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:**

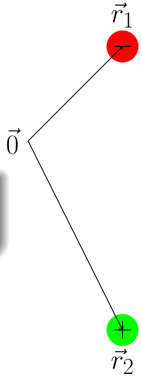
  Spin- Coherence Time
  Tune
  Feedback
  Tracking

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 Å= 10^{-8}cm	
EDM		
naive expectation	$10^{-8} e \cdot \mathrm{cm}$	
observed	water molecule	
	$2 \cdot 10^{-8} e \cdot$ cm	

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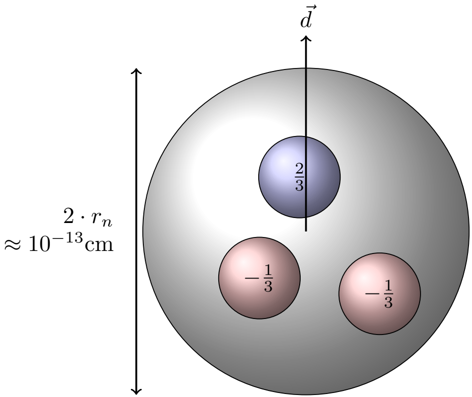
$\|\vec{r}_1 - \vec{r}_2\|$	1 Å= 10^{-8}cm	$1\mathrm{fm} = 10^{-13}$cm
EDM		
naive expectation	$10^{-8} e \cdot \mathrm{cm}$	$10^{-13} e \cdot \mathrm{cm}$
observed	water molecule	neutron
	$2 \cdot 10^{-8} e\cdot$ cm	$< 3 \cdot 10^{-26} e\cdot$ cm

Neutron EDM



neutron EDM of $d_n = 3 \cdot 10^{-26} e{\cdot}\text{cm}$ 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 ($\vec{r} \to -\vec{r}$):

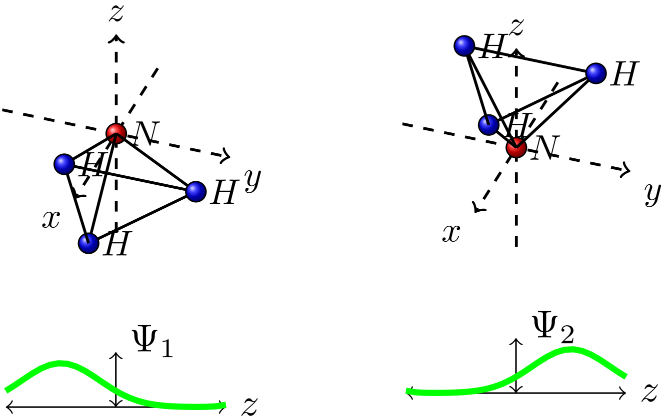
$$\mathcal{P}^{-1}\vec{d}\mathcal{P} = -\vec{d}$$

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

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

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

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

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

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

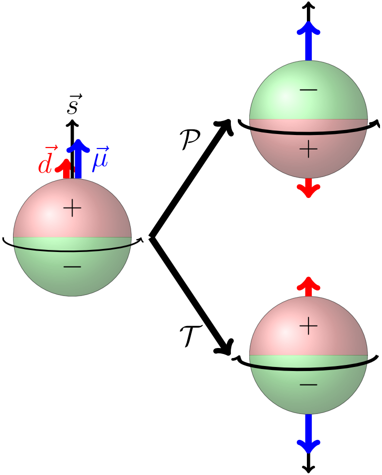
unless

$\mathcal{P}$ 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

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



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

Symmetry (Violations) in Standard Model

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

- $\mathcal{C}$ 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)

Sources of $\mathcal{CP}-$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

Why is it interesting?

Matter-Antimatter Asymmetry

Excess of matter in the universe:

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

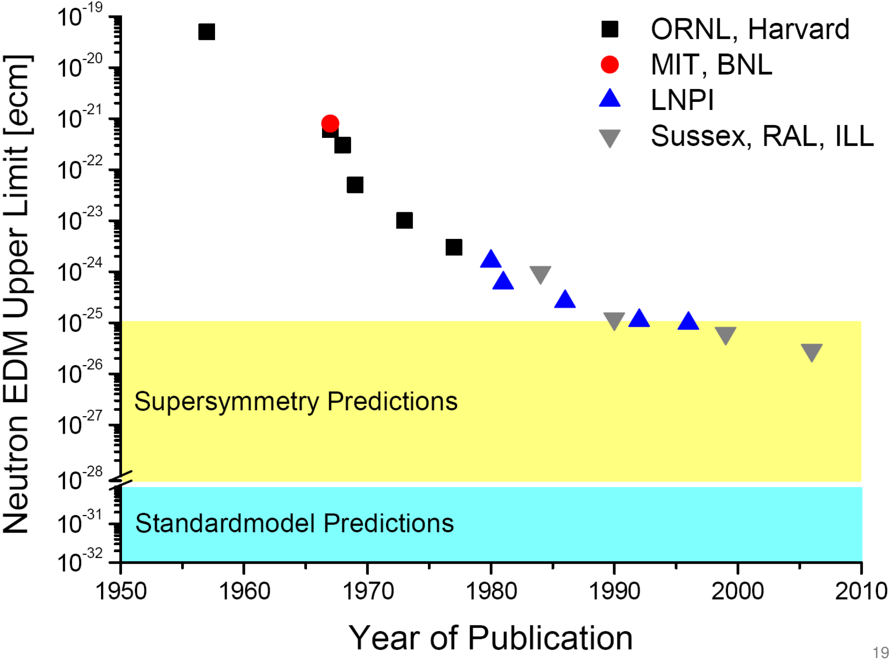
Sakharov (1967): $\mathcal{CP}$ violation needed for baryogenesis

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

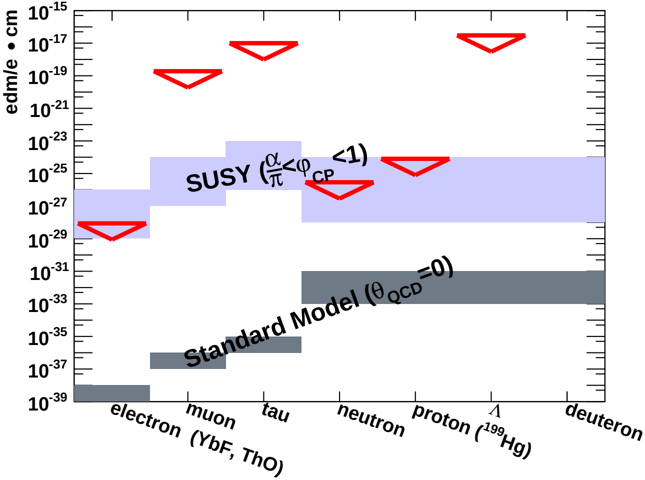
They could manifest in EDMs of elementary particles

What do we know about EDMs?

