

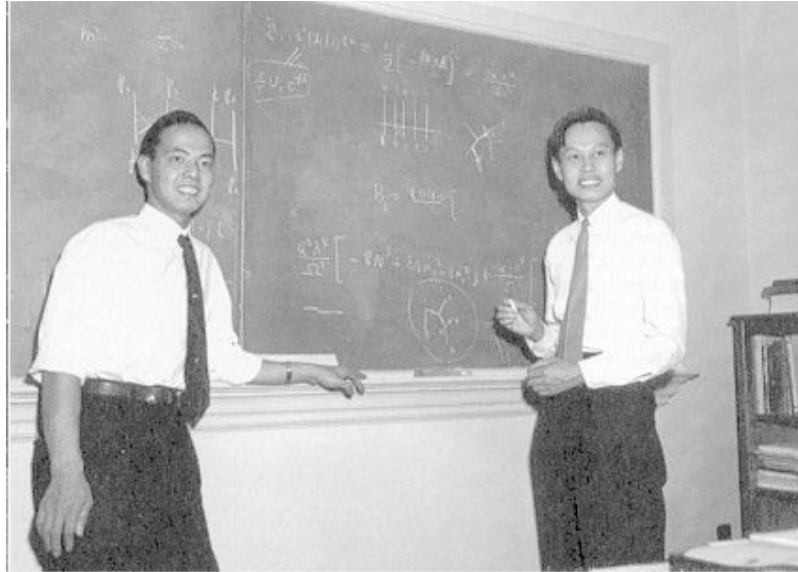
Electric Dipole Moments of Charged Particles: Probing Fundamental Symmetries with Storage Rings

Yannis K. Semertzidis
KAIST, retired

PBT2026, Huizhou, IMP-CAS
30 March to 3 April 2026

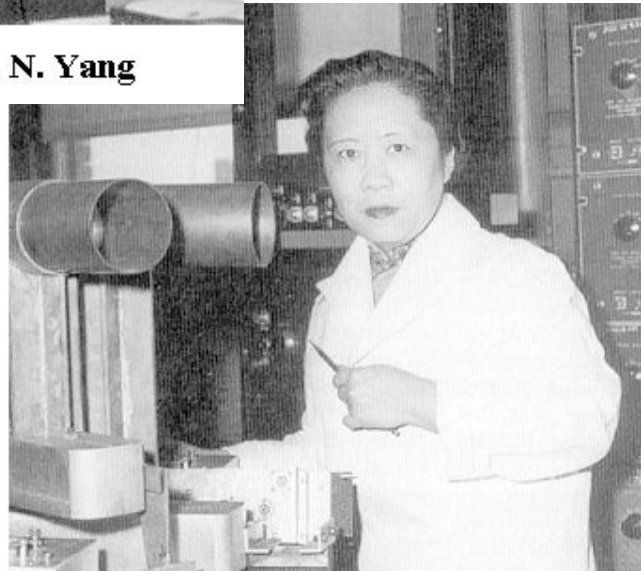
- Why does anything exist at all?
- According to our best understanding, the Big Bang should have produced equal amounts of matter and antimatter.
- And yet, we live in a universe made almost entirely of matter.
- The role of symmetries in our world

Parity violation has been observed in weak interactions in the 1950's

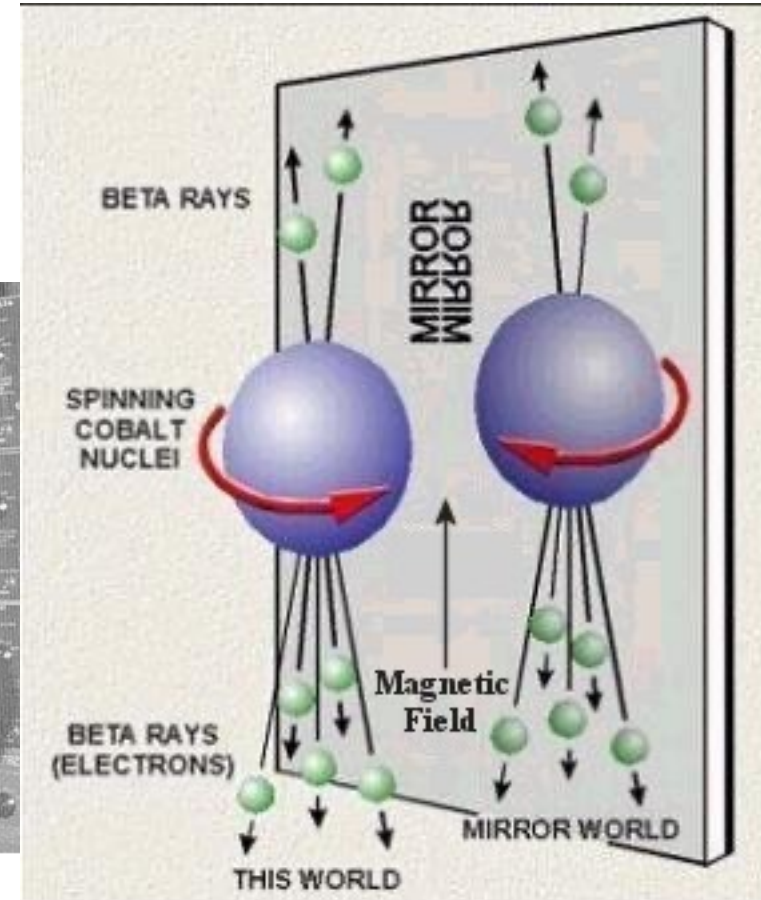


T. D. Lee

C. N. Yang



C. S. Wu



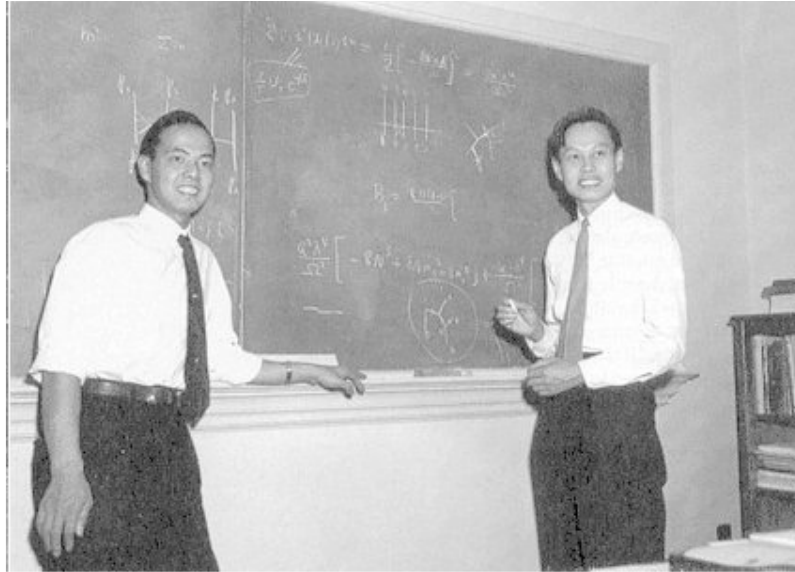
The ellipsoid on the left is the real world, and all cobalt-60 nuclei, all with their spins in the same direction, and all emitting beta rays in any one direction. On the right this procedure is the mirror image, which most beta rays are emitted in the opposite direction. The mirror world is the real world.

The parity transformation is completed by turning the mirror world. The spins of the cobalt nuclei are reversed, and their original direction of spin is now aligned with the direction of the emitted beta rays. The parity-transformed world is the real world; parity is conserved.

Note that the asymmetry in the beta rays emitting in the other direction is not observed in the actual experiment, the experiment was performed at low temperature and low pressure to achieve.

Parity violation has been observed in weak interactions in the 1950's

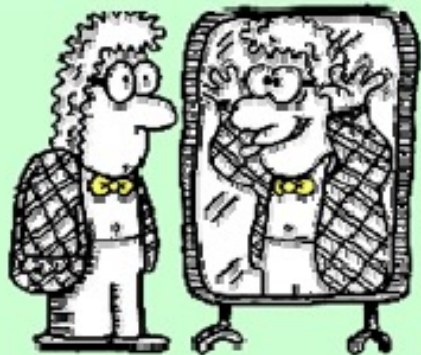
Weak interactions violate parity symmetry maximally!



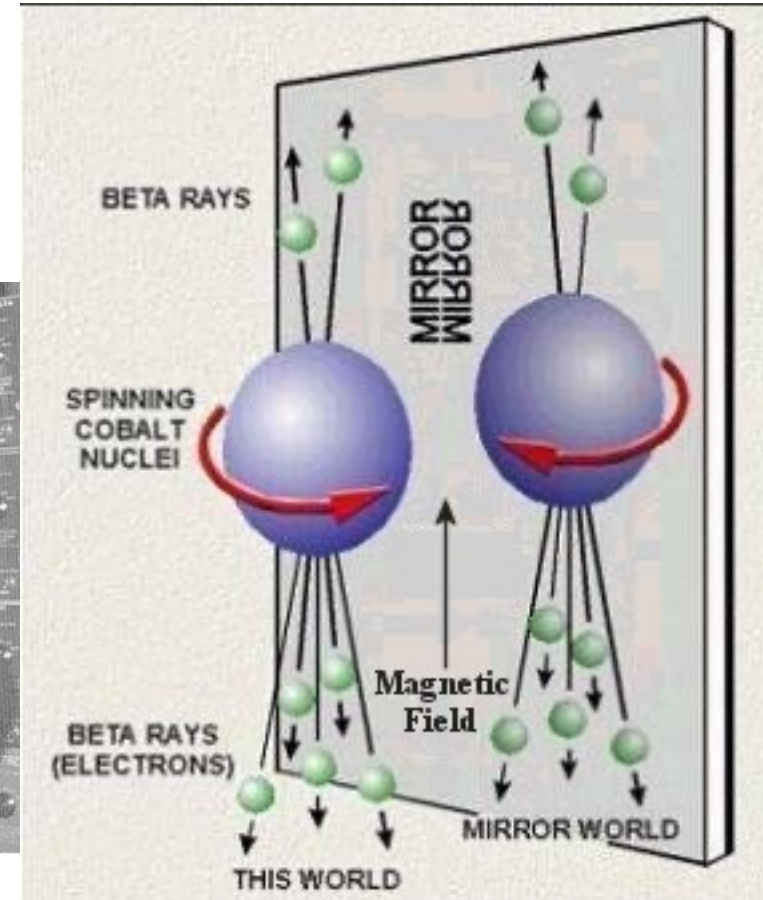
T. D. Lee

C. N. Yang

THE MIRROR DID NOT SEEM TO BE OPERATING PROPERLY.



C. S. Wu



The ellipsoid on the left is the real world. The ellipsoid on the right is the mirror world. In the real world, all cobalt-60 nuclei spin in the same direction, and all emit beta rays in the same direction. In the mirror world, any one cobalt nucleus is transforming itself through the parity operation. On the right this process is the mirror image of the real world. The direction of spin is reversed, which most beta rays are emitted in. The mirror world is the real world.

The parity transformation is completed by turning the mirror world upside down. The spins of the cobalt nuclei are now aligned in their original direction. The beta rays are now emitted upward - consistent with the real world; parity is conserved.

Note that the asymmetry in the real world is not observed in the other direction. The beta rays are aligned perfectly with the spin. In the actual experiment, the cobalt-60 nuclei were at low temperature and the beta rays were emitted in the same direction.

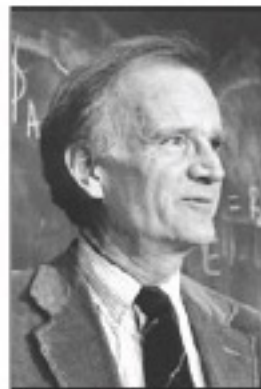
CP-violation was discovered at BNL in 1964

James W. Cronin and Val L. Fitch, both then of Princeton University, proposed using Brookhaven's AGS to verify a fundamental tenet of physics, known as CP symmetry, by showing that two different particles did not decay into the same products. They picked as their example neutral K mesons, which are routinely produced in collisions between a proton beam and a stationary metal target.

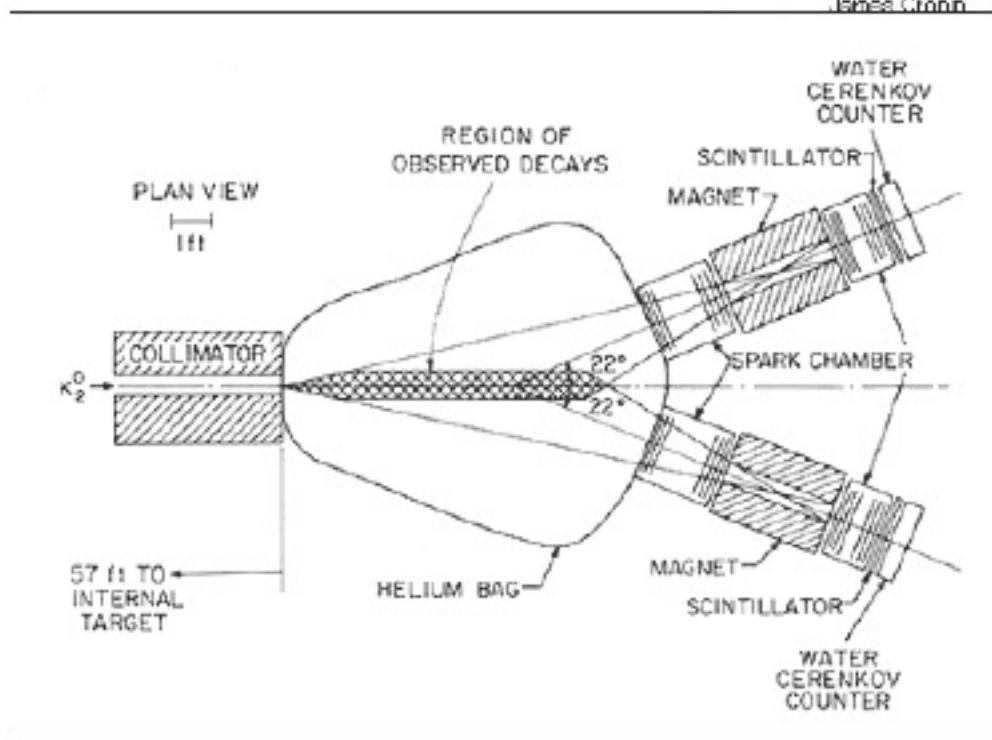
The experiment set out to show that in millions of collisions, the short-lived variety of K meson always decayed into two pi mesons, while the long-lived variety never did. But to their surprise, a "suspicious-looking hump" in the data showed an unexpected result that years of subsequent experimentation and theory have been unable to explain: occasionally, the long-lived neutral K meson does decay into two pi mesons. Cronin and Fitch had found an example of CP violation.



James Cronin



Val Fitch



Schematic of the experimental apparatus used by Cronin and Fitch.

T-Violation $\xrightarrow{\text{CPT}}$ CP-Violation

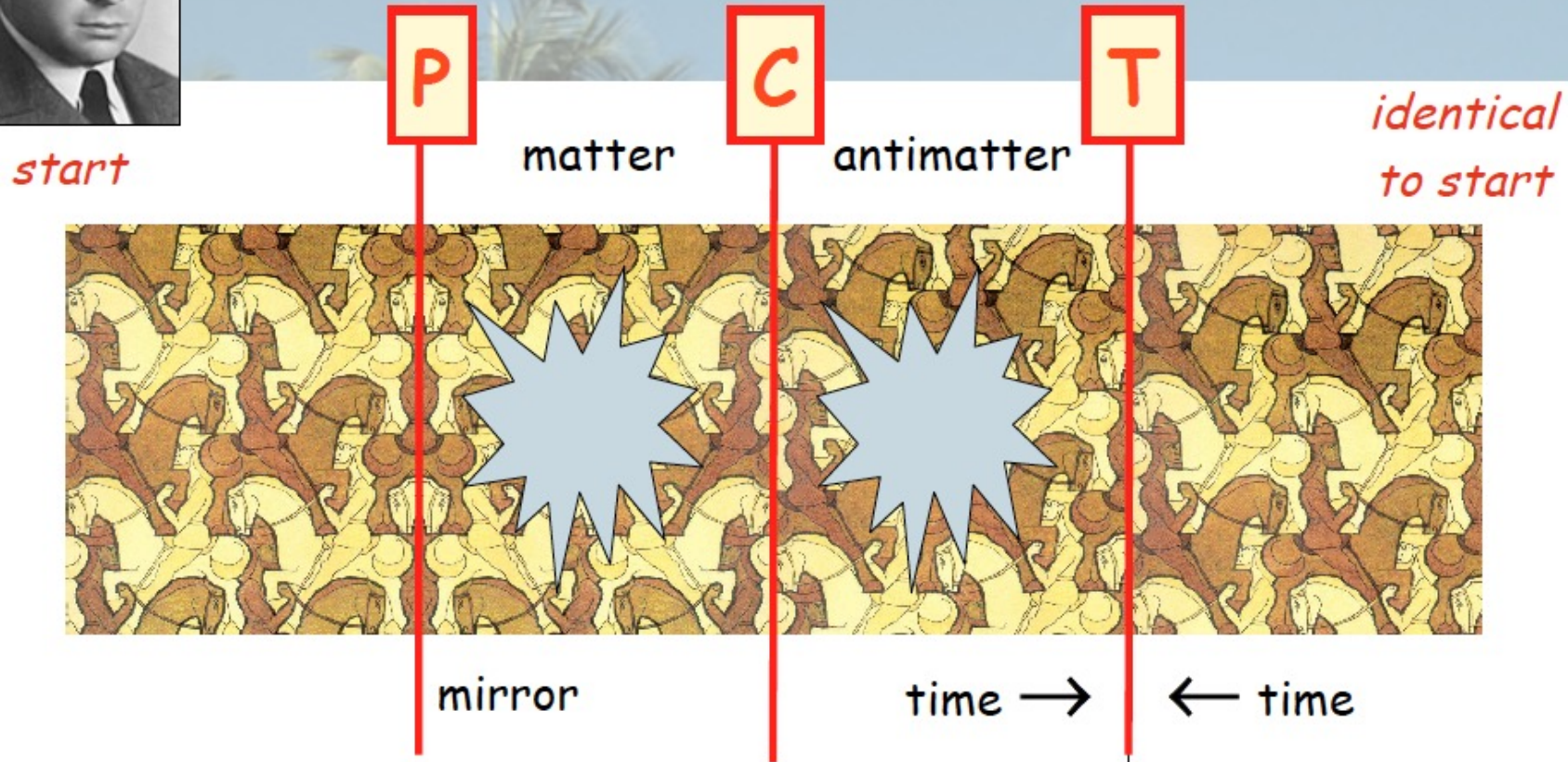


Andrei Sakharov 1967:

CP-Violation is one of three conditions to enable a universe containing initially equal amounts of matter and antimatter to evolve into a matter-dominated universe, which we see today....



The CPT theorem (Pauli *et al.*, 1955)



antiparticle

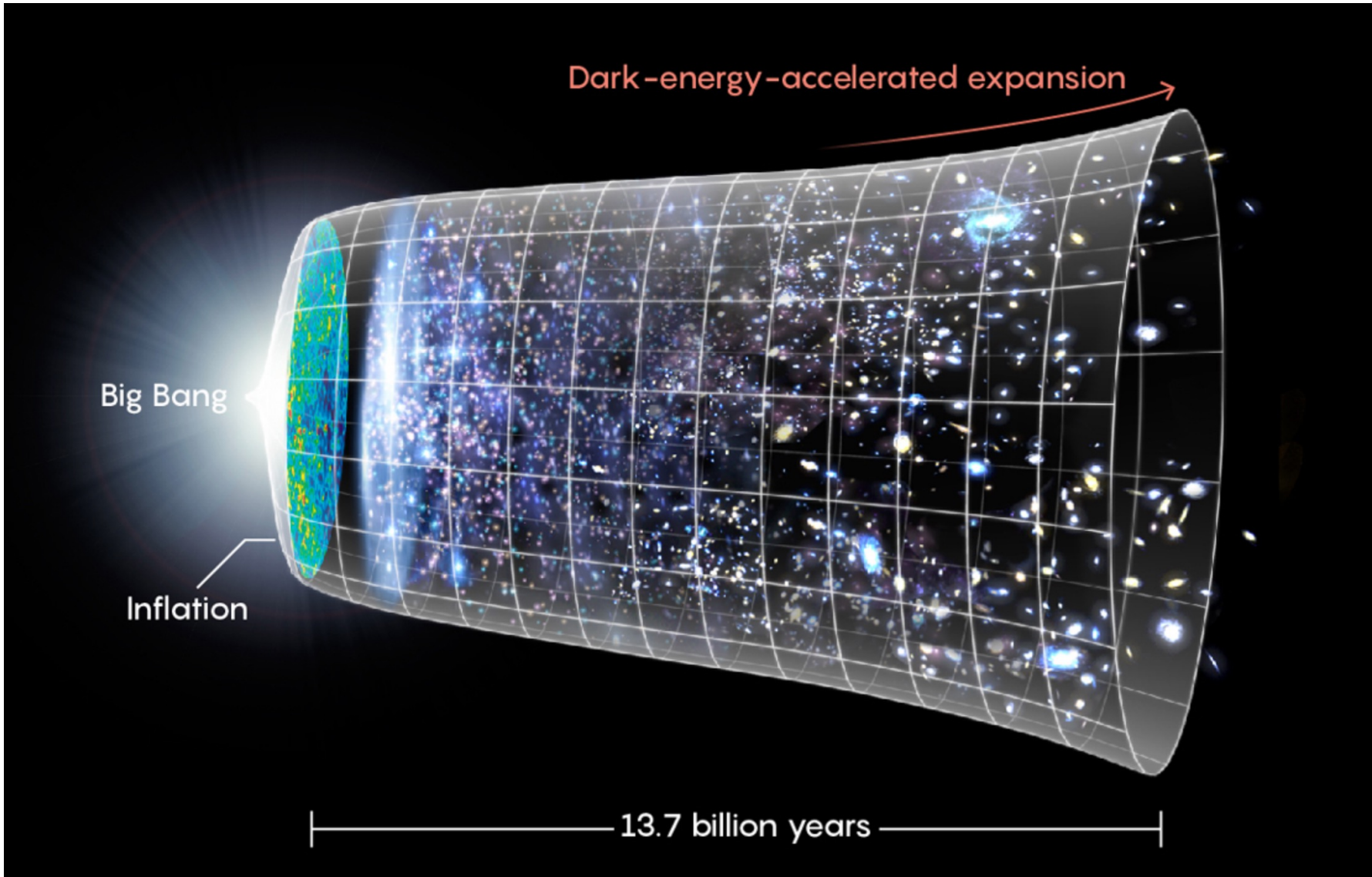


particle

Holds on very general grounds:
 Nature is local, causal & Lorentz invariant.
 True for all gauge theories!

After H. Wilschut

Why is there so much matter after the Big Bang:



We see:

$$\frac{n_B}{n_\gamma} \approx (6.08 \pm 0.14) \times 10^{-10}$$

From the SM:

$$\frac{n_B}{n_\gamma} \approx 10^{-18}$$

Electric Dipole Moments

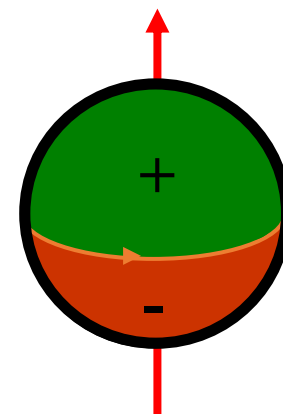
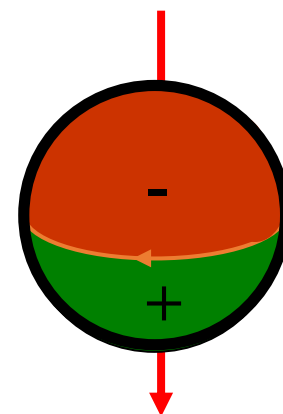
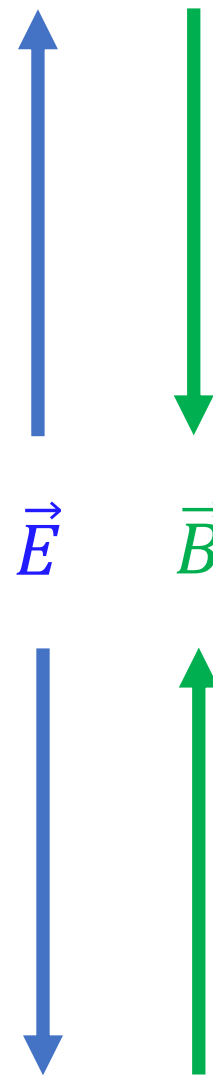
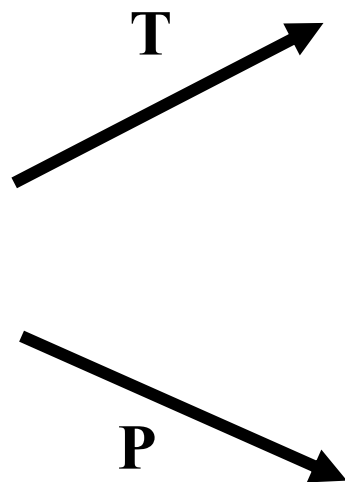
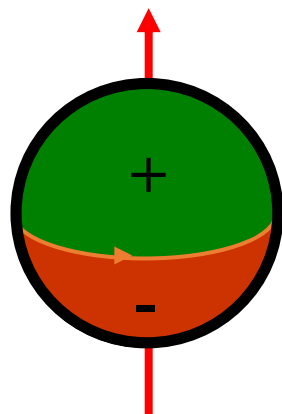
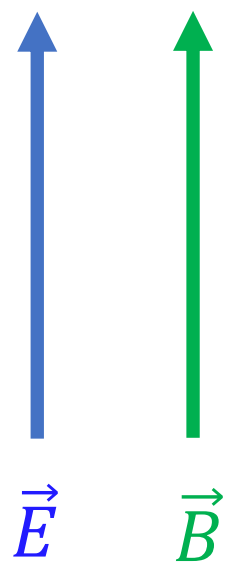
One of the most sensitive ways to search for BSM CP violation

A Permanent EDM Violates both T & P Symmetries:

$$\vec{\mu} = g \left(\frac{q}{2m} \right) \vec{s}, \quad \mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

$$\vec{d} = \eta \left(\frac{q}{2mc} \right) \vec{s}$$

The EDM is *caused* by the spin



Reminder: batteries are allowed in the SM!

