Search for electric dipole moments of charged particles in storage rings

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Motivation
Physics case

Problems

- Preponderance of matter over antimatter
- Nature of Dark Matter (DM)

Approach

- Measurements of static Electric Dipole Moments (EDM) of fundamental particles.
- Searches for axion-like particles as DM candidates through oscillating EDM
Electric Dipole Moment (EDM)

- Permanent separation of + and - charge
- Fundamental property of particles (like magnetic moment, mass, charge)

### Orders of magnitude

| $|r_1 - r_2|$ | Atomic Physics | Hadron Physics |
|----------------|----------------|----------------|
| Å = 10^{-8} cm | 10^{-8} e · cm | 10^{-13} e · cm |
| < 2 · 10^{-8} e · cm | < 10^{-26} e · cm |

→ possible via violation of time-reversal (T) and parity (P)
T and P violation of EDM

EDM meas. test violation of P and T symmetries (\(\text{CPT} = \text{CP}\))
Matter dominance:

- Excess of Matter in the Universe:
  \[ \eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \]
  
<table>
<thead>
<tr>
<th>observed</th>
<th>SM prediction</th>
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<tbody>
<tr>
<td>$6 \times 10^{-10}$</td>
<td>$10^{-18}$</td>
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- Sacharov (1967): CP-violation needed for baryogenesis

  \[ \Rightarrow \text{New CP-V sources beyond SM needed} \]
  \[ \Rightarrow \text{Could show up in EDMs of elementary particles} \]
Why charged particles EDMs?

- **Static EDM**: complementary informations from different systems required
  - Direct measurement and statistical improvement with respect to neutron

- **Oscillating EDM**: axion as a solution to the $\theta_{QCD}$ problem
  - Limit on $\theta_{QCD}$ comes from $n_{EDM}$

J. de Vries
Experimental method
Spin Precession in a storage ring

**Thomas-BMT equation**

\[
\frac{d \vec{s}}{dt} = \vec{\Omega} \times \vec{s} = \left[ (\vec{\Omega}_{MDM} + \vec{\Omega}_{EDM}) - \vec{\Omega}_{cycl} \right] \times \vec{s} = \\
= \frac{-q}{m} \left[ G \vec{B} + \left( G - \frac{1}{\gamma^2 - 1} \right) \vec{v} \times \vec{E} + \frac{\eta}{2} \left( \vec{E} + \vec{v} \times \vec{B} \right) \right] \times \vec{s}
\]

- Mag. dip. mom. (MDM): \( \mu = 2(G + 1) \frac{aq}{2m} \vec{s} \) (G=1.79 for proton)
- El. dip. mom. (EDM): \( d = \eta \frac{aq}{2mc} \vec{s} \) (\( \eta = 2 \cdot 10^{-15} \) for \( d = 10^{-29} \text{e} \cdot \text{cm} \))

**Frozen spin**

\[
\frac{d \vec{s}}{dt} = \vec{\Omega} \times \vec{s} = \frac{-q}{m} \left[ G \vec{B} + \left( G - \frac{1}{\gamma^2 - 1} \right) \vec{v} \times \vec{E} + \frac{\eta}{2} \left( \vec{E} + \vec{v} \times \vec{B} \right) \right] \times \vec{s}
\]

- Achievable with pure electric field for proton (\( G > 0 \)): \( G = \frac{1}{\gamma^2 - 1} \)
- Requires special combination of E, B fields and \( \gamma \) for \( d, ^3\text{He} \) (\( G < 0 \))
Search for static EDM in storage rings

Measurement concept

1. Inject particles in storage ring
2. Align spin along momentum (\(\rightarrow\) freeze horiz. spin-precession)
3. Search for time development of vertical polarization

\[ \vec{\omega}_a = 0 \]

\[ \frac{d\vec{s}}{dt} = \vec{d} \times \vec{E} \]

\( ds/\!\!d t = \vec{d} \times \vec{E} \)

**Frozen-spin condition:**

- Pure E ring for \( p \)
- Combined E/B ring for \( d \) and \(^3\text{He}\)
Search for oscillating EDM in storage rings

