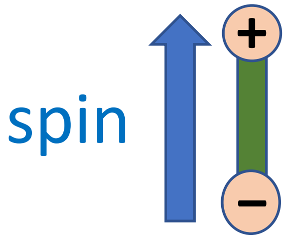
The search for the proton electric dipole moment (EDM) using an electric storage ring

On behalf of the Storage Ring EDM Collaboration
Edward J. Stephenson
Indiana University
March 23, 2023

presented at the P5 Town Hall
2023

Spin requires any electric dipole moment (EDM) to be along its axis.

This arrangement violates time reversal and CP invariance.



EDM Unit: e·cm

Experiment: Put EDM in electric field, watch it rotate.

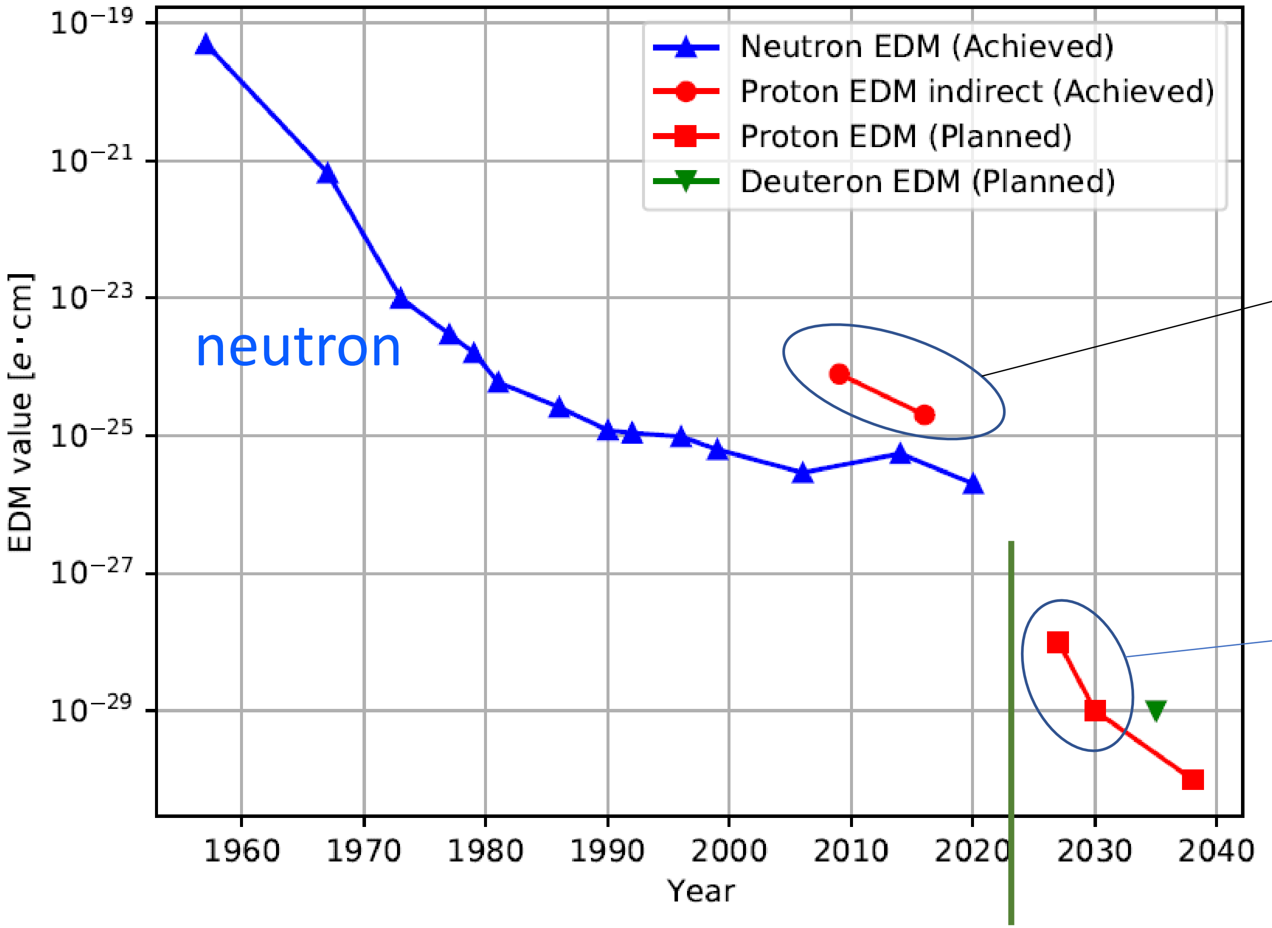
Sensitivity goal: 10^{-29} e·cm

Physics reach (Marciano): $\Lambda_{NP} > 3000$ TeV

At this level, a new source of CP-violation would be needed. This may have implications for the matter-antimatter asymmetry of the universe.

Snowmass EDM references: arXiv 2203.08103, 2209.08401

History of nucleon EDM upper bounds



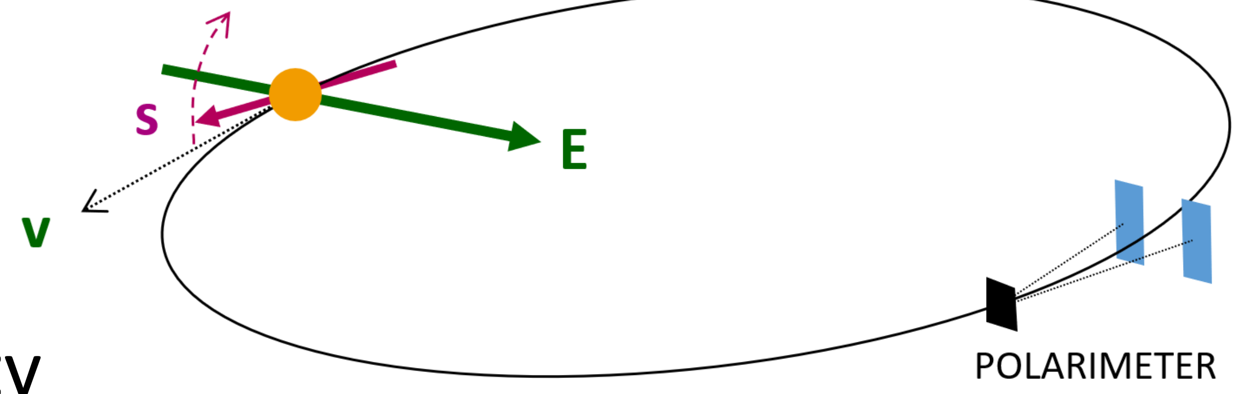
today

proton taken from ^{199}Hg limit using a screening calculation

goal of experiment by end of decade

Storage ring features:

EDM along spin axis



based on p+C elastic scattering

Facility opportunity at BNL

Electric storage ring

Frozen spin: p=0.7007 GeV/c makes spin rotate with velocity

Start with spin along velocity, then signal is rising vertical polarization component.

