Electric Dipole Moment Measurements at Storage Rings

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PSI, March 2015

Outline

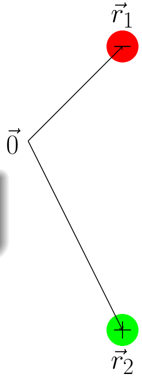
- **Introduction: Electric Dipole Moments (EDMs):**
  What is it?
  Why is it interesting?
  What do we know about EDMs?
- **Experimental Method:**
  How to measure charged particle EDMs?
- **Results of first test measurements:**
  Spin Coherence time and Spin tune

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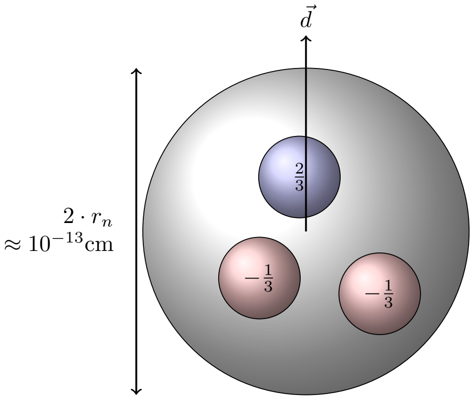
charges	e	e
$\lvert \vec{r}_1 - \vec{r}_2 \rvert$	1 Å= 10^{-8}cm	$1\mathrm{fm} = 10^{-13}$cm
EDM		
naive expectation	$10^{-8} e \cdot \mathrm{cm}$	$10^{-13} e \cdot \mathrm{cm}$
observed	water molecule	neutron
	$2 \cdot 10^{-8} e \cdot$ cm	$< 3 \cdot 10^{-26} e \cdot$ cm

Order of magnitude



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

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

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

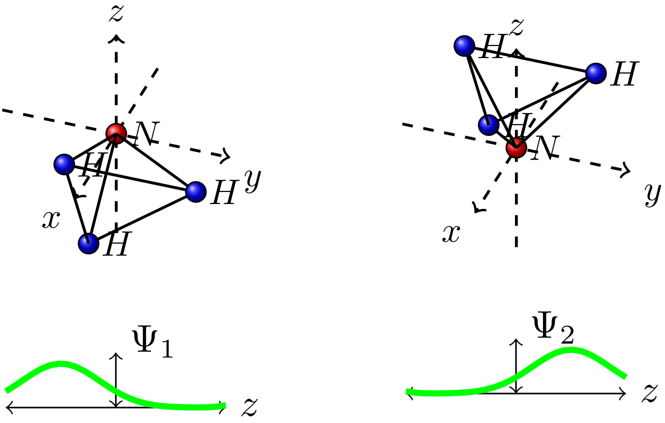
$$\mathcal{P}^{-1}\vec{d}\mathcal{P} = -\vec{d}$$

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

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

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

Order of magnitude

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!

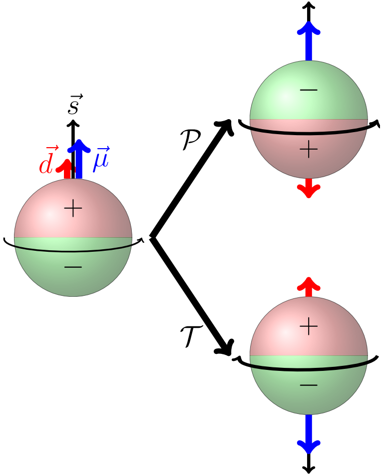
$\mathcal{T}$ and $\mathcal{P}$ violation of EDM

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

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

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

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



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

Symmetries in Standard Model

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

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

Sources of $\mathcal{CP}-$Violation

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

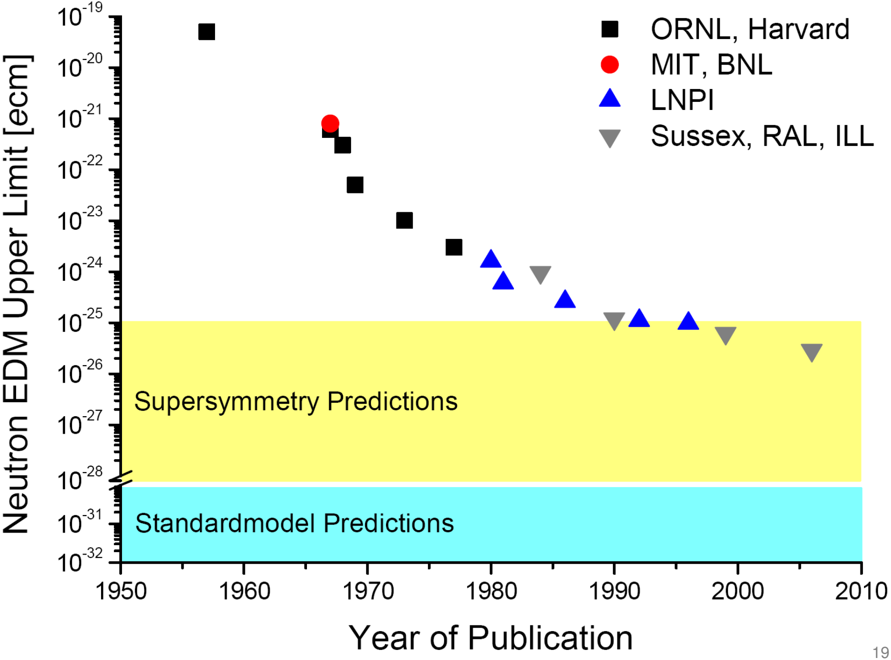
Sakharov (1967): $\mathcal{CP}$ violation needed for baryogenesis

