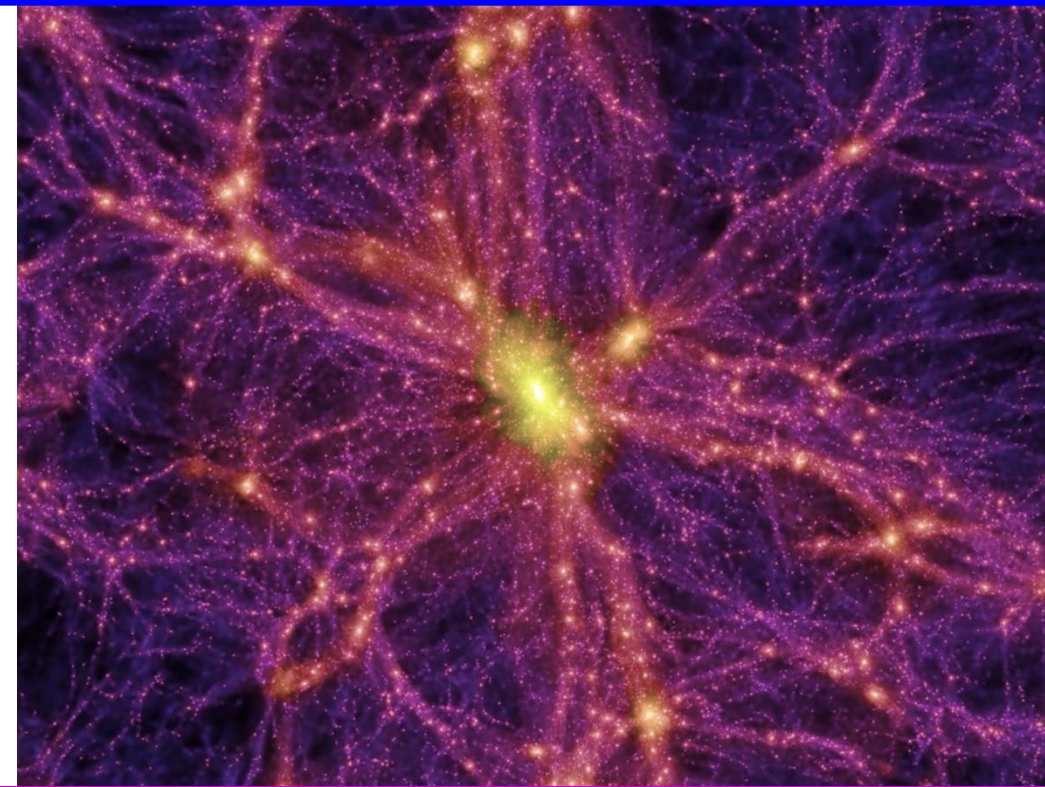
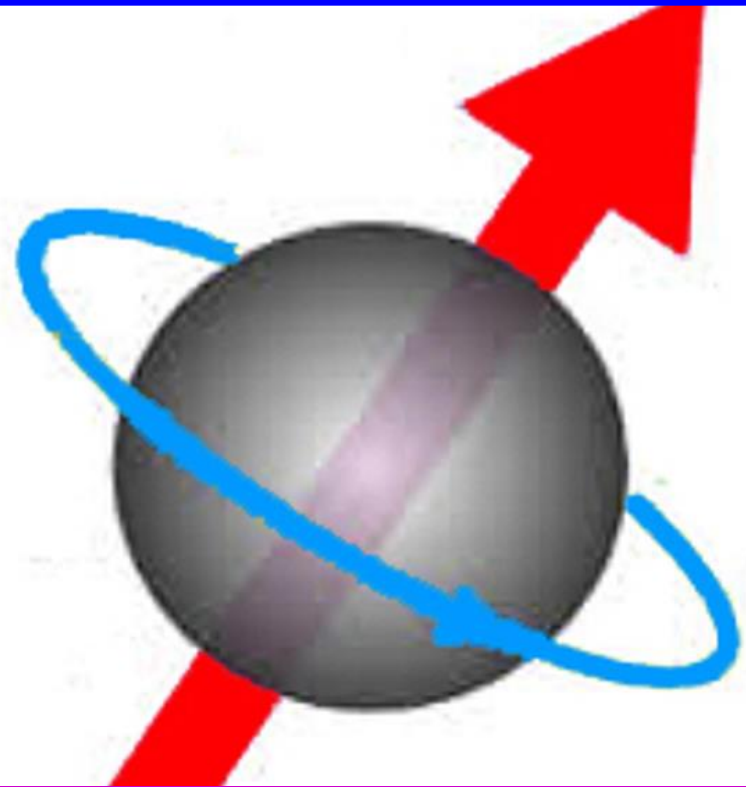


High Precision Fundamental Physics Experiments with Particle Accelerator Compact Spin-transparent Storage Rings of Low-energy Polarized Electron / Positron Beams



Vladimir Khachatryan
Mississippi State University

Riad Suleiman
Jefferson Lab

Low Energy Electron Positron Physics Workshop
Jefferson Lab, Newport News, VA
March 23-27, 2026



Outline

1. Introduction and Motivation
2. Spin-transparent (ST) Storage Ring Concept and Design
3. Polarized Electron Source and Mott Polarimetry
4. Electron EDM Expected Statistical Limit / Systematic Uncertainties
5. Ultra-light (Axion) Dark Matter Search
6. ST Concept Development in Progress: Positron Beams
7. Summary and Outlook

1. Introduction and Motivation

- Presentation slides mostly based on three papers of Riad and collaborators

High precision fundamental physics experiments using compact spin-transparent storage rings of low energy polarized electron beams; Phys Lett B 843, 138058 (2023)

On Possibilities of High Precision Fundamental Physics Experiments in Spin-Transparent Storage Rings of Low Energy Polarized Electron Beams; [arXiv:2105.11575v3 [physics.acc-ph]]

Particle Accelerator Spin-Transparent Storage Rings for Beyond State-Of-The-Art Science; Proceedings of the 15th International Particle Accelerator Conference (pp. 1897-1900)

- EDM very sensitive to physics beyond Standard Model and new sources of Charge-conjugation and Parity (CP) violation
- Such CP violation to indicate presence of new physics and potentially explain matter-antimatter asymmetry puzzle in Universe
- Many current experiments searching for nonzero atomic or neutron EDMs
- But no direct measurements of electron and proton EDMs available up to date

1. Introduction and Motivation

Measure EDM by measuring spin precession rate in electric field in particle rest frame

$$\frac{d\vec{S}}{d\tau} = \vec{\mu} \times \vec{B}_{\text{rest}} + \vec{d} \times \vec{E}_{\text{rest}}$$

MDM

$$\vec{\mu} = (G + 1)(q/mc)$$

EDM

$$\vec{d} = (\eta/2)(q/mc)$$

particle mass

speed of light

magnetic anomaly

particle charge

electric dipole factor

Thomas-BMT equation of spin precession

$$\frac{d\vec{S}}{dt} = (\vec{\omega}_{\text{MDM}} + \vec{\omega}_{\text{EDM}}) \times \vec{S}$$

with

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

$\vec{v} = \vec{\beta}c$ particle velocity

Lorentz energy factor

Flat reference orbit generally employed with vertical magnetic & horizontal transverse electric fields

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

All-electric ring in "magic energy" approach

$$B_y = 0 \text{ and } \gamma^2 = 1 + 1/G$$

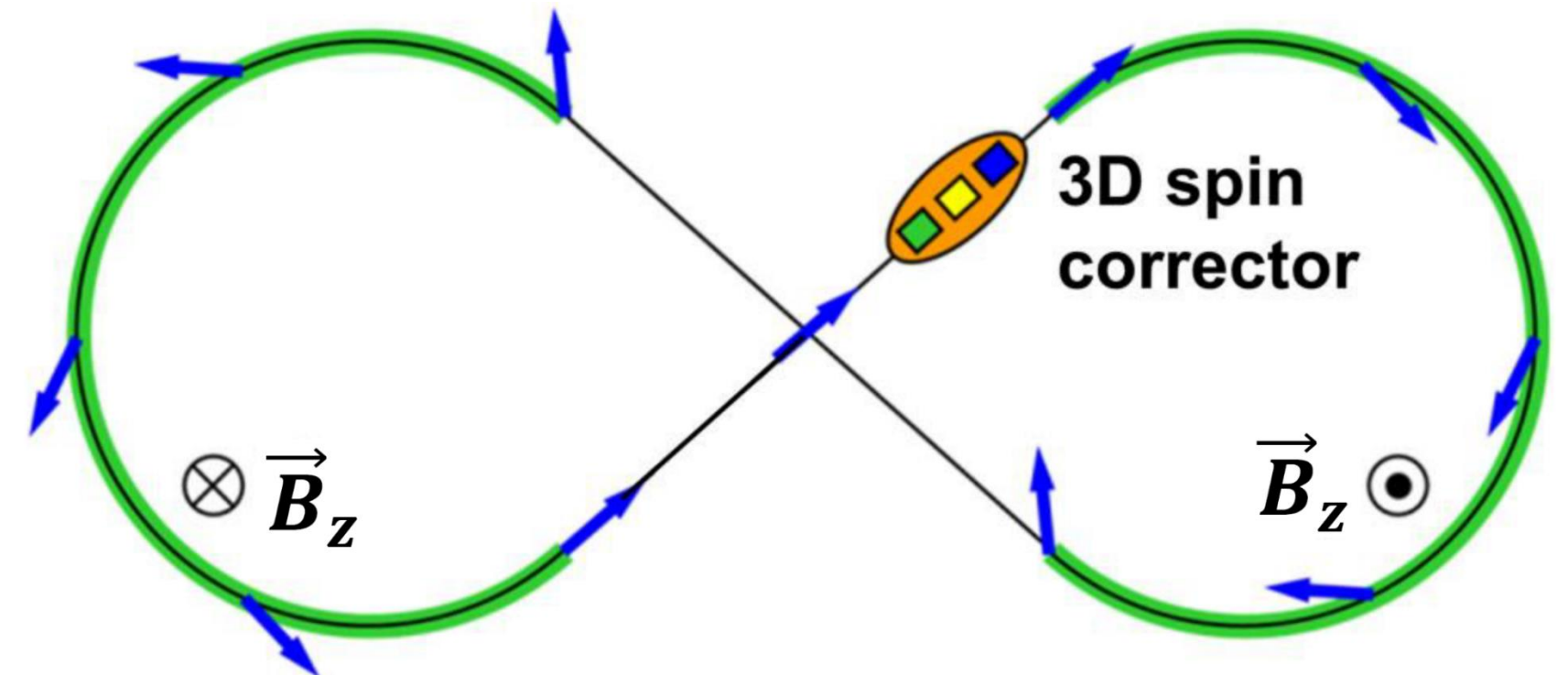
Combined electric and magnetic ring

$$GB_y = \frac{1 - \gamma^2 \beta^2 G}{\gamma^2 \beta} E_x$$

1. Introduction and Motivation

- New design of highly specialized small storage all-electric rings for low-energy (≤ 1 MeV) polarized electron beams to be discussed now
- Design based on transparent spin methodology
 - cancels spin precession due to magnetic dipole moment at any beam energy
 - but allows for spin precession induced by fundamental physics of interest to accumulate
- ST storage rings such as Figure-8
 - exhibit coherence times of many hours
 - store a large number of particles
- Vertical component of beam polarization sensitive to spin precession
 - measured using standard Mott polarimetry

