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

Status of the studies and collaboration

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Contents

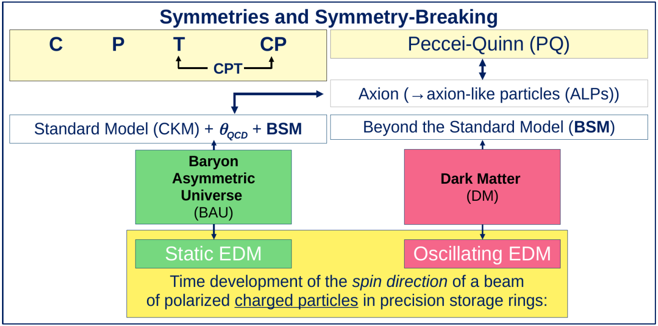
Motivation

Issues we are addressing

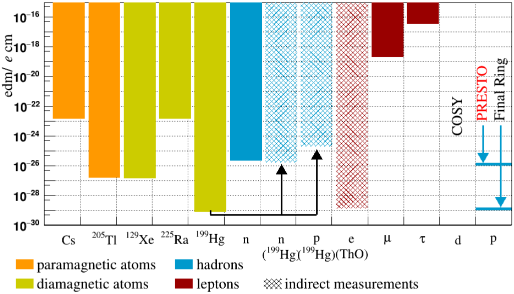
- Matter over antimatter dominance / Baryon asymmetry in the Universe
- Nature of Dark Matter (DM)

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]



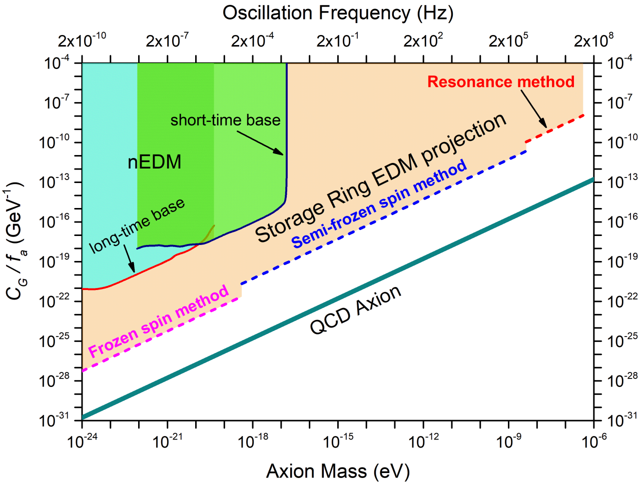
Missing are *direct* EDM measurements:

- 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



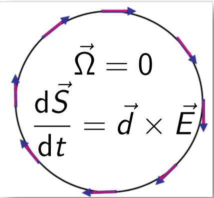
Experimental limits for axion-gluon coupled oscillating EDM measurements (from [3]).

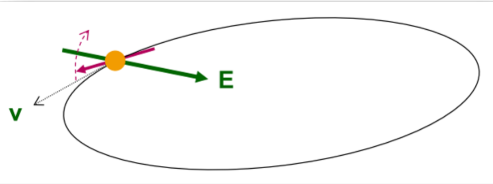
Measurement of EDM in storage ring

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 $p_y(t) \propto d$.

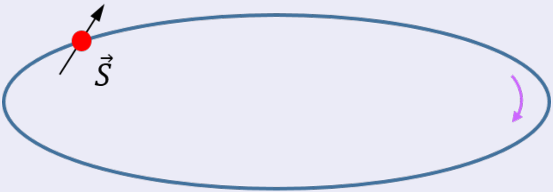
Spin precession of particles with MDM and EDM

In rest frame of particle

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

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

With protons in a ring



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

Frozen-spin

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

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

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

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

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

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

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

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

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] → 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 → unperturbed spin precession → RF Wien filter on resonance.
    - observe p_y oscillations over many periods
    - pilot bunch → co-magnetometer [publ. in prep.]

Accumulated knowledge compiled in

2021 CERN Yellow Report [2]

Strength of EDM resonance

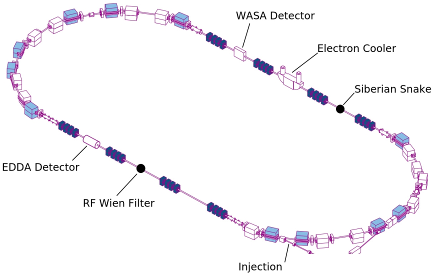
EDM induced polarization oscillation,

- 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:

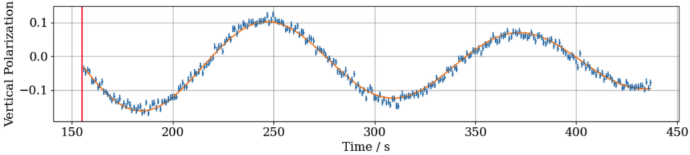
1. RF Wien filter rotated by a small angle → generates small radial magnetic RF field → affects the spin evolution.
2. In addition, there is longitudinal magnetic field in ring opposite to Wien filter, about which spins rotate as well.