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

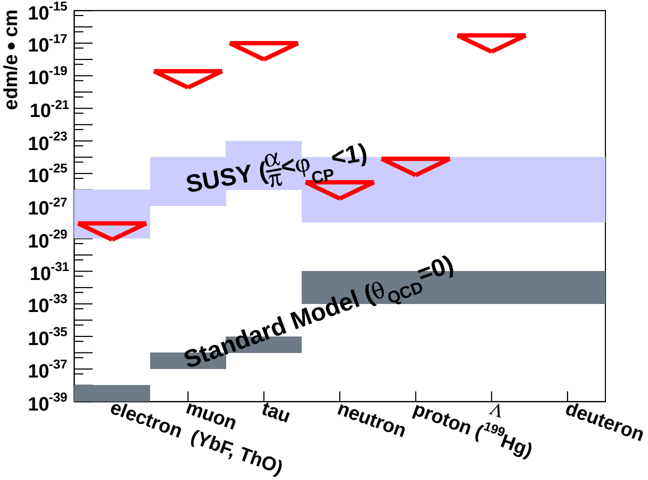
They could manifest in EDMs of elementary particles

What do we know about EDMs?

History of Neutron EDM



EDM: Current Upper Limits



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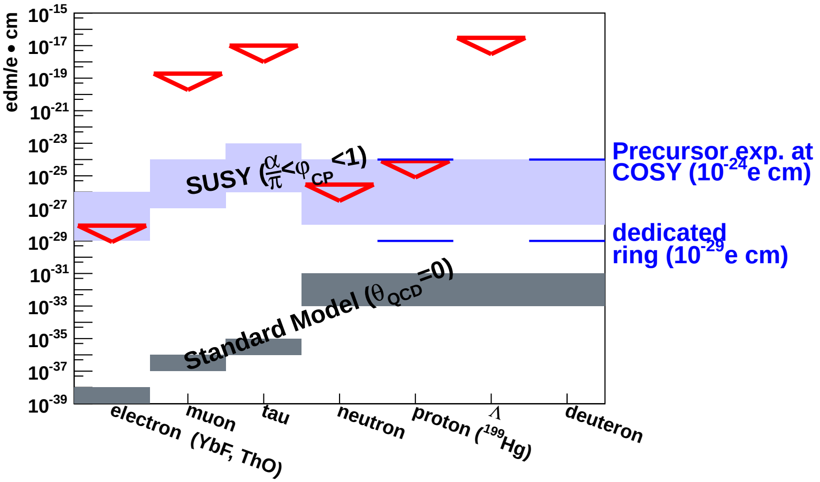
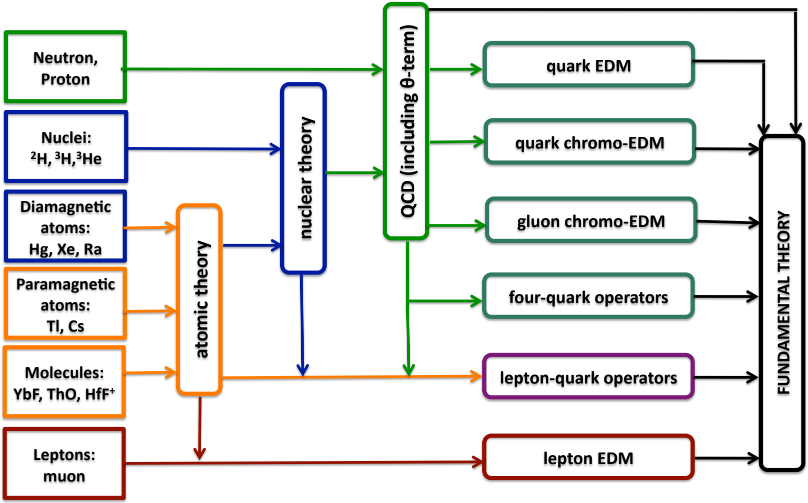


FZ Jülich: EDMs of **charged** hadrons: *p*, *d*, ^{3}He

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

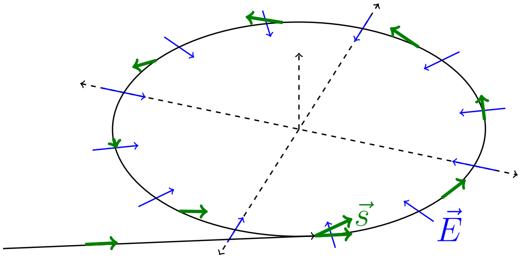


J. de Vries

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:

