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in-person presentation

Storage ring proton EDM comprehensive systematic errors study for an experiment at 10^{-29} *e*-cm

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for the Storage Ring EDM Collaboration

- Statistics for 10^{-29} *e*-cm for pEDM, for best hadronic EDM experiment
- Matching systematic error levels, using symmetries

Snowmass paper on EDMs, why many EDMs:

Operator	Loop order	Mass reach
Electron EDM	1	$48\,\mathrm{TeV}\sqrt{10^{-29}\,e\,\mathrm{cm}/d_e^{\max}}$
	2	$2\,\mathrm{TeV}\sqrt{10^{-29}\,e\,\mathrm{cm}/d_e^{\max}}$
Up/down quark EDM	1	$130\,\mathrm{TeV}\sqrt{10^{-29}\,e\,\mathrm{cm}/d_q^{\max}}$
	2	$13\,\mathrm{TeV}\sqrt{10^{-29}\,e\,\mathrm{cm}/d_q^{\max}}$
Up-quark CEDM	1	$210\,\mathrm{TeV}\sqrt{10^{-29}\,\mathrm{cm}/\tilde{d}_u^{\max}}$
	2	$20\,\mathrm{TeV}\sqrt{10^{-29}\,\mathrm{cm}/\tilde{d}_u^{\max}}$
Down-quark CEDM	1	$290\,\mathrm{TeV}\sqrt{10^{-29}\,\mathrm{cm}/\tilde{d}_d^{\max}}$
	2	$28\,\mathrm{TeV}\sqrt{10^{-29}\,\mathrm{cm}/\tilde{d}_d^{\max}}$
Gluon CEDM	2 ($\propto m_t$)	$22\,\mathrm{TeV}\sqrt[3]{10^{-29}\,\mathrm{cm}/(100\,\mathrm{MeV})/\tilde{d}_G^{\max}}$
	2	$260\,\mathrm{TeV}\sqrt{10^{-29}\,\mathrm{cm}/(100\,\mathrm{MeV})/\tilde{d}_G^{\max}}$

TABLE I. Crude estimate of the mass reach of different operators. See text for explanation of the notation and assumptions used in deriving the estimates.

$$
\begin{aligned}
d_n = &-(1.5\pm0.7)\cdot10^{-3}\,\bar{\theta}\,e\,\mathrm{fm}\\
&-(0.20\pm0.01)d_u + (0.78\pm0.03)d_d + (0.0027\pm0.016)d_s\\
&-(0.55\pm0.28)e\tilde{d}_u - (1.1\pm0.55)e\tilde{d}_d + (50\pm40)\,\mathrm{MeV}\,e\,\tilde{d}_G\,.
\end{aligned}
$$

Electric dipole moments and the search for new physics

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Snowmass papers on EDMs

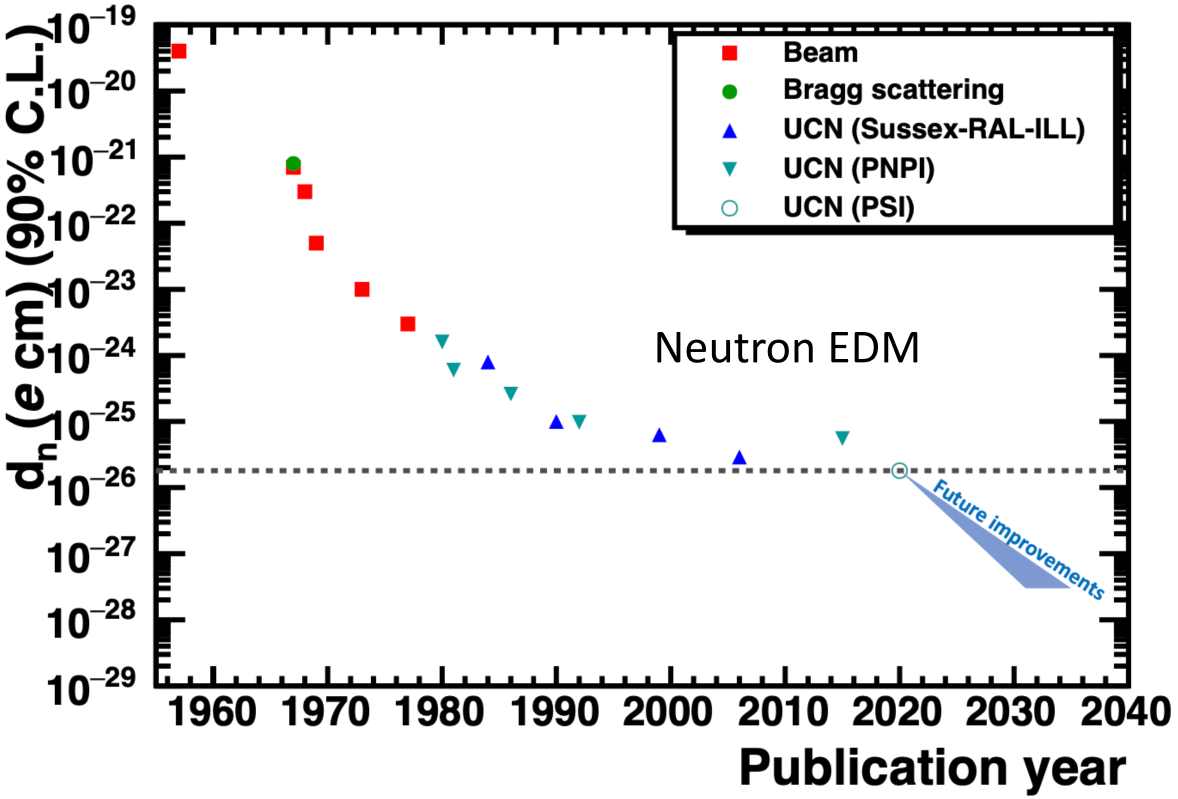
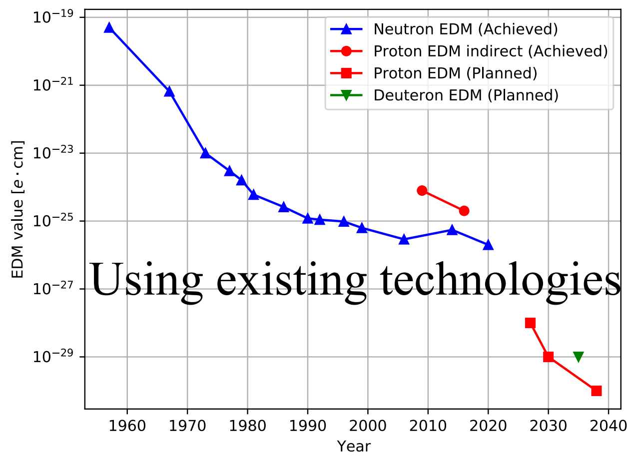


FIG. 3. Evolution of the nEDM results along with projected future results



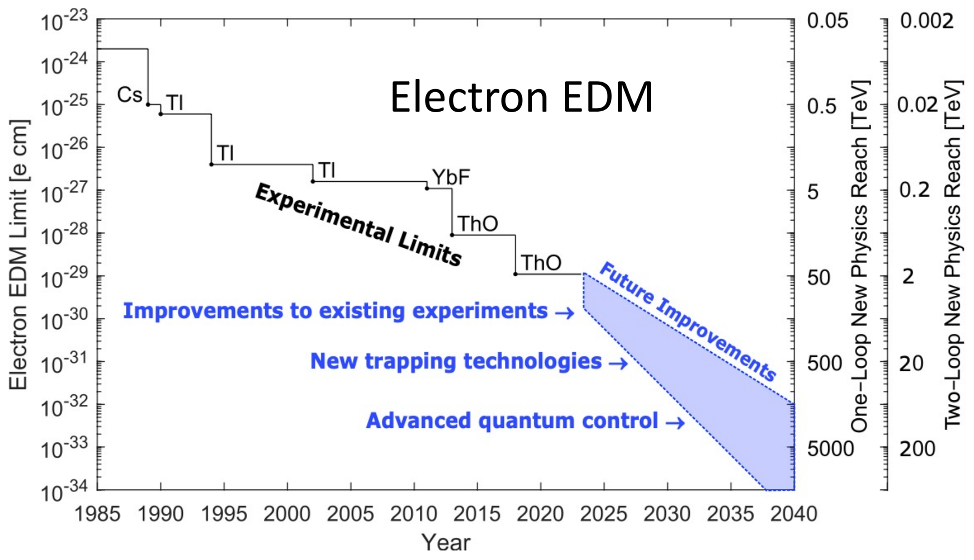
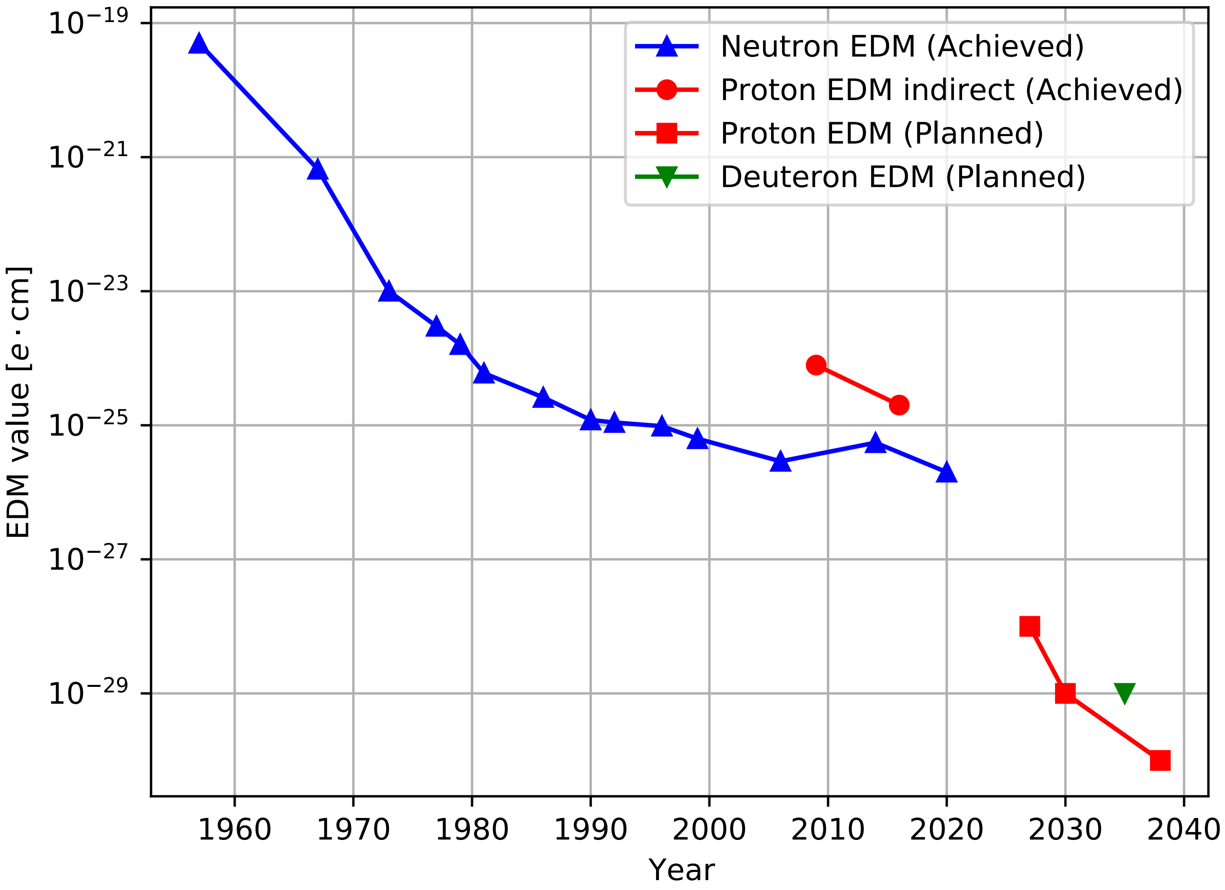


FIG. 5. Electron EDM limits versus time, along with new physics reach for one-loop and two-loop effects (see Eq. 2). All electron EDM experiments to date use AMO techniques. The solid line indicates the most sensitive experimental limit, including the species used. The shaded area indicates potential future improvements discussed in the text. Improvements in the next few years are driven largely by improvements to existing experiments and are quite likely, though as we go more into the future the projection becomes increasingly speculative and uncertain.