Purcell and Ramsey:

“The question of the possible existence of an electric dipole moment of a nucleus or of an elementary particle...becomes a purely experimental matter”



Phys. Rev. 78 (1950)



Input to hadronic EDM

- Theta-QCD (θ_{QCD} part of the SM, implying P&T violation in strong interactions)
- CP-violation sources beyond the SM

A number of alternative simple systems could provide invaluable complementary information (e.g. neutron, proton, deuteron,...).

- At $10^{-29} e\cdot\text{cm}$ the proton would be the most sensitive hadronic EDM experiment

Proton edm SR goal: $d_p \sim 10^{-29} \text{e-cm}$
Improvement by more than 4 orders!
Sensitivity similar to $d_e < 10^{-30} \text{e-cm}$

In a renormalizable quantum field theory, at
lowest order $d_p = 0$ (No dim. 5 operators)

$d_p \sim e m / \Lambda_{\text{NP}}^2 \sin \phi^{\text{NP}}$ quantum loop induced

Λ_{NP} scale of “new physics”

ϕ^{NP} = Complex CP violation phase of New Physics

phase misalignment with m_p

$\sim 10^{-22} (1 \text{TeV} / \Lambda_{\text{NP}})^2 \sin \phi^{\text{NP}} \text{e-cm}$

If ϕ^{NP} is of $O(1)$, $\Lambda_{\text{NP}} \sim \underline{3000 \text{TeV}}$ Probed! (very roughly)

If $\Lambda_{\text{NP}} \sim O(1 \text{TeV})$, $\phi_{\text{NP}} \sim 10^{-6}$ Probed!

a_f vs d_f (very roughly)

- Two loop Higgs contribution: $a_\mu(H) \approx \text{few} \times 10^{-11}$
Both **Unobservably Small** $a_e(H) \approx 5 \times 10^{-16}$

EDM Higgs contribution: $d_e(H) \approx 10^{-26} \sin\phi$ e-cm

$$|d_n(H)| \approx |d_p(H)| \approx 3 \times 10^{-25} \sin\phi \text{ e-cm}$$

Already d_e bound implies $\sin\phi_e \leq 0.002$ (smaller?)

Altmannshofer, Brod, Schmaltz JHEP (updated)

CP violation in $BR(H \rightarrow \gamma\gamma)$ $\gamma\gamma$ Collider?

Unlikely to be observable, but edm experiments can

Explore down to $\tan\phi \approx O(10^{-4})$! Unique!

Motivation of pEDM at 10^{-29} e-cm

- Probe New Physics, at $\sim 10^3$ TeV mass scale, Higgs CPV
- Could help explain level of baryon-antibaryon asymmetry in our universe
- Improve sensitivity to θ_{QCD} by three orders of magnitude
- Direct search for axion dark matter (axion-gluon coupling).
 - Could cross-check gluonic coupling, should axions are detected with microwave cavities.

EDM timelines, from Snowmass 2021 (2022).

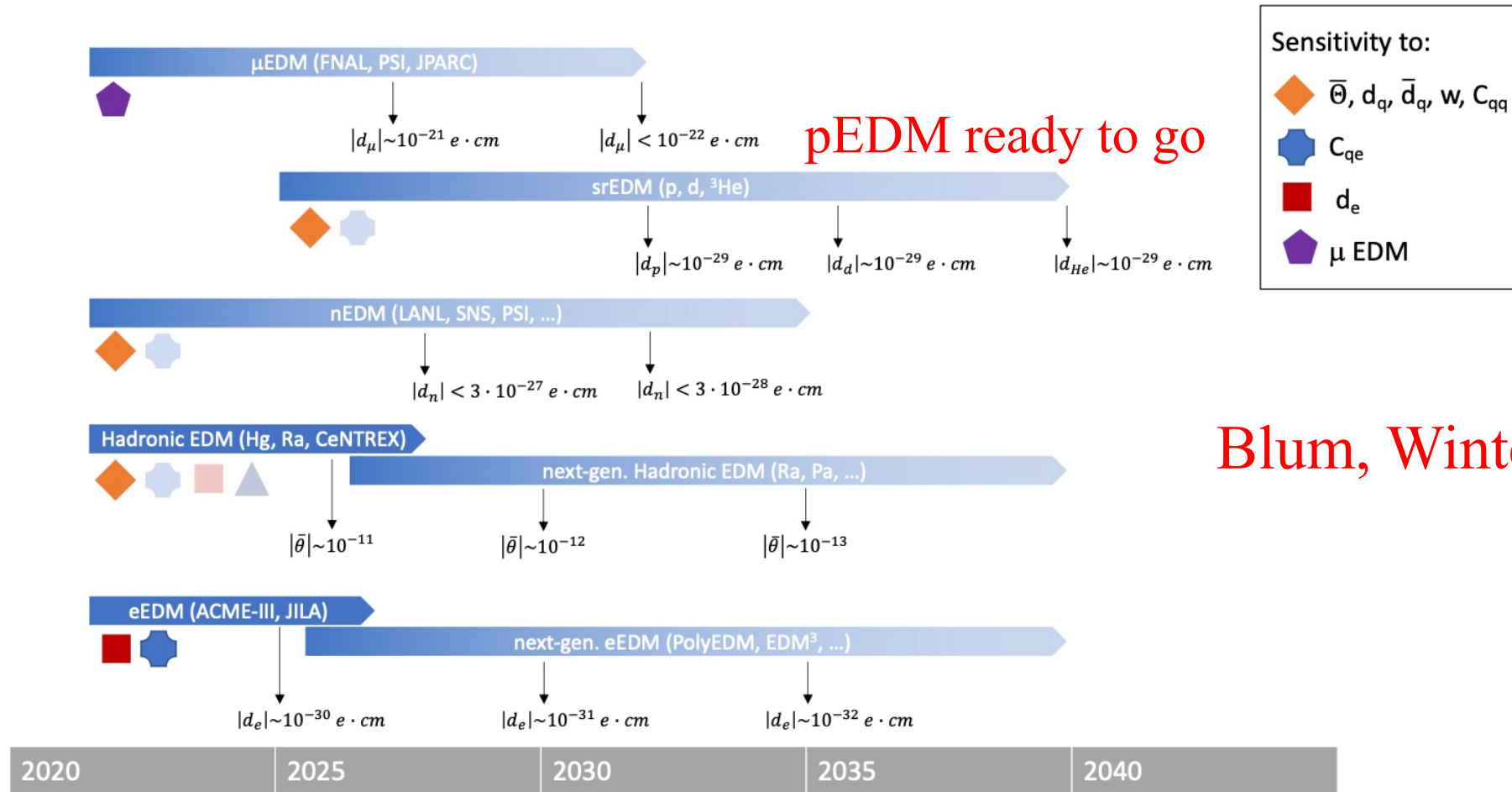


Figure 3-1. Timelines for the major current and planned EDM searches with their sensitivity to the important parameters of the effective field theory (see Fig. 3-2 for details). Solid (shaded) symbols indicate each experiment’s primary (secondary) sensitivities. Measurement goals indicated by the black arrows are based on current plans of the various groups.

Snowmass paper on EDMs, why many EDMs:

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

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.

$$\begin{aligned}
 d_n = & -(1.5 \pm 0.7) \cdot 10^{-3} \bar{\theta} e \text{ fm} \\
 & -(0.20 \pm 0.01)d_u + (0.78 \pm 0.03)d_d + (0.0027 \pm 0.016)d_s \\
 & -(0.55 \pm 0.28)e\tilde{d}_u - (1.1 \pm 0.55)e\tilde{d}_d + (50 \pm 40) \text{ MeV} e \tilde{d}_G .
 \end{aligned}$$

arXiv:2203.08103v1 [hep-ph] 15 Mar 2022

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Other news on EDMs

arXiv:2511.03786v1 [hep-ph] 5 Nov 2025

Light new physics and the τ lepton dipole moments

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$$a_{\mu}^{\text{exp}} = 116\,592\,071.5(14.5) \times 10^{-11}$$

$$a_e^{\text{exp}} = 115\,965\,218\,059(13) \times 10^{-14}$$

$$d_e^{\text{exp}} < 4.1 \times 10^{-30} e \text{ cm}$$

$$d_{\mu}^{\text{exp}} < 2 \times 10^{-19} e \text{ cm}$$

Testing New-Physics (NP) scenarios that couple predominantly to the third generation is notoriously difficult experimentally, as exemplified by comparing limits for the τ lepton dipole moments to those of electron and muon. In this case, extracting limits from processes such as $e^+e^- \rightarrow \tau^+\tau^-$ often relies on effective-field-theory (EFT) arguments, which allows for model-independent statements, but only applies if the NP scale is sufficiently large compared to the center-of-mass energy. In this work we offer a comprehensive analysis of light NP contributions to the τ dipole moments, providing a detailed account of the interpretation of asymmetry measurements in $e^+e^- \rightarrow \tau^+\tau^-$ that are tailored towards the extraction of dipole moments, for the test cases of new light spin-0 and spin-1 bosons. Moreover, we study the decoupling to the EFT limit in these scenarios and discuss the complementarity to constraints from other related processes, such as production in e^+e^- reactions. While covering a wide range of light NP scenarios, as specific case study we present a detailed discussion of a tauphilic gauge vector boson at Belle II.

U.S. Secretary of Energy, Chris Wright, visited Fermilab on July 17 (Photo: Brendan Casey)

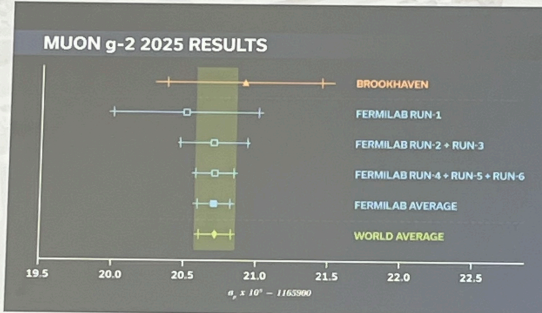
- The very first poster he saw when he entered the Wilson Hall at Fermilab: Muon g-2, about an amazing experiment.
- 2021-2025 media coverage with 15.53 billion potential readers and 6,525 media stories!

Muon g-2 experiment at Fermilab

The Muon g-2 experiment probes the magnetic properties of the muon—a heavy sibling of the electron—in the search for new physics. Muon g-2 (pronounced gee-minus-two) is an international collaboration of national labs and universities from seven countries hosted at Fermilab.

On June 3, 2025, scientists announced the **most precise measurement** of the magnetic anomaly of the muon. The final result combined the last three years of data with the first two results, yielding a precision of 127 parts-per-billion, surpassing the original experimental design goal of 140 parts-per-billion.

The third and final result is in **perfect agreement** with the experiment's previous results, further solidifying the experimental world average. **This long-awaited value will be the world's most precise measurement of the muon magnetic anomaly for many years to come.**



"The anomalous magnetic moment, or g-2, of the muon is important because it provides a sensitive test of the Standard Model of particle physics. This is an exciting result and it is great to see an experiment come to a definitive end with a precision measurement," said Regina Rameika, the U.S. Department of Energy's Associate Director for the Office of High Energy Physics.



The mass of the magnet from the Brookhaven National Laboratory began on June 22, 2015, when it was loaded onto a 40-foot truck with a driver's seat equipped with the magnet's weight as far as possible. The magnet was transported to the Fermilab, in the Gulf of Mexico, and on the Mississippi River in New Orleans on July 27 and was moved to Fermilab on the 28th.



The 100-ton magnet ring weighs during the assembly stage. It is a set of over 50 individual magnetizing coils. The heavy metal magnet is the government's most sensitive magnet because of its high precision and accuracy.



The fully assembled magnet ring is shown with the white insulation and the experiment's service structure.

The Muon g-2 experiment at Fermilab has attracted worldwide news since 2021

2021-2025 media coverage:

- Stories on 6 continents and over 20 countries
- Media coverage includes the Associated Press, BBC News, Daily Mail, Japan News, National Geographic, NBC News, The New York Times, NPR, Popular Mechanics, Popular Science, Reuters, La Repubblica (Italy) and TGR (Italy)

15.53 billion

Potential readers of Muon g-2 media stories from 2021-2025

6,525

Media stories posted from 2021-2025



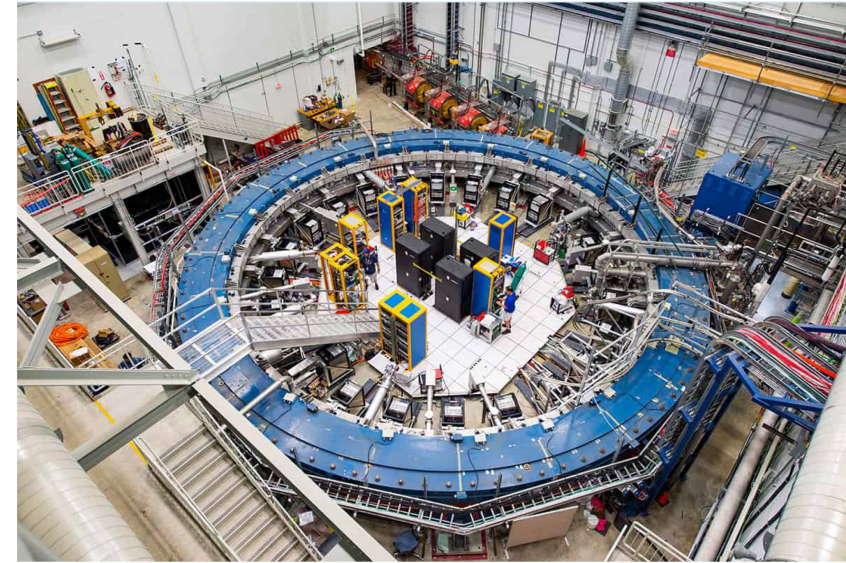
Social media in 2025:

- The final results video on YouTube has over 56k views since June 3
- Total social media impressions: 778,190
- Total social media engagement: 34,239
- Total posts: 81

Social media influencer and STEM communicator, Ashley Christine, reported on the Muon g-2 result. She has over 350k followers, and her Muon g-2 video has over 9k likes.

Bill Morse, Lee Roberts 2023 Panofsky Prize

- We built the largest single diameter (15m) superconducting magnet coil at the time. Moved it across the country to repeat the experiment.
- Uniformity of B-field (1.5T) in cross-section to better than 10^{-6} measured it (absolute) to better than 10^{-7} calibrated with two independent methods
- Developed a trolley system measuring the B-field in situ (>5000 points)
- Introduced a new DC inflector with innovative B-field shield at 3T without being detectable at storage region <10 cm away
- Built a fast (200ns, 300G) magnet (kicker) without ferrite, measured the pulsed B-field eddy currents to 10^{-8} requiring enormous dynamic range
- Developed electrostatic quads with twice the CERN gradient; measured the Electric field gradient.
- Our calorimeter detectors had to have time stability, early to late in storage, of <20 ps, measured it <2 ps; gain stability to 10^{-4}
- Used combinatorics to remove pileup pulses; segmented calo detectors
- Traceback system monitoring motion in real time, without affecting muons
- Used RF, riding on the quads, for 30μ s to adjust coherent beam motion and reduce muon losses, both by an order of magnitude
- ...
- Project manager (Chris Polly, Fermilab) received DOE management Prize!



Magnetic muons The Muon g-2 experiment at the Fermi National Accelerator Laboratory. (Courtesy: Reidar Hahn/Fermilab, US Department of Energy)



On time, on budget! We deliver!

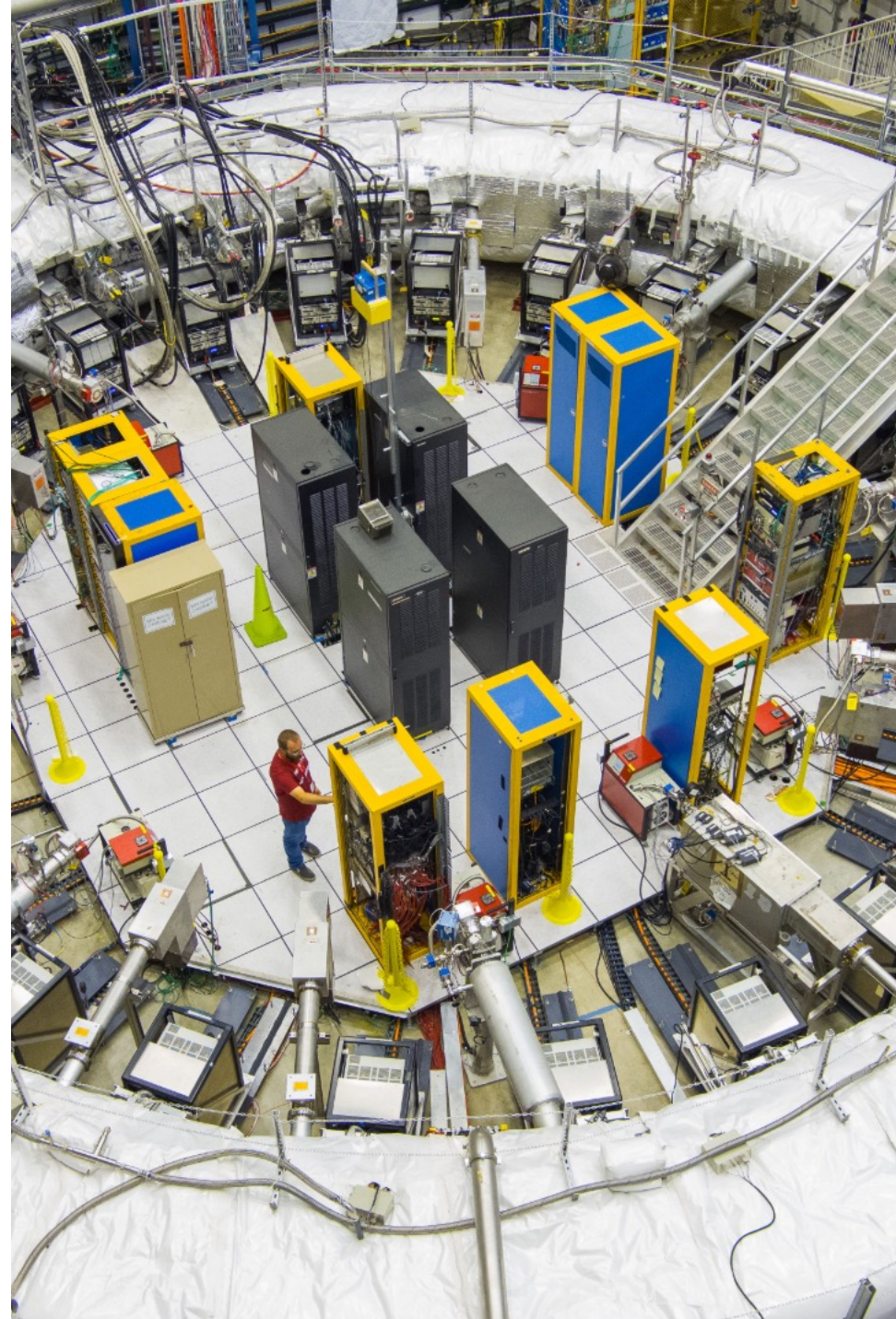
From $g-2$ to EDM — Precision Spin Physics at Work

- Muon $g-2$ @ Fermilab: World's most precise SM magnetic moment test.
- Since 1987: From BNL to Fermilab — over 35 years storage ring magnetic/electric dipole moment work
- Final $g-2$ result announced last year — historic milestone.
- $g-2$ and EDM use spin precession in storage rings to probe fundamental physics.

From muons to protons

- Muons:
- Observe time and energy
- Muon lifetime: $64.4 \mu\text{s}$ (a whole storage time lasts $\sim 1\text{ms}$)

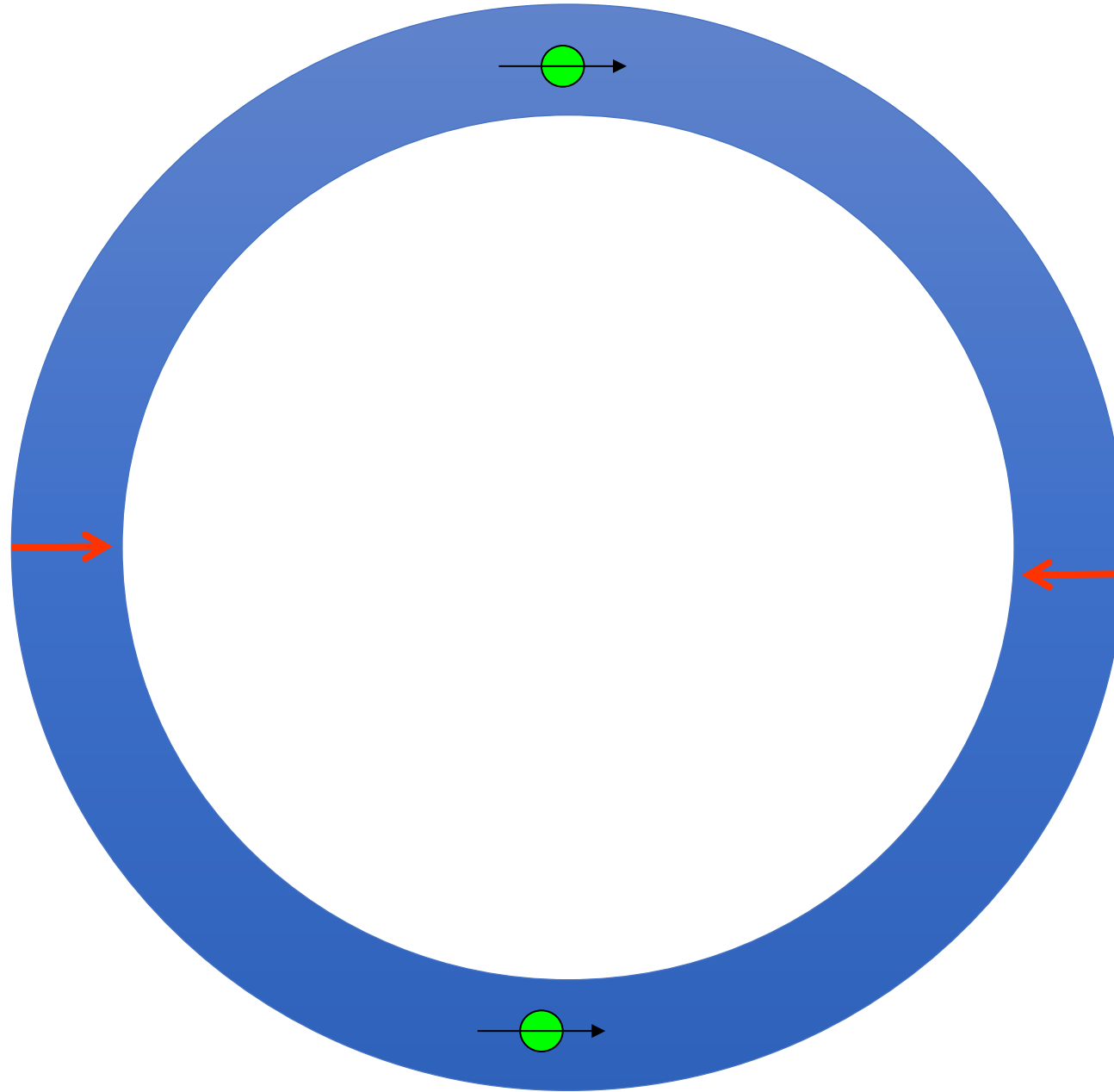
- Proton EDM:
- Proton polarimetry
- Proton beam with “infinite” lifetime and small phase-space for huge statistics gain



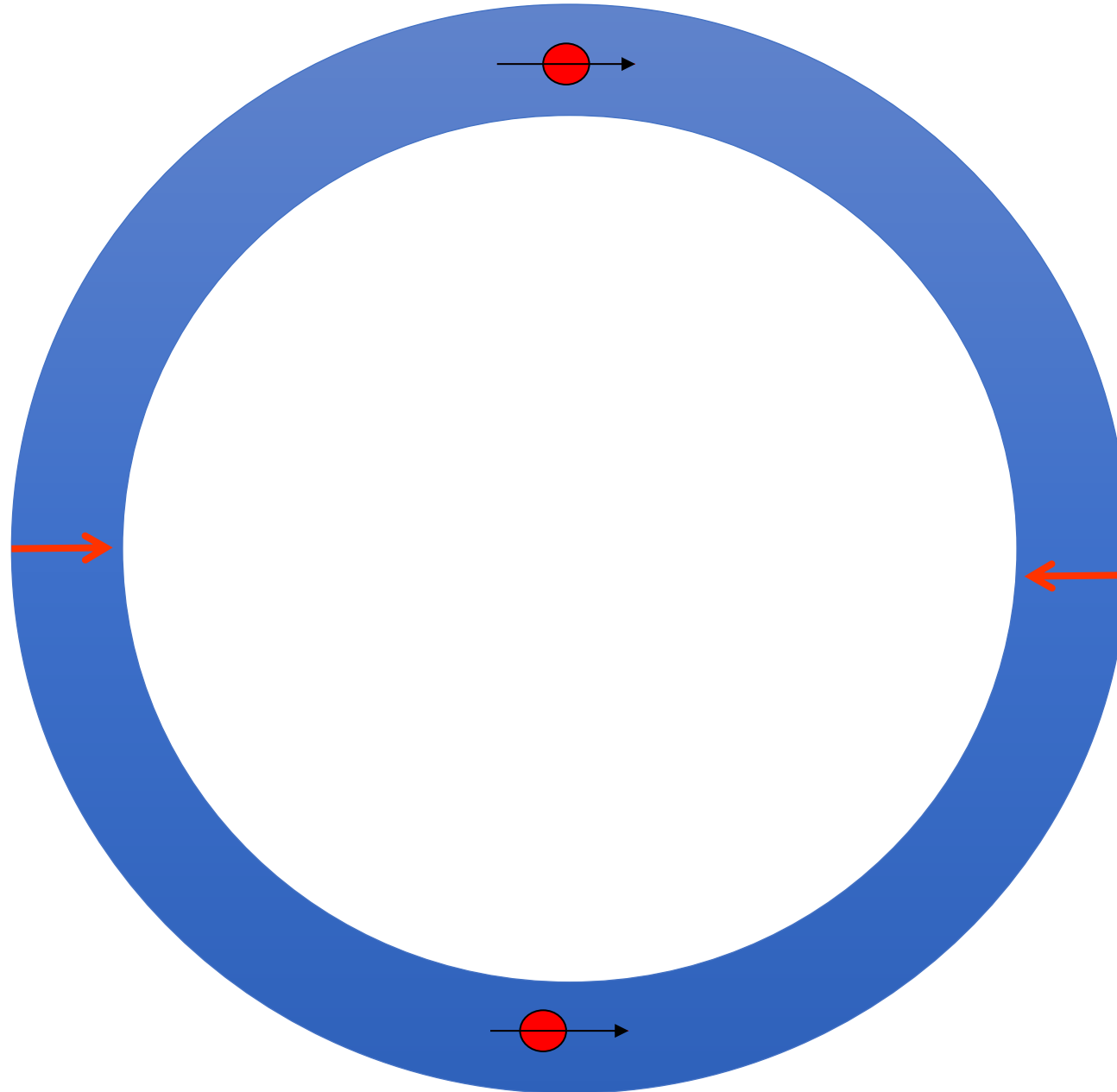
T-time symmetry

- T-symmetry describes physics phenomena that are independent of the direction of time.