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

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

Experimental Requirements

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

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

challenge: get σ_{sys} to the same level

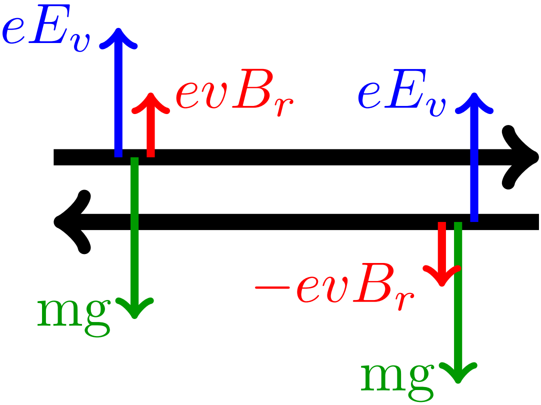
Systematics

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:
  $B_r = \dfrac{dE_r}{\mu_N} = \dfrac{10^{-22} e\mathrm{V}}{3.1 \cdot 10^{-8} e\mathrm{V}/\mathrm{T}} \approx 3 \cdot 10^{-17}\mathrm{T}$

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 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

d: electric dipole moment

G: anomalous magnetic moment

γ: Lorentz factor

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dedicated ring: pure electric field,
freeze horizontal spin motion $\left(G - \frac{1}{\gamma^2 - 1}\right) = 0$

Spin Precession: Thomas-BMT Equation

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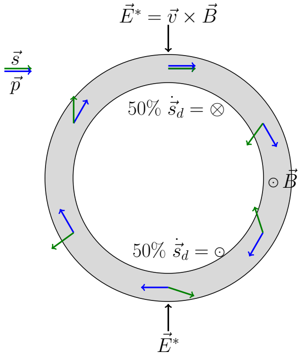
COSY: pure magnetic ring
access to EDM via motional electric field $\vec{v} \times \vec{B}$,
requires additional radio-frequency E and B fields
to suppress $G\vec{B}$ contribution

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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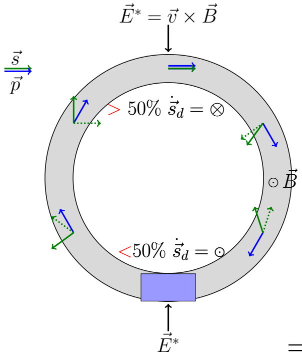

E^* field in the particle rest frame tilts spin due to EDM up and down
⇒ **no net EDM effect**

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

⇒ **net EDM effect can be observed!**

Spin Precession: Thomas-BMT Equation

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

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

Results of first test measurements

Cooler Synchrotron COSY

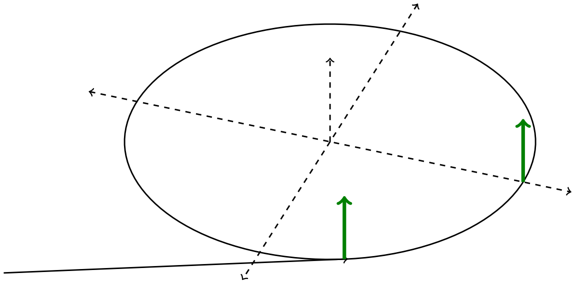
COSY provides (polarized) protons and deuterons with
$p = 0.3 - 3.7 \text{GeV}/c$
⇒ **Ideal starting point for charged particle EDM searches**

R & D at COSY

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

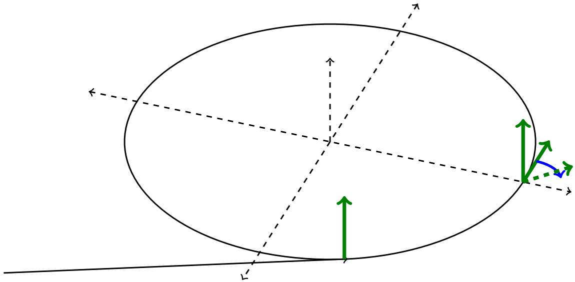
Experimental Setup

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



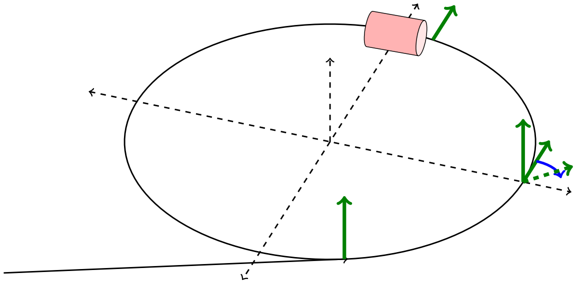
Experimental Setup

- 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



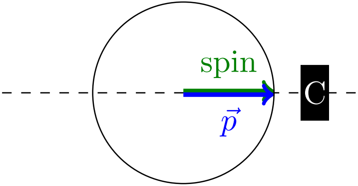
Asymmetry Measurements

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

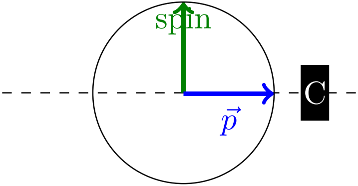
$$A_{up,dn} = \frac{N^{up} - N^{dn}}{N^{up} + N^{dn}} = P\,A\,\sin(\gamma G f_{rev} t) = P\,A\,\sin(\nu_s n_{turn})$$

