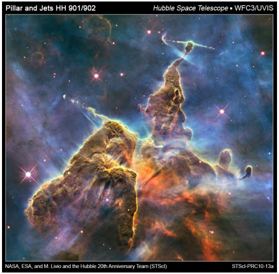
Search for Electric Dipole Moments and Axions/ALPs of charged particles using storage rings

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

25th International Symposium on Spin Physics
Sept 24 – 29, 2023
https://spin2023.phy.duke.edu/

Contents

Baryon asymmetry in the Universe



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

Observation and expectation from Standard Cosmological Model (SCM):

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

- 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:

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

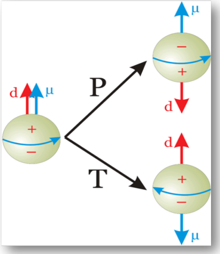
- **Energy of magnetic dipole** invariant under P and T:

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

  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

$$\vec{s} \cdot \vec{E} \overset{P \text{ or } T}{\overbrace{\longrightarrow}} -\vec{s} \cdot \vec{E}, \qquad (1)$$



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 4th quantum number to fundamental particles (besides m, q, and s).

Naive estimate of scale of nucleon EDM

From Khriplovich & Lamoreux [4] and Nikolaev [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 $\theta_{\mathrm{QCD}} = 0$:

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

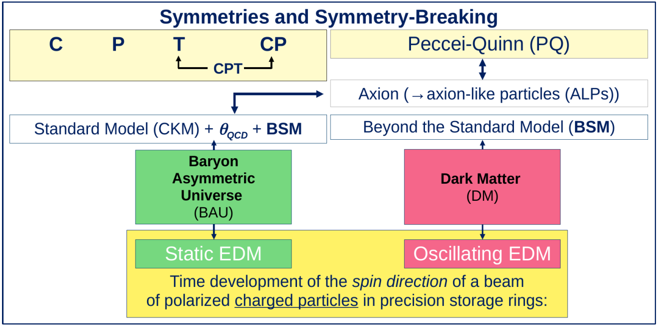
Motivation

Issues we are addressing

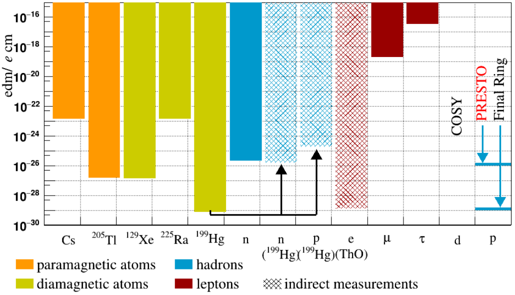
- Matter over antimatter dominance / Baryon asymmetry in the Universe
- Nature of Dark Matter (DM)

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 [7, CYR '21]



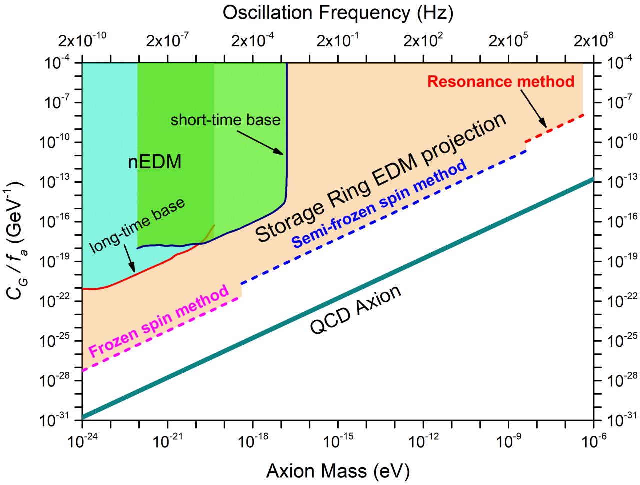
Missing are *direct* EDM measurements:

- 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 [6]

Axion Dark Matter search with Storage Ring EDM method



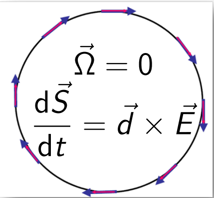
Experimental limits for axion-gluon coupled oscillating EDM measurements (from [8]).

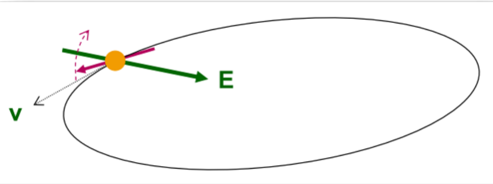
Measurement of EDM in storage ring

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 $p_y(t) \propto d$.

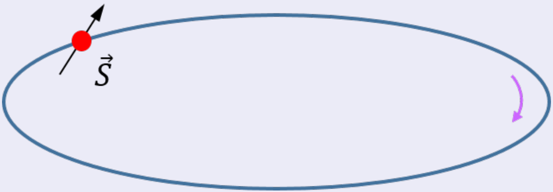
Spin precession of particles with MDM and EDM

In rest frame of particle

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

$$\frac{\mathrm{d}\vec{S}}{\mathrm{d}t} = \vec{\Omega} \times \vec{S} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}. \quad (2)$$

With protons in a ring



→ Spin-precession with MDMs and EDMs described by Thomas-BMT Eq. [9].

Frozen-spin

Spin-precession of particle MDM *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 for particles with $G > 0$: proton ($G = 1.793$) or electron ($G = 0.001$).

