

EDM in Small Rings

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

R. Suleiman, V. S. Morozov, and Ya. S. Derbenev

 Jefferson Lab

SPIN2021



Matsue, Japan

24th International Spin Symposium
October 18 -22, 2021

EDM Searches in Storage Rings

- Choices for storage rings:

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

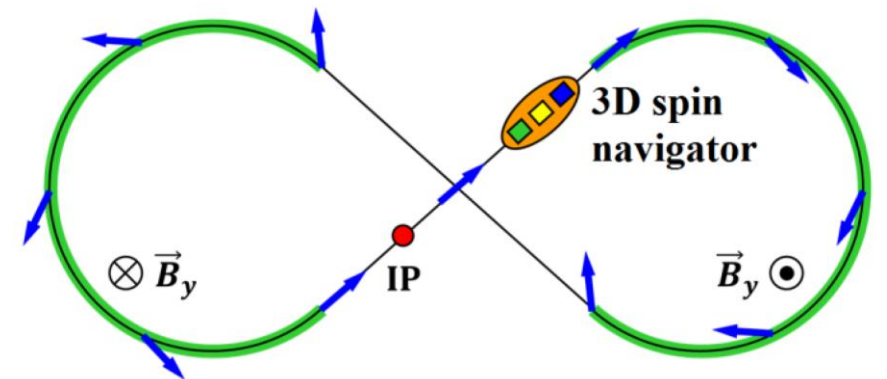
1. All-electric ring ($B_y=0$) with $\gamma^2 = 1 + \frac{1}{G}$, described as Magic-Energy (ME) or Frozen-Spin approach, works only for $G > 0$:
 - Two experiments have been proposed to measure d_p with a sensitivity of $10^{-29} e \cdot cm$ at ME of 232.8 MeV (<https://indico2.riken.jp/event/3082/contributions/17020/>)
 - **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 ($G = -0.143$) 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

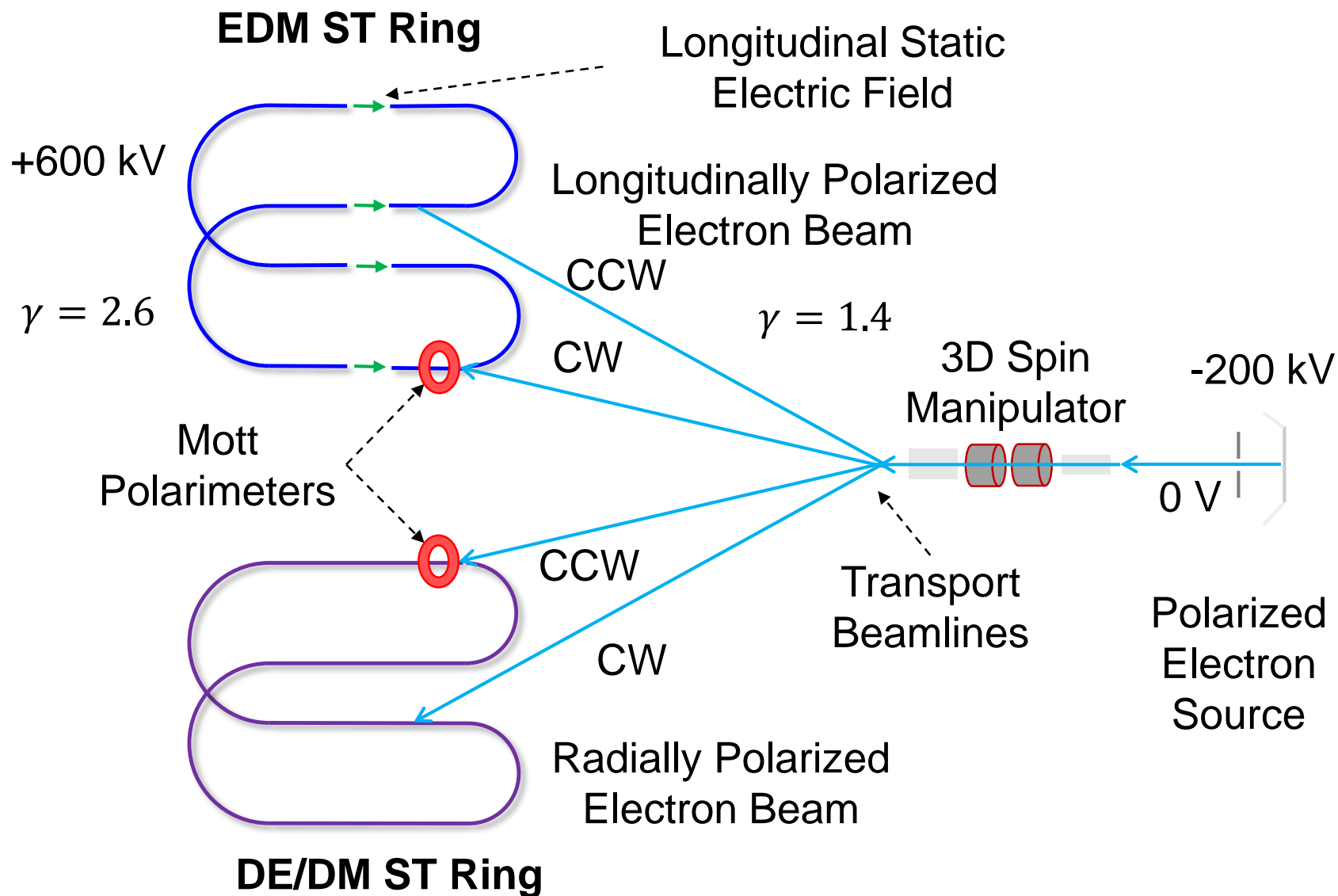
<https://doi.org/10.1103/PhysRevLett.124.194801>

