

Charged Particle Electric Dipole Moment Searches in Storage Rings

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for the JEDI collaboration



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Outline

- **Introduction: Electric Dipole Moments (EDMs):**

- What is it?

- Why is it interesting?

- What do we know about EDMs?

- **Experimental Method:**

- How to measure charged particle EDMs?

- **Recent Achievements:**

- Spin-** Coherence Time

- Tune

- Feedback

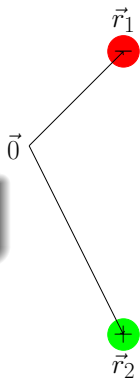
- Tracking

What is it?

Electric Dipoles

Classical definition:

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



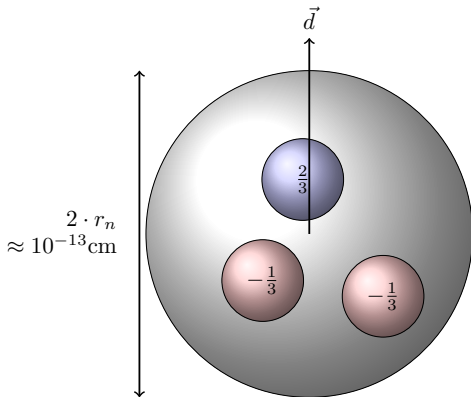
Order of magnitude

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

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

Neutron EDM



neutron EDM of $d_n = 3 \cdot 10^{-26} \text{e}\cdot\text{cm}$ corresponds to separation of u - from d -quarks of $\approx 5 \cdot 10^{-26} \text{cm}$

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

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

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

Consequences:

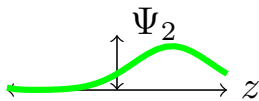
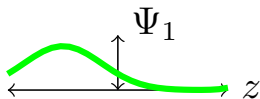
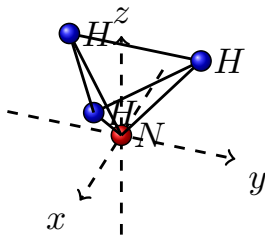
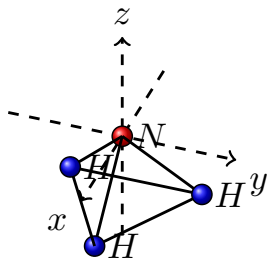
In a state $|a\rangle$ of given parity the expectation value is 0:

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

but if $|a\rangle = \alpha|P = +\rangle + \beta|P = -\rangle$

in general $\langle a|\vec{d}|a\rangle \neq 0 \Rightarrow$ 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 possess an EDM

$$P|\text{had}\rangle = \pm 1|\text{had}\rangle$$

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 possess an EDM

$$P|\text{had}\rangle = \pm 1|\text{had}\rangle$$

unless

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

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

\vec{d} : EDM

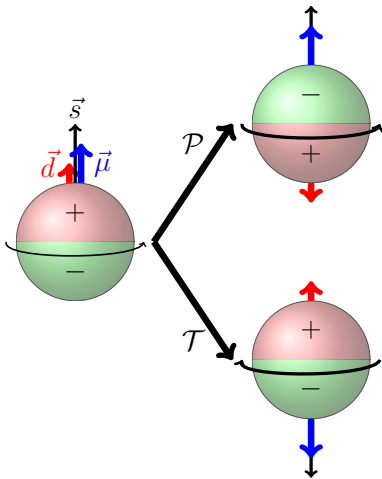
$\vec{\mu}$: magnetic moment

both \parallel to spin

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

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

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



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

Symmetry (Violations) in Standard Model

	electro-mag.	weak	strong
\mathcal{C}	✓	✗	✓
\mathcal{P}	✓	✗	(✓)
$\mathcal{T} \xrightarrow{CPT} \mathcal{CP}$	✓	(✗)	(✓)

- \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 $\theta_{QCD} \lesssim 10^{-10}$ (strong \mathcal{CP} -problem)

Sources of \mathcal{CP} -Violation

and connection to EDMs

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

Why is it interesting?

Matter-Antimatter Asymmetry

Excess of matter in the universe:

	observed	SM prediction
$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$	6×10^{-10}	10^{-18}

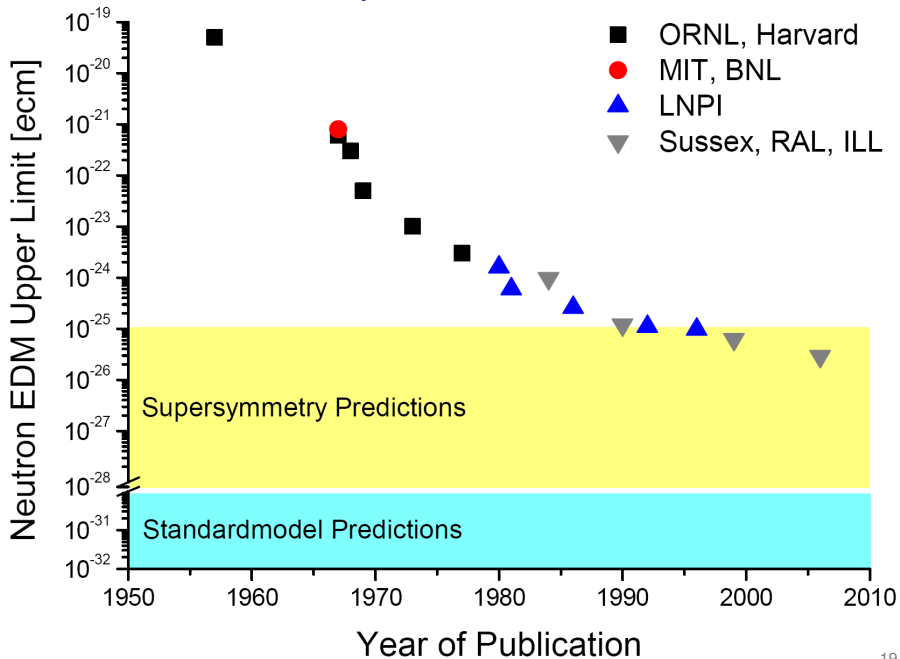
Sakharov (1967): \mathcal{CP} violation needed for baryogenesis

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

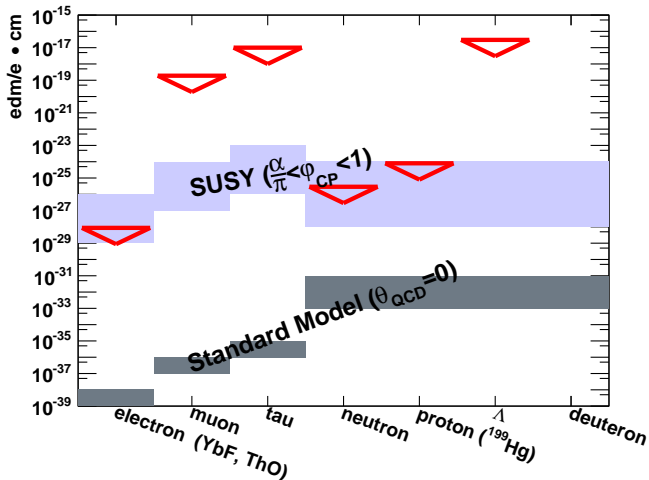
They could manifest in EDMs of elementary particles

What do we know about
EDMs?

