Electric Dipole Moment Searches using Storage Rings

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Contents

Baryon asymmetry in the Universe

Carina Nebula: Largest-seen star-birth regions in the galaxy

Observation and expectation from Standard Cosmological Model (SCM):

	$\eta = (n_b - n_{\bar{b}})/n_\gamma$	
Observation	$(6.11^{+0.3}_{-0.2}) \times 10^{-10}$	Best Fit Cosmological Model [1]
	$(5.53 - 6.76) \times 10^{-10}$	WMAP [2]
Expectation from SCM	$\sim 10^{-18}$	Bernreuther (2002) [3]

Precision frontier

EDMs possibly constitutes missing cornerstone

to explain surplus of matter over antimatter in the Universe:

- SCM gets it wrong by about 8 orders of magnitude.

Large worldwide effort to search for EDMs of fundamental particles:

- hadrons, solids, atoms and molecules.
- ~ 500 researchers (estimate by Harris, Kirch).
- Total of ≈ 20 talks at Spin 2018 on EDM related R&D.

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Why search for charged particle EDMs using a storage ring?

So far, no direct measurement of charged hadron EDMs:

- potentially higher sensitivity than for neutrons:
  - longer lifetime,
  - more stored polarized protons/deuterons available than neutrons, and
  - one can apply larger electric fields in storage ring.
- Approach complimentary to neutron EDM searches.
- **EDM of single particle not sufficient to identify *CP* violating source [4]**

Naive estimate of scale of nucleon EDM

From Khriplovich & Lamoreux [5]:

- *CP* and *P* conserving magnetic moment $\approx$ nuclear magneton μ_N.

$$\mu_N = \frac{e}{2m_p} \sim 10^{-14}\,\mathrm{e\,cm}.$$

- A non-zero EDM requires:
  - *P* violation: price to pay is $\approx 10^{-7}$, and
  - *CP* violation (from *K* decays): price to pay is $\sim 10^{-3}$.
- In summary:

$$\boxed{|d_N| \sim 10^{-7} \times 10^{-3} \times \mu_N \sim 10^{-24}\,\mathrm{e\,cm}}$$

- In Standard model (without θ_{QCD} term):

$$\boxed{|d_N| \sim 10^{-7} \times 10^{-24}\,\mathrm{e\,cm} \sim 10^{-31}\,\mathrm{e\,cm}}$$

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Region to search for BSM physics ($\theta_{\mathrm{QCD}} = 0$) from nucleon EDMs:

$$10^{-24}\,\mathrm{e\,cm} > |d_N| > 10^{-31}\,\mathrm{e\,cm}.$$

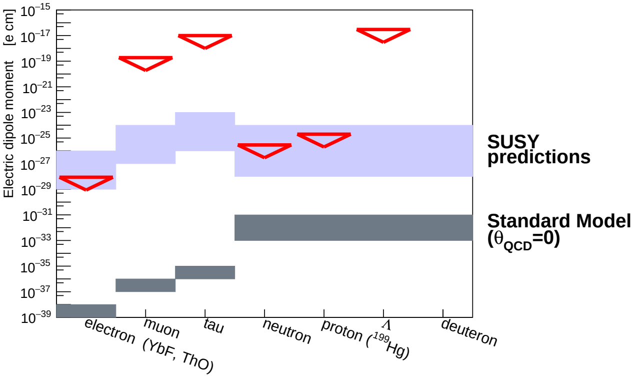
Status of EDM searches I

EDM limits in units of [e cm]:

- Long-term goals for neutron, $^{199}_{80}\mathrm{Hg}$, $^{129}_{54}\mathrm{Xe}$, proton, and deuteron.
- Neutron equivalent values indicate value for neutron EDM d_n to provide same physics reach as indicated system:

Particle	Current limit	Goal	d_n equivalent	date [ref]
Electron	$< 8.7 \times 10^{-29}$	$\approx 10^{-29}$		2014 [6]
Muon	$< 1.8 \times 10^{-19}$			2009 [7]
Tau	$< 1 \times 10^{-17}$			2003 [8]
Lambda	$< 3 \times 10^{-17}$			1981 [9]
Neutron	$(-0.21 \pm 1.82) \times 10^{-26}$	$\approx 10^{-28}$	10^{-28}	2015 [10]
$^{199}_{80}\mathrm{Hg}$	$< 7.4 \times 10^{-30}$	10^{-30}	$< 1.6 \times 10^{-26}$ [11]	2016 [12]
$^{129}_{54}\mathrm{Xe}$	$< 6.0 \times 10^{-27}$	$\approx 10^{-30}$ to 10^{-33}	$\approx 10^{-26}$ to 10^{-29}	2001 [13]
Proton	$< 2 \times 10^{-25}$	$\approx 10^{-29}$	10^{-29}	2016 [12]
Deuteron	not available yet	$\approx 10^{-29}$	$\approx 3 \times 10^{-29}$ to 5×10^{-31}	

Status of EDM searches II



Missing are *direct* EDM measurements:

- No direct measurements of electron: limit obtained from (ThO molecule).
- No direct measurements of proton: limit obtained from $^{199}_{80}\mathrm{Hg}$.
- **No measurement at all of deuteron EDM.**

Experimental requirements for storage ring EDM searches

High precision, primarily electric storage ring

- Crucial role of alignment, stability, field homogeneity, and shielding from perturbing magnetic fields.
- High beam intensity: $N = 4 \times 10^{10}$ particles per fill.
- High polarization of stored polarized hadrons: $P = 0.8$.
- Large electric fields: $E = 10\,\mathrm{MV/m}$.
- Long spin coherence time: $\tau_{\mathrm{SCT}} = 1000\,\mathrm{s}$.
- Efficient polarimetry with
  - large analyzing power: $A_y \simeq 0.6$,
  - and high efficiency detection $f \simeq 0.005$.

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In terms of numbers given above:

- This implies:

$$\sigma_{\mathrm{stat}} = \frac{1}{\sqrt{N f}\,\tau_{\mathrm{SCT}}\,P\,A_y\,E} \quad \Rightarrow \quad \boxed{\sigma_{\mathrm{stat}}(1\,\mathrm{yr}) = 10^{-29}\,\mathrm{e\,cm}}\,. \tag{1}$$

- **Experimentalist's goal is to provide σ_{syst} to the same level.**

Particles with magnetic and electric dipole moment

For particles with EDM $\vec{d}$ and MDM $\vec{\mu}$ ($\propto \vec{s}$),

- non-relativistic Hamiltonian:

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

  - **Energy of magnetic dipole** invariant under P and T:

$$-\vec{\mu}\cdot\vec{B} \overset{P \text{ or } T}{\overbrace{\longrightarrow}} -\vec{\mu}\cdot\vec{B}, \tag{2}$$

    No other direction than spin $\Rightarrow$ $\vec{d}$ parallel to $\vec{\mu}$ ($\vec{s}$).

