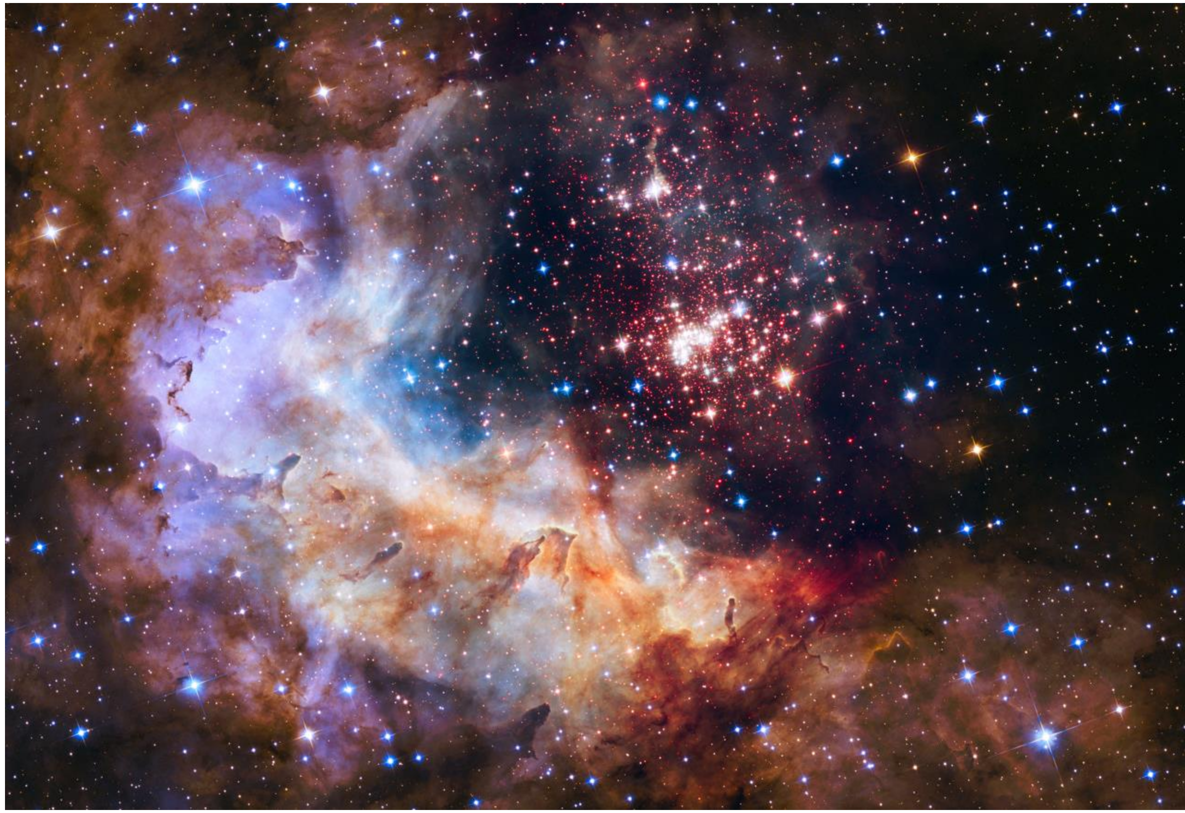
EDM Measurement in Small Rings

High Precision Fundamental Physics Experiments Using Compact Storage Rings of Low Energy Polarized Electron Beams



https://arxiv.org/abs/2105.11575

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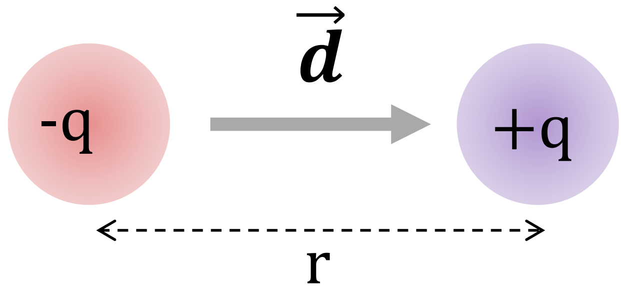
Outline

- Motivation: EDM, CP Violation, and Matter-Antimatter Asymmetry
- EDM Searches in Storage Rings
- Spin-Transparent Storage Ring and EDM Precession Rate
- Electron EDM Ring Details:
  - Ring Optics Design
  - Intra-Beam Scattering and Stochastic Cooling
  - Beam Lifetime and Spin Coherence Time
- Polarized Electron Source and Electron Polarimetry
- Statistical and Systematic Uncertainties
- Dark Matter and Dark Energy Searches
- Spin-Transparency and Proton EDM Search
- Summary

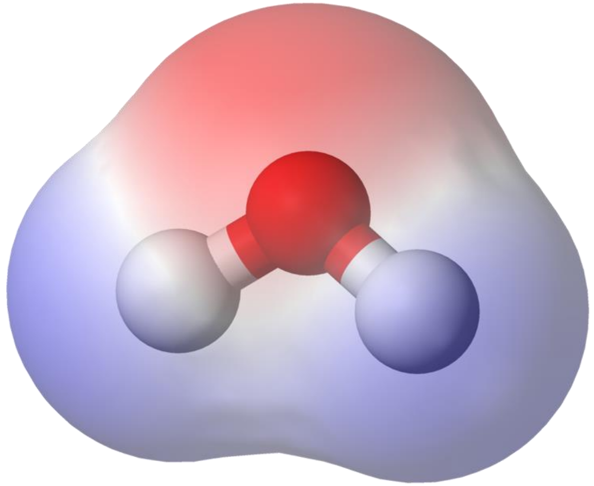
Motivation

Electric Dipole Moment (EDM)

Definition: Permanent spatial separation of positive and negative charge distributions



$$\vec{d} = q \cdot \vec{r}$$

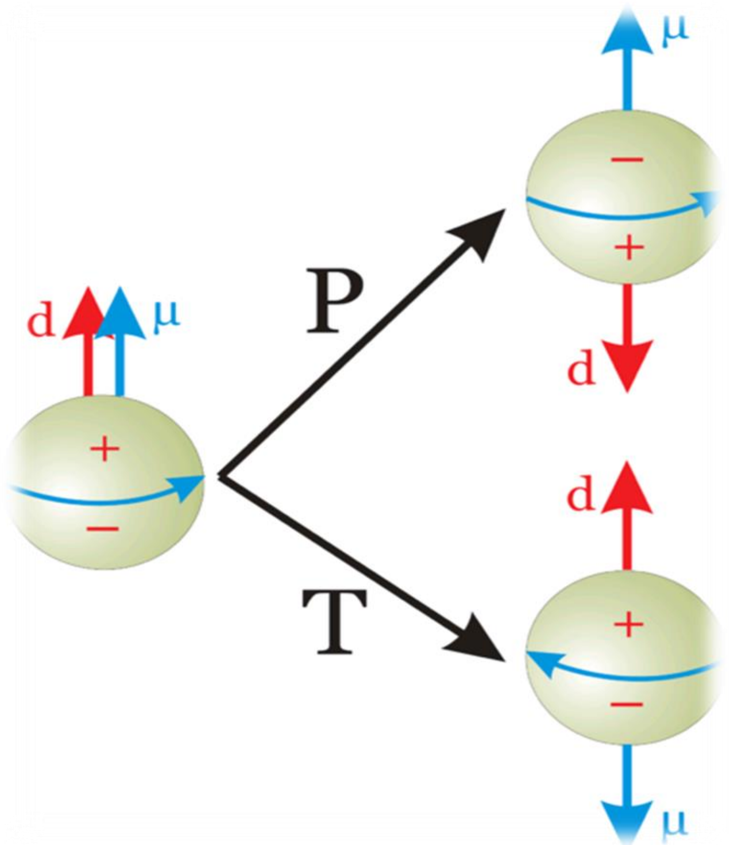


- Example: water molecule has large permanent EDM because of degenerate ground state with different parity (does not violate parity; not a parity eigenstate):

$$d_{H_2O} \sim 6.15 \times 10^{-30}\ \mathrm{C \cdot m} \sim 3.84 \times 10^{-9}\ \mathrm{e \cdot cm}$$