Snowmass paper on pEDM



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]

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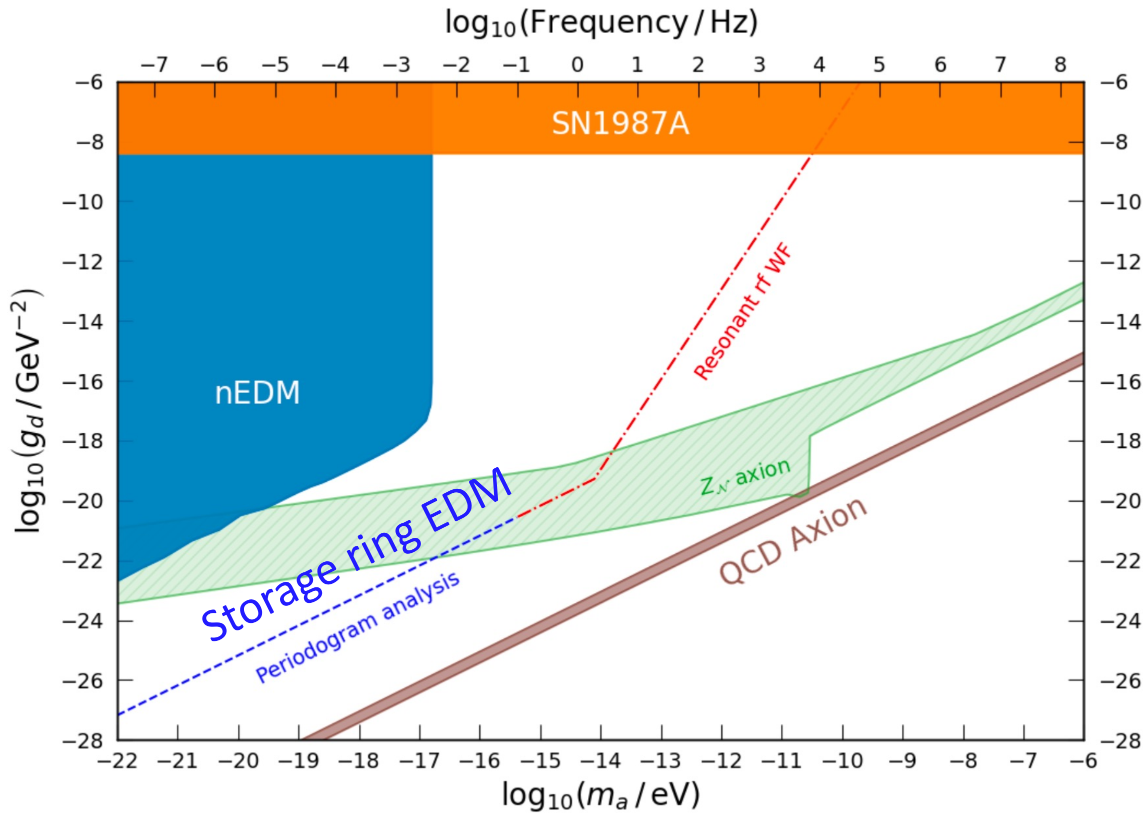
Snowmass paper on pEDM



Graph by On Kim

The storage ring proton EDM experiment

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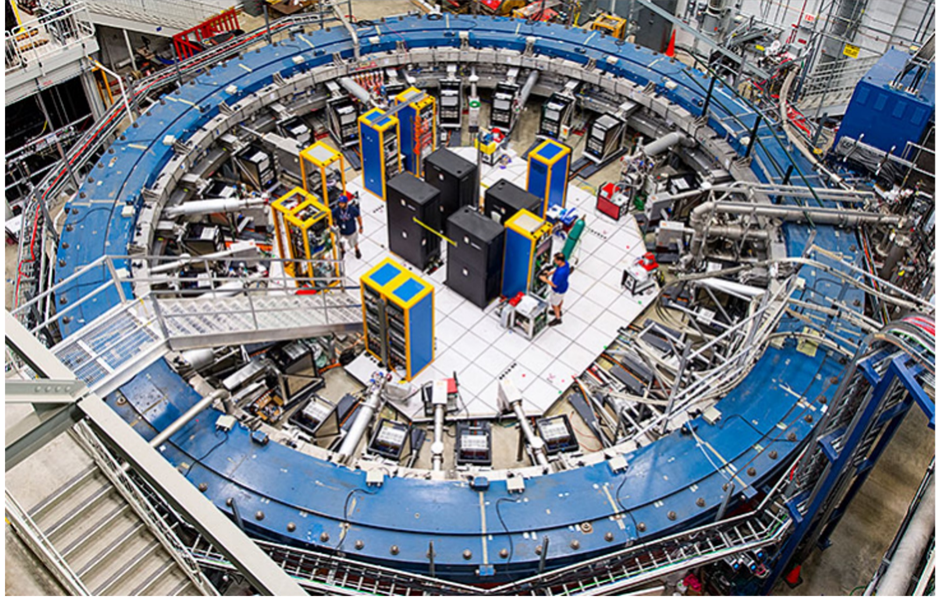
Storage ring pEDM at 10^{-29} *e*-cm, best hadronic EDM exp.

- High physics reach at hundreds of TeV New-Physics mass scale, enhanced sensitivity to θ_{QCD} by 3-orders of magnitude. Best sensitivity to Higgs CPV
- If found, it can help explain the matter-antimatter asymmetry of the universe.
- Direct search for low/very low frequency axion dark matter
- High intensity polarized proton and deuteron beams available. The natural beam lifetime is very long, opportunity for even larger statistical accuracy.

Muon g-2 experiment



- Muon g-2 results announcement at Fermilab, April 2021 reached >3B people.

- Muon g-2 success. The collaboration developed several high-precision numerical integrators for beam/spin dynamics simulations probing systematic errors.

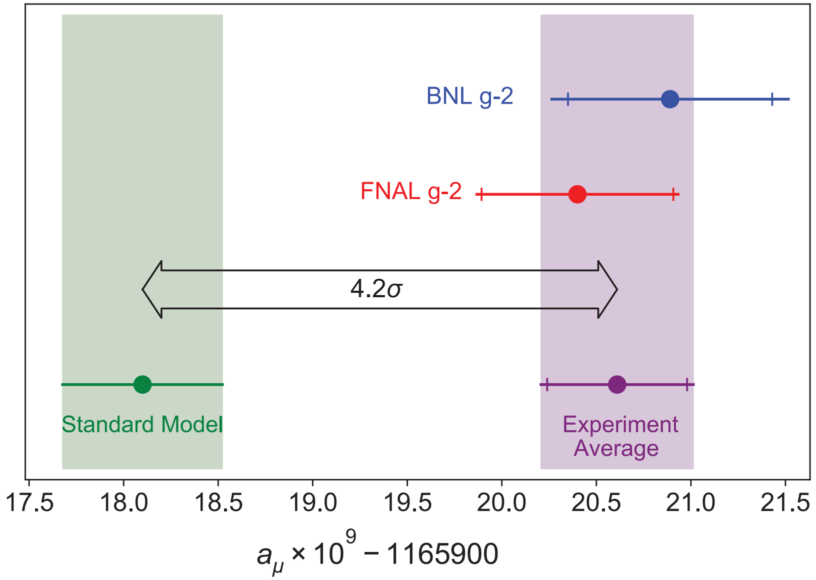


FIG. 4. From top to bottom: experimental values of a_μ from BNL E821, this measurement, and the combined average. The inner tick marks indicate the statistical contribution to the total uncertainties. The Muon $g-2$ Theory Initiative recommended value [13] for the standard model is also shown.

Hadronic Electric Dipole Moments

Input to hadronic EDM

- Theta-QCD (part of the SM)

- CP-violation sources beyond the SM

A number of alternative simple systems could provide invaluable complementary information (e.g. proton, neutron and ^{3}He, deuteron,…).

- At 10^{-29}e•cm pEDM is at least an order of magnitude more sensitive than the current nEDM plans.

EDMs of different systems (Marciano)

Theta_QCD:

$$d_n \simeq -d_p \simeq 3\times10^{-16}\bar{\theta}\ \mathrm{e\cdot cm}$$

$$d_D\left(\bar{\theta}\right)/d_N\left(\bar{\theta}\right) \approx 1/3$$

Super-Symmetry (SUSY) model predictions:

$$d_n \simeq 1.4\left(d_d - 0.25d_u\right) + 0.83e\left(d_u^c + d_d^c\right) - 0.27e\left(d_u^c - d_d^c\right)$$

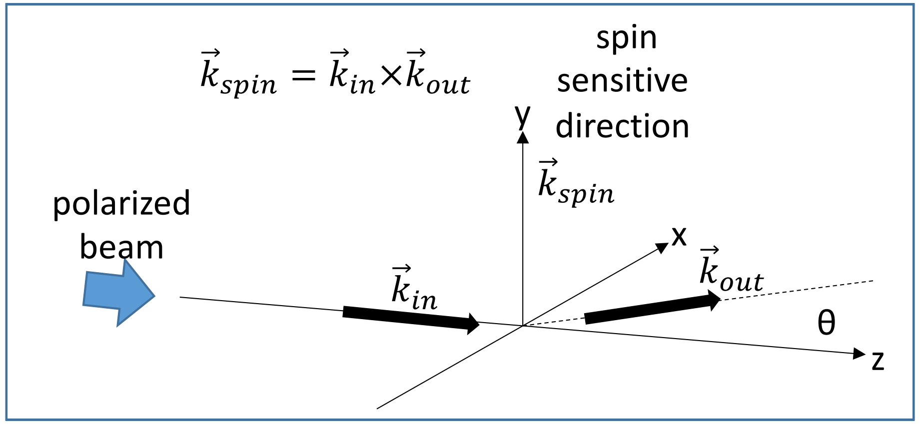
$$d_p \simeq 1.4\left(d_d - 0.25d_u\right) + 0.83e\left(d_u^c + d_d^c\right) + 0.27e\left(d_u^c - d_d^c\right)$$

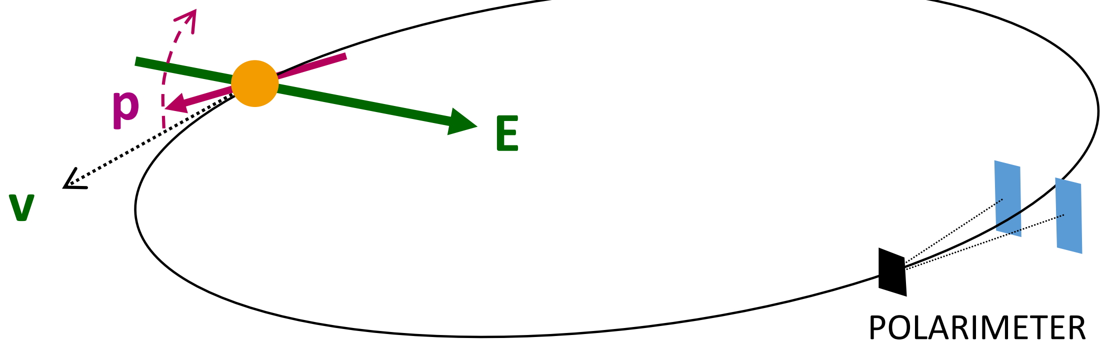
$$d_D \simeq \left(d_u + d_d\right) - 0.2e\left(d_u^c + d_d^c\right) - 6e\left(d_u^c - d_d^c\right)$$

$$d_N^{I=1} \simeq 0.87\left(d_u - d_d\right) + 0.27e\left(d_u^c - d_d^c\right) \qquad d_N^{I=1} = \left(d_p - d_n\right)/2$$

$$d_N^{I=0} \simeq 0.5\left(d_u + d_d\right) + 0.83e\left(d_u^c + d_d^c\right) \qquad d_N^{I=0} = \left(d_p + d_n\right)/2$$

Storage ring Electric Dipole Moments





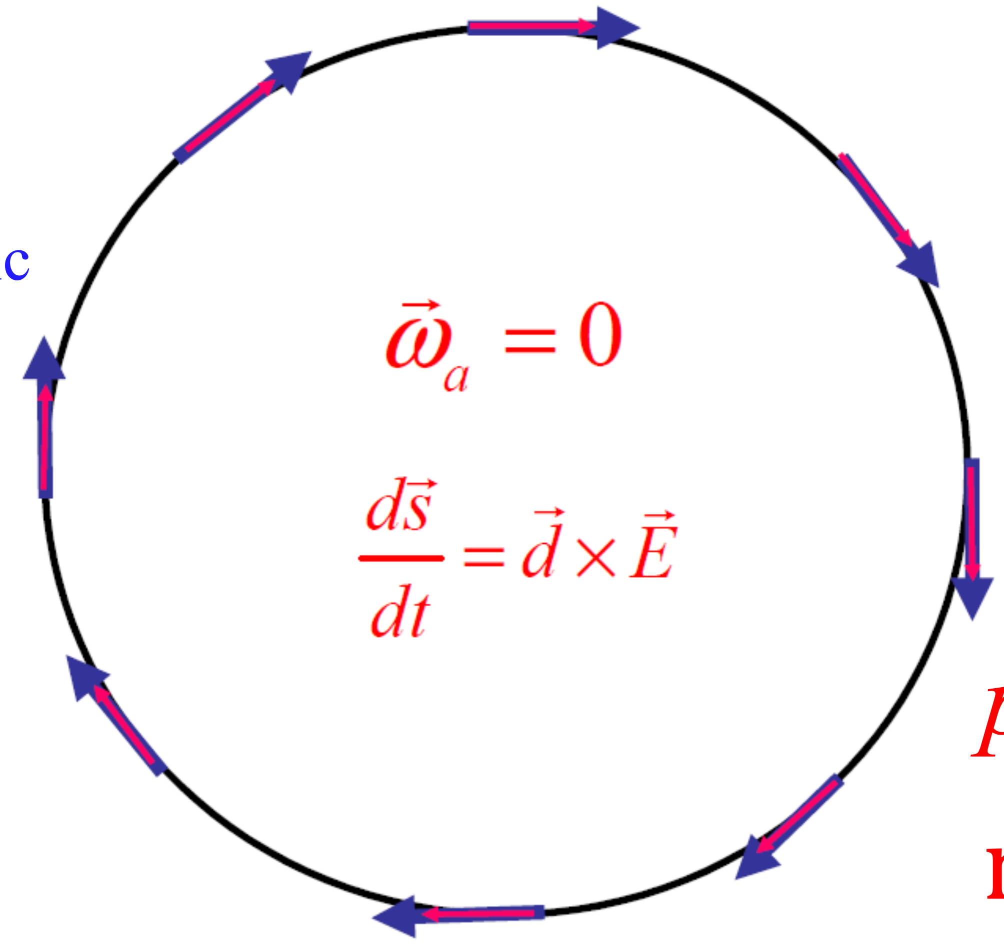
Frozen spin method:

- Spin aligned with the momentum vector
- Radial E-field precesses EDM/spin vertically
- Monitoring the spin using a polarimeter

Storage Ring EDM experiments, frozen spin method

Pure electric bending, w/ “magic” momentum

F.J.M. Farley *et al.*, “A new method of measuring electric dipole moments in storage rings,” Phys. Rev. Lett. 93, 052001 (2004)



$p = \frac{mc}{\sqrt{a}}$, a: magnetic moment anomaly

Electric fields: Freezing the g-2 spin precession

$$\vec{\omega}_a = -\frac{q}{m}\left[a - \left(\frac{mc}{p}\right)^2\right]\frac{\vec{\beta}\times\vec{E}}{c} = 0$$

- The g-2 spin precession is zero at "magic" momentum (3.1GeV/c for muons,…), so the focusing system can be electric

$$p = \frac{mc}{\sqrt{a}}, with\ a = G = \frac{g-2}{2}, \gamma_m = \sqrt{1 + 1/a}$$

- The "magic" momentum concept with electric focusing was first used in the last muon g-2 experiment at CERN, at BNL & FNAL.