Simultaneous beams in both directions for error rejection

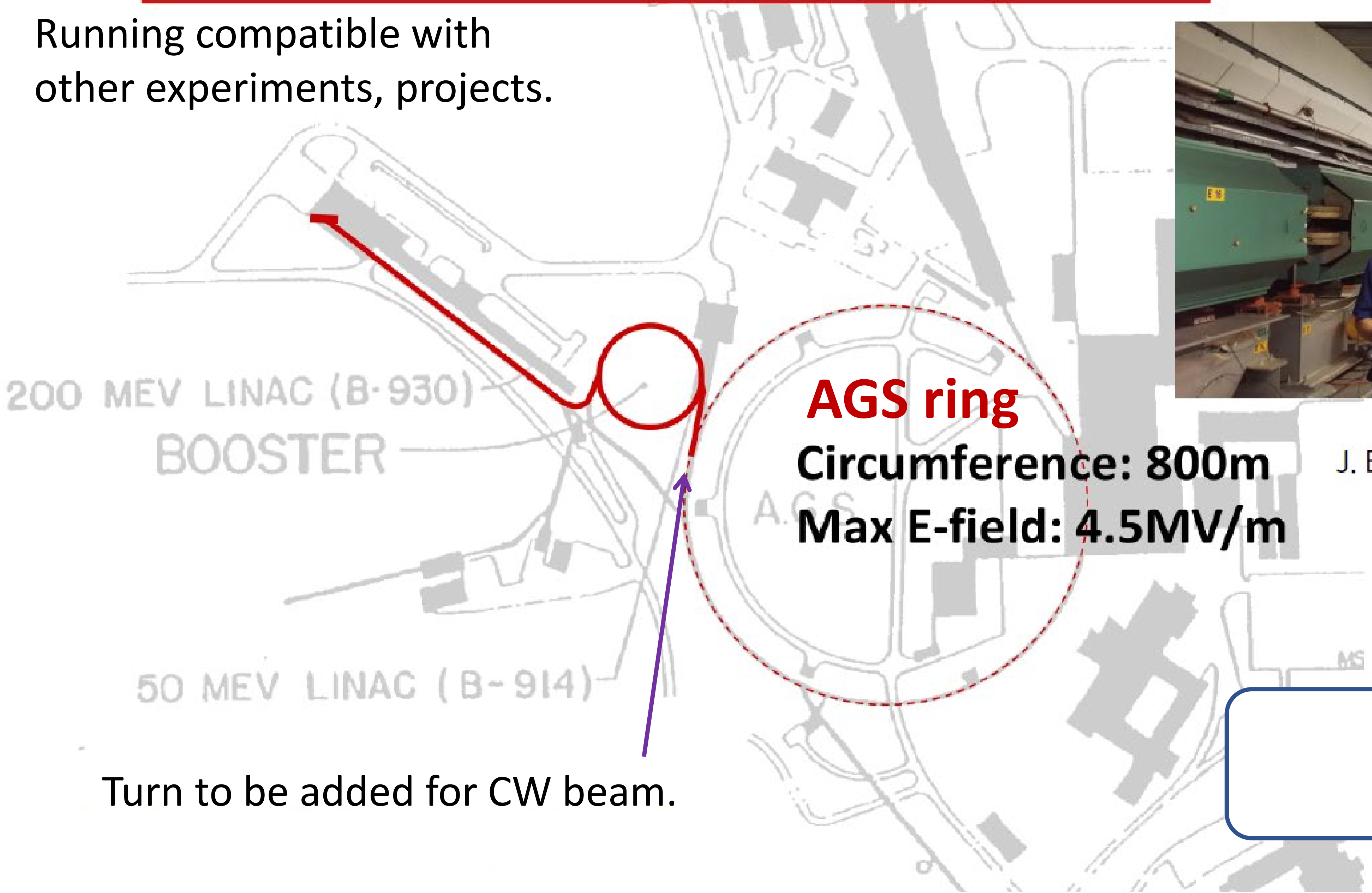
Ring lattice designed by V. Lebedev.

$$\frac{d\vec{s}}{dt} = \vec{s} \times \vec{\Omega}_{EDM}$$

$$\vec{\Omega}_{EDM} = \frac{\eta q}{2mc}\left(\vec{E} + c\vec{\beta} \times \vec{B}\right)$$

The proton EDM in the AGS tunnel at BNL

Running compatible with other experiments, projects.



