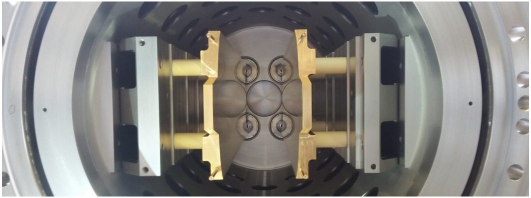


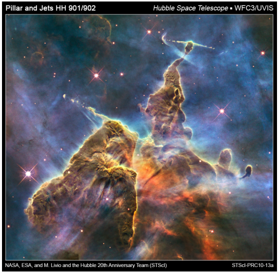
Electric Dipole Moment Searches using Storage Rings

Frank Rathmann (part A) and Alexander Nass (part B)
(on behalf of the JEDI collaboration)

Kick-off workshop muon EDM search at PSI, Villigen, CH, 17.02.2020

Contents I

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]

- SCM gets it wrong by about 9 orders of magnitude.

Electric dipole moments (EDMs)

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:

$$-\vec{\mu} \cdot \vec{B} \overbrace{\longrightarrow}^{P \text{ or } T} -\vec{\mu} \cdot \vec{B}$$

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

$$\vec{s} \cdot \vec{E} \overbrace{\longrightarrow}^{P \text{ or } T} -\vec{s} \cdot \vec{E}, \tag{1}$$

Thus, EDMs violate both P and T symmetry

- EDMs possibly constitute the missing cornerstone to explain surplus of matter over antimatter in the Universe.
  - Non-vanishing EDMs would add 4^{th} quantum number to fundamental particles (besides m, q, and s).

Motivation

Large worldwide effort to search for EDMs of fundamental particles:

- hadrons, leptons, solids, atoms and molecules.
- $\sim$ 500 researchers (estimate by Harris, Kirch).

Why search for charged particle EDMs using a storage ring?

1. Up to now, no direct measurement of charged hadron EDM available:
2. Charged hadron EDM experiments provide 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.
3. Approach complimentary to neutron EDM searches.

Theorists keep repeating that

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):

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

Region to search for Beyond Standard Model (BSM) physics

- from nucleon EDMs with $\theta_{\mathrm{QCD}} = 0$:

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

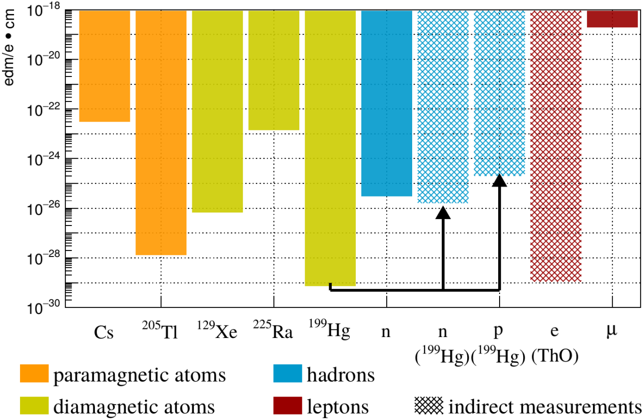
Status of EDM searches I

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
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	$(0.0 \pm 1.1 \pm 0.2) \times 10^{-26}$	$\approx 10^{-28}$	10^{-28}	2020 [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 [14, Fig. 2.1]



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.**

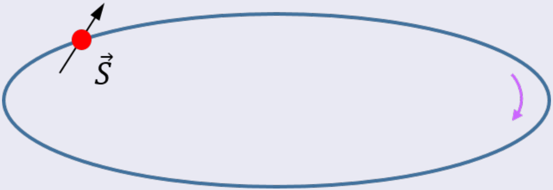
Spin precession of particles with MDM and EDM

In rest frame of particle,

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

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}. \tag{2}$$

Put the protons in a ring



→ Spin-precession in presence of MDMs and EDMs is described by Thomas-BMT equation [15].

Frozen-spin

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

$$\vec{\Omega} = \vec{\Omega}_{\text{MDM}} - \vec{\Omega}_{\text{cyc}} = -\frac{q}{\gamma m}\left[G\gamma\vec{B}_{\perp} + (1+G)\vec{B}_{\parallel} - \left(G\gamma - \frac{\gamma}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]. \quad (3)$$

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

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

$$\vec{\Omega} = 0, \text{ if } \left(G\gamma - \frac{\gamma}{\gamma^2-1}\right) = 0. \quad (4)$$

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

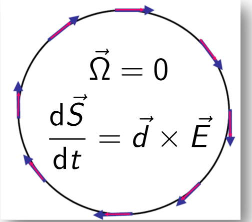
For protons, (4) leads to *magic momentum*:

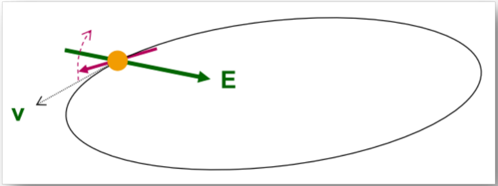
$$G - \frac{1}{\gamma^2-1} = 0 \Leftrightarrow G = \frac{m^2}{p^2} \quad \Rightarrow \quad \boxed{p = \frac{m}{\sqrt{G}} = 700.740\,\text{MeV}\,\text{c}^{-1}} \quad (5)$$

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.





