# The Proton EDM

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**The Strong CP problem**

*"The most underrated puzzle in all of physics."*

Forbes, 2019.

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# Strong CP Problem

QCD (& The SM) has a glaring hole in it…

$$\mathcal{L}_{QCD} = (\dots) + \boxed{\frac{g^2}{32\pi^2}\,\bar{\theta}\,\tilde{G}^a_{\mu\nu}\,G^{\mu\nu a}}$$

P-violating

T-violating

**CP-violating**

**Non-zero nucleon (N) Electric Dipole Moment (EDM)** → $\left|\vec{d}_N\right| = \vartheta(\theta)$.

BUT, no CP violation in strong interactions…

[$\bar{\theta} = \theta + \varphi$ = QCD $\theta$ -term + quark mass phase.]

→ No CP violation implies: $\bar{\theta} = \theta + \varphi = 0$ **(Fine tuning!)**

→ No EDM implies $|\bar{\theta}| \lesssim 10^{-10} \to |\vec{d}_N^{SM}| \lesssim 10^{-31}\, e \cdot cm$ **(Fine tuning!)**

**The Strong CP problem is a whole community problem…**

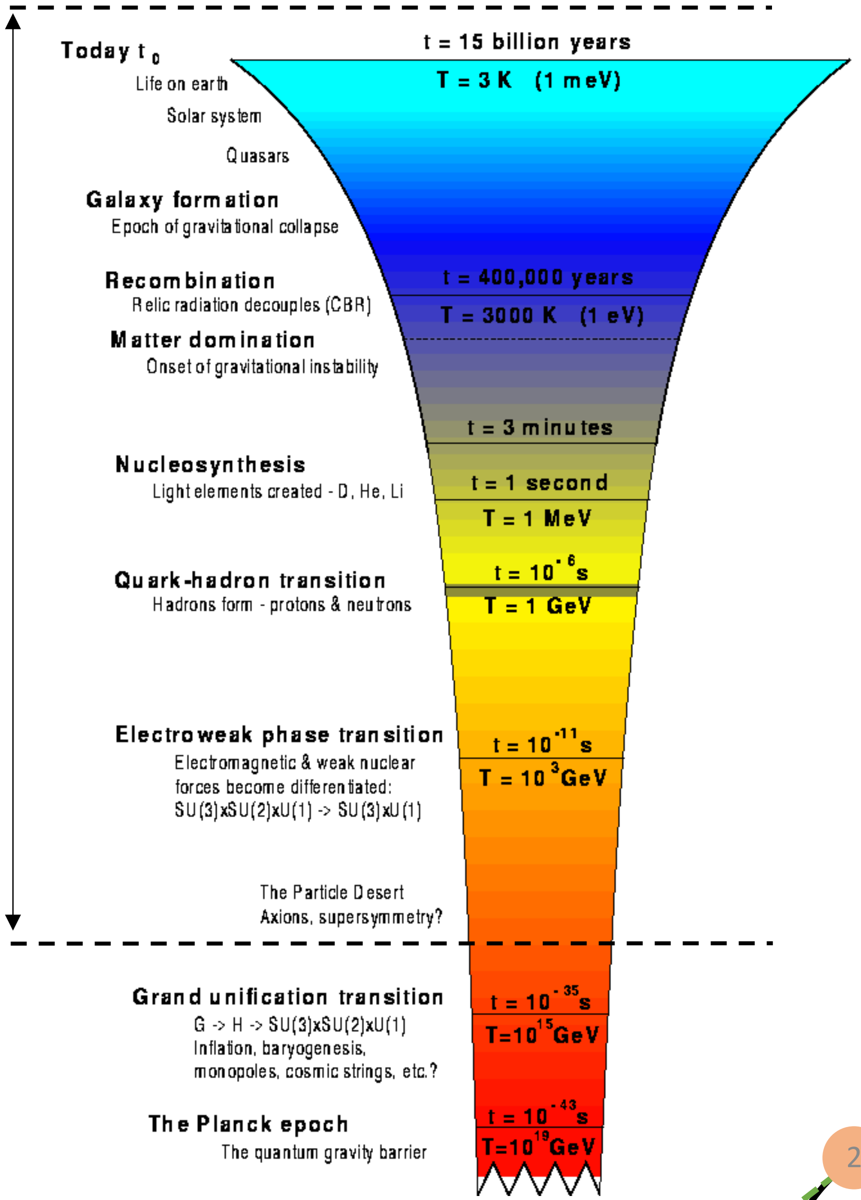
Non-zero proton EDM (pEDM), e.g. $10^{-25}\, e \cdot cm \gtrsim \left|\vec{d}_N\right| \gtrsim 10^{-30}\, e \cdot cm$:

= Solves strong CP-problem!

= CP-violation source for Baryon Asymmetry!

= Unambiguous new physics (with no SM theory needed!).

**Must understand the Strong CP Problem**



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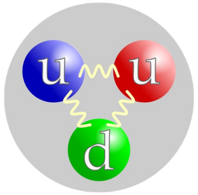
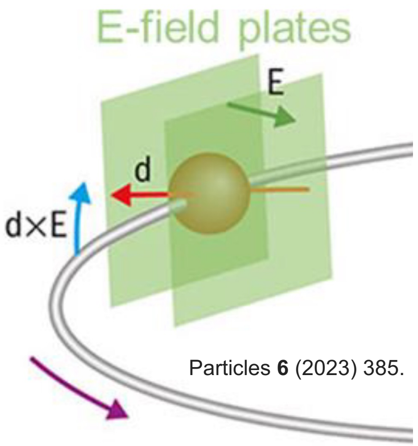
# The Proton EDM

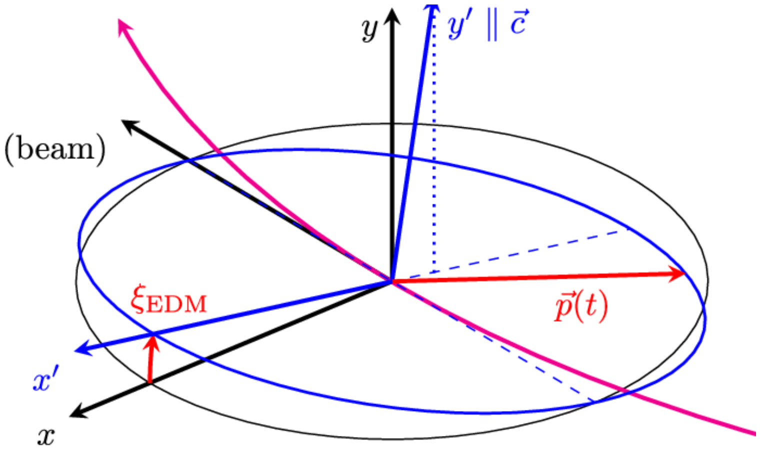
- Measure of charge separation of the system:
  - i.e. distribution of positive (u) and negative (d) charge within the proton.




- Uneven charge + electric field = EDM-induced torque.
- Results in vertical tilt the spin/polarisation:
  - We just need to measure an angle!



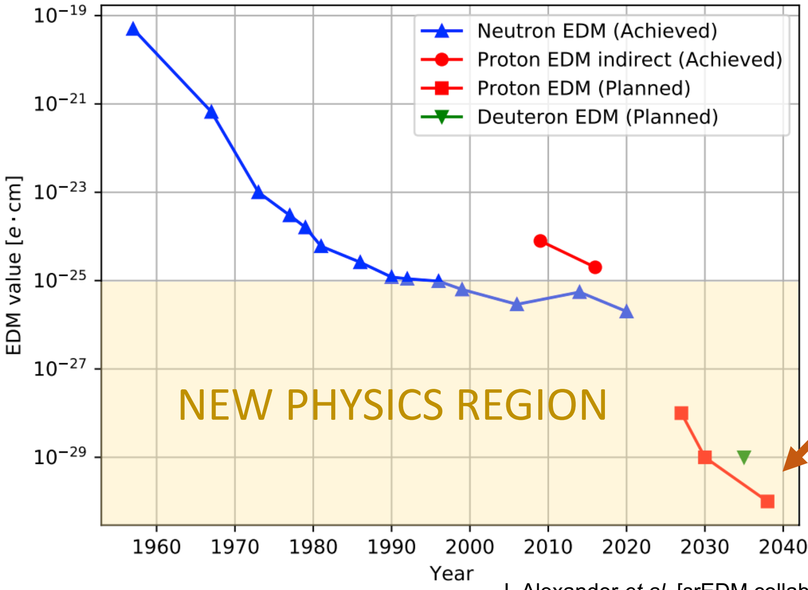

Particles **6** (2023) 385.




Phys. Rev. Accel. Beams **23** (2020) 024601.

- Requires:
  - Longitudinally polarised protons.
  - Electric storage ring (electric field bending).
  - Polarimeters to measure polarisation.

- Direct nEDM limit: $|\vec{d}_n| < 1.8 \times 10^{-26}\ e \cdot cm.$
- No direct limit on pEDM!
- Best indirect limit: $|d_p^{\downarrow 199\text{Hg}}| < 2.0 \times 10^{-25}\ e \cdot cm.$




**New paradigm of sensitivity**

[Statistics > nEDM.]

J. Alexander *et al.* [srEDM collaboration], arXiv:2205.00830.

**Proton EDM experiment** sensitivity ~ $10^{-30}\ e \cdot cm$!

[That's 0.000000000000000000000000000001 $e \cdot cm$]

→ **pEDM improved >** $\mathcal{O}(10^4)$.

→ $\theta_{\text{QCD}}$ **(strong CP problem) improved >** $\mathcal{O}(10^3)$.

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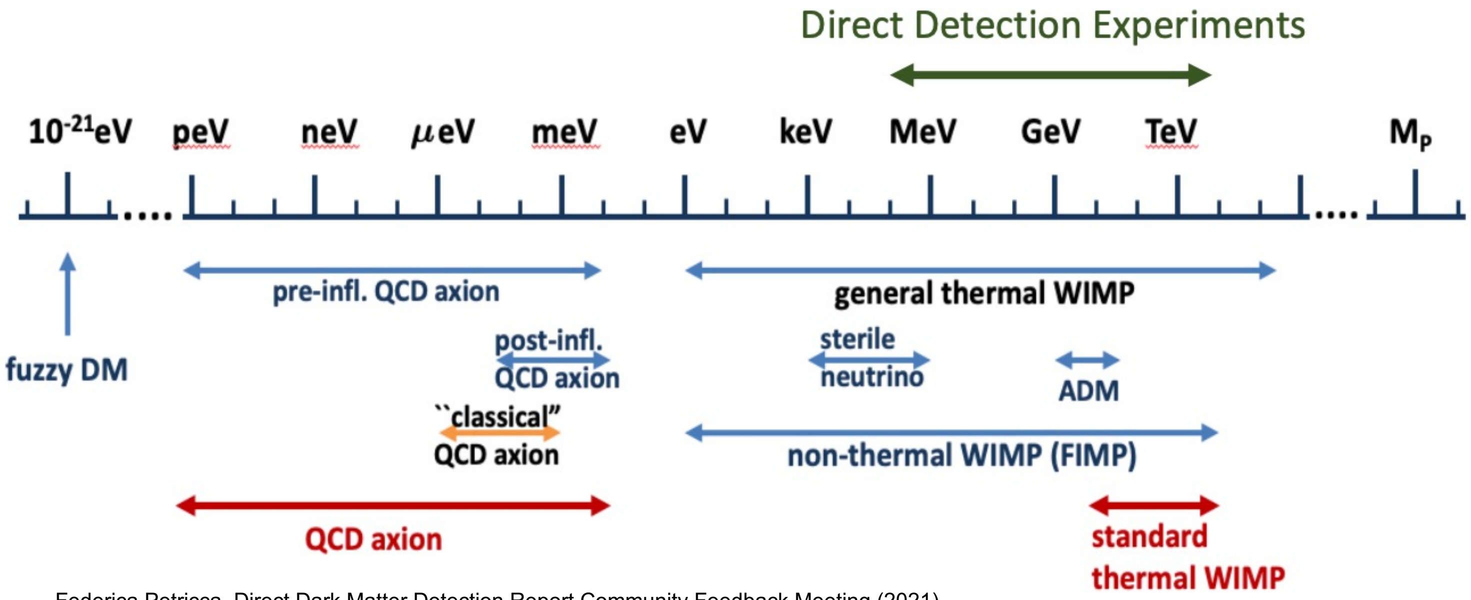
# pEDM Experiment: New Physics Reach

| Strong CP Problem | Matter-Antimatter Asymmetry | Dark Matter | EDM loop induced = wide range of interactions/energy scales<br>$d_p \sim (g^2/16\pi^2)\,(e\,m_q)/\Lambda_{\rm NP}^2\ \sin\phi^{\rm NP}\ \ e\cdot cm$<br>$m_q$ = mass of 1-loop quark, $\phi^{\rm NP}$ = complex CP violation phase of NP | |
|---|---|---|---|---|
| Solved! | Model-independent CP-violation. | Oscillating pEDM signature = **<u>axion</u>**<br>[$\mathcal{O}(10^2)$ larger than nEDM!].<br>ERJC **84** (2024) 12, arXiv:2308.16135, PRD **99** (2019) 083002, PRD **104** (2021) 096006 | Light, weak new physics:<br>$\Lambda_{\rm NP} \sim 1$ GeV, $g \lesssim 10^{-5}$, $\phi^{\rm NP} \sim 10^{-10}$.<br>[e.g. LZ, LDMX, FASER, SHiP.] | $\mathcal{O}$(PeV) mass scale:<br>$\phi^{\rm NP} \sim 1$, $\Lambda_{\rm NP} \sim 3\times 10^3$ TeV.<br>[e.g. LHC/FCC.] |




Federica Petricca, Direct Dark Matter Detection Report Community Feedback Meeting (2021).

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# pEDM Experiment: a Muon g-2 spin-off

Consider Muon g-2 experiment: charged particle in magnetic ($\vec{B}$) and electric ($\vec{E}$) fields:

$$\vec{\omega}_{spin} = \vec{\omega}_{MDM} \approx \frac{e}{m}\left[a\vec{B} + \left(a - \frac{1}{\gamma^2-1}\right)\left(\vec{\beta}\times\vec{E}\right)\right].$$

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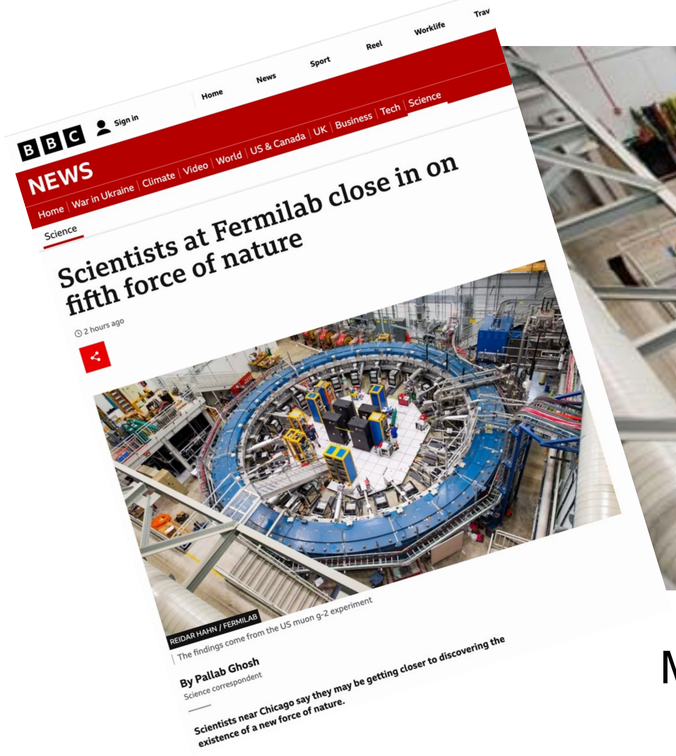
Muon → storage ring magnet $R_0 = 7.112\ \mathrm{m}$ and $B = 1.45\ \mathrm{T}$ ...