Spin Transparency



Example of a spin-transparent storage ring

Most natural ST topology as the Figure-8 ring configuration

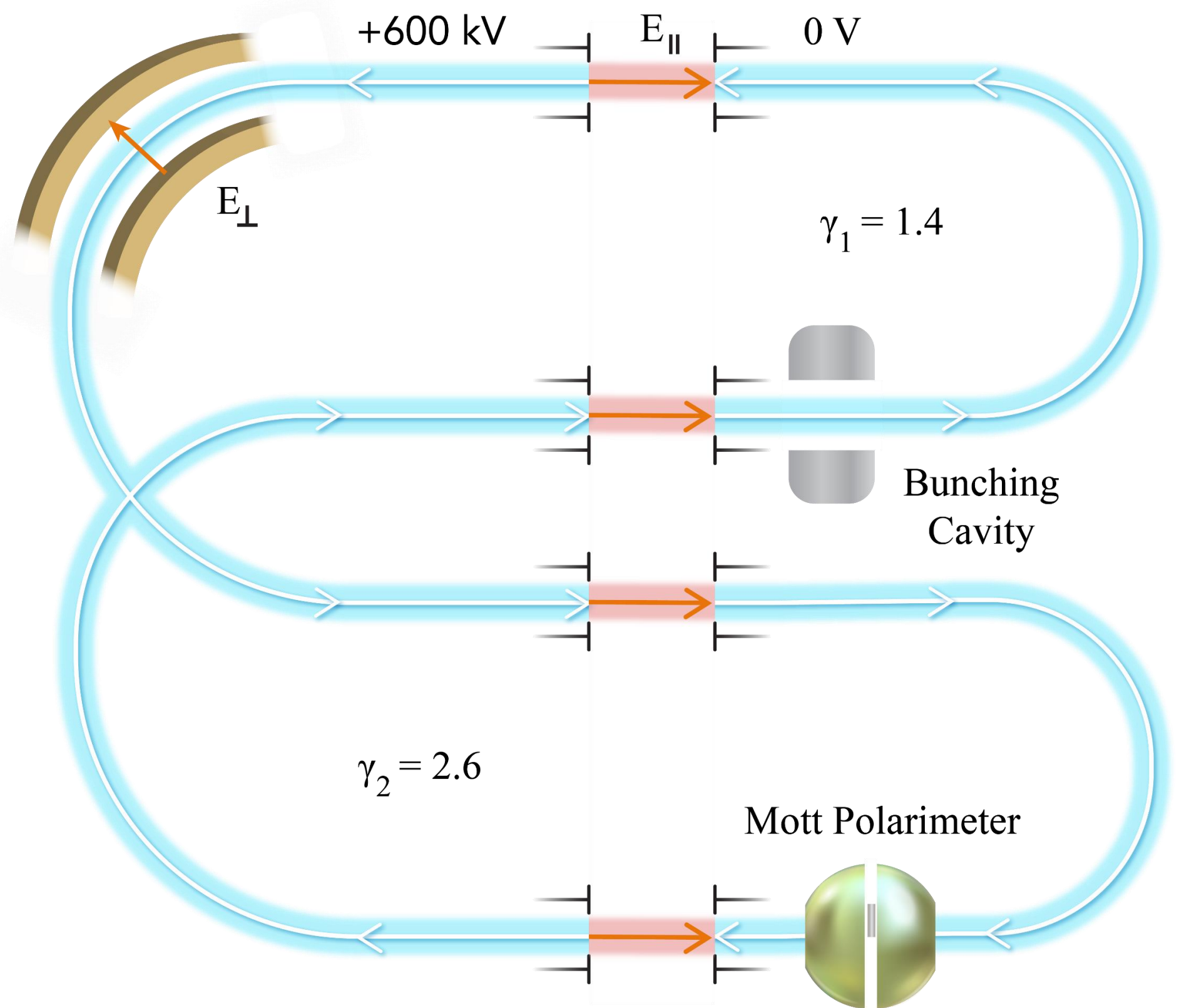
- Any spin direction repeats after a particle turn along periodic orbit in ST storage ring
- Global spin precession is zero independent of particle energy: spin-echo effect

2. ST Storage Ring Concept and Design

- EDM effect as tiny signal on top of relatively large MDM spin precession
- Suppress MDM signal to leave EDM one
- MDM suppression as natural consequence of ST ring topology
- Systematic effects associated with
 - beam emittances, field errors
 - background magnetic fields
- Figure-8 configuration with two-rings
- Systematic effects mostly suppressed by introducing two CR beams
- Employ static longitudinal electric field sections for acceleration and deceleration
- Stochastic cooling necessary to maintain beam bunch intensities

Layout of a two-energy ST storage ring for measuring the electron EDM

Both vertical and horizontal polarization components can be simultaneously measured using a Mott polarimeter



2. ST Storage Ring Concept and Design

- Treat EDM signal as perturbation to MDM spin motion

EDM effect considered as perturbation in natural spin reference frame $\longrightarrow (\hat{e}_1, \hat{e}_2, \hat{e}_3)$

Spin reference frame aligned with accelerator reference frame $\longrightarrow \hat{e}_1(s=0) = \hat{x}, \quad \hat{e}_2(s=0) = \hat{y}, \quad \hat{e}_3(s=0) = \hat{z}$

Spin rotation components per particle turn due to EDM given by integral over ring circumference

$$(\psi_{\text{EDM}}^{\text{OT}})_i = \oint \vec{\omega}_{\text{EDM}}(s) \hat{e}_i(s) ds \quad \text{with} \longrightarrow \vec{\omega}_{\text{EDM}}^{E_{\perp}} = -\frac{\eta\gamma\beta}{2} \frac{d\theta}{ds} \hat{x} \quad \vec{\omega}_{\text{EDM}}^{E_{\parallel}} = -\frac{\eta q E_{\parallel}}{2mcv\gamma} \hat{z}$$

Magnitude of spin rotation due to EDM in one turn

$$\omega_M^n \equiv -\frac{1 + G - \gamma_n^2 G}{\gamma_n}$$

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

2. ST Storage Ring Concept and Design

- Need to evaluate EDM spin rotation rate per unit time

Electron revolution time in two-energy ST ring

$$T = 2 \frac{mc^2/e}{c|E|} \left(2\pi\gamma_1\beta_1 + 2\pi\gamma_2\beta_2 + 4 \left[\sqrt{\gamma_2^2 - 1} - \sqrt{\gamma_1^2 - 1} \right] \right)$$

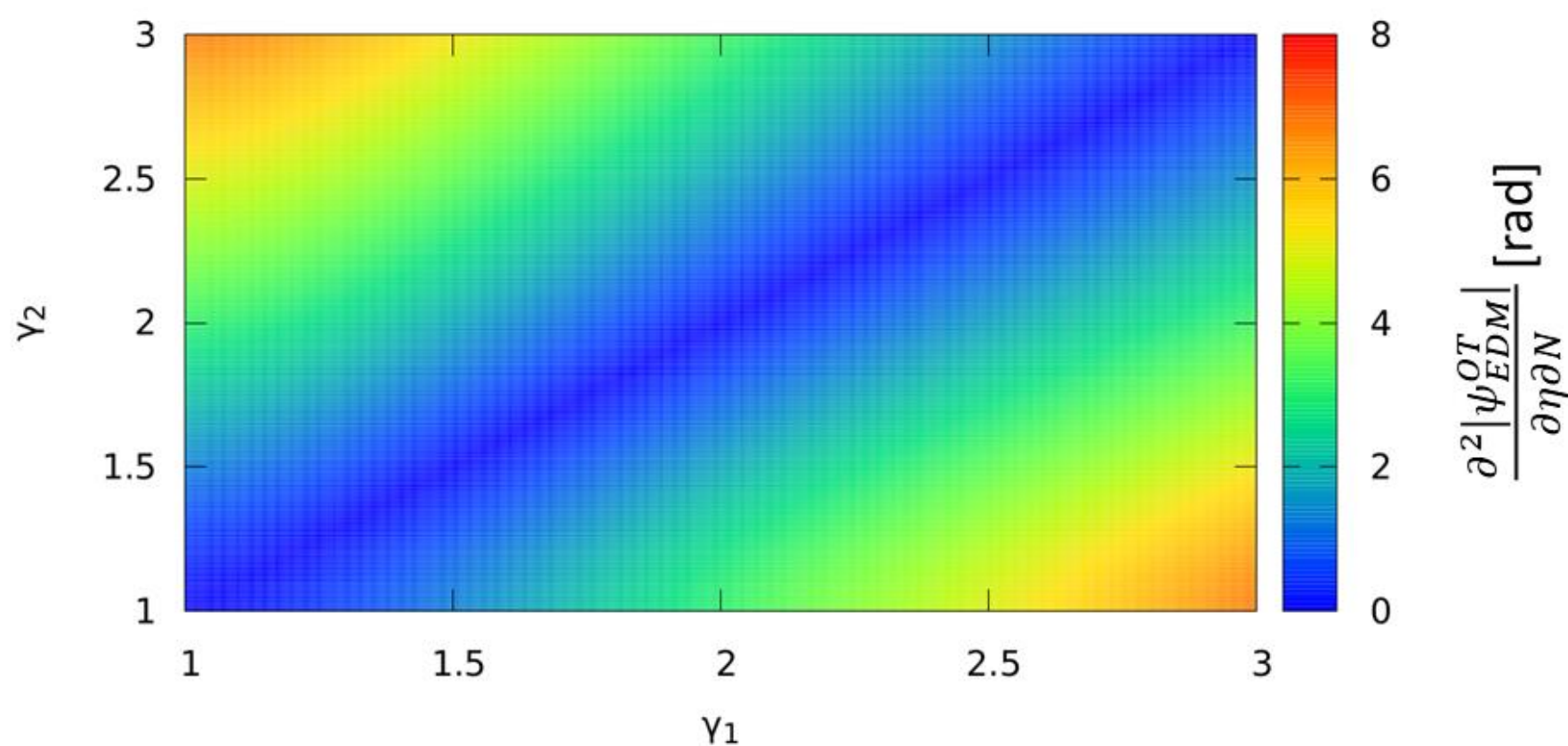
EDM spin rotation per unit time

$$\frac{\partial^2 |\psi_{EDM}^{OT}|}{\partial\eta\partial t} = \frac{1}{T} \frac{\partial^2 |\psi_{EDM}^{OT}|}{\partial\eta\partial N}$$

