Progress on Storage Ring EDMs

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Future Accelerators – Corfu 2025

STRONG CP

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

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

BUT, no CP violation in strong interactions…

Quark Mass Terms

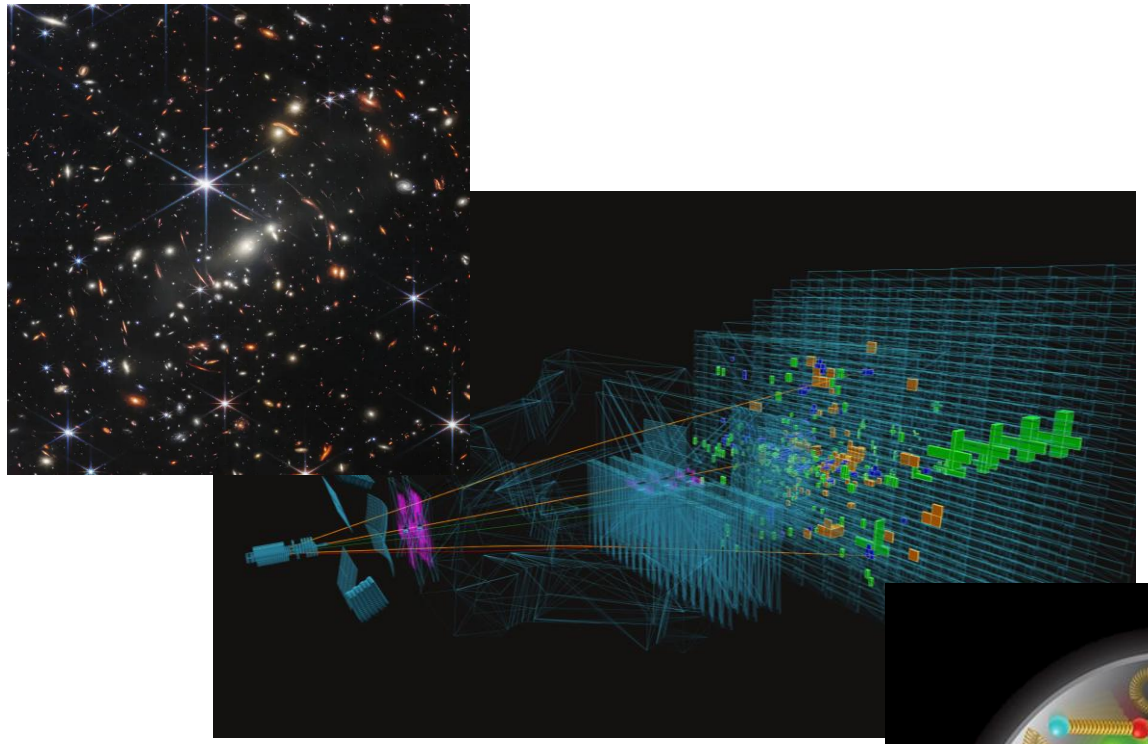
→ No CP violation implies: $\bar{\theta} = \theta_{QCD} + \varphi = 0$ **(famous "fine" tuning!)**

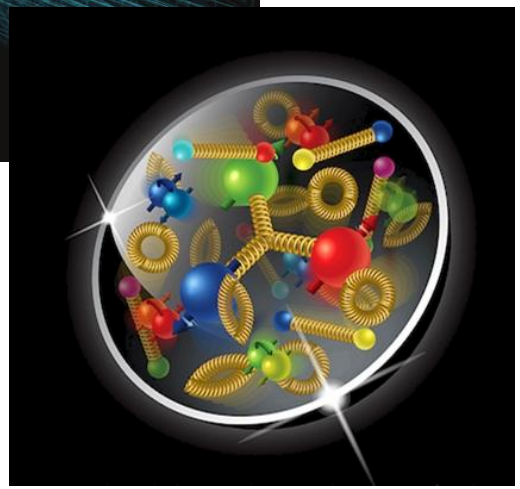
But non-zero nucleon EDM (pEDM), e.g. expected IN BSM

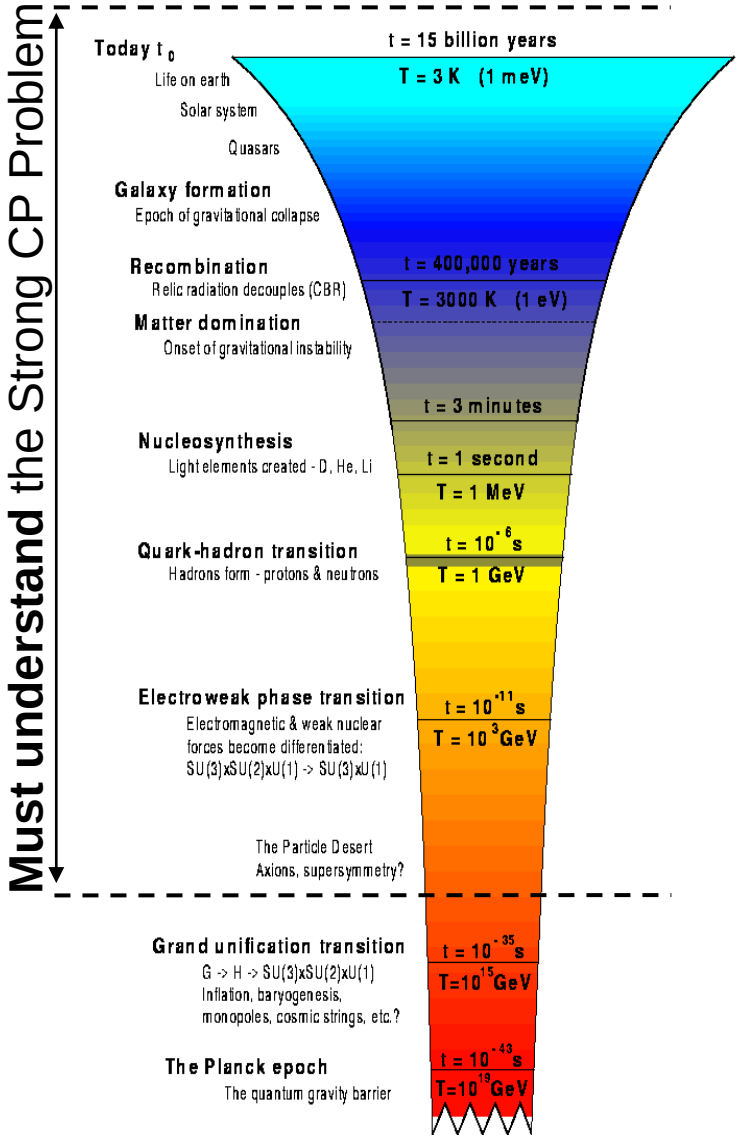
Understand the strong CP-problem!

CP-violation source for Baryon Asymmetry!

Possibility (?) of super-suppression of EDMs below SM expectation







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Nucleon EDMs (d_N)

Nucleon (proton or neutron) are suppressed in the SM.

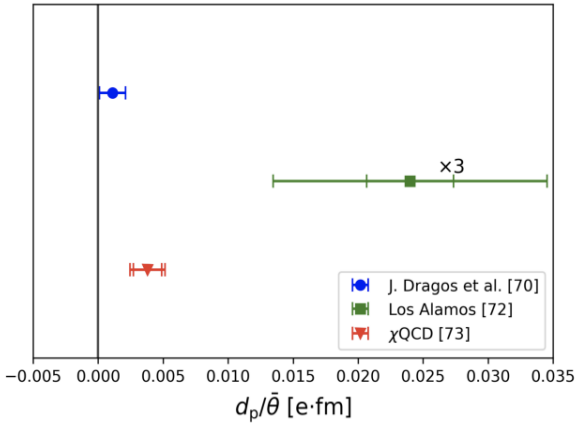
[Tiny CP violating phase in CKM matrix through higher-order loop processes involving quark interactions.]

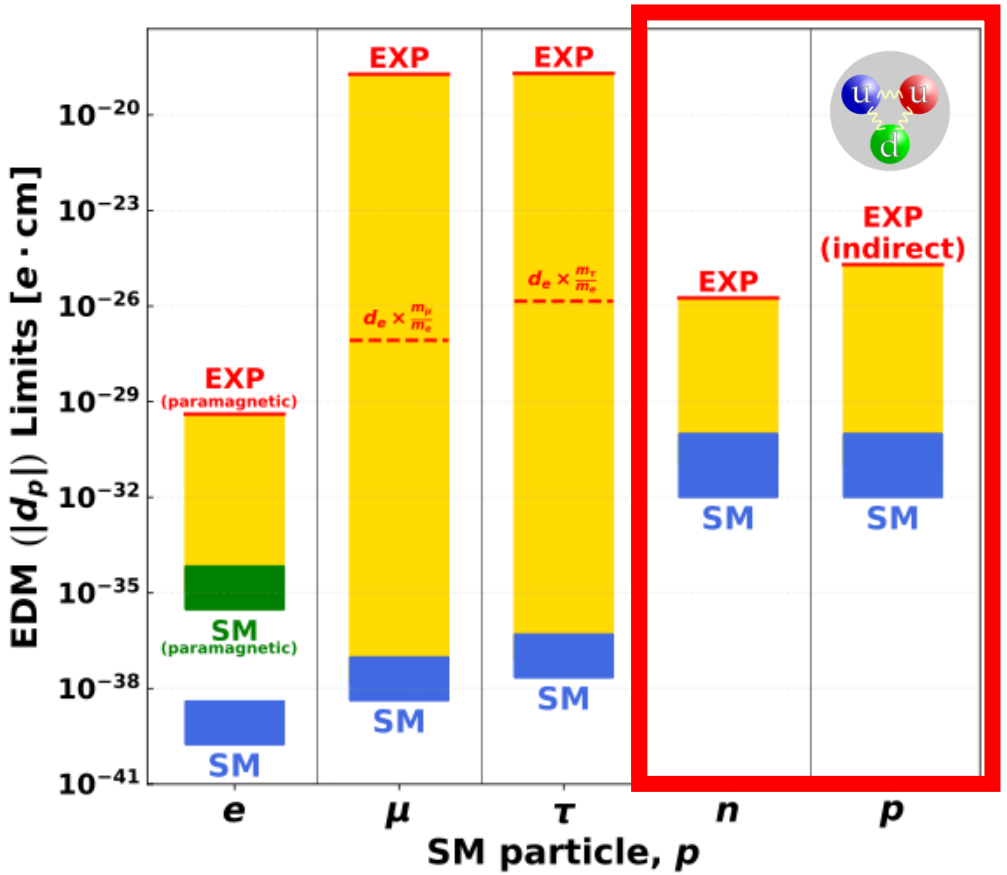
The SM prediction for d_N is:

$$\left|d_N^{SM}\right| \sim 10^{-31}\ e \cdot cm$$

Larger EDMs can arise from:

- BSM models which generate new, CP-violating CKM matrix contributions (SUSY, 2HDM, dark Z, leptoquarks, Extra dimensions).





Ultimately transfers from quark EDMs.

Lattice QCD calculations of nucleon EDMs also an active area of research and progressing, see e.g. article on arXiv : https://arxiv.org/abs/2411.15198

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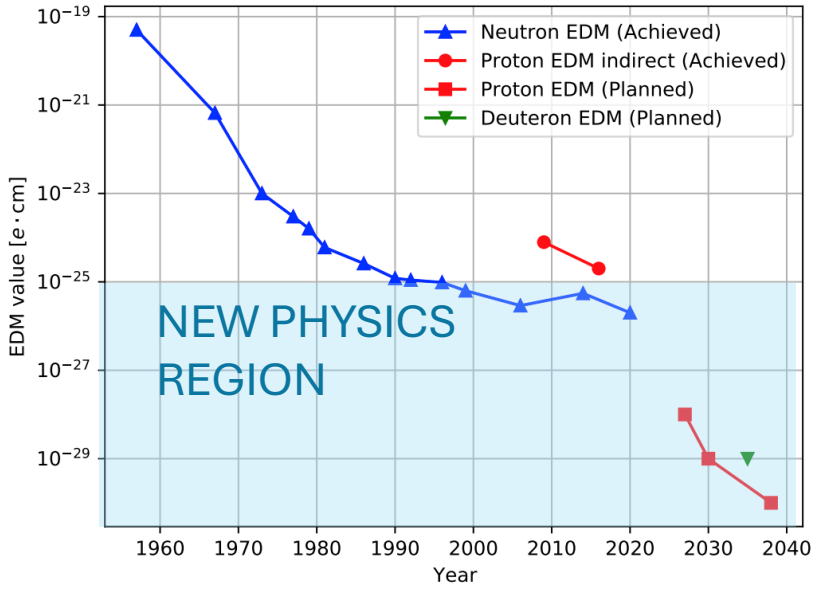
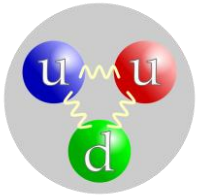
The Proton EDM

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



Can we measure nucleon EDMs at 10^{-31} e·cm ?

If the "natural scale" is O(e · fm) this is 10^{16} down on that. *Measuring human height to better than 1/10 proton.*



- Measure of charge separation of the system:
- Uneven charge + electric field = EDM-induced torque.
  - How do the experiment???