Clock-wise (CW) motion in a storage ring



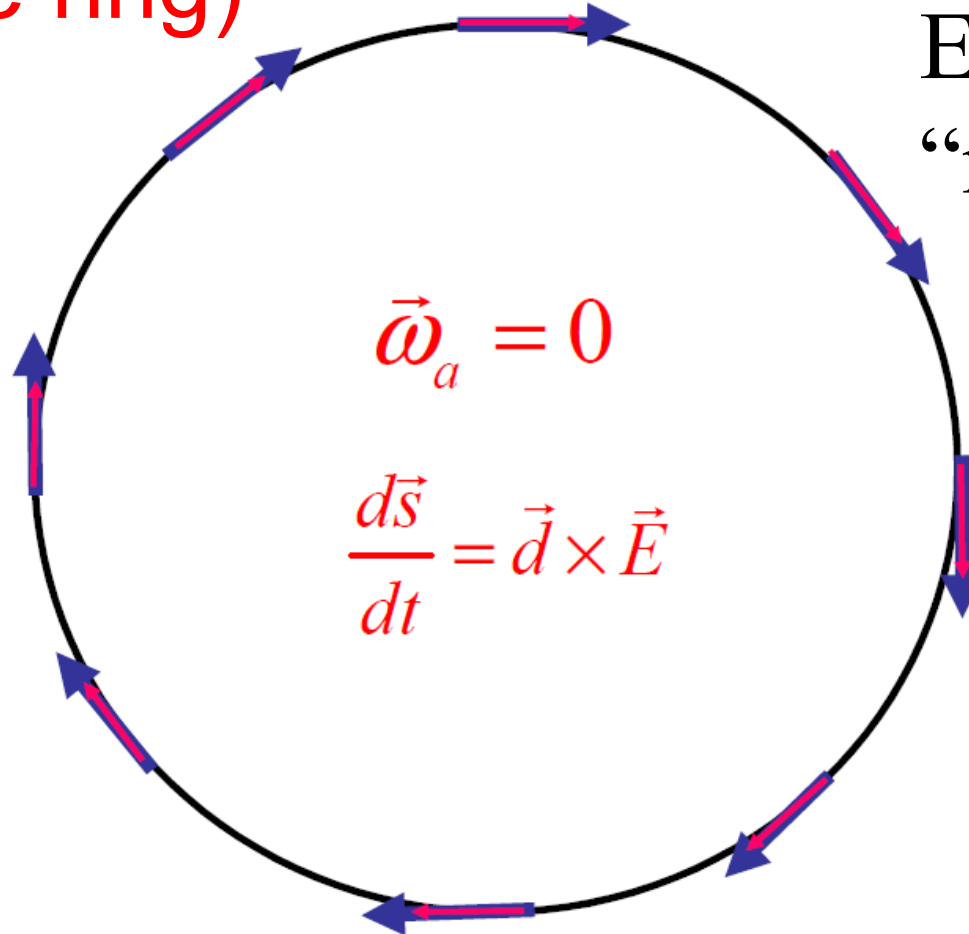
Counter-Clock-wise (CCW) motion



Storage Ring EDM experiments

(or how to create a Dirac-like particle in a storage ring)

Electric bending, w/
“magic” momentum



Electric fields: Freezing the g-2 spin precession

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

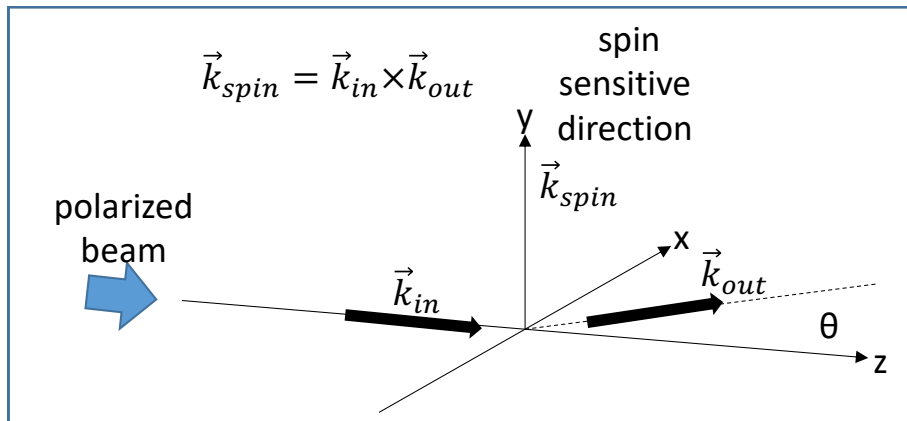
- The g-2 spin precession is zero at “magic” momentum (3.1 GeV/c for muons,...), so the focusing system can be electric

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

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

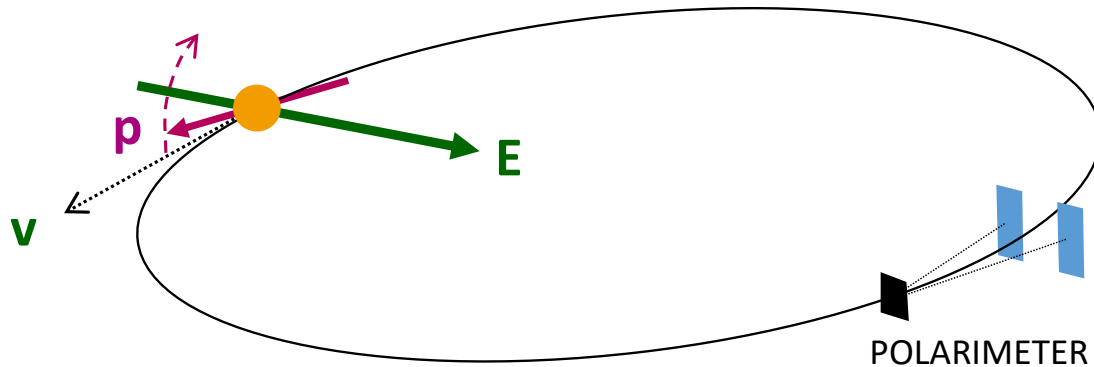
Storage ring Electric Dipole Moments

Phys. Rev. Lett. 93, 052001 (2004)

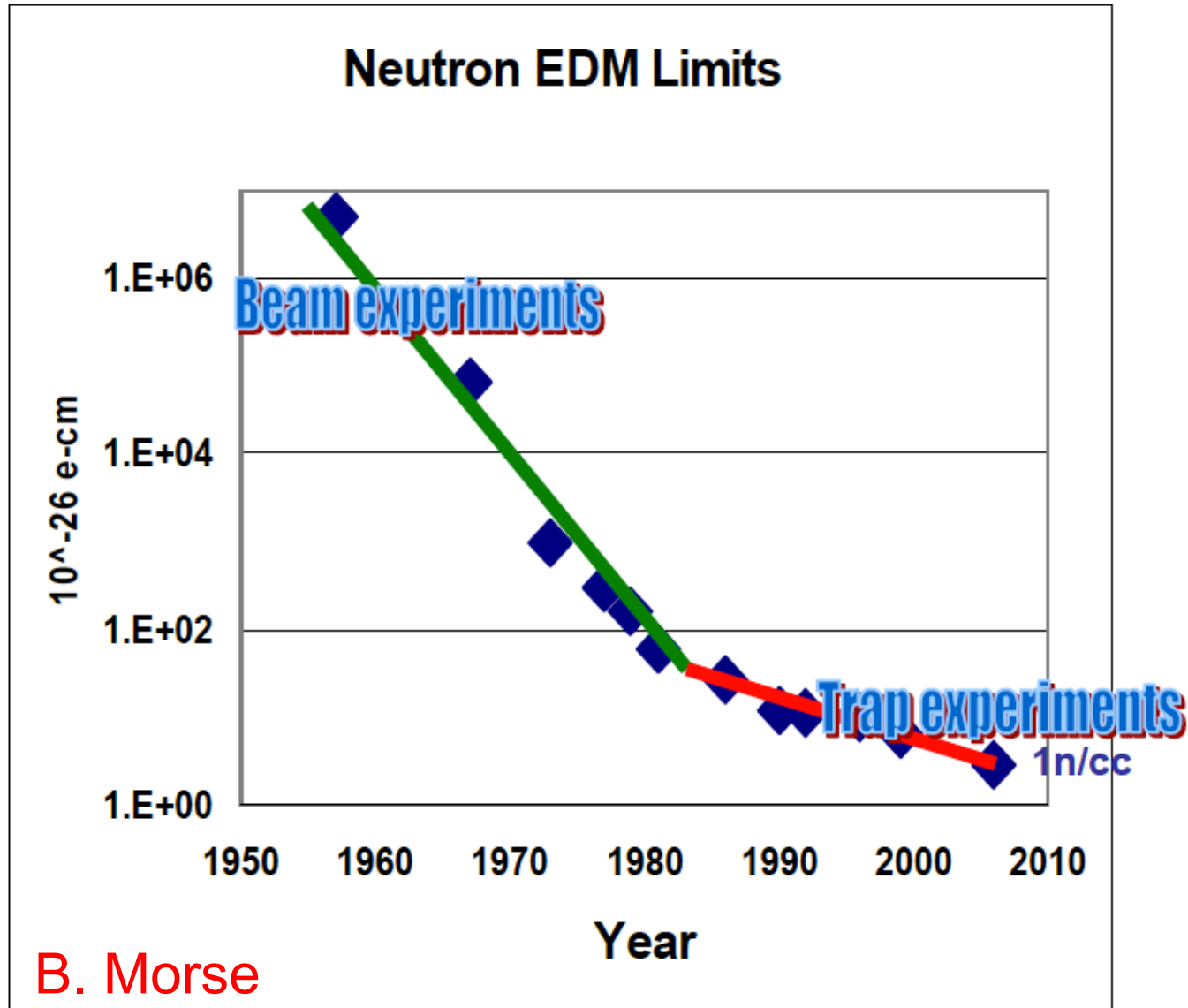


Frozen spin method:

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

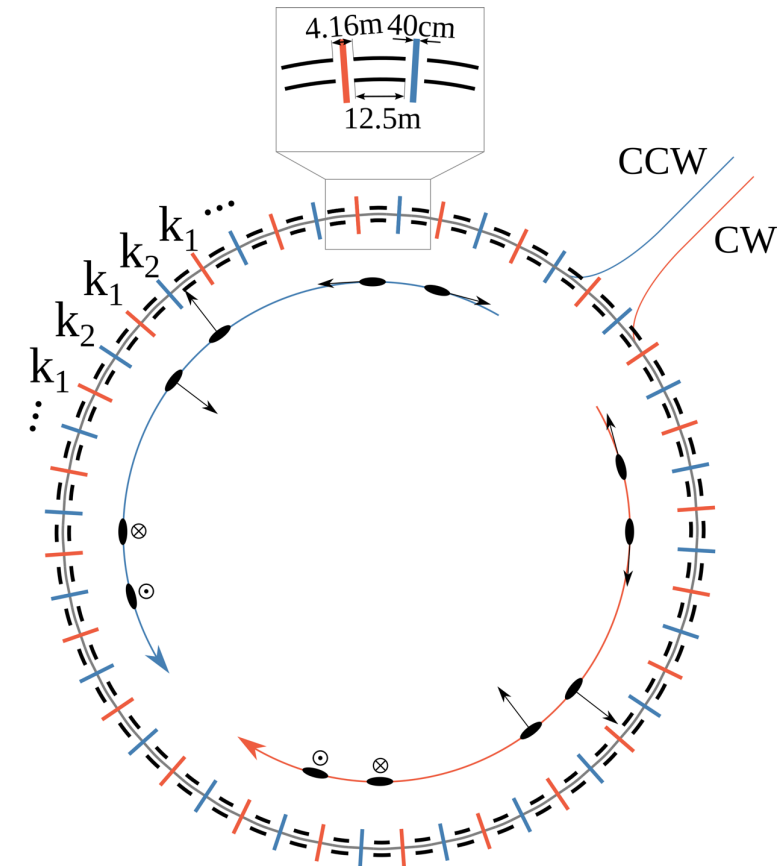
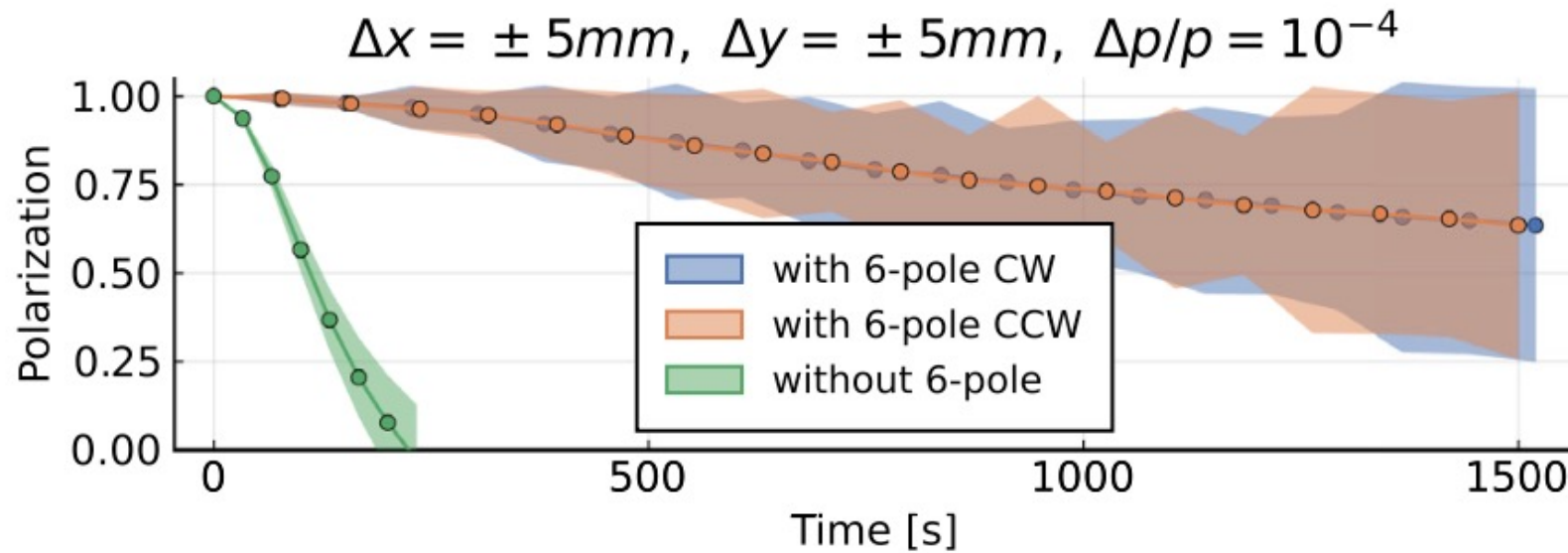


Proton storage ring EDM experiment is combination of beam + a trap



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

Z. Omarov *et al.*, Phys. Rev. D **105**, 032001 (2022)



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

SCT with Intra-Beam-Scattering/Stochastic-Cooling is $\gg 10$ longer

Main Devices



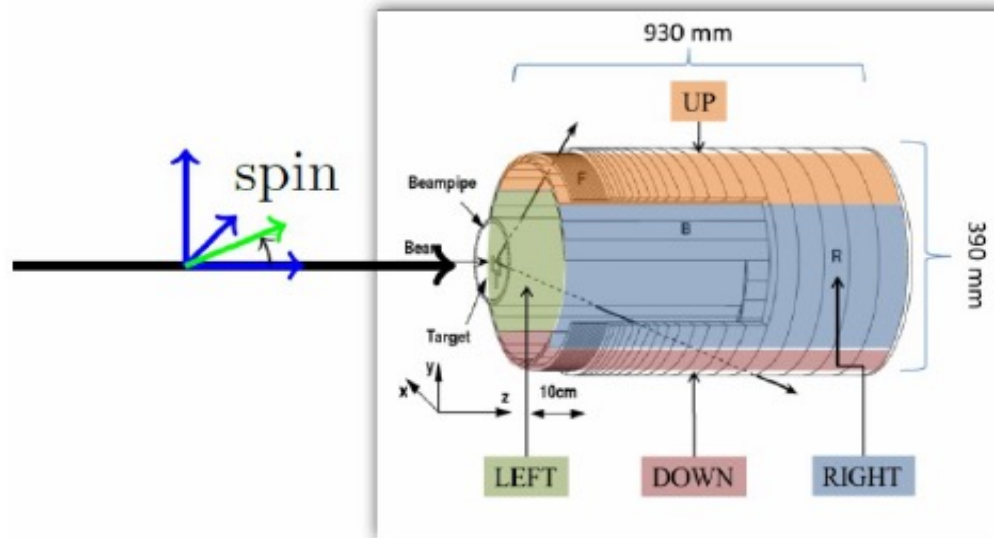
COSY:

Martin Gaisser

- $\approx 184\text{m}$ circumference
- (Un)polarized proton/deuteron beams
- Momentum range: $0.3\text{-}3.7\text{GeV}/c$
- Electron/stochastic cooling

Edda Polarimeter:

- Scintillator rings and bars
- Carbon target
- Polarimeter not ideal but best we have!



Measurement Principle

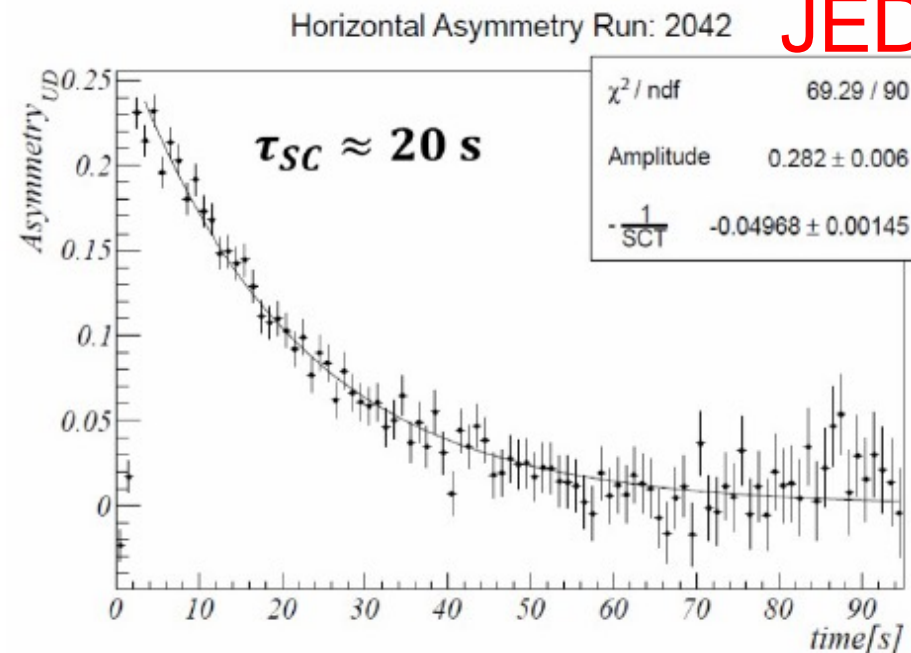
Beam Preparation:

- Inject vertically polarized deuteron beam
- Accelerate
- Cool (with e-cooler) and bunch
- Put spin into horizontal plane (with rf-solenoid on spin tune resonance)

Martin Gaisser, COSY/Juelich

Watch decay of up-down asymmetry (horizontal polarization)

JEDI Collaboration



2015.6.18

Proton Statistical Error (233MeV): 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 : 2×10^3 s 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 (10^3 s)

T_{Tot} : 2×10^7 s Total running time per year

f : 1% Useful event rate fraction (efficiency for EDM)

E_R : 4.5 MV/m Radial electric field strength

Studying ways to increasing efficiency; Quantum readout? ³²

Can we do better than $10^{-29} e\cdot\text{cm}$?

More efficient
polarimeter
(quantum
readout?)

Spin coherence time
(SCT) $\gg 2000\text{s}$

Stochastic cooling
(more beam, even
longer-“infinite”
SCT)

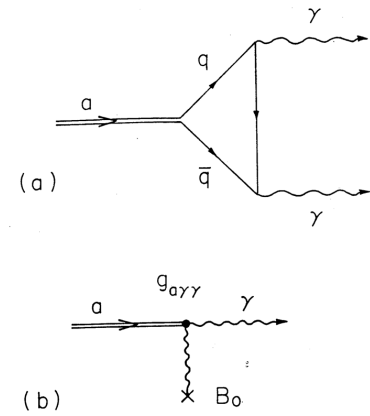
Combined electric
bending/magnetic
focusing ring

Possible, perhaps
at least on
statistics, to reach
down to SM

Issues/solutions: Electric bending, IBS and SCT

- In storage rings where a significant part of bending is provided by electric fields: Critical impact on IBS (intra-beam-scattering) and SCT (spin-coherence-time).
- IBS and negative slip factor (**below transition for stable storage**) prolongs SCT very effectively due to the exchange of phase-space populations.
- Stochastic cooling can be further used to effectively combat IBS and prolong **SCT to “infinity”**.

Axion (strong dark matter candidate) and its Couplings



- Gauge fields:

- Electromagnetic fields

$$L_{\text{int}} = -\frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

- Gluon Fields (Oscillating EDM,...)

$$L_{\text{int}} = \frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

- Fermions (coupling with axion field gradient, pseudomagnetic field)

$$L_{\text{int}} = \frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

Storage ring pEDM experiment at BNL

Storage ring probes of DM/DE

P. Graham and S. Rajendran, PRD **88**, 035023 (2013)

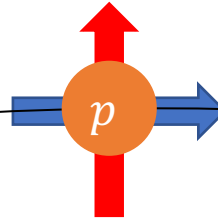
P. Graham et al., PRD **103**, 055010 (2021)

- Couplings with dark matter (DM) and dark energy (DE)
 - **ALP DM-EDM** ($g_{aN\gamma} a \hat{\sigma}_N \cdot \mathbf{E}$) \Rightarrow oscillating EDM at m_a . For the QCD axion: $d_N^{\text{QCD}} \approx 10^{-34} \cos(m_a t) e \cdot \text{cm}$.
 - **ALP or vector DM wind** ($g_{aNN} \nabla a \cdot \hat{\sigma}_N$) \Rightarrow anomalous longitudinal oscillating B field.
 - **DE wind** \Rightarrow anomalous longitudinal B field.

$$\boldsymbol{\omega}_{\text{axion-EDM}} \propto \cos(m_a t) \hat{x}$$

$$\boldsymbol{\omega}_{\text{DM}} \propto \cos(m_a t) \hat{\beta}$$

$$\boldsymbol{\omega}_{\text{DE}} \propto \hat{\beta}$$



These are spin **angular frequency vectors**.
Spin precesses around the net $\boldsymbol{\omega}$ vector.