AGS ring

Circumference: 800m

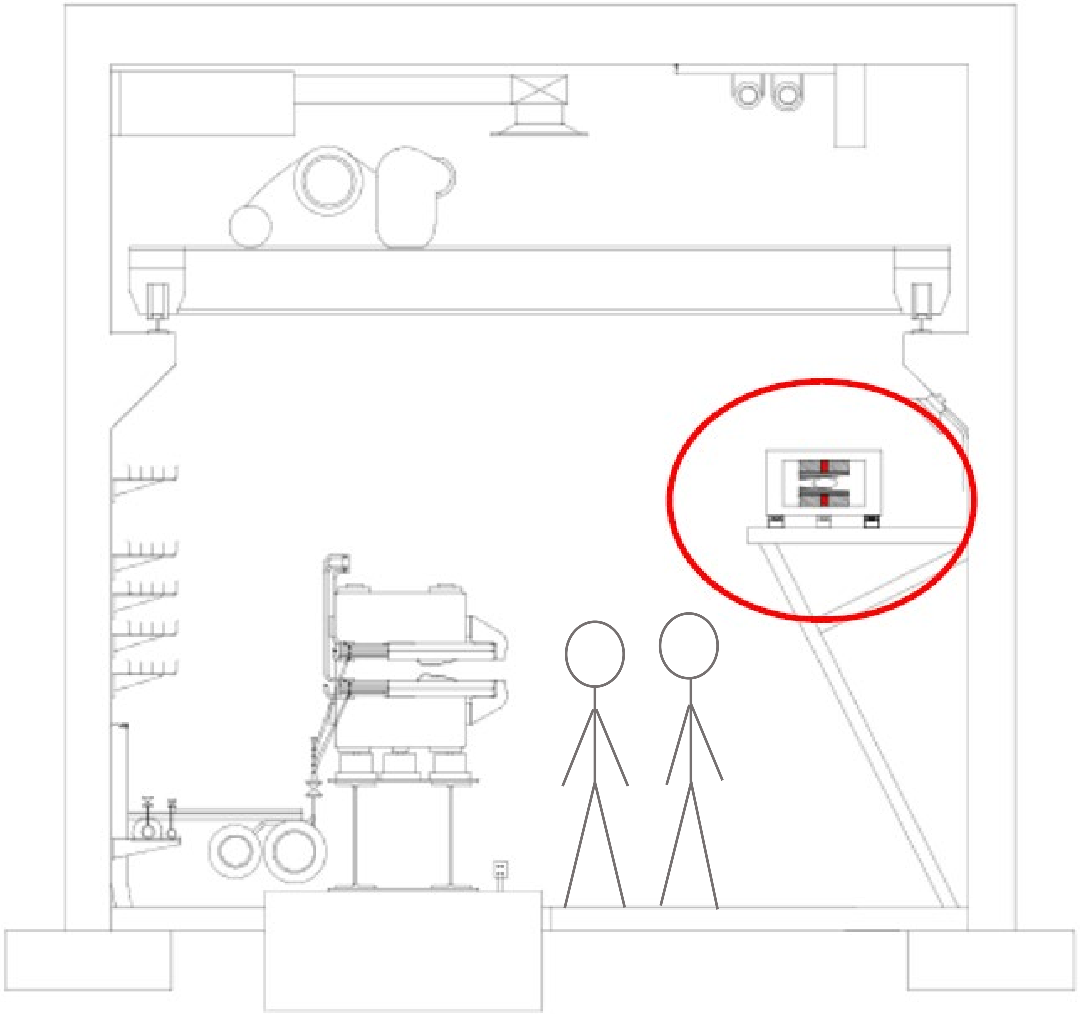
Max E-field: 4.5MV/m

Turn to be added for CW beam.

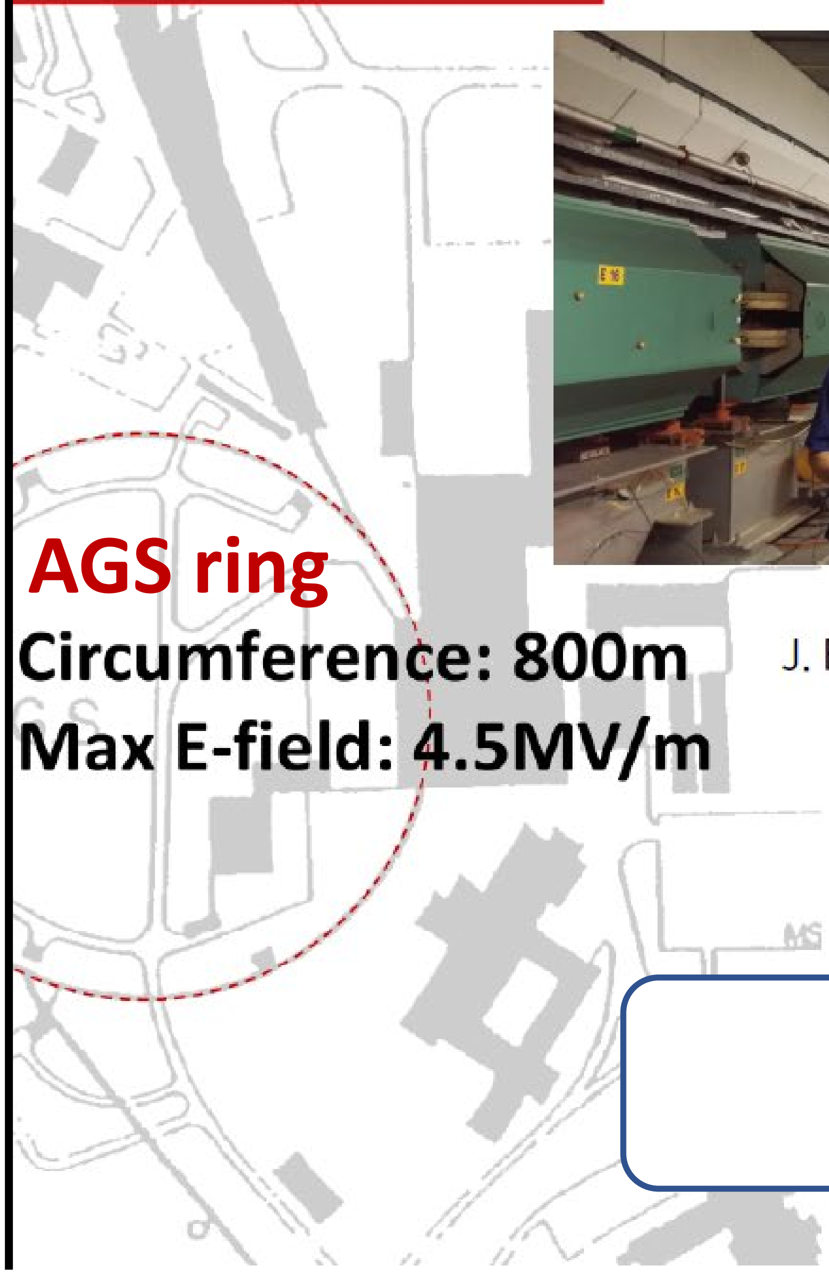
AGS tunnel
J. Benante and W. Morse

Storage ring fits into a 40-cm tube mounted on the wall to the right.