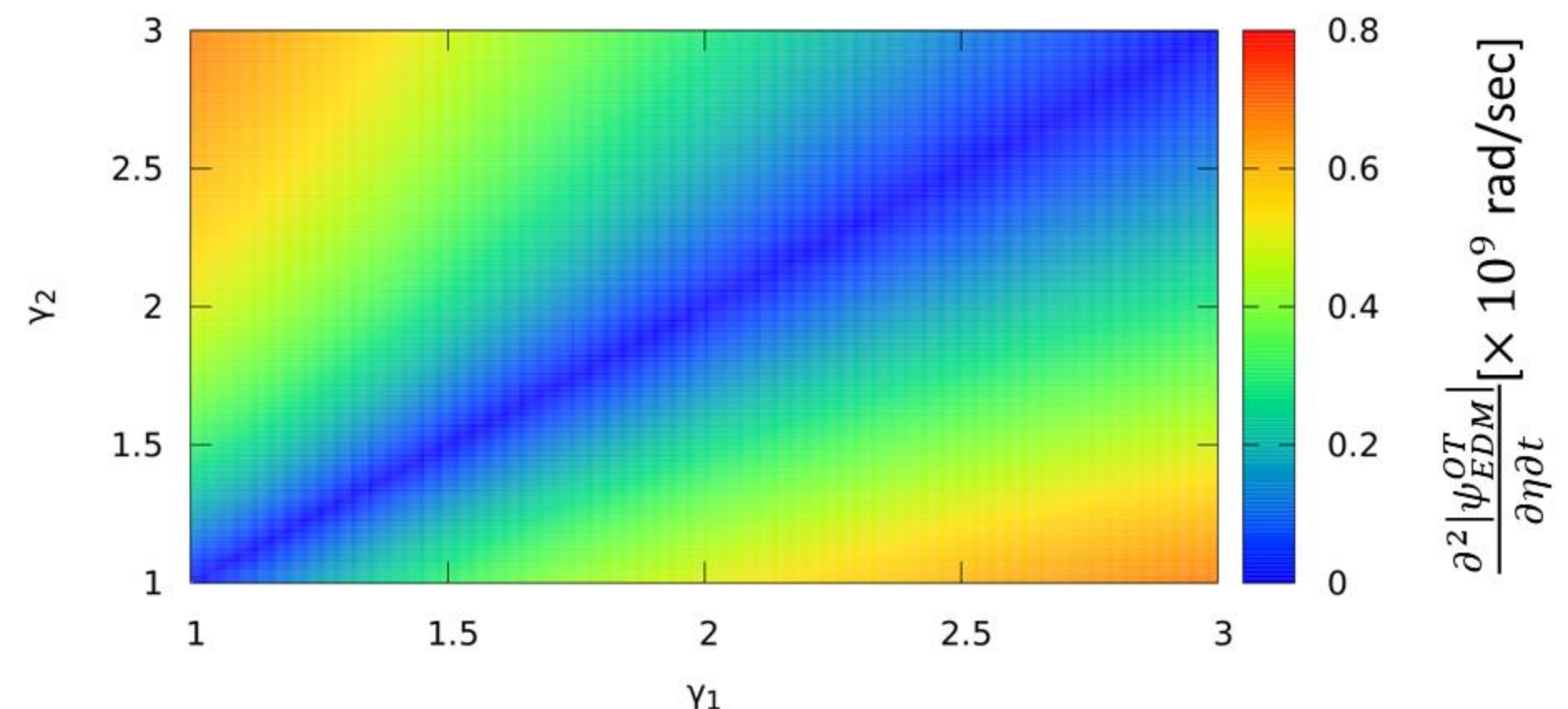
Determine EDM precession rate for $\gamma_1 = 1.4$ and $\gamma_2 = 2.6$ to be

$$\partial^2 |\psi_{EDM}^{OT}| / (\partial\eta\partial t) = 0.46 \times 10^9 \text{ rad/s}$$

EDM spin rotation magnitude in the two-energy ST ring per unit η per turn N as a function of γ_1 and γ_2



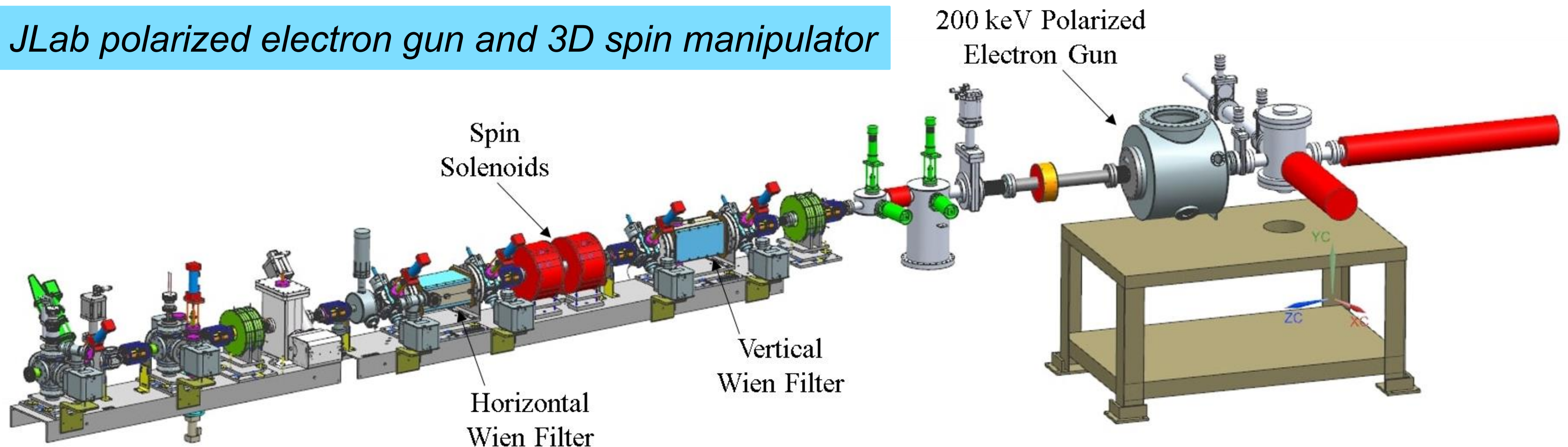
EDM spin rotation magnitude in the two-energy ST ring per unit η per time t as a function of γ_1 and γ_2



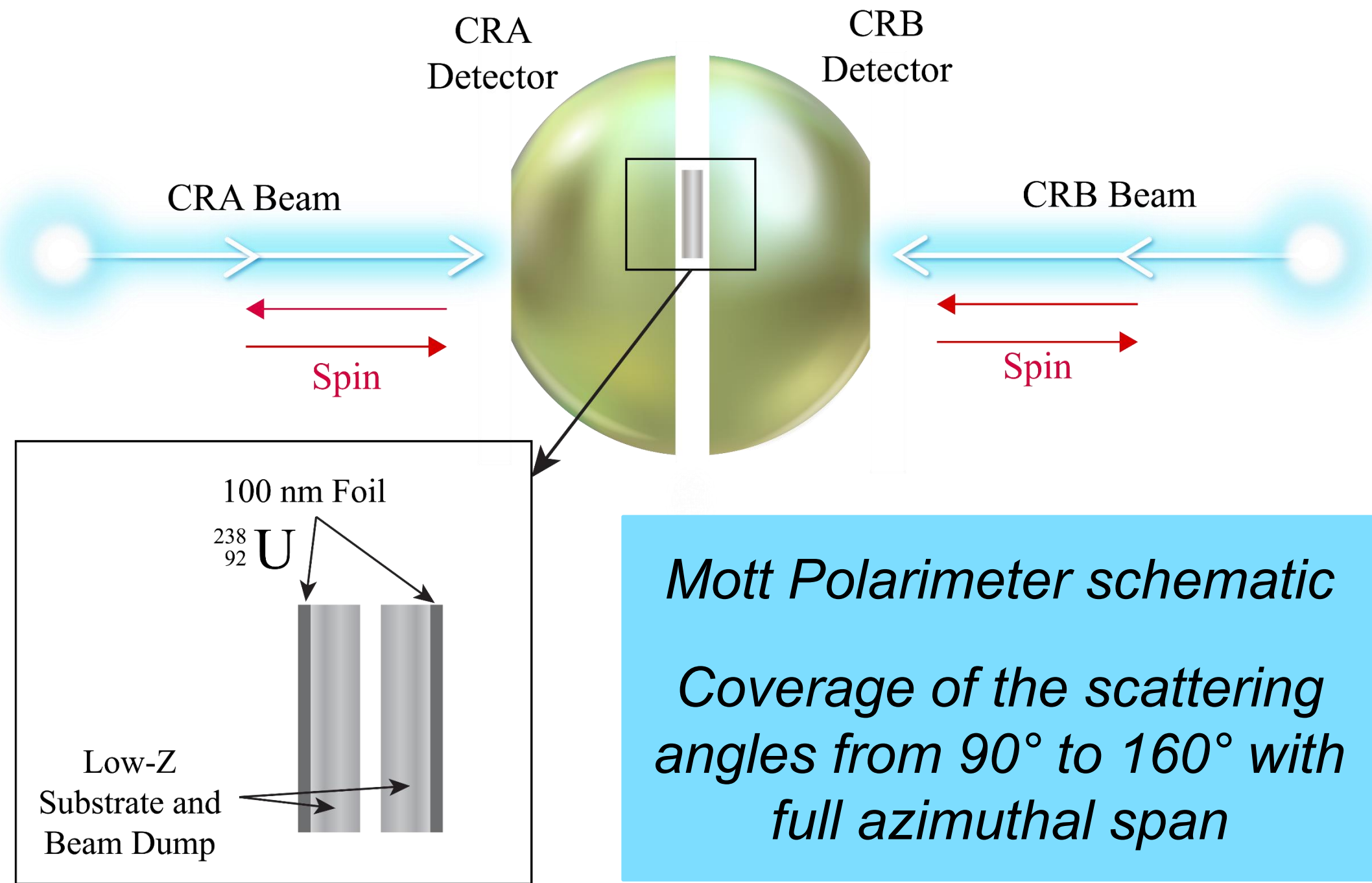
3. Polarized Electron Source and Mott Polarimetry

- Figure below showing main parts of polarized electron source
- Polarized electron beam to be generated with 780 nm laser light incident on photocathode
- Polarized electron sources deliver beam polarization of 90%
- Beamline equipped with 3D spin manipulator to rotate electron spin in any direction
- Spin manipulator used at JLab over last 15 years