For protons: (4) $\Rightarrow$ *magic momentum*:

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

Measurement of EDM in a magnetic ring

First-ever direct EDM measurement using this method

In magnetic ring

- When external electric fields in ring vanish, $\vec{E} = 0$, spin motion governed by radial field $\vec{E} = c\vec{\beta} \times \vec{B}$, induced by relativistic motion in vertical $\vec{B}$ field:

$$\frac{\mathrm{d}\vec{S}}{\mathrm{d}t} \propto \vec{d} \times \vec{E} \quad \text{(see [10])} \tag{6}$$

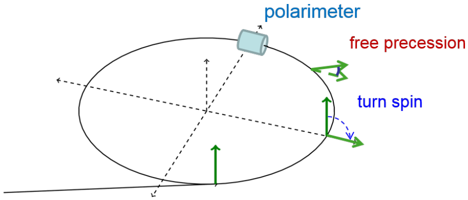
  $\rightarrow$ only small oscillation of vertical component p_y due to EDM.

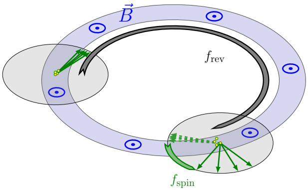
- **Use RF Wien filter to accumulate EDM signal** [11, 10]:
  - + Long spin-coherence time $> 1000\,\mathrm{s}$ [12]
  - + Spin tune determination $\Delta\nu_s/\nu_s \approx 10^{-10}$ [13] $\rightarrow$ tune RF Wien filter frequency
  - + Phase-lock of spin phase relative to Wien filter RF [14].
  - + Two-bunch method: pilot and signal bunch [15, 16]
    - 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-magnetometry**

Accumulated knowledge compiled in

2021 CERN Yellow Report [7]

Principle of spin-coherence time measurement

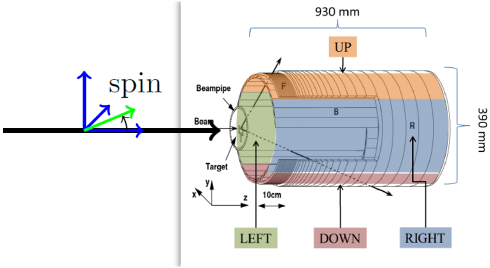


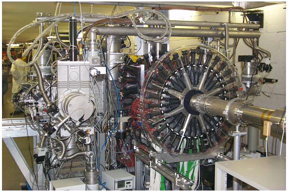


Measurement procedure:

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 [17]





EDDA 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:

$$N_{\mathrm{U,D}} \propto 1 \pm \frac{3}{2} p_x A_y \sin(\underbrace{\nu_s \cdot f_{\mathrm{rev}}}_{f_s = -120.7\,\mathrm{kHz}} \cdot t), \text{ where } f_{\mathrm{rev}} = 750.0\,\mathrm{kHz}. \quad (7)$$

JEPO polarimeter

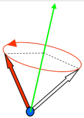
Lateron, EDDA replaced by dedicated new polarimeter, based on LYSO crystals.

Spin coherence time

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

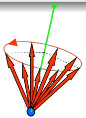
Spins aligned:

Ensemble *coherent*



Spin vectors out of phase:

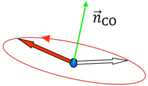
Ensemble *decoherent*



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

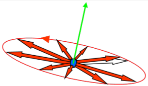
With frozen spins: $\vec{S} \perp \vec{n}_{co}$:

Spins aligned



With time:

Spins out of phase in horizontal plane



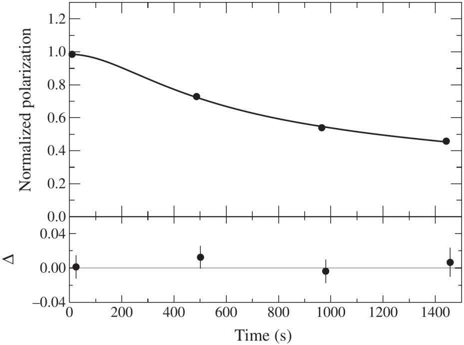
$\Rightarrow$ **In-plane polarization vanishes**

In machines with frozen spins:

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

Optimization of spin-coherence time [12]

Precise adjustments of three sextupole families in the ring



JEDI progress on τ_{SCT}:

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

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

Spring 2015: Way beyond anybody's expectation:

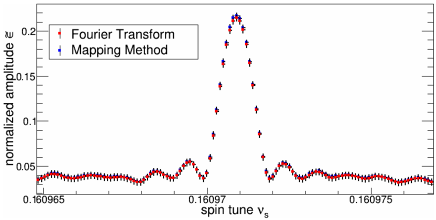
- With about 10^9 stored deuterons.
- Long spin coherence time was one of main obstacles of srEDM experiments.
- Large value of τ_{SCT} of crucial importance (11), since $\sigma_{\mathrm{stat}} \propto \tau_{\mathrm{SCT}}{}^{-1}$.

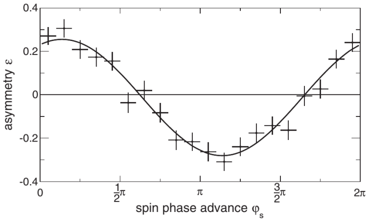
Precision determination of spin tune [13] I

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

$$\varepsilon(\varphi_s) = \tilde{\varepsilon}\sin(\varphi_s + \tilde{\varphi})\,. \tag{8}$$



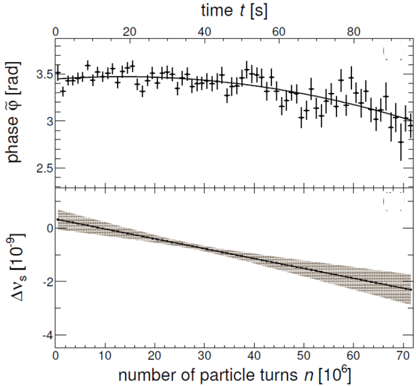


Precision determination of the spin tune [13] II

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:

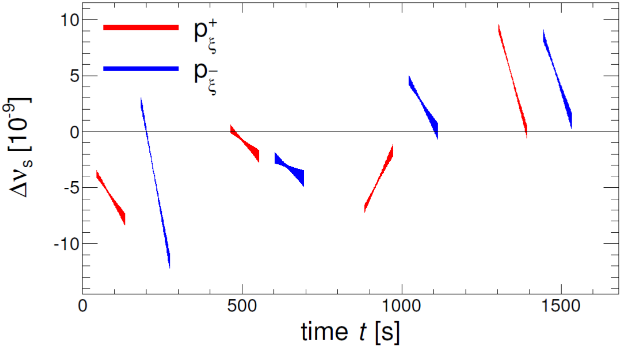
$$\nu_s(n) = \nu_s^{\text{fix}} + \frac{1}{2\pi}\frac{\mathrm{d}\tilde{\phi}}{\mathrm{d}n} = \nu_s^{\text{fix}} + \Delta\nu_s(n) \qquad (9)$$



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.**

Precision determination of the spin tune III



Walk of spin tune ν_s [13].

