Status and physics reach of the proton EDM experiment

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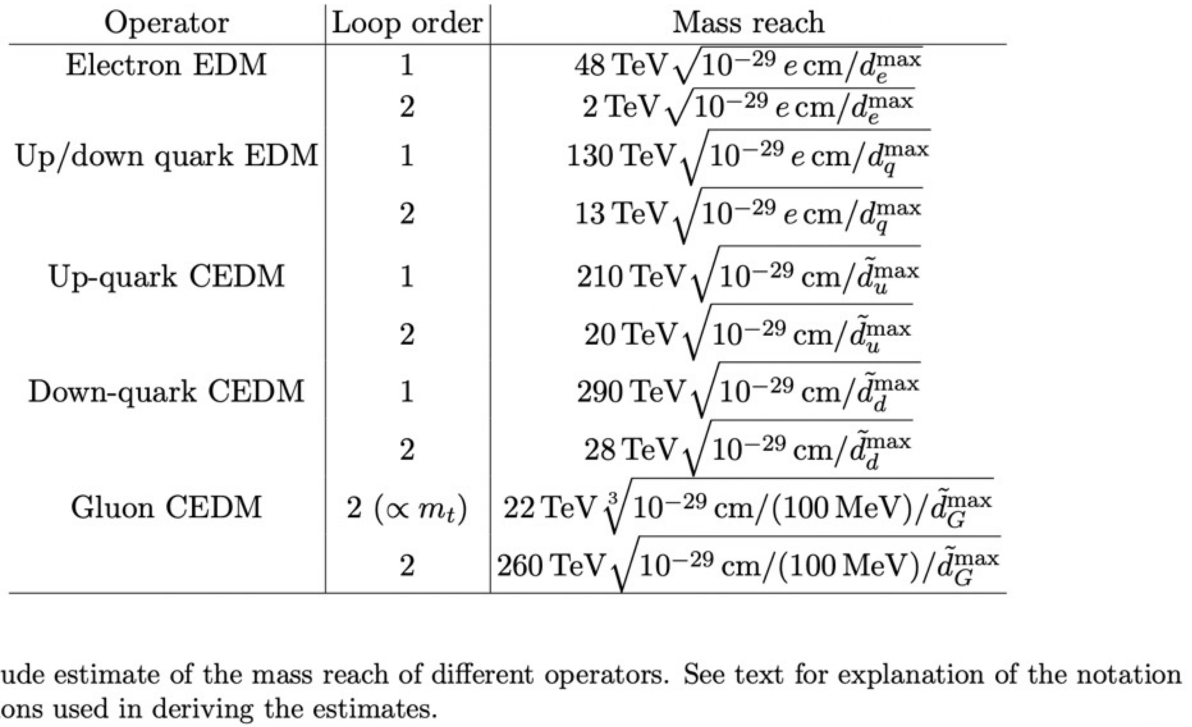
MMP2023, Liverpool
In-person presentation
November 7, 2023

Our Collaborators work(ed) on:

- Muon g-2; Hadronic storage rings; hadronic polarimeters; High precision beam and spin dynamics simulations; High voltage; Magnetic field measurements, shielding/shimming; EDM Theory…

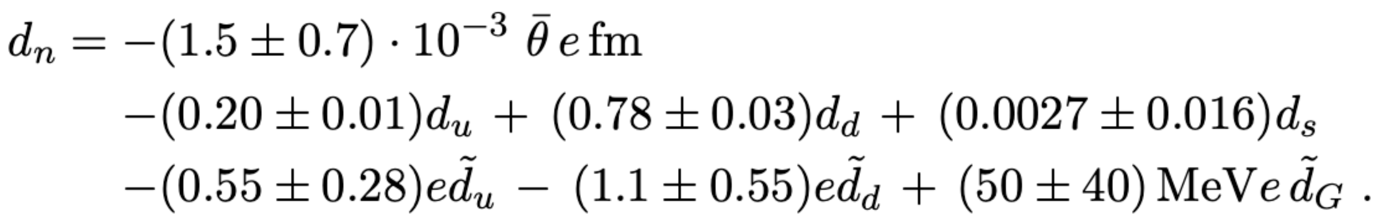
Electric Dipole Moments

Snowmass paper on EDMs, why many EDMs:



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

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.



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

Electric dipole moments and the search for new physics

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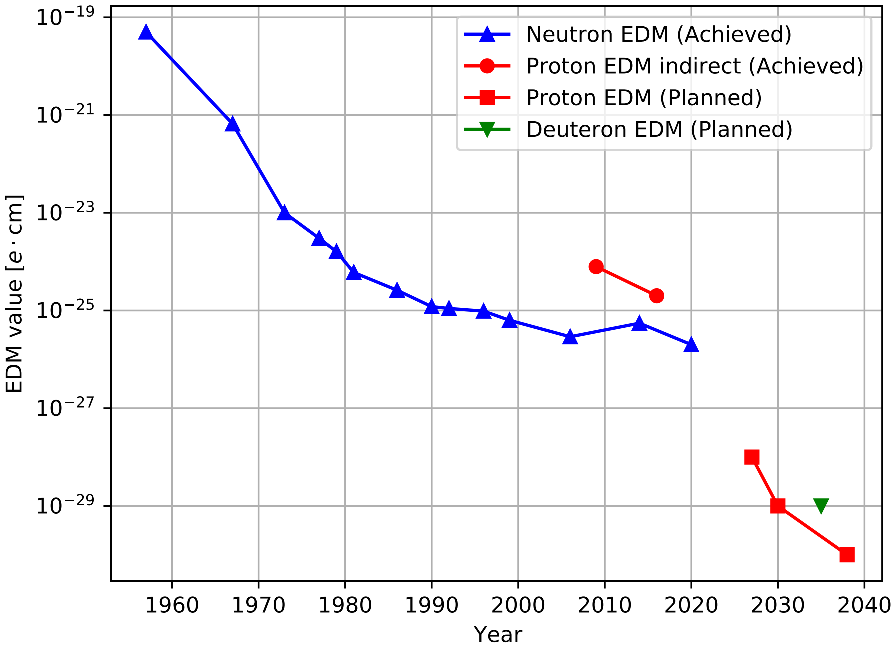
Storage ring EDM experiment

- Snowmass white paper: next steps - CDR, proposal, TDR
- 10^{-29} *e*-cm; fits in BNL AGS tunnel
  - World-class, high intensity polarized sources for protons, deuterons, ^{3}He, other nuclei
  - ring design PRD105:032001 (2022), storage ring experiment Rev.Sci.Instrum.87:115116 (2016)
- Possible interesting results within a decade (compatible with EIC schedule)
- Competitive EDM sensitivity:
  - New-Physics reach ~10^3 TeV.
  - Best probe on Higgs CPV, Marciano
    - proton is better than H→ $\gamma\gamma$
    - 30x better than electron with same EDM.
  - Three orders of magnitude improvement in θ_{QCD} sensitivity.
  - Direct axion dark matter reach (best exp. sensitivity at very low frequencies).



The storage ring proton EDM experiment

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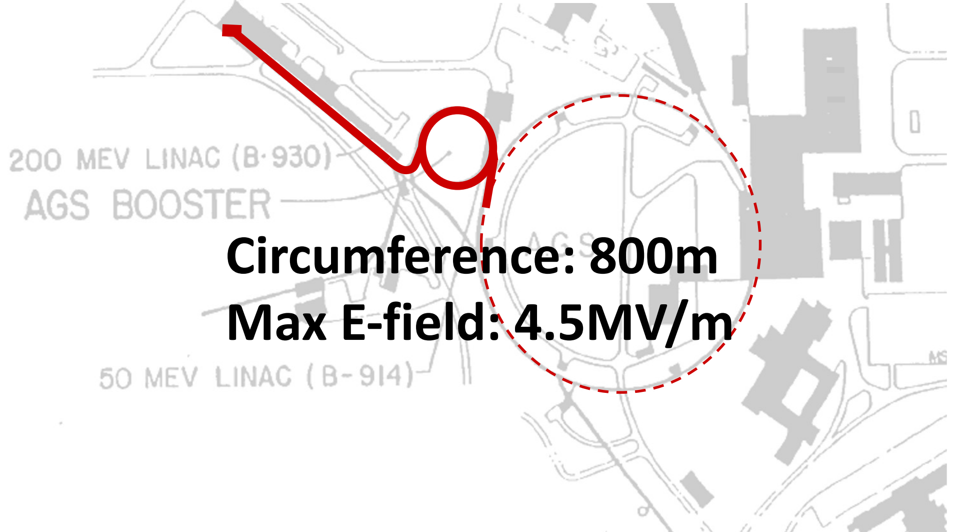
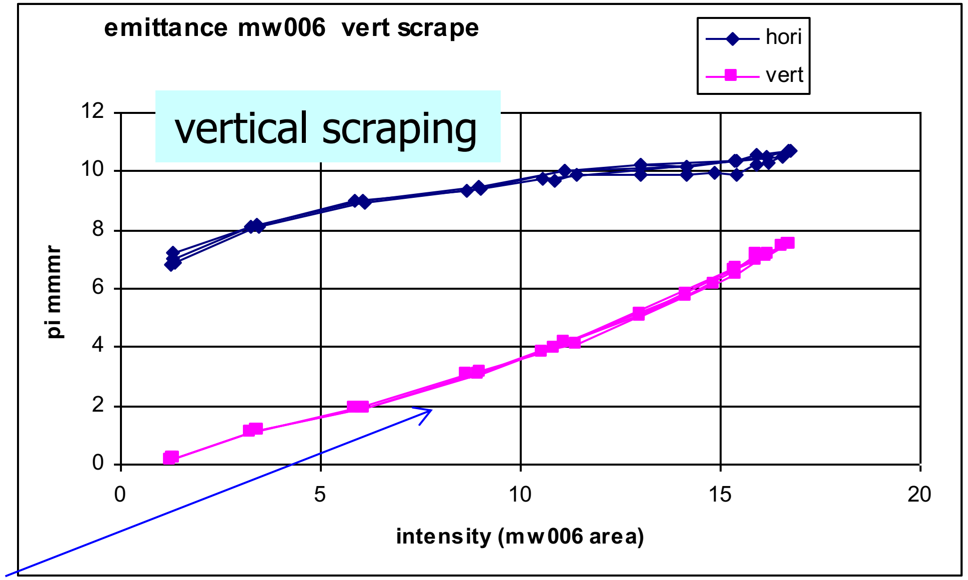


Circumference: 800m
Max E-field: 4.5MV/m

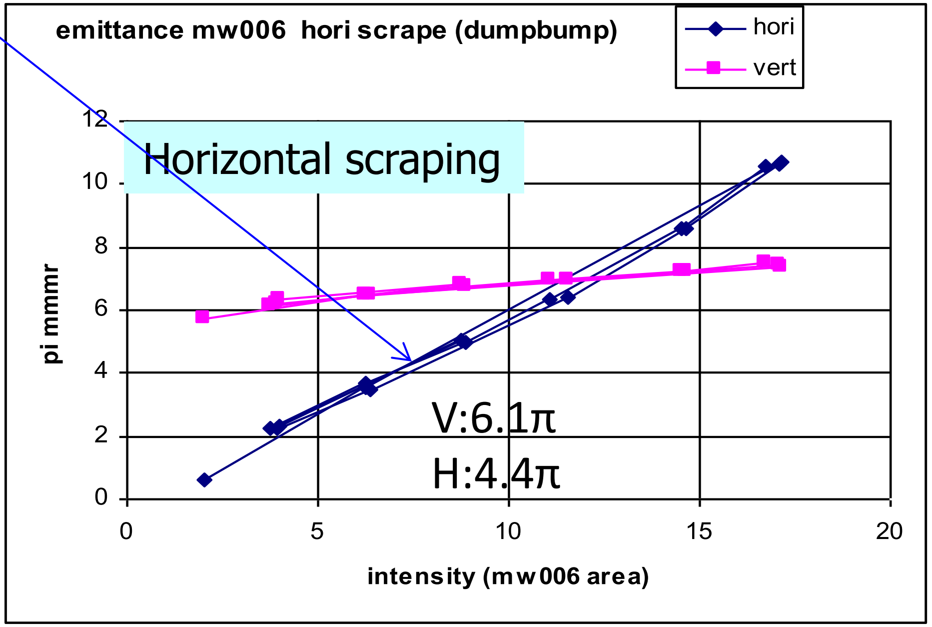
High intensity polarized proton Beam at BNL

Proton intensity at Booster input $3*10^{11}$. The vertical scale is normalized 95% emittance.

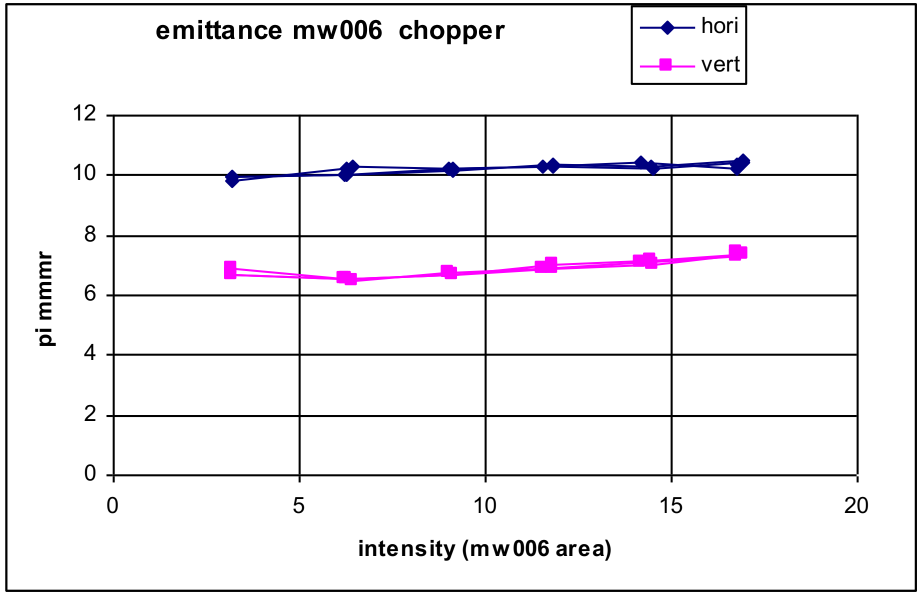
The corresponding normalized rms emittance at 10^{11} is 0.7π horizontal, 1.0π vertical for horizontal scraping.



@10^{11}

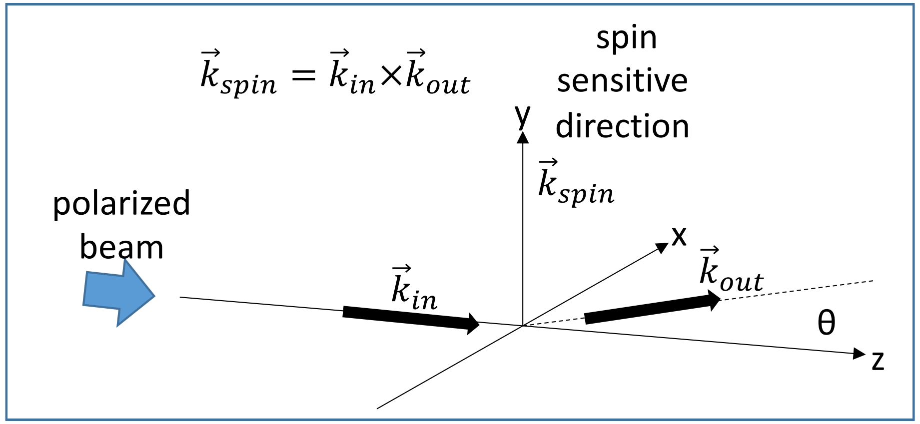


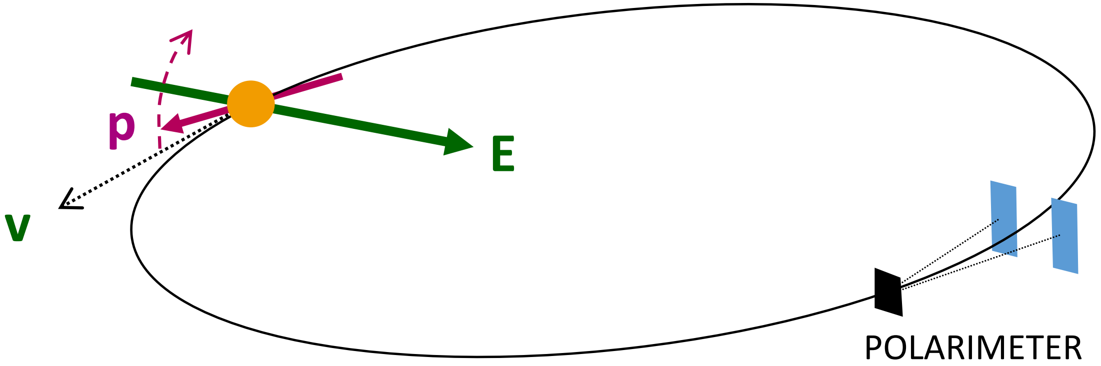
Intensity: 15~2e11 protons



Large statistics available, opportunity for great sensitivity improvement in EDMs

Storage ring Electric Dipole Moments





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

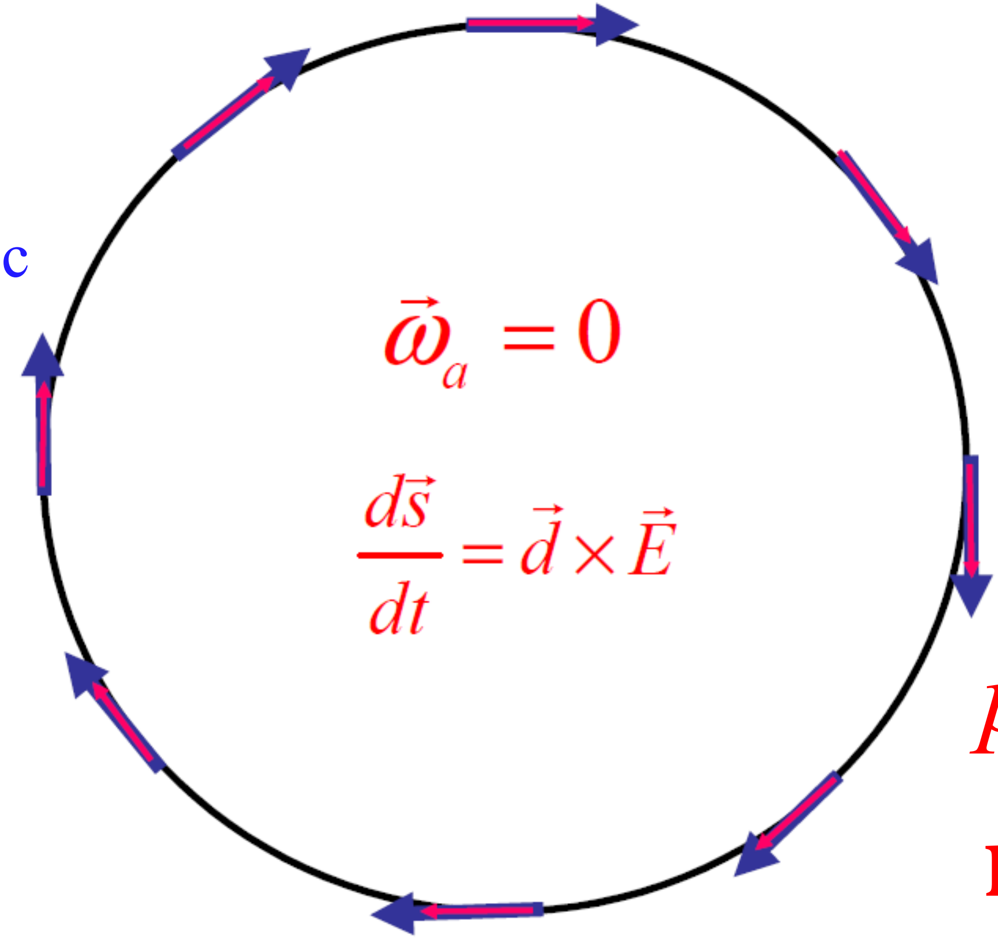
Frozen spin method:

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

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).



$$\vec{\omega}_a = 0$$

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

The origins of the method trace right back to the muon g-2 experiment.

$p = \frac{mc}{\sqrt{a}}$, 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 (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

Systematic errors

^{3}He Co-magnetometer in nEDM experiment

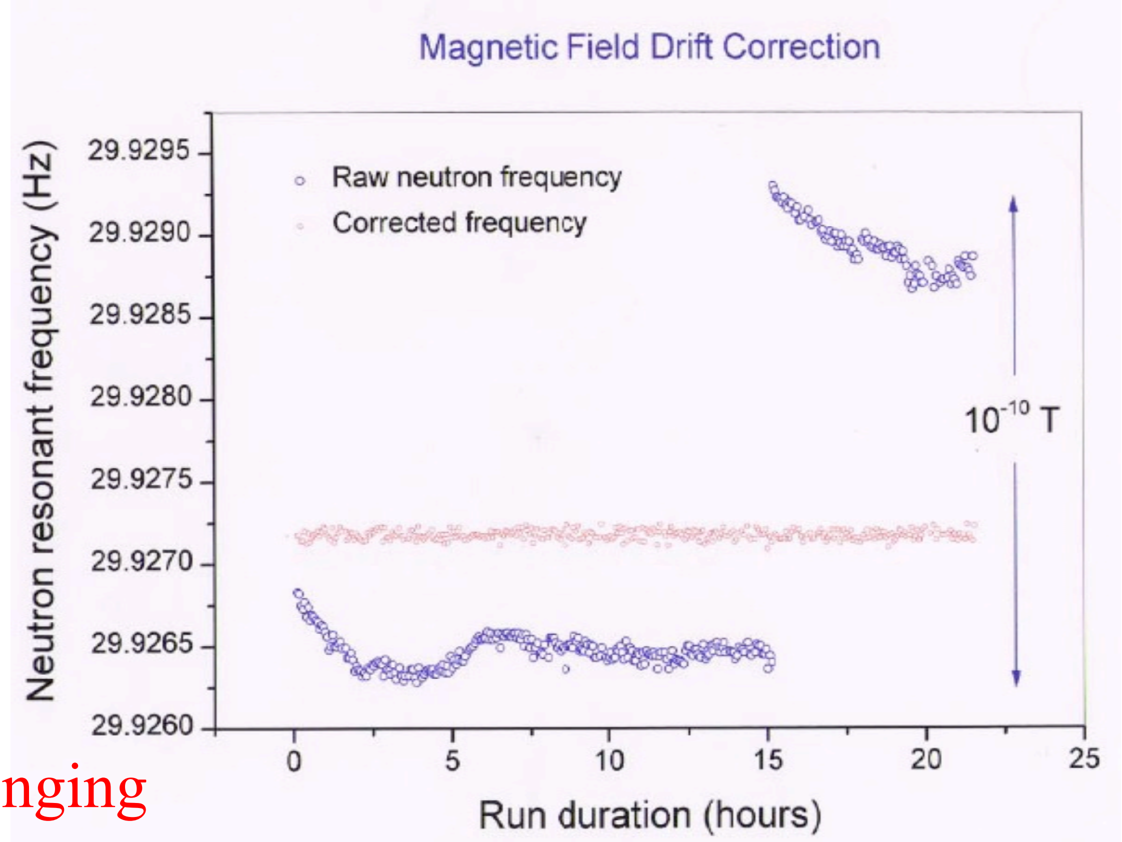
If nEDM = 10^{-26} e·cm,

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.