A: analyzing power, P : polarization

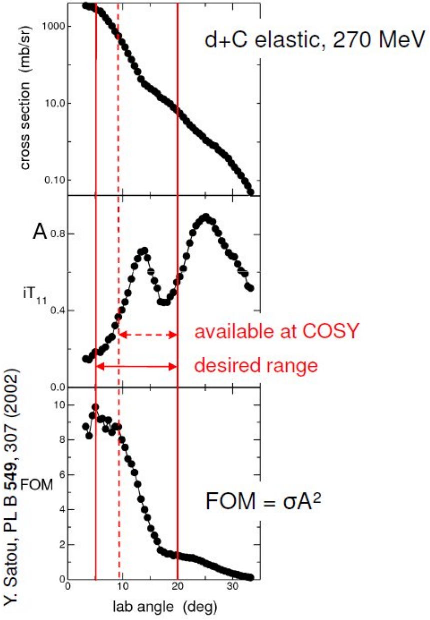
$A_{up,dn} = 0$



$A_{up,dn} = PA$



Polarimetry



Cross Section &
Analyzing Power
for deuterons

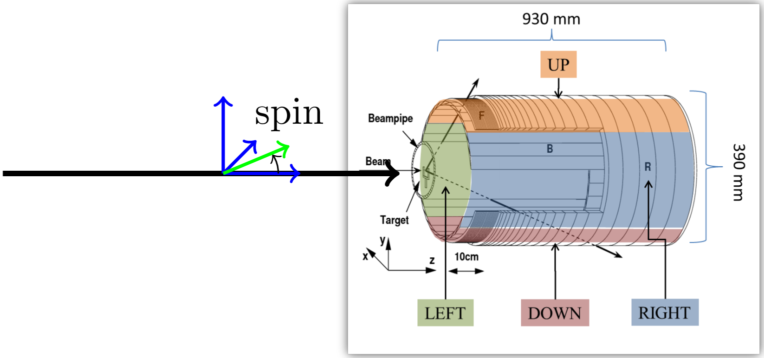
$N_{up,dn} \propto$
$(1 \pm P\,A\,\sin(\nu_s f_{rev}\, t))$

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

A : analyzing power
P : beam polarization

Polarimeter

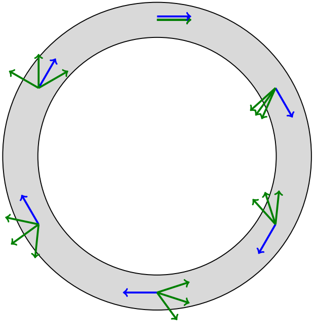
elastic deuteron-carbon scattering
Up/Down asymmetry $\propto$ horizontal polarization $\rightarrow \nu_s = \gamma G$
Left/Right asymmetry $\propto$ vertical polarization $\rightarrow d$

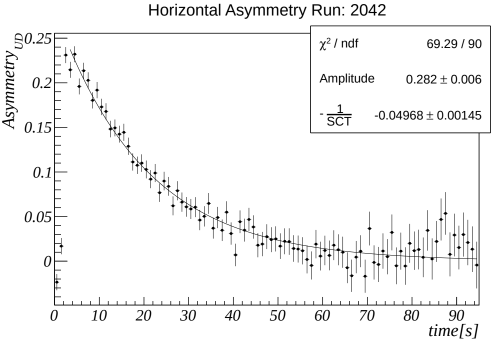


$N_{up,dn} \propto 1 \pm PA \sin(\nu_s n_{turn}), \quad f_{rev} \approx 750\,\text{kHz}$

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

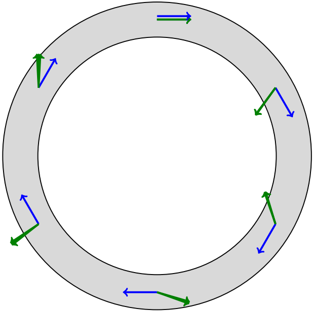
$\Rightarrow$ decoherence after < 1 s

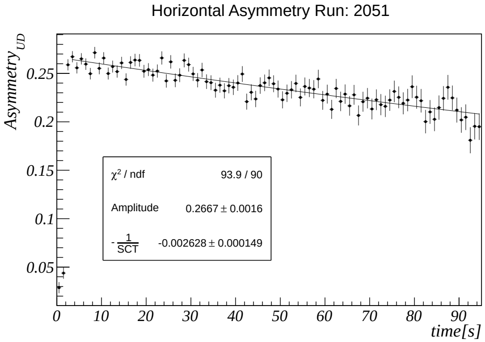
cooled bunched beam eliminates 1st order effects in $\Delta p/p$

$\Rightarrow$ SCT τ = 20 s

Results: Spin Coherence Time (SCT)

Long Spin Coherence Time

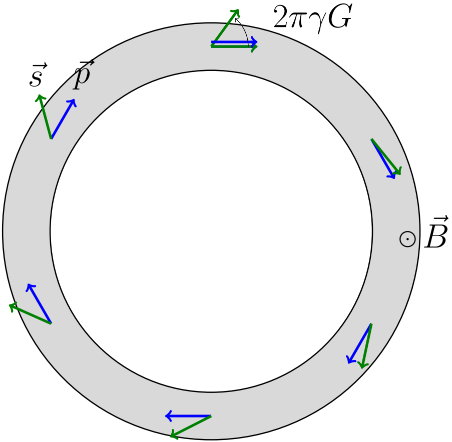




using correction sextupole to correct for higher order effects leads to SCT of $\tau =$400 s