Axions as light dark matter candidates

- Axion interaction with ordinary matter: $\frac{a}{f_0} F_{\mu\nu} \tilde{F}_{\mu\nu}, \frac{a}{f_0} G_{\mu\nu} \tilde{G}_{\mu\nu}, \frac{\partial_{\mu} a}{f_a} \bar{\Psi} \gamma^\mu \gamma_5 \Psi$

- $\frac{a}{f_0} G_{\mu\nu} \tilde{G}_{\mu\nu} \rightarrow$ coupling to gluons with same structure as QCD-$\theta$ term

- Generation of an oscillating EDM

Combined E/B ring

- Mag. dipole moment (MDM) $\rightarrow$ spin prec. in B field $\rightarrow$ nullifies static EDM effect

- Oscillating EDM resonant condition $\rightarrow$ buildup of out-of-plane spin rotation

- Search of resonance (axion/ALP mass) via change of beam momentum

$d\uparrow + \mu \rightarrow \bar{d} = \eta \frac{q\hbar}{2mc} \vec{s}$

$\eta = \eta_0 + \eta_1 \sin(\omega_{\text{axion}} t + \varphi_a)$

$\omega_{\text{axion}} = \frac{m_a c^2}{\hbar}$
Requirements

High precision, primarily electric storage ring

- **Crucial role** of alignment, stability, field homogeneity and shielding from *unwanted* magnetic fields.
- High beam intensity: \( N = 4 \cdot 10^{10} \) per fill
- Polarized hadron beams: \( P = 0.8 \)
- Long spin coherence time: \( \tau = 1000 \text{ s} \)
- Large electric fields: \( E \sim 10 \text{ MV/m} \)
- Efficient polarimetry with:
  - large analyzing power: \( A = 0.6 \)
  - high efficiency detection: \( \text{eff.} = 0.005 \)

Expected statistical sensitivity in 1 year of data taking:

\[
\sigma_{\text{stat}} = \frac{\hbar}{\sqrt{N_f \tau \text{PAE}}} \Rightarrow \sigma_{\text{stat}} = 2.6 \times 10^{-29} \text{ e } \cdot \text{cm}
\]

- Experimentalist’s goal: provide \( \sigma_{\text{syst}} \) to the same level.
Objective: EDMs of charged hadrons: \( p, d, ^3\text{He} \)

- Note: current limit on \( p \)-EDM: \( 2.0 \times 10^{-25} \text{ e} \cdot \text{cm} \) (ind. from \( d_p^{199\text{Hg}} \))

Final goal: to bring the limit on \( p \) to \( 10^{-29} \text{ e} \cdot \text{cm} \)
OSCILLATING EDM: axion mass vs gluon coupling

Experimental limits accessible in one year per single frequency measurement.
Achievements at COSY
The COSY storage ring at FZ-Jülich (Germany)
COoler SYnchrotron COSY
- Cooler and storage ring for (pol.) protons and deuterons.
- Momenta $p = 0.3-3.7$ GeV/c
- Phase-space cooled internal and extracted beams

Previously used as spin-physics machine for hadron physics:
- Ideal starting point for Storage Ring EDM related R&D
- Dedicated and unique experimental effort worldwide
Experiment preparation

1. Inject and accelerate vertically polarized deuterium to $p \approx 1 \text{ GeV/c}$
2. Flip spin with RF-solenoid into horizontal plane
3. Extract beam slowly (100 s) on Carbon target
4. Measure asymmetry and determine spin precession
Optimization of spin-coherence time

\[ \tau_{SCT} = (782 \pm 117) \text{s} \]

Previously:
\[ \tau_{SCT}^{(VEPP)} \approx 0.5 \text{ s} \]
\( \approx 10^7 \text{ spin revolutions} \)

SCT of crucial importance, since
\[ \sigma_{STAT} \propto \frac{1}{\tau_{SCT}} \]

I major achievement

Precise determination of the spin-tune

Spin-tune $\nu_s$

$\nu_s = \gamma G = \frac{\text{nb. spin-rotations}}{\text{nb. particle-revolutions}}$


- Interpolated spin tune in 100 s:
  - $|\nu_s| = (16097540628.3 \pm 9.7) \times 10^{-11}$ ($\Delta \nu_s/\nu_s \approx 10^{-10}$)
  - Angle precision: $2\pi \times 10^{-10} = 0.6$ nrad
  - Previous best: $3 \times 10^{-8}$ per year (g-2 experiment)
  - $\rightarrow$ new tool to study systematic effects in storage rings
Phase locking spin precession in machine to device RF