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.

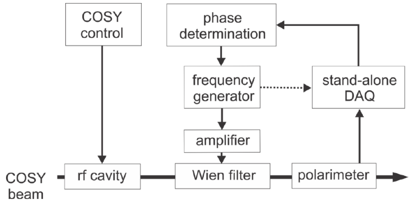
Phase locking spin precession in machine to device RF

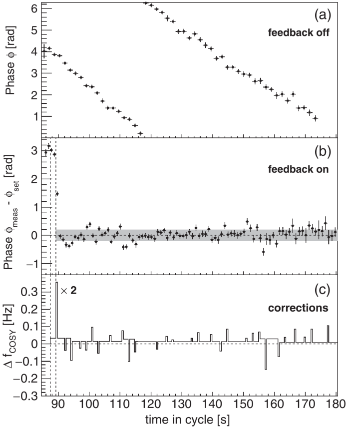
At COSY, one cannot freeze the spin precession

$\Rightarrow$ 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)

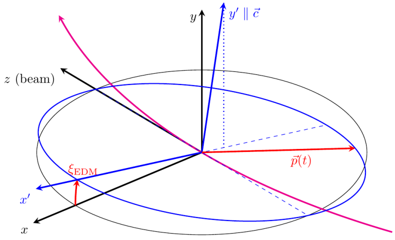




Major achievement : Error of phase-lock $\sigma_\phi = 0.21\,\text{rad}$ [14].

Effect of EDM on stable spin axis of the ring [10]

Without accumulation (RF WF off)

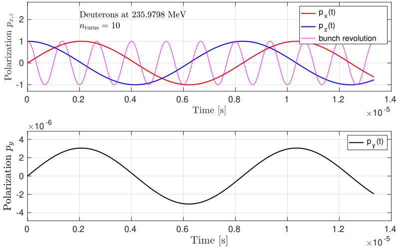


Beam particles move along z direction

- 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 [$\vec{p}_0 = (0, 0, 1)$]

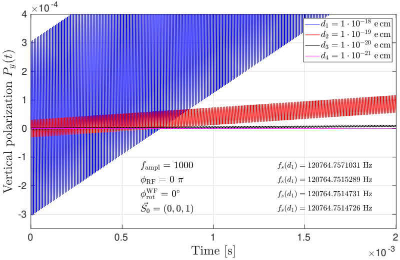
- $p_x(t)$, $p_z(t)$ and $p_y(t)$.
- Bunch revolution indicated as well.
- p_y oscillation amplitude corresponds to tilt angle ξ_{EDM}.

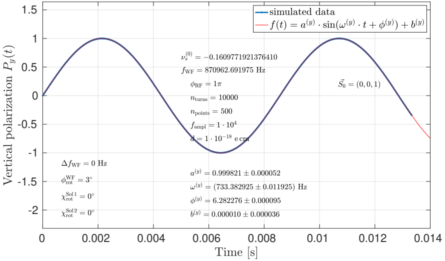
Model calculation of polarization buildup due to EDM [10]

With RF Wien filter

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

- $G = -0.143$, $\gamma = 1.126$, $\boxed{f_s = f_{\mathrm{rev}}(\gamma G + K_{(=0)})} \approx 120.765\,\mathrm{kHz}$
- Enhanced RF field integral $f_{\mathrm{ampl}} \times \int E_{\mathrm{WF}} \cdot \mathrm{d}\ell \approx 2200\,\mathrm{kV}$ (w/o ferrites) [11].





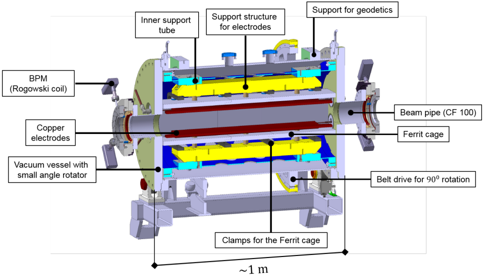
Features of EDM induced vertical polarization buildup

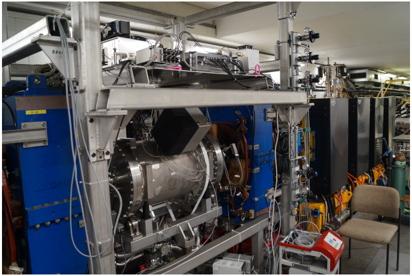
- EDM accumulates in vertical polarization $p_y(t) \propto d$ [19, 5, 20].
- $\rightarrow$ Full oscillation of $p_y(t)$ with proper feedback via pilot bunch.

