Electric Dipole Moment Measurements at Storage Rings

J. Pretz
RWTH Aachen & FZ Jülich

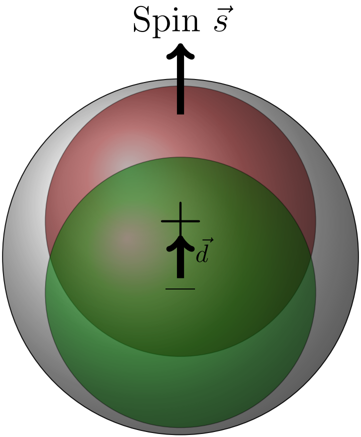
Trento, ECT*, October 2018
"Discrete symmetries in particle, nuclear and atomic physics
and implications for our universe".

Outline

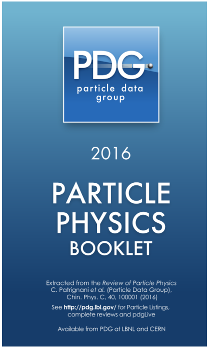
- Motivation for Electric Dipole Moment (EDM) Measurements
- **Charged** particle EDM measurements achievements, activities, plans

Motivation for Electric Dipole Moment (EDM) Measurements

Electric **D**ipole **M**oments (EDM)



- permanent separation of positive and negative charge
- fundamental property of particles
  (like magnetic moment, mass, charge)
- existence of EDM only possible via violation of time reversal $\mathcal{T}$ and parity $\mathcal{P}$ symmetry
- has nothing do due with electric dipole moments observed in some molecules (e.g. water molecule)



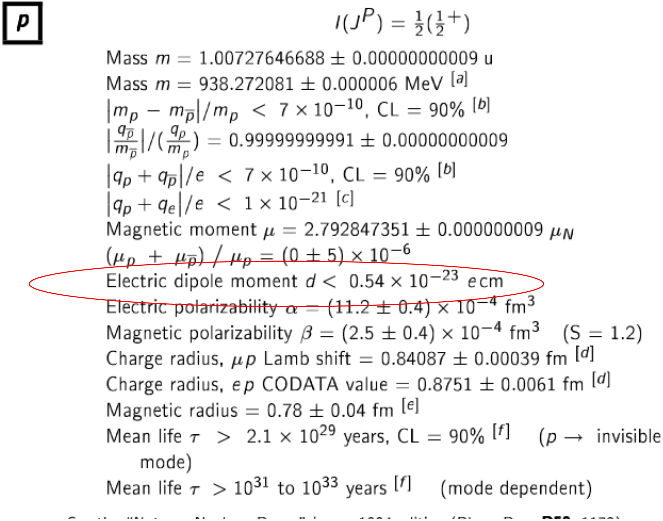
PDG
particle data group

2016

PARTICLE PHYSICS BOOKLET

Extracted from the *Review of Particle Physics*
C. Patrignani *et al.* (Particle Data Group),
Chin. Phys. C, 40, 100001 (2016)
See **http://pdg.lbl.gov/** for Particle Listings,
complete reviews and pdgLive

Available from PDG at LBNL and CERN



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

Mass $m = 1.00727646688 \pm 0.00000000009$ u

Mass $m = 938.272081 \pm 0.000006$ MeV [a]

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

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

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

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

Magnetic moment $\mu = 2.792847351 \pm 0.000000009\ \mu_N$

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

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

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

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

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

Charge radius, $e p$ CODATA value $= 0.8751 \pm 0.0061$ fm [d]

Magnetic radius $= 0.78 \pm 0.04$ fm [e]

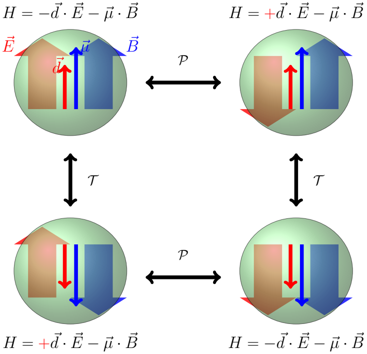
Mean life $\tau > 2.1 \times 10^{29}$ years, CL = 90% [f] ($p \rightarrow$ invisible mode)