New method to measure EDMs of charged particles:

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

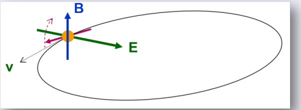
Search for charged particle EDMs with frozen spins

Magic storage rings

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

- Generalized solution for magic momentum

$$\frac{E_x}{B_y} = \frac{Gc\beta\gamma^2}{G\beta^2\gamma^2 - 1}, \qquad (6)$$



where $\vec{E} = E_x\vec{e}_x$ is radial, and $\vec{B} = B_y\vec{e}_y$ vertical field (where $\vec{e}_x \times \vec{e}_y = \vec{e}_z$) .

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

particle	G	$p\,[\mathrm{MeV\,c^{-1}}]$	$T\,[\mathrm{MeV}]$	$E_x\,[\mathrm{MV\,m^{-1}}]$	$B_y\,[\mathrm{T}]$
proton	1.793	700.740	232.792	−16.772	0.000
deuteron	−0.143	1000.000	249.928	4.032	0.162
helion	−4.184	1200.000	245.633	−14.654	−0.044

Offers possibility to determine EDMs of

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

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 $f \simeq 0.005$.

In terms of numbers given above:

- This implies:

$$\sigma_{\mathrm{stat}} = \frac{1}{\sqrt{N f}\,\tau_{\mathrm{SCT}}\,P\,A_y\,E} \quad \Rightarrow \quad \boxed{\sigma_{\mathrm{stat}}(1\,\mathrm{yr}) = 10^{-29}\,\mathrm{e\,cm}}. \tag{7}$$

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

Progress toward storage ring EDM experiments

Complementing the spin physics tool box

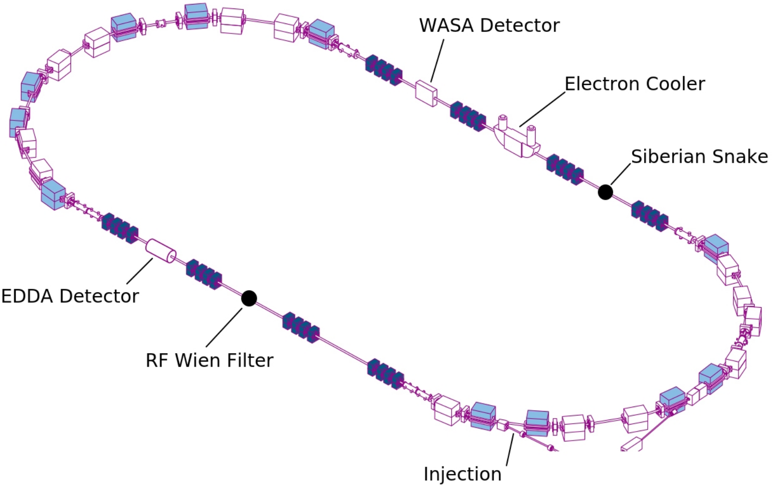
COoler SYnchrotron COSY

- 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.

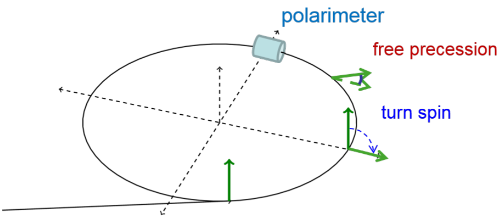
COSY formerly used as spin-physics machine for hadron physics:

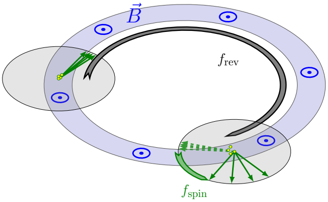
- Provides an ideal starting point for srEDM related R&D.
- Will be used for a first direct measurment of deuteron EDM.

COSY Landscape



Principle of spin-coherence time measurement

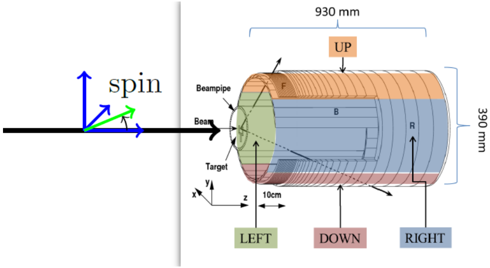


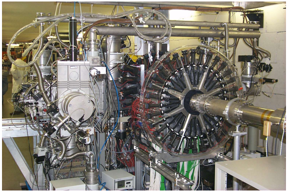


Measurement procedure:

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

Detector system: EDDA [16]





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:

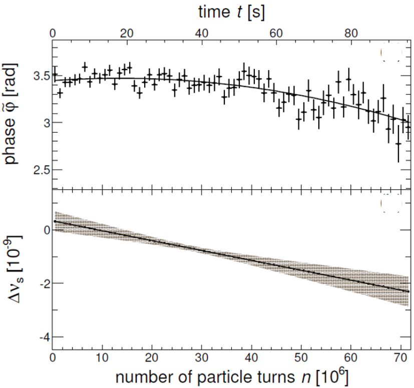
$$N_{\mathrm{U,D}} \propto 1 \pm \frac{3}{2} p_z A_y \sin(\underbrace{\nu_s \cdot f_{\mathrm{rev}}}_{f_s=-120.7\,\mathrm{kHz}} \cdot t), \text{ where } f_{\mathrm{rev}} = 750.0\,\mathrm{kHz}. \qquad (8)$$

Precision determination of the spin tune [17, PRL 2015]

