Search for Electric Dipole Moments and Axions/ALPs of charged particles using storage rings

Frank Rathmann
Institut für Kernphysik, Forschungszentrum Jülich
(on behalf of the JEDI collaboration)

EDM/Storage Rings Meeting
Nov 28 – 30, 2022
https://wiki.jlab.org/ciswiki/index.php/EDM/Storage_Rings_Meeting_(29-30_November_2022)

Contents

1. Motivation & Status EDM and Axion/ALP searches
2. Measurement principles & experimental techniques
3. Technical developments
4. Recent results
5. Staged approach toward dedicated EDM ring
6. Summary

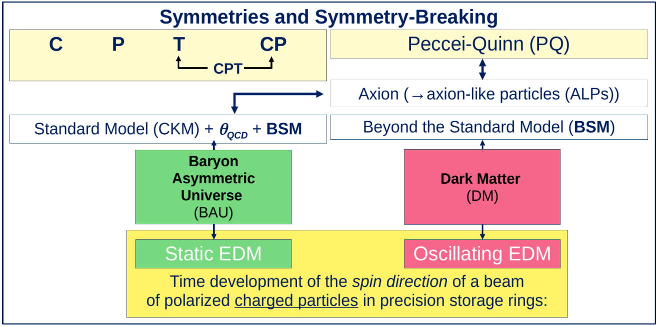
Motivation

Issues we are addressing

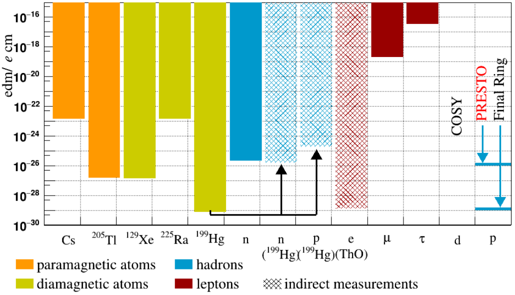
- Matter over antimatter dominance / Baryon asymmetry in the Universe
- Nature of Dark Matter (DM)

Experimental approach

- Measure of static Electric Dipole Moments (EDM) of fundamental particles
- Search for axion-like particles as DM candidates through oscillating EDMs



Status of static EDM searches [2, CYR '21]



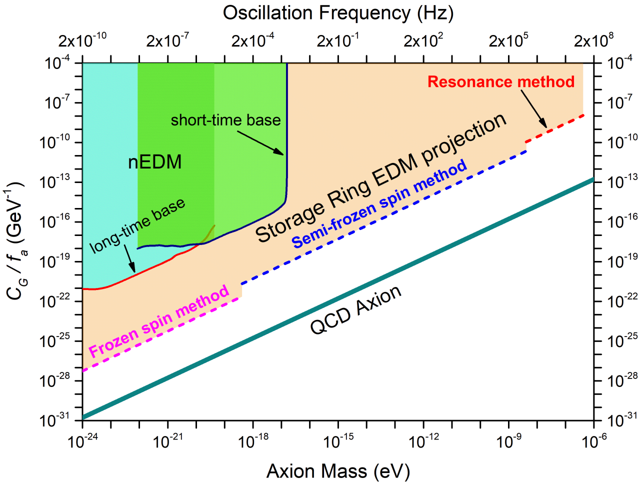
Missing are *direct* EDM measurements:

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

Theory stresses that

EDM of single particle not sufficient to identify *CP* violating source [1]

Axion Dark Matter search with Storage Ring EDM method



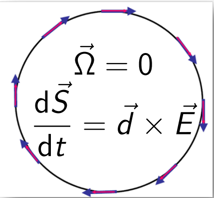
Experimental limits for axion-gluon coupled oscillating EDM measurements (from [3]).

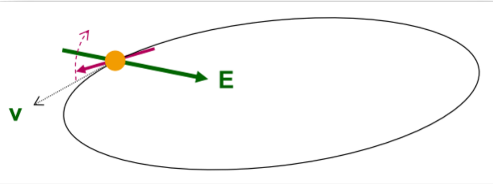
Measurement of EDM in storage ring

Protons at magic momentum in pure electric ring

How 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.





Storage ring method to measure EDMs of charged particles:

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

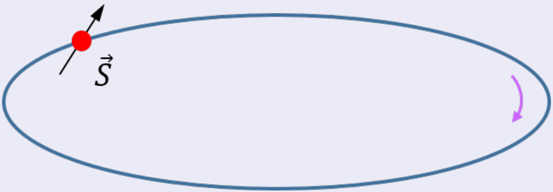
Spin precession of particles with MDM and EDM

In rest frame of particle

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

$$\frac{\mathrm{d}\vec{S}}{\mathrm{d}t} = \vec{\Omega} \times \vec{S} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}. \tag{1}$$

With protons in a ring



$\rightarrow$ Spin-precession with MDMs and EDMs described by Thomas-BMT Equ. [4].

Frozen-spin

Spin-precession of particle MDM *relative* to direction of flight:

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

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

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

$$\vec{\Omega} = 0, \text{ if } \left(G\gamma - \frac{\gamma}{\gamma^2-1}\right) = 0. \tag{3}$$

  - Possible for particles with $G > 0$: proton ($G = 1.793$) or electron ($G = 0.001$).

For protons: (3) $\Rightarrow$ *magic momentum*:

$$G - \frac{1}{\gamma^2-1} = 0 \Leftrightarrow G = \frac{m^2}{p^2} \quad \Rightarrow \quad \boxed{p = \frac{m}{\sqrt{G}} = 700.740\,\mathrm{MeV\,c^{-1}}} \tag{4}$$

Measurement of EDM in a magnetic ring

First-ever direct EDM measurement using this method

In magnetic ring

- When external electric fields in the ring vanish, $\vec{E} = 0$, the spin motion is governed by the radial field $\vec{E} = c\vec{\beta} \times \vec{B}$, induced by the relativistic motion in the vertical $\vec{B}$ field, so that $\frac{\mathrm{d}\vec{S}}{\mathrm{d}t} \propto \vec{d} \times \vec{E}$ (see, e.g., [5]).
- But this yields only small oscillation of vertical component p_y due to EDM.
- **Use RF Wien filter to accumulate EDM signal** [6]:
  - \+ Long spin coherence time $> 1000\,\mathrm{s}$ [7]
  - \+ Spin tune determination $\Delta\nu_s/\nu_s \approx 10^{-10}$ [8] $\rightarrow$ tune RF Wien filter frequency
  - \+ Phase-lock of spin phase relative to Wien filter RF [9].
  - \+ Two-bunch method: pilot and signal bunch
    - pilot bunch shielded from Wien filter RF by fast RF switches
    - pilot bunch $\rightarrow$ unperturbed spin precession $\rightarrow$ RF Wien filter on resonance.
    - observe p_y oscillations over many periods
    - pilot bunch $\rightarrow$ co-magnetometer [publ. in prep.]

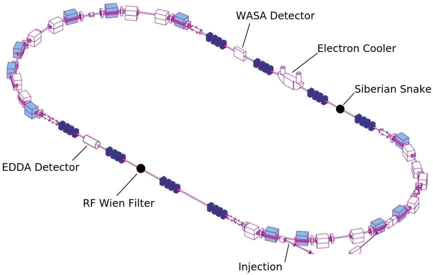
Accumulated knowledge compiled in

2021 CERN Yellow Report [2]

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}[5],
$$\varepsilon^{\mathrm{EDM}} = \frac{\Omega^{p_y}}{\Omega^{\mathrm{rev}}}\,,$$



How is the EDM effect actually measured?

Two features are simultaneously applied in the ring:

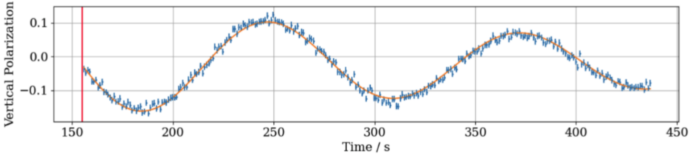
1. RF Wien filter rotated by a small angle $\rightarrow$ generates small radial magnetic RF field $\rightarrow$ affects the spin evolution.
2. In addition, there is longitudinal magnetic field in ring opposite to Wien filter, about which spins rotate as well.

Measurement of EDM resonance strength using pilot bunch

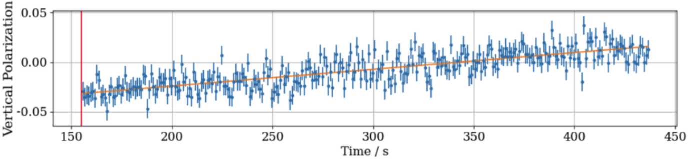
RF Wien filter mapping

Observation of $p_y(t)$ with two stored bunches: **Signal and pilot bunch (PB)**

- Signal bunch



- Pilot bunch



- Decoherence clearly visible in signal bunch.
- No oscillations in pilot bunch.
- Determine oscillation frequencies $\Omega^{p_y} \to$ Wien filter map via $\varepsilon^{\text{EDM}} = \frac{\Omega^{p_y}}{\Omega^{\text{rev}}}$

Technical challenges of storage ring EDM experiments

Overview

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

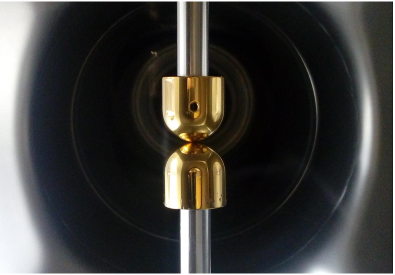
Main issues:

- Spin coherence time $\tau_{\mathrm{SCT}} \sim 1000\,\mathrm{s}$ [7, 2016].
- Continuous polarimetry with relative errors $< 1\,\mathrm{ppm}$ [29, 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 $20\,\mathrm{MV/m}$.
- 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 [30]

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.

