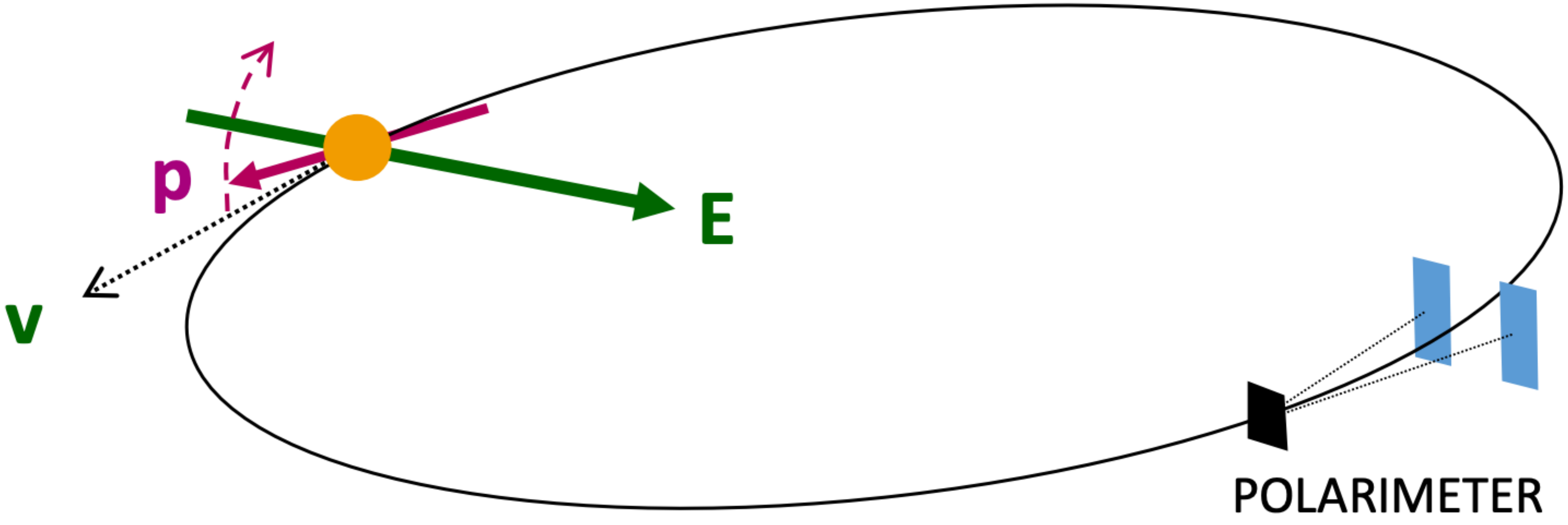


Storage Ring Proton EDM Experiment and Search for Axionlike Dark Matter

On Kim
On behalf of Storage Ring EDM Collaboration

Brookhaven Forum 2023

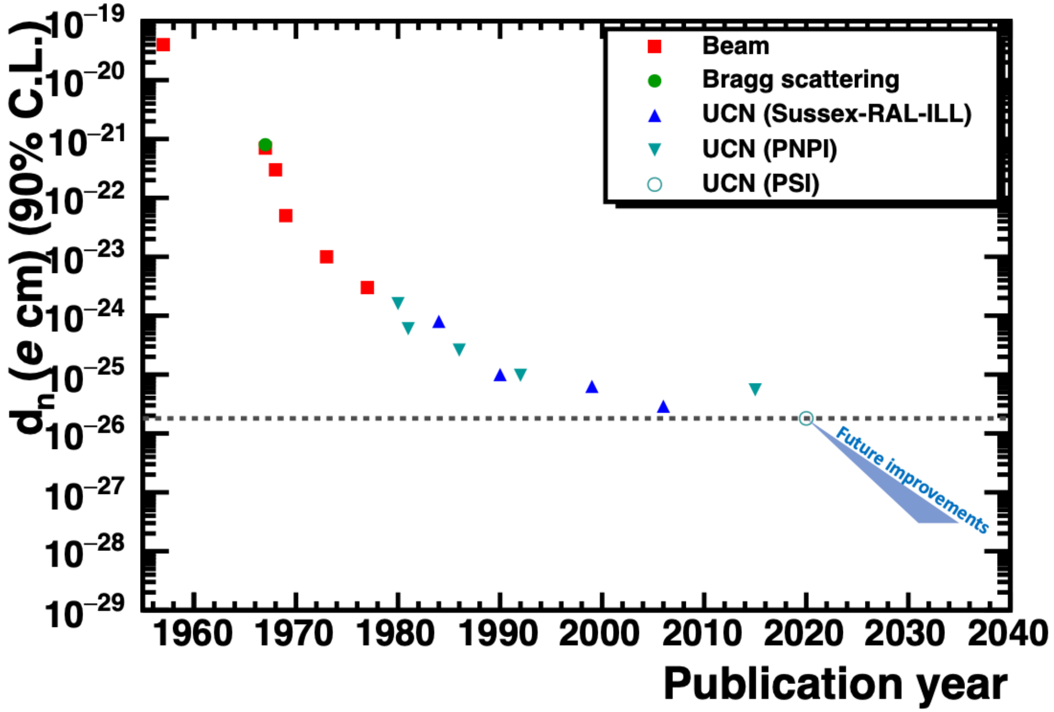
2023 Oct. 4th

Permanent EDM in a System with Spin

$$H = -\boldsymbol{\mu} \cdot \mathbf{B} - \mathbf{d} \cdot \mathbf{E}, \quad \boldsymbol{\mu} = g \frac{q}{2m} \mathbf{s}, \quad \mathbf{d} = \eta \frac{q}{2mc} \mathbf{s}$$

Magnetic Dipole Moment (MDM) Electric Dipole Moment (EDM)

- Predicted EDMs for the nucleons and leptons from SM are frustratingly small.
  - The current EDM upper limits are orders of magnitude higher. No EDM has been observed so far.
- EDM violates P and T symmetries.
  - If it exists (>SM), a CP-violating new physics exists (under CPT assumption).
- Current (direct) nEDM limit $\sim\mathcal{O}(10^{-26})\ e \cdot \mathrm{cm}$.
- Current (indirect) pEDM limit $\sim\mathcal{O}(10^{-25})\ e \cdot \mathrm{cm}$.
- Target pEDM sensitivity: $10^{-29}\ e \cdot \mathrm{cm}$.

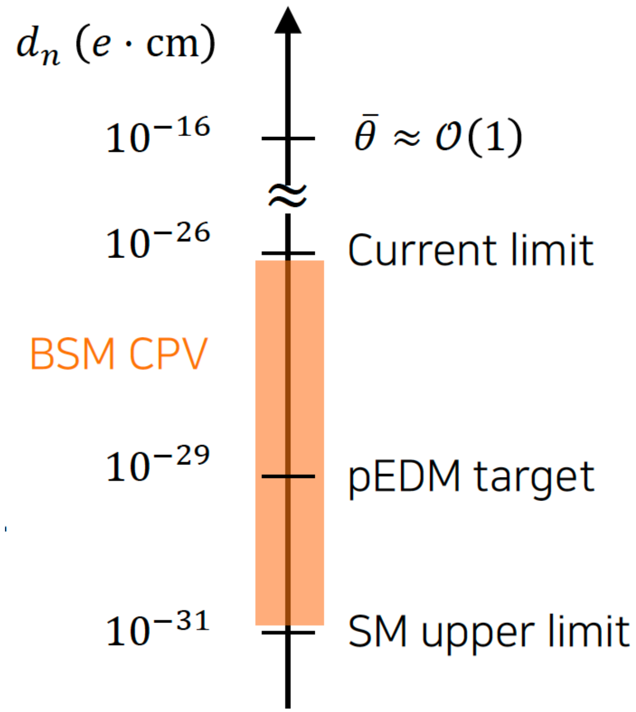


EDM Snowmass WP: 2203.08103

Physics Reach of Storage Ring pEDM at $10^{-29}\ e\cdot\mathrm{cm}$

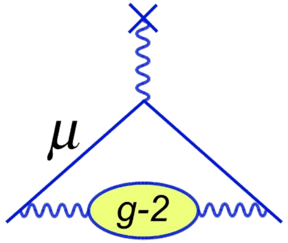
1. Competitive sensitivity to new physics up to 1000 TeV.
2. Three orders of magnitude improvement in θ_{QCD}.
3. Sensitive to specific Baryogenesis models: $\approx 10^{-28}\ e\cdot\mathrm{cm}$ in MSSM.
4. Best probe of Higgs CPV.
    - Two-loop Higgs coupling: $\tan\phi_{\mathrm{NP}} \approx \mathcal{O}(10^{-4})$.
    - x30 more sensitive than electrons with the same EDM.
5. Direct axion-like dark matter or fifth force search.
    - Best experimental sensitivity at ultra-low frequency.
    - Also sensitive to dark energy or vector DM with a different experimental knob.

$$d_n \approx \mathcal{O}(10^{-16})\ \bar{\theta}\ \ e\cdot\mathrm{cm}$$

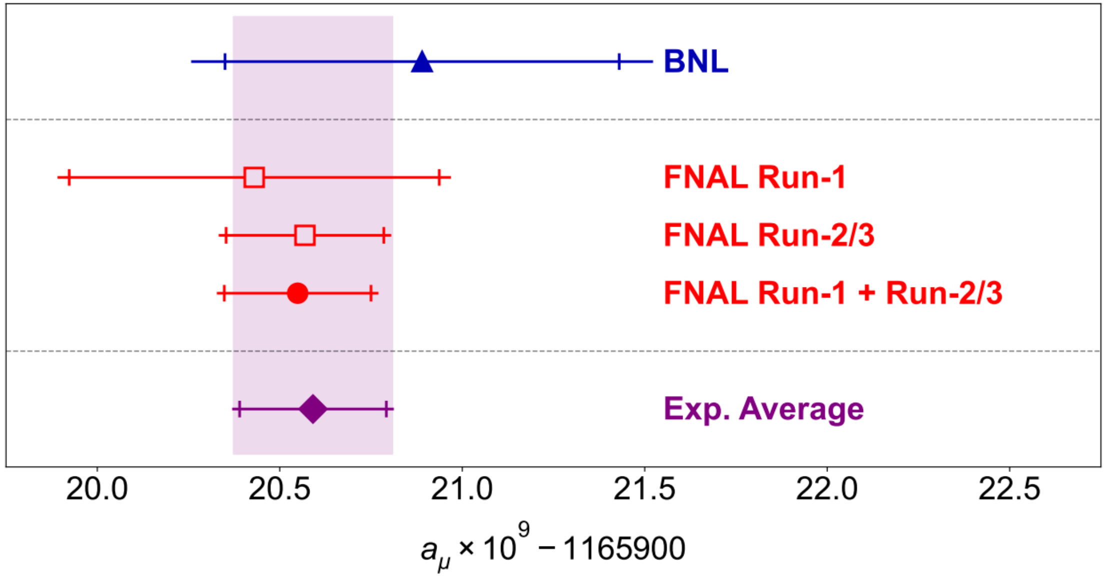


- First-ever "direct" measurement/constraint of d_p.
    - With 10^3 improvement from the best current d_n limit.
    - Complementary to atomic & molecular and optical (AMO) EDM experiments. E.g., complementary with the eEDM to sort out possible CPV sources.