Choose muon g-2 <u>magic-momentum</u>, $\gamma_{\mathrm{magic}} = \sqrt{1 + 1/a} \rightarrow p = 3.094\ \mathrm{GeV/c}$.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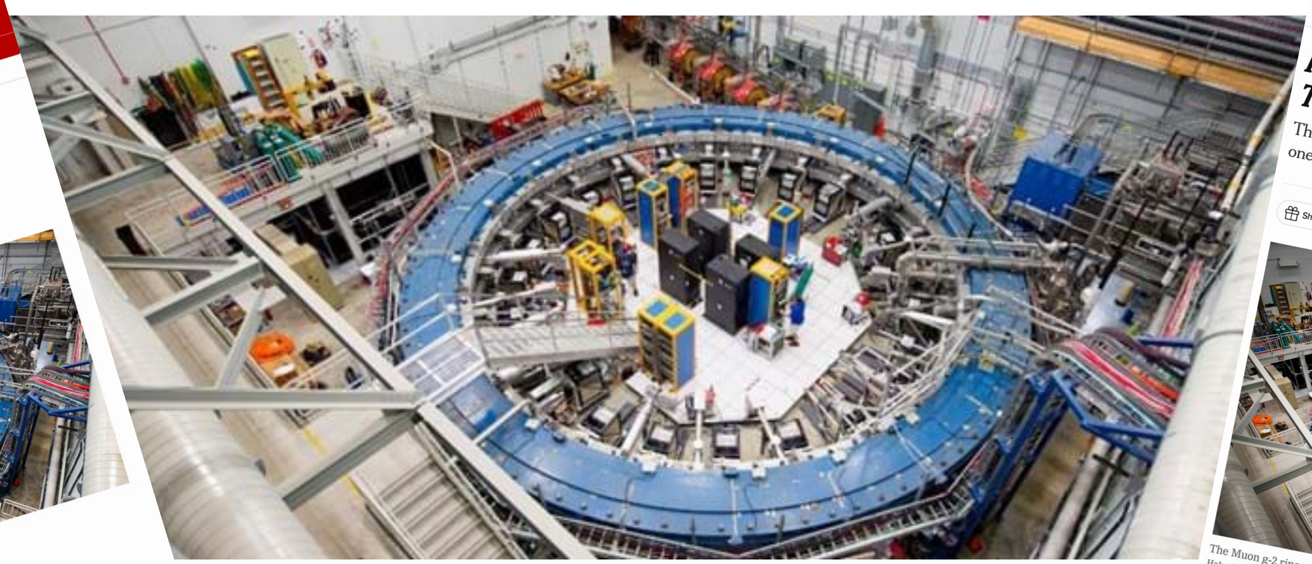
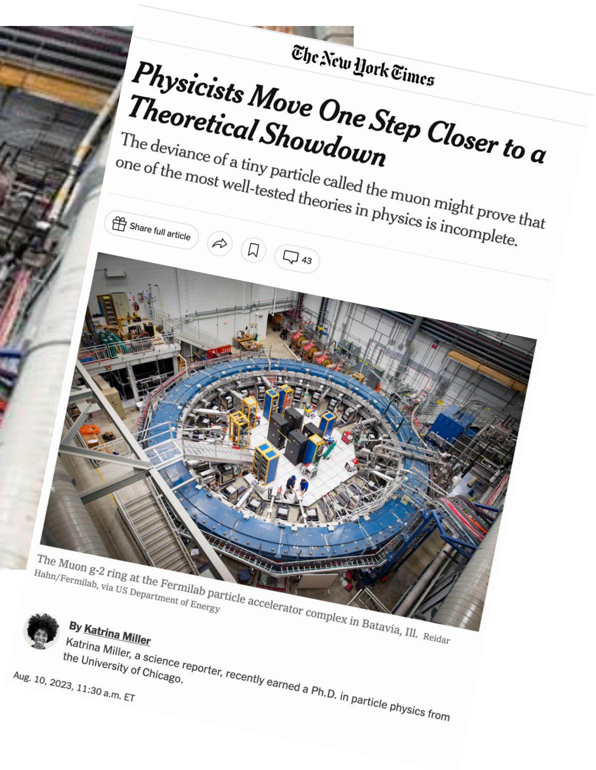
Science
Scientists at Fermilab close in on fifth force of nature
2 hours ago
REIDAR HAHN / FERMILAB
The findings come from the US muon g-2 experiment
By Pallab Ghosh
Science correspondent
Scientists near Chicago say they may be getting closer to discovering the existence of a new force of nature.




The New York Times
Physicists Move One Step Closer to a Theoretical Showdown
The deviance of a tiny particle called the muon might prove that one of the most well-tested theories in physics is incomplete.
Share full article 43
The Muon g-2 ring at the Fermilab particle accelerator complex in Batavia, Ill. Reidar Hahn/Fermilab, via US Department of Energy
By Katrina Miller
Katrina Miller, a science reporter, recently earned a Ph.D. in particle physics from the University of Chicago.
Aug. 10, 2023, 11:30 a.m. ET

Major experimental and particle physics success!
**Currently 200ppb precision!**

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Use Muon g-2 principles: charged particle with EDM in magnetic ($\vec{B}$) and electric ($\vec{E}$) fields:

$$\vec{\omega}_{spin} = \vec{\omega}_{MDM} + \vec{\omega}_{EDM} \approx \frac{e}{m}\left[a\vec{B} + \left(a - \frac{1}{\gamma^2-1}\right)\left(\vec{\beta}\times\vec{E}\right) + \frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right], \quad \vec{d} = \eta\frac{q\hbar}{2mc}\vec{S}\,.$$

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Frozen-spin technique!

Proton → electric storage ring $R_0 = 800\ \mathrm{m}$ and $E = 4.4\ \mathrm{M/m}$ ...

Choose pEDM magic-momentum: $a\vec{B} + \left(a - \frac{1}{\gamma^2-1}\right)\left(\vec{\beta}\times\vec{E}\right) = 0 \rightarrow p = 0.7\ \mathrm{GeV/c}$.

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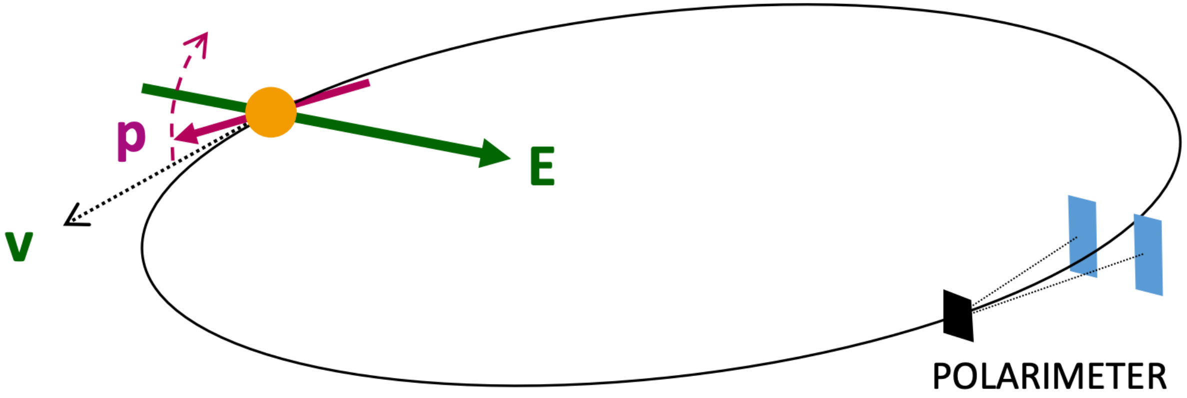


- Inject $\mathcal{O}(10^{10})$ polarized protons every twenty minutes.
- $\vec{E}$-field bending and $\vec{B}$-field focusing.
- Vertical polarization in polarimeter = static EDM.

**And no SM calculation to compare to!**

What about large, T-conserving systematics that mimic vertical, T-violating EDM, e.g. radial $\vec{B}$ field?

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Frozen-spin technique!

Proton → electric storage ring $R_0 = 800$ m and $E = 4.4$ M/m ...

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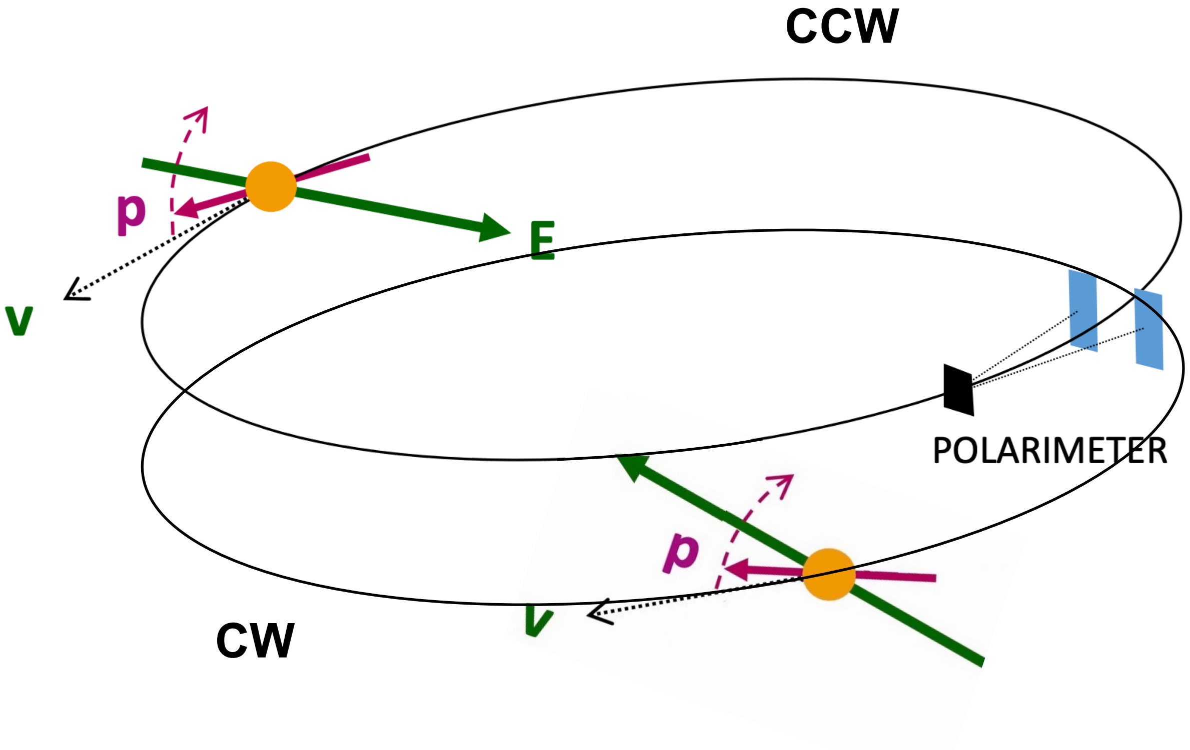


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**→ Store CW and CCW beams (time reverse of each other) to cancel these effects!**

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# pEDM potential locations

## BNL

- R&D and planning done for 800m ring at AGS:
    - Well-understood polarised proton delivery.
    - Viable site with thought-out ring.
    - Ground stability already understood.
- Genesis of current g-2 team and expertise.
- Construction/engineering can be done in UK/EU.
- Least work to realisation.

## COSY

- Home of pEDM precursor experiment.
- R&D/ testing ongoing at COSY (e.g. polarimeters).
- But $\mathcal{O}(10^2)$ less polarised proton intensity c.f. BNL.
- End of COSY operations after 2024 (??).

## CERN

- Could make use of old ISR (CW/CCW beams).
- Could do polarised protons (or BNL polarisers).
- Cheaper than U.S. (but 950m ring = more expensive).
- More work to be done compared to BNL.
- Approved/balanced against CERN/LHC/FCC programme.

## Fermilab

- Ambition to continue storage ring programme.
- High-intensity proton facility ready-to-go.
- Could borrow/use BNL polarised proton technology.
- Use substantial g-2/EDM expertise.
- Interplay with DUNE/neutrino programme.
- Continue Fermilab's wide-ranging particle physics output beyond just neutrinos in long-term.

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# (Short) path to readiness

**<u>Main message:</u> no showstoppers! Due diligence, physics case studies, moving to TDR phase…**

<u>Already completed…</u>

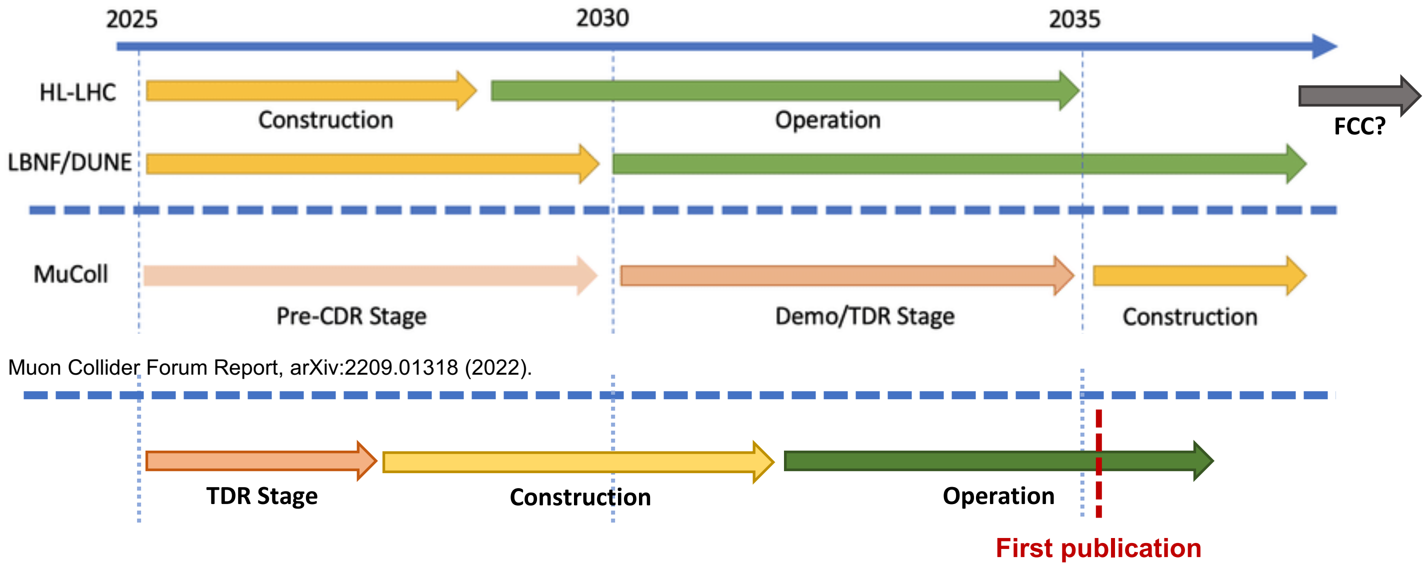
- Experiment design, engineering and modelling complete. ✅
- Prototype components under construction. ✅
- Measurement techniques understood. ✅
- Key systematics understood. ✅

<u>Work to be done…</u>

- 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 (estimated $\mathcal{O}$(\$100M)).

**<u>Build community/collaboration!</u>**

- Increased involvement (you are invited!).
- New generation to start and finish experiment.