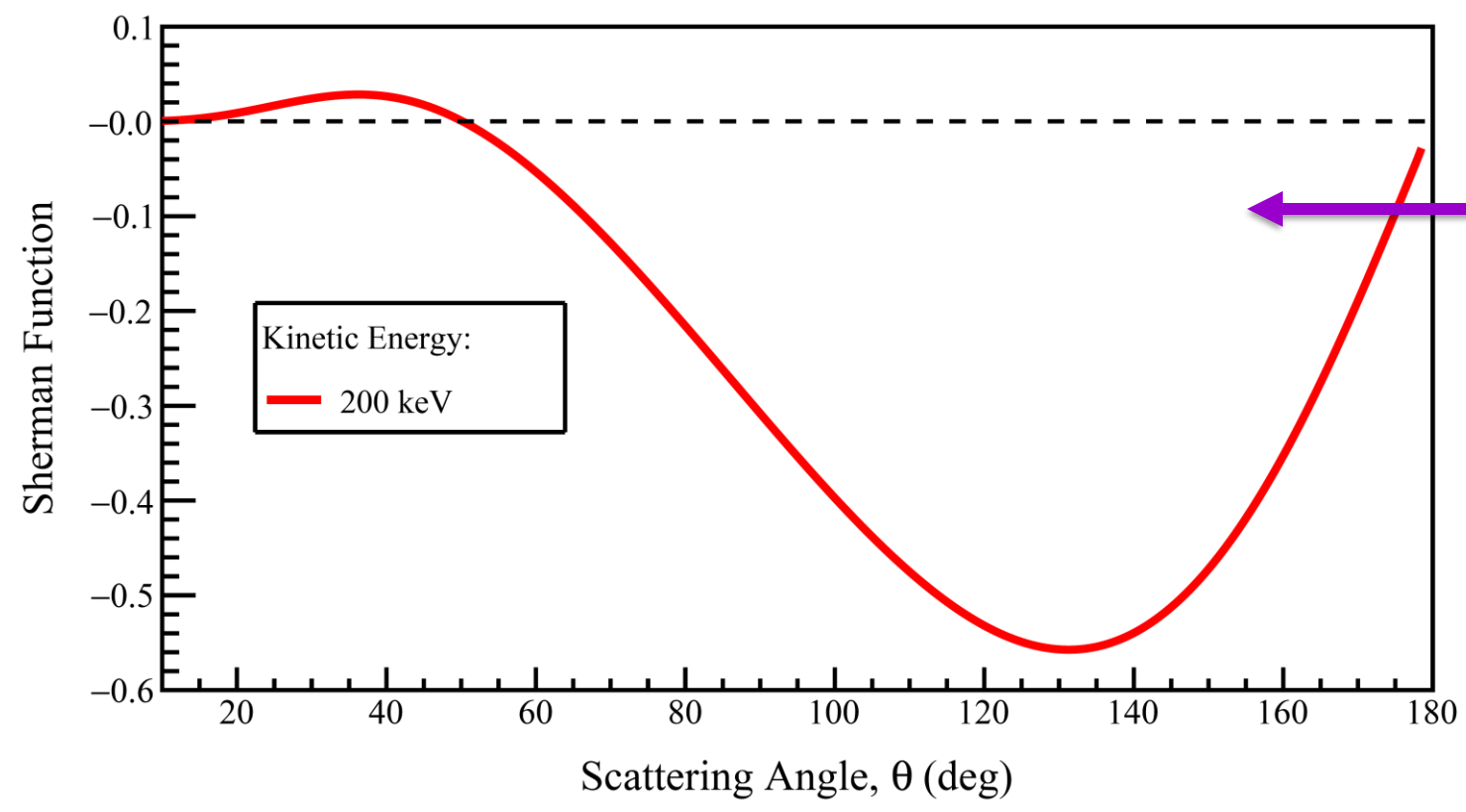
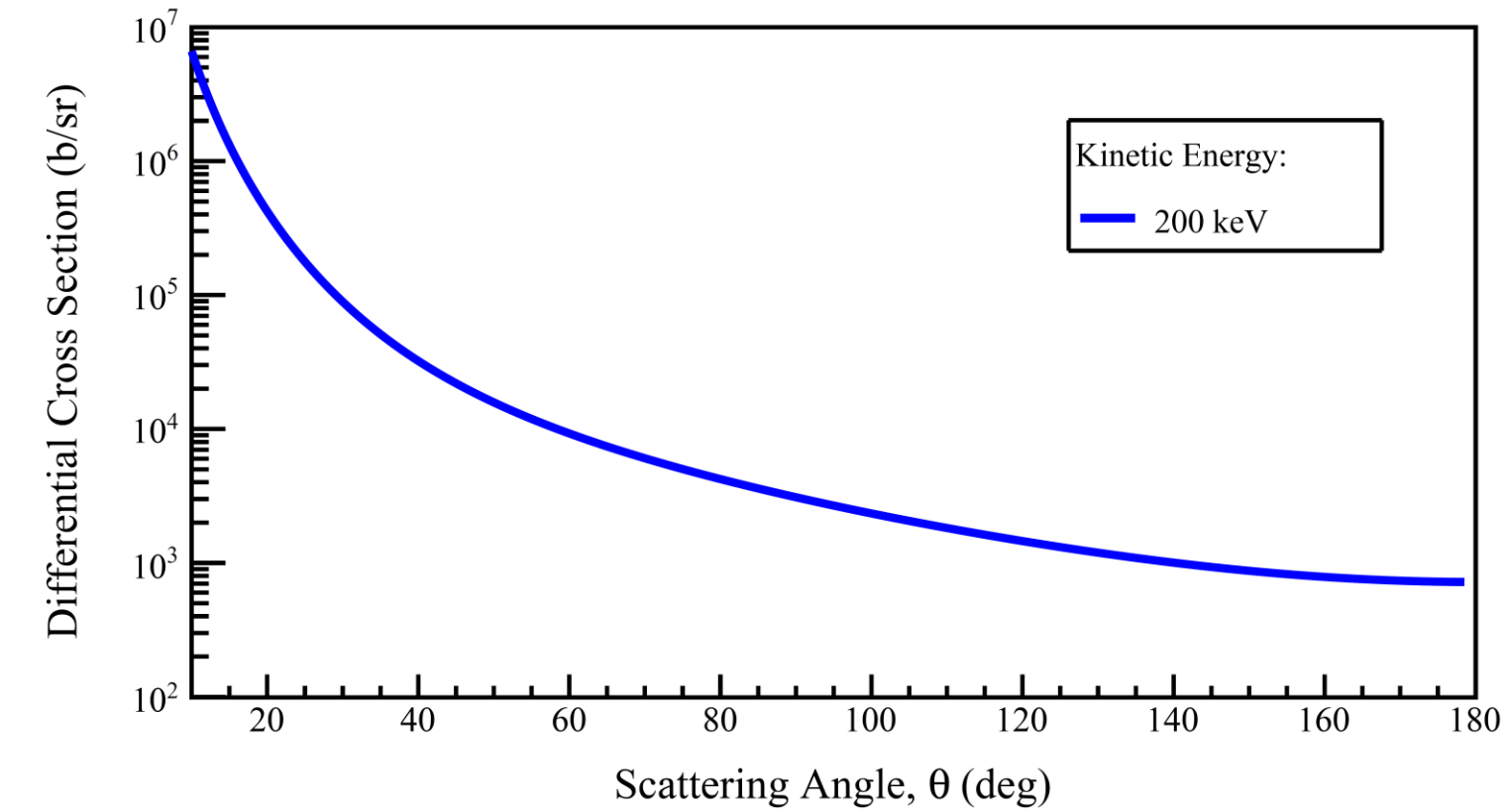
JLab polarized electron gun and 3D spin manipulator



3. Polarized Electron Source and Mott Polarimetry

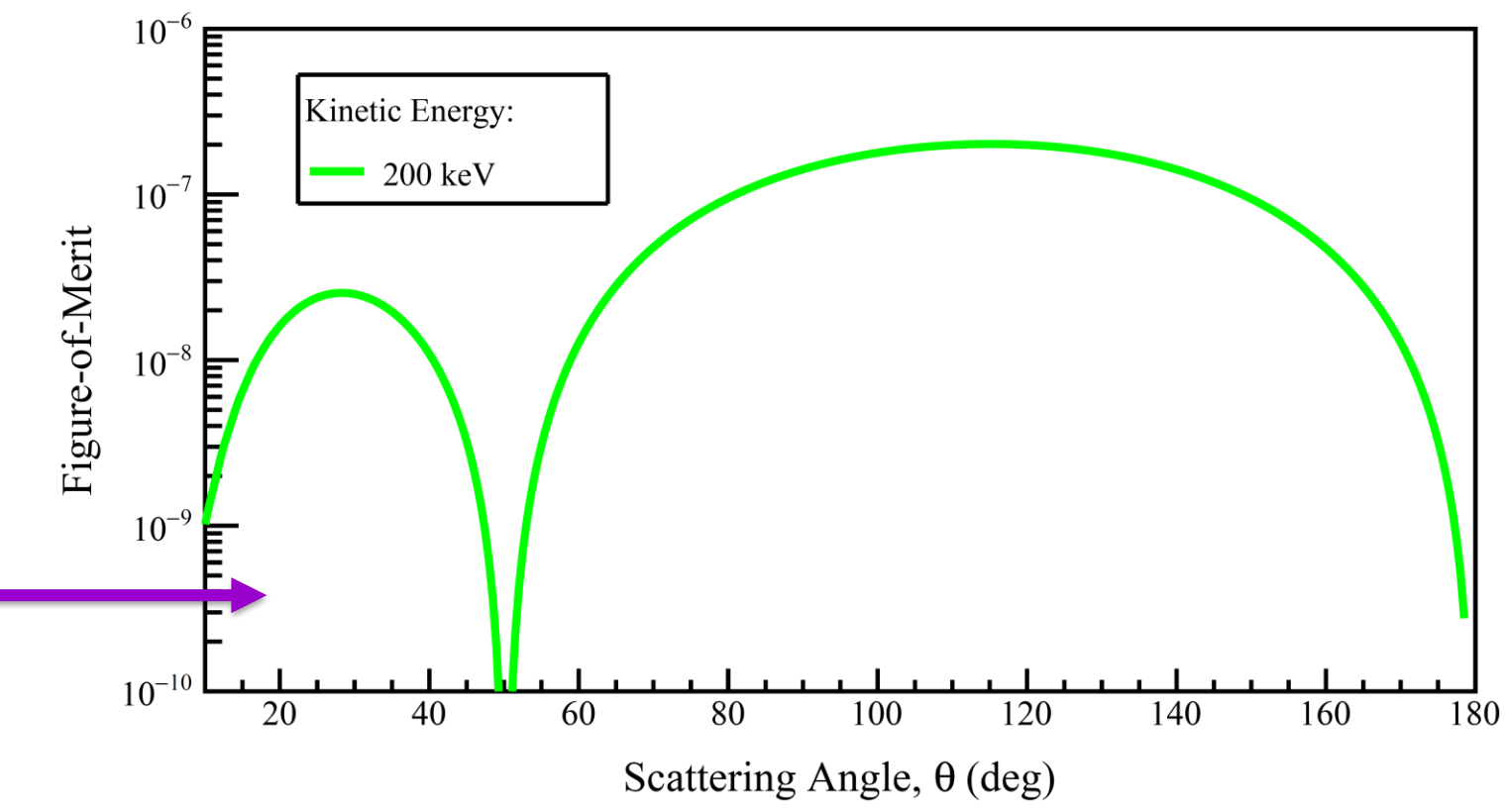


Differential cross section of Mott scattering from ^{238}U nucleus



Analyzing Power (Sherman Function) of Mott scattering

Polarimeter Figure-of-Merit of Mott scattering



3. Polarized Electron Source and Mott Polarimetry

➤ List relevant quantities to Mott polarimetry

Detector solid angle acceptance $\longrightarrow \int_{-\pi/2}^{\pi/2} \int_{90^\circ}^{160^\circ} \sin\theta d\theta d\phi = 3.0$ steradian

Integrated total cross section $\longrightarrow \int_{-\pi/2}^{\pi/2} \int_{90^\circ}^{160^\circ} cs(\theta) \sin\theta d\theta d\phi = 4876$ b