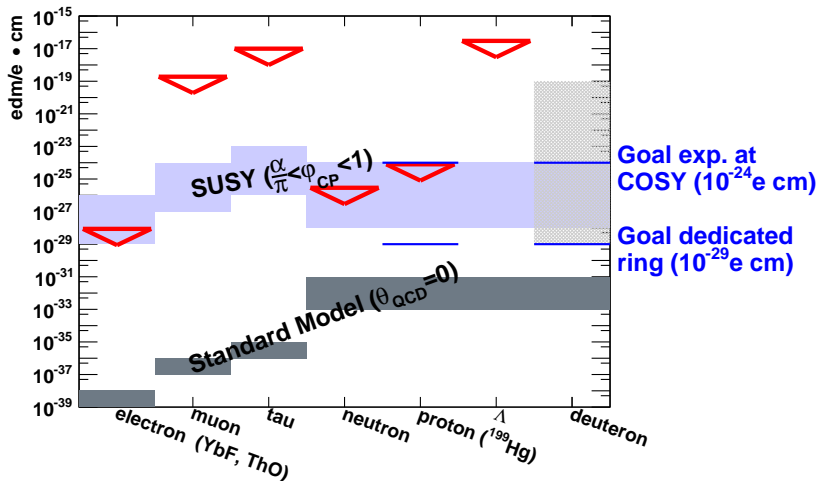
History of Neutron EDM



EDM: Current Upper Limits



EDM: Current Upper Limits

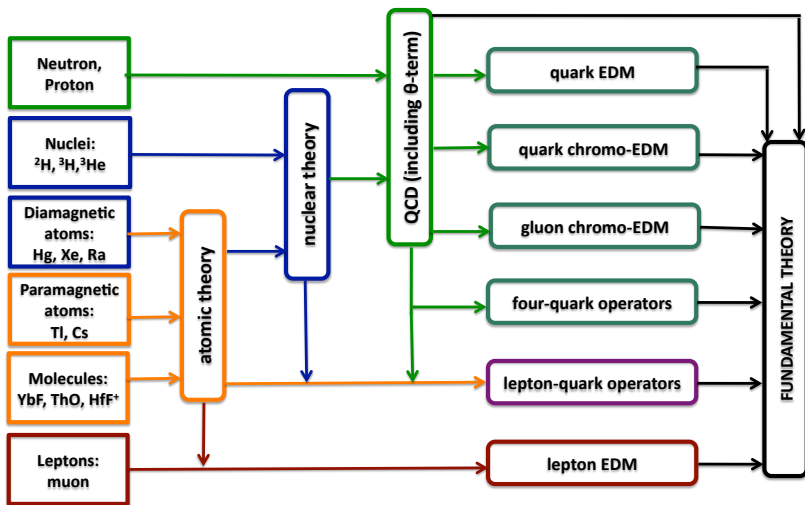


FZ Jülich: EDMs of **charged** hadrons: $p, d, {}^3\text{He}$

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

Sources of CP Violation



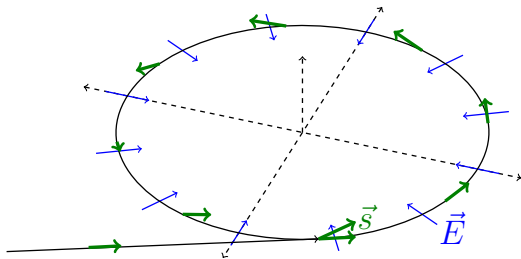
How to measure charged
particle EDMs?

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 → **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 ($\tau = 1000$ s),
- large electric fields ($E = 10$ MV/m)
- polarimetry (analyzing power $A = 0.6$, acc. $f = 0.005$)

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

challenge: get σ_{sys} to the same level

Systematics

Major source:

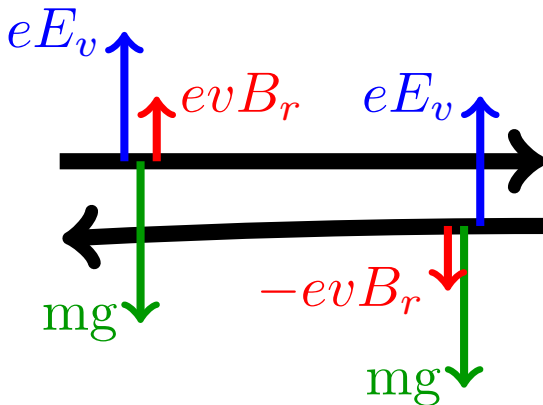
Radial B field mimics an EDM effect:

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

$$B_r = \frac{dE_r}{\mu_N} = \frac{10^{-22} \text{ eV}}{3.1 \cdot 10^{-8} \text{ eV/T}} \approx 3 \cdot 10^{-17} \text{ T}$$

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 $d = 10^{-29} \text{ e cm}$
(possible with SQUID technology)

Spin Precession: Thomas-BMT Equation

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

Ω : angular precession frequency \vec{d} : electric dipole moment
 G : anomalous magnetic moment γ : Lorentz factor

BMT: Bargmann, Michel, Telegdi

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dedicated ring: pure electric field,
freeze horizontal spin motion $\left(G - \frac{1}{\gamma^2 - 1}\right) \stackrel{!}{=} 0$
only possible if $G > 0$ (i.e. protons)

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combined E/B ring

$$G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right) \vec{v} \times \vec{E} \stackrel{!}{=} 0$$

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COSY: pure magnetic ring

access to EDM via motional electric field $\vec{v} \times \vec{B}$,
requires additional radio-frequency E and B fields
to suppress $G\vec{B}$ contribution

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COSY: pure magnetic ring
access to EDM via motional electric field $\vec{v} \times \vec{B}$,
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to suppress $G\vec{B}$ contribution

neglecting EDM term

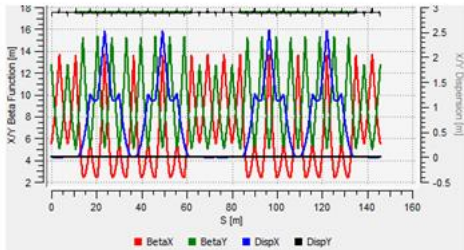
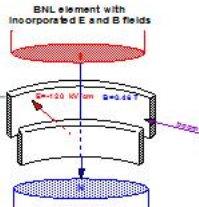
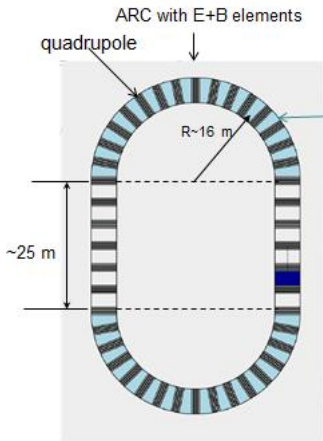
$$\text{spin tune: } \nu_s \approx \frac{|\vec{\Omega}|}{|\omega_{\text{cyc}}|} = \gamma G, \quad (\vec{\omega}_{\text{cyc}} = \frac{e}{\gamma m} \vec{B})$$

Summary of different options



1.) pure magnetic ring	existing (upgraded) COSY ring can be used , shorter time scale	lower sensitivity
2.) pure electric ring	no \vec{B} field needed	works only for p
3.) combined ring	works for $p, d, {}^3\text{He}, \dots$	both \vec{E} and \vec{B} required

Ring Design with E/B elements



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

Y. Senichev

Results of first test measurements

Cooler Synchrotron COSY



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

⇒ **Ideal starting point for charged particle EDM searches**

COSY

RF $E \times B$ dipole

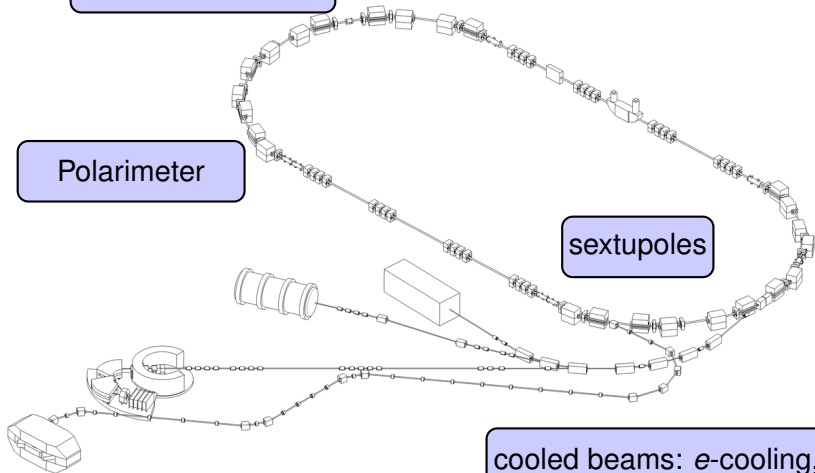
RF solenoid

Polarimeter

sextupoles

cooled beams: e-cooling,
stochastic cooling

Polarized proton & deuterons

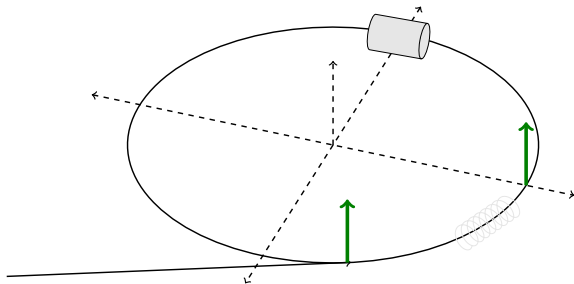


R & D at COSY

- maximize spin coherence time (SCT)
- precise measurement of spin precession (spin tune)
- spin feed back
- spin tracking simulation tools
- 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