- 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!**

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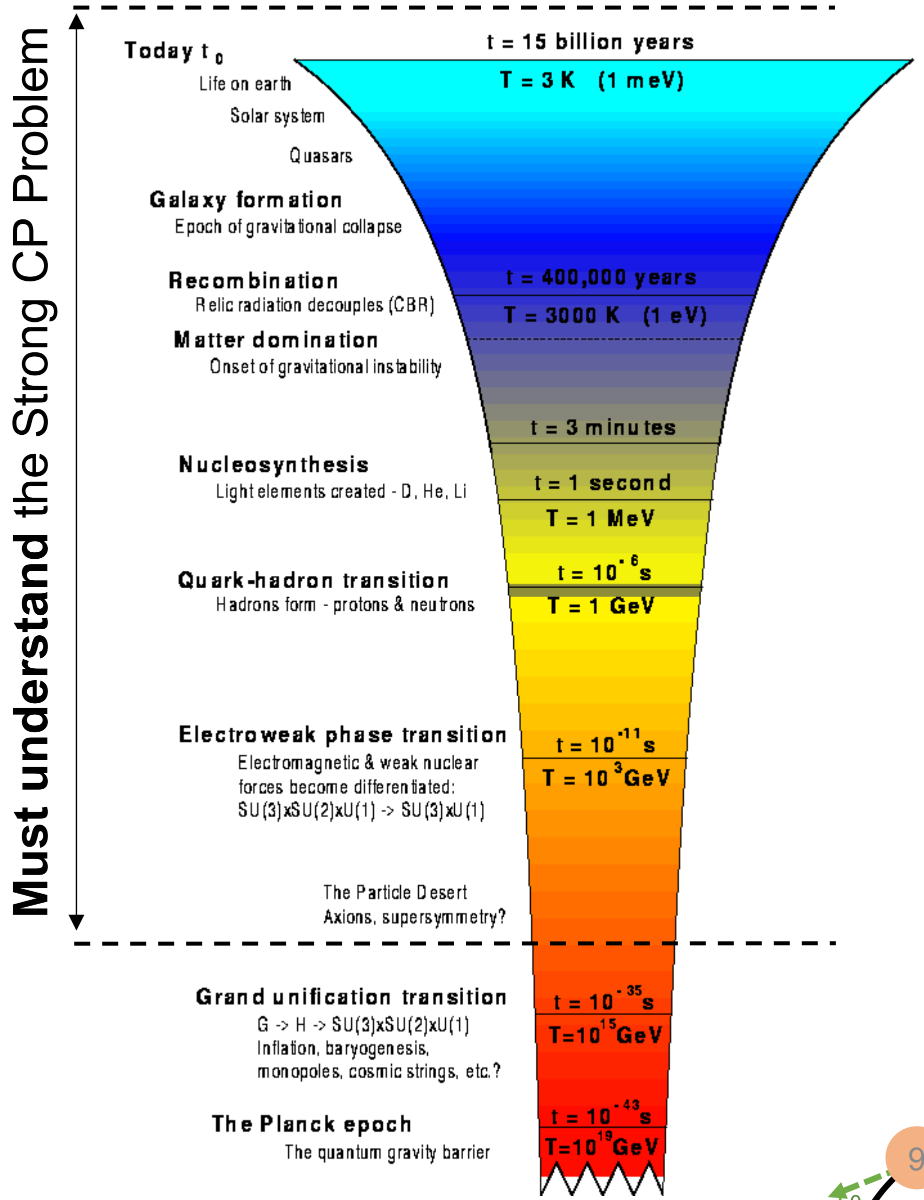
# Conclusions

- pEDM experiment is the first direct search for the proton EDM.
- Improves on current (indirect) limit by $> \mathcal{O}(10^4)$.
- Directly address/solves the strong CP problem.
  - Strong CP/pEDM ↔ Astro + Particle + Nuclear.
- Significant new physics drivers:
  - CP-violation source for Baryon Asymmetry.
  - Sensitive probe for axionic dark-matter.
  - Probe light-weak new particles → PeV-scale new physics.
  - No EDM would also be dramatic → at SM limit.
- Major R&D completed / systematics understood.
- From TDR to final publication in < 20 years.
- One of the most low-cost/high-return proposals in particle physics today.



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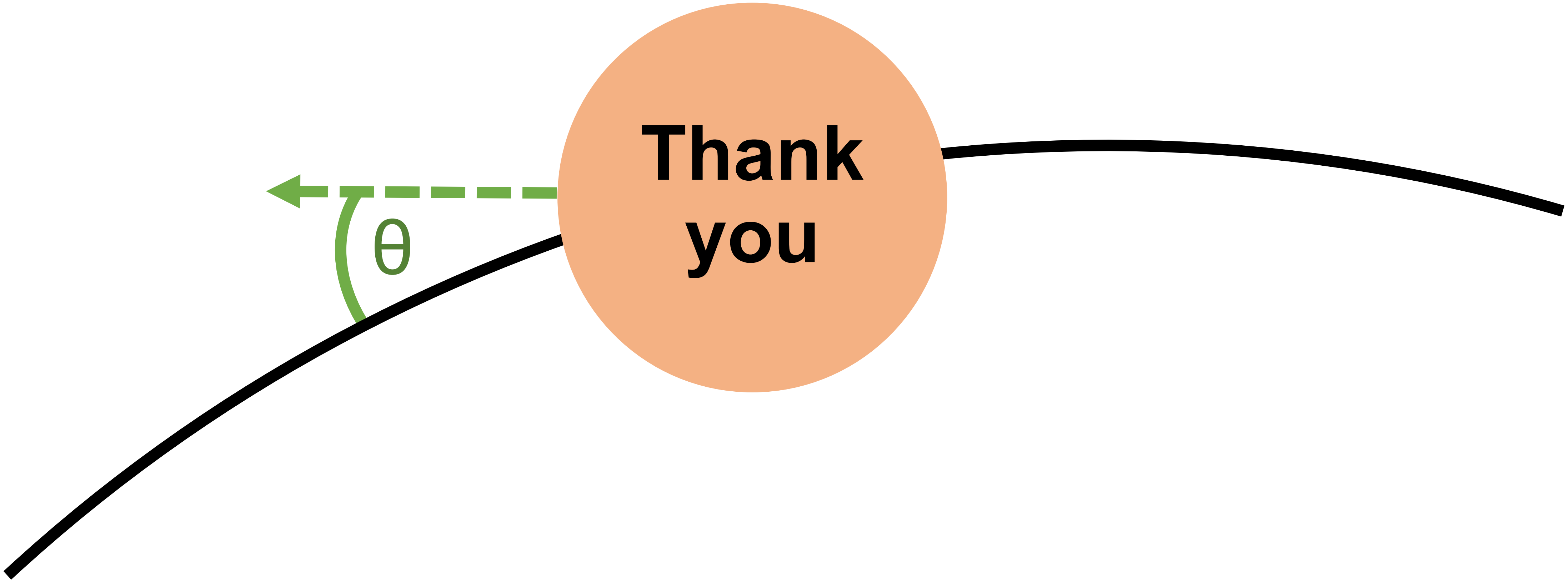
# Conclusions

This is a beautiful experiment to precisely measure an angle…

You can be a part of it.



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# Backups

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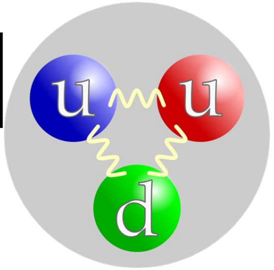
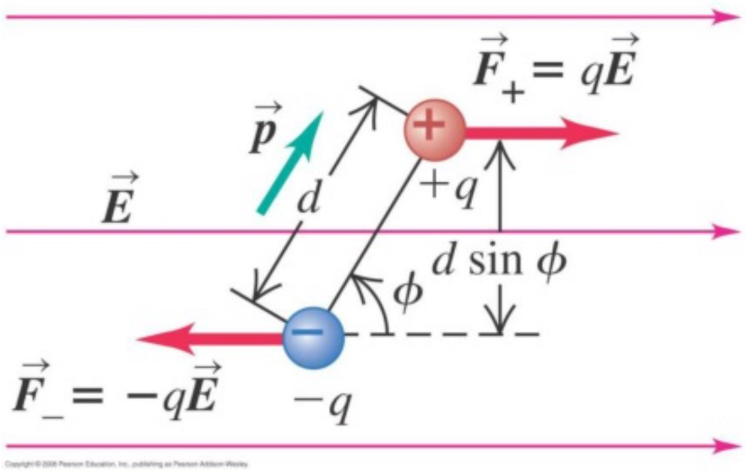
# What is the proton EDM?

- The Dirac equation in an electric field gives rise to the EDM form factor, $F_3$:

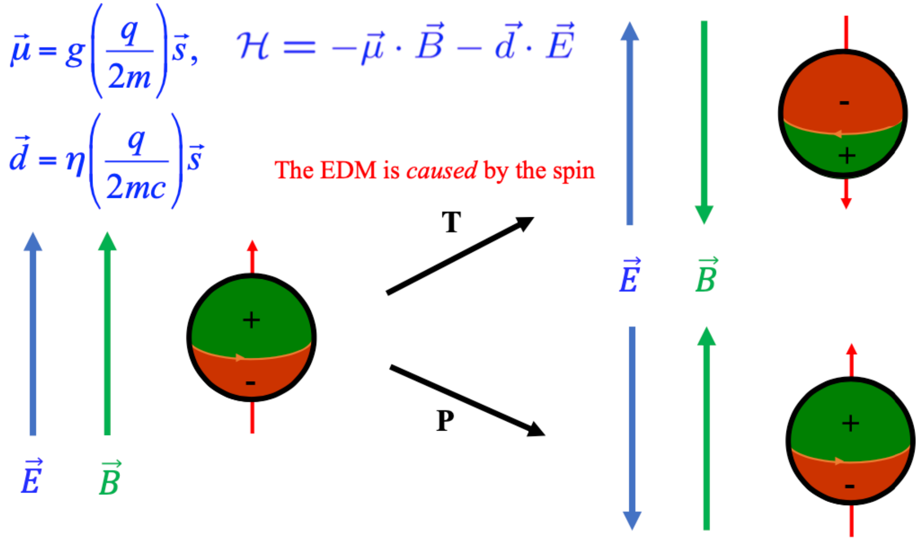
$$\Gamma^\mu = -ie\left[\gamma^\mu F_1(q^2) + \left(F_2(q^2) + iF_3(q^2)\gamma_5\right)\frac{i\sigma^{\mu\nu}q_\nu}{2m}\right]$$




For the Proton (mass $m_p$, EDM $d_p$) $\rightarrow$ $F_3(0) \propto 2m_p d_p$




- It is a measure of the overall polarity of the system:
  - i.e. the separation/distribution of positive (u) and negative (d) charge within the proton.
  - Charge asymmetry along the spin axis.
- External electric field + a non-zero, static EDM of the proton induces mechanical torque:
  - Uneven charge distribution + electric field = EDM-induced motion.
  - Not to be confused with magnetic dipole moment (g-2).
- A permanent EDM violates both P and T.
  - From CPT symmetry → model-independent CP violation.



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# Strong CP Problem

$$\mathcal{L}_{QCD} = (\ldots) + \boxed{\frac{g^2}{32\pi^2}\bar{\theta}\,\tilde{G}^a_{\mu\nu}G^{\mu\nu a}}$$

- P-violating
- T-violating
- **CP-violating**

$\bar{\theta}\tilde{G}G$ leads to non-zero nucleon (N) EDM → $|\vec{d}_N| = \vartheta(\theta)$.

**SM:** $|\bar{\theta}| \lesssim 10^{-10} \rightarrow |\vec{d}_N^{SM}| \lesssim 10^{-31}\ e\cdot cm \rightarrow$ **More fine tuning!**

A non-zero proton EDM (pEDM), e.g. $10^{-24}\ e\cdot cm \gtrsim |\vec{d}_N| \gtrsim 10^{-30}\ e\cdot cm$:

- Unambiguous evidence of new physics (with no SM theory needed!).
- Solves strong CP-problem!

BUT, we do not overserve CP violation in strong interactions…

$$\bar{\theta} = \theta + \varphi$$

= QCD $\theta$ -term (non-perturbative) + quark mass phase.

→ No CP violation implies:

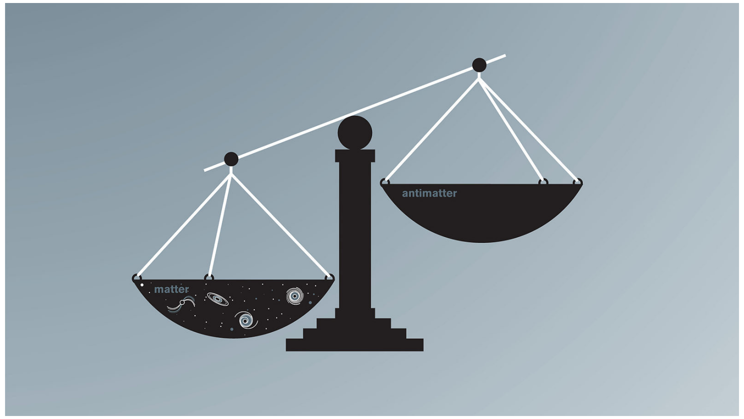
$\boldsymbol{\bar{\theta} = \theta + \varphi = 0}$ **(Fine tuning!)**

**Strong CP problem**

- **Baryon asymmetry** - Model-independent source of CP-violation needed.
- **Dark matter -** new U(1) symmetry + SSB → pseudo-Goldstone boson, a = **axion**

$$\mathcal{L}_{QCD+a} = (\ldots) + \cancel{\frac{g^2}{32\pi^2}\bar{\theta}\,\tilde{G}^a_{\mu\nu}G^{\mu\nu a} - \frac{g^2}{32\pi^2}\frac{f_a\bar{\theta}}{f_a}\tilde{G}^a_{\mu\nu}G^{\mu\nu a}}$$

→ Observed oscillating pEDM = possible signature of an axion-like DM particle.