- This not true for elementrary particles (electron, proton, ...): existance of permanant EDM violates both Time-reversal (T) and Parity (P) symmetries. Assuming CPT invariance (combined symmetry over C-charge-conjugation, P-parity and T-time), T and P violations imply CP violation

T and P Violation of Permanent EDM



$\vec{d}$: EDM (aligned with spin)

$$\vec{d} = \frac{\eta}{2}\frac{q\hbar}{mc}\vec{S}$$

$\vec{\mu}$: Magnetic Dipole Moment

$$\vec{\mu} = \frac{g}{2}\frac{q\hbar}{mc}\vec{S}$$

Anomalous magnetic moment: $G = \frac{g-2}{2}$

Spin precession for particle at rest ($\vec{v} = 0$):

$$\frac{d\vec{S}}{dt} = \frac{e\hbar}{mc}\left((G+1)\vec{S}\times\vec{B} + \frac{\eta}{2}\vec{S}\times\vec{E}\right)$$

$$\begin{array}{llll} \boldsymbol{P} & \vec{E}\rightarrow -\vec{E}, & \vec{B}\rightarrow +\vec{B}, & \vec{S}\rightarrow +\vec{S} \\ \boldsymbol{T} & \vec{E}\rightarrow +\vec{E}, & \vec{B}\rightarrow -\vec{B}, & \vec{S}\rightarrow -\vec{S} \end{array}$$

Permanent EDMs of elementary particles violate both P and T symmetry, therefore CP must be violated

EDM Physics Motivation

- Standard Model has two explicit CP-violating parameters:
  - Complex phase appears in the Cabibbo–Kobayashi–Maskawa (CKM) matrix parametrizing quark weak interaction
  - $\bar{\theta}_{\mathrm{QCD}}$, coefficient of an allowed CP-violating term in Quantum Chromo-Dynamics (QCD) Lagrangian
- CKM contribution to EDM is many orders of magnitude smaller than current upper limits set by measurements
- Neutron EDM induced by strong CP violation scales as $d_n^{\bar{\theta}_{QCD}} \sim \bar{\theta}_{QCD} \times 10^{-16}\ e \cdot cm$. From neutron EDM upper limit, measured value of $\bar{\theta}_{\mathrm{QCD}}$ is $\leq 10^{-10}$, much smaller than naturally expected value of order of unity:
  - ➢ This apparent anomaly where QCD does not seem to violate CP symmetry is known as the Strong CP Problem
  - ➢ Existence of nonzero hadronic EDM may thus provide first evidence of CP violation in QCD, or evidence of CP-violating physics beyond Standard Model
- New sources of CP violation (beyond that present in Standard Model) are needed to explain matter-antimatter asymmetry in universe – more details in next slide

CP Violation and Matter-Antimatter Asymmetry

- Asymmetry parameter (relates overall number density difference between baryons and antibaryons and number density of cosmic background radiation photons):

$$\alpha = \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

- Measured: $\alpha = 10^{-10}$, Standard Model: $\alpha = 10^{-18}$

- CP violation would allow matter and antimatter to decay at different rates leading to a possible matter–antimatter asymmetry as observed today

- New CP violation sources beyond Standard Model are needed to explain predominance of matter over antimatter

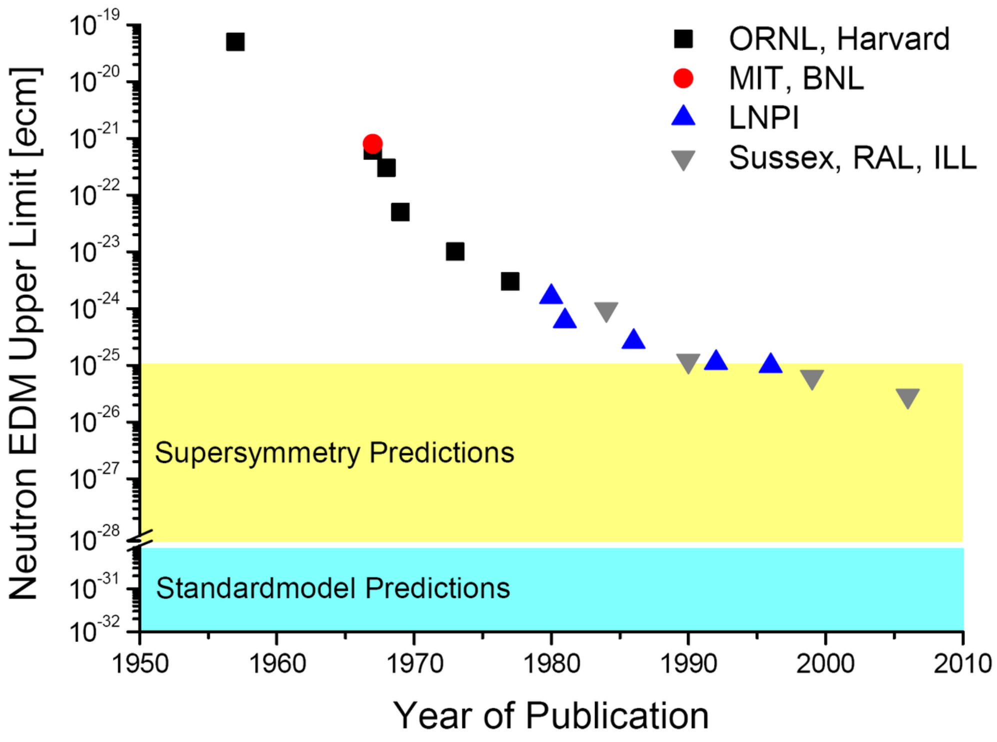
- Could show up in EDMs of elementary particles

EDM Searches in Storage Rings

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 $(\mathrm{e} \cdot \mathrm{cm})$**	**Standard Model $(\mathrm{e} \cdot \mathrm{cm})$**
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}



https://doi.org/10.1103/RevModPhys.91.015001

If neutron is size of Earth, this corresponds to charge separation of up and down quarks of size of an atom

Why Storage Rings?

