Status of the proton EDM experiment

(A hybrid ring approach)

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Overview

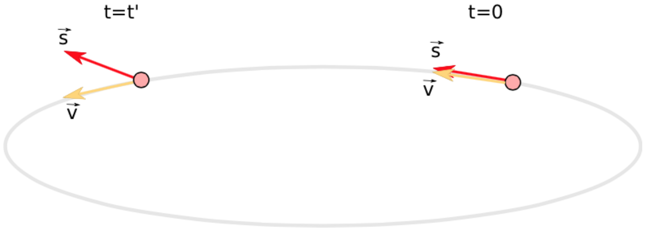
- Proton EDM experiment is designed to be done in a storage ring
- Some systematics in a storage ring appear in different ways
  - misplacement of the ring elements
  - image charge effects
  - beam size effects, etc.
- On the other hand,
  - large statistics and spin coherence time can be achieved
  - 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

Standard model	:	$< 10^{-30} - 10^{-31}\ e \cdot \text{cm}$
Experimental limit (^{199}Hg)	:	$< 7 \times 10^{-30}\ e \cdot \text{cm}$
Experimental limit (n)	:	$< 3 \times 10^{-26}\ e \cdot \text{cm}$
Experimental limit (p)	:	$< 7.9 \times 10^{-25}\ e \cdot \text{cm}$
pEDM experiment	:	$< 10^{-29}\ e \cdot \text{cm}$

pEDM experiment

- Coupling between radial E-field and EDM $\longrightarrow$ 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.

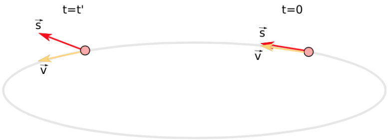


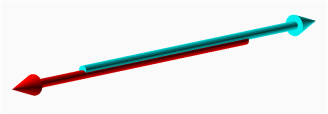
Spin precession rate in the ideal case

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

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 $E_{\text{rad}} = 8\text{MV/m}$).

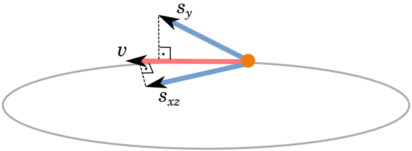




Frozen spin method

T-BMT equation without magnetic field terms

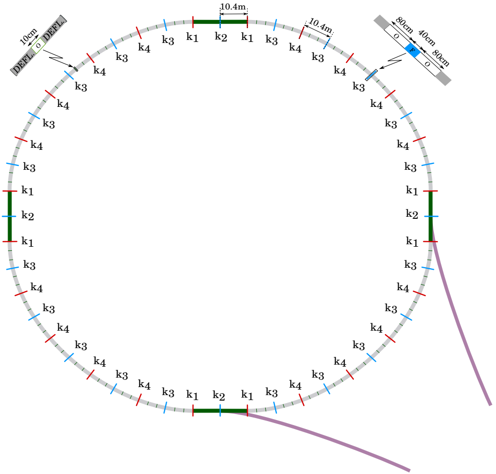
$$\frac{d\vec{s}}{dt} = \frac{e}{m}\vec{s} \times \left[\frac{\eta}{2c}\vec{E} - \left(G - \frac{m^2}{p^2}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right]$$



- 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

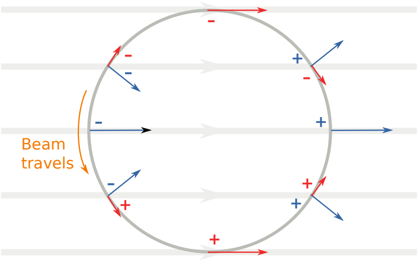
All-electric ring

- 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



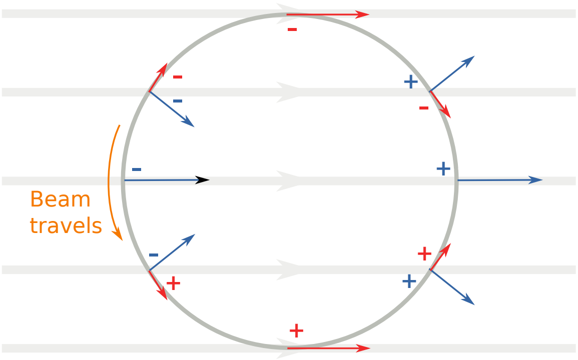
What is different in a storage ring

- 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. 1pm $\rightarrow \quad \approx 1$ aT
- Vertical B-field can be indirectly measured by measuring spin polarization



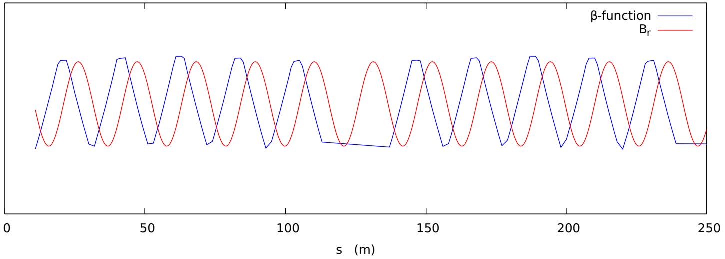
Static vs alternating B-field

- 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 β-function and radial B-field multipoles
- Vertical position does not cancel if β-function and the B-field multipoles correlate.
- This misleads the BPMs as y changes sign with CW vs. CCW.

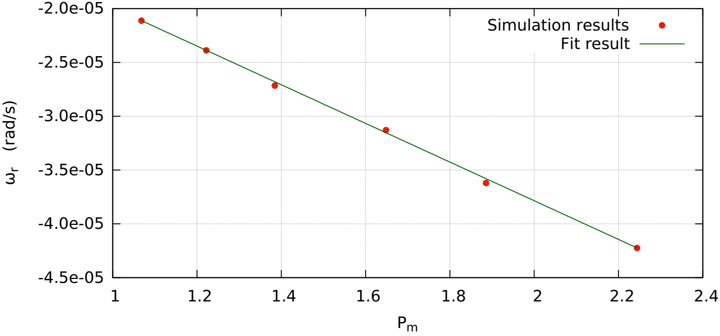


Magnetic focusing

- 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.
- $\omega_r \approx \omega_{EDM} + \omega_{Br} Q_{per}^2 P_{mag} \qquad [\, P_{mag} \equiv 1/Q_{mag}^2 \,]$
- Simulating with various vertical focusing (Q_{mag}), we get a linear change in precession rate of vertical spin component ω_r
- Constant term in the linear fit gives ω_{EDM}

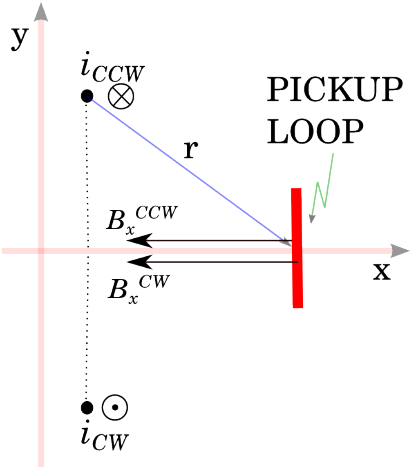


Summary

- In the all-electric ring design, the magnetic field imposed some strict requirements like BPMs with aT level sensitivity
- Non-uniform β-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