<https://doi.org/10.3390/sym13030398>

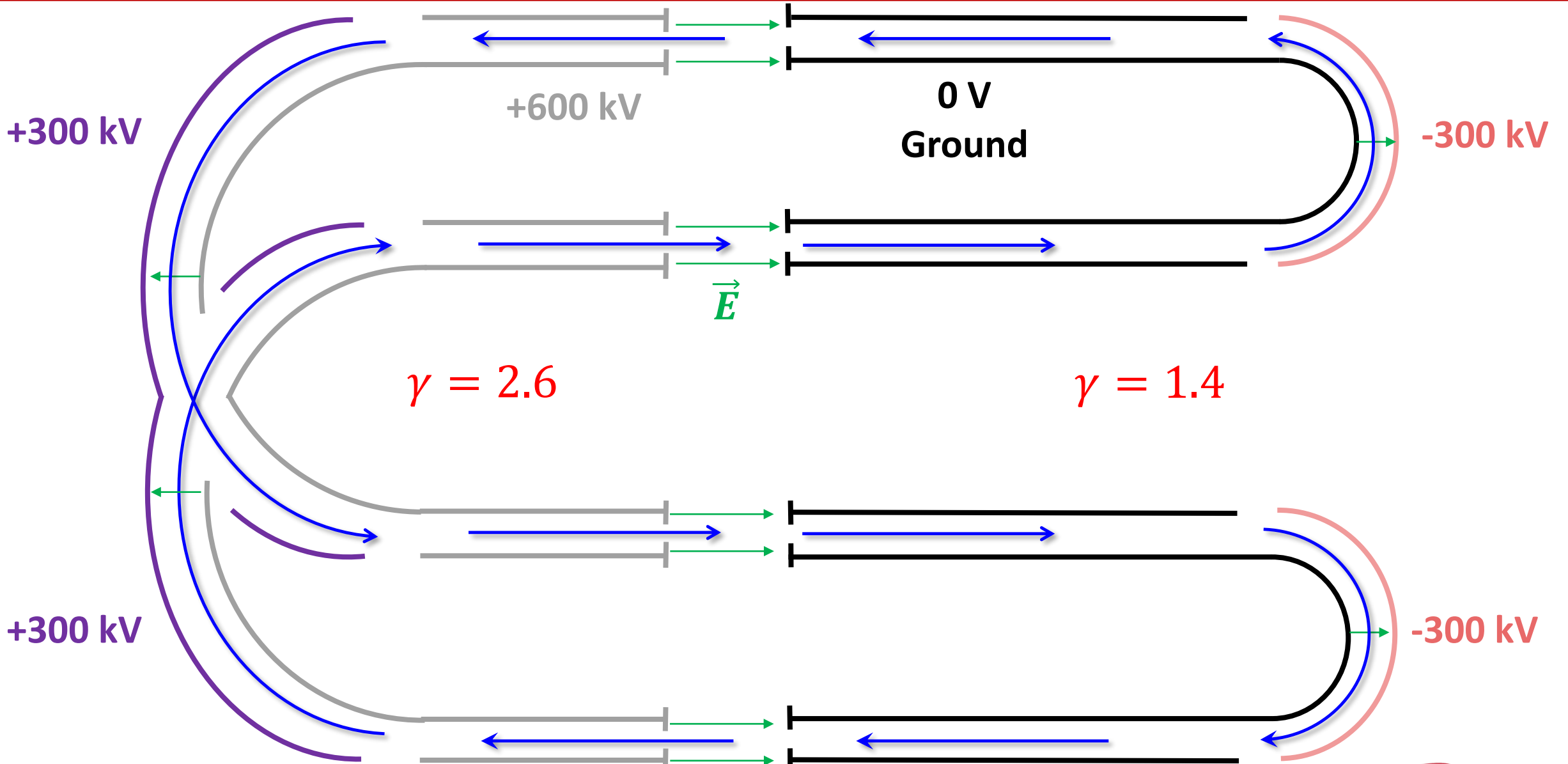


- Remaining challenge is to compensate for misalignments and spin decoherency due to beam emittances
- Details about Spin Transparency are presented in this talk:
<https://indico2.riken.jp/event/3082/contributions/17054/>

