Measuring the Electric Dipole Moment of the Electron in a Two-energy Spin-Transparent Storage Ring

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Introduction

This contribution proposes a new design of a two-energy storage ring for low energy (0.2-2 MeV) polarized electron bunches [1]. 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.

EDM Measurements

- Electron and Proton EDMs are deduced from neutral atom/molecule measurements
- Direct measurements only for neutron and muon
- Muon EDM limit is from muon $g-2$ experiment
- No measurement of deuteron or any other nucleus

Particle/Atom/Molecule	Measured Upper Limit (e · cm)	Standard Model (e · cm)
ThO → Electron	$< 1.1 \times 10^{-29}$	10^{-40}
^{199}Hg → Proton	$< 2 \times 10^{-25}$	10^{-32}
Neutron	$< 3.6 \times 10^{-26}$	10^{-32}
Muon	$< 1.8 \times 10^{-19}$	10^{-36}

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Electron Spin-Transparent Storage Ring

- In ST mode, any spin direction repeats after a particle turn along periodic orbit in storage ring – an ideal definition; but it can be approached with a high precision
- Best example is a figure-8 magnetic or electric ring; here global spin tune is zero independent of particle energy
- Remaining challenge is to compensate for misalignments and spin decoherency due to beam emittances

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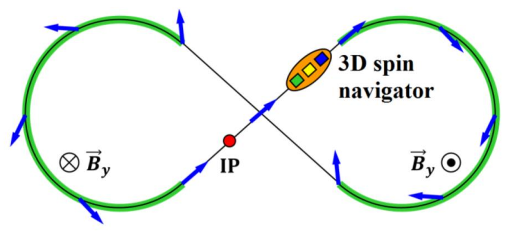
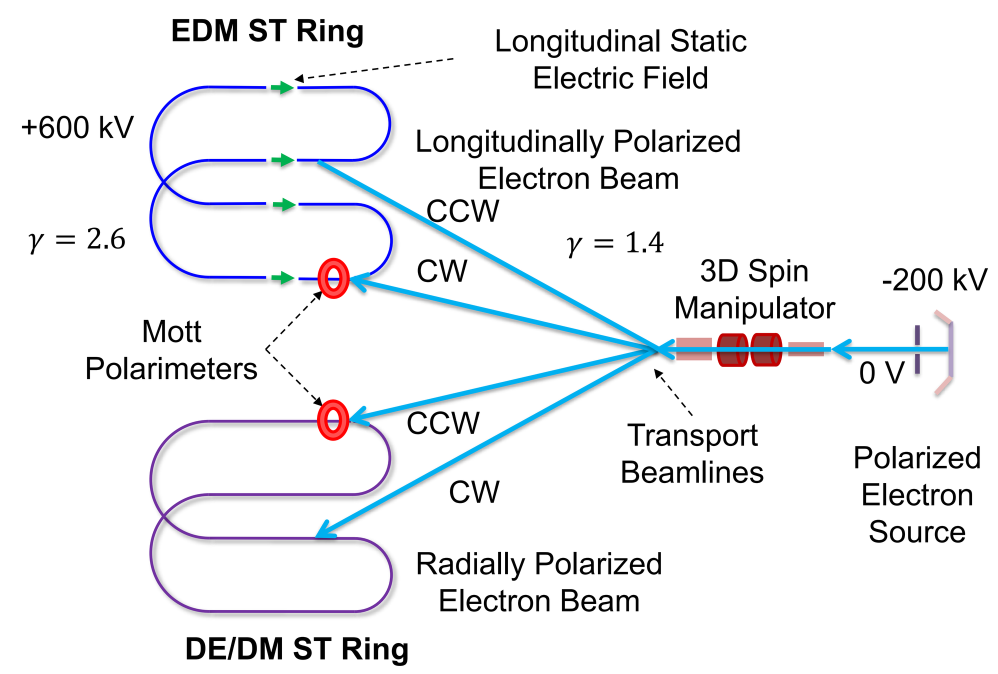
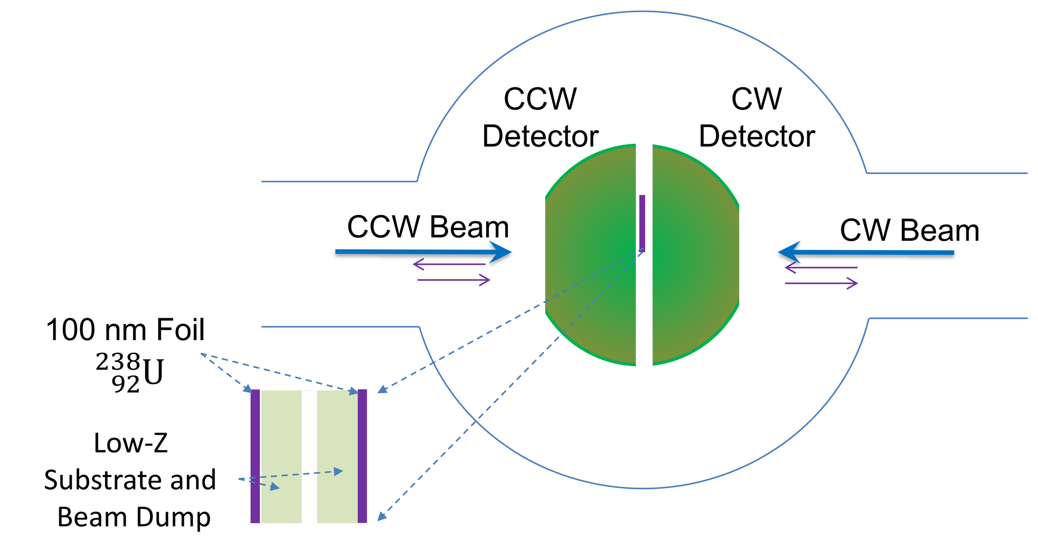