Design of waveguide RF Wien filter

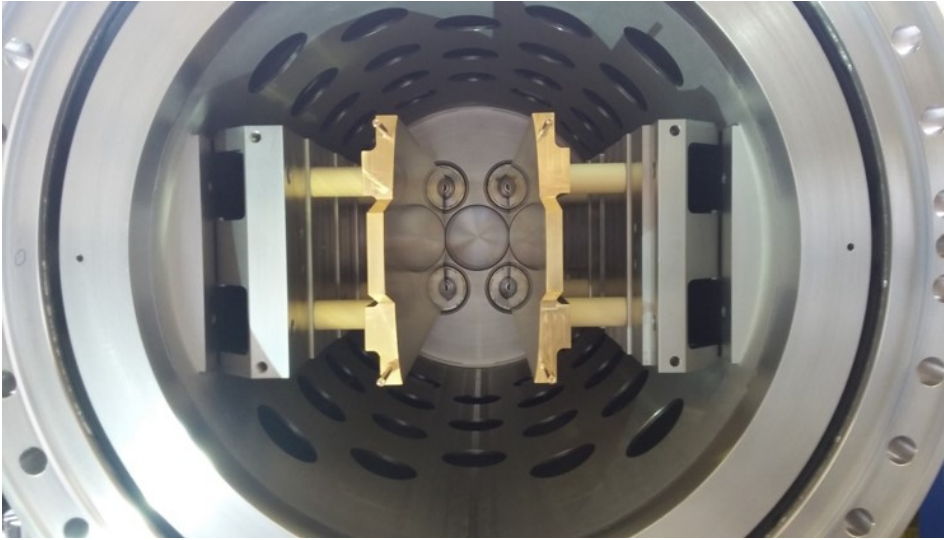
Joint Jülich – RWTH Aachen development:

- 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 [11].



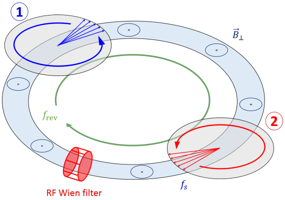


View along the beam axis in the RF Wien filter



Bunch-selective spin manipulation → co-magnetometry I

World-first (September 2020 JEDI, with *d* at 970 MeV/c) [15, 16]

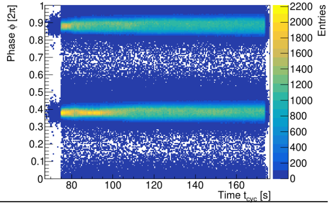


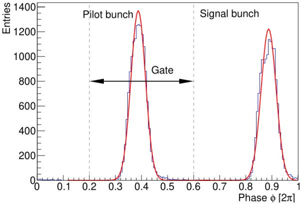
- signal (1) and pilot bunches (2):
  - spin-coherent ensembles in ring plane orbit at $f_{\rm rev} \approx 750\,$kHz
  - precessing at $f_s \approx 120\,$kHz
- waveguide RF WF [11] (*radial* field $\vec{B}_r$), kept on resonance[1] in (1) by spin tune measured in (2)

Selective gating of one of the two stored bunches at RF Wien filter:

(1) RF WF enhancement of $p_y(t)$ of signal bunch

(2) pilot bunch, unperturbed by RF WF, acts as co-magnetometer

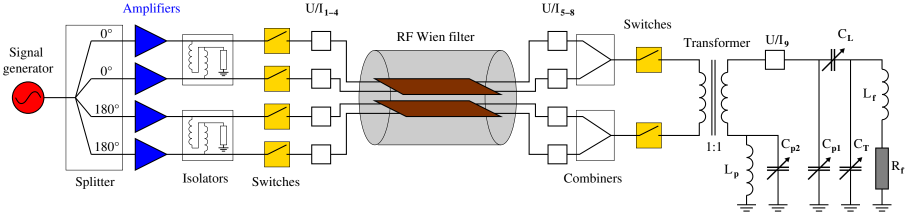




[1] $f_{\rm WF} = K \cdot f_{\rm rev} + f_s = (K + \nu_s) f_{\rm rev}$, where $K \in \mathbb{Z}$ and ν_s spin tune, $f_{\rm WF}^{(K=-1)} \approx 871.431\,$kHz

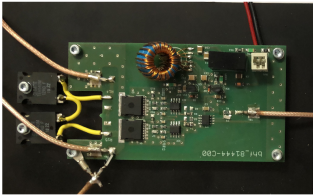
Implementation of fast switches[2] at RF Wien filter

Modification of driving circuit



GaN HEM FET-based solution:

- Short switch on/off times (≈ few ns).
- High power capabilities (≈ few kV).
- On board power damping (−30 dB).
- Symmetric switch on/off times (≈ few ns).



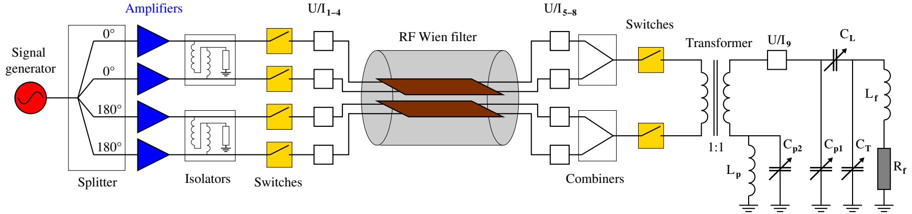
Switches

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

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

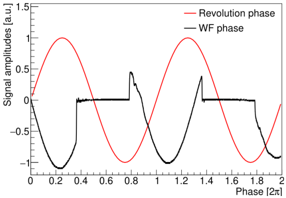
Implementation of fast switches[2] at RF Wien filter

Modification of driving circuit



GaN HEM FET-based solution:

- Short switch on/off times (≈ few ns).
- High power capabilities (≈ few kV).
- On board power damping (−30 dB).
- Symmetric switch on/off times (≈ few ns).



