proton EDM

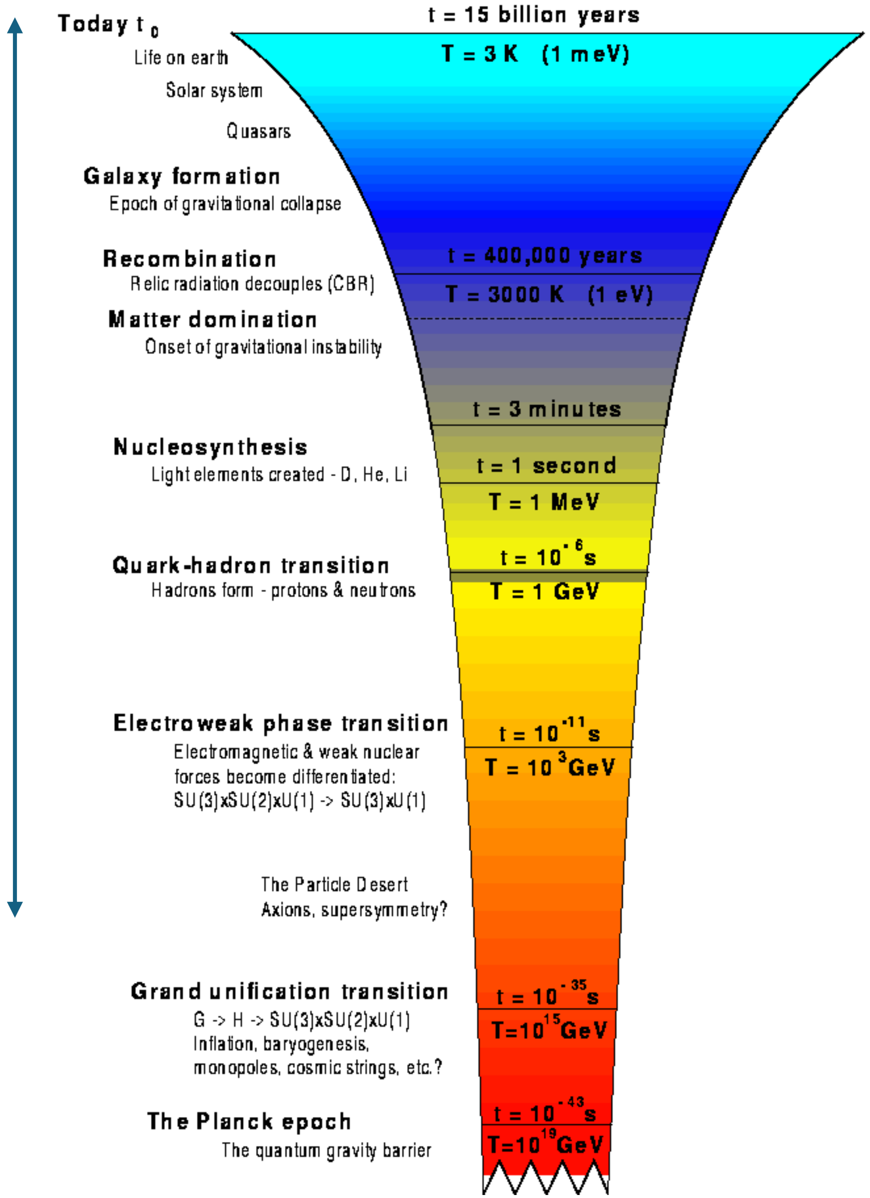
T. Bowcock

JV, GC, g-2 team, Eva Vilella and CMOS team, John Carroll, Kevin McCormick

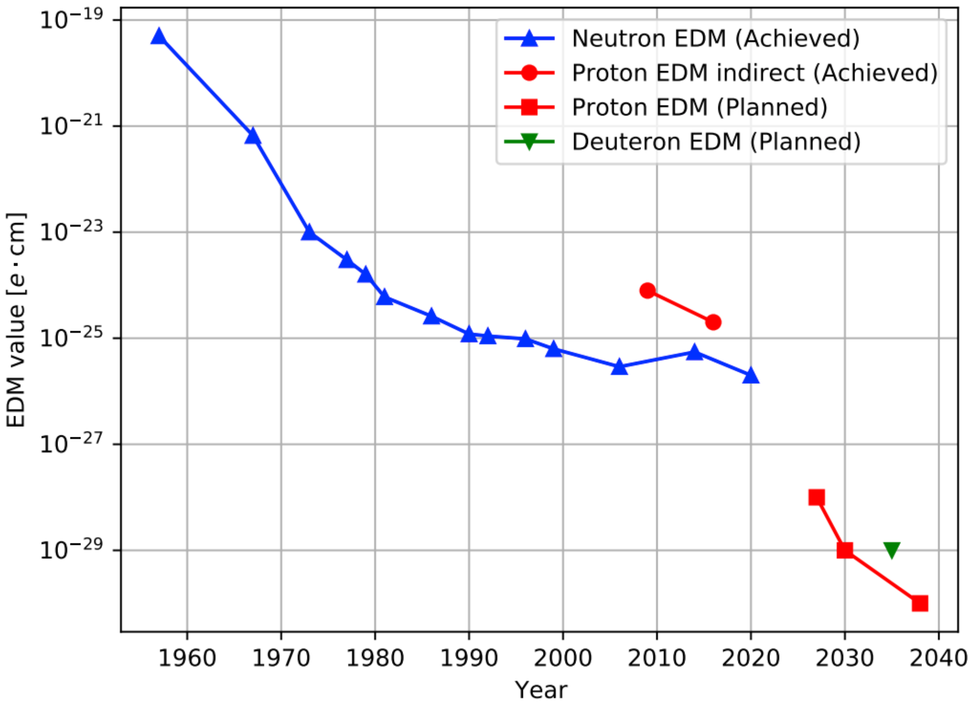
+ Manchester, BNL, CAPP …

Why is this of interest?

- In standard model QCD can/will violate CP
  - Unless it is "fine tuned" away
  - Expected d_p O(10^{-31}) e.cm in SM
- Applies to huge range of physics
  - Including DM type searches



Where are we?



New papers suggest pEDM is 100 times more sensitive to some NP axions than n ...i.e. Effectively red line goes to SM value....

0.000000000000000000000000000001 $\boldsymbol{e} + \boldsymbol{cm}$]

1 part in 10^{-31} same as measuring dimension of universe to 10 microns

Where do fundamental EDMs come from?

Also replace photon with gluon

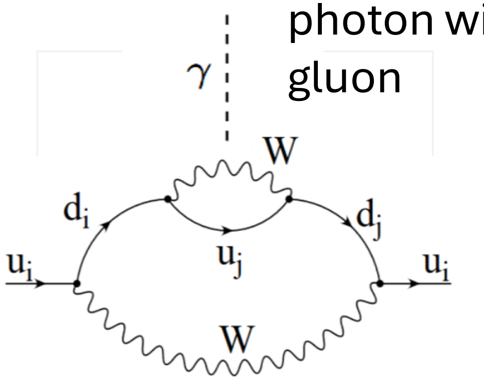


Figure 1: Two loop diagram that could contribute to the quark EDM. The photon line represents attaching the photon to each charged particle and a summation.

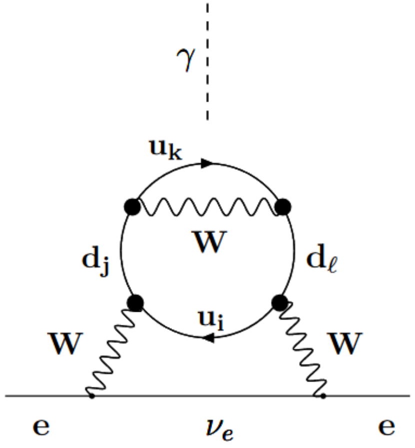