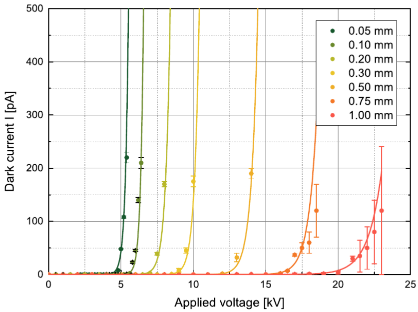


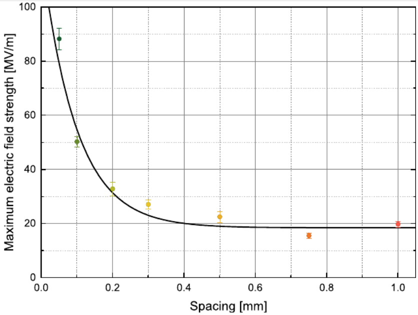
Recent results, published in [30, RSI 2019]

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

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

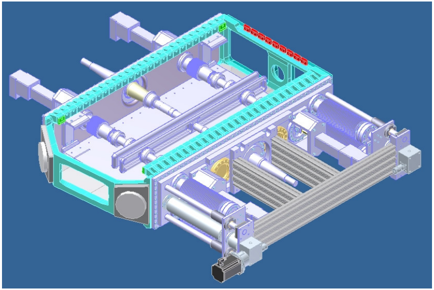
$$E_{\max} = \frac{U}{S} \cdot F\,, \text{ where } F = \frac{1}{4}\left[1 + \frac{S}{R} + \sqrt{\left(1 + \frac{S}{R}\right)^2 + 8}\right]\,, \tag{5}$$





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

E/B deflector development using real-scale lab setup



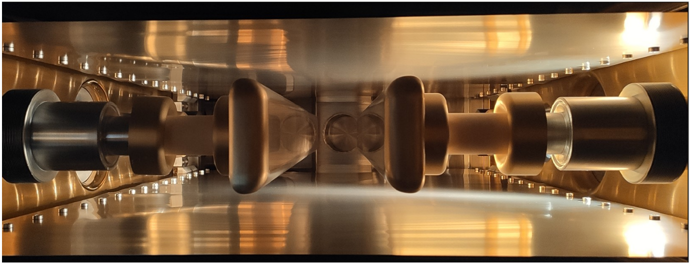
Equipment:

- 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. applied voltage $= \pm 200\,\text{kV}$
- Material: Aluminum coated by TiN

Current status of tests with real-scale setup



View along deflector plates into vacuum chamber

Continue work until end of this year

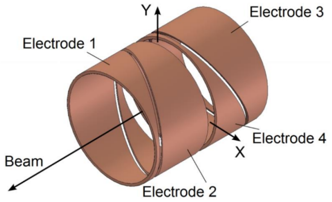
1. Conditioning underway (since few months)
   - $U = 125\,\text{kV}$ ($\pm 62.5\,\text{kV}$ at each plate) at distance of $\Delta = 91\,\text{mm}$:
   $$E = \frac{125\,\text{kV}}{0.091\,\text{m}} = 1.37\,\text{MV/m} \tag{6}$$
2. Slowly raise $U \rightarrow 400\,\text{kV}$ ($\pm 200\,\text{kV}$)
3. Reduce $\Delta \rightarrow 60\,\text{mm}$

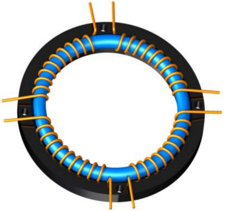
Beam position monitors for srEDM experiments

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

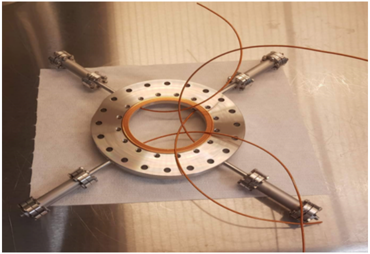
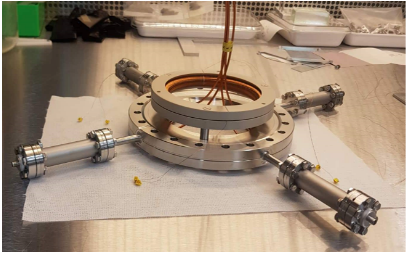
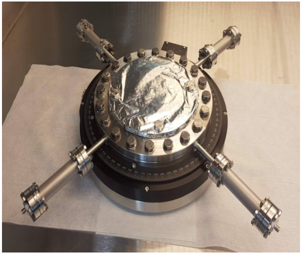
- Easy to manufacture
- length $= 20\,\text{cm}$
- resolution $\approx 10\,\mu\text{m}$

Rogowski BPM (warm)

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

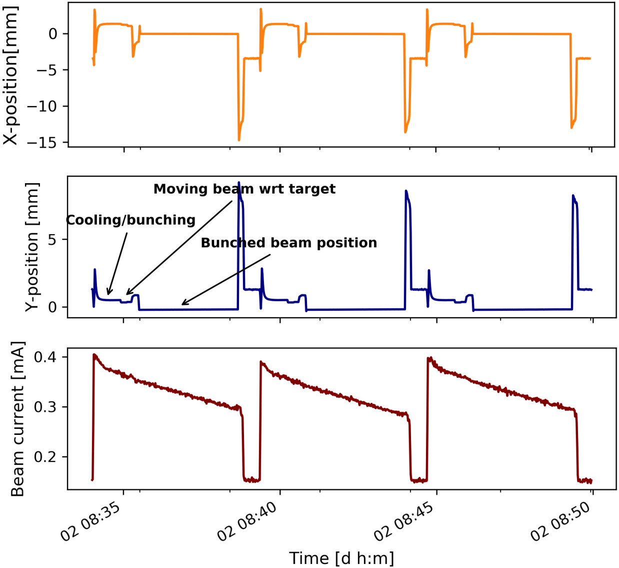
- Two Rogowski coil BPMs installed at entrance and exit of RF Wien filter

Assembly stages of one Rogowski-coil BPM

Measured beam positions at entrance of RF Wien filter

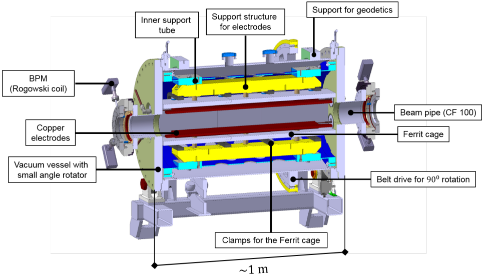
from a run in 2019

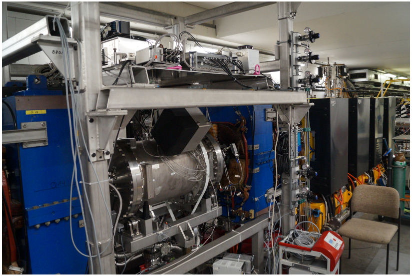


Design of waveguide RF Wien filter

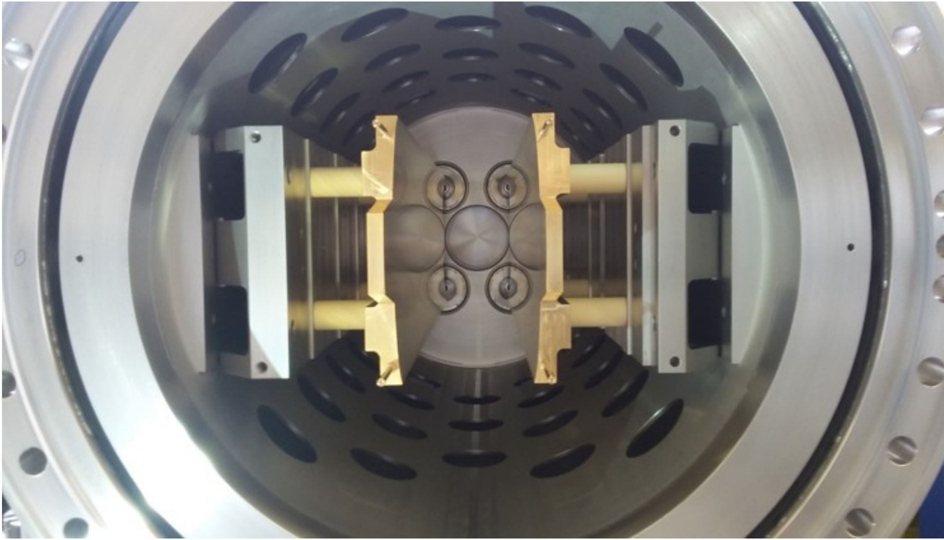
Joint Jülich – RWTH Aachen development:

- 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 [6].





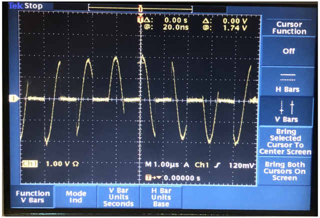
View along the beam axis in the RF Wien filter

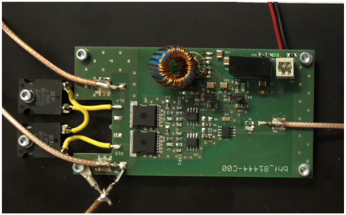


Fast switches[1] for RF power of Wien filter

GaN HEMT-based solution (Gallium Nitride Transistors):

- Short switch on/off times (≈ few ns).
- High power capabilities (≈ few kV).
- On board power damping.





- symmetric switch on/off times (≈ few ns).
- $-30\,$dB power damping.

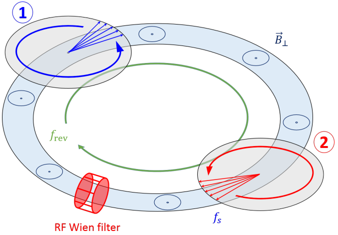
Installed switches:

- capable to handle up to $200\,$W each
- permits system to run near a total power of $0.8\,$kW in pulsed mode

[1] developed together with Fa. barthel HF-Technik GmbH, Aachen

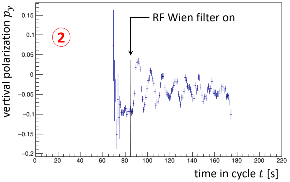
Bunch-selective spin manipulation (co-magnetometry) I

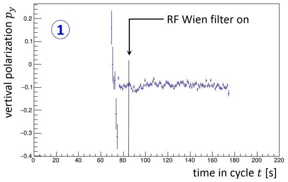
World-first (September 2020 JEDI, with d at 970 MeV/c)



- bunches 1 and 2 orbit at $f_{\rm rev} \approx 750\,\text{kHz}$:
  - coherent ensembles in ring plane
  - precessing at $f_s \approx 120\,\text{kHz}$
- waveguide RF WF [6] with *radial* field $\vec{B}_r$
  - on resonance[2] at $f_{\rm WF} = 871.430\,646\,\text{kHz}$

- **Apply bunch-selective gating of RF Wien filter in 1:**
  - 2 **oscillating** $p_y(t)$, 1 **not affected** (pilot bunch → co-magnetometer)