Electron Experimental Schematics



Static Electric Fields of Electron EDM ST Ring



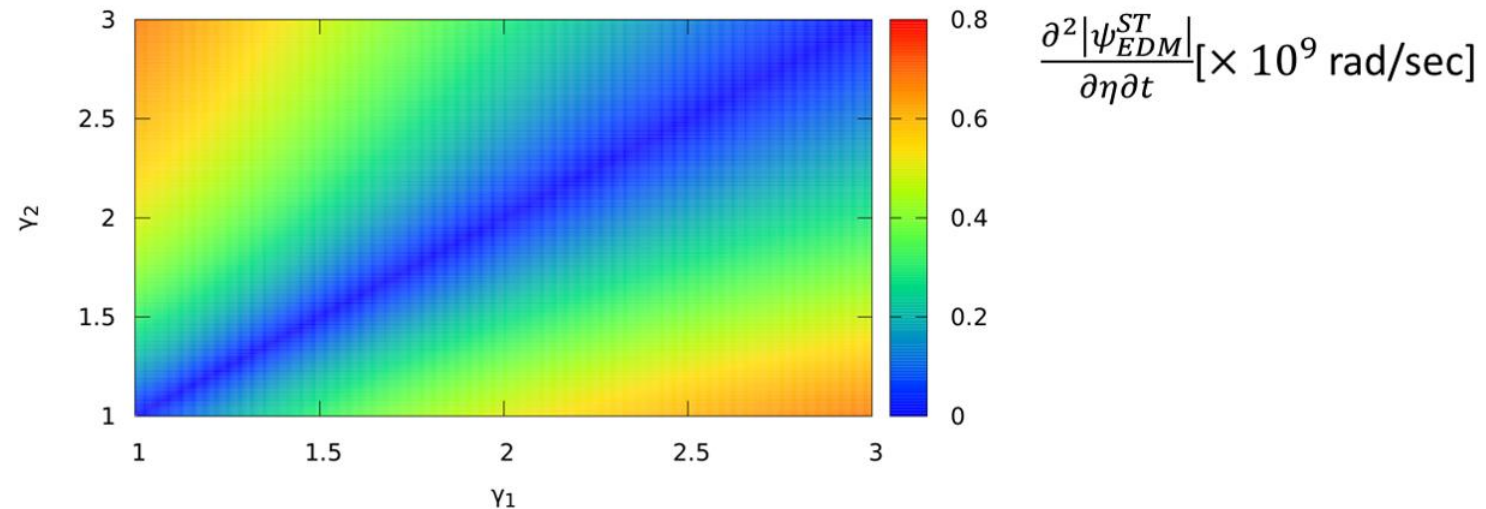
EDM Spin Field

- 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

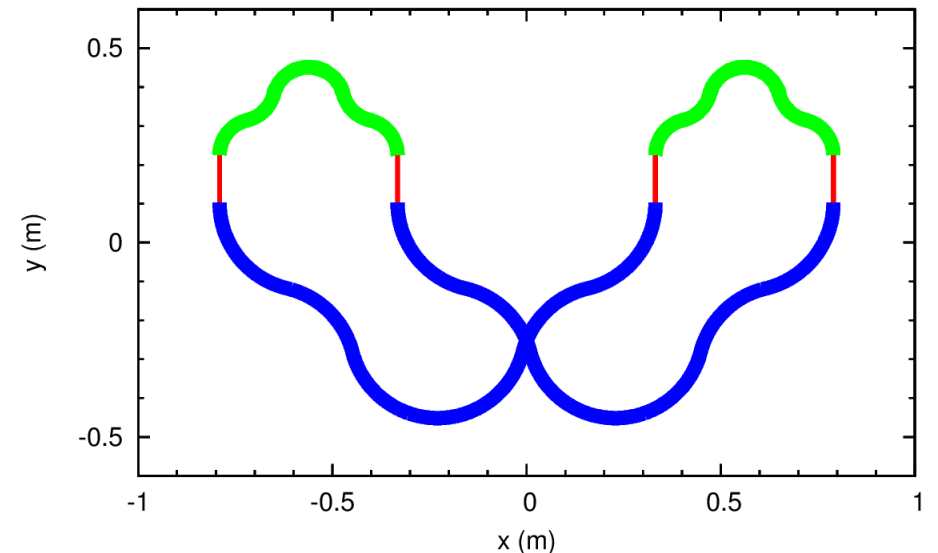
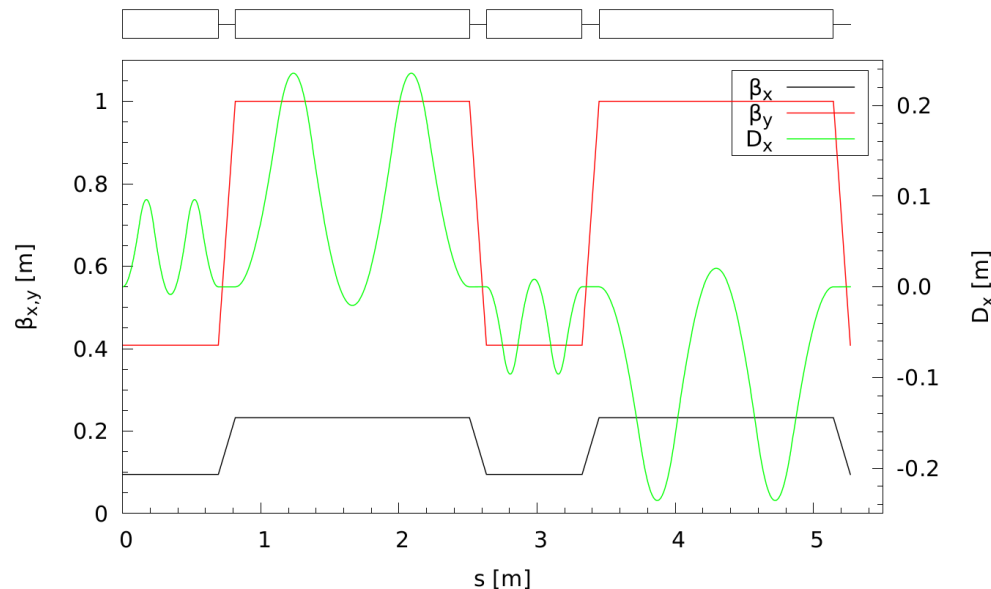
- $d_e = 10^{-29} e \cdot cm, \eta = 1.04 \cdot 10^{-18}$
- EDM spin rotation per unit η and unit time is $\frac{\partial^2 |\psi_{EDM}|}{(\partial\eta\partial t)} = f_c \frac{\partial^2 |\psi_{EDM}|}{(\partial\eta\partial N)}$ where f_c is beam circulation frequency
- Assume bending and accelerating/decelerating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



Scheme	γ	$\left \frac{\partial^2 \psi_{EDM} }{\partial\eta\partial N} \right $ [rad]	$\left \frac{\partial^2 \psi_{EDM} }{\partial\eta\partial t} \right $ [$\times 10^9$ rad/sec]	$\left \frac{\partial \psi_{EDM} }{\partial t} \right $ [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

- 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](https://doi.org/10.1016/0168-9002(85)90585-6)
- Assuming bending electric field of $E = 5$ MV/m and $\gamma = 2.6$, $\rho_{min} = \frac{m\gamma v^2}{|qE|} = \frac{mc^2(\gamma^2-1)}{|qE|\gamma} \simeq 22.6$ 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 $\varepsilon_x, \varepsilon_y$ 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 $\varepsilon_x, \varepsilon_y$ 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, 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