All EDM experiments are extremely challenging
Same with storage rings, muon g-2/EDM, proton EDM,…

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

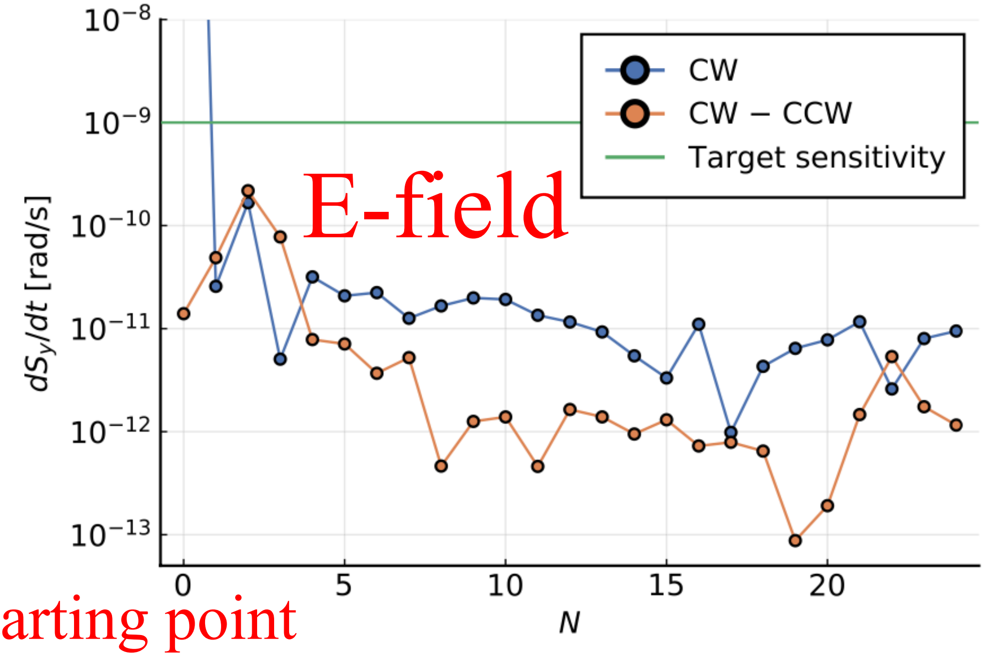
Under gravity, the center of mass of He-3 is higher than UCN by $\Delta h \approx 0.13$ cm, sets ΔB = 30 pGauss (1 nA of leakage current). $\Delta B/B=10^{-3}$.

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: $\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \left(\vec{v} \times \vec{B}\right)}$	High statistical sensitivity. **Requires consecutive CW and CCW injection with main fields flipping sign to eliminate systematic errors**
Radial Electric field **(E)** & Electric focusing **(E)** **(All electric lattice)**	Proton, etc.	$\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}}$	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.	$\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}}$	Large ring, CW & CCW storage. **Only lattice to achieve direct cancellation of main systematic error sources (its own "co-magnetometer").** GOLDEN STANDARD!

Effect as a function of azimuthal harmonic *N*

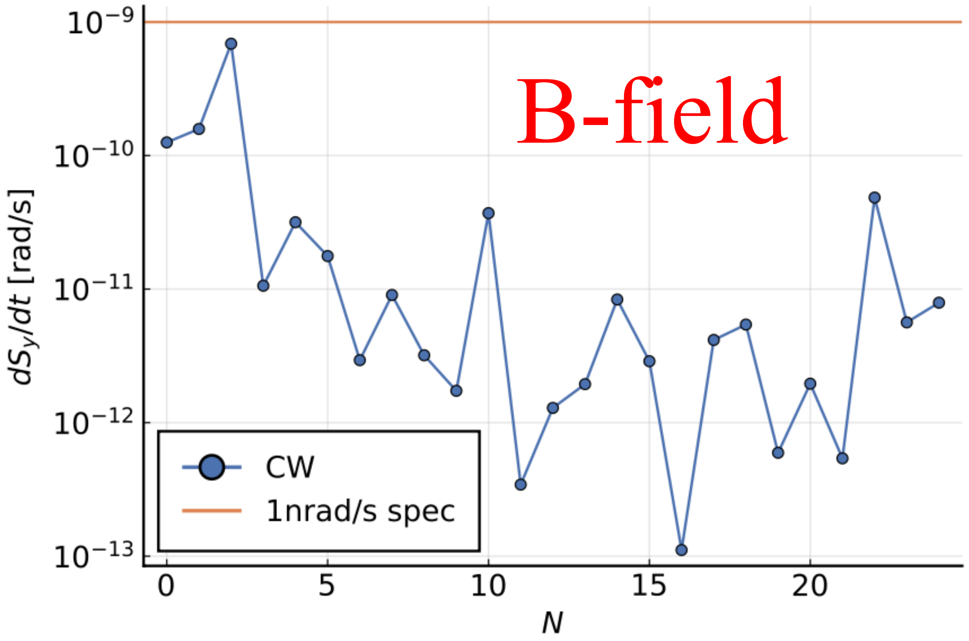
COMPREHENSIVE SYMMETRIC-HYBRID RING DESIGN FOR A … PHYS. REV. D **105,** 032001 (2022)



E-field

A solid starting point

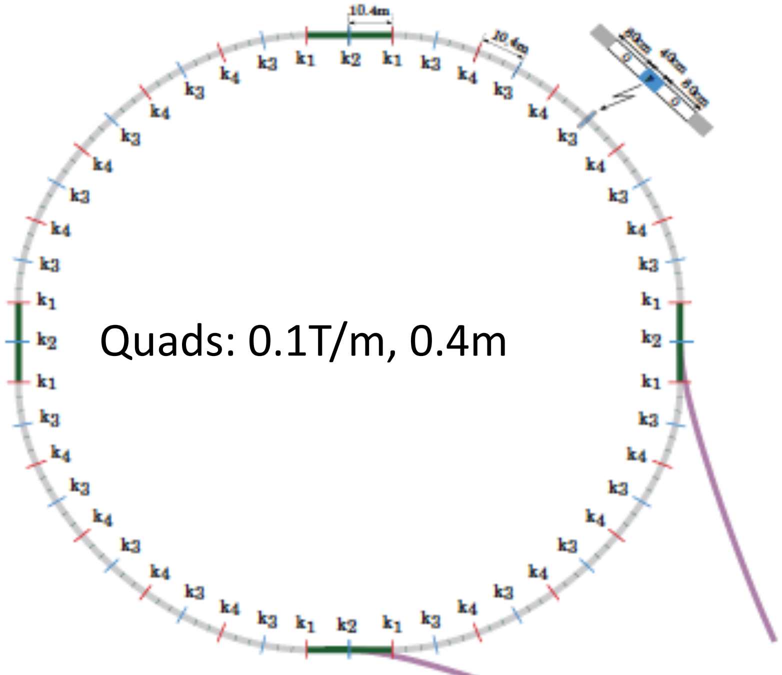
FIG. 7. *Longitudinal polarization case* $S_s = 1$, sensitive to EDM. Vertical spin precession rate vs $E_y = 10$ V/m field N harmonic around the ring azimuth. For $N = 0$, the precession rate for the CW (or CCW) beam is around 5 rad/s. The difference of the precession rates for CR beams (orange) is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



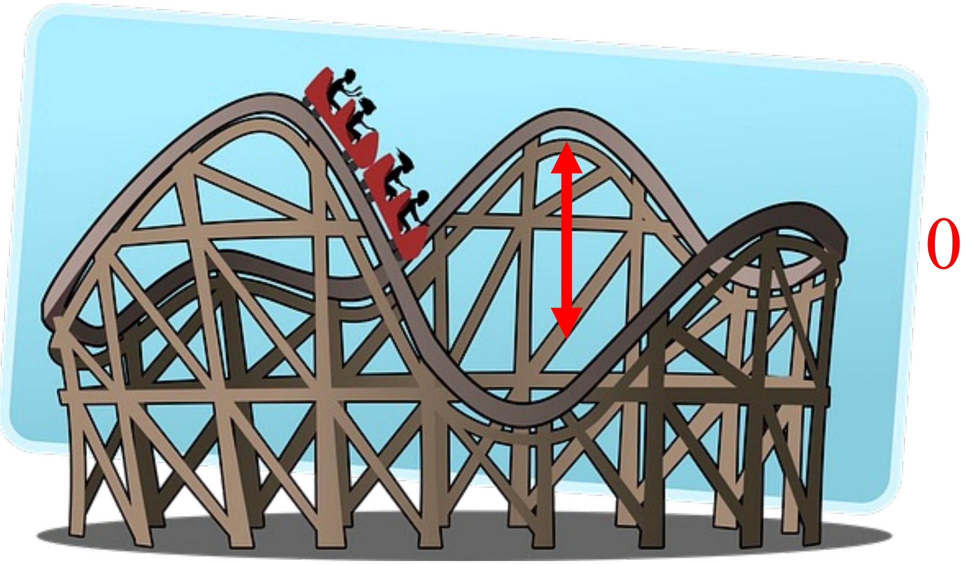
B-field

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!



Quads: 0.1T/m, 0.4m



0.1 mm

Ring planarity critical to control geometrical phase errors

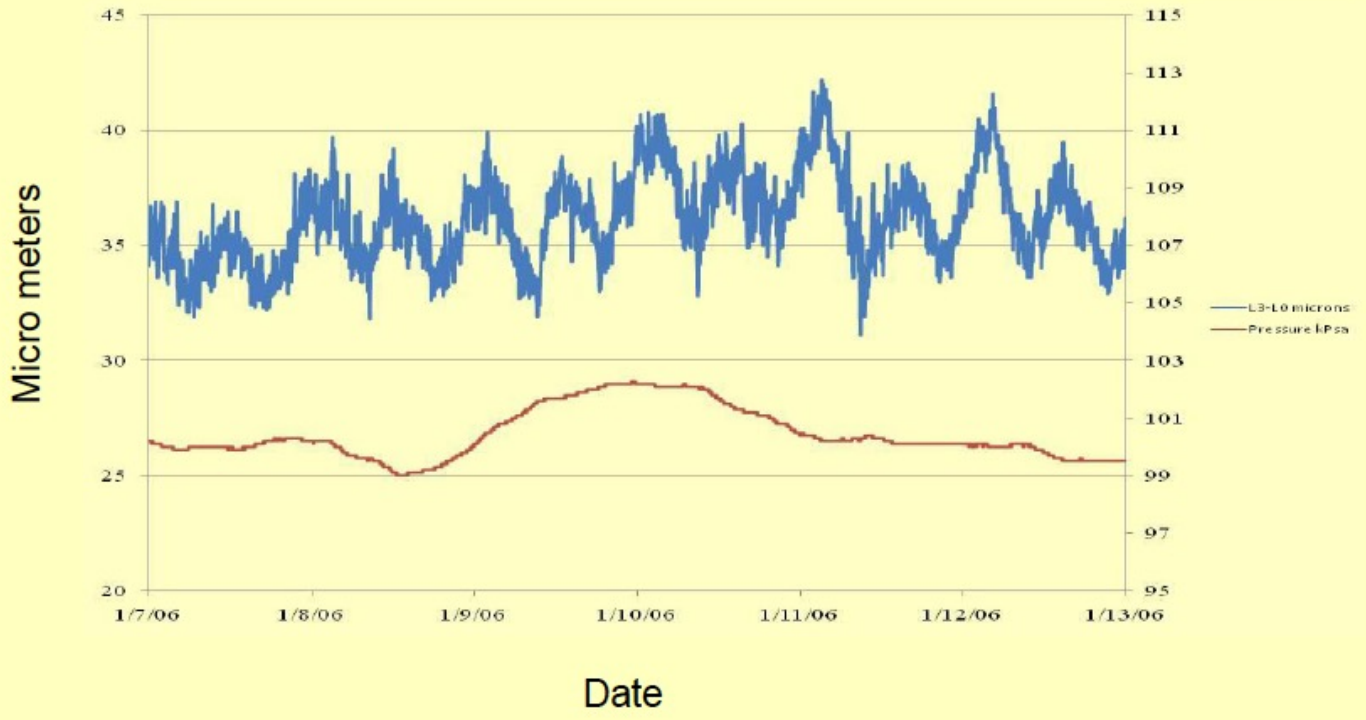
- Numerous studies on slow ground motion in accelerators, Hydrostatic Level System for slow ground motion studies at Fermilab.

- Thorough review by Vladimir Shiltsev (FNAL):

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

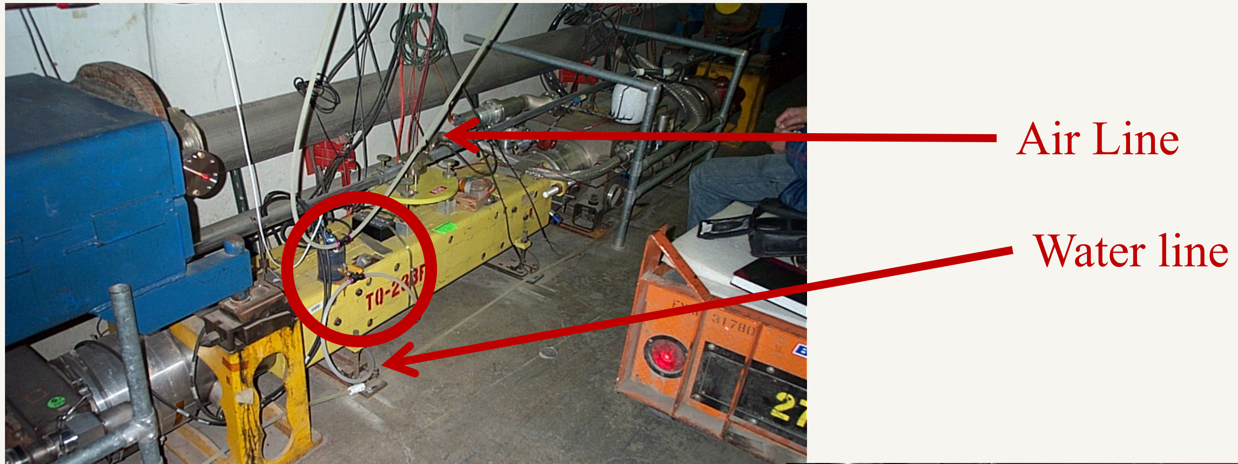
MINOS Tidal Data

Difference in two sensors 90 meters apart

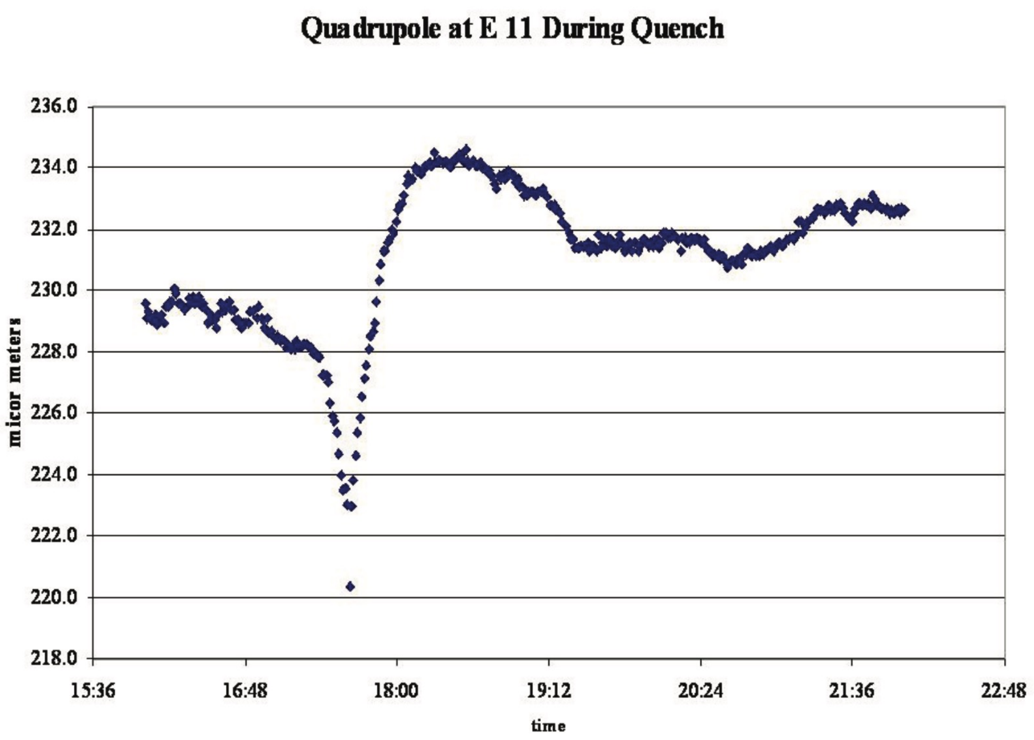


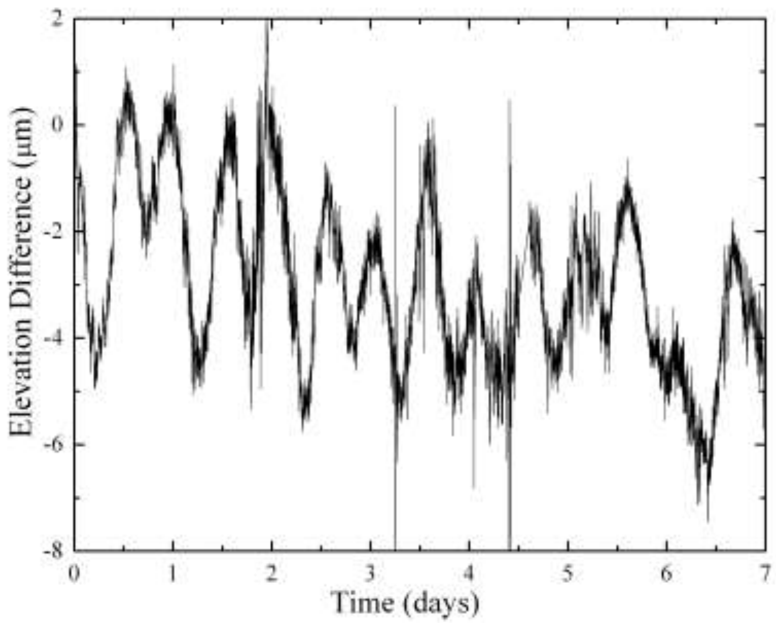
J T Volk Fermilab Dec 2008

Tevatron Sensors on Quad



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





Ring planarity critical to control geometrical phase errors

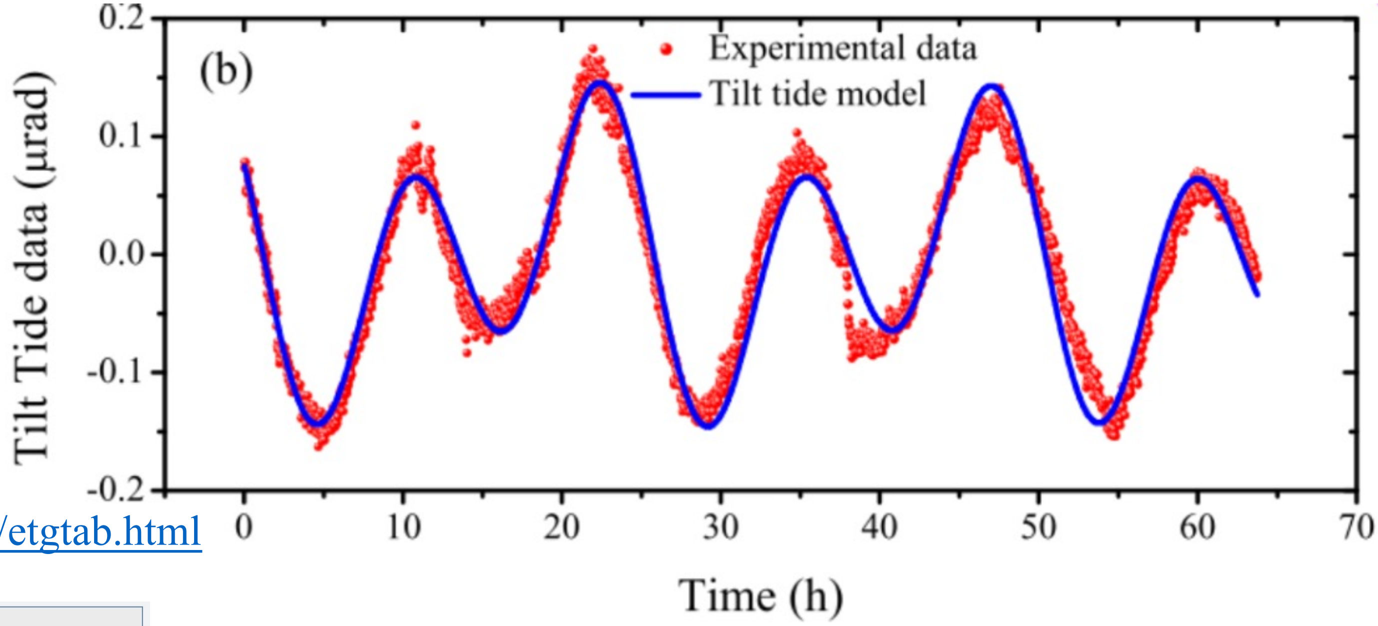
- Hydrostatic Level System is used for ground motion monitoring
- Ground tilt measured with a quantum tiltmeter and compared to prediction:

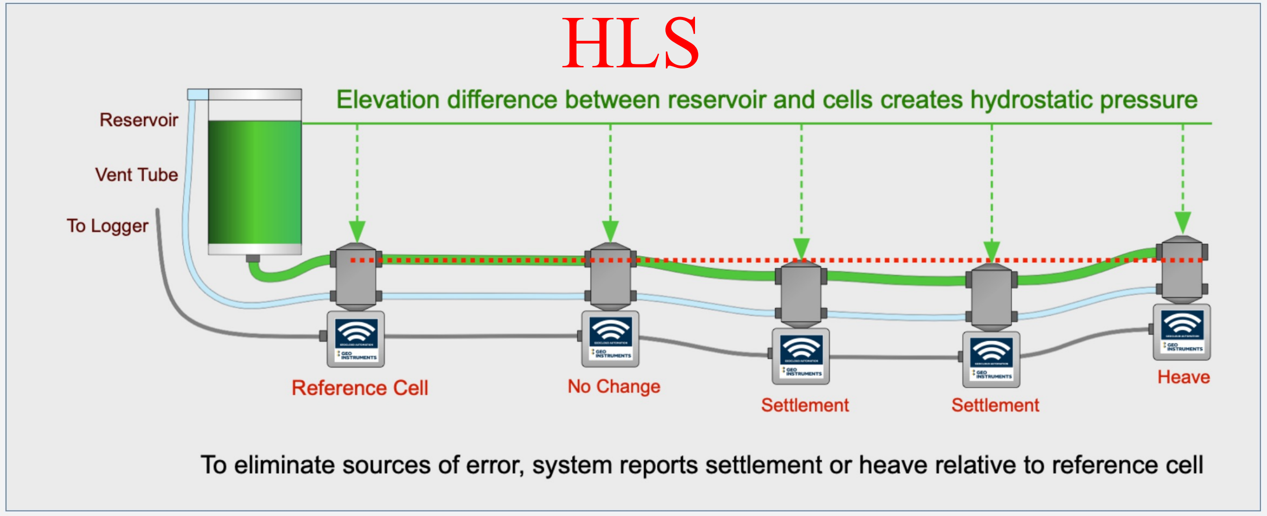
https://www.black-forest-observatory.de/Old_Stuttgart_Webpages/etgtab.html