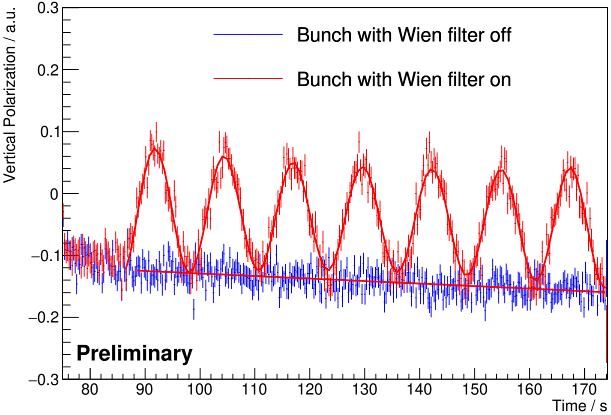


[2] $f_{\rm WF} = K \cdot f_{\rm rev} + f_s = (K + \nu_s) f_{\rm rev}$, where $K \in \mathbb{Z}$ and ν_s is spin tune

Bunch-selective spin manipulation (co-magnetometry) II

World-first (September 2020 JEDI, with *d* at 970 MeV/c)

Preliminary results: to be submitted soon by JEDI

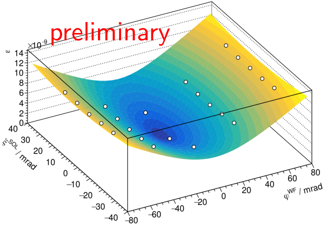


Analysis of pilot bunch run by Jamal Slim

Results from dEDM precursor experiment

Precursor I: 3 maps with initial-slope method (IS). Precursor II: 2 maps IS + 5 maps with PB

EDM resonance strength map for ε^{EDM}. It includes tilts of invariant spin axis due to EDM and magnetic ring imperfections.



Determination of minimum via fit with theoretical surface function yields:

- $\boxed{\phi_0^{\text{WF}}/\text{mrad} = -2.05 \pm 0.02}$
- $\boxed{\xi_0^{\text{Sol}}/\text{mrad} = 4.32 \pm 0.06}$

Extraction of deuteron EDM:

1. Minimum determines spin rotation axis (3-vector) at RF WF, *including EDM*.
2. Spin tracking in COSY lattice $\to$ orientation of stable spin axis *w/o* EDM.
3. EDM is obtained from the difference of 1. and 2.

EDM analysis now focuses more on systematics

- Data analysis close to final & EDM results in preparation.
- Goal: Describe observed tilts of stable spin axis by spin tracking.

Measurement of axion-like particle in storage ring

First-ever search for axion-like particles using this method

Basic idea

- Axion field $a(t) = a_0 \cos(\omega_a(t - t_0) + \phi_a(t_0))$ induces an oscillating EDM [10] $d(t) = d_{\mathrm{DC}} + d_{\mathrm{AC}} \cos(\omega_a(t - t_0) + \phi_a(t_0))$ with frequency related to the mass via $\hbar\omega_a = m_a c^2$, f_a is decay constant.
- This affects the spin rotations in the ring,

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \left(\vec{\Omega}_{\mathrm{MDM}} - \vec{\Omega}_{\mathrm{rev}} + \vec{\Omega}_{\mathrm{EDM}} + \vec{\Omega}_{\mathrm{wind}}\right) \times \vec{S}\,,$$

because two axion-related terms enter: (EDM: [10], wind: [11])

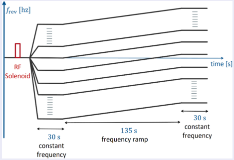
$$\begin{aligned} \vec{\Omega}_{\mathrm{EDM}} &= -\frac{1}{S\hbar} d(t) c \vec{\beta} \times \vec{B}\,, \quad \text{and} \\ \vec{\Omega}_{\mathrm{wind}} &= -\frac{1}{S\hbar}\frac{C_N}{2f_a}\left(\hbar \partial_0 a(t)\right)\vec{\beta} \quad \begin{cases} \text{coupling constant } C_N \\ \text{time derivative } \partial_0 \end{cases} \end{aligned} \tag{7}$$

$\Rightarrow$ **Resonant build-up of vertical polarization, when** $\omega_a = \omega_s$

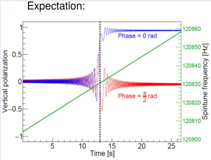
Details about axion/ALP experiment

(see [12] for details)

Momentum ramps (f_{rev}) in COSY searching for polarization changes

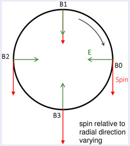


Organization of frequency ramps

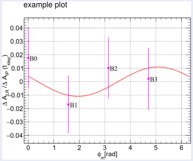


Jump of vertical polarization jump when resonance is crossed, for $\omega_a = \omega_s$.

Cover different oscillating EDM phases using multiple bunches

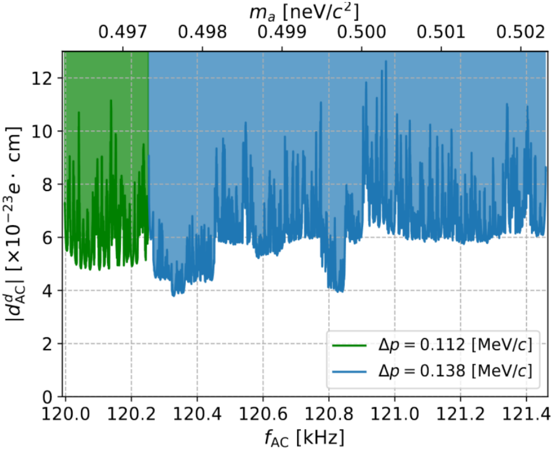


ϕ_a not known $\rightarrow$ use perpendicular beam polarization with 4 bunches



LR asymmetry for one cycle and four bunches simultaneously orbiting.

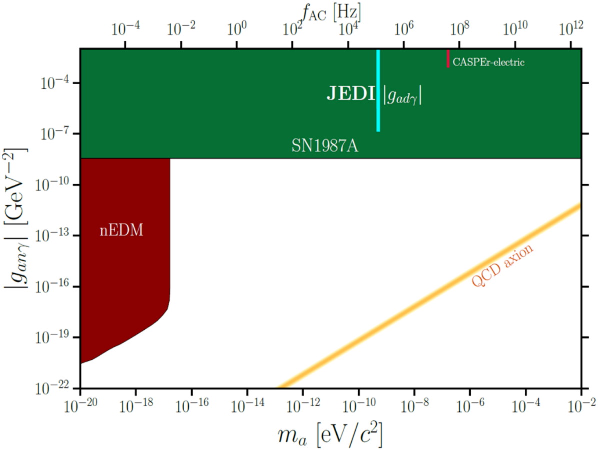
Bound on oscillating EDM of deuteron [12]



Observed oscillation amplitudes from 4 bunches

- 90% CL upper limit on the ALPs induced oscillating EDM
- Average of individual measured points $d_{\mathrm{AC}} < 6.4 \times 10^{-23}\,\mathrm{e\,cm}$

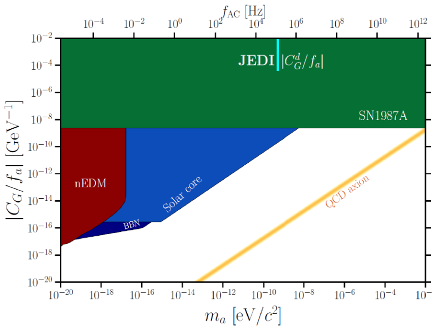
Bound on ALP-EDM coupling



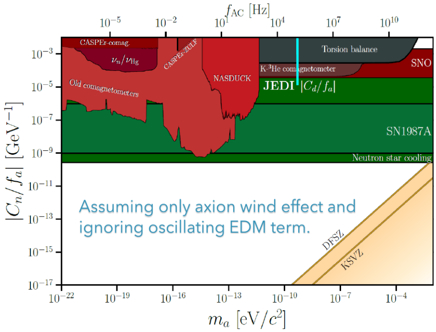
Coupling of ALP to deuteron EDM

- Obtained limit of $g_{ad\gamma} < 1.7 \times 10^{-7}\,\mathrm{GeV}^2$ during few days of data taking.
- For further details and various ALP couplings, see [12].

ALP-gluon and ALP-nucleon coupling[3]



ALP-gluon coupling, assuming 100% oscillating EDM.



ALP-nucleon coupling, only axion wind effect, ignoring oscillating EDM term.

[3]Figures courtesy of C. O'Hare, "cajohare/axionlimits: Axionlimits," (2020), https://doi.org/10.5281/zenodo.3932430

Strategy toward dedicated EDM ring

Project stages and time frame [2, CYR '21]

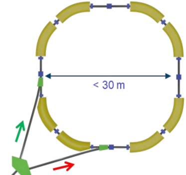
Stage 1

- **Precursor experiment**

- magnetic ring
- proof-of-capability
- 1st dEDM & 1st axion measurement using ring
- orbit/polarization control
- **now**

Stage 2

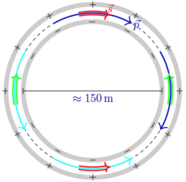
- **Prototype ring**



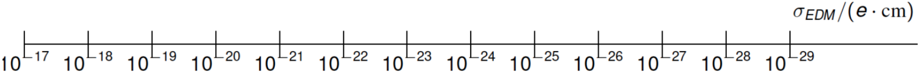
- Key technologies
- electric/magnetic bends
- simultaneous ⟲ and ⟳
- first pEDM measurement
- **5 years**

Stage 3

- **Dedicated storage ring**



- magic $E_m = 232.79\,\text{MeV}$
- sensitivity goal $10^{-29}\,\text{e cm}$
- **10 years**



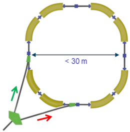
Next step: Stage 2: Prototype EDM storage ring (PTR)

Build demonstrator for charged-particle EDM

- Project prepared by CPEDM collaboration (CERN + JEDI + srEDM).
- Physics Beyond Collider process (CERN) & ESPP Update.

100 m circumference

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



Challenges – open issues

- All electric & E/B combined bends
- Storage time
- CW-CCW operation with orbit difference to pm
- Spin-coherence time
- Polarimetry
- Magnetic moment effects
- Stochastic cooling

Primary purpose of PTR

- **Study open issues and perform first direct proton EDM measurement**.

Summary I

Search for charged hadron particle EDMs (p, d, light ions) in rings:

- New window to disentangle sources of CP violation, and to possibly explain matter-antimatter asymmetry of the Universe.
- Search for static charged particle EDMs (p, d, ^{3}He)
  - EDMs $\rightarrow$ probes of CP-violating interactions $\rightarrow$ Matter-antimatter asymmetry
- Search for oscillating EDMs:
  - Axion coupling to gluons and nucleons
  - Dark matter search
- Potential sensitivity to gravitational effects [2, 13].
- **New class of (primarily) electrostatic rings is needed.**
- Dedicated (final) ring with anticipated sensitivity of $\leq 10^{-29}\,\mathrm{e\,cm}$.