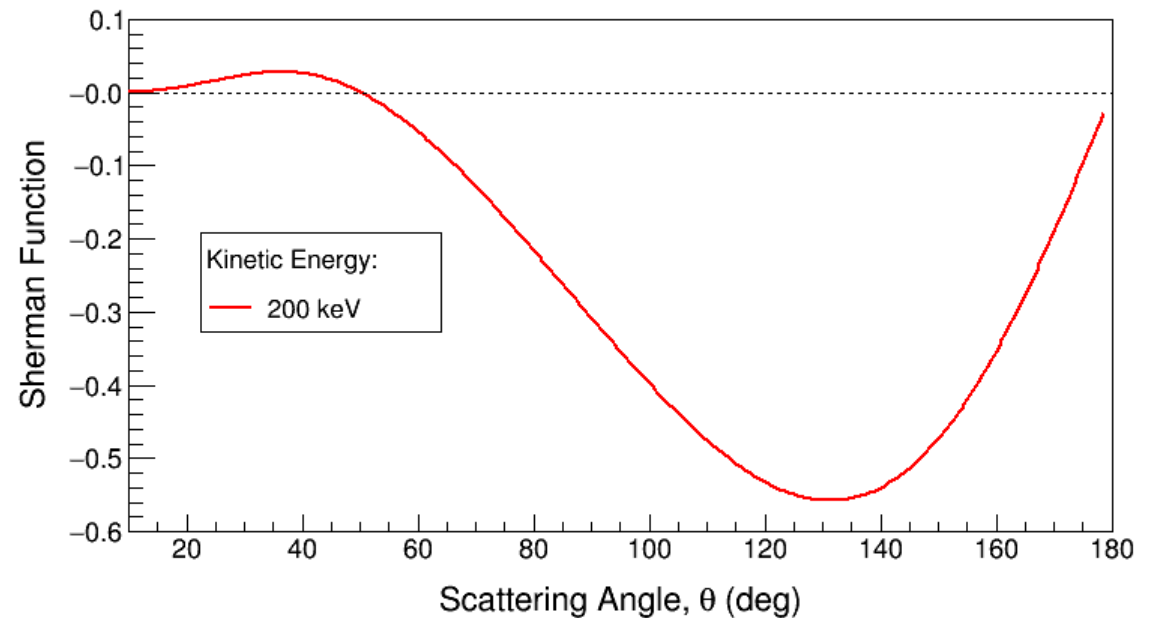
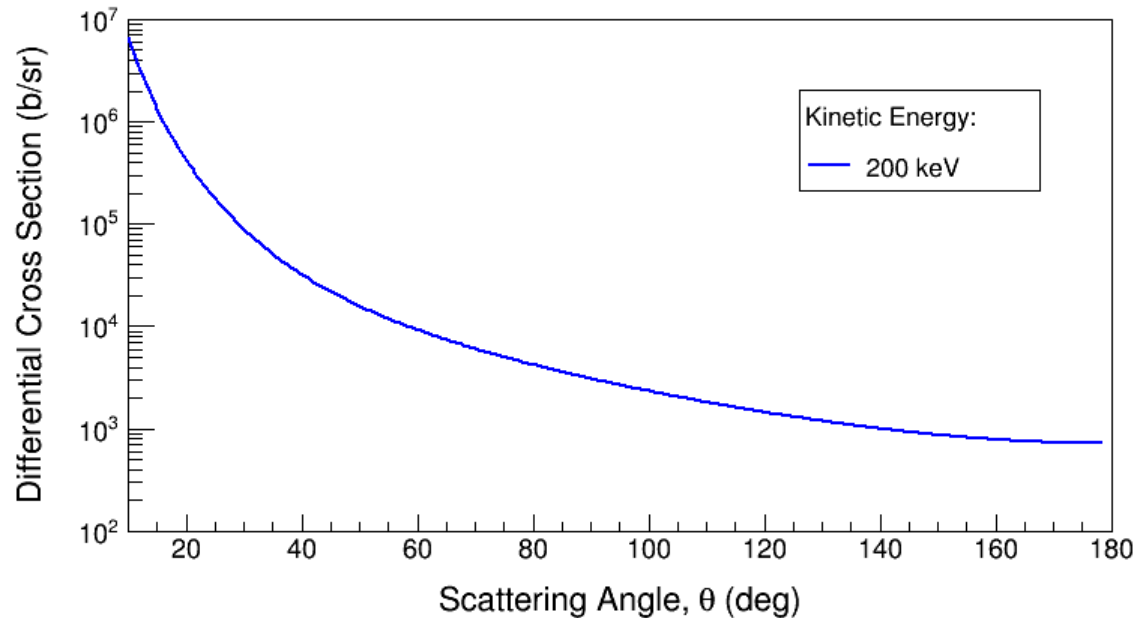
- Another potential limitation on amount of stored charge comes from betatron tune shifts $\Delta\nu_{x/y}^{SC}$ due to space charge fields
- Using cooled beam parameters, direct space-charge tune shift is $\Delta\nu_{x/y}^{SC} = 0.84/2.7 \times 10^{-3}$
- More importantly, each stored beam experiences 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