  - **Energy of electric dipole** $H = -\vec{d}\cdot E$, includes term

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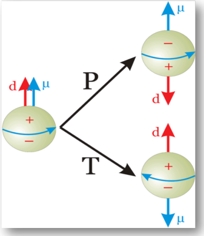
- **Thus, EDMs violate both P and T symmetry.**



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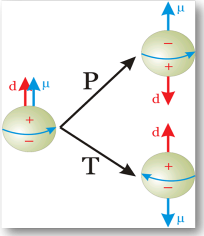

In rest frame of particle,

- equation of motion for spin vector $\vec{S}$:

$$\frac{\mathrm{d}\vec{S}}{\mathrm{d}t} = \vec{\Omega} \times \vec{S} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}. \tag{4}$$

Frozen-spin

Spin precession frequency of particle *relative* to direction of flight:

$$\begin{aligned}\vec{\Omega} &= \vec{\Omega}_{\text{MDM}} - \vec{\Omega}_{\text{cyc}} \\ &= -\frac{q}{\gamma m}\left[G\gamma\vec{B}_{\perp} + (1+G)\vec{B}_{\parallel} - \left(G\gamma - \frac{\gamma}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right].\end{aligned} \tag{5}$$

$\Rightarrow$ $\vec{\Omega} = 0$ **called frozen spin, because momentum and spin stay aligned.**

- In the absence of magnetic fields ($B_{\perp} = \vec{B}_{\parallel} = 0$),

$$\vec{\Omega} = 0, \text{ if } \left(G\gamma - \frac{\gamma}{\gamma^2-1}\right) = 0. \tag{6}$$

  - Possible only for particles with $G > 0$, such as proton ($G = 1.793$) or electron ($G = 0.001$).

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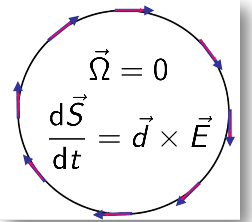
For protons, (6) leads to *magic momentum*:

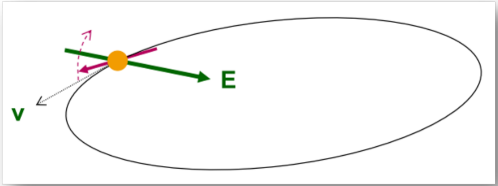
$$G - \frac{1}{\gamma^2-1} = 0 \Leftrightarrow G = \frac{m^2}{p^2} \quad \Rightarrow \quad \boxed{p = \frac{m}{\sqrt{G}} = 700.740\,\mathrm{MeV\,c^{-1}}} \tag{7}$$

Protons at magic momentum in pure electric ring:

Recipe to measure EDM of proton:

1. Place polarized particles in a storage ring.
2. Align spin along direction of flight at magic momentum.
   $\Rightarrow$ *freeze* horizontal spin precession.
3. Search for time development of vertical polarization.





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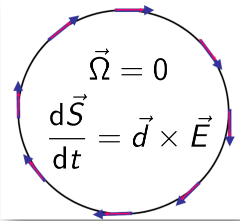
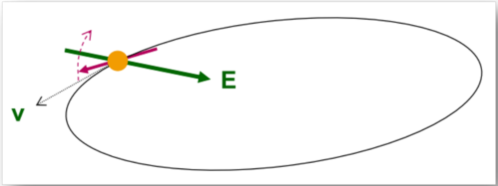




New method to measure EDMs of charged particles:

- **Magic rings with spin frozen** along momentum of particle.
- Polarization buildup $P_y(t) \propto d$.

Search for charged particle EDMs with frozen spins

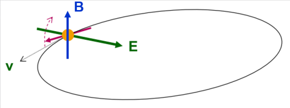
Magic storage rings

For any sign of G, in *combined* electric and magnetic machine:

- Generalized solution for magic momentum

$$E_r = \frac{G B_y c \beta \gamma^2}{1 - G \beta^2 \gamma^2}, \qquad (8)$$

where E_r is radial, and B_y vertical field.



- Some configurations for circular machine with fixed radius $r = 25\,\mathrm{m}$:

particle	G	$p\,[\mathrm{MeV\,c^{-1}}]$	$T\,[\mathrm{MeV}]$	$E\,[\mathrm{MV\,m^{-1}}]$	$B\,[\mathrm{T}]$
proton	1.793	701	232.8	16.789	0.000
deuteron	−0.143	1000	249.9	−3.983	0.160
helion	−4.184	1285	280.0	17.158	−0.051

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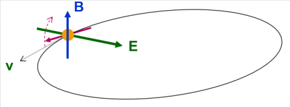

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Offers possibility to determine

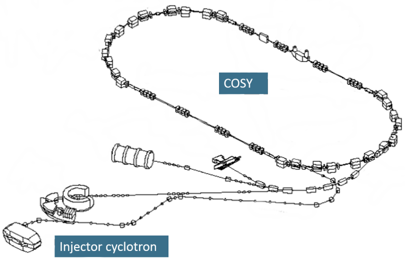
EDMs of protons, deuterons, and helions in one and the same machine.

Progress toward storage ring EDM experiments

Complementing the spin physics tool box

COoler SYnchrotron COSY

- Cooler and storage ring for (polarized) protons and deuterons.
- Momenta $p = 0.3 - 3.7\,\mathrm{GeV}/c$.
- Phase-space cooled internal and extracted beams.



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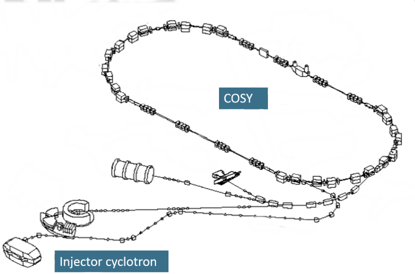
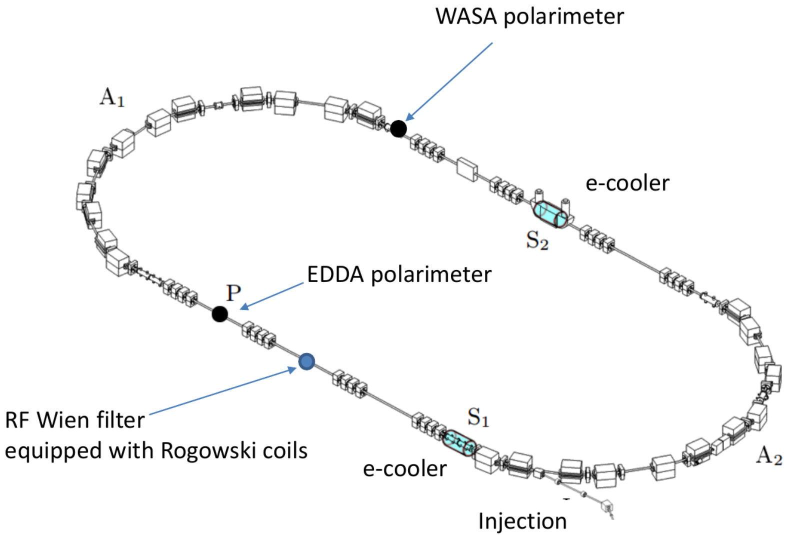


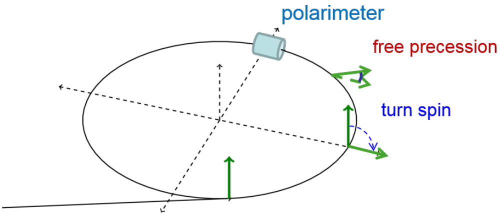
COSY formerly used as spin-physics machine for hadron physics:

- Provides an ideal starting point for srEDM related R&D.
- Will be used for a first direct measurment of deuteron EDM.

COSY Landscape



Principle of spin-coherence time measurement



Measurement procedure:

1. Vertically polarized deuterons stored at $p \simeq 1\,\mathrm{GeV\,c^{-1}}$.
2. Polarization flipped into horizontal plane with RF solenoid ($\approx 200\,\mathrm{ms}$).
3. Beam extracted on Carbon target with ramped bump or by heating.
4. Horizontal (in-plane) polarization determined from $U - D$ asymmetry in polarimeter.