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

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pEDM Experiment: a Muon g-2 spin-off

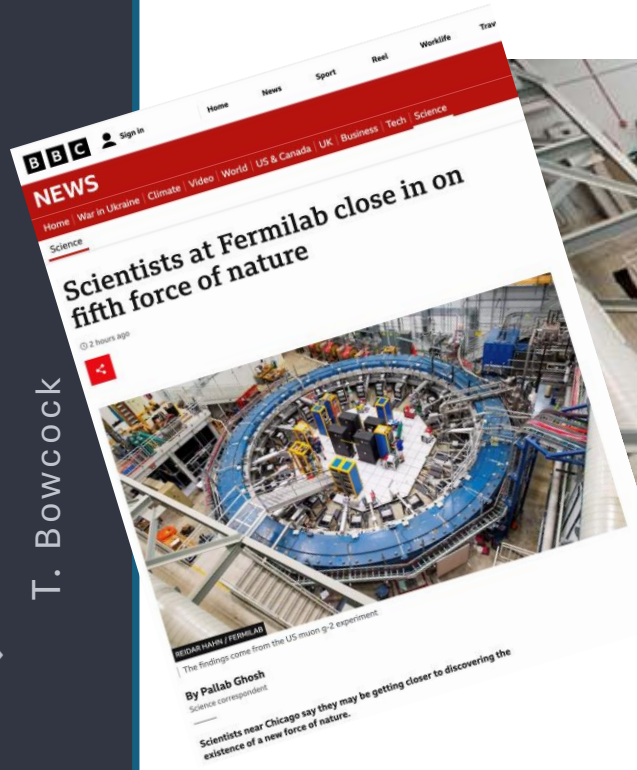
Consider Muon g-2 experiment: charged particle in magnetic ($\vec{B}$) and electric ($\vec{E}$) fields:

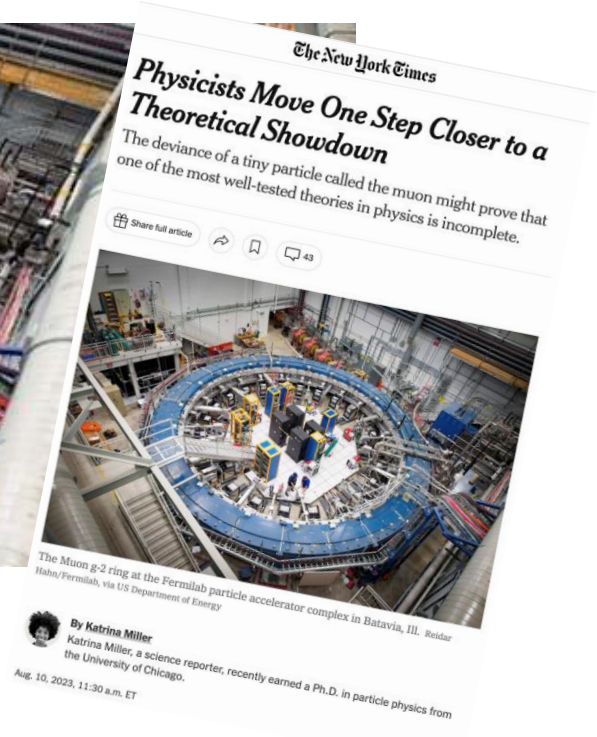
$$\vec{\omega}_{spin} = \vec{\omega}_{MDM} \approx \frac{e}{m}\left[a\vec{B} + \left(a - \frac{1}{\gamma^2-1}\right)\left(\vec{\beta} \times \vec{E}\right)\right].$$

Kill sensitivity to E

Muon → storage ring magnet $R_0 = 7.112$ m and $B = 1.45$ T ...

Choose muon g-2 magic-momentum, $\gamma_{\text{magic}} = \sqrt{1 + 1/a} \rightarrow p = 3.094$ GeV/c.





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

Evolution of pEDM Experiment

Note in g-2 a muon EDM oscillates 90° (up down) out of phase with magnetic dipole precession (used to measure g-2). You can measure EDM but DO NOT benefit from cumulative (time) development of the polarization.

(g-2) term

EDM

Modify 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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g-2 to EDM

- Sublety is that experimental technique (physics) is g-2 is OK with the muon precession (wiggle is what we measure)
- We want to “accumulate” effect of “torque” on proton. We need to *freeze* the spin of the proton along direction of motion

Choose pEDM magic-momentum: $a\vec{B} + \left(a - \frac{1}{\gamma^2 - 1}\right)\left(\vec{\beta} \times \vec{E}\right) = 0$

Choosing the momentum carefully we ensure the spin is always aligned with the direction of travel round the ring (zero precesion)

Note: if no B-fields (purely electrostatic) then polarization depends on E (assume radial bending field)

Proton → electric storage ring $R_0 = 800\ \mathrm{m}$ and $E = 4.4 \frac{\mathrm{MV}}{\mathrm{m}},\ \mathrm{p} = 0.7\ \mathrm{GeV/c}$

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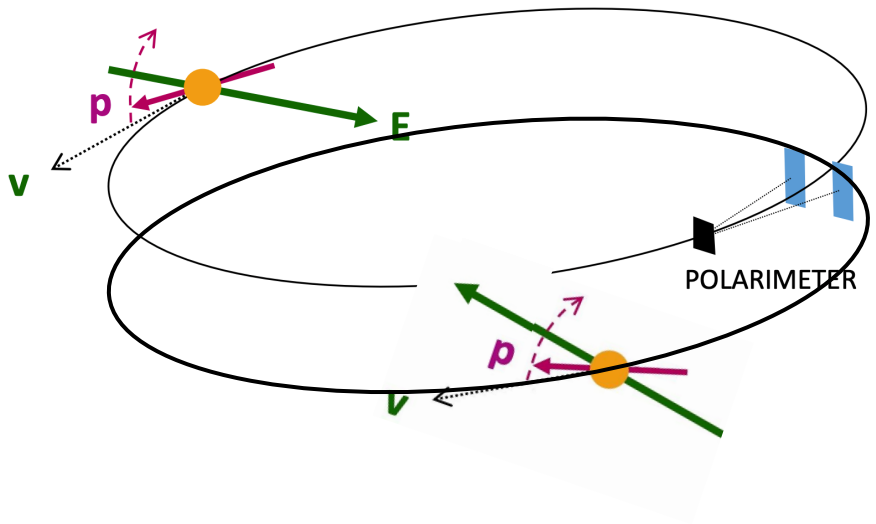
pEDM Experiment: a Muon g-2 spin-off



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

What about large, T-conserving systematics that mimic vertical, T-violating EDM, e.g. unwanted vertical electric fields?

see later...

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

pEDM Statistical Sensitivity

PRD 104, 096006 (2021)

$$\sigma_d = \frac{2.33s\hbar}{P_0AE\sqrt{kNT_{\exp}\tau_p}}$$

P_0 = Beam polarisation = ~ 0.8

A = asymmetry = ~ 0.6

E = electric field strength = 4.4 MV/m

k = polarimetry efficiency = ~ 0.01

N = number of stored protons/injection = ~ 2×10^{10}

$T_{\exp}$ = total experiment duration = ~ 10^8 s

τ_p = polarisation lifetime = ~ 2×10^3 s

NOTE: High fields (needed for small radii) give higher precision!!!

Spin Coherence Time (SCT)

JÜLICH Forschungszentrum

Measurement and Optimization of the Spin Coherence Time for Protons in COSY

V. Hejny, I. Keshelashvili, A. Lehrach, E. Stephenson, A. Wrońska on behalf of the JEDI collaboration

December 6, 2019

14th International Particle Accelerator Conference IOP Publishing
Journal of Physics: Conference Series **2687** (2024) 052025 doi:10.1088/1742-6596/2687/5/052025

easuring electric dipole moments (EDMs) using -precision all-electric ring with counter-rotating n intermediate step a demonstrator for key tech- as well as for frozen spin is planned. One prereq- tion is a large spin coherence time in the order of ital program at COSY has focused on deuterons. like to start a similar effort for protons by asking MD + 3 experiment) in Q2 of 2020.

Studies of the spin coherence time of protons at COSY

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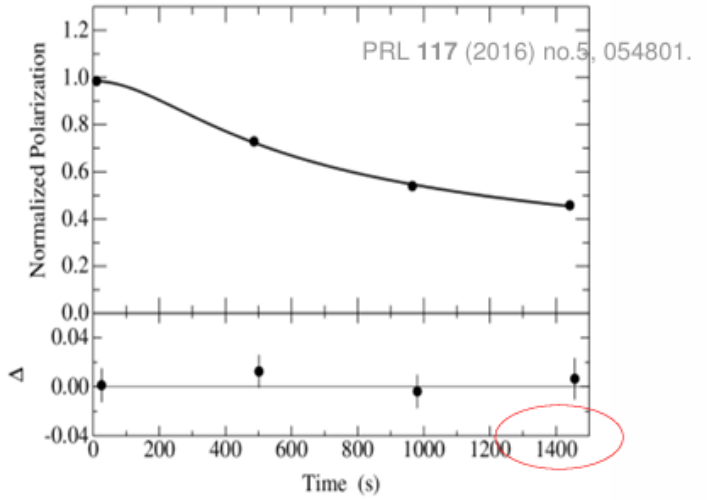
Abstract. The search for the Electric Dipole Moments (EDM) of charged particles in storage rings necessitates polarized beams with long Spin Coherence Time (SCT) of the circulating beam. The SCT is the time during which the RMS spread of the orientation of spins of all particles in the bunch reaches one radian. A long SCT is needed to observe the coherent effect of a polarization build-up induced by the EDM. For deuterons the SCT of 1000 s has been achieved at the COoler SYnchrotron COSY (Jülich, Germany). Accomplishing such long SCT for protons is far more challenging due to their higher anomalous magnetic moment, but essential for the planned EDM experiments. It has been shown that for protons the SCT is strongly influenced by nearby intrinsic and integer spin resonances. The strengths of the latter have been calculated for a typical optics setting of COSY and the overall influence on the SCT was predicted. In addition, the efficiency of proton spin flipping with an RF solenoid from initially vertical direction into the ring plane is also investigated.

lectric dipole moment (EDM) experiment grew out of ment of the muon magnetic dipole moment (MDM) at for EDMs on charged particles could be made using a he EDM signal was a rotation of the polarization direc- lectric field in the particle frame. It was also recognized e as a general platform to investigate the EDM of sev- ault from the muon MDM was just barely inconsistent ation that new physics (such as supersymmetry) might re further investigations such as the EDM search. A experiment at Brookhaven [2, 3] that emphasized the cleus to supersymmetry [4, 5]. This led to work, first at COSY (E174), on highly efficient deuteron polarimetry errors [6].

anagement would be central to the success of the EDM like effects for beams circulating in either direction in alization of time reversal), a large number of problems on, however, this required that the magnetic field of the

1.) Spin Coherence Time (SCT)



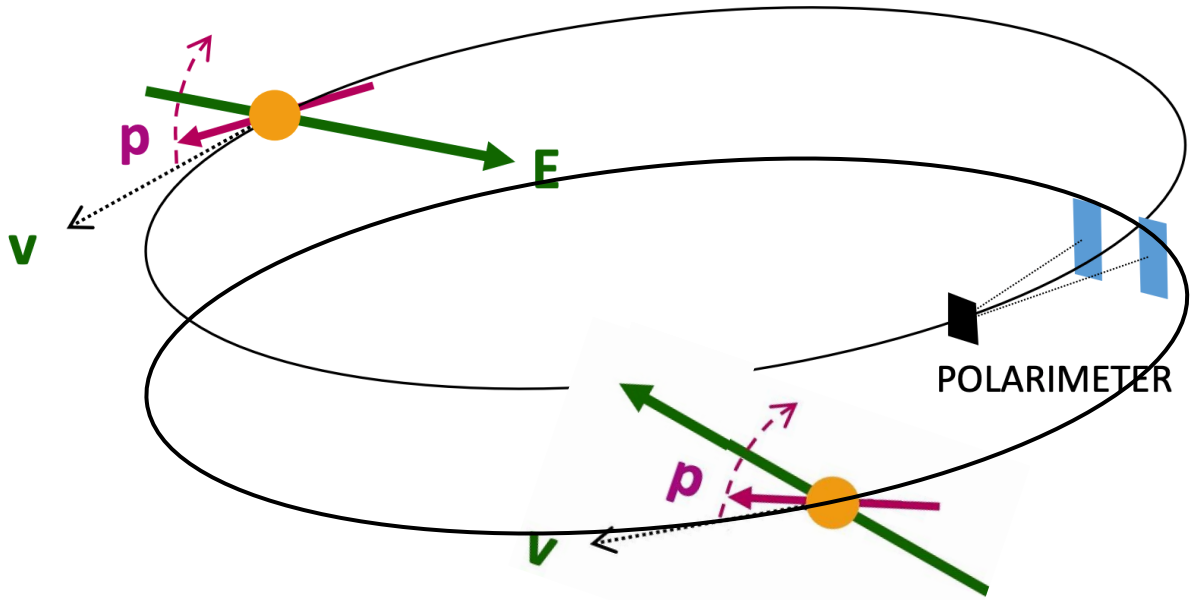
Magic momentum

- Electron Beam Cooling (Prior to Injection) learned needed
  - Stochastic cooling during operation
- Sextupole Field Tuning
  - Sextupole magnets were used to correct for momentum-dependent path length differences in the ring.
- Precision Orbit Control
- **Feedback and Active Control Systems**

pEDM: Spin Coherence Time

- Orlov → how to get them right with three sextupole families.

