Prototype Ring Facility for charged-particle EDM search

Toward a Technical Design Report

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(on behalf of the CPEDM collaboration)

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1. Search for electric dipole moments using storage rings

2. Technical Design Report for Prototype EDM storage ring (PTR)
   - PTR lattice design, beam transfer and injection system
   - Electrostatic deflectors, magnetic bends, and multipole elements
   - Storage ring, stochastic cooling, RF cavity
   - Spin manipulation tools, beam polarimeter, beam diagnostics

3. Conclusions
Search for electric dipole moments using storage rings

One of the most intriguing puzzles of contemporary physics

Open issues

- Predominance of matter over antimatter in the Universe
- Nature of Dark Matter

Approach

- Measurements of static EDMs of fundamental particles ($p$, $d$, ...).
- Searches for axions and axion-like particles (ALPs) as Dark Matter candidates through oscillating EDMs.
Grants and evaluations

- ERC Advanced Grant srEDM (Hans Ströher, Proposal No. 694340)
- Helmholtz Evaluation Report, Topic 2, Cosmic Matter in Lab., 01/2020:
  - **Goals** in Program Oriented Funding IV period
    - Initiation of the proton Electric Dipole Moment (EDM) project at COSY-ring to open an opportunity to explore physics beyond the standard model.
  - **Work program:**
    - Use COSY, the world’s only storage ring for polarized proton and deuterium beams at the IKP facility at FZJ. This will explore the scientific potential for proton/deuteron EDM experiments in the COSY-ring.
    - Perform within PoF IV an Axion search via oscillating EDMs at COSY, which may open the way to new concepts that may extend the reach in precision down to $1 \times 10^{-29}$ e cm.

- Deliberation Document 2020 Update European Strategy for Particle Physics:
  - [...] the COSY facility could be used as a demonstrator for measuring the electric dipole moment of the proton at Jülich. These initiatives should be strongly encouraged and supported. [...]

Prototype Ring for EDM searches
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Strategy toward dedicated EDM ring


Project stages and time frame toward a dedicated EDM ring:

Stage 1
- precursor experiment
- magnetic storage ring
- Now

Stage 2
- prototype ring
- electric/magnetic bends
- simultaneous $\bigcirc$ and $\bigcirc$ beams
- 5 years

Stage 3
- dedicated storage ring
- at magic $p$ momentum
- 10 years

Prototype Ring for EDM searches

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Stage 2: Prototype EDM storage ring (PTR)

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 deflection
- Storage time
- CW-CCW
  - operation
  - orbit difference to pm
- Spin-coherence time
- Polarimetry
- Magnetic moment effects
- Stochastic cooling

Primary purpose of PTR

- study open issues.
- first direct proton EDM measurement.
Technical Design Report (ready end of 2022)

- Present status summarized in CERN Yellow Report (CYR)
  - Storage Ring to Search for Electric Dipole Moments of Charged Particles – Feasibility Study [1]
- Next step: CPEDM prepares Technical Design Report
  - PTR Lattice design
  - Beam transfer and injection system
  - Electrostatic deflectors
  - Magnetic bends
  - Multipole elements
  - Ring vacuum system
  - Stochastic cooling
  - RF Cavity
  - Spin manipulation tools
  - Polarimeter
  - Beam diagnostics
- Along with: Systematic studies, Spin tracking, error evaluation

**red:** needs strong support (CERN, MPIK-HD, Liverpool U., ...)

**green:** already addressed
PTR lattice design (protons)

Basic beam parameters and layout [1, Chap. 7]

<table>
<thead>
<tr>
<th></th>
<th>$E$ only</th>
<th>$E$ &amp; $B$ frozen spin</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending radius</td>
<td>8.86</td>
<td>8.86</td>
<td>m</td>
</tr>
<tr>
<td>Kinetic energy</td>
<td>30</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>$\beta = v/c$</td>
<td>0.247</td>
<td>0.247</td>
<td>0.299</td>
</tr>
<tr>
<td>$\gamma$ (kinetic)</td>
<td>1.032</td>
<td>1.032</td>
<td>1.048</td>
</tr>
<tr>
<td>Momentum</td>
<td>239</td>
<td>239</td>
<td>294</td>
</tr>
<tr>
<td>Electric field $E$</td>
<td>6.67</td>
<td>4.56</td>
<td>7.00</td>
</tr>
<tr>
<td>Magnetic field $B$</td>
<td></td>
<td>0.0285</td>
<td>0.0327</td>
</tr>
<tr>
<td>rms $\epsilon_x = \epsilon_y$</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Transv. acc. $a_x = a_y$</td>
<td>&gt; 10</td>
<td>&gt; 10</td>
<td></td>
</tr>
</tbody>
</table>

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

Needs strong support
S. Martin, R. Talman, C. Carli, M. Haj Tahar: [1, Chapter 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

Needs strong support
Electrostatic deflector
with additional magnetic bend

- Concept for electrostatic deflector element available [1, Ch. 7.6].