- Any measurement of EDM relies on measuring spin precession rate in an electric field of a particle's rest frame, $\frac{d\vec{S}}{dt} = \vec{\mu} \times \vec{B}_{rest} + \vec{d} \times \vec{E}_{rest}$

- However, since an electric field leads to acceleration for charged particles, such measurement cannot be made while keeping particle at rest

- Therefore, to both apply an electric field and trap a charged particle, a storage ring must be used

- 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:

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

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

EDM Searches in Storage Rings

- Choices for storage rings:

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

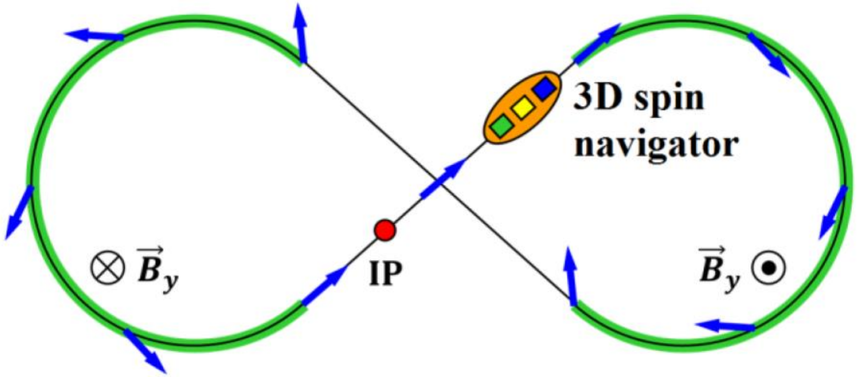
1. All-electric ring (B_y=0) with $\gamma^2 = 1 + \frac{1}{G}$, described as Magic-Energy (ME) or Frozen-Spin approach, works only for $\mathrm{G} > 0$ ($G_\mathrm{p} = 1.79$, $G_\mathrm{e} = 0.00116$):
   - ➢ Two experiments have been proposed to measure d_p with a sensitivity of $10^{-29}\ e \cdot cm$ at ME of 232.8 MeV: http://collaborations.fz-juelich.de/ikp/jedi/ , https://www.bnl.gov/edm/
   - ➢ **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 ($G_\mathrm{d} = -0.143$) 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

What is Spin Transparency (ST)

- In ST mode, any spin direction repeats after a particle turn along periodic orbit in storage ring
- It is 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

https://doi.org/10.1103/PhysRevLett.124.194801

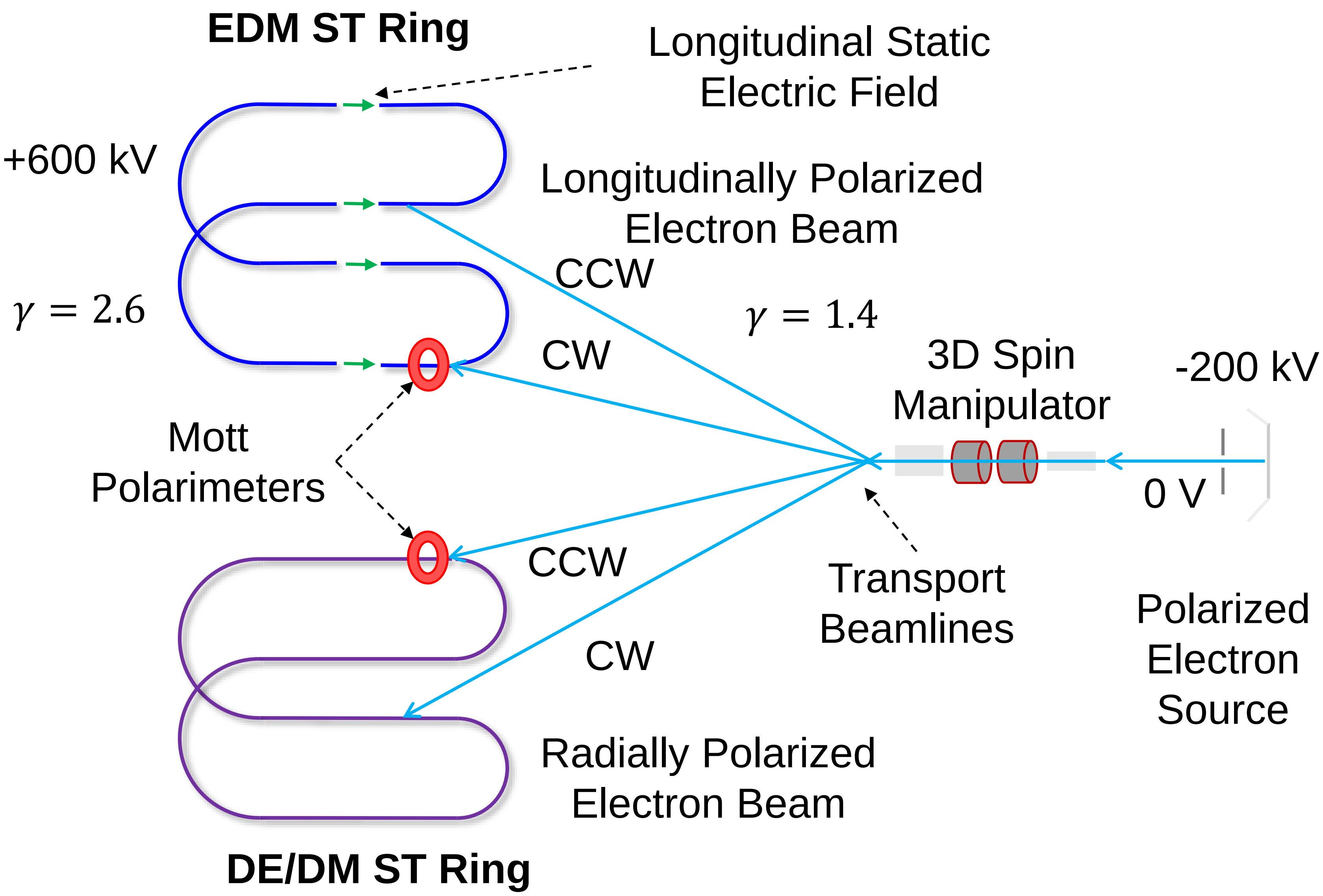
https://doi.org/10.3390/sym13030398



- Remaining challenge is to compensate for misalignments and spin decoherency due to beam emittances