Time-stamping events accurately,

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

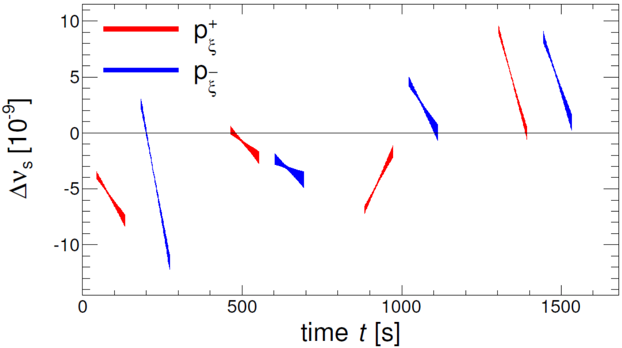
$$\begin{aligned}\nu_s(n) &= \nu_s^{\text{fix}} + \frac{1}{2\pi}\frac{\mathrm{d}\tilde{\phi}}{\mathrm{d}n} \\ &= \nu_s^{\text{fix}} + \Delta\nu_s(n)\end{aligned} \qquad (9)$$



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

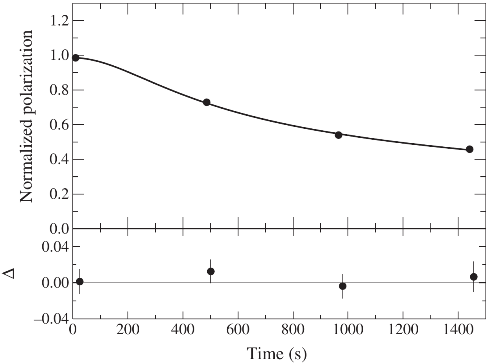


Walk of spin tune ν_s [17].

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**).
- Studies of machine imperfections.

Optimizations of spin-coherence time: [19, PRL 2016]



JEDI progress on τ_{SCT}:

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

- Previous record: $\tau_{SCT}(\mathrm{VEPP}) \approx 0.5\,\mathrm{s}$ [18] ($\approx 10^7$ spin revolutions).

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 (7), since $\sigma_{stat} \propto {\tau_{SCT}}^{-1}$.

Phase locking spin precession in machine to device RF

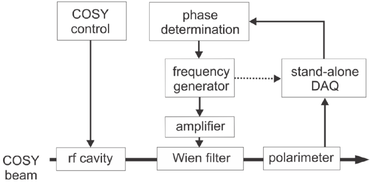
PhD work of Nils Hempelmann

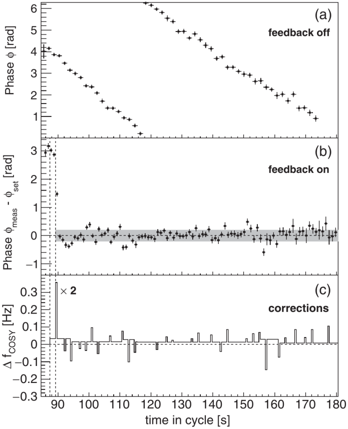
At COSY, one cannot freeze the spin precession

$\Rightarrow$ 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 $\sigma_\phi = 0.21\,\text{rad}$ [20, PRL 2017].

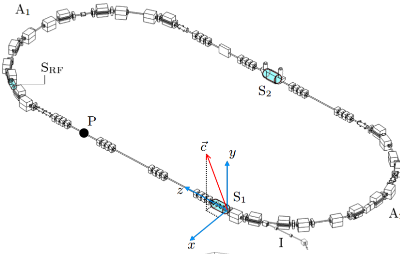
Study of machine imperfections

PhD work of Artem Saleev

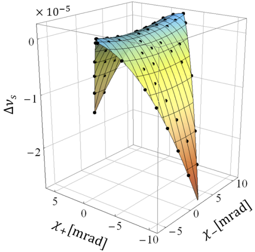
JEDI developed new method to investigate magnetic machine imperfections based on highly accurate determination of spin-tune [21, PRAB 2017].

Spin tune mapping

- Two cooler solenoids act as spin rotators ⇒ 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.



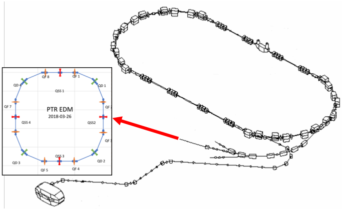
Prototype EDM storage ring

Next step:

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

Scope of prototype ring of 100 m circumference:

- p at 30 MeV all-electric CW-CCW beams operation.
- p at 45 MeV frozen spin including additional vertical magnetic fields



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

Charged Particle Electric Dipole Moment Collaboration[1]

Stages of project and time frame toward dedicated EDM ring: [14, arXiv 2019]

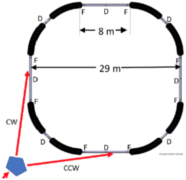
Stage 1

- precursor experiment

- magnetic storage ring
- Now

Stage 2

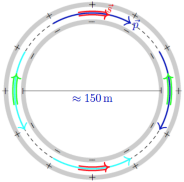
- prototype ring



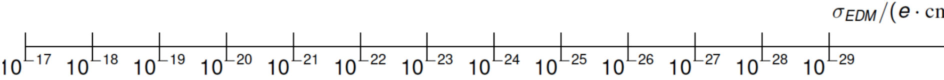
- electric/magnetic bends
- simultaneous ↺ and ↻ beams
- 5 years

Stage 3

- dedicated storage ring



- at magic p momentum
- 10 years



[1] http://pbc.web.cern.ch/edm/edm-default.htm

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:

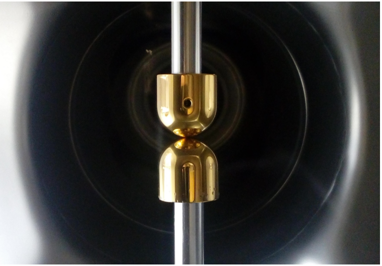
Main issues:

- Spin coherence time $\tau_{SCT} \sim 1000\,s$ [19, 2016].
- Continuous polarimetry with relative errors < 1 ppm [22, 2012].
- Beam position monitoring with precision of 10 nm.
- Alignment of ring elements, ground motion, ring imperfections.
- Magnetic shielding.
- Large electric field gradients ~ 10 to 20 MV/m.
- High-precision spin tracking.
- d EDM with frozen spin $\rightarrow$ precise B field reversal for CW and CCW beams.