Sensitive quantum tiltmeter with nanoradian resolution

Jie Liu, Wen-Jie Xu, Cheng Zhang, Qin Luo, Zhong-Kun Hu, and Min-Kang Zhou

Phys. Rev. A **105**, 013316 – Published 21 January 2022



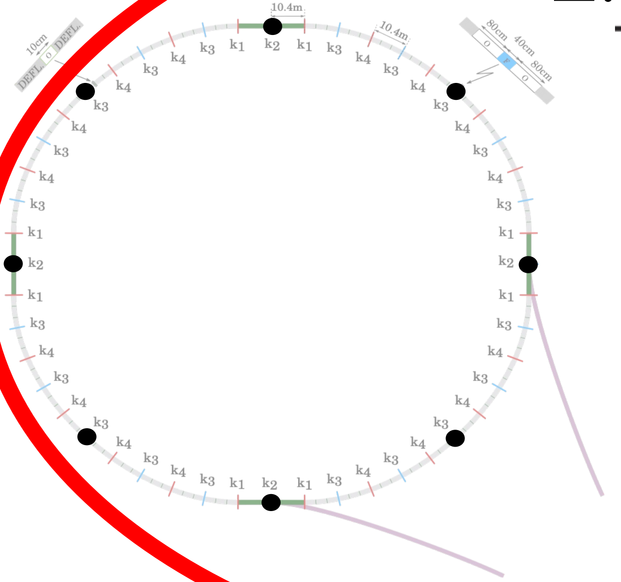


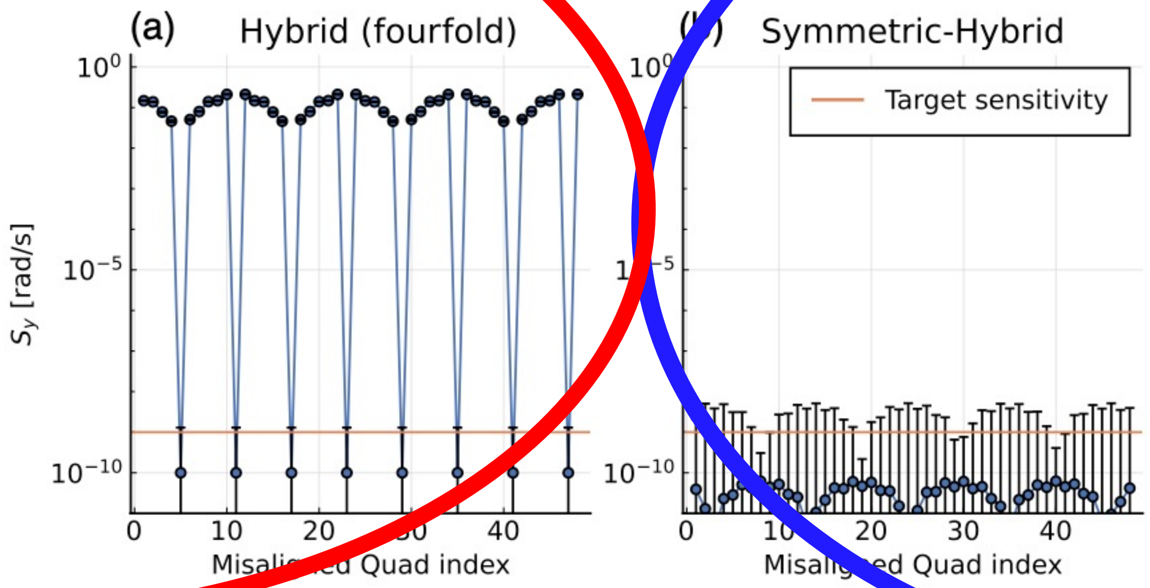
Elevation difference between reservoir and cells creates hydrostatic pressure

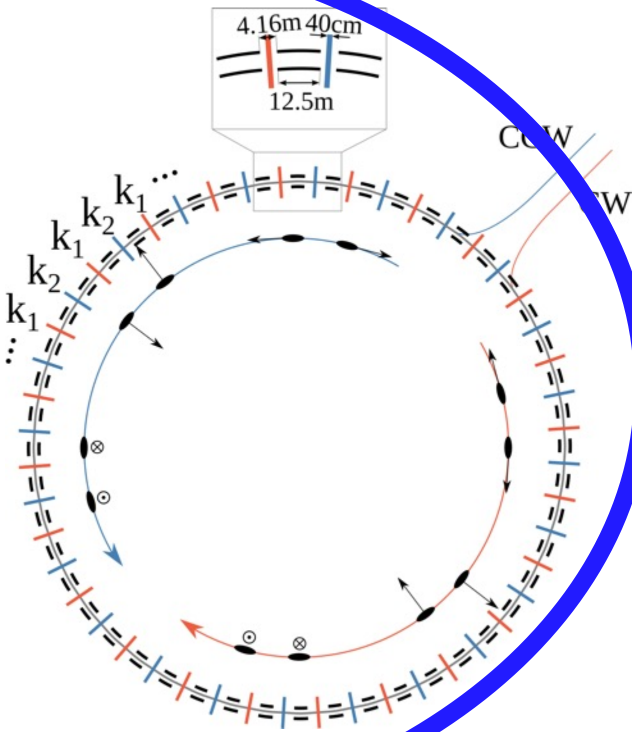
To eliminate sources of error, system reports settlement or heave relative to reference cell

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

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







Sensitivity of radially polarized beams, most sensitive to vertical velocity problem

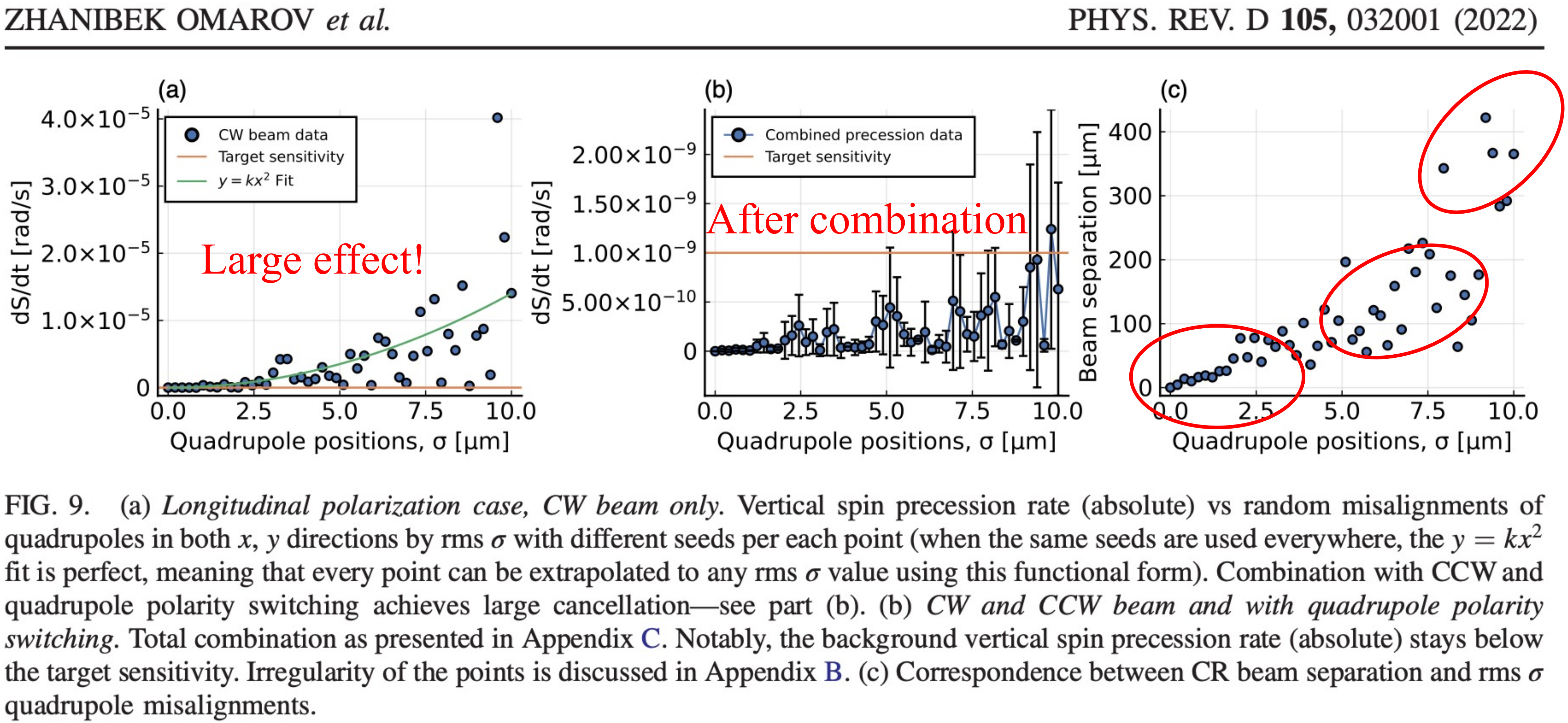
EDM is probed with longitudinally polarized beams, less sensitive to this effect by $>10^3$

Use radially polarized beams to align the ring (spin based alignment) and monitor background

Vertical velocity and geometrical phase effects:

Magnetic quadrupoles 0.2T/m, positioning accuracy dominates background B-fields

Mitigation by flipping quad polarity in ~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.

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

✓Alternate magnetic focusing allows simultaneous CW & CCW storage and

  Effectively 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

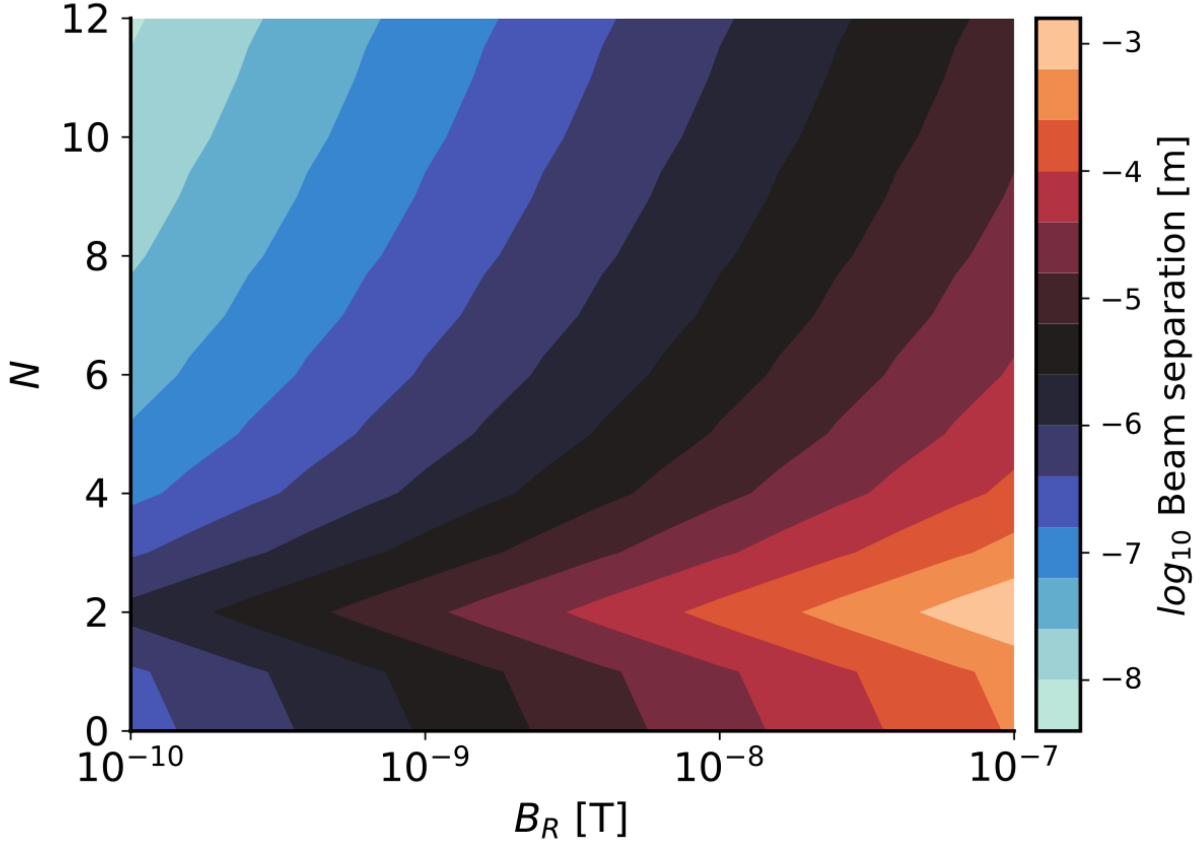
  Radial polarization direction for first ring lattice alignment.

  Longitudinal, radial and vertical polarization directions, sensitive to EDM and/or systematic errors.

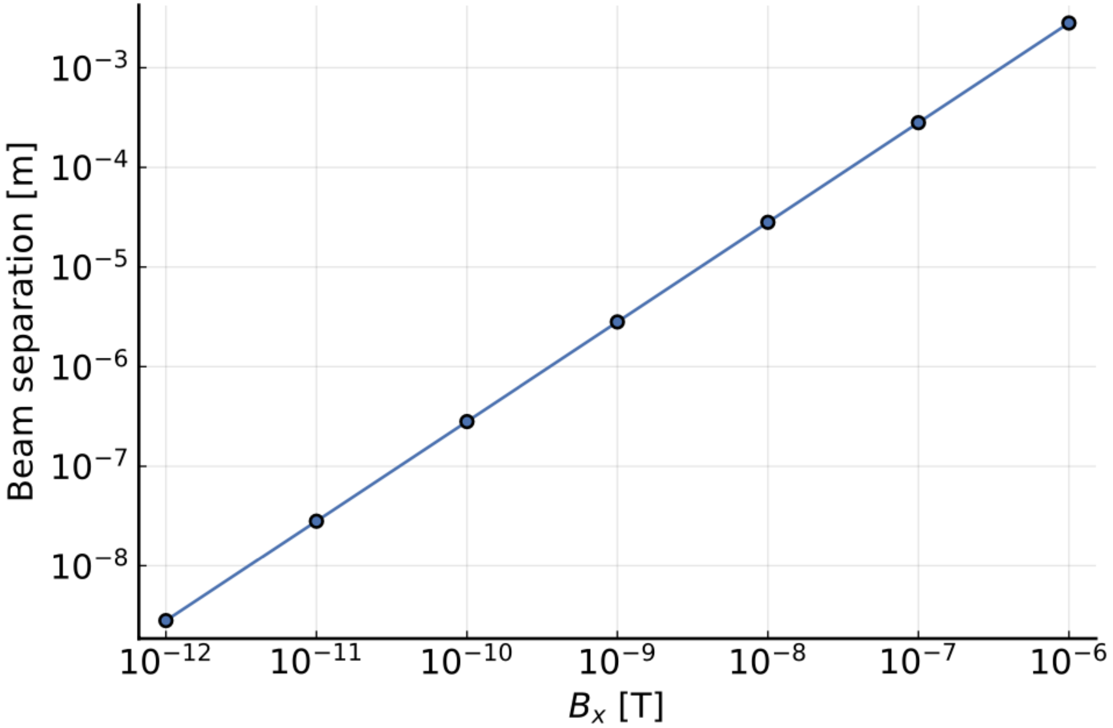
✓Set strict ring planarity requirements <0.1mm; CW & CCW beam separation <0.01mm, and quad current flipping resolve issues with geometrical phases. Key issue: stability. Design the ring with stability in mind.

Radial magnetic field calibration

- The beam separation depends on the radial (B_x).
- The low N-values are more important.



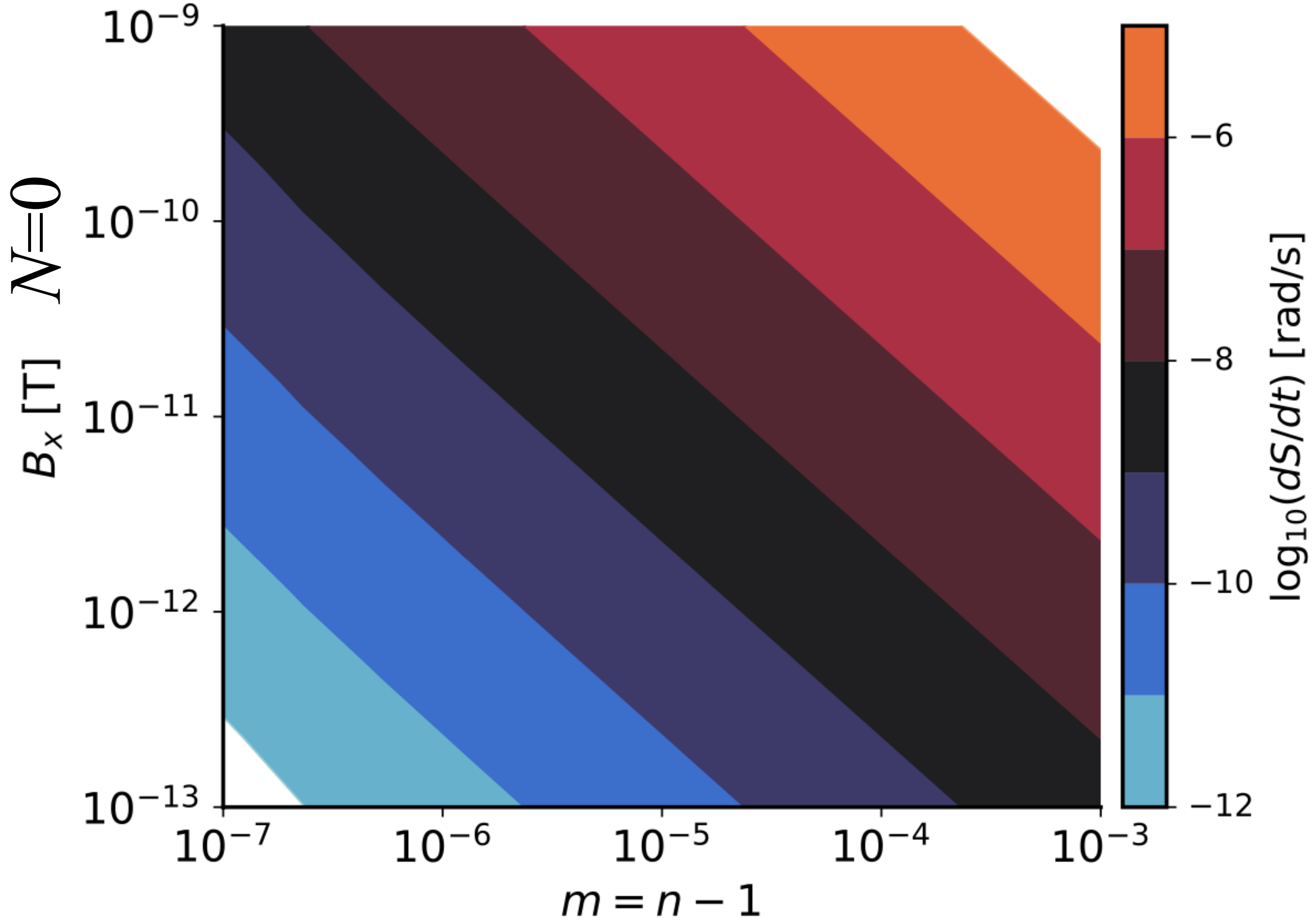
N=0



Spin-based alignment/background reduction for greater order than dipole E-fields

- Electric quadrupole is a second-order systematic error source

- We probe it and eliminate it.

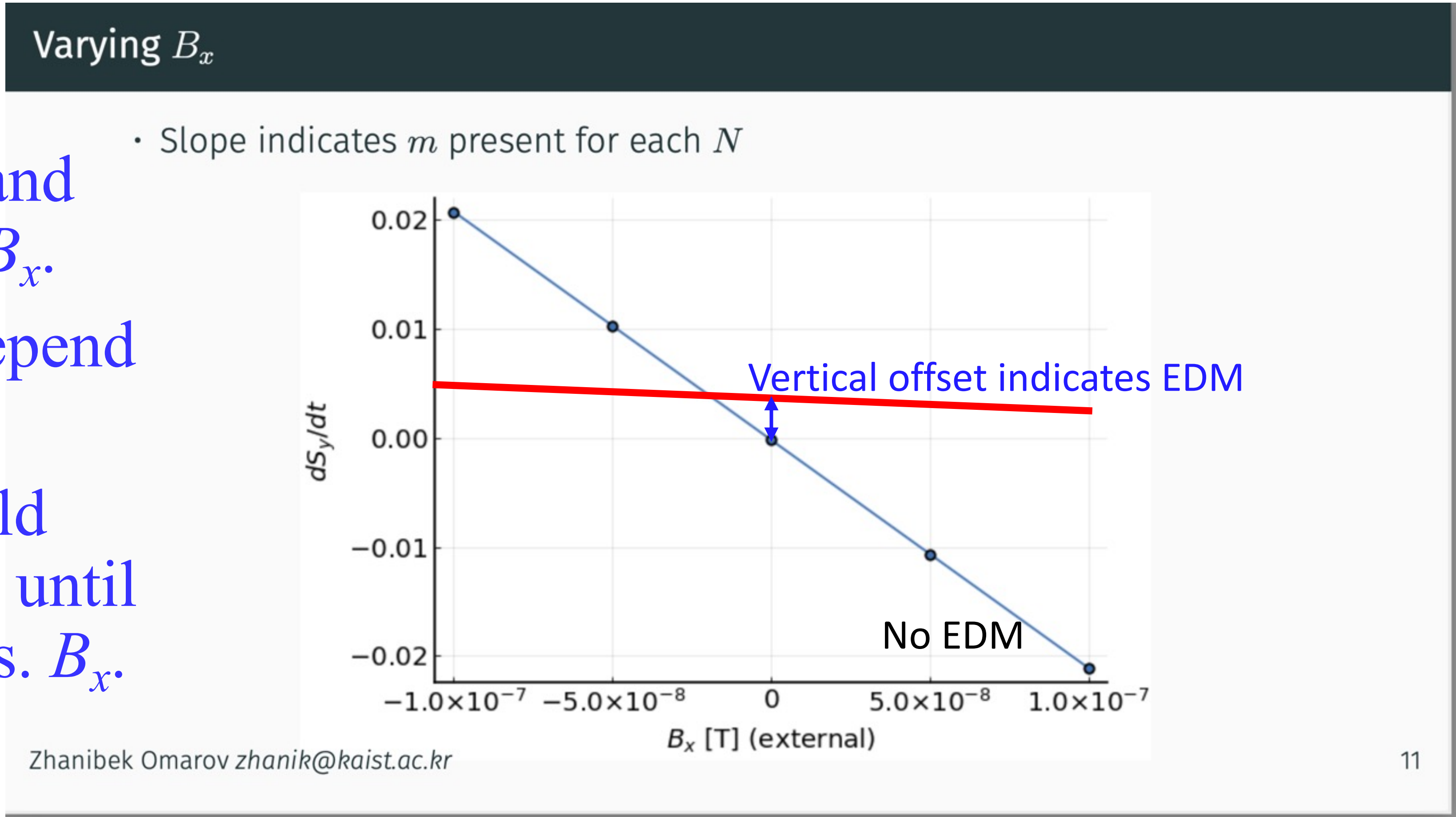


Spin-based alignment/background reduction for greater order than dipole E-fields

- 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

- 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.