History of Neutron EDM



EDM: Current Upper Limits



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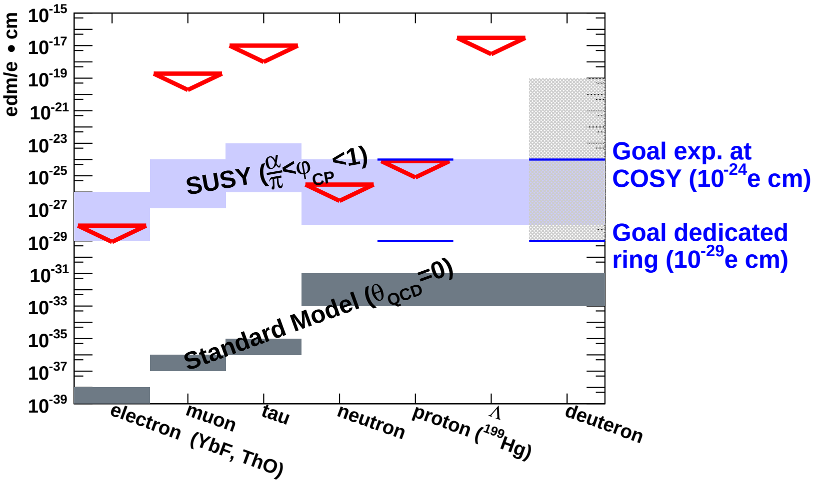
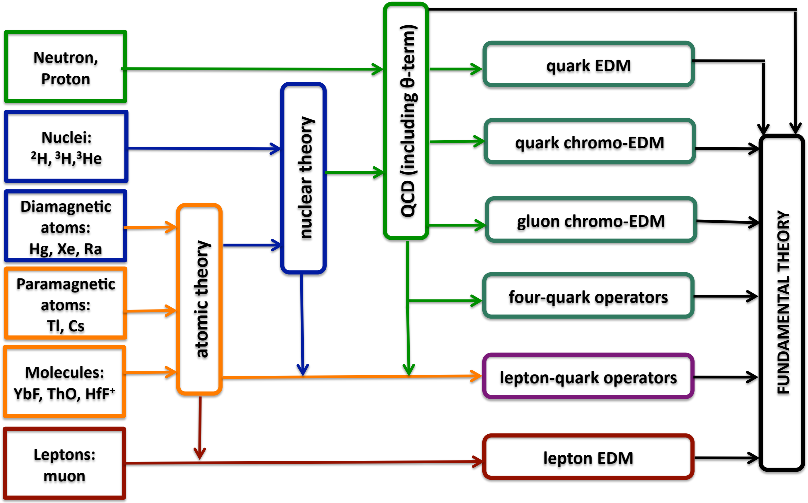


FZ Jülich: EDMs of **charged** hadrons: p, d, ^{3}He

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

Sources of $\mathcal{CP}$ Violation

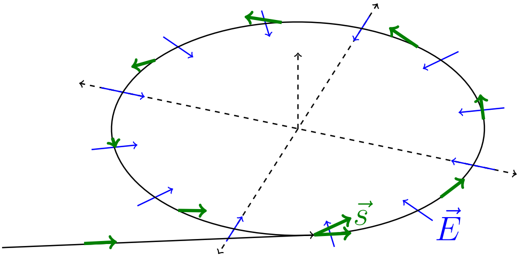


J. de Vries

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 $s_\perp \propto |d|$

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

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

challenge: get σ_{sys} to the same level

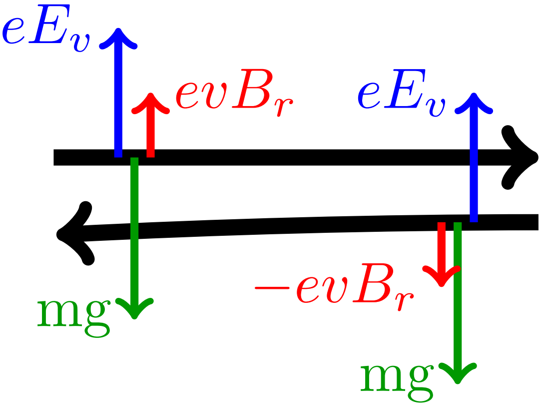
Systematics

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

Spin Precession: Thomas-BMT Equation

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

Ω: angular precession frequency

G: anomalous magnetic moment

d: electric dipole 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

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

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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

Spin Precession: Thomas-BMT Equation

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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

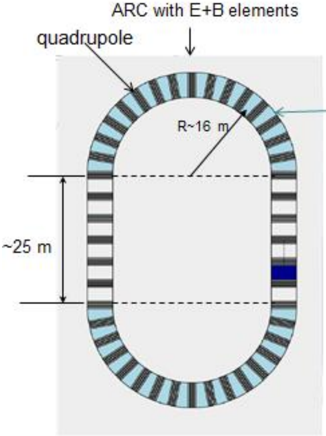
neglecting EDM term

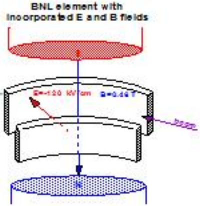
spin tune: $\nu_s \approx \frac{|\vec{\Omega}|}{|\omega_{\mathrm{cyc}}|} = \gamma G$, $\quad (\vec{\omega}_{cyc} = \frac{e}{\gamma m}\vec{B})$

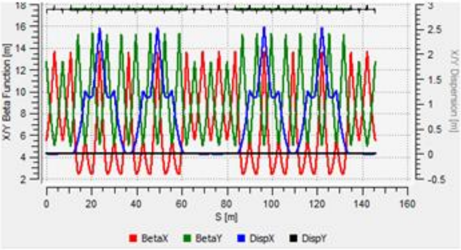
Summary of different options

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}He, …	both $\vec{E}$ and $\vec{B}$ required