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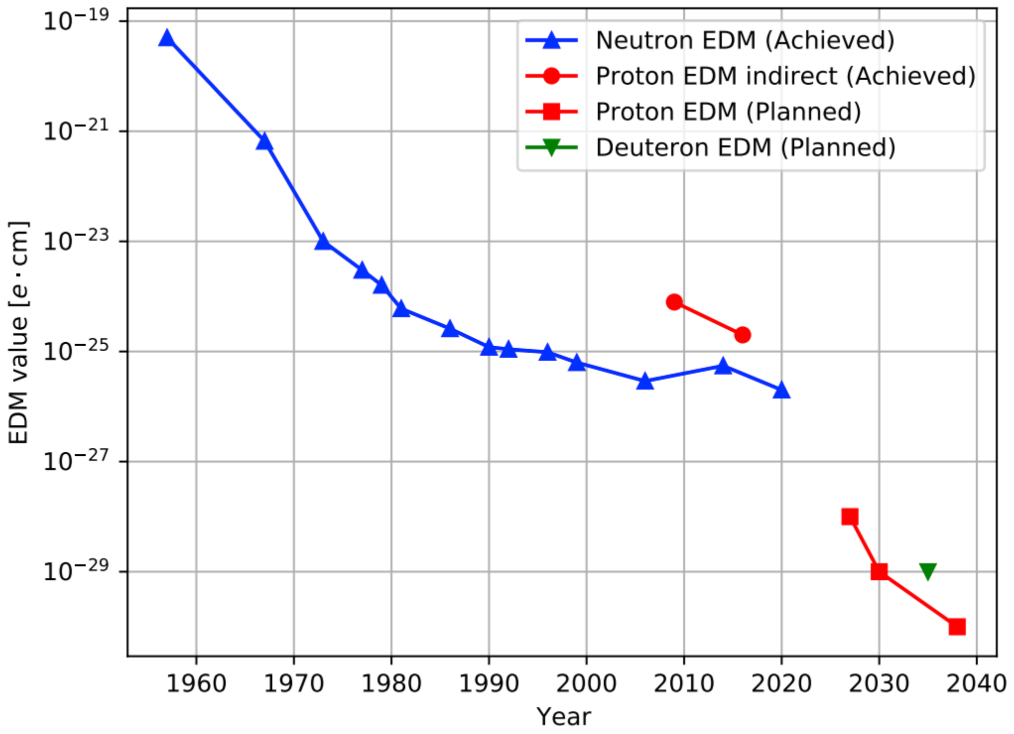
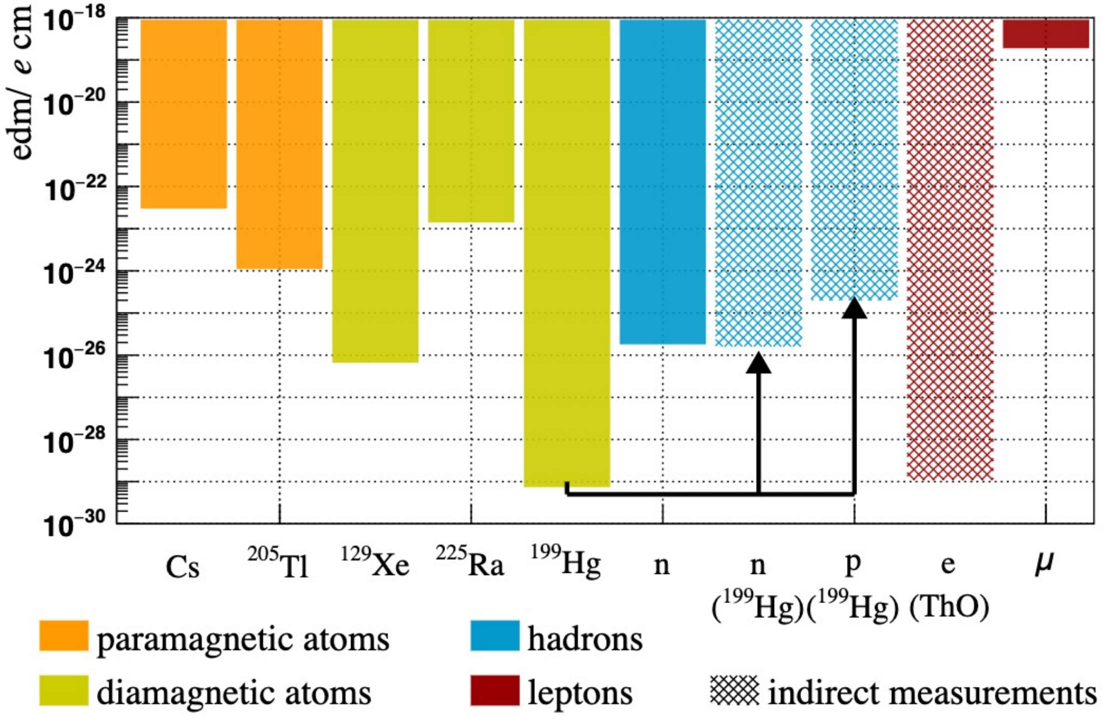
# Proton EDM experiment sensitivity

- No current direct limit on pEDM! Best indirect limit from atomic physics is $\left|\vec{d}_p^{\,199\mathrm{Hg}}\right| < \mathbf{2.0 \times 10^{-25}}\ \boldsymbol{e \cdot cm}$.
- Best current (direct) nEDM limit is $\left|\vec{d}_n\right| < \mathbf{1.8 \times 10^{-26}}\ \boldsymbol{e \cdot cm}$.
- Remember, new physics in nucleon EDM range: $\mathbf{10^{-24}}\ \boldsymbol{e \cdot cm} \gtrsim \left|\vec{d}_N\right| \gtrsim \mathbf{10^{-30}}\ \boldsymbol{e \cdot cm}$...

J. Alexander *et al*. [srEDM collaboration], arXiv:2205.00830.




F. Abusaif *et al*. [CPEDM collaboration], arXiv:1912:07881.




First-ever direct proton EDM measurement will have a sensitivity of $\mathbf{10^{-29}}\ \boldsymbol{e \cdot cm}$!

**Take-home message: <u>4 orders of magnitude on pEDM</u>, <u>three orders of magnitude on $\theta_{\mathrm{QCD}}$</u>.**

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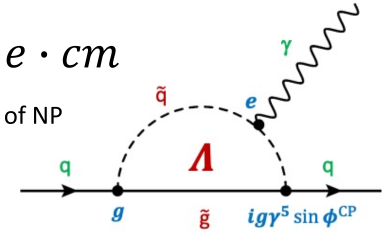
# Physics complementarity

pEDM new physics (NP) with scale $\Lambda_{\mathrm{NP}}$ is quantum loop induced (by virtue of uncertainty principle):

$$d_p \sim (g^2/16\pi^2)\,(e\,m_q)/\Lambda_{\mathrm{NP}}^2\ \sin\phi^{\mathrm{NP}}\ \ e\cdot cm$$

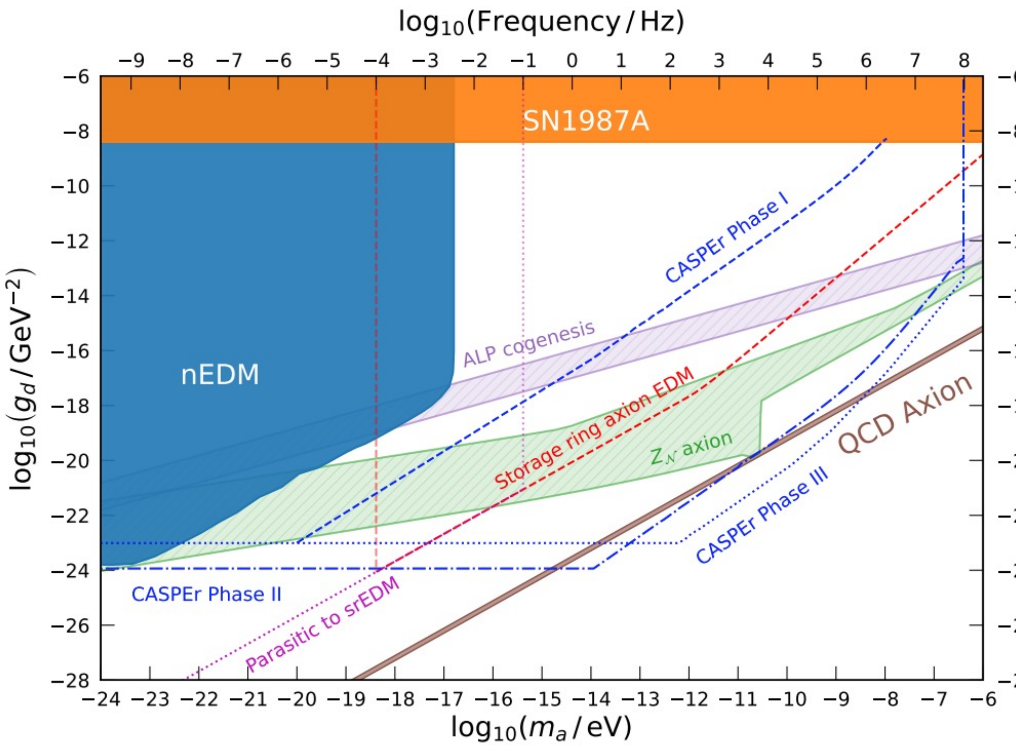
$m_q$ = mass of 1-loop quark, $\phi^{\mathrm{NP}}$ = complex CP violation phase of NP




[Pospelov & Ritz, 2005]

- Probe new physics of $\mathcal{O}(\mathrm{PeV})$ mass scale!
  - $\phi^{\mathrm{NP}} \sim 1,\ \Lambda_{\mathrm{NP}} \sim 3\times 10^3$ TeV. W. Marciano (2020)
  - Complementary to e.g. LHC/FCC programme.
- Probe light, weakly-interacting new physics.
  - $\Lambda_{\mathrm{NP}} \sim 1$ GeV, $g \lesssim 3\times 10^{-5}$, $\phi^{\mathrm{NP}} \sim 10^{-10}$. Z. Omarov *et al.*, PRD 105 (2022) 032001.
  - Complementary to e.g. LZ, LDMX, FASER, SHiP.
- Highly complementary to atomic/molecular EDM experiments.
  - Potential to also measure deuteron / $^3$He EDMs.

J. Alexander *et al.* [srEDM collaboration], arXiv:2205.00830.




Importantly, pEDM will clearly be highly complementary to nEDM experiments…

→ **But, pEDM wins the statistics battle.**

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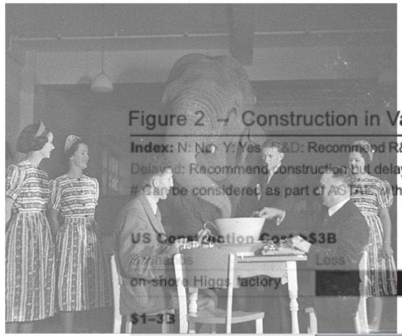
# pEDM Experiment: funding and timeline

Recent P5 report was not good for proton EDM at BNL



Report of the 2023 Particle Physics Project Prioritization Panel

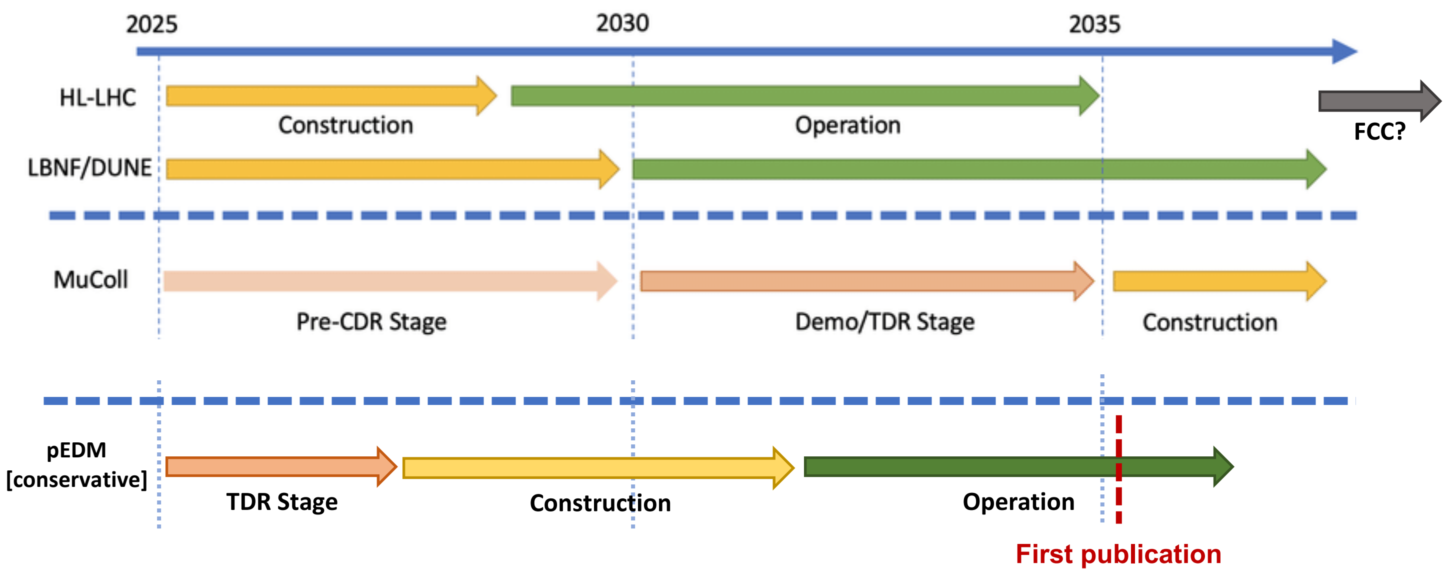
Figure 2 – Construction in Various Budget Scenarios

**Index:** N: No Y: Yes R&D: Recommend 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
# Can be considered as part of ASTAE with reduced scope

| Scenarios | Less | Baseline | More | Neutrinos | Higgs Boson | Dark Matter | Cosmic Evolution | Direct Evidence | Quantum Imprints | Astronomy & Astrophysics |
|---|---|---|---|---|---|---|---|---|---|---|
| **US Construction Cost >$3B** | | | | | | | | | | |
| on-shore Higgs factory | N | N | N | | P | S | | P | P | |
| **$1–3B** | | | | | | | | | | |
| off-shore Higgs factory | Delayed | Y | Y | | P | S | | P | P | |
| ACE-BR | R&D | R&D | C | P | | | | 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 | | | | |
| Mu2e-II | 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 | | |

- 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!**

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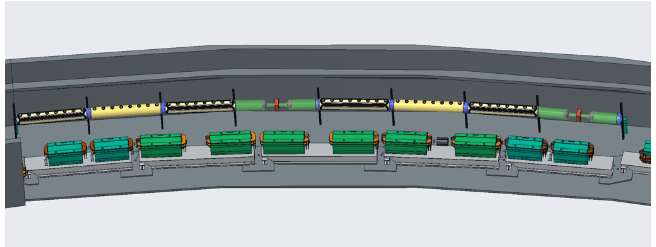
# (Short) path to readiness

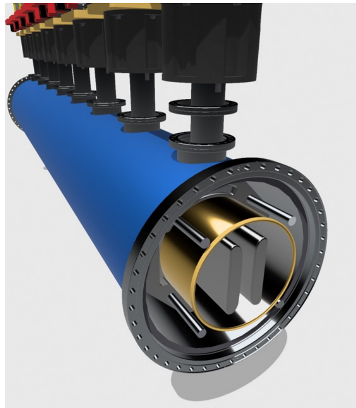
**<u>Main message:</u> no showstoppers! Due diligence, physics case studies, moving to TDR phase…**

<u>Already completed…</u>

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 ✅

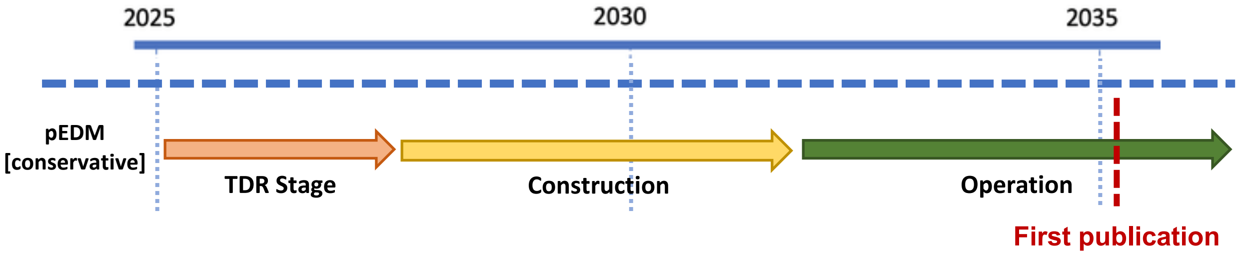




Top: 1/24 section (15°) of pEDM ring.
Right: pEDM deflector (designed and under construction in the UK).

<u>Work to be done…</u>

- 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.
- **<u>Build community/collaboration!</u>**
  - Bring current pEDM communities together.
  - Increased UK involvement (you are invited!).
  - New generation to start and finish experiment.




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

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# UK involvement in proton EDM

What the UK can provide:

**World class physicists, accelerator scientists and engineering.**

- 50-100% of critical bending components.
- Engineering/construction for deflectors/adjustors.
- Developing/building polarimeters (Si, CMOS).
    - In-line with recent STFC investment.
- Project management.
- Alignment experience.
- Simulation + high-statistics modelling.
- Accelerator experience (e.g. Cockcroft/JAI) – UK experiment??
- Lower cost that U.S. estimates.
- Building a UK pEDM consortium/collaboration.
    - Substantial UK expertise available.
    - New generation of physicists.
    - Please get in touch.