Proton Statistical Error (232MeV): 10^{-29} *e*-cm

Phys. Rev. D **104**, 096006 (2021)

$$\sigma_d = \frac{2.33\hbar}{E_R P A \sqrt{N_c f \tau_p T_{tot}}}$$

τ_p : 2×10^3s Polarization Lifetime (Spin Coherence Time)
A : 0.6 Left/right asymmetry observed by the polarimeter
P : 0.8 Beam polarization
N_c : 4×10^{10}p/cycle Total number of stored particles per cycle (10^3s)
T_{Tot}: 2×10^7s Total running time per year
f : 1% Useful event rate fraction (efficiency for EDM)
E_R : 4.5 MV/m Radial electric field strength

Systematic errors

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: $\frac{d\vec{s}}{dt} = \vec{d} \times (\vec{v} \times \vec{B})$	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!

Background effects as a function of azimuthal harmonic N

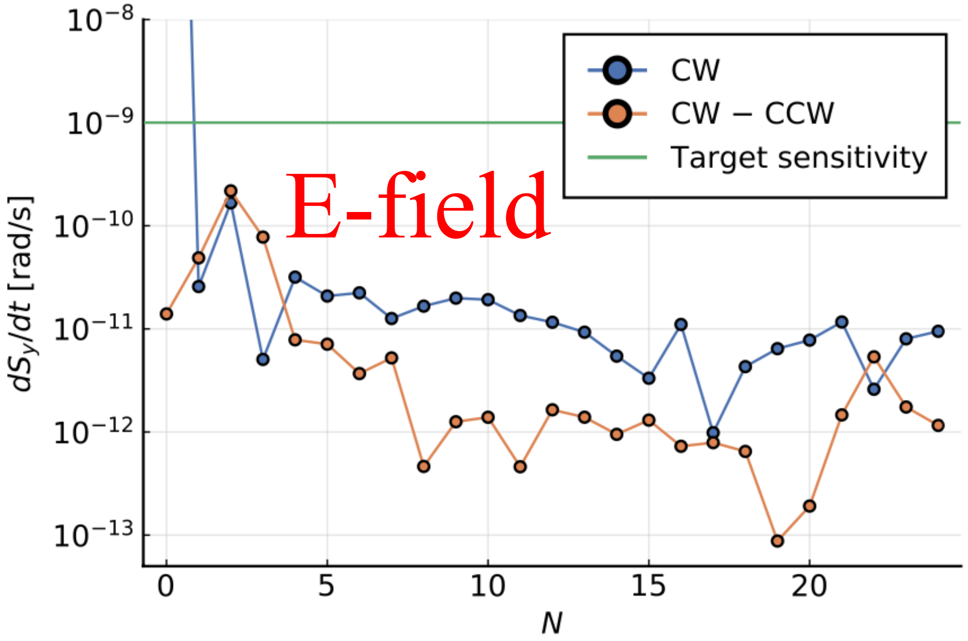


FIG. 7. *Longitudinal polarization case* $S_s = 1$, sensitive to EDM. Vertical spin precession rate vs $E_y = 10$ V/m field N harmonic around the ring azimuth. For $N = 0$, the precession rate for the CW (or CCW) beam is around 5 rad/s. The difference of the precession rates for CR beams (orange) is 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.

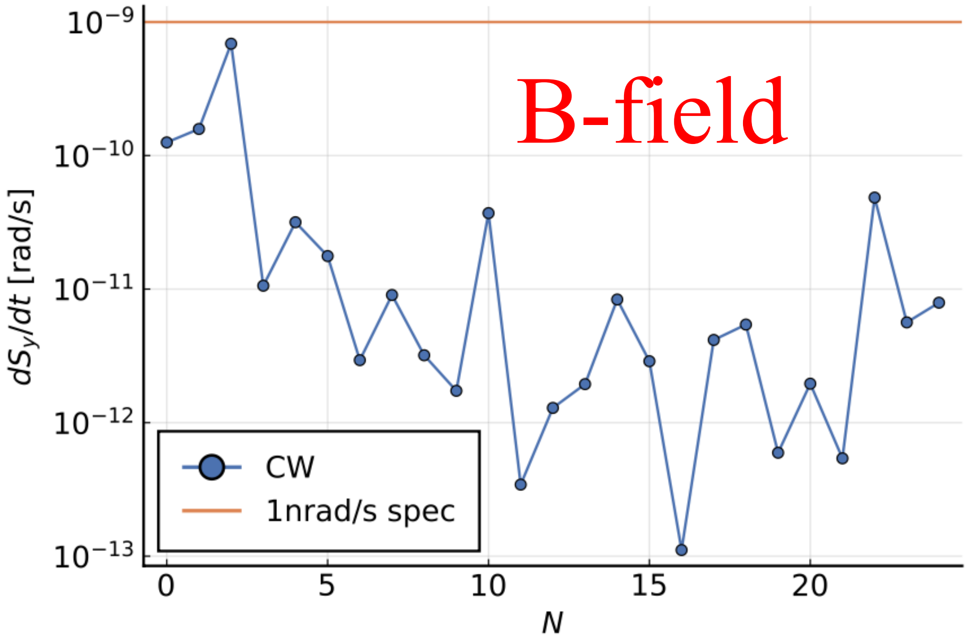
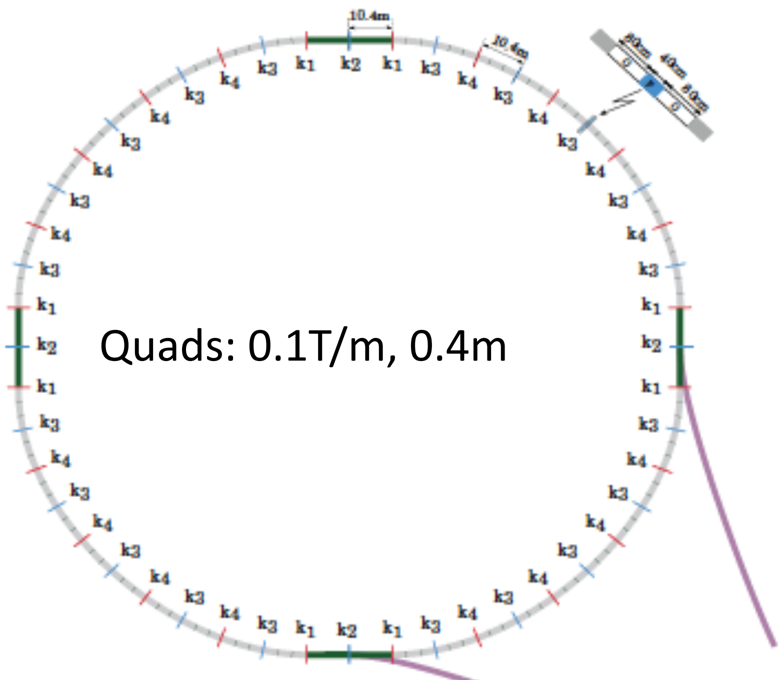
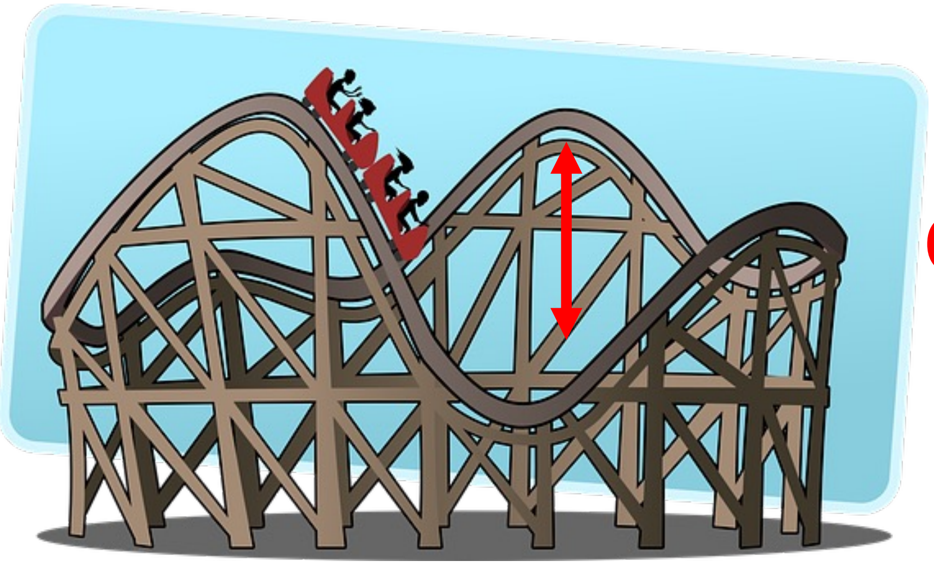


FIG. 8. *Longitudinal polarization case* $S_s = 1$, *CW beam only.* Vertical spin precession rate vs $B_x = 1$ nT field N harmonic around the ring azimuth. The magnetic field amplitude is chosen to be similar to beam separation requirements in Sec. IV A, and more than $B_x = 1$ nT splits the CR beams 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.

Ring planarity:
The average vertical speed in deflectors needs to be zero!

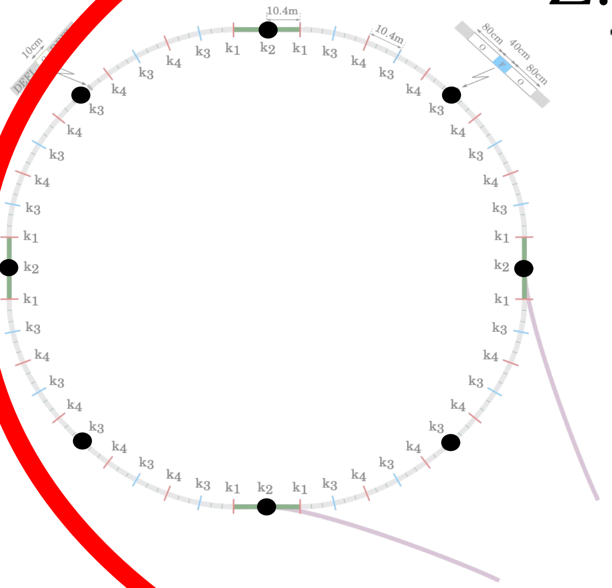


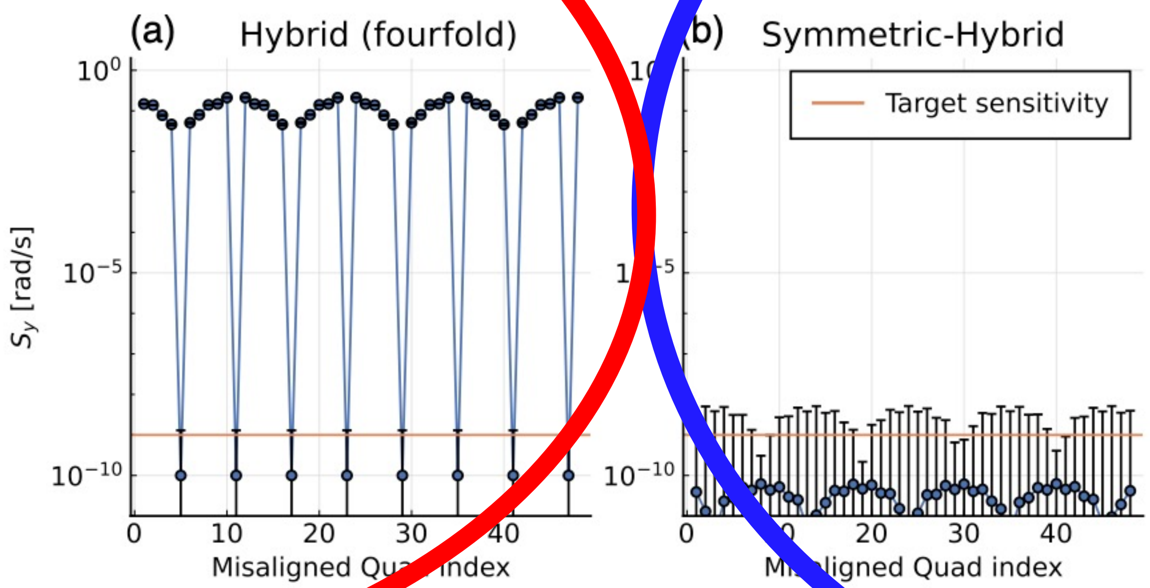


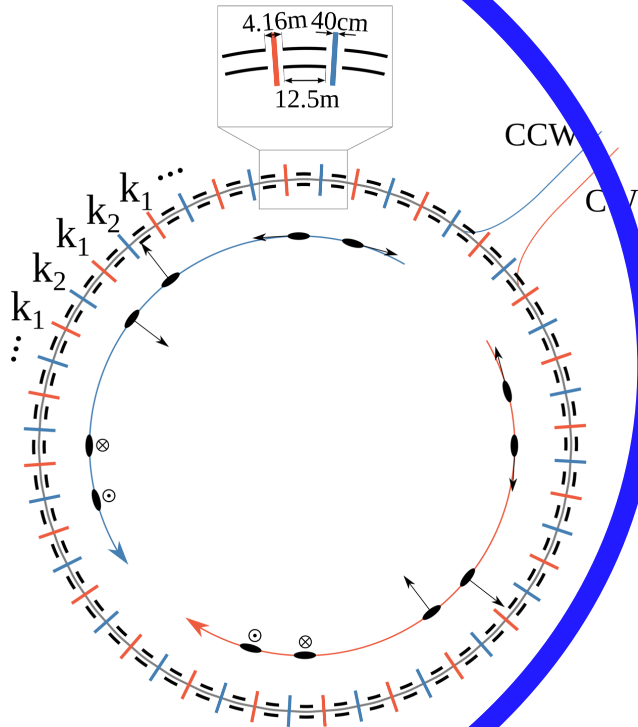
0.1 mm

Hybrid, symmetric lattice storage ring. Great for systematic error reduction.

