Storage ring EDM experiment
Yannis Semertzidis, IBS/CAPP and KAIST

Proton, and deuteron

- Storage ring p,d EDMs @ $<10^{-29}\text{e-cm level}$, $10^3\text{TeV}$ physics reach.
- Priority on the proton EDM

- srEDM axion dark matter sensitivity 1710.05271, Korea
CPEDM collaboration with executive board

- Charged Particle EDM, a new collaboration, part of PBC at CERN
- Storage ring EDM collaboration (srEDM), BNL, Korea, …
- Juelich EDM Investigations (JEDI), COSY/Juelich
- CERN
CPEDM collaboration

What we bring on the table

- Storage ring EDM collaboration (srEDM)
  - First proposal to BNL, 2011
  - SQUID-based beam position monitors
  - High precision beam/spin dynamics simulations
  - Methods to achieve $>10^3 \text{s}$ polarization lifetime; polarim.; Polariz. dependence cross sections in GEANT4
  - Methods to reduce critical systematic errors (non-planarity of orbits, radial B-fields, …)
  - Additional physics with same ring (axion dark matter)
What we bring on the table

- Juelich EDM Investigations (JEDI)
  - Polarimeter systematic errors
  - State of the art polarimeter
  - Studies with polarized deuteron beams (stability of tune to better than $10^{-9}$ per hour, etc…)
  - Beam-based alignment (10um), Rogowski coils, etc.
  - RF-Wien filter for deuteron EDM studies
  - E-field deflectors (under development)
CPEDM collaboration

What we bring on the table

- CERN
  - Critical review of systematic error studies (fresh look at all levels - critically important)
  - Feasibility of polarized beams: creation, transfer, injection and storage into a ring
CPEDM collaboration
The ultimate goal is to design, build, and operate an all-electric ring for protons at their magic momentum (233MeV, 0.7 GeV/c) with CW/CCW injections & a sensitivity of order $10^{-29}$e-cm. Build 30MeV prototype.

- Design of a realistic lattice
- Spin tracking
- Systematic error budget
- Technical realization

Feasibility study by December 2018
## CPEDM Work

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<td>KAIST/FZJ/CERN</td>
<td>Frank Rathmann</td>
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<td>Yannis Semertzidis (CAPP/IBS &amp; KAIST)</td>
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<td>- Site&lt;br&gt;- Civil engineering&lt;br&gt;- Cost</td>
<td>CERN</td>
<td>Mike Lamont (CERN)</td>
</tr>
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</table>
What has CERN got to offer?

• Existing accelerator complex and associated infrastructure
  – Wide range of beams, intensities, energies
• Technical expertise
  – Vacuum, magnets, power converters, RF, instrumentation, beam transfer, targets, cryogenics, accelerator physics, engineering...
• Experience
• Support
  – workshops, test facilities, engineering...
• Resources, size, and flexibility

  • Maximize performance of existing complex
  • Harness existing expertise and resources
  • New facilities exploiting existing complex
  • Novel exploitation of existing facilities
The proton EDM ring (alternate gradient)

Straight sections are instrumented with quads, BPMs, polarimeters, injection points, etc, as needed.

Requirements:
Weak vertical focusing (B-field sensitivity)
Below transition (reduce IBS)
Currently: CSR, Heidelberg, 35 m circ., $10^{-13}$ Torr
COoler SYnchrotron (COSY)

- 184 m circumference
- Protons and Deuterons
- Polarized or un-polarized
- $p$: 295 MeV/c - 3.65 GeV/c
- Stochastic and electron cooling
- 2 $e^-$ cooler: 100 keV and 2 MeV
- Typ. amount of stored particles: $10^{10}$
- Internal experiments and 3 external beam lines
- $H^-$ stripping injection
Measurement Principle

Beam Preparation:
- Inject vertically polarized deuteron beam
- Accelerate
- Cool (with e-cooler) and bunch
- Put spin into horizontal plane (with rf-solenoid on spin tune resonance)

Watch decay of up-down asymmetry (horizontal polarization)

\[ \tau_{SC} \approx 20 \text{ s} \]
Sextupole Scans

obtain this picture by rastering the MXS-MXG plane, maximum SCT lies on zero chromaticity lines

SCT goal accomplished!
BEAM BASED ALIGNMENT
Why is it needed?

- For an EDM measurement the orbit has to be as good as possible
- Orbit RMS should be lower than 100 μm
  → Orbit Control
- Orbit Control corrects the beam to the BPM zero position
- Goal is to go central through all magnets (i.e. quadrupoles)
- Thus BPM to quadrupole offset has to be known
  → Beam Based Alignment
BEAM BASED ALIGNMENT

How does it work?