Muon $g-2$ at FNAL: Overlap



- Both first (2021.4) and second (2023.8) results made headlines.



- Muon $g-2$ and pEDM have a lot in common.
  - Storage ring spin precision measurement.
  - Magic momentum ($p_\mu = 3.09$ GeV, $p_p = 0.7$ GeV/c).
  - Similar cost of the experiment.
  - Many pEDM Snowmass WP coauthors are from the muon $g-2$.

Snowmass 2021

- Storage Ring pEDM White Paper: 2205.00830.
  - Many coauthors are from the Muon $g - 2$.

The storage ring proton EDM experiment

Jim Alexander[7], Vassilis Anastassopoulos[36], Rick Baartman[28], Stefan Baeßler[39,22], Franco Bedeschi[19], Martin Berz[17], Michael Blaskiewicz[4], Themis Bowcock[33], Kevin Brown[4], Dmitry Budker[9,31], Sergey Burdin[33], Brendan C. Casey[8], Gianluigi Casse[34], Giovanni Cantatore[38], Timothy Chupp[34], Hooman Davoudiasl[4], Dmitri Denisov[4], Milind V. Diwan[4], George Fanourakis[20], Antonios Gardikiotis[30,36], Claudio Gatti[18], James Gooding[33], Renee Fatemi[32], Wolfram Fischer[4], Peter Graham[26], Frederick Gray[23], Selcuk Haciomeroglu[6], Georg H. Hoffstaetter[7], Haixin Huang[4], Marco Incagli[19], Hoyong Jeong[16], David Kaplan[13], Marin Karuza[37], David Kawall[29], On Kim[6], Ivan Koop[5], Valeri Lebedev[14,8], Jonathan Lee[27], Soohyung Lee[6], Alberto Lusiani[25,19], William J. Marciano[4], Marios Maroudas[36], Andrei Matlashov[6], Francois Meot[4], James P. Miller[3], William M. Morse[4], James Mott[3,8], Zhanibek Omarov[15,6], Cenap Ozben[11], SeongTae Park[6], Giovanni Maria Piacentino[35], Boris Podobedov[4], Matthew Poelker[12], Dinko Pocanic[39], Joe Price[33], Deepak Raparia[4], Surjeet Rajendran[13], Sergio Rescia[4], B. Lee Roberts[3], Yannis K. Semertzidis [*6,15], Alexander Silenko[14], Amarjit Soni[4], Edward Stephenson[10], Riad Suleiman[12], Michael Syphers[21], Pia Thoerngren[24], Volodya Tishchenko[4], Nicholaos Tsoupas[4], Spyros Tzamarias[1], Alessandro Variola[18], Graziano Venanzoni[19], Eva Vilella[33], Joost Vossebeld[33], Peter Winter[2], Eunil Won[16], Anatoli Zelenski[4], and Konstantin Zioutas[36]

- Snowmass talks:
  - Snowmass Cincinnati (2022) talk by Yannis K. Semertzidis.
  - Snowmass Seattle (2022) talk by On Kim.

- Snowmass 2021 encourages BNL and the srEDM collaboration to come up with a technically strong proposal.
  - CDR is being written.

Storage Ring pEDM Experiment in a nutshell

- The method proposed by Y. K. Semertzidis *et al.*: PRL **93**. 052001.
- Frozen-spin method:

Spin precession frequency with respect to momentum (ω_a).

$$\boldsymbol{\omega}_a = -\frac{q}{m}\left[G\mathbf{B} - \left(G - \frac{m^2}{p^2}\right)\boldsymbol{\beta}\times\mathbf{E} + \frac{\eta}{2}(\mathbf{E} + \boldsymbol{\beta}\times\mathbf{B})\right]$$

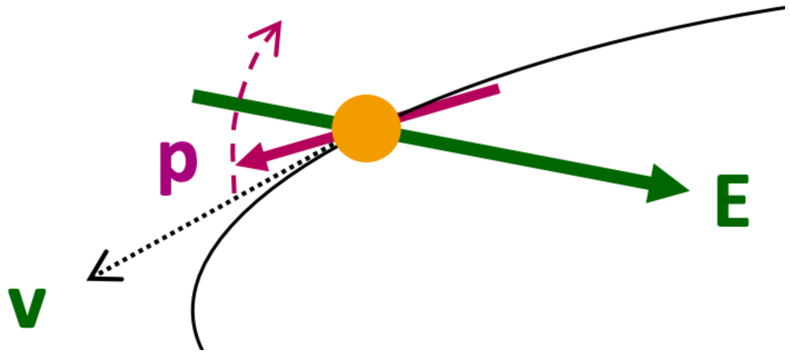
Electric ring ($B = 0$)

$$\boldsymbol{\omega}_a = \frac{q}{m}\left(G - \frac{m^2}{p^2}\right)\boldsymbol{\beta}\times\mathbf{E} - \eta\frac{q}{2m}\mathbf{E}$$

Magic momentum ($p_m \equiv m/\sqrt{G}$)

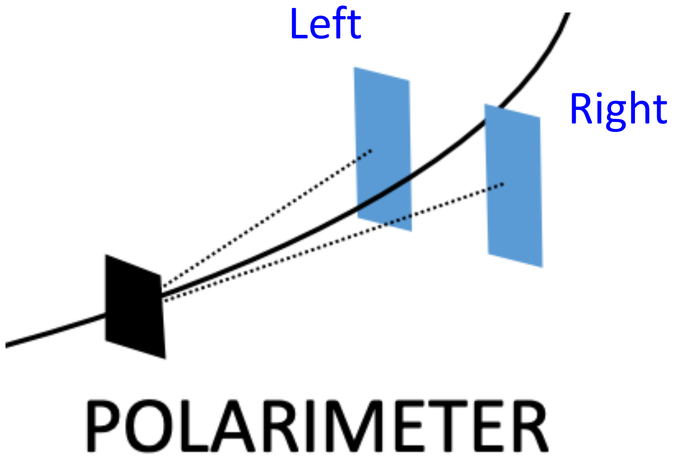
$$\boldsymbol{\omega}_a = -\eta\frac{q}{2m}\mathbf{E}$$

- Without EDM: the spin is “frozen” to the momentum.
- With EDM: the spin precesses vertically.



Storage Ring pEDM Experiment in a nutshell

- Vertical polarization measurement by the polarimeter.
  - Gradually hit the proton beam to the polarimeter target.
  - Due to spin-dependent elastic scattering, the left-right asymmetry gives information on average vertical polarization.
  - Target sensitivity $d_p = 10^{-29}\ e \cdot \mathrm{cm}$ corresponds to 1 nrad/s vertical precession rate.
  - ~ 1 year of data accumulation to achieve the target statistics.



- As an ultra-high precision measurement, understanding/controlling systematic uncertainties counts a lot.
  - Field errors, beam distribution, geometrical phases, closed-orbit planarity, etc.

Systematic Effects

- Vertical spin precession can arise from various systematic sources (false EDM).

$$\boldsymbol{\omega}_a = -\frac{q}{m}\left[\underbrace{G\mathbf{B}}_{1} - \underbrace{\left(G - \frac{m^2}{p^2}\right)\boldsymbol{\beta}\times\mathbf{E}}_{2,\,3} + \frac{\eta}{2}\left(\mathbf{E} + \boldsymbol{\beta}\times\mathbf{B}\right)\right]$$

Any of

1. Radial magnetic field (B_r) : $\sim 10\ \mathrm{aT}$
2. Vertical electric field (E_y) : $\sim 1\ \mathrm{nV/m}$
3. Vertical velocity (β_y) : $\sim 1\ \mathrm{nm}$ (vertical misalignment of magnetic quadrupoles)