Axion dark matter search in storage rings

- First experimental application at COSY/Juelich 2019-2022, JEDI coll., Phys. Rev. X13, 031004 (2023)

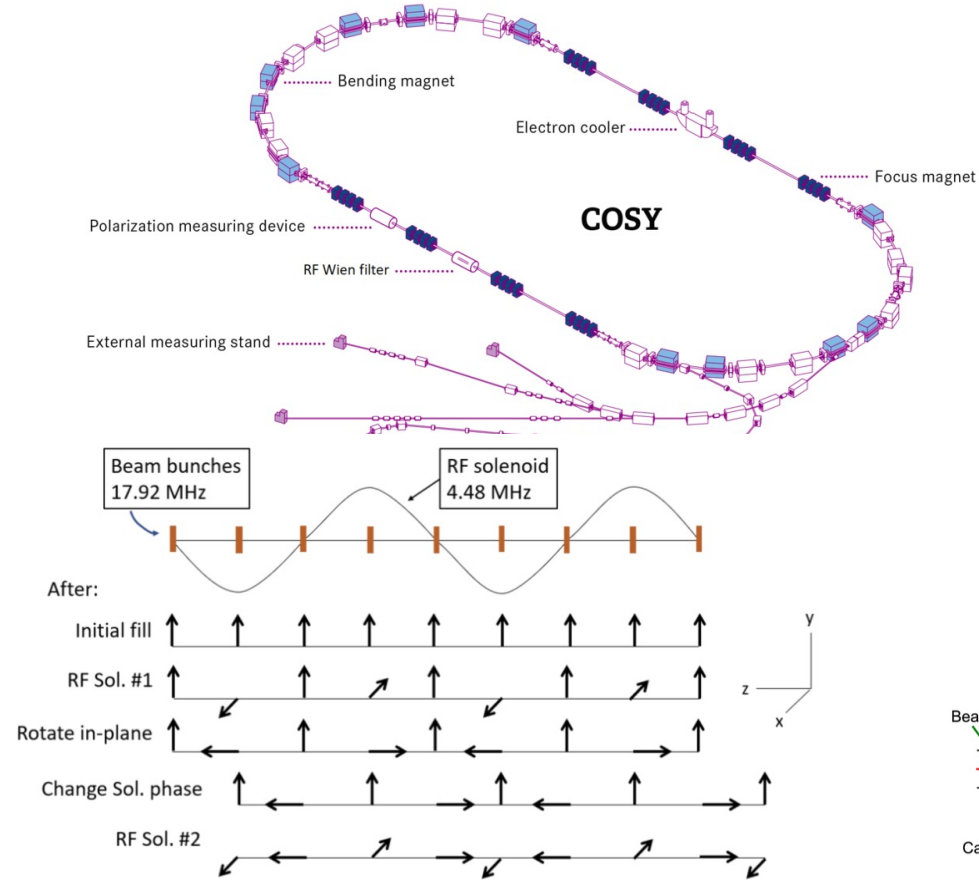
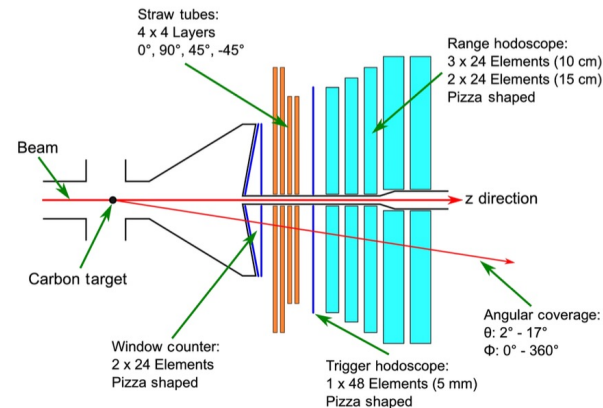
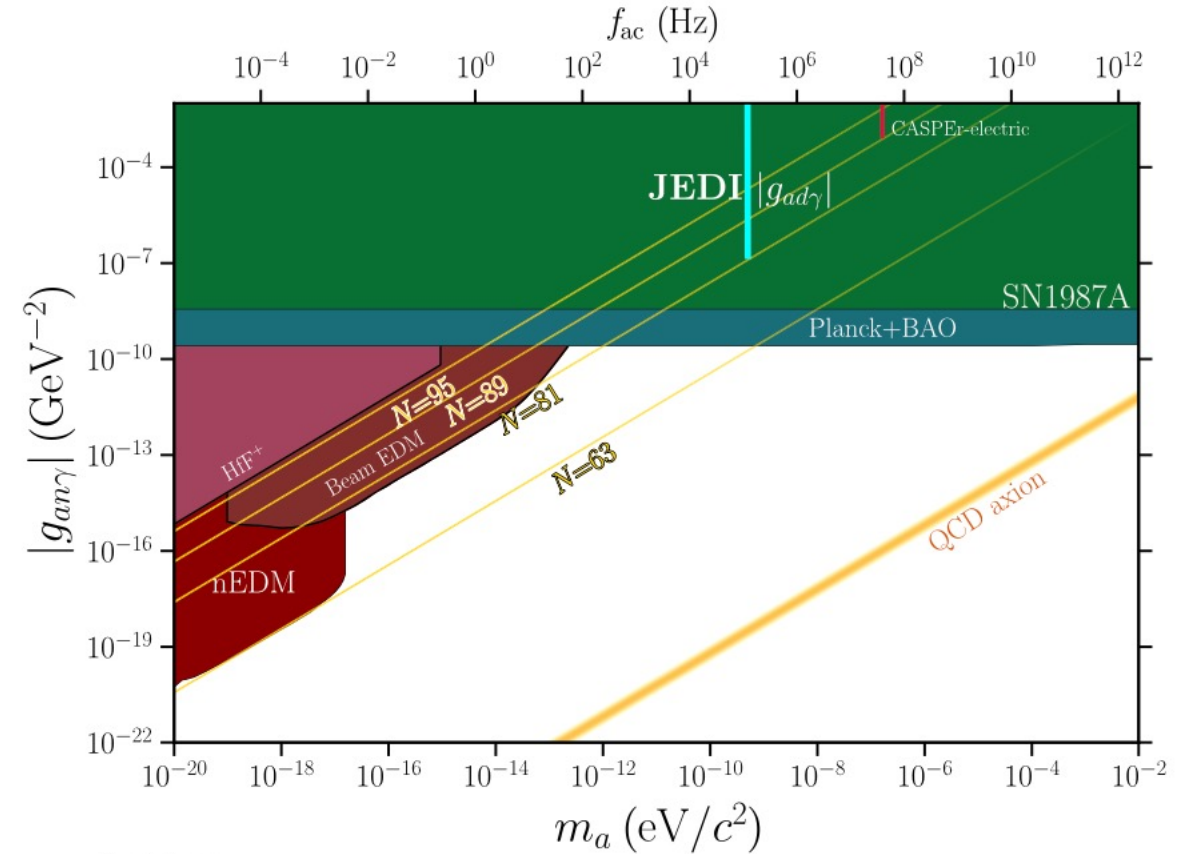


Figure 4: The figure illustrates the steps needed to produce in-plane polarization in four directions. The stored beam in, e.g., the CW direction, has all bunches polarized in the vertical direction, represented by the vertical arrows in line 1 (labeled "Initial fill"). The RF-solenoid is powered to rotate two bunches at a time, shown in line 2, and then in line 5.



When the particle g-2 frequency is in resonance with the axion dark matter frequency, then the spin precesses in the vertical direction

Systematics

^3He Co-magnetometer

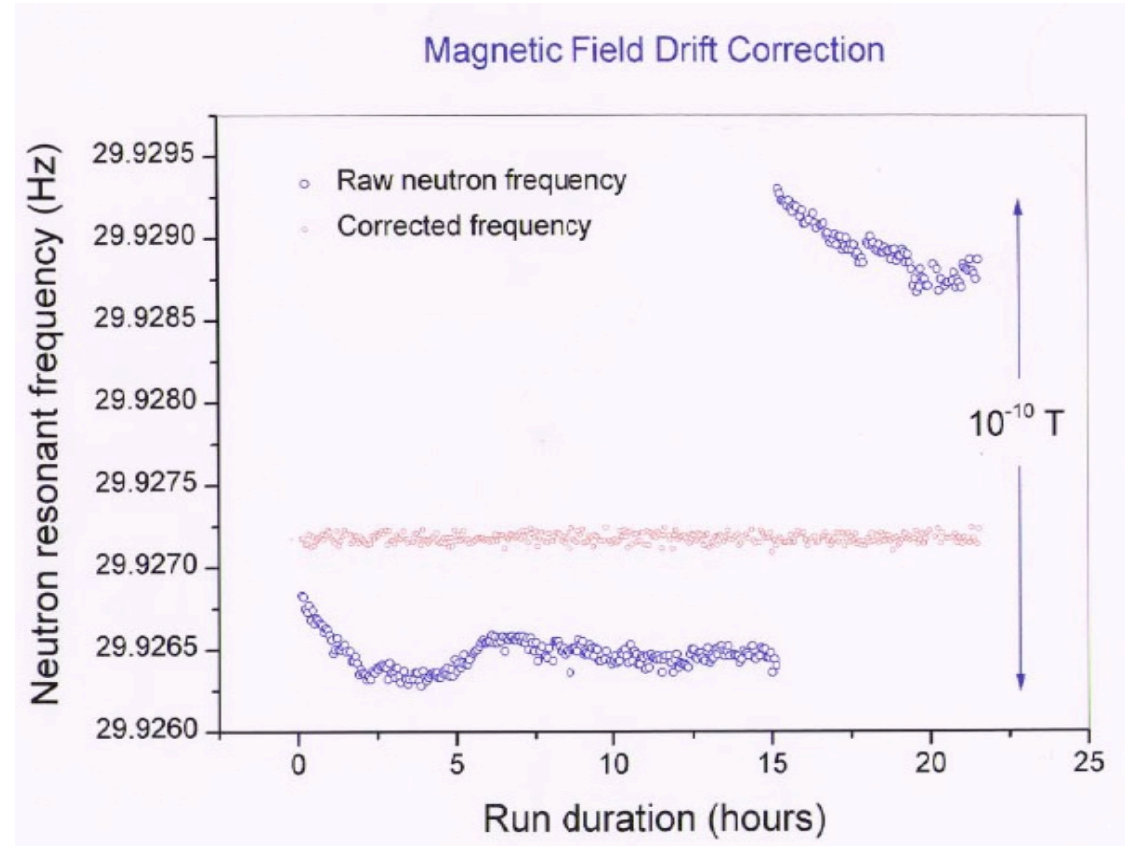
If $n\text{EDM} = 10^{-26} \text{ e}\cdot\text{cm}$,

$10 \text{ kV/cm} \rightarrow 0.1 \mu\text{Hz shift}$

$\cong \text{B field of } 2 \times 10^{-15} \text{ T}$.

Co-magnetometer :

Uniformly samples the B Field
faster than the relaxation time.

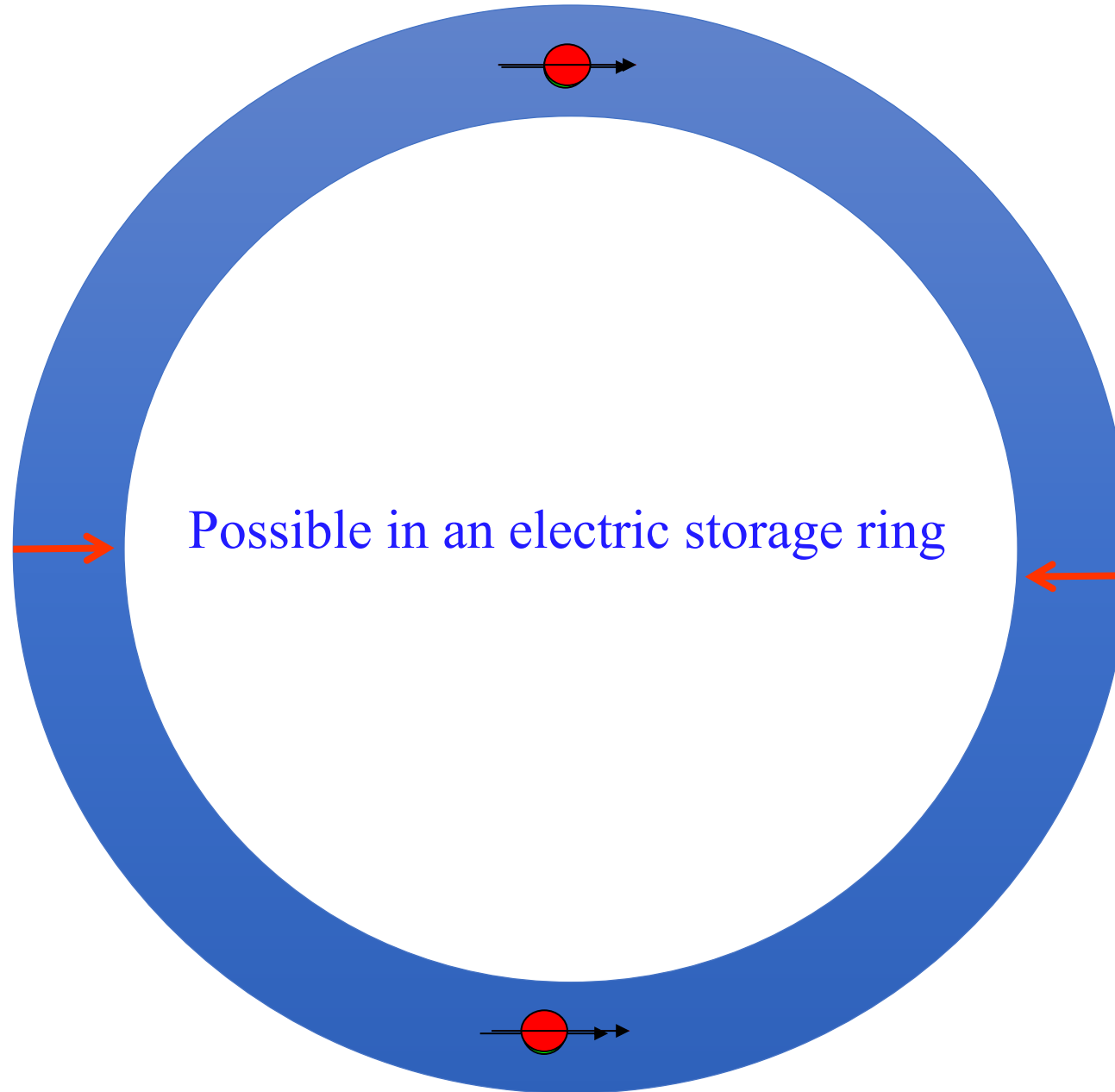


Data: ILL nEDM experiment with ^{199}Hg co-magnetometer

EDM of $^{199}\text{Hg} < 10^{-28} \text{ e}\cdot\text{cm}$ (measured); atomic EDM $\sim Z^2 \rightarrow ^3\text{He EDM} \ll 10^{-30} \text{ e}\cdot\text{cm}$

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

Simultaneous clock-wise and counter-clock-wise motion



E_y and B_x effects as a function of azimuthal harmonic N

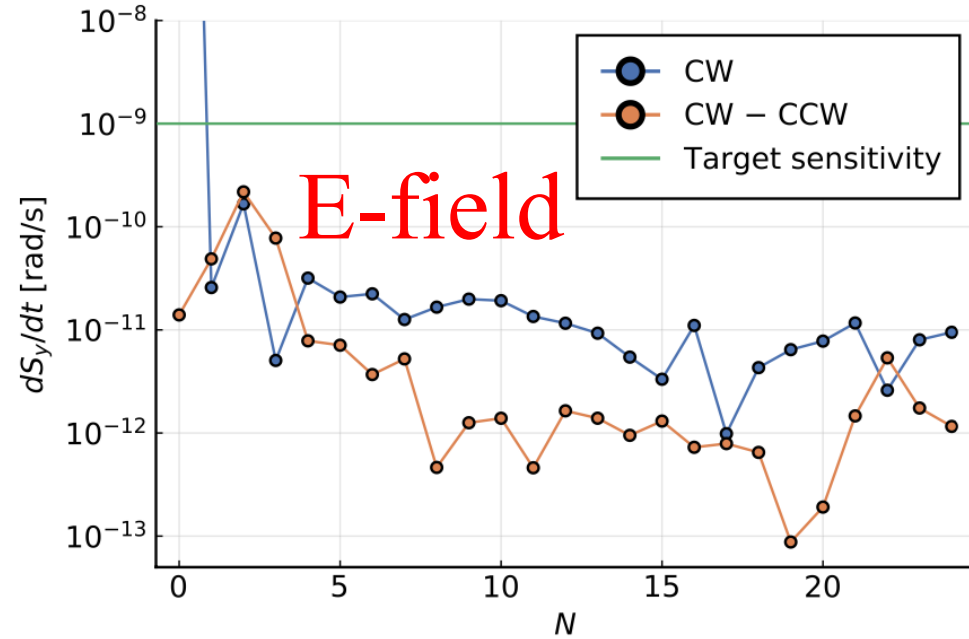


FIG. 7. *Longitudinal polarization case $S_s = 1$, sensitive to EDM. Vertical spin precession rate vs $E_y = 10$ V/m field N harmonic around the ring azimuth. For $N = 0$, the precession rate for the CW (or CCW) beam is around 5 rad/s. The difference of the precession rates for CR beams (orange) is below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

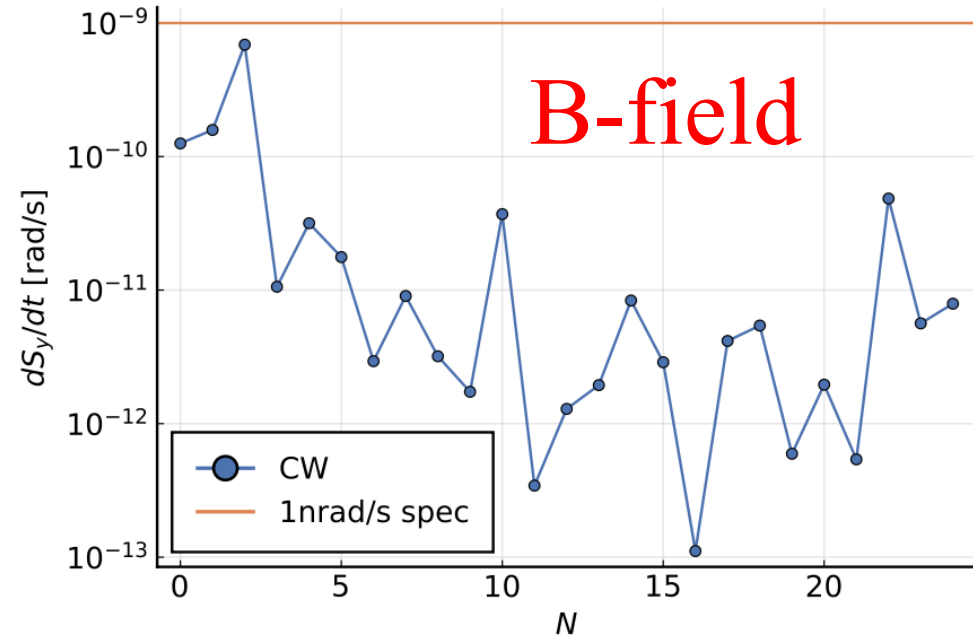
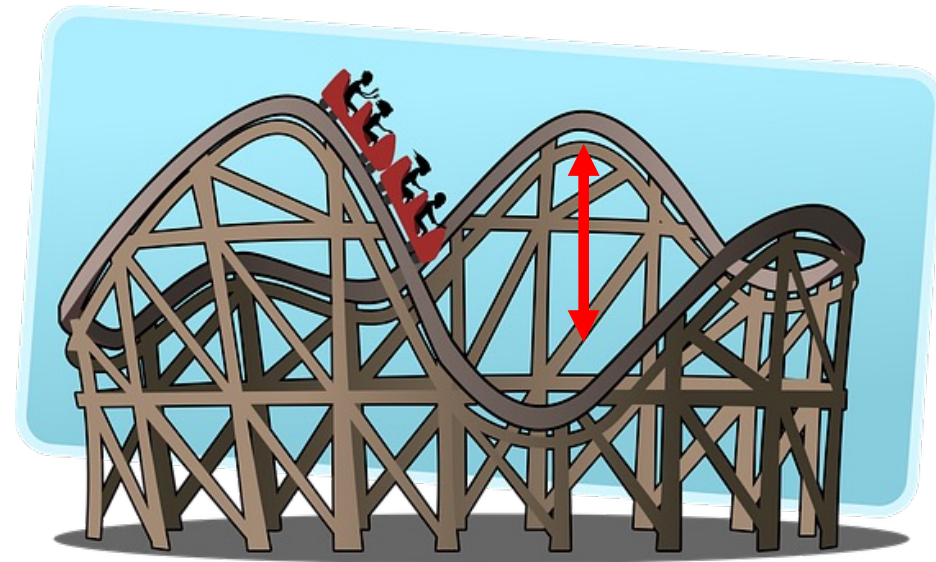
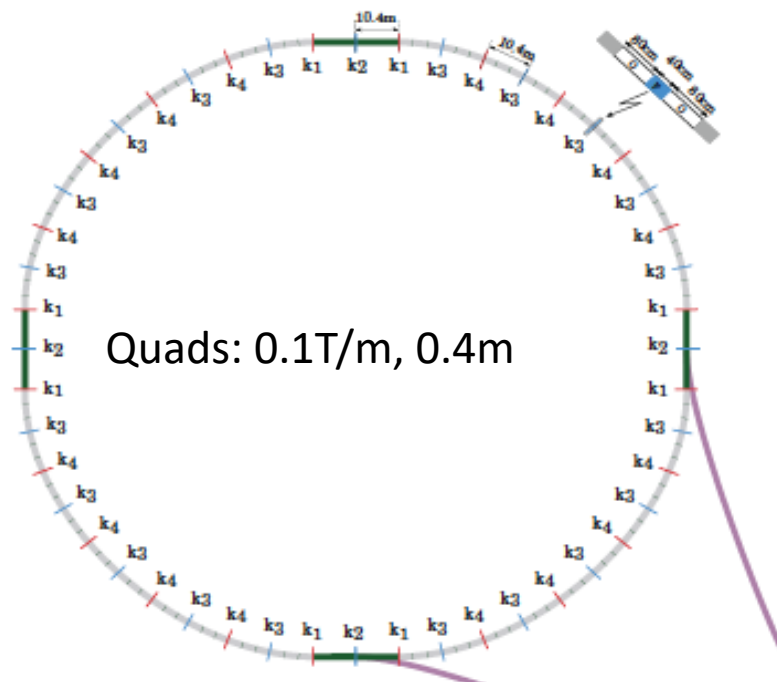


FIG. 8. *Longitudinal polarization case $S_s = 1$, CW beam only. Vertical spin precession rate vs $B_x = 1$ nT field N harmonic around the ring azimuth. The magnetic field amplitude is chosen to be similar to beam separation requirements in Sec. IV A, and more than $B_x = 1$ nT splits the CR beams too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

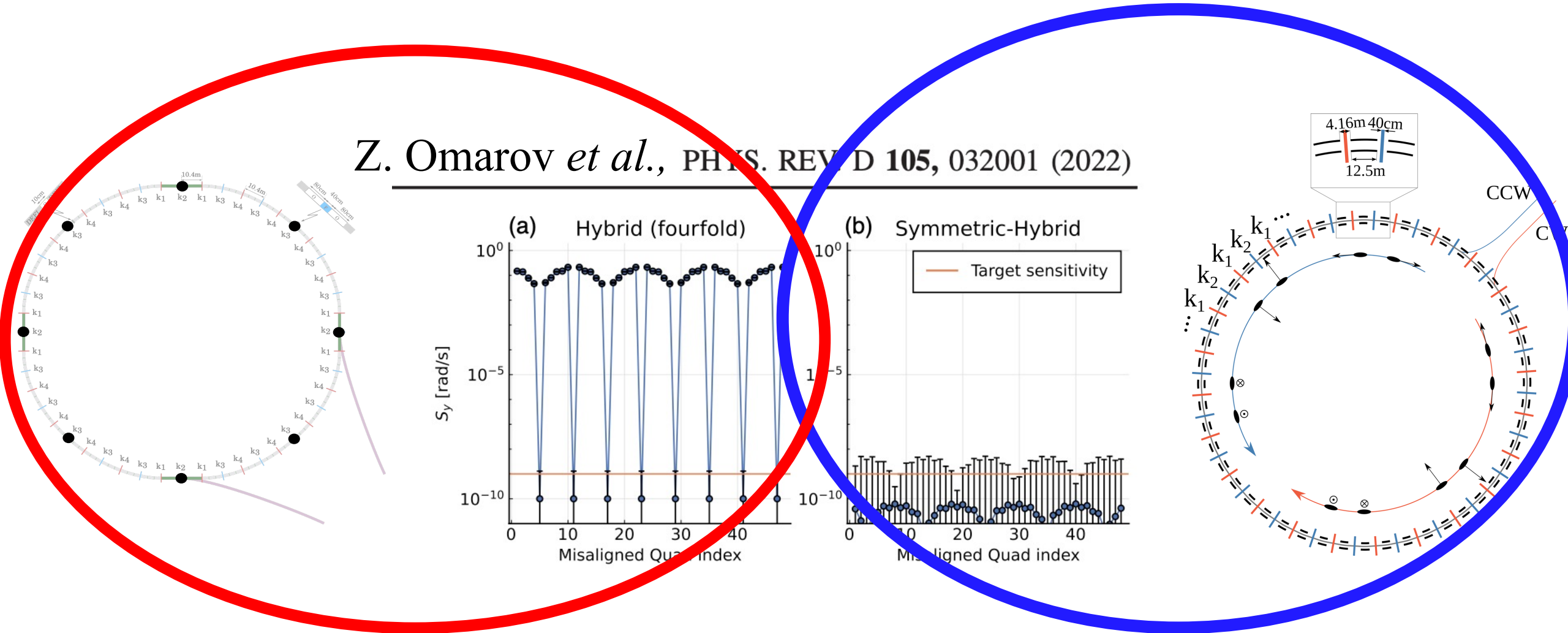
Ring planarity is important



0.1 mm

Symmetries play a critical role in combating systematic errors due to vertical velocity.

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



Radially polarized beam is shown here; sensitive to Vector Dark Matter/Dark Energy, P. Graham *et al.*, PRD, 055 010, 2021. Use longitudinally polarized bunches for sensitivity to EDM ($>10^4$ times less sensitive to vertical velocity effect).