Electron Spin-Transparent Storage Ring and EDM Precession Rate

Electron Experimental Schematics



EDM ST Ring

Longitudinal Static
Electric Field

+600 kV

Longitudinally Polarized
Electron Beam

CCW

$\gamma = 2.6$

$\gamma = 1.4$

CW

3D Spin
Manipulator

-200 kV

Mott
Polarimeters

0 V

CCW

Transport
Beamlines

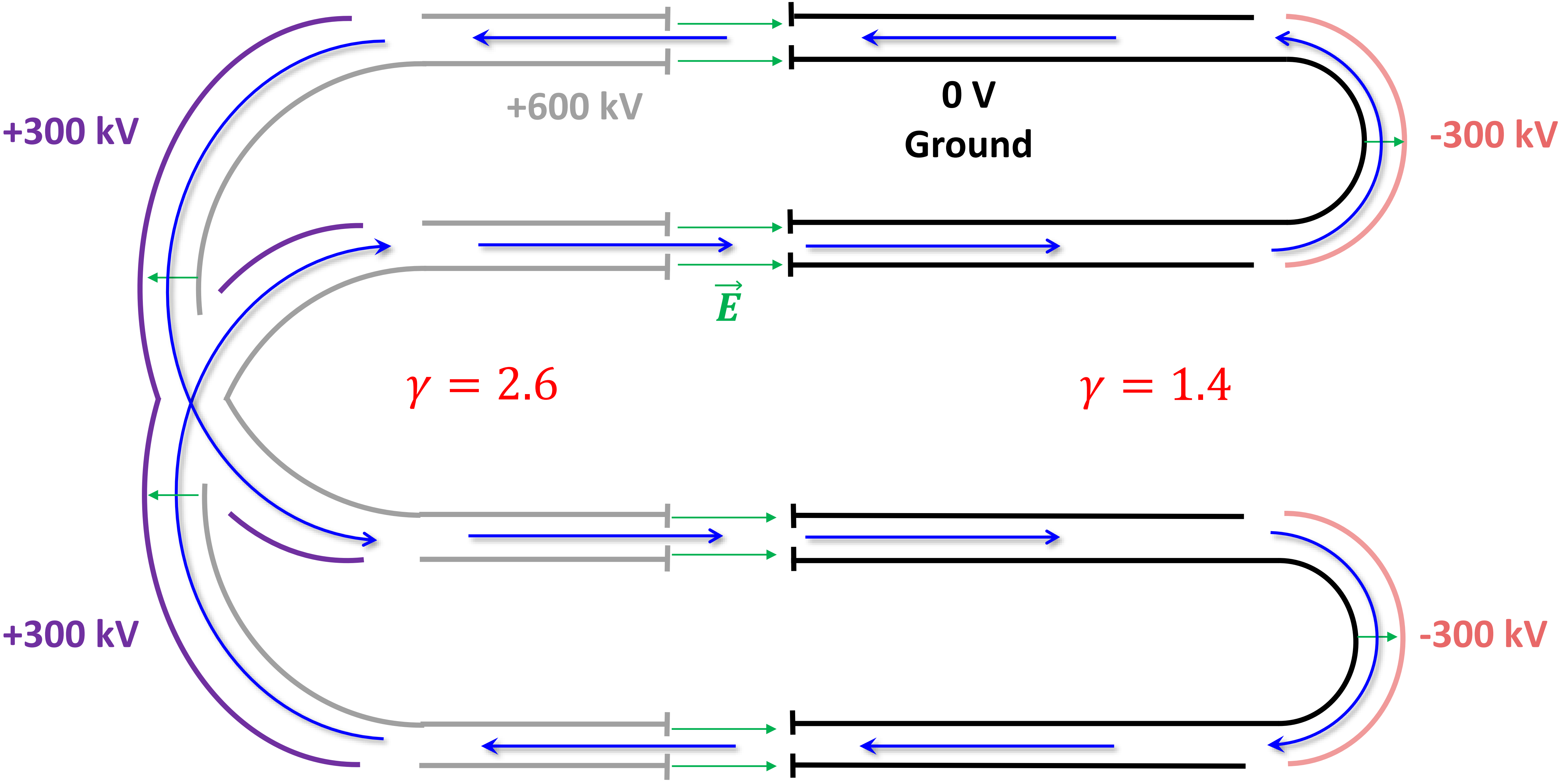
Polarized
Electron
Source

CW

Radially Polarized
Electron Beam

DE/DM ST Ring

Static Electric Fields of Electron EDM ST Ring



Example of Electrostatic Storage Ring

- https://www.desiree-infrastructure.com/
- https://doi.org/10.1063/1.3602928

- Two 8.6 m circumference storage rings in a 13 K chamber

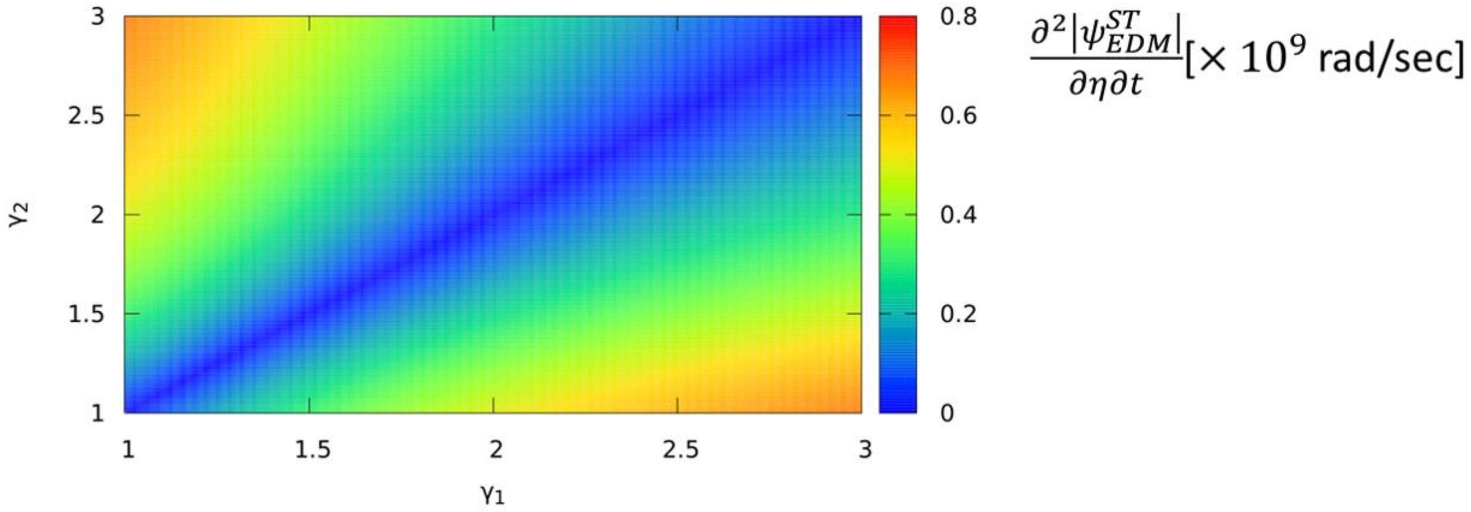
EDM Spin Field

- ST ring consists of two low-energy and two high-energy arcs connected by longitudinal field sections to provide acceleration/deceleration
- This preserves suppression of MDM effect but removes degeneracy of EDM spin precession
- Spin transparency condition satisfied when each arc bends by exactly π radians
- A straightforward way to obtain EDM spin rotation per turn, $\partial|\psi_{EDM}|/\partial N$, is to treat EDM signal as a perturbation of MDM spin motion on closed orbit:

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

EDM in ST Storage Ring

- $d_e = 10^{-29}\ e \cdot cm,\ \eta = 1.04 \cdot 10^{-18}$
- 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

