Status of the proton EDM experiment
(A hybrid ring approach)

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Overview

- Proton EDM experiment is designed to be done in a storage ring
- Some systematics in a storage ring appear in different ways
  - misplacement of the ring elements
  - image charge effects
  - beam size effects, etc.
- On the other hand,
  - large statistics and spin coherence time can be achieved
  - beam dynamics is a very efficient tool for measuring and eliminating the systematic errors
  - geometric phase is under control
- Previously we presented an all-electric ring design (RSI 87,115116 (2016))
- Currently under technical evaluation at CERN
- Magnetic field should be shielded to nT with radial component cancelled to aT level
- Recent work with hybrid ring design makes the field and misalignment requirements much more flexible
Experimental goal

<table>
<thead>
<tr>
<th>Standard model</th>
<th>$&lt; 10^{-30} - 10^{-31} \ e \cdot \ cm$</th>
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<tbody>
<tr>
<td>Experimental limit ($^{199}$Hg)</td>
<td>$&lt; 7 \times 10^{-30} \ e \cdot \ cm$</td>
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<tr>
<td>Experimental limit (n)</td>
<td>$&lt; 3 \times 10^{-26} \ e \cdot \ cm$</td>
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<tr>
<td>Experimental limit (p)</td>
<td>$&lt; 7.9 \times 10^{-25} \ e \cdot \ cm$</td>
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<tr>
<td>pEDM experiment</td>
<td>$&lt; 10^{-29} \ e \cdot \ cm$</td>
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pEDM experiment

- Coupling between radial E-field and EDM $\rightarrow$ out-of-plane spin precession.
- Polarized beams will be injected at magic momentum into the ring.
- Radial E-field will couple with the EDM to grow vertical spin component.

Spin precession rate in the ideal case

$$\frac{d\vec{s}}{dt} = \frac{e}{m} \frac{\eta}{2c} \vec{s} \times \vec{E}$$
pEDM experiment

- Counter-rotating beams of $10^{11}$ particles.
- Spin coherence time is $\approx 10^3$ seconds.
- These counter-rotating beams of a few cm$^2$ size will pass through each other.
- They will be extracted continuously within 1000s for polarization measurement.
- The rate of change in the polarization is proportional to the EDM value (estimated as a few nrad/s for $d_p = 10^{-29} e \cdot \text{cm}$ and $E_{\text{rad}} = 8 \text{MV/m}$).
Frozen spin method

T-BMT equation without magnetic field terms

\[
\frac{d\vec{s}}{dt} = \frac{e}{m} \vec{s} \times \left[ \frac{\eta}{2c} \vec{E} - \left( G - \frac{m^2}{p^2} \right) \vec{\beta} \times \vec{E} \right]
\]

- The 2nd term determines the horizontal spin component \( s_{xz} \) and it is cancelled at magic momentum: \( p_0 = m/\sqrt{G} \)
- But there has to be deviation from \( p_0 \).
- The spread \( s_{xz} \) should not go beyond 90°
- We call the time of reaching 90° as spin coherence time
- JEDI Coll. reports \( \approx 10^3 \) is achievable (Phys. Rev. Accel. Beams 21, 024201)
- With some ring designs we obtained \( > 10^4 \) seconds in simulations
We presented a lattice RSI 87,115116 (2016)

- 500m long electric ring
- No magnetic field
- 8MV/m gradient
- Quads in each drift
- Beam position monitors (BPMs) in some drifts
- Polarimeters in 4 long drifts
What is different in a storage ring

- Static field in the lab frame is an alternating field in the particle’s rest frame
- Focusing mechanism may naturally compensate external field
- or cause systematic error (!)
- Spin coherence time of $> 10^3$ s shown to be achievable at COSY
- Average B-field can be measured through beam dynamics: Proportional to the split between counter-rotating beams.

\[ 1 \text{pm} \rightarrow \approx 1 \text{ aT} \]

- Vertical B-field can be indirectly measured by measuring spin polarization
Static vs alternating B-field

- With static, we mean static at the particle’s rest frame.
- For instance earth’s field is alternating in particle’s rest frame.
- We studied possible alternating B-field scenarios and found it to be harmless in a continuous ring, mostly because of CW/CCW cancellation.
B-field in a non-continuous ring

- Previously we have shown that alternating B-field along a continuous ring does not cause trouble: **No vertical spin accumulation**

- Recently a new potential systematic error was found (and solved by hybrid ring design)

- It is basically related to the coupling between $\beta$-function and radial B-field multipoles

- Vertical position does not cancel if $\beta$-function and the B-field multipoles correlate.

- This misleads the BPMs as $y$ changes sign with CW vs. CCW.
Magnetic focusing

- It is possible to store counter-rotating beams in an alternating focusing ring.
- Then, external B-field can be compensated by the focusing field naturally, because the Lorentz force becomes zero.
- This can cause a systematic error if E-field has a contribution to the Lorentz force.
- Simulation results show that dipole E-field is OK thanks to the cancellation of counter-rotating beams.
- Effect of the quadrupole E-field is solved by **varying magnetic focusing**
Varying magnetic focusing

\[ \omega_r = \omega_{EDM} + \omega_{Br} \frac{Q_{per}^2}{Q_{mag}^2 + Q_{per}^2} \]

\( Q_{per} \) refers to (de)focusing electric fields like quadrupole, beam-beam interaction, image charge, etc.

\[ \omega_r \approx \omega_{EDM} + \omega_{Br} Q_{per}^2 P_{mag} \quad \left[ P_{mag} \equiv \frac{1}{Q_{mag}^2} \right] \]

Simulating with various vertical focusing \((Q_{mag})\), we get a linear change in precession rate of vertical spin component \( \omega_r \).

Constant term in the linear fit gives \( \omega_{EDM} \)
In the all-electric ring design, the magnetic field imposed some strict requirements like BPMs with aT level sensitivity.

- Non-uniform $\beta$-function puts even more restrictions.
- Hybrid ring design solves the problem of external magnetic field because of the natural cancellation by the magnetic focusing.
- Simulations show that making the experiment with varying focusing strength eliminates the effects related to focusing electric fields ($Q_{per}$).
Thanks for your attention...
Additional slides - How BPM works
Additional slides - SQUID measurements

B-field (fT) vs. Freq (Hz) for different time intervals:
- 1 second
- 1 minute
- 10 minute

Data courtesy of S. Haciomeroglu, CAPP/IBS