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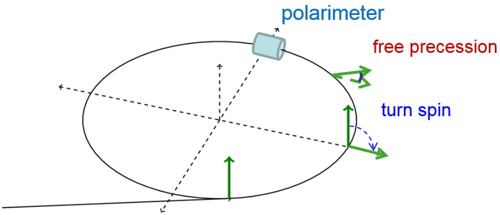

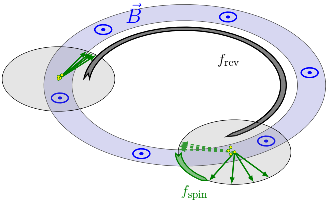

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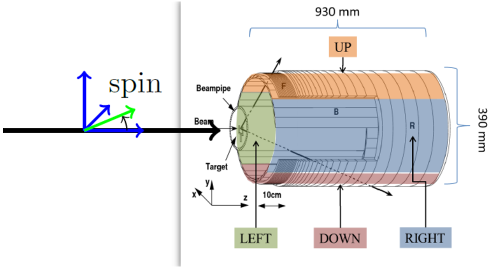
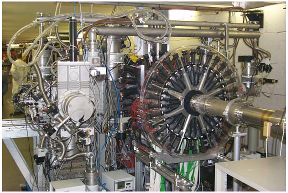
Detector system: EDDA [14]





EDDA previously used to determine $\vec{p}\vec{p}$ elastic polarization observables:

- Deuterons at $p = 1\,\mathrm{GeV\,c^{-1}}$, $\gamma = 1.13$, and $\nu_s = \gamma G \simeq -0.161$
- Spin-dependent differential cross section on unpolarized target:

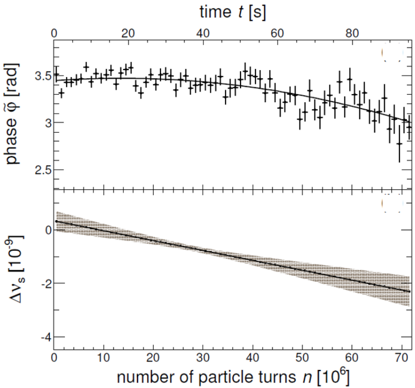
$$N_{\mathrm{U,D}} \propto 1 \pm \frac{3}{2} p_z A_y \sin(\nu_s\, f_{\mathrm{rev}}\, t), \text{ where } f_{\mathrm{rev}} = 781\,\mathrm{kHz}. \quad (9)$$

Precision determination of the spin tune [15, JEDI 2015 PRL]

Time-stamping events accurately,

- allows us to monitor phase of measured asymmetry with (assumed) fixed spin tune ν_s in a 100 s cycle:

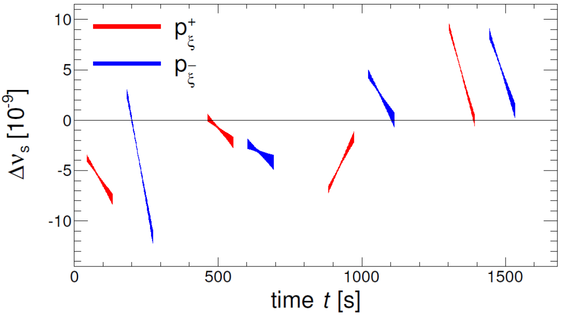
$$\nu_s(n) = \nu_s^{\text{fix}} + \frac{1}{2\pi}\frac{\mathrm{d}\tilde{\phi}}{\mathrm{d}n} = \nu_s^{\text{fix}} + \Delta\nu_s(n) \tag{10}$$



Experimental technique allows for:

- Spin tune ν_s determined to $\approx 10^{-8}$ in 2 s time interval.
- In a 100 s cycle at $t \approx 38$ s, interpolated spin tune amounts to $|\nu_s| = (16097540628.3 \pm 9.7) \times 10^{-11}$, *i.e.*, $\Delta\nu_s/\nu_s \approx 10^{-10}$.
- $\Rightarrow$ **new precision tool to study systematic effects in a storage ring.**

Spin tune as a precision tool for accelerator physics

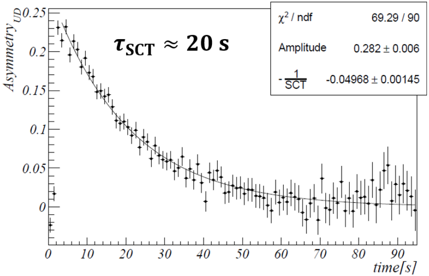


Walk of spin tune ν_s [15].

Applications of new technique:

- Study long term stability of an accelerator.
- Feedback system to stabilize phase of spin precession relative to phase of RF devices (so-called **phase-lock**).
- Study of machine imperfections **(see N.N. Nikolaev on Tu at 17:20)**.

Optimization of spin-coherence time: JEDI 2014 PRL [16]



2012: Observed experimental decay of asymmetry

$$\epsilon_{\mathrm{UD}}(t) = \frac{N_D(t) - N_U(t)}{N_D(t) + N_U(t)}. \qquad (11)$$

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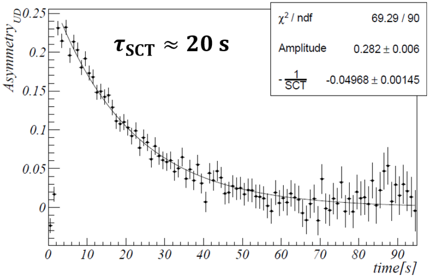

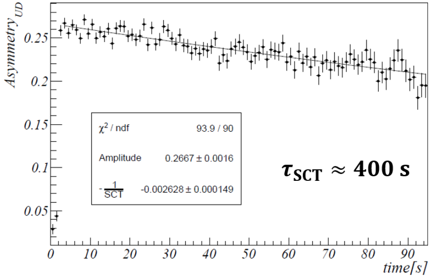

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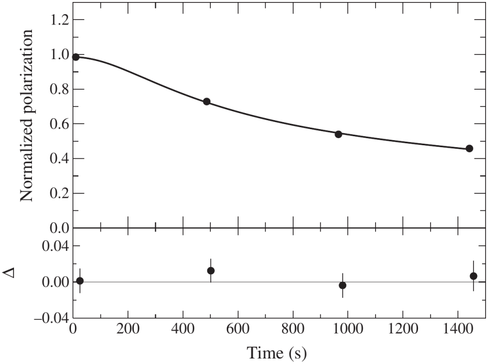
2013: Using sextupole magnets, higher order effects are corrected, and spin coherence substantially increased.

More optimizations of spin-coherence time: JEDI 2016 PRL [18]



Recent progress on τ_{SCT}:

$$\tau_{\mathrm{SCT}} = (\mathbf{782} \pm \mathbf{117})\,\mathrm{s}$$

- Previously: $\tau_{\mathrm{SCT}}(\mathrm{VEPP}) \approx 0.5\,\mathrm{s}$ [17] ($\approx 10^7$ spin revolutions).

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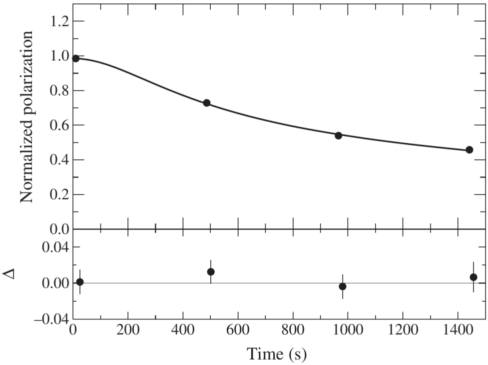

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Spring 2015: Way beyond anybody's expectation:

- With about 10^9 stored deuterons.
- Long spin coherence time was one of main obstacles of srEDM experiments.
- Large value of τ_{SCT} of crucial importance (1), since $\sigma_{\mathrm{stat}} \propto \frac{1}{\tau_{\mathrm{SCT}}}$.