Polarimeter efficiency $\longrightarrow \epsilon = \frac{\rho_U d_{\text{foil}} N_A}{M_U} \int_{-\pi/2}^{\pi/2} \int_{90^\circ}^{160^\circ} cs(\theta) \sin\theta d\theta d\phi = 0.0024$

Polarimeter average analyzing power $\longrightarrow A_y = - \frac{\int_{-\pi/2}^{\pi/2} \int_{90^\circ}^{160^\circ} A_y(\theta) cs(\theta) \sin\theta d\theta d\phi}{\int_{-\pi/2}^{\pi/2} \int_{90^\circ}^{160^\circ} cs(\theta) \sin\theta d\theta d\phi} = 0.45$

Polarimeter FOM $\longrightarrow fom = \frac{\rho_U d_{\text{foil}} N_A}{M_U} \int_{-\pi/2}^{\pi/2} \int_{90^\circ}^{160^\circ} cs(\theta) A_y^2(\theta) \sin\theta d\theta d\phi = 4.9 \times 10^{-4}$

➤ Stat. uncertainty of vertical polarization due to EDM spin precession $\delta P = 0.029\%$

4. Electron EDM Expected Statistical Limit / Systematic Uncertainties

- Final electron beam polarization to be performed at $t = \text{SCT}$
- Stat. uncertainty of EDM measurement per fill to be calculated by

$$\sigma_{\text{EDM}} = \sqrt{8} \frac{d_e}{\sqrt{Q/e} \epsilon A_y P \Omega_{\text{EDM}} \text{SCT}}$$

- Stat. uncertainty per fill -- $2.5 \times 10^{-28} e \cdot \text{cm}$

Parameters for evaluating the statistical uncertainty of the EDM measurement

Spin quantum number	s	$\frac{1}{2}$
Electrons per fill	N_e	5.0×10^{10}
Longitudinal polarization	P	0.90
Polarimeter efficiency	ϵ	0.0024
Analyzing power	A_y	0.45
Spin rotation per η per time	Ω_{EDM}	$0.29 \times 10^9 \text{ rad/s}$
Spin coherence time	SCT	1 day (86400 s)

4. Electron EDM Expected Statistical Limit / Systematic Uncertainties

- Possible way to operate EDM storage ring
- Fill the ring with four polarized electron bunches in two opposite directions
- Use four possible filling schemes for each beam, dependent on different helicity and polarization arrangements
- Longitudinally polarized bunches to be used to measure EDM
- Radial and vertical polarized bunches to be used to measure systematic uncertainties related to background electromagnetic fields
- Accumulate for EDM
 - positive vertical polarization component for (CRA,+h) and (CRB,-h) beams
 - negative vertical polarization component for (CRA,-h) and (CRB,+h) beams

4. Electron EDM Expected Statistical Limit / Systematic Uncertainties

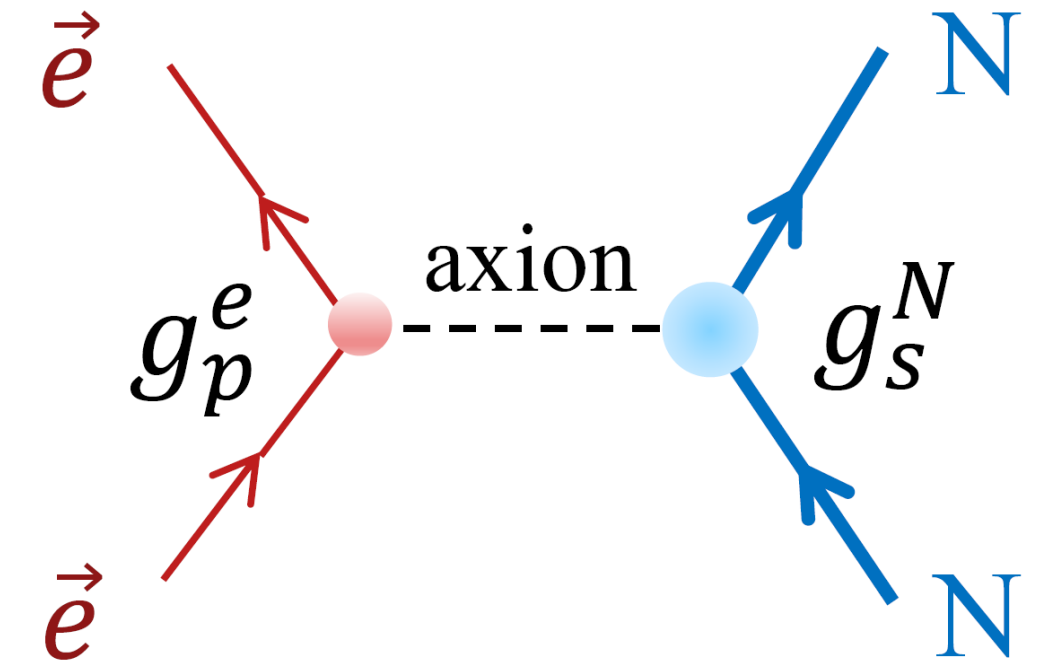
- MDM spin rotations should average to zero over single turn
- But fringe/background electromagnetic fields, construction errors and alignment of ring elements may introduce non-zero MDM spin rotations
- Apply approaches to further suppress residual MDM effects
 - state-of-the-art shielding of background fields
 - Electron helicity ($\pm h$) reversal and combining data collected during EDM measurements

$$\frac{(CRA,+h) - (CRA,-h) + (CRB,-h) - (CRB,+h)}{4}$$

- two of four bunches, with either radial or vertical polarization, in each ring direction to control background electromagnetic fields
- Not all systematic effects cancel
- Expected syst. uncertainty due to Mott polarimeter $\delta P = 1 \mu rad$

5. Ultra-light Axion Dark Matter Search

- Ultra-light axion particles as candidates for new physics beyond Standard Model
- Motivated by dark matter puzzle and strong CP problem
- Axions representing very light spinless fields to couple to matter and mediate long-range macroscopic forces
- Low-energy ST storage rings usable to measure spin precession induced by axion fields
- Axion field gradient to couple to transversely polarized electron spin with sensitivity proportional to relativistic beam velocity, β , and SCT
- Longitudinally polarized electrons to measure EDM while transversely polarized electrons to search for axions



*Axion-mediated
electron-nucleon interaction*

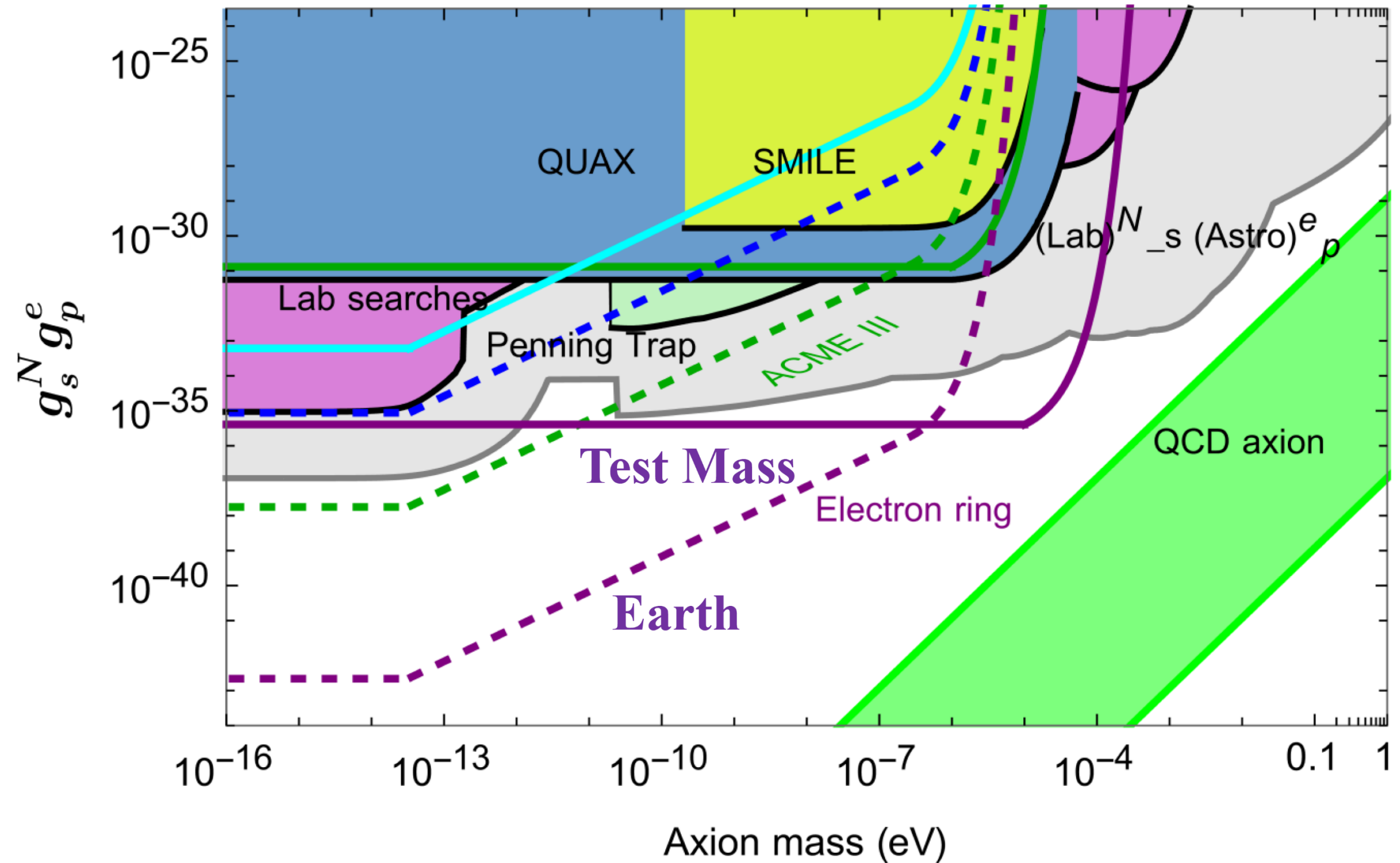
*Axions also as viable
candidates for dark matter
that dominates mass
of Universe*

*Earth produces vertical
axion field*

- Axion ring analogous to EDM ring; Figure-8 electric ring without longitudinal electric fields

5. Ultra-light Axion Dark Matter Search

- In axion search experiment
 - spin rotates around electron's velocity
 - longitudinal background magnetic field as main source of systematic uncertainty
 - rotates spin of CRA and CRB beams in same direction
 - axion interaction rotates spin in opposite directions, resulting in cancellation of background effect when combining CRA & CRB data



- ST axion ring to measure \sim nHz (10^{-9} Rad/s) spin precession frequency
- ST axion ring to give strongest bound to surpass any existing search by several orders of magnitude

Different spin precession experiments with their bounds projected on the parameter space of scalar-pseudoscalar nucleon-electron couplings versus axion mass

Expected sensitivity to axion-mediated forces in the electron ring sourced from the earth nucleons

6. ST Concept Development in Progress: Positron Beams

- ST ring concept potentially extendable to low-energy polarized proton, deuteron, muon beams
 - using rings of comparable dimensions to those described for electrons
 - but more difficult to create substantial difference in γ for heavier particles
- Meanwhile, consider low-energy positron beams to be similar to electron case
- In general, generating and accumulating polarized positron bunches to be achievable
- Same systematic effect suppression pattern for ST rings
- **For electrons**
 - CRA and CRB beam currents – 274 mA; with ≤ 1 MeV energy
 - Projected EDM statistical precision for 5-year data-taking determined to be $\delta d_e = 5.8 \times 10^{-30} e \cdot cm$
- **For positrons**
 - Again CRA and CRB beam currents, but polarization different, Mott polarimetry to be studied
 - Optimization possible with beam energies, stat. limit could be an order of magnitude larger

7. Summary and Outlook

- Spin-transparent storage rings showing important and exciting applications
- To measure electron/positron permanent electric dipole moment and search for axions
- Presented approach gives following advantages
 - Counter-rotating A and B electron beams to circulate concurrently
 - Long spin coherence time ~1 day
 - Bunched beam and no synchrotron radiation
 - Straightforward polarimetry
 - Good control of systematic effects and ring imperfections with background magnetic fields
 - Minimum safety issues and manageable cost
 - Testbed for larger-scale experiments
- LOI being prepared for this PAC

Thanks for attention !