Vertical velocity and geometrical phase effects:

Magnetic quadrupoles 0.1T/m, positioning accuracy dominates background B-fields
Mitigation by flipping quad polarity in $\sim 10^5$ separate beam injections

ZHANIBEK OMAROV *et al.*

PHYS. REV. D **105**, 032001 (2022)

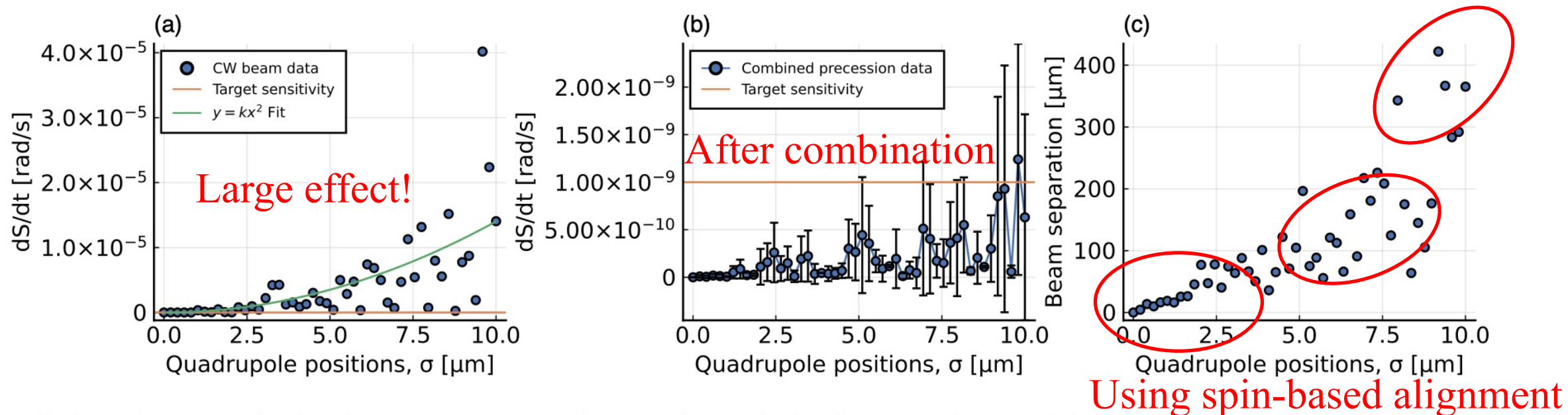
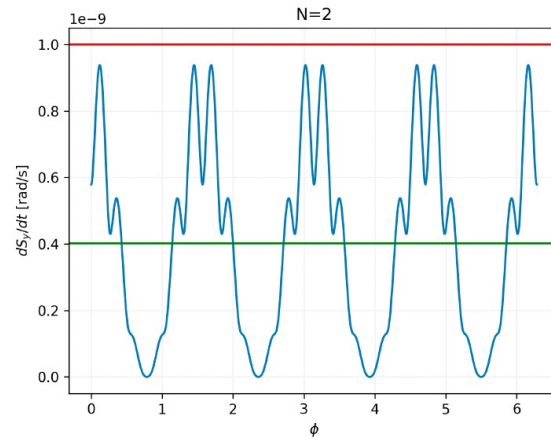
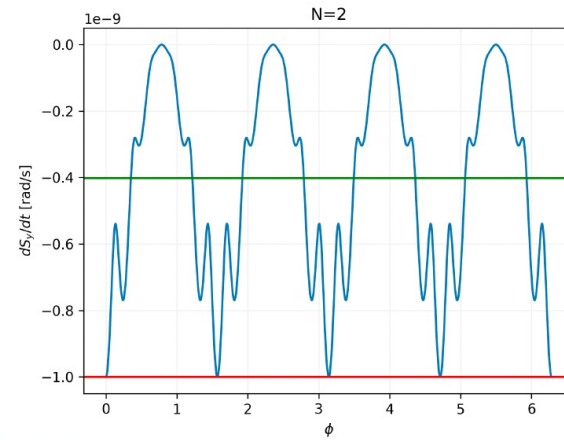


FIG. 9. (a) *Longitudinal polarization case, CW beam only.* Vertical spin precession rate (absolute) vs random misalignments of quadrupoles in both x, y directions by rms σ with different seeds per each point (when the same seeds are used everywhere, the $y = kx^2$ fit is perfect, meaning that every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

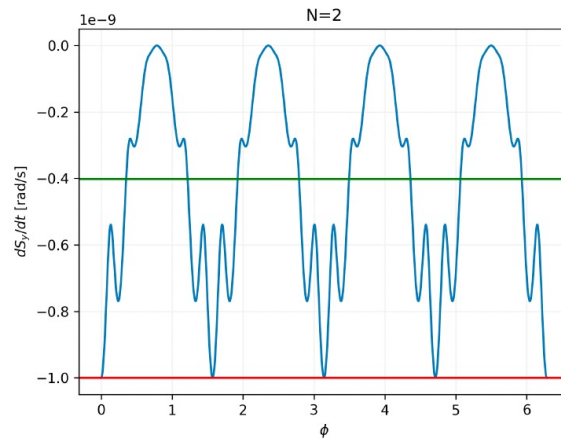
Systematic effects due to unwanted electric quadrupole fields



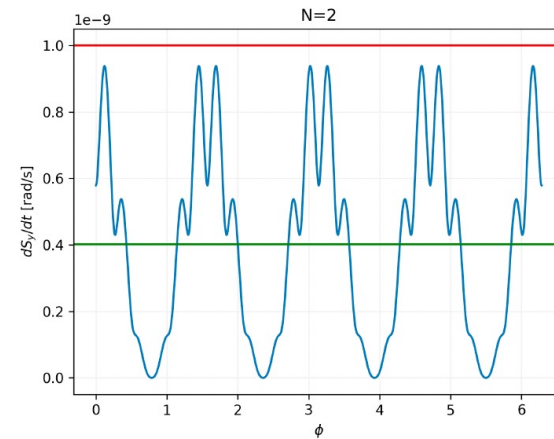
a) CW+



b) CCW+



c) CW-



d) CCW-

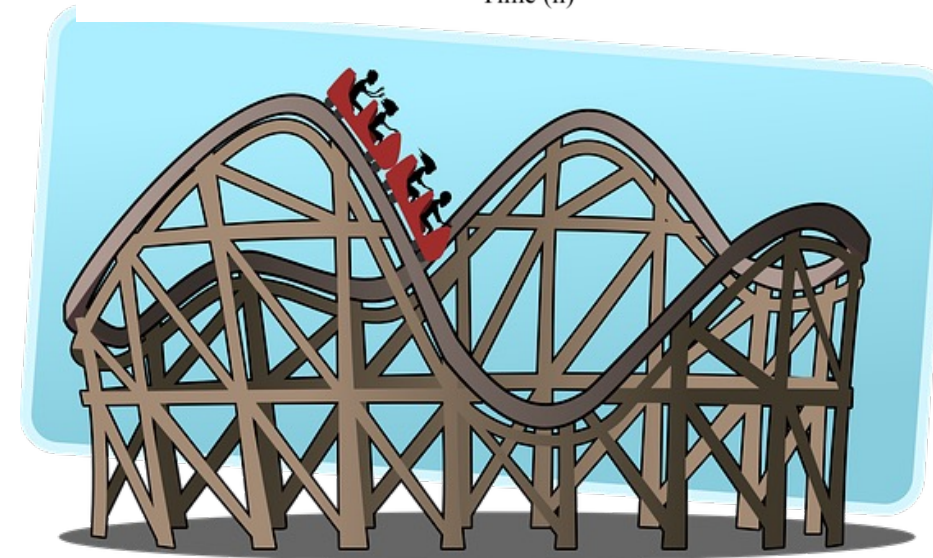
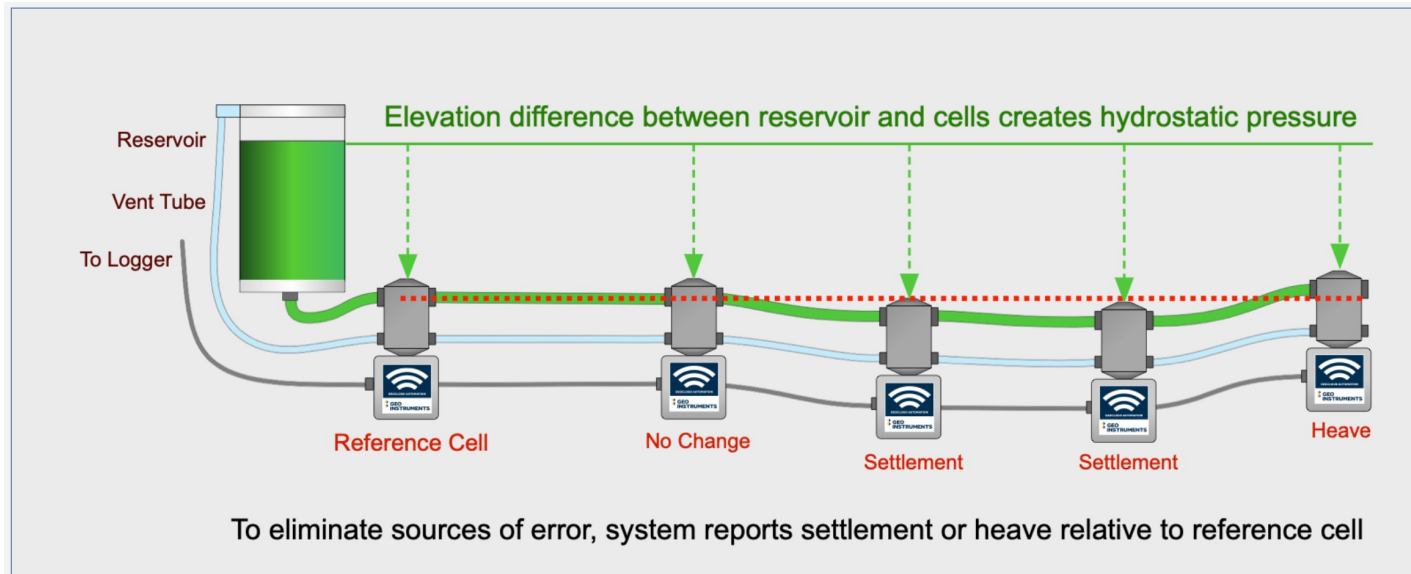
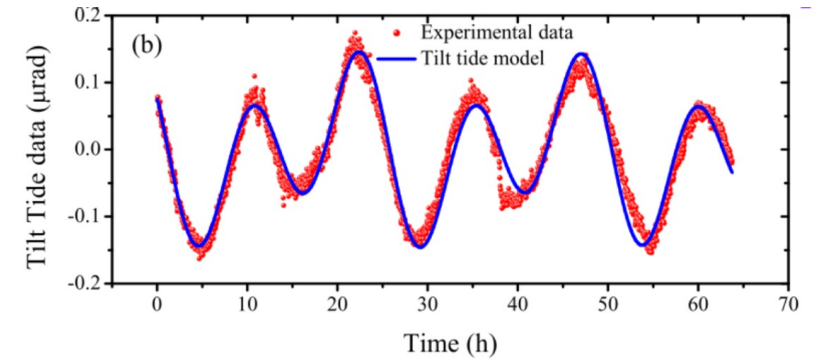
Figure: Longitudinal polarization case. Vertical spin precession rate vs $B_x = 1 \text{ nT}$ field with the presented E_y - vertical electric quadrupole field N harmonics around the ring azimuth ϕ for $N = 2$.

Jonathan Lee (SBU)
PhD thesis defense

Ring planarity critical to control geometrical phase errors

- Numerous studies on slow ground motion in accelerators, **H**ydrostatic **L**evel **S**ystem for slow ground motion studies at Fermilab.

- Thorough review by Vladimir Shiltsev (FNAL):
<https://arxiv.org/pdf/0905.4194.pdf>



3. THE HLS AT THE SWISS LIGHT SOURCE SYNCHROTRON (SLS)

For monitoring the underground of the new at the Paul Scherrer Institute (PSI), Switzerland over more than 10 years was required. As liquid was eliminated, the use of a differential pressure sensor in the half-filled pipes was chosen, where a sensor in the SLS was designed to meet the following requirements: resolution 0.0005 mm, accuracy better than 0.001 mm (Fig. 4a) is subdivided into 12 sectors, each with 16 electromagnets are mounted. Every girder in the SLS (Fig. 4b). This leads to a total amount of 192 pipes with a total length of 450 m.



Fig. 4a): Storage ring of the SLS.

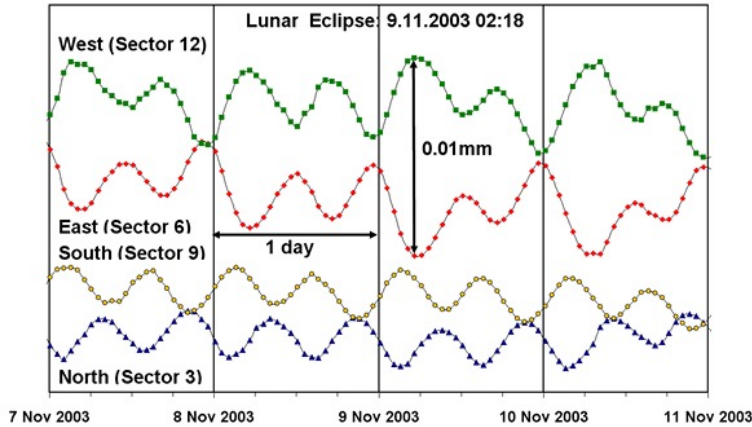


Fig. 5a): A four day period of the year 2003 with a time resolution of 1 hour. The influence of the Earth tides with 2 periods a day is clearly visible. Note the high amplitude difference between East and West during the eclipse of the moon.

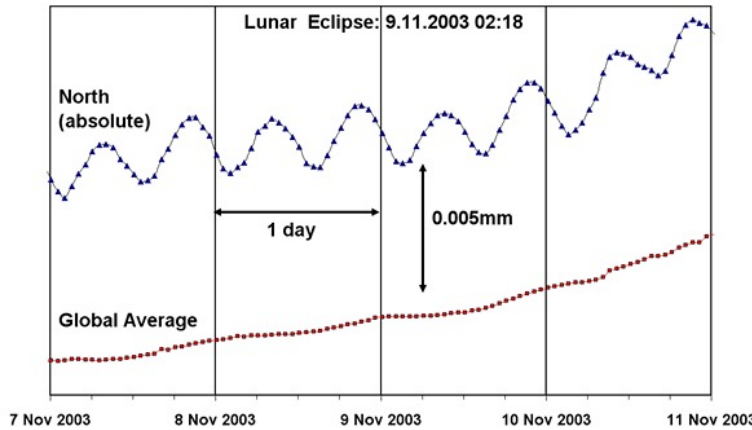


Fig. 6a): Average of the absolute values of sector north and the average value of all 192 signals, which is subtracted to balance the liquid loss.

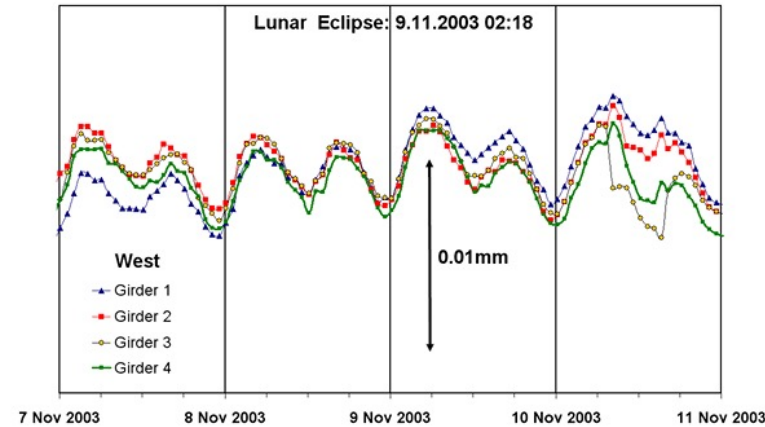


Fig. 5b): Variation of single signals in sector west. Signals of the first HLS sensor on each girder are plotted.

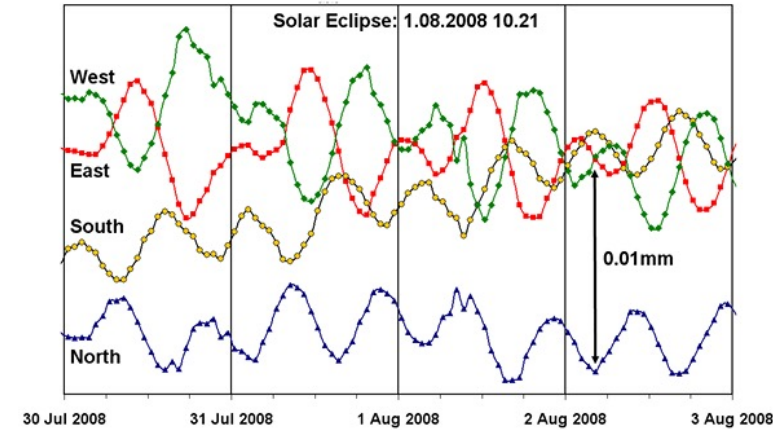
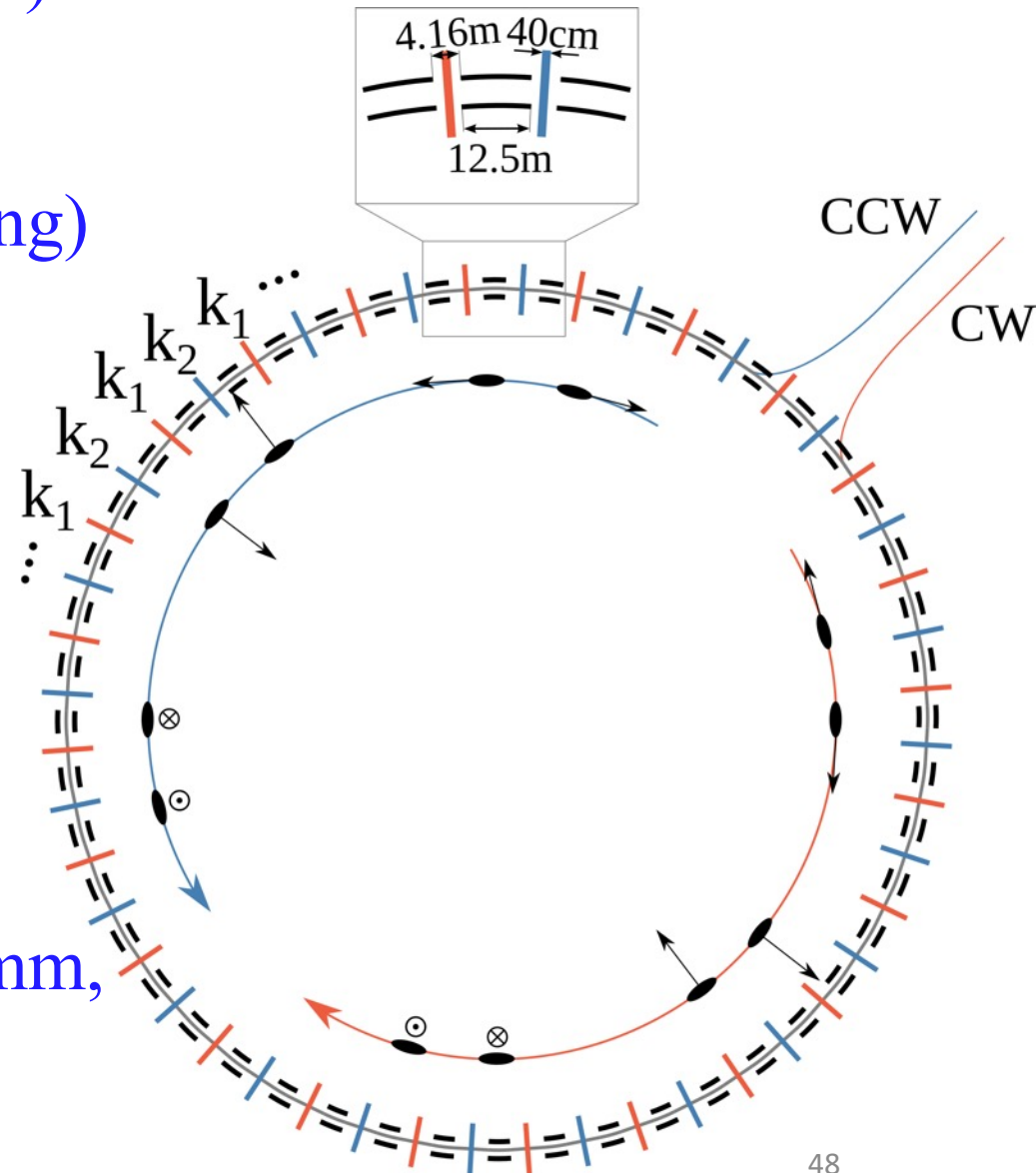


Fig. 6b): Same sensors as in Fig. 5a during a solar eclipse 5 years later. The signals are slightly more unstable, but they show good long-time stability.

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
 - Handles polarimeter systematic errors
- Flat ring to 0.1 mm, beams overlap within 0.01 mm, spin-based alignment, quad current flipping
 - Geometrical phases; High-order vertical E-fields



Spin-based alignment

- Spin-based alignment for effects that depend on combination of two or more background fields.
- Use spin of stored particles to provide information on the background fields
- Counter-act the background fields to level the ring lattice (0.1mm) and reduce the CW and CCW beam separation to the specs (0.01mm).

Spin-based alignment/background reduction

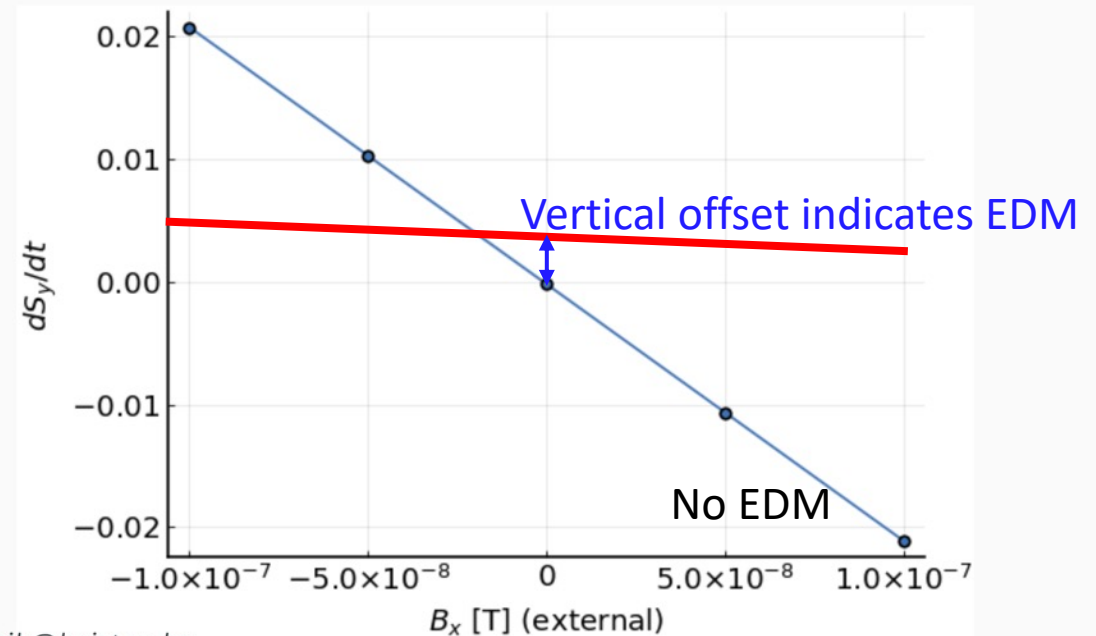
- Omarov's method: a combination of background fields can create false EDM signals. Artificially inflate one component to reduce the other.

From Zhanibek Omarov's presentation

Varying B_x

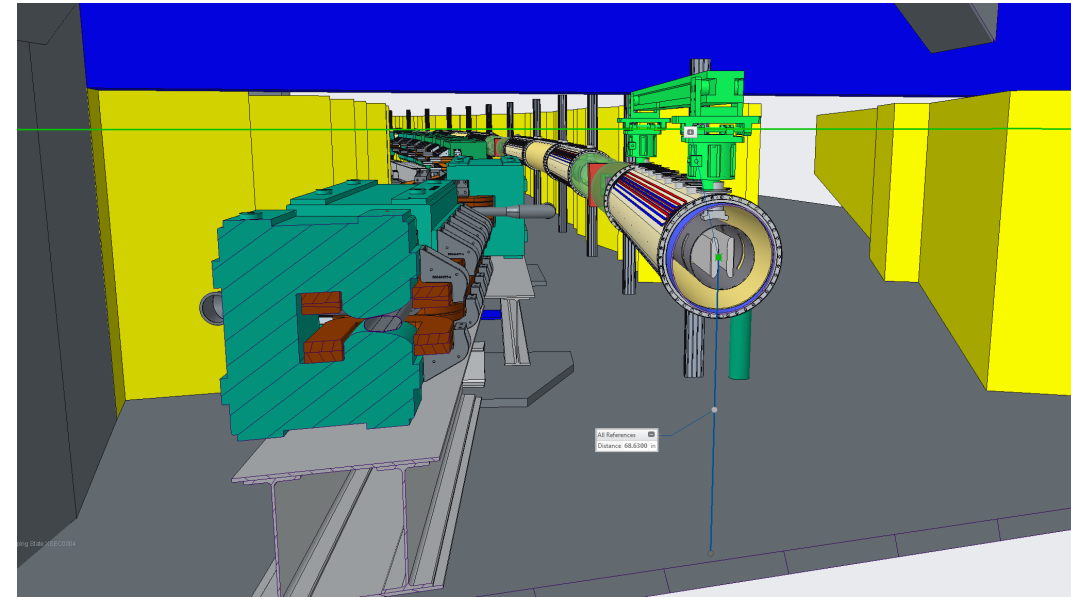
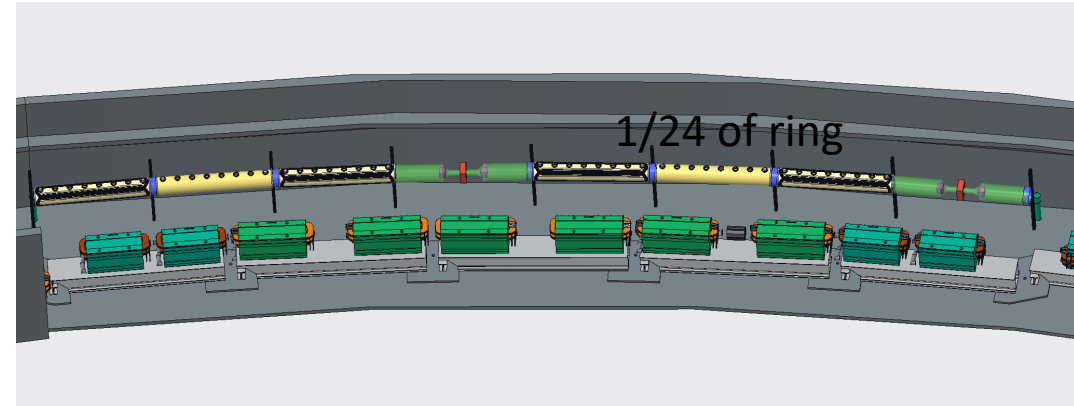
- Vary the radial B-field (B_x) and observe the ds_y/dt slope vs. B_x .
- The EDM signal does not depend on the value of B_x .
- Tune out the background field (here electric field focusing) until we get zero slope in ds_y/dt vs. B_x .

- Slope indicates m present for each N



What's next?

- BNL is funding an ongoing R&D, building one unit of the symmetric lattice for a ring in the AGS tunnel.
- Develop electric field plates with advanced coating (TiN) for high-voltage (HV). Need DC HV 4.5MV/m and low cathode current.
- Studying stochastic cooling for even better statistics experiment with large spin coherence time (SCT).
- Simulate beam/spin dynamics of thousands of protons at the same time.



Riad Suleiman's slide

Titanium Nitride (TiN) Coated Aluminum Electrodes

- A. Mamun *et al.*, "TiN coated aluminum electrodes for DC high voltage electron guns", *Journal of Vacuum Science & Technology A* **33**, 031604 (2015)

TABLE I. Relevant characteristics of candidate electrode materials at room temperature.