Varying B_x

- Slope indicates m present for each N

Vertical offset indicates EDM

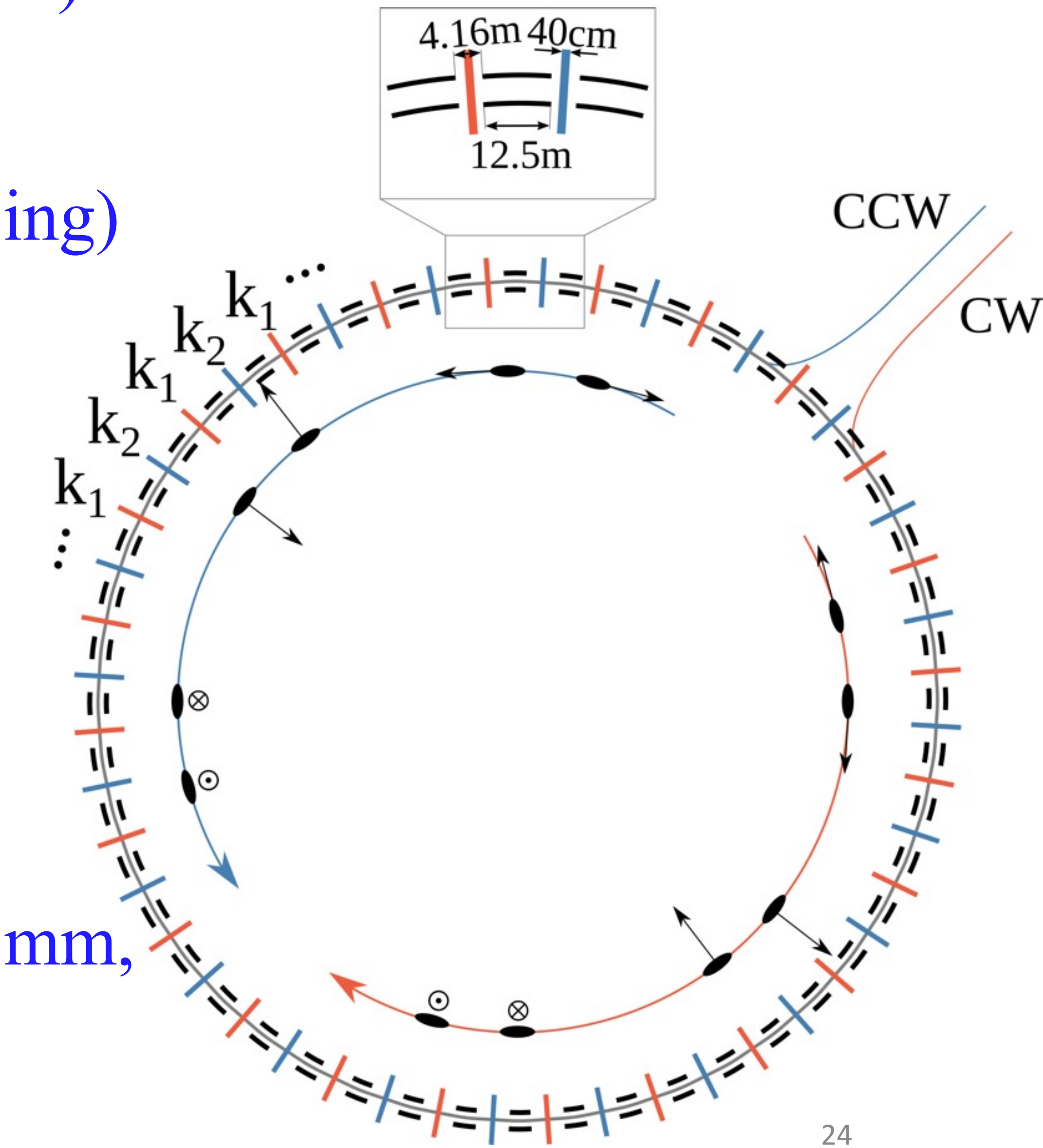
No EDM

Zhanibek Omarov *zhanik@kaist.ac.kr*

11

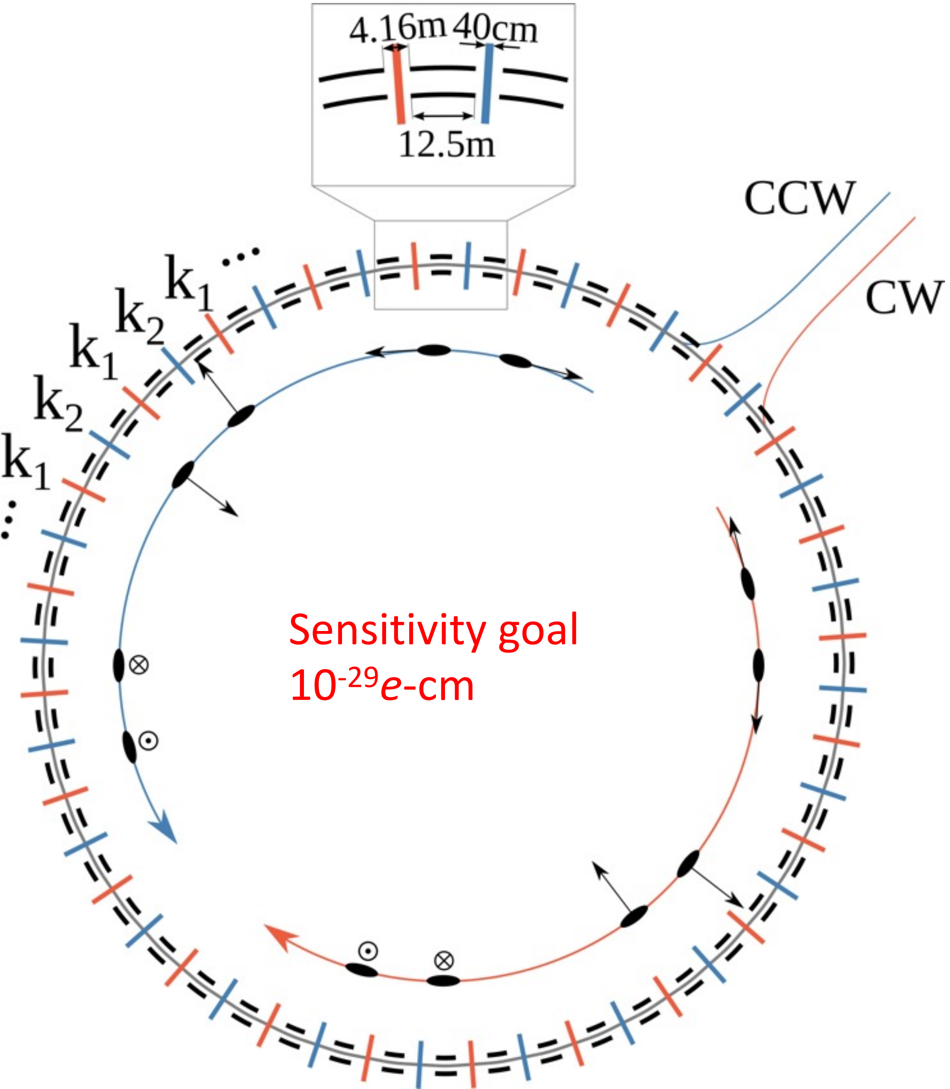
Symmetries against systematic errors

- 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, spin-based alignment, quad current flipping
  - Geometrical phases; High-order vertical E-fields



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

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



Sensitivity goal 10^{-29}*e*-cm

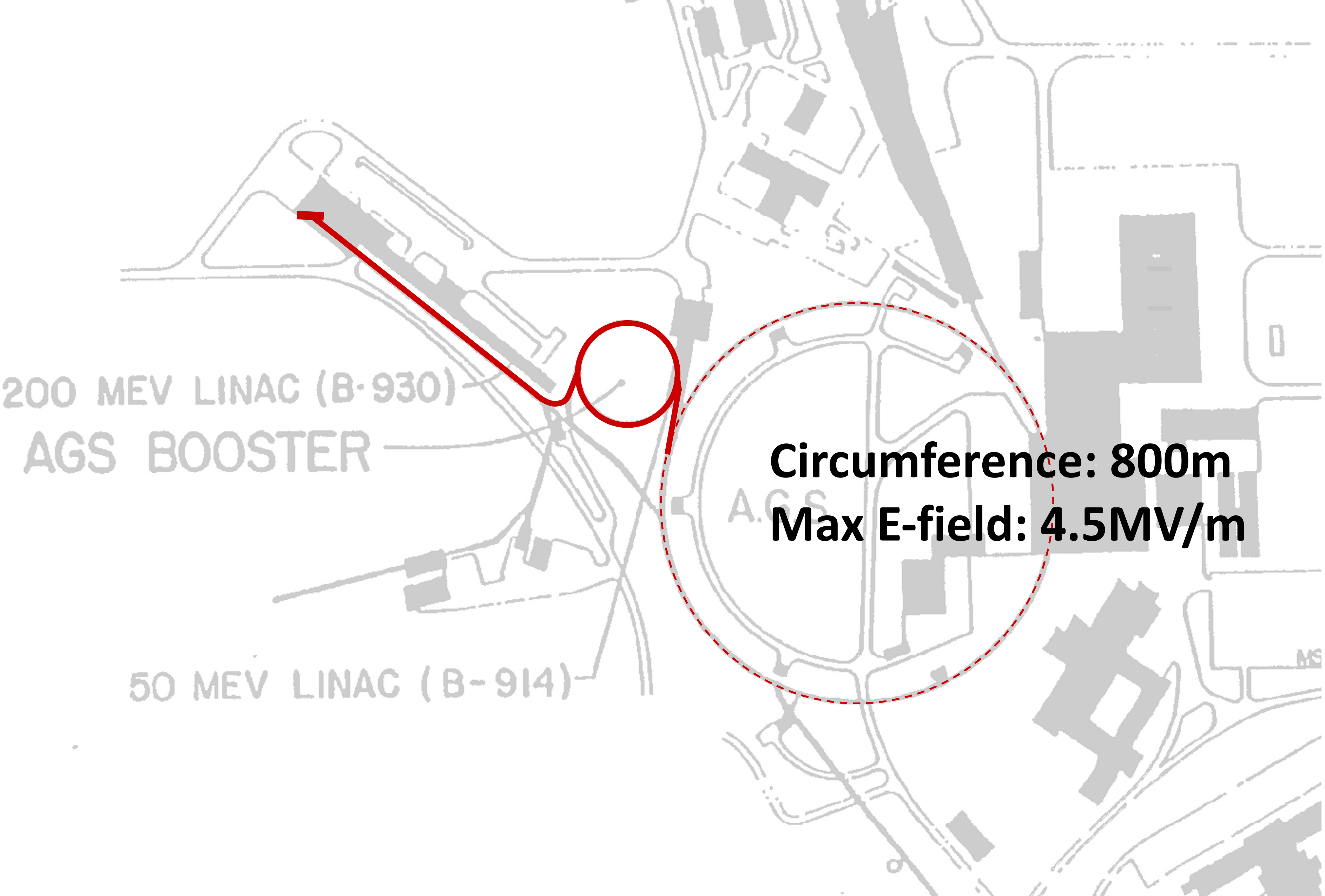
TABLE I. Ring and beam parameters for Symmetric Hybrid ring design

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
$\beta_x^{\max}$, $\beta_y^{\max}$	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

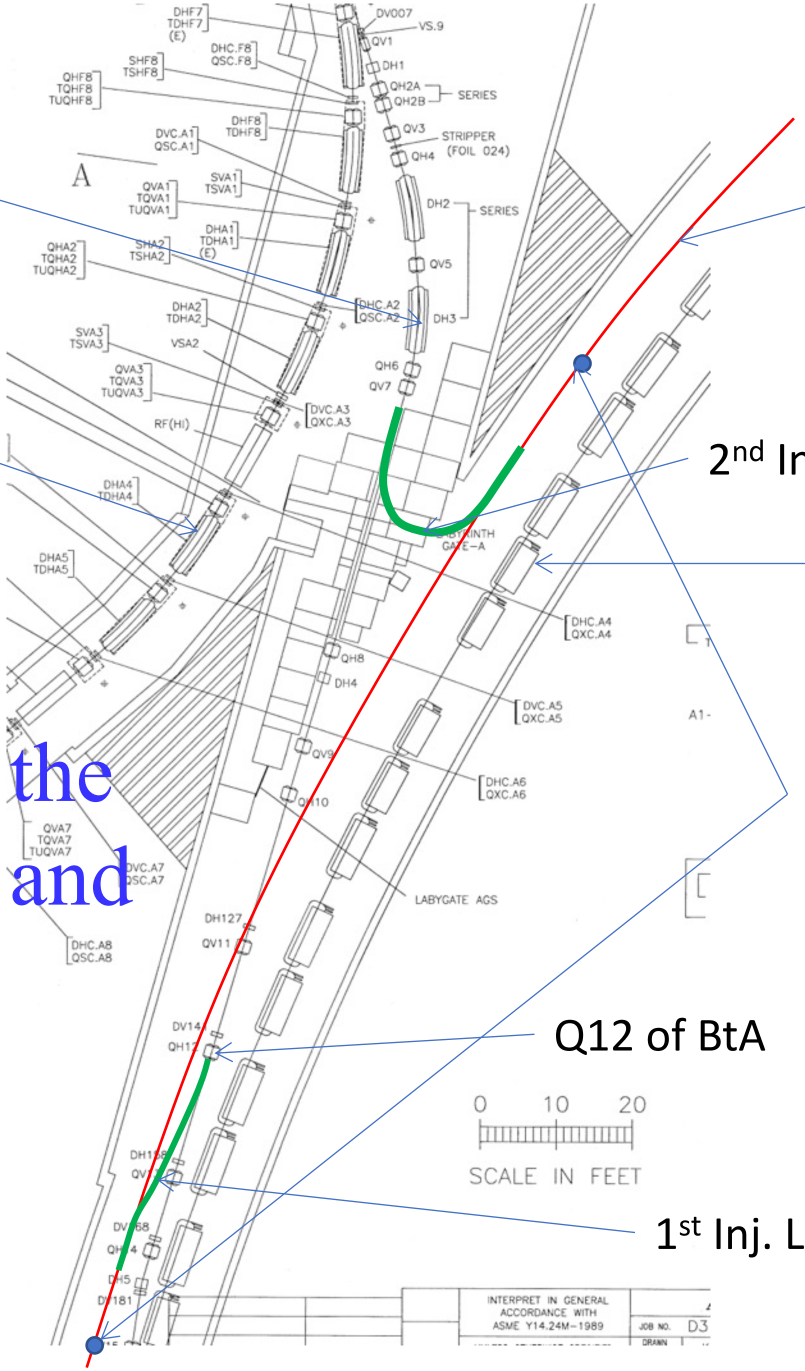
Strong focusing

The proton EDM in the AGS tunnel at BNL



Circumference: 800m
Max E-field: 4.5MV/m

Phase-space matched injection from Booster to the proton EDM ring studied and shown to be possible.