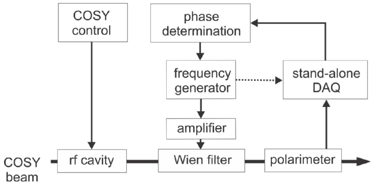
Phase locking spin precession in machine to device RF

At COSY, frozen spin is not possible

$\Rightarrow$ To achieve precision for EDM, phase-locking is next best thing to do.

Feedback system maintains

1. resonance frequency, and
2. phase between spin precession and device RF (solenoid or Wien filter)



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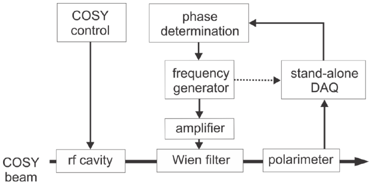
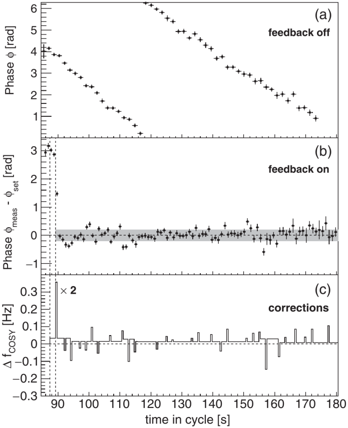




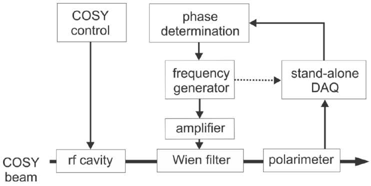
Phase locking spin precession in machine to device RF

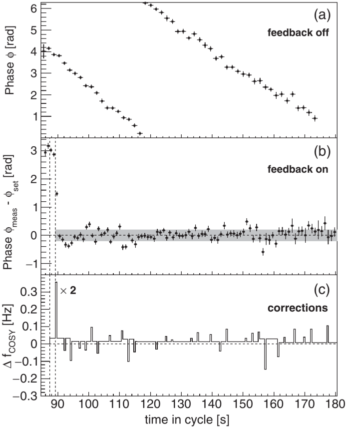
At COSY, frozen spin is not possible

$\Rightarrow$ To achieve precision for EDM, phase-locking is next best thing to do.

Feedback system maintains

1. resonance frequency, and
2. phase between spin precession and device RF (solenoid or Wien filter)





Major achievement : Error of phase-lock $\sigma_\phi = 0.21\,\text{rad}$ JEDI 2017 PRL [19].

More technical challenges of storage ring EDM experiments

Overview

Charged particle EDM searches require development of new class of high-precision machines with mainly electric fields for bending and focussing:

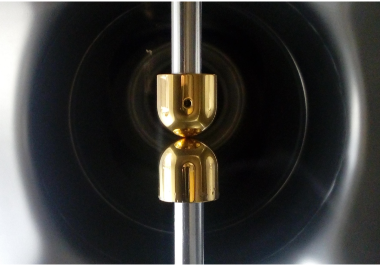
Main issues:

- Large electric field gradients ~ 10 to $20\,\mathrm{MV/m}$.
- Spin coherence time $\tau_{\mathrm{SCT}} \sim 1000\,\mathrm{s}$ [18].
- Continuous polarimetry with relative errors $< 1\,\mathrm{ppm}$ [20].
- Beam position monitoring with precision of $10\,\mathrm{nm}$.
- High-precision spin tracking.
- Alignment of ring elements, ground motion, ring imperfections.
- Magnetic shielding.
- For deuteron EDM with frozen spin: precise reversal of magnetic fields for CW and CCW beams required.

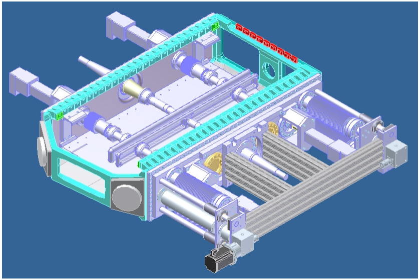
E/B Deflector development using small-scale lab setup

Kirill Grigoriev (IKP, RWTH Aachen and FZJ)

- Polished stainless steel
  - 240 MV/m reached at distance of 0.05 mm with half-sphere facing flat surface.
  - 17 MV/m with 1 kV at 1 mm with two small half-spheres.
- Polished aluminum
  - 30 MV/m measured at distance of 0.1 mm using two small half-spheres.
- TiN coating
  - Smaller breakdown voltage.
  - Zero dark current.



E/B deflector development using real-scale lab setup



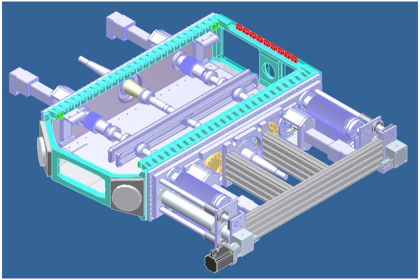
Equipment:

- Dipole magnet $B_{\text{max}} = 1.6\,\text{T}$
- Mass $= 64\,\text{t}$
- Gap height $= 200\,\text{mm}$
- Protection foil between chamber wall and deflector

Parameters:

- Electrode length $= 1020\,\text{mm}$
- Electrode height $= 90\,\text{mm}$
- Electrode spacing $= 20$ to $80\,\text{mm}$
- Max. electric field $= \pm 200\,\text{MV}$
- Material: Aluminum coated by TiN

E/B deflector development using real-scale lab setup



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- Material: Aluminum coated by TiN

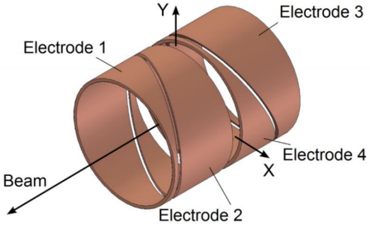
Next steps:

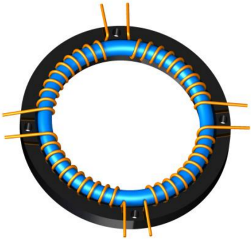
Equipment ready for assembling. First test results expected before Christmas.

Beam position monitors for srEDM experiments

Compact new development based on segmented Rogowski coil

- Main advantage is short installation length of ≈ 1 cm (along beam direction)





Conventional BPM

- Easy to manufacture
- length = 20 cm
- resolution ≈ 10 μm

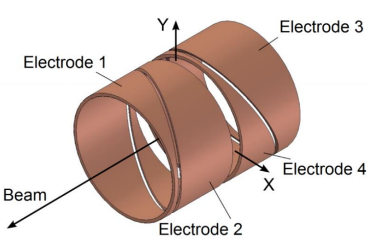
Rogowski BPM

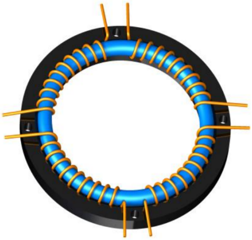
- Excellent rf-signal response
- length = 1 cm
- resolution ≈ 1.25 μm

Beam position monitors for srEDM experiments

Compact new development based on segmented Rogowski coil

- Main advantage is short installation length of $\approx 1\,\text{cm}$ (along beam direction)





Conventional BPM

- Easy to manufacture
- length $= 20\,\text{cm}$
- resolution $\approx 10\,\mu\text{m}$

Rogowski BPM

- Excellent rf-signal response
- length $= 1\,\text{cm}$
- resolution $\approx 1.25\,\mu\text{m}$

- Two Rogowski coils already installed at entrance and exit of RF Wien filter

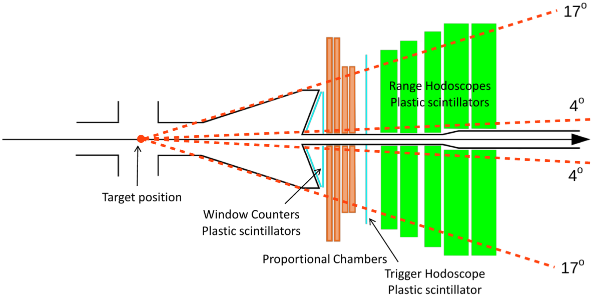
dC polarimetry data base I

Motivation: Optimize polarimetry for ongoing JEDI activities:

- Determine vector and tensor analyzing powers A_y, A_{yy}, and differential cross sections $d\sigma/d\Omega$ of dC elastic scattering at
  - deuteron kinetic energies $T = 170 - 380\,\mathrm{MeV}$.