- In pure electric rings we only needed two families; Omarov finding using high-precision simulation



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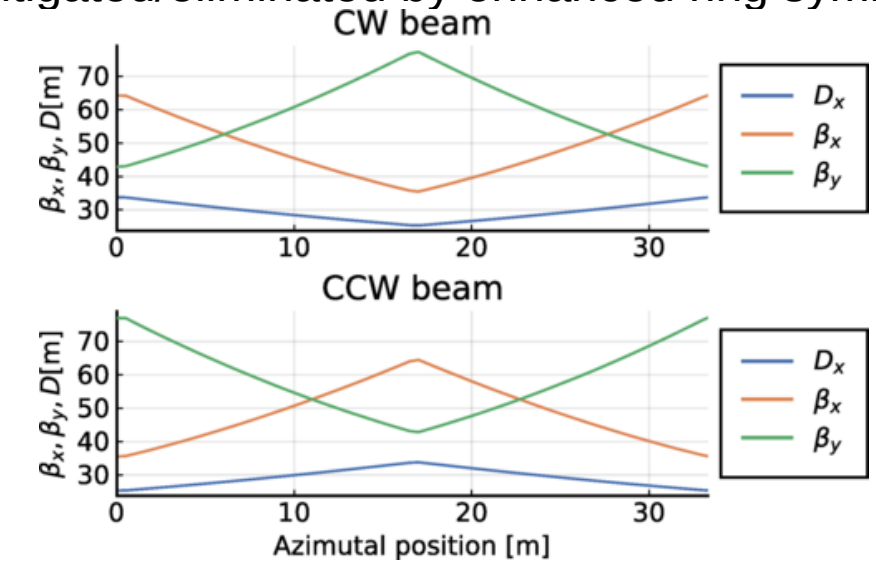
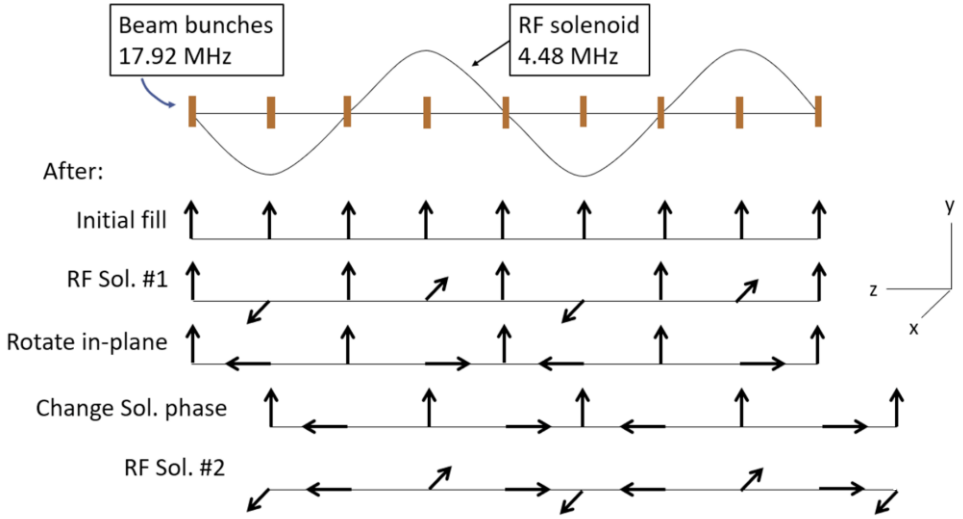
Storage Ring Systematics

Major systematic efforts from protons in storage ring mitigated/eliminated by enhanced ring symmetry:

Systematic Error Source	Ring Symmetry Mitigation
Unwanted (background) vertical electric fields, when magnetic focusing is used	CW vs. CCW storage
Unwanted (background) radial magnetic fields, when electric focusing exists	Spin based alignment to probe and cancel unwanted electric focusing
Unbalanced vertical velocity component of beam in a region with strong radial E-fields	Symmetric lattice; quad current flip; radial polarization
Geometrical phases originating from spin rotations in three dimensions	CW vs. CCW storage; magnetic quad current flip
Polarimeter related systematic errors	Storing simultaneously oppositely polarized bunches

PRD **105** (2022) 032001, arxiv:2205.00830.





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A Storage Ring EDM Experiment

Advanced design currently considered (*PRIOR TO P5*)

- Highly symmetric, storage ring lattice to control systematics
- Proton magic momentum = 0.7 GeV/c for frozen-spin.
- Proton polarimetry peak sensitivity at frozen-spin momentum.
- Optimal electric bending (and maybe magnetic focusing).
- 2×10^{10} polarized protons per fill. One fill every twenty minutes.
- Simultaneously store clockwise (CW) and counterclockwise (CCW) bunches.
- Simultaneously store longitudinally polarized bunches with positive and negative helicities as well as radially polarized bunches.
- 24-fold symmetric storage ring lattice.
- Closed orbit automatically compensates spin precession from radial magnetic fields.
- Circumference = 800 m with E = 4.4 MV/m, a conservative electric field strength.

PRD **105** (2022) 032001, arxiv:2205.00830.

"I suppose I'll be the one to mention the elephant in the room."

Effect: NO srEDM specific R&D in US

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

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

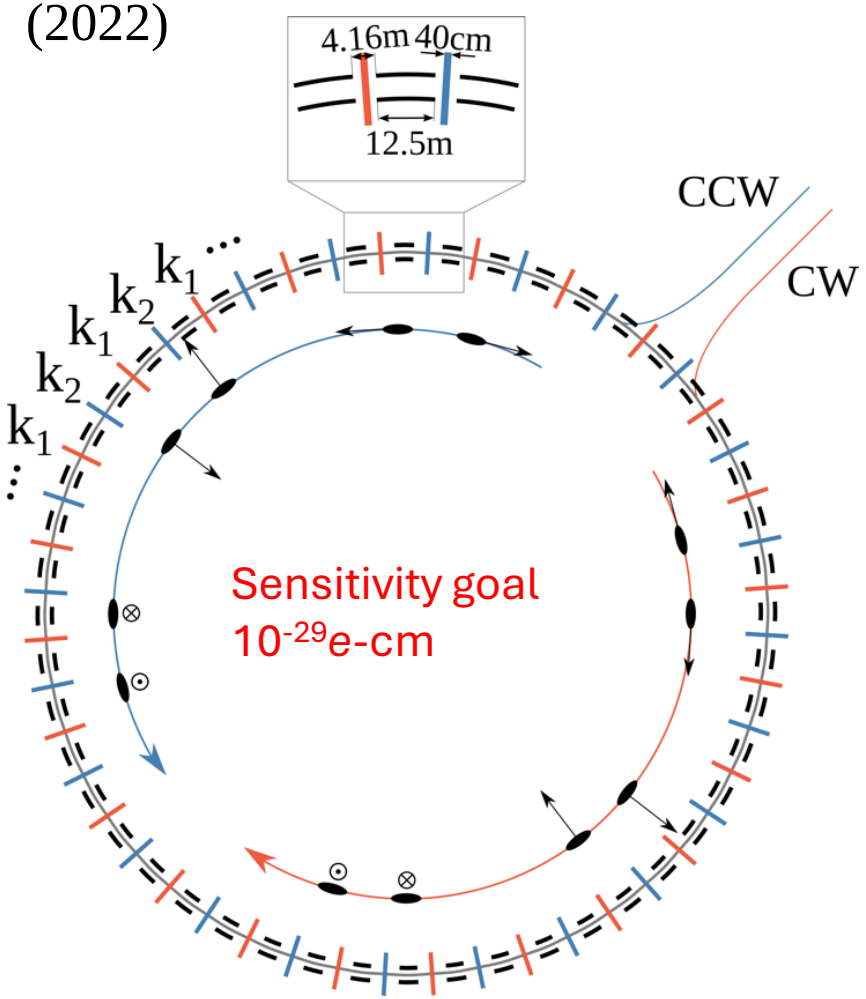

TABLE I. Ring and beam parameters for Symmetric Hybrid ring design

Quantity	Value
Bending Radius R_0	95.49 m
Number of periods	24
Electrode spacing	4 cm
Electrode height	20 cm
Deflector shape	cylindrical
Radial bending E-field	4.4 MV/m
Straight section length	4.16 m
Quadrupole length	0.4 m
Quadrupole strength	± 0.21 T/m
Bending section length	12.5 m
Bending section circumference	600 m
Total circumference	799.68 m
Cyclotron frequency	224 kHz
Revolution time	4.46 μs
$\beta_x^{\max}$, $\beta_y^{\max}$	64.54 m, 77.39 m
Dispersion, $D_x^{\max}$	33.81 m
Tunes, Q_x, Q_y	2.699, 2.245
Slip factor, $\frac{\delta\rho}{\rho} \frac{dt}{t} / \frac{dp}{p}$	-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

(Short) path to readiness

Main message: no showstoppers!,

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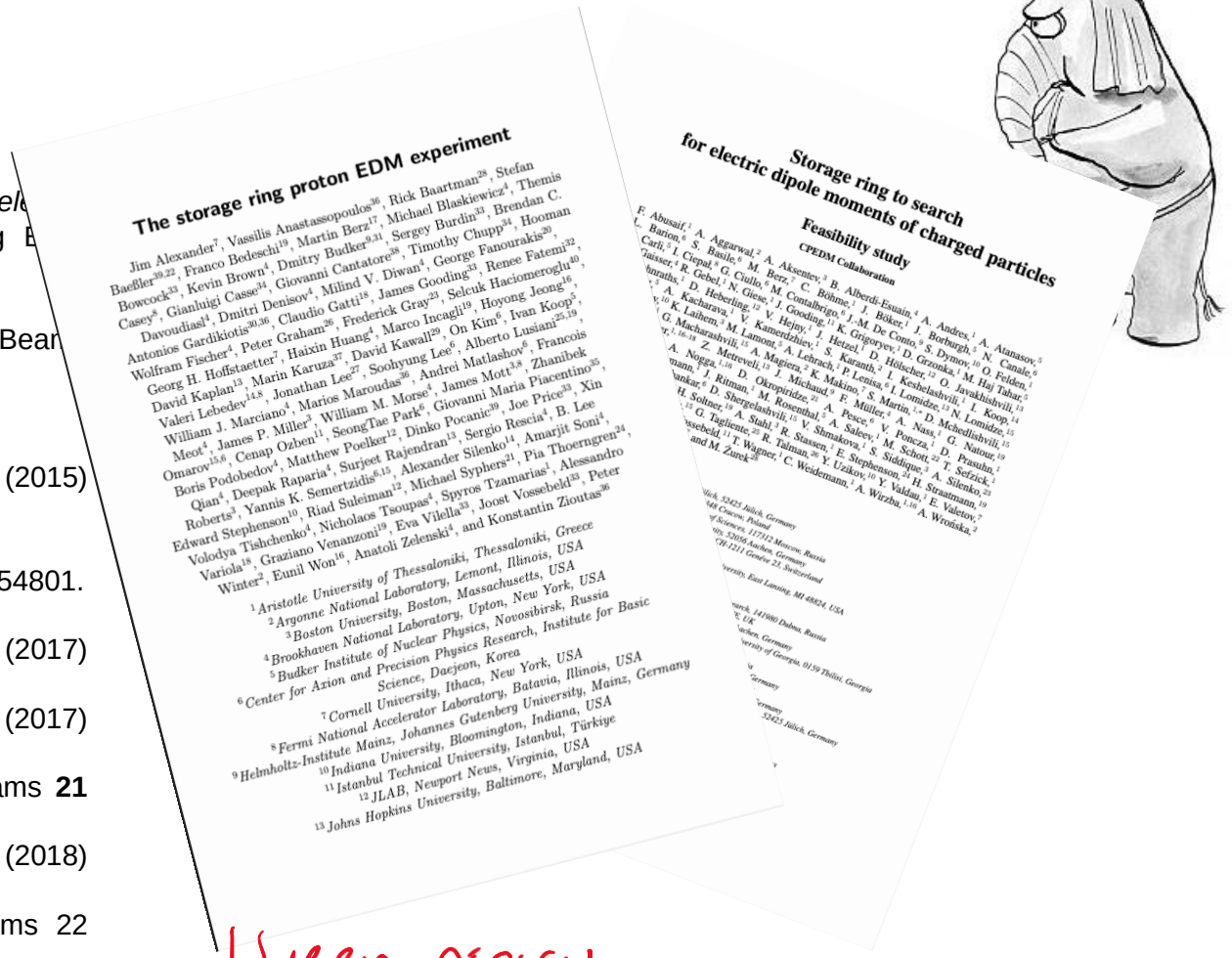
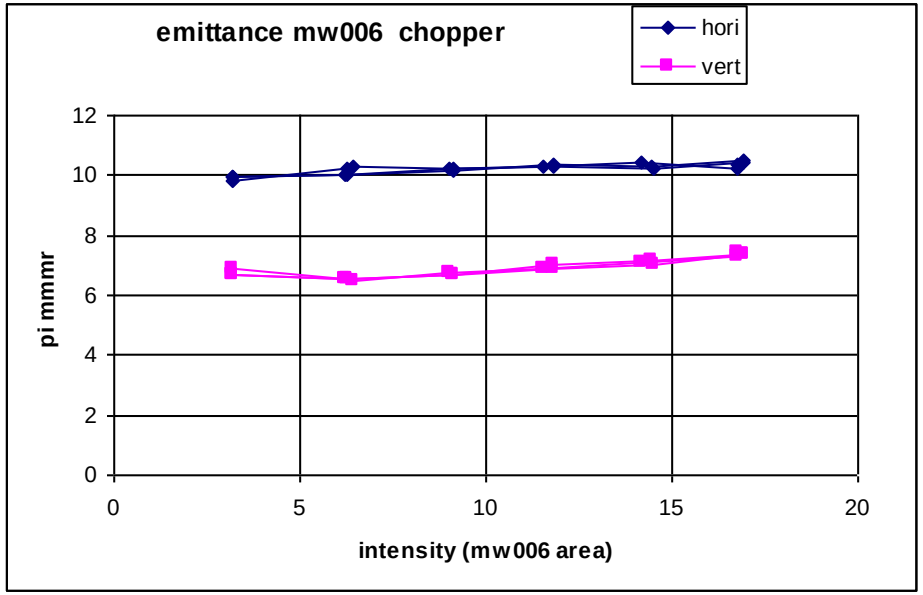