Backups

Two-energy ST Electron EDM Ring: Optics design

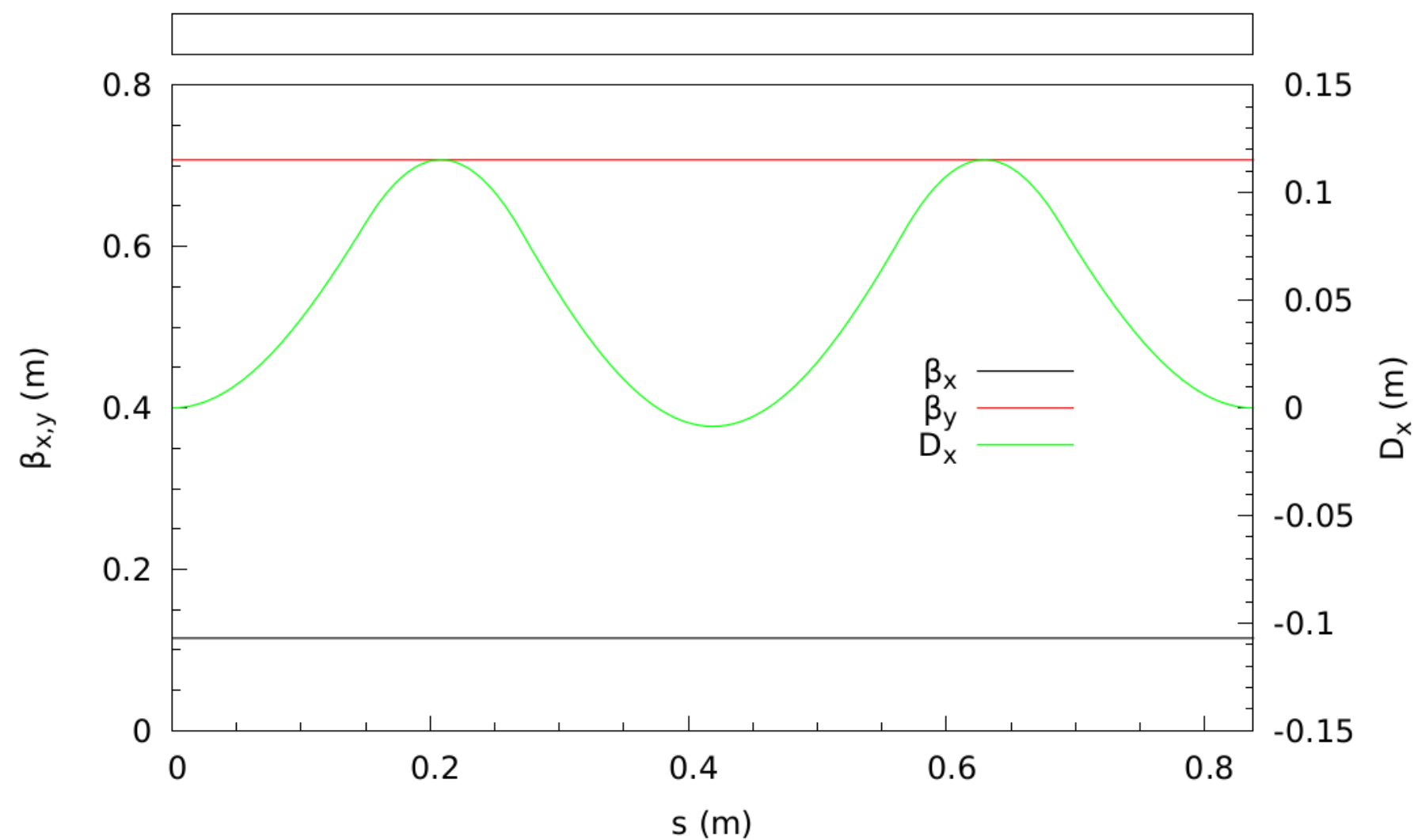
- Specific ring design to be discussed gives rate $\partial^2 |\psi_{\text{EDM}}^{\text{OT}}| / (\partial\eta\partial t) = 0.29 \times 10^9 \text{ rad/s}$
- EDM ring optics to provide
 - EDM spin rotation rate high efficiency, long spin coherence time
 - low emittance growth rates due to IBS, reasonable stored beam size
- Choose specific design consisting of five alternating bends in arcs of ST ring
- High-energy arcs with bending angle θ_i^{high} and banding radius ρ_i^{high}
- Low-energy arcs with bending angle θ_i^{low} and banding radius ρ_i^{low}
- Weak-focusing optics employed
 - horizontal focusing set by orbit bend radius
 - vertical one provided by weak vertical-focusing gradient of electric field
- Compact arc structure to be used to maximize EDM spin rotation rate

Two-energy ST Electron EDM Ring: Transverse Dynamics

- Provide sufficient beam and maintain long beam lifetime with requirement $\rho \gg a_x \gg \sigma_x$
- Optical matching requirement on the Twiss β functions: $\frac{(\beta_{x,y})_{low}}{(\beta_{x,y})_{high}} = \frac{\rho_{low}}{\rho_{high}}$
- Twiss parameters used to describe distribution of positions and velocities of beam particles

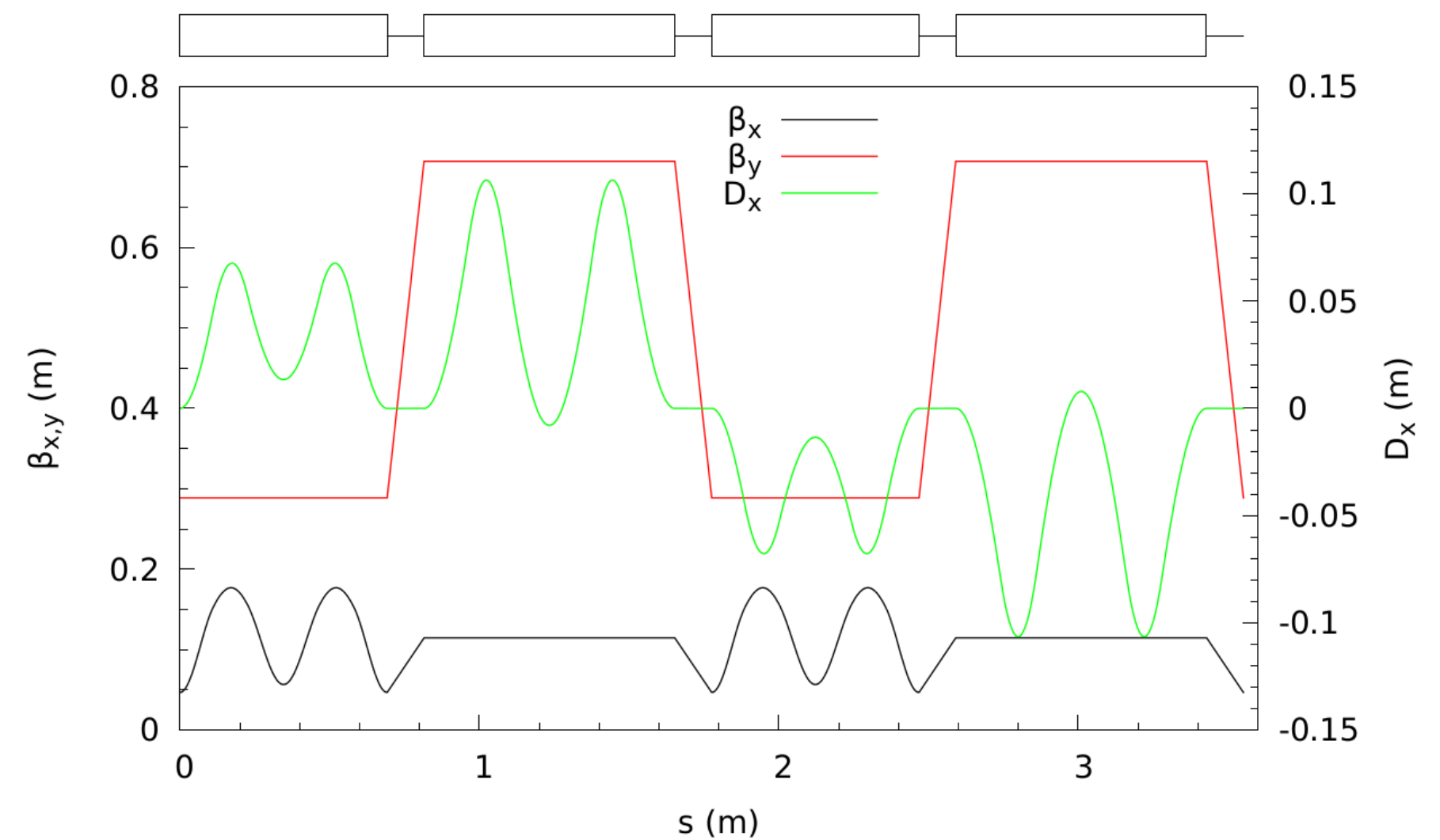
High-energy arc optics

Twiss β functions in both planes ($\beta_{x,y}$) and horizontal dispersion (D_x) along the arc