E/B Deflector development using small-scale lab setup [23]

Work by 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.

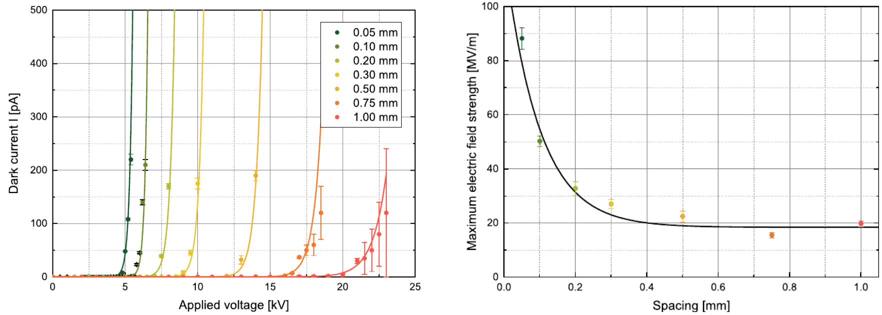


Recent results, published in [23, RSI 2019]

Dark current of stainless-steel half-sphere electrodes (10 mm radius)

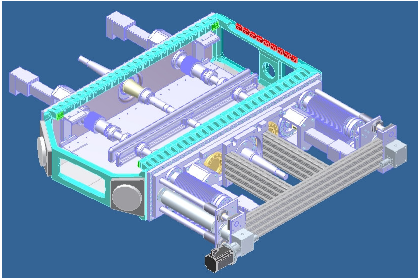
- distances $S = 1, 0.75, \ldots, 0.05\,\text{mm}$, where

$$E_{\text{max}} = \frac{U}{S} \cdot F\,, \text{ where } F = \frac{1}{4}\left[1 + \frac{S}{R} + \sqrt{\left(1+\frac{S}{R}\right)^2 + 8}\,\right]\,, \tag{10}$$



Results promising, but tests with real size deflector elements are necessary.

E/B deflector development using real-scale lab setup



Equipment:

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

Parameters:

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

Next steps:

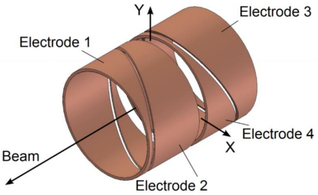
Equipment ready for assembling. First test results expected in the near future.

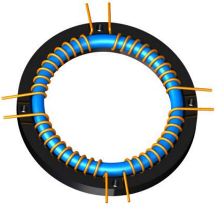
Beam position monitors for srEDM experiments

PhD work of Falastine Abusaif, improving earlier work by F. Trinkel

Development of compact BPM based on segmented Rogowski coil

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





Conventional BPM

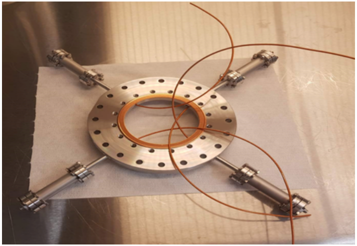
- Easy to manufacture
- length $= 20\,\text{cm}$
- resolution $\approx 10\,\mu\text{m}$

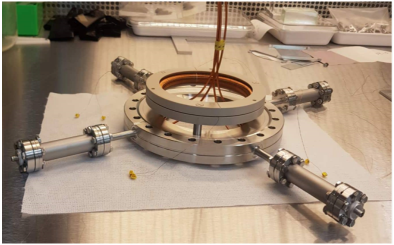
Rogowski BPM (warm)

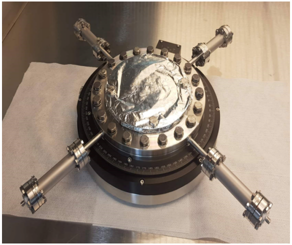
- Excellent RF-signal response
- length $= 1\,\text{cm}$
- resolution $\approx 1.25\,\mu\text{m}$