Spin-feedback system maintains:

- resonance frequency
- phase between spin-precession and device RF


Error of phase-lock $\sigma_\phi = 0.21$ rad

At COSY freezing of spin precession not possible
\[\rightarrow\text{phase-locking} \text{ required to achieve precision for EDM}\]
COSY precursor experiment
EDM measurement in a magnetic storage ring

Exploitation of motional electric field in particle rest frame: \( E^* = v \times B \)

**Problem**
- Momentum \( \uparrow \uparrow \) spin
  - spin \( \Rightarrow \) spin kicked up
- Momentum \( \uparrow \downarrow \) spin
  - \( \Rightarrow \) spin kicked down
- \( \Rightarrow \) no accumulation of vert. asymmetry

**Solution: RF-Wien filter**
- Lorentz force:
  \[ \vec{F}_L = q(\vec{E} + \vec{v} \times \vec{B}) = 0 \]
- \( \vec{B} = (0, B_y, 0) \) and \( \vec{E} = (E_x, 0, 0) \)
Effect of EDM on stable spin-axis

EDM absence

EDM effect

Magnetic misalignm.

EDM tilts the stable spin-axis

- Presence of EDM \( \Rightarrow \varepsilon_{EDM} > 0 \)
  - \( \Rightarrow \) spin precess around the \( \vec{c} \) axis
  - \( \Rightarrow \) oscill. vert. polarization \( p_y(t) \)
Preliminary results from run in Dec. 18 + Feb./Apr. 21

Spin-tracking simulations necessary

- Orientation of stable spin axis at location of RF Wien filter including EDM determined by minimum of map
- Spin tracking simulation shall provide orientation of stable spin axis without EDM
- Results foreseen by end of 2021

Compatible with $d_{\text{EDM}} < 10^{-17}$ e·cm
Strategy: staged approach
Strategy: staged approach to a storage ring for precision physics

On the basis of the preparedness of the required technological developments

**Stage 1**
precursor experiment
at COSY (FZ Jülich)

**Stage 2**
prototype ring

- magnetic storage ring
- electrostatic storage ring
- simultaneous $\bigcirc$ and $\bigcirc$ beams

5 years

**Stage 3**
dedicated storage ring

- magic momentum
  (701 MeV/c)

10 years

Planned Design Study application: Prototype Storage Ring for the Precision Frontier
Stage 2: prototype EDM storage ring

- Build demonstrator for charged particle EDM
  - Key-performance enabler for the final ring
- Project prepared by CPEDM working group (CERN+JEDI)
  - P.B.C. process (CERN) & European Strategy for Particle Physics Update
- Possible host sites: COSY or CERN
- S.R. to Search for EDMs of Charg. Part. - Feas. Study (arXiv:1912.07881)

100 m circumference

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

Challenges

- All electric & E-B combined deflection
- Storage and spin-coher. time in elec. machine
- CW-CCW operation
- Orbit control
- Polarimetry
- Magnetic moment effects
- Stochastic cooling
Stage 3: precision EDM ring

500 m circumference (with $E = 8$ MV/m)
- All-electric deflection
- Magic momentum for protons ($p = 701$ MeV/c)

Challenges
- All-electric deflection
- Simultaneous CW/CCW beams
- Phase-space cooled beams
- Long spin coherence time ($> 1000$ s)
- Non-destructive precision polarimetry
- Optimum orbit control
- Optimum shielding of external fields
- Control of residual (intentional) $B_r$ field

"Holy Grail" of storage rings (largest electrostatic ever conceived)
Research Infrastructure Concept Development:
"Prototype Storage Ring for the Precision Frontier"
Framework

INFRADEV-01-01-2022 - Concept Development

- Application deadline: 10.01.22 - 20.04.22
- Duration: 4 years
  - Possible project development: 2023-2026
- Budget: total 3 M euro
- Coordinator + 6 beneficiaries
  - INFN (Coord.), CERN, RWTH-Aachen, GSI, MPI-HD, Univ. Liverpool, Univ. Cracow
- Other potential participants
  - Research Institute for Nuclear Problems (Belarus), Joint Institute for Nuclear Research (Russia), Landau Institute for Theoretical Physics (Russia), Budker Institute of Nuclear Physics (Russia), Indiana University (USA), Cornell University (USA), Tbilisi State University (Georgia), Paul Scherrer Institute (CH), University of Ferrara (IT)
1 - Excellence