High intensity polarized proton Beam (at BNL)

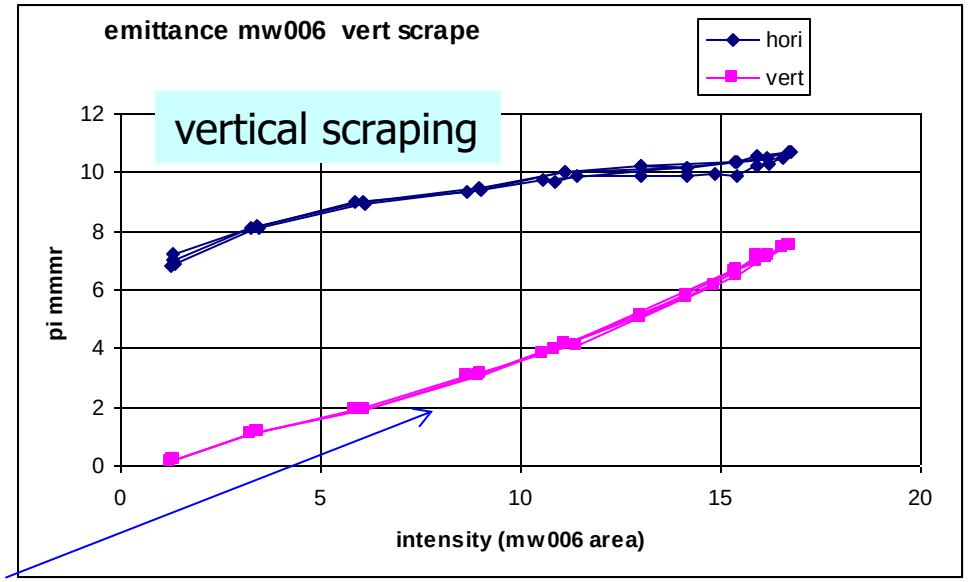
Proton intensity at Booster input $3*10^{11}$. The vertical scale is normalized 95% emittance.

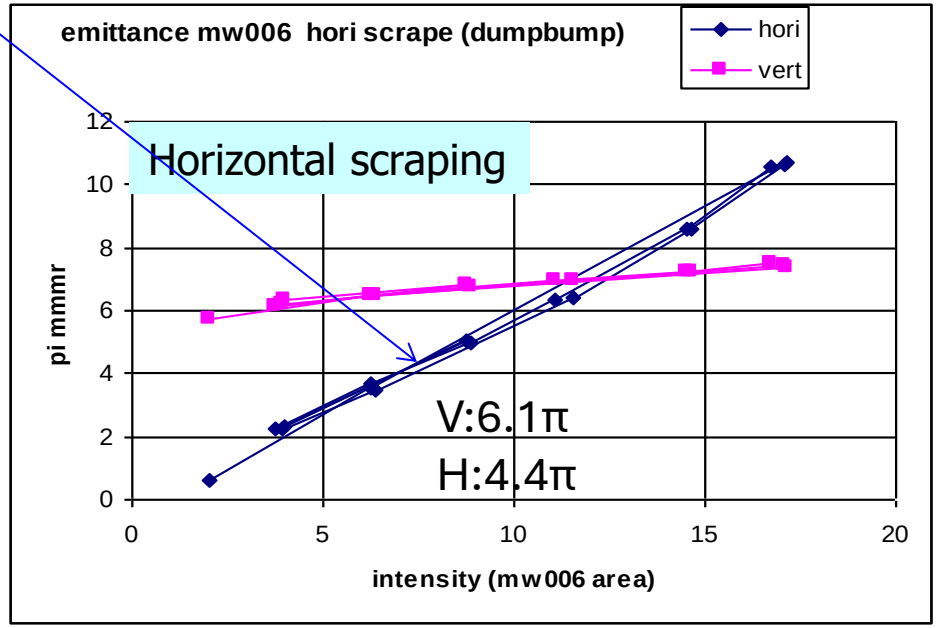
The corresponding normalized rms emittance at 10^{11} is 0.7π horizontal, 1.0π vertical for horizontal scraping.

Intensity: 15~2e11 protons



@10^{11}



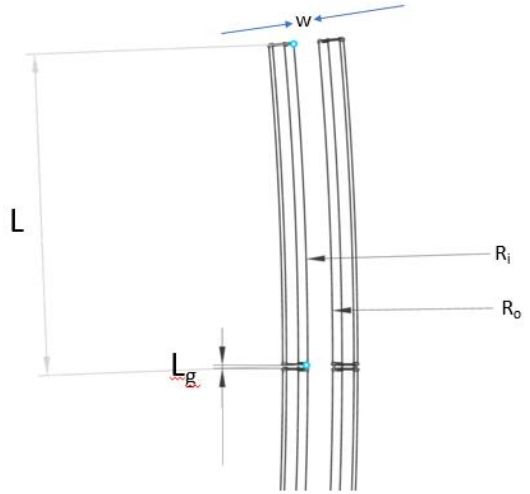


Large statistics available, opportunity for great sensitivity improvement in EDMs

Deflectors

In perfect world curve the deflectors
Practically – **much easier to build flat.** Note trajectory is not perfectly down the middle

- Design
- Roll/Pitch/Yaw/Radial
  - Inclinometers
  - Roll sub-arc second (motorized)
  - Parallel O(5 microns)
- No “power-on” distortion
- Alignments
  - Radial (few microns)
  - Yaw (few microns adjust – motorized)
  - Pitch(not sensitive – O(10) microns)
  - Height (not sensitive - O(10) microns)



All motion adjusts are decoupled

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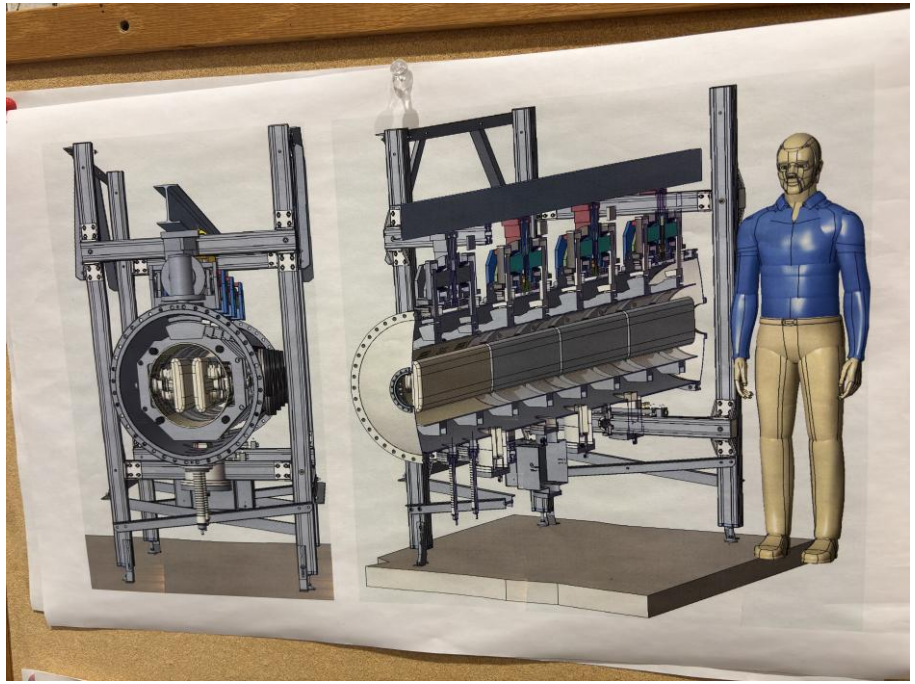
Ongoing Related Development

Following P5, DOE + BNL approved 3-year LDRD to develop and demonstrate electric field plates at 4.4 MV/m and supporting low energy ion storage rings (see below)



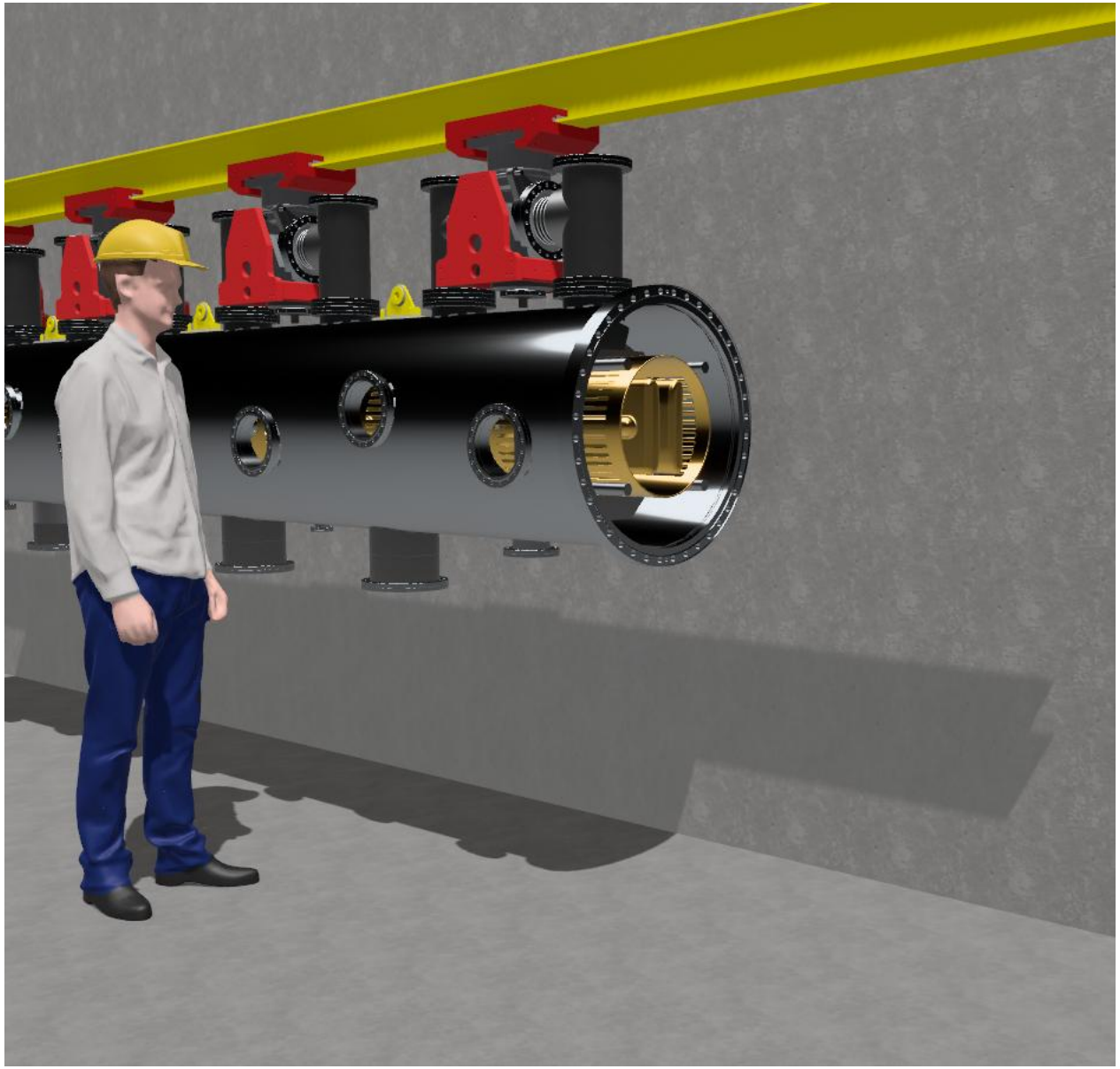
→ This in being done in collaboration with the UK.
(Constructing and shipping plates to BNL.)