Science & Technology Facilities Council
Rutherford Appleton Laboratory

University of Liverpool

University of Sussex

The Cockcroft Institute of Accelerator Science and Technology

UCL

University of Oxford

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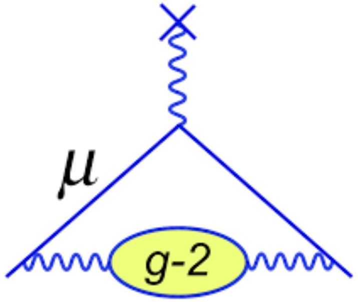
Imperial College London



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# Ring lattice systematic studies

*Table 8: Classification of systematic error sources*

| Source | Severity of effect; counter-measures | Risk level; Comments |
|---|---|---|
| Vertical electric field. | Primary effect, unavoidable when magnetic focusing is used. It cancels with clock-wise (CW) vs. counter-clock-wise (CCW) storage simultaneously. | Risk level: Low. If CW vs. CCW storage is not simultaneous it may become medium-high risk due to the unknown time-stability of vertical electric fields (not considered in present experiment). |
| Background radial magnetic fields. | They can be a systematic error source when electric focusing is present. Applying large radial magnetic fields around the ring can probe electric focusing in the ring (spin-based alignment). | Risk level: Low. No need for expensive magnetic field shielding, just Helmholtz wires mounted on the vacuum chambers. Time dependent small B-fields OK if their amplitude and direction are monitored. Applying appropriate electric focusing can also probe background magnetic fields. |
| Vertical velocity effect. | A major issue with non-symmetric lattices, not an issue here. Symmetry: Placing the magnetic quads at highly symmetric locations, greatly reduces their required placement accuracy. | Risk level: Low. Moving vertically in a radial E-field region, creates a longitudinal magnetic field in the particle's rest frame. The experiment will start with 0.1 mm accuracy in the quad placement. Eventually, we aim to achieve a placement accuracy better than 0.01 mm for each magnetic quad using spin-based alignment. |
| Geometrical phases, high-order vertical E-fields. | Under control with placement accuracy of lattice elements better than 0.1 mm and by flipping the current of the magnetic quadrupoles to better than 0.1% at each storage. | Risk level: Low. It's important to keep the beam planarity to within 0.1 mm and the beam separation between CW and CCW beams to below 0.01 mm. The risk comes from the time stability of the lattice elements if they move more than the 0.01 mm level per hour. Spin-based alignment can be used as needed to realign lattice. |
| Polarimeter related systematic errors. | Need paying attention to the relevant issues at design level. Storing beam with opposite polarization direction is critical in canceling rate related effects as well as effects related to beam-motion. | Risk level: Medium-low. Potentially serious issues can also come from beam-profile vertical polarization dependence. Prototype polarimeter-related systematic errors were studied first at KVI/The Netherlands and at COSY/Germany. Opposite polarizations were used to cancel the asymmetry systematic errors to $10^{-5}$ level, limited by statistics within a factor of ten to needed accuracy. It is not expected to be any issue improving the accuracy with more statistics available. |

*Table 9: Electric field alignment sequence including magnetic quad current flipping.*

| E-field direction alignment | Vertical spin precession rate | Comments |
|---|---|---|
| Mechanical, < 1 mrad average alignment. (It is also possible to mechanically align the electric field plates to better than 10 $\mu$rad with respect to gravity, which we will evaluate further later on, but here we assume much more relaxed alignment specs.) | < 2.5 krad/s. | Beam planarity of 0.1 mm out of specs; CW and CCW beam separation difference of 0.01 mm out of specs. We need to be able to align the plates of each section to better than 0.1 mrad to be able to store beam. |
| Beam-based alignment, to obtain an average electric field plate alignment of better than 2 $\mu$rad, with an average $E_V <$ 10 V/m. Aligning the plates to few $\mu$rad per section (12.5m) using trim electric field plates. | < 5 rad/s. | Compensate the average vertical E-field better than $E_V$ = 10 V/m by keeping the beam planarity to better than $\pm 50\,\mu$m. Keep one beam direction (e.g., CW) at zero vertical spin precession rate within available statistics. |
| Spin-based alignment, to obtain an average vertical electric field alignment of $E_V < 20\,\mu$V/m every second. | < 10 $\mu$rad/s. | Always keep one beam direction (e.g., CW) at zero vertical spin precession rate within available statistics by applying correction voltage on the trim electric field plates. |
| Spin-based alignment to reduce electric focusing below $m < 10^{-7}$ and align each magnetic quad better than 10 $\mu$m. | < 1 $\mu$rad/s. | Always keep one beam direction (e.g., CW) at zero vertical spin precession rate within available statistics. Measure and reduce the CW and CCW beam separation to less than $\pm 5\,\mu$m. The ring is designed with stability of the electric focusing and quad offset parameters in mind. |
| Spin-based alignment, $E_V < 2\,\mu$V/m every second using the trim electric field plates. | < 0.1 $\mu$rad/s. | Flip the magnetic quadrupole currents. Always keep one beam direction (e.g., CW) at zero vertical spin precession rate within available statistics. The EDM signal is the difference between the CW and CCW vertical precession rates while combining all quad current settings including information from radially polarized bunches. |

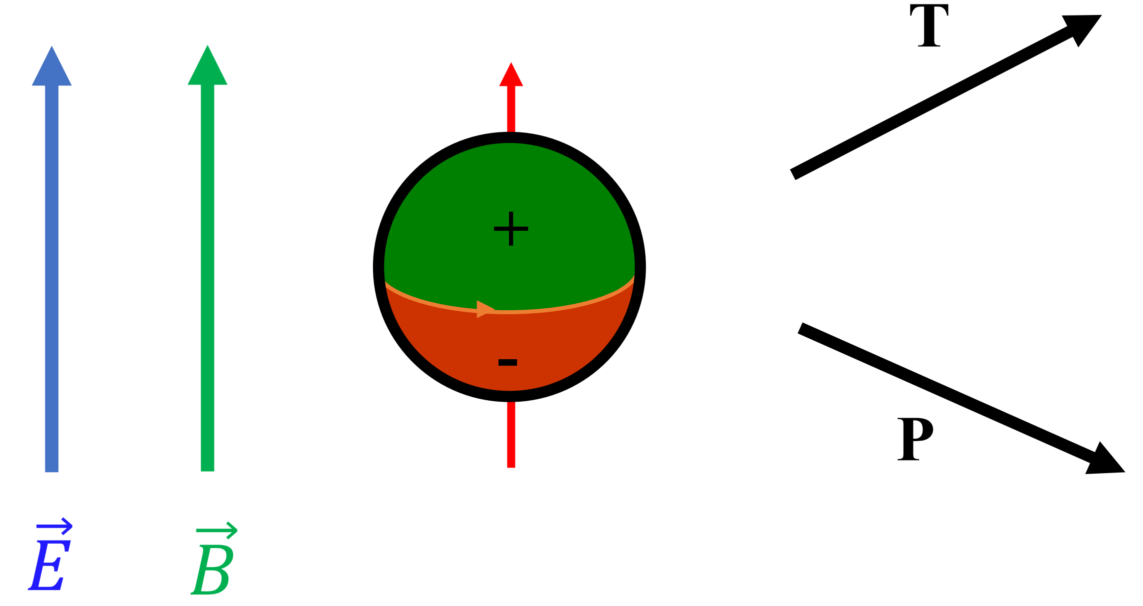
Z. Omarov et al, Phys. Rev. D 105, 032001.

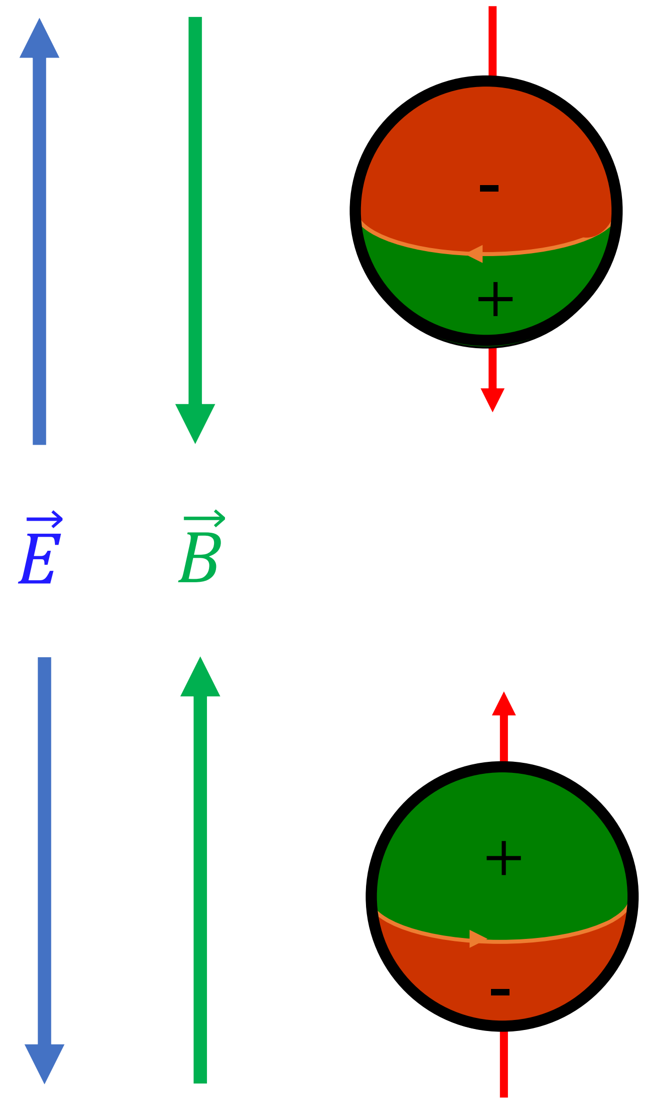
# A Permanent EDM Violates both T & P Symmetries:

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

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

The EDM is *caused* by the spin

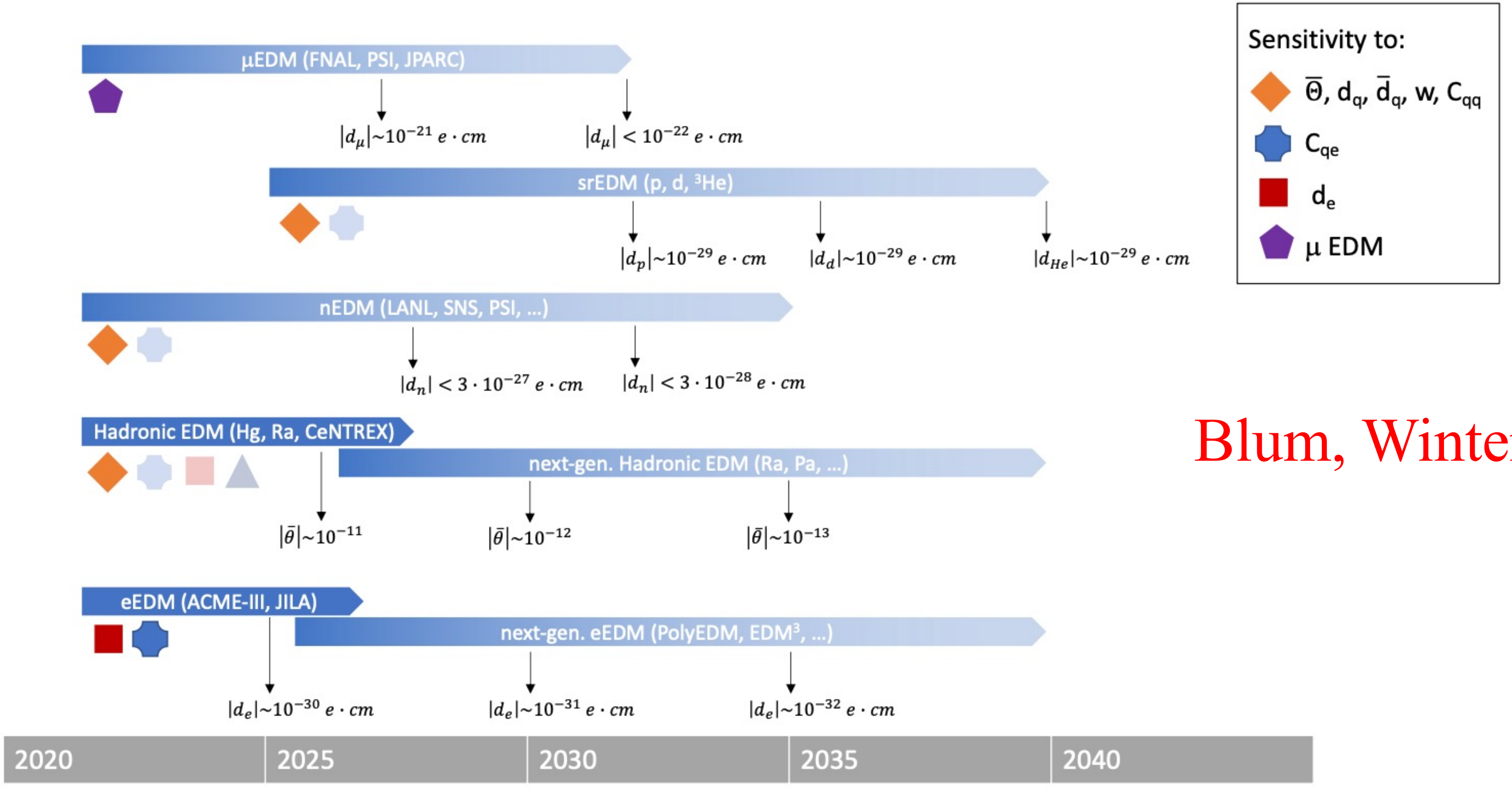



Reminder: batteries are allowed in the SM!