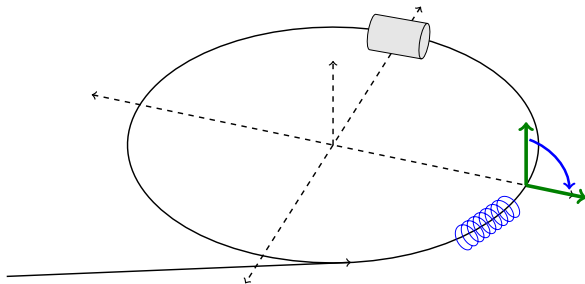
Experimental Setup

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



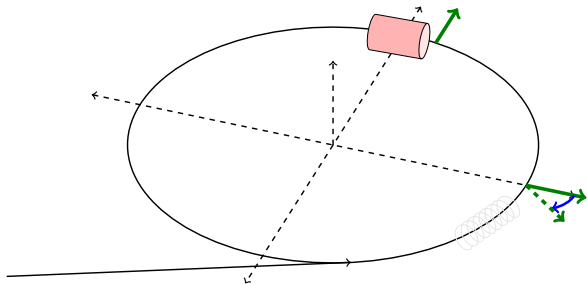
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Experimental Setup

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



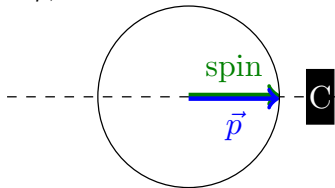
Asymmetry Measurements

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

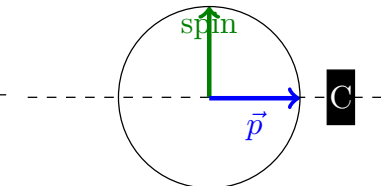
$$A_{up,dn} = \frac{N^{up} - N^{dn}}{N^{up} + N^{dn}} = PA \sin(\gamma G\omega_{rev}t)$$

A : analyzing power, P : polarization

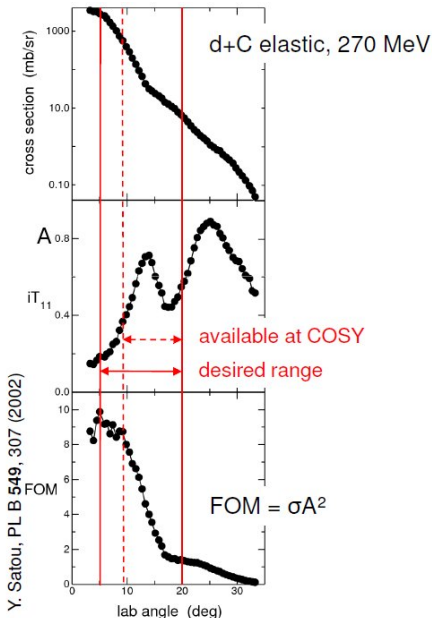
$$A_{up,dn} = 0$$



$$A_{up,dn} = PA$$



Polarimetry



Cross Section &
Analyzing Power
for deuterons

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

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

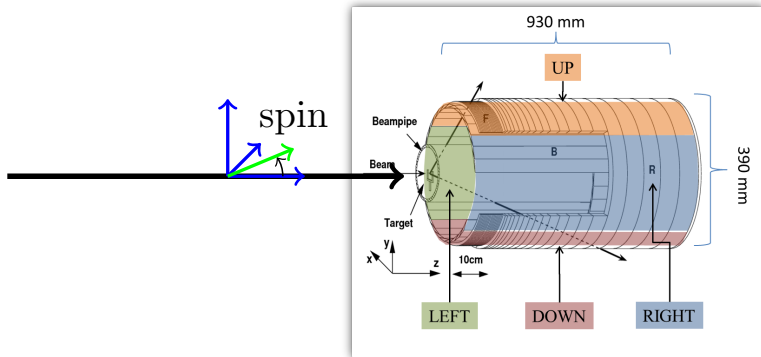
A : analyzing power
 P : beam polarization

Polarimeter

elastic deuteron-carbon scattering

Up/Down asymmetry \propto horizontal polarization $\rightarrow \nu_s = \gamma G$

Left/Right asymmetry \propto vertical polarization $\rightarrow d$



$$N_{up,dn} \propto 1 \pm PA \sin(\nu_s \omega_{rev} t), \quad f_{rev} \approx 750 \text{ kHz}$$

Up - dn asymmetry $A_{up,dn}$

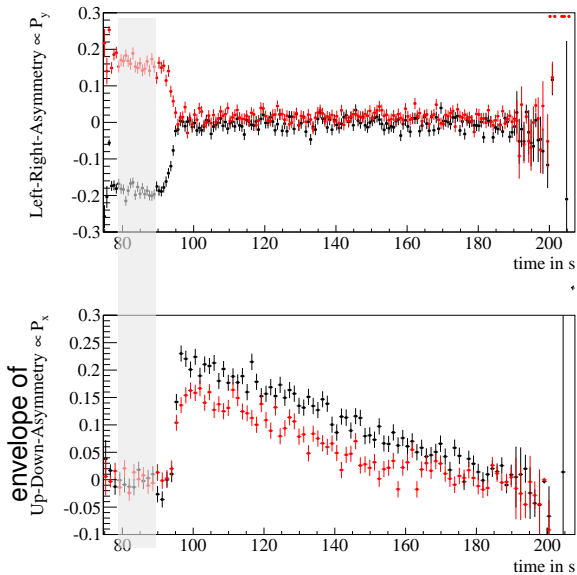
$$A_{up,dn}(t) = AP_0 e^{-t/\tau} \sin(\nu_s \omega_{rev} t + \varphi)$$

- $\tau \rightarrow$ spin decoherence
- $\nu_s \rightarrow$ spin tune

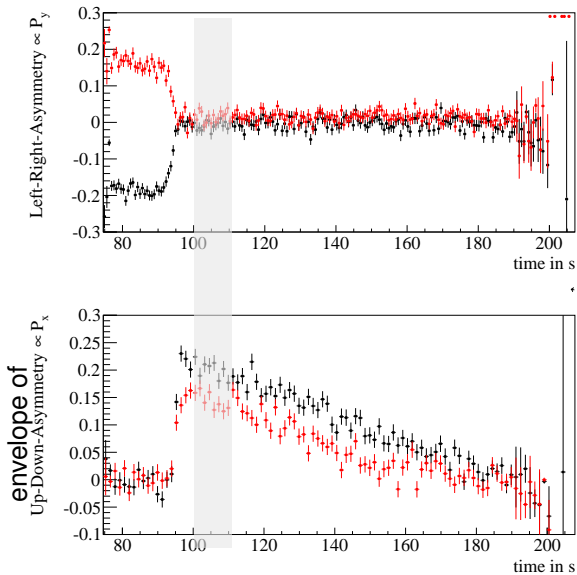
time scales: $\nu_s f_{rev} \approx 120$ kHz

τ in the range 1-1000 s

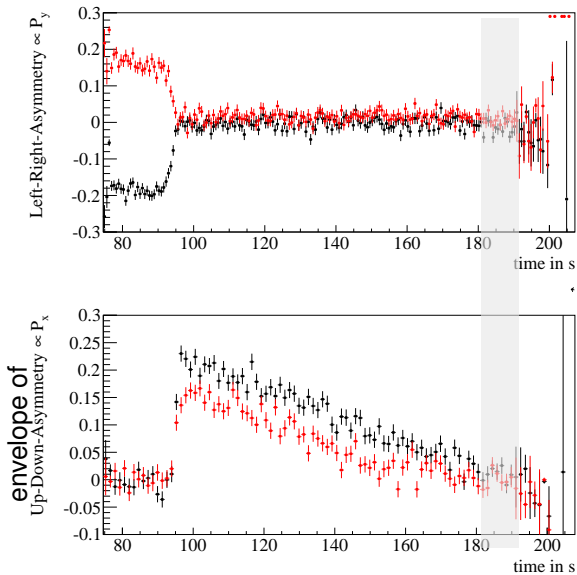
Polarization Flip



Polarization Flip

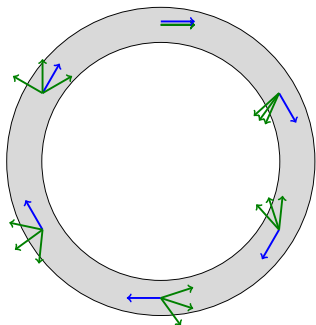


Polarization Flip

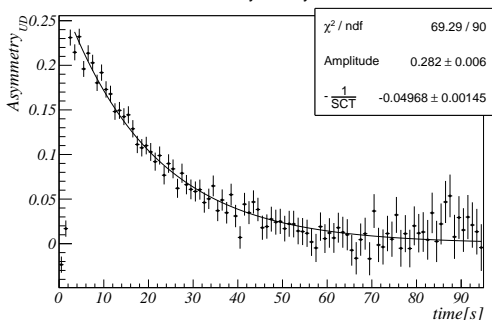


Results: Spin Coherence Time (SCT)