Figure 2: Lowest order diagram that could contribute to the electron EDM via a CKM phase. The photon line represents attaching the photon to each charged particle and a summation

	limit ($e \cdot$ cm) @ 90% c.l. *=@95% cl.	expected improvement	standard model ($e \cdot$ cm)	experiment	Species/ method	dominant uncertainty
electron	8.7×10^{-29}		$\sim 3 \times 10^{-37}$	ACME[35, 36]	ThO	
	1.3×10^{-28}			ion trap[39]	HfF^+	
muon	1.9×10^{-19} *	$< 10^{-21}$	$\sim 10^{-34}$	g-2 (BNL)[41]	free particle	
tau	5×10^{-17} *		$\sim 10^{-33}$	BELLE[43]	$e^+e^- \to \tau^+\tau^-$	
	1×10^{-17} *			LEP/theory[44]	Z decays	
neutrinos	5×10^{-17}		$O(10^{-43})$	LEP/theory[44]	Z decays	
quark (u)	1.15×10^{-24}	$< 6 \times 10^{-24}$		$d_n d_p$/theory[49]		g_T
quark (d)	1.06×10^{-24}	$< 9 \times 10^{-25}$		$d_n d_p$/theory[49]		
neutron	3.0×10^{-26}	$< 10^{-28}$	$\bar{\theta} \cdot (6 \times 10^{-17})$	ILL[52]	Trapped n	B-field drift
proton	2.1×10^{-25}			^{199}Hg/theory[57]		theory
		$< 10^{-29}$		CPEDM	Storage Ring	B-field