Complete optics of the EDM two-energy ST ring

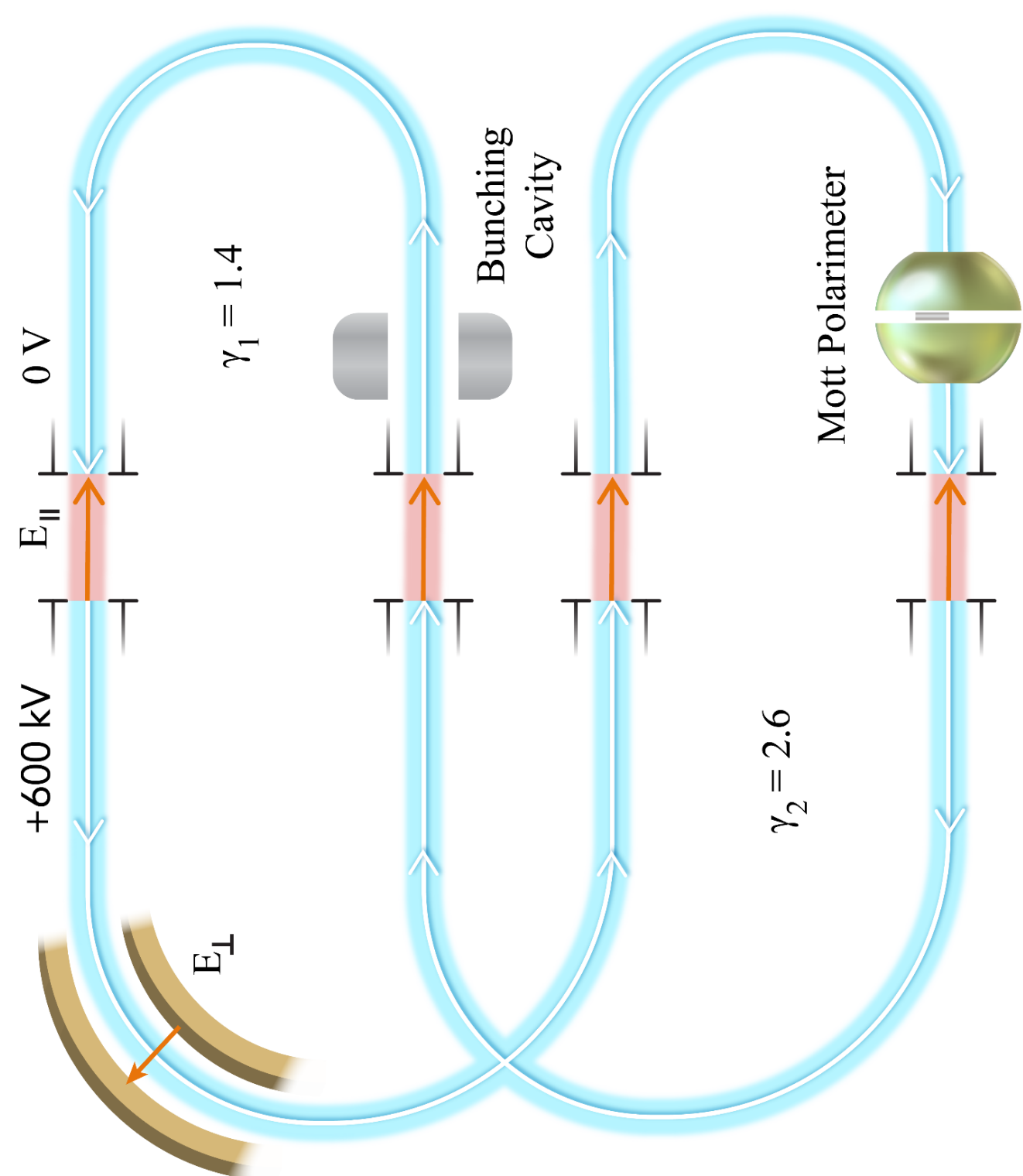
Twiss β functions in both planes ($\beta_{x,y}$) and horizontal dispersion (D_x) along the ring



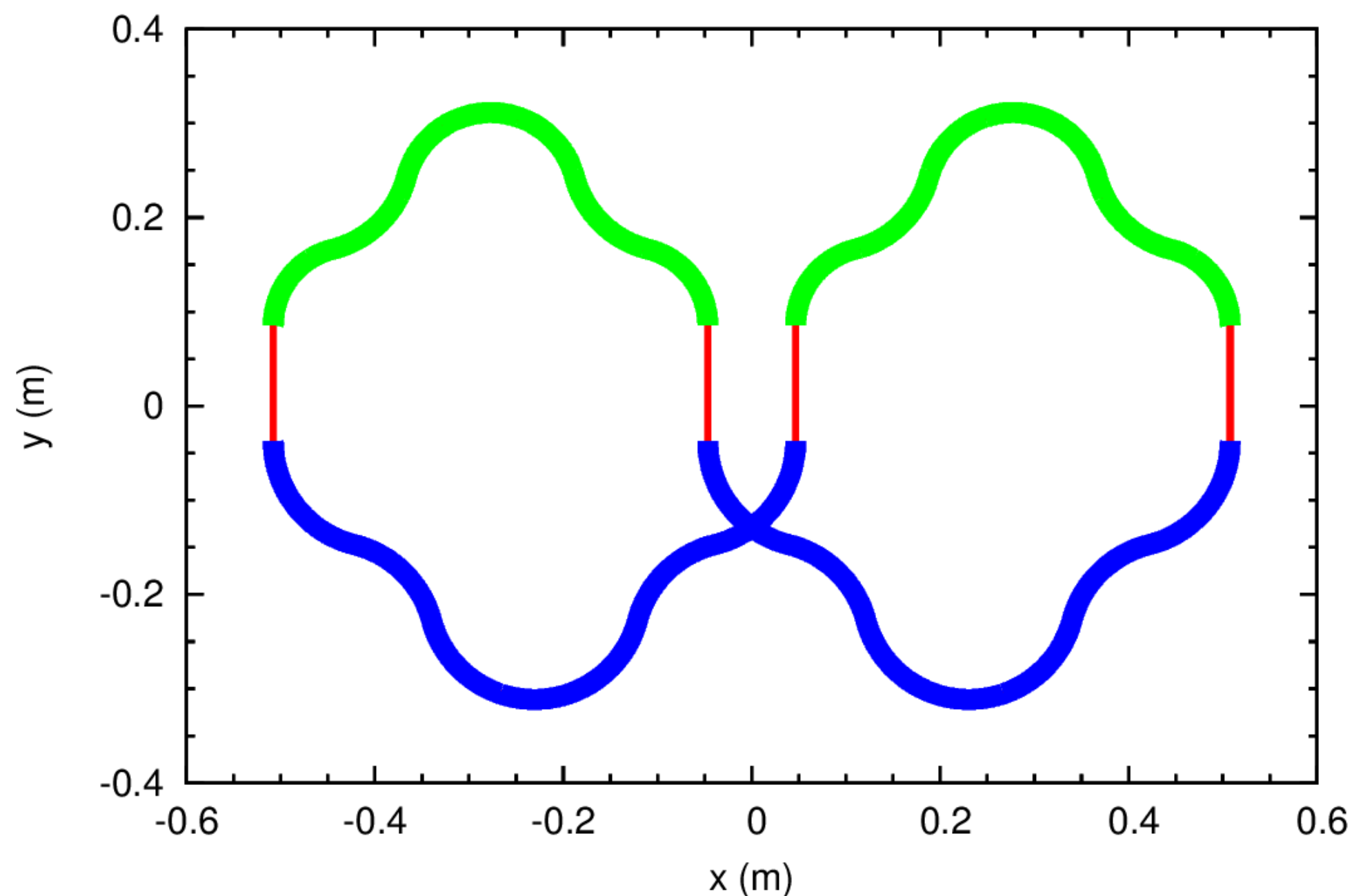
Two-energy ST Electron EDM Ring: Longitudinal Dynamics

- For beam bunches: four buckets to be filed, one bucket to be kept empty for injection, and ion cloud clearing

Figure on slide 6 rotated 90° to the left to compare to the right figure



*Footprint of the EDM ST ring drawn to scale
High-energy arcs in blue, low-energy arcs in green,
and longitudinal static electric field sections in red*



Two-energy ST Electron EDM Ring: Longitudinal Dynamics

Geometrical and optical ring parameters

Quantity	Value
Ring circumference	3.55 m
Circulation frequency f_c	68.5 MHz
Horizontal/vertical Q_x/Q_y betatron tunes	4.(53)/1.(14)
Straight section length	12.3 cm
Beam pipe aperture $\pm a_x$	± 3 cm
Longitudinal $E_{acc/dec}$ field	5 MV/m
M_{56} of accelerating/decelerating straight	22.3/54.8 mm
M_{66} of accelerating/decelerating straight	0.31/3.23

Section	Low-energy	High-energy
Relativistic γ	1.4	2.6
Arc bending angles θ_i	$\pm 75.0^\circ, \mp 61.0^\circ, \pm 76.0^\circ$	$\pm 75.0^\circ, \mp 61.0^\circ, \pm 76.0^\circ$
Arc bending radii ρ_i	$\pm 8.3, \mp 10.8, \pm 9.2$ cm	$\pm 11.3, \mp 11.3, \pm 11.3$ cm
Arc bending $(E_x)_i$ field	$\mp 4.2, \pm 3.3, \mp 3.8$ MV/m	$\mp 10, \pm 10, \mp 10$ MV/m
Maximum Twiss β_x/β_y	17.7/28.9 cm	11.5/70.7 cm
Maximum horizontal dispersion D_x	9.7 cm	11.5 cm
Horizontal/vertical ξ_x/ξ_y chromaticities per 180° arc	-0.37/-1.93	-0.63/-4.14
M_{56} per 180° arc	18.9 cm	10.2 cm
Ring slip factor η	-0.314	-0.769

Use stochastically cooled bunched beams for having

low emittances

and

comparatively high beam intensities

Longitudinal dynamics parameters for a stochastically cooled beam

Bunching cavity is placed in the low energy section

Quantity	Value
Harmonic number h	5
RF frequency f_{rf}	342.6 MHz
Bunch length σ_z	17.8 cm
Bunching voltage amplitude V_{rf}	1.67 kV
Synchrotron tune ν_{syn}	0.029

Beam Physics Limitations: IBS and Stochastic Cooling

- EDM measurement precision to be determined by statistical error
- Sufficiently large number of particles to be stored in ring
 - 2 nC electron charge initially injected into each RF bucket
 - reduce bunch charge down to 1 nC after polarization measurement
- With such bunch charge, IBS causing concern for beam lifetime
- In equilibrium, IBS balanced by stochastic cooling

Beam parameters without and with stochastic cooling

Quantity	Value			
Number of bunches	4 CRA and 4 CRB			
Charge per bunch Q_b	2 nC at injection immediately reduced to 1 nC at store			
Beam current I	274 mA CRA and 274 mA CRB			
Stochastic cooling	Off			On
IBS growth times $\tau_x^{IBS} / \tau_y^{IBS} / \tau_z^{IBS}$	$10^4 / 10^4 / 10^4$ s		40/40/4 s	
Section	Low-energy	High-energy	Low-energy	High-energy
rms momentum spread $\sigma_{\Delta p/p}$	0.22	0.091	0.034	0.014
rms geometric $\varepsilon_x / \varepsilon_y$ emittances	0.88/1.23 mm	0.36/0.50 mm	0.14/0.11 mm	0.056/0.045 mm
Maximum rms beam size $\sigma_x^{max} / \sigma_y^{max}$	25/19 mm	12/19 mm	5.9/5.6 mm	3.0/5.6 mm



Beam Physics Limitations: Space Charge and Other Effects

➤ Potential limitation on stored charge amount from betatron tune shift $\Delta\nu_{x/y}^{SC}$