Short Spin Coherence Time



Horizontal Asymmetry Run: 2042



unbunched beam

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

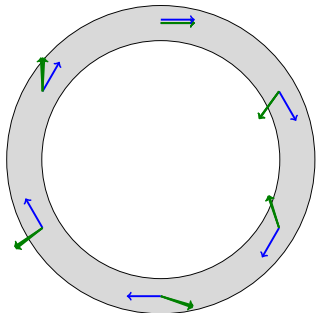
\Rightarrow decoherence after < 1 s

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

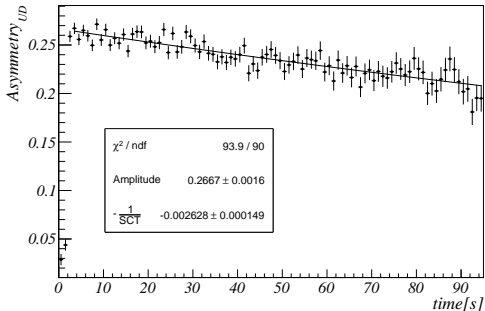
\Rightarrow SCT $\tau = 20$ s

Results: Spin Coherence Time (SCT)

Long Spin Coherence Time

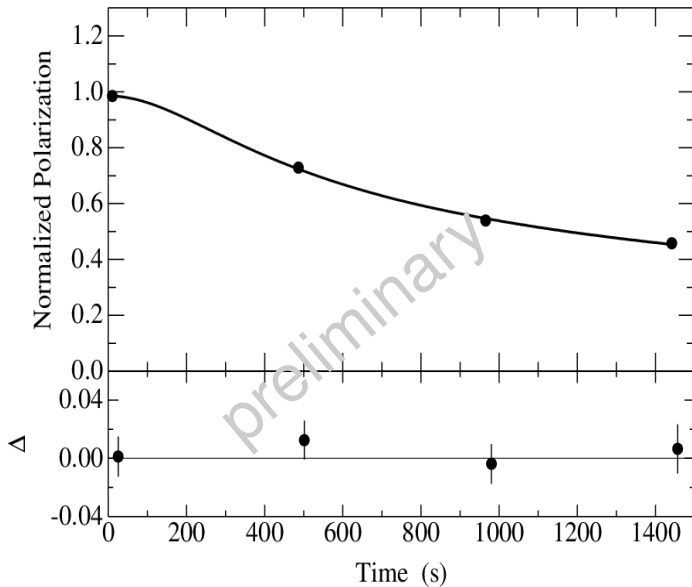


Horizontal Asymmetry Run: 2051



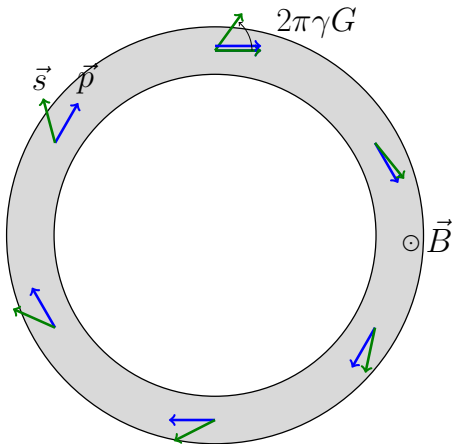
SCT of $\tau = 400$ s, after correction with sextupoles
(chromaticities $\xi \approx 0$)

SCT: Longer Cycles



Spin Tune ν_s

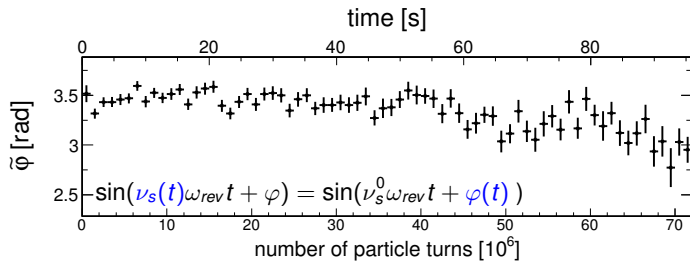
Spin tune: $\nu_s = \gamma G = \frac{\text{nb. of spin rotations}}{\text{nb. of particle revolutions}}$



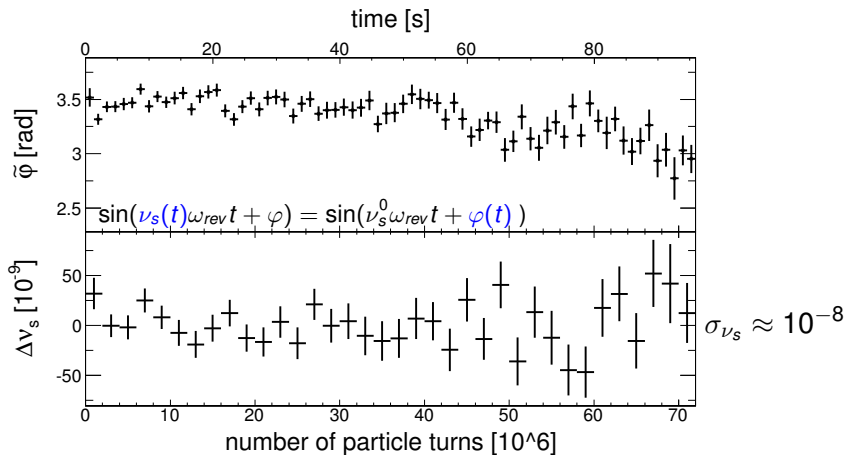
deuterons: $p_d = 1 \text{ GeV}/c$ ($\gamma = 1.13$), $G = -0.14256177(72)$