Spin Tune ν_s

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

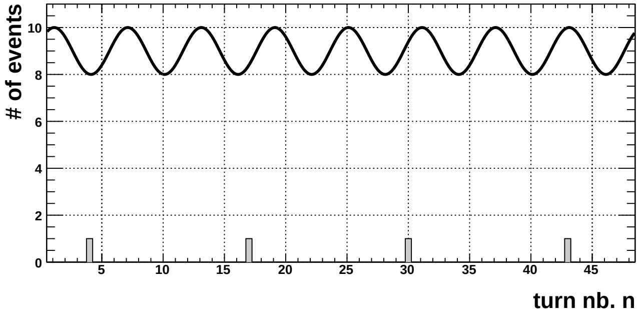


deuterons: $p_d = 1$ GeV/c ($\gamma = 1.13$), $G = -0.14256177(72)$

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

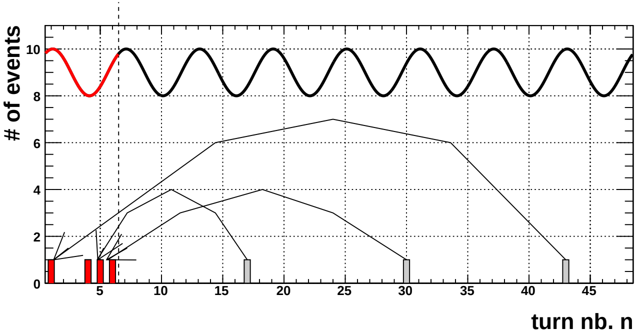
Spin Tune ν_s measurement

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

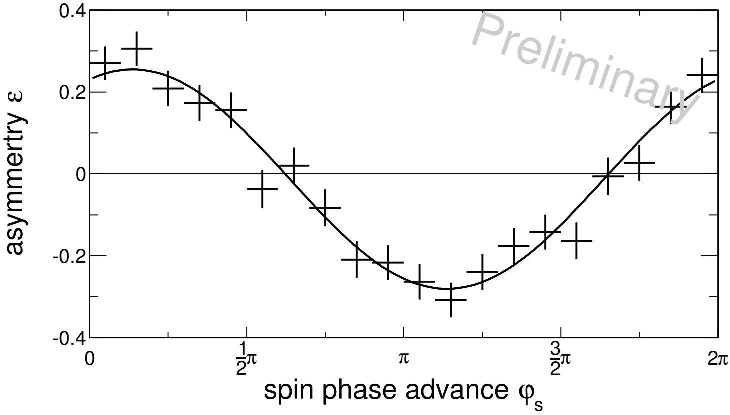


Spin Tune ν_s measurement

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

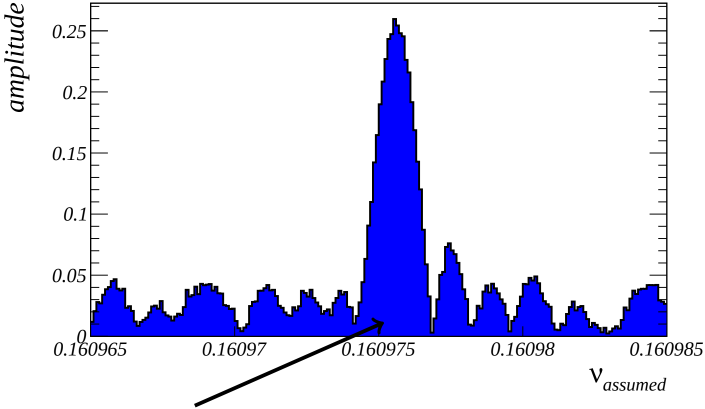


Asymmetry in 1st period



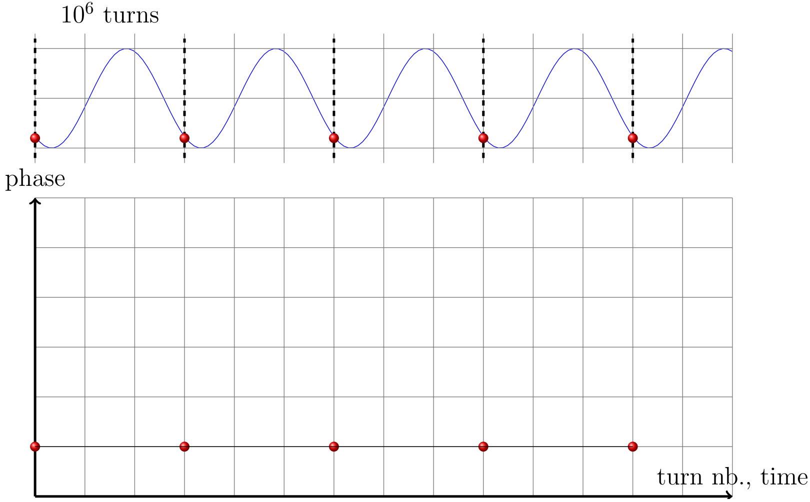
- only works if $T_s = \frac{1}{\nu_s f_{rev}}$ is correct.