Summary II

Recent results

- Results & achievements of collaboration summarized in CYR [2].
- Determination of limit of coupling of ALPs to deuteron EDM at COSY [12]:

$$\boxed{g_{ad\gamma} < 1.7 \times 10^{-7}\,\mathrm{GeV}^2}$$

  - Frequency range: 119 997 Hz to 121 457 Hz, total width ≈ 1500 Hz.
  - ALP mass range: 0.496 neV to 0.502 neV.
  - Potential to enlarge scanned frequency range at expense of lower sensitivity.
  - High sensitivity for *dedicated* frequency (mass) scans.
  - Technique can also exploit sidebands $\omega_a = \omega_s + k \cdot \omega_{\mathrm{rev}},\ k \in \mathbb{Z}$.
- Deuteron EDM measurements at COSY:
  - Good data from both Precursor I (3 maps with IS method) and Precursor II (2 maps IS + 5 maps with pilot bunch).
  - Data analysis close to final & EDM results in preparation.
  - Focus on systematic studies → understand observed tilts of stable spin axis.

Summary III

Next step: **Prototype ring development**

- Intermediate step between precursor experiment (stage 1) and dedicated EDM storage ring (stage 3)
- Goal: **Study open issues & perform first direct pEDM measurement**
- **Design study** call in INFRADEV-01-01-2022 still pending.
  - Final decision by EU expected soon.
  - **Partners:** INFN, CERN, Aachen, GSI, MPI-HD, Liverpool, Krakow, Tbilisi
- For dedicated EDM storage ring, possible host sites presently conceived are CERN or COSY.

Thank you for your attention!

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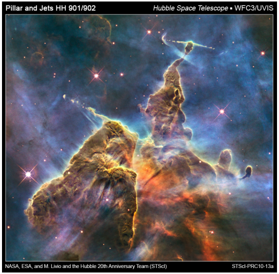
Spare slides

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 [14]
	$(5.53 - 6.76) \times 10^{-10}$	WMAP [15]
Expectation from SCM	$\sim 10^{-18}$	Bernreuther (2002) [16]

- SCM gets it wrong by more than 8 orders of magnitude.

Electric dipole moments (EDMs)

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

- non-relativistic Hamiltonian:

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

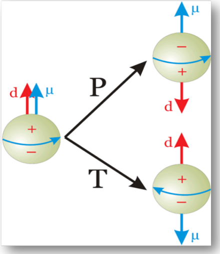
- **Energy of magnetic dipole** invariant under P and T:

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

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

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

$$\vec{s} \cdot \vec{E} \overset{P \text{ or } T}{\overbrace{\longrightarrow}} -\vec{s} \cdot \vec{E}, \tag{8}$$



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 [1]

Naive estimate of scale of nucleon EDM

From Khriplovich & Lamoreux [17] and Nikolaev [18]:

- 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	$\mathrm{d_n}$ equivalent	date [ref]
Electron	$< 8.7 \times 10^{-29}$	$\approx 10^{-29}$		2014 [19]
Muon	$< 1.8 \times 10^{-19}$			2009 [20]
Tau	$< 1 \times 10^{-17}$			2003 [21]
Lambda	$< 3 \times 10^{-17}$			1981 [22]
Neutron	$(-0.21 \pm 1.82) \times 10^{-26}$	$\approx 10^{-28}$	10^{-28}	2015 [23]
${}^{199}_{80}\mathrm{Hg}$	$< 7.4 \times 10^{-30}$	10^{-30}	$< 1.6 \times 10^{-26}$ [24]	2016 [25]
${}^{129}_{54}\mathrm{Xe}$	$< 6.0 \times 10^{-27}$	$\approx 10^{-30}$ to 10^{-33}	$\approx 10^{-26}$ to 10^{-29}	2001 [26]
Proton	$< 2 \times 10^{-25}$	$\approx 10^{-29}$	10^{-29}	2016 [25]
Deuteron	not available yet	$\approx 10^{-29}$	$\approx 3 \times 10^{-29}$ to 5×10^{-31}	

Search for charged particle EDMs with frozen spins

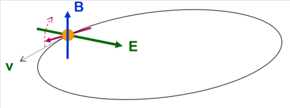
Magic storage rings

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

- Generalized solution for magic momentum

$$\frac{E_x}{B_y} = \frac{Gc\beta\gamma^2}{1 - G\beta^2\gamma^2}, \qquad (9)$$

where E_x is radial, and B_y vertical field.



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

particle	G	$p\,[\mathrm{MeV\,c^{-1}}]$	$T\,[\mathrm{MeV}]$	$E_x\,[\mathrm{MV\,m^{-1}}]$	$B_y\,[\mathrm{T}]$
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:

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

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

Progress toward storage ring EDM experiments

Complementing the spin physics tool box

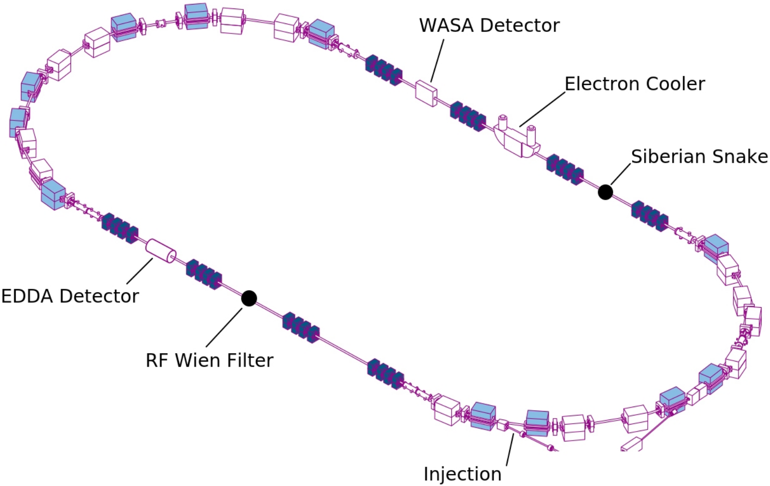
COoler SYnchrotron COSY

- 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.

Until 2010, COSY used for spin-physics with hadrons:

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

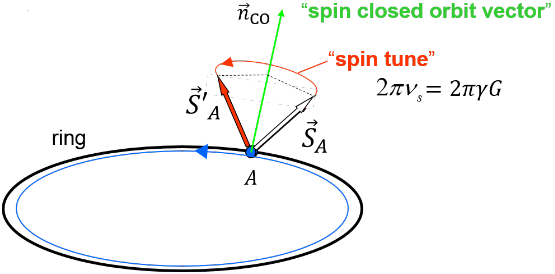
COSY Landscape



Spin closed orbit and spin tune

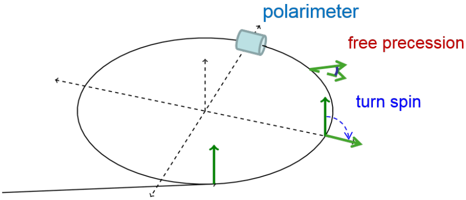
One particle with magnetic moment makes one turn in machine $(A - A)$:

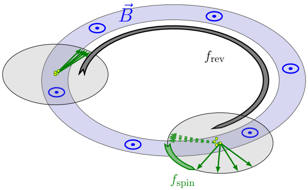
- Stable direction of polarization in ring, if $\vec{S} \, // \, \vec{n}_{\text{co}}$.
- Vector $\vec{n}_{\text{co}}$ around which spins precess called spin-closed orbit:
  - stable direction $\vec{n}_{\text{co}} = \vec{n}_{\text{co}}(s)$ (in general a function of position in the ring).



Number of spin precessions per turn is called spin tune ν_s.

Principle of spin-coherence time measurement





Measurement procedure:

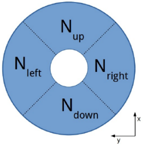
1. Vertically polarized deuterons stored at $p \simeq 1\,\mathrm{GeV\,c^{-1}}$.
2. Polarization flipped into horizontal plane with RF solenoid ($\approx 200\,\mathrm{ms}$).
3. Beam extracted on Carbon target with ramped bump or by heating.
4. Horizontal (in-plane) polarization determined from $U - D$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

Detector system for polarimetry

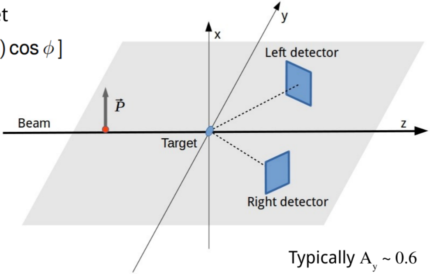
POLARIZATION MEASUREMENT

Scattering from Carbon target

$$\sigma^{pol}(\theta,\phi) = \sigma_0(\theta)[1 + \tfrac{3}{2} P A_y(\theta) \cos\phi\,]$$



2π detector - “beam” view



Typically $A_y \sim 0.6$

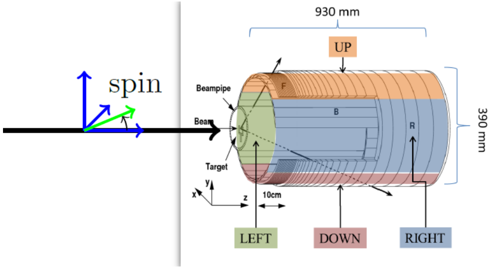
Right/Left asymmetry ∝ vertical component of polarization P_y

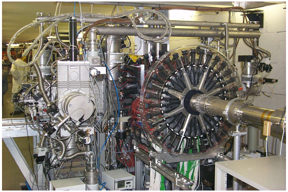
$$\epsilon_{LR} = \frac{N_L - N_R}{N_L + N_R} = P_y A_y$$ ⇒ EDM signal appears here

Up/Down asymmetry ∝ horizontal component of polarization P_x

$$\epsilon_{UD} = \frac{N_U - N_D}{N_U + N_D} = P_x A_y$$ ⇒ Needed to maintain “frozen spin” condition

Detector system: EDDA [27]





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

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

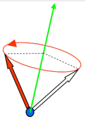
$$N_{\text{U,D}} \propto 1 \pm \frac{3}{2} p_x A_y \sin(\underbrace{\nu_s \cdot f_{\text{rev}}}_{f_s = -120.7\,\text{kHz}} \cdot t), \text{ where } f_{\text{rev}} = 750.0\,\text{kHz}. \tag{11}$$

Spin coherence time

Most polarization experiments unaffected by coherence of spins along $\vec{n}_{co}$

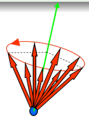
Spins aligned:

Ensemble *coherent*



Spin vectors out of phase:

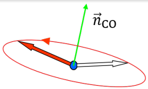
Ensemble *decoherent*



$\Rightarrow$ **Polarization along $\vec{n}_{co}$ not affected**

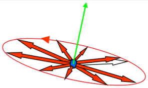
With frozen spins: $\vec{S} \perp \vec{n}_{co}$:

Spins aligned



With time:

Spins out of phase in horizontal plane



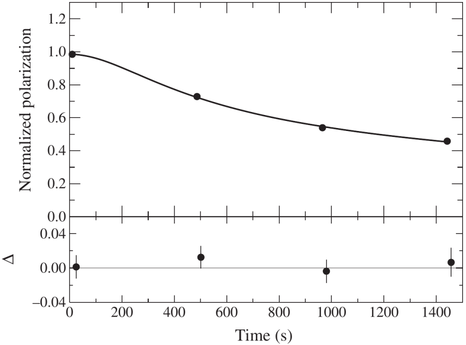
$\Rightarrow$ **In-plane polarization vanishes**

In machines with frozen spins:

Buildup time t to observe polarization $p_y(t)$ is limited by τ_{SCT}.