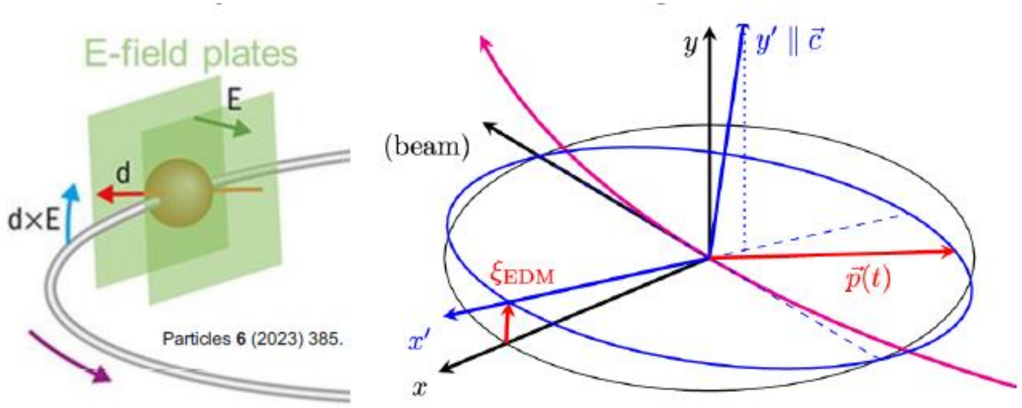
Table 1: *Limits on electric dipole moments of (selected) fundamental particles and nucleons.*

quarks

leptons

Propose to measure it using a storage ring

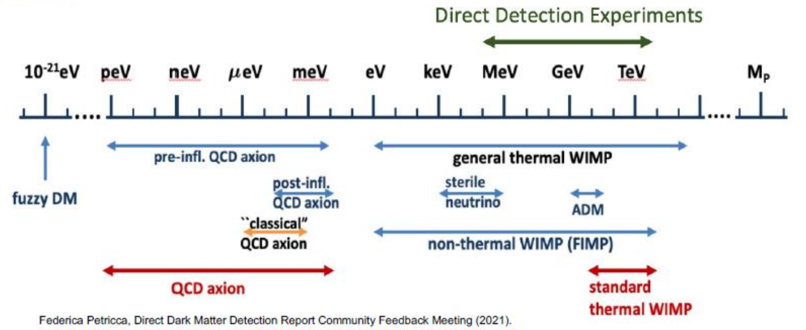
- Based on method developed by g-2 (muon EDM)
  - Same team
  - Uses a technique called frozen spin which selects the momentum to a value where the spin is locked to the direction of momentum
- Put protons into a storage ring and measure their polarization
  - For a circular ring with electrostatic bending



Aside

- This is a critical measurement to corroborate SM. It will either:
  - See the SM value of the pEDM (in final form) and confirm the prediction of the SM
    - Still have the fine tuning problem!!!
  - See a larger value (NP)
    - Typical scale1PeV + but
  - Put strong limits on axionic matte

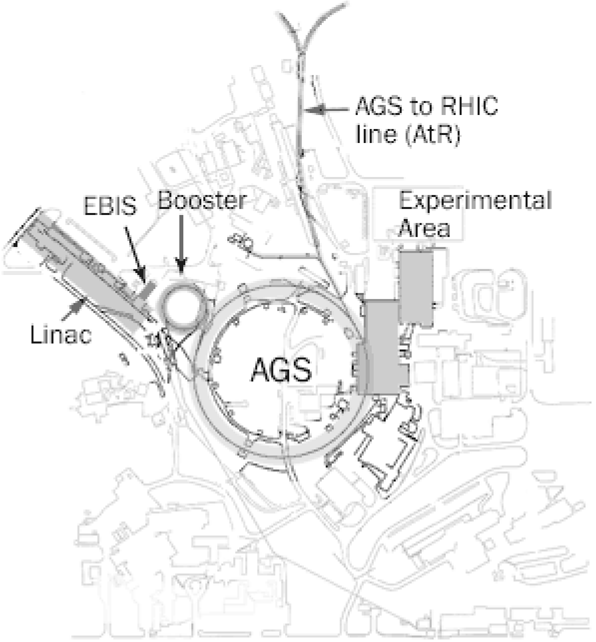
Strong CP Problem	Matter-Antimatter Asymmetry	Dark Matter	EDM loop induced = wide range of interactions/energy scales $d_p \sim (g^2/16\pi^2)\,(e\,m_q)/\Lambda^2_{NP}\ \sin\phi^{NP}\ \ e\cdot cm$ m_q = mass of 1-loop quark, ϕ^{NP} = complex CP violation phase of NP	
Solved!	Model-independent CP-violation.	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: $\Lambda_{NP}\sim 1\ \text{GeV},\ g \lesssim 10^{-5},\ \phi^{NP}\sim 10^{-10}.$ [e.g. LZ, LDMX, FASER, SHiP.]	$\mathcal{O}(\text{PeV})$ mass scale: $\phi^{NP}\sim 1,\ \Lambda_{NP}\sim 3\times 10^3\ \text{TeV}.$ [e.g. LHC/FCC.]