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

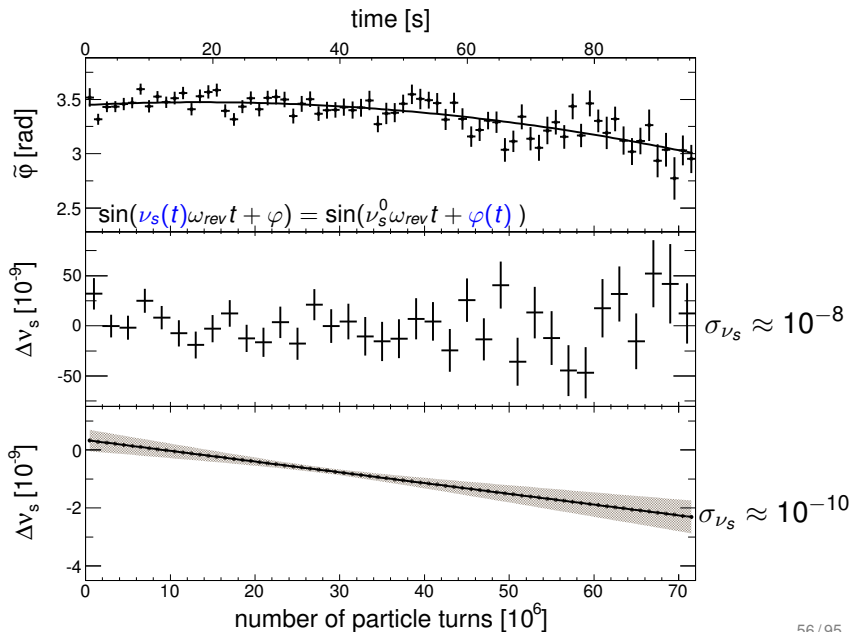
Results spin tune



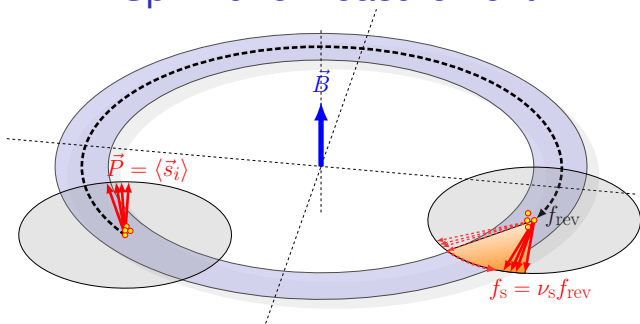
Results spin tune



Results spin tune

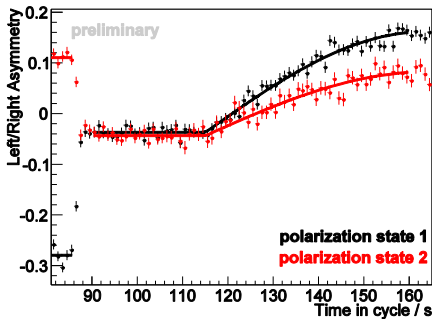


Spin Tune Measurement



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

Spin Feed back system

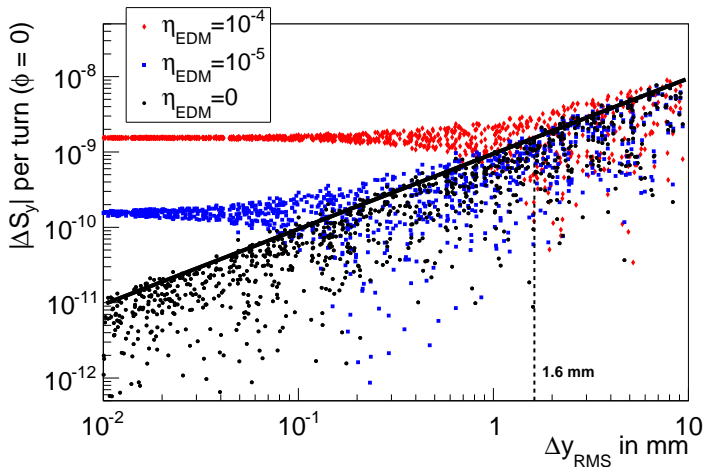


- polarisation rotation in horizontal plane at $t = 85$ s
 - COSY rf changed during cycle in steps of 3.7 MHz ($f_{\text{rev}}=750603$ Hz) according to online ν_S measurement to
- keep spin precession and solenoid RF constant
- solenoid (low amplitude) switched on at $t = 115$ s
 - polarisation goes back to vertical direction

Simulations

- EDM signal is build-up of vertical polarisation
- 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



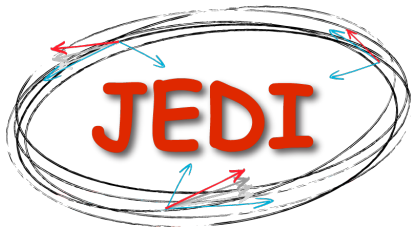
Random Misalignments from $1\mu\text{m}$ to 1 mm

$\eta = 10^{-5}$ corresponds to edm of $5 \times 10^{-20} \text{ e}\cdot\text{cm}$

M. Rosenthal

JEDI Collaboration

- **JEDI** = **J**ülich **E**lectric **D**ipole Moment **I**nvestigations
- \approx 100 members
(Aachen, Bonn, Daejeon, Dubna, Ferrara, Grenoble, Indiana, Ithaca, Jülich, Krakow, Michigan, Minsk, Novosibirsk, St. Petersburg, Stockholm, Tbilisi, ...)
- \approx 10 PhD students
- close collaboration with srEDM collaboration in US/Korea



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

Summary & Outlook

- **EDMs** of elementary particles are of high interest to disentangle various sources of *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:** few hundred seconds
 - spin tune:** 10^{-10} in 100 s
 - feed back system** allows to control spin
 - simulations** to understand systematics

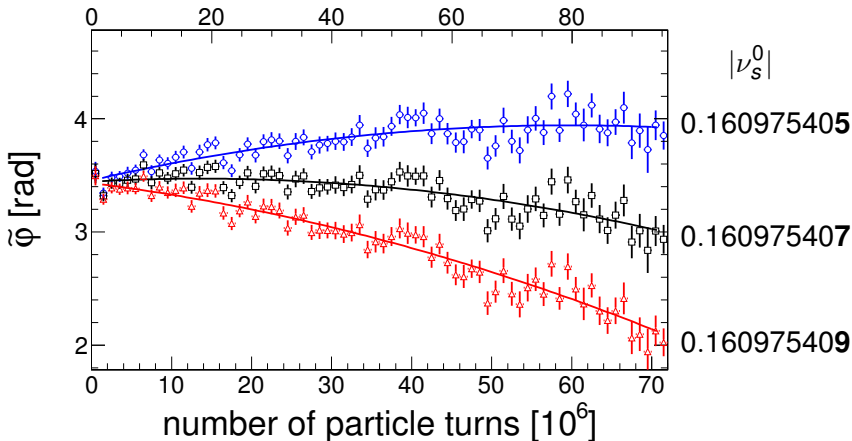
Spare

Up - dn asymmetry $A_{up,dn}$

Long SCT τ allows now to observe $\nu_s(t) \approx \gamma G$,
respectively $\varphi(t)$

$$\begin{aligned} A_{up,dn}(t) &= AP_0 e^{-t/\tau} \sin(\nu_s(t) \omega_{rev} t + \varphi) \\ &= AP_0 e^{-t/\tau} \sin(\nu_s^0 \omega_{rev} t + \varphi(t)) \end{aligned}$$

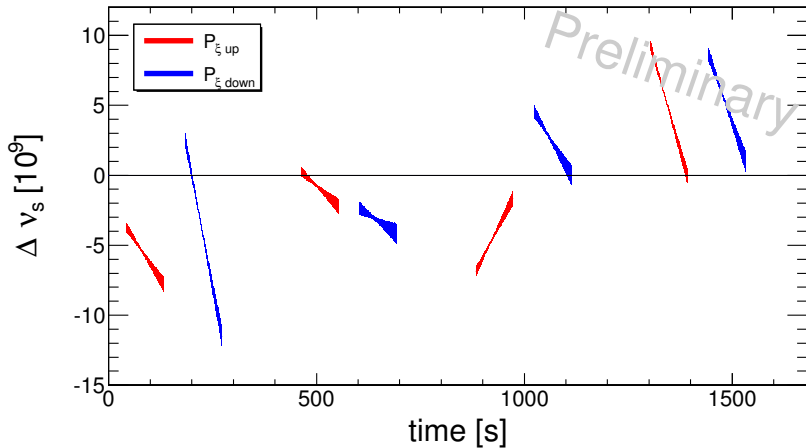
Phase vs. turn number time [s]



$$|\nu_s(t)| = |\nu_s^0| + \frac{1}{\omega_{rev}} \frac{d\tilde{\varphi}}{dt}$$

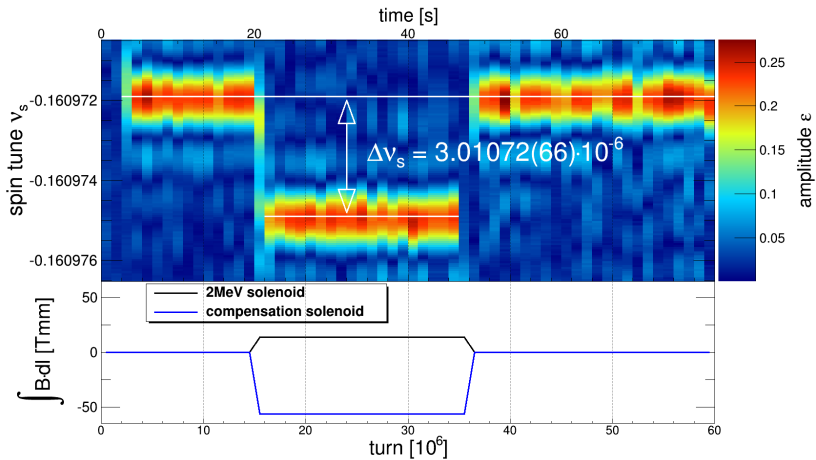
$$\Rightarrow |\nu_s(38 \text{ s})| = (16\,097\,540\,628.3 \pm 9.7) \times 10^{-11}$$