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

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

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

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

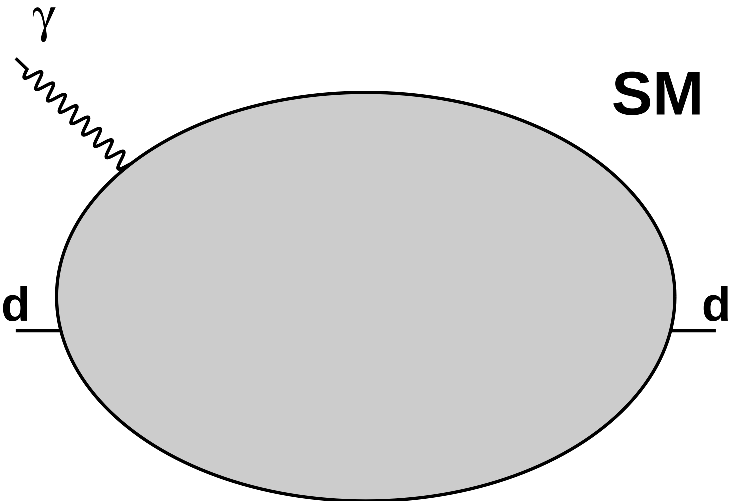


⇒ EDM measurement tests violation of fundamental symmetries $\mathcal{P}$ and $\mathcal{T}(\overset{\mathcal{CPT}}{=}\mathcal{CP})$

$\mathcal{CP}-$Violation & 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

EDM in SM and SUSY



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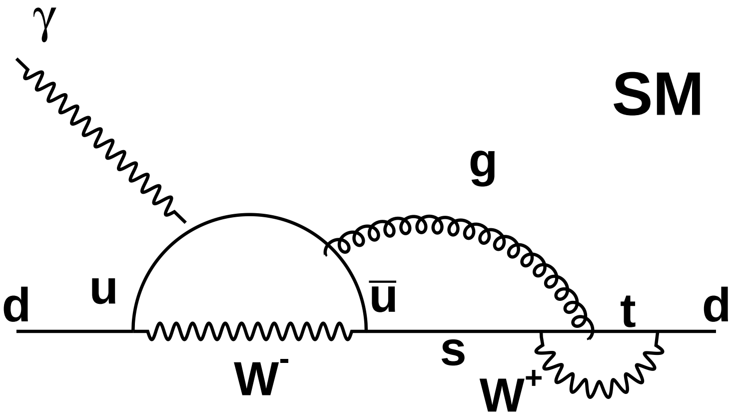

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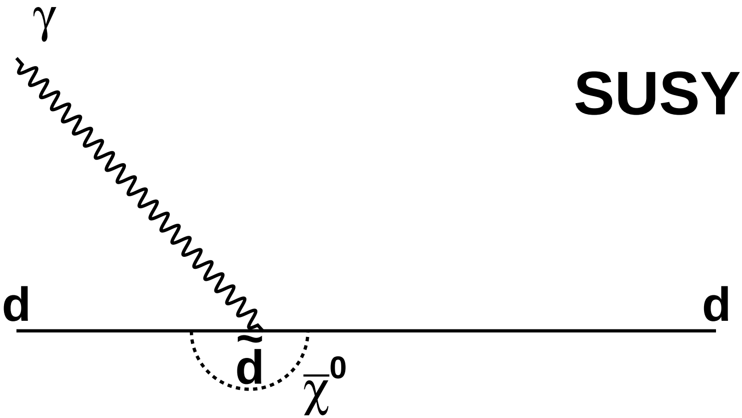


…implications for our universe

Excess of matter in the universe:

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

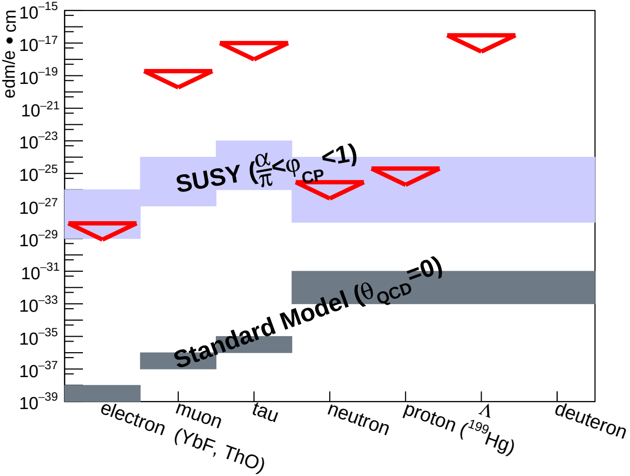
Sakharov (1967): $\mathcal{CP}$ violation needed for baryogenesis