Booster-to-AGS BtA

Booster

Proposed EDM Ring

2^{nd} Inj. Line

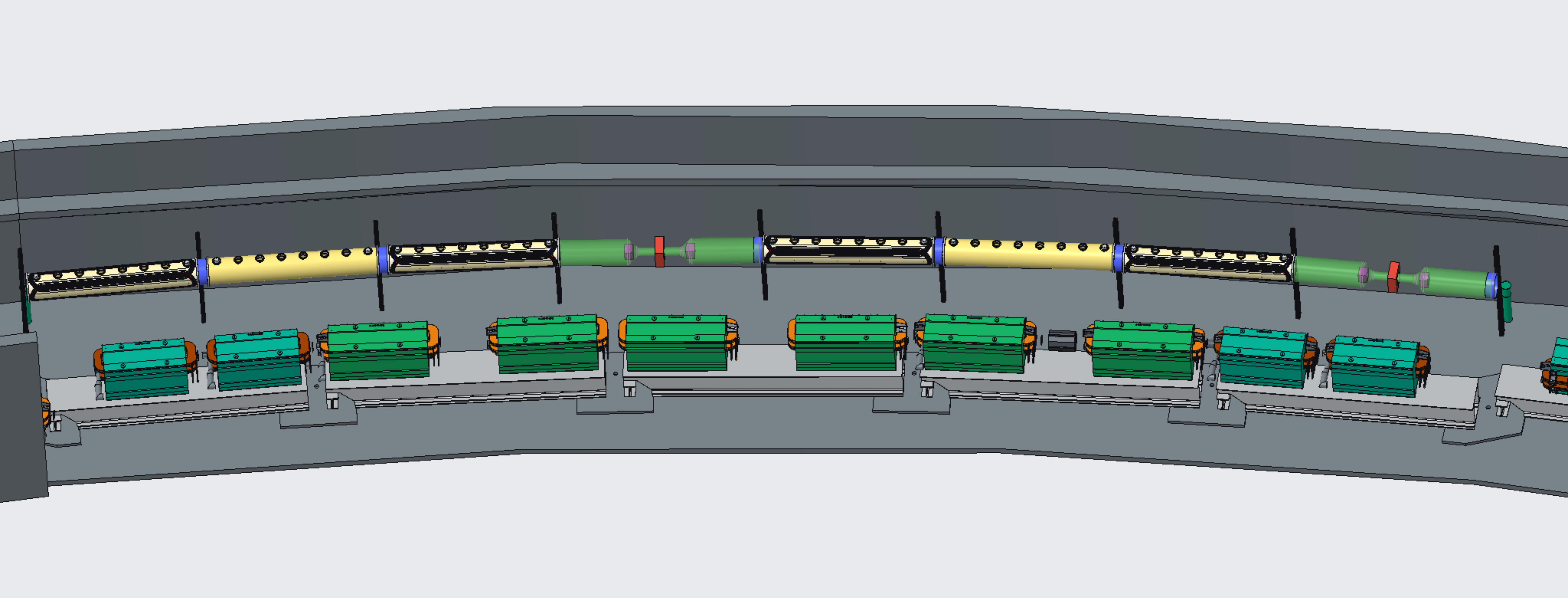
AGS

Beam Injection points

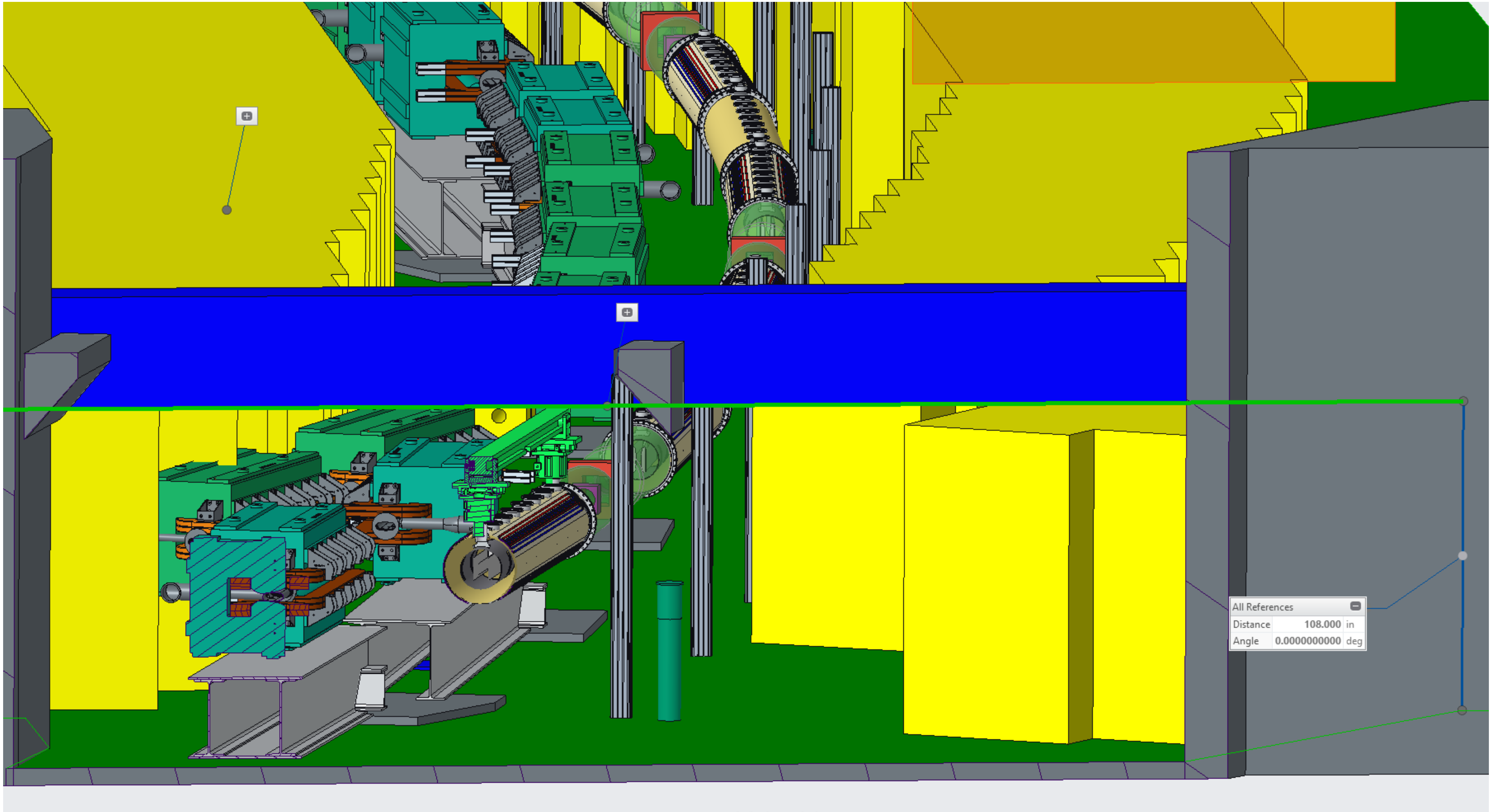
Q12 of BtA

1^{st} Inj. Line

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



1/24 section (15°) of pEDM ring

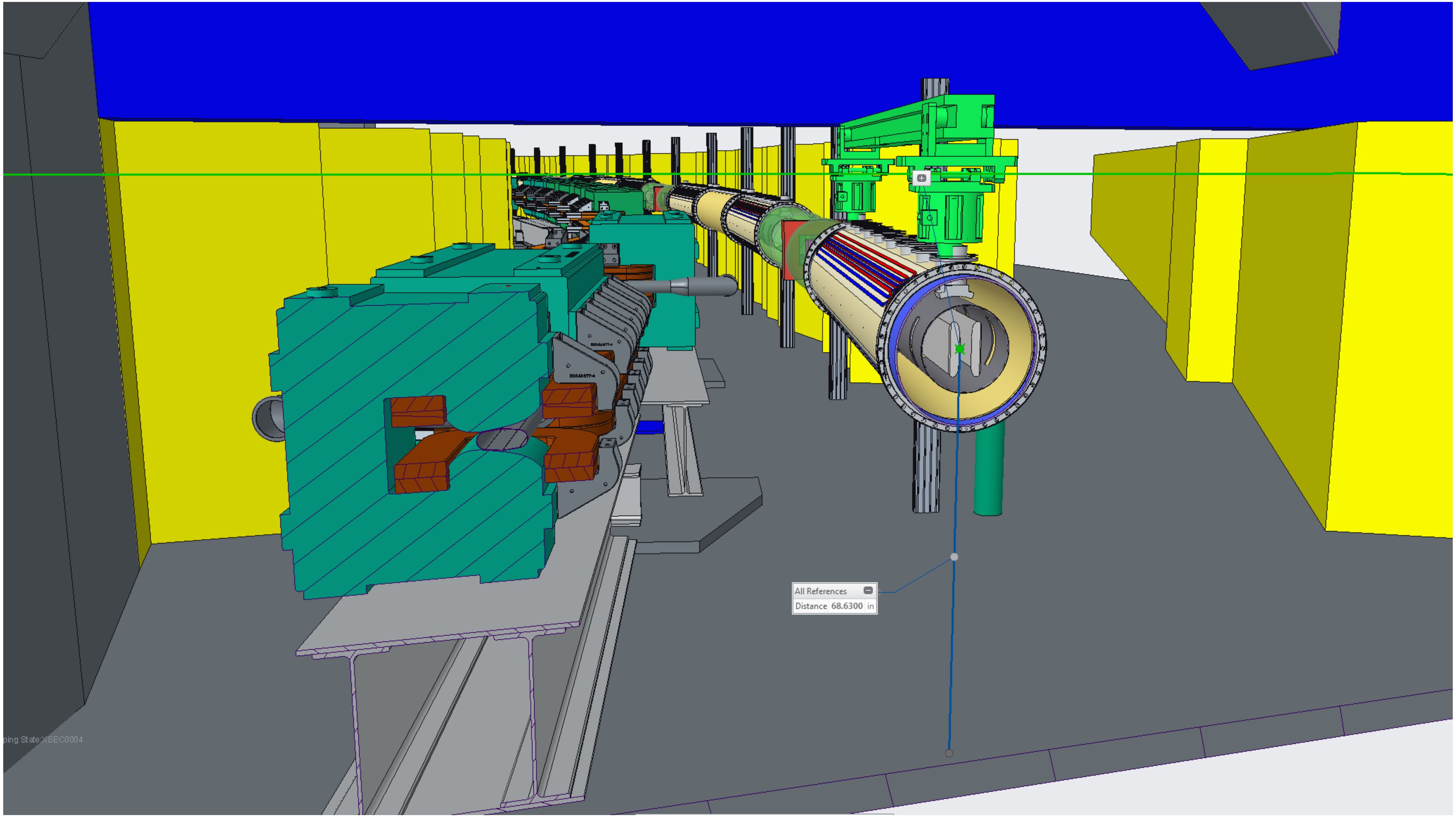


Distance 108.000 in

Angle 0.0000000000 deg

Section at F20 experimental blockhouse

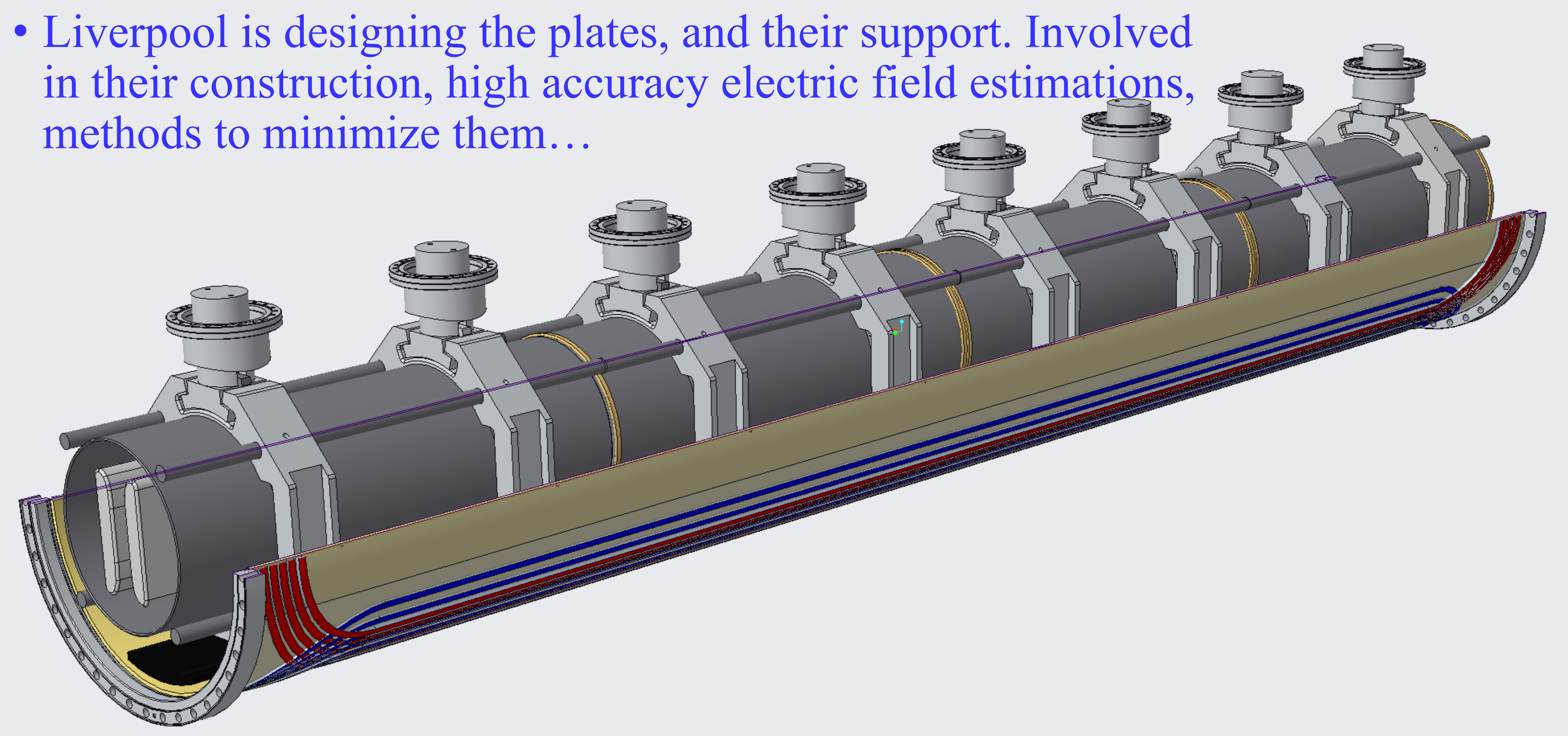
Note: ceiling elevation = 108” (9’-0”)



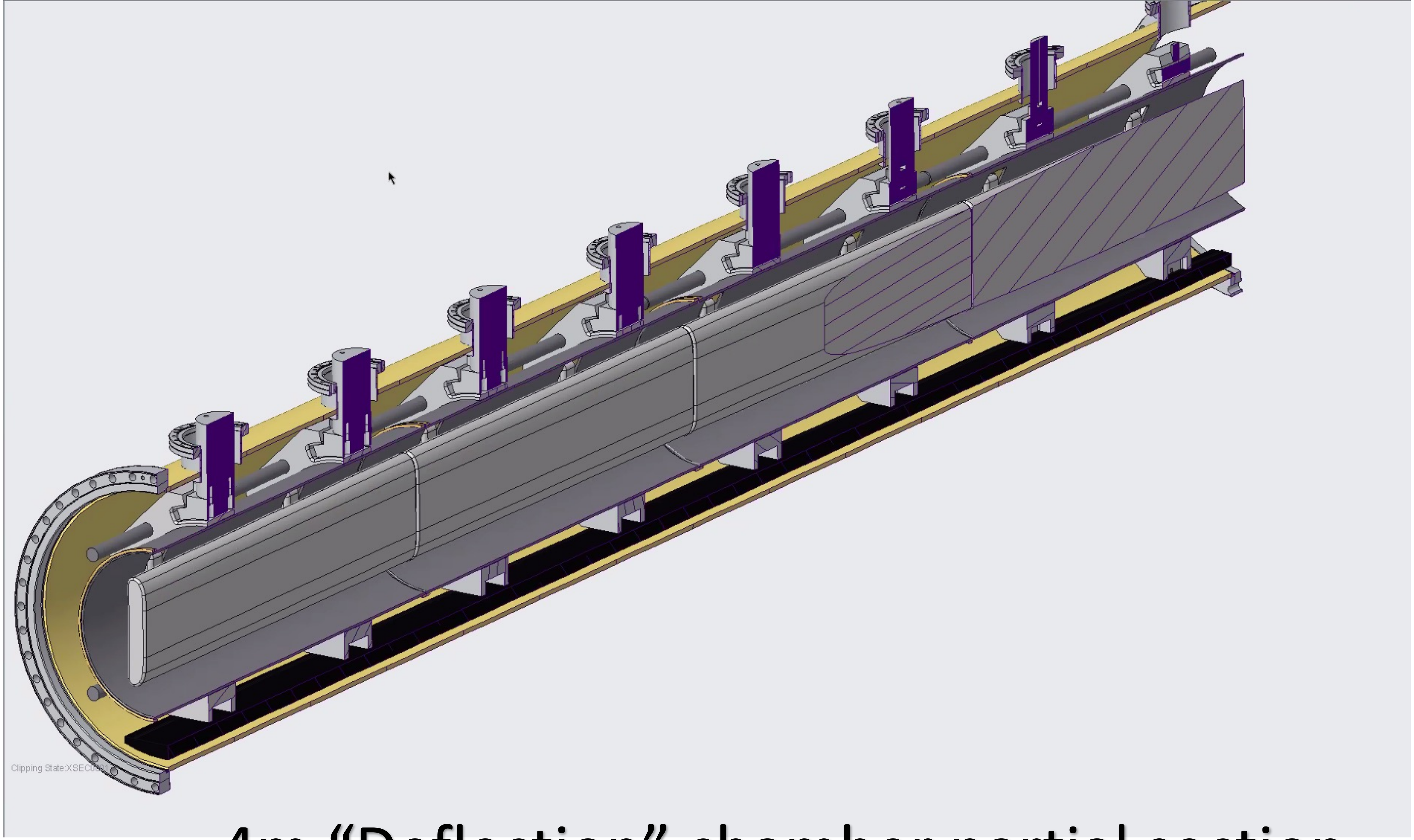
Section at F20 experimental blockhouse

Note: preliminary ring elevation (centerline) = 68.63”

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



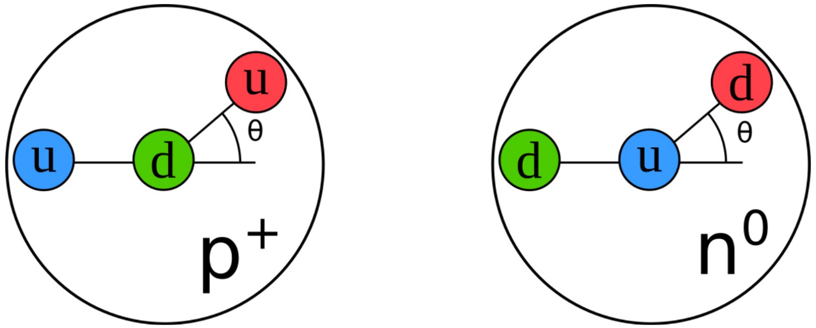
4m “Deflection” chamber partial section



4m “Deflection” chamber partial section

Strong CP-problem: the neutron EDM is too small…

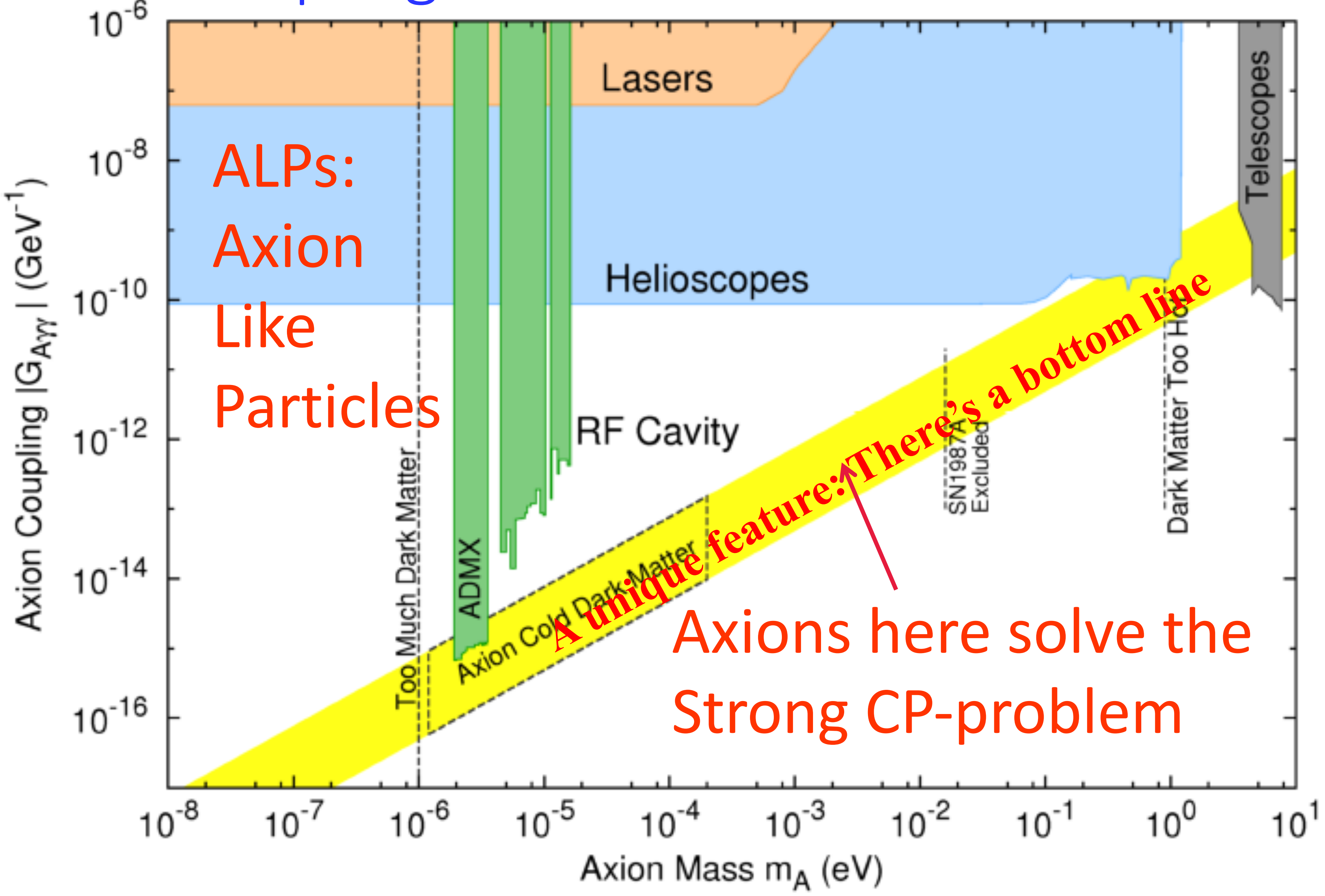
Roberto Peccei
(1942-2020)



$$L_{QCD,\bar{\theta}} = \left(\bar{\theta} - \frac{a(x)}{f_a} \right) \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

- Peccei-Quinn: θ_{QCD} is a dynamical variable (1977), *$a(x)/f_a$*. It goes to zero naturally.
- Weinberg and Wilczek pointed out that a new particle must exist, axion.

Axion coupling vs. axion mass

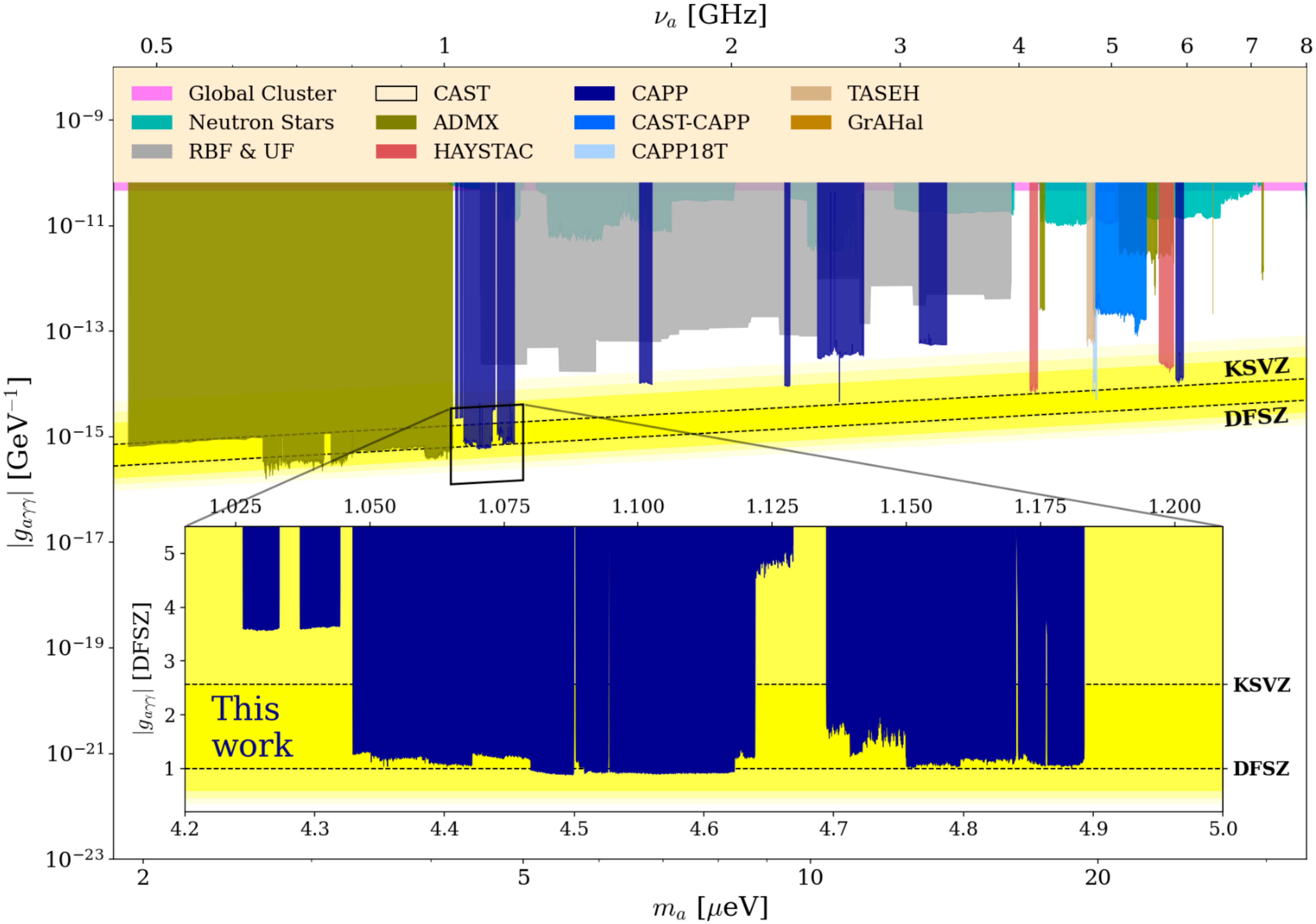


ALPs:
Axion
Like
Particles

A unique feature: There's a bottom line

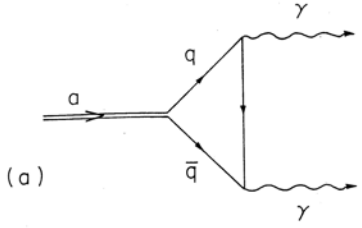
Axions here solve the Strong CP-problem

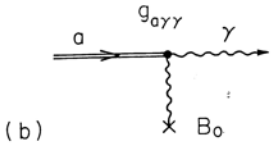
IBS-CAPP, May 2023



Scanned ~120 MHz. Currently, running at 1.2-1.5 GHz (2023) with DFSZ sensitivity

Axion Couplings





- Gauge fields:
  - Electromagnetic fields (microwave cavities)
  - $$L_{\text{int}} = -\frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$
  - Gluon Fields (Oscillating EDM: CASPEr, storage ring EDM)

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

- Fermions (coupling with axion field gradient, pseudomagnetic field, CASPEr-Electric, ARIADNE; GNOME)

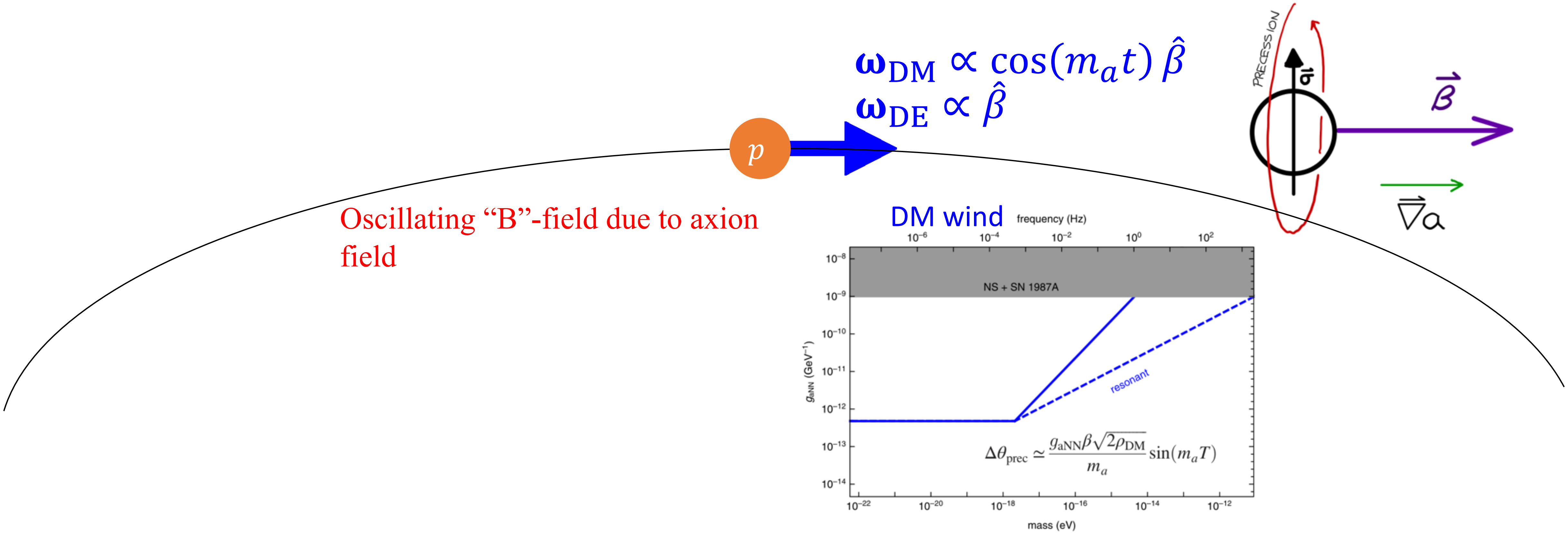
$$L_{\text{int}} = \frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