Z. Omarov *et al.*, PHYS. REV. D **105**, 032001 (2022)







Sensitivity of radially polarized beam (sensitive to V. Dark Matter/Dark Energy, P. Graham *et al.*, PRD, 055 010, 2021), most sensitive to vertical velocity problem

Vertical velocity effect cancels

ZHANIBEK OMAROV *et al.* PHYS. REV. D **105**, 032001 (2022)

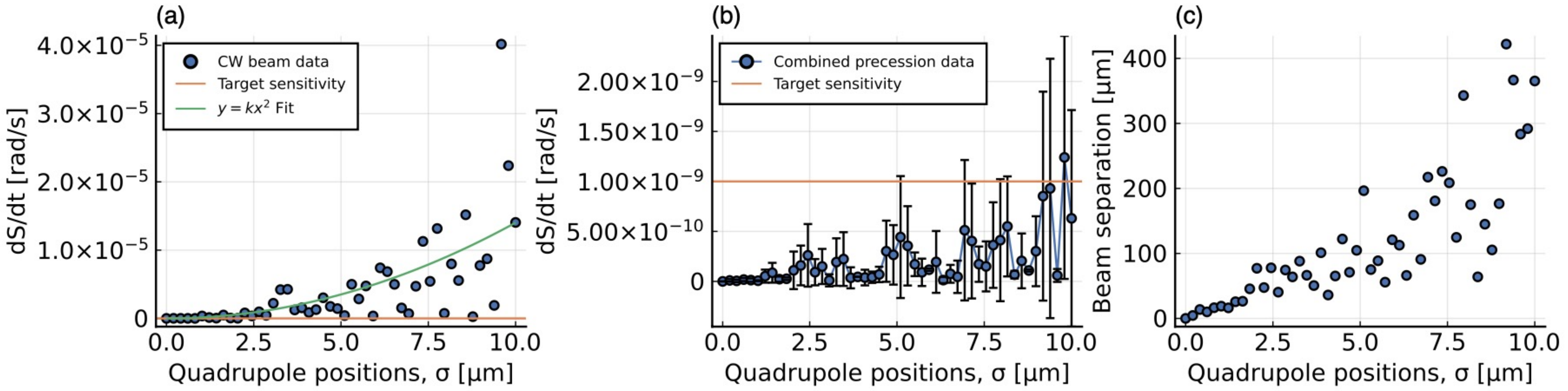


FIG. 9. (a) *Longitudinal polarization case, CW beam only.* Vertical spin precession rate (absolute) vs random misalignments of quadrupoles in both x, y directions by rms σ with different seeds per each point (when the same seeds are used everywhere, the $y = kx^2$ fit is perfect, meaning that every 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.

Classification of systematic errors at 10^{-29} e-cm for hybrid-symmetric lattice

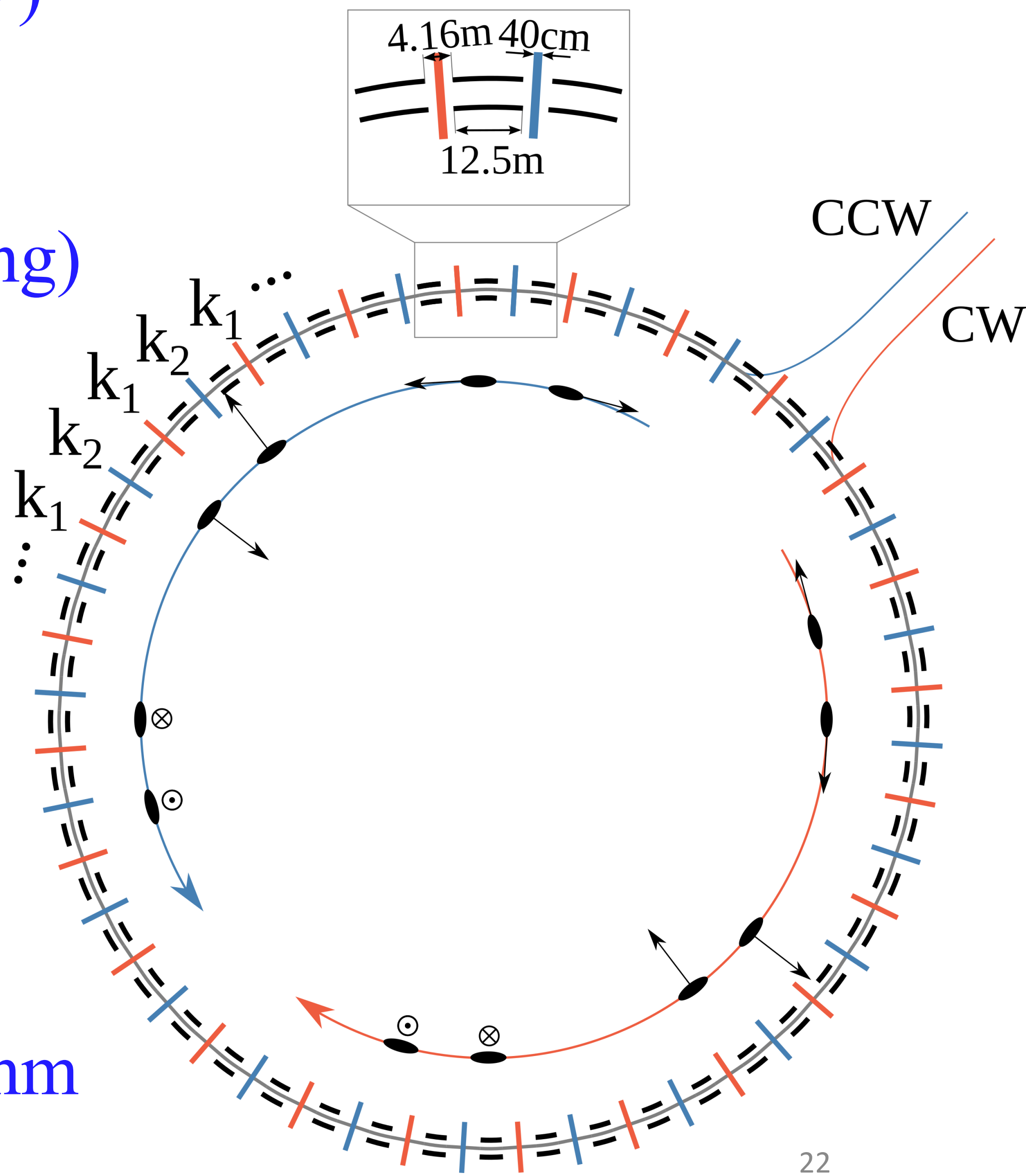
- ✓Alternate magnetic focusing allows simultaneous CW & CCW storage and shields against external B-fields. Vertical dipole E-fields eliminated (its own "co-magnetometer"), unique feature of this lattice.

- ✓Symmetric lattice significantly reduces systematic errors associated with vertical velocity (major source). Using longitudinal, radial and vertical polarization directions, sensitive to different physics/systematic errors.

- ✓Required ring planarity <0.1mm; CW & CCW beam separation <0.01mm, resolves issues with geometrical phases

Symmetries against systematic errors

- 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



Protons in a hybrid-symmetric ring: no new technology

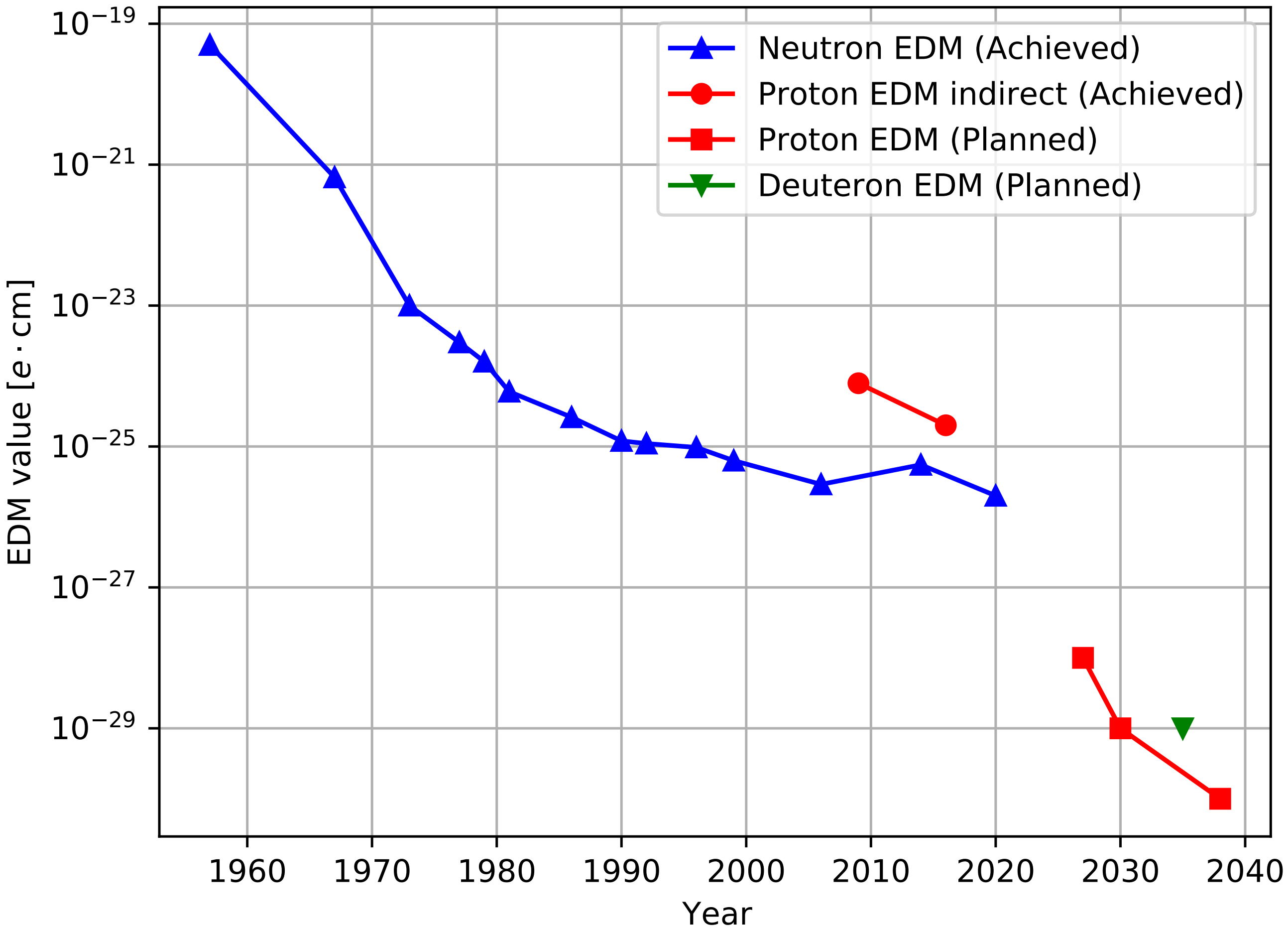
- No need to develop/test new technology
  - Simultaneous CW/CCW beam storage is possible
  - Electric field ~4.5 MV/m with present technology
  - Magnetic fields from misplaced quads are self-shielded by the magnetic focusing
  - Hybrid/symmetric ring options are simple. Large tune in both planes, beam position monitor (BPM) tasks are achievable with present technology.
  - Estimated SCT are large, injection into ring works, while all primary systematic error sources are kept small.

- After protons, add dipole magnetic field in bending sections:
  - Can do proton, deuteron, ^{3}He, (and muons)

System	Risk factor, comments
Ring construction, beam storage, stability, IBS	Low. Strong (alternate) focusing, a ring prototype has been built (AGS analog at BNL) in 60's. Lattice elements placement specs are ordinary. Intra-beam-scattering (IBS) OK below transition.
E-field strength	Low. Plate-units are similar to those ran at Tevatron with higher specs.
E-field plates shape	Medium. Make as flat as conveniently possible. Probe and shim out high order fields by intentionally splitting the CR-beams
Spin coherence time	Low. Ordinary sextupoles will provide $>10^3$s.
Beam position monitors (BPM), SQUID-based BPMs.	Medium. Ordinary BPMs and hydrostatic level system (HLS) to level the ring to better than 0.1mm; SQUID-based or more conventional BPMs to check CR-beams split to 0.01mm.
High-precision, efficient software	Low. Cross-checking our results routinely
Polarimeter	Low. Mature technology available

Timeline

- Snowmass/white paper, CDR, proposal/TDR, prototype/string-test, ring construction (3-5 years), storage (2-3 years) to first publication
- Effort similar to muon g-2 experiments.
- Possible interesting results within a decade.



Summary

- ✓EDM physics is must do, exciting and timely, CP-violation, ~10^3 TeV New-Physics reach, axion physics, DM/DE.

- ✓Hybrid, symmetric ring lattice works well. Minimized systematic error sources. Statistics and systematics to better than 10^{-29}*e*-cm.

- ✓E-field strength needed is less than TEVATRON (FNAL) ES-separators, operated reliably for >decade... At 4.4 MV/m, minimum risk. Working EDM lattice with long SCT and large enough acceptance provides the statistics. Ring planarity <0.1mm, CW & CCW beam separation <0.01mm.