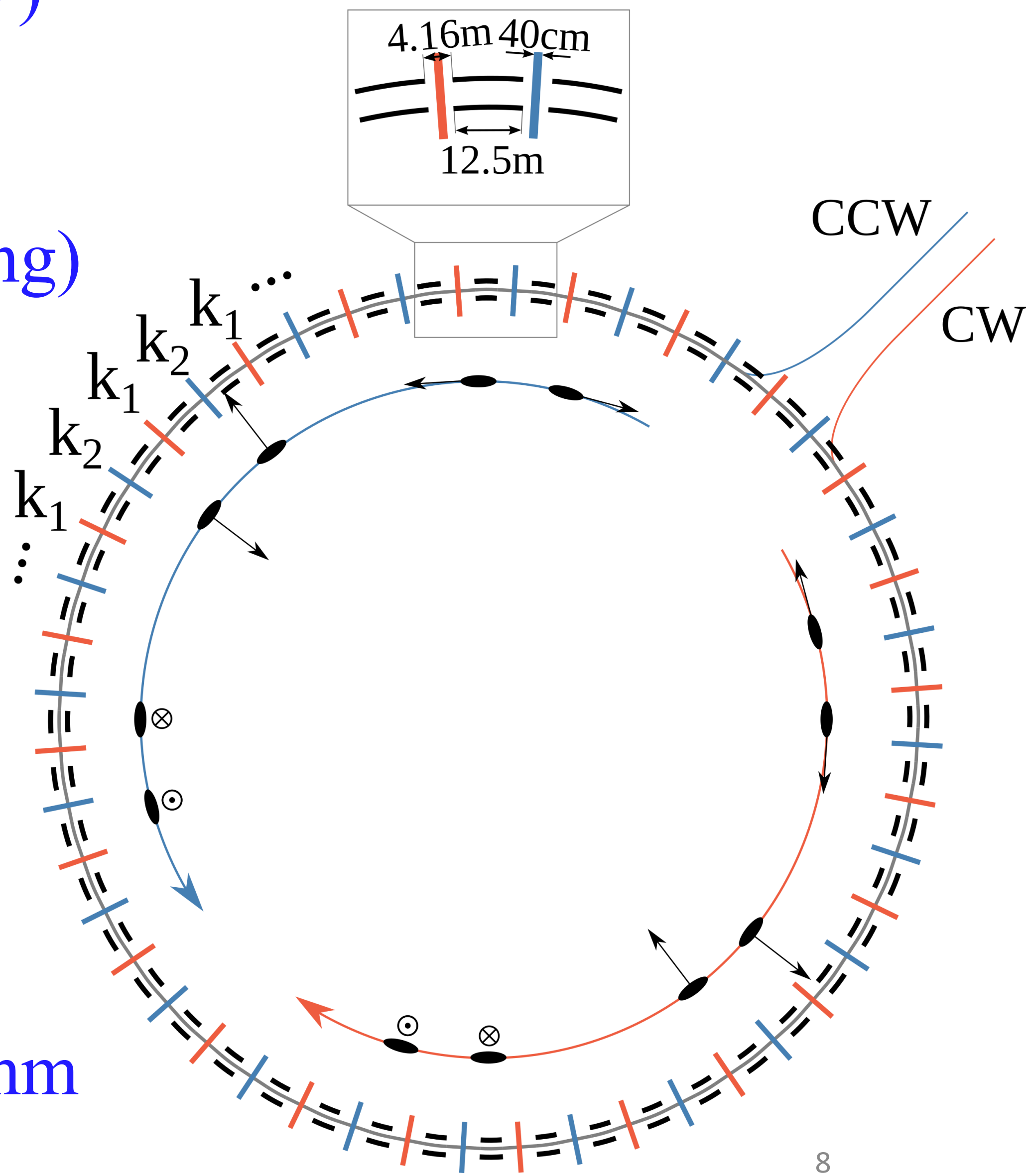
can induce a false EDM signal of $1\ \mathrm{nrad/s}$.

- The field/misalignment requirements are highly stringent and technically challenging.
- There are other systematic effects, but the above three are the dominant ones.

Symmetries against systematic errors

From Yannis K. Semertzidis

- Clock-wise (CW) vs. Counter-Clock-Wise (CCW)
    - Eliminates vertical Electric field background
- Hybrid lattice (electric bending, magnetic focusing)
    - Shields against background magnetic fields
- Highly symmetric lattice (24 FODO systems)
    - Eliminates vertical velocity background
- Positive and negative helicity
    - Reduce polarimeter systematic errors
- Flat ring to 0.1 mm, beams overlap within 0.01 mm
    - Geometrical phases; High-order vertical E-field



Counter-Rotating Beams: Killing E_y Effect

- Some systematic false EDM signals tend to point in the same direction in the counter-rotating (CR) beams.

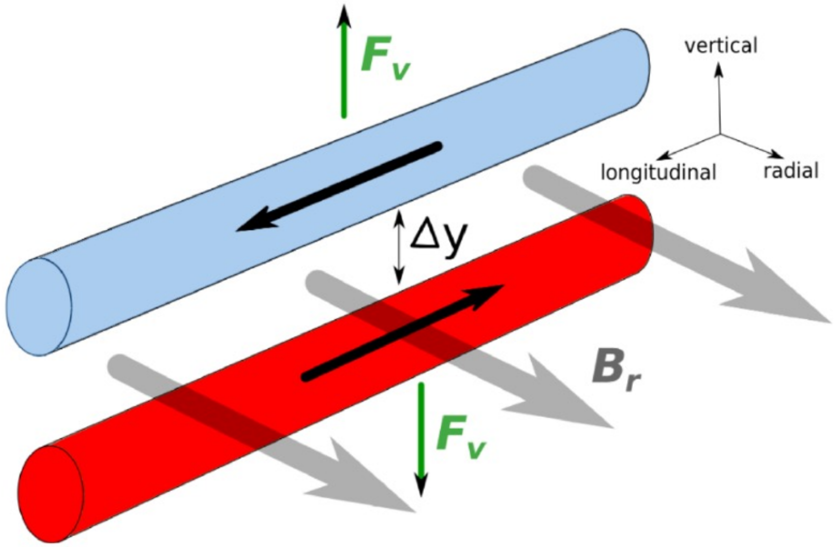
- Vertical electric field effect is one of them and thus can be suppressed by CW & CCW beams.

$$\left(\frac{\mathrm{d}S_y}{\mathrm{d}t}\right)_{\mathrm{EDM}} = \frac{1}{2}\left(\frac{\mathrm{d}S_y}{\mathrm{d}t}\right)_{\mathrm{CW}} - \frac{1}{2}\left(\frac{\mathrm{d}S_y}{\mathrm{d}t}\right)_{\mathrm{CCW}}$$

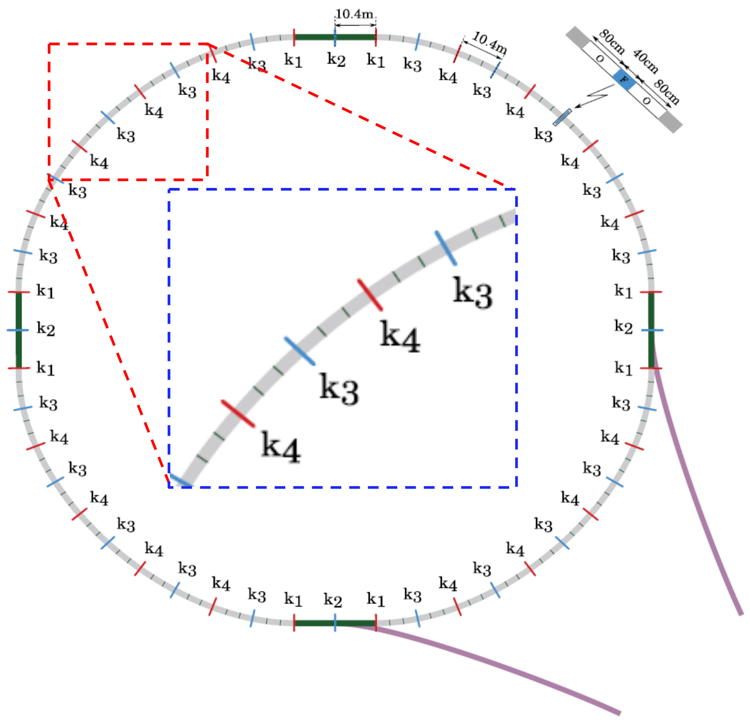
- The lattice should be an electric ring to store the CR beams.

Hybrid Lattice: Killing B_r Effect

- The originally proposed lattice is an all-electric ring.
- One of the primary efforts to mitigate the radial magnetic field effect was to develop a beam position monitor (BPM) using a superconducting quantum interference device (SQUID): $\sim 10\ \mathrm{fT}/\sqrt{\mathrm{Hz}}$ sensitivity for a state-of-the-art SQUID-based BPM.

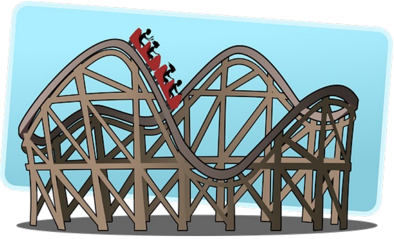


- Later, S. Hacıömeroğlu and Y. K. Semertzidis proposed a novel way of using natural shielding with magnetic focusing: PRAB **22**, 034001 (2019).
  - Alternative-gradient (a.k.a strong focusing) FODO cells to store the CR beams.