Mott Polarimeter & Statistical Uncertainties

Detector Coverage:
- $\varphi: 0 \rightarrow 2\pi$
- $\theta: 90° \rightarrow 160°$



- Statistical uncertainty per fill with continuous Mott measurements:

$$\sigma_{EDM} = \sqrt{24}\frac{d_e}{\sqrt{N_e\, \epsilon\, Ay\, P\, \Omega_{EDM}\, SCT}}$$

$$\sigma_{EDM} = 4.7 \cdot 10^{-27}\ e \cdot cm$$

- In one year:

$$\sigma_{EDM} = 8.4 \cdot 10^{-29}\ e \cdot cm$$

- Current limit from ThO molecule: $d_e < 1.1 \times 10^{-29}\ e \cdot cm$ (90% C.L.)

Electrons per Fill	N_e	$1.2 \cdot 10^{10}$ $6 \cdot 10^9$ **CW,** $6 \cdot 10^9$ **CCW**
Polarimeter Efficiency	ϵ	0.0024
Analyzing Power	A_y	0.45
Beam Polarization	P	0.9
Precession Frequency	Ω_{EDM}	0.48 nrad/s (calculated assuming $1 \cdot 10^{-29}$ e·cm)
Spin Coherence Time	SCT	10000 s

> **Further optimization and improvements will lower this limit to less than $1.0 \times 10^{-29}\ e \cdot cm$**

EDM Searches in Storage Rings

- Measurement of EDM relies on measuring spin precession rate in an electric field of a particle's rest frame, $\frac{d\vec{S}}{dt} = \vec{\mu} \times \vec{B}_{rest} + \vec{d} \times \vec{E}_{rest}$
- For a charged particle moving in electric and magnetic fields given in lab frame, generalized Thomas-BMT equation of spin precession is: $\frac{d\vec{S}}{dt} = (\vec{\omega}_{MDM} + \vec{\omega}_{EDM})\vec{S}$, with:

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

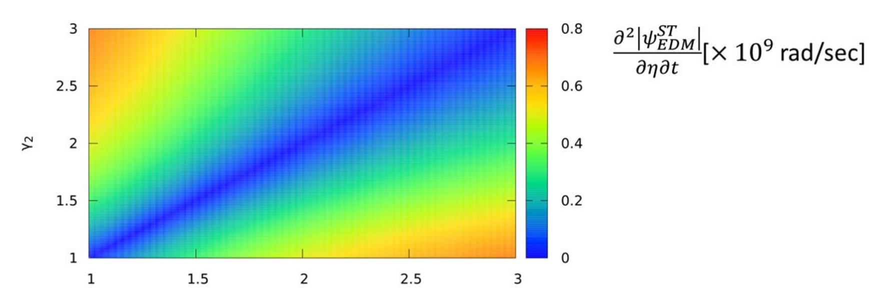
Choices for storage rings: $$\omega_{y,MDM} = -\frac{q}{mc}\left(GB_y - \frac{1-\gamma^2\beta^2 G}{\gamma^2\beta}E_x\right)$$

1. All-electric ring (B_y=0) with $\gamma^2 = 1 + \frac{1}{G}$, described as Magic-Energy (ME) or Frozen-Spin approach, works only for $G > 0$ ($G_p = 1.79$, $G_e = 0.00116$):
   - Two experiments have been proposed to measure d_p with a sensitivity of $10^{-29}\ e \cdot cm$ at ME of 232.8 MeV
   - **No electron EDM proposal at magic energy (14.5 MeV) because there is no viable polarimetry**
2. Combined electric/magnetic ring with $GB_y = \frac{1-\gamma^2\beta^2 G}{\gamma^2\beta}E_x$. An experiment is planned to measure deuteron ($G_d = -0.143$) EDM at 1.0 GeV/c with such a ring
3. Spin-Transparent (ST) Storage Rings: Transverse and longitudinal electric fields and no magic energies – this work

EDM Spin Field

$$\frac{\partial|\psi_{EDM}|}{\partial N} = \left|2\eta\left[\frac{\gamma_2^2\beta_2}{1-\gamma_2^2\beta_2^2 G} - \frac{\gamma_1^2\beta_1}{1-\gamma_1^2\beta_1^2 G} - \ln\frac{\gamma_2+\sqrt{\gamma_2^2-1}}{\gamma_1+\sqrt{\gamma_1^2-1}}\right]\sin\left(\frac{\omega_M^1}{2}\pi\right)\sin\left(\frac{\omega_M^2}{2}\pi\right)\right|$$

- $d_e = 10^{-29}\ e \cdot cm$, $\eta = 1.04 \cdot 10^{-18}$
- EDM spin rotation per unit η and unit time is $\partial^2|\psi_{EDM}|/(\partial\eta\partial t) = f_c\, \partial^2|\psi_{EDM}|/(\partial\eta\partial N)$ where f_c is beam circulation frequency
- Assume bending and accelerating/decelerating electric fields of $|E| = 10$ MV/m and a packing factor of 0.5