# EDM timelines, from Snowmass 2021 (2022).






Blum, Winter *et al.*

**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

Neutron EDM

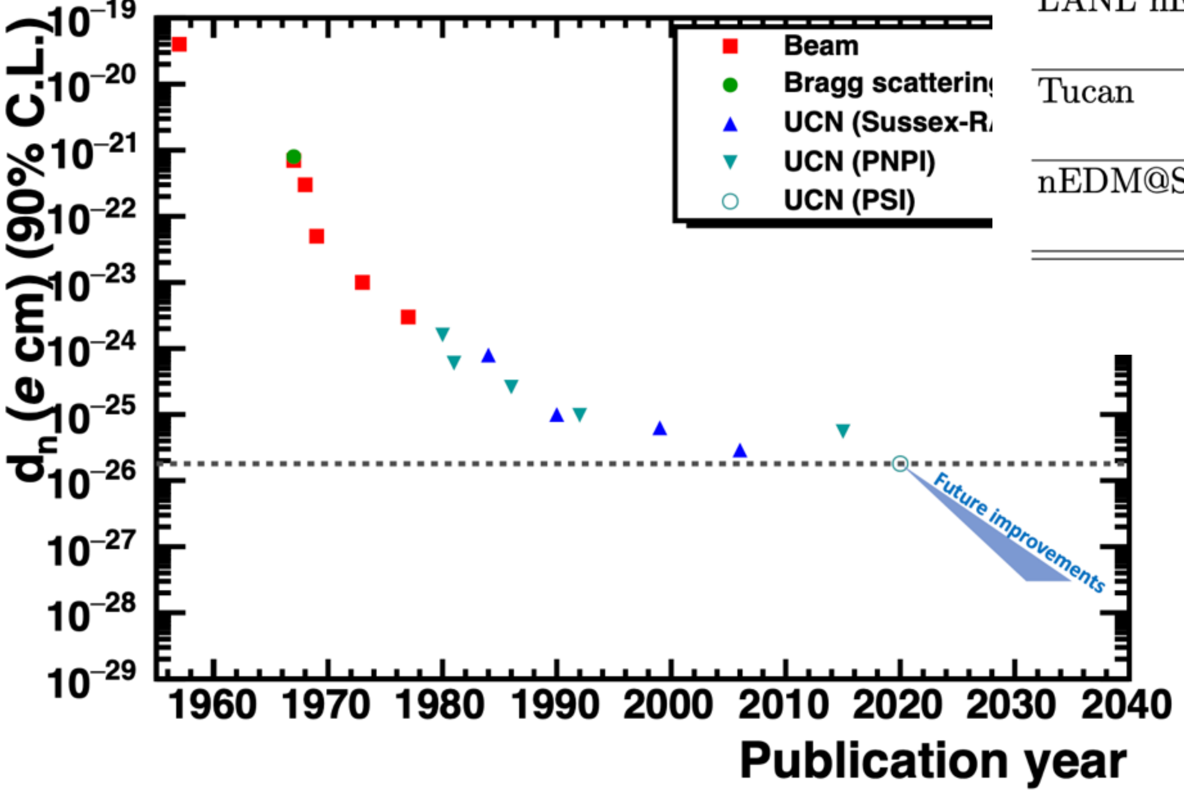



FIG. 3. Evolution of the nEDM results along with projected future results

| Experiment | Location | UCN source | Features | Ref. |
|---|---|---|---|---|
| n2EDM | PSI | Spallation, $SD_2$ | Ramsey method, double cell, $^{199}$Hg comagnetometer | [152] |
| PanEDM | ILL | Reactor, LHe | Ramsey method, double cell, $^{199}$Hg comagnetometer | [153] |
| LANL nEDM | LANL | Spallation, $SD_2$ | Ramsey method, double cell, $^{199}$Hg comagnetometer | [135] |
| Tucan | TRIUMF | Spallation, LHe | Ramsey method, double cell, $^{129}$Xe comagnetometer | [154] |
| nEDM@SNS | ORNL | In-situ production in LHe | Cryogenic, double cell, $^3$He comagnetometer, $^3$He as the spin analyzer | [139] |

TABLE III. A list of the nEDM experiments that are being developed

# Snowmass paper on EDMs

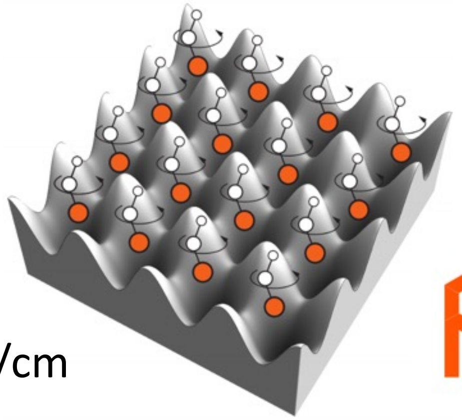
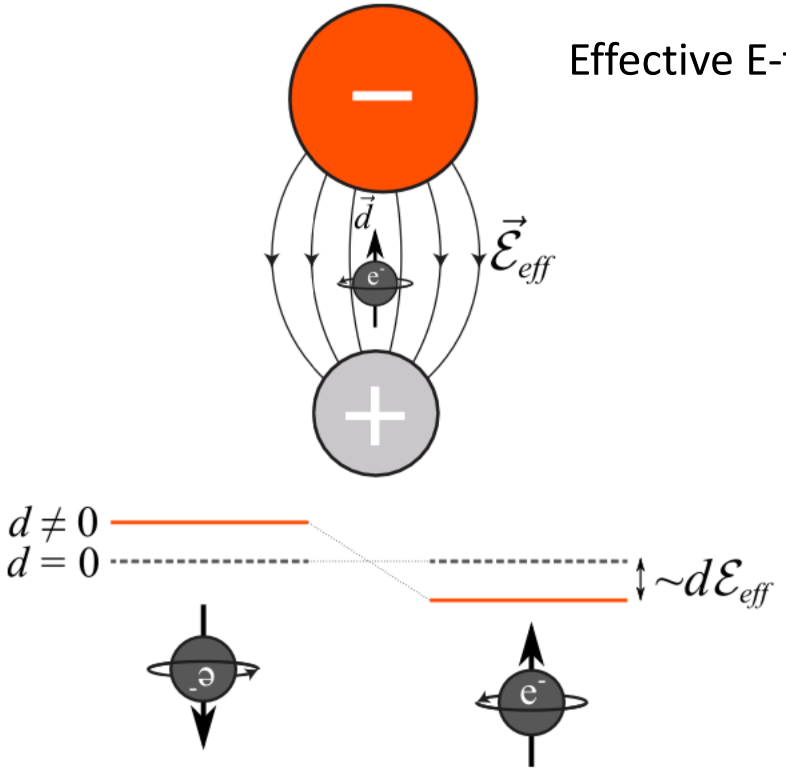


Figure: Laser-cooled polyatomic molecules, optically trapped, with full quantum control. Such a platform can be used to access new physics at the PeV scale.

Effective E-field with polar molecules: order GV/cm



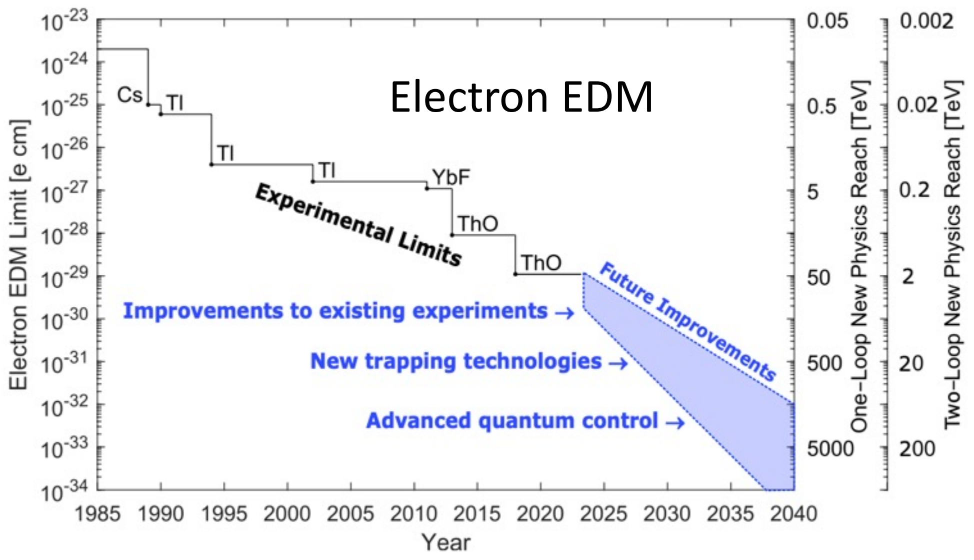
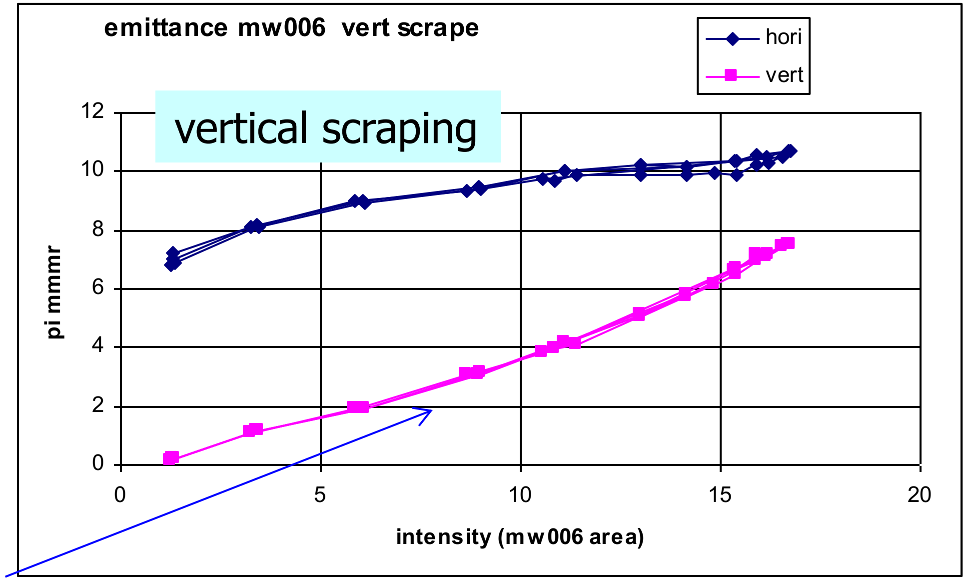




FIG. 5. Electron EDM limits versus time, along with new physics reach for one-loop and two-loop effects (see Eq. 2). All electron EDM experiments to date use AMO techniques. The solid line indicates the most sensitive experimental limit, including the species used. The shaded area indicates potential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

# High intensity polarized proton Beam at BNL

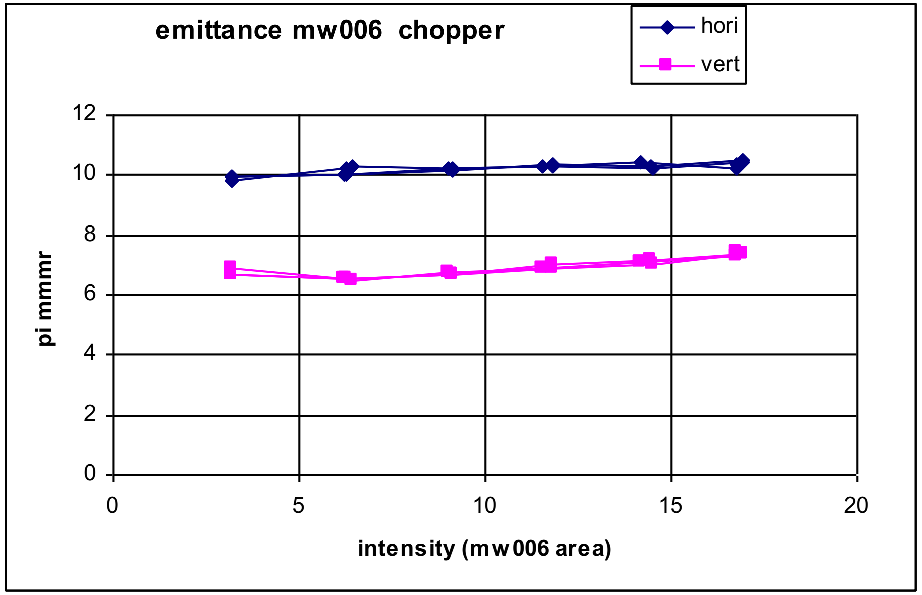
Proton intensity at Booster input $3 \times 10^{11}$. The vertical scale is normalized 95% emittance.

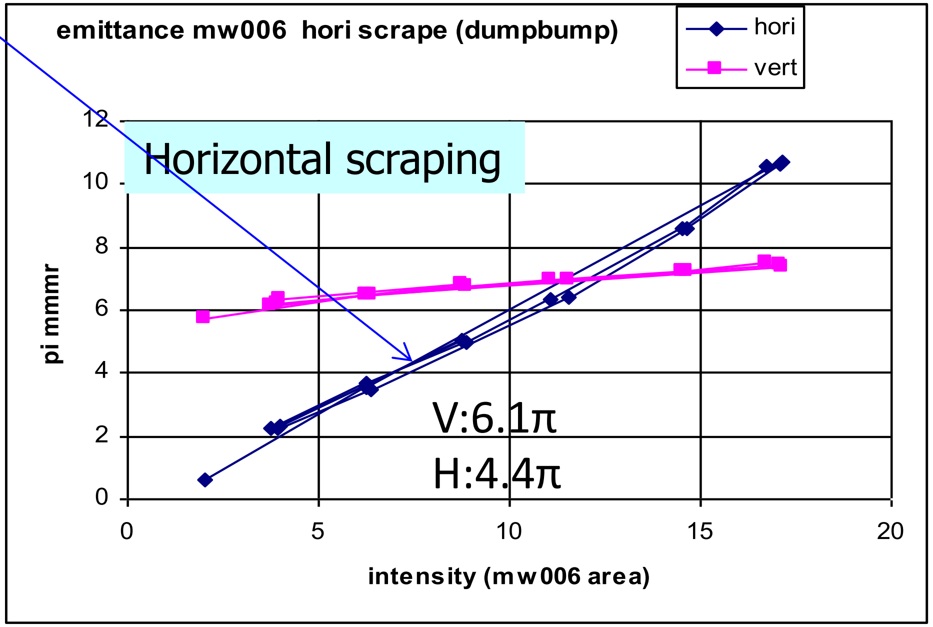
The corresponding normalized rms emittance at $10^{11}$ is $0.7\pi$ horizontal, $1.0\pi$ vertical for horizontal scraping.




Intensity: 15~2e11 protons

@$10^{11}$

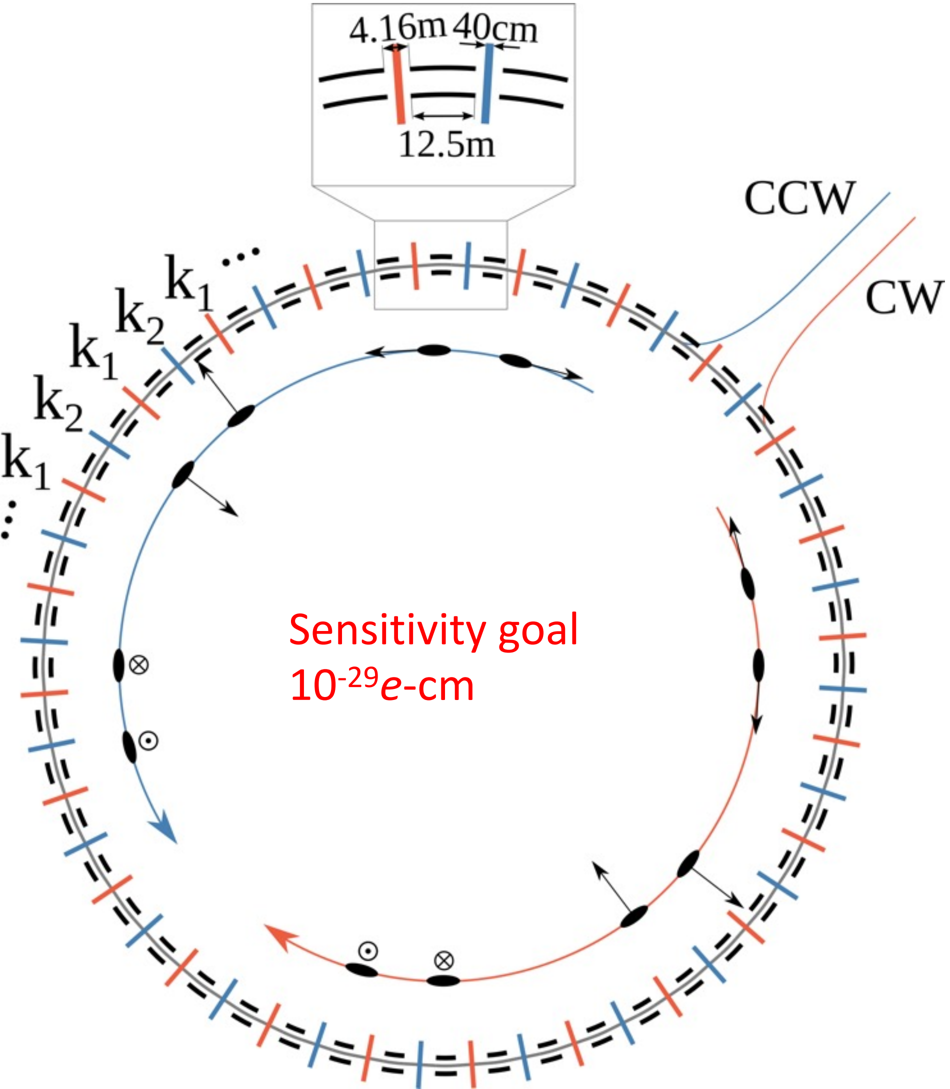



Large statistics available, opportunity for great sensitivity improvement in EDMs