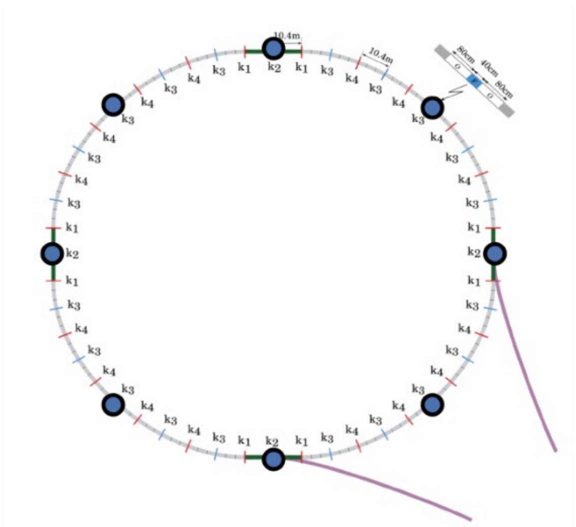
Symmetric Lattice: Killing β_y Effect

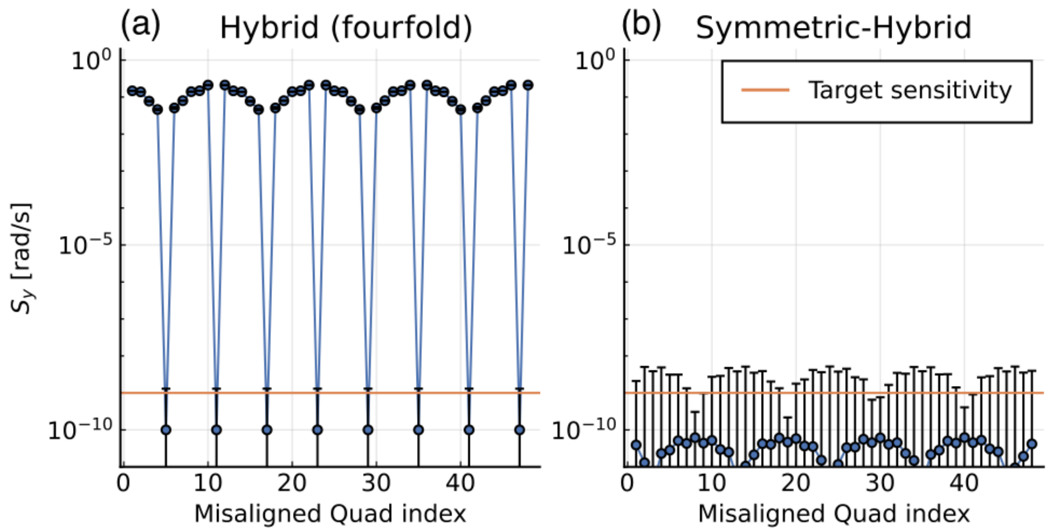
- Vertical velocity may not average out in bending regions $\left(\langle\beta_y\rangle_{\mathbf{bending}} \neq 0\right)$ if the quadrupoles are not perfectly aligned vertically.
- Vertical orbit corrugation exists unless we have flat closed-orbit planarity.

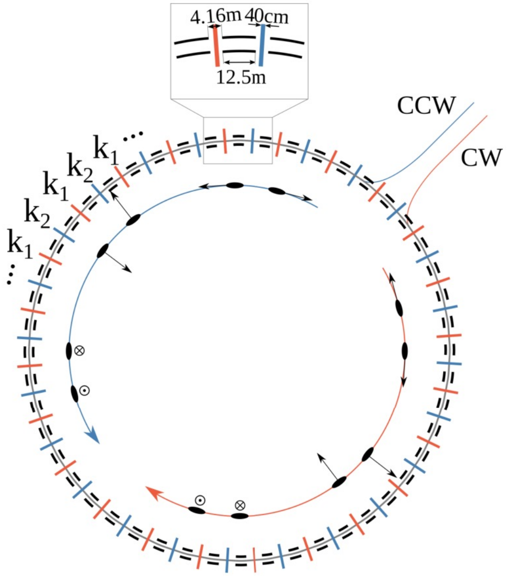


- The radial polarization ($s_x = 1$) maximizes the effect. Symmetry is a key to suppressing it!
  - Vertically misalign one quadrupole at a time by $100\ \mu\text{m}$.

Z. Omarov *et al.*, PRD 105, 032001 (2022)







Combined Systematic Effects

Z. Omarov *et al.*, [PRD 105, 032001 (2022)](#)

- Symmetric-hybrid + CR beams suppress all the dominant systematic effects.

$$\left(\frac{\mathrm{d}S_y}{\mathrm{d}t}\right)_{\mathrm{EDM}} = \frac{1}{2}\left(\frac{\mathrm{d}S_y}{\mathrm{d}t}\right)_{\mathrm{CW1,2}} - \frac{1}{2}\left(\frac{\mathrm{d}S_y}{\mathrm{d}t}\right)_{\mathrm{CCW1,2}}$$

All systematic effects combined. Filtering out false EDM. Misalignment and the beam separation.

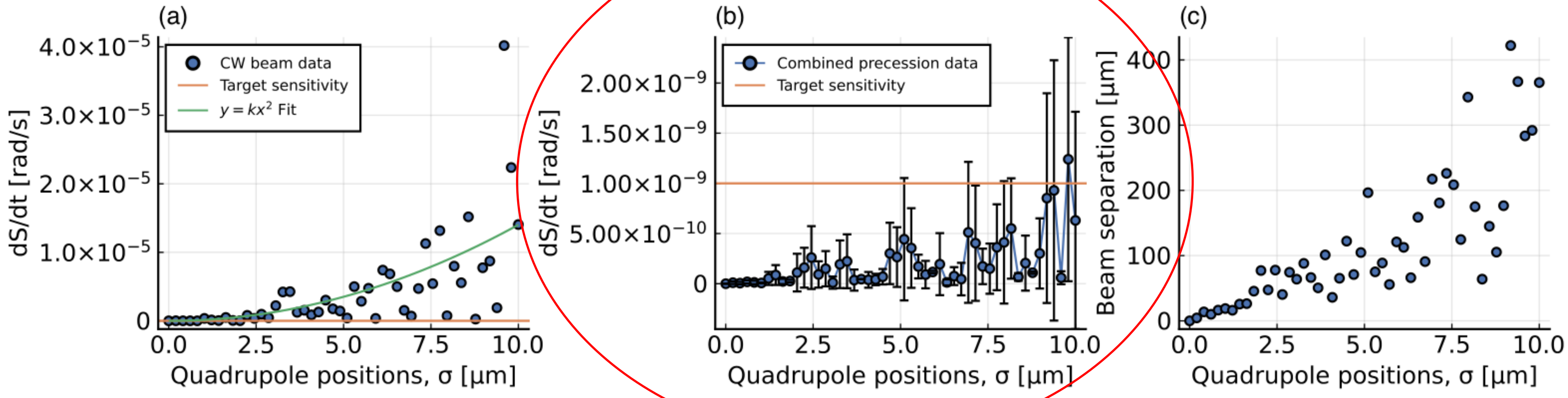


FIG. 9. (a) *Longitudinal polarization case, CW beam only*. Vertical spin precession rate (absolute) vs random misalignments of quadrupoles in both x, y directions by rms σ with different seeds per each point (when the same seeds are used everywhere, the $y = kx^2$ fit is perfect, meaning that every point can be extrapolated to any rms σ value using this functional form). Combination with CCW and quadrupole polarity switching achieves large cancellation—see part (b). (b) *CW and CCW beam and with quadrupole polarity switching*. Total combination as presented in Appendix C. Notably, the background vertical spin precession rate (absolute) stays below the target sensitivity. Irregularity of the points is discussed in Appendix B. (c) Correspondence between CR beam separation and rms σ quadrupole misalignments.

Storage Ring Probes of DM/DE

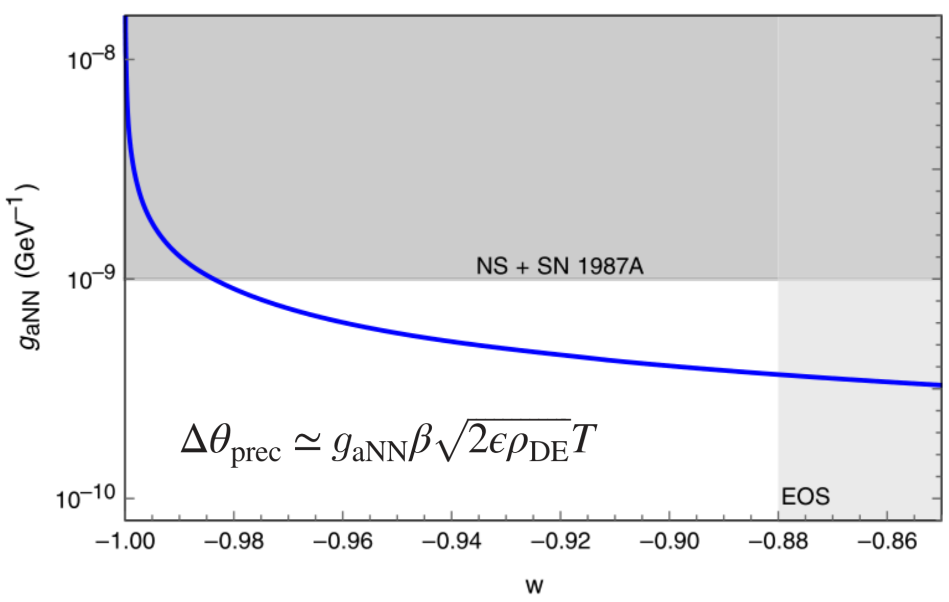
P. Graham and S. Rajendran, PRD **88**, 035023 (2013)
P. Graham et al., PRD **103**, 055010 (2021)

- Couplings with dark matter (DM) and dark energy (DE).
  - ALP or vector DM gradient ($g_{aNN}\nabla a \cdot \hat{\sigma}_N$) ⇒ anomalous longitudinal oscillating B field.
  - DE gradient ⇒ anomalous longitudinal B field.

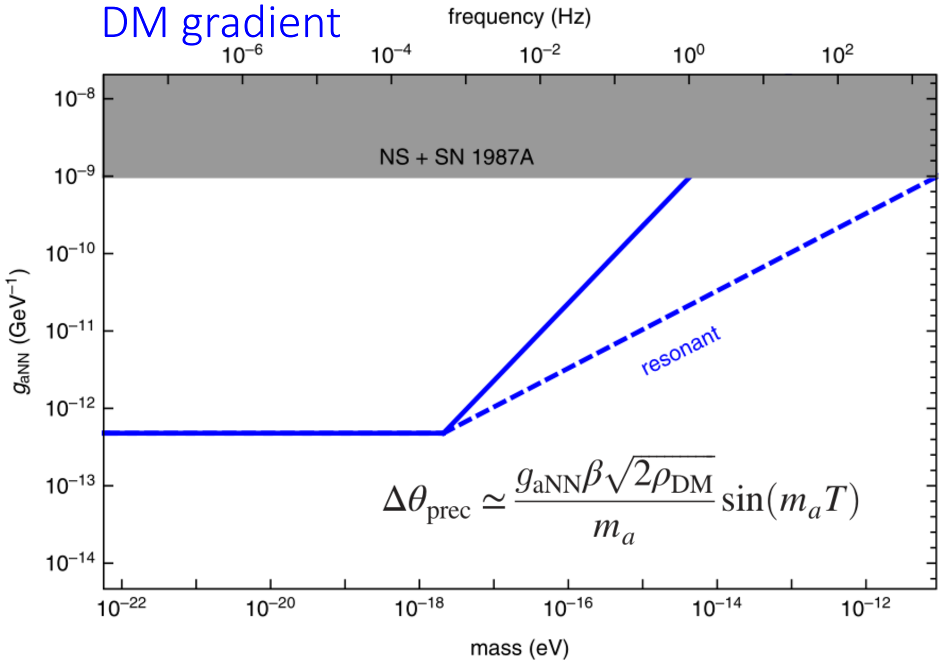
$$\boldsymbol{\omega}_{\mathrm{DM}}(t) \propto \cos(m_a t)\,\hat{\beta}, \qquad \boldsymbol{\omega}_{\mathrm{DE}} \propto \hat{\beta}$$

  - Projected sensitivity assuming the radial initial polarization.