- Two Rogowski coil BPMs installed at entrance and exit of RF Wien filter

Assembly stages of one Rogowski-coil BPM

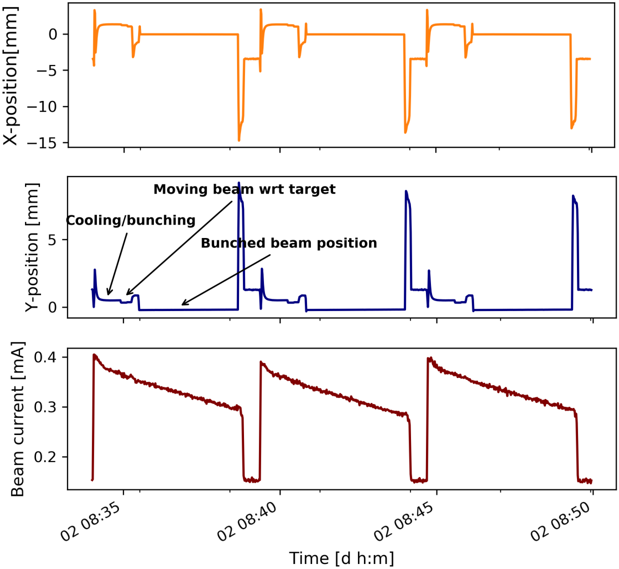






Measured beam positions at entrance of RF Wien filter

from a run in 2019



dC polarimetry data base I

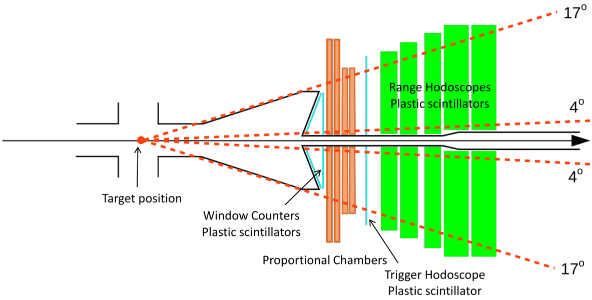
Data analysis mainly by Maria Zurek and PhD Fabian Müller

Motivation: Optimize polarimetry for ongoing JEDI experiments:

- 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 $T = 170 - 380\,\text{MeV}$.

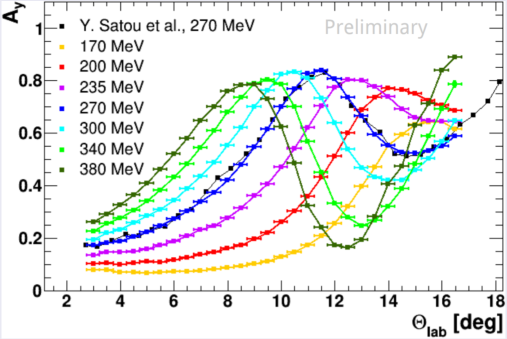
Detector system: former WASA forward detector, modified

- Targets: C and CH2
- Full azimuthal coverage, scattering angle 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.
- Similar data base measurements carried out to provide *pC* data base.

High-precision beam polarimeter with internal C target

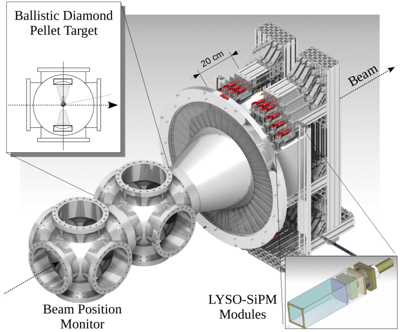
Development led by Irakli Keshelashvili

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 external beam:

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



Beam-based aligment for EDM measurement at COSY

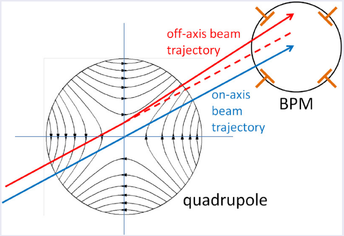
PhD work of Tim Wagner

Surveys and alignment campaigns of accelerator ensure magnets aligned properly

- Surveys makes use of markers mounted on magnets as reference points.
- When COSY was built, nobody thought of precision experiments
  $\rightarrow$ no markers on Beam position monitors (BPMs), exact positions are unknown.
- EDM measurements require as good an orbit as possible
  - small RMS deviation to ideal orbit
- Goal: develop and implement method to determine exact positions of BPMs:
  $\rightarrow$ **Beam-based alignment**

Machine orbit is defined by potential minimum in quadrupole magnets

- Beam is deflected when it passes through a misaligned quad.
- Beam-based alignment minimizes steering effect of quadrupoles



Beam-based aligment II

PhD work of Tim Wagner

Orbit change when quadrupole strength k is varied

$$\Delta x(s) = \frac{\Delta k \cdot x(s_0) I}{B\rho} \cdot \frac{1}{1 - k\frac{I\beta(s_0)}{2B\rho\tan\pi\nu}} \cdot \frac{\sqrt{\beta(s)\beta(s_0)}}{2\sin\pi\nu}\cos\left[\phi(s) - \phi(s_0) - \pi\nu\right] \quad (11)$$

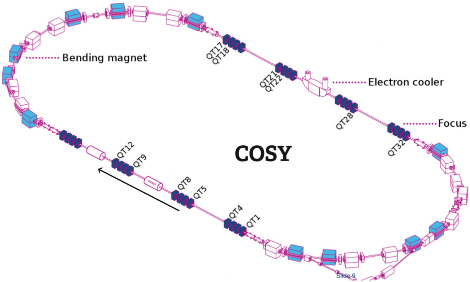
- s, s_0 positions along orbit, β betatron functions, ν working point, ϕ betatron phase advance, B magnetic field, I magnet current, ρ bending radius.
- Not all parameters in (11) known well $\rightarrow$ not possible to determine $x(s_0)$.
- Instead, use merit function

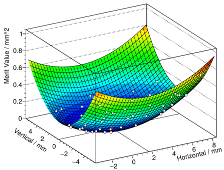
$$f = \frac{1}{N_{\mathrm{BPM}}}\sum_{i=1}^{N_{\mathrm{BPM}}}\left[x_i(+\Delta k) - x_i(-\Delta k)\right]^2 \propto x(s_0)^2 \quad (12)$$

from which optimum ($f \rightarrow 0$) is found by minimization.