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

“Where” is the project?

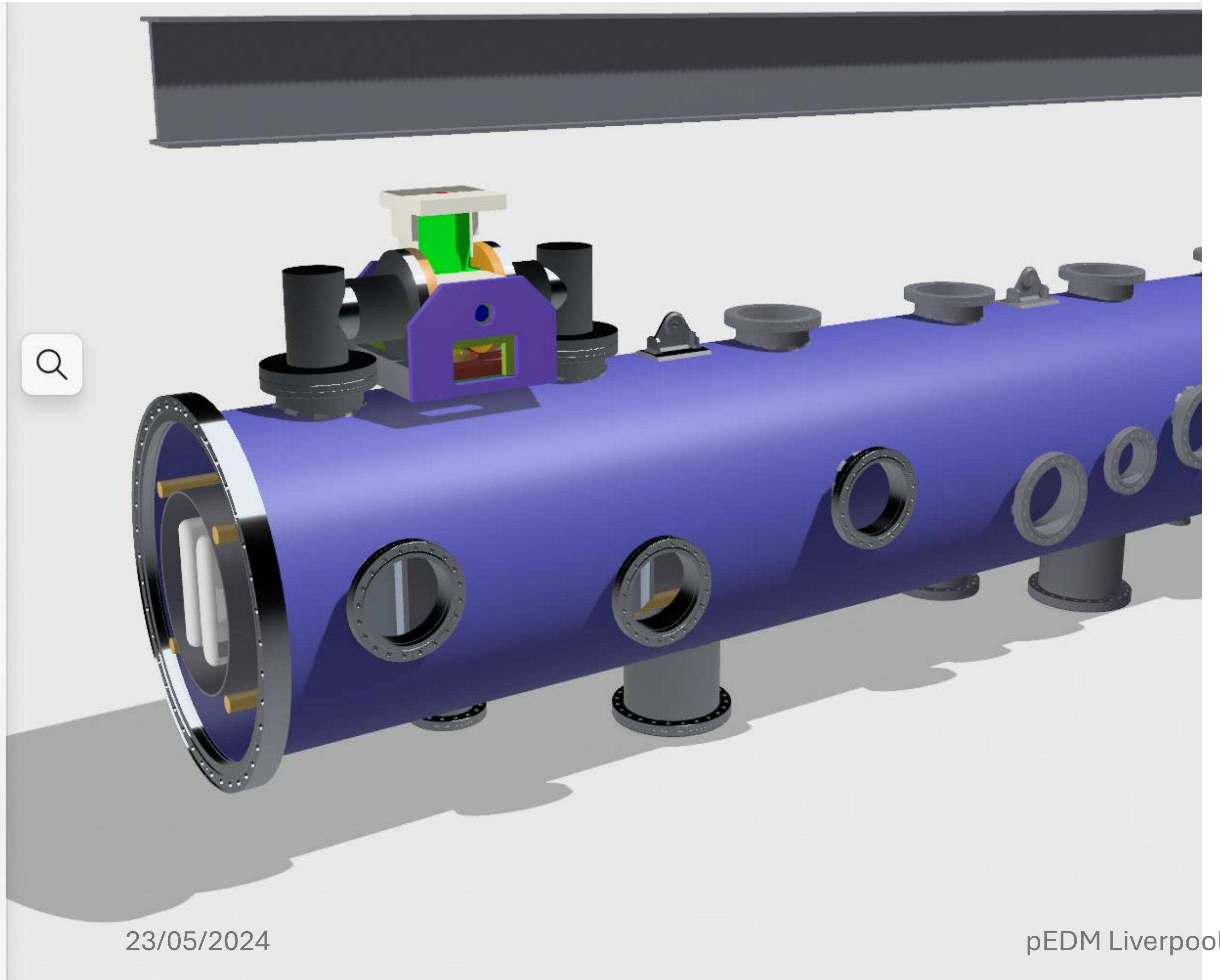
- Well developed “concept”
  - PBC CERN 2015 (CERN accelerator team)
  - Snowmass 2023 (Physics)
  - European collaborations and interest
    - COSY Germany
    - Italy
- Nuclear Physics or Particle Physics?
  - Part of the P5 issue for proposal at BNL