Switches

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

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

Bunch-selective spin manipulation → co-magnetometry II

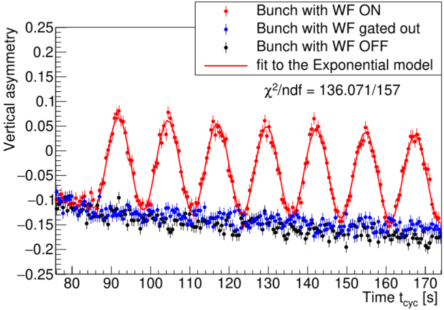
World-first (September 2020 JEDI, with d at 970 MeV/c)

See recent JEDI preprints for more details:

- *Pilot bunch and co-magnetometry of polarized particles stored in a ring* [15]
- *Spin decoherence and off-resonance behavior of radiofrequency-driven spin rotations in storage rings* [16]

Exponential model [15]:

$$A(t) = a(t - t_0) + b + c\exp(-\Gamma(t - t_0)) \cos[2\pi f_{SF}(t - t_0)]$$



Works close to perfection

- allows spin manipulations on *individual* stored bunches **on flattop**
- application of principle on the horizon for EIC and NICA

Bunch-selective spin manipulation → co-magnetometry II

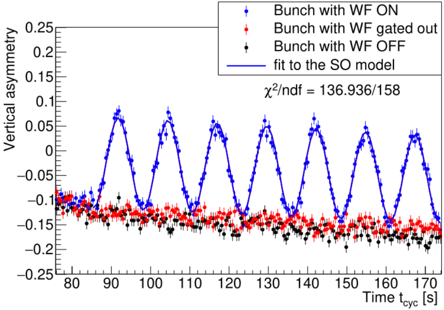
World-first (September 2020 JEDI, with d at 970 MeV/c)

See recent JEDI preprints for more details:

- *Pilot bunch and co-magnetometry of polarized particles stored in a ring* [15]
- *Spin decoherence and off-resonance behavior of radiofrequency-driven spin rotations in storage rings* [16]

Synchrotron-oscillations model [16]:

$$A_{sy}(t) = a(t - t_0) + b + \frac{c}{\sqrt{1 + [2\pi Q_{sy} f_{SF}(t - t_0)]^2}} \times \cos\left[2\pi f_{SF}(t - t_0) - \arctan(2\pi Q_{sy} f_{SF}(t - t_0))\right]$$



Works close to perfection

- allows spin manipulations on *individual* stored bunches **on flattop**
- application of principle on the horizon for EIC and NICA

Strength of EDM resonance

EDM induced polarization oscillation,

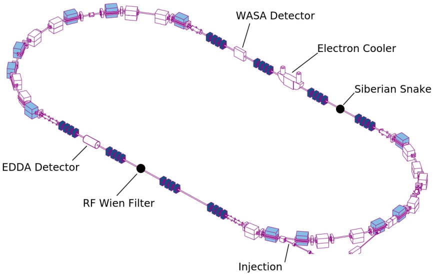
- can generally be described by

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

y perpendicular to ring plane.

- **EDM resonance strength** defined as ratio of angular frequency Ω^{p_y} to orbital angular frequency Ω^{rev} [10],

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



How is the EDM effect actually measured?

Two *simultaneously* applied spin rotations, one in each opposite straight section:

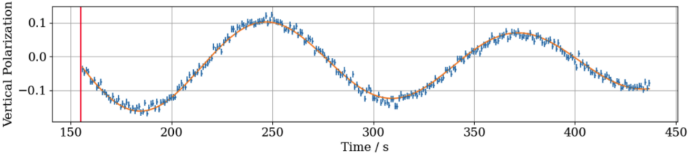
1. **RF Wien filter** magnetic axis ($\vec{e}_z^{\perp}$) rotated by small angle $\rightarrow$ generates radial magnetic RF field about which spins precess.
2. Longitudinal magnetic field of **Siberian snake** opposite to Wien filter $\rightarrow$ rotates spins about $\vec{e}_z$.

Measurement of EDM resonance strength using pilot bunch

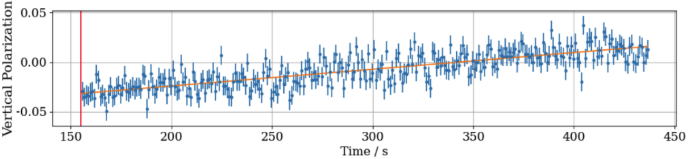
RF Wien filter mapping

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 $\Omega^{p_y} \rightarrow$ Wien filter map via $\varepsilon^{\text{EDM}} = \frac{\Omega^{p_y}}{\Omega^{\text{rev}}}$

Measurement of EDM resonance strength using pilot bunch

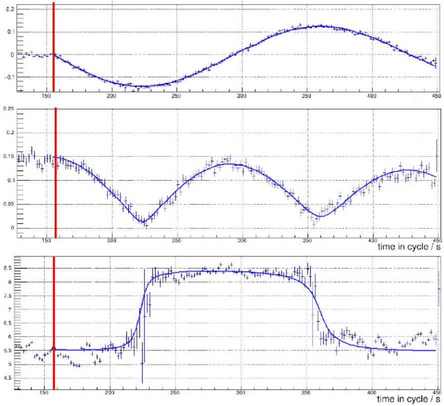
Polarization evolution of signal bunch during measurement cycle

Combined fit (p_y, p_{xz}, phasewalk) by Vera Shmakova (see her talk from Mo)

$p_y(t)$

$p_{xz}(t)$

in-plane phase walk of $p_{xz}(t)$



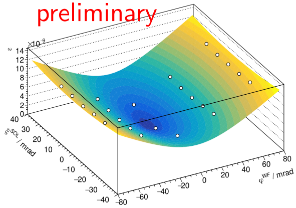
Extensive analysis of 3D polarization evolution in recent preprint, N.N. Nikolaev et al. [16]

- vertical and in-plane polarization evolution, phase walk, off-resonance behavior, finite-spin coherence and synchrotron-oscillation effects

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}, includes tilts of invariant spin axis due to EDM and magnetic ring imperfections.