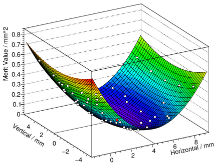
Beam-based aligment III

PhD work of Tim Wagner

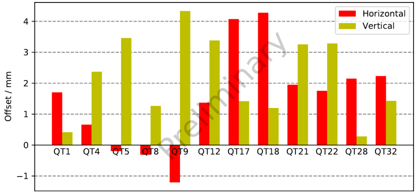




QT1, $\frac{\chi^2}{\text{d.o.f.}} = 0.96$



QT18, $\frac{\chi^2}{\text{d.o.f.}} = 1.77$



Beam-based aligment IV

Preliminary results for a subset of quadrupoles

Obtained offsets of the beam-position monitors:

BPM	s [m]	hor. corr. [mm]	vert. corr. [mm]
BPM02	10.4	1.705 ± 0.008	0.416 ± 0.005
BPM06	29.5	1.371 ± 0.007	3.382 ± 0.011
BPM18	100.2	4.177 ± 0.007	1.308 ± 0.005
BPM19	110.1	1.868 ± 0.005	3.273 ± 0.010
BPM20	123.3	2.149 ± 0.007	0.281 ± 0.007
BPM21	133.2	2.232 ± 0.008	1.430 ± 0.006

Remarkable precision of better than 10 μm reached

$\rightarrow$ orbit improvement: $RMS_y = 1.21\,\text{mm} \rightarrow 1.01\,\text{mm}$ with only 20% of BPMs.

- Extended data set (run in Sept. '19) now covers all quadrupoles and BPMs.

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).

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 (~ 1000 s).

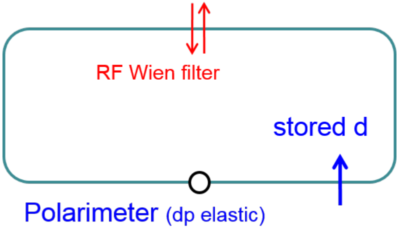
Goal of proof-of-principle experiment:

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 $\vec{E} = (E_x, 0, 0)$.



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

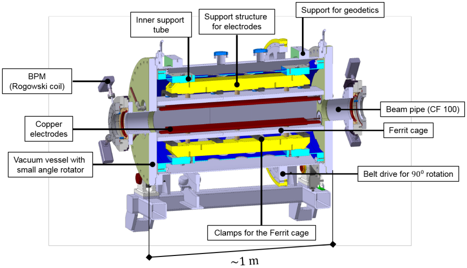
Statistical sensitivity:

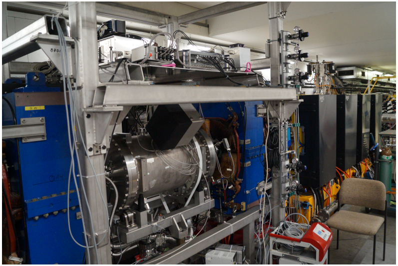
- in the range 10^{-23} to 10^{-24} e cm for $d(deuteron)$ possible.
- Systematic effects: Alignment of magnetic elements, magnet imperfections, imperfections of RF-Wien filter etc.

Design of waveguide RF Wien filter

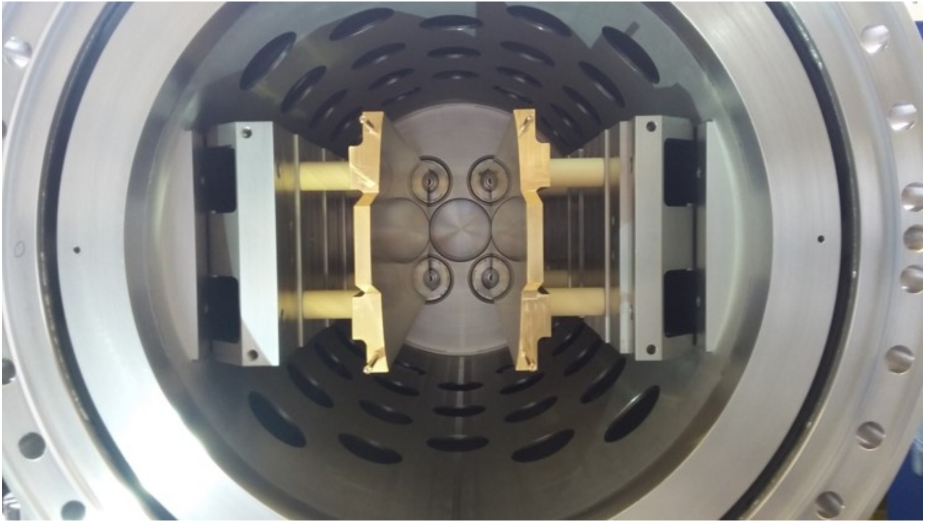
Joint Jülich – RWTH Aachen development:

- Institute of High Frequency Technology, RWTH Aachen University:
- **Waveguide provides $\vec{E} \times \vec{B}$ by design.**
- Minimal $\vec{F}_L$ by careful electromagnetic design of all components [24, 2016].





Installation at COSY

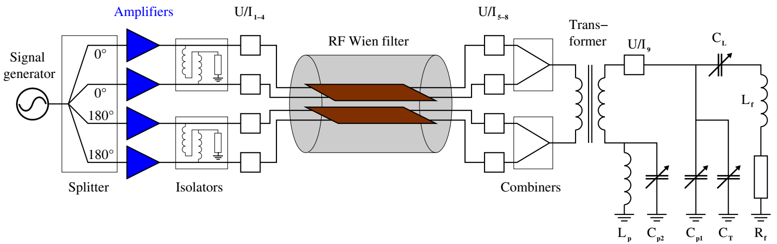


View along the beam axis in the RF Wien filter.