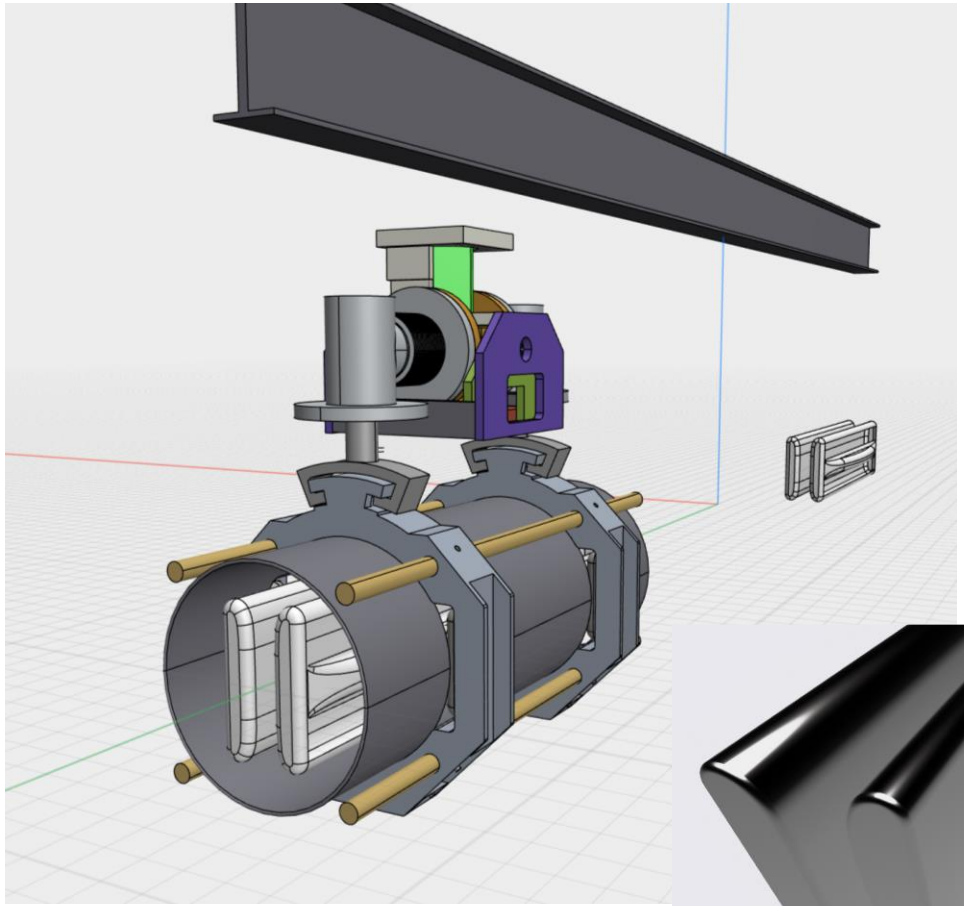


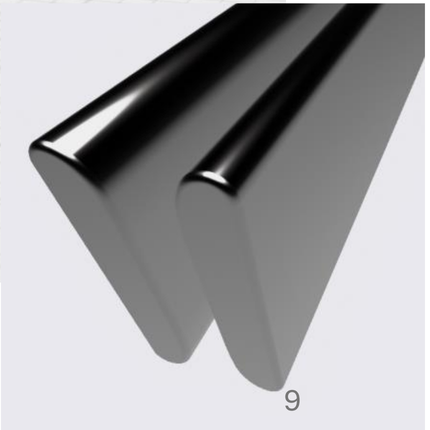
We are currently funded LDRD BNL

- US DOE funded (!)
- Produce a 4m section of the bending dipole as a demonstrator
  - BNL, Liverpool, Manchester
- Deliver by 2026
  - At that point we believe BNL will take this to DOE as part of their NP programme