Determination of minimum via fit with theoretical surface function yields:

- $\phi_0^{\text{WF}}/\text{mrad} = 2.51 \pm 0.04$
- $\xi_0^{\text{Sol}}/\text{mrad} = -3.93 \pm 0.06$

Analysis by Vera Shmakova and Achim Andres

Extraction of deuteron EDM:

1. Minimum determines spin rotation axis (3-vector) at RF WF, *including EDM*.
2. Spin tracking in COSY lattice → 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 [21] $d(t) = d_{\mathrm{DC}} + d_{\mathrm{AC}} \cos(\omega_a(t - t_0) + \phi_a(t_0))$ with frequency related to axion mass via $\hbar\omega_a = m_a c^2$, f_a is decay constant.
- This affects the spin rotations in the ring,

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

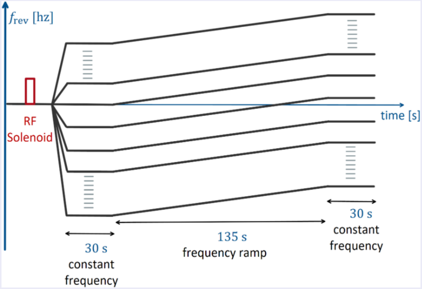
because two axion-related terms enter: (EDM: [21], wind: [22])

$$\begin{aligned} \vec{\Omega}_{\mathrm{EDM}} &= -\frac{1}{S\hbar} d(t) c \vec{\beta} \times \vec{B}\,, \quad \text{and} \\ \vec{\Omega}_{\mathrm{wind}} &= -\frac{1}{S\hbar}\frac{C_N}{2f_a}\left(\hbar\partial_0 a(t)\right)\vec{\beta} \quad \begin{cases} \text{coupling constant } C_N \\ \text{time derivative } \partial_0 \end{cases} \end{aligned} \tag{10}$$

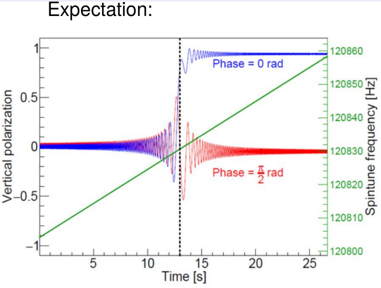
$\Rightarrow$ **Resonant build-up of vertical polarization, when** $\omega_a = \omega_s$

Details about axion/ALP experiment ([23, PRX] I

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



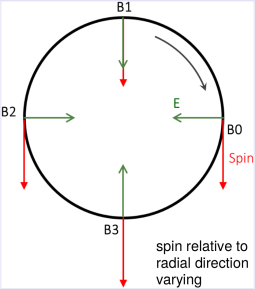
Organization of frequency ramps

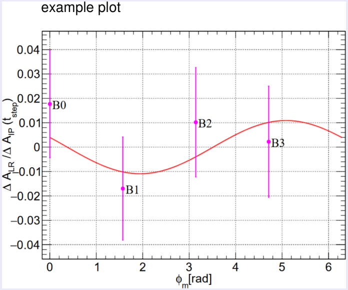


Jump of vertical polarization jump when resonance is crossed, for $\omega_a = \omega_s$.

Details about axion/ALP experiment ([23, PRX] II

Cover different oscillating EDM phases using multiple bunches

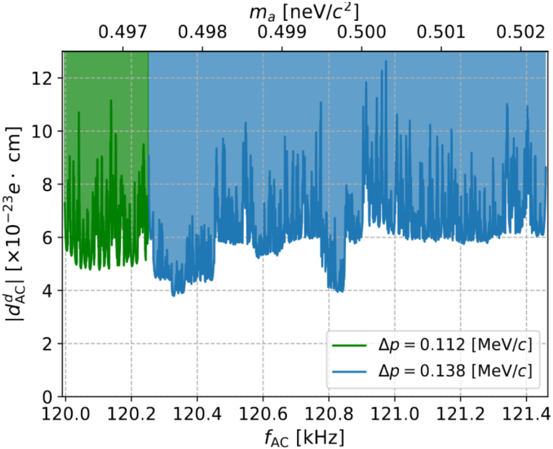




ϕ_a not known → use perpendicular beam polarization with 4 bunches

Left-Right asymmetry for one cycle and four bunches simultaneously orbiting.

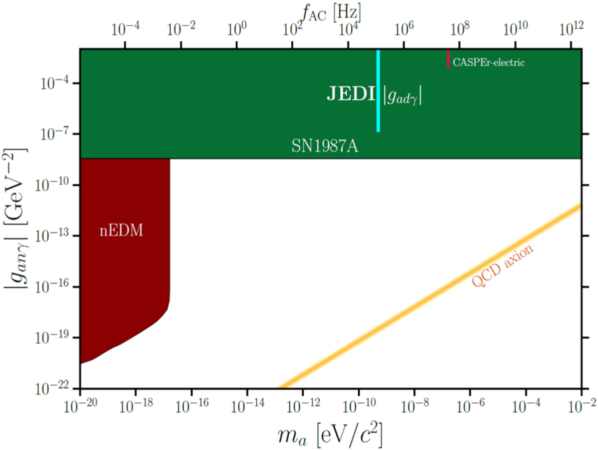
Bound on oscillating EDM of deuteron [23]



Observed oscillation amplitudes from 4 bunches

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

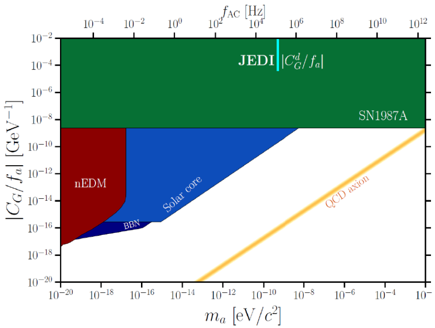
Bound on ALP-EDM coupling



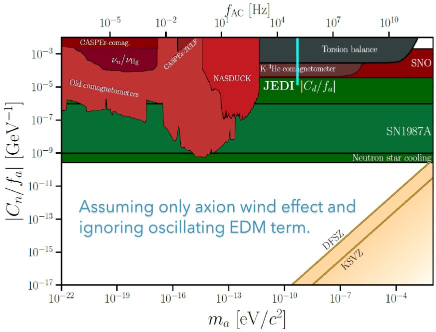
Coupling of ALP to deuteron EDM

- 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 [23].