Driving circuit

Realization with load resistor and tunable elements (L's and C's):

- Design layout using four separate 1 kW power amplifiers.

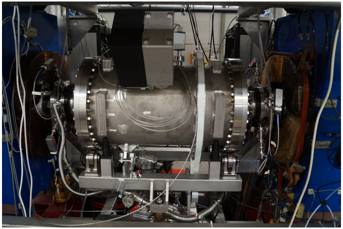
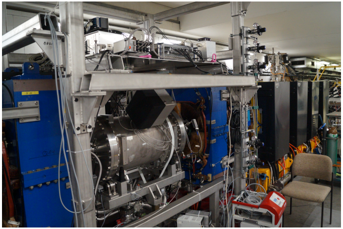
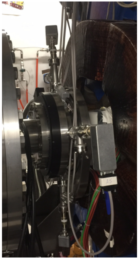


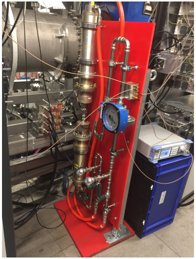
Circuit fully operational

- Tuneable elements[a] allow [24]:
  - minimization of Lorentz-force, and
  - velocity matching to β of the beam.
- Power upgrade to 4×2 kW: $\int B_z dz = 0.218$ T mm possible.

[a] built by Fa. Barthel, http://www.barthel-hf.de.

RF Wien filter
Installation at COSY

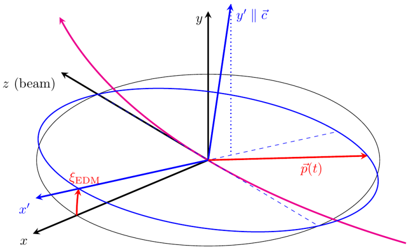






- RF Wien filter between PAX magnets. Upstream Rogowski coil; racks with power amplifiers, each unit delivers up to 500 W; water-cooled 25 Ω resistor.

Effect of EDM on stable spin axis of the ring

Without RF WF

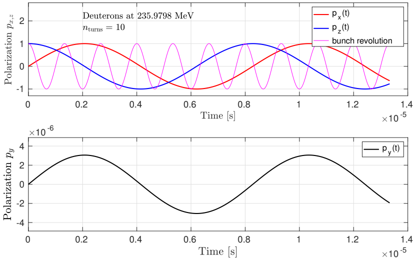


Beam particles move along z direction

- Presence of an EDM $\Rightarrow \xi_{\mathrm{EDM}} > 0$.

$\Rightarrow$ Spins precess around the $\vec{c}$ axis.

$\Rightarrow$ Oscillating vertical polarization component $p_y(t)$ is generated.



Evolution for 10 turns $[\vec{p}_0 = (0, 0, 1)]$

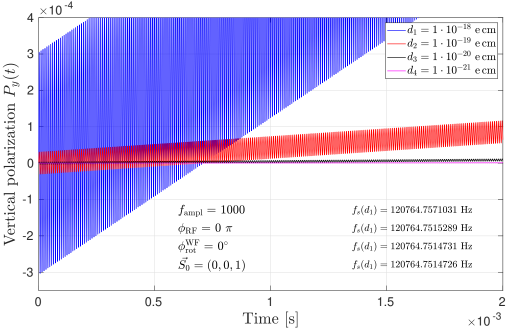
- $p_x(t)$, $p_z(t)$ and $p_y(t)$.
- Bunch revolution indicated as well.
- p_y oscillation amplitude corresponds to tilt angle ξ_{EDM}.

Model calculation of EDM buildup [27, arXiv 2019]

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) [24, 2016].



EDM accumulates in $P_y(t) \propto d_{\mathrm{EDM}}$ [21, 25, 26].

Strength of EDM resonance

EDM induced polarization oscillation,

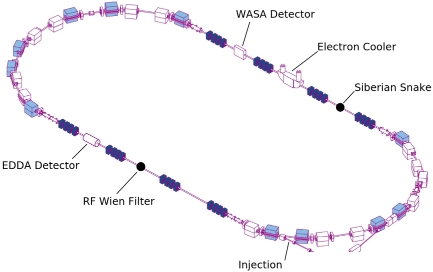
- can generally be described by

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

  y perpendicular to ring plane.

- **EDM resonance strength** defined as ratio of angular frequency Ω^{p_y} to orbital angular frequency Ω^{rev},

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

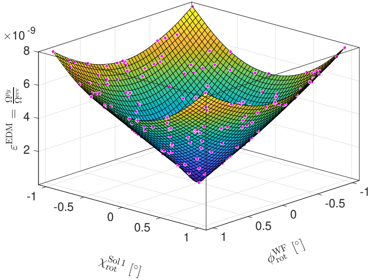


How is the EDM effect actually measured?

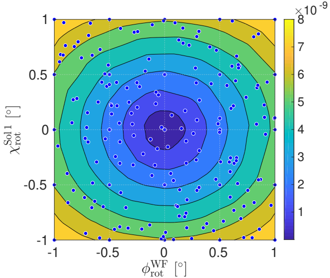
Two features are simultaneously applied in the ring:

1. the RF Wien filter is rotated by a small angle. This generates a tiny radial magnetic RF field, which affects the spin evolution.
2. In addition, a longitudinal magnetic field in the ring opposite to the Wien filter, about which the spins rotate as well.

Expectation for $d = 10^{-20}$ e cm in ideal COSY ring
[27, arXiv 2019]



(a) $\varepsilon^{\mathrm{EDM}}$ for $d = 10^{-20}$ e cm.