- ✓Snowmass: A strong endorsement → ... interesting results within a decade. Total effort similar to muon g-2 exp.

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16. …

Extra slides

Hybrid, symmetric lattice storage ring, designed by Val. Lebedev (FNAL)

Z. Omarov *et al.*, PHYS. REV. D **105**, 032001 (2022)

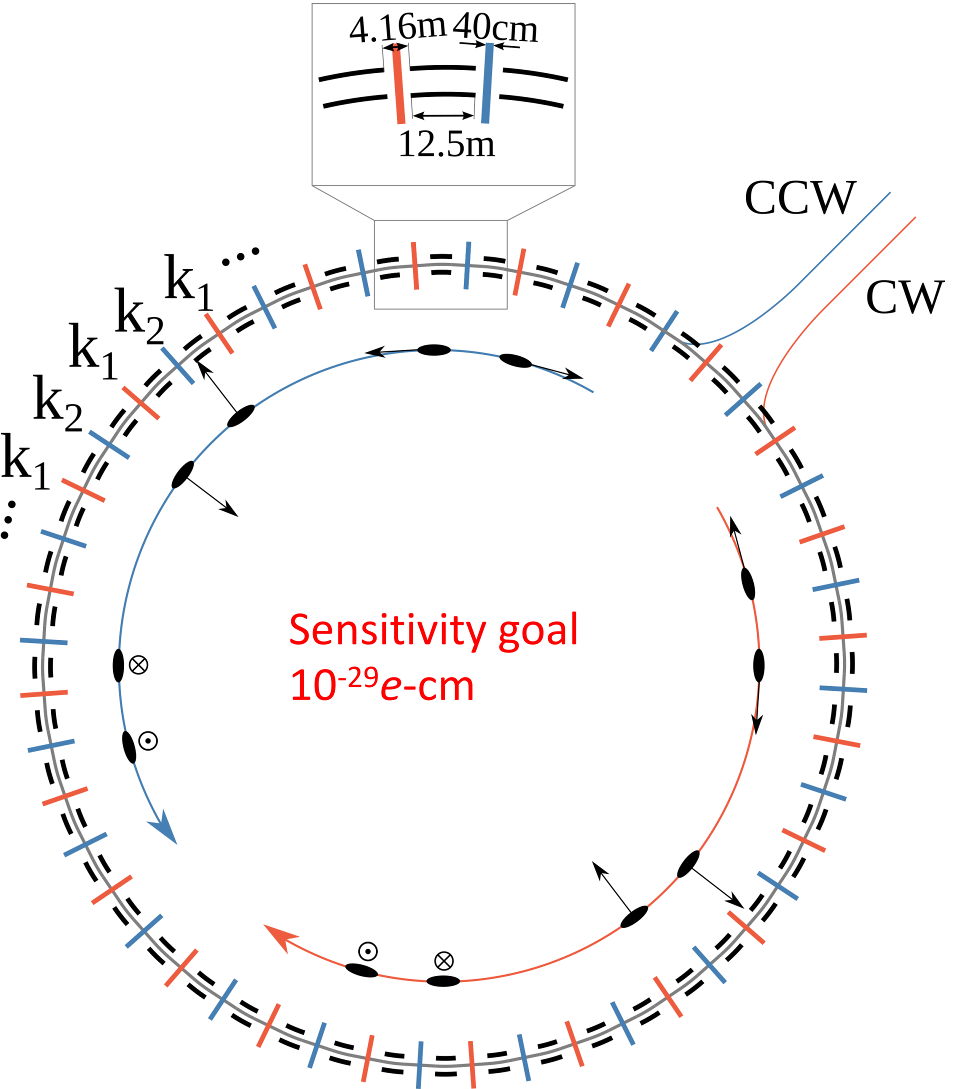


TABLE I. Ring and beam parameters for Symmetric Hybrid ring design

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	799.68 m
Cyclotron frequency	224 kHz
Revolution time	4.46 µs
β_x^{max}, β_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, $\eta = \frac{dt}{t} / \frac{dp}{p}$	-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, $\Delta p/p_{bucket}$	3.77×10^{-4}
Bucket length	10 m
RMS bunch length, σ_s	0.994 m

Low risk

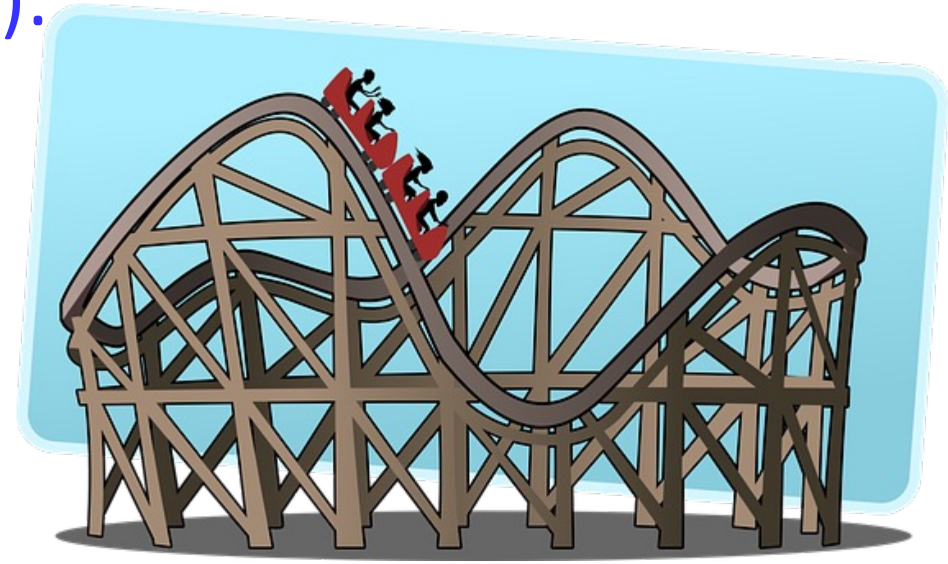
Strong focusing

Ring planarity critical to control geometrical phase errors

- Numerous studies on slow ground motion in accelerators, Hydrostatic Level System for slow ground motion studies at Fermilab. (Part of the linear collider studies!)

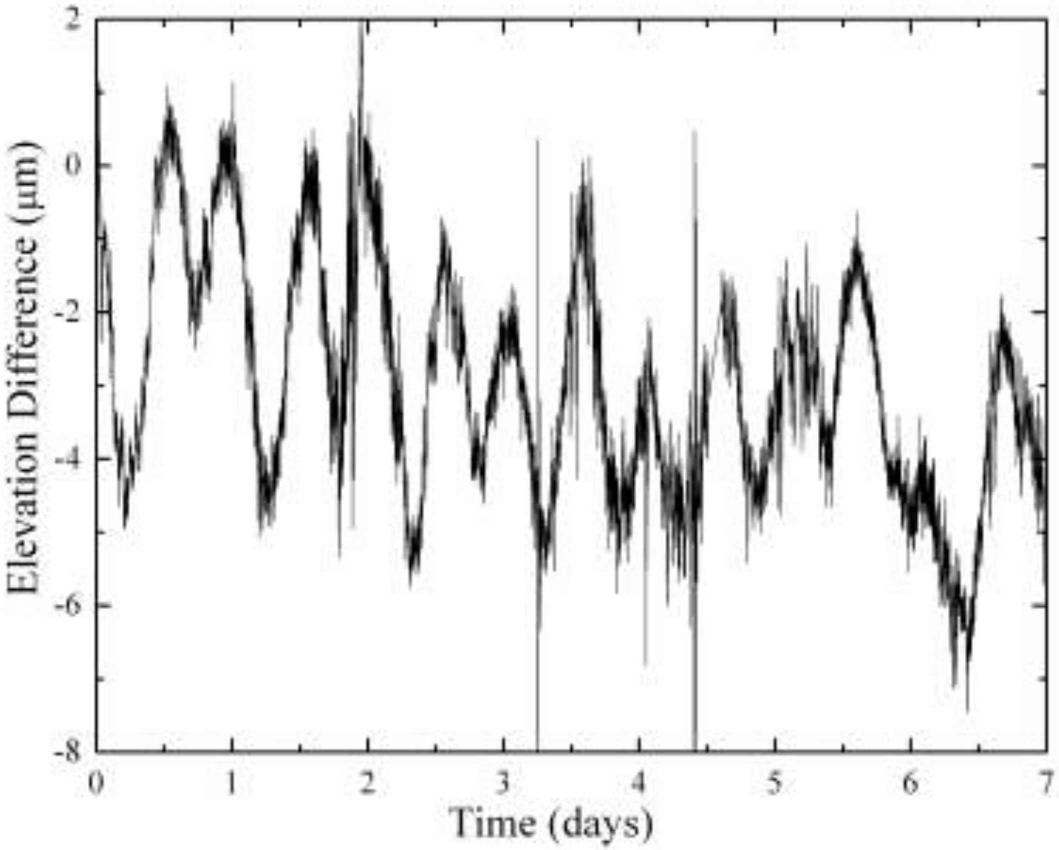
- Thorough review by Vladimir Shiltsev (FNAL):

https://arxiv.org/pdf/0905.4194.pdf

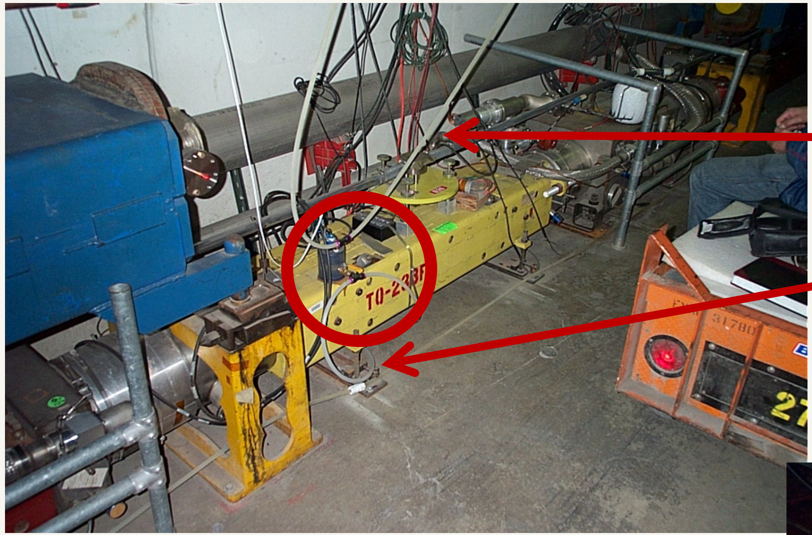


HLS measurements at Fermilab

Fig.35. HLS probe on Tevatron accelerator focusing magnet.



Tevatron Sensors on Quad

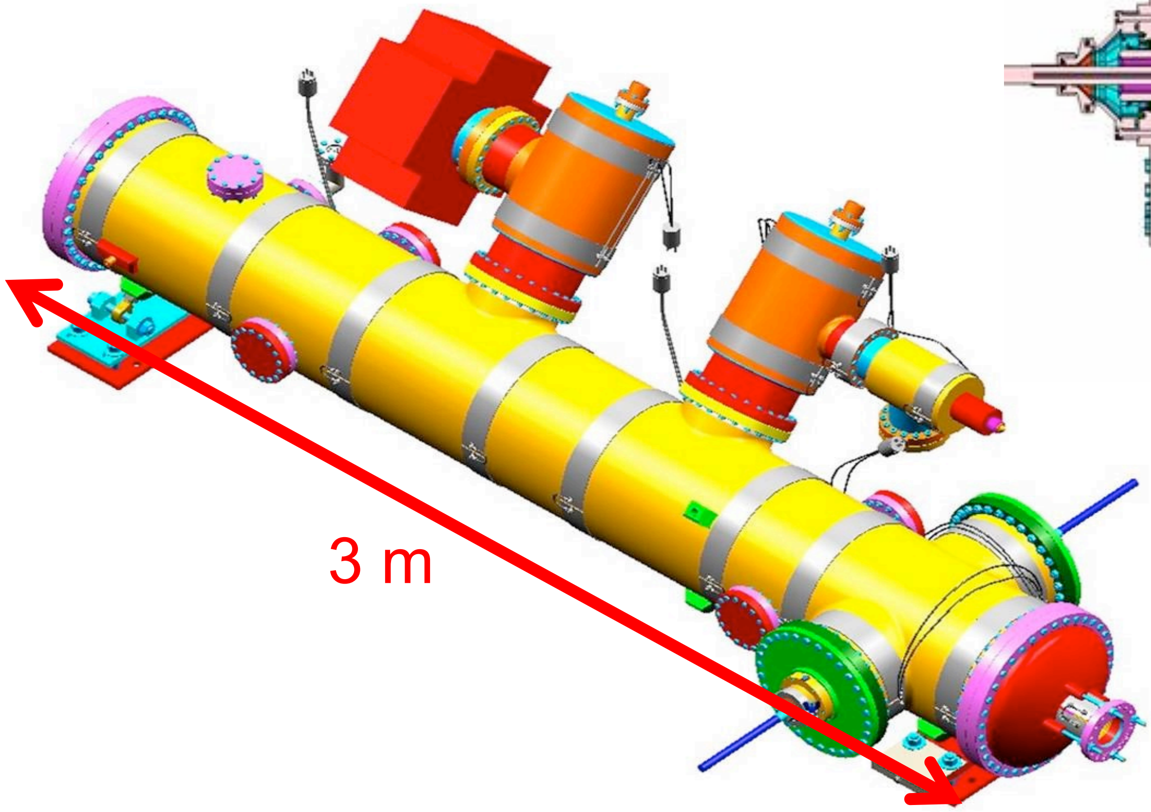


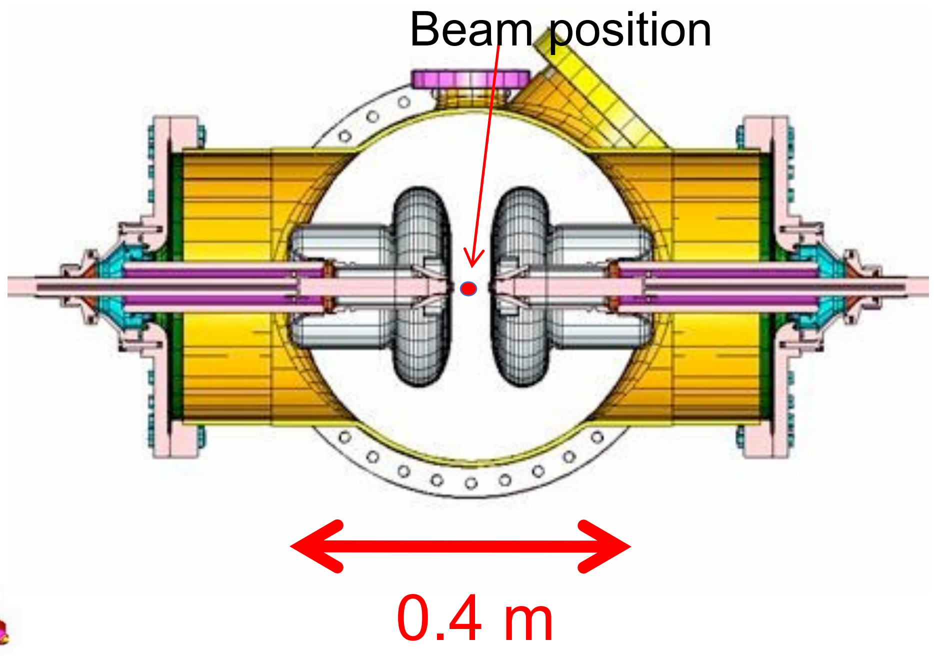
In the circle is a water level pot on a Tevatron quadrupole

