ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-WEPA22

MEASURING THE ELECTRIC DIPOLE MOMENT OF THE ELECTRON IN A TWO-ENERGY SPIN-TRANSPARENT STORAGE RING*

R. Suleiman†, Ya. S. Derbenev
Thomas Jefferson National Accelerator Facility, Newport News, VA, USA
V. S. Morozov, Oak Ridge National Laboratory, Oak Ridge, TN, USA

Abstract

This contribution presents a new design of a two-energy storage ring for low energy (0.2–2 MeV) polarized electron bunches. The new design is based on the transparent spin methodology that cancels the spin precession due to the magnetic dipole moment at any energy while allowing for spin precession induced by the fundamental physics of interest to accumulate. The buildup of the vertical component of beam polarization can be measured using standard Mott polarimetry that is optimal at low electron energy. These rings can be used to measure the permanent electric dipole moment of the electron, relevant to CP violation and matter-antimatter asymmetry in the universe, and to search for dark energy and ultra-light dark matter.

INTRODUCTION

The electric dipole moment (EDM) is very sensitive to physics beyond the Standard Model and new sources of Charge-conjugation and Parity (CP) violation [1,2]. Such CP violation, beyond what is present in the weak interaction, could signal the presence of new physics and explain the puzzle of the matter-antimatter asymmetry in the universe. However, there are no direct measurements of the electron or proton EDMs. The EDM upper limit of the electron ($d_e < 1.1 \times 10^{-29}\ e \cdot \mathrm{cm}$) has been extracted from a measurement using ThO molecule while the proton limit was obtained using ^{199}Hg atom. Direct measurements of the EDM upper limits only exist for the neutron and the muon where the muon limit was measured in conjunction with the anomalous magnetic dipole moment, $g - 2 (\equiv 2G)$.

Any measurement of EDM relies on measuring the spin precession rate in an electric field of a particle's rest frame, $\mathrm{d}\vec{S}/\mathrm{d}\tau = \vec{\mu}\times\vec{B}_{\mathrm{rest}}+\vec{d}\times\vec{E}_{\mathrm{rest}}$, where the magnetic (MDM) and electric dipole moments are defined as $\vec{\mu} = (G+1)(q/mc)\vec{S}$ and $\vec{d} = (\eta/2)(q/mc)\vec{S}$, q and m are the particle charge and mass, c is the speed of light, η is the electric dipole factor, and $\vec{S}$ represents spin in the particle's rest frame. For a charged particle moving in electric and magnetic fields given in the lab frame, the generalized Thomas-BMT equation of spin precession is $\mathrm{d}\vec{S}/\mathrm{d}t = (\vec{\omega}_{\mathrm{MDM}} + \vec{\omega}_{\mathrm{EDM}}) \times \vec{S}$ with [3]:

$$\vec{\omega}_{\mathrm{EDM}} = -\frac{\eta q}{2mc}\left(\frac{1}{\gamma}\vec{E}_{\parallel} + \vec{E}_{\perp} + \vec{\beta}\times\vec{B}\right), \qquad (1)$$

where $\vec{v} \equiv \vec{\beta}c$ and γ are the particle's velocity and Lorentz energy factor.

The basic principle of the EDM measurement in a ring relies on making MDM spin rotation effectively vanish. Observation of a spin rotation then indicates the presence of EDM. Strategies to cancel MDM spin precession can be formulated for particle motion along a closed reference design orbit, traditionally (but not necessarily) in a plane, that permit the effective stacking of the EDM precession turn by turn around the orbit. A flat reference orbit generally employs vertical magnetic (B_y) and horizontal transverse electric (E_x) fields. In the accelerator reference frame, spin then precesses due to MDM about vertical axis with angular frequency, ω_y:

$$\omega_{y,\mathrm{MDM}} = -\frac{q}{mc}\left(GB_y - \frac{1-\gamma^2\beta^2 G}{\gamma^2\beta}E_x\right). \qquad (2)$$