- How does the orbit change when varying the quadrupole strength?

\[
\Delta x(s) = \left( \frac{\Delta k x(\bar{s}) l}{B\rho} \right) \left( \frac{1}{1 - k \frac{l\beta(\bar{s})}{2B\rho \tan \pi \nu}} \right) \\
\times \frac{\sqrt{\beta(s)} \sqrt{\beta(\bar{s})}}{2 \sin \pi \nu} \cos(\phi(s) - \phi(\bar{s}) - \pi \nu)
\]
BEAM BASED ALIGNMENT

Measurement

COSY

COSY scetch with position of quadrupole QT12 indicated

J. Slim (modified)
**BEAM BASED ALIGNMENT**

Results

<table>
<thead>
<tr>
<th>Optimal Position</th>
<th>in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>−0.255±0.028</td>
</tr>
<tr>
<td>Vertical</td>
<td>2.329±0.011</td>
</tr>
</tbody>
</table>

- Optimal position given in script setting
- The values in mm are the BPM 6 readings nearby

**SUMMARY**

- Beam based alignment works
- The change of the magnet strength with additional coils works
- Optimal beam position inside the quadrupole could be determined to be \((-1.98 \pm 0.01)\) mm horizontally and \((1.15 \pm 0.01)\) mm vertically
- Now additional quadrupole magnets need to be changed to be individually controlled in order to measure this at more positions
Putting together the pEDM experiment

• Mechanically place all elements to 0.1mm local resolution (or as well it is possible)

• Using button BPMs/Rogowski coils to achieve resolution at the 10 micron level.

• Run the experiment with 90 & 180 degrees (radial) spin direction. Use vertical E-field trim plates around the ring to cancel the effect of distortions.
Major systematic error: Radial B-field
The all-electric proton EDM ring

Total circumference: ~400 m
Bending radius: 40 m
E: 10 MV/m

Allows for simultaneous clock-wise and counter-clock-wise beam storage
Weak vertical focusing
Stronger horizontal focusing
Total current: zero. Any radial magnetic field in the ring sensed by the stored particles will cause their vertical splitting.
Distortion of the closed orbit due to $N^{th}$-harmonic of radial B-field

$$y(\vartheta) = \sum_{N=0}^{\infty} \frac{\beta R_0 B_{rN}}{E_0 (Q_y^2 - N^2)} \cos(N\vartheta + \varphi_N)$$

Clockwise beam

The N=0 component is a first order effect!

Counter-clockwise beam

Time [s]
SQUID BPM to sense the vertical beam splitting at 1-10kHz

FIG. 3. A schematic of a possible SQUID BPM station. The system is shielded with a superconducting Nb tube, Al tube for RF-shield, and several mu-metal layers.
Total noise of (65) commercially available SQUID gradiometers at KRISS

From YongHo Lee’s group
KRISS/South Korea
SQUID-based BPMs, Korea

SQUID Hardware - Signal acquisition

Optical receiver

Optical transmitter

16 channel readout

Signal acquisition PCB

DC power

Computer (Digital in/out)

FLL input (digital/serial)

FLL control output

Trigger input

Axial gradiometer

Planar gradiometer

Selcuk Haciomeroglu, IBS/CAPP
SQUID-based BPMs, Korea

Preliminary setup

- We currently have a preliminary setup to play with
- 3 fT/√Hz sensitivity
- Currently we are making wire tests.
- We will use the same electronics in the next design

Prototype

Status of the B-field studies for the pEDM experiment

- The new design is to be delivered by summer
- Will be 2fT/√Hz
- We will make wire tests in Korea
- Would be good to test here at COSY

Selcuk Haciomeroglu, IBS/CAPP
Fig. 21. Arrangement of the pickup coils. Blue lines are pickup coils, and yellow oval is the hypothetical proton beam shape. (a) Two pickup surfaces facing each other to measure two radial field components, and (b) 8 pickup coils are arranged along the beam propagation direction.

Main configuration of the SQUIDs and dewar are as following:
- Inter-coil distance: about 40 mm
- Rectangular coil: 15 mm x 40 mm
- Interval between pickup coils: about 50 mm
- 8 channels/side: 16 channels/dewar
- Either thin film or wire-wound pickup coil
Andrei Matlashov, IBS/CAPP
BMP Systems in the Storage Ring

Interference-free control
Noise-free acquisition
No time-delay bet. modules

YongHo Lee, KRISS
The First generation (G1) of BMP system: tested at KRISS and moved to CAPP for further tests and research.