Measurement of EDM resonance strength using pilot bunch

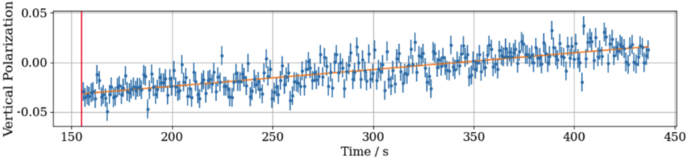
RF Wien filter mapping

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

- Signal bunch



- Pilot bunch

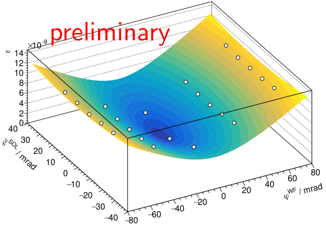


- Decoherence clearly visible in signal bunch.
- No oscillations in pilot bunch.
- Determine oscillation frequencies $\Omega^{p_y} \rightarrow$ Wien filter map via $\varepsilon^{\text{EDM}} = \frac{\Omega^{p_y}}{\Omega^{\text{rev}}}$

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:

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

Extraction of deuteron EDM:

1. Minimum determines spin rotation axis (3-vector) at RF WF, *including EDM*.
2. Spin tracking in COSY lattice → 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])

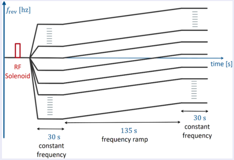
$$\vec{\Omega}_{\mathrm{EDM}} = -\frac{1}{S\hbar} d(t) c \vec{\beta} \times \vec{B}\,, \quad \text{and}$$
$$\vec{\Omega}_{\mathrm{wind}} = -\frac{1}{S\hbar}\frac{C_N}{2f_a}\left(\hbar\partial_0 a(t)\right)\vec{\beta} \quad \begin{cases} \text{coupling constant } C_N \\ \text{time derivative } \partial_0 \end{cases} \tag{5}$$

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

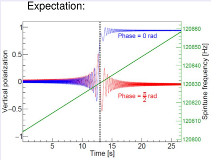
Details about axion/ALP experiment

(see [12] for details)

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

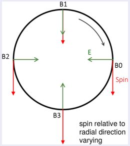


Organization of frequency ramps

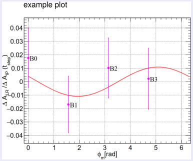


Jump of vertical polarization jump when resonance is crossed, for $\omega_a = \omega_s$.

Cover different oscillating EDM phases using multiple bunches

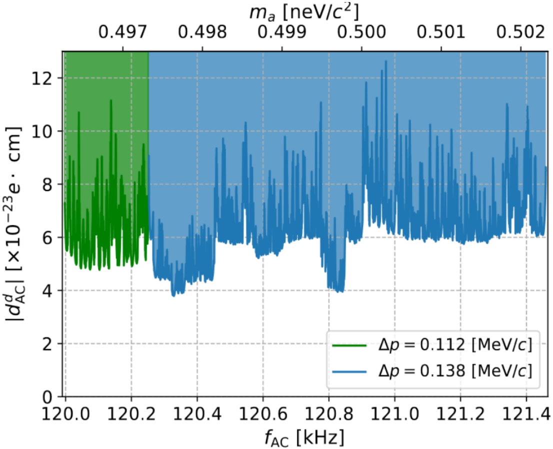


ϕ_a not known $\rightarrow$ use perpendicular beam polarization with 4 bunches



LR asymmetry for one cycle and four bunches simultaneously orbiting.