Ring Design with E/B elements







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

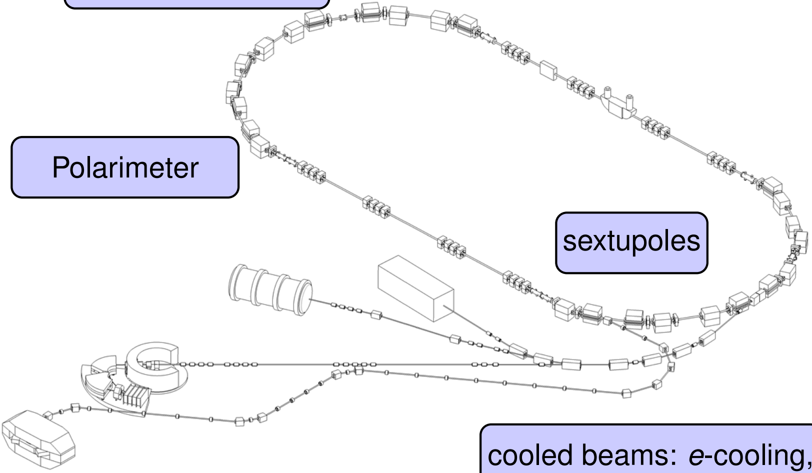
Y. Senichev

Results of first test measurements

Cooler Synchrotron COSY

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

COSY

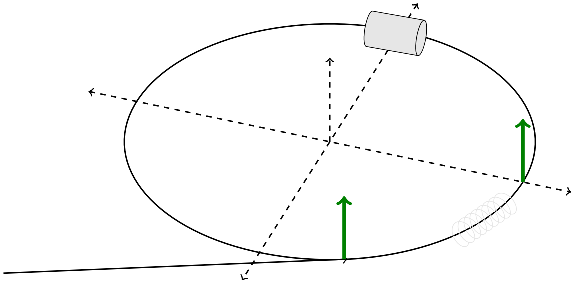

RF $E \times B$ dipole
RF solenoid
Polarimeter
sextupoles
cooled beams: e-cooling,
stochastic cooling
Polarized proton & deuterons

R & D at COSY

- maximize spin coherence time (SCT)
- 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

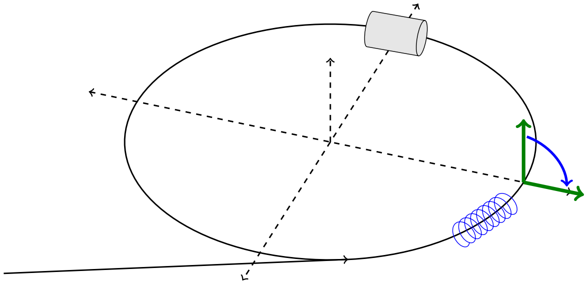
Experimental Setup

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



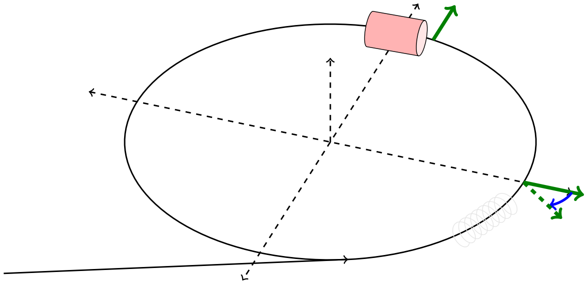
Experimental Setup

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



Experimental Setup

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



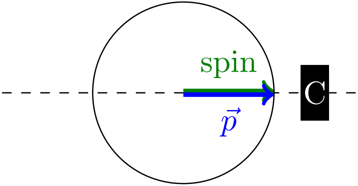
Asymmetry Measurements

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

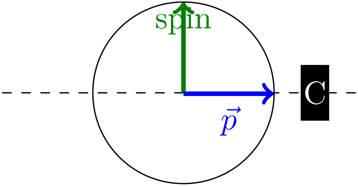
$$A_{up,dn} = \frac{N^{up} - N^{dn}}{N^{up} + N^{dn}} = P\,A\,\sin(\gamma G \omega_{rev} t)$$

A: analyzing power, P : polarization

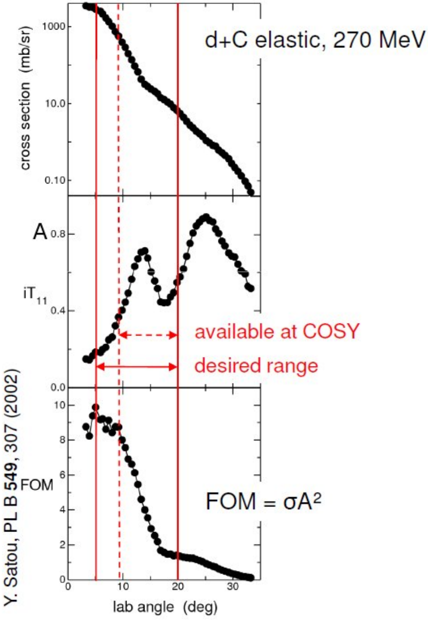
$A_{up,dn} = 0$



$A_{up,dn} = PA$



Polarimetry



Cross Section &
Analyzing Power
for deuterons

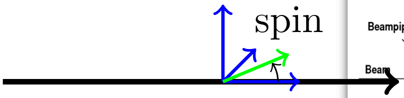
$N_{up,dn} \propto$
$(1 \pm P\,A\,\sin(\nu_s \omega_{rev} t))$

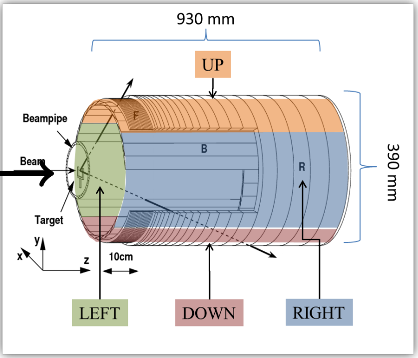
$$A_{up,dn} = \frac{N^{up} - N^{dn}}{N^{up} + N^{dn}}$$
$$= P\,A\,\sin(\nu_s \omega_{rev} t)$$

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 $A_{up,dn}$

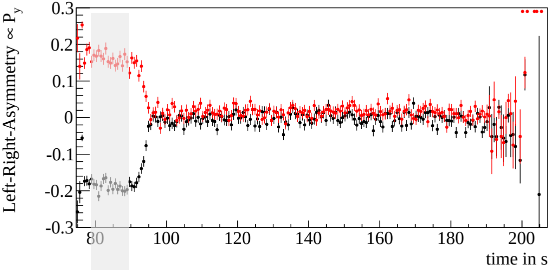
$$A_{up,dn}(t) \quad = \quad AP_0 e^{-t/\tau} \sin(\nu_s \omega_{rev} t + \varphi)$$