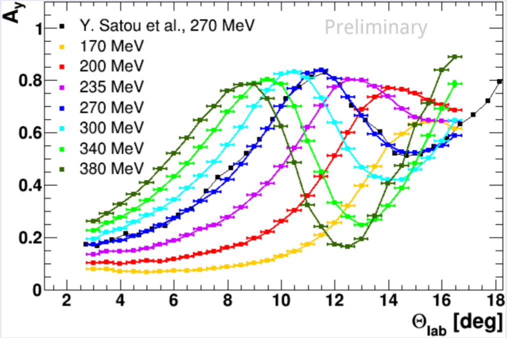
Detector system: former WASA forward detector, modified

- Targets: C and CH2
- Full azimuthal coverage, scattering angl range $\theta = 4^\circ - 17^\circ$.



dC polarimetry data base II

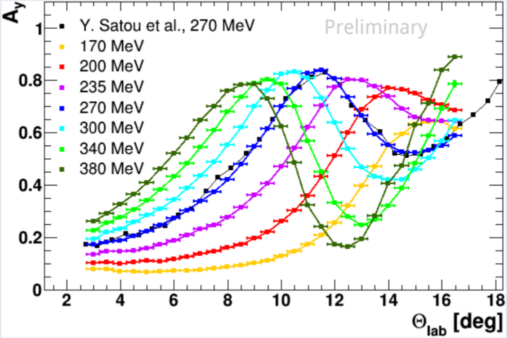
Preliminary results of elastic dC analyzing powers



- Analysis of differential dC cross sections in progress.
- JEDI just finished another similar data base run to provide pC data base.

dC polarimetry data base II

Preliminary results of elastic dC analyzing powers



- Analysis of differential *dC* cross sections in progress.
- JEDI just finished another similar data base run to provide *pC* data base.

see talk by Fabian Müller on We at 17:20

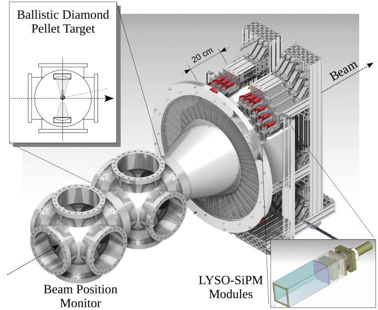
High-precision beam polarimeter with internal C target

Based on LYSO Scintillation Material

- Saint-Gobain Ceramics & Plastics: $Lu_{1.8}Y_{.2}SiO_5$:Ce
- Compared to NaI, LYSO provides
  - high density (7.1 vs 3.67 g/cm^3),
  - very fast decay time (45 vs 250 ns).

After several runs with externl beam:

- System ready for installation at COSY in 2019.
- Not yet ready: Ballistic diamond pellet target for homogeneous beam sampling.



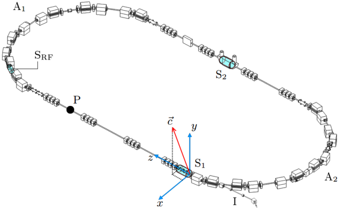
see talk by Dito Shergelashvili on We at 17:00

Study of machine imperfections

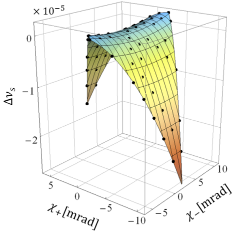
JEDI developed a new method to investigate magnetic machine imperfections based on the highly accurate determination of the spin-tune Saleev PR AB 2017 [21].

Spin tune mapping

- Two cooler solenoids act as spin rotators $\Rightarrow$ generate artificial imperfection fields.
- Measure spin tune shift vs spin kicks.



- Position of saddle point determines tilt of stable spin axis by magnetic imperfections.
- Control of background from MDM at level $\Delta c = 2.8 \times 10^{-6}$ rad.
- Systematics-limited sensitivity for deuteron EDM at COSY $\sigma_d \approx 10^{-20}$ e cm.



see talk of N.N. Nikolaev on Tu at 17:20.

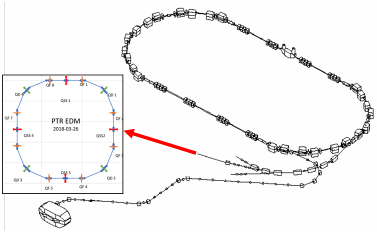
Prototype EDM storage ring

Next step:

- Build **demonstrator for charged-particle EDM**.
- Project prepared by a new CPEDM collaboration (CERN + JEDI).
  - Physics Beyond Collider process (CERN), and the
  - European Strategy for Particle Physics Update.
- Possible host sites: COSY or CERN

Scope of the project

30 MeV protons, all-electric operation, CW-CCW beams, 100 m circumference



- Storage time
- CW/CCW operation
- Spin coherence time
- Polarimetry
- magnetic moment effects
- (pEDM measurement)
- Stochastic cooling

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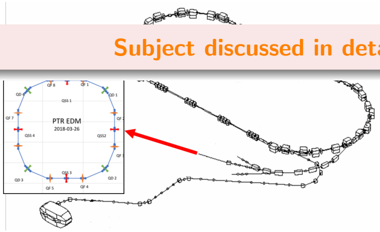

- Storage time

Subject discussed in detail by Sig Martin on We at 16:40

- Polarimetry
- magnetic moment effects
- (pEDM measurement)
- Stochastic cooling

Proof of principle experiment using COSY
Precursor experiment

Highest EDM sensitivity shall be achieved with a new type of machine:

- An **electrostatic circular storage** ring, where
  - centripetal force produced primarily by electric fields.
  - E field couples to EDM and provides required sensitivity ($< 10^{-28}$ e cm).
  - In this environment, magnetic fields mean evil (since μ is large).

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Idea behind proof-of-principle experiment with novel RF Wien filter ($\vec{E} \times \vec{B}$):

- In magnetic machine, particle spins (deuterons, protons) precess about stable spin axis ($\simeq$ direction of magnetic fields in dipole magnets).
- Use RF device operating on some harmonic of the spin-precession frequency:

  $\Rightarrow$ *Phase lock* between spin precession and device RF.

  $\Rightarrow$ Allows one to accumulate EDM effect as function of time in cycle ($\sim 1000\,\mathrm{s}$).

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  $\Rightarrow$ Allows one to accumulate EDM effect as function of time in cycle ($\sim 1000\,\mathrm{s}$).

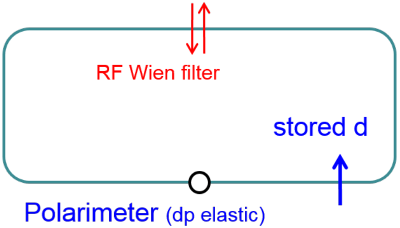
Goal of proof-of-principle experiment:

Show that conventional storage ring useable for first direct EDM measurement

RF Wien filter

A couple more aspects about the technique:

- RF Wien filter ($\vec{E} \times \vec{B}$) avoids coherent betatron oscillations in the beam:
  - Lorentz force $\vec{F}_L = q(\vec{E} + \vec{v} \times \vec{B}) = 0$.
  - EDM measurement mode: $\vec{B} = (0, B_y, 0)$ and $\vec{E} = (E_x, 0, 0)$.



