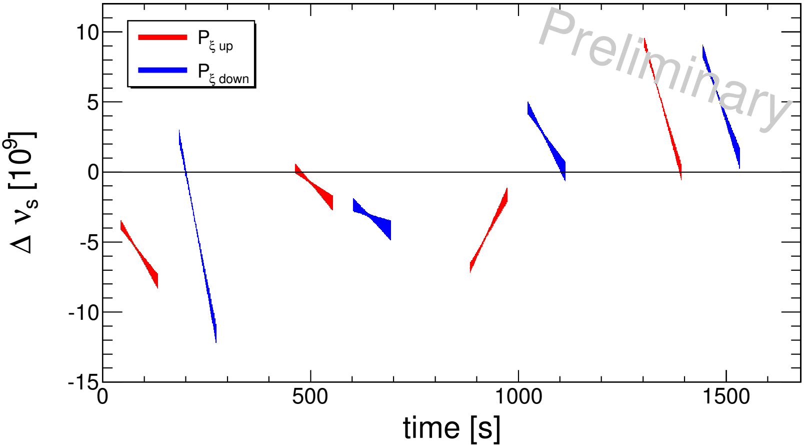
Results: Spin Tune ν_s



Results: Spin Tune ν_s



Spin Tune for different cycles



$\Delta\nu_s = 10^{-8} \rightarrow \Delta p/p \approx 10^{-7}$

Spin Feed back system