Considering Eq. 2, two experimental approaches have been developed to compensate MDM spin rotation and thereby measure EDM in storage rings:

1. All-electric ring with $B_y = 0$ and $\gamma^2 = 1 + 1/G$, described as the Magic Energy (ME) approach. This works only for $G > 0$ (e.g., electron or proton) and at a very specific energy. Two experiments have been proposed to measure d_p with a sensitivity of $10^{-29}\ e \cdot \mathrm{cm}$ at ME of 232.8 MeV in rings with ≥ 500 m circumference [4,5]. To reduce systematic effects, clock-wise (CW) and counter clock-wise (CCW), beams will circulate concurrently.

2. Combined electric/magnetic ring with $GB_y = (1 - \gamma^2\beta^2 G)/(\gamma^2\beta)E_x$. An experiment is planned to measure the deuteron ($G = -0.143$) EDM (d_d) at 1.0 GeV/c with such a ring.

Notably, these experiments propose to measure d_p and d_d but not d_e. In fact, there is no d_e proposal at ME ($\gamma = 29.38$, 15.01 MeV) because there is no viable polarimetry at this energy.

This contribution presents a method to measure d_e in a small storage rings with beam energy below 1 MeV [6]. It is based on the Figure-8 spin-transparent (ST) configuration [7] where the MDM signal is naturally suppressed at any energy due to the ring topology and symmetry. Thus, there is no spin decoherence due to the beam energy spread. We consider an all-electric design with no magnetic fields to allow for counter-rotating (CR) electron beams.

* This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177 and by UT-Battelle, LLC, under contract DE-AC05-00OR22725.
† suleiman@jlab.org

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-WEPA22

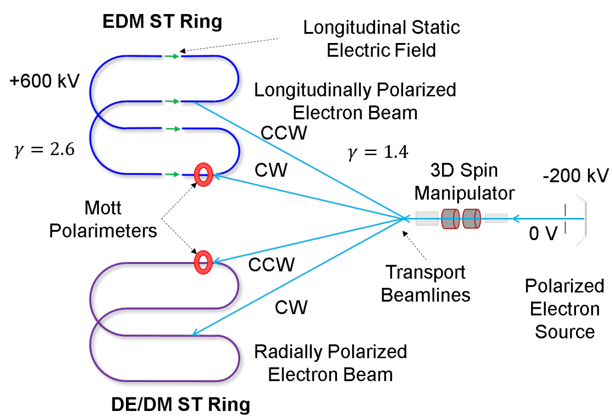

Figure 1: Layout of ST storage rings with only static electric fields for measuring d_e (top) and to search for dark energy and ultra-light (axion) dark matter (DE/DM) (bottom). Other required hardware is also shown schematically: polarized electron source, 3D spin manipulator, transport beamlines, and Mott polarimeters.

RING DESIGN

The EDM ST ring illustrated in Fig. 1 consists of two low-energy and two high-energy arcs connected by longitudinal field sections to provide acceleration/deceleration. They preserve suppression of the MDM effect but remove the degeneracy of the EDM spin precession. The beam directions in the two arcs of each energy are opposite making the net bending angle zero. A straightforward way to obtain the EDM spin rotation per turn around the ring, $\partial\,|\psi_{\mathrm{EDM}}|\,/\partial N$, is to treat the EDM signal as a perturbation of the MDM spin motion on the closed orbit.

The EDM spin rotation per unit η and unit time is $\partial^2|\psi_{\mathrm{EDM}}|/\partial\eta\partial t = f_c\ \partial^2|\psi_{\mathrm{EDM}}|/\partial\eta\partial N$ where f_c is the beam circulation frequency. Examining $\partial^2\,|\psi_{\mathrm{EDM}}|\,/(\partial\eta\partial t)$ as a function of γ_1 and γ_2 where we assumed bending and accelerating/decelerating electric fields of $|E| = 10$ MV/m and a packing factor of 0.5, indicates that reaching a substantial EDM signal requires a significant difference between γ_1 and γ_2. As an example, for $\gamma_1 = 1.4$ and $\gamma_2 = 2.6$, corresponding to 200 keV beam from the electron source and the high-energy arcs floating at high voltage of 600 kV, $\partial^2\,|\psi_{\mathrm{EDM}}|/(\partial\eta\partial t) = 0.46\times10^9$ rad/s.