Activities that EDM can benefit from

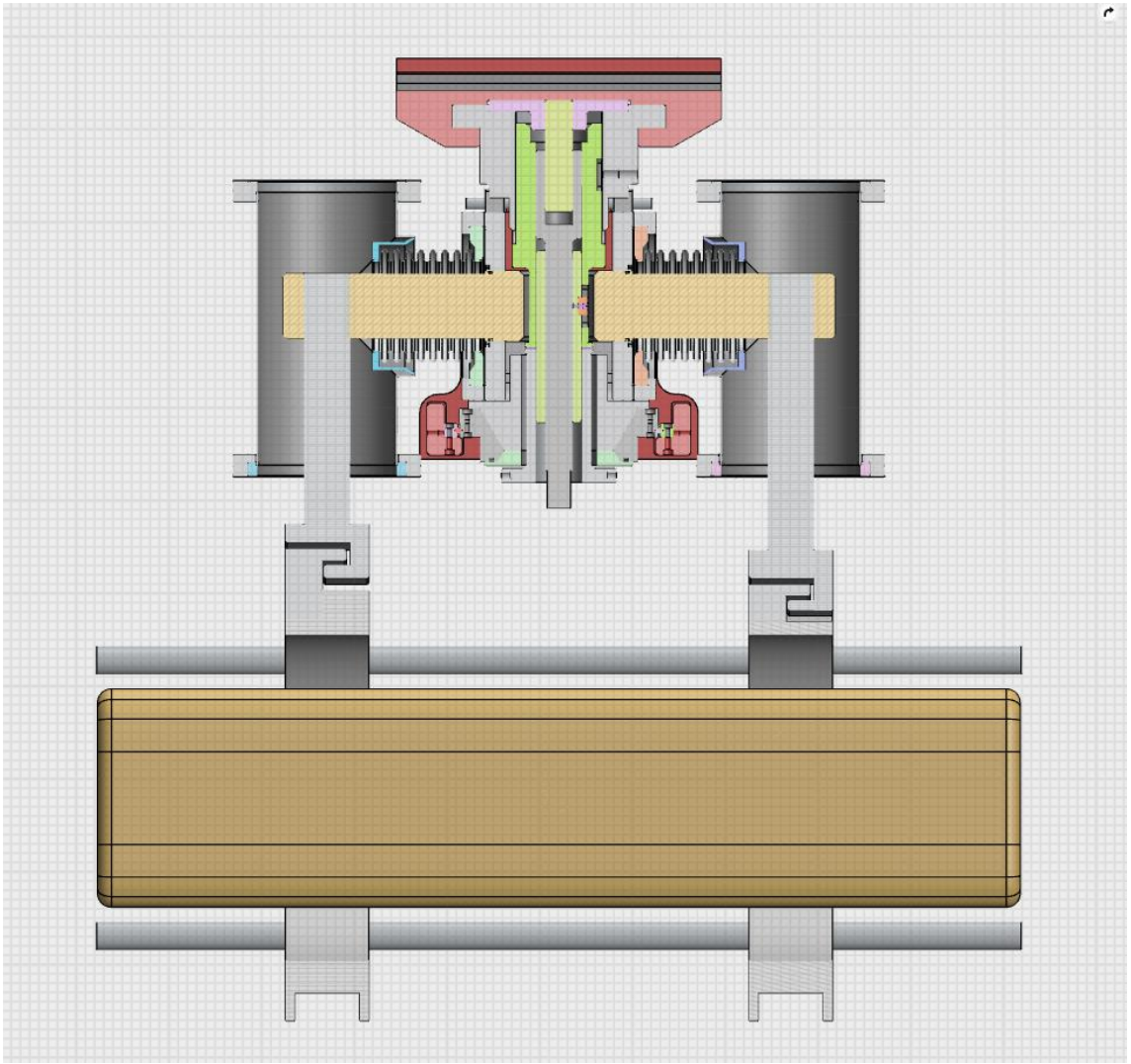
1. Spin tune adjusters (Wien filter application)
2. Velocity Filters
3. Beam separators
4. Low energy ion storage rings

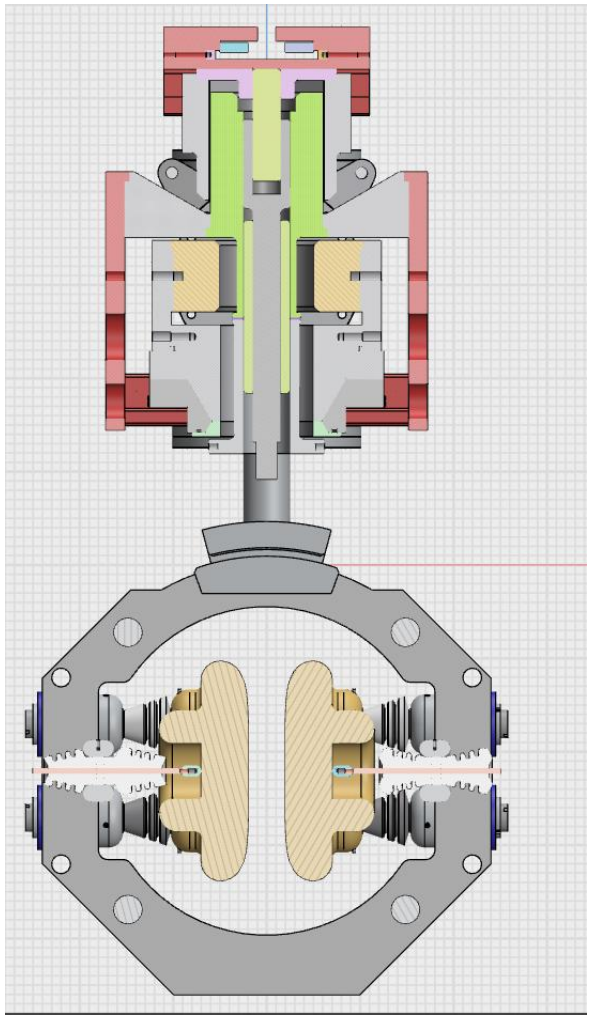
UK related activity

- Long standing interest in EDMs
- Collaborate on Velocity Filters/Beam Separators …
- Polarimetry
- Physics



Unit pre-aligned
- Adjust height, radial, pitch
- Micro adjust yaw and roll
- Motions decoupled
- UHV compliant





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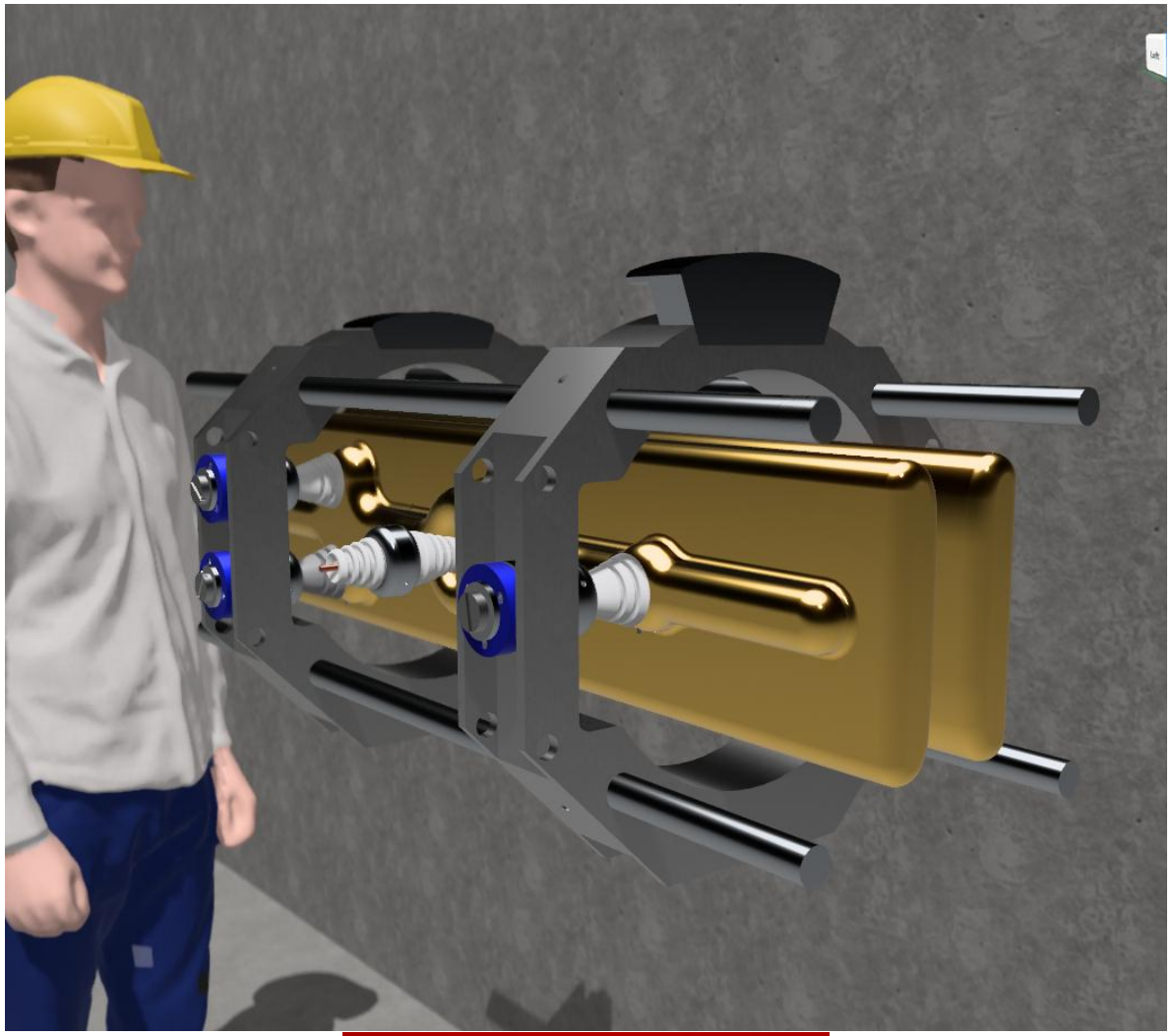
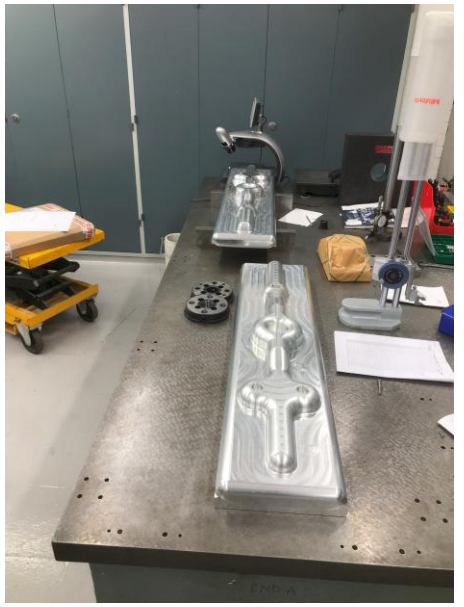
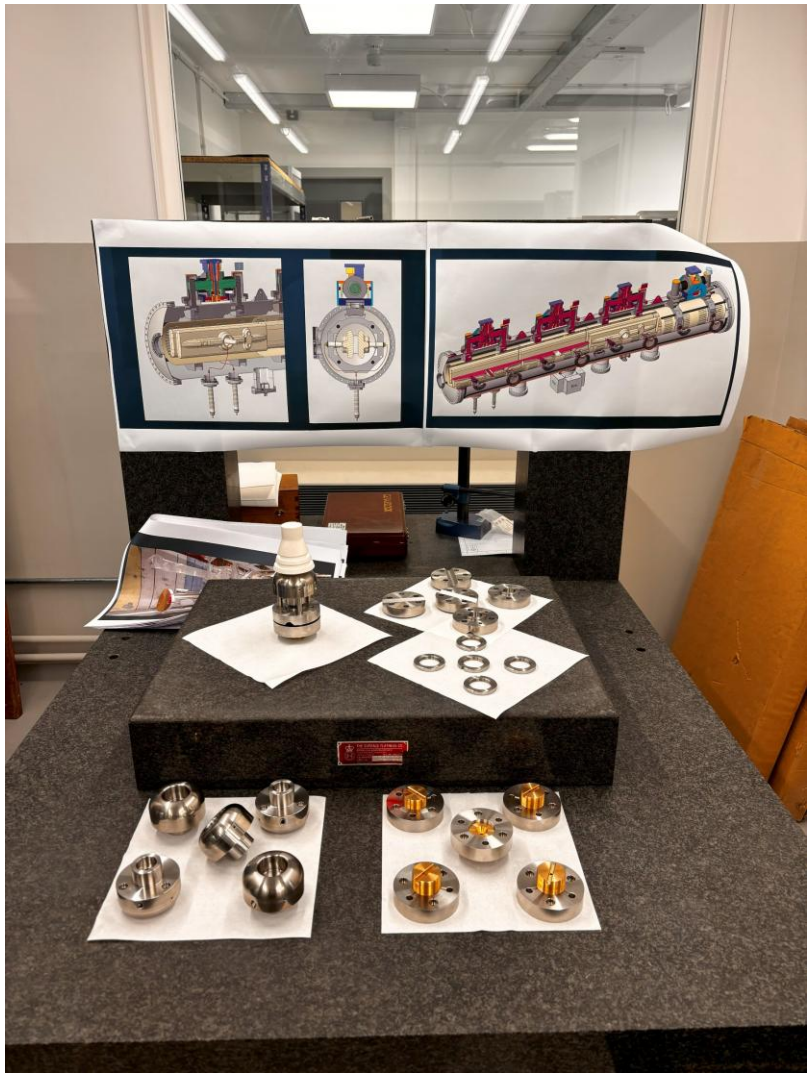