Material	Work function ϕ (eV)	Thermal conductivity (W/m K)	Electrical resistivity ($\mu\Omega$ cm)	Hardness (GPa)	Elasticity modulus (GPa)	Density (g/cc)
SS316L	4.5 (Ref. 5)	16.3 (Ref. 6)	74 (Ref. 3)	1.5 (Ref. 6)	193 (Ref. 6)	8.0 (Ref. 6)
Niobium	4.3 (Ref. 7)	52 (Ref. 8)	14 (Ref. 8)	1.3 (Ref. 8)	104 (Ref. 8)	8.6 (Ref. 8)
Molybdenum	4.6 (Ref. 7)	142 (Ref. 8)	5.7 (Ref. 8)	2.2 (Ref. 8)	310 (Ref. 8)	10.9 (Ref. 8)
Ti-6Al-4V	4.5 (Ref. 1)	6.7 (Ref. 9)	178 (Ref. 9)	3.4 (Ref. 9)	114 (Ref. 9)	4.4 (Ref. 9)
Al6061	3.5 (Ref. 10)	167 (Refs. 9 and 11)	4 (Refs. 9 and 11)	1.47 ^a	70 ^a	2.7 (Refs. 9 and 11)
TiN coating	5.0 (Ref. 12)	11–67 (Ref. 13)	14 (Ref. 13), 270 (Ref. 14)	18.2 ^a	270 ^a	3.3 (Ref. 13)

^aProperties of ion-beam enhanced deposition grown TiN coating on Al were measured in the present work.

- Aluminum electrodes were manufactured from Al6061 alloy
- Aluminum electrodes required only hours of mechanical polishing using silicon carbide paper
- Coating is about 2.5 μm thick
- Baked at 200°C for 30 hours and achieved 10⁻¹¹ Torr

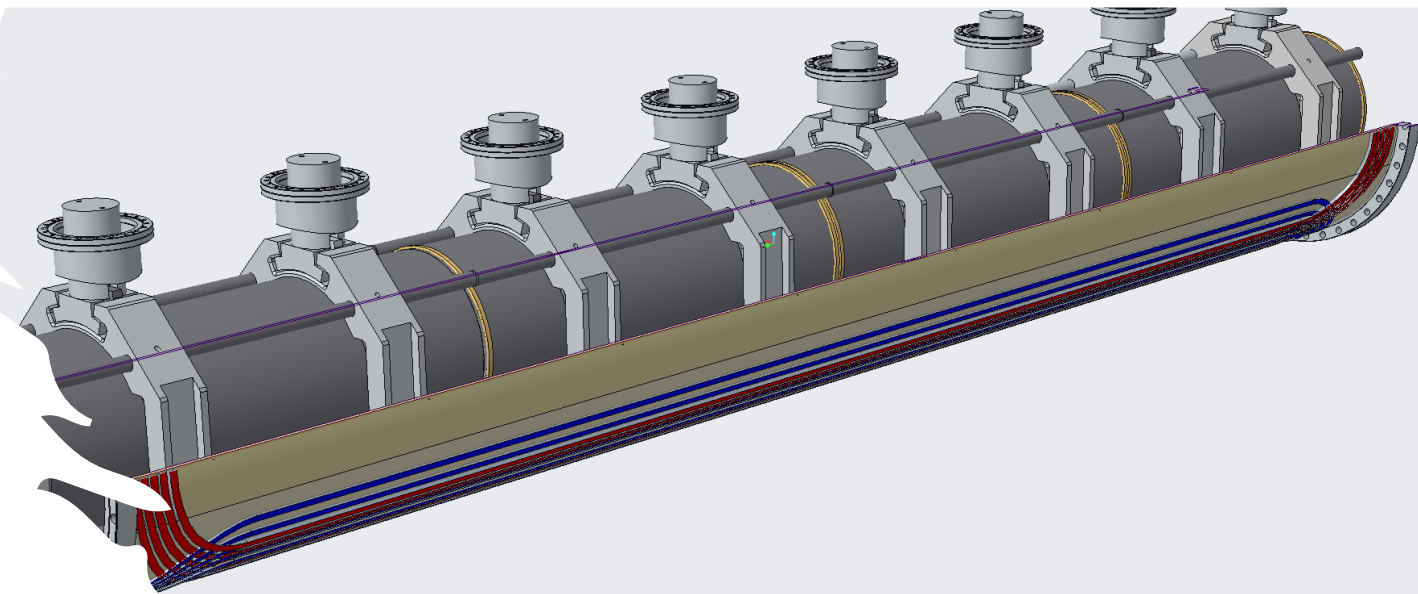
LDRD work, building 1 E-bending sector, CDR by end of 2026

- HV measurements, requiring 4.5MV/m, tested at 5MV/m and measuring spark rate
- Dark current, can live with $<1\mu\text{A}$, targeting $<1\text{nA}$ for every 1m section
- Vacuum requirements, 10^{-10} Torr a few hundred of seconds beam lifetime from IBS
- Stochastic cooling, reduce gas-pressure requirement, 'infinite' SCT, prolong storage time
- Control shape of fringe fields
- Ability to apply fields for probing geometric phase effects (combination of two fields)
- Probe and cancel electric focusing
- Study lattice impedance issues
- Alignment stability, make sure fields rotate locally within specs
- Equipment cross-compatibility, cross-talk
- Spin/beam dynamics simulation of $\sim 10^3$ particles at a time by multiple teams

Electric field plates made with sub-micron finish, at Liverpool University.



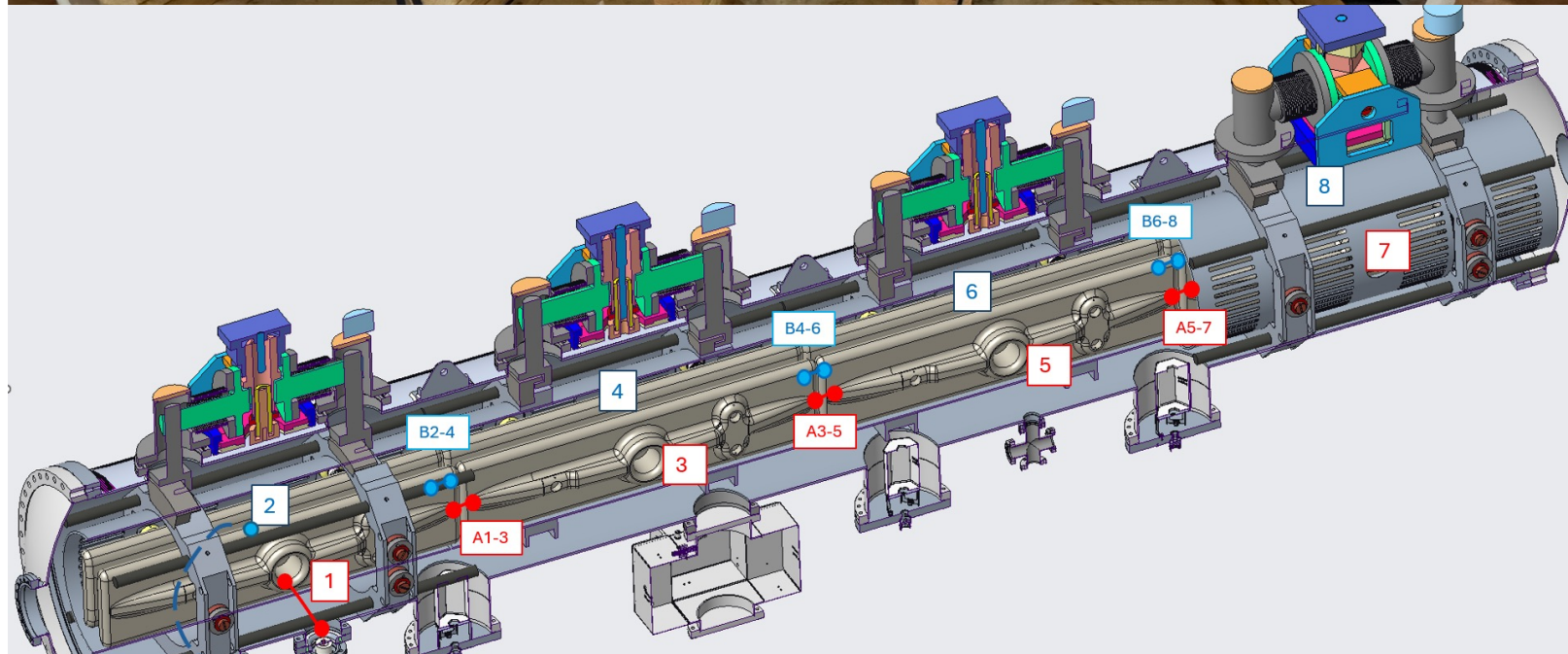
Liverpool University is designing the plates, and their support. Involved in their construction, high accuracy electric field estimations, methods to minimize high-order fields...



4m “Deflection” chamber, partial section, at BNL.



Liverpool University
1m long unit plate



Storage ring proton EDM at 10^{-29} e-cm at BNL

- Statistics for better than 10^{-29} e-cm for pEDM, $\sim 10^3$ TeV New-Physics reach
- Matching systematic error levels, controlled by symmetries
- Build with a facility in mind
 - Proton EDM, simultaneous CW and CCW storage
 - Deuteron EDM (hybrid lattice, E-field direction stability within 20 minutes is very strict)
 - ^3He EDM (neutron equivalent) and if needed pEDM with a hybrid lattice (better statistical sensitivity, much more demanding on systematics)

Hybrid, symmetric lattice storage ring PRD105, 032001 (2021)

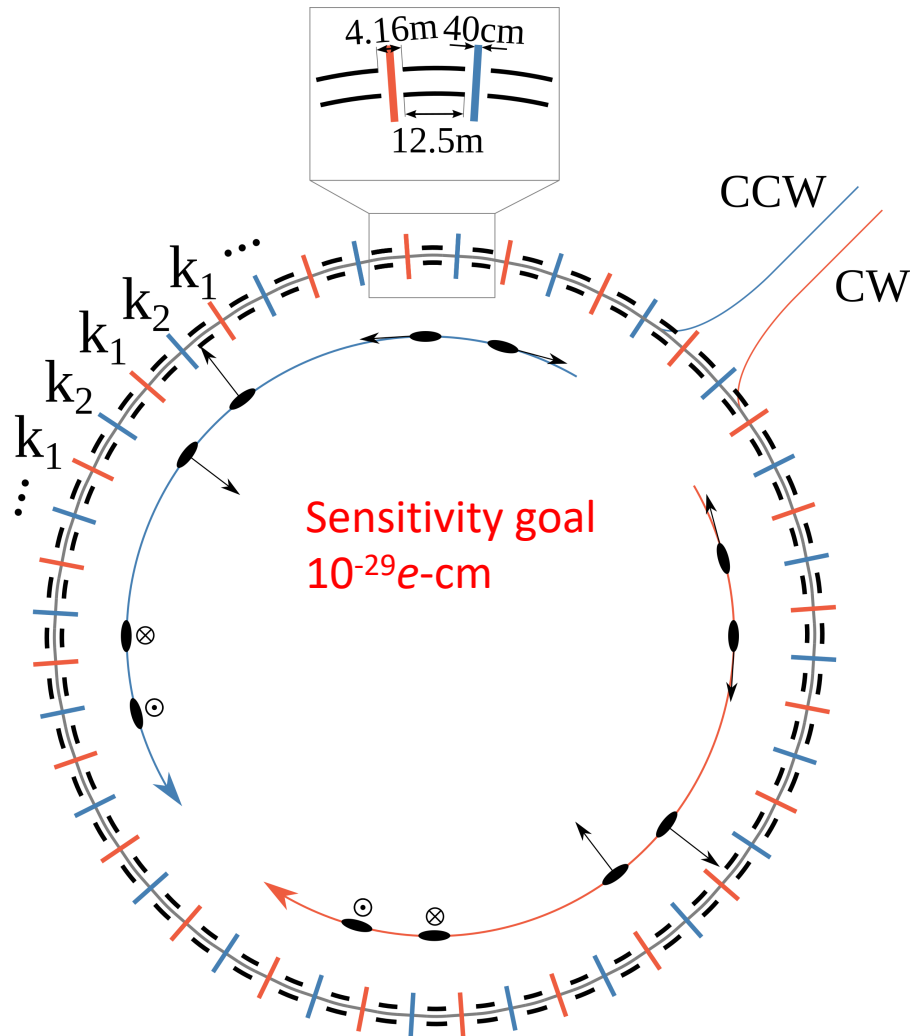


TABLE I. Ring and beam parameters for Symmetric Hybrid ring design

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 μ s
$\beta_x^{\max}, \beta_y^{\max}$	64.54 m, 77.39 m
Dispersion, D_x^{\max}	33.81 m
Tunes, Q_x, Q_y	2.699, 2.245
Slip factor, $\eta = \frac{dt}{t} / \frac{dp}{p}$	-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, $\Delta p/p_{\text{bucket}}$	3.77×10^{-4}
Bucket length	10 m
RMS bunch length, σ_s	0.994 m

Low risk



Strong focusing



The storage ring pEDM exp. at 10^{-29} e-cm

- ✓ Required radial E-field < 5 MV/m, for 40mm plate separation
- ✓ Beam and spin dynamics stable for required beam intensity
- ✓ Spin coherence time $> 10^3$ s using sextupoles, no stochastic cooling (SC).
- ✓ With SC, SCT $\rightarrow \infty$

The srEDM exp. at 10^{-29} e-cm

- ✓ Alternate magnetic focusing all but eliminates external B-field sensitivity
- ✓ Symmetric lattice significantly reducing systematic error sources
- ✓ Required ring planarity $<0.1\text{mm}$; CW & CCW beam separation $<0.01\text{mm}$
- ✓ Geometrical phases require a combination of two unwanted fields. Enhance one to probe and reduce the other.

References

1. S. Karanth *et al.*, First search for axionlike particles in a storage ring using polarized deuteron beam, *Phys. Rev. X*13, 031004 (2023)
2. Z. Omarov *et al.*, Comprehensive Symm.-Hybrid ring design for pEDM experiment at below $10^{-29}e\text{-cm}$, *Phys. Rev. D* 105, 032001 (2023)
3. P.W. Graham *et al.*, Storage ring Probes for Dark Matter and Dark Energy, *Phys. Rev. D* 103 (2021) 5, 055010
4. S. Haciomeroglu and Y.K. Semertzidis, Hybrid ring design in the storage-ring proton EDM experiment, *Phys. Rev. Accel. Beams* 22 (3), 034001 (2019)
5. S.P. Chang *et al.*, Axionlike dark matter search using the storage ring EDM method, *Phys. Rev. D* 99 (8), 083002 (2019)
6. S. Haciomeroglu *et al.*, SQUID-based Beam Position Monitor, *PoS ICHEP2018* (2019) 279
7. N. Hempelmann *et al.*, Phase locking the spin precession in a storage ring, *Phys. Rev. Lett.* 119 (1), 014801 (2017)
8. G. Guidoboni *et al.*, How to reach a Thousand-second in-plane Polarization Lifetime with 0.97 GeV/c Deuterons in a storage ring, *Phys. Rev. Lett.* 117 (5), 054801 (2016)
9. V. Anastassopoulos *et al.*, A storage ring experiment to detect a proton electric dipole moment, *Rev. Sci. Instrum.* 87 (11), 115116 (2016)
10. E.M. Metodiev *et al.*, Analytical benchmarks for precision particle tracking in electric and magnetic rings, *NIM A*797, 311 (2015)
11. E.M. Metodiev *et al.*, Fringe electric fields of flat and cylindrical deflectors in electrostatic charged particle storage rings, *Phys. Rev. Accel. Beams* 17 (7), 074002 (2014)
12. W.M. Morse *et al.*, rf Wien filter in an electric dipole moment storage ring: The “partially frozen spin” effect, *Phys. Rev. Accel. Beams* 16 (11), 114001 (2013)
13. N.P.M. Brantjes *et al.*, Correction systematic errors in high-sensitivity deuteron polarization measurements, *Nucl. Instrum. Meth. A*664, 49 (2012)
14. G.W. Bennett *et al.*, An improved limit on the muon electric dipole moment, *Phys. Rev. D* 80, 052008 (2009)
15. F.J.M. Farley *et al.*, A new method of measuring electric dipole moments in storage rings, *Phys. Rev. Lett.* 93, 052001 (2004)
16. ...

Why COSY/Jülich mattered for storage-ring EDM R&D

Although the conceptual foundations of storage-ring EDM physics were developed at BNL and elsewhere, COSY/Jülich was the place where key hardware and beam methods were actually tested and validated

1. Polarimeter systematics studied below 10ppm
 2. Spin coherence times $>10^3$ s achieved with polarized deuterons
 3. Spin tune stability better than 10^{-9} over hours demonstrated
 4. Polarization-direction feedback established (“windshield-wiper effect”)
 5. First hadronic axion dark matter search in a storage ring performed
 6. First hadronic (deuteron) EDM probing in a storage ring carried out
- ...

COSY is now gone-a real loss for the field

But the scientific opportunity remains, and new labs can now step in and lead.

Exciting development: The very first frozen spin storage ring EDM measurement for the muon at PSI!



Injection and statistical sensitivity

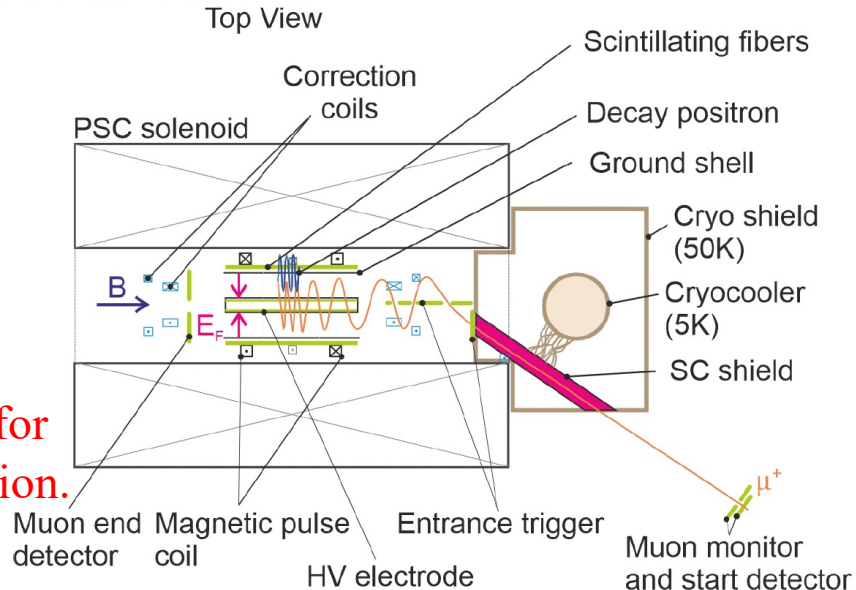


- Large phase space at exit of beam, collimated by passage through SC -shield
- Due to adiabatic magnetic collimation large part of transmitted μ^+ are reflected.
- Simulations show, only about 0.4×10^{-3} muons can be stored

$$\sigma(d_\mu) = \frac{\hbar}{2Pc\beta\gamma B\sqrt{N} \tau_\mu \alpha}$$

Slide by Philipp Schmidt-Wellenburg.

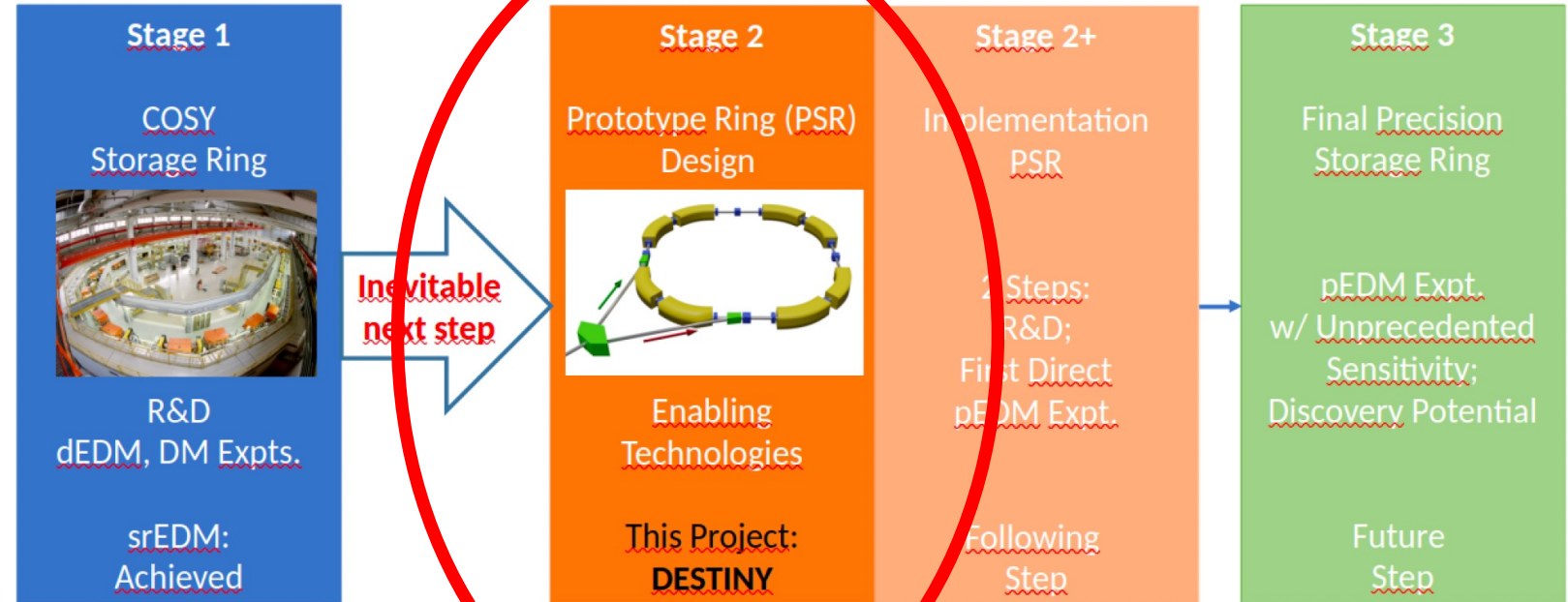
Uses CW vs. CCW injections plus spin flips for systematic error suppression.



	$\pi E1$ "28 MeV/c"	$\mu E1$ "125 MeV/c"
Muon flux (μ^+/s)	4×10^6	1.2×10^8
Channel transmission	0.03	0.005
Injection efficiency	0.004	0.60
Muon storage rate (1/s)	5×10^2	360×10^3
Gamma factor γ	1.024	1.56
e^+ detection rate (1/s)	400	90×10^3
Detections per 200 days	5.8×10^9	1.5×10^{12}
Mean decay asymmetry A	0.32	0.32
Initial polarization P_0	0.95	0.95
Sensitivity in one year ($e \cdot cm$)	$< 4 \times 10^{-21}$	$< 6 \times 10^{-23}$

A proposal for hadronic EDM storage ring: DESTINY, by Paolo Lenisa, Ferrara

Requesting support to develop the tools to study, design and next to build a prototype storage ring EDM



Baryon Asymmetric Universe
BSM CP Violation

Static EDMs
of Fundamental Particles

Charged Particles (Proton, Deuteron):
Time Development of the Spin Direction of a Beam of Polarized Particles
in a Precision Storage Ring

Dark Matter in Universe
BSM Particles (Axions, ALPs)

Oscillating EDMs
of Fundamental Particles

Storage-Ring EDM: A Ready, High-Impact Opportunity

- Physics Case
 - Direct probe of CP violation → sensitivity to BSM and axion physics
 - Clean, discovery-level observable with strong theoretical motivation
- Technical Readiness
 - Hybrid symmetric lattices → built-in systematics suppression
 - High-precision simulation demonstrated path to $\sim 10^{-29} e\cdot\text{cm}$ sensitivity
 - Long SCT + large acceptance → statistics-dominated regime
 - Realistic tolerances: planarity < 0.1 mm, CW/CCW separation < 0.01 mm
- Program Power
 - One ring → p, d, ^3He EDMs
 - Strong synergy with collider programs (e.g. EIC)
 - Compelling, long-term program for young scientists
- Bottom Line
 - Copy COSY model: staged storage-ring R&D → full experiment

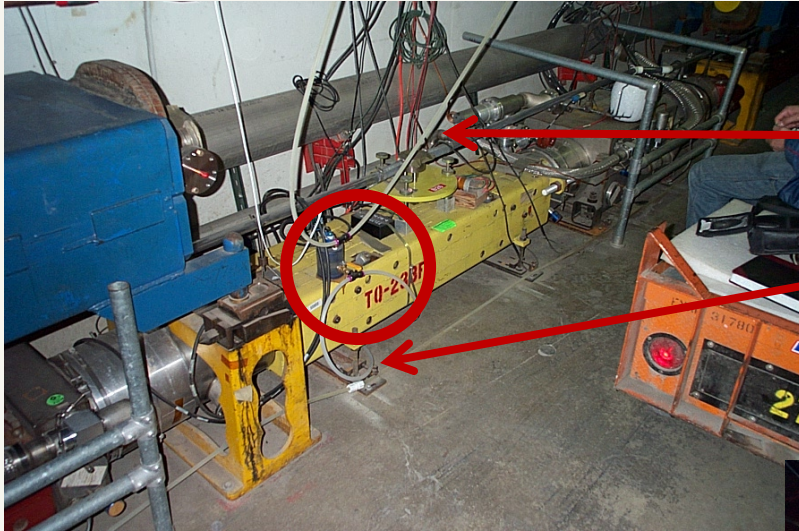
Extra slides

Summary

- ✓ EDM physics is must do, exciting and timely, CP-violation, axion physics.
- ✓ Hybrid, symmetric ring lattice works well. Minimized systematic error sources. Statistics and systematics to $10^{-29}e\text{-cm}$. Recent PhD work confirmed studies by independent tools and gave insight into the symmetry workings.
- ✓ pEDM lattice with “infinite” SCT and large acceptance provides the statistics
- ✓ Ring planarity $<0.1\text{mm}$, CW & CCW beam separation $<0.01\text{mm}$
- ✓ Great complementarity between collider and high-precision physics!

- ✓ The same ring can be used for the deuteron, and ^3He nuclei EDM too. Great Physics program for young people to be done in less than 20 years (Alex K.)