Mounting concept:
need 40-cm diameter pipe on shelf



tunnel at BNL



AGS ring

Circumference: 800m

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AGS tunnel
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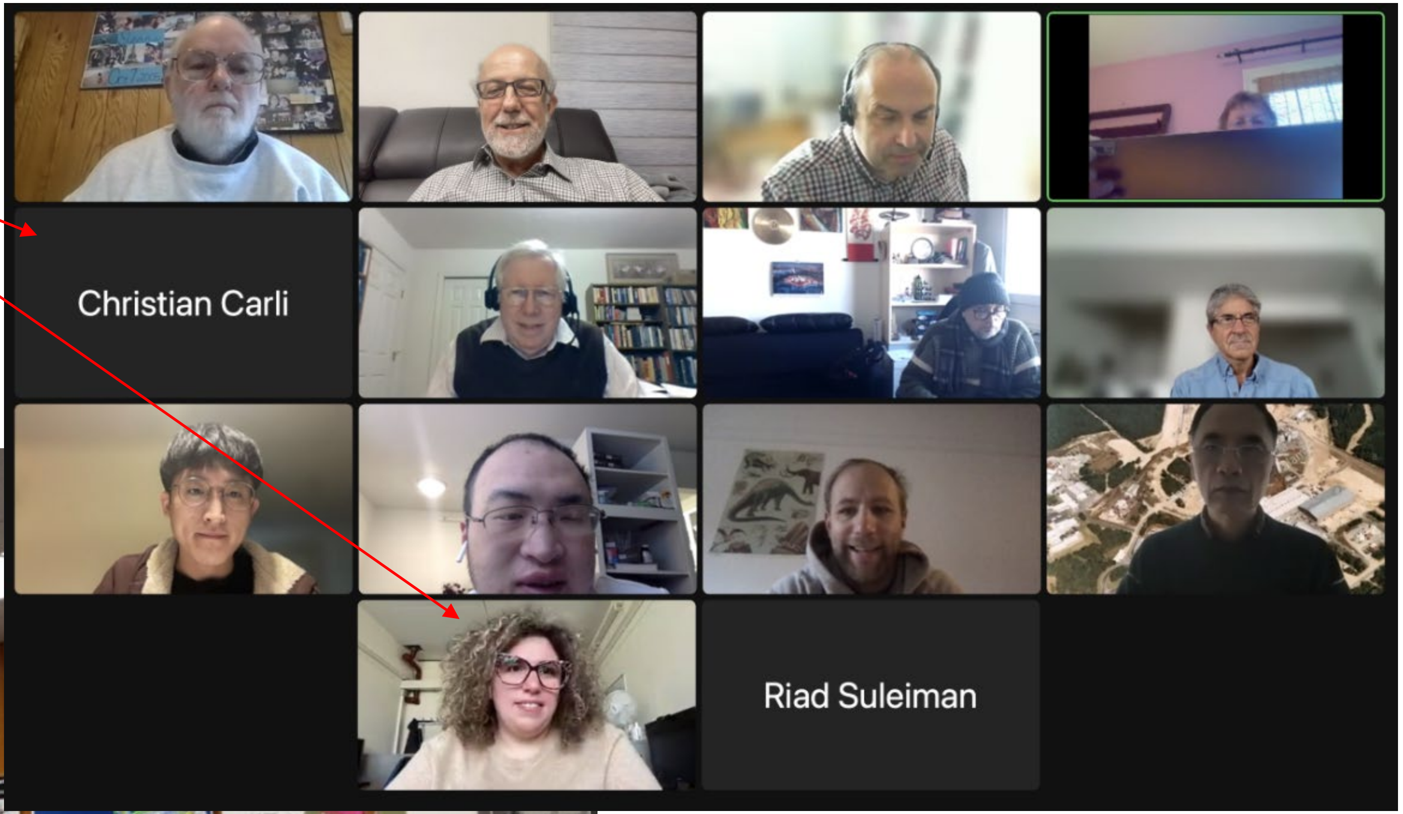
Storage ring fits into a 40-cm tube mounted on the wall to the right.

Visitors from CPEDM
(CERN and COSY)

Collaboration meeting
Nov. 11, 2014



Recent group meeting

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]

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

Recent status report:

73 co-authors,

39 institutions

The storage ring proton EDM experiment

Jim Alexander[7], Vassilis Anastassopoulos[36], I
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Marin Karuza[37], David Kawall[29], On Kim[6], Ivan
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Marios Maroudas[36], Andrei Matlashov[6], Franco
William M. Morse[4], James Mott[3,8], Zhanibek O
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arXiv:2205.00830v1 [hep-ph] 25 Apr 2022

Current activities outside US:

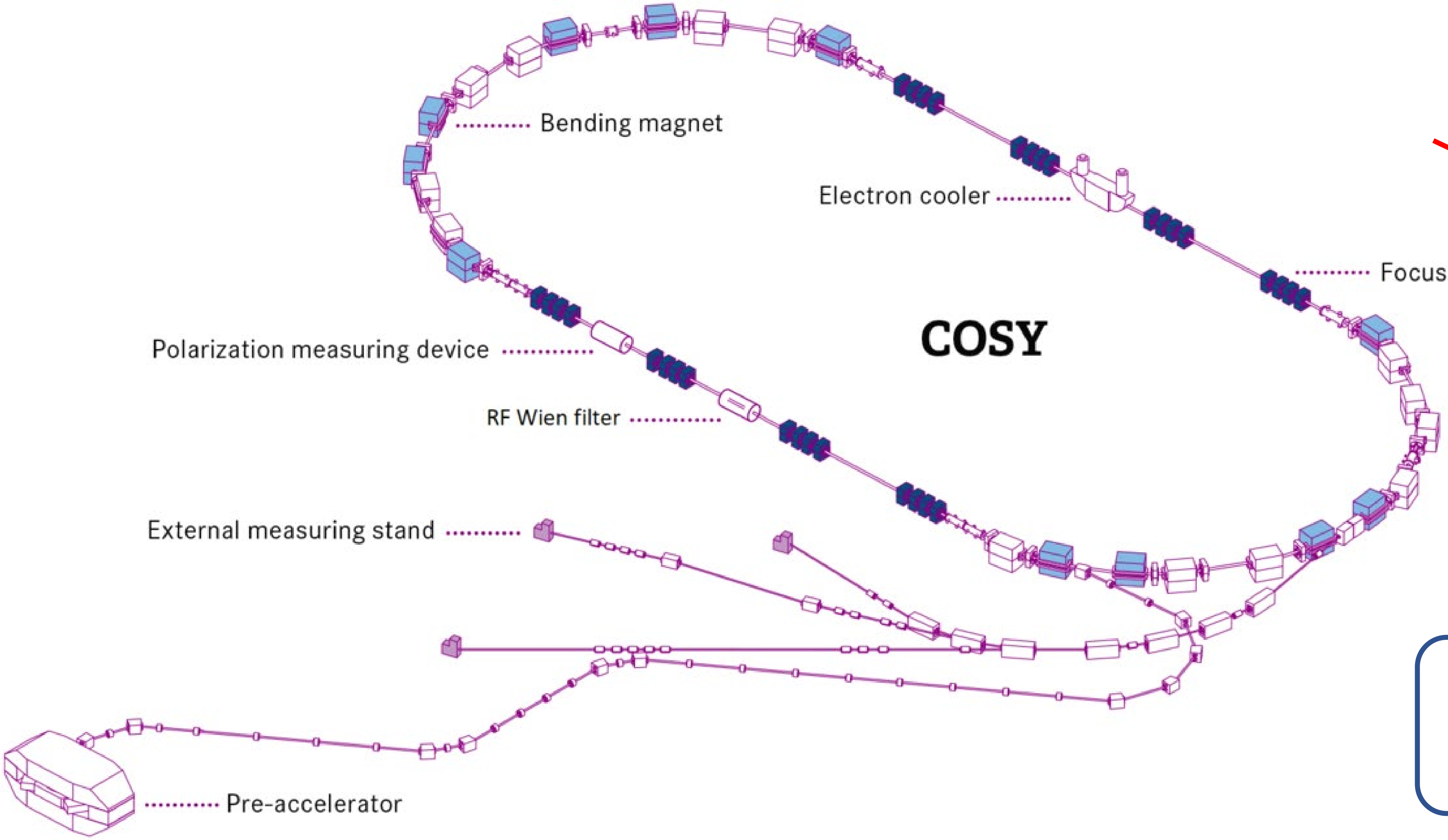
- UK: Design HV plates
- Türkiye: Simulations
  - Magnetic quads
- S. Korea: Simulations