Spin Tune for different cycles

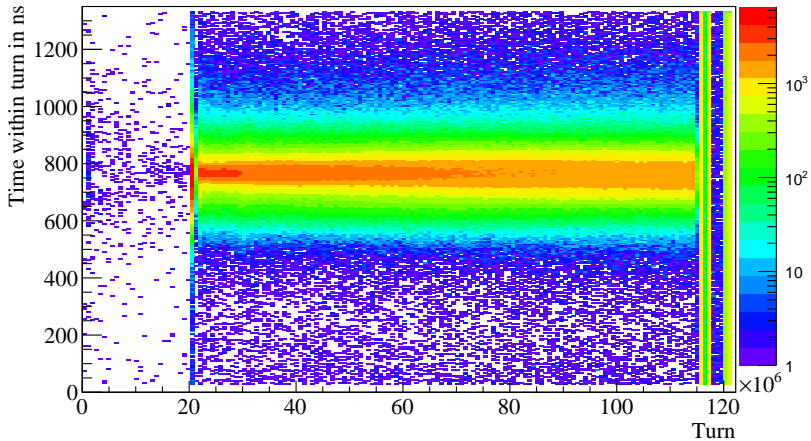


$$\Delta \nu_s = 10^{-8} \rightarrow \Delta p/p \approx 10^{-7}$$

Spin Tune jumps

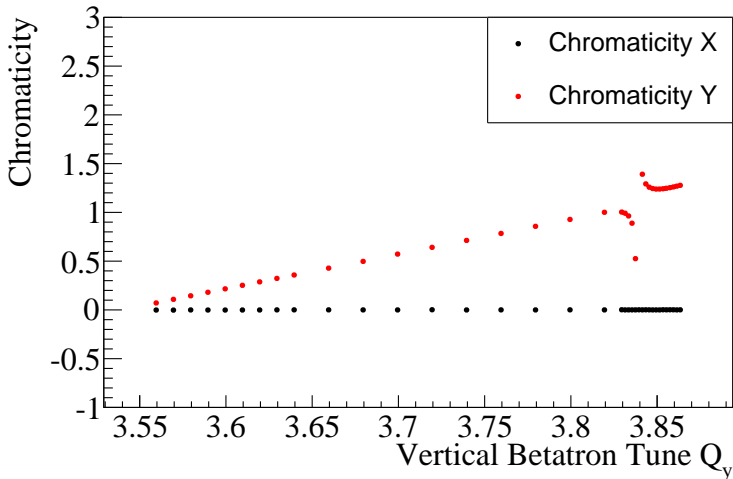


Event Distribution



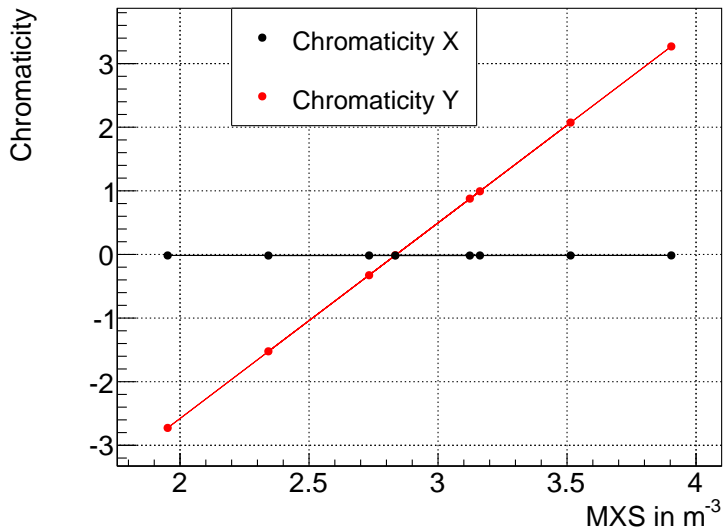
SCT \leftrightarrow Chromaticity I

Chromaticities vs. tune giving maximal SCT according to simulation



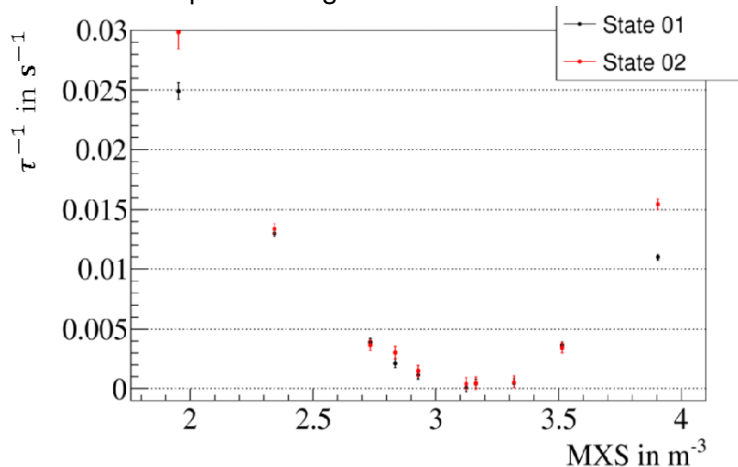
SCT ↔ Chromaticity II

Chromaticities vs. sextupole setting



SCT \leftrightarrow Chromaticity I

SCT vs. sextupole setting



Maximal SCT for predicted sextupole setting

SCT \leftrightarrow chromaticity

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

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

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

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

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

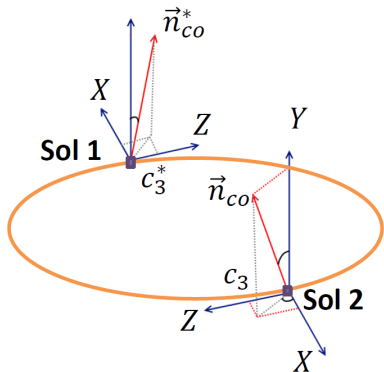
$$\Rightarrow \frac{\Delta \beta}{\beta_0} \neq 0 \Rightarrow \frac{\Delta \nu_s}{\nu_s} \neq 0$$

sextupole settings gives access to

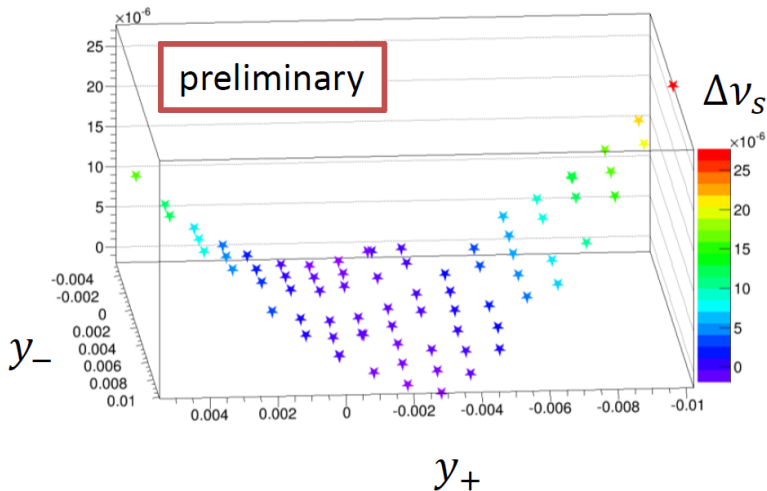
$$\left\langle \frac{\Delta L}{L_0} \right\rangle_{x,y} = \frac{\pi}{L_0} \epsilon_{x,y} \xi_{x,y}$$

Spin Tune as tool to investigate systematics

$$\nu_s = \gamma G + \text{imperfections kicks}$$

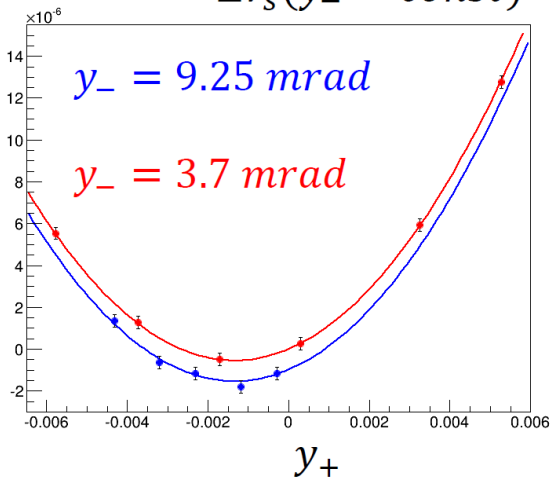


- Create artificial imperfections with solenoids/steerers
- measure spin tune change $\Delta\nu_s$
- expectation $\Delta\nu_s \propto (y_{\pm} - a_{\pm})^2$
 a_{\pm} : kicks due to imperfections,
 y_{\pm} : kicks due to solenoids