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

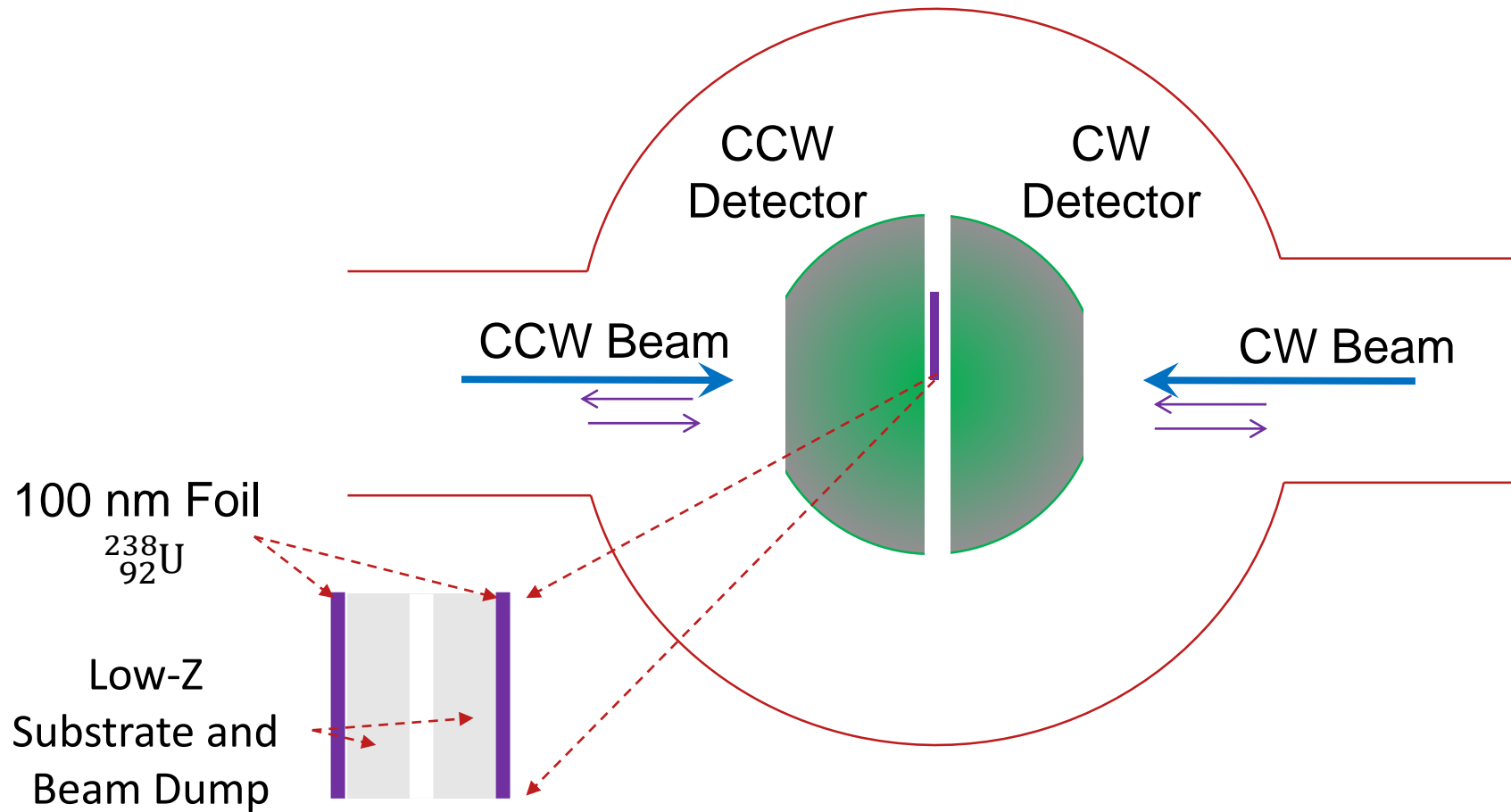
Mott Polarimetry

- Electron kinetic energy of 200 keV ($\gamma = 1.4$, $\beta = 0.70$) scattering from 100 nm uranium-238 foil (5×10^{17} atoms/cm²)
- Measure both vertical polarization and horizontal polarization at same time



- An example of Mott polarimeter: <https://indico2.riken.jp/event/3082/contributions/17131/>

Mott Polarimeter Design



Detector Coverage:

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

EDM Statistical Uncertainty

- Statistical uncertainty per fill with continuous Mott measurements:

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

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

- In one year:

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

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 $1 \cdot 10^{-29} e \cdot cm$)
Spin Coherence Time	SCT	10000 s

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.)

<https://indico2.riken.jp/event/3082/contributions/17317/>

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 (DE/DM)

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

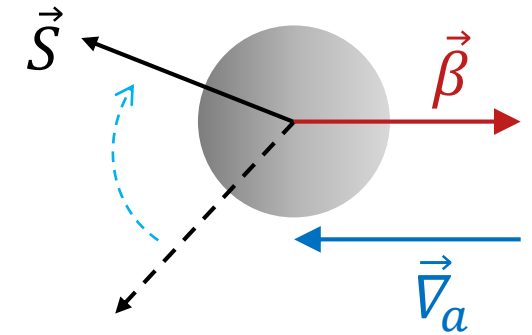
$$\mathcal{H} \ni -g_a \vec{\nabla}_a \cdot \vec{S}$$

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

[10.1103/PhysRevD.103.055010](https://arxiv.org/abs/10.1103/PhysRevD.103.055010)