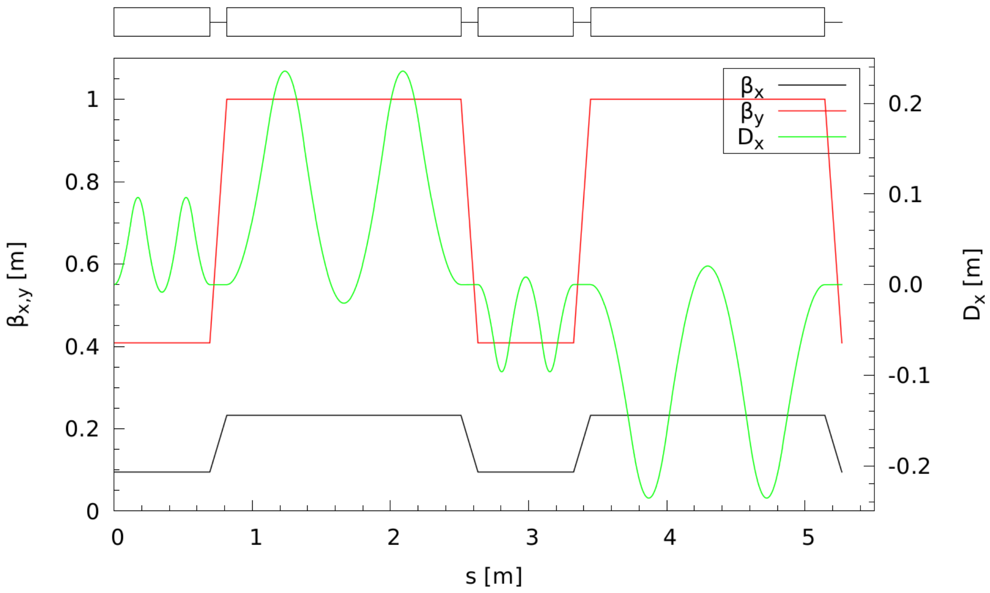


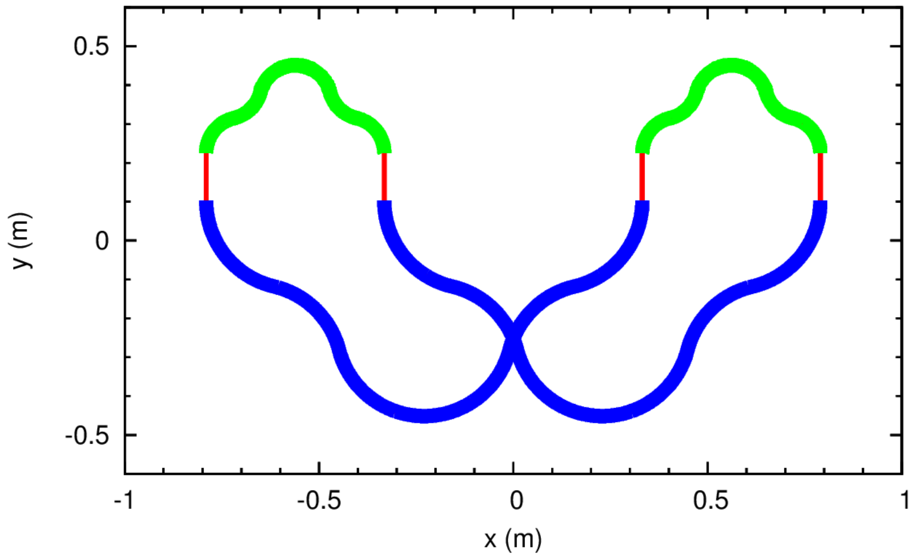
Scheme	γ	$\left\lvert\frac{\partial^2|\psi_{EDM}|}{\partial\eta\partial N}\right\rvert$ **[rad]**	$\left\lvert\frac{\partial^2|\psi_{EDM}|}{\partial\eta\partial t}\right\rvert$ **[$\times 10^9$ rad/sec]**	$\left\lvert\frac{\partial|\psi_{EDM}|}{\partial t}\right\rvert$ **[nrad/sec]**
ME ring	29.38	92.24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

Electron EDM Ring Details

EDM Optics Design and Ring Footprint

- Due to change of bending direction from arc to arc, each arc has to be achromatic
- Use weak-focusing achromatic arc design – https://doi.org/10.1016/0168-9002(85)90585-6
- Assuming bending electric field of $E = 5$ MV/m and $\gamma = 2.6$, $\rho_{min} = \frac{m\gamma v^2}{|qE|} = \frac{mc^2(\gamma^2-1)}{|qE|\gamma} \simeq 22.6\ \mathrm{cm}$
- Optics and ring size scales with momentum
- Combined function electrostatic elements
- Optical match by scaling arc size





Intra-Beam Scattering and Stochastic Cooling

- Use Conte-Martini in MAD-X to find a combination of transverse emittances and momentum spread resulting in adequate IBS times for cooled and uncooled cases
- Coasting beam
- Accounts for
  - coupling of IBS rates
  - damping/anti-damping
  - optics scaling
  - difference in geometric size of and in amount of charge stored in each energy section
- 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

➢ Typical time of stochastic cooling with $N = 6.25 \cdot 10^9$ particles and bandwidth $W = 0.5$ GHz:

$$\tau \sim \frac{N}{2W} \sim 6 \text{ sec}$$

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, $\mathrm{N_e}$	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

Space Charge

- Another potential limitation on amount of stored charge comes from betatron tune shifts $\Delta\nu_{x/y}^{sc}$ due to space charge fields
- Using cooled beam parameters, direct space-charge tune shift is $\Delta\nu_{x/y}^{sc} = 0.84/2.7 \times 10^{-3}$
- More importantly, each stored beam experiences field of counter-rotating beam. Its local effect is a factor of $\gamma^2(1+\beta^2)$ stronger than self-field interaction. Resulting tune shift is a factor of about 6.5 greater than that of a single beam. Fortunately, it is still much less than typical threshold of 0.1.
- Strong Landau damping due to large energy spread at equilibrium prevents development of Coulomb intra-beam and counter-beams instabilities

Incoherent (Single Electron) Synchrotron Radiation

- For electrons with $\gamma_2 = 2.6$, power radiated by a single electron in free space is estimated to be about 187 eV/s and for $\gamma = 29.38$ (ME case) synchrotron radiation is about 35 keV/s per single electron

$$P_{FS} = \frac{e^2 c \beta^4 \gamma^4}{6\pi\epsilon_0 \rho^2}$$

- For ST ring, and since $\gamma_2 < \sqrt{R_2/a}$ where R_2 is ring bending radius and a is half electrode spacing, synchrotron radiation is drastically suppressed by shielding effect

- In contrast, there is no such shielding effect in ME ring and synchrotron radiation is another major drawback when compared to low energy ST ring

Beam Lifetime and Spin Coherence Time (SCT)

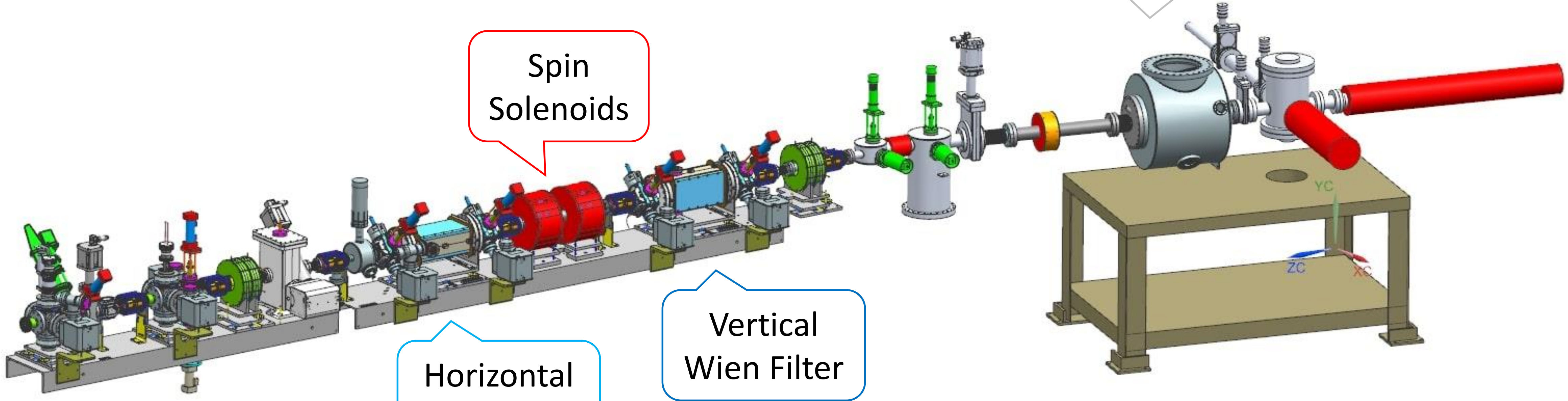
- Beam lifetime:
  - Stochastic Cooling will overcome IBS effect
  - Expected lifetime due to beam-beam interaction is estimated to be 15000 s
- SCT is time beam stays polarized in storage ring – a long polarization lifetime is required since this is time available to accumulate and observe EDM signal
  - ST ring spin tune is energy independent, energy spread does not contribute to depolarization in first order
  - Main limitation comes from spin tune spread due to beam emittances
  - Limitation due to emittance of beam under stochastic cooling still needs to be analyzed
  - SCT was estimated to be around 10000 s, which is comparable to beam lifetime noted above