DE gradient



DM gradient

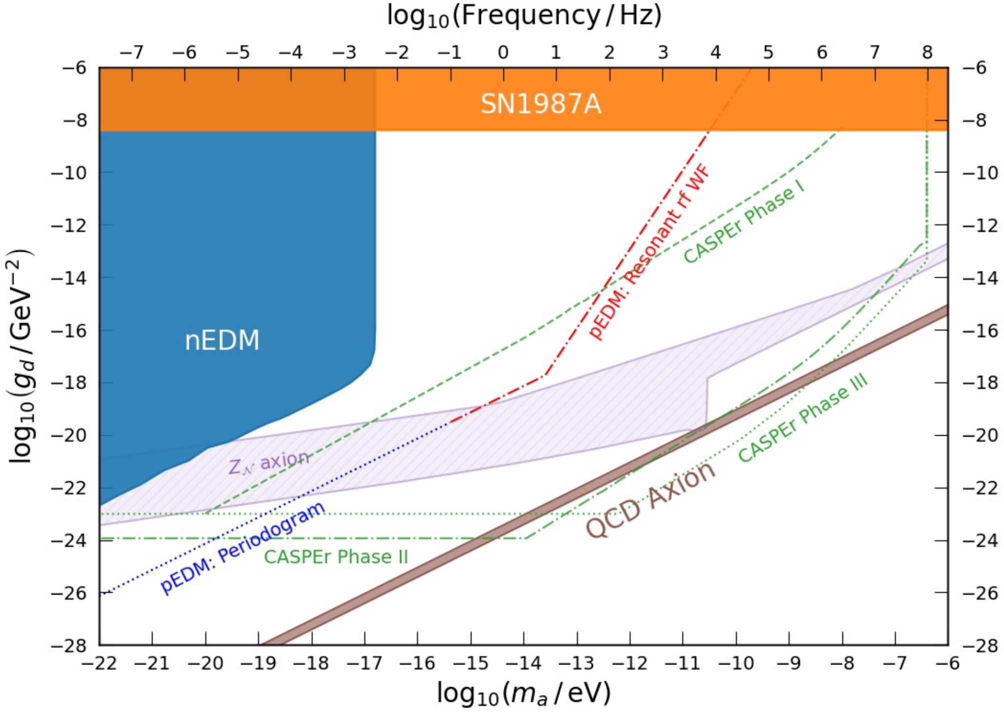


Storage Ring Probes of DM/DE

P. Graham and S. Rajendran, PRD **88**, 035023 (2013)
P. Graham et al., PRD **103**, 055010 (2021)

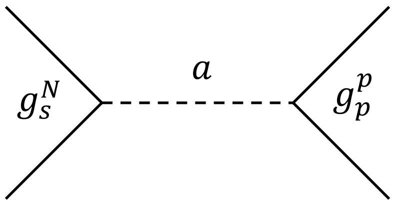
- Couplings with dark matter (DM) and dark energy (DE).
  - ALP-EDM ($g_{aN\gamma} a \hat{\sigma}_N \cdot \mathbf{E}$) $\Rightarrow$ oscillating EDM at m_a.
    For the QCD axion: $d_N^{\mathrm{QCD}} \approx 10^{-34} \cos(m_a t)\ e \cdot \mathrm{cm}$.
    $$\boldsymbol{\omega}_{\mathrm{ALP-EDM}} \propto \cos(m_a t)\, \hat{x}$$
- Storage ring probes of axion-induced oscillating EDM.
  S. Chang *et al.*, PRD **99**, 083002 (2019)
- Complementary method using an RF Wien filter.
  On Kim and Y. Semertzidis, PRD **104**, 096006 (2021)
- Parasitic measurement with pEDM experiment.
  - Low frequency: Periodogram analysis.
  - High frequency: Resonant RF Wien filter.

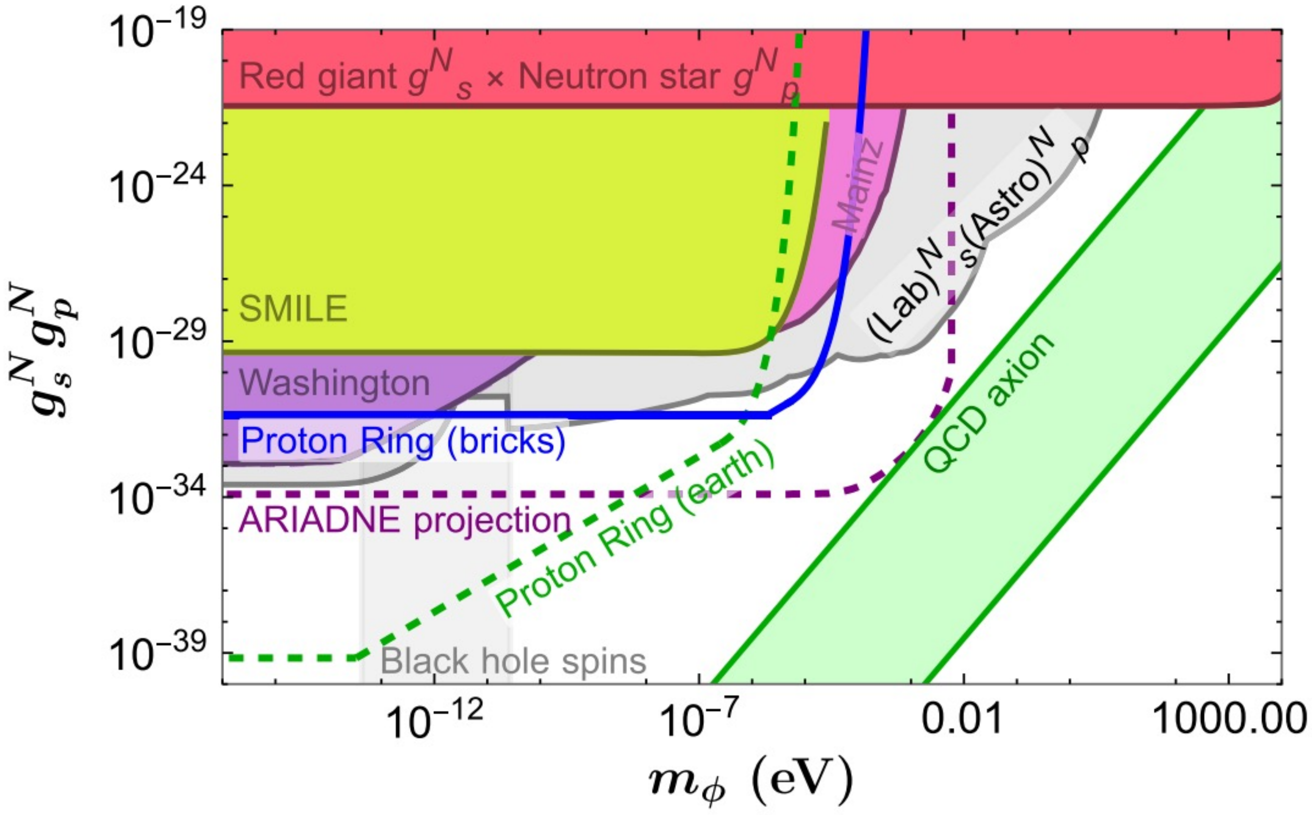
ALP-EDM coupling



Search for Axion Forces with pEDM

- Probe axion-mediated spin precession from nucleon sources.
  P. Agrawal *et al.*, PRD **108**, 015017 (2023).