800m of parallel bending plates

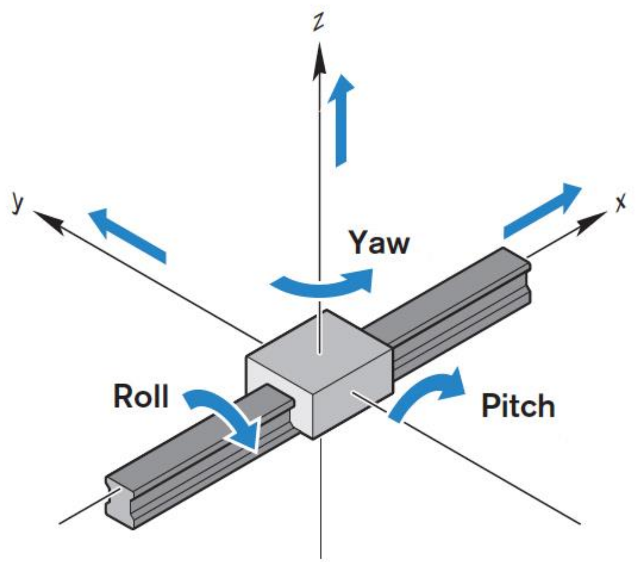






A few specs

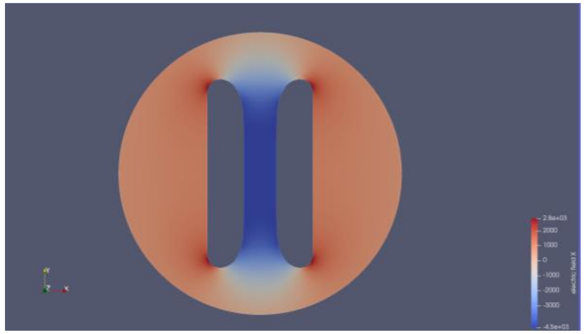
- O(10MV) bending across 40mm gap
- Precision O(10um) - Liverpool only
- Control (with adjusters)
  - Roll order of an arc-second
  - Pitch +/- 100um over 1m
  - Yaw < 10um over 1m
- Precise engineering – contract £££!



Liverpool

- Has done all the electro-static design (up to sextupole contributions)
  - Some field effects need to be known to ppb (!!)
  - Image field calculations
    - Clever maths allowing much more precise (and faster) semi-analytical calculation of fields than obtainable by
- Engineering design and production of bending dipole (John, Kevin, Workshop)
  - Plates
  - Adjustors
  - Metrology System
- Electric field termination/shunt concept
- Polarimeters (Eva/Joost CMOS team) – pre 2024
  - Critical for physics

Electric Fields



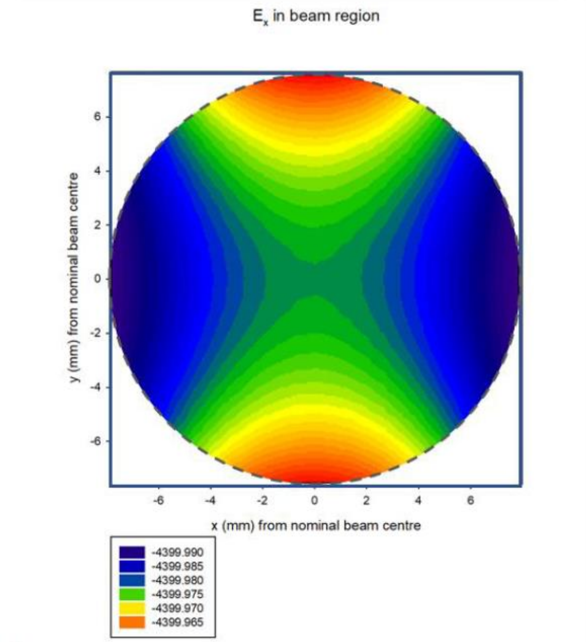


Figure 16: Field, Ex, in Volts/mm as a function of position around the nominal beam centre.