Storage ring probes of DM/DE

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

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

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



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

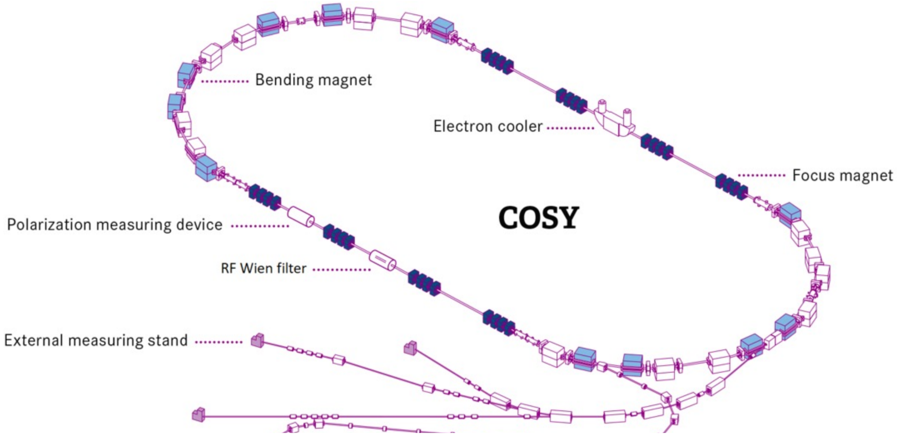
Oscillating “B”-field due to axion field

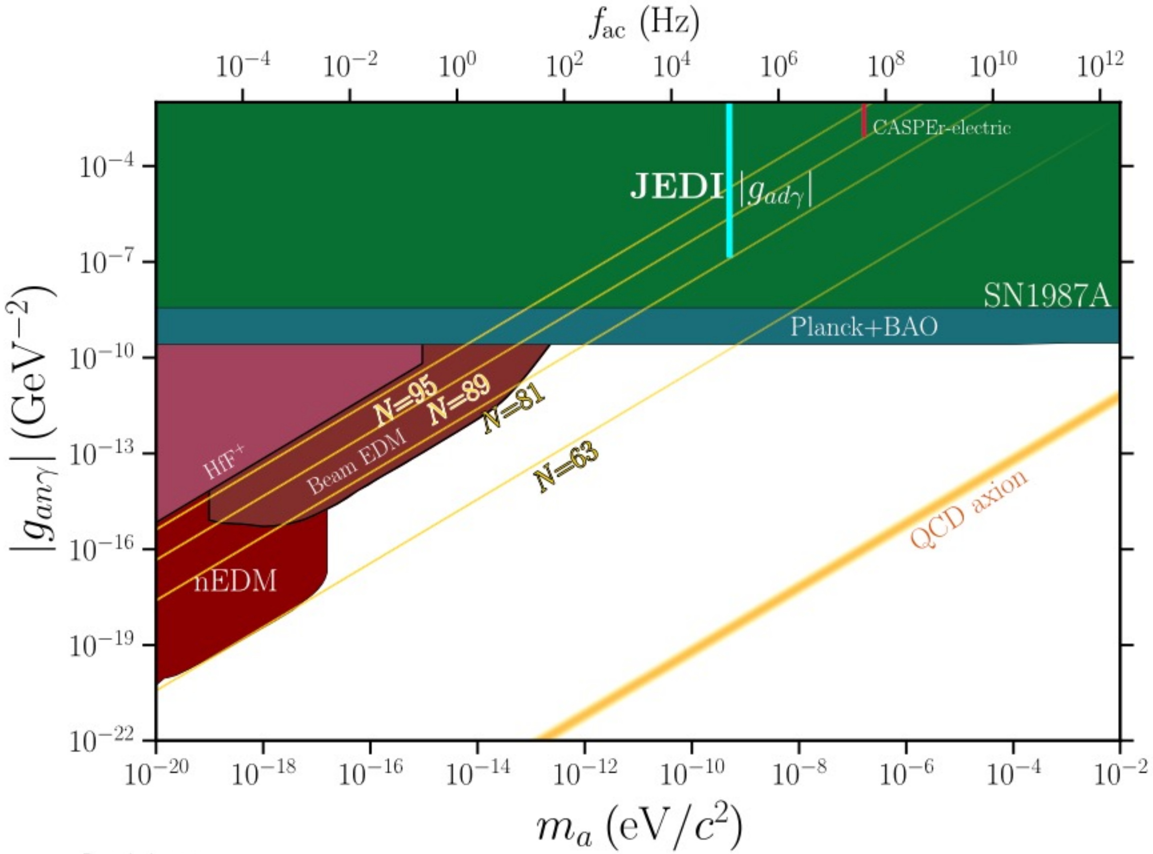
DM wind

$$\Delta\theta_{\mathrm{prec}} \simeq \frac{g_{\mathrm{aNN}}\beta\sqrt{2\rho_{\mathrm{DM}}}}{m_a}\sin(m_a T)$$

Axion dark matter search in storage rings

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





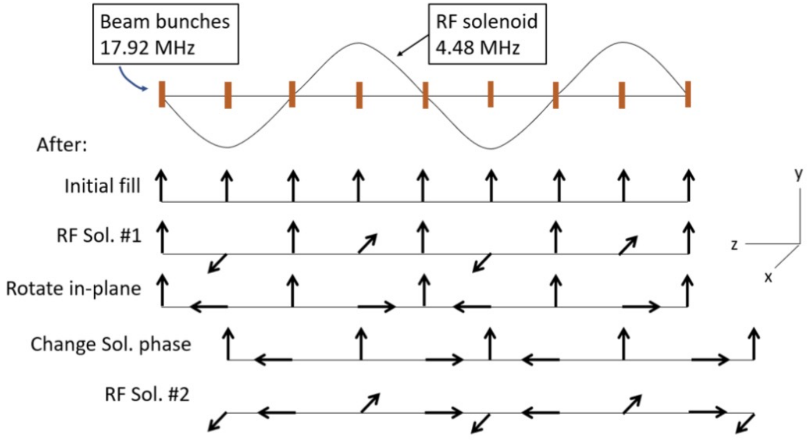
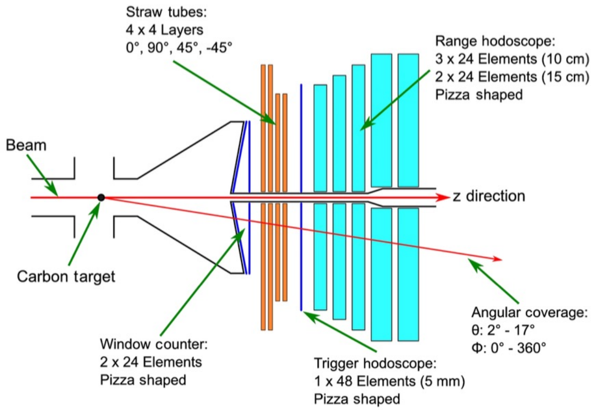


Figure 4: The figure illustrates the steps needed to produce in-plane polarization in four directions. The stored beam in, e.g., the CW direction, has all bunches polarized in the vertical direction, represented by the vertical arrows in line 1 (labeled "Initial fill"). The RF-solenoid is powered to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

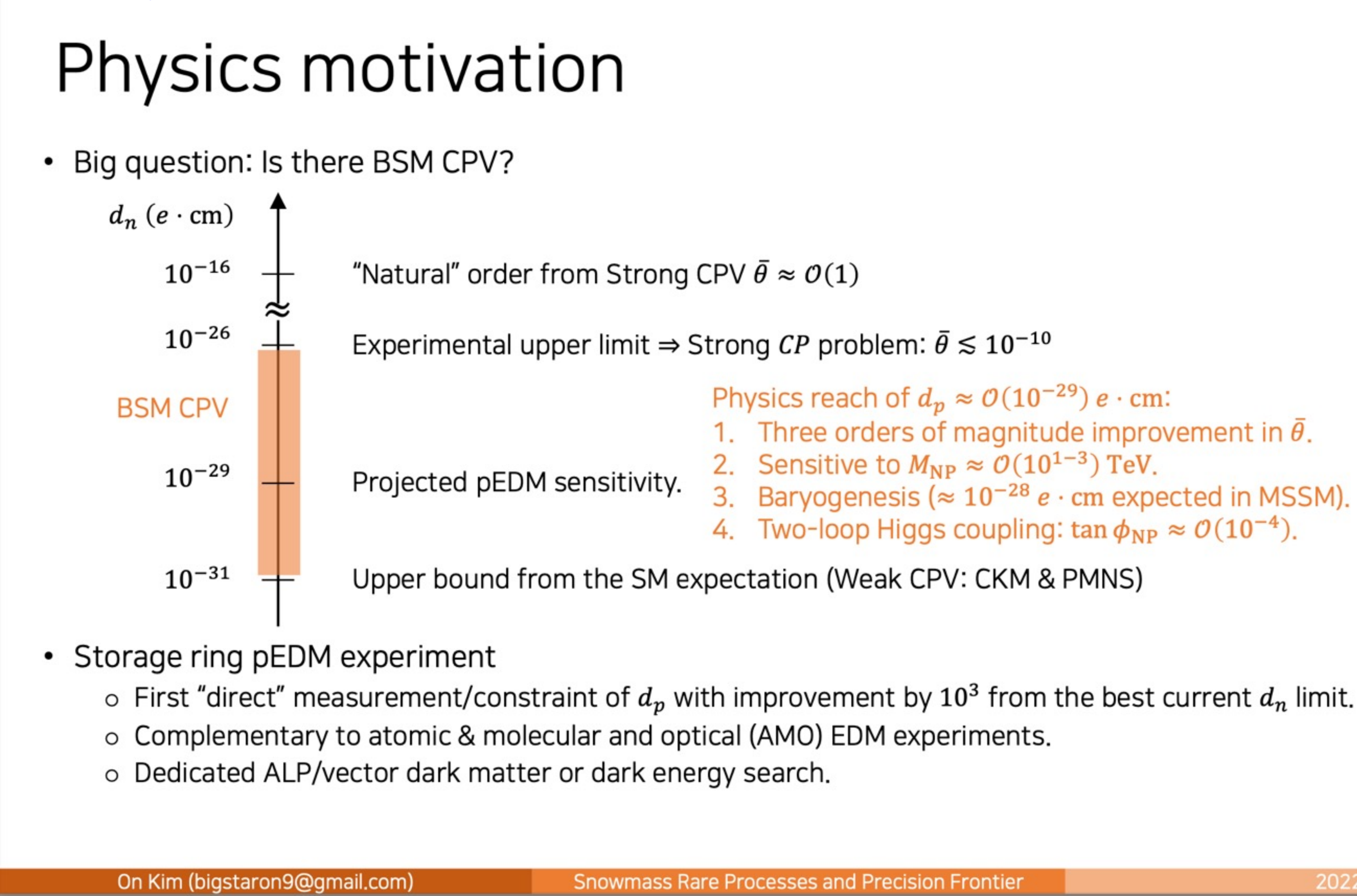


When the particle g-2 frequency is in resonance with the axion dark matter frequency, then the spin precesses in the vertical direction

The storage ring EDM Physics

Two main physics goals of pEDM

- CP-violation probing New Physics up to 10^3 TeV
- θ_{QCD} and axion dark matter



Physics motivation

- Big question: Is there BSM CPV?

$d_n\ (e \cdot \mathrm{cm})$

10^{-16} "Natural" order from Strong CPV $\bar{\theta} \approx \mathcal{O}(1)$

10^{-26} Experimental upper limit ⇒ Strong CP problem: $\bar{\theta} \lesssim 10^{-10}$

BSM CPV

10^{-29} Projected pEDM sensitivity.

Physics reach of $d_p \approx \mathcal{O}(10^{-29})\ e \cdot \mathrm{cm}$:

1. Three orders of magnitude improvement in $\bar{\theta}$.
2. Sensitive to $M_{NP} \approx \mathcal{O}(10^{1-3})$ TeV.
3. Baryogenesis ($\approx 10^{-28}\ e \cdot \mathrm{cm}$ expected in MSSM).
4. Two-loop Higgs coupling: $\tan\phi_{NP} \approx \mathcal{O}(10^{-4})$.

10^{-31} Upper bound from the SM expectation (Weak CPV: CKM & PMNS)

- Storage ring pEDM experiment
  - First "direct" measurement/constraint of d_p with improvement by 10^3 from the best current d_n limit.
  - Complementary to atomic & molecular and optical (AMO) EDM experiments.
  - Dedicated ALP/vector dark matter or dark energy search.

On Kim (bigstaron9@gmail.com) Snowmass Rare Processes and Precision Frontier 2022 July 20th 9

arXiv:2205.00830v1 [hep-ph] 25 Apr 2022

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]

[1] *Aristotle University of Thessaloniki, Thessaloniki, Greece*
[2] *Argonne National Laboratory, Lemont, Illinois, USA*
[3] *Boston University, Boston, Massachusetts, USA*
[4] *Brookhaven National Laboratory, Upton, New York, USA*
[5] *Budker Institute of Nuclear Physics, Novosibirsk, Russia*
[6] *Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon, Korea*
[7] *Cornell University, Ithaca, New York, USA*
[8] *Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
[9] *Helmholtz-Institute Mainz, Johannes Gutenberg University, Mainz, Germany*
[10] *Indiana University, Bloomington, Indiana, USA*
[11] *Istanbul Technical University, Istanbul, Turkey*

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

- High physics reach at hundreds of TeV New-Physics mass scale, improve sensitivity to θ_{QCD} by three orders of magnitude. Best sensitivity to Higgs CPV

- If found, it can help explain the matter-antimatter asymmetry of the universe

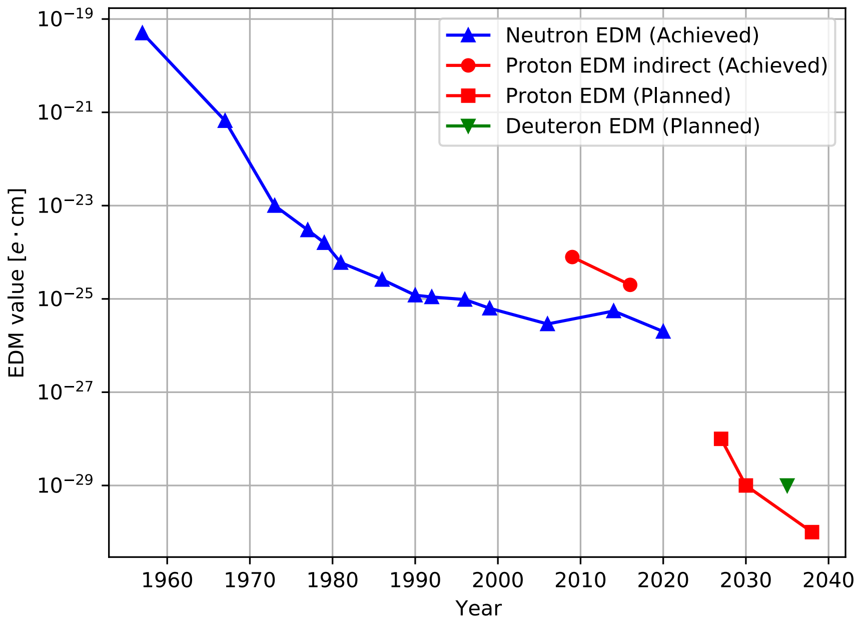
- Direct search for low/very low frequency axion dark matter

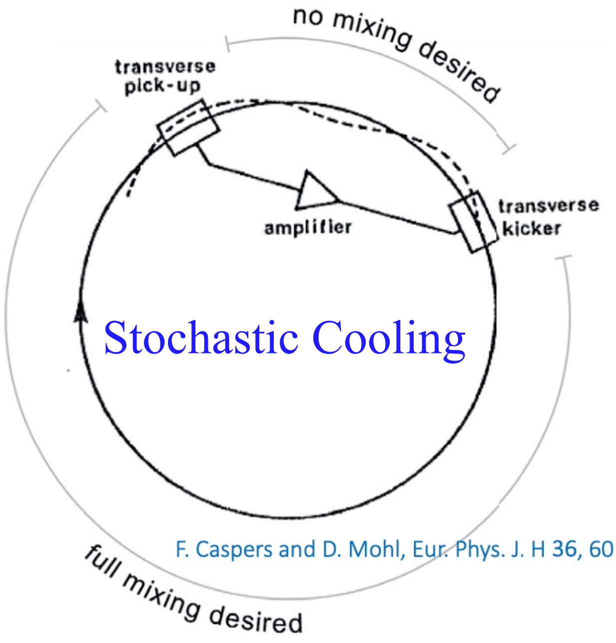
- The opportunity: High intensity polarized proton and deuteron beams available. The natural beam lifetime is also long, potential for very high statistical accuracy

- The challenge: Systematics, mostly related to ring alignment, high statistical accuracy helps...

Status of pEDM at BNL

- BNL cost estimate: $140-190M for a ring at AGS tunnel. Schedule compatible with EIC.
- BNL approved a three-year LDRD on electric field plate development (High Voltage, support structure), vacuum, stochastic cooling (SC).
- Project is part of the P5 deliberations, expect announcement Dec. 7, 2023.
- A long road to final sensitivity, but confident we can reach the goals based on muon g-2, … experience.





Stochastic Cooling

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

Summary

- ✓EDM physics is must do, exciting and timely, CP-violation, ~10^3 TeV New-Physics reach, Unique axion physics, DM/DE. Effort level similar to muon g-2.

- ✓Hybrid, symmetric ring lattice and spin-based alignment. Minimized systematic error sources. Statistics and systematics of pEDM to better than 10^{-29}*e*-cm.

- ✓Snowmass encouraged BNL to come up with a technically strong proposal for a storage ring proton EDM. BNL funded the cost estimate of the experiment. Next, critical, do well in P5 process (Dec. 11, 2023 is the report announcement meeting date). Need strong support to finish all studies, TDR → proposal → construction.

- ✓Great progress in statistics and systematics promises two to three orders improvement in sensitivity of eEDM, nEDM, μEDM, and pEDM/dEDM within the current and next decade. Very exciting!

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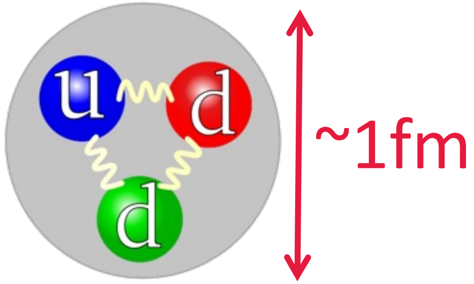
14. N.P.M. Brantjes *et al.,* Correction systematic errors in high-sensitivity deuteron polarization measurements, Nucl. Instrum. Meth. A664, 49 (2012)
15. G.W. Bennett *et al.,* An improved limit on the muon electric dipole moment, Phys. Rev. D 80, 052008 (2009)
16. F.J.M. Farley *et al.,* A new method of measuring electric dipole moments in storage rings, Phys. Rev. Lett. 93, 052001 (2004)
17. …

Extra slides

Strong CP-problem and neutron EDM

$$L_{QCD,\bar{\theta}} = \bar{\theta}\ \frac{g^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$



Dimensional analysis (naïve) estimation of the neutron EDM:

$$d_n\left(\bar{\theta}\right) \sim \bar{\theta}\,\frac{e}{m_n}\frac{m_*}{\Lambda_{QCD}} \sim \bar{\theta}\cdot\left(6\times 10^{-17}\right)\mathrm{e\cdot cm}, \quad m_* = \frac{m_u m_d}{m_u + m_d}$$

$$d_n\left(\bar{\theta}\right) \approx -d_p\left(\bar{\theta}\right) \approx 3.6\times 10^{-16}\,\bar{\theta}\ \mathrm{e\cdot cm}$$

M. Pospelov,
A. Ritz, Ann. Phys.
318 (2005) 119.

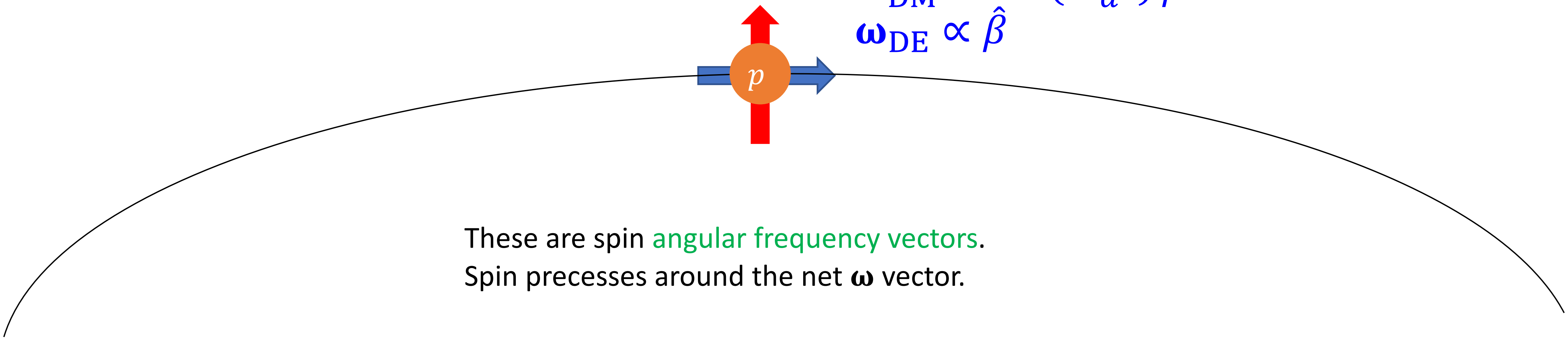
$$\text{Exp.:}\ d_n < 3\times 10^{-26} e\cdot\mathrm{cm} \rightarrow \bar{\theta} < 10^{-10}$$

In simple terms: the theory of strong interactions demands a large neutron EDM. Experiments show it is at least ~9-10 orders of magnitude less! WHY?