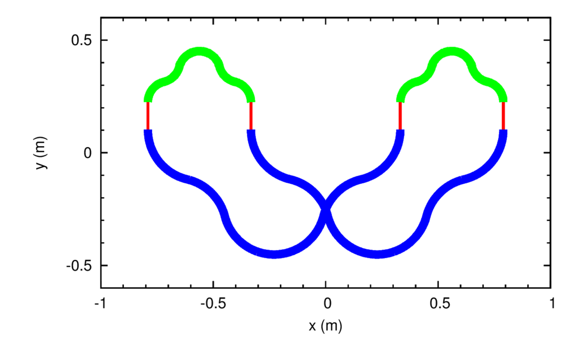


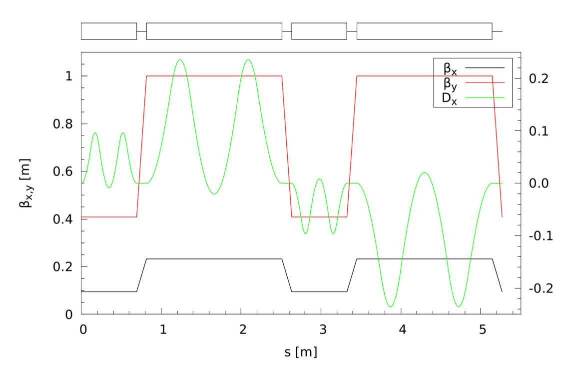
Scheme	γ	$\left\lvert\frac{\partial^2\lvert\psi_{EDM}\rvert}{\partial\eta\partial N}\right\rvert$ [rad]	$\left\lvert\frac{\partial^2\lvert\psi_{EDM}\rvert}{\partial\eta\partial t}\right\rvert$ [× 10^9 rad/sec]	$\left\lvert\frac{\partial\lvert\psi_{EDM}\rvert}{\partial t}\right\rvert$ [nrad/sec]
ME ring	29.38	92.24	1.47	1.53
ST ring	(1.4,2.6)	4.24	0.46	0.48

EDM Optics Design and Ring Footprint

- No stochastic cooling
  Find ε_x, ε_y and σ_δ such that $\tau_x^{IBS} = \tau_y^{IBS} = \tau_z^{IBS} = 10^4$ s:
  $\varepsilon_x^N = 0.63$ mm, $\varepsilon_y^N = 0.61$ mm, $\sigma_\delta = 0.09$
  Beam size: $\sigma_x = 12$ mm, $\sigma_y = 16$ mm
- With stochastic cooling
  Find ε_x, ε_y and σ_δ such that $\tau_x^{IBS} = \tau_y^{IBS} = 10^2$ s and $\tau_z^{IBS} = 10$ s: $\varepsilon_x^N = 0.15$ mm, $\varepsilon_y^N = 0.08$ mm, $\sigma_\delta = 0.015$
  Beam size: $\sigma_x = 4$ mm, $\sigma_y = 5.8$ mm

Quantity	Value
γ_1, γ_2	1.4, 2.6
Bending radii: R_1, R_2	9.2 cm, 22.6 cm
Slip factor	-0.0586 at γ_1
Straight section length	12.3 cm
Total circumference	5.27 m
Electrode spacing	6 cm
Revolution time	20.9 ns
Electrons per fill, N_e	1 nC CW and 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





Systematic Uncertainties

- Counter-rotating beams (with both helicities) will suppress some uncertainties
- Elaborate state-of-art shielding of background magnetic fields is practical since ST ring is very small but electron lighter mass (relative to proton) increases sensitivity to these fields
- With coasting beam, ST ring cannot store all polarization states (longitudinal, vertical, and radial) and with both helicities (positive and negative) at same time – a major challenge to control systematic uncertainties

> **New Design: use bunched instead of coasting beam**

Summary

- **Presented approach has 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, counter-rotating 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
- **Future Plans:**
  - **Explore bunched beam to address systematic uncertainties**
  - Techniques of compensation and control for spin coherent and decoherent detunes due to background magnetic fields, imperfections, and beam emittances are under consideration. In particular, an intriguing possibility of implementing **Spin Echo** trick.
  - ST ring concept could potentially be extended to low-energy polarized proton, deuteron, and muon beams using electric/magnetic or all-electric rings of comparable dimensions to those described here for electrons, although for this all-electric design, it is harder to create a substantial modulation of γ for heavy particles

[1] 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, arXiv:2105.11575 [physics.acc-ph] (2021). https://doi.org/10.48550/arXiv.2105.11575

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