➤ Beam stability requires

$$\Delta\nu_{x/y}^{SC} < \Delta\nu_{x/y}^{thr} \sim 0.3$$

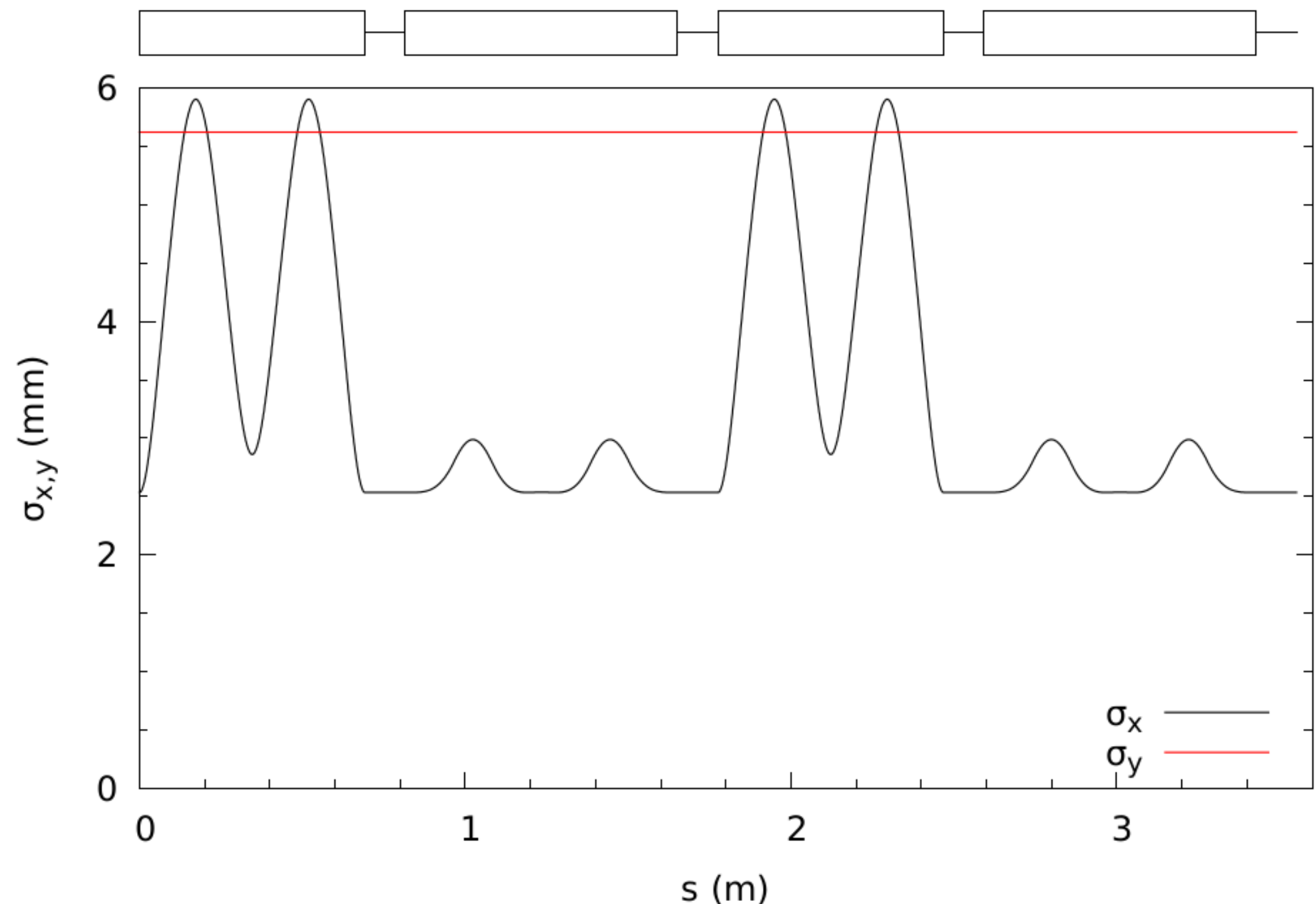
➤ With cooled beam parameters

$$\Delta\nu_{x/y}^{SC} \sim 10^{-2}$$

➤ Each stored beam to experience field of CR beam

- local effect is factor of $\gamma^2(1 + \beta^2)$ stronger than self-field interaction
- resulting tune shift factor of 6 greater than that of single beam
- overall result still consistent with threshold value 0.3

Beam sizes along the EDM ring when stochastic cooling is applied



Spin Stability and Precision Control

- Need to have long SCT to accumulate and observe EDM signal
 - time for beam staying polarized in ST
- Spin tune energy independent in ST ring
 - beam emittance → spin tune spread → depolarization
- Spin motion governed by spin resonance in ST ring
 - spin resonance strength defined as number of spin precessions per unit turn
- Spin resonance strength consisting of coherent and incoherent parts
 - coherent part determined by ring imperfections, same for all particles
 - limit on SCT primarily determined by incoherent part, causes spins of particles to precess at slightly different rates
- For, now give upper limit

$$\varepsilon_{inc} < \frac{1}{6 \tau_{coh} f_c} = 2.4 \cdot 10^{-14}$$

Quantum Computing with ST Rings

- Preserving quantum coherence and implementing scalability known as greatest challenges in constructing quantum computers
- Apparatus providing long coherence times for large and scalable systems of qubits needed
- ST rings with charged polarized particles very promising candidates
 - Long quantum coherence times of up to several hours; Long storage lifetimes
 - Large numbers of stored qubits; Operation in room temperatures
- Ion trap combined with ST ring to provide ion qubits to increase coherence time and scalability
- Ion qubits represented by two hyperfine ground states: $|F = 0, m_F = 0\rangle$ and $|F = 1, m_F = 0\rangle$
- Polarized Ytterbium ($^{171}\text{Yb}^+$) atoms to be prepared in ion trap by their optical pumping into single hyperfine state \longrightarrow then injected into ST ring
 - $^{171}\text{Yb}^+$ ion atoms highly suitable for use as qubits in ST rings due to existing long-lived hyperfine states
 - Ion traps used to prepare single-ion qubits and entangled ion qubits
- $^{171}\text{Yb}^+$ qubit spin to be measured based on utilizing state-dependent resonant fluorescence

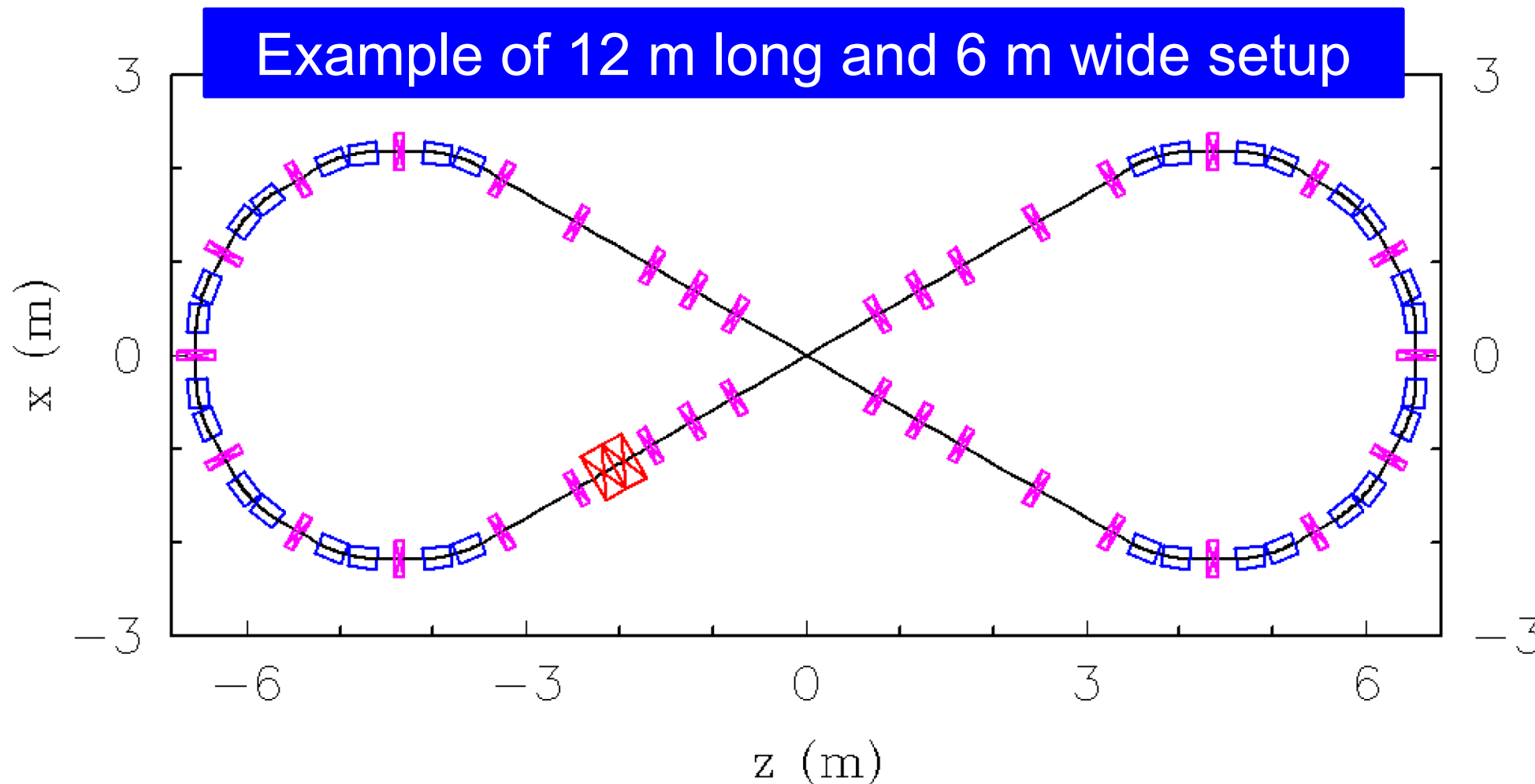
Quantum Computing with ST Rings

- Spin-based qubit states stable, unlike techniques relying on orbital motion quantization
- Spin states being decoupled from orbital motion and being robust to external factors
- Largest limitation from Doppler shift of state transition frequencies \longrightarrow still manageable

Layout of all-electric ST ring with injected $^{171}\text{Yb}^+$ ions

*Bending electrodes in blue
Focusing elements in magenta
RF bunching cavity in red*

$^{171}\text{Yb}^+$ ion ST ring parameters



Kinetic energy, K	10 keV
Momentum, p	56.4 MeV/c
Velocity, β	3.54×10^{-4}
Relative longitudinal momentum offset, $\Delta p_{\parallel}/p$	$< 10^{-3}$
Longitudinal temperature, $T_{\parallel} = mc^2 \beta^2 (\Delta p_{\parallel}/p)^2 / k_B$	< 200 K
Angular deviation, $\Delta \theta_{\perp}$	1 mrad
Transverse temperature, $T_{\perp} = mc^2 \beta^2 \gamma^2 (\Delta \theta_{\perp})^2 / k_B$	232 K
Ring circumference, L	33.5 m
Circulation frequency, f_c	3.17 kHz
No. of qubits / RF harmonic number	3, 300
Time separation of qubits, Δt	95.7 ns
Electric bending field, E	17.3 kV/m