Tevatron Sensors on Quad



Air Line

Water line

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

James T Volk May 2009



Quadrupole at E 11 During Quench

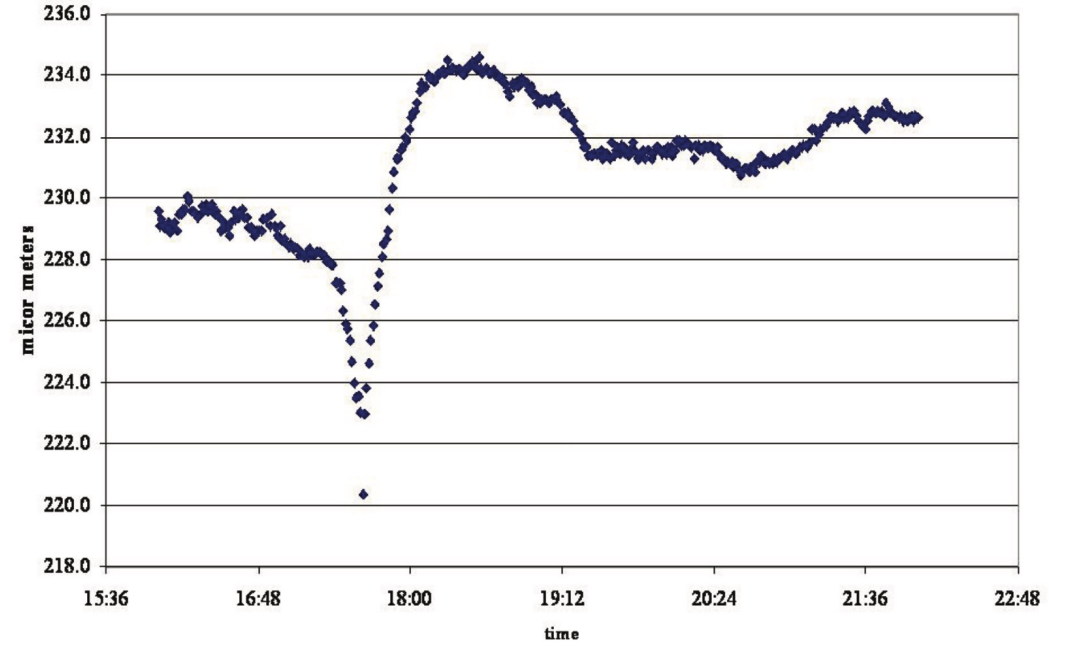


Figure 6 Quench near Quadrupole E11

3. THE HLS AT THE SWISS LIGHT SOURCE SYNCHROTRON (SLS)

For monitoring the underground of the new built storage ring of the Swiss Light Source (SLS) at the Paul Scherrer Institute (PSI), Switzerland, highest resolution and long-term stability over more than 10 years was required. As liquid loss over such long periods cannot be eliminated, the use of a differential pressure system was not suitable. Thus, the principle of the half-filled pipes was chosen, where a slow liquid loss is irrelevant. The HLS installed at the SLS was designed to meet the following specifications: measuring range 14 mm, resolution 0.0005 mm, accuracy better than 0.01 mm. The storage ring of the synchrotron (Fig. 4a) is subdivided into 12 sectors, each containing four girders on which the focusing electromagnets are mounted. Every girder is monitored by four installed level sensors (LS) (Fig. 4b). This leads to a total amount of 192 LS, which are linked together by half-full steel pipes with a total length of 450 m.

HLS at the Swiss Light Source Synchrotron



Fig. 4a): Storage ring of the SLS.

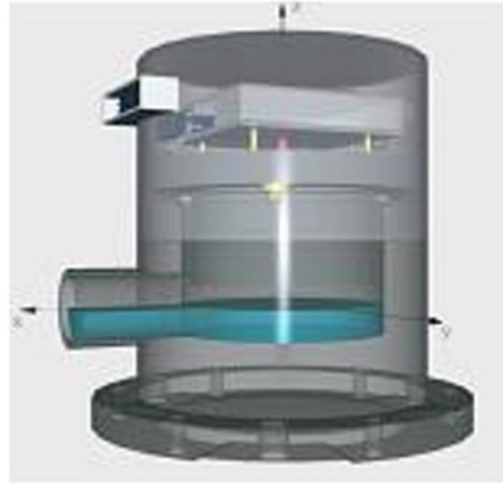


Fig.4b): HLS level sensor.



Figure 8a: Synchrotron Swiss Light Source SLS at the Paul Scherrer Institute, Switzerland, near the German border and near the river Aare.

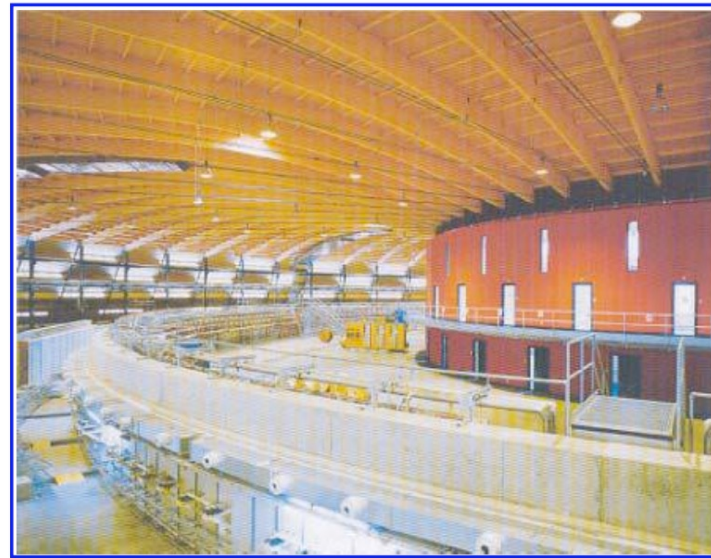


Figure 8b: Storage ring of the SLS during construction.

HLS at the Swiss Light Source Synchrotron

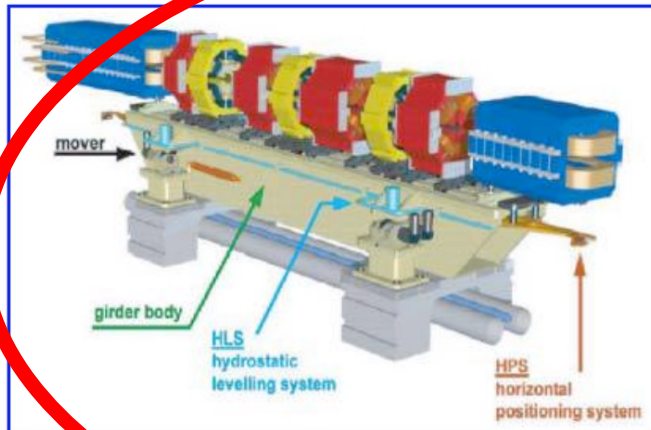


Figure 9a: Girder body carrying the electromagnets. The movers are intended to move the whole girder in order to re-adjust the electromagnets. The girder movement is monitored by the HLS.



Figure 9b: Level sensor (LS) mounted on the girder. Below it an eccentric cam disc is visible.

Proton edm SR goal: $d_p \sim 10^{-29} \text{e-cm}$
Improvement by more than 4 orders!
Sensitivity similar to $d_e < 10^{-30} \text{e-cm}$

In a renormalizable quantum field theory, at
lowest order $d_p = 0$ (No dim. 5 operators)

$d_p \sim em / \Lambda_{\text{NP}}^2 \sin \phi^{\text{NP}}$ quantum loop induced

Λ_{NP} scale of “new physics”

ϕ^{NP} = Complex CP violation phase of New Physics

phase misalignment with m_p

$\sim 10^{-22} (1 \text{TeV} / \Lambda_{\text{NP}})^2 \sin \phi^{\text{NP}} \text{e-cm}$

If ϕ^{NP} is of $O(1)$, $\Lambda_{\text{NP}} \sim \underline{3000 \text{TeV}}$ Probed! (very roughly)

If $\Lambda_{\text{NP}} \sim O(1 \text{TeV})$, $\phi_{\text{NP}} \sim 10^{-6}$ Probed!

a_f vs d_f (very roughly)

- Two loop Higgs contribution: $a_\mu(H) \approx \text{few} \times 10^{-11}$
Both **Unobservably Small** $a_e(H) \approx 5 \times 10^{-16}$

EDM Higgs contribution: $d_e(H) \approx 10^{-26} \sin\phi$ e-cm

$$|d_n(H)| \approx |d_p(H)| \approx 3 \times 10^{-25} \sin\phi \text{ e-cm}$$

Already d_e bound implies $\sin\phi_e \leq 0.002$ (smaller?)

Altmannshofer, Brod, Schmaltz JHEP (updated)

CP violation in $BR(H \rightarrow \gamma\gamma)$ $\gamma\gamma$ Collider?

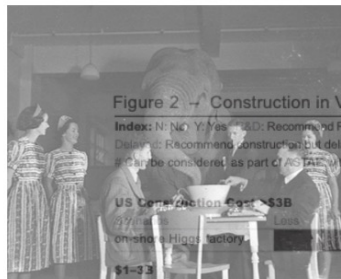
Unlikely to be observable, but edm experiments can

Explore down to $\tan\phi \approx O(10^{-4})$! Unique!

P5 didn't rank it well despite the excellent Snowmass endorsement!

pEDM Experiment: funding and timeline

Alex Keshavarzi's slide



Recent P5 report was not good for proton EDM at BNL

Figure 2 - Construction in Various Budget Scenarios

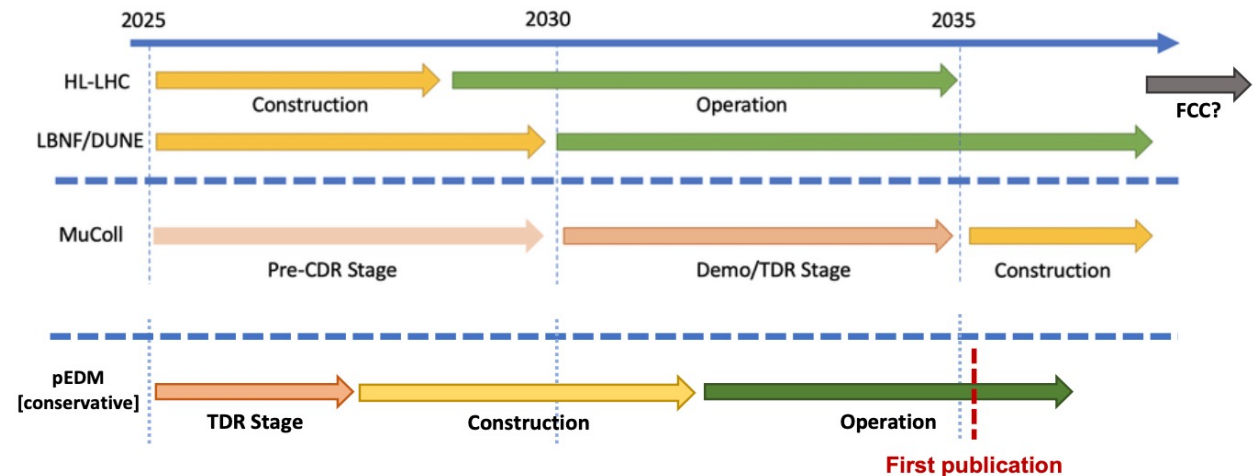
Index: N: No; Y: Yes; R&D: Recommended R&D but no funding for project; C: Conditional yes based on review; P: Primary; S: Secondary
Delayed: Recommend construction but delayed to the next decade
N/A: Not to be considered as part of the panel with reduced scope

	Baseline	More	Neutrinos	Higgs	Dark Matter	Evolution	Chronic	Direct	Quantum	Astronomy & Astrophysics
US Completion Report #33B										
off-shore Higgs factory	Delayed									
ACE-BR	R&D	R&D	C	P	S			P	P	
\$400-1000M										
CMB-S4	Y	Y	Y	S	S	P				P
Spec-S5	R&D	R&D	Y	S	S	P				P
\$100-400M										
IceCube-Gen2	Y	Y	Y	P	S					P
G3 Dark Matter 1	Y	Y	Y	S		P				
DUNE FD3	Y	Y	Y	P				S	S	S
test facilities & demonstrator	C	C	C		P	P		P	P	
ACE-MIRT	R&D	Y	Y	P						
DUNE FD4	R&D	R&D	Y	P				S	S	S
G3 Dark Matter 2	N	N	Y	S		P				
Muon Collider	R&D	R&D	R&D							P
srEDM	N	N	N				S?	S?		P
\$60-100M										
SURF Expansion	N	Y	Y	P		P				
DUNE MCND	N	Y	Y	P				S	S	
MATHUSLA #	N	N	N			P		P		
FPF #	N	N	N	P		P		P		

Report of the 2023 Particle Physics Project Prioritization Panel

- U.S. labour costs – cost engineering underway.
 - Realistic savings already identified!
- May be substantially cheaper if constructed in UK/Europe!

Muon Collider Forum Report, arXiv:2209.01318 (2022).

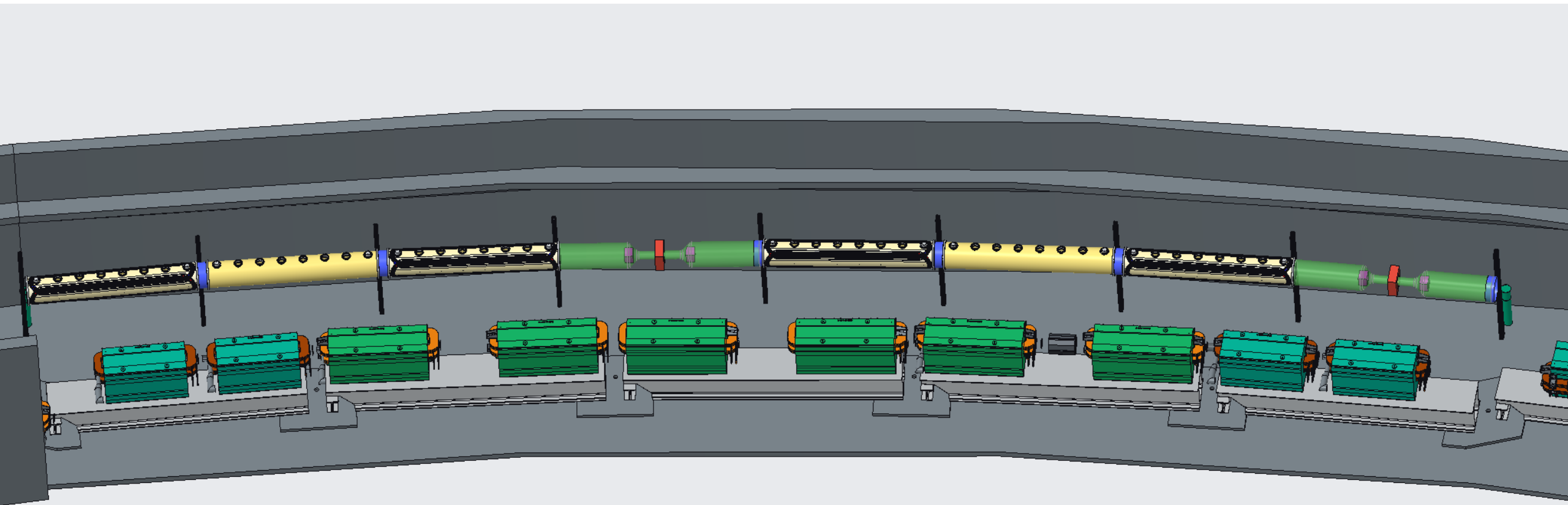


- From TDR to final publication in < 20 years.
- Can be started and finished by the new generation.
- Paramount physics drivers:
 - Solve strong CP problem.
 - Baryon asymmetry.
 - Dark matter.

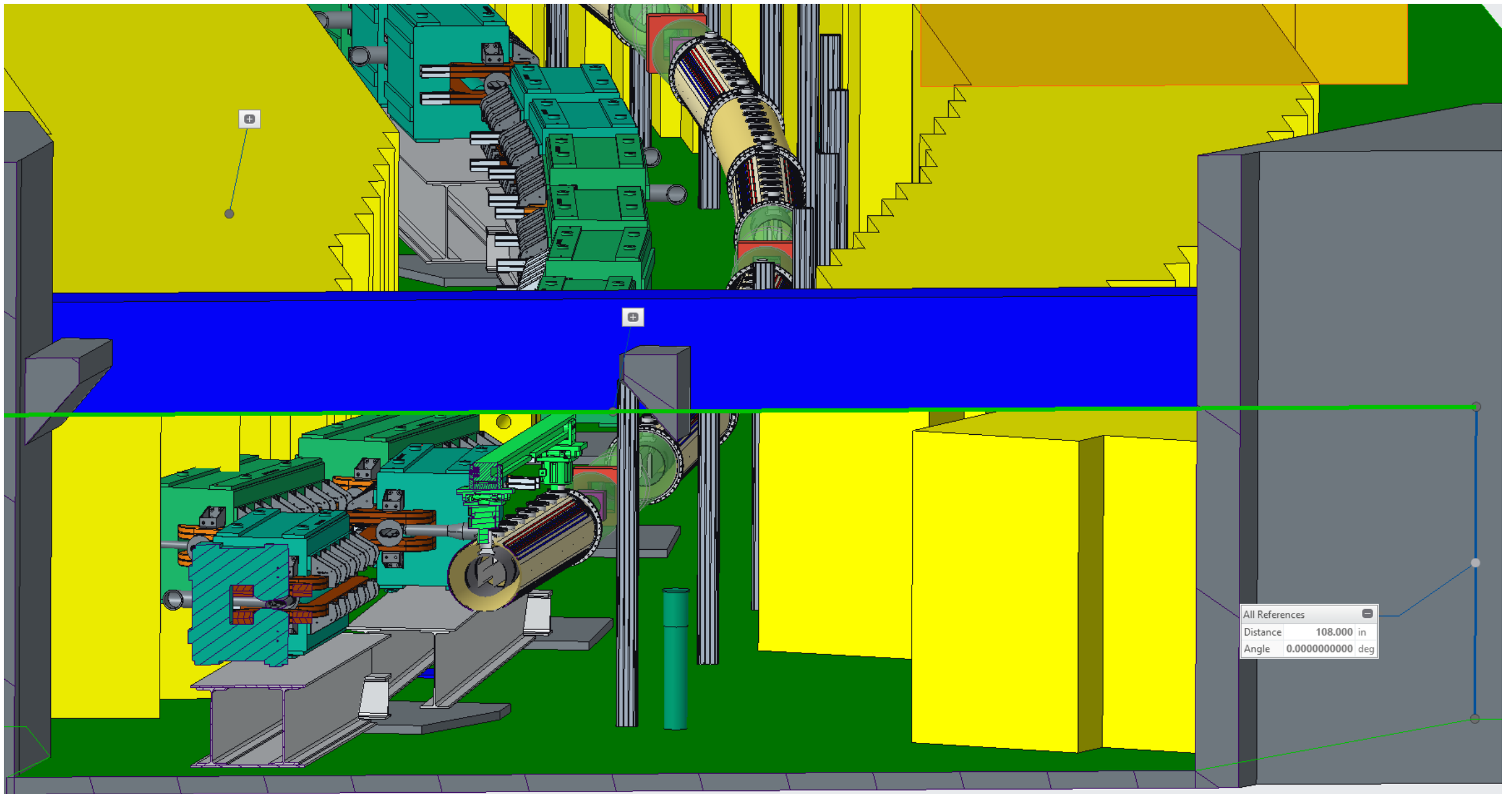
Arguably one of the most low-cost/high-return proposals in particle physics today!

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





1/24 section (15°) of pEDM ring



Section at F20 experimental blockhouse
Note: ceiling elevation = 108" (9'-0")

Classification of systematic errors at 10^{-29} e-cm

- ✓ Alternate magnetic focusing allows simultaneous CW & CCW storage and shields against external B-fields. Vertical dipole E-fields eliminated (major syst. err. source), its own “co-magnetometer”; unique feature of this lattice.
- ✓ Symmetric lattice significantly reduces systematic errors associated with vertical velocity (major syst. err. source). Additionally, using longitudinal, radial and vertical polarization directions, monitor potential systematic error sources.
- ✓ Required ring planarity $<0.1\text{mm}$; CW & CCW beam separation $<0.01\text{mm}$, resolves issues with geometrical phases

Storage ring probes of DM/DE

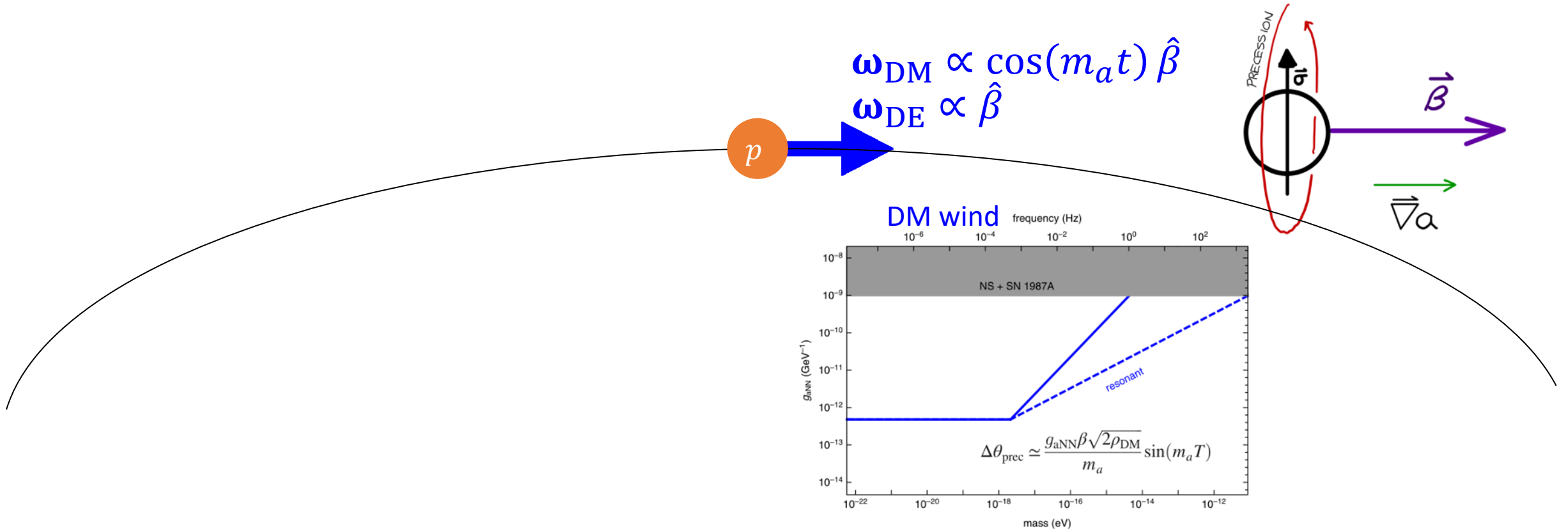
- Couplings with dark matter (DM) and dark energy (DE)

P. Graham and S. Rajendran, PRD **88**, 035023 (2013)

P. Graham et al., PRD **103**, 055010 (2021)

- ALP or vector DM wind ($g_{aNN} \nabla a \cdot \hat{\sigma}_N$) \Rightarrow anomalous longitudinal oscillating B field.
- DE wind \Rightarrow anomalous longitudinal B field.

Storage ring is an optimal probe for wind coupling since β is large!



Storage ring probes of DM/DE


- Couplings with dark matter (DM) and dark energy (DE)

o **ALP DM-EDM** ($g_{aN\gamma} a \hat{\sigma}_N \cdot \mathbf{E}$) \Rightarrow oscillating EDM at m_a . For the QCD axion: $d_N^{\text{QCD}} \approx 10^{-34} \cos(m_a t) e \cdot \text{cm}$.

P. Graham and S. Rajendran, PRD **88**, 035023 (2013)

P. Graham et al., PRD **103**, 055010 (2021)

First experimental application at COSY 2019-2022

$$\omega_{\text{axion-EDM}} \propto \cos(m_a t) \hat{x}$$


The diagram shows a particle labeled 'p' in a circular storage ring. A red arrow points upwards from the particle, representing the oscillating EDM vector \hat{x} .

- Storage ring probes of axion-induced oscillating EDM

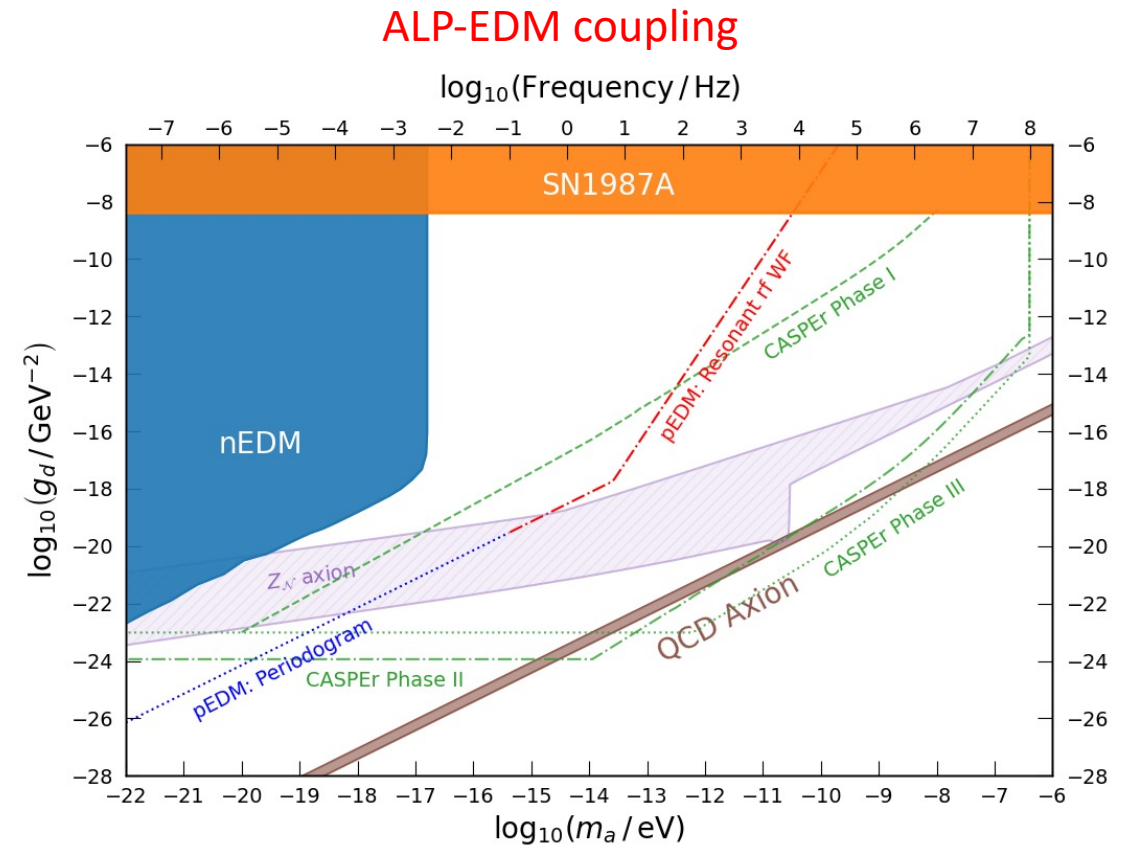
S. Chang et al., PRD **99**, 083002 (2019).