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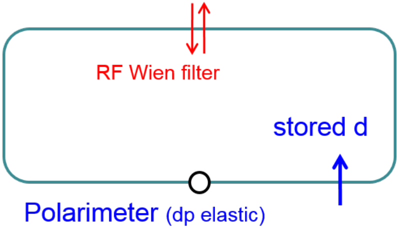

- Deuteron spins lie in machine plane.
- If $d \neq 0 \Rightarrow$ *accumulation* of vertical polarization P_y, during spin coherence time $\tau_{\mathrm{SCT}} \sim 1000\,\mathrm{s}$.

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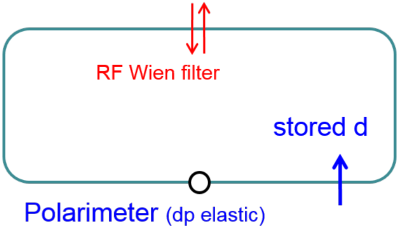

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- If $d \neq 0 \Rightarrow$ *accumulation* of vertical polarization P_y, during spin coherence time $\tau_{\mathrm{SCT}} \sim 1000\,\mathrm{s}$.

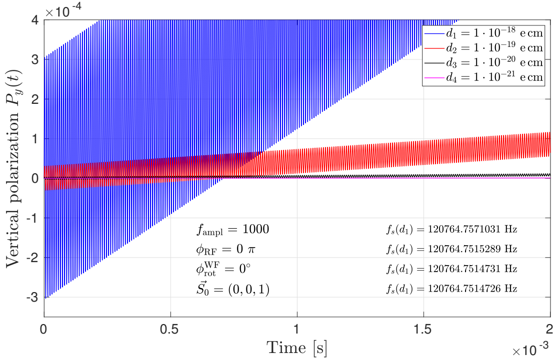
Statistical sensitivity:

- in the range 10^{-23} to $10^{-24}\,\mathrm{e\,cm}$ for $d(deuteron)$ possible.
- Systematic effects: Alignment of magnetic elements, magnet imperfections, imperfections of RF-Wien filter etc.

Model calculation of EDM buildup with RF Wien filter

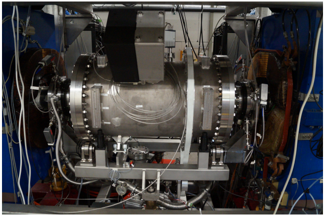
Ideal COSY ring with deuterons at $p_d = 970\,\mathrm{MeV/c}$:

- $G = -0.143$, $\gamma = 1.126$, $f_s = |f_{\mathrm{rev}}(\gamma G + K_{(=0)})| \approx 120.765\,\mathrm{kHz}$
- Electric RF field integral assumed $1000 \times \int E_{\mathrm{WF}} \cdot d\ell \approx 2200\,\mathrm{kV}$ (w/o ferrites) Slim 2016 NIM [22].



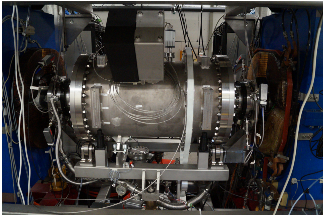
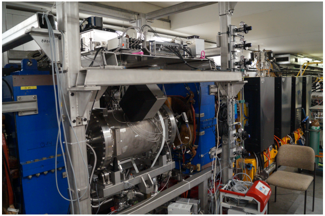
EDM accumulates in $P_y(t) \propto d_{\mathrm{EDM}}$ [21, 23, 24].

RF Wien filter
Overview



- RF Wien filter between PAX magnets.

RF Wien filter
Overview

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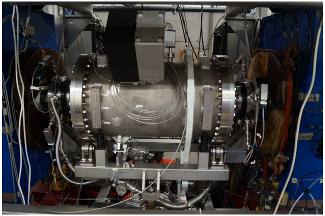
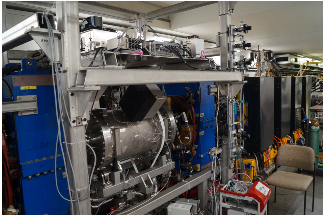
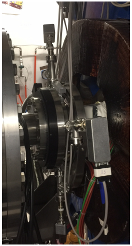
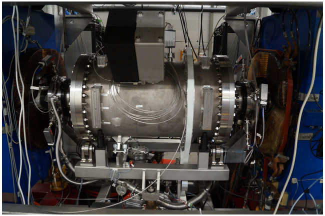
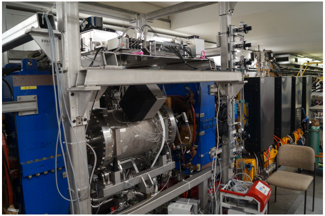
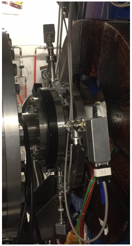




- RF Wien filter between PAX magnets. Upstream Rogowski coil;

RF Wien filter
Overview

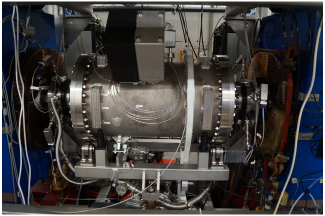
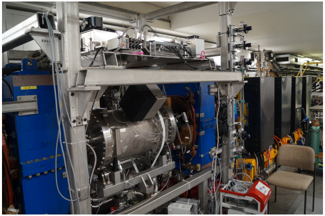
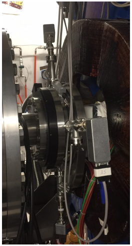


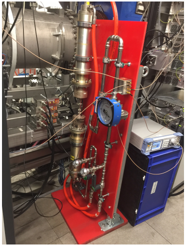




- RF Wien filter between PAX magnets. Upstream Rogowski coil; racks with power amplifiers, each unit delivers up to 500 W;

RF Wien filter
Overview

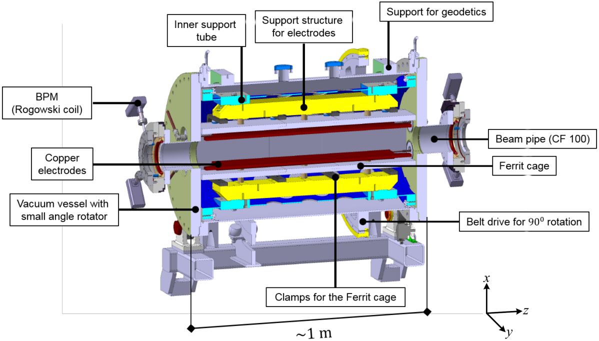


- RF Wien filter between PAX magnets. Upstream Rogowski coil; racks with power amplifiers, each unit delivers up to 500 W; water-cooled 25 Ω resistor.

Design of RF Wien filter

Device developed at Jülich in cooperation with RWTH Aachen:

- Institute of High Frequency Technology, RWTH Aachen University:
  - Heberling, Hölscher, and PhD Student **Jamal Slim**, and ZEA-1 of Jülich.
- **Waveguide provides $\vec{E} \times \vec{B}$ by design.**
- Minimal $\vec{F}_L$ by careful electromagnetic design of all components [22].