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


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

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

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

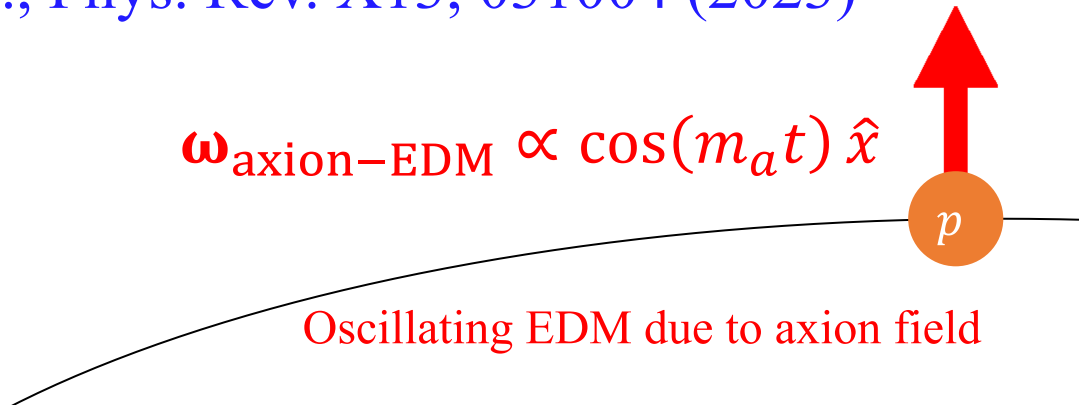
These are spin angular frequency vectors.
Spin precesses around the net $\boldsymbol{\omega}$ vector.

Storage ring probes of DM/DE

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

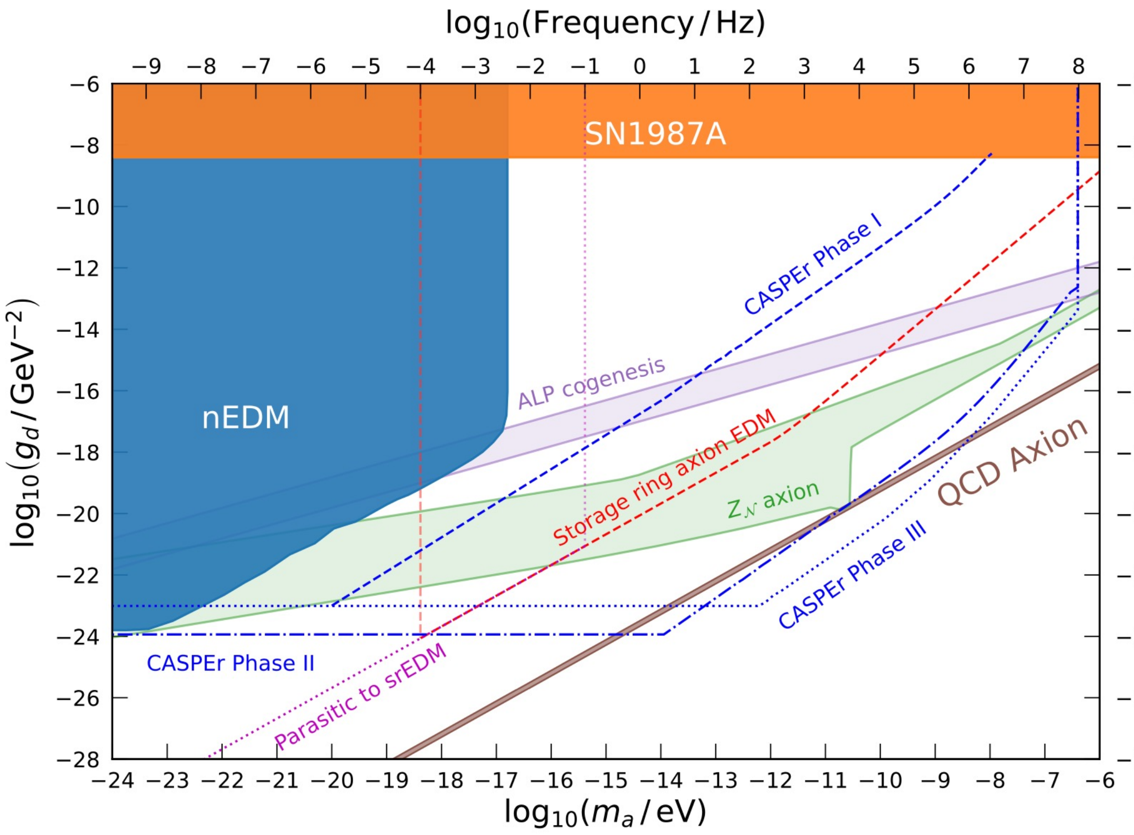
- Couplings with dark matter (DM) and dark energy (DE)
  - ○ ALP DM-EDM ($g_{aN\gamma} a \hat{\sigma}_N \cdot \mathbf{E}$) $\Rightarrow$ oscillating EDM at m_a. For the QCD axion: $d_N^{\text{QCD}} \approx 10^{-34} \cos(m_a t)\ e \cdot \text{cm}$.

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



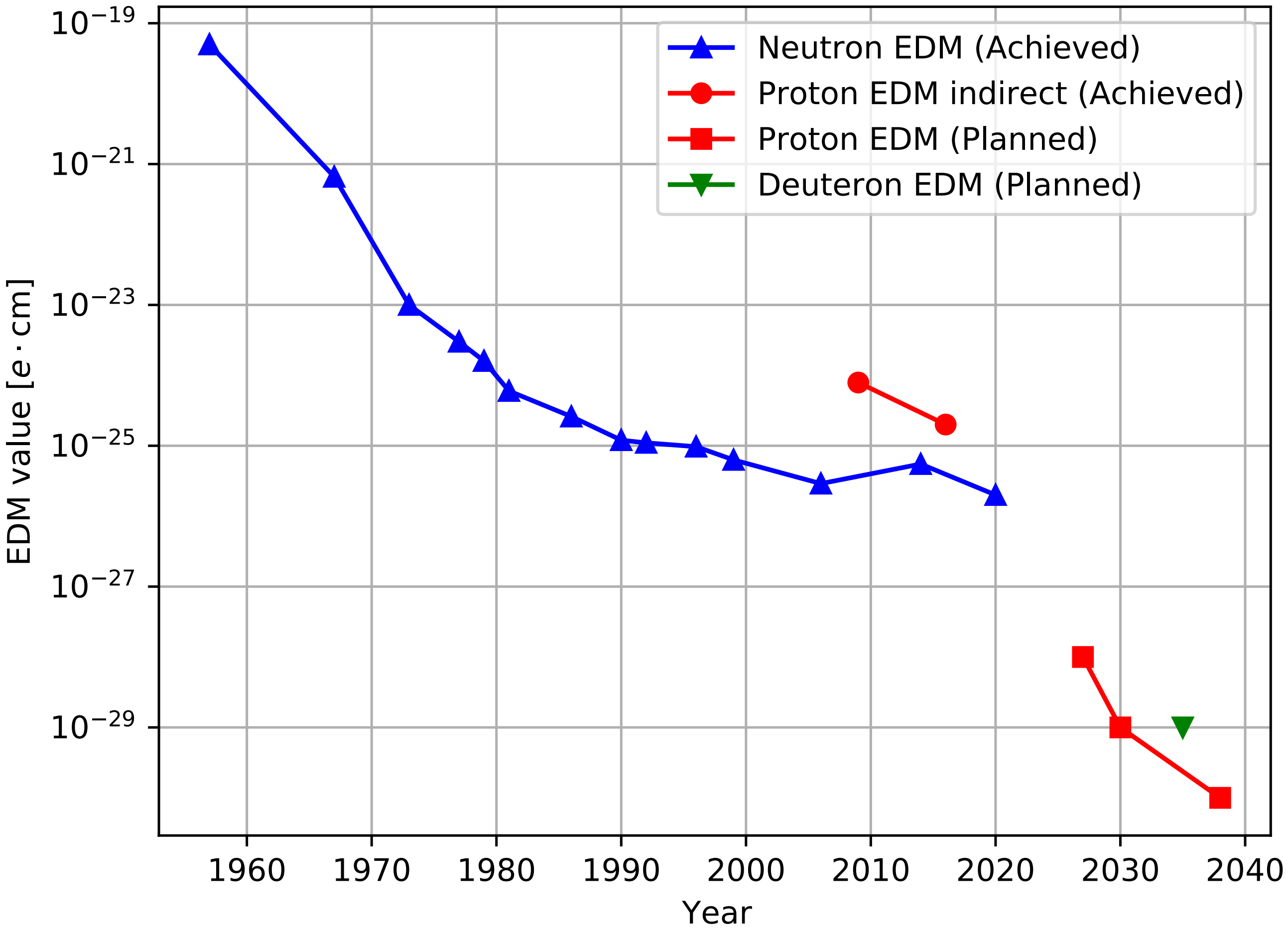
- Storage ring probes of axion-induced oscillating EDM
  S. Chang *et al.*, PRD **99**, 083002 (2019).
- Complementary method using an rf Wien filter
  On Kim and Y. Semertzidis, PRD **104**, 096006 (2021)
- Parasitic measurement with pEDM experiment
  - ○ Low frequency: Periodogram analysis.
  - ○ High frequency: Resonant rf Wien filter.

ALP-EDM coupling



Timeline

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



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 (using B_r)
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 beam/spin simulations, efficient software	Low. Cross-checking our results routinely with independent programs and by several teams
Polarimeter	Low. Mature technology available

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

Protons in a hybrid-symmetric ring: no new technology required

- No need to develop/test new technology
  - Simultaneous CW/CCW beam storage is possible
  - Electric field ~4.5 MV/m with present technology
  - 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.

- Do a “lattice string test”, assemble 1/48th of the ring and test for
  - Cross talk between systems (E-field bending plates, magnetic quads, BPMs,…)
  - Time stability of voltage, position and direction of fields
  - Check/monitor ground stability alignment due to tides, vehicle motion, magnet powering,…

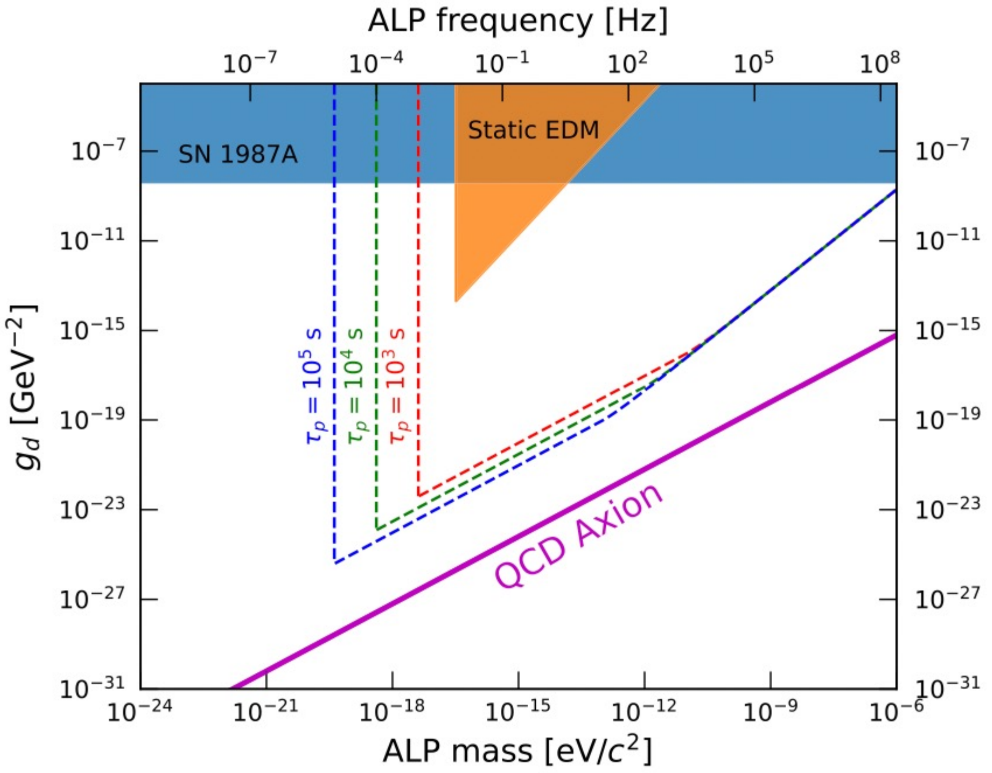
- After protons, add dipole magnetic field in bending sections:
  - Can do proton, deuteron, ^{3}He, muons,…

Storage ring proton/deuteron EDM

- Oscillating EDMs, Graham & Rajendran, PRD88, 035023, 2013
- Resonance: axion dark matter and g-2 frequencies (PRD99, 083002, 2019 and EPJ C80, 107, 2020). First run spring 2019 at COSY/Juelich/Germany.
- Storage ring probe of DM and DE (PRD103, 055010, 2021)
- New method with RF-Wien…, On Kim (PRD104, 096006, 2021), great advantage on systematic errors

The RF-Wien filter is NOT operating at the g-2 frequency, avoiding spin dynamics systematic error!

It can be fully implemented in the present muon g-2 ring by injecting polarized protons and/or deuterons



Hadronic Electric Dipole Moments

Input to hadronic EDM

- Theta-QCD (part of the SM)

- CP-violation sources beyond the SM

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

EDMs of different systems (Marciano)

θ_{QCD}:

$$d_n \simeq -d_p \simeq 3\times 10^{-16}\,\overline{\theta}\ \mathrm{e\cdot cm}$$

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

Super-Symmetry (SUSY) model predictions:

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

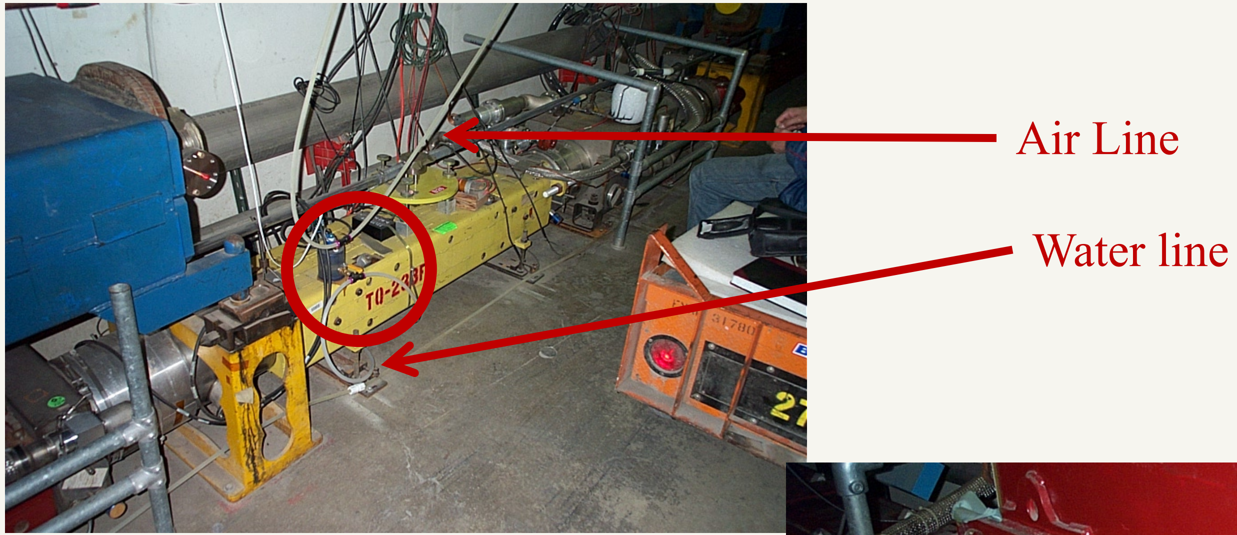
$$d_p \simeq 1.4\left(d_d - 0.25 d_u\right) + 0.83e\left(d_u^c + d_d^c\right) + 0.27e\left(d_u^c - d_d^c\right)$$

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

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

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

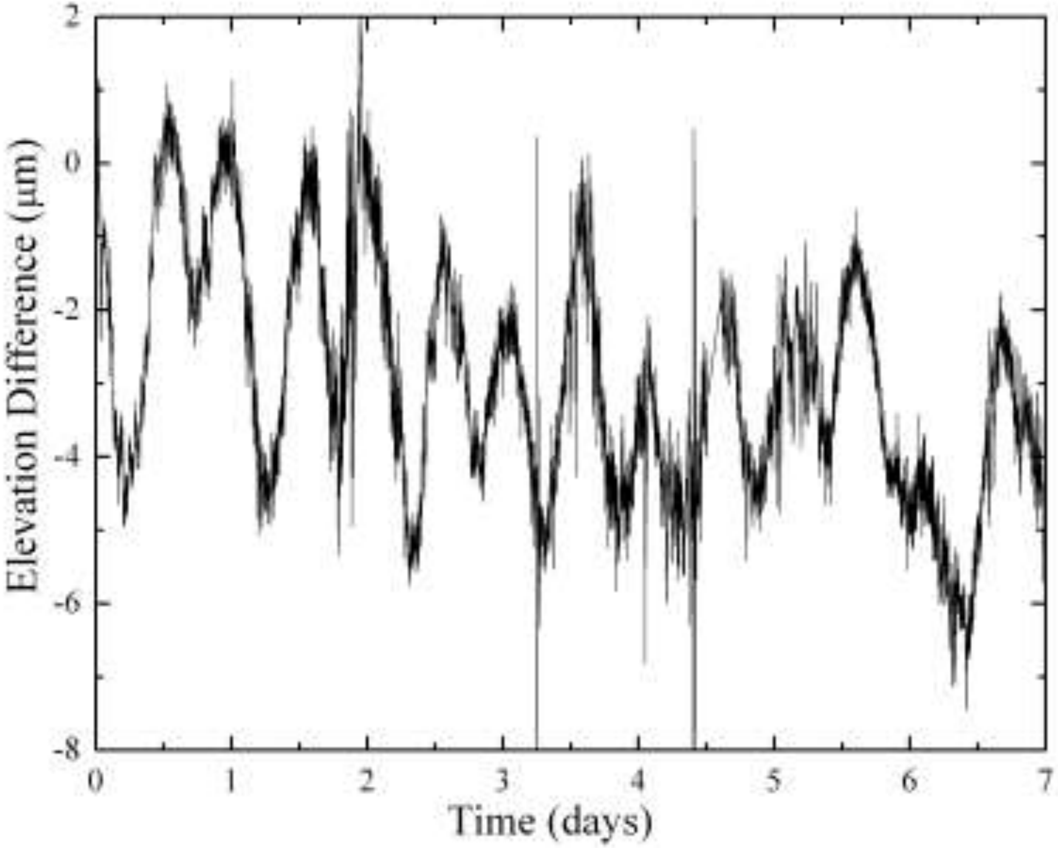
Tevatron Sensors on Quad



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

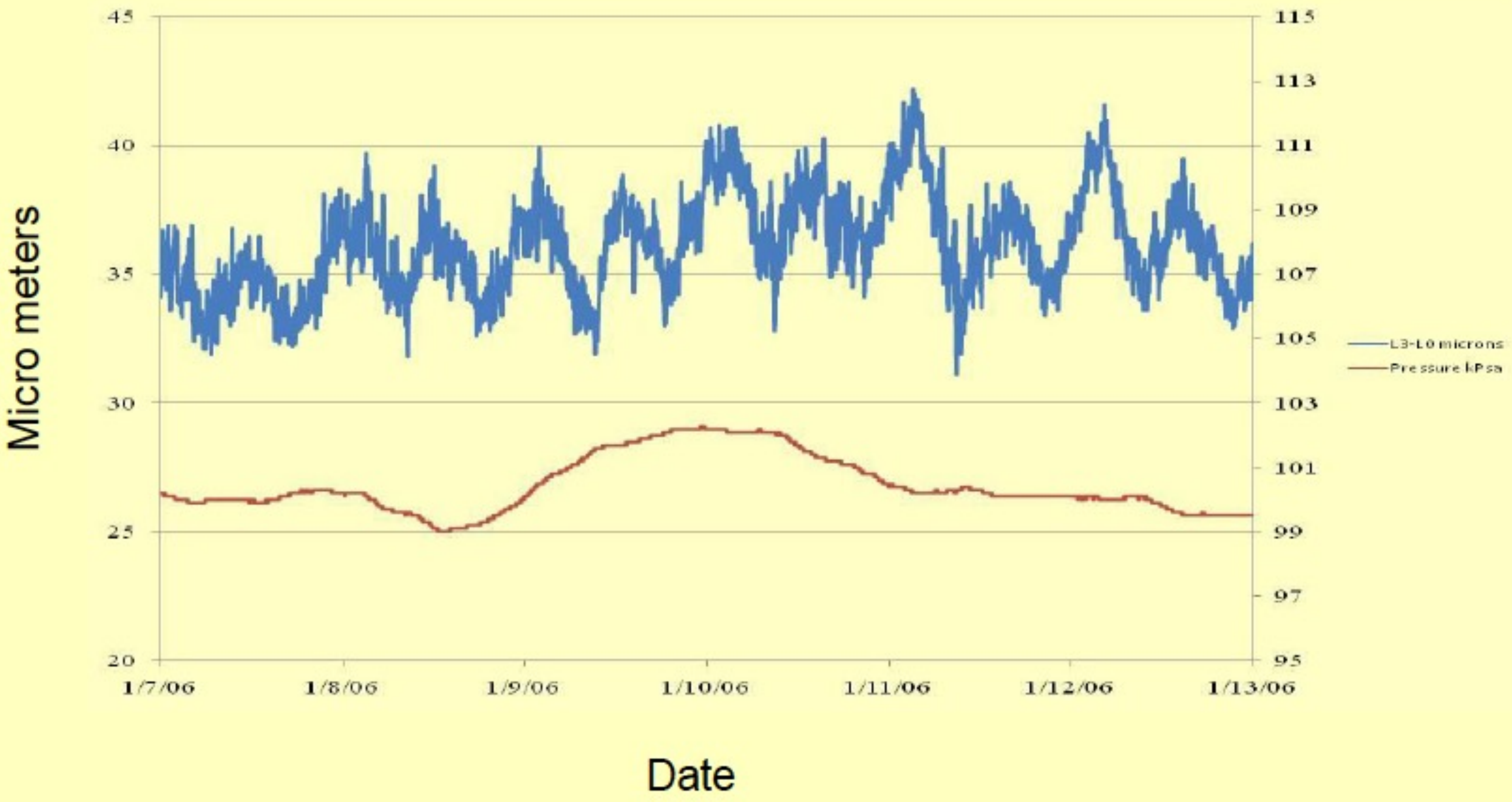
HLS measurements at Fermilab

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



MINOS Tidal Data

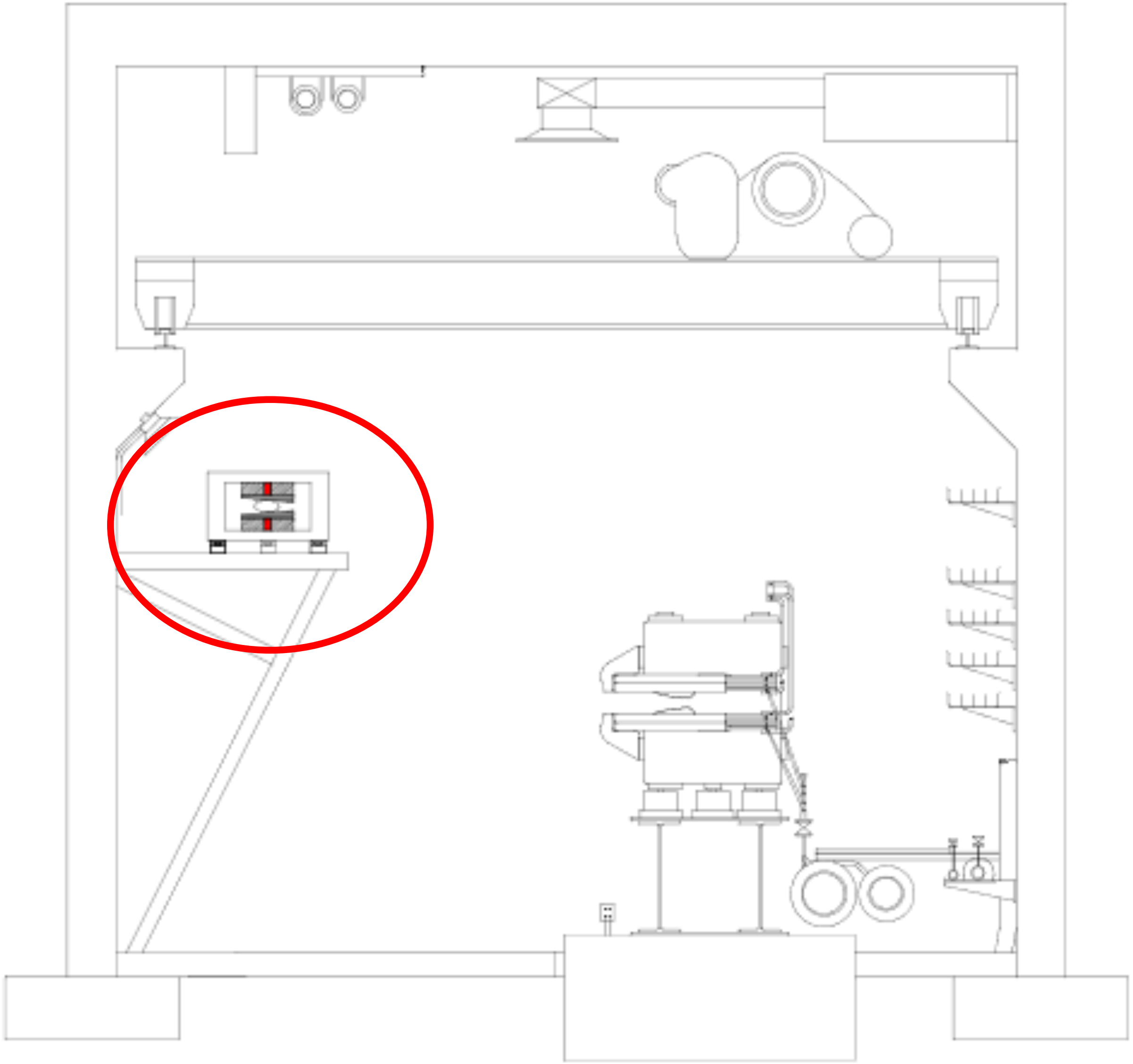
Difference in two sensors 90 meters apart