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

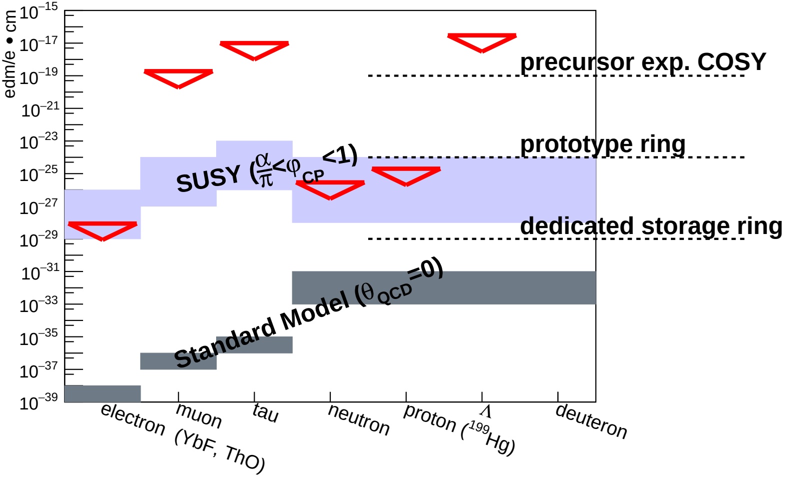
They could show up in EDMs of elementary particles

* SCM: Standard Cosmological Model

EDM: Current Upper Limits



EDM: Current Upper Limits



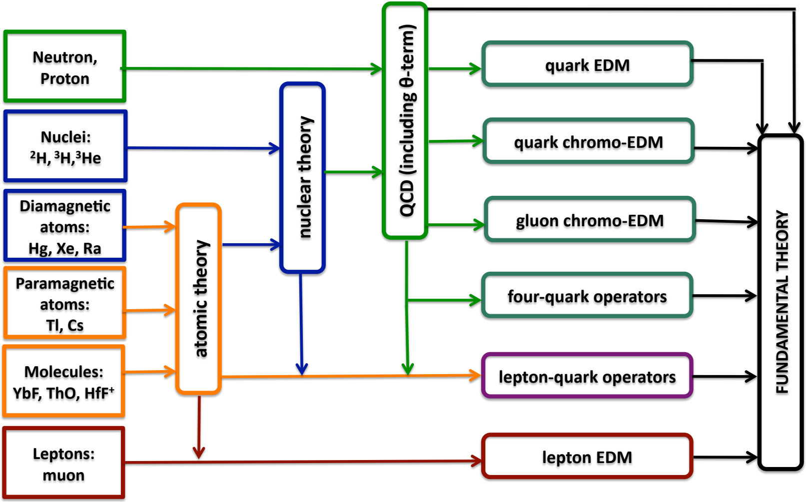
FZ Jülich: EDMs of **charged** hadrons: p, d, ^{3}He

Why Charged Particle EDMs?

- no direct measurements for charged hadrons exist
- potentially higher sensitivity (compared to neutrons):
  - longer life time,
  - more stored protons/deuterons
- complementary to neutron EDM:
  $d_d, d_p, d_n \Rightarrow$ access to θ_{QCD}
  (A. Wirzba, J. Bsaisou, A. Nogga, Int.J.Mod.Phys. E26 (2017) no.01n02, 1740031)

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

Sources of $\mathcal{CP}$ Violation



J. de Vries

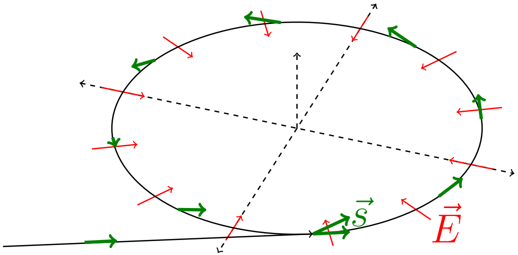
Charged particle EDM measurements achievements, activities, plans

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 polarisation $s_\perp \propto |d|$
(can be measured via elastic scattering on carbon)