For the ME racetrack approach, EDM spin precession per turn is $\partial^2\left|\psi_{\mathrm{EDM,ME}}\right|/\partial\eta\partial N = \pi/\sqrt{G}$. Under the same field and packing factor assumptions as above, $\partial^2\left|\psi_{\mathrm{EDM,ME}}\right|/(\partial\eta\partial t) = 1.47\times10^9$ rad/s. Thus, the ST ring provides an EDM precession rate that is only a factor of 3 smaller than that of an ME ring but with vastly smaller footprint, and other advantages. The results of the ST and ME ring comparison are summarized in Table 1 where the last column gives the expected EDM spin precession rate assuming $d_e = 10^{-29}\ e\cdot$cm ($\eta = 1.04\times10^{-18}$).

For the optical structure of the arcs of an ST ring, we choose a design which employs weak-focusing optics. The

Table 1: Comparison of EDM Spin Rotations in the ME and ST Rings

Approach	γ	$\left\|\frac{\partial^2\|\psi_{\mathrm{EDM}}\|}{\partial\eta\partial N}\right\|$ (rad)	$\left\|\frac{\partial^2\|\psi_{\mathrm{EDM}}\|}{\partial\eta\partial t}\right\|$ ($\times10^9$ rad/s)	$\left\|\frac{\partial\|\psi_{\mathrm{EDM}}\|}{\partial t}\right\|$ (nrad/s)
ME ring	29.38	92.24	1.47	1.53
ST ring	(1.4, 2.6)	4.24	0.46	0.48

Table 2: EDM ST Ring and Beam Parameters

Quantity	Value
γ_1, γ_2	1.4, 2.6
Bending radii: R_1, R_2	9.2 cm, 22.6 cm
Straight section length	12.3 cm
Total circumference	5.27 m
Electrode gap, $2a$	6 cm
Radial bending E-field	5 MV/m
Revolution time	20.9 ns
Electrons per fill, N_e	1 nC CW/1 nC CCW
Normalized x/y emittance:	
without (with) cooling	628/610 μm (146/79 μm)
Momentum spread, σ_δ:	
without (with) cooling	8.8 % (1.5 %) at γ_1

horizontal focusing is set by the orbit bend radius, while the vertical one is provided by a weak vertical-focusing gradient of the electric field. The dispersion is controlled by changing the bending direction. The main parameters of the ring design are summarized in Table 2.

Measuring d_e to $10^{-29}\ e\cdot$cm requires a relatively high stored charge of 1 nC. In combination with our choice of low beam energies, intra-beam scattering (IBS) will cause large beam sizes. We use the optics design and the ring parameters listed in Table 2 to estimate the emittance limitations imposed by IBS for a coasting beam. We find transverse emittances and momentum spread that give equal IBS growth times $\tau^{\mathrm{IBS}}_{x/y/z}$ of 10^4 s in the three dimensions. These are listed in Table 2 and correspond to a fairly large maximum rms horizontal/vertical beam size of $\sigma_x/\sigma_y = 12/16$ mm.

To reduce beam sizes, we must apply stochastic cooling. A typical time of stochastic cooling assuming the number of electrons N of 6.24×10^9 and the cooling system's bandwidth W of 0.5 GHz, $\tau^{\mathrm{cool}}_z \sim N/2W \sim 6$ s. We conservatively use a longitudinal cooling time τ^{cool}_z of 10 s. We assume that cooling is primarily longitudinal with 10 % of the total cooling decrement coupled into the transverse dimensions. Since the IBS rates are determined by the equilibrium with the cooling rates, we find $\varepsilon_{x/y}$ and σ_δ resulting in $\tau^{\mathrm{IBS}}_x = \tau^{\mathrm{IBS}}_y = 100$ s and $\tau^{\mathrm{IBS}}_z = 10$ s. The results are listed in Table 2. Using these parameters gives beam sizes of $\sigma_x/\sigma_y = 4.0/5.8$ mm, which are manageable.