Large Surface Area Electrodes

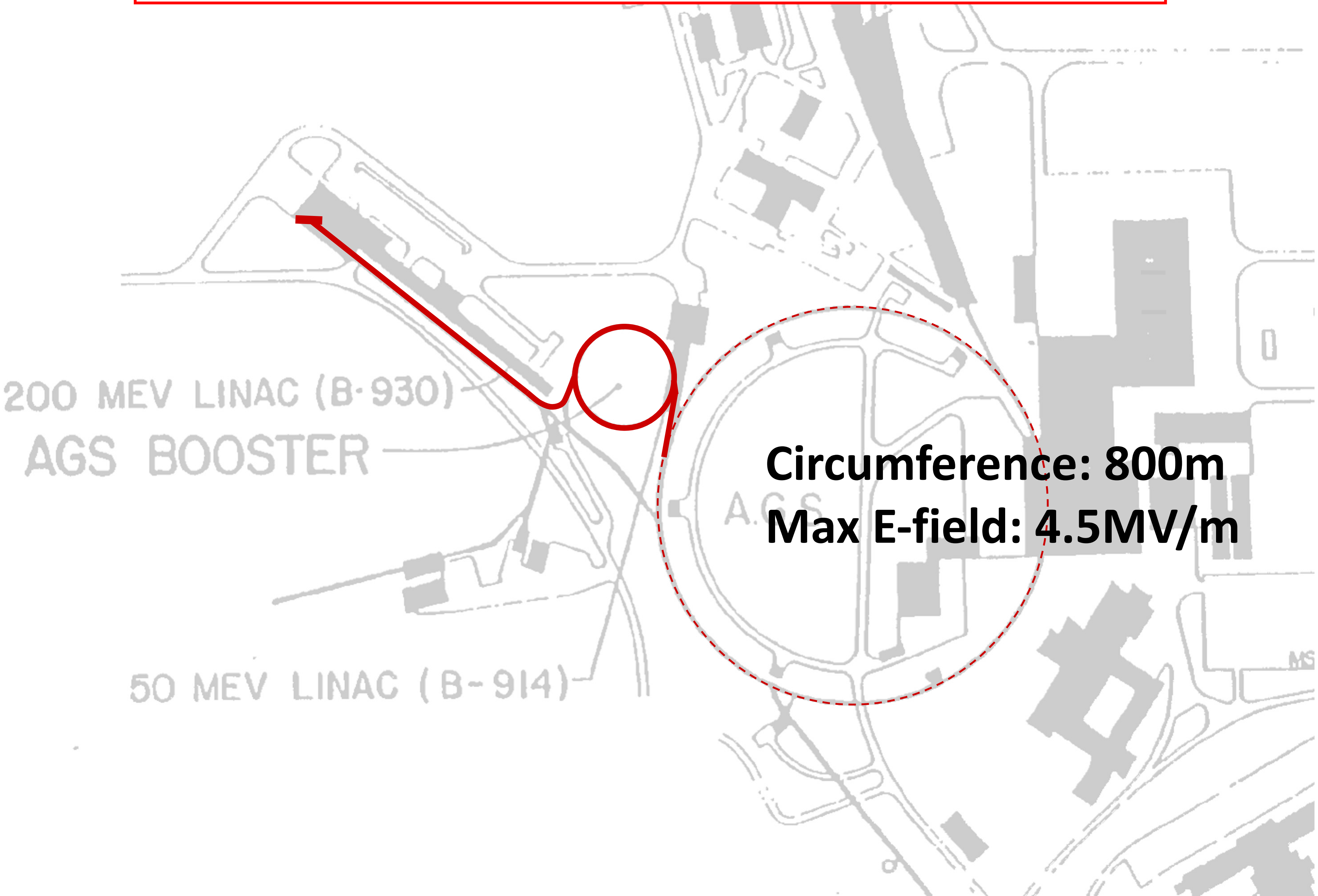
Parameter	Tevatron pbar-p Separators	BNL K-pi Separators	pEDM (low risk)
Length/unit	2.6m	4.5m	5×2.5m
Gap, E-field	5cm, 7.2 MV/m	10cm, 4 MV/m	4cm, 4.5 MV/m
Height	0.2m	0.4m	0.2m
Number	24	2	48
Max. HV	±(150-180)KV	±200KV	±90KV

E-field plate modules: The (24) FNAL Tevatron ES-separators ran for years with harder specs





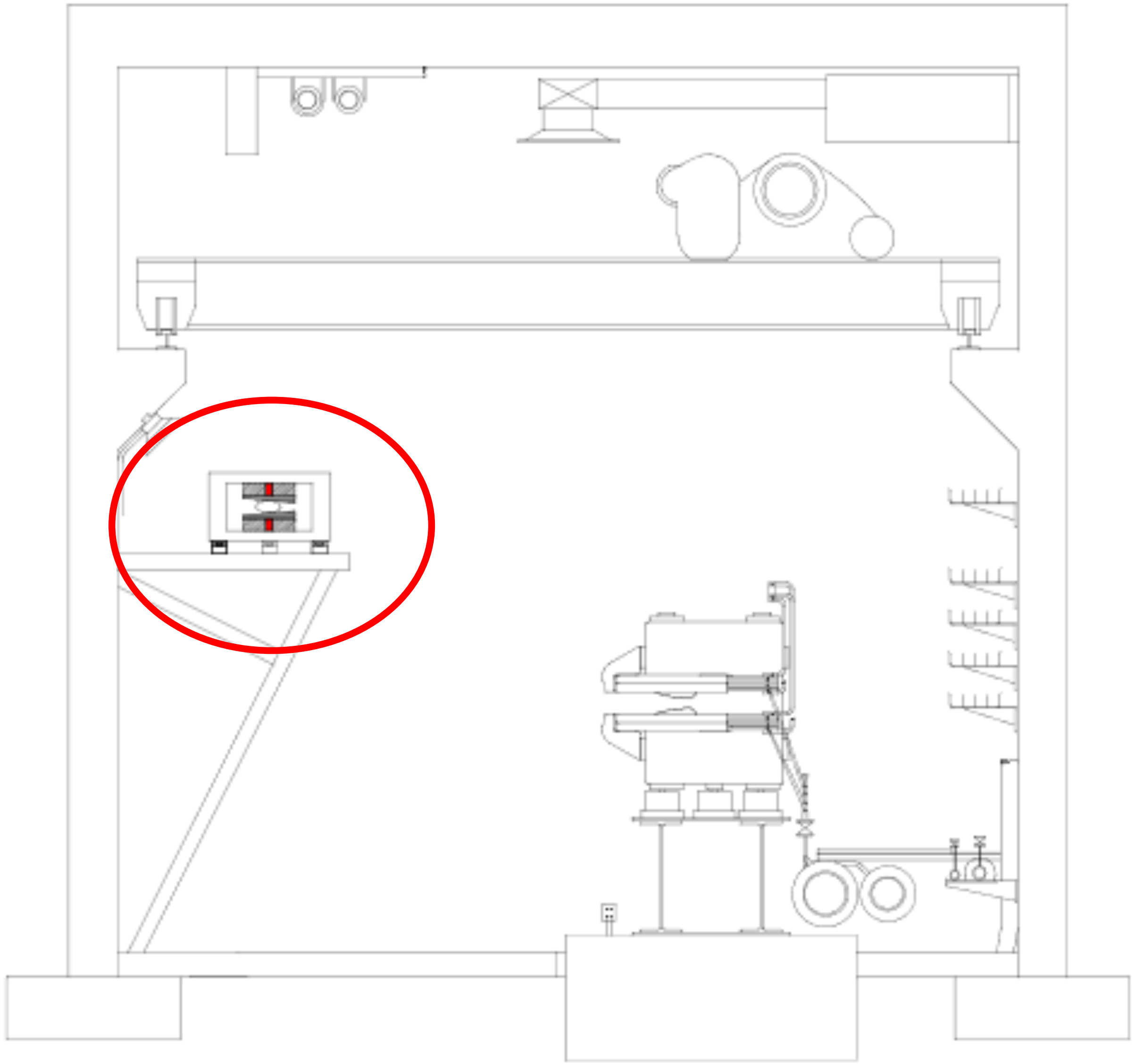
The proton EDM in the AGS tunnel at BNL

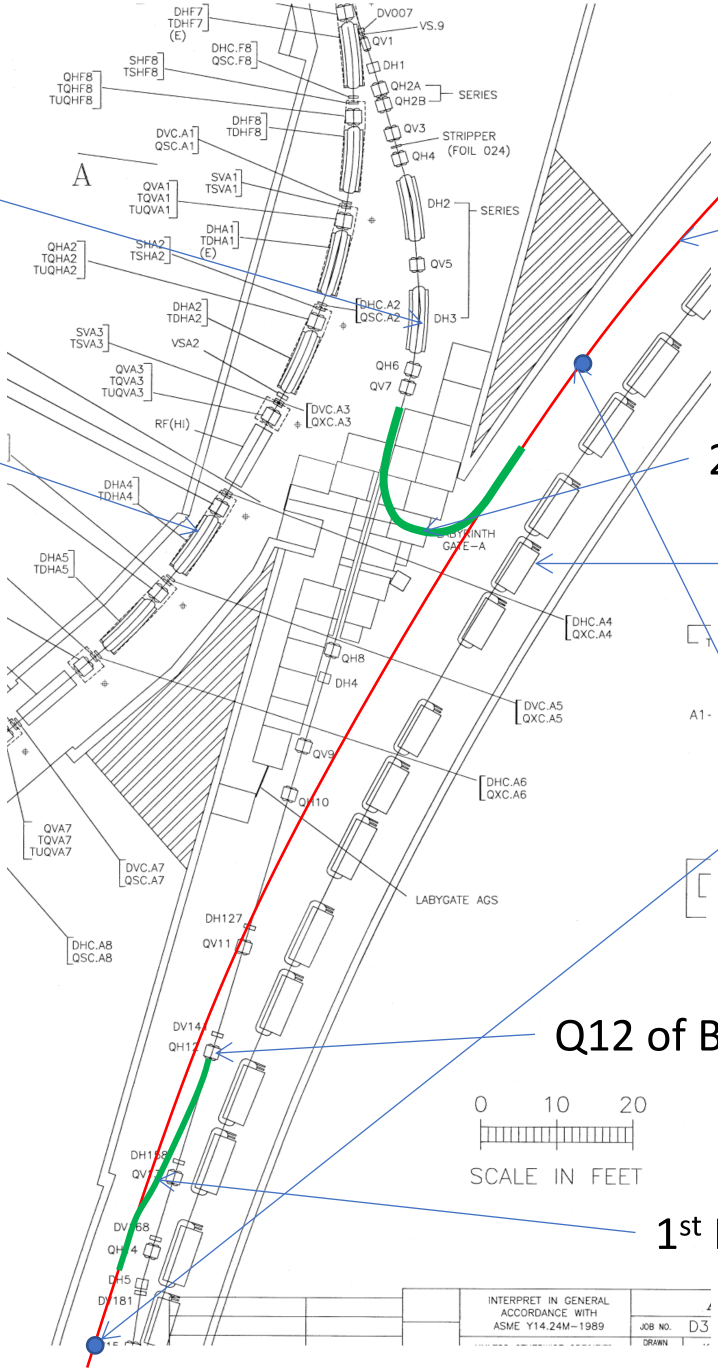


John Benante, Bill Morse in AGS tunnel, plenty of room for the EDM ring.

Sketch of the AGS Accumulator Ring

- It was sketched for 1.5GeV ring. Space needed: 1mX1m.