Current activities inside US:

- BNL: Cost estimates
  - Ground stability
  - Injection
  - Systematic errors
- Indiana: Polarization experiments
  - Axion search

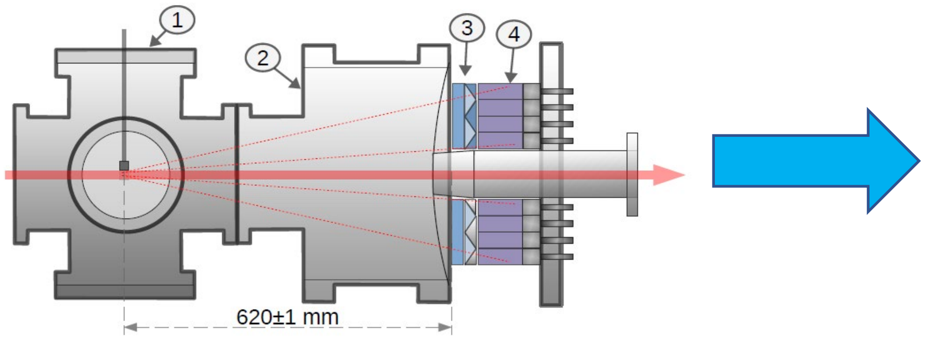
Recent status report:
73 co-authors,
39 institutions

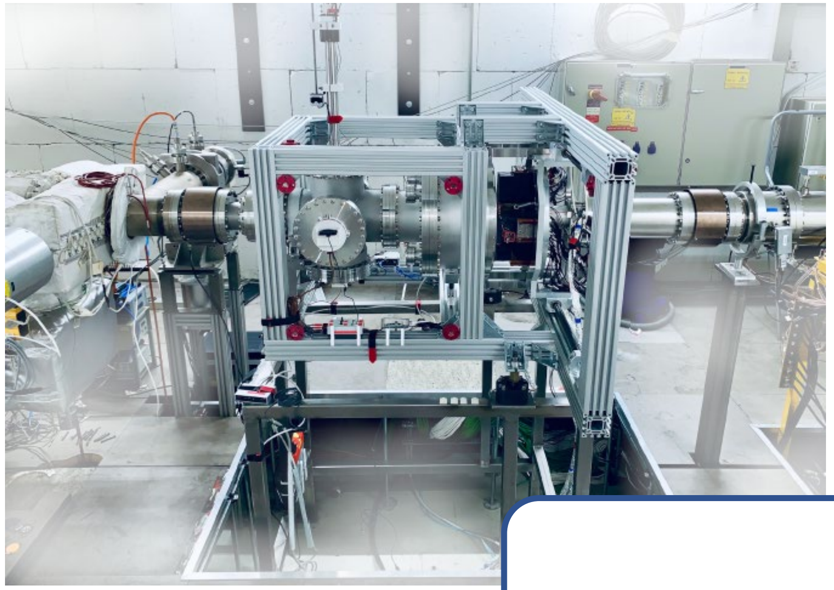
R&D results from Forschungszentrum Jülich Cooler Synchrotron



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)

Features of ring design

Reducing errors using symmetries:[1]

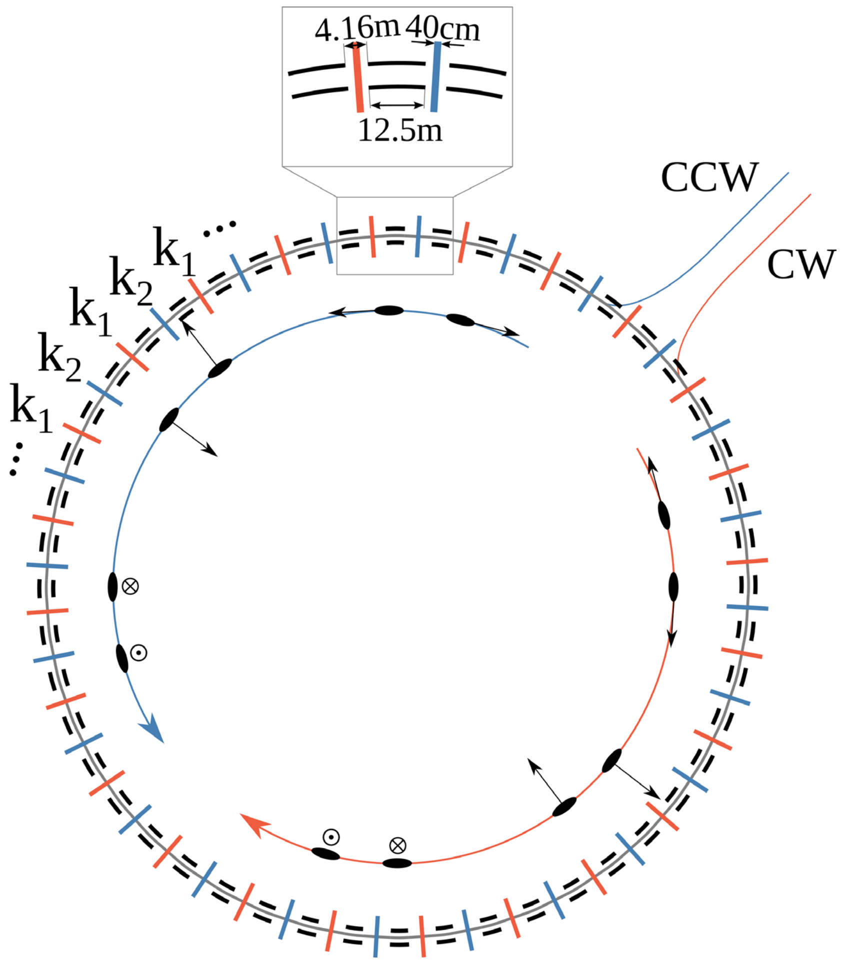
Use beams going in opposite directions simultaneously.

Large number (48) of ring sections.

Ring sections with alternately focusing and defocusing magnetic sextupoles. Swap $k_1 - k_2$.

Maintain flat ring using water level (good to <0.1 mm).

Overlap counter-rotating beams to better than 0.01 mm by checking stray magnetic field.