Optimization of spin-coherence time [7]

Precise adjustments of three sextupole families in the ring



JEDI progress on τ_{SCT}:

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

- Previous record: $\tau_{\text{SCT}}(\text{VEPP}) \approx 0.5\,\text{s}$ [28] ($\approx 10^7$ spin revolutions).

Spring 2015: Way beyond anybody's expectation:

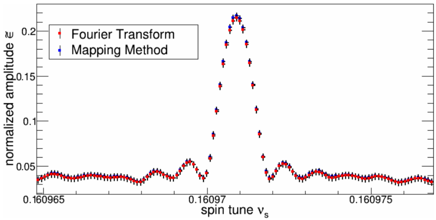
- With about 10^9 stored deuterons.
- Long spin coherence time was one of main obstacles of srEDM experiments.
- Large value of τ_{SCT} of crucial importance (10), since $\sigma_{\text{stat}} \propto {\tau_{\text{SCT}}}^{-1}$.

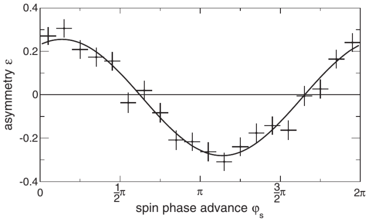
Precision determination of spin tune [8] I

Time-stamping events in each detector quadrant accurately:

1. Based on turn number n, 100 s measurement interval split into turn intervals of $\Delta n = 10^6$ turns, each interval lasting ≈ 1.3 s.
2. For all events, spin phase advance $\varphi_s = 2\pi|\nu_s^{\text{fix}}|n$ calculated assuming certain fixed spin tune ν_s^{fix}.
3. Either map events into one full polarization oscillation in range $\varphi_s \in [0, 2\pi)$, or perform Fourier analysis of rates in detector $\Rightarrow$ determine $\tilde{\varepsilon}$ and $\tilde{\phi}$ in

$$\varepsilon(\varphi_s) = \tilde{\varepsilon}\sin(\varphi_s + \tilde{\varphi})\,. \tag{12}$$



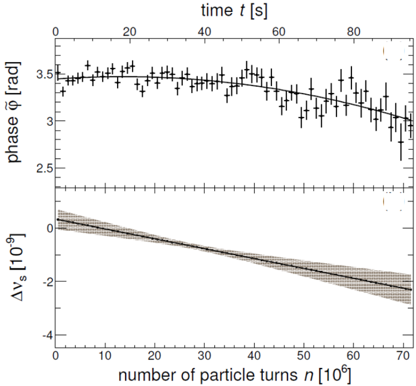


Precision determination of the spin tune [8] II

Precise time-stamping of events,

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

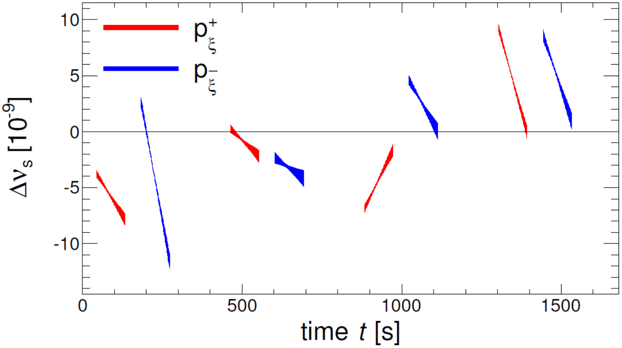
$$\begin{aligned}\nu_s(n) &= \nu_s^{\text{fix}} + \frac{1}{2\pi}\frac{\mathrm{d}\tilde{\phi}}{\mathrm{d}n} \\ &= \nu_s^{\text{fix}} + \Delta\nu_s(n)\end{aligned} \qquad (13)$$



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.**

Precision determination of the spin tune [8] III



Walk of spin tune ν_s [8].

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 ($\rightarrow$ **phase-lock**).
- Studies of machine imperfections.

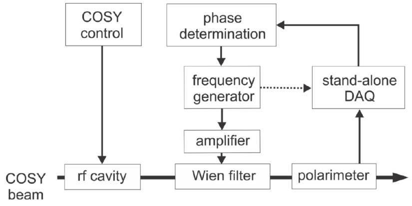
Phase locking spin precession in machine to device RF

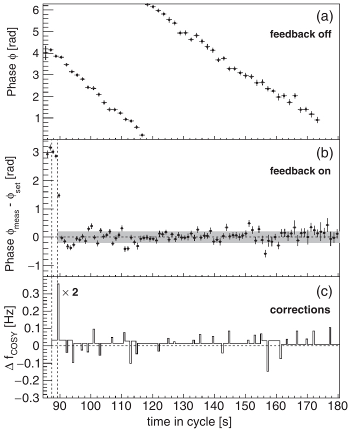
At COSY, one cannot freeze the spin precession

$\Rightarrow$ 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 WF)





Major achievement : Error of phase-lock $\sigma_\phi = 0.21\,\text{rad}$ [9].

First direct deuteron EDM measurement 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 ($< 10^{-28}\,\mathrm{e\,cm}$).
  - In this environment, magnetic fields mean evil (since μ is large).

Idea of proof-of-principle experiment with 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 ($\sim 1000\,\mathrm{s}$).

Goal of proof-of-principle experiment:

Show that conventional storage ring useable for first direct EDM measurement

dC polarimetry data base I

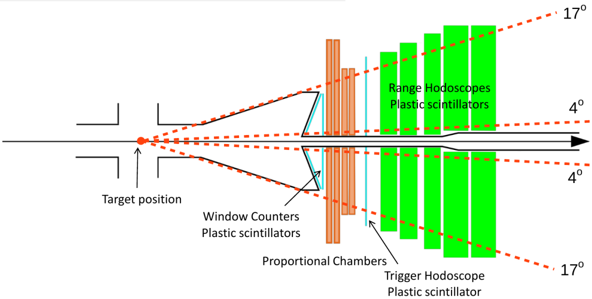
Data analysis mainly by Maria Zurek and PhD Fabian Müller

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

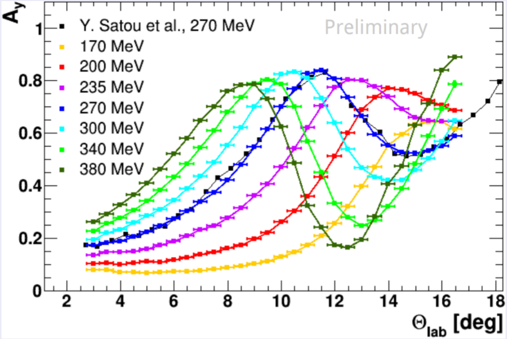
Detector system: former WASA forward detector, modified

- 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

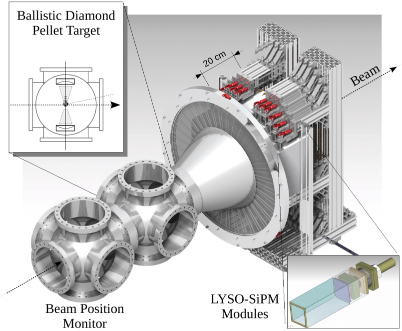
Development led by Irakli Keshelashvili

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 alignment for EDM measurement at COSY

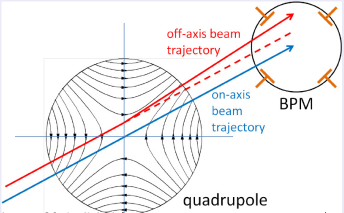
PhD work of Tim Wagner

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 is varied

$$\Delta x(s) = \frac{\Delta k \cdot x(s_0) I}{B\rho} \cdot \frac{1}{1 - k \frac{I\beta(s_0)}{2B\rho \tan \pi\nu}} \cdot \frac{\sqrt{\beta(s)\beta(s_0)}}{2 \sin \pi\nu} \cos\left[\phi(s) - \phi(s_0) - \pi\nu\right] \quad (14)$$

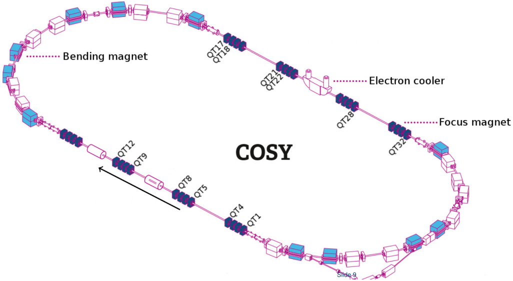
- s, s_0 positions along orbit, β betatron functions, ν working point, ϕ betatron phase advance, B magnetic field, I magnet current, ρ bending radius.
- Not all parameters in (14) known well $\rightarrow$ not possible to determine $x(s_0)$.
- Instead, use merit function

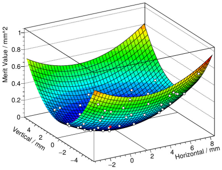
$$f = \frac{1}{N_{\text{BPM}}} \sum_{i=1}^{N_{\text{BPM}}} \left[x_i(+\Delta k) - x_i(-\Delta k)\right]^2 \propto x(s_0)^2 \quad (15)$$

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

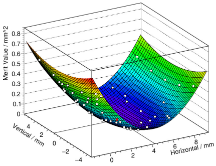
Beam-based aligment III

PhD work of Tim Wagner

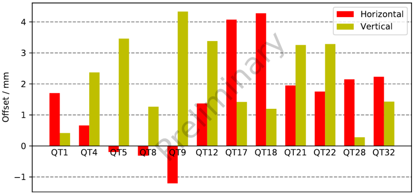




QT1, $\frac{\chi^2}{\text{d.o.f.}} = 0.96$



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 sensitivity 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 provide required sensitivity ($< 10^{-28}\,\mathrm{e\,cm}$).
  - In this environment, magnetic fields mean evil (since μ is large).