Polarized Electron Source and Electron Polarimetry

Polarized Source and 3D Spin Manipulator

https://link.aps.org/doi/10.1103/PhysRevSTAB.13.010101

https://accelconf.web.cern.ch/pac2011/papers/tup025.pdf



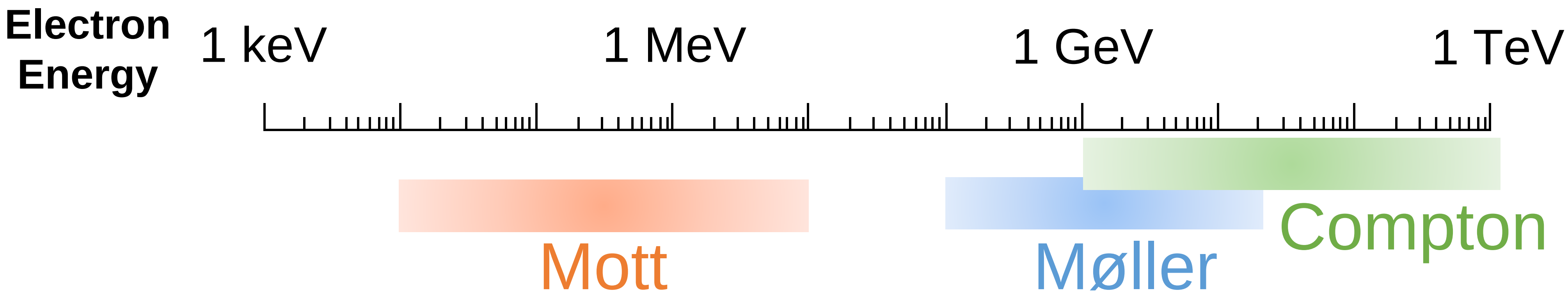
200 keV polarized Electron Gun

Spin Solenoids

Vertical Wien Filter

Horizontal Wien Filter

Practical Electron Polarimetry



- Mott Polarimeter: Measure transverse polarization. Above 10 MeV maximum analyzing power close to 180 degrees (cross section very small and approaches incident beam direction).

- Møller Polarimeter: Measure longitudinal polarization. Requires magnetized ferromagnetic materials as a source of polarized target electrons. Below 20 GeV to separate scattered electrons from incident beam.

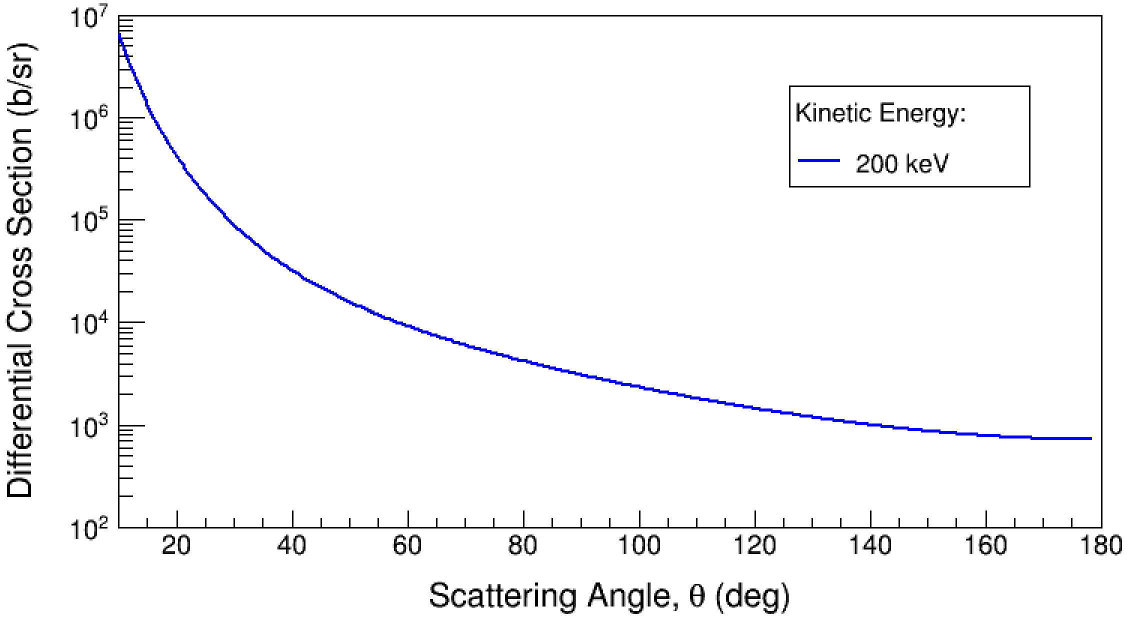
- Laser Compton Polarimeter: Measure longitudinal polarization. Below 1 GeV asymmetry is too small.

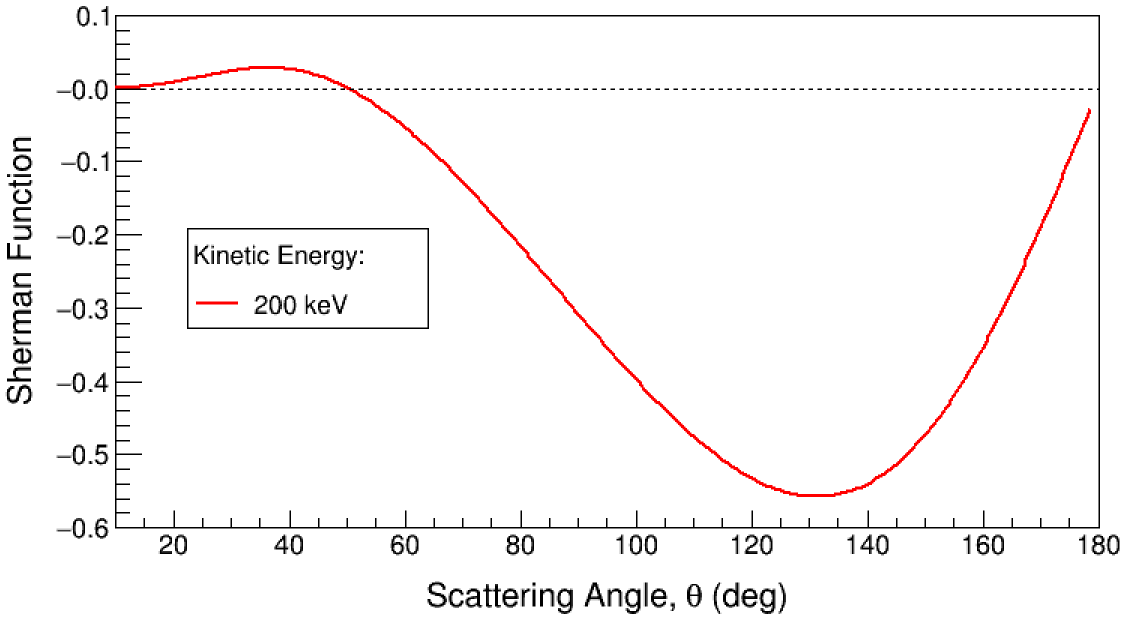
- Compton Transmission Polarimeter: Measure longitudinal polarization. Associated with beam dumps. Detects secondary gammas after passing through magnetized iron. Works above few MeV.