Scan of ν_s



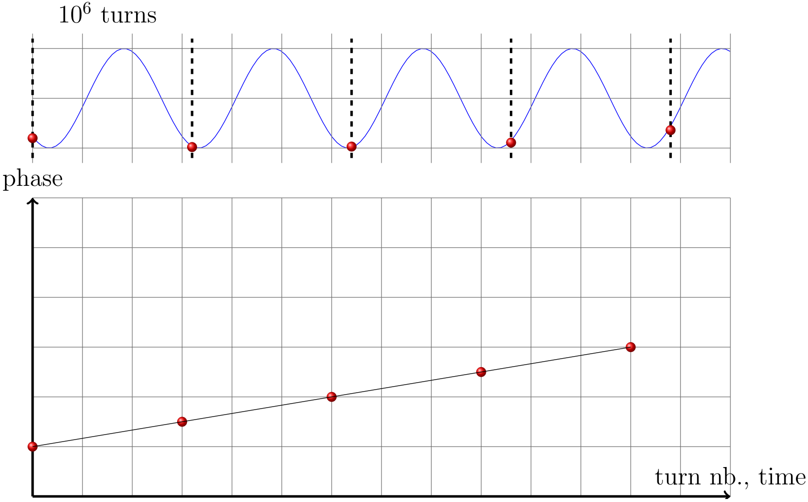
- allows for $\sigma_{\nu_s} \approx 10^{-6}$
- now fix ν_s at maximum and look at phase vs. turn number
  phase is determined for turn intervals of 10^6 turns

Phase Measurements



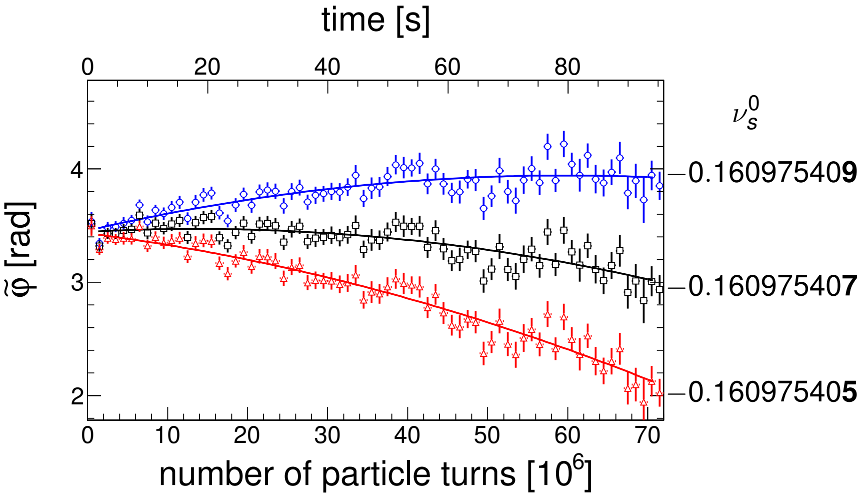
1st derivative gives deviation from assumed spin tune

Phase Measurements



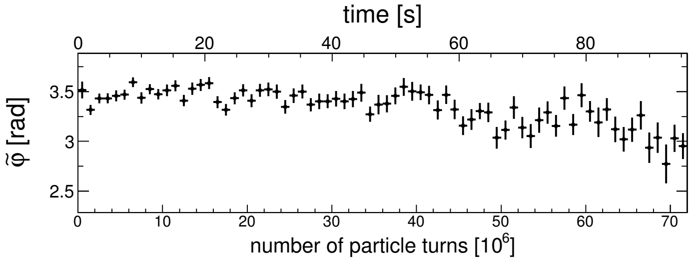
1st derivative gives deviation from assumed spin tune

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



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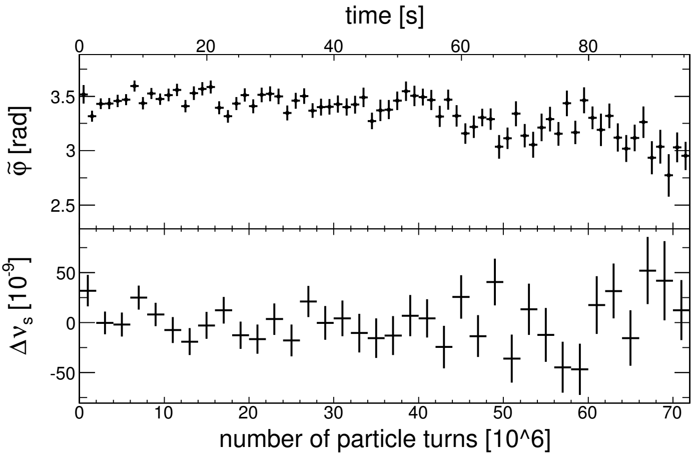
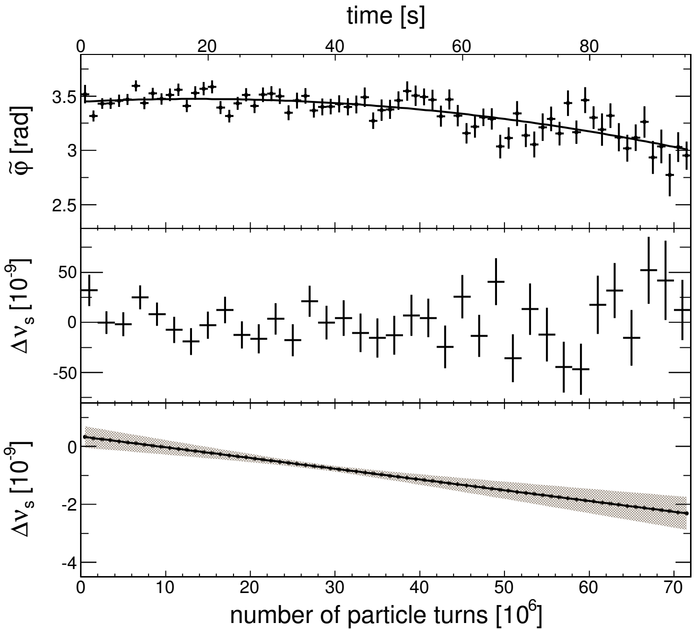