Strength of EDM resonance

EDM induced vertical polarization oscillations,

- can generally be described by

$$p_y(t) = a \sin(\Omega^{p_y}\, t + \phi_{\mathrm{RF}})\,. \tag{12}$$

- Define **EDM resonance strength** $\varepsilon^{\mathrm{EDM}}$ as ratio of angular frequency Ω^{p_y} relative to orbital angular frequency Ω^{rev},

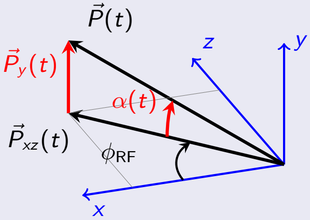
$$\varepsilon^{\mathrm{EDM}} = \frac{\Omega^{p_y}}{\Omega^{\mathrm{rev}}}\,, \tag{13}$$

Alternatively, $\varepsilon^{\mathrm{EDM}}$ is determined from the measured initial slopes $\dot{p}_y(t)|_{t=0}$

- through variation of ϕ_{RF}

$$\varepsilon^{\mathrm{EDM}} = \frac{\dot{p}_y(t)|_{t=0}}{a \cos\phi_{\mathrm{RF}}} \cdot \frac{1}{\Omega^{\mathrm{rev}}}\,. \tag{14}$$

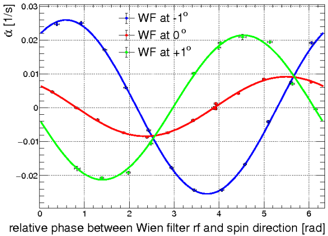
- If $|\vec{P}| = 1 \quad \Rightarrow \quad \dot{p}_y(t) = \dot{\alpha}(t)$



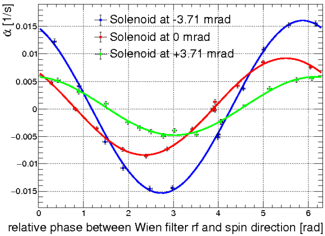
First measurement of EDM-like buildup signals

Rate of out-of-plane rotation angle $\dot{\alpha}(t)|_{t=0}$ as function of Wien filter RF phase ϕ_{RF}

- B field of RF Wien filter normal to the ring plane.
- Wien filter operated at $f_{\mathrm{WF}} = 871\,\mathrm{kHz}$.
- Variations of $\phi^{\mathrm{WF}}_{\mathrm{rot}}$ and $\chi^{\mathrm{Sol\,1}}_{\mathrm{rot}}$ affect the pattern of observed initial slopes $\dot{\alpha}$.



$\dot{\alpha}$ for $\phi^{\mathrm{WF}}_{\mathrm{rot}} = -1°, 0°, +1°$ and $\chi^{\mathrm{Sol\,1}}_{\mathrm{rot}} = 0$.



$\dot{\alpha}$ for $\chi^{\mathrm{Sol\,1}}_{\mathrm{rot}} = -1, 0, +1°$ and $\phi^{\mathrm{WF}}_{\mathrm{rot}} = 0$.

Next steps:

- After commissioning, first EDM run scheduled for Nov-Dec/2018.
- **see talk by Alexander Nass on Tu at 18:00**

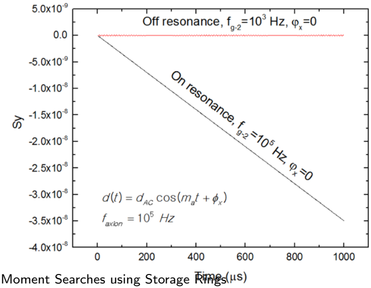
Axion-EDM (oscillating) search using storage ring

Motivation: Paper by Graham and Rajendran [25, 2011]

- Oscillating axion field is coupled with gluons and induces an oscillating EDM in hadronic particles.

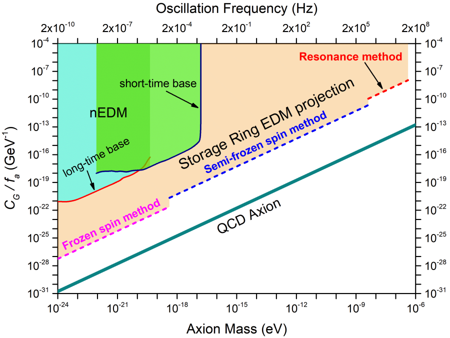
Measurement principle:

- When oscillating EDM resonates with particle $g-2$ precession frequency in the storage ring, the EDM precession can be accumulated.
- Due to strong effective electric field (from $\vec{v} \times \vec{B}$), sensitivity is improved significantly.



Courtesy of Seongtae Park (IBS, Daejeon, ROK)

Limits for axion-gluon coupled to oscillating EDM



from Ref. [26]

Realization

- No new/additional equipment required!
- Can be done in magnetic storage ring (*i.e.*, COSY)
- Proposal for test beam time accepted by CBAC.
- Experiment scheduled for I/2019.

Summary

Search for charged particle EDMs:

- New window to disentangle sources of *CP* violation, and to possibly explain matter-antimatter asymmetry of the Universe.

- JEDI is making steady progress in spin dynamics of relevance to future searches for EDM.
- COSY remains a unique facility for such studies.
- First direct JEDI deuteron EDM measurement at COSY well underway.
  - Run scheduled for Nov-Dec.
  - Sensitivity $10^{-19} - 10^{-20}$ e cm.
- Strong interest of high energy community in storage ring searches for EDM of protons and light nuclei as part of physics program of the post-LHC era.
- Proposal for prototype all-electric 30 MeV EDM storage ring being prepared (possible hosts: CERN or COSY).
- Crossed $\vec{E} \times \vec{B}$ field prototype EDM storage ring might be an option before going to a TDR for the ultimate EDM machine.

JEDI Collaboration

JEDI = Jülich Electric Dipole Moment Investigations

- ~ 140 members (Aachen, Daejeon, Dubna, Ferrara, Indiana, Ithaka, Jülich, Krakow, Michigan, Minsk, Novosibirsk, St Petersburg, Stockholm, Tbilisi, ...
- `http://collaborations.fz-juelich.de/ikp/jedi`

Spares

Thomas-BMT equation with EDM and MDM

When particles orbit in an accelerator,

- Spin equation expressed in curvilinear laboratory reference frame.
- Solution called Thomas-BMT equation [27, 28] (historically ignoring EDM).
- Generalized form of Thomas-BMT equation, including EDMs [29]:

$$\boxed{\frac{\mathrm{d}\vec{S}}{\mathrm{d}t} = \vec{\Omega}_{\text{MDM}} \times \vec{S} + \vec{\Omega}_{\text{EDM}} \times \vec{S}}, \quad \text{where}$$

$$\vec{\Omega}_{\text{MDM}} = -\frac{q}{m}\left[\left(G + \frac{1}{\gamma}\right)\vec{B} - \frac{G\gamma}{\gamma+1}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \left(G + \frac{1}{\gamma+1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right], \tag{15}$$

$$\vec{\Omega}_{\text{EDM}} = -\frac{q}{mc}\frac{\eta_{\text{EDM}}}{2}\left[\vec{E} - \frac{\gamma}{\gamma+1}\left(\vec{\beta}\cdot\vec{E}\right)\vec{\beta} + c\vec{\beta}\times\vec{B}\right].$$

- $\vec{S}$ given in particle rest frame, $\vec{E}$ and $\vec{B}$ in laboratory system.
- MDM and EDM defined via dimensionless quantities g and η_{EDM}:

$$\boxed{\vec{\mu} = g\frac{q}{2m}\vec{S}}, \quad \text{and} \quad \boxed{\vec{d} = \eta_{\text{EDM}}\frac{q}{2m\,c}\vec{S}}, \quad \text{with } G = \frac{g-2}{2}. \tag{16}$$

MDM precession (from [30])