0.654 µm
Mahr
MarSurf PS1





COUPONS FOR IONBOND COATING

HV Coatings for Fields

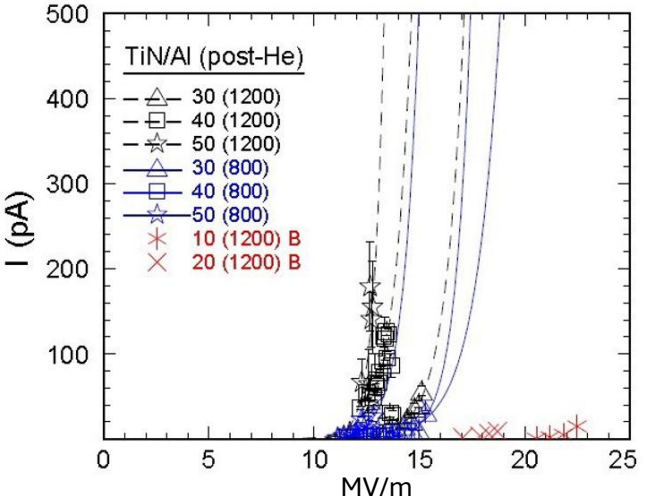
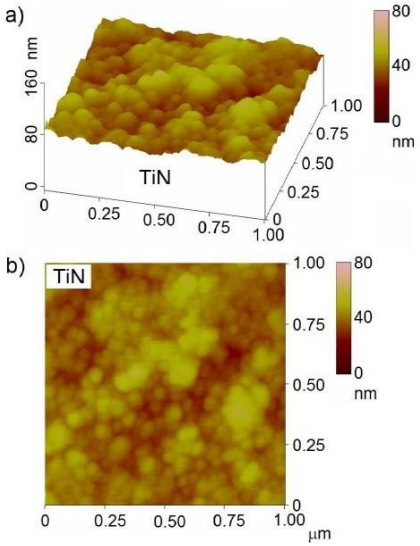


Figure 3: HV performance of samples of polished aluminium coated with TiN. The breakdown voltage demonstrated is a least afactor 2 higher han the 4.4MV/m operating field for the pEDM experiment.



http_s:f/doi.org/10.1116/_1.t,._9-165_7-t,._

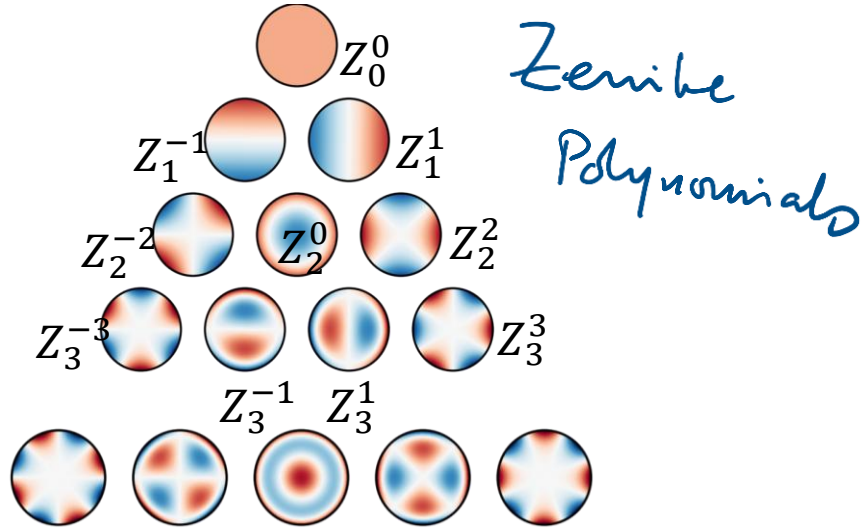
_(http_s:f/doi.org/10.1116b.t,._9.165_7_1,.))

Electrostatics

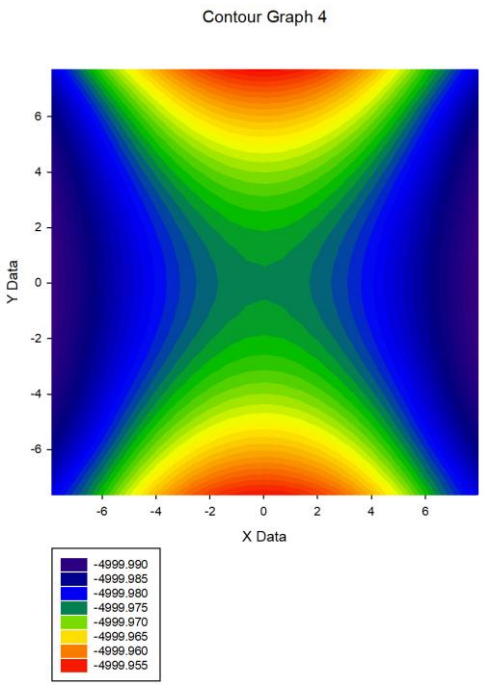
- Useful to study
  - Shape of electrodes (discharge – limiting field), uniformity in x,y
    - BUILD PROTOTYPES!
  - Understand effect of distortions/misalignments (spacing, tilts- see later)
  - Image fields
    - Second order effect but systematic EDM

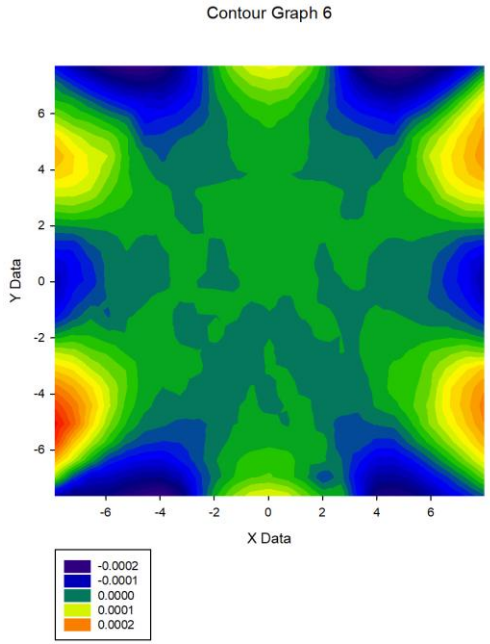
E_x at centre

Detailed parameterization of fields on/off axis



Zernike Polynomials

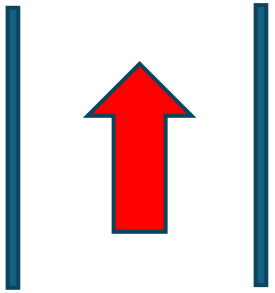


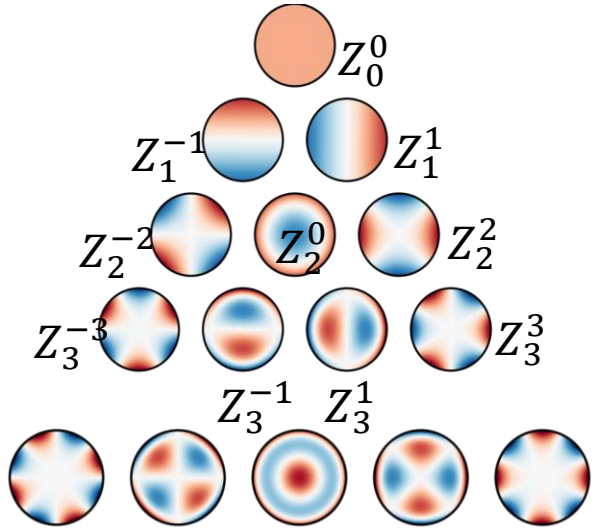


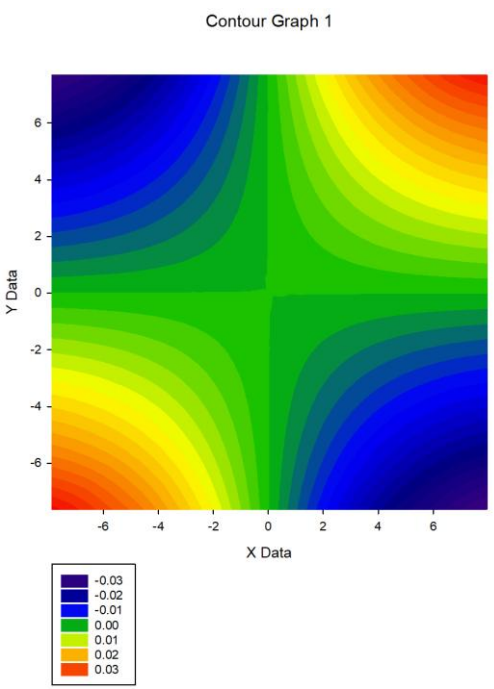
	Coefficient	Std. Error
Z00	-4999.9751	4.4161E-06
Z1M1	-5.8431E-07	1.0734E-06
Z11	1.1520E-06	1.0838E-06
Z2M2	-3.8522E-08	9.4210E-08
Z20	5.3207E-08	9.4244E-08
Z22	-0.0001	9.4151E-08
Z3M3	4.6192E-09	3.0404E-09
Z3M1	-5.6368E-10	2.8942E-09
Z31	4.0786E-09	2.8650E-09
Z33	-1.7331E-09	2.9673E-09
Z4M4	1.3222E-10	3.7844E-10
Z4M2	6.0060E-12	3.7666E-10
Z40	-2.8318E-10	3.7629E-10
Z42	-8.0468E-11	3.7535E-10
Z44	1.9919E-07	3.7488E-10

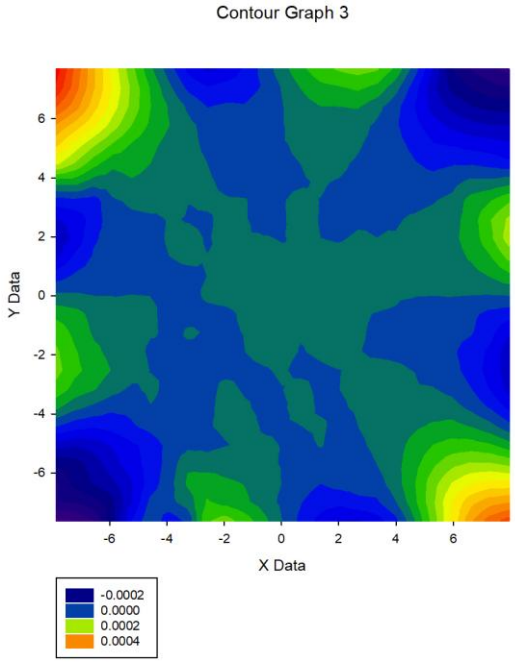
Note approx 10ppm less than the “set value” (2V/d)

E_y at centre









	Coefficient	Std. Error
Z00	1.3953E-05	4.5041E-06
Z1M1	-9.2948E-07	1.1450E-06
Z11	-2.4375E-07	1.1552E-06
Z2M2	0.0001	9.6141E-08
Z20	6.5396E-08	9.6029E-08
Z22	-7.0883E-08	9.5936E-08
Z3M3	-1.5079E-09	3.0992E-09
Z3M1	2.2096E-09	3.0867E-09
Z31	-1.7726E-10	3.0335E-09
Z33	-1.4467E-09	3.0255E-09
Z4M4	-1.9929E-07	3.8581E-10
Z4M2	-3.5677E-11	3.8434E-10
Z40	-3.4150E-10	3.8329E-10
Z42	2.0594E-10	3.8256E-10
Z44	8.0607E-12	3.8216E-10

y field << x field

FEM < 10^{-9}

Errors of this order

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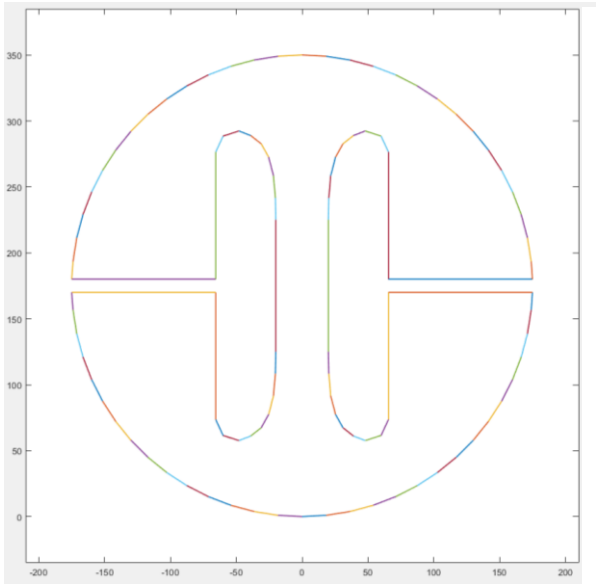
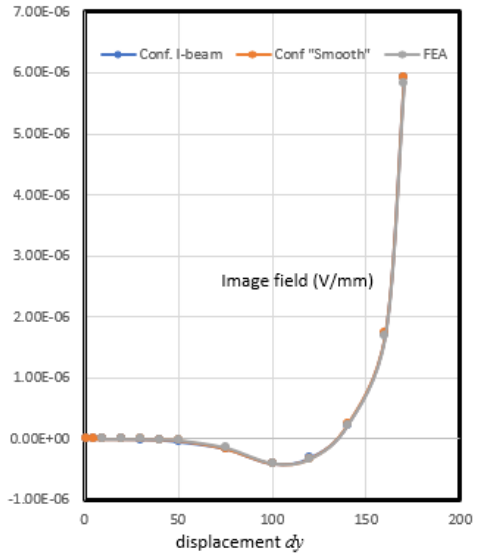
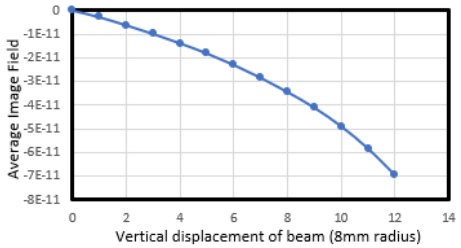
Calculation of Image Forces

