The Proton Storage Ring EDM Experiment (srEDM)

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for the Storage Ring EDM Collaboration, 2020/08/30

The proton storage ring proposed here is a hybrid that uses the frozen spin method. Electric bending plates steer the particles and magnetic focusing replaces electric—hence the label "hybrid." Longitudinally polarized protons are steered with just enough velocity to cause a horizontal spin precession rate to match its momentum precession—hence "frozen spin." The EDM signal is an out-of-plane (vertical) spin precession rate due to the radial E-field [1,2]. We seek strong community support for CD-0 approval.

The proposed ring solves or bypasses numerous technical issues, highlighted below in italics, significantly reducing costs and increasing efficiency. This is an experiment that can hit the ground running.

The major conceptual and technological strengths of the srEDM method render it ready for technical evaluation [1-5]. Its critical conceptual strength is the realization that a ring with purely electric bending sections and alternate magnetic focusing (a hybrid-ring lattice) permits simultaneous clock-wise (CW) and counter-clock-wise (CCW) storage, thus *eliminating first-order systematic error sources*, i.e., out-of-plane electric fields, *as well as the need to significantly shield the ring from external magnetic fields*. Another major strength is *elimination of errors related to the magnetic quadrupole fields* (e.g., geometrical phases) by beam-based alignment with about 10μm resolution, similar to the level demonstrated recently in a hadron machine [6]. Finally, the development of a SQUID-based beam position monitor (S-BPM) [4] with a demonstrated sensitivity of 10nm/√Hz means that *the separation of the counter-rotating (CR) beams can be effectively sensed a few orders of magnitude better than the previous state of the art*. The required overlap between CW and CCW beams is 10μm rms around the ring, *eliminating issues related to the unwanted presence of electric quadrupole fields*.

Moreover, the srEDM method promises a substantial increase in sensitivity to the proton EDM by *making the effect of spin precession when traversing an electric field a feature and not a potential background*. This is a significant departure from the EDM experiments complementary to it in the search for the CP-violation source. Like those experiments, the proton EDM experiment requires an application of strong electric fields to precess the EDM vector. However, even a small magnetic field in its own reference frame can present a serious background due to the presence of the magnetic dipole moment. For example, neutrons traveling in a purely electric field can still produce an irreducible EDM-like source of systematic error, and the use of ultra-cold-neutrons (UCN) to overcome it severely restricts the statistical sensitivity of the method, even with recent advances over the past several decades, which have improved the neutron EDM limit by almost a factor of two [7,8], currently near 10^{-26} e-cm.

Further technical strengths of the srEDM method include *bypassing the issue of efficient storage of high-intensity beams* (a major uncertainty in an all-electric ring), because an ultra-low vertical tune is not required [3], and *mitigating potential intra-beam scattering (IBS) issues,* since strong magnetic focusing can be afforded.

The value of the srEDM experiment is that it can provide substantial insight into the strong CP-problem by improving our sensitivity to θ_{QCD}, the P and T-violating parameter in the QCD Lagrangian, by more than three orders of magnitude; can establish the energy scale of the next international collider by probing New Physics at high-mass scales of the order 10^3 TeV [1-3]; and at 10^{-29} e-cm can probe CP-violation with the greatest existing sensitivity, in what could turn out to be the field responsible not only for the generation of lepton masses, but also the matter-antimatter asymmetry of our universe, i.e., the Higgs sector. Like the EDMs of the electron and neutron, it can be the only practical possibility of accessing the very small coupling to first-generation fermions, assuming they do violate CP-symmetry in the $H_{\gamma\gamma}$ coupling interaction [1-3, 7-10]. Finally, recent theoretical work on oscillating hadronic EDMs points to a new method of looking for axion dark matter and dark energy, one more-sensitive than the neutron EDM experiments by several orders of magnitude [11,12].

It is worth noting some advantages of doing the experiment at Brookhaven National Laboratory. High-intensities of the order of 10^{11} polarized proton beams are routinely available at BNL, and there are potential synergies with the electron ion collider (EIC) recently approved to be built at BNL. For example, a connection between the anomalous magnetic moments, EDMs and spin distributions could be revealed, since a major physics target of the EIC is the exploration of the spin distribution of the quarks inside the proton. Another example: The EIC program's high-intensity polarized sources could provide polarized beams for the proton—as well as the deuteron and neutron (^{3}He nucleus)—in a storage-ring EDM experiment studying the corresponding nucleus. The ring construction would need to be consistent with the EIC construction and operational plans.

The EDM, DM/DE sensitivity timeline, after the ring is built, is shown below.

Sensitivity timeline of EDM and DM/DE

Year	Lattice alignment specs per 10^3s storage time (quads, e-field plates)	EDM sensitivity target $\times 10^{-29}\ e \cdot \text{cm}$	DM/DE sensitivity $\times 10^{-29}\ e \cdot \text{cm}$ equiv.	Physics and main alignment methods
Year 1	100μm, 1mm	$<10^4$	N/A	EDM. Optical alignment
Years 2 & 3	100μm, 100μm	$<10^2$	N/A	EDM. Beam-based alignment and radial polarization
Years 4 & 5	10μm, 100μm	1	N/A	EDM. Beam-based alignment and radial polarization
Year 6	10μm, 10μm	1	$<10^6$	DM/DE and EDM. BPM and S-BPM
Years 7 - 9	1μm, 1μm →<0.1μm	1	$<10^4$ → 1	DM/DE and EDM. BPM and S-BPM
Years 10 - 14	TBD	1	1	Studying deuteron and ^{3}He nuclei EDM

References
1. F.J.M. Farley *et al.*, Phys. Rev. Lett. **93**, 052001 (2004).
2. V. Anastassopoulos *et al.*, Rev. Sci. Instrum. **87**, 115116 (2016).
3. S. Haciomeroglu *et al.*, Phys. Rev. Accel. Beams **22**, 3, 034001 (2019). 1806.09319.
4. S. Haciomeroglu *et al.*, PoS (ICHEP2018) 279, doi:10.22323/1.340.0279.
5. Z. Omarov *et al.*, "Systematic error analysis of the Symmetric Hybrid ring design in the storage-ring proton EDM experiment," 2007.10332 [acc-ph] (2020).
6. T. Wagner *et al.*, Hyperfine Interact 239:61 (2018).
7. C. Abel *et al.*, Phys. Rev. Lett. **124**, 081803 (2020).
8. J.M. Pendlebury *et al.*, Phys. Rev. **D92,** 092003 (2015).
9. B. Graner *et al.*, Phys. Rev. Lett. **116**, 161601 (2016).
10. V. Andreev *et al.*, Nature **562**, 355-60 (2018).
11. S.P. Chang *et al.*, Phys. Rev. **D99,** 8, 083002 (2019). 1710.05271 [hep-ex].
12. P.W. Graham *et al.*, "Storage Ring Probes of Dark Matter and Dark Energy," 2005.11867 hep-ph (2020).

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