Spin Precession: Thomas-BMT Equation

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

$$\vec{d} = \eta \frac{q}{2m}\vec{s}, \quad \vec{\mu} = 2(G+1)\frac{q}{2m}\vec{s}$$

BMT: Bargmann, Michel, Telegdi

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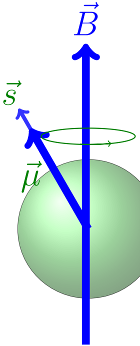

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	☺	☹
1.) pure electric ring	no $\vec{B}$ field needed, CW/CCW beams simultaneously	works only for particles with $G > 0$ (e.g. p)
2.) combined ring	works for p, d, ^{3}He, . . .	both $\vec{E}$ and $\vec{B}$ required
3.) pure magnetic ring	existing (upgraded) COSY ring can be used, shorter time scale	lower sensitivity, precession due to G, i.e. no **frozen spin**

ideal: suppress precession due to magentic dipole moment (**frozen spin**)

$$\vec{d} = \eta \frac{q}{2m}\vec{s}\,, \quad \vec{\mu} = 2(G + 1)\frac{q}{2m}\vec{s}$$

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Different Options

- First measurement with existing magnetic ring COSY at FZ Jülich

  Jülich **E**lectric **D**ipole Moment **I**nvestigations
- Plans for a prototype/dedicated ring:
  CPEDM collaboration (CERN,JEDI,Korea, . . .)

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

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

challenge: get σ_{sys} to the same level

Test Measurements at COSY

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

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

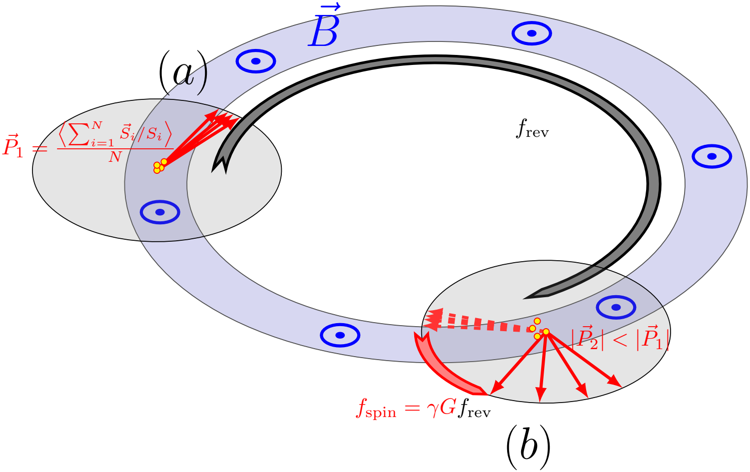
Recent achievements

1. **Spin coherence time:** $\tau > 1000$ s (PRL 117, 054801 (2016))
2. **Spin tune:** $\overline{\nu_s} = -0.16097\cdots \pm 10^{-10}$ in 100 s (PRL 115, 094801 (2015))
3. **Spin feedback:** polarisation vector kept within 12 degrees (PRL 119 (2017) no.1, 014801)

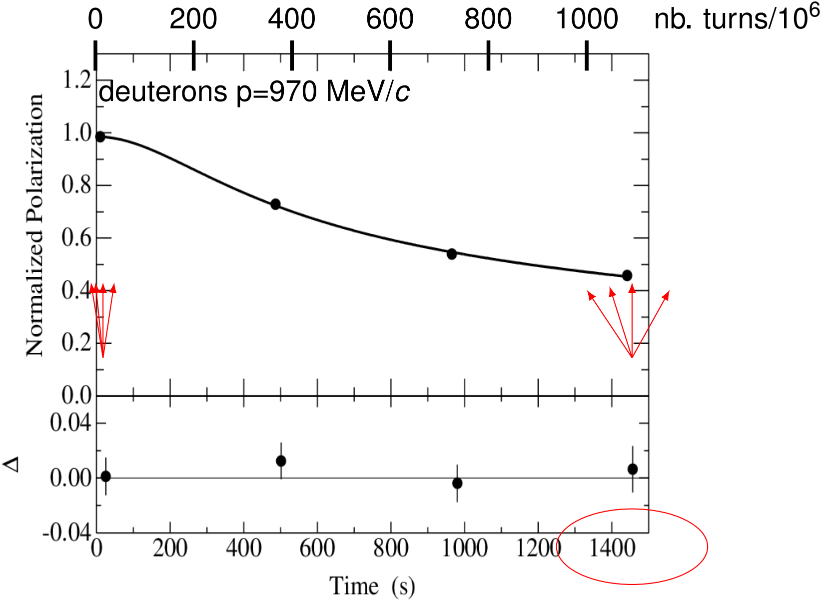
(all data shown were taken with deuterons, with $p \approx 1$ GeV/c)