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

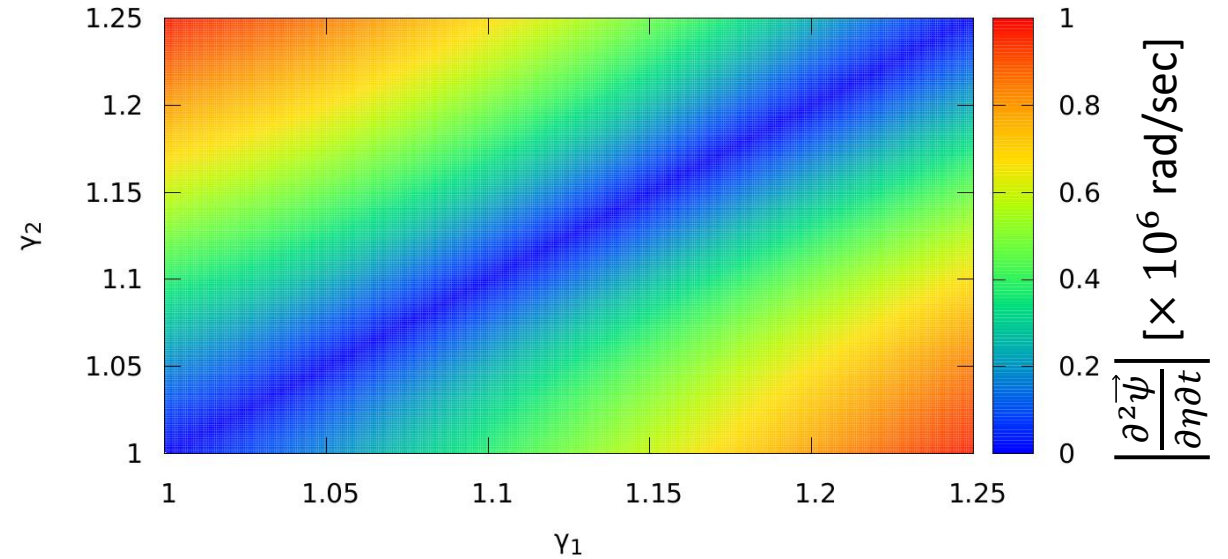
- m_a Axion Mass
- β_a Axion Velocity in Electron Rest Frame
- γ Lorentz Factor (cancels in Lab Frame due to Time Dilation)



- 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

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

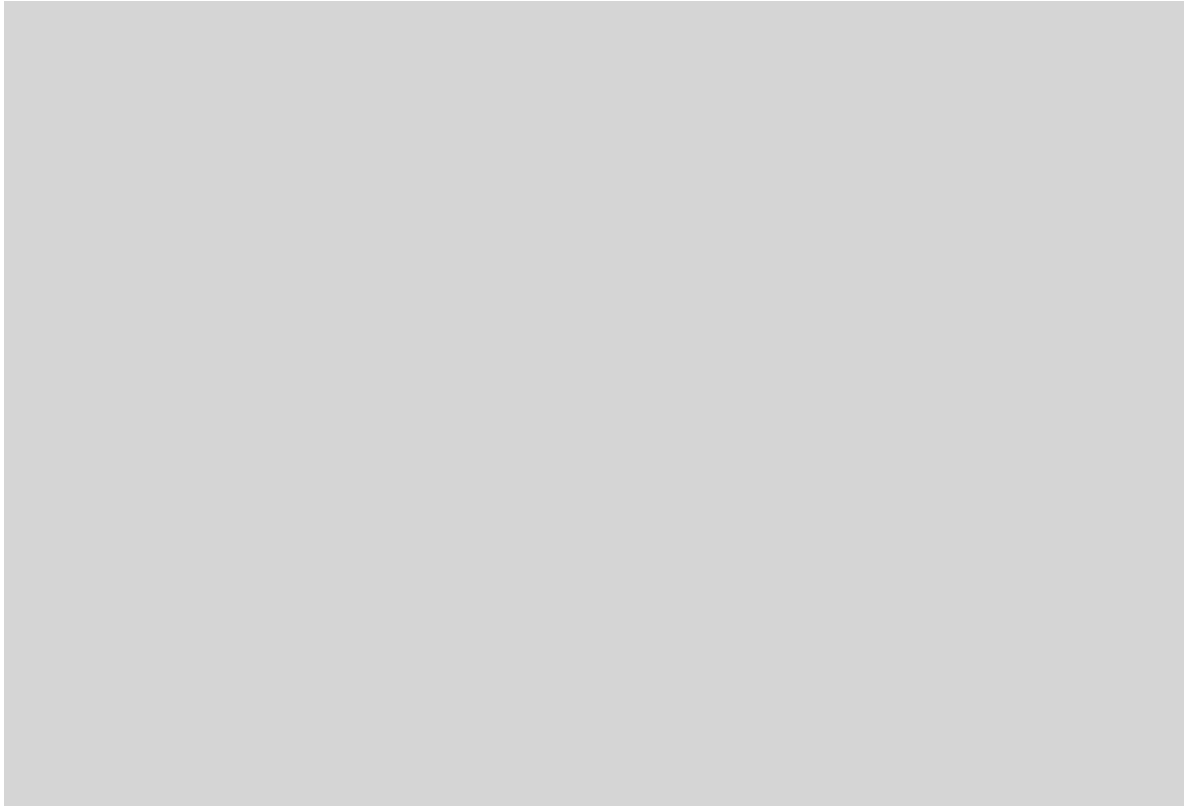
- Hard to generate a sufficiently large modulation of γ , especially with static fields, for protons to compete with ME