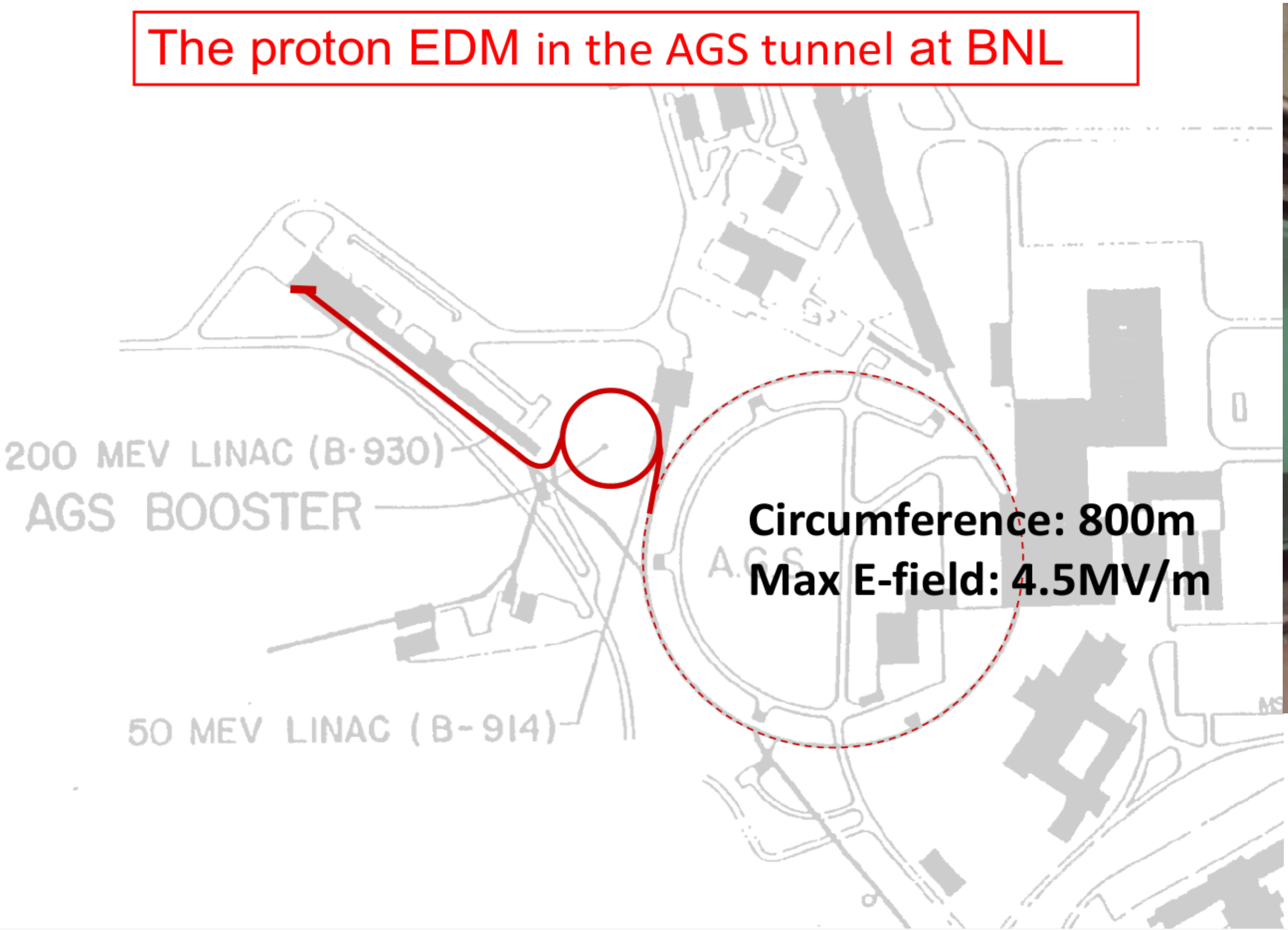


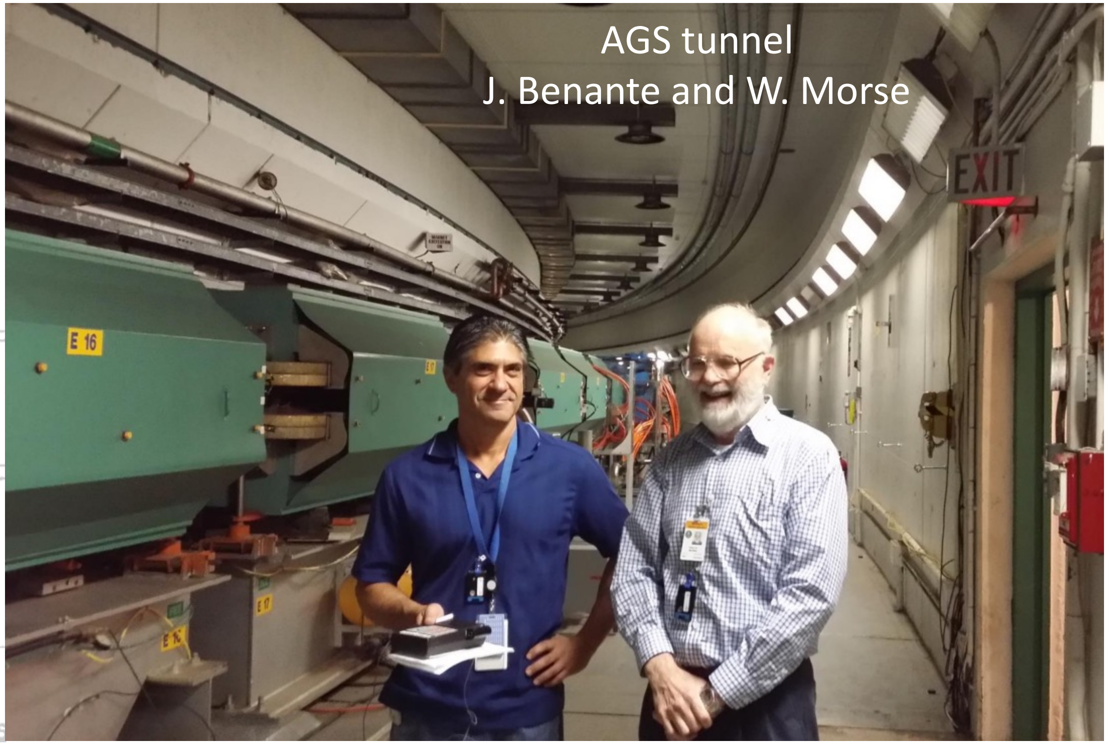


Also look at 2210.14959 and 2105.03422 for references.

pEDM: Where It Stands

- BNL funded the cost estimate of the project at the AGS ($140-190M) to build and commission the experiment in the AGS tunnel. Its schedule is compatible with EIC.

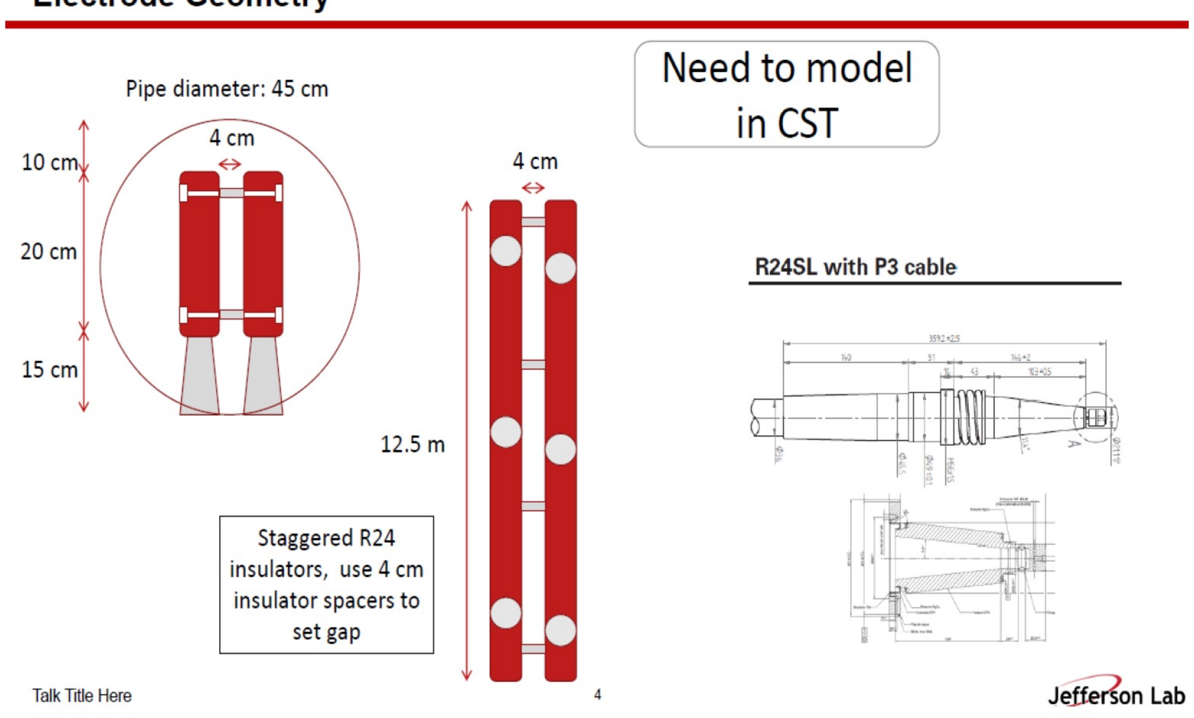


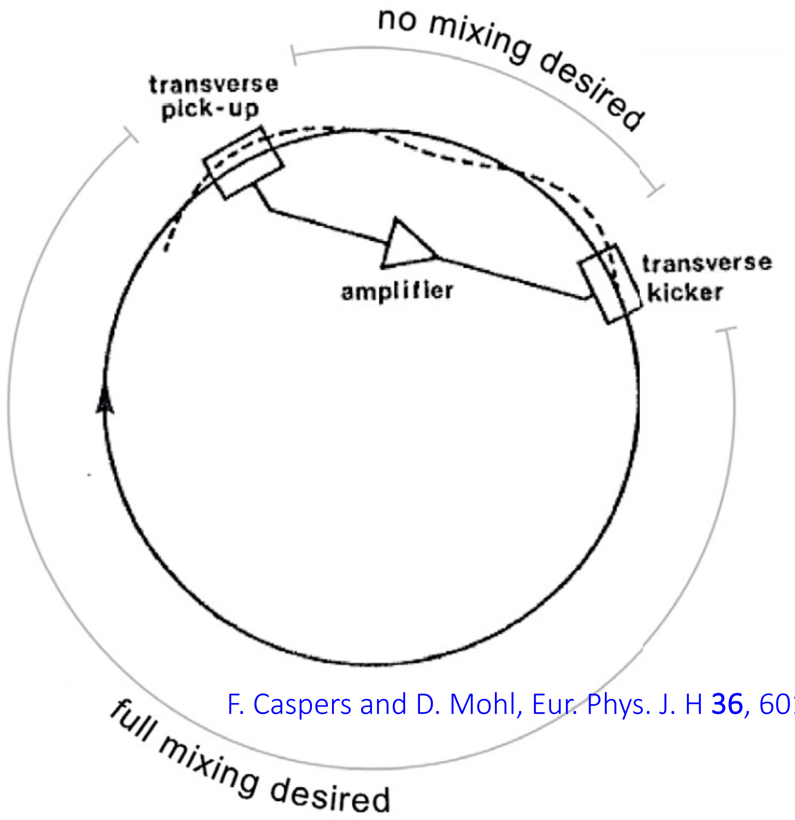


pEDM: Where It Stands

- BNL funded the cost estimate of the project at the AGS ($140-190M) to build and commission the experiment in the AGS tunnel. Its schedule is compatible with EIC.
- BNL approved a three-year LDRD on developing the electric field plates and supporting a study on stochastic cooling.