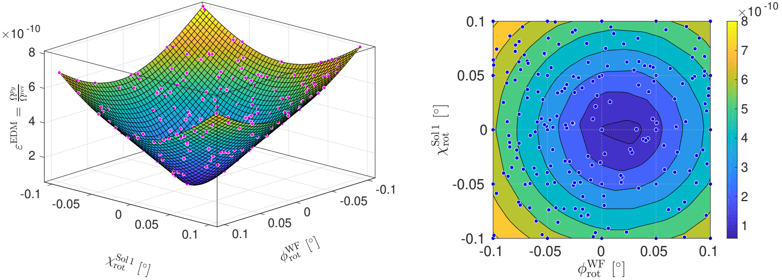


(b) Contour plot of (a).

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

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

Expectation for $d = 10^{-18}$ e cm in ideal COSY ring
[27, arXiv 2019]



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

(d) Contour plot of (c).

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

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

Preliminary results of Wien filter mapping I

Nov.-Dec. 2018 run

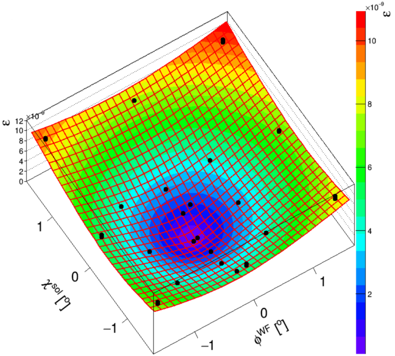
Function describing the surface

- As shown in [27, arXiv 2019], the resulting surface can be described by an *elliptic paraboloid*:

$$\left(\varepsilon^{\text{EDM}}\right)^2 = \frac{\psi_{\text{WF}}^2}{16\pi^2} \cdot \left[A\left(\phi^{\text{WF}} - \phi_0^{\text{WF}}\right)^2 + B\left(\frac{\chi^{\text{Sol}\,1}}{2\sin\pi\nu_s^{(2)}} + \chi_0^{\text{Sol}\,1}\right)^2 + C\right]. \quad (13)$$

  - Eq. (13) contains two parameters (not required) A and B to account for possible deviations of the magnitude of ε^{EDM} along ϕ^{WF} and $\chi^{\text{Sol}\,1}$.

Preliminary results of Wien filter mapping II
Nov.-Dec. 2018 run



First data

- $9 + 9 + 14$ data points on 3 maps
- took $\approx$ 2 weeks pure measuring time
- Preliminary results of fit using Eq. (13):

$$\begin{aligned} \phi_0^{\text{WF}} &= -3.9 \pm 0.05\,\text{mrad} \\ \chi_0^{\text{Sol 1}} &= -6.8 \pm 0.04\,\text{mrad} \\ A &= 0.559 \pm 0.005 \\ B &= 0.583 \pm 0.005 \\ C &= (-1.2 \pm 0.1) \cdot 10^{-10} \end{aligned} \tag{14}$$

Where are we today?

1. Minimum determines spin rotation axis (3-vector) at RF WF *including EDM*.
2. Spin tracking shall determine orientation of stable spin axis *w/o* EDM.
3. EDM is obtained from the difference of 1. and 2.

Summary I

Search for charged hadron particle EDMs (proton, deuteron, light ions):

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

Present EDM measurement using RF Wien filter

- 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 underway.
  - 6 wk run Nov. -Dec. ’18, and foreseen 6 wk run in ’20.
  - Planned upgrades:
    - consolidation of beam-based alignment,
    - implementation of multi-channel frequency generator,
    - test of pilot bunch technique,
    - measurement of spin tune change as function of orbit bumps.
  - Sensitivity 10^{-18} to 10^{-20} e cm.

Summary II

Strong interest of high energy community in storage ring EDM searches

- protons and light nuclei as part of physics program of the post-LHC era:
  - Physics Beyond Collider process (CERN), and
  - European Strategy for Particle Physics Update.
  - As part of this process, proposal for prototype EDM storage ring prepared by CPEDM ([14] → CERN Yellow Report)
    - possible host sites: CERN or COSY.

JEDI Collaboration

JEDI = Jülich Electric Dipole Moment Investigations

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

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Spare Slides

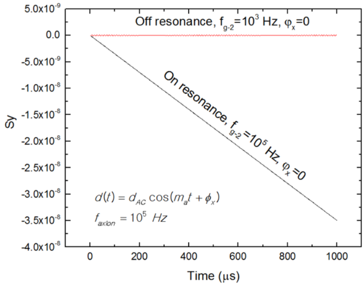
(Oscillating) Axion-EDM search using storage ring

Motivation: Paper by Graham and Rajendran [28, 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 improved significantly.



Courtesy of Seongtae Park (IBS, Daejeon, ROK)

Limits for axion-gluon coupled to oscillating EDM

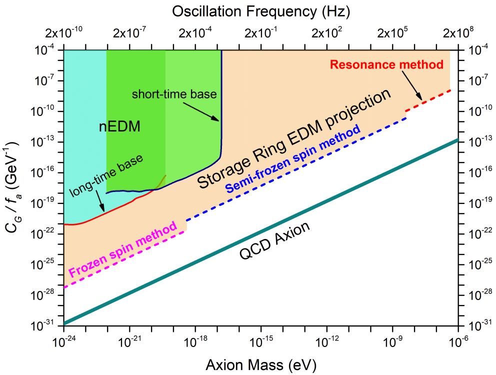


Figure from S.P. Chang et al. [29]

Realization

- No new/additional equipment required!
- Can be done in magnetic storage ring (*i.e.*, COSY).
- First test experiment carried out in I/2019.