Booster-to-AGS BtA
Booster
Proposed EDM Ring
2nd Inj. Line
AGS
Beam Injection points
Q12 of BtA
1st Inj. Line
0 10 20
SCALE IN FEET

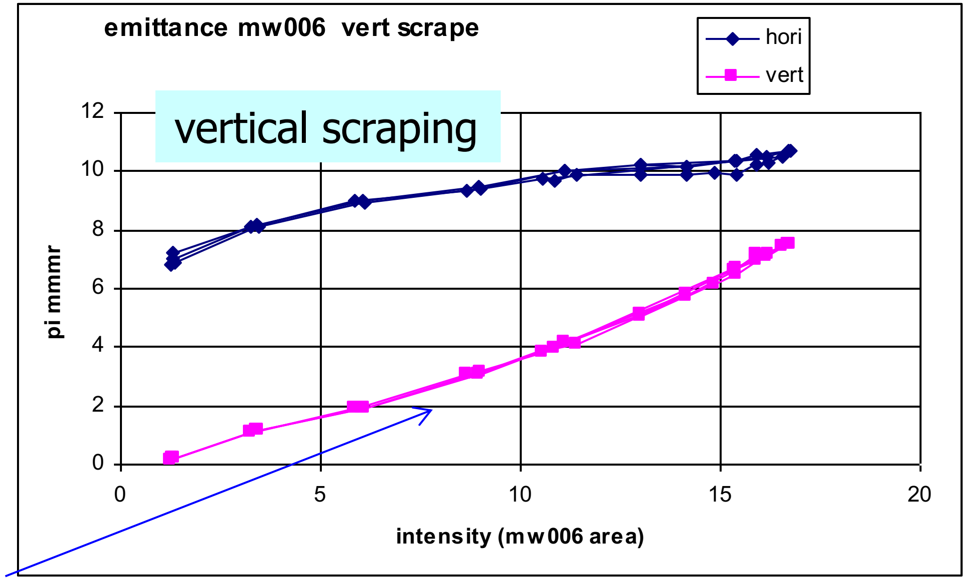
Emittance out of Booster

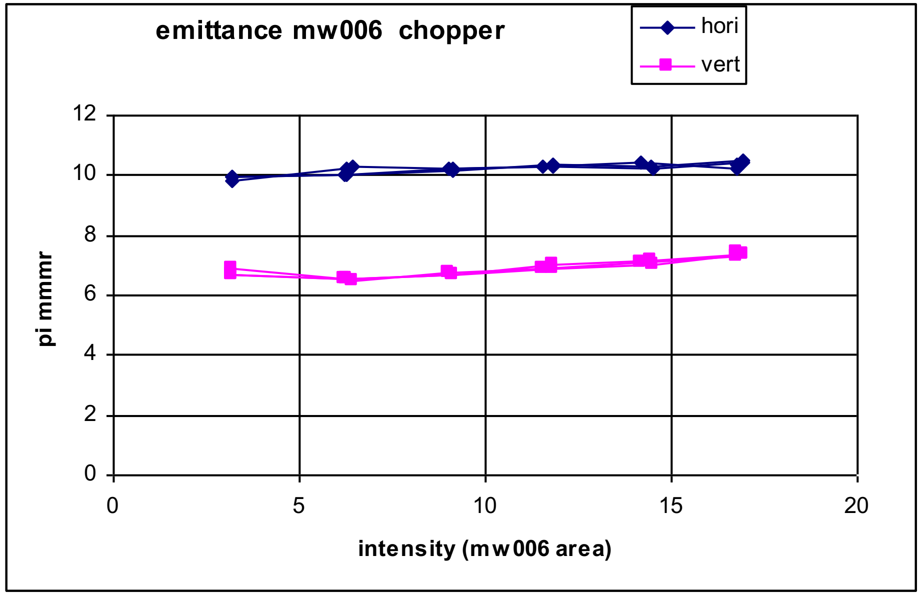
These intensity scan was done in 2009 with Booster input $3*10^{11}$. Not much horizontal scan was done since then. The vertical scale is normalized 95% emittance.

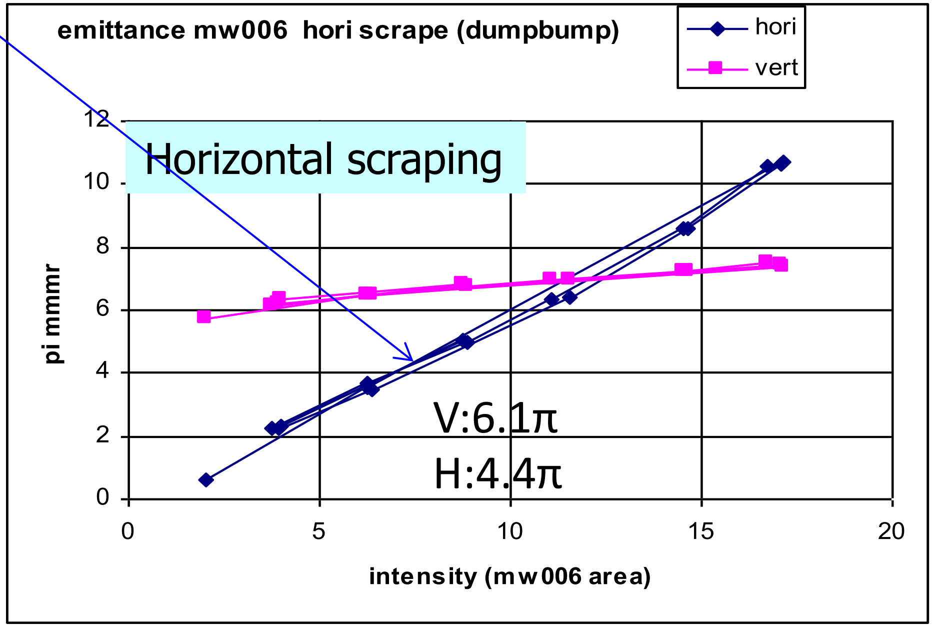
The corresponding normalized rms emittance at 10^{11} is 0.7π horizontal, 1.0π vertical for horizontal scraping.

Intensity: 15~2e11 protons

@10^{11}







^{3}He Co-magnetometer in nEDM experiment

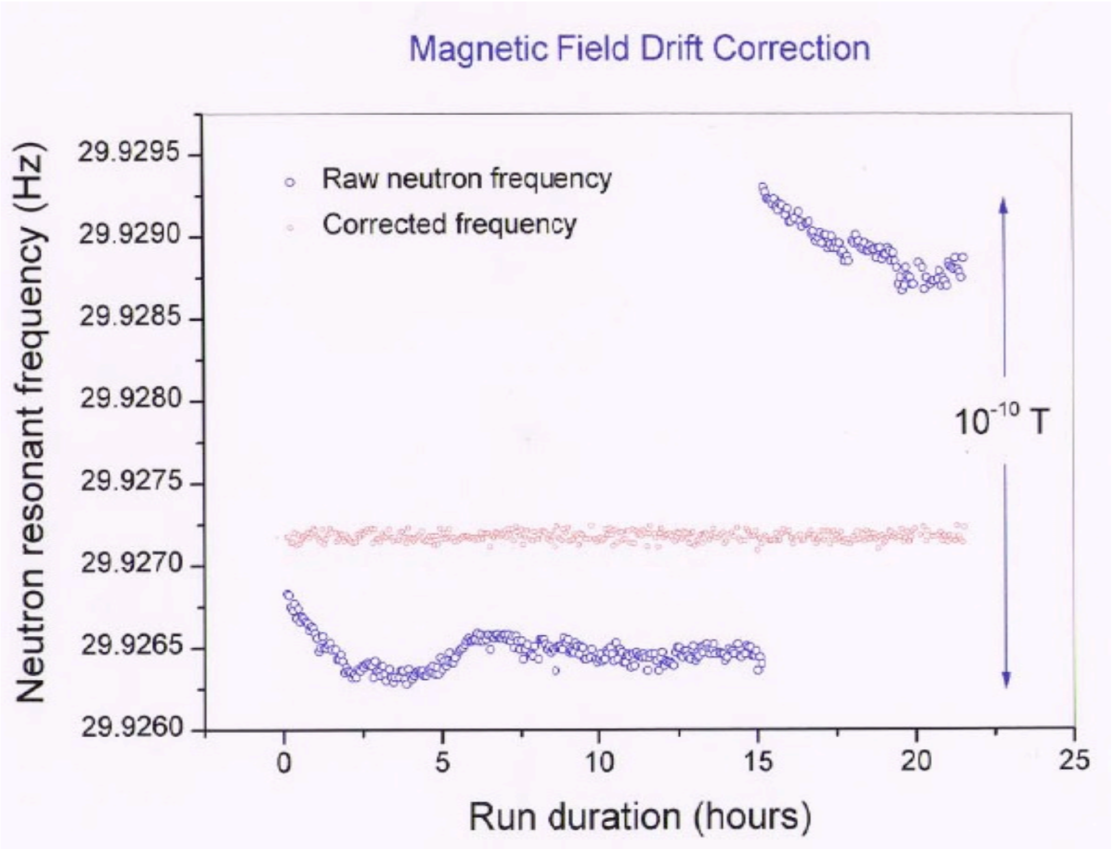
If nEDM = 10^{-26} e·cm,

10 kV/cm → 0.1 μHz shift

≅ B field of 2×10^{-15} T.

Co-magnetometer :

Uniformly samples the B Field faster than the relaxation time.