Riad Suleiman *et al.*





F. Caspers and D. Mohl, Eur. Phys. J. H **36**, 601–632 (2011)

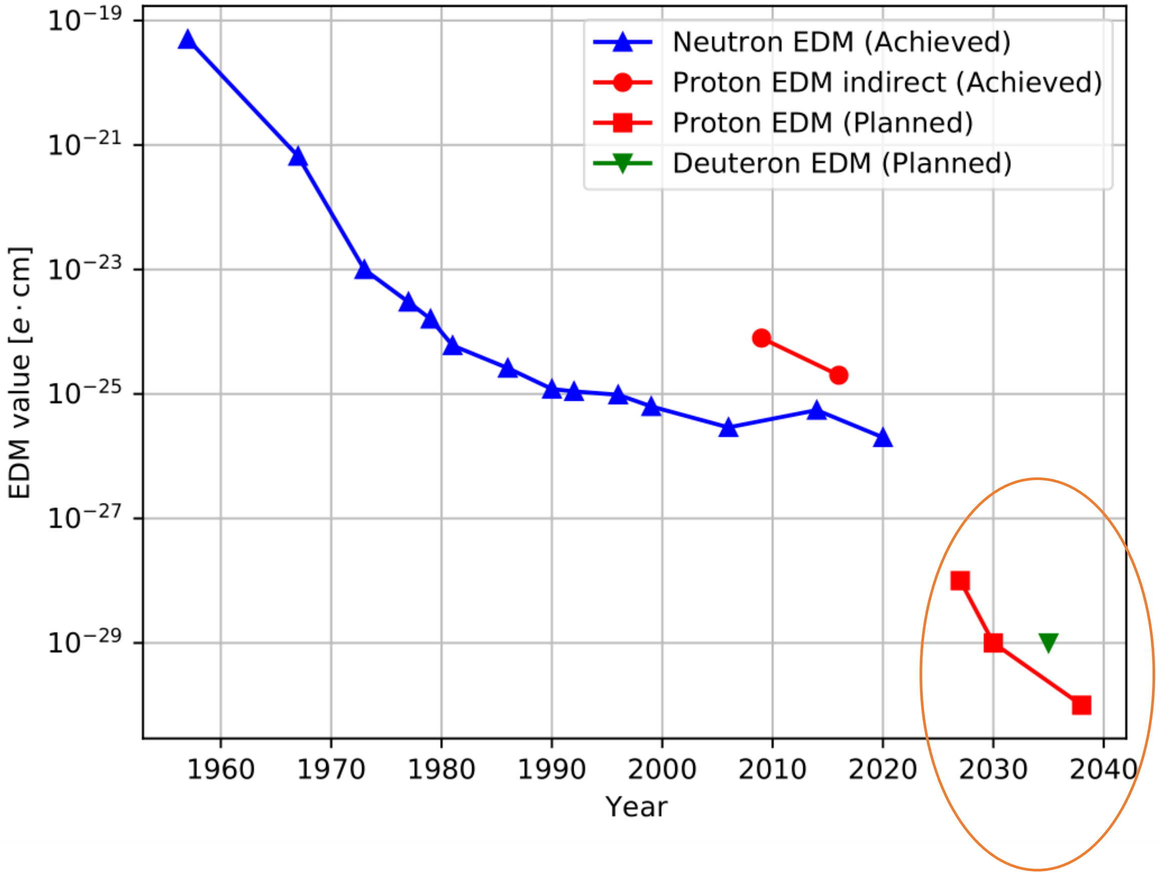
pEDM: Where It Stands

- BNL funded the cost estimate of the project at the AGS ($140-190M) to build and commission the experiment in the AGS tunnel. Its schedule is compatible with EIC.
- BNL approved a three-year LDRD on developing the electric field plates and supporting a study on stochastic cooling.
- The project is part of the P5 deliberations, and we expect its prioritization announcement on Dec. 7th.

Summary and Outlook

- Storage ring proton EDM at $10^{-29}\ e \cdot \mathrm{cm}$ within the decade (BNL/AGS option). Great physics reach, including ultralight axion-like dark matter search.
- No need to develop new technologies.
- Comprehensive systematic error studies with realistic experimental parameters were conducted. The R&D phase for the pEDM ring has been completed.
  Z. Omarov *et al.*, PRD 105, 032001 (2022)
- After protons, a natural extension is to have deuterons, ^{3}He, and other particles with the inclusion of magnetic fields (further work required).

Technically driven schedule



Backups

Storage ring EDM

- Proton "magic" values PRD **105**, 032001 (2022):

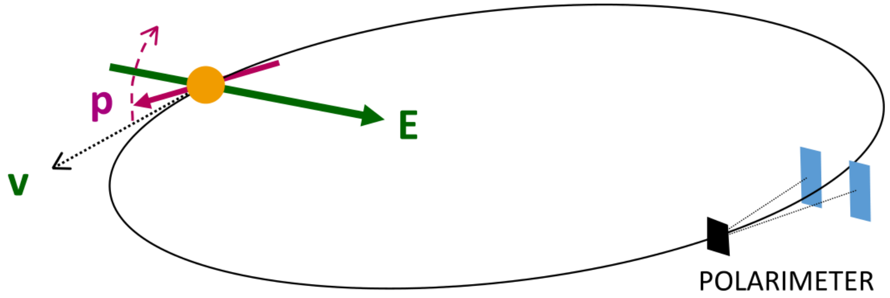
G	β	γ	p	KE
1.793	0.598	1.248	0.7 GeV/c	233 MeV

- EDM precession:

$$\omega_d = \frac{d}{s}E \approx 1\ \mathrm{nrad/s}\left(\frac{d}{10^{-29}\ e\cdot\mathrm{cm}}\right)\left(\frac{1/2}{s}\right)\left(\frac{E}{3.3\ \mathrm{MV/m}}\right)$$

- Statistical uncertainty PRD **104**, 096006 (2021):

$$\sigma_{\omega_d} = \frac{2.3}{PA\sqrt{N_{\mathrm{cyc}} f \tau_p T_{\mathrm{tot}}}} \approx 1\ \mathrm{nrad/s}\left(\frac{0.8}{P}\right)\left(\frac{0.6}{A}\right)\sqrt{\left(\frac{4\times10^{10}}{N_{\mathrm{cyc}}}\right)\left(\frac{1\%}{f}\right)\left(\frac{2\times10^{3}\ \mathrm{s}}{\tau_p}\right)\left(\frac{1\ \mathrm{year}}{T_{\mathrm{tot}}}\right)}$$



P : Initial polarization.
A : Analyzing power (coefficient for LR asymmetry from polarimeter).
N_{cyc}: Number of stored particles per cycle.
f : Detector efficiency.
τ_p : Spin coherence time (SCT).
T_{tot} : Total measurement time.

TABLE III. Ring and beam parameters for the Symmetric-Hybrid ring design.

Quantity	Value
Bending radius R_0	95.49 m
Number of periods	24
Electrode spacing	4 cm
Electrode height	20 cm
Deflector shape	Cylindrical
Radial bending E field	4.4 MV/m
Straight section length	4.16 m
Quadrupole length	0.4 m
Quadrupole strength	±0.21 T/m
Bending section length	12.5 m
Bending section circumference	600 m
Total circumference	800 m
Cyclotron frequency	224 kHz
Revolution time	4.46 μs
$\beta_x^{max}, \beta_y^{max}$	64.54 m, 77.39 m
Dispersion, D_x^{max}	33.81 m
Tunes, Q_x, Q_y	2.699, 2.245
Slip factor, $\frac{dt}{t} / \frac{dp}{p}$	−0.253
Momentum acceptance, (dp/p)	5.2×10^{-4}
Horizontal acceptance (mm · mrad)	4.8
RMS emittance (mm · mrad), ϵ_x, ϵ_y	0.214, 0.250
RMS momentum spread	1.177×10^{-4}
Particles per bunch	1.17×10^{8}
RF voltage	1.89 kV
Harmonic number, h	80
Synchrotron tune, Q_s	3.81×10^{-3}
Bucket height, $\Delta p/p_{\mathrm{bucket}}$	3.77×10^{-4}
Bucket length	10 m
RMS bunch length, σ_s	0.994 m

Storage Ring Electric Dipole Moments exp. options

Fields	Example	EDM signal term	Comments
Dipole magnetic field **(B)** **(Parasitic)**	Muon g-2	Tilt of the spin precession plane. **(Limited statistical sensitivity due to spin precession)**	Eventually limited by geometrical alignment. **Requires consecutive CW and CCW injection to eliminate systematic errors**
Combination of electric & and magnetic fields **(E, B)** **(Combined lattice)**	Deuteron, ^{3}He, proton, muon, etc.	Mainly: $\frac{d\vec{s}}{dt} = \vec{d} \times \left(\vec{v} \times \vec{B}\right)$	High statistical sensitivity. **Requires consecutive CW and CCW injection with main fields flipping sign to eliminate systematic errors**
Radial Electric field **(E)** & Electric focusing **(E)** **(All electric lattice)**	Proton, etc.	$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$	Large ring, CW & CCW storage. **Requires demonstration of adequate sensitivity to radial B-field syst. error**
Radial Electric field **(E)** & Magnetic focusing **(B)** **(Hybrid, symmetric lattice)**	Proton, etc.	$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$	Large ring, CW & CCW storage. **Only lattice to achieve direct cancellation of main systematic error sources (its own “co-magnetometer”).** GOLD STANDARD!