![Electrostatic deflector diagram]

<table>
<thead>
<tr>
<th>Electric</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>electric field</td>
<td>7.00</td>
</tr>
<tr>
<td>gap between plates</td>
<td>60</td>
</tr>
<tr>
<td>plate height (straight part)</td>
<td>151.5</td>
</tr>
<tr>
<td>plate length</td>
<td>6.959</td>
</tr>
<tr>
<td>total bending length</td>
<td>55.673</td>
</tr>
<tr>
<td>total straight length</td>
<td>44.800</td>
</tr>
<tr>
<td>bend angle per unit (45°)</td>
<td></td>
</tr>
</tbody>
</table>

- **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.

**Needs some support/consulting**
Magnetic bends

- Concept for magnetic add-on to deflector available [1, Ch. 7.6].
- Magnetic system ($\cos \theta$) placed outside the vacuum tube.

<table>
<thead>
<tr>
<th>Magnetic</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>magnetic field</td>
<td>0.0327</td>
<td>T</td>
</tr>
<tr>
<td>current density</td>
<td>5.000</td>
<td>A/mm²</td>
</tr>
<tr>
<td>windings/element</td>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>

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

Needs some support/consulting
Multipole elements
Quadrupoles

- Design of electrostatic elements by J. Borburgh (CERN) [1, 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\textsubscript{2} partial pressures below $10^{-12}$ mbar
  - H\textsubscript{2} partial pressures below $5 \times 10^{-11}$ mbar.
- Stochastic cooling rate better than $5 \times 10^{-3}$ 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.
- Mechanical alignment of elements inside vacuum pipe of 400 mm diameter
  - active compensation of oscillations/ground motion
- Shielding (passive versus active)

Needs strong support
Stochastic cooling

- Control proton beam emittance during measurements: 30 MeV to 45 MeV.
- Cooling should compensate emittance growth of $5 \times 10^{-3}$ 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.

Needs some support/consulting
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.

Needs strong support
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 $\approx 200$ ms.
  - Optimize design for PTR.

- **RF Wien filter** [3] applies **transverse magnetic fields** to spin, while exerting 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.

Needs some support/consulting
High-precision beam polarimeter (… with pellet extraction)

- dC (pC) scattering using white noise extraction works for relative polarization errors $\Delta p/p = 10^{-6}$ [4].
- Polarimeter system for dedicated ring described in [5–7].

- Polarization profile determination at low energies:
  - Carbon multifoil polarimeter [8] based on Silicon detectors with pellet extraction
    - (PhD J. Gooding, University of Liverpool).
  - Ballistic Si pellet target for homogeneous beam sampling [1, App. K].
  - Eloss of 100 keV in 50 $\mu$m pellet $\rightarrow$ track displaced by 2.5 cm behind 90° bend.

Needs strong support
Beam diagnostics

Beam Position Monitors

Development of prototype BPM based on segmented toroidal coil [9]

- Rogowski coil

![Prototype BPM prototype](image)

- 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

Needs some support/consulting

Prototype Ring for EDM searches

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Conclusion

Search for charged hadron particle EDMs ($p$, $d$, light ions):
▶ New window to disentangle sources of $CP$ violation, and to possibly explain matter-antimatter asymmetry of the Universe.
  ▶ Search for static charged particle EDMs ($p$, $d$, $^{3}\text{He}$)
    ▶ 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 [10].
▶ Results and achievements at COSY are summarized in [1, App. A].

Staged approach:
▶ **Next:** Design of the prototype ring (PTR)
  ▶ key components
  ▶ first direct proton EDM measurement
▶ Contributions/support from PBC community / CERN required
References


References II


Search for charged particle EDMs with frozen spins

Magic storage rings see CERN Yellow Report [1]

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

- Generalized solution for magic momentum

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

where $E_x$ is radial, and $B_y$ vertical field.

- Some configurations for circular machine with fixed radius $r = 25$ m:

<table>
<thead>
<tr>
<th>particle</th>
<th>$G$</th>
<th>$p$ [MeV c$^{-1}$]</th>
<th>$T$ [MeV]</th>
<th>$E_x$ [MV m$^{-1}$]</th>
<th>$B_y$ [T]</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton</td>
<td>1.793</td>
<td>700.740</td>
<td>232.792</td>
<td>16.772</td>
<td>0.000</td>
</tr>
<tr>
<td>deuteron</td>
<td>−0.143</td>
<td>1000.000</td>
<td>249.928</td>
<td>−4.032</td>
<td>0.162</td>
</tr>
<tr>
<td>helion</td>
<td>−4.184</td>
<td>1200.000</td>
<td>245.633</td>
<td>14.654</td>
<td>−0.044</td>
</tr>
</tbody>
</table>

Offers possibility to determine EDMs of protons, deuterons, and helions in one and the same machine.