Science case

- Search for static charged particle EDMs
  - EDMs $\rightarrow$ probes of CP-violating interactions
  - Matter-antimatter asymmetry

- Search for oscillating EDMs
  - Axion-gluon coupling
  - Dark matter search

- Potential sensitivity to gravitational effects

Objectives

- New class of (precision) storage rings (p: all-E; d, $^3$He: comb. E/B);
- design demonstrator as:
  key performance enabler for the final precision storage ring;
- capable of providing a wealth of science already.
# 2 - Impact

## Fundamental Science
- Physics beyond the SM-BAU, DM

## Accelerator Science
- New class of precision storage rings
- All-electric ring (high field, field homogeneity and stability)
- E/B combined bending
- Storage time
- CW-CCW injection and operation
- Spin-coherence time in electric machine
- Optimum orbit control
- Systematic effects from magnetic moments
- Multi-bunch approach to co-magnetometry
- Stochastic cooling

## Metrology
- Polarimetry (efficient, sampling, non-destructive)
## 3 - Implementation

<table>
<thead>
<tr>
<th>WP #</th>
<th>Item</th>
<th>MM</th>
<th>Institutions</th>
<th>Objectives</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Project coordination</td>
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<td><strong>Beam diagnostics and instrumentation</strong></td>
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<td>1. Beam position monitors, incl phase-space detection (Rogowski type)</td>
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<td>INFN (Variola)</td>
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<tr>
<td>8</td>
<td><strong>Dissemination and outreach</strong></td>
<td>14</td>
<td>Krakow (Wronska)</td>
<td>publications, meetings, talks</td>
</tr>
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</table>
Conclusions

EDM searches in Storage Rings
- Outstanding scientific case with high discovery potential
- Key developments in accelerator technology

Fundamental achievements at COSY
- Spin-control tools
- First measurement of (static and oscillating) deuteron EDM

Staged approach to face challenges in accelerator technology
- Precursor measurements at COSY
- Feasibility study of a *pure electrostatic* EDM proton ring

Funding
- Planned: Research Infrastructure Concept Development
  - Interdisciplinary impact
    - Fundamental and particle physics
    - Astroparticle and hadron physics
    - Accelerator and data science

Unique chance that Europe should not miss!
Spares
Momentum and ring radius for proton in frozen spin condition

Two options:

- Pure electric ring:
  \( p = 707 \text{MeV}, \text{bending radius} \approx 50 \text{ m at } E=8 \text{ MV/m} \)

- Combined prototype ring:
  \( p = 300 \text{MeV}, \text{bending radius} \approx 9 \text{ m at } E=7 \text{ MV/m} \)
Electrostatic deflectors & magnetic bends

- Concept for electrostatic deflector available
- Next step: build prototype with RWTH Aachen
- Studies of straight E/B deflector to improve voltage holding capability at Jülich

Concept for magnetic add-on to deflector available.
- Magnetic system ($\cos \theta$) outside the vacuum tube.
- System included in prototype development with RWTH-Aachen
Electrostatic multipole elements

- Design of electrostatic elements by J. Burbough (CERN)
- Electrostatic quadrupoles
  - aperture diameter 80mm, applied $\pm 20$ kV.
  - Simulated design with vacuum chamber of 400mm diameter.

- PTR quadrupoles max. pole tip potential 30 kV (margin for conditioning)
  - 3D design available;
  - sextupole, octupole and higher harmonics reasonable
# Beam position monitors for srEDM experiments

## Development of compact BPM based on Rogowski coil

- **Main adv.:** short install. length ($\approx 1$ cm in beam direction)

## Conventional BPM

- Easy to manufacture
- Length = 20 cm
- Resolution $\approx 10 \ \mu$m

## Rogowski BPM (warm)

- Excellent RF-signal response
- Length = 1 cm
- Resolution $\approx 1.25 \ \mu$m

- 2 coils installed at entrance and exit of RF Wien filter
Simulations

- Beam and spin-tracking simulations to scrutinise and validate concepts and ideas
- Code bench-marking on existing COSY data
- Working group established