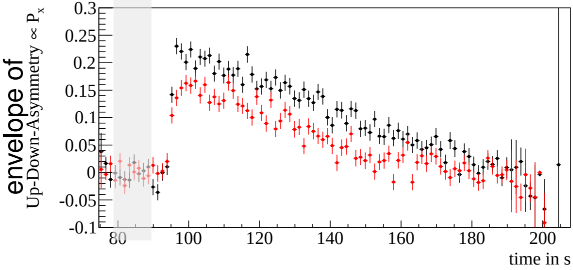
- $\tau \rightarrow$ spin decoherence
- $\nu_s \rightarrow$ spin tune

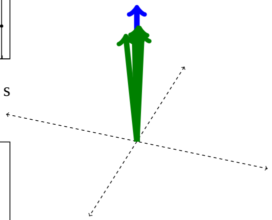
time scales: $\nu_s f_{rev} \approx 120$ kHz

τ in the range 1-1000 s

Polarization Flip







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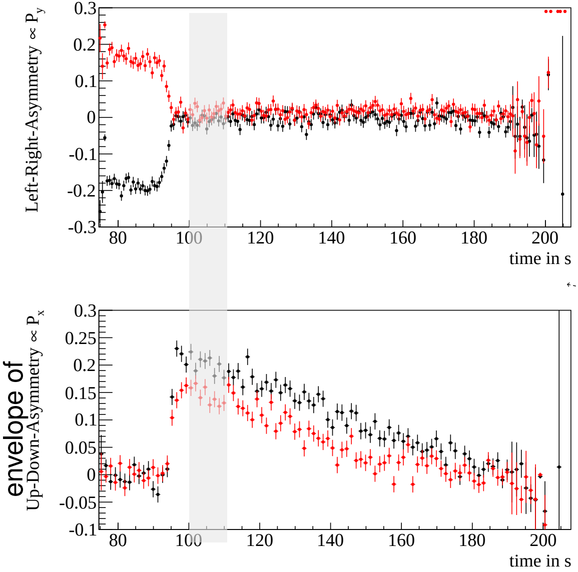

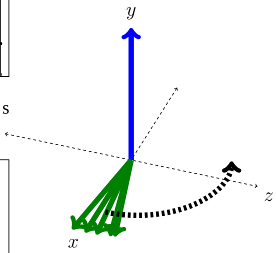

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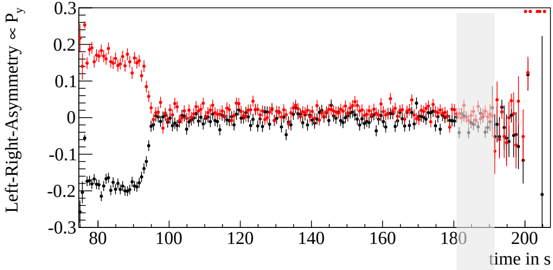
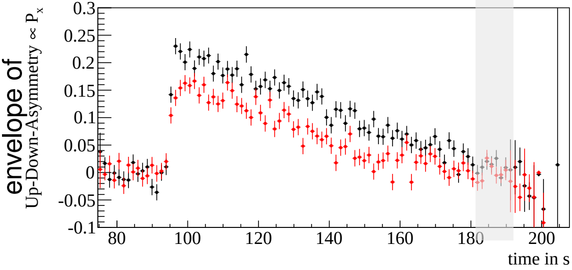
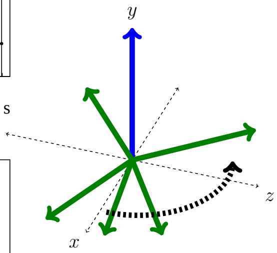
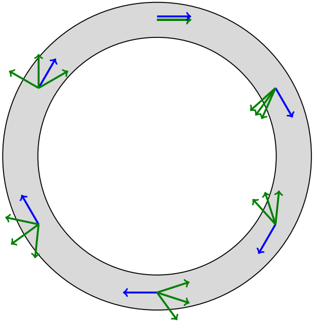


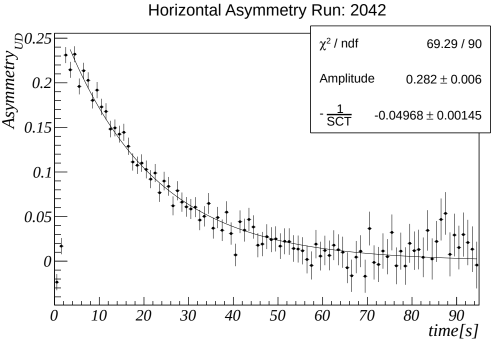




Results: Spin Coherence Time (SCT)

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

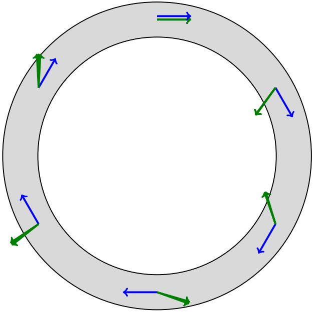
$\Rightarrow$ decoherence after < 1 s

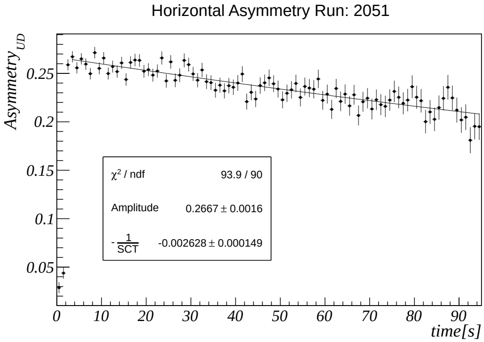
bunched beam eliminates 1st order effects in $\Delta p/p$

$\Rightarrow$ SCT τ = 20 s

Results: Spin Coherence Time (SCT)