① mandatory to reach statistical sensitivity
② & ③ shows that we can measure and manipulate polarisation vector with high accuracy

Spin Precession



1.) Spin Coherence Time (SCT)



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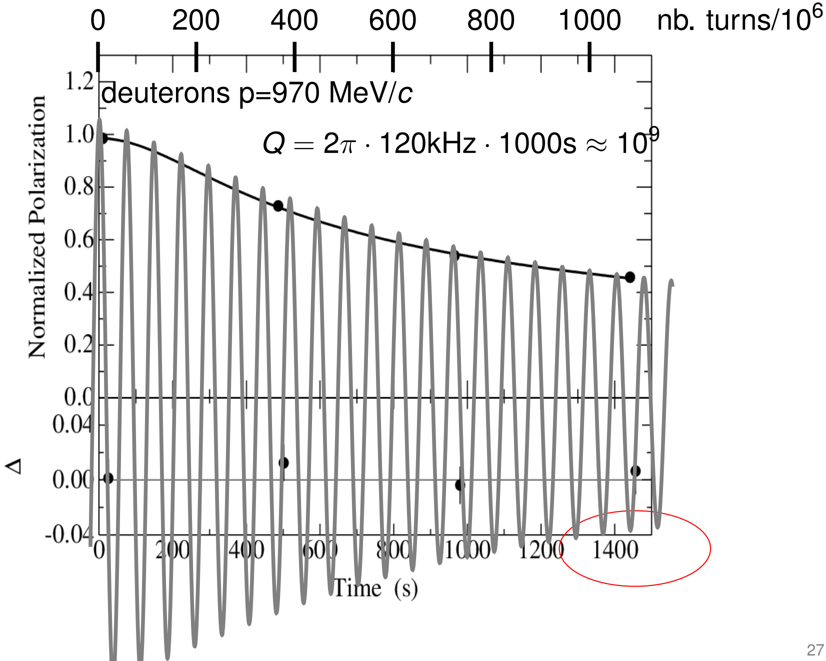
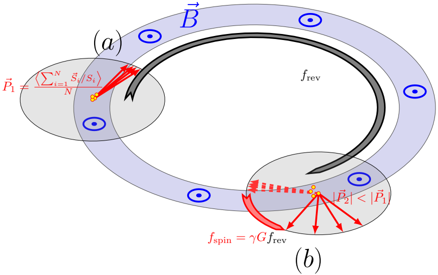
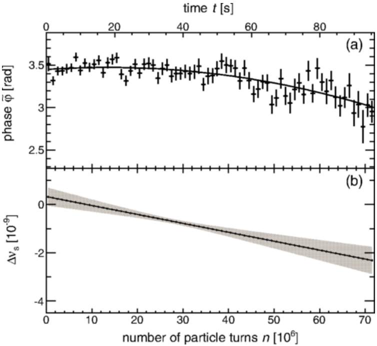


2.) Spin Tune ν_s

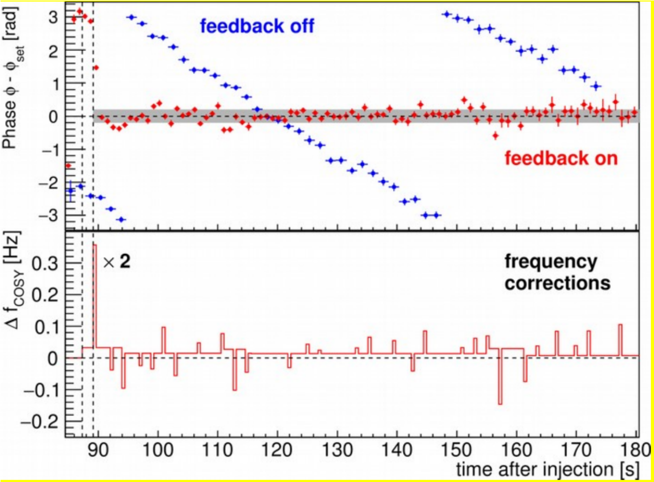




$$\sigma(\nu_s = \gamma G) \approx 10^{-10} \text{ in } 100\,\text{s}$$
$$\sigma(\nu_s = \gamma G) \approx 10^{-8} \text{ in } 2\,\text{s}$$