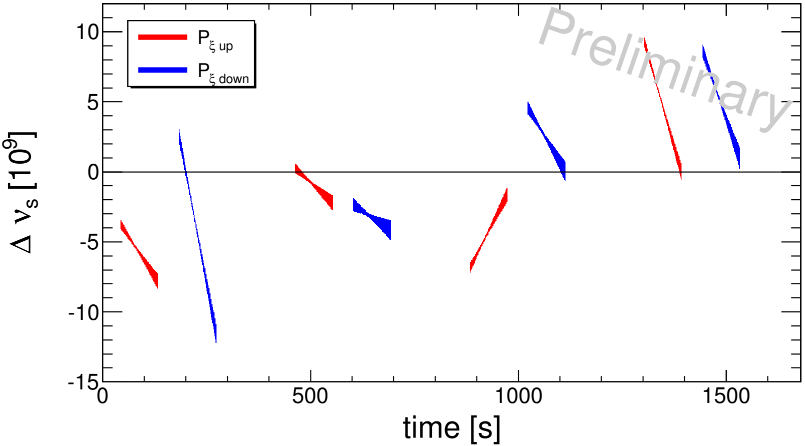
Results: Spin Tune ν_s



Spin Tune Measurement

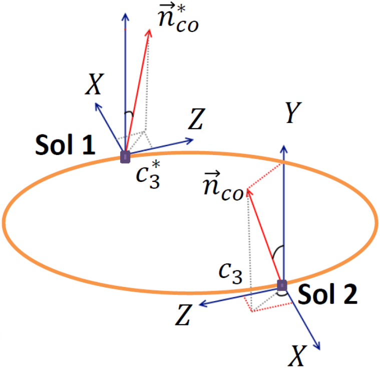
- precision of spin tune measurement 10^{-10} in one cycle
- spin rotation due to electric dipole moment:
  $\nu_s = \frac{vm\gamma d}{es} = 5 \cdot 10^{-11}$ for $d = 10^{-24} e\,\mathrm{cm}$
  (in addition rotations due to G and imperfections)
- Compare to muon $g-2$: $\sigma_{\nu_s} \approx 3 \cdot 10^{-8}$ per year
  main difference: measurement duration 600μ s compared to 100 s
- spin tune measurement can now be used as tool to investigate systematic errors

Spin Tune as tool to investigate systematics



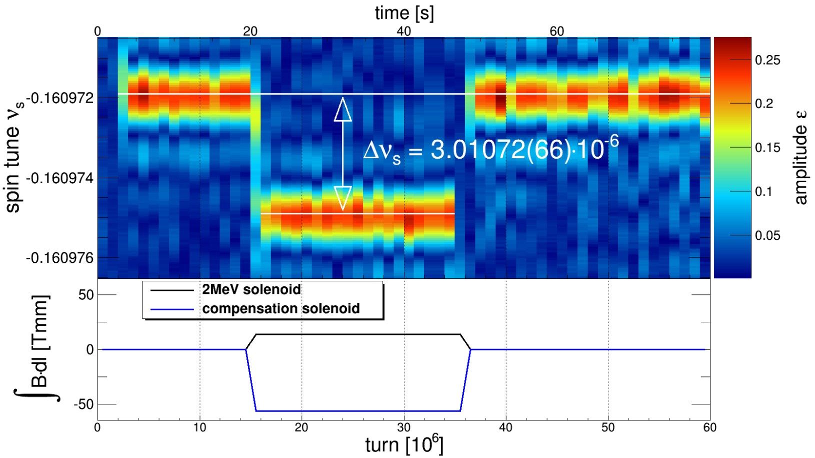
Spin Tune as tool to investigate systematics

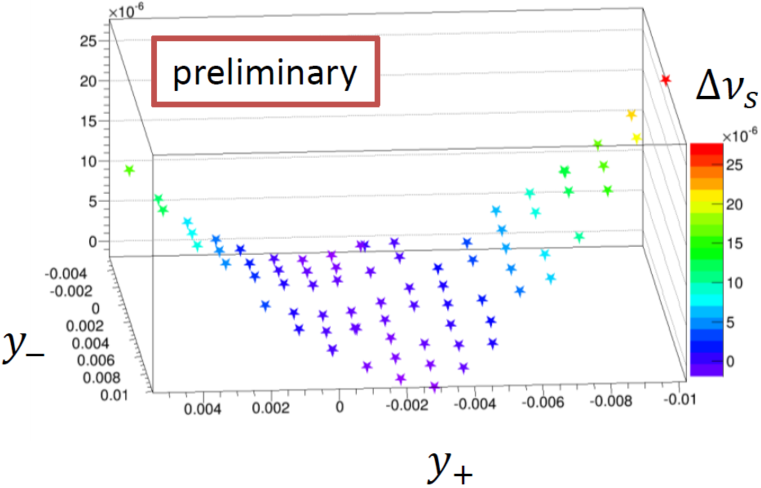
$\nu_s = \gamma G +$ imperfections kicks