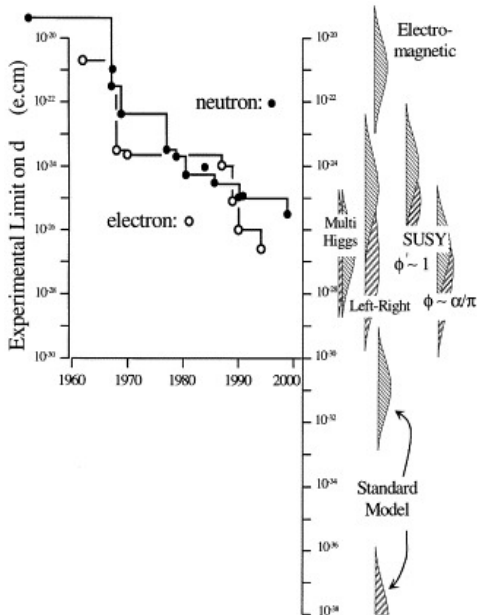
- parabolic behavior expected from simulations
- $y^\pm = \frac{\chi_1 \pm \chi_2}{2}$, $\chi_{1,2}$: solenoid strength
for perfect machine, minimum should be at $y^+ = 0$

$$\Delta v_s(y_- = \text{const})$$



- 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:

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

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

neutron:

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

SM EDM values

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

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

$$d_n = \mathcal{O}(g_w^4 g_s^2) = \mathcal{O}(G_F^2 g_s^2) \quad (3\text{loop})$$

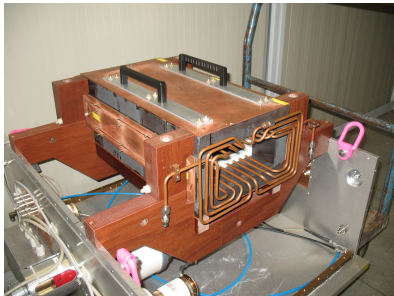
$$d_e = \mathcal{O}(g_w^6 g_s^2) = \mathcal{O}(G_F^3 g_s^2) \quad (4\text{loop})$$

Electrostatic Deflectors

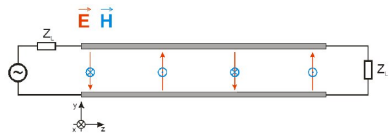


- Electrostatic deflectors from Fermilab ($\pm 125\text{kV}$ at 5 cm $\hat{=} 5\text{MV/m}$)
- large-grain Nb at plate separation of a few cm yields $\approx 20\text{MV/m}$

Wien Filter



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



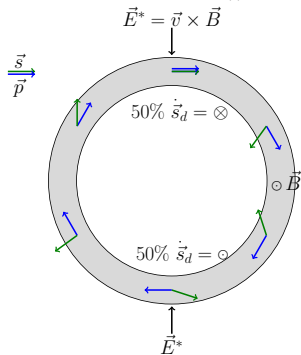
stripline design
D. Hölscher, J. Slim
(IHF RWTH Aachen)

Pure Magnetic Ring

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

Problem:

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



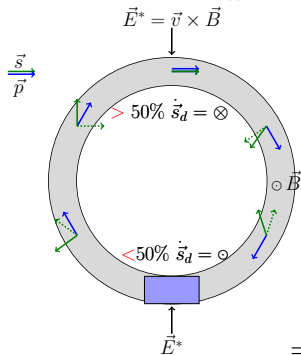
E^* field in the particle rest frame tilts spin due to EDM up and down
 \Rightarrow **no net EDM effect**

Pure Magnetic Ring

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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!**

Spin Precession: Thomas-BMT Equation

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

Ω : angular precession frequency d : electric dipole moment
 G : anomalous magnetic moment γ : Lorentz factor

COSY: pure magnetic ring
access to EDM via motional electric field $\vec{v} \times \vec{B}$,
requires additional radio-frequency E and B fields
to suppress $G\vec{B}$ contribution

neglecting EDM term

$$\text{spin tune: } \nu_s \approx \frac{|\vec{\Omega}|}{|\omega_{cyc}|} = \gamma G, \quad (\vec{\omega}_{cyc} = \frac{e}{\gamma m} \vec{B})$$

2. Pure Electric Ring

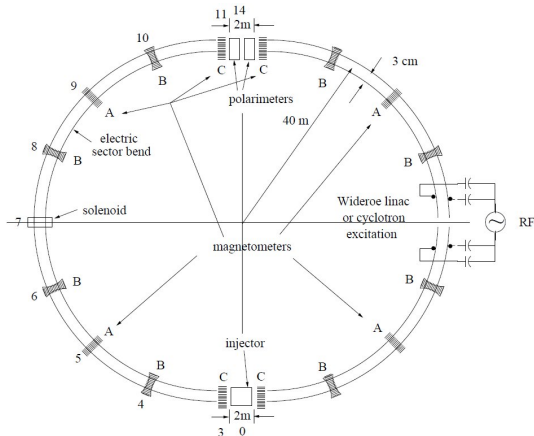


Figure 3: An all-electric storage ring lattice for measuring the electric dipole moment of the proton. Except for having longer straight sections and separated beam channels, the all-in-one lattice of Fig. 1 is patterned after this lattice. Quadrupole and sextupole families, and tunes and lattice functions of the all-in-one lattice of Fig. 1 will be quite close to those given for this lattice in reference[3]. The match will be even closer with magnetic field set to zero for proton operation.

Brookhaven National Laboratory (BNL) Proposal

3. Combined \vec{E}/\vec{B} ring

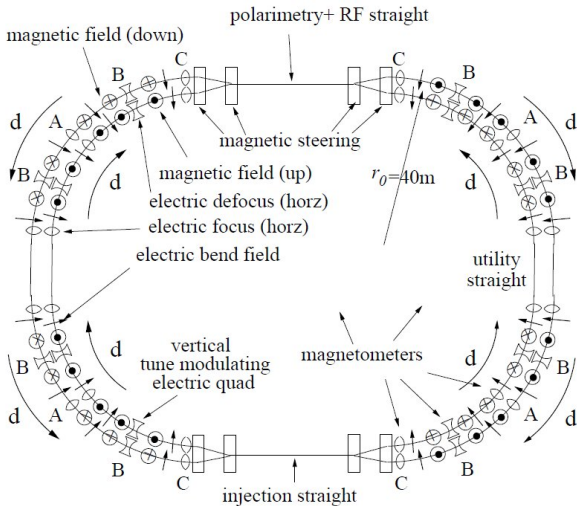


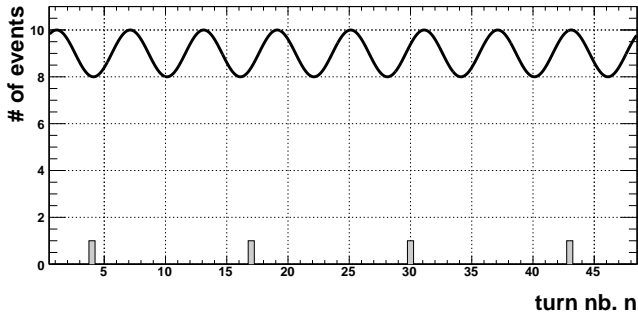
Figure 1: "All-In-One" lattice for measuring EDM's of protons, deuterons, and helions.

Under discussion at Forschungszentrum Jülich (design: R. Talman)

Details of spin tune analysis

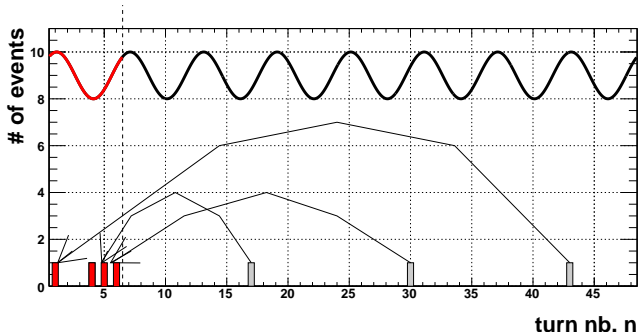
Spin Tune ν_s measurement

- Problem: detector rate ≈ 5 kHz, $f_{rev} = 750$ kHz
 \Rightarrow only 1 hit every 25th period
- not possible to use usual χ^2 -fit
- use unbinned Maximum Likelihood (under investigation)