[1] Omarov, PRD 105, 032001 (2022)

‘23 ‘24 ‘25 ‘26 ‘27 ‘28 ‘29 ‘30 ‘31 ‘32 ‘33

Cost estimation underway

Detailed design, procurement

Construction starts

[polarimeters, individual section, mass-produced parts

Ring installation, alignment

First beam (injection, bunching)

Beams in opposite directions

Polarization studies, first results

Systematic adjustments

Data running, publication

Summary:

Storage ring EDM project needs support to begin work at BNL.

Electric storage ring operating at magic momentum looks feasible for a search on the proton to a sensitivity of 10^{-29} e·cm.

No major technical obstacles are apparent.

Experiment has reach of $\Lambda_{NP} > 3000$ TeV

Design has been checked and appears robust.

COSY ring with polarized beam was recently used to look for an axion resonance by scanning the RF frequency of the machine. This project has a future working on other physics experiments.[1]

[1] arXiv 2208.07293

END

Thank you

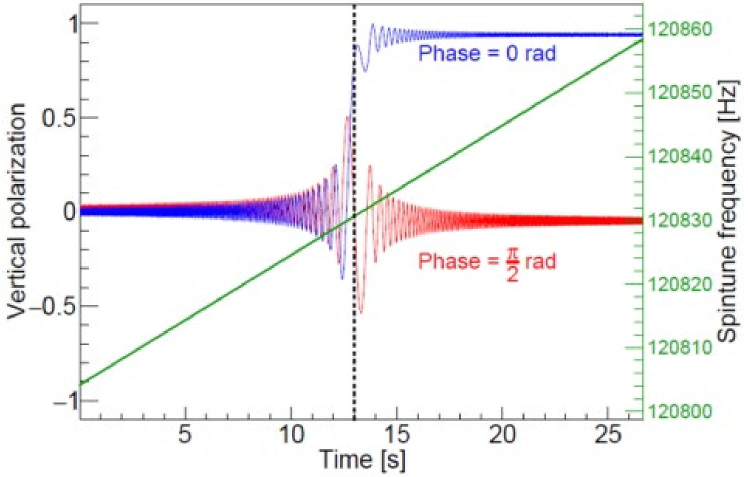
Ring parameters

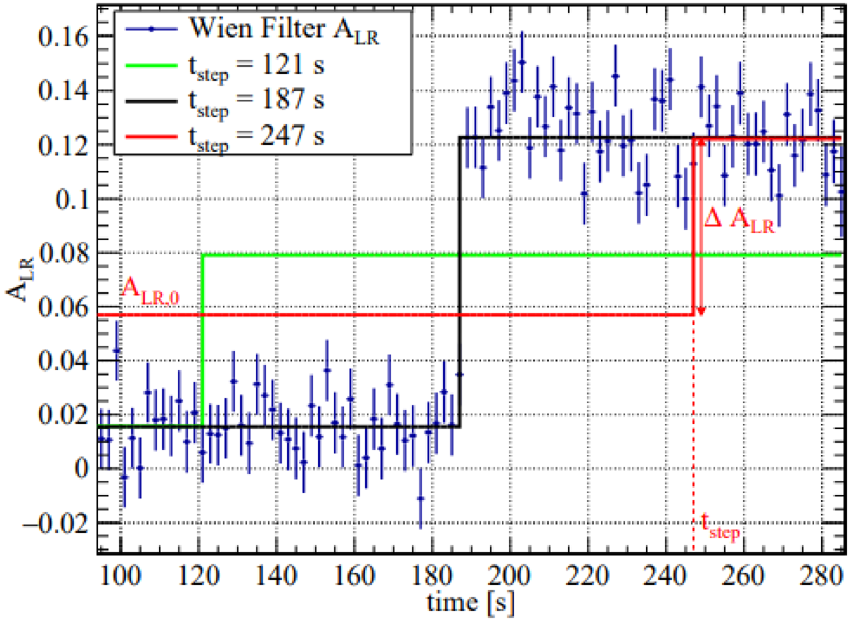
Quantity	Value
Bending Radius R_0	95.49 m
Number of periods	24
Electrode spacing	4 cm
Electrode height	20 cm
Deflector shape	cylindrical
Radial bending E-field	4.4 MV/m
Straight section length	4.16 m
Quadrupole length	0.4 m
Quadrupole strength	±0.21 T/m
Bending section length	12.5 m
Bending section circumference	600 m
Total circumference	800 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, $\frac{dt}{t}/\frac{dp}{p}$	-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
Beam planarity	0.1 mm
CR-beam splitting	0.01 mm

Karanth: arXiv: 2208.07203

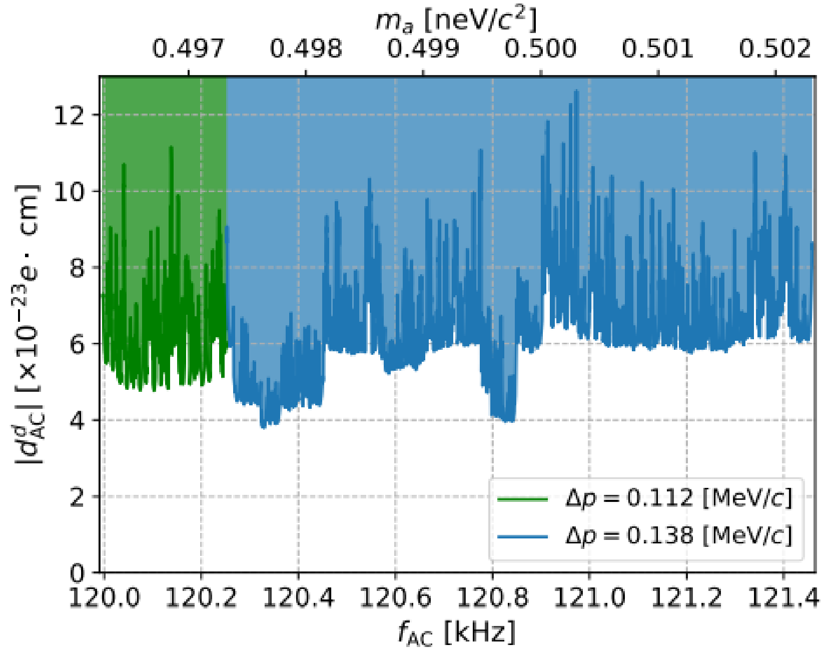
Axion search uses non-frozen spin
- Ramp machine frequency
- Precession frequency (spin tune) scans axion frequency
- Resonance when frequencies cross: polarization jumps