# 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

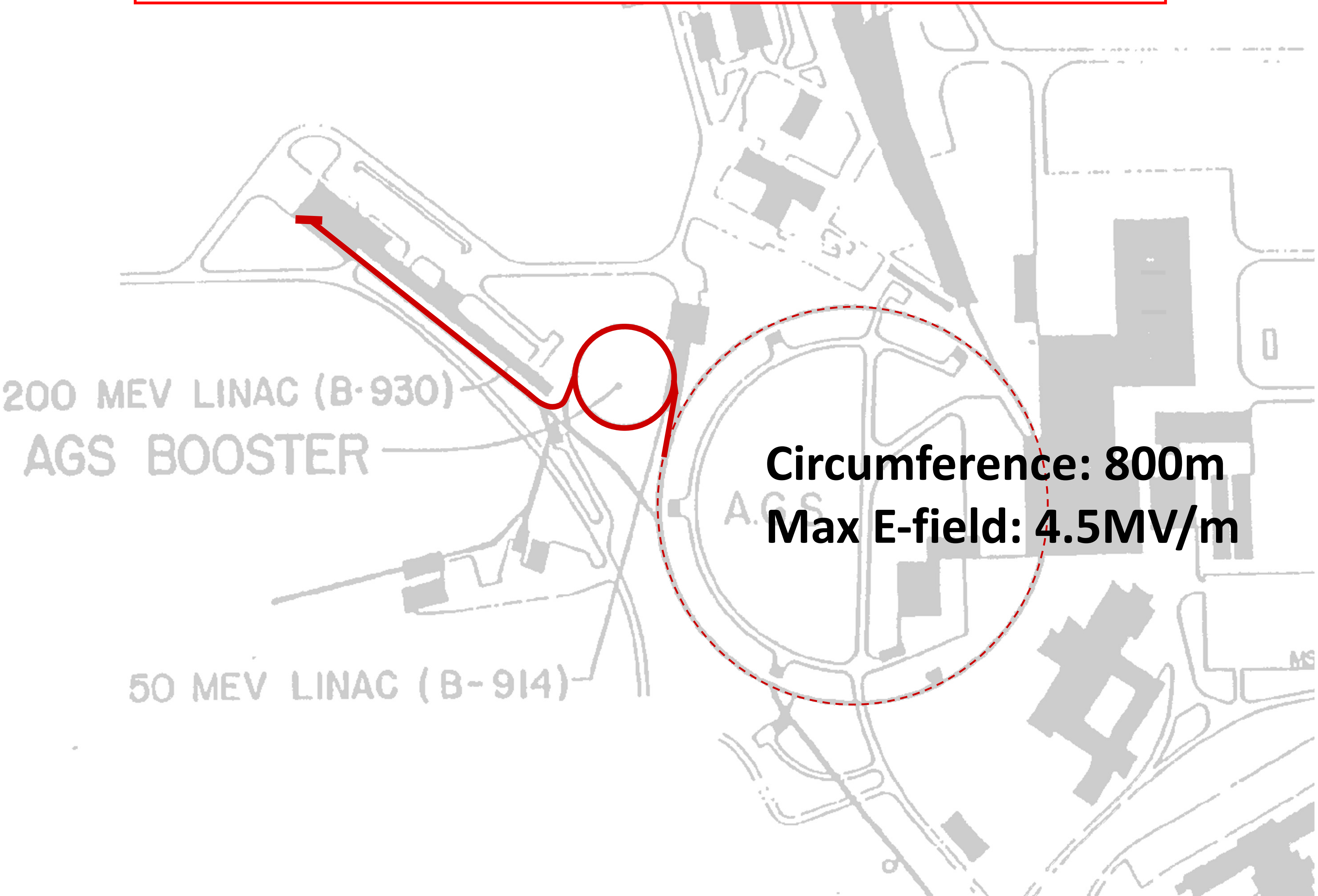
TABLE I. Ring and beam parameters for Symmetric Hybrid ring design

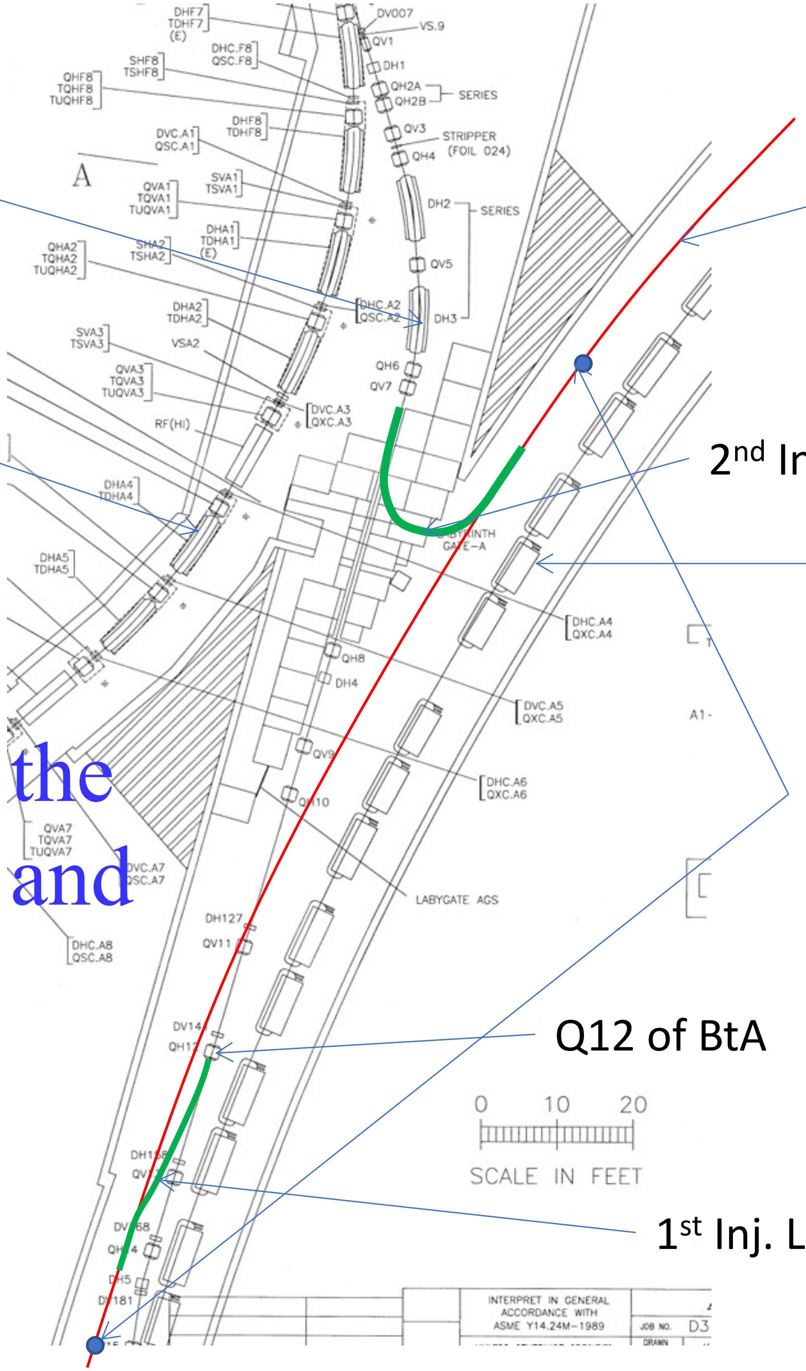
| Quantity | Value |
|---|---|
| Bending Radius $R_0$ | 95.49 m |
| Number of periods | 24 |
| Electrode spacing | 4 cm |
| Electrode height | 20 cm |
| Deflector shape | cylindrical |
| Radial bending $E$-field | 4.4 MV/m |
| Straight section length | 4.16 m |
| Quadrupole length | 0.4 m |
| Quadrupole strength | $\pm 0.21$ 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, $(dp/p)$ | $5.2 \times 10^{-4}$ |
| Horizontal acceptance [mm mrad] | 4.8 |
| RMS emittance [mm mrad], $\epsilon_x$, $\epsilon_y$ | 0.214, 0.250 |
| RMS momentum spread | $1.177 \times 10^{-4}$ |
| Particles per bunch | $1.17 \times 10^8$ |
| RF voltage | 1.89 kV |
| Harmonic number, $h$ | 80 |
| Synchrotron tune, $Q_s$ | $3.81 \times 10^{-3}$ |
| Bucket height, $\Delta p/p_{\text{bucket}}$ | $3.77 \times 10^{-4}$ |
| Bucket length | 10 m |
| RMS bunch length, $\sigma_s$ | 0.994 m |