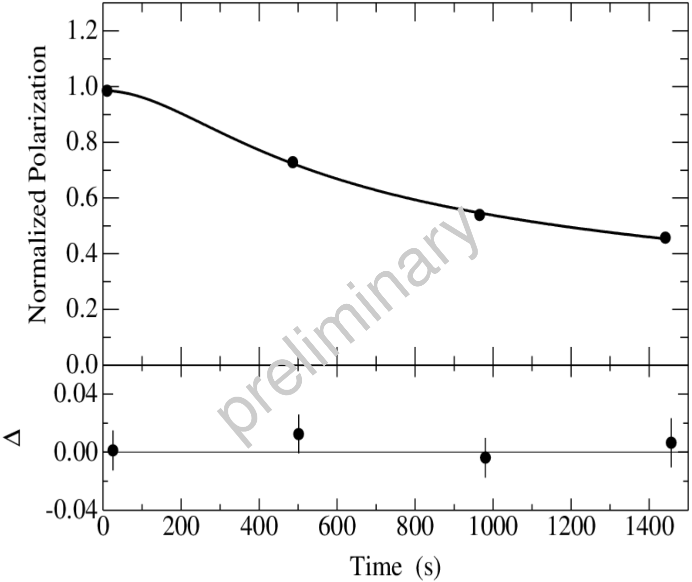
Long Spin Coherence Time





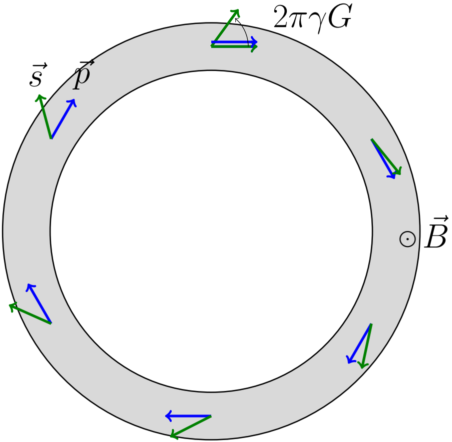
SCT of τ =400 s, after correction with sextupoles (chromaticities $\xi \approx 0$)

SCT: Longer Cycles



Spin Tune ν_s

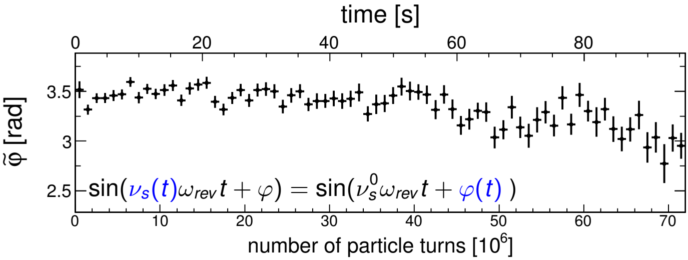
Spin tune: $\nu_s = \gamma G = \dfrac{\text{nb. of spin rotations}}{\text{nb. of particle revolutions}}$



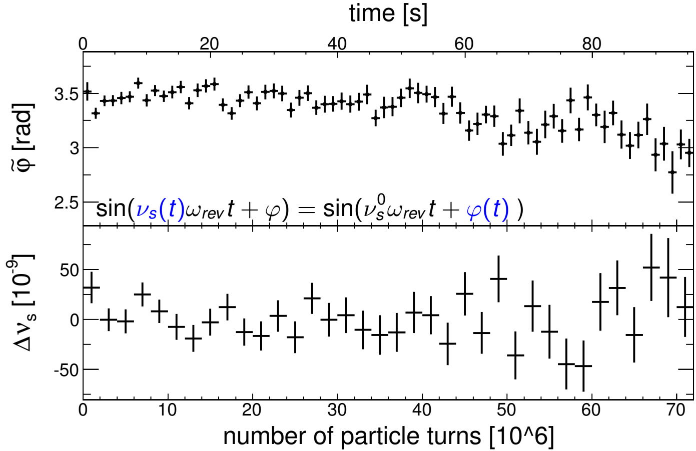
deuterons: $p_d = 1$ GeV/c ($\gamma = 1.13$), $G = -0.14256177(72)$

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

Results spin tune

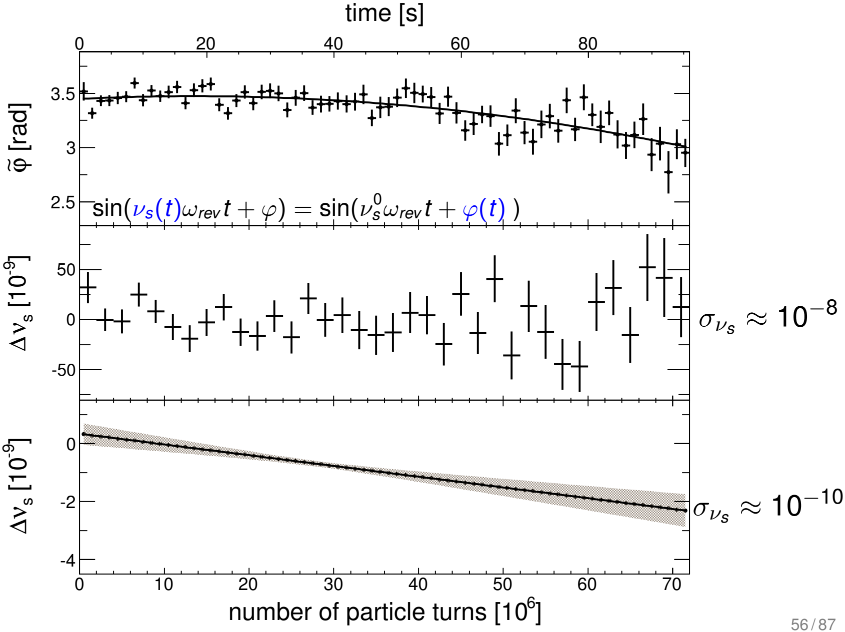


Results spin tune

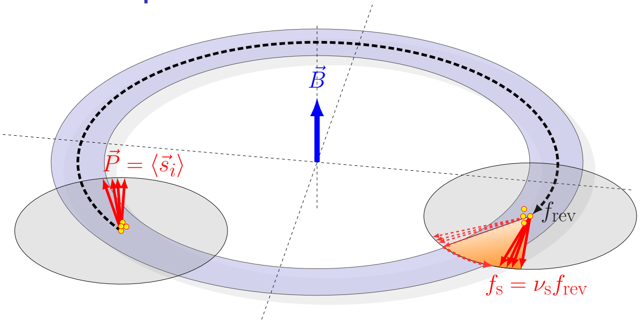


$\sigma_{\nu_s} \approx 10^{-8}$

Results spin tune

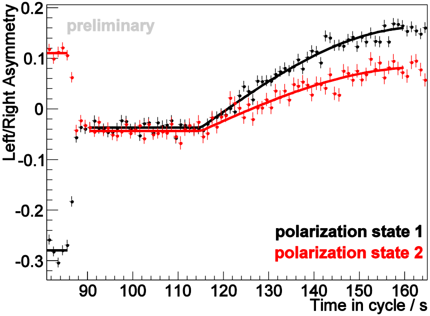


Spin Tune Measurement



- 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 polarisation aligned with momentum vector for dedicted ring or at a given phase with respect to radiofrequency Wien filter