Simulated signal using RF Wien filter

90% confidence upper limit

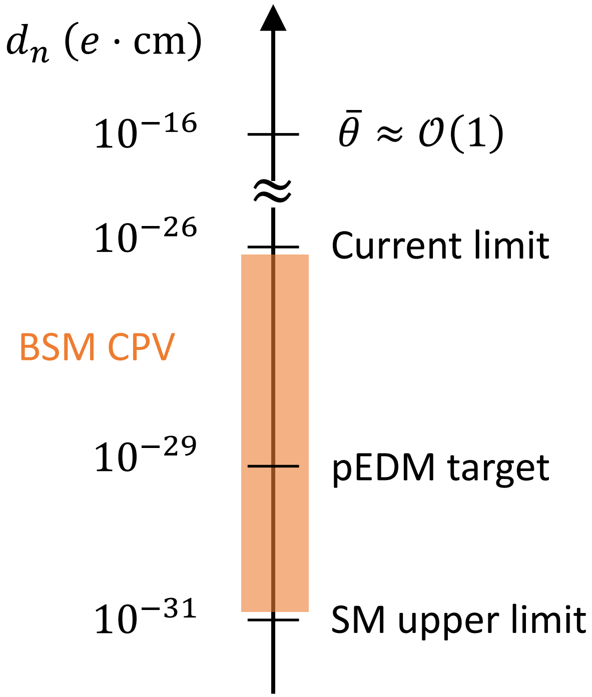


Physics reach of storage ring pEDM at $10^{-29}\ e \cdot \text{cm}$

1. Competitive sensitivity to New Physics up to $1000\ \text{TeV}$.
2. Three orders of magnitude improvement in θ_{QCD}.
3. Sensitive to certain Baryogenesis models: $\approx 10^{-28}\ e \cdot \text{cm}$ in MSSM.
4. Best probe of Higgs CPV.
   - Two-loop Higgs coupling: $\tan \phi_{\text{NP}} \approx \mathcal{O}(10^{-4})$.
   - x30 more sensitive than electrons with the same EDM.
5. Direct axion-like dark matter or fifth force search.
   - Best experimental sensitivity at ultra-low frequency.
   - Also sensitive to dark energy or vector DM with a different experimental knob.

- First-ever "direct" measurement/constraint of d_p.
  - With 10^3 improvement from the best current d_n limit.
  - Complementary to atomic & molecular and optical (AMO) EDM experiments. E.g., complementary with the eEDM to sort out possible CPV sources.

$$d_n \approx \mathcal{O}(10^{-16})\ \bar{\theta}\ \ e \cdot \text{cm}$$



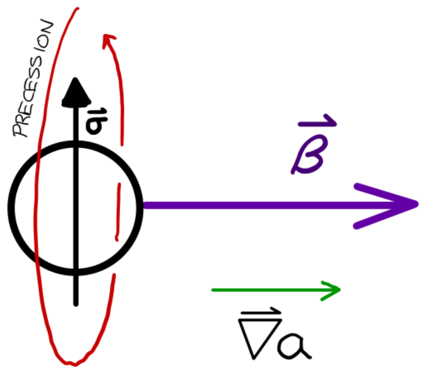
Dark Matter and Dark Energy “Wind”

- DM/DE wind will look like an anomalous longitudin l on the spin.
  P. Graham *et al.*, PRD **103**, 055010 (2021)

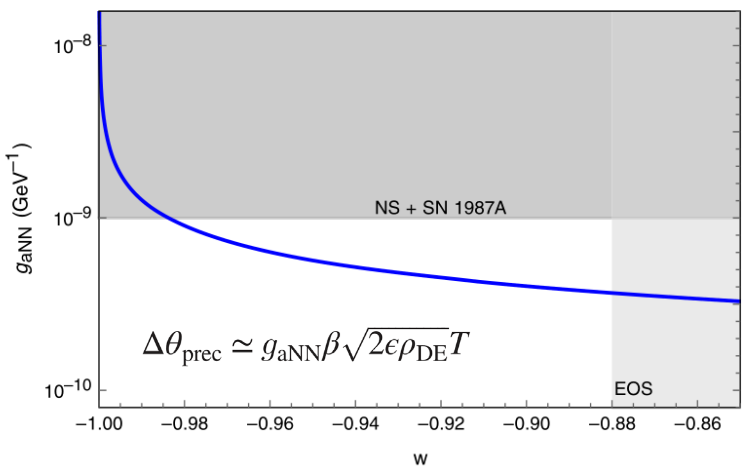
$$\boldsymbol{\omega}_{\mathrm{DM}} \propto \cos(m_a t)\,\hat{\beta}$$

- The best sensitivity with a radially polarized frozen-

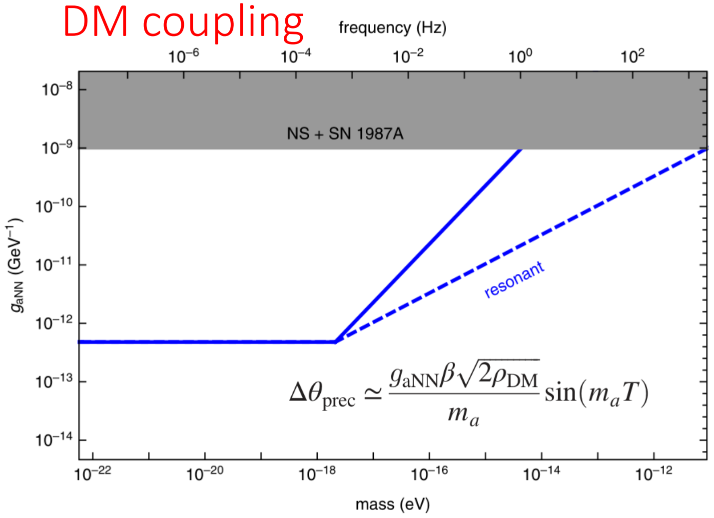
$$\boldsymbol{\omega}_{\mathrm{DE}} \propto \hat{\beta}$$