The Second generation (G2) of BMP system: designed, all key components manufactured; it will be assembled in May 2018.

Field Resolution: current G1 system \(\rightarrow 3.5 \text{ fT}/\sqrt{\text{Hz}} \ @ 1 \text{ kHz}\)

Field Resolution: under construction G2 system \(\rightarrow 1.2 \text{ fT}/\sqrt{\text{Hz}} \ @ 1 \text{ kHz}\)

Field Resolution: new generation SQUIDs \(\rightarrow 0.15 \text{ fT}/\sqrt{\text{Hz}} \ @ 1 \text{ kHz}\)

Andrei Matlashov, IBS/CAPP
Under development by Selcuk Haciomeroglu at CAPP.
Need absolute field: <1nT
Need gradient field: <1nT/m
Achieved so far:
Absolute field: <1nT
Gradient field: <1nT/m

Shielding - Prototype
Shielding - Preliminary measurements

The graph shows the magnetic field strength (B [nT]) along the axial position for different components: octagon, cylinder, and ring, after degaussing. The graph indicates the endcap and correction ring positions. The axial position ranges from 0 to 50, with a length of 1.5 m. The magnetic field strength varies across the axial position, with distinct peaks and troughs.
Christian Carli, CERN

- <1nT B-field shielding is adequate when lattice beta-functions are uniform

- Much stricter specs when there’s a variation of vertical beta-function.

- Selcuk Haciomeroglu: confirmed specs with high-precision beam/spin simulations
Plan

• Use as uniform vertical beta-function as possible (need <nT shielding)

• Investigate on how to reach <pT level B-field shielding with non-uniform vertical beta-function

• ...

Most hardware built & tested

E.g.: passive magnetic shielding factor > 6 million @ 1 mHz (without ext. compensation coils!)

- The smallest gradients over an extended volume ever realized: < 50 pT/m stable gradient over EDM cell volume
- Residual field drift < 5 fT in typical Ramsey cycle time
- Hg and Cs magnetometry on < 20 fT level:
  - Cs sensor head assembly
  - Raw 199-Hg FPD signal
  - Basically all magnetic field related systematics under control

I. Altarev et al., arXiv:1501.07408
I. Altarev et al., arXiv:1501.07861
Peter Fierlinger, TUM, magnetic shielding factor > 6M at 1mHz!

Physics Today, August 2015
Search for axion dark matter in storage rings

Axion dark matter search with the storage ring EDM method

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Abstract

We propose using a modified storage ring EDM method to search for the axion dark matter induced EDM oscillation in nucleons. The method uses a combination of \( B \) and \( E \)-fields to produce a resonance between the \( g - 2 \) precession frequency and the background axion field oscillation to greatly enhance the sensitivity to it. An axion frequency range of \( 100\text{Hz} \) to \( 100\text{MHz} \) can be scanned with large sensitivity, corresponding to \( f_a \) range of \( 10^{13} \text{GeV} \leq f_a \leq 10^{19} \text{GeV} \) the breakdown scale of the global symmetry generating the axion or axion like particles (ALPs).
Search for axion dark matter in storage rings

- Dark matter axion background field is oscillating
  - $a = a_0 \cos(\omega_a t)$
  - $\omega_a \approx m_a c^2 / \hbar$, $m_a$: axion mass

- The oscillating axion field is coupled with
  - Photon
    - $\rho_{\gamma \gamma} = \eta_{a,\gamma}^2 \left( \frac{\rho_a}{m_a^2} \right) B_{L} B_{Q}$
    - $a \rightarrow \gamma \gamma$
  - gluons, fermions, nucleon, etc. $\rightarrow$ Oscillating EDM

$$a(t) = a_0 \cos(m_a t) \Rightarrow d(t) = d_0 \cos(m_a t + \phi_x)$$

- Generic feature

$$d_n = 2.4 \times 10^{-16} \frac{a}{f_a} e \cdot cm \approx 9 \times 10^{-35} \cos(m_a t) [e \cdot cm]$$

Peter W. Graham and Surjeet Rajendran. 
Search for axion dark matter in storage rings