Another way to look at $\vec{\Omega}_{\mathrm{MDM}}$:

- Decomposing precession frequencies: $\vec{\Omega}_{B_\parallel}$, $\vec{\Omega}_{B_\perp}$, and $\vec{\Omega}_{E_\perp}$ leads to

$$\begin{aligned} \vec{\Omega}_{\mathrm{MDM}} &= \vec{\Omega}_{B_\parallel} + \vec{\Omega}_{B_\perp} + \vec{\Omega}_{E_\perp} \\ &= -\frac{q}{\gamma m}\left[(1+G\gamma)\vec{B}_\perp + (1+G)\vec{B}_\parallel - \left(G\gamma + \frac{\gamma}{\gamma+1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] \end{aligned} \tag{17}$$

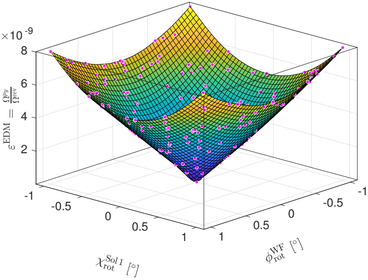
- Including an *electric* field, cyclotron frequency becomes

$$\vec{\Omega}_{cyc} = -\frac{q}{\gamma m}\left(\vec{B}_\perp - \frac{\vec{\beta}\times\vec{E}}{\beta^2 c}\right), \text{ and} \tag{18}$$

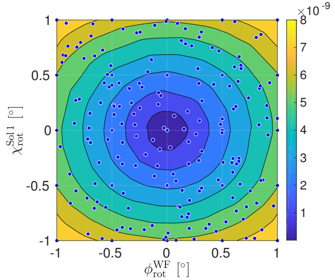
- particle momentum vector $\vec{p}$ rotates with

$$\frac{\mathrm{d}\vec{p}}{\mathrm{d}t} = \vec{\Omega}_{\mathrm{cyc}} \times \vec{p}. \tag{19}$$

Expectation for $d = 10^{-20}$ e cm in ideal COSY ring



(a) ε^{EDM} for $d = 10^{-20}$ e cm.

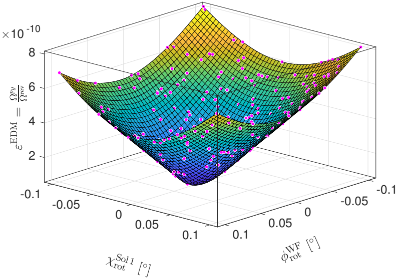


(b) Contour plot of (a).

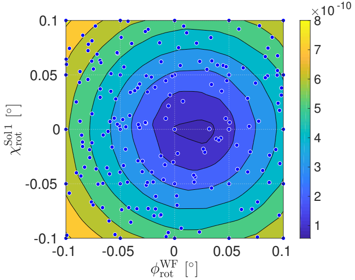
Resonance strengths ε^{EDM} from Eq. (13) ($\approx$ 175 random-points)

- $\phi_{\text{rot}}^{\text{WF}} = [-1\,^\circ, \ldots, +1\,^\circ]$,
- $\chi_{\text{rot}}^{\text{Sol 1}} = [-1\,^\circ, \ldots, +1\,^\circ]$ (100 keV cooler), and
- $\chi_{\text{rot}}^{\text{Sol 2}} = 0$ (2 MeV cooler).
- Each point from calculation with $n_{\text{turns}} = 50\,000$ and $n_{\text{points}} = 200$.

Expectation for $d = 10^{-18}\,\mathrm{e\,cm}$ in ideal COSY ring



(c) $\varepsilon^{\mathrm{EDM}}$ for $d = 10^{-18}\,\mathrm{e\,cm}$.



(d) Contour plot of (c).

Resonance strengths $\varepsilon^{\mathrm{EDM}}$ from Eq. (13) ($\approx$ 175 random-points)

- $\phi_{\mathrm{rot}}^{\mathrm{WF}} = [-0.1\,°, \ldots, +0.1\,°]$,
- $\chi_{\mathrm{rot}}^{\mathrm{Sol\,1}} = [-0.1\,°, \ldots, +0.1\,°]$ (100 keV cooler), and
- $\chi_{\mathrm{rot}}^{\mathrm{Sol\,2}} = 0$ (2 MeV cooler).
- Each point from calculation with $n_{\mathrm{turns}} = 200\,000$ and $n_{\mathrm{points}} = 100$.

References I

[1] C. L. Bennett et al., Astrophys. J. Suppl. **148**, 1 (2003).

[2] V. Barger, J. P. Kneller, H.-S. Lee, D. Marfatia, and G. Steigman, Phys. Lett. **B566**, 8 (2003).

[3] W. Bernreuther, Lect. Notes Phys. **591**, 237 (2002).

[4] J. Bsaisou et al., Journal of High Energy Physics **2015**, 1 (2015).

[5] I. B. Khriplovich and S. K. Lamoreaux, *CP violation without strangeness: Electric dipole moments of particles, atoms, and molecules*, 1997.

[6] J. Baron et al., Science **343**, 269 (2014).

[7] G. W. Bennett et al., Phys. Rev. D **80**, 052008 (2009).

[8] K. Inami et al., Physics Letters B **551**, 16 (2003).

[9] L. Pondrom et al., Phys. Rev. D **23**, 814 (1981).

[10] J. M. Pendlebury et al., Phys. Rev. **D92**, 092003 (2015).

[11] V. F. Dmitriev and R. A. Sen'kov, Phys. Rev. Lett. **91**, 212303 (2003).

[12] B. Graner, Y. Chen, E. G. Lindahl, and B. R. Heckel, Phys. Rev. Lett. **116**, 161601 (2016).

[13] M. A. Rosenberry and T. E. Chupp, Phys. Rev. Lett. **86**, 22 (2001).

References II

[14] D. Albers et al., Eur. Phys. J. **A22**, 125 (2004).

[15] D. Eversmann et al., Phys. Rev. Lett. **115**, 094801 (2015).

[16] Z. Bagdasarian et al., Phys. Rev. ST Accel. Beams **17**, 052803 (2014).

[17] I. Vasserman et al., Physics Letters B **198**, 302 (1987).

[18] G. Guidoboni et al., Phys. Rev. Lett. **117**, 054801 (2016).

[19] N. Hempelmann et al., Phys. Rev. Lett. **119**, 014801 (2017).

[20] N. Brantjes et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **664**, 49 (2012).

[21] A. Saleev et al., Phys. Rev. Accel. Beams **20**, 072801 (2017).

[22] J. Slim et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **828**, 116 (2016).

[23] F. Rathmann, A. Saleev, and N. N. Nikolaev, J. Phys. Conf. Ser. **447**, 012011 (2013).

References III

[24] Y. F. Orlov, W. M. Morse, and Y. K. Semertzidis, Phys. Rev. Lett. **96**, 214802 (2006).

[25] P. W. Graham and S. Rajendran, Phys. Rev. D **84**, 055013 (2011).

[26] S. P. Chang et al., PoS **PSTP2017**, 036 (2018).

[27] L. H. Thomas, Nature **117**, 514 (1926).

[28] V. Bargmann, L. Michel, and V. L. Telegdi, Phys. Rev. Lett. **2**, 435 (1959).

[29] T. Fukuyama and A. J. Silenko, Int. J. Mod. Phys. **A28**, 1350147 (2013).

[30] M. Rosenthal, *Experimental Benchmarking of Spin Tracking Algorithms for Electric Dipole Moment Searches at the Cooler Synchrotron COSY*, PhD thesis, Fakultät für Mathematik, Informatik und Naturwissenschaften der RWTH Aachen University, 2016.