Low risk

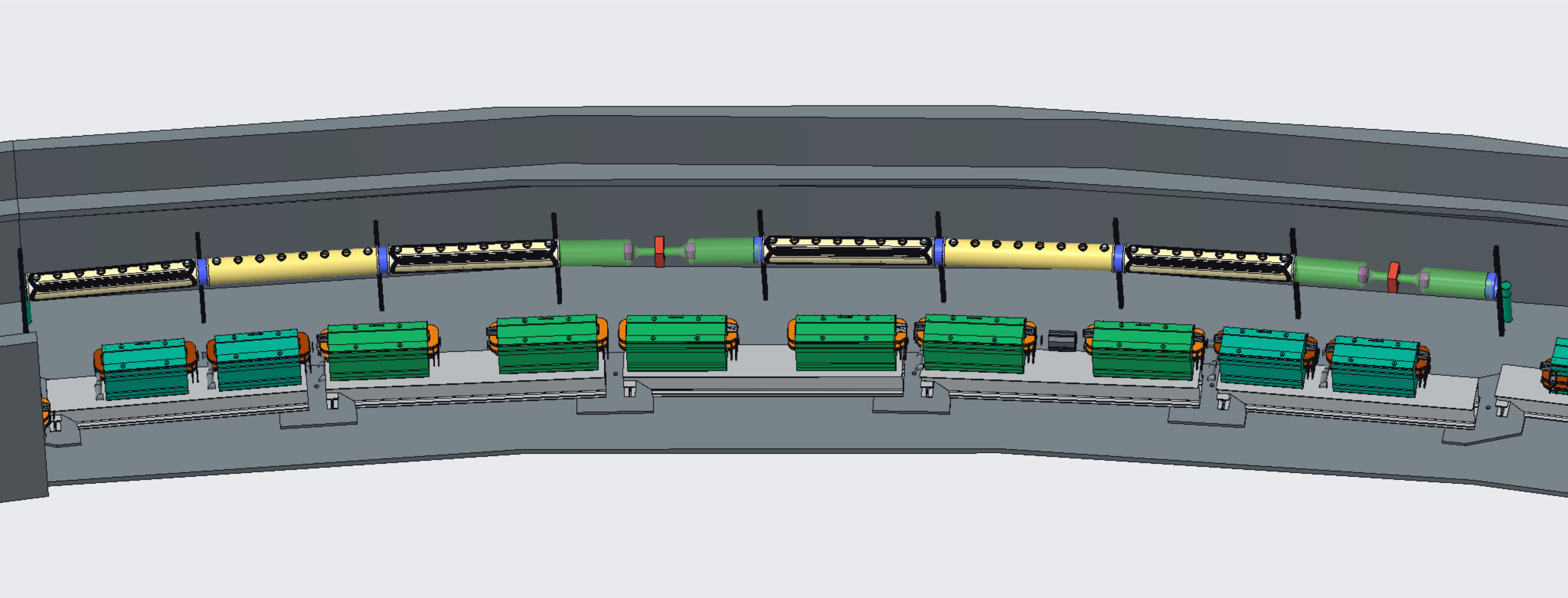
Strong focusing

# The proton EDM in the AGS tunnel at BNL

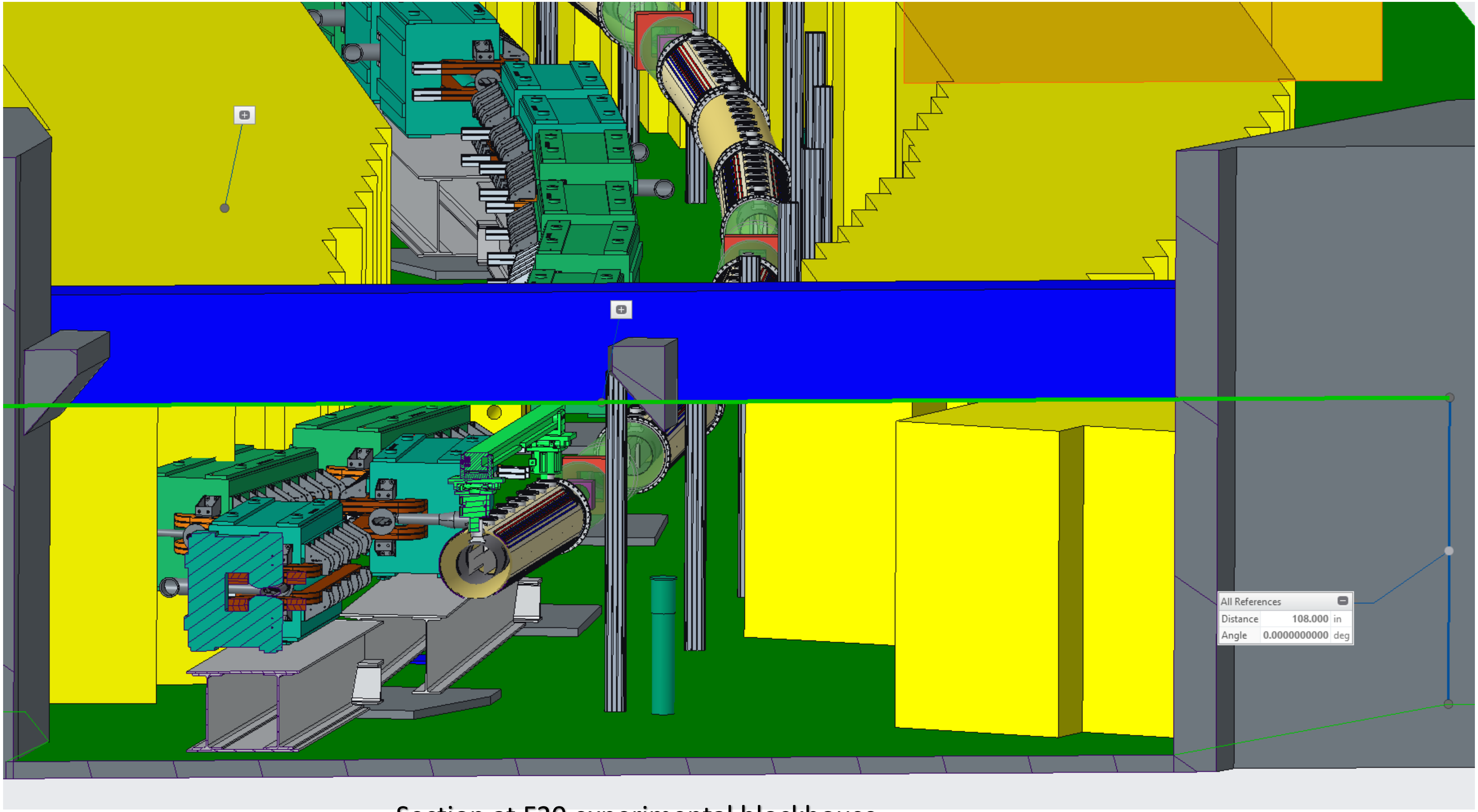




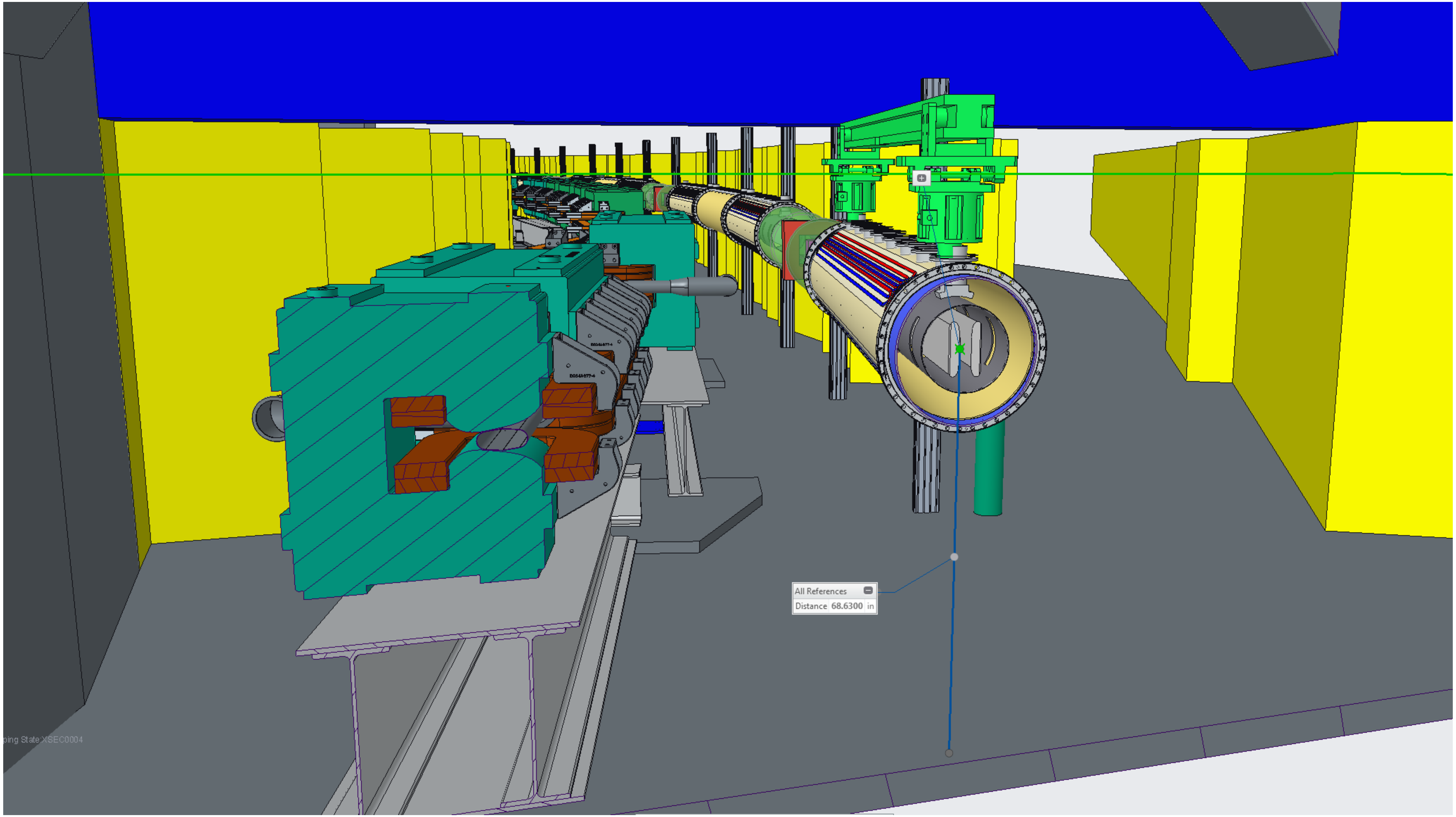

Phase-space matched injection from Booster to the proton EDM ring studied and shown to be possible.



1/24 section (15°) of pEDM ring




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




Section at F20 experimental blockhouse

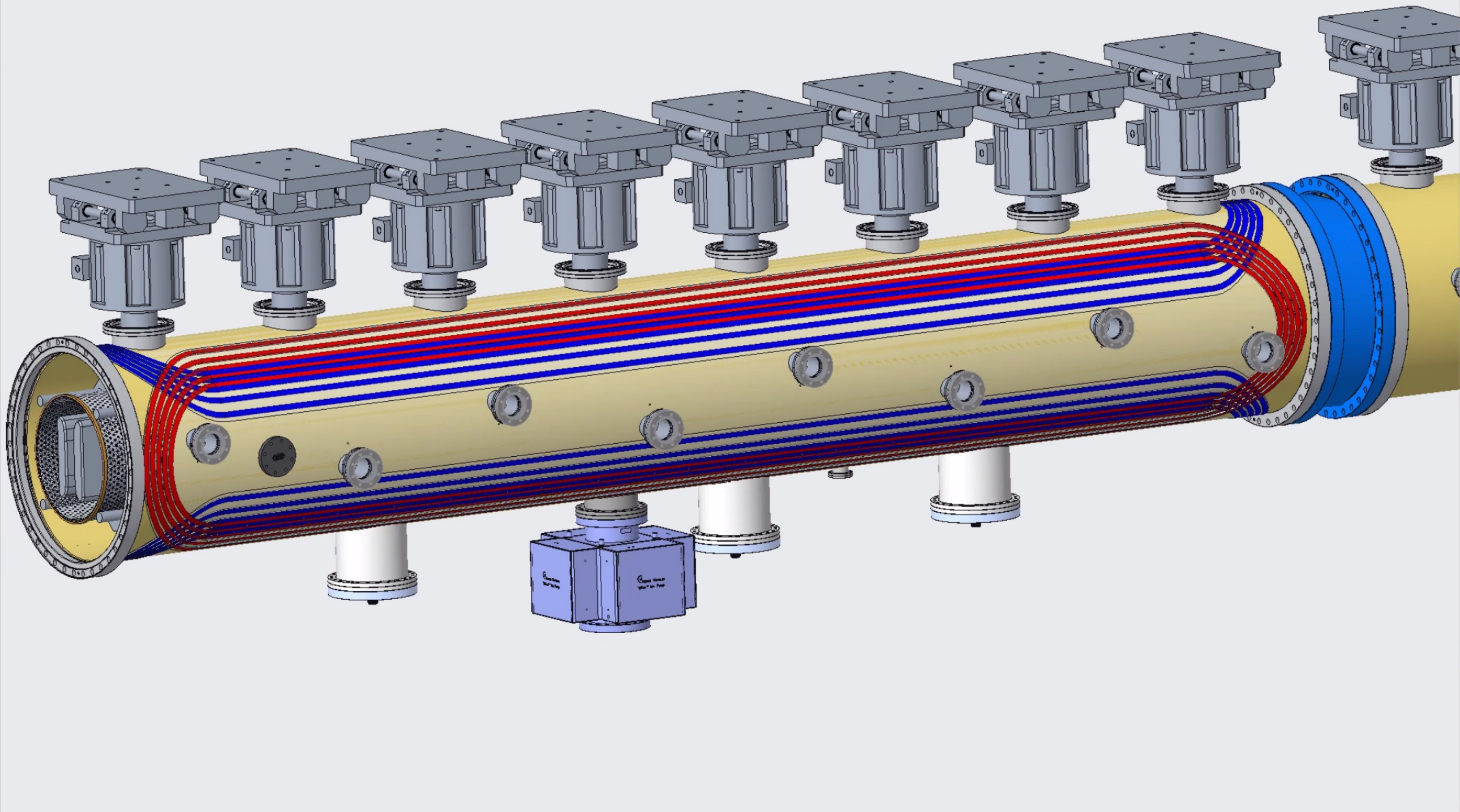
Note: preliminary ring elevation (centerline) = 68.63”

# Magnetic field corrections/generation

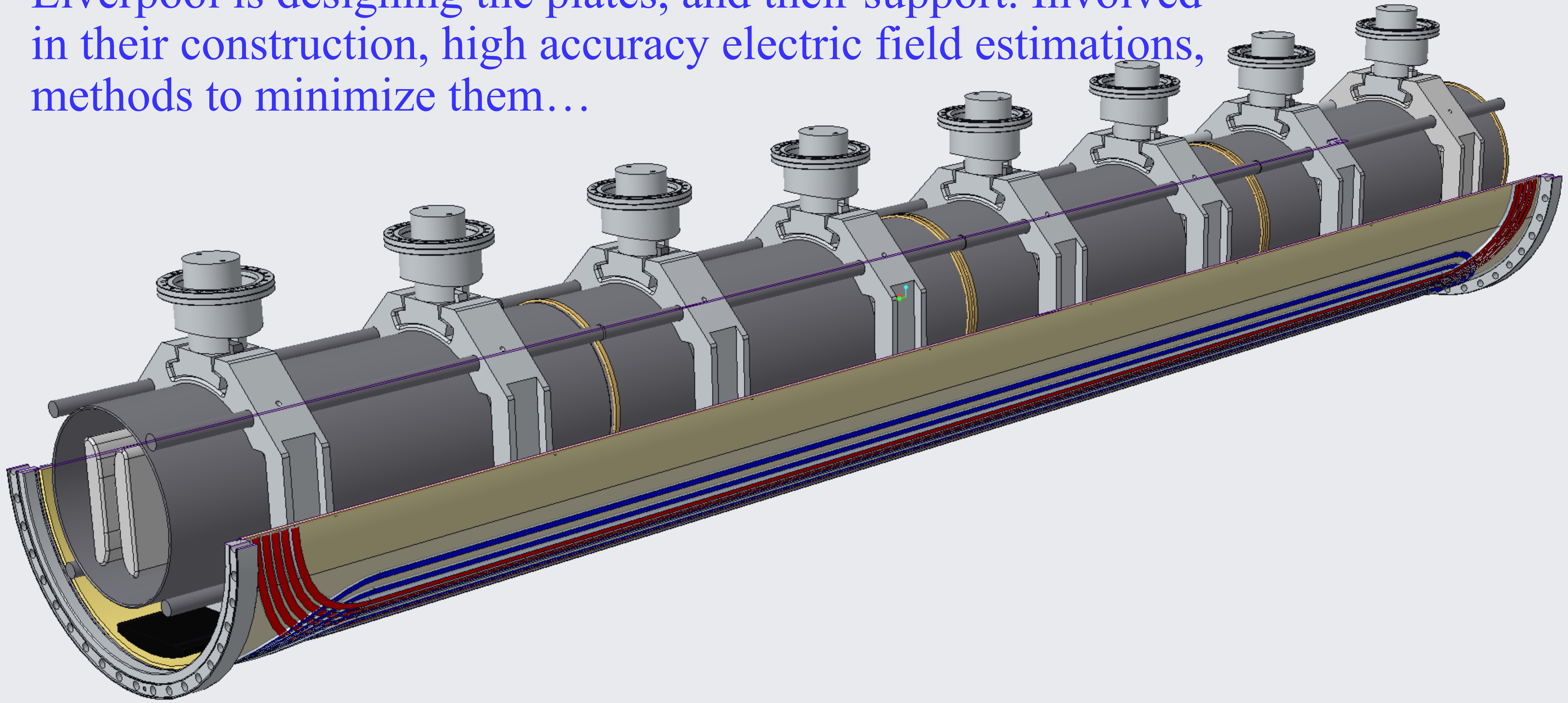
- Outside coils to generate vertical, and radial magnetic fields. Perhaps longitudinal B-fields too.

- Correction coils are used to
  - Eliminate outside B-fields
  - Probe electric field multipoles

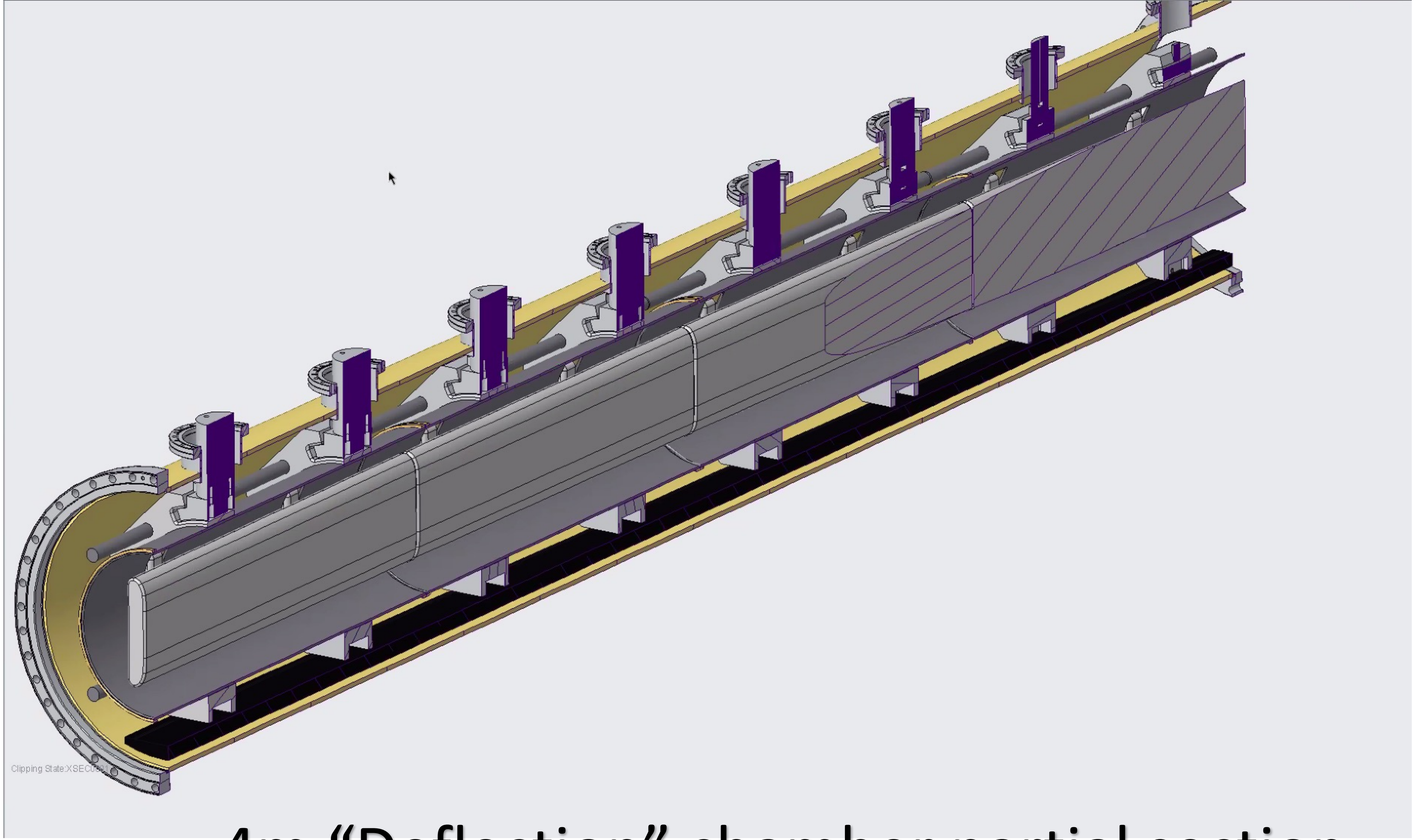
- Our correction coils should not generate unwanted longitudinal B-fields (needs to be specked)



- 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