DE coupling



DM coupling



ALP-induced oscillating EDM

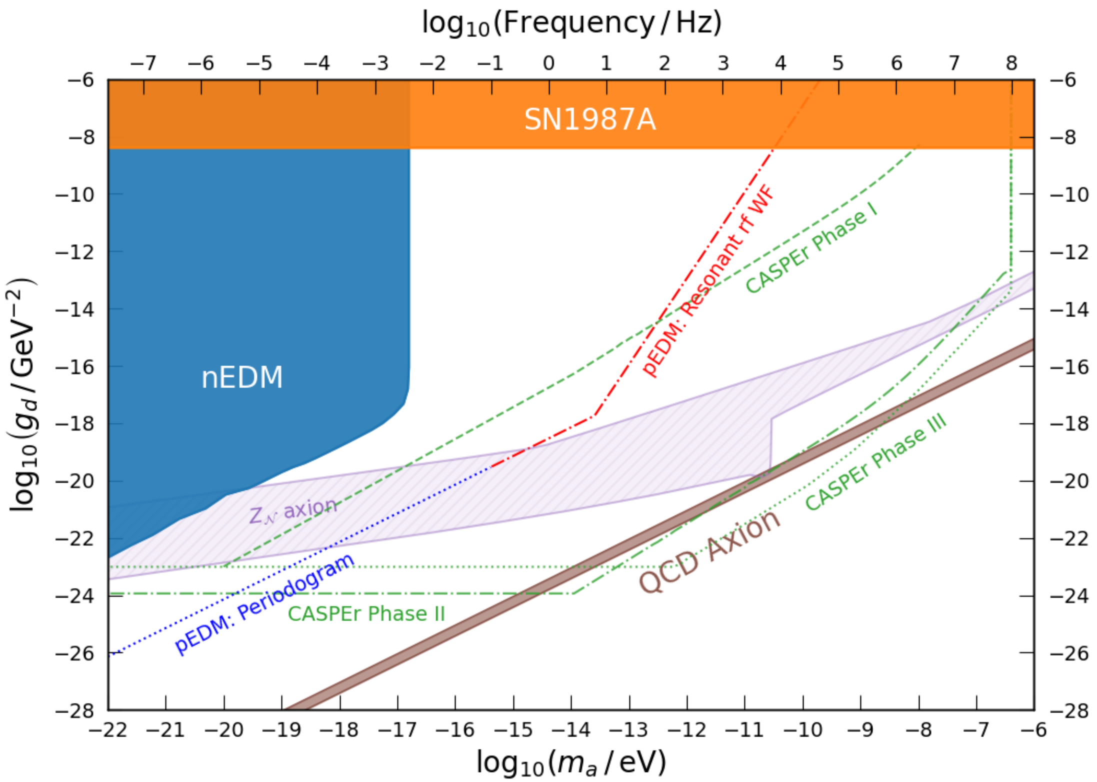
P. Graham and S. Rajendran, PRD **88**, 035023 (2013)
P. Graham et al., PRD **103**, 055010 (2021)

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

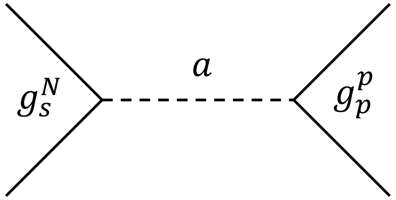
ALP-EDM coupling

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

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



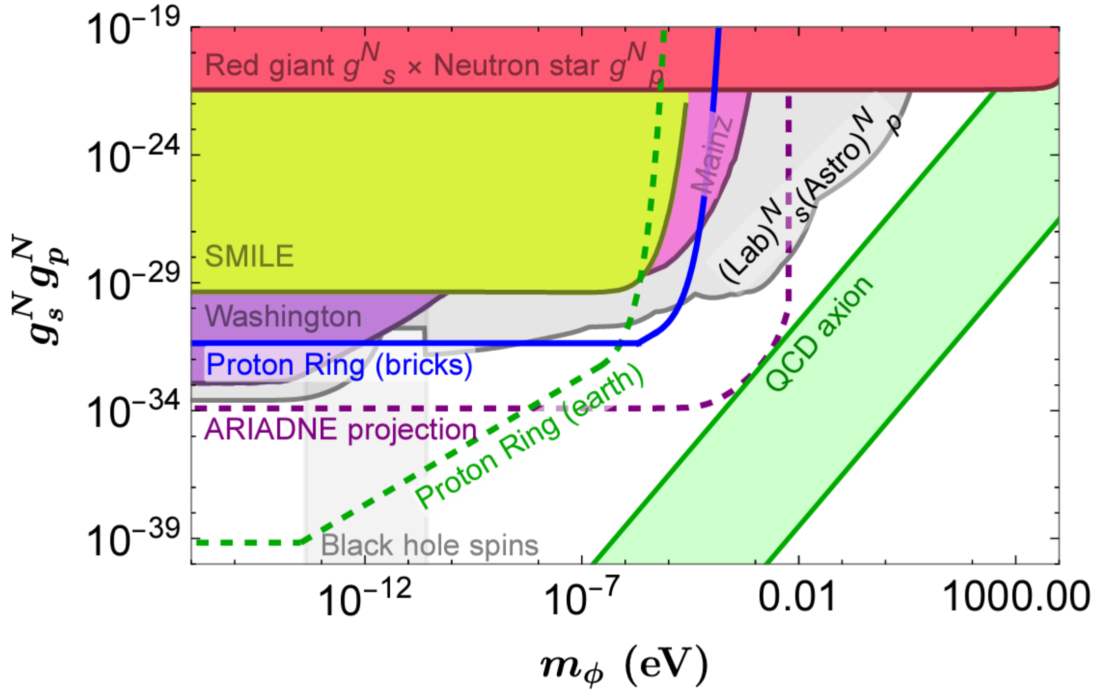
Search for axion forces with pEDM



Searching for axion forces with precision precession in storage rings 2210.17547

Prateek Agrawal, David E. Kaplan, On Kim, Surjeet Rajendran, Mario Reig

We consider different types of storage rings as precision probes of axion-mediated monopole-dipole forces. We show that current and planned experiments aiming to measure magnetic and electric dipole moments of protons, muons and electrons very precisely may explore new parts of the parameter space beyond existing laboratory bounds and, in some cases, beyond astrophysical constraints. Remarkably, a light axion coupled to muons may explain the FNAL/BNL $(g-2)_\mu$ anomaly as an environmental effect -- the coherent axion field generated by the earth nucleons induces an extra contribution to the anomalous precession frequency of the muon explaining the discrepancy with respect to the SM prediction.



Parasitic measurement with pEDM experiment.

Also look at 2210.14959 and 2105.03422 for references.

Storage Ring Probes of Axion Dark Matter

- The axion feebly interacts with SM particles.

$$\mathcal{L} \supset g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B} + g_{aff} \nabla a \cdot \hat{\mathbf{S}} + g_{\mathrm{EDM}} a \hat{\mathbf{S}} \cdot \mathbf{E}$$

Primakoff effect — Axion gradient — Oscillating nucleon EDM

- If the axion is dark matter, it's abundant around us.
- High-precision storage ring spin experiments are suitable to probe the last two interactions.
  - Search for DM/DE from the wind coupling: P. Graham *et al.*, PRD **103**, 055010 (2021).
  - Search for DM axion from the EDM coupling: S. P. Chang *et al.*, PRD **99**, 083002 (2019).
    - First implementation with deuterons: S. Karanth *et al.*, 2208.07293.
- The physics signatures are basically the same: out-of-plane spin rotation (either frozen or precessing in the storage ring plane).