In a storage ring

\[
\frac{d\vec{\beta}}{dt} = \frac{e}{\gamma m} \left[ \vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} - \frac{\vec{\beta} \cdot \vec{E}}{c} \right]
\]

\[
\frac{d\vec{s}}{dt} = \frac{e}{m} \left[ \frac{\gamma - 1}{\gamma} \right] \vec{\beta} \left[ \frac{\gamma - 2}{\gamma + 1} \right] (\vec{\beta} \cdot \vec{B}) \vec{B} - \frac{\gamma}{\gamma + 1} \left( \frac{\gamma}{c} \vec{E} - \frac{\gamma - 1}{\gamma + 1} (\vec{\beta} \cdot \vec{E}) \vec{\beta} + \vec{\beta} \times \vec{B} \right)
\]

\[d(t) = d_0 \cos(\omega_a t + \phi)\]

\[\eta(t) = \frac{d(t) 4mc}{e\hbar}\]
Projected, preliminary

Experiment limit

Oscillation Frequency (Hz)

$C_G / f_a$ (GeV$^{-1}$)

Axion Mass (eV)

nEDM: Ultra-cold neutron trap experiment

Seongtae Park/Center for Axion and Precision Physics
Summary

• The charged particle EDM collaboration is formed, joining forces between srEDM and JEDI

• Working towards a feasibility study by December 2018

• Prototype of all-electric ring, 30MeV protons to study storage issues, spin coherence time, SQUID-based BPMs, B-field shielding issues, alignment issues, etc.
Extra slides
Physics relevance, comparison with other activities

• The physics reach of a proton and a deuteron experiment at the $10^{-29}$ e-cm is unique:

• Theta\_QCD vs. New Physics: help from n, p, and d, $^{199}$Hg, electron EDM values.

• Certain systematic errors, e.g., geometrical phases, cancel in clockwise vs. counterclockwise. Unique to storage ring method.
<table>
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<th>Current limit [e cm]</th>
<th>Future goal</th>
<th>Neutron equivalent</th>
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<tr>
<td>Neutron</td>
<td>&lt;1.6 × 10^{-26}</td>
<td>~10^{-28}</td>
<td>10^{-28}</td>
</tr>
<tr>
<td>$^{199}$Hg atom</td>
<td>&lt;0.7 × 10^{-29}</td>
<td></td>
<td>10^{-25}-10^{-26}</td>
</tr>
<tr>
<td>$^{129}$Xe atom</td>
<td>&lt;6 × 10^{-27}</td>
<td>~10^{-30}-10^{-33}</td>
<td>10^{-26}-10^{-29}</td>
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<tr>
<td>Deuteron nucleus</td>
<td></td>
<td>~10^{-29}</td>
<td>3 × 10^{-29}-5 × 10^{-31}</td>
</tr>
<tr>
<td>Proton nucleus</td>
<td>&lt;5 × 10^{-25}</td>
<td>~10^{-29}-10^{-30}</td>
<td>10^{-29}-10^{-30}</td>
</tr>
</tbody>
</table>
CP-violation phase from Higgs

EDMs will eventually be discovered: $d_e, d_n, d_p \ldots d_D$
Magnitudes of $\approx 10^{-28}$ expected for Baryogenesis
Atomic, Molecular, Neutron, **Storage Ring** (All important)

CP violation phase in: **Hee, $H_{\gamma\gamma}$, $H_{tt}$, 2HD Model**...
Uniquely explored by 2 loop edms! Barr-Zee effect
May be our only window to Hee, Huu and Hdd couplings
Guided by experiment: $H \rightarrow \gamma\gamma$ ($H \rightarrow \tau^+\tau^-, \mu^+\mu^-$) etc.

*Updates Anxiously Anticipated!*

*The Higgs may be central to our existence!*
EDM goals (done)

• The EDM experiments are gearing up, getting ready:

• $^{199}$Hg EDM <0.7x10^{-29} e-cm sensitivity

• nEDM at PSI 10^{-26} e-cm sensitivity, 1^{st} stage
• nEDM at PSI 10^{-27} e-cm sensitivity, 2^{nd} stage

• nEDM at SNS $\sim2 \times 10^{-28}$ e-cm starting data taking 2021
Generic Physics Reach of $d_p \sim 10^{-29}$ e-cm

$$d_p \sim 0.01 \left( \frac{m_p}{\Lambda_{NP}} \right)^2 \tan \phi_{NP} \frac{e}{2m_p} \sim 10^{-22} \left( \frac{1 \text{ TeV}}{\Lambda_{NP}} \right)^2 \tan \phi_{NP} \text{e-cm}$$

If $\phi_{NP}$ is of $O(1)$, $\Lambda_{NP} \sim 3000 \text{TeV}$ Probed!
If $\Lambda_{NP} \sim O(1 \text{ TeV})$, $\phi_{NP} \sim 10^{-7}$ Probed!

**Unique Capabilities!**
EDM status (cont’d)

• ThO, current limit on eEDM: $10^{-28}$ e-cm, next goal $\times 10$ improvement.