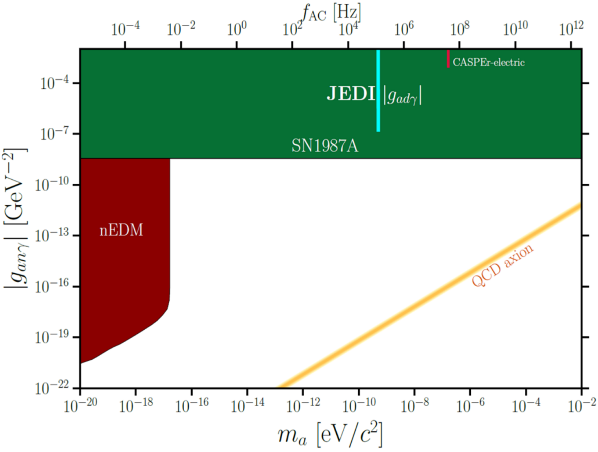
Bound on oscillating EDM of deuteron [12]



Observed oscillation amplitudes from 4 bunches

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

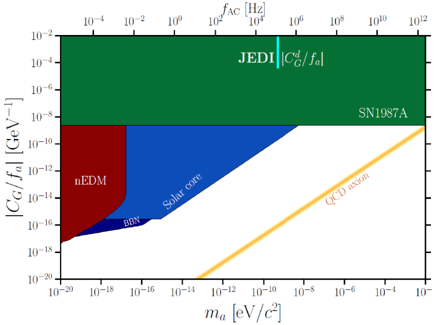
Bound on ALP-EDM coupling



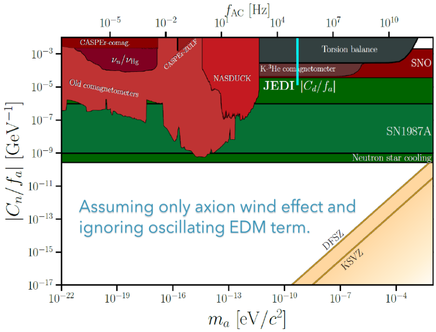
Coupling of ALP to deuteron EDM

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

ALP-gluon and ALP-nucleon coupling[1]



ALP-gluon coupling, assuming 100% oscillating EDM.



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

[1] 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]

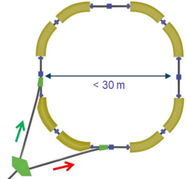
Stage 1

- **Precursor experiment**

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

Stage 2

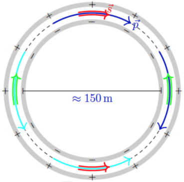
- **Prototype ring**



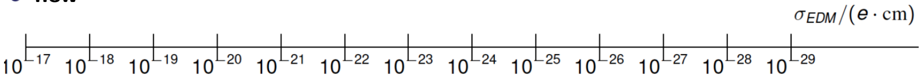
- Key technologies
- electric/magnetic bends
- simultaneous ↺ and ↻
- first pEDM measurement
- **5 years**

Stage 3

- **Dedicated storage ring**



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



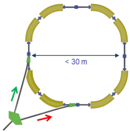
Next step: Stage 2: Prototype EDM storage ring (PTR)

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**.

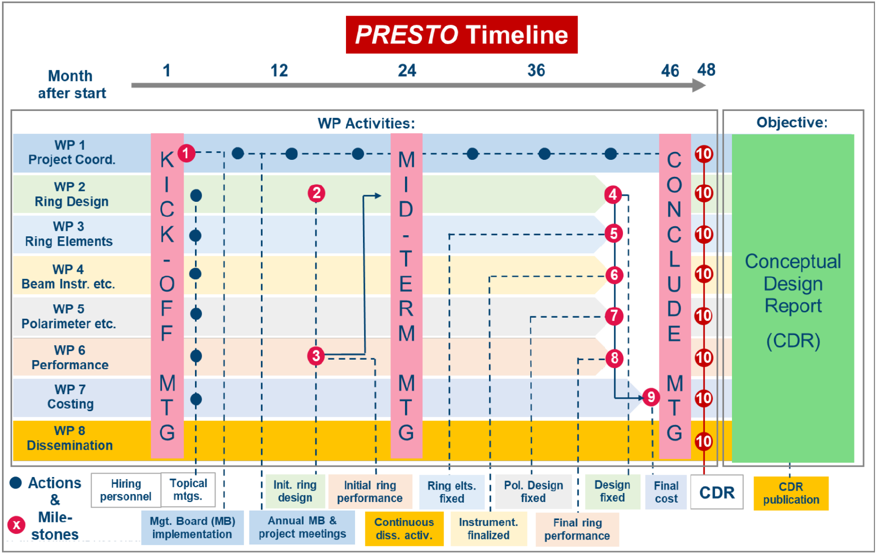
Status PRESTO Design Study application for PTR

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).

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 $\leq 10^{-29}\,$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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[13] 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.