Spin Feed back system



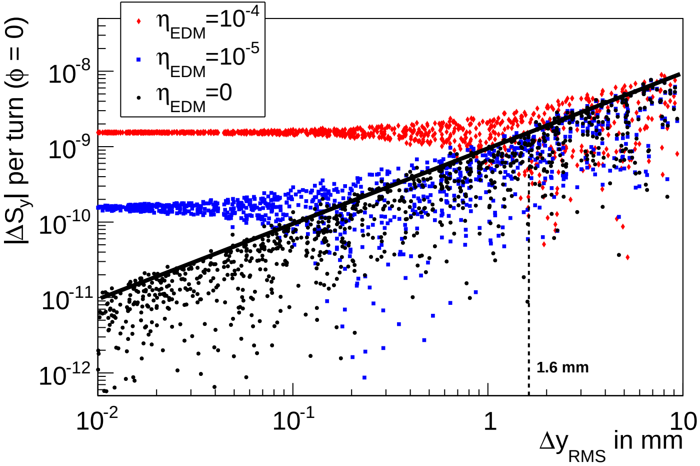
- polarisation rotation in horizontal plane at $t = 85$ s
- COSY rf changed during cycle in steps of 3.7 mHz (f_{rev}=750603 Hz) according to online ν_s measurement to

  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 1μm to 1 mm

$\eta = 10^{-5}$ corresponds to edm of 5×10^{-20} e·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 $\mathcal{CP}$ **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:	few hundred seconds
spin tune:	10^{-10} in 100 s
feed back system	allows to control spin
simulations	to understand systematics

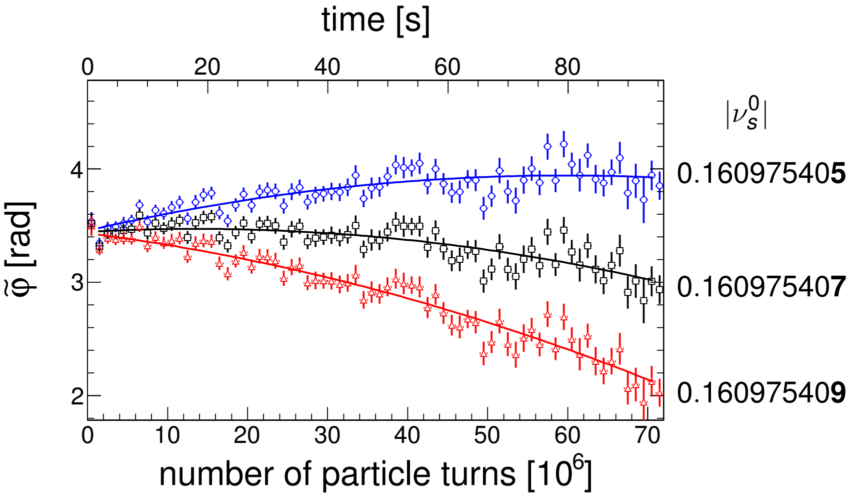
Spare

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

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

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

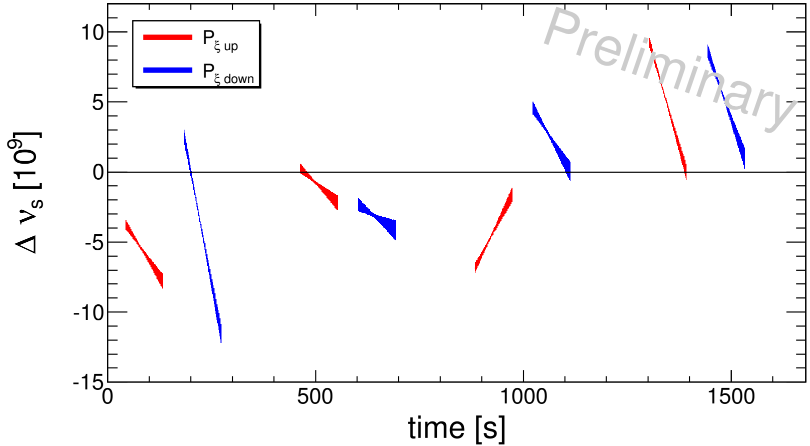
Phase vs. turn number



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

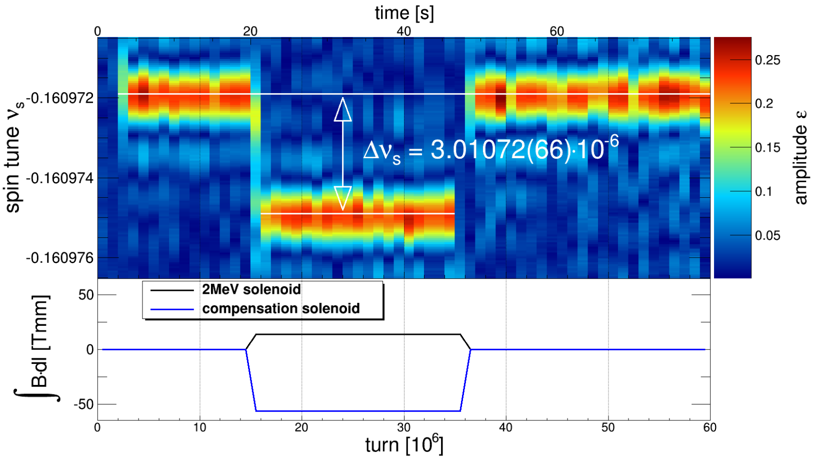
$$\Rightarrow |\nu_s(38\,\mathrm{s})| = (16\,097\,540\,628.3 \pm 9.7) \times 10^{-11}$$