Beam lifetime should be at least as long as the spin coherence time (SCT). As discussed above, stochastic cooling can overcome the IBS effect. Thus, the beam lifetime will

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-WEPA22

be limited by other mechanisms. The expected lifetime due to the CR beam-beam interaction is estimated to be 15000 s.

SCT is the time the beam stays polarized in a storage ring. A long polarization lifetime is required since this is the time available to accumulate and observe the EDM signal. The polarized electron source can deliver beam polarization (P) of 0.90 on a routine basis. The proton EDM proposals at ME are limited by SCT of 1000 s (beam lifetime is much longer), where depolarization is caused by MDM spin precession mainly due to energy spread and being slightly off exact ME. Since in our case the spin tune is energy independent, the energy spread does not contribute to depolarization in the first order. The main limitation comes from the spin tune spread due to beam emittances. The SCT time was estimated to be around 10000 s, which is comparable to the beam lifetime noted above.

MOTT POLARIMETER

The build-up of the vertical component of the electron beam polarization due to spin precession from longitudinal to vertical caused by EDM (or from radial to vertical caused by DE/DM) can be measured using a conventional Mott polarimeter [8]. For 200 keV kinetic energy electrons scattered from ^{238}U, the analyzing power of Mott scattering from a single atom can be as large as 0.56 at 130°.

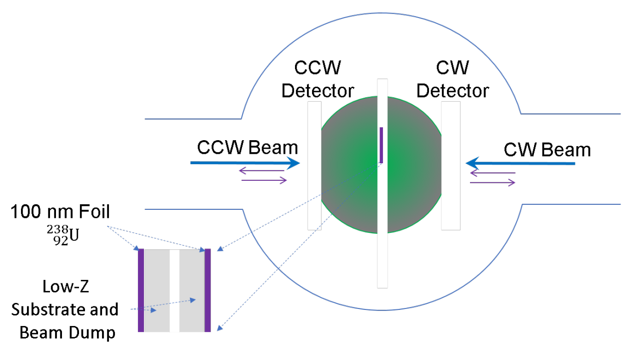

Figure 2: Schematic of the Mott polarimeter.

A schematic of a Mott polarimeter is shown in Fig. 2. The target is composed of two foils - 100 nm thick ^{238}U with a low-Z substrate - one foil for each beam. The substrate will serve also as a beam dump. The detectors cover the scattering angles from 90° to 160° with full azimuthal coverage. For this design, the polarimeter efficiency (ϵ) is 0.0024 and the average analyzing power (A_y) is 0.45.

For a continuous electron beam polarization measurement where the Mott target in periodically inserted to intercept a fraction of the beam, the statistical uncertainty of the EDM measurement per fill is 4.7×10^{-27} $e \cdot$ cm. In one year of data taking, the projected statistical limit is 8.4×10^{-29} $e \cdot$ cm with the expectation that further optimization and improvements will lower this limit.

Since the spin rotation due to EDM is much smaller than that of the MDM ($\eta/G \approx 10^{-15}$), uncontrolled MDM spin rotations limit the smallest EDM that can be measured and introduce systematic uncertainties. In the ST ring, MDM spin rotations should average to zero over a single turn, however, fringe and background electromagnetic fields and errors in the construction and alignment of the ring elements may introduce non-zero MDM spin rotations. One approach to further suppress residual MDM effects is the use of state-of-the-art shielding of background fields where the small size of the ST ring makes elaborate shielding very practical. Another approach relies on the use of CR beams.