- 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

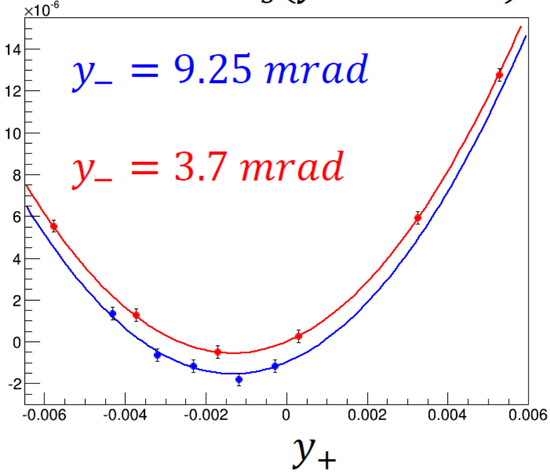
Spin Tune jumps





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

JEDI Collaboration

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

Storage Ring EDM Efforts

Common R&D work

- Spin Coherence Time
- BPMs
- Spin Tracking
- Polarimetry
- electric fields
- ...

BNL

- all electric ring (p)

Jülich

- first direct measurement with upgraded COSY
- dedicated ring (p,d,^{3}He)

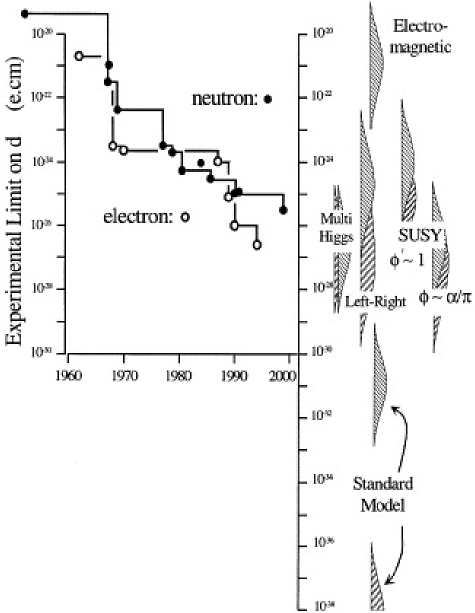
Summary & Outlook

- 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 from test measurements at COSY:

spin coherence time:	few hundred seconds
spin tune precision:	10^{-10} in one cycle

Spare

Electron and Neutron EDM



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

EDM: SUSY Limits

electron:

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

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

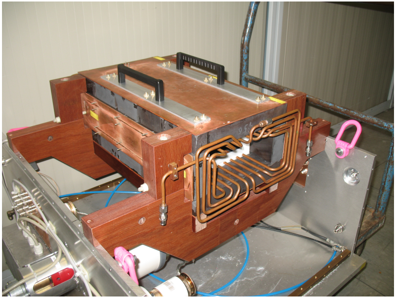
neutron:

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

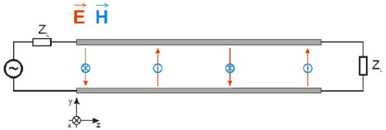
Electrostatic Deflectors

- 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)

2. Pure Electric Ring

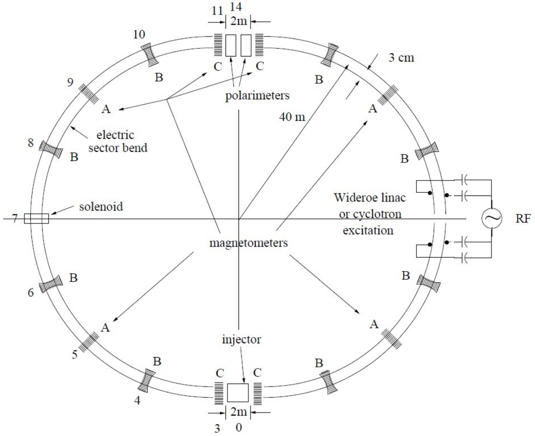


Figure 3: An all-electric storage ring lattice for measuring the electric dipole moment of the proton. Except for having longer straight sections and separated beam channels, the all-in-one lattice of Fig. 1 is patterned after this lattice. Quadrupole and sextupole families, and tunes and lattice functions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

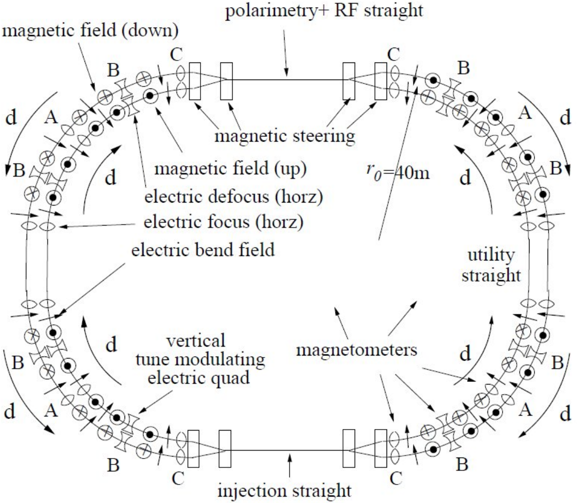


Figure 1: "All-In-One" lattice for measuring EDM's of protons, deuterons, and helions.

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

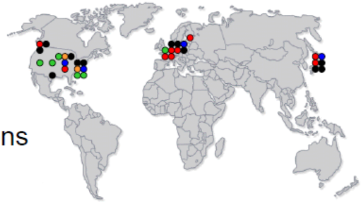
Summary of different options

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

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 $1.25\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$

Systematics