Effect as a function of azimuthal harmonic *N*

COMPREHENSIVE SYMMETRIC-HYBRID RING DESIGN FOR A … PHYS. REV. D **105,** 032001 (2022)

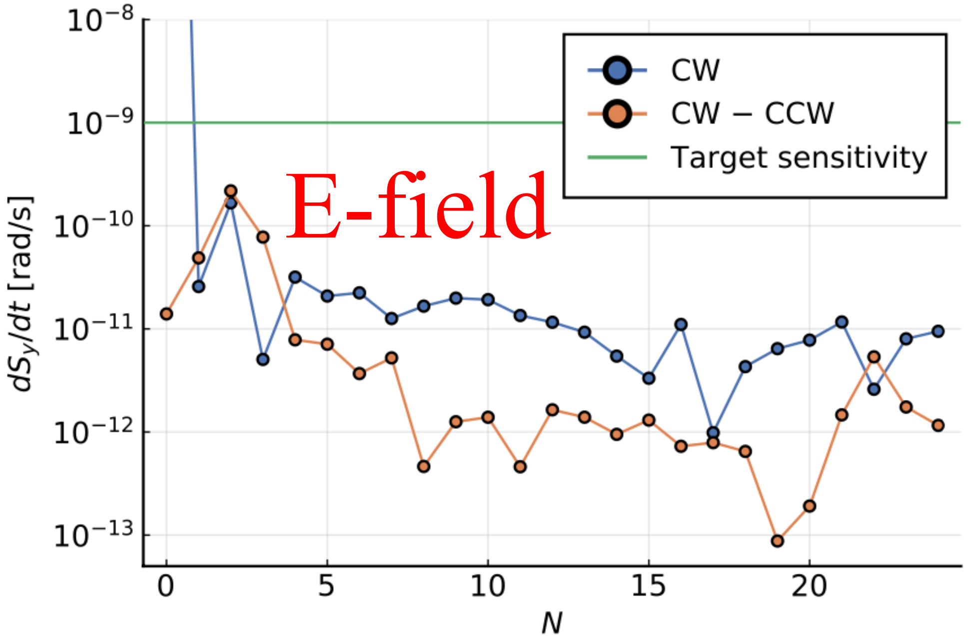


FIG. 7. *Longitudinal polarization case* $S_s = 1$, sensitive to EDM. Vertical spin precession rate vs $E_y = 10$ V/m field N harmonic around the ring azimuth. For $N = 0$, the precession rate for the CW (or CCW) beam is around 5 rad/s. The difference of the precession rates for CR beams (orange) is below the target sensitivity for all N. Irregularities of the low values are due to the inability to determine the exact precession rate from the simulation results. Hence, the points only show a statistical upper limit of the possible vertical precession rate; actual rates could be lower. More about this is in Appendix B.

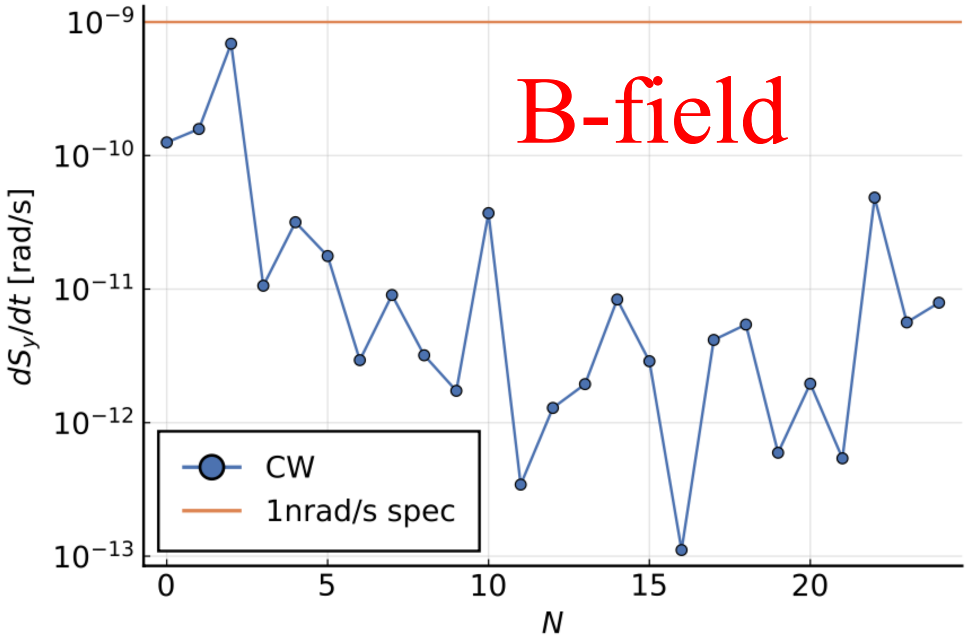
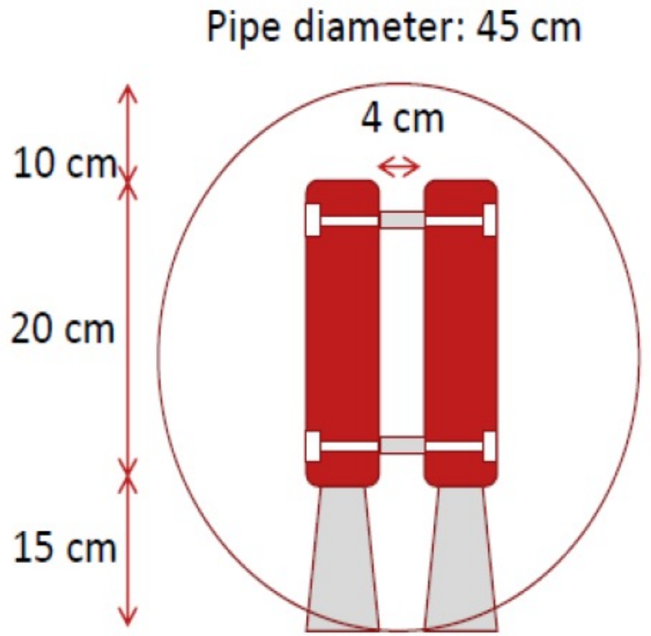


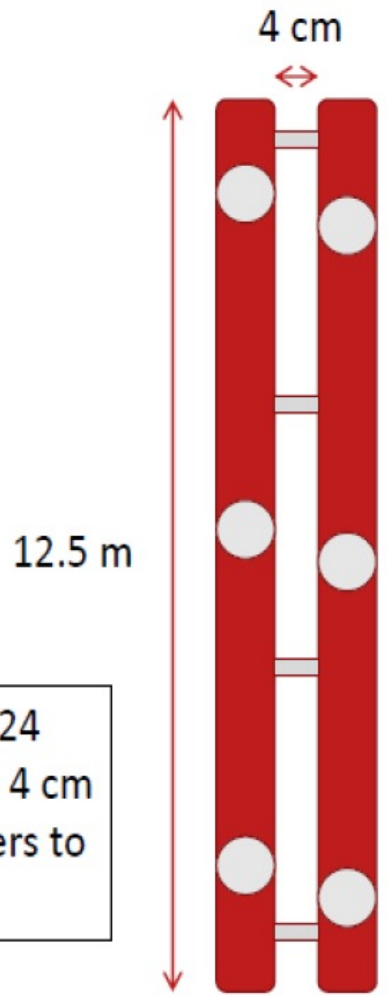
FIG. 8. *Longitudinal polarization case* $S_s = 1$, *CW beam only.* Vertical spin precession rate vs $B_x = 1$ nT field N harmonic around the ring azimuth. The magnetic field amplitude is chosen to be similar to beam separation requirements in Sec. IV A, and more than $B_x = 1$ nT splits the CR beams too much. Irregularities of the low values are due to the inability to determine the exact precession rate from the simulation results. Hence, the points only show a statistical upper limit of the possible vertical precession rate; actual rates could be lower. More about this is in Appendix B.

Large Surface Area Electrodes

Parameter	Tevatron pbar-p Separators	BNL K-pi Separators	pEDM (low risk)
Length/unit	2.6m	4.5m	5×2.5m
Gap, E-field	5cm, 7.2 MV/m	10cm, 4 MV/m	4cm, 4.5 MV/m
Height	0.2m	0.4m	0.2m
Number	24	2	48
Max. HV	±(150-180)KV	±200KV	±90KV

Electrode Geometry

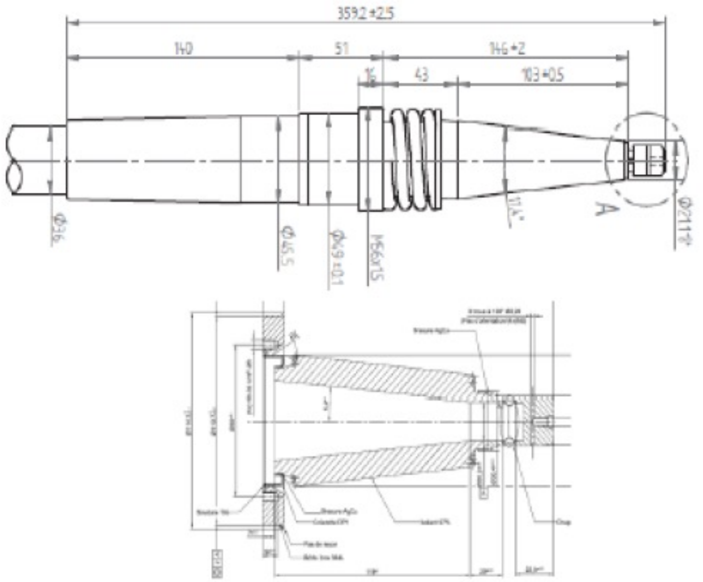




Staggered R24 insulators, use 4 cm insulator spacers to set gap

Need to model in CST

R24SL with P3 cable



Demonstration of SQUID-based BPM

- R&D work by Selcuk Haciomeroglu & Zhanibek Omarov.