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

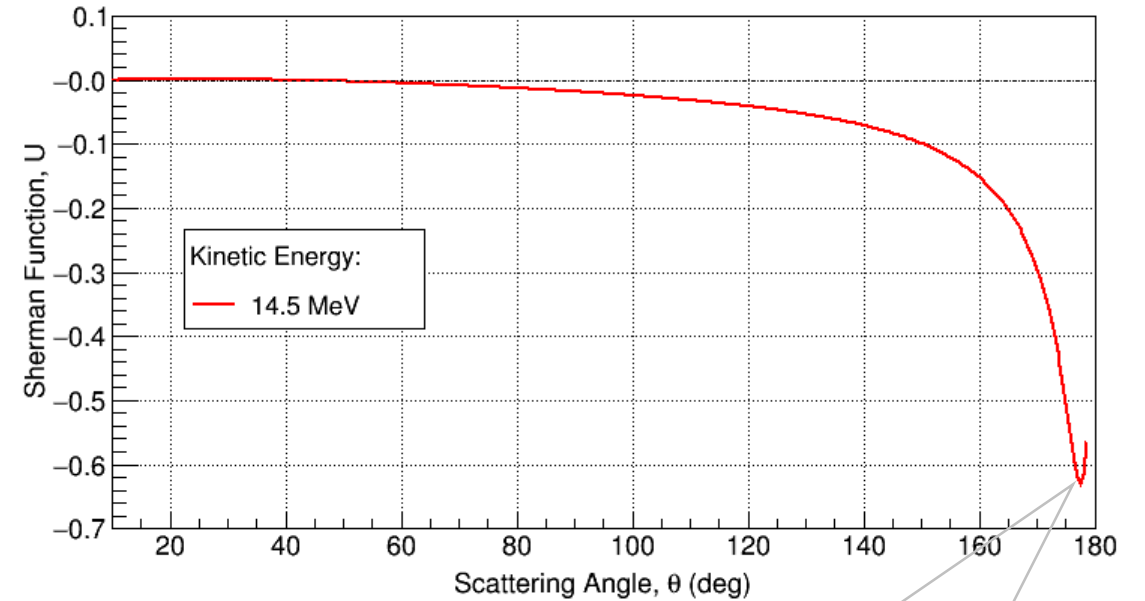
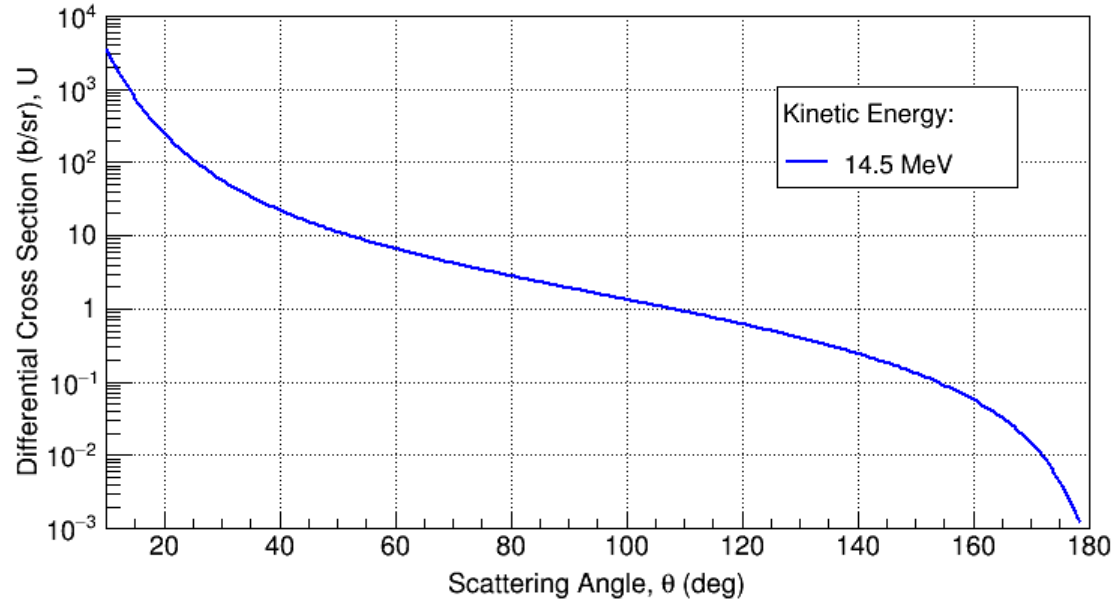
Summary

- 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: <https://arxiv.org/abs/2105.11575>
 - **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	$\theta: 90^\circ \rightarrow 160^\circ$ 100 nm ^{238}U	0.0024	0.45	4.9×10^{-4}
14.5 MeV	$\theta: 90^\circ \rightarrow 177^\circ$ 4 μm ^{238}U	0.000044	0.033	6.2×10^{-8}