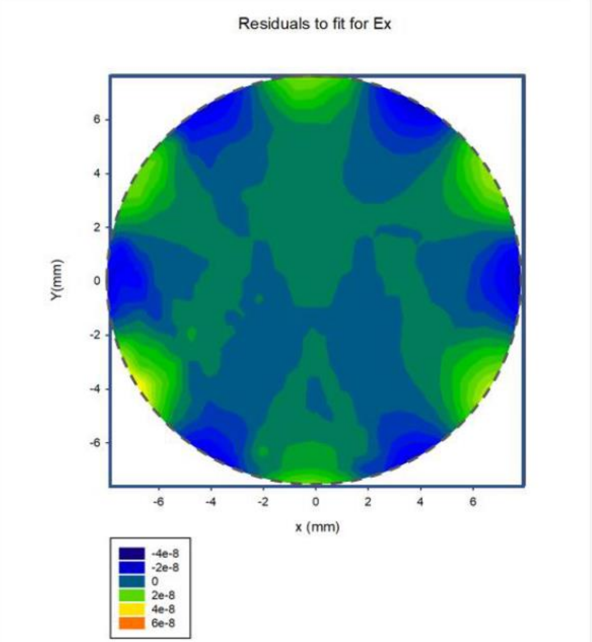
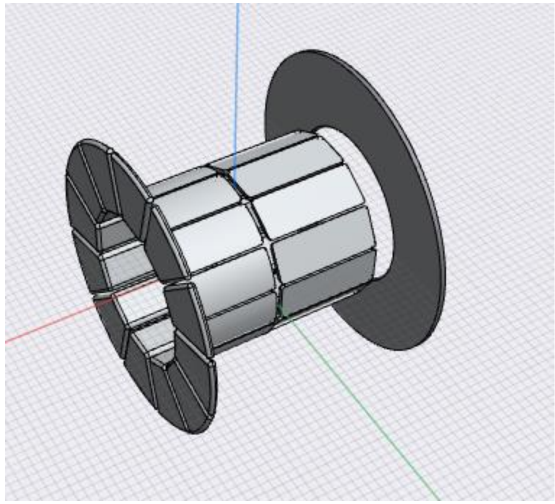


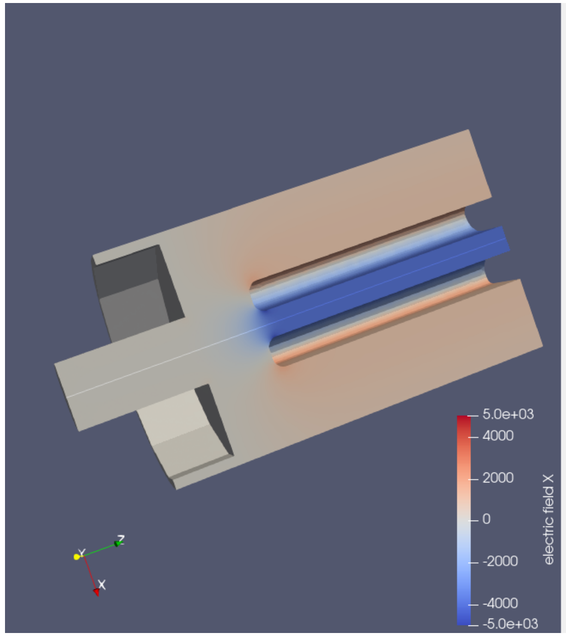
Figure 17: Residuals to the E_x field (Volts/mm) after removal of the mean, quadrupole, and octopole contributions.

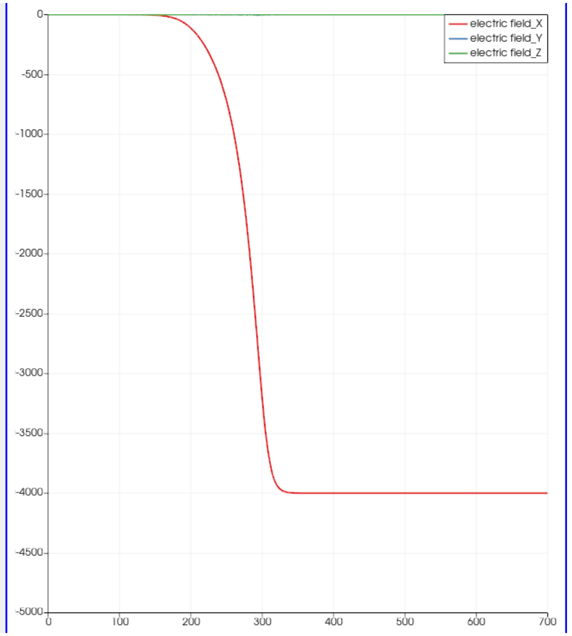
“Simple” FEA

Removal of known contributions up to octopole

Termination/Shunt







Shunt for field control at end of bending section

More advanced calculations (Image fields)

Modelling the Image Charges for the proton EDM experiment

12/08/2023

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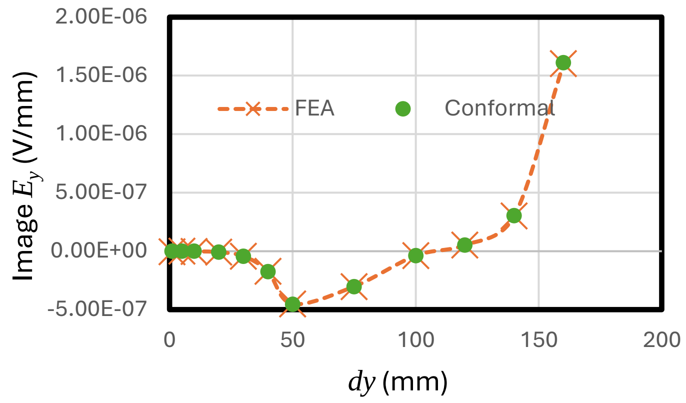
P. Bowcock – Dept. of Mathematics, University of Durham. UK