3.) Polarisation feedback

Controlling 120kHz precession

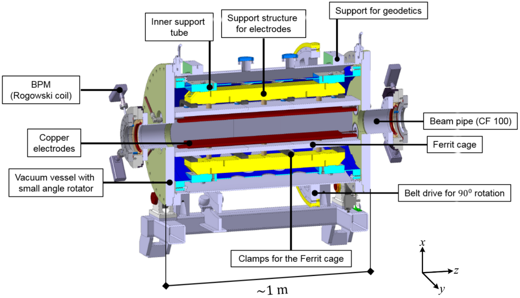


Towards a first deuteron EDM measurement

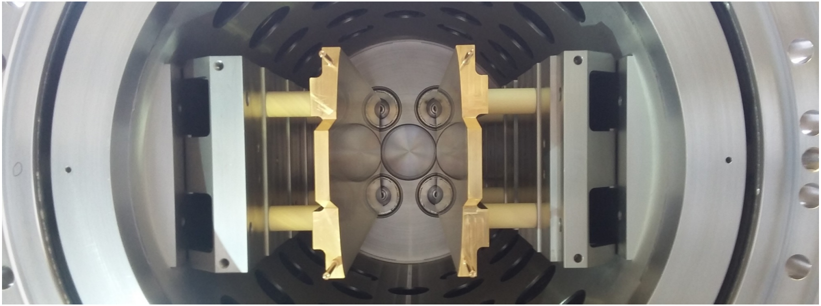
- Spin Manipulation and Measurement ✓
- In magnetic storage ring EDM just causes oscillation with tiny oscillation in vertical plane
- **Wien-filter** operating at spin precession frequency leads to vertical polarisation build-up due to EDM
  (and unfortunately also due to misalignments of storage ring elements)

$\Rightarrow$ EDM measurement possible at magnetic storage ring

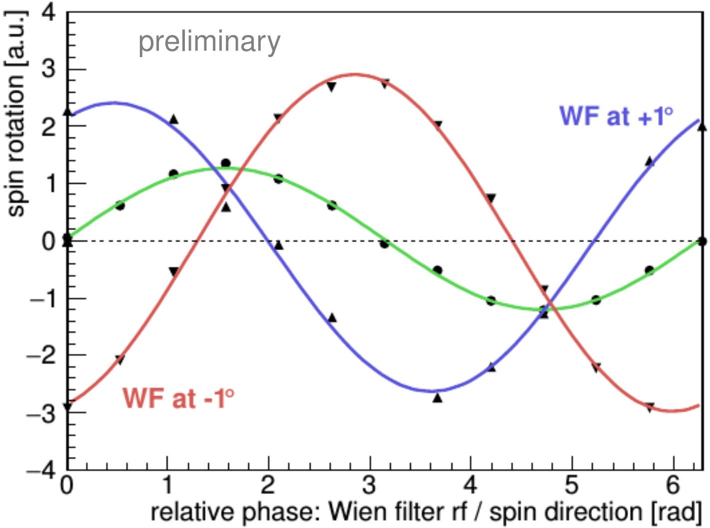
Wien filter



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



Results from Nov. 2017 Beam Time



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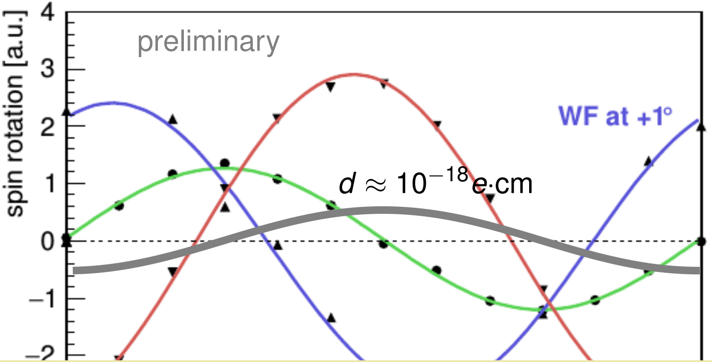