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 [7, CYR '21]

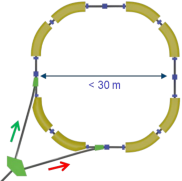
Stage 1

- **Precursor experiment**

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

Stage 2

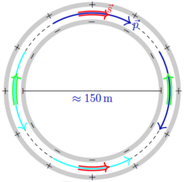
- **Prototype ring**



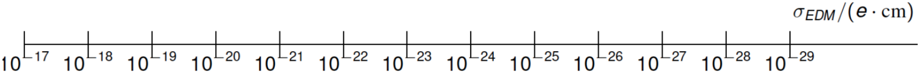
- Key technologies
- electric/magnetic bends
- simultaneous ↺ and ↻
- first pEDM measurement
- **5 years**

Stage 3

- **Dedicated storage ring**



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



Summary I

Status of JEDI experiments on EDMs and axions/ALPs

- **Results & achievements** CPEDM summarized in CERN Yellow Report [7].
- **Determination of coupling limit ALPs to deuteron EDM** at COSY [23]:

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

  - 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) Precursor II (2 maps IS + 5 maps with pilot bunch)
  - Data analysis in final stages, EDM results in preparation
  - Focus on systematic studies → understand observed tilts of stable spin axis.

Summary II

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**
  - Potential sensitivity to gravitational effects [7, 24].
- **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
- **New class of (primarily) electrostatic rings required**
  - Dedicated (final) ring with anticipated sensitivity of $\leq 10^{-29}$ e cm
- **Next step:** Prototype EDM ring development
  - Intermediate step between precursor (stage 1) and dedicated ring (stage 3)
  - Goal: **Study open issues & perform first direct pEDM measurement**
  - Pending **ERC Advanced Research Grant** application to EU, **Partners:** INFN, CERN, and Aachen, decision in March/April 2024

Thank you for your attention!

Spare slides

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:

$$\sigma_{\mathrm{stat}} = \frac{1}{\sqrt{N f}\,\tau_{\mathrm{SCT}}\,P\,A_y\,E} \quad \Rightarrow \quad \boxed{\sigma_{\mathrm{stat}}(1\,\mathrm{yr}) = 10^{-29}\,\mathrm{e\,cm}}\,. \tag{11}$$

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

High-precision beam polarimeter with internal C target

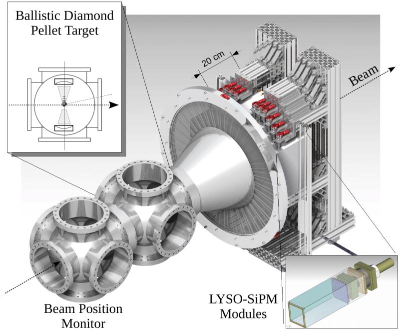
Development led by I. Keshelashivili [25]

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).

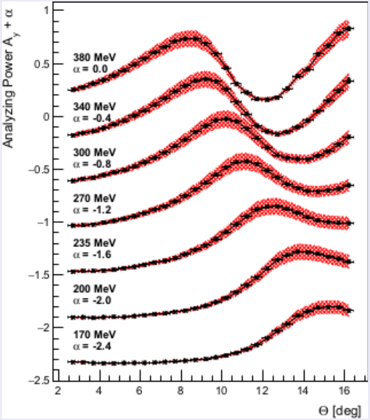
After several runs with external beam:

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



dC polarimetry data base

Results of JEDI elastic *dC* analyzing powers measurement [26]



- Analysis of differential *dC* cross sections in progress.
- Similar data base measurements carried out to provide *pC* data base.

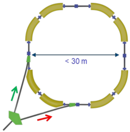
Stage 2: Prototype EDM storage ring (PTR)

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 (shielding)
- Stochastic cooling

Primary purpose of PTR

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

References I

[1] C. L. Bennett et al. (WMAP), "First year Wilkinson Microwave Anisotropy Probe (WMAP) observations: Preliminary maps and basic results," Astrophys. J. Suppl. **148**, 1 (2003), astro-ph/0302207.

[2] V. Barger, J. P. Kneller, H.-S. Lee, D. Marfatia, and G. Steigman, "Effective number of neutrinos and baryon asymmetry from BBN and WMAP," Phys. Lett. **B566**, 8 (2003), hep-ph/0305075.

[3] W. Bernreuther, "CP violation and baryogenesis," Lect. Notes Phys. **591**, 237 (2002), hep-ph/0205279.

[4] I. B. Khriplovich and S. K. Lamoreaux, *CP violation without strangeness: Electric dipole moments of particles, atoms, and molecules* (Berlin, Germany: Springer (1997) 230 p, 1997).

[5] F. Rathmann, A. Saleev, and N. N. Nikolaev, "The search for electric dipole moments of light ions in storage rings," J. Phys. Conf. Ser. **447**, 012011 (2013).

[6] J. Bsaisou, J. de Vries, C. Hanhart, S. Liebig, U.-G. Meißner, D. Minossi, A. Nogga, and A. Wirzba, "Nuclear electric dipole moments in chiral effective field theory," Journal of High Energy Physics **2015**, 1 (2015), ISSN 1029-8479, URL http://dx.doi.org/10.1007/JHEP03(2015)104.

[7] F. Abusaif et al. (CPEDM), *Storage Ring to Search for Electric Dipole Moments of Charged Particles – Feasibility Study* (CERN, Geneva, 2021), 1912.07881.

[8] S. P. Chang, S. Haciomeroglu, O. Kim, S. Lee, S. Park, and Y. K. Semertzidis, "Axion dark matter search using the storage ring EDM method," PoS **PSTP2017**, 036 (2018), 1710.05271.