FUTURE WORK

As in the ME based design, the ST ring can be used to measure spin precession induced by DE/DM. The low-mass axion couples to the spin of radially polarized electrons stored in the ring with a sensitivity proportional to beam velocity, β, and SCT. The DE/DM ring can be identical to the EDM ring or a ST ring without longitudinal electric fields as illustrated in Fig. 1.

The ST ring concept could potentially be extended to low-energy polarized proton, deuteron, and muon beams using rings of comparable dimensions to those described here for electrons, although for this all-electric design, it is harder to create a substantial difference in γ for heavy particles. At a minimum, the all-electric, modulated beam energy design presented here can serve as a testbed for EDM searches of these other particles.

Instead of coasting beam, we are considering bunched beam. Counter-rotating electron beams of multiple bunches, with different polarizations (longitudinal and radial) and with both positive and negative helicities, provide adequate control of systematic effects.

Techniques of compensation and control for spin coherent and decoherent detunes due to background magnetic fields, imperfections, and beam emittances are under consideration by several collaborations. In particular, an intriguing possibility of implementing the Spin Echo technique in low-energy rings with bunched beams is under study.

CONCLUSION

We described a new method to measure d_e to less than 10^{-28} $e \cdot$ cm and to search for DE/DM using small ST rings in the energy range below 1 MeV. The presented approach has the following advantages: energy-independent spin tune, long SCT, bunched and un-bunched (coasting) beam, any energy, spin-achromatic beam transport, no synchrotron radiation, minimum safety issues, straightforward polarimetry, CR beams, room-sized facility, good control of systematic effects and imperfections including background magnetic fields, manageable, low cost, and finally, such rings can serve as testbed for larger-scale experiments. We are now considering bunched beams and further improvements to be able to measure d_e to less than 10^{-29} $e \cdot$ cm.

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-WEPA22

REFERENCES

[1] T. E. Chupp, P. Fierlinger, M. J. Ramsey-Musolf, and J. T. Singh, "Electric dipole moments of atoms, molecules, nuclei, and particles", *Rev. Mod. Phys.*, vol. 91, p. 015001, 2019. doi:10.1103/RevModPhys.91.015001

[2] N. Yamanaka, "Review of the electric dipole moment of light nuclei", *International Journal of Modern Physics E*, vol. 26, p. 1730002, 2017. doi:10.1142/S0218301317300028

[3] T. Fukuyama and A. J. Silenko, "Derivation of generalized Thomas-Bargmann-Michel-Telegdi equation for a particle with electric dipole moment", *International Journal of Modern Physics A*, vol. 28, p. 1350147, 2013. doi:10.1142/S0217751X13501479

[4] F. Abusaif *et al.*, "Storage Ring to Search for Electric Dipole Moments of Charged Particles – Feasibility Study", CERN, Geneva, Switzerland, Rep. CERN-2021-003, CERN-PBC-REPORT-2019-002, Dec. 2019. doi:10.48550/arXiv. 1912.07881

[5] Z. Omarov *et al.*, "Comprehensive symmetric-hybrid ring design for a proton EDM experiment at below 10^{-29} $e \cdot$ cm", *Phys. Rev.*, vol. D, no. 105, p. 032001, 2022. doi:10.1103/PhysRevD.105.032001

[6] R. Suleiman, V. S. Morozov, and Y. S. Derbenev, "On possibilities of high precision experiments in fundamental physics in storage rings of low energy polarized electron beams", preprint submitted to arXiv, May 2021. doi:10.48550/arXiv.2105. 11575

[7] Y. N. Filatov, A. M. Kondratenko, M. A. Kondratenko, Y. S. Derbenev, and V. S. Morozov, "Transparent Spin Method for Spin Control of Hadron Beams in Colliders", *Phys. Rev. Lett.*, vol. 124, p. 194801, 2020. doi:10.1103/PhysRevLett.124.194801

[8] J. M. Grames *et al.*, "High precision 5 MeV Mott polarimeter", *Phys. Rev. C*, vol. 102, p. 015501, 2020. doi:10.1103/PhysRevC.102.015501