https://doi.org/10.1142/S0218301318300047

Mott Polarimetry

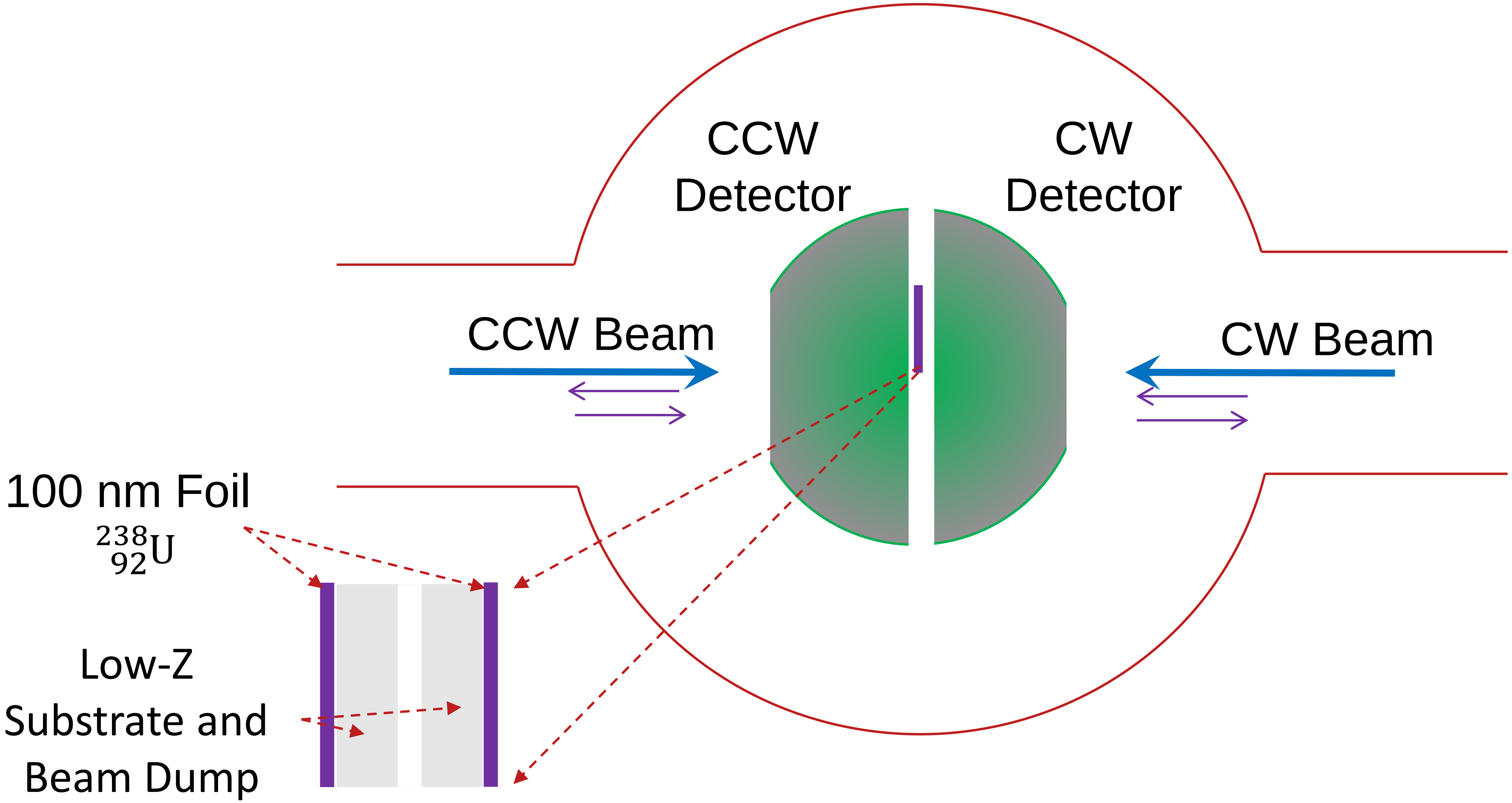
- Electron kinetic energy of 200 keV ($\gamma = 1.4$, $\beta = 0.70$) scattering from 100 nm uranium-238 foil (5×10^{17} atoms/cm^2)
- Measure both vertical polarization and horizontal polarization at same time





- An example of Mott polarimeter: https://doi.org/10.1103/PhysRevC.102.015501

Mott Polarimeter Design



Detector Coverage:

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

Statistical and Systematic Uncertainties

EDM Statistical Uncertainty

- Statistical uncertainty per fill with continuous Mott measurements:

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

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

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

- In one year:

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

With expectation that further optimization and improvements will lower this limit

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

Sources of Systematic Uncertainties

- Both proton EDM collaborations have done extensive studies:
  - Many sources have been identified: background magnetic fields, vertical velocity, errors in construction and alignment, vertical E-field, …

    https://doi.org/10.23731/CYRM-2021-003

    https://arxiv.org/abs/2007.10332

  - Counter-rotating beams (and 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
- Mott Polarimetry related systematic uncertainties

➢ **New Design: use RF accelerating/deaccelerating instead of static electric field, *i.e.*, bunched instead of coasting beam**

Dark Energy and Dark Matter

Dark Energy and Dark Matter (DE/DM)

- Interaction of axion (ultra-light dark matter and dark energy particle) with electrons contains this term:

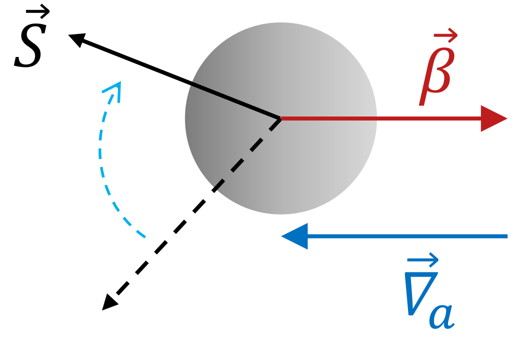
https://doi.org/10.1103/PhysRevD.103.055010

$$\mathcal{H} \ni -g_a \vec{\nabla}_a \cdot \vec{S}$$

$$\vec{\nabla}_a = \gamma m_a \beta_a$$

Gradient of axion field (axion momentum)
Note: Relativistic speed enhances signal

m_a	Axion Mass
β_a	Axion Velocity in Electron Rest Frame
γ	Lorentz Factor (cancels in Lab Frame due to Time Dilation)



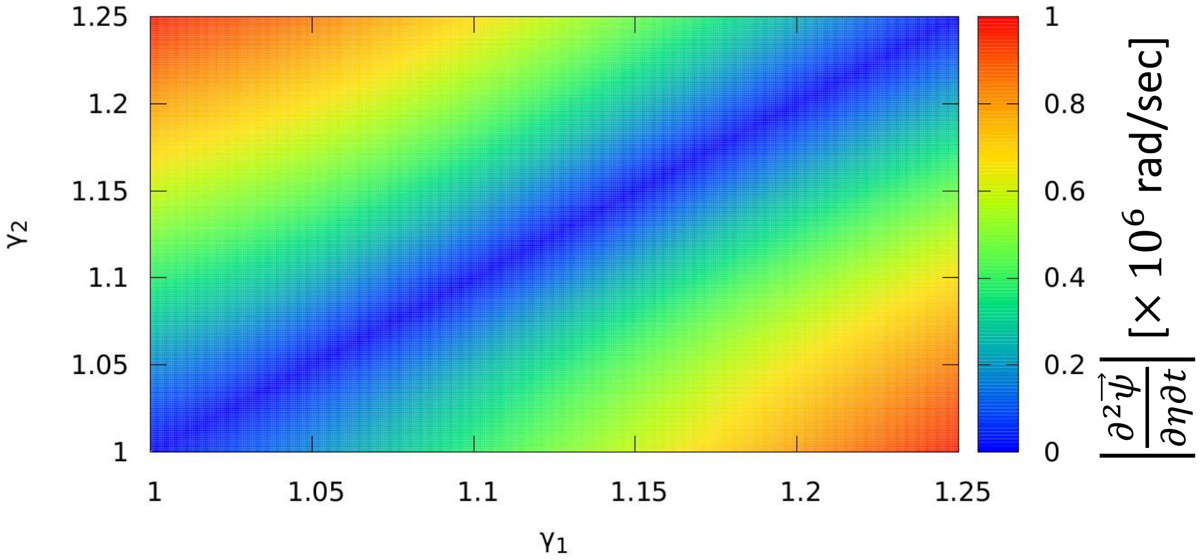
- Spin of radially polarized electrons will precess around electron’s velocity

- DE/DM ring is similar to EDM ring but without longitudinal electric field – counter rotating electron beams stay at one energy level

Spin-Transparency and Proton EDM Search

Applying ST to Proton EDM Search (Similar to Electron)?