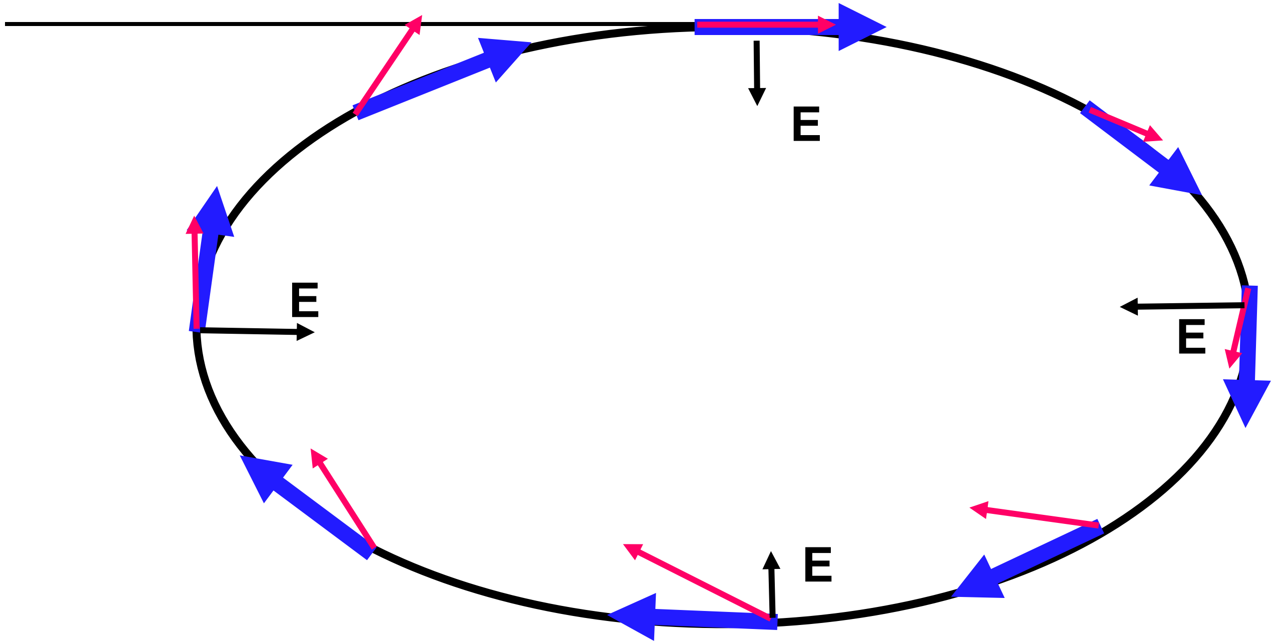
J T Volk Fermilab Dec 2008

Sketch of the AGS Accumulator Ring

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

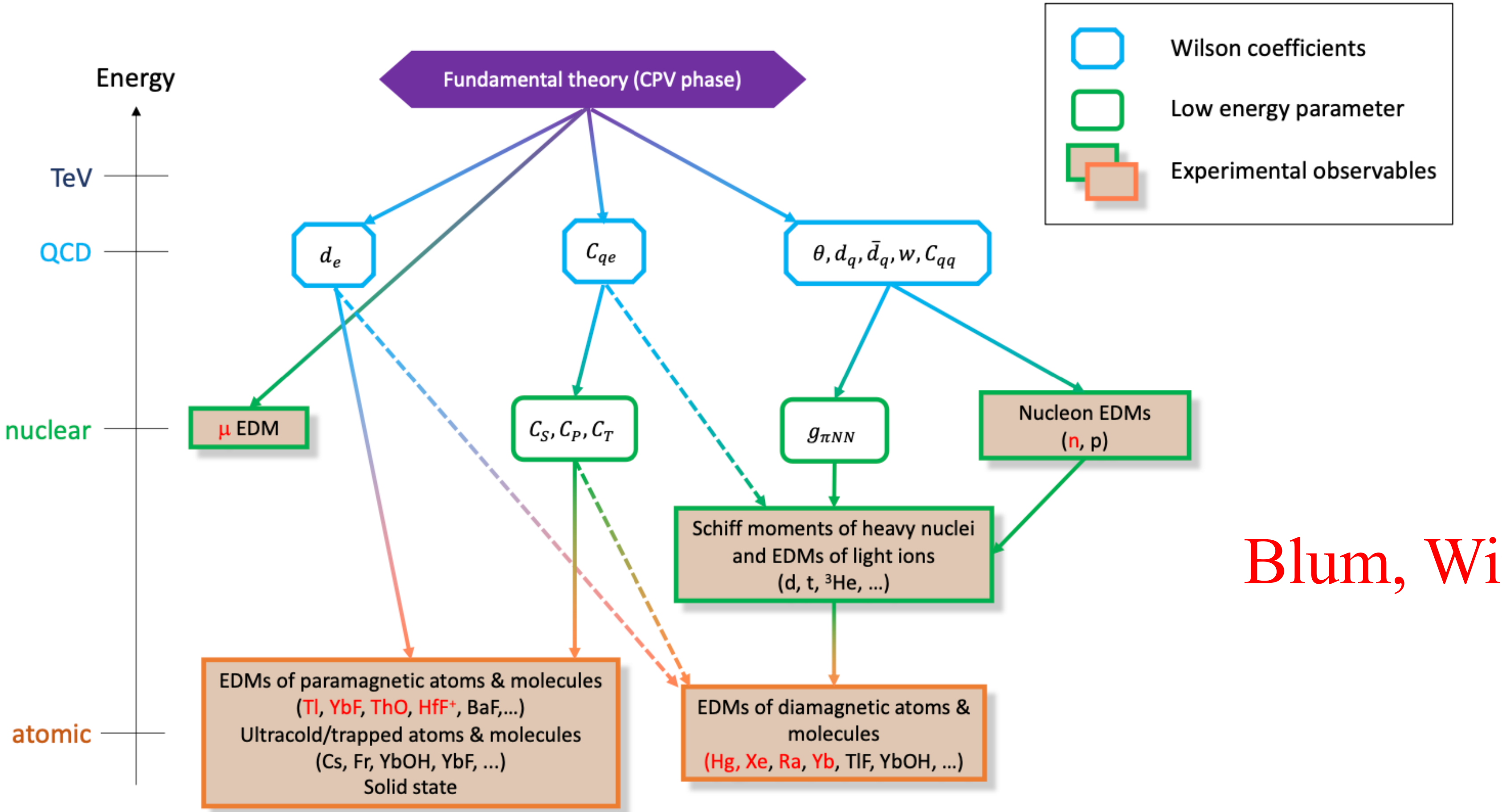


The spin precession relative to momentum in the plane is kept near zero. A vert. spin precession vs. time is an indication of an EDM (*d*) signal.



$$\vec{\omega}_a = 0 \qquad \frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

EDM theory, from Snowmass process.

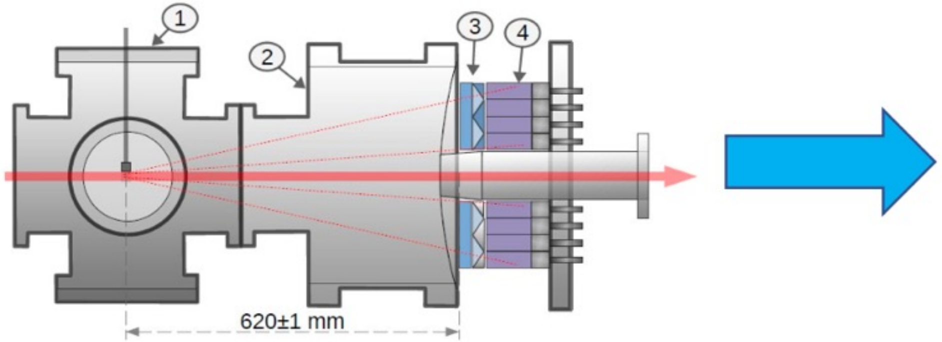


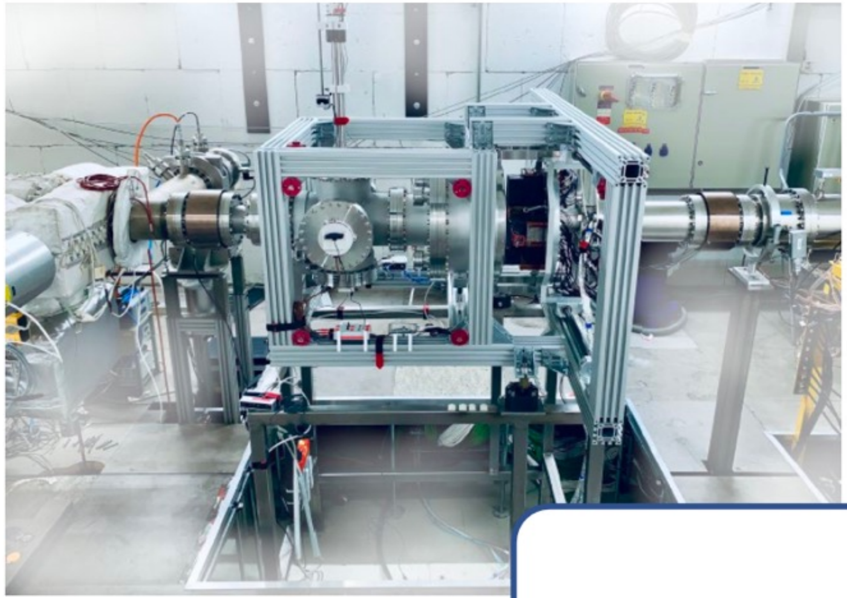
Blum, Winter *et al.*

Figure 3-2. *Flowdown diagram from the fundamental physics at high energy scales, to the Wilson coefficients of the effective field theory, low energy parameters, and the experimental CPV observables. Color outlines of the various boxes inidcate the different energy scales. Solid arrows between the boxes indicate strong connection, whereas dashed arrows indicate weaker influence onto the lower lying parameter. Experimental systems shown in red have already been used in EDM searches; those shown in black (as well as many of those in red) are being developed for future searches. This figure was adapted from [12].*

COSY results

1. With left-right detectors, forward-reverse polarization, there is enough redundancy to correct polarimeter systematic errors below 10 μrad (achieved, 4-day run). No obstacles see to further reductions to 1 μrad.[1]
2. Although unstable against depolarization, field corrections extend polarization lifetime past 1000 s.[2]
3. Feedback tied to polarization phase in plane can hold spin direction constant to within 0.1 rad.[3]
4. A polarimeter prototype works.[4]





All tests were made with 0.97 GeV/c deuteron beam.

[1] NIM A 664, 49 (2012)

[2] PRL 117, 054801 (2016)

[3] PRL 119, 014801 (2017)

[4] JINST 15, P12005 (2020)

Slide by Ed Stephenson

Polarimeter analyzing power at P_{magic} is great

Analyzing power can be further optimized

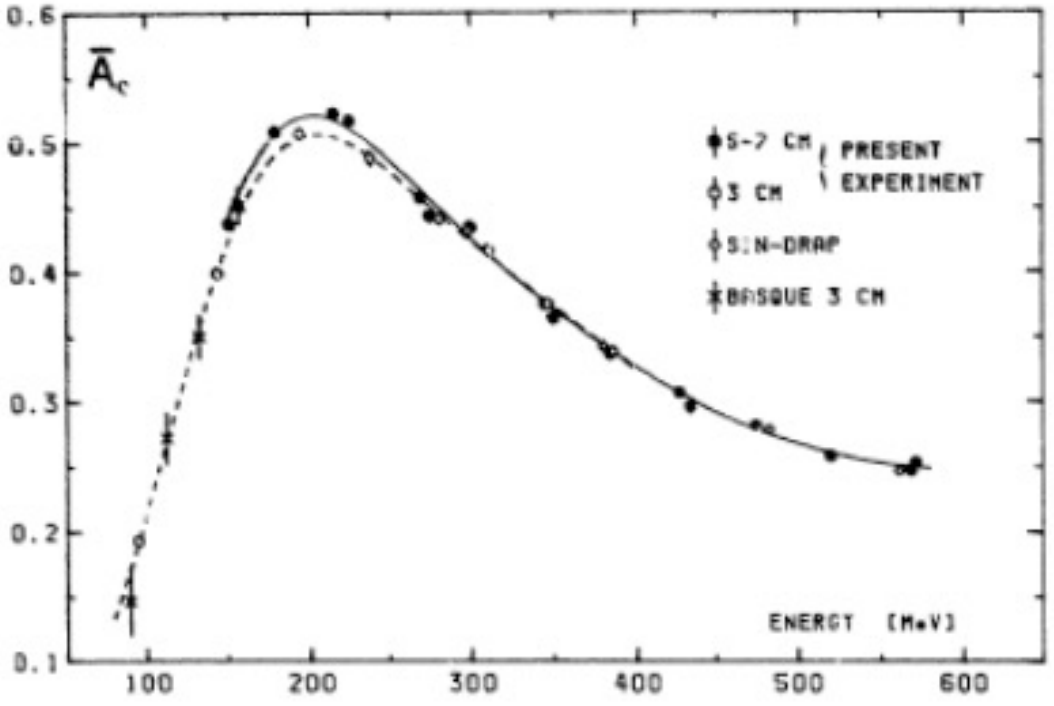
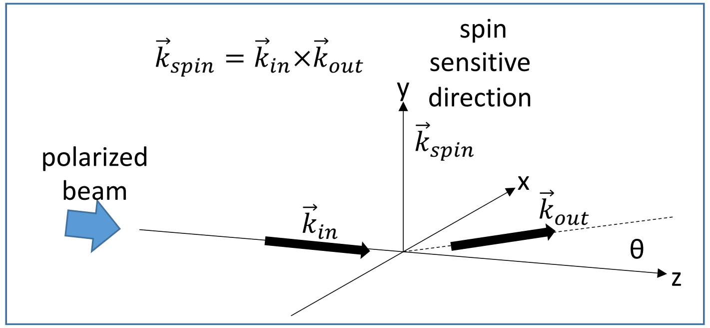
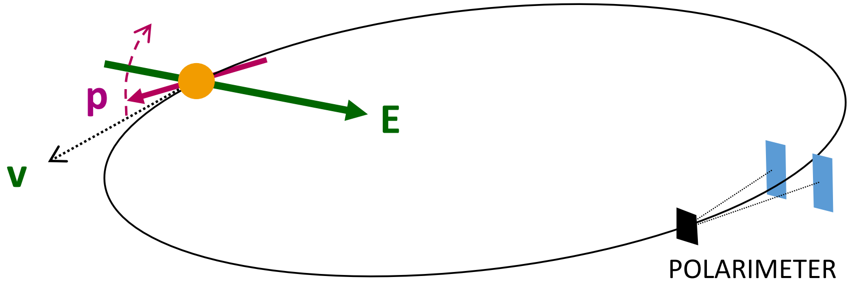


Fig. 4. Angle-averaged effective analyzing power. Curves show our fits. Points are the data included in the fits. E only

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





Concept and systematics tested with polarized beams at KVI/The Netherlands and COSY/Germany since late 2000’s

Spin Coherence Time

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

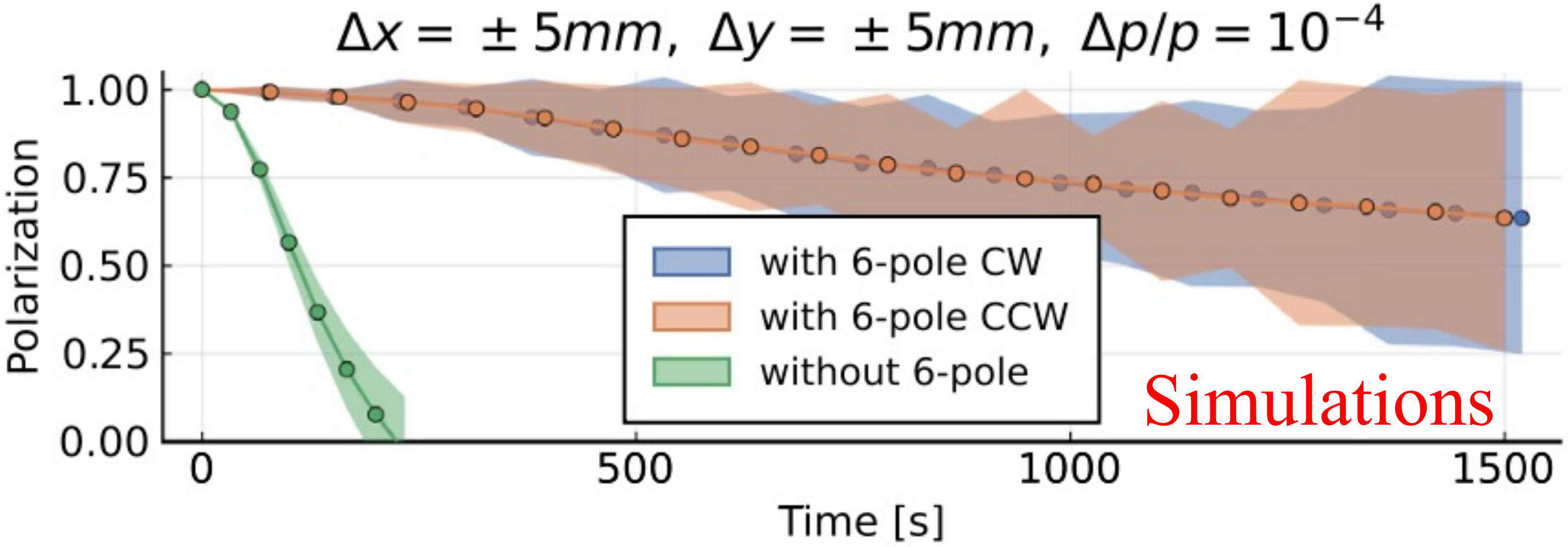
- They Cause a spread in the g-2 frequencies:

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

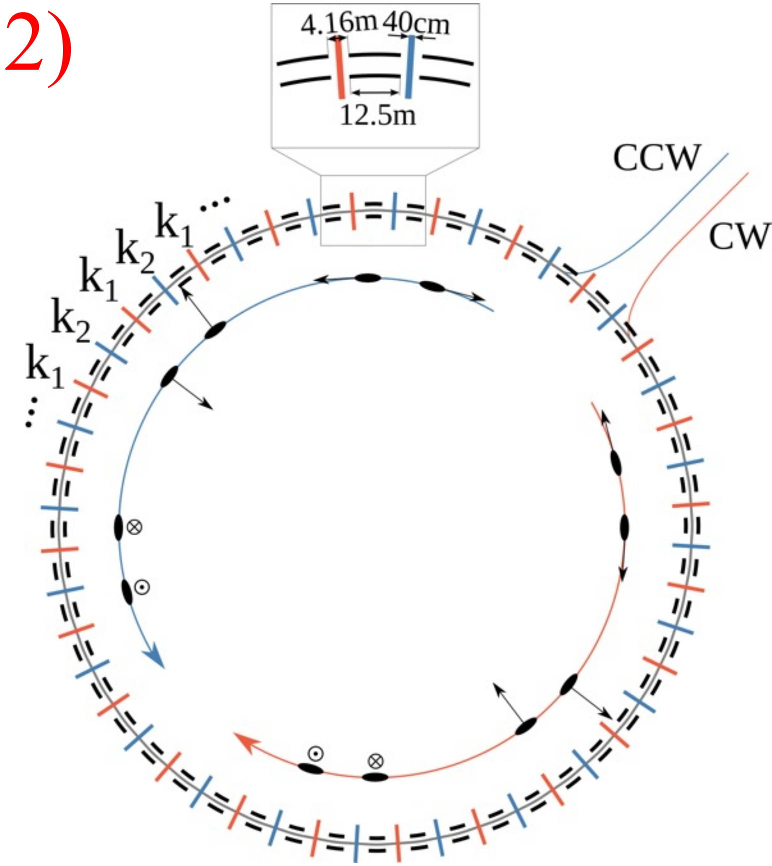
- Correct by tuning plate shape/straight section length plus fine tuning with sextupoles (current plan) or cooling (mixing) during storage (under evaluation).

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

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



Simulations



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

Concept using sextupoles developed by Yuri Orlov early in 2000’s (Deuterons),
Novosibirsk in the 1980’s (electrons/positrons)
Confirmed with polarized Deuteron beams at COSY in 2010’s