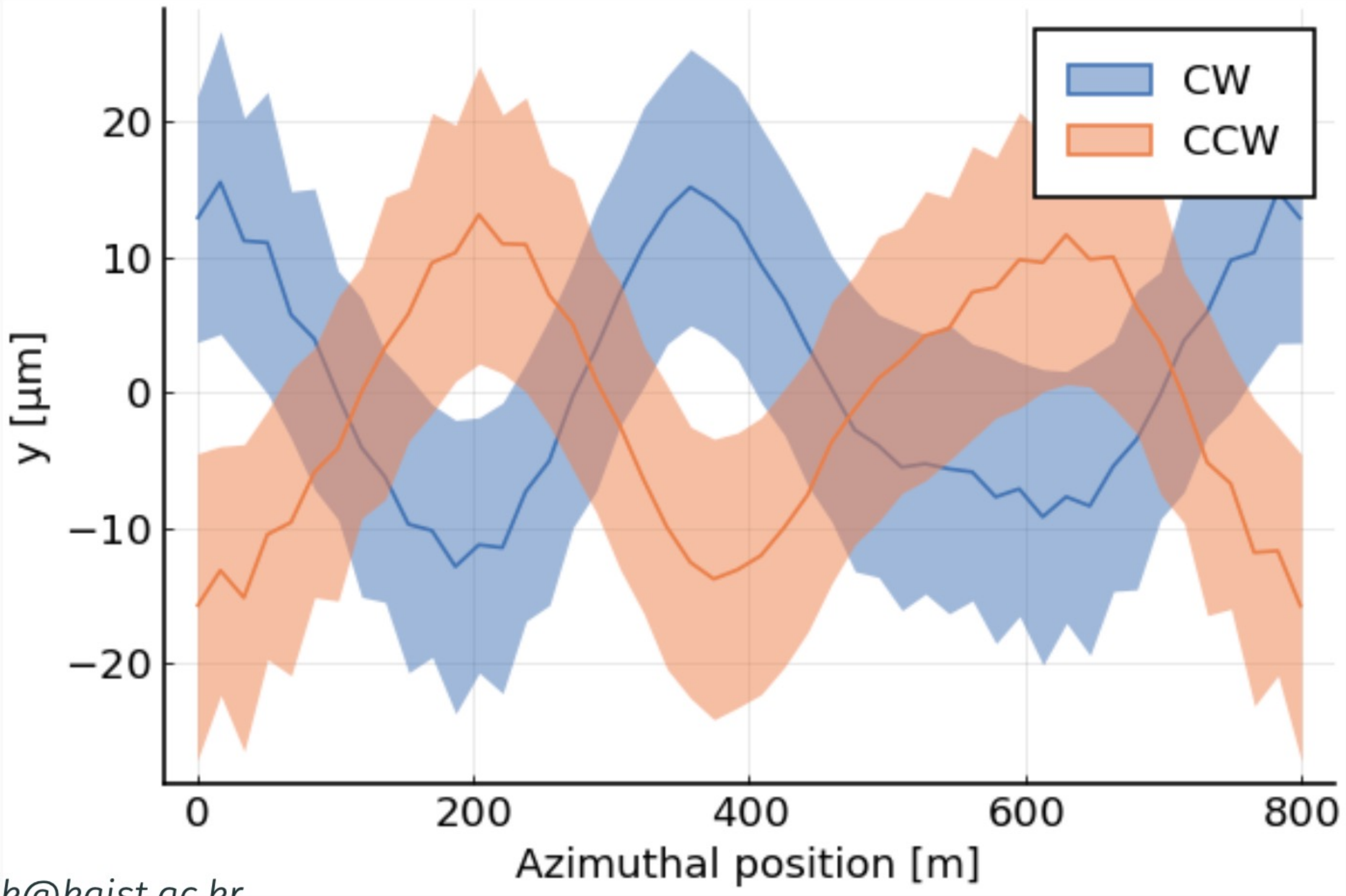


Data: ILL nEDM experiment with ^{199}Hg co-magnetometer

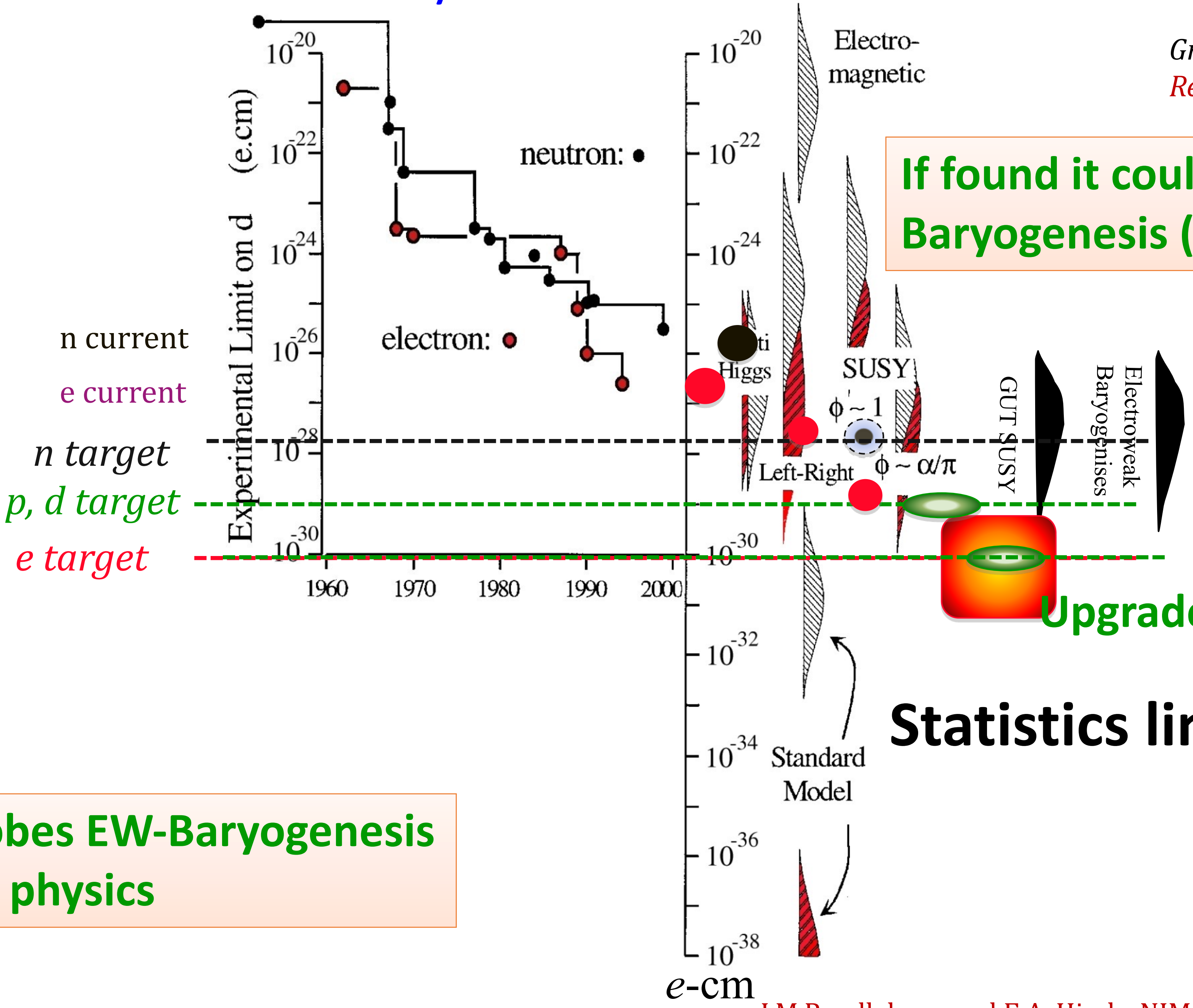
EDM of ^{199}Hg < 10^{-28} e-cm (measured); atomic EDM ~ Z^2 → ^{3}He EDM << 10^{-30} e-cm

Under gravity, the center of mass of He-3 is higher than UCN by $\Delta h \approx 0.13$ cm, sets ΔB = 30 pGauss (1 nA of leakage current). $\Delta B/B=10^{-3}$.

- Misalign quadrupoles randomly:



Sensitivity to Rule on Several New Models



Gray: Neutron
Red: Electron

If found it could explain Baryogenesis (p, d, n (or ^{3}He))

Statistics limited

pEDM probes EW-Baryogenesis and axion physics

J.M.Pendlebury and E.A. Hinds, NIMA 440 (2000) 471

Electric quad-field from a displaced sextupole

m value for electric sextupoles

$$E_y = -2k^e xy$$
$$E_x = k^e(x^2 - y^2).$$

- Assume 100 um misalignment

$$E_y = 2 \times 200\,\mathrm{kV/m^3} \times 100\,\mathrm{um} \times y$$
$$E_y = \left(\frac{E_0(n-1)}{R_0}\right)y = \left(\frac{E_0 m}{R_0}\right)y$$

- Expected electric focusing: $m_6 = 2 \times 10^{-5}$
- Should be less with randomness

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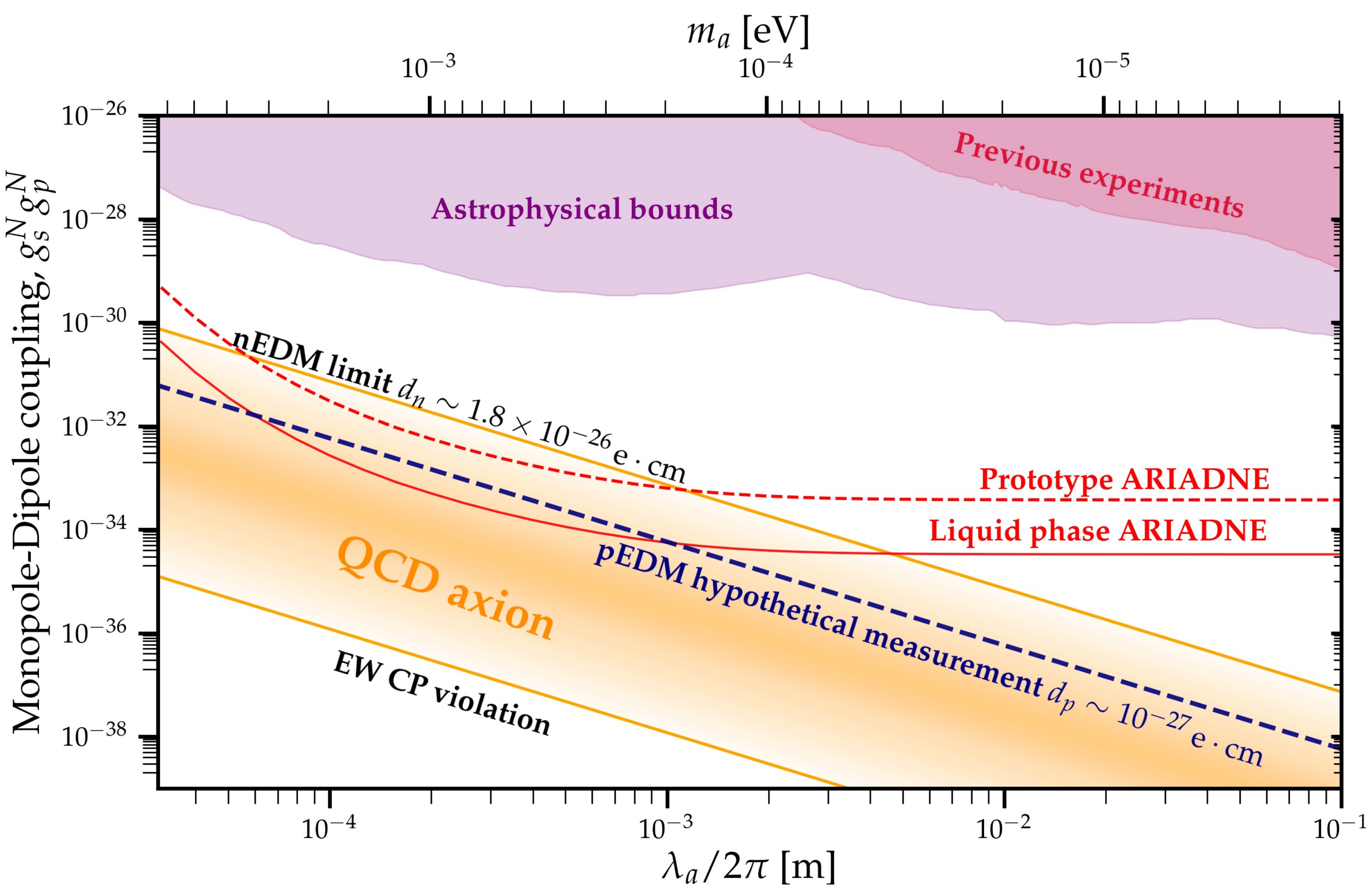
ARIADNE and nucleon EDMs



Y. K. Semertzidis and S. Youn. , 2104.14831

- Combine with ARIADNE and nucleon EDM provides decisive information
- Scenario:
  - ARIADNE: Null axion
  - pEDM measure: $d_p \sim 10^{-27}\mathrm{e}\cdot\mathrm{cm}$
  - Exclude QCD axion independent of axion DM:

$$0.2\ \mathrm{meV} \lesssim m_a \lesssim 3\mathrm{meV}$$

Spin Coherence Time

- Not all particles have same deviation from magic momentum, or same horizontal and vertical divergence (second order effects)

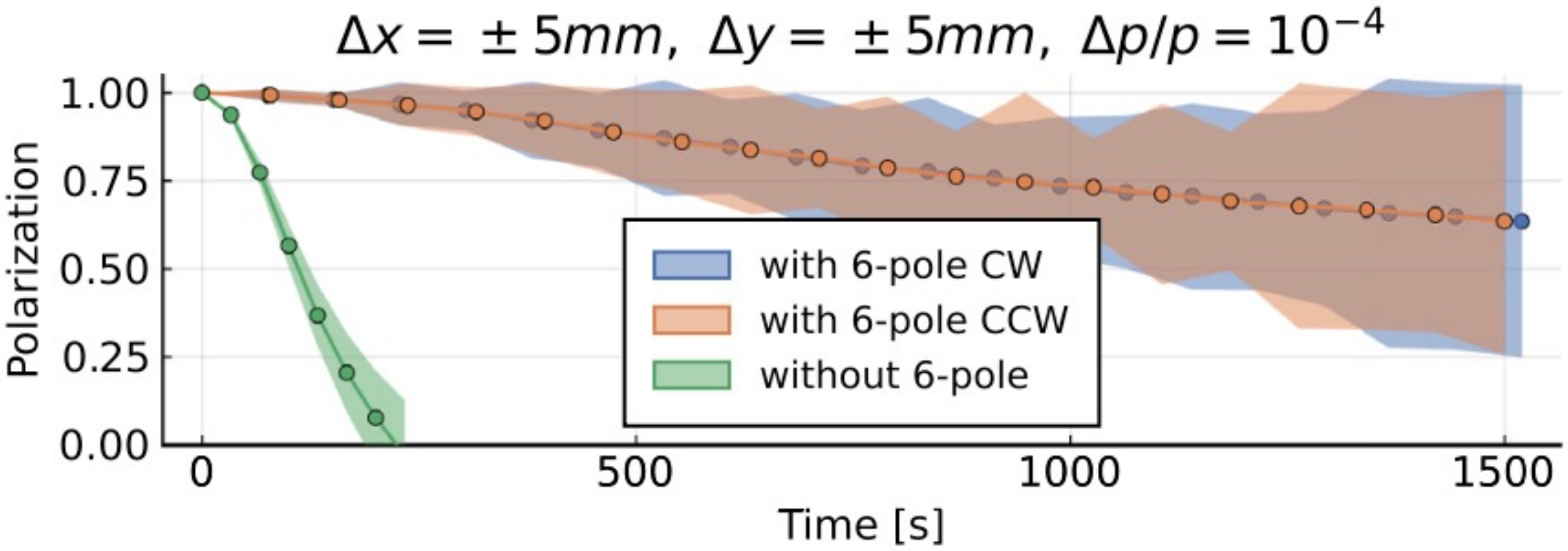
- They Cause a spread in the g-2 frequencies:

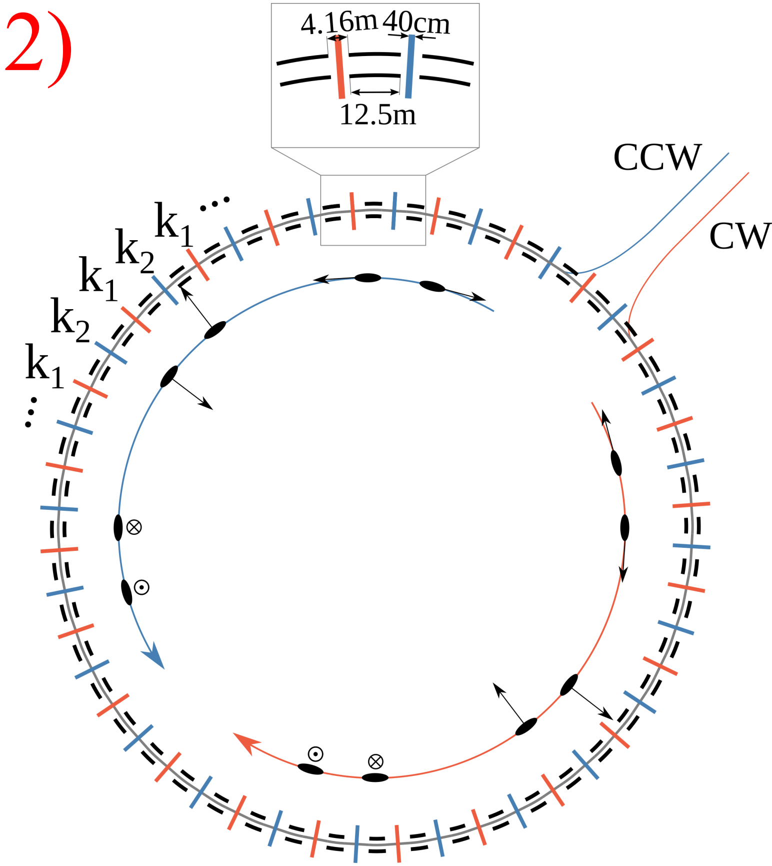
$$d\omega_a = a\vartheta_x^2 + b\vartheta_y^2 + c\left(\frac{dP}{P}\right)^2$$

- Correct by tuning plate shape/straight section length plus fine tuning with sextupoles (current plan) or cooling (mixing) during storage (under evaluation).

Hybrid, symmetric lattice storage ring. Spin Coherence Time with sextupoles

Z. Omarov *et al.*, PHYS. REV. D **105**, 032001 (2022)





Hybrid (magnetic and elecric) sextupoles were used to achieve long SCT.