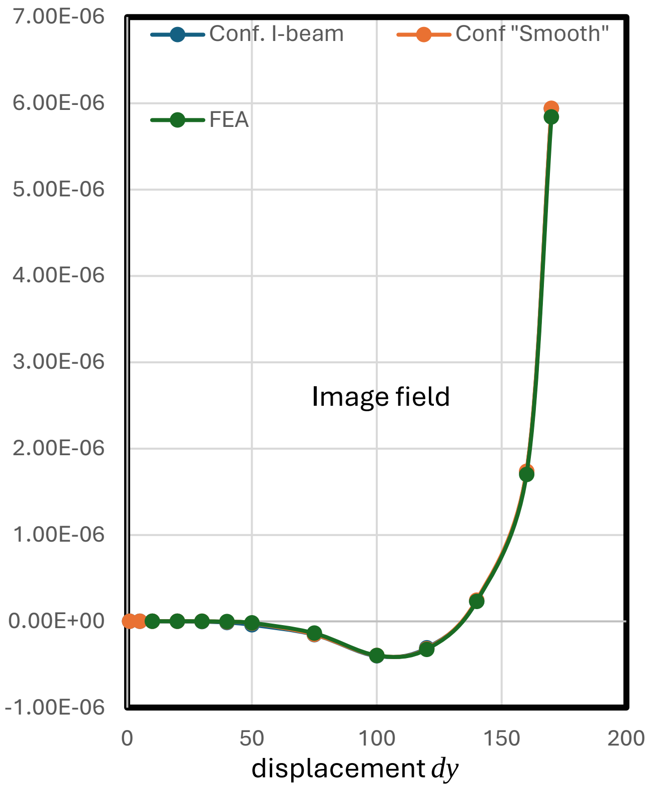
Summary

We have studied methods for estimating the image electric field for the pEDM experiment. We have shown that neither a box nor a cylinder may be used to approximate these forces. We have developed a semi-analytical technique, based on conformal mapping, that enables us to estimate the image field anywhere in any closed polygonal volume using conformal mapping. This allows higher accuracy over finite element techniques (FEA), which are limited due to the large size of the problem. Our method also offers a substantial (over 3 orders of magnitude) improvement in computation time. This technique relies on the mapping of a closed polygon onto the half plane. The image force is shown to be easily calculable using the Schwarz-Christoffel transformations. For small vertical displacements the pEDM the force is shown, for a line charge of 3.34×10^{-15} Cmm^{-1} *to be less than* 6×10^{-11} Vmm^{-1}*. This applies to the configuration as submitted to P5 (2023) with an approximately 8 mm proton beam profile radius. In contradiction to previous estimates this image field is vertically towards the centre of the electrodes structure, rather than towards the ground cylinder and will tend to suppress the EDM signal.*



$$F = F_x - iF_y = -\frac{\lambda^2}{4\pi\epsilon_0 C}\left(\prod_{i=1}^{n}(w_0 - w_i)^{1-\alpha_i/\pi}\right)\left(\frac{2}{\left(w(z_0) - \overline{w(z_0)}\right)} - \sum_{i}^{n}\frac{1-\alpha_i/\pi}{(w_0 - w_i)}\right)$$

New results – not possible with FEA



New way to calculate image field and forces quickly and accurately in this configuration

- Without problems of convergence in FEA
- Seconds instead of hours (even on supercomputer)

This year – launch prototype

- Will machine electrodes
- Build prototype adjusters
- Metrology system (non-contact) pneumatic
- Transport
- Get funding for coating – for HV (Ionbond UK)
    - Grant prepared last year
- 1m prototype
- Look towards building 4m
- Visit BNL

Issues

- Site at AGS and US programme not part of PP ☹
- UK strategy - work
- CERN strategy – work
- Build UK consensus interest
  - Manchester

not

- Get Cockcroft to help on longitudinal and transverse impedance calculations....
- Avoid

Summary

- Beautiful physics experiment to search for one of the unsolved problems in PP – based on g-2
- L'pool Contracted to build and deliver 2024 (1m) and 2026 (4m)
- Substantial effort on fields, mechanics of bending
- Building community
- New ideas for polarimeters (CMOS)
- Can we build a quantum polarimeter? (Super useful !!)
- If this flies it is a 15 year programme!!