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

- In magnetic machine, particle spins (deuterons, protons) precess about vertical (B field) direction.
- 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 fct of time (cycle time $\sim 1000\,\mathrm{s}$).

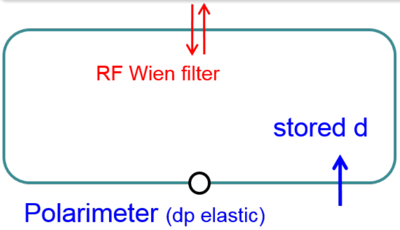
Goal of proof-of-principle experiment:

Show that storage ring (COSY) can be used for a first direct EDM measurement.

RF Wien filter method

More aspects about the technique:

- RF Wien filter ($\vec{E} \times \vec{B}$) avoids coherent betatron oscillations in the beam:
  - Lorentz force $\vec{F}_L = q(\vec{E} + \vec{v} \times \vec{B}) = 0$ [31, 32]
  - EDM measurement mode: $\vec{B} = (0, B_y, 0)$ and $\vec{E} = (E_x, 0, 0)$.



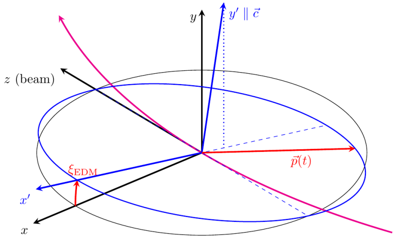
- Deuteron spins lie in machine plane.
- For $d \neq 0 \Rightarrow$ *accumulate* EDM signal during spin coherence time

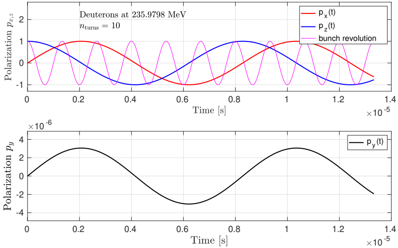
Statistical sensitivity:

- 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.

Effect of EDM on stable spin axis of the ring [5]

Without accumulation (RF WF off)





Beam particles move along z direction

- Presence of an EDM $\Rightarrow \xi_{\text{EDM}} > 0$.
- $\Rightarrow$ Spins precess around the $\vec{c}$ axis.
- $\Rightarrow$ Oscillating vertical polarization component $p_y(t)$ is generated.

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

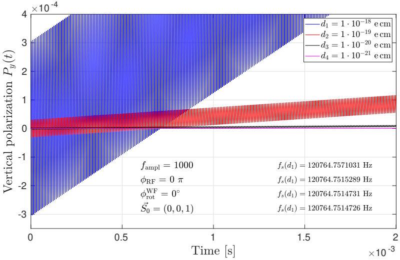
- $p_x(t)$, $p_z(t)$ and $p_y(t)$.
- Bunch revolution indicated as well.
- p_y oscillation amplitude corresponds to tilt angle ξ_{EDM}.

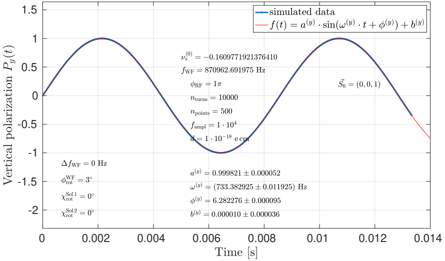
Model calculation of polarization buildup due to EDM [5]

With RF Wien filter

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

- $G = -0.143$, $\gamma = 1.126$, $\boxed{f_s = f_\text{rev}(\gamma G + K_{(=0)})} \approx 120.765\,\text{kHz}$
- Enhanced RF field integral $f_\text{ampl} \times \int E_\text{WF} \cdot \mathrm{d}\ell \approx 2200\,\text{kV}$ (w/o ferrites) [6].

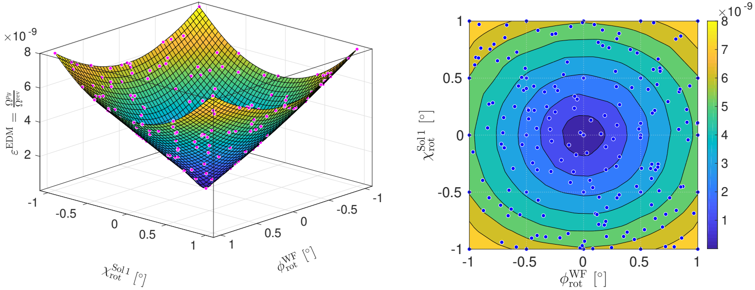




Features of EDM induced vertical polarization buildup

- EDM accumulates in vertical polarization $p_y(t) \propto d$ [33, 18, 34].
- $\rightarrow$ Full oscillation of $p_y(t)$ with proper feedback via pilot bunch.

Expectation: $d = 10^{-20}\,\mathrm{e\,cm}$ in ideal COSY ring [5]



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

(b) Contour plot of (a).

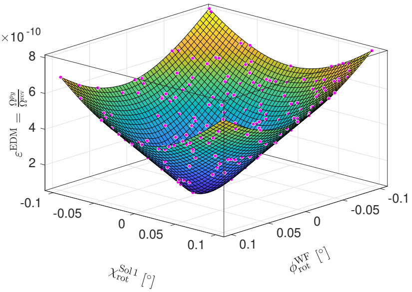
Function describing the surface

- Surface described by *elliptic paraboloid* [5]:

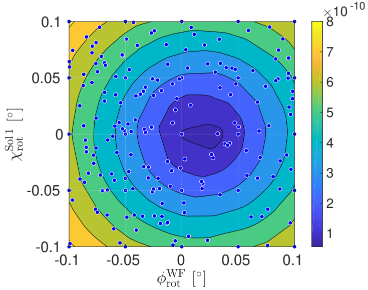
$$\left(\varepsilon^{\mathrm{EDM}}\right)^2 = \frac{\psi^2_{\mathrm{WF}}}{16\pi^2}\cdot\left[A\left(\phi^{\mathrm{WF}} - \phi^{\mathrm{WF}}_0\right)^2 + B\left(\frac{\chi^{\mathrm{Sol}}}{2\sin\pi\nu_s^{(2)}} + \chi^{\mathrm{Sol}}_0\right)^2 + C\right].$$

  - A and B account for possible deviations of $\varepsilon^{\mathrm{EDM}}$ along ϕ^{WF} and χ^{Sol}.

Expectation: $d = 10^{-18}\,\mathrm{e\,cm}$ in ideal COSY ring [5]



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



(d) Contour plot of (c).

Function describing the surface

- Surface described by *elliptic paraboloid* [5]:

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

  - A and B account for possible deviations of $\varepsilon^{\mathrm{EDM}}$ along ϕ^{WF} and χ^{Sol}.

Preliminary results of Wien filter mapping I

Nov.-Dec. 2018 run

Function describing the surface

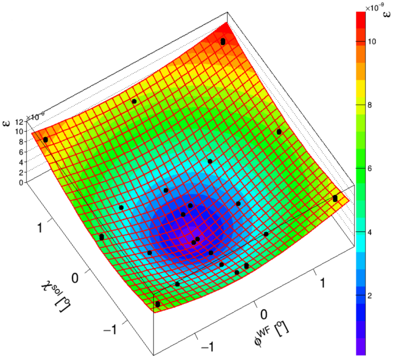
- Surface described by *elliptic paraboloid* [5, PRAB '20]:

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

  - A and B account for possible deviations 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. (16):

$$
\begin{aligned}
\phi_0^{\mathrm{WF}} &= -3.9 \pm 0.05\,\mathrm{mrad} \\
\chi_0^{\mathrm{Sol\,1}} &= -6.8 \pm 0.04\,\mathrm{mrad} \\
A &= 0.559 \pm 0.005 \\
B &= 0.583 \pm 0.005 \\
C &= (-1.2 \pm 0.1) \cdot 10^{-10}
\end{aligned}
\tag{17}
$$

Where are we today?

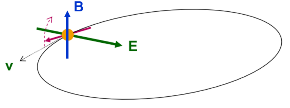
1. Minimum determines spin rotation axis (3-vector) at RF WF *including EDM*.
2. Spin tracking shall determine orientation of stable spin axis *w/o* EDM.
3. EDM is obtained from the difference of 1. and 2.

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

- Generalized solution for magic momentum

$$\frac{E_x}{B_y} = \frac{Gc\beta\gamma^2}{1 - G\beta^2\gamma^2}, \qquad (18)$$

where E_x is radial, and B_y vertical field.



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

particle	G	$p\,[\mathrm{MeV\,c^{-1}}]$	$T\,[\mathrm{MeV}]$	$E_x\,[\mathrm{MV\,m^{-1}}]$	$B_y\,[\mathrm{T}]$
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

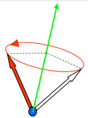
protons, deuterons, and helions in one and the same machine.

Spin coherence time

Most polarization experiments don't care about coherence of spins along $\vec{n}_{\text{co}}$

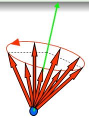
Spins aligned:

Ensemble *coherent*



Spin vectors out of phase:

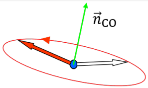
Ensemble *decoherent*



$\Rightarrow$ **Polarization along $\vec{n}_{\text{co}}$ not affected**

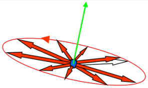
With frozen spins: $\vec{S} \perp \vec{n}_{\text{co}}$:

Spins aligned



With time:

Spins out of phase in horizontal plane



$\Rightarrow$ **Longitudinal polarization vanishes**

In machines with frozen spins:

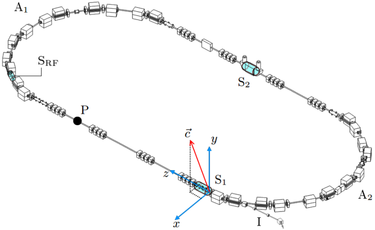
Buildup time t to observe polarization $P_y(t)$ limited by τ_{SCT}.