Spin Tune for different cycles

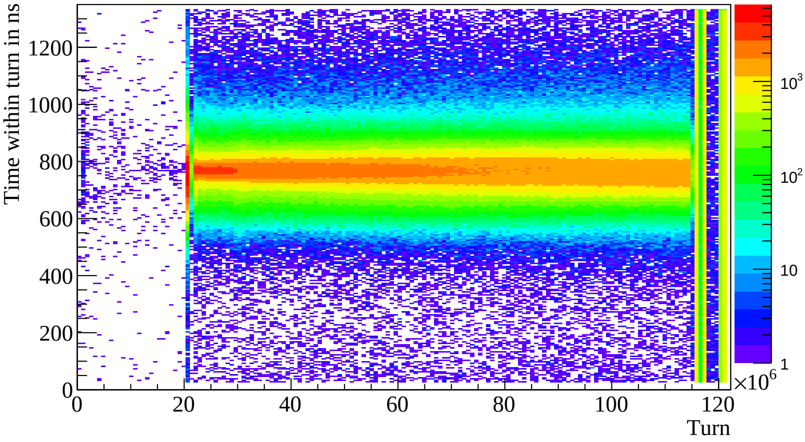


$\Delta\nu_s = 10^{-8} \rightarrow \Delta p/p \approx 10^{-7}$

Spin Tune jumps

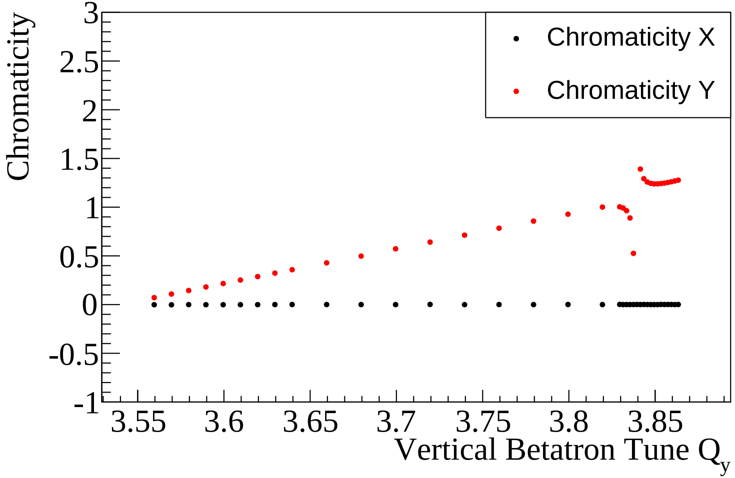


Event Distribution



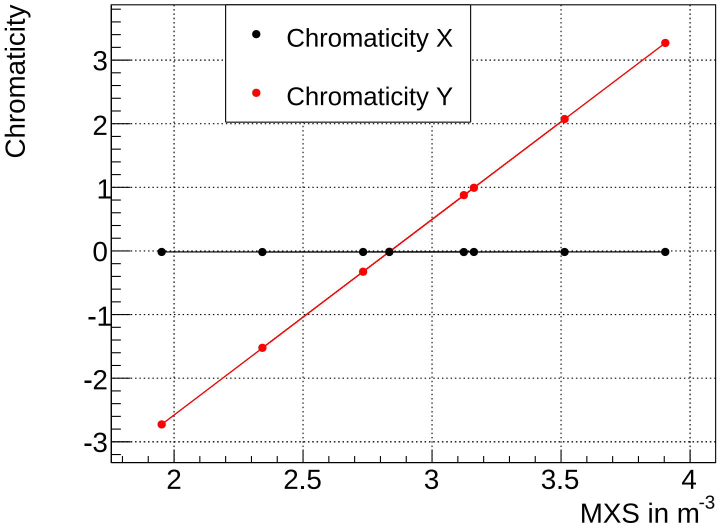
SCT $\leftrightarrow$ Chromaticity I

Chromaticities vs. tune giving maximal SCT according to simulation



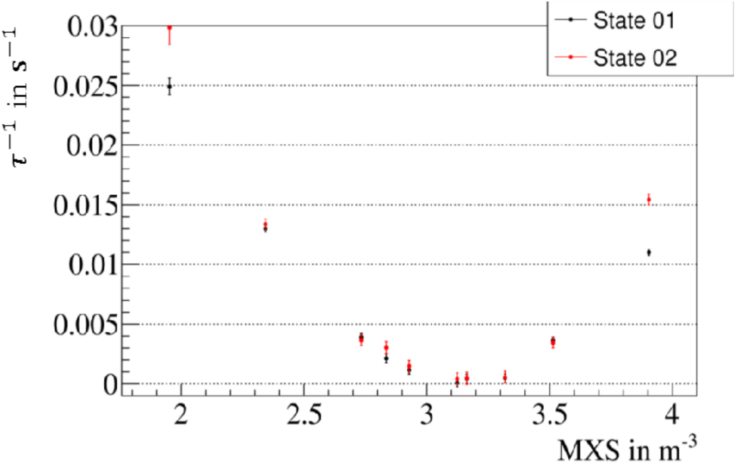
SCT ↔ Chromaticity II

Chromaticities vs. sextupole setting



SCT $\leftrightarrow$ Chromaticity I

SCT vs. sextupole setting



Maximal SCT for predicted sextupole setting

SCT $\leftrightarrow$ chromaticity

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

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

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

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

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

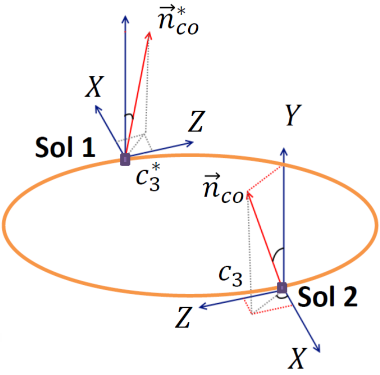
$\Rightarrow \frac{\Delta\beta}{\beta_0} \neq 0 \Rightarrow \frac{\Delta\nu_s}{\nu_s} \neq 0$

sextupole settings gives access to

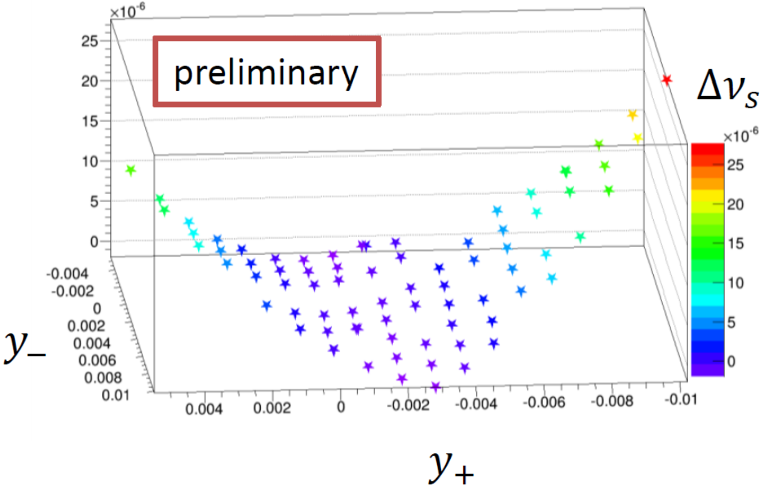
$\langle\frac{\Delta L}{L_0}_{x,y}\rangle = \frac{\pi}{L_0}\,\epsilon_{x,y}\,\xi_{x,y}$