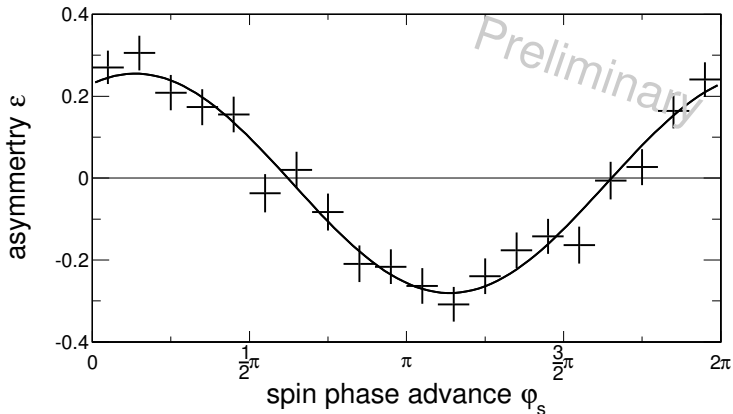


Spin Tune ν_s measurement

- map all events into first period ($T = 1/(\nu_s f_{rev}) \approx 8\mu\text{s}$) and perform χ^2 -fit (requires knowledge of $\nu_s f_{rev}$)
- Analysis is done in macroscopic time bins of 10^6 turns (≈ 1.3 s)

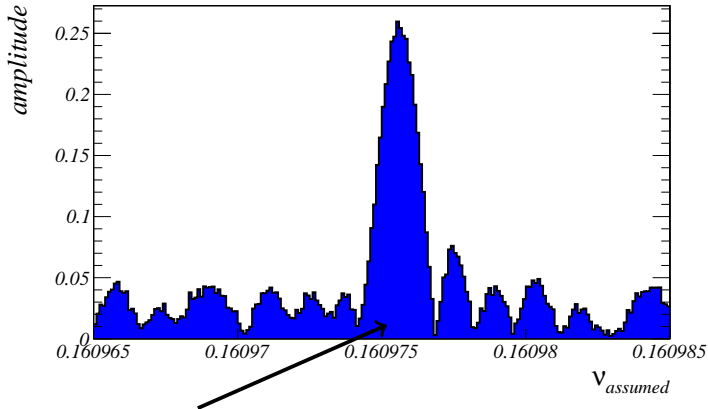


Asymmetry in 1st period



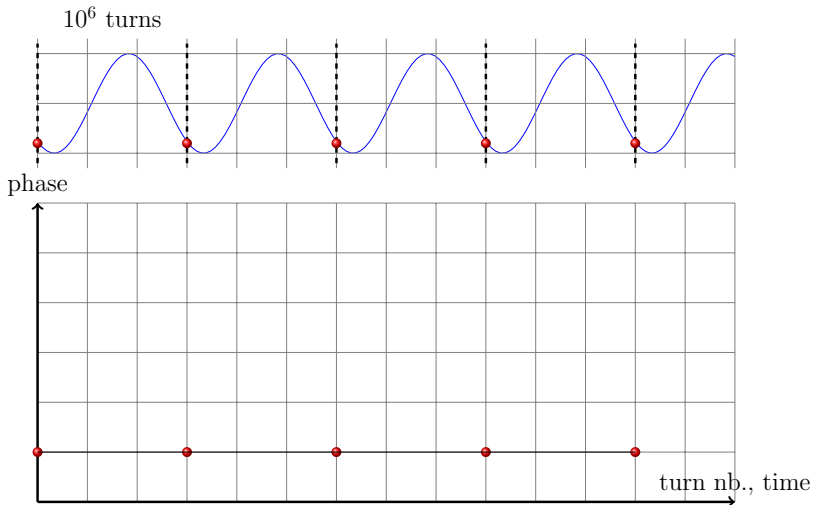
- only works if $T_s = \frac{1}{\nu_s f_{rev}}$ is correct.

Scan of ν_s



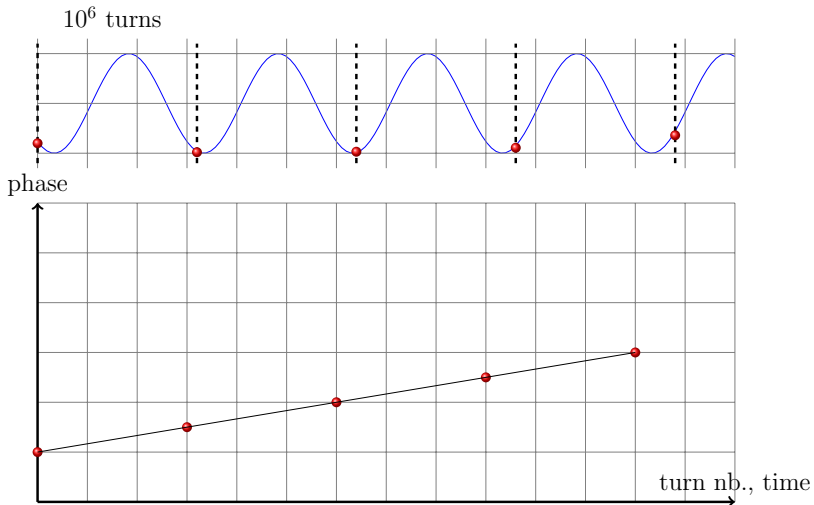
- allows for $\sigma_{\nu_s} \approx 10^{-6}$
- now fix ν_s at maximum and look at phase vs. turn number
phase is determined for turn intervals of 10^6 turns

Phase Measurements



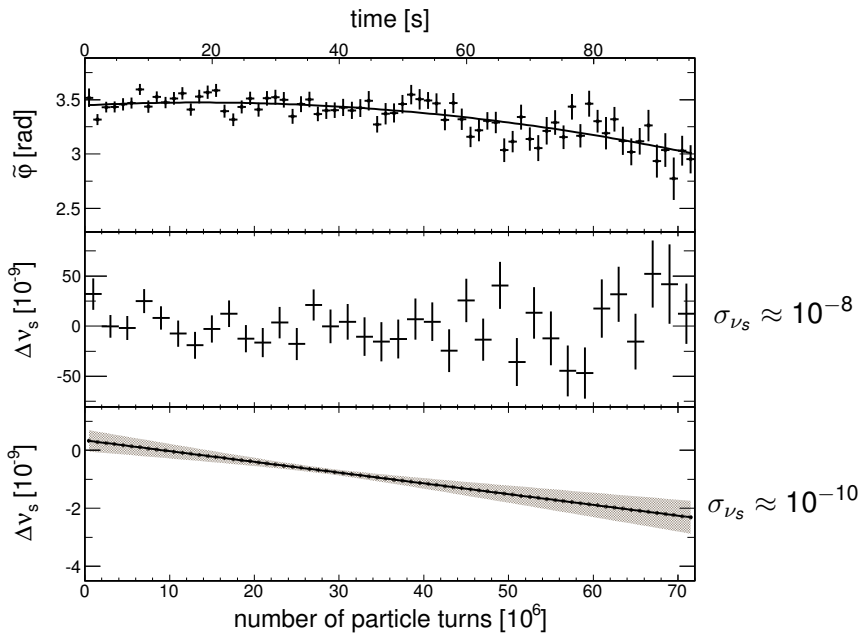
1st derivative gives deviation from assumed spin tune

Phase Measurements

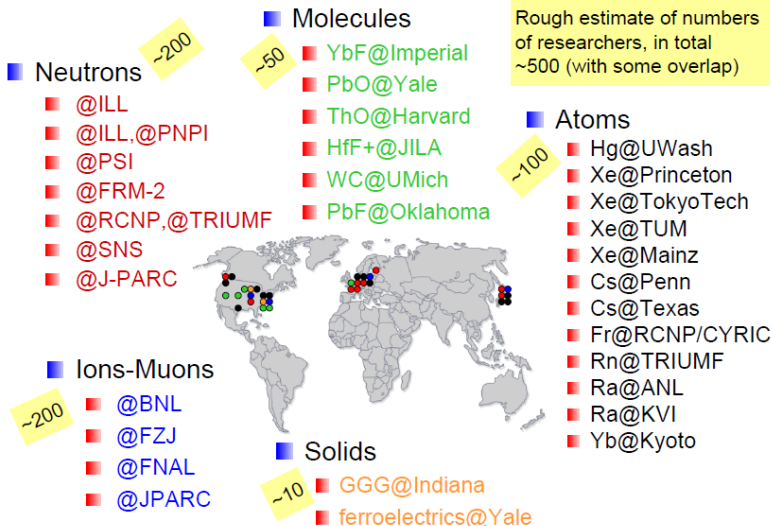


1st derivative gives deviation from assumed spin tune

Results: Spin Tune ν_s



EDM Activities Around the World



K. Kirch

Systematics

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

D. Kaway