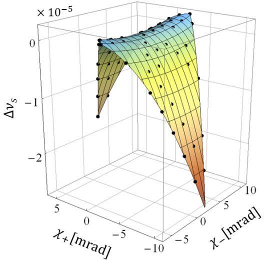
Study of machine imperfections

JEDI developed new method to investigate magnetic machine imperfections based on highly accurate determination of spin-tune [33, PRAB '17].

Spin tune mapping

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



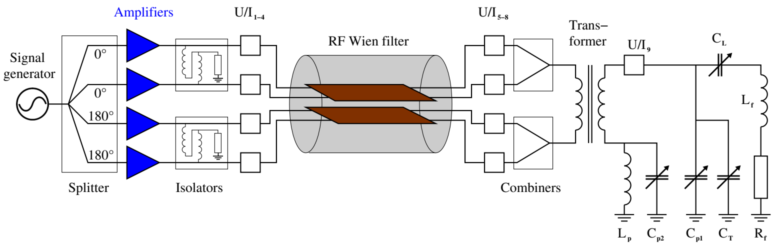


- Position of saddle point determines tilt of stable spin axis by magnetic imperfections.
- Control of background from MDM at level $\Delta c = 2.8 \times 10^{-6}$ rad.
- Systematics-limited sensitivity for deuteron EDM at COSY $\sigma_d \approx 10^{-20}$ e cm.

Driving circuit [36]

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

- Design layout using four separate 1 kW power amplifiers.



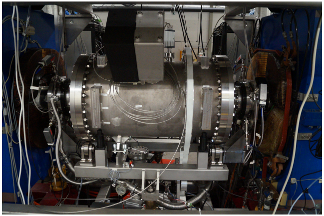
Circuit fully operational

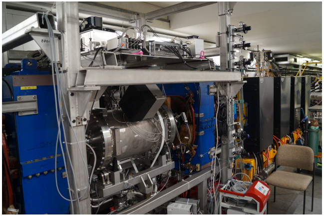
- Tuneable elements[a] allow [6]:
  - minimization of Lorentz-force, and
  - velocity matching to β of the beam.
- Power upgrade to 4×2 kW: $\int B_z dz = 0.218$ T mm possible.

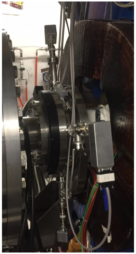
[a] built by Fa. Barthel, `http://www.barthel-hf.de`.

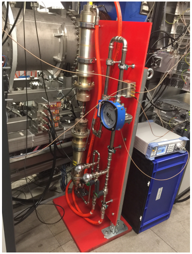
RF Wien filter

Installation at COSY









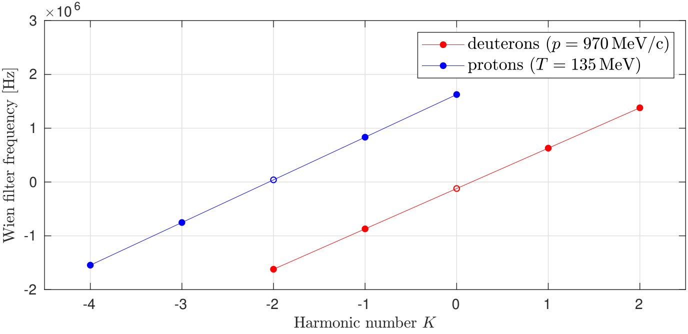
- RF Wien filter between PAX magnets. Upstream Rogowski coil; racks with power amplifiers, each unit delivers up to 500 W; water-cooled 25 Ω resistor.

Frequencies of RF Wien filter [5]

Spin resonance condition:

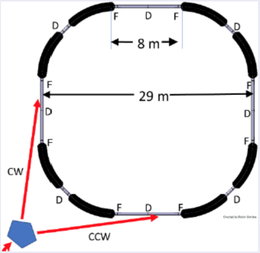
$$f_{\mathrm{WF}} = f_{\mathrm{rev}} \left(\gamma G \pm K \right) \,, k \in \mathbb{Z}.$$

- RF Wien filter operates at frequencies between 0 to 2 MHz,
- Open symbols not reachable with present setup of driving circuit, *i.e.*,
  - deuterons at $K = 0$ ($-120.8\,\mathrm{kHz}$), and
  - protons at $K = -2$ ($39.4\,\mathrm{kHz}$).



PTR lattice design (protons)

Basic beam parameters and layout [2, chap. 7]



	E only	E & B frozen spin		unit
Bending radius	8.86	8.86		m
Kinetic energy	**30**	**30**	**45**	**MeV**
$\beta = v/c$	0.247	0.247	0.299	
γ (kinetic)	1.032	1.032	1.048	
Momentum	239	239	294	MeV/c
Electric field E	**6.67**	**4.56**	**7.00**	**MV/m**
Magnetic field B		**0.0285**	**0.0327**	**T**
rms $\epsilon_x = \epsilon_y$	1	1		π mm mrad
Transv. acc. $a_x = a_y$	> 10	> 10		π mm mrad

- p at 30 MeV all-electric CW-CCW beams operation
- p at 30 to 45 MeV frozen spin, with additional vertical B field

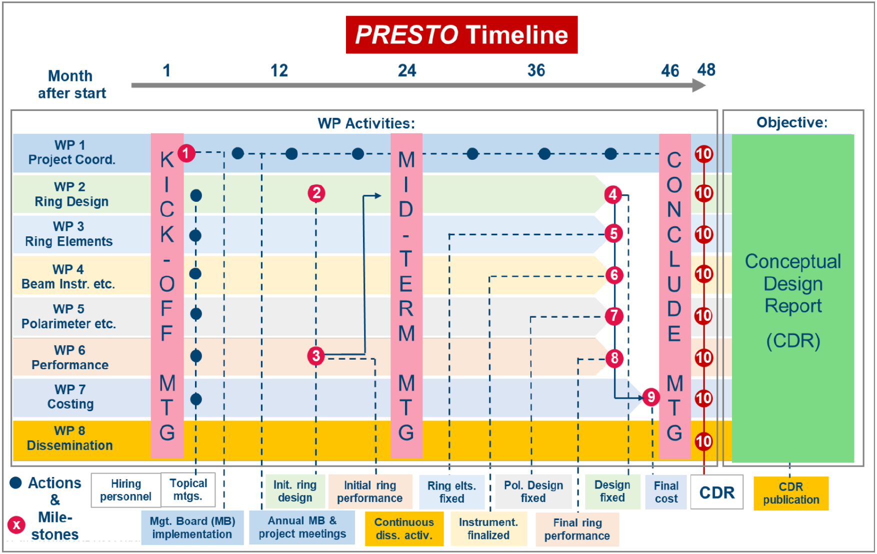
Status PRESTO Design Study application for PTR

Pathfinder facility for a new class of PREcision-physics STOrage rings

Framework

- Call: INFRADEV-01-01-2022 - Concept Development
  - Application deadline: 20.04.22
  - Duration: 4 years
  - Project development: 2023-2026
  - Budget: total 3 M€;
- Coordinator + 7 beneficiaries
  - INFN (Coord.) (Italy)
  - CERN; RWTH-Aachen (Germany)
  - GSI (Germany)
  - MPI-HD (Germany)
  - Univ. Liverpool (United Kingdom)
  - Univ. Krakow (Poland)
  - Univ. Tbilisi (Georgia)
- PRESTO status:
  - presently on top of reserve list, but no final decision yet.
  - Program Committee will meet before end of year. Members ask EU for transparent criteria to assign residual budget.

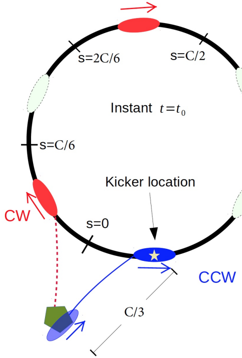
Timeline and Milestones of the project

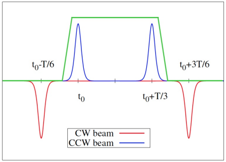


Alternative, if `PRESTO` not funded by '22 INFRADEV call

- Submit `PRESTO` project case as an ERC-AdG in early 2023:
- **Objective:** Feasibility study for electrostatic storage ring for precision physics
- Three participants/beneficiaries:
  - **INFN:** coordination and direct responsibility for the low-energy polarimeter
  - **CERN:** lattice design and systematic studies
  - **RWTH/GSI:** electrostatic deflector and beam diagnostics
- Focus on validation of the machine concepts by simulations for various ring designs ($\rightarrow$ access to supercomputing facilities).

S. Martin, R. Talman, C. Carli, M. Haj Tahar: [2, chap. 7.8]





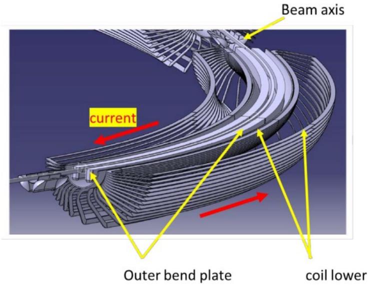
Test at COSY: spin manipulation after injection appears feasible:

- could simplify injection scheme, no need for fast switches
- orient spin directions in bunches after injection of DC beam

Electrostatic deflector

with additional magnetic bend

- Concept for electrostatic deflector element available [2, chap. 7.6].

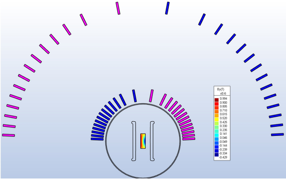


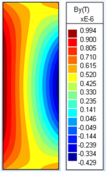
		units
Electric		
electric field	7.00	MV/m
gap between plates	**60**	**mm**
plate height (straight part)	**151.5**	**mm**
plate length	**6.959**	**m**
total bending length	55.673	m
total straight length	44.800	m
bend angle per unit	**45**	deg

- **Next step:** build prototype with RWTH-Aachen (IAEW High Voltage)
- Studies of straight E/B deflector element to improve voltage holding capability ongoing at Jülich.

Magnetic bends

- Concept for magnetic add-on to deflector available [2, chap. 7.6].
- Magnetic system ($\cos\theta$) placed outside the vacuum tube.