- $d_p = 10^{-29}\ e \cdot cm,\ \eta = 1.9 \cdot 10^{-15}$
- Assume E fields of 10 MV/m
- When $\gamma_1 = 1.050$ and $\gamma_2 = 1.051$, $|\psi| \simeq 0.006\eta$



Scheme	γ	$\left\lvert\frac{\partial^2\vec{\psi}}{\partial\eta\partial N}\right\rvert$ **[rad]**	$\left\lvert\frac{\partial^2\lvert\psi_{EDM}\rvert}{\partial\eta\partial t}\right\rvert$ **[**$\times 10^6$ **rad/sec]**	$\left\lvert\frac{\partial\lvert\psi_{EDM}\rvert}{\partial t}\right\rvert$ **[nrad/sec]**
ME ring	1.248	2.35	1.60	3.04
ST ring	$(1.050, 1.051)$	0.006	0.0047	0.009

- Hard to generate a sufficiently large modulation of γ, especially with static fields, for protons to compete with ME

However, applying ST as a new approach to proton and deuteron is under study by a German-Russian collaboration

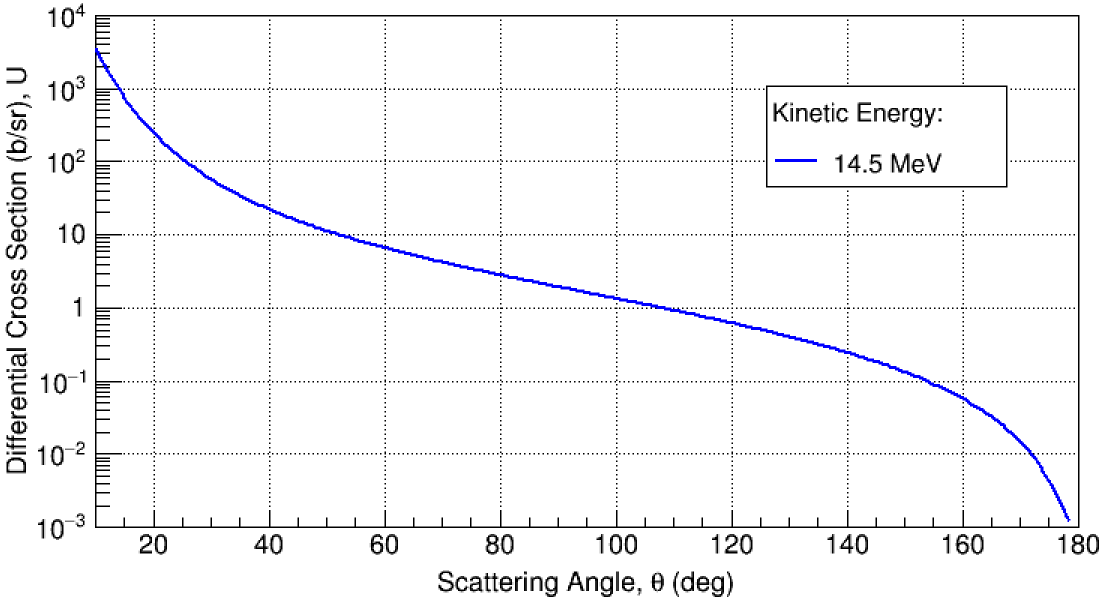
Summary

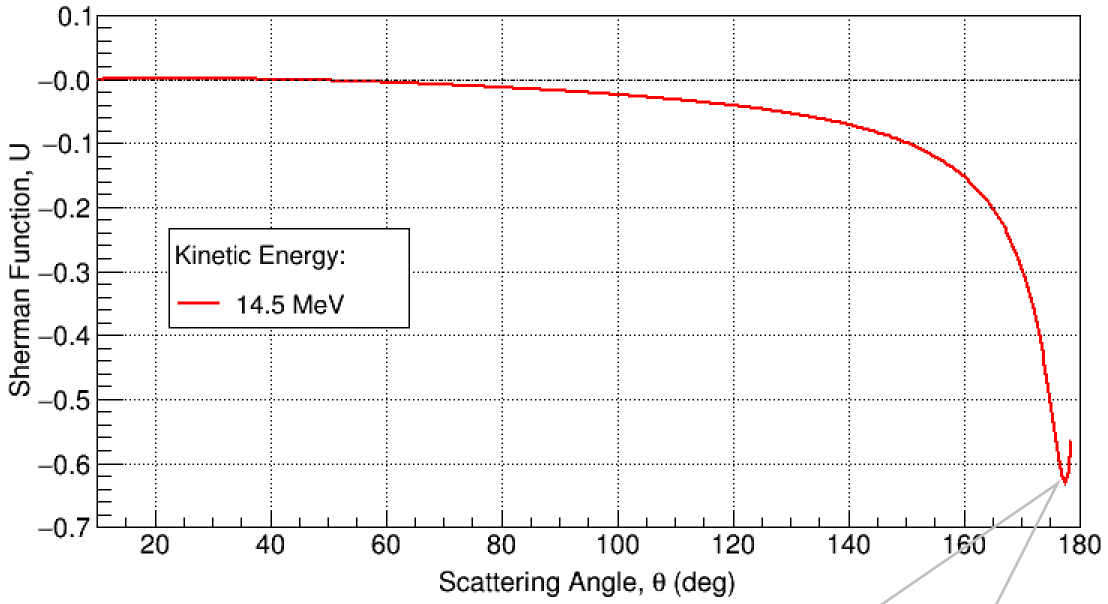
- We presented new method for a direct measurement of $d_e = 10^{-29}\ e \cdot cm$ and to search for DE/DM using small ST rings in energy range below 1 MeV
- Presented approach has following advantages:

  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

Thank you

Mott Polarimetry at Electron Magic Energy





Maximum at 177.5 deg, very close to incident beam direction

Electron Kinetic Energy	Mott Polarimeter	ϵ	A_y	FOM
200 keV	$\theta: 90° \rightarrow 160°$ 100 nm ^{238}U	0.0024	0.45	$\mathbf{4.9 \times 10^{-4}}$
14.5 MeV	$\theta: 90° \rightarrow 177°$ 4 µm ^{238}U	0.000044	0.033	$\mathbf{6.2 \times 10^{-8}}$

Particle/ Nucleus	**Anomalous Magnetic Moment** $G_M = \frac{g-2}{2}$	**Spin - Parity**
e	0.00116	$\frac{1}{2}^+$
μ	0.00117	$\frac{1}{2}^+$
n	-2.91	$\frac{1}{2}^+$
p	1.79	$\frac{1}{2}^+$
d	-0.143	1^+