Spin Tune as tool to investigate systematics

$\nu_s = \gamma G +$ imperfections kicks

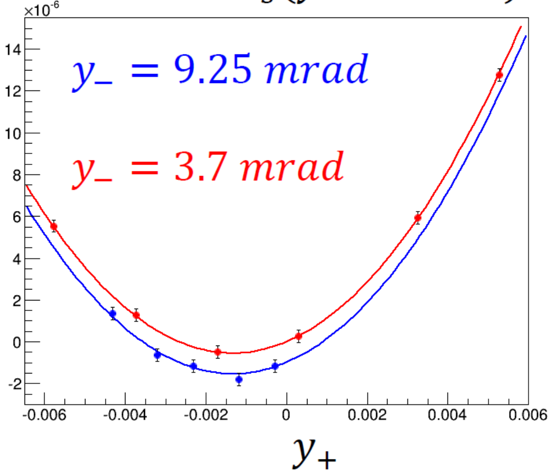


- Create artificial imperfections with solenoids/steerers
- measure spin tune change $\Delta\nu_s$
- expectation $\Delta\nu_s \propto (y_\pm - a_\pm)^2$
  $a_\pm$: kicks due to imperfections,
  $y_\pm$: kicks due to solenoids



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

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



- parabolic behavior expected from simulations
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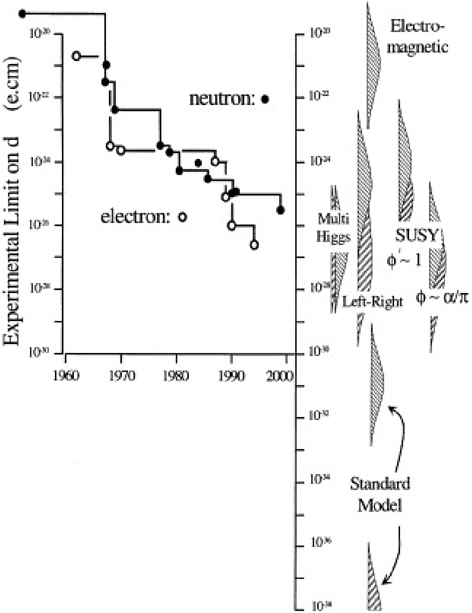
Electron and Neutron EDM



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

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

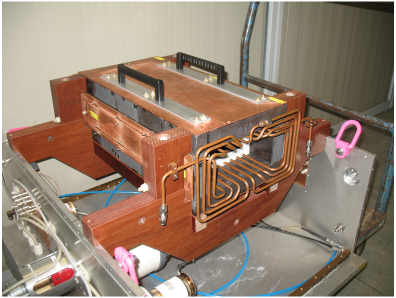
$$d_n = 10^{-14} \times \underbrace{10^{-7}}_{P-violation} \times \underbrace{10^{-3}}_{CP-violation} \times \underbrace{G_F F_\pi}_{\text{no flavor change}} = 10^{-31} e\text{cm}$$

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

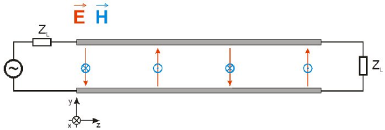
Electrostatic Deflectors

- 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)

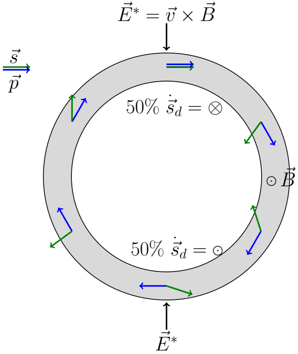


stripline design
D. Hölscher, J. Slim
(IHF RWTH Aachen)

Pure Magnetic Ring

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

Problem:
Due to precession caused by magnetic moment, 50% of time longitudinal polarization component is $||$ 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**

Pure Magnetic Ring

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

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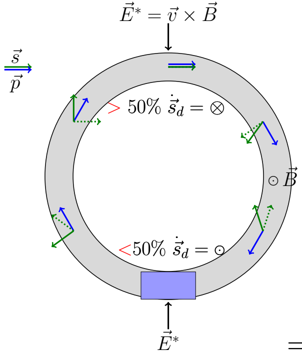
Due to precession caused by magnetic moment, 50% of time longitudinal polarization component is || to momentum, 50% of the time it is anti-||.



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

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

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

Ω: angular precession frequency

G: anomalous magnetic moment

d: electric dipole 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

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

2. Pure Electric Ring

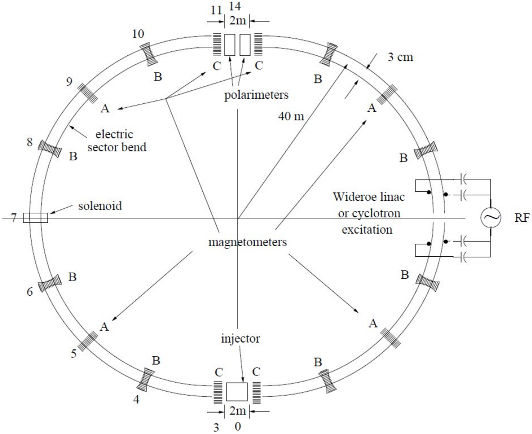


Figure 3: An all-electric storage ring lattice for measuring the electric dipole moment of the proton. Except for having longer straight sections and separated beam channels, the all-in-one lattice of Fig. 1 is patterned after this lattice. Quadrupole and sextupole families, and tunes and lattice functions 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

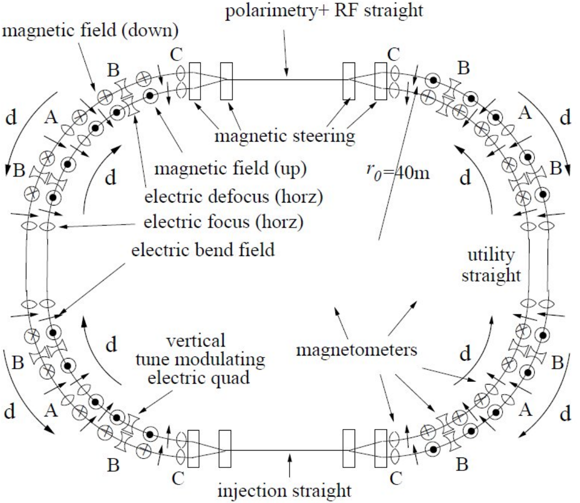


Figure 1: "All-In-One" lattice for measuring EDM's of protons, deuterons, and helions.

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

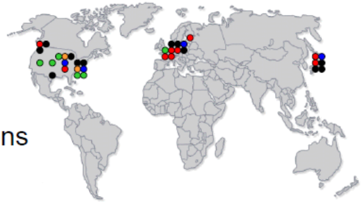
EDM Activities Around the World

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