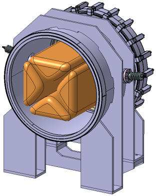
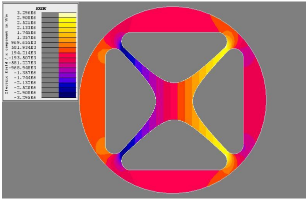


Magnetic		
magnetic field	0.0327	T
current density	5.000	A/mm^2
windings/element	60	

- Magnet system included in prototype development with RWTH-Aachen (IAEW High Voltage)

Multipole elements
Quadrupoles

- Design of electrostatic elements by J. Borburgh (CERN) [2, chap. 9])
- Electrostatic quadrupoles
  - aperture diameter 80 mm, applied ±20 kV.
  - Simulated design with vacuum chamber of 400 mm diameter.

- PTR quadrupoles max. pole tip potential 30 kV (margin for conditioning)
- 3D design available:
  - sextupole, octupole and higher harmonics reasonable
  - 800 mm longitudinal length and radial diameter of 620 mm.

Needs strong support

Vacuum system

- Ring vacuum given by minimum required beam lifetime of about 1000 s.
  - N_2 partial pressures below 10^{-12} mbar
  - H_2 partial pressures below 5×10^{-11} mbar.
- Stochastic cooling rate better than 5×10^{-3} mm mrad/s.
- non-vibrational system that avoids generation of magnetic fields
  - Cryogenic or NEG pumping systems may be used:
    1. NEG material becomes saturated after several pump-downs.
    2. Aging NEG material leaves dust particles in vacuum vessel.
    3. PTR will have significant number of pump-downs during program.
    4. High-voltage system requires excellent vacuum.
    5. System based on NEG cartouches [37] under discussion.
- Mechanical alignment of elements inside vacuum pipe of 400 mm diameter
  - active compensation of oscillations/ground motion
- Shielding (passive versus active)

Stochastic cooling

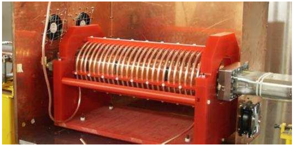
- Control proton beam emittance during measurements: 30 MeV to 45 MeV.
- Cooling should compensate emittance growth of 5×10^{-3} mm mrad/s.
  - Used successfully at COSY to compensate emittance growth of beam during interaction with internal gas targets.
  - Interplay between stochastic cooling and evolution of horizontally polarized ensemble of particles unknown.
  - **Studies of emittance growth and spin coherence time not possible at any other ring prior to PTR**.
- **Aim: provide basic design of stochastic cooling system for PTR.**

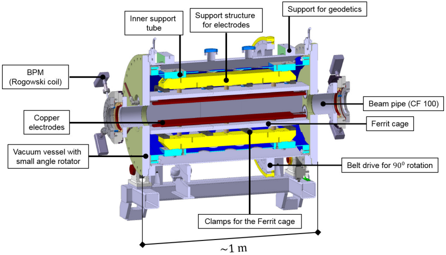
RF Cavity

- Azimuthal magnetic fields of RF cavities lead to spin rotations of the magnetic moment.
- Even in case of a perfectly aligned cavity, individual particles experience horizontal magnetic fields and spin rotations into vertical and horizontal directions.
- Effect on EDM measurement strongly suppressed:
  - cancellation of effect for different particles crossing cavity gap each turn with different betatron phases and transverse positions.
- Design of RF cavity required that minimizes unwanted spin rotations.

Spin manipulation tools

- Vertical polarisation of stored beam rotated into horizontal plane by **longitudinal field** of **RF solenoid**.
  - Typical ramp-up times from vertical to horizontal polarisation are $\approx 200\,\mathrm{ms}$.
  - optimize design for PTR.



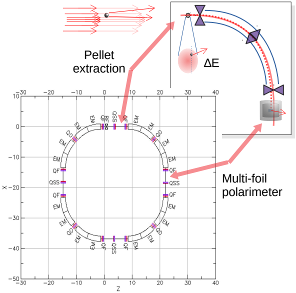


- **RF Wien filter** [6] applies **transverse magnetic fields** to spin, while excerting minimal Lorentz force on beam:
  - COSY: spin manipulation of individual bunches by fast RF switches feasible.
  - optimize design for PTR, need two of them for CW-CCW operations.

High-precision beam polarimeter (... with pellet extraction)

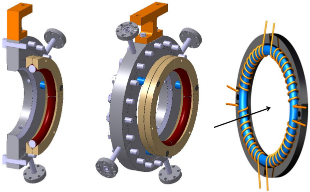
- dC (pC) scattering using white noise extraction works for relative polarization errors $\Delta p/p = 10^{-6}$ [29].
- Polarimeter system for dedicated ring described in [38–40].

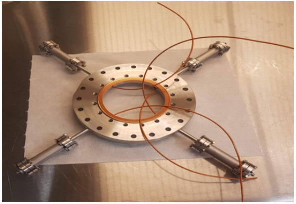
- Polarization profile determination at low energies:
  - Carbon multifoil polarimeter [41] based on Silicon detectors with pellet extraction
    - ★ (PhD J. Gooding, University of Liverpool).
  - Ballistic Si pellet target for homogeneous beam sampling [42, App. K].
  - Eloss of 100 keV in 50 μm pellet $\rightarrow$ track displaced by 2.5 cm behind 90° bend.



Development of prototype BPM based on segmented toroidal coil [43]

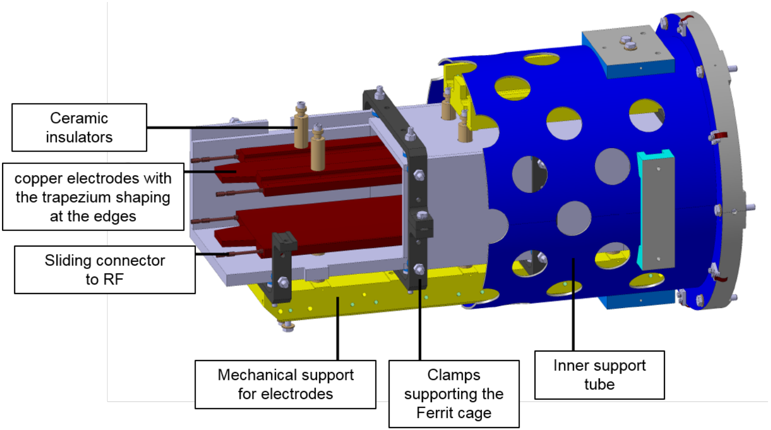
- Rogowski coil





- advantages over conventional split-cylinder BPMs
  - short insertion length → many BPMs can be installed
  - inexpensive
  - high sensitivity to position of bunched beams
- Other diagnostics needed:
  - Beam profile monitor, non-destructive for emittance measurement
  - BCT, also to adjust CW/CCW beam currents

Internal structure



Aim was to build the best possible device, with respect to

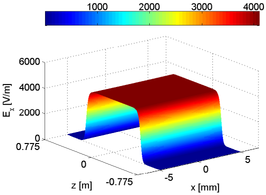
- Electromagnetic performance [6] and mechanical tolerances [44].
- Excellent cooperation with RWTH Aachen University and ZEA-Jülich.

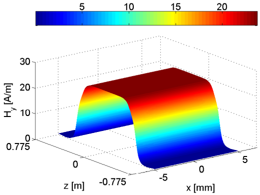
Electromagnetic field simulations (incl. ferrites) [45]

Full-wave simulations

- using CST Microwave Studio[a].

[a] Computer Simulation Technology AG, Darmstadt, Germany, http://www.cst.com





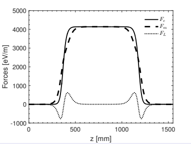
At an input power of 1 kW, magnetic and electric field integrals are ($\ell = 1.550\,\mathrm{m}$):

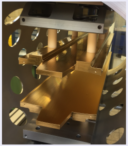
$$\int_{-\ell/2}^{\ell/2} \vec{B} dz = \begin{pmatrix} 2.73 \times 10^{-9} \\ \mathbf{2.72 \times 10^{-2}} \\ 6.96 \times 10^{-7} \end{pmatrix} \mathrm{T\,mm}\,, \quad \int_{-\ell/2}^{\ell/2} \vec{E} dz = \begin{pmatrix} \mathbf{3324.577} \\ 0.018 \\ 0.006 \end{pmatrix} \mathrm{V} \tag{19}$$

Lorentz force compensation [6]

Integral Lorentz force is of order of $-3\,\mathrm{eV/m}$:

- Electric force F_{e}, magnetic force F_{m}, and Lorentz force F_{L} inside RF Wien filter.
- Trapezoid-shaped electrodes determine crossing of electric and magnetic forces.





Lorentz force

$$\vec{F}_{\mathrm{L}} = q\left(\vec{E} + \vec{v} \times \vec{B}\right) \,, \tag{20}$$

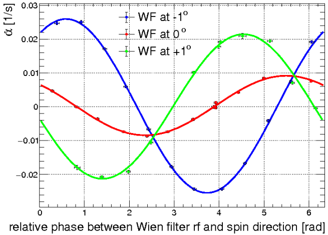
- particle charge q, velocity vector $\vec{v} = c(0, 0, \beta)$, fields $\vec{E} = (E_x, E_y, E_z)$ and $\vec{B} = \mu_0(H_x, H_y, H_z)$, μ_0 vacuum permeability.
- For vanishing Lorentz force $\vec{F}_{\mathrm{L}} = 0$, field quotient Z_q given by

$$E_x = -c \cdot \beta \cdot \mu_0 \cdot H_y \quad \Rightarrow \quad \boxed{Z_q = -\frac{E_x}{H_y} = c \cdot \beta \cdot \mu_0 \approx 173\ \Omega} \,. \tag{21}$$

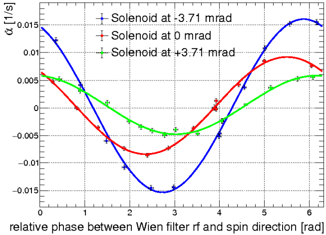
First measurement of EDM-like buildup signals

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 $\phi_{\mathrm{rot}}^{\mathrm{WF}}$ and $\chi_{\mathrm{rot}}^{\mathrm{Sol\,1}}$ affect the pattern of observed initial slopes $\dot{\alpha}$.



$\dot{\alpha}$ for $\phi_{\mathrm{rot}}^{\mathrm{WF}} = -1^\circ, 0^\circ, +1^\circ$ and $\chi_{\mathrm{rot}}^{\mathrm{Sol\,1}} = 0$.



$\dot{\alpha}$ for $\chi_{\mathrm{rot}}^{\mathrm{Sol\,1}} = -1, 0, +1^\circ$ and $\phi_{\mathrm{rot}}^{\mathrm{WF}} = 0$.

Planned measurements:

- 1st EDM measurement run Nov-Dec/2018 (6 wk, ongoing).
- 2nd run planned for Fall/Winter 2019 (6 wk).