[9] T. Fukuyama and A. J. Silenko, "Derivation of Generalized Thomas-Bargmann-Michel-Telegdi Equation for a Particle with Electric Dipole Moment," Int. J. Mod. Phys. **A28**, 1350147 (2013), URL https://www.worldscientific.com/doi/abs/10.1142/S0217751X13501479.

[10] F. Rathmann, N. N. Nikolaev, and J. Slim, "Spin dynamics investigations for the electric dipole moment experiment," Phys. Rev. Accel. Beams **23**, 024601 (2020), URL https://link.aps.org/doi/10.1103/PhysRevAccelBeams.23.024601.

References II

[11] J. Slim, R. Gebel, D. Heberling, F. Hinder, D. Hölscher, A. Lehrach, B. Lorentz, S. Mey, A. Nass, F. Rathmann, et al., "Electromagnetic simulation and design of a novel waveguide rf wien filter for electric dipole moment measurements of protons and deuterons," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **828**, 116 (2016), ISSN 0168-9002, URL `http://www.sciencedirect.com/science/article/pii/S0168900216303710`.

[12] G. Guidoboni, E. Stephenson, S. Andrianov, W. Augustyniak, Z. Bagdasarian, M. Bai, M. Baylac, W. Bernreuther, S. Bertelli, M. Berz, et al. (JEDI), "How to reach a thousand-second in-plane polarization lifetime with 0.97 gev/c deuterons in a storage ring," Phys. Rev. Lett. **117**, 054801 (2016), URL `http://link.aps.org/doi/10.1103/PhysRevLett.117.054801`.

[13] D. Eversmann, V. Hejny, F. Hinder, A. Kacharava, J. Pretz, F. Rathmann, M. Rosenthal, F. Trinkel, S. Andrianov, W. Augustyniak, et al. (JEDI), "New method for a continuous determination of the spin tune in storage rings and implications for precision experiments," Phys. Rev. Lett. **115**, 094801 (2015), URL `https://link.aps.org/doi/10.1103/PhysRevLett.115.094801`.

[14] N. Hempelmann, V. Hejny, J. Pretz, E. Stephenson, W. Augustyniak, Z. Bagdasarian, M. Bai, L. Barion, M. Berz, S. Chekmenev, et al. (JEDI), "Phase locking the spin precession in a storage ring," Phys. Rev. Lett. **119**, 014801 (2017), URL `https://link.aps.org/doi/10.1103/PhysRevLett.119.014801`.

[15] J. Slim et al., "Pilot bunch and co-magnetometry of polarized particles stored in a ring," (2023), `2309.06561`.

[16] N. N. Nikolaev et al., "Spin decoherence and off-resonance behavior of radiofrequency-driven spin rotations in storage rings," (2023), `2309.05080`.

[17] D. Albers et al., "A Precision measurement of pp elastic scattering cross-sections at intermediate energies," Eur. Phys. J. **A22**, 125 (2004).

References III

[18] I. Vasserman, P. Vorobyov, E. Gluskin, P. Ivanov, I. Koop, G. Kezerashvili, A. Lysenko, I. Nesterenko, E. Perevedentsev, A. Mikhailichenko, et al., "Comparison of the electron and positron anomalous magnetic moments: Experiment 1987," Physics Letters B **198**, 302 (1987), ISSN 0370-2693, URL http://www.sciencedirect.com/science/article/pii/0370269387915152.

[19] A. Saleev, N. N. Nikolaev, F. Rathmann, W. Augustyniak, Z. Bagdasarian, M. Bai, L. Barion, M. Berz, S. Chekmenev, G. Ciullo, et al. (JEDI), "Spin tune mapping as a novel tool to probe the spin dynamics in storage rings," Phys. Rev. Accel. Beams **20**, 072801 (2017), URL https://link.aps.org/doi/10.1103/PhysRevAccelBeams.20.072801.

[20] Y. F. Orlov, W. M. Morse, and Y. K. Semertzidis, "Resonance method of electric-dipole-moment measurements in storage rings," Phys. Rev. Lett. **96**, 214802 (2006), URL http://link.aps.org/doi/10.1103/PhysRevLett.96.214802.

[21] P. W. Graham and S. Rajendran, "Axion dark matter detection with cold molecules," Phys. Rev. D **84**, 055013 (2011), URL https://link.aps.org/doi/10.1103/PhysRevD.84.055013.

[22] P. W. Graham and S. Rajendran, "New observables for direct detection of axion dark matter," Phys. Rev. D **88**, 035023 (2013), URL https://link.aps.org/doi/10.1103/PhysRevD.88.035023.

[23] S. Karanth, E. J. Stephenson, S. P. Chang, V. Hejny, S. Park, J. Pretz, Y. K. Semertzidis, A. Wirzba, A. Wrońska, F. Abusaif, et al. (JEDI Collaboration), "First search for axionlike particles in a storage ring using a polarized deuteron beam," Phys. Rev. X **13**, 031004 (2023), URL https://link.aps.org/doi/10.1103/PhysRevX.13.031004.

[24] see, e.g., the presentations at the ARIES WP6 Workshop: Storage Rings and Gravitational Waves "SRGW2021", 2 February - 11 March 2021, available from https://indico.cern.ch/event/982987.

[25] F. Müller, O. Javakhishvili, D. Shergelashvili, I. Keshelashvili, D. Mchedlishvili, F. Abusaif, A. Aggarwal, L. Barion, S. Basile, J. Böker, et al., "A new beam polarimeter at COSY to search for electric dipole moments of charged particles," Journal of Instrumentation **15**, P12005 (2020), URL https://doi.org/10.1088/1748-0221/15/12/p12005.

References IV

[26] F. Müller et al. (JEDI), "Measurement of deuteron carbon vector analyzing powers in the kinetic energy range 170-380 MeV," Eur. Phys. J. A **56**, 211 (2020), 2003.07566.