- Image currents in vertical direction cause systematic (increased EDM)
- Calculation by FEA slow and not accurate for small displacements
  - Even with millions of grid points around key area
  - FEA seems to be unreliable at fields $< 10^{-8}$V/mm (even with millions of mesh points in ROI)
- Use conformal mapping for complex shape (e.g. electrodes)
- Fast and accurate (MATLAB) – 1000 to 10000 time faster than FEA







FEA + Conformal methods agree.
Small displacement "errors" are controlled @ 10^{-11} V/mm

"Modelling Image Charges" P. Bowcock ... Arxiv

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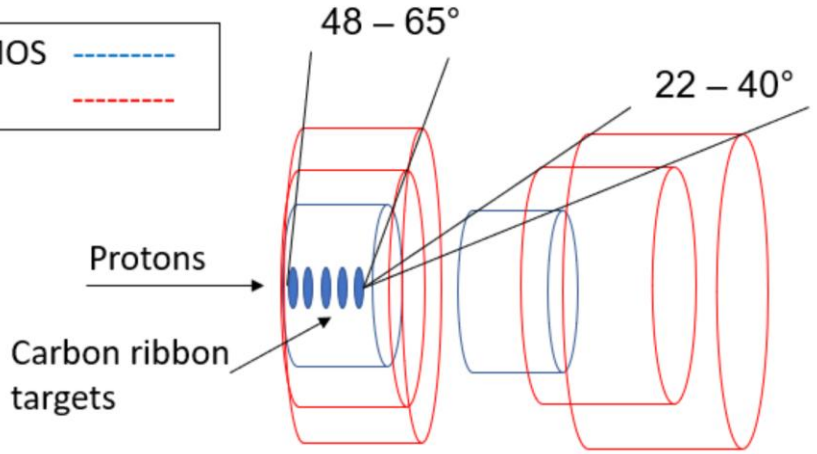
UK Polarimeter Work

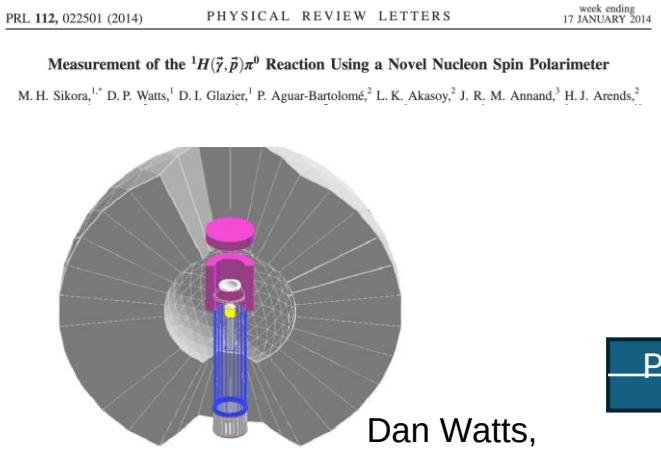
JINST **17** (2022) C09010; J. Gooding, PhD thesis, University of Liverpool

- State-of-the-art polarimeter designed and initially tested in the UK with proton beams.
- Measure proton's polarisation after elastic scattering off a carbon target.
- Inner silicon-based HV-CMOS sensors for precision position measurements (scattering angle).
- Outer Low Gain Avalanche Diodes (LGADs) for time-of-flight (ToF) measurements (energy).
- Build and test full prototype soon.



< 100 µm HV-CMOS layer. Pixel dimensions of 80 µm x 80 µm.

100 µm LGAD sub-layer ToF resolution ~ 30ps – 50ps.

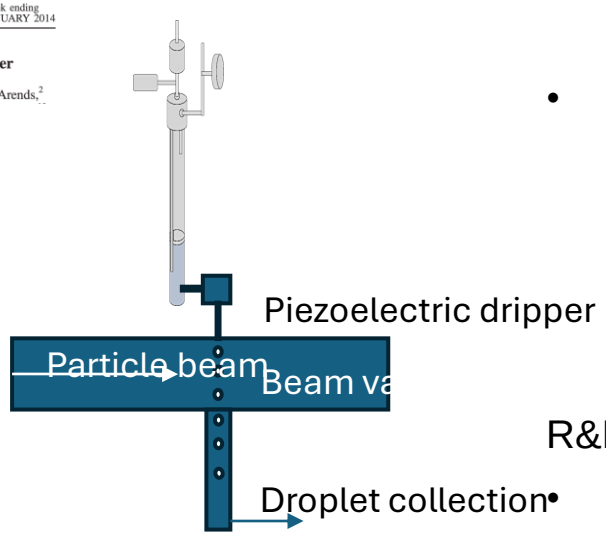


PRL 112, 022501 (2014) PHYSICAL REVIEW LETTERS week ending 17 JANUARY 2014

Measurement of the $^1H(\vec{\gamma},\vec{p})\pi^0$ Reaction Using a Novel Nucleon Spin Polarimeter

M. H. Sikora,[1,*] D. P. Watts,[1] D. I. Glazier,[1] P. Aguar-Bartolomé,[2] L. K. Akasoy,[2] J. R. M. Annand,[3] H. J. Arends,[2]

Dan Watts, University of York (UK)



- Very new collaboration with EIC nuclear physicists at University of York.
- They are developing proton polarimeters for the EIC.

  at BNL.
- Chemical hyper-polarisation (pyridine liquid droplets in beam).
  - Measurable transfer of spin-state for more efficient polarimetry.
  - Plus tracking polarimetry from proton scatter from with different distribution depending on spin.

R&D planned York for EDM collaboration.

- Already have polarised nucleon scattering in GEANT4.

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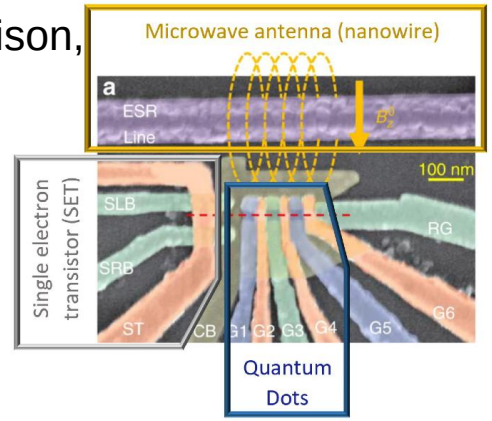
UK: Quantum Polarimeter

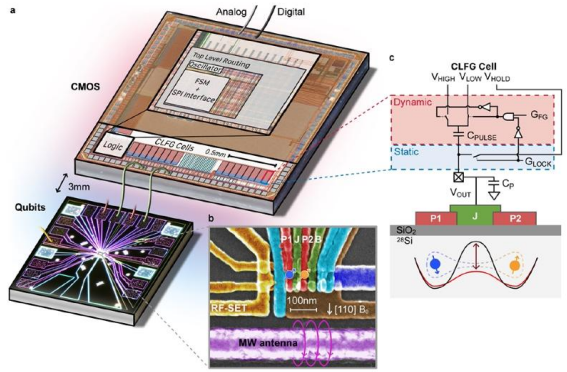
Can quantum detectors be used for and improve high-flux environments like pEDM $\mathcal{O}(100\,\mathrm{kHz})$?

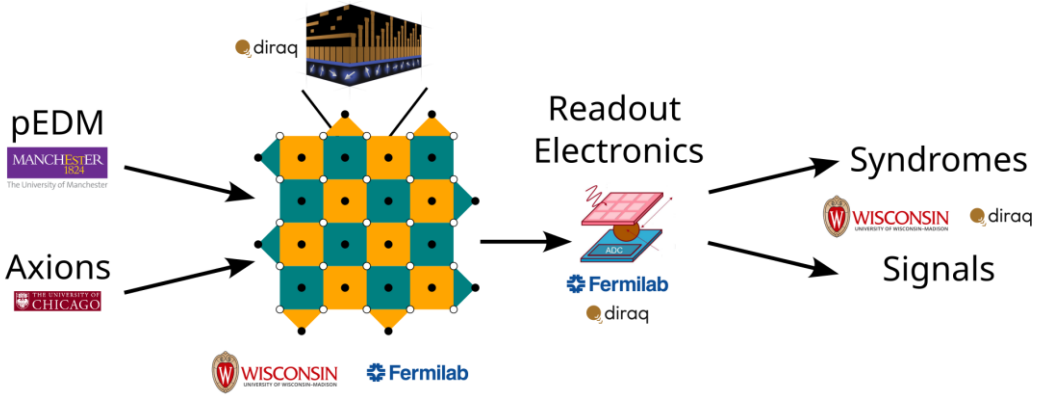
- Partnered with Fermilab, University of Wisconsin-Madison, University of Chicago and Diraq (industry).

  $4M awarded in January 2025 as part of US DOE QuantISED 2.0 scheme.

  - Silicon electron spin qubits + CMOS = quantum sensing.
  - Scale to 10^4 silicon spin qubits.
  - Quantum error correction to maintain qubits ensemble in superposition.
  - Sensitive measurements through spatio-temporal correlations of qubit disturbances.
  - R&D for spin qubit sensing elements and develop prototypes.
  - Single-electron resolution cryoCMOS skipper readout electronics (cryogenic temperature readout essential).
  - Few-channel proof of concept and advance to a highly-scaled array with 10^4 elements.







- Study the prototypes EM characteristics to develop better models of the underlying technology.
- Develop models and algorithms to enable physics extraction from spin qubit ensembles (quantum polarimeters) for pEDM.

What does it take to run the experiment

- Beam polarization and injection of cold beam
- Polarimetry
  - Quantum applications
- Squids for measuring position of beam (original) ?
- Alignment (or lasers)
- Voltage control (monitoring)
- Beam control
- RF
- Cooling
- Vacuum 10^{-10} torr (UHV for beam lifetime)

Physics Groups

- Extracting polarization
  - SM Group –e measuring the SM values
  - Theta QCD
- Time dependent Oscillations
  - ALPs
- Matter-antimatter tests (CPT)
  - anti-protons
  - Lorentz tests (time dependent polarization)
- Astro
  - EDMs of neutron stars (?)
- Interface to theory
  - Lattice …
- Large group

LOTS OF ROOM FOR NEW IDEAS..

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A Probe for Axionic Dark Matter (DM)

The Strong CP problem has a longstanding hypothesis solution:

- The Peccei-Quinn Mechanism (Phys. Rev. Lett. **38** (1977) 1440).
- Gives rise to the (undiscovered) axion → common DM candidate.

Axion DM field oscillates as background field in the universe:

- Frequency amplitude = universe's DM density.
- Axion frequency related to axion mass.

If axion exists, oscillating field = time-varying CP-violating interaction with Proton EDM.

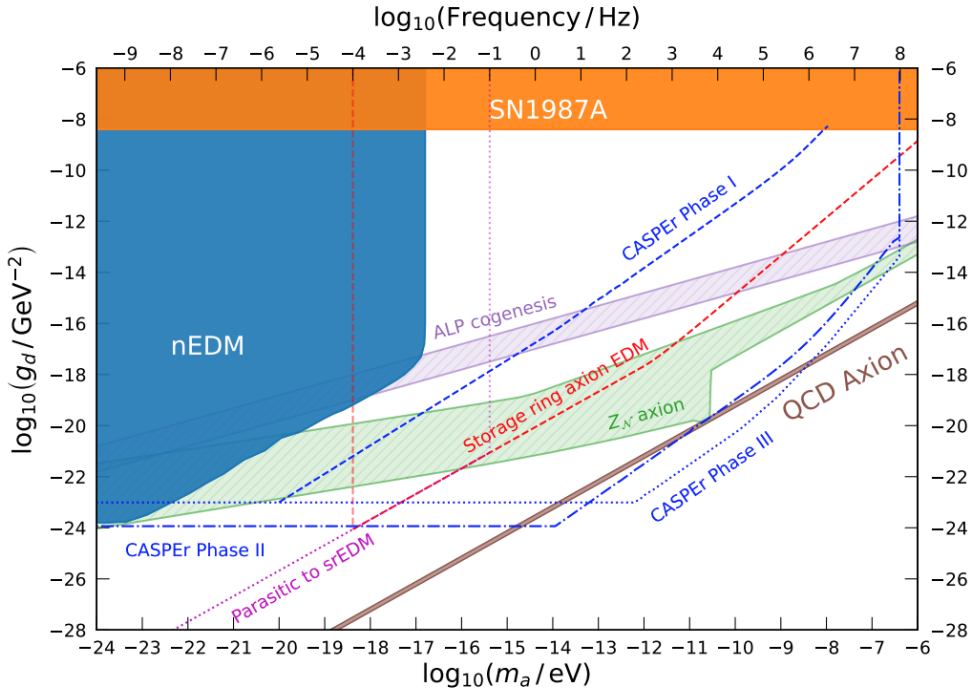
- Proton EDM would oscillate at the frequency of the axion field!