- Complementary method using an rf Wien filter

On Kim and Y. Semertzidis, PRD **104**, 096006 (2021)

- Parasitic measurement with pEDM experiment

- o Low frequency: Periodogram analysis.
- o High frequency: Resonant rf Wien filter.



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. IBS OK below transition.
E-field strength	Low. Plate-units are similar to those ran at Tevatron with higher specs.
E-field plates shape	Low. Make as flat as conventionally possible. Shim out high order fields by intentionally splitting the CR-beams
Spin coherence time	Low. Ordinary sextupoles will provide $\sim 10^3$ s, with stochastic cooling we expect much longer, under study.
Beam position monitors (BPM), SQUID-based BPMs.	Low, medium. Ordinary BPMs and HLS (similar to FNAL's) to level the ring to better than 0.1mm, Regular split-geometry and/or SQUID-based BPMs to check CR-beams split to 0.01mm.
High-precision, efficient simulations software	Low. We have several of them already, cross-checking our results routinely. Need to scale it up (thousands of particles)
Polarimeter	Low. Mature technology available

Status: what we already have done, what's missing

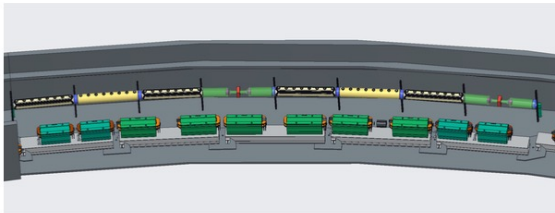
(Short) path to readiness

Main message: no showstoppers! Due diligence, physics case studies, moving to TDR phase...

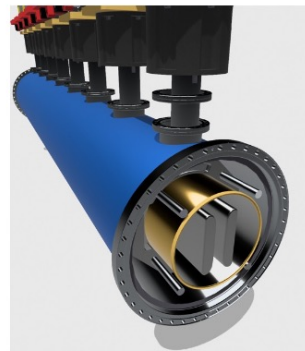
Already completed...

Engineering/modelling complete + key systematics solved.

- Storage ring lattice ✓
 - Polarized proton delivery ✓
 - Viable site + ground stability ✓
 - Prototype being built (strong UK input) ✓
- Main EDM measurement and systematics ✓
 - Counter-rotating beams/spin-alignment ✓
 - Hybrid ring + systematics from field limits ✓
 - Beam dimensions/polarisations/measurement ✓



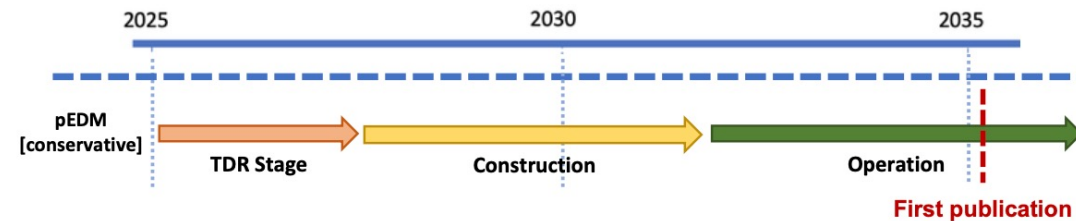
Top: 1/24 section (15°) of pEDM ring.
Right: pEDM deflector (designed and under construction in the UK).



Work to be done...

- Precision beams studies (Muon g-2 experts).
- Options for improved polarimetry (e.g. CMOS).
- Alignment system, methodology and studies.
- Simulate 10^3 particles for 10^3 seconds beam lifetime.
- More realistic costing.
- **Build community/collaboration!**
 - Bring current pEDM communities together.
 - Increased UK involvement (you are invited!).
 - New generation to start and finish experiment.

Alex Keshavarzi's slide



You can do this experiment and publish hugely important physics (e.g. solve the strong CP problem!) in < 20 years!

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).

Is the polarimeter analyzing power good at P_{magic} ? **YES!**

Analyzing power can be further optimized

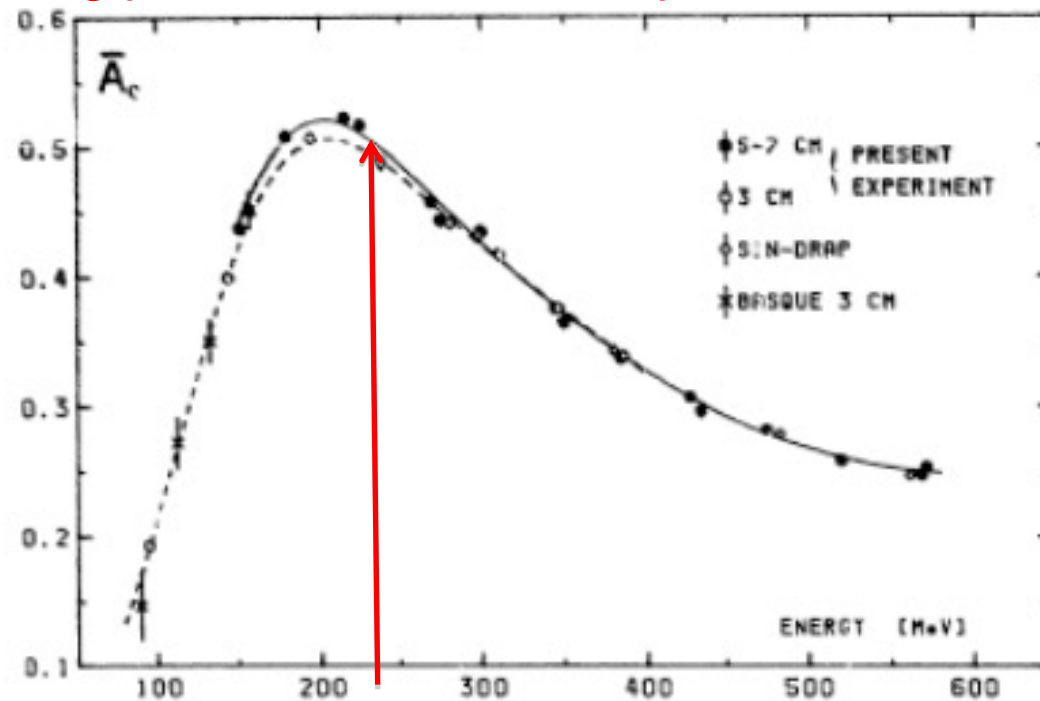
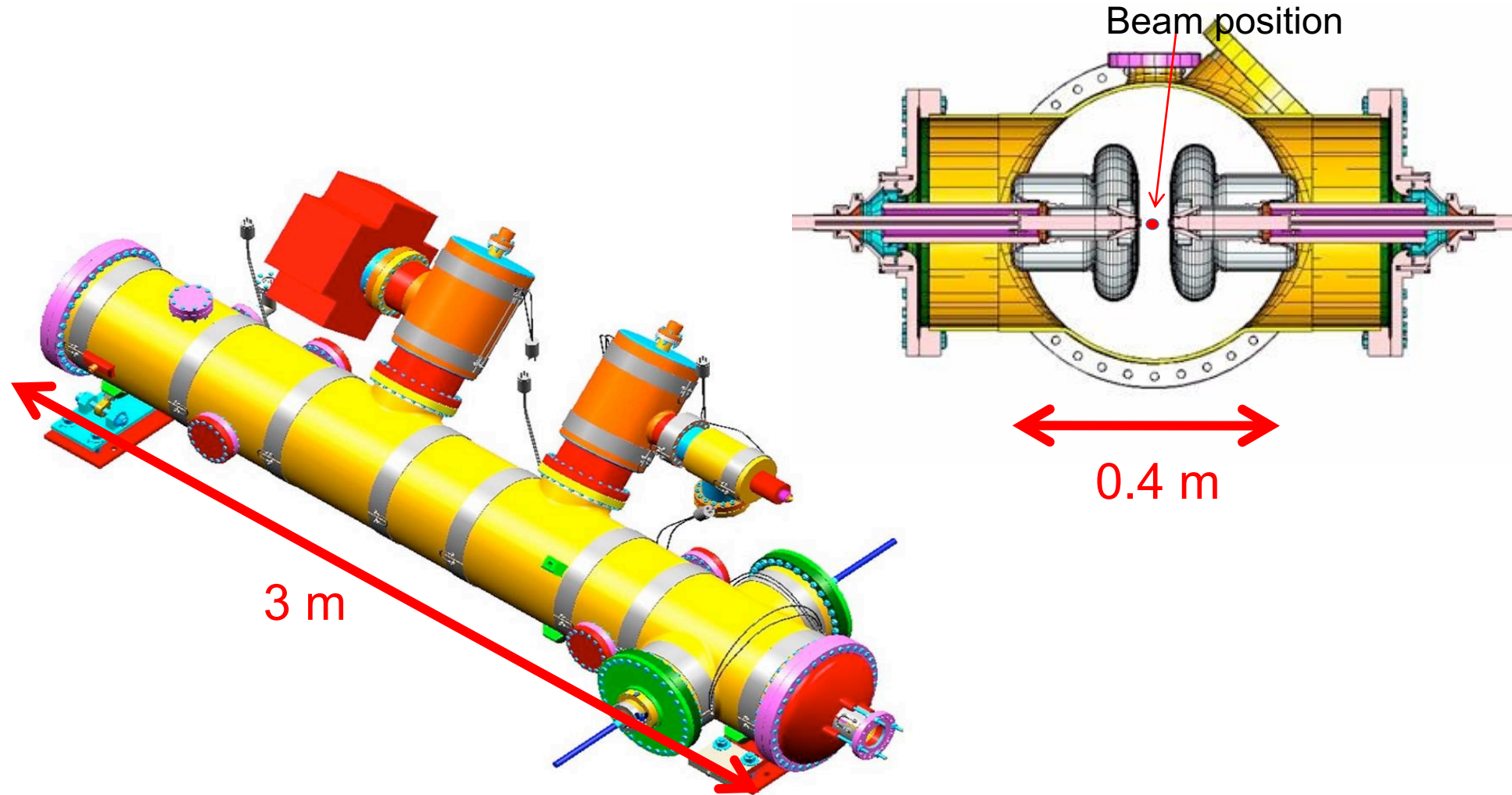


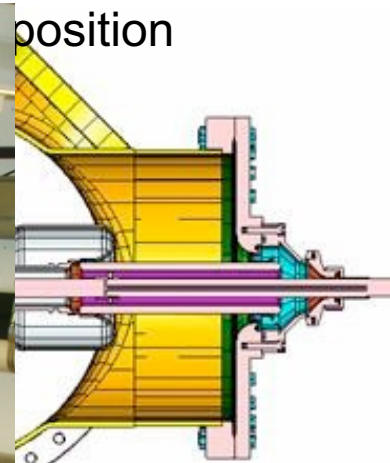
Fig. 4. Angle-averaged effective analyzing power. Curves show our fits. Points are the data included in the fits. Errors are statistical only

Fig.4. The angle averaged effective analyzing power as a function of the proton kinetic energy. The magic momentum of $0.7\text{GeV}/c$ corresponds to 232MeV .

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



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



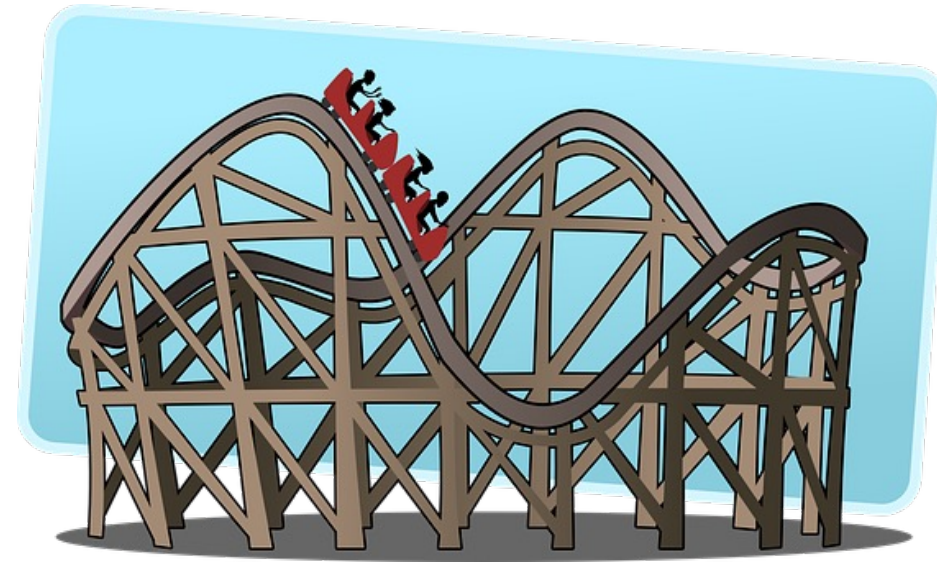
Their specs were
<1spark/year at 6MV/m
& 5cm plate separation

Large Scale Electrodes

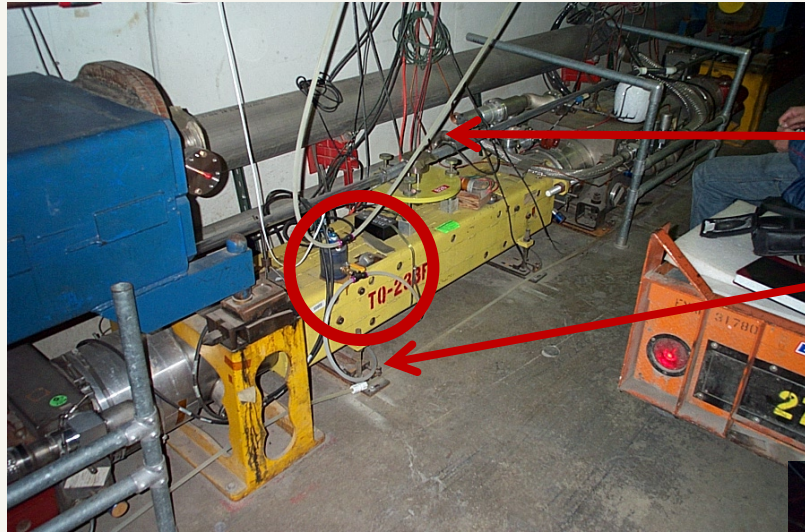
Parameter	Tevatron pbar-p Separators	BNL K-pi Separators	pEDM (low risk)
Length	2.6m	4.5m	12.5m
Gap	5cm	10cm	4cm
Height	0.2m	0.4m	0.2m
Number	24	2	48
Max. HV	$\pm(150-180)KV$	$\pm 200KV$	$\pm 90KV$

Ring planarity critical to control geometrical phase errors

- The beam planarity requirement: $<0.1\text{mm}$, within existing technology
- Clock-wise (CW) and counter-clock-wise (CCW) beam storage split to $<0.01\text{mm}$. SQUID-based BPMs (S-BPM) resolution: $10\text{nm}/\sqrt{\text{Hz}}$!



Tevatron Sensors on Quad



Air Line

Water line

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

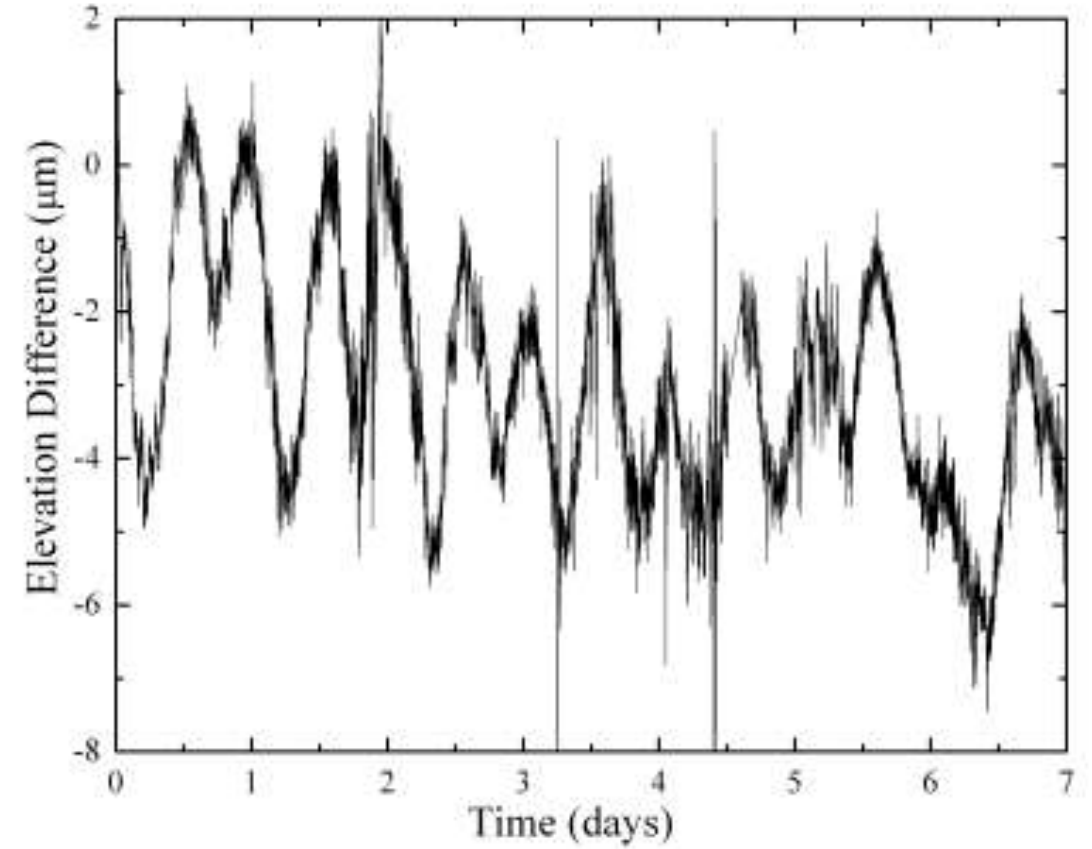


James T Volk May 2009

HLS measurements at Fermilab

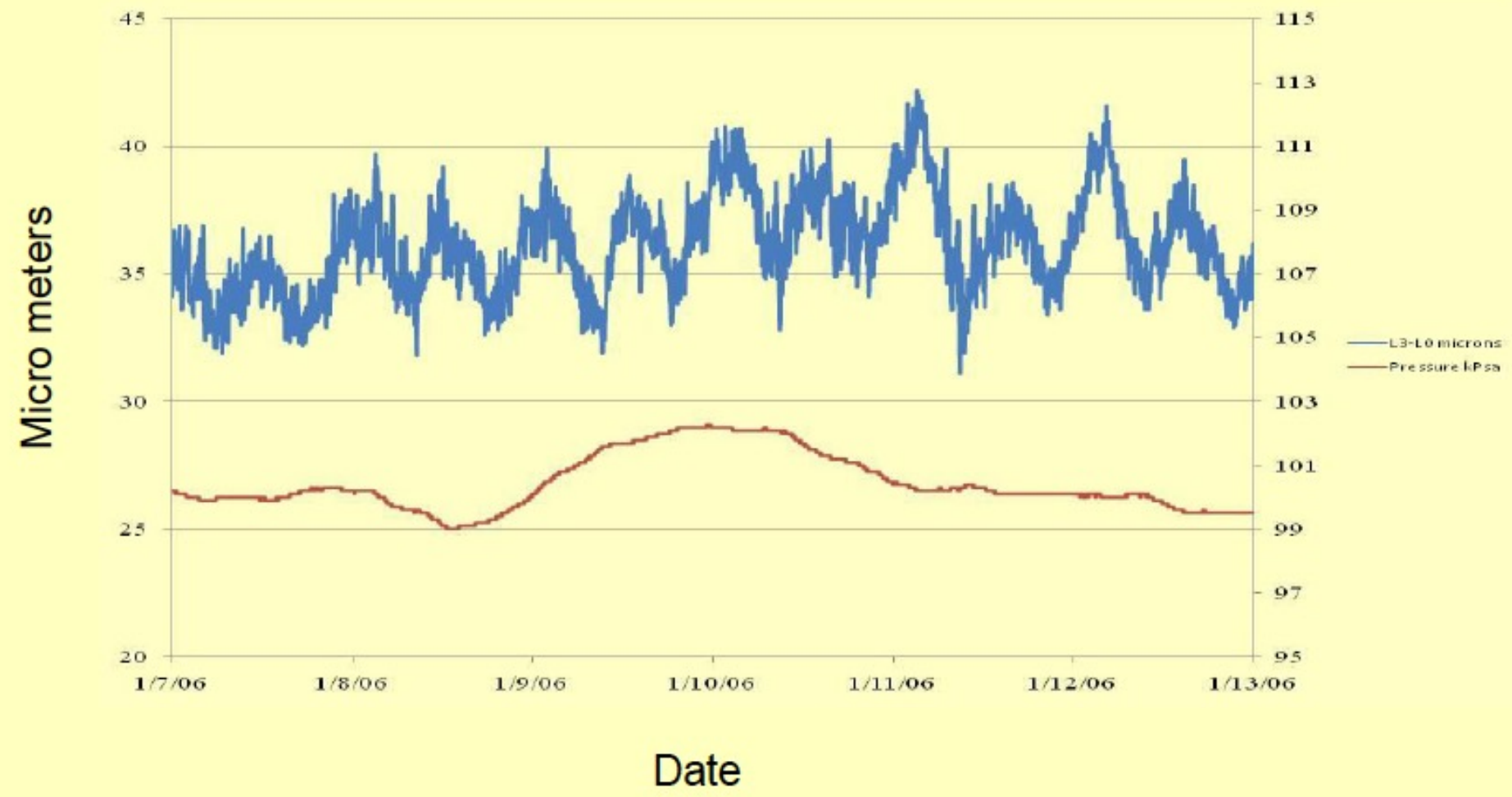


Fig.35. HLS probe on Tevatron accelerator focusing magnet.



MINOS Tidal Data

Difference in two sensors 90 meters apart



Physics strength comparison (Marciano)

System	Current limit [e·cm]	Future goal	Neutron equivalent
Neutron	$<1.6 \times 10^{-26}$	$\sim 10^{-28}$	10^{-28}
^{199}Hg atom	$<7 \times 10^{-30}$	$<10^{-30}$	10^{-26}
^{129}Xe atom	$<6 \times 10^{-27}$	$\sim 10^{-29}\text{-}10^{-31}$	$10^{-25}\text{-}10^{-27}$
Deuteron nucleus		$\sim 10^{-29}$	$3 \times 10^{-29}\text{-}$ 5×10^{-31}
Proton nucleus	$<2 \times 10^{-25}$	$\sim 10^{-29}$	10^{-29}

From theta-QCD



From SUSY-like CPV



^3He Co-magnetometer

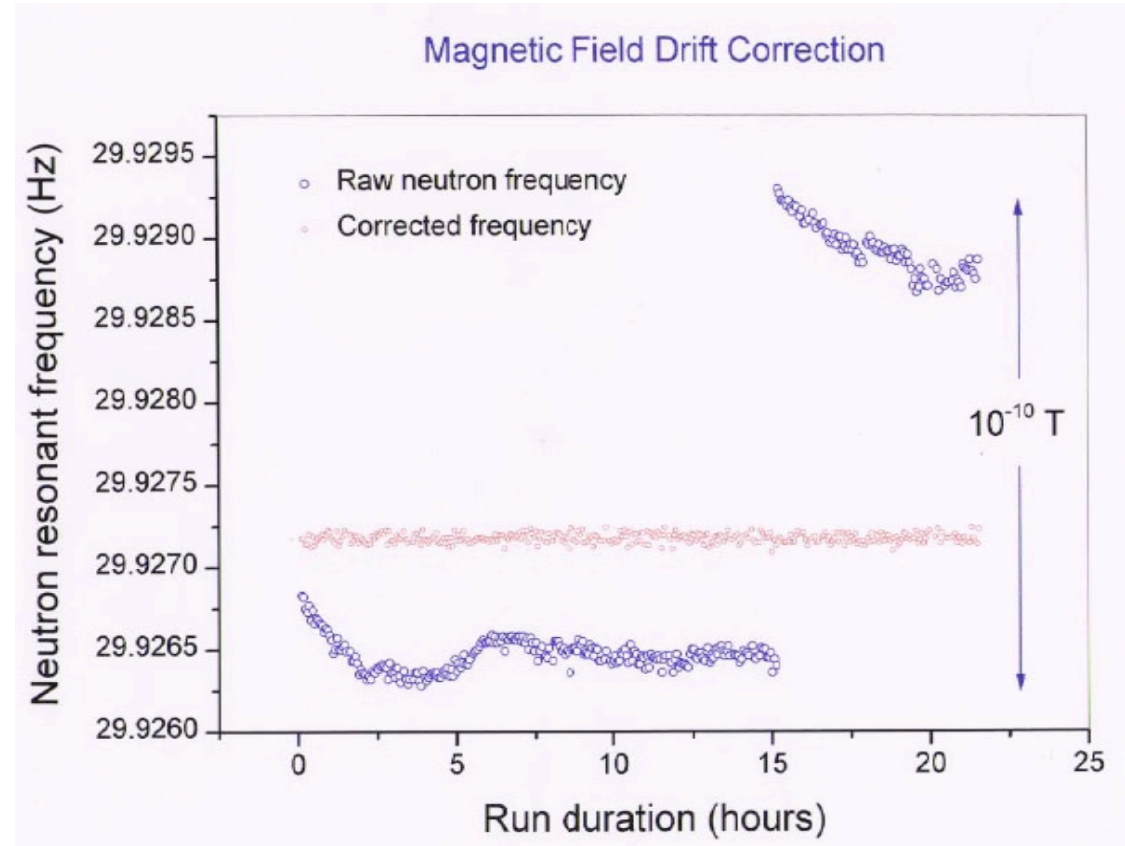
If $n\text{EDM} = 10^{-26} \text{ e}\cdot\text{cm}$,

$10 \text{ kV/cm} \rightarrow 0.1 \mu\text{Hz shift}$

$\cong \text{B field of } 2 \times 10^{-15} \text{ T}$.

Co-magnetometer :

Uniformly samples the B Field
faster than the relaxation time.



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

EDM of $^{199}\text{Hg} < 10^{-28} \text{ e}\cdot\text{cm}$ (measured); atomic EDM $\sim Z^2 \rightarrow ^3\text{He EDM} \ll 10^{-30} \text{ e}\cdot\text{cm}$

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