- $\approx$ 1 day of data taking $\Rightarrow$ stat. error $\approx 10^{-19} e$cm not a problem
- simulations are ongoing to understand effects of misalignments (here mimicked by rotation of WF)

Activities

- required for first EDM measurement:
  - maximize spin coherence time (SCT)
  - precise measurement of spin precession (spin tune)
  - polarisation feed back
  - RF- Wien filter

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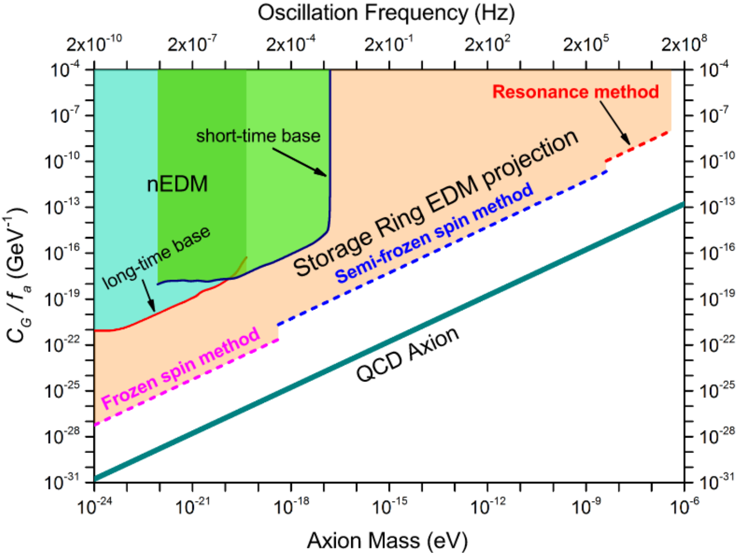
- other observables:
  - axion searches
    (axions may lead to oscillating EDM)

Summary

- EDMs are unique probe to search for new CP-violating interactions
- **charged** particle EDMs can be measured in storage rings
- step wise approach: precursor at COSY → prototype ring (100 m) → dedicated ring (400 m)

Spare

Axion Search



S.P. Chang, PoS PSTP2017 (2018) 036

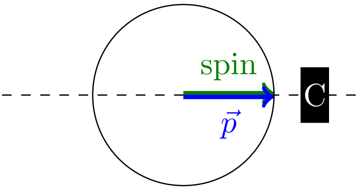
Asymmetry Measurements

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

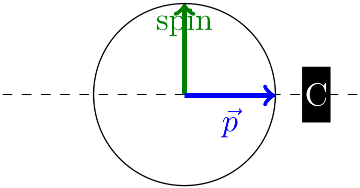
  $$A_{up,dn} = \frac{N^{up} - N^{dn}}{N^{up} + N^{dn}} = P\,A \sin(\gamma G \omega_{rev} t)$$

  A: analyzing power, P : polarization

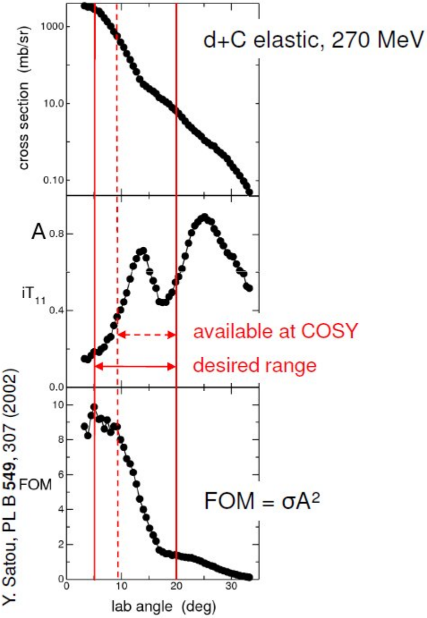
$A_{up,dn} = 0$



$A_{up,dn} = PA$



Polarimetry



d+C elastic, 270 MeV

available at COSY

desired range

FOM = σA^2

Y. Satou, PL B **549**, 307 (2002)

Cross Section &
Analyzing Power
for deuterons

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A : analyzing power
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