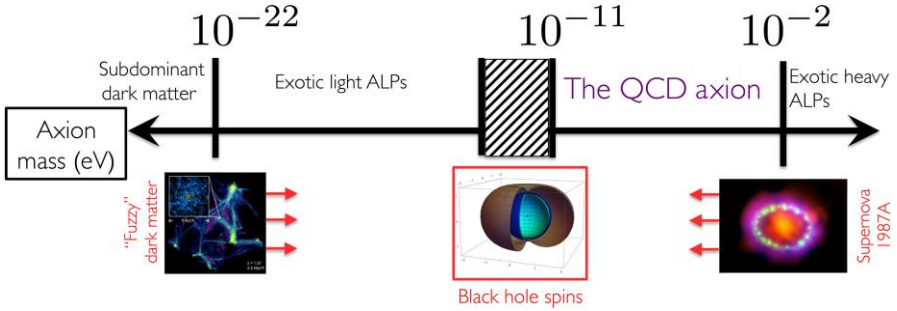
$$d_p(t) \approx \frac{a(t)}{f_a} \times 10^{16} \approx 5 \times 10^{-35} \cos\left(\frac{1}{\hbar} m_a c^2 (t - t_0) + \phi_0\right) e \cdot \mathrm{cm}\,.$$

The Proton EDM Experiment is extremely sensitive to such time variations:

- Would stand out as a distinct signature from background.

Axion frequency / mass sensitivity:
Frequency: 1 mHz → 1MHz
Mass: 10^{-7} eV → 10^{-16} eV





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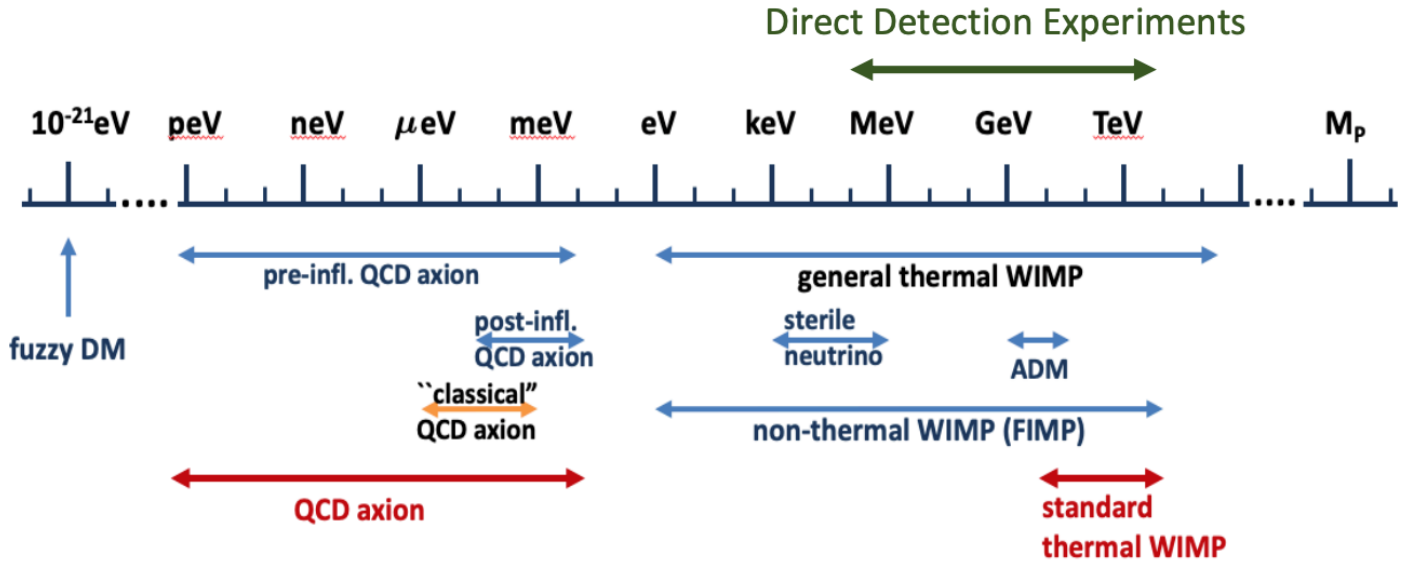
pEDM Experiment: New Physics Reach

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

Recent work suggests magnitude of d_N & BSM sensitivity are charge-dependent…

L. Di Luzio *et al.*, Phys. Rept. **870** (2020) 1; C. Smith, Eur. Phys. J. C **84** (2024) 12; L. Di Luzio *et al.*, JHEP **04** (2024) 076.

→ Proton potentially more sensitive probe than neutron.



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

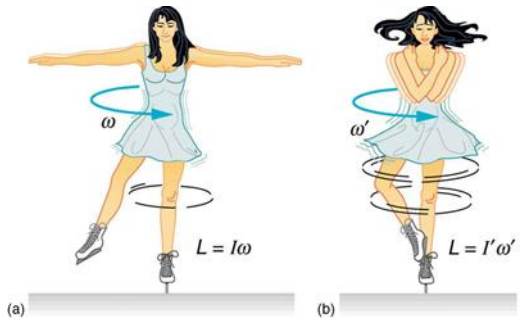
A Probe for Neutron Star Spin (maybe)

What is a neutron star?

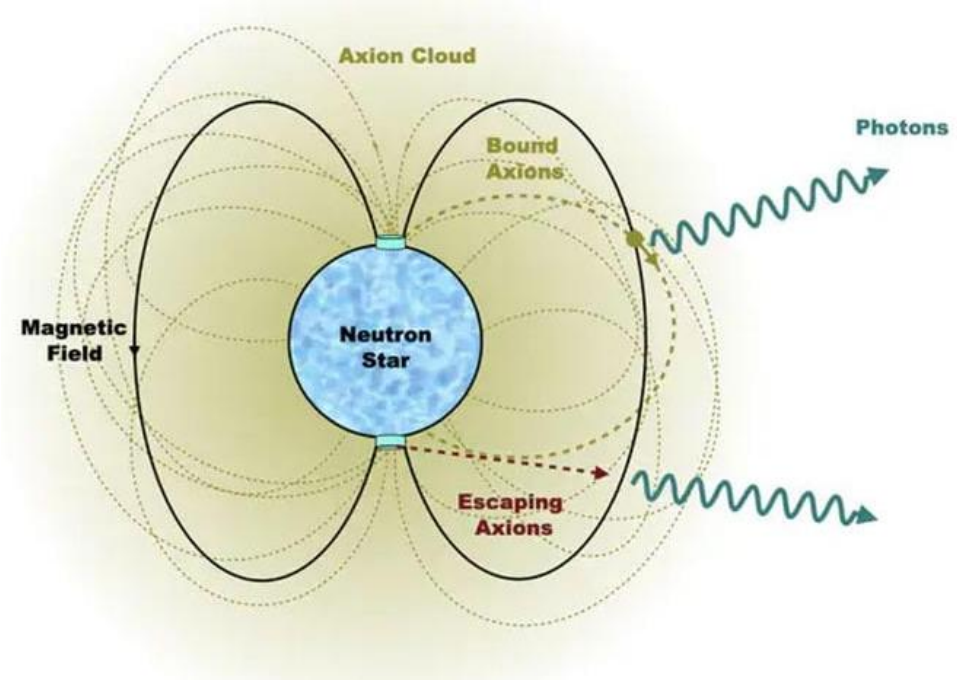
- Collapsed core of a massive, supergiant star not massive enough to produce black hole.
- Massive star supernova + gravity compresses star core (mostly neutrons) to atomic nucelli density: ~ 1.4 $M_\odot$ in ~ 10 km.

Neutron stars spin as fast as 60 times per second:

- As it collapses, its radius decreases with constant mass.
- Angular momentum causes the star to spin faster.
- Like how an ice skater spins faster when they pull in their arms.



PHYSICAL REVIEW X 14, 041015 (2024)



Neutron star spins are aligned…

- In presence of axionic DM field, θ_{QCD} oscillates at axion mass frequency.
- Whole spin (EDM) of neutron star would oscillate at same frequency.
- Resulting in strong radiation.
- Neutron star spin (EDM) potentially detectable by pEDM experiment:
  - Possible interactions with EDMs (e.g. proton, neutron) in lab on earth.
  - And EM radiation on earth that could be observed (e.g. with a resonant cavity).

Not yet proven, but work ongoing by theorists to understand this effect.

→ Could make pEDM a LIGO-like experiment...

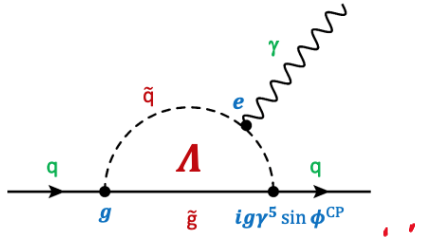
Building an srEDM Collaboration and Facility

- Is it big or small?
  - It is a small-medium facility
  - Potential for large buy-in of physicists, engineers, analysts (500+?)
    - Many threads, wide expertise
    - Many fields of analysis – some we havene even thought of
  - Experience of g-2
  - EXCELLENT and fertile ground for early career researchers
  - Modern technology
- International collaboration bringing plenty of expertise

REMINDER

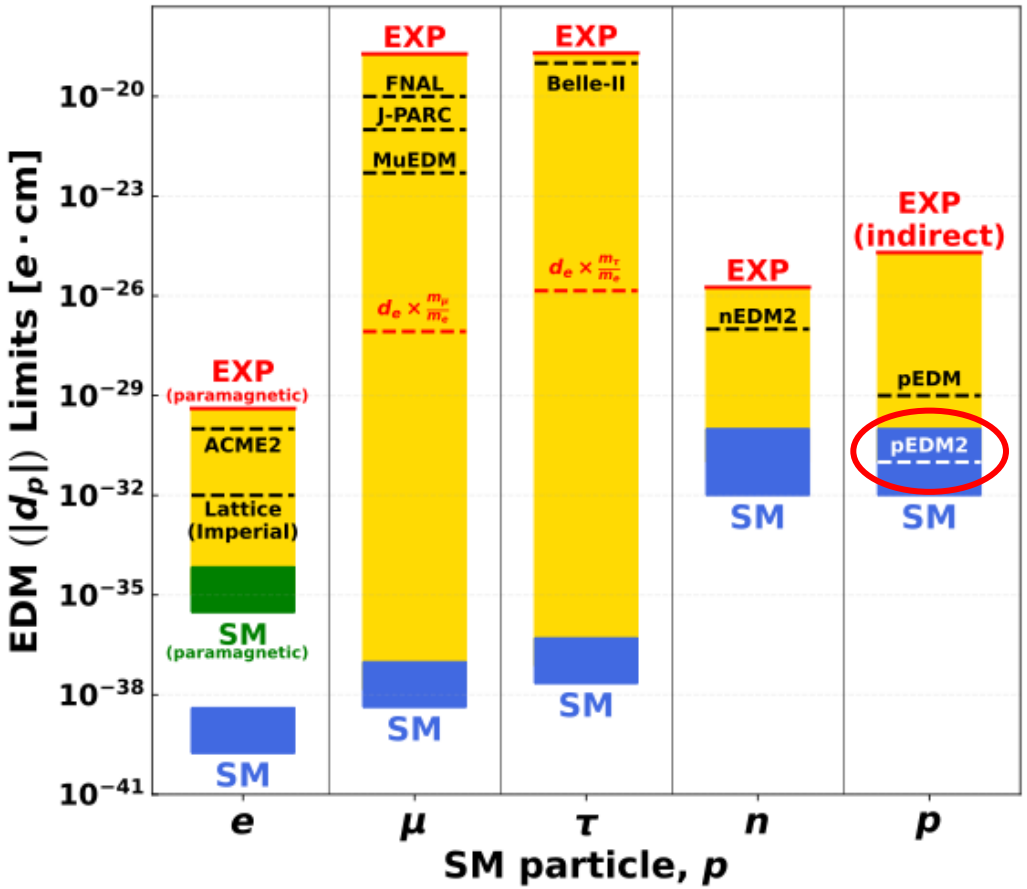
Impact and Importance of pEDM

- pEDM will be the state-of-the-art in experimental EDM searches for generations to come.
- First ever measurement of the proton EDM.
- Only experiment with the potential to measure a particle EDM down to its SM prediction (by improving on the current limit by $\mathcal{O}(10^6)$).
- Will either discover or rule out a particle EDM with a magnitude above the SM's highly suppressed value for the first time.
- Probe new Physics at the PeV Scale



[Pospelov & Ritz, 2005]

- Huge consequences for baryon asymmetry, DM and the Strong CP problem.



European Strategy

- EDMs highlighted as area of strategic importance in previous ESPPU update.
- Physics is entirely complementary to future colliders
- BSM mass range extends beyond what is possible at foreseen colliders
- Shorter- timescale experiment relative to whatever future collider programme is decided upon.
- Cost is order of O(1%) required to deliver a major facility (excluding STAFF which reduces this further)
- Guaranteeing room for experiments like pEDM provide continuity and risk mitigation against stagnation, provides motivation, training, discovery
  - Cannot be strictly funding “blind”
- Experiment is environmentally friendly
  - “Green” – doesn’t boil with AI needs.
  - Little CO_2 (e.g. concrete/power)
- **Provides continuity for ECRs during gaps in major collider operations.**

Conclusions

- Very significant physics drivers:
  - Understanding CP in QCD is a grand challenge
- From TDR to final publication in < 20 years.
- pEDM experiment is required for the health and the balance the programme