• TUM nEDM effort, making progress in B-field shielding, met B-field specs, goal: $10^{-28}$ e-cm, staged approach

• $^{225}$Ra EDM, $\sim 5 \times 10^{-22}$ e-cm now, $\sim 3 \times 10^{-28}$ e-cm w/ FRIB

• Storage ring EDM: p,dEDM goals $\sim 10^{-29} - 10^{-30}$ e-cm Strength: statistics, CW-CCW storage.
EDM experiments

• The neutron EDM experiments are making progress. Best goal: $\sim 10^{-28}$ e-cm

• $^{199}$Hg limits keep getting better. Currently setting best nEDM limit $1.6 \times 10^{-28}$ e-cm & pEDM $5 \times 10^{-25}$ e-cm

• eEDM limit $\sim 10^{-28}$ e-cm (equivalent to $10^{-27}$ e-cm for nEDM and pEDM: by a factor of $m_q/m_e$).
Currently, on systematic errors

- The magnetic field shielding work is under control. Simulations, consistent with analytical estimations, show Clockwise (CW) and Counter-clockwise (CCW) B-field geometrical phase cancel. Reset the shielding requirements to 10-100 nT.

- Hardware dev. achieved specs: <10 nT

- The SQUID-based gradiometer to specs is done. Proceeding for 5x better sensitivity system
Currently, on systematic errors

- Electrostatic quadrupole position tolerances by high precision beam/spin dynamics simulations are underway.

- An independent application is being used to study the same. Teleconferences are used to communicate the results.

- We will have a workshop early (March?) next year to summarize all progress.
Currently, on systematic errors

• A consensus is building up to go with the proton EDM first as simpler.

• We are considering various lattices for an all-electric field

• Working on the prototype scale and purpose
Indirect Muon EDM limit from the g-2 Experiment

\[ \vec{\omega} = \frac{e}{m} \left\{ a \vec{B} + \frac{\eta}{2c} (\vec{v} \times \vec{B}) \right\} \]

\[ \vec{\omega} = \vec{\omega}_a + \vec{\omega}_{edm} \]

\[ \tan \theta = \frac{\omega_{edm}}{\omega_a} \]

Ron McNabb’s Thesis 2003:

\[ < 2.7 \times 10^{-19} \text{ e} \cdot \text{cm} \quad 95\% \text{ C.L.} \]

Yannis Semertzidis
Axion dark matter search in storage rings

- A modified storage ring EDM method can search for the oscillating theta term.

- Oscillating axion field in resonance with the g-2 frequency.

- Frequency range: 100MHz all the way down to sub-micro-Hz.

- Great physics output, simpler systematic errors
Search for axion dark matter in storage rings


- A combination of the storage ring EDM method plus the g-2 principle we can search for axion dark matter!
- Large effective E-field
- High statistical power
- Large axion frequency coverage
- Can take advantage of large axion coherence time since the stability of the g-2 tune is shown to be at the $10^{-10}$ level! (Work at COSY)
Storage Ring EDM potential (preliminary)
Summary

- Physics reach strong for p,dEDM < $10^{-29}$ e-cm
- Physics reach enriched with oscillating theta_QCD sensitivity! Probing axion dark matter for axion mass below 0.5 micro-eV.

- Systematics: Hardware development is going well.
- High precision software work in parallel. Workshop early next year.
Search for axion dark matter in storage rings (1710.05271)

- Large effective E-field
- Statistics
- Superb tune stability, long spin coherence time

Figure 2: E/B combined ring for $g - 2$ frequency tuning
Spin direction

Figure 4: Vertical spin precession with different initial polarization
### Table 1: Examples of experiment parameters for frequency tuning and results of sensitivity calculation (Deuteron).

The analyzing power was assumed to be $A = 0.36$ for both B-ring and E/B combined ring.

<table>
<thead>
<tr>
<th>$B$ (T)</th>
<th>$P$ (GeV/c)</th>
<th>$f_{g-2}$ (Hz)</th>
<th>$E_r$ (V/m)</th>
<th>$E^*$ (V/m)</th>
<th>Sensitivity (e·cm)</th>
<th>Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$a$</td>
<td></td>
</tr>
<tr>
<td>0.38</td>
<td>0.9429</td>
<td>$10^2$</td>
<td>$8.82 \times 10^6$</td>
<td>$4.23 \times 10^7$</td>
<td>$1.9 \times 10^{-31}$</td>
<td>E/B ring</td>
</tr>
<tr>
<td>0.38</td>
<td>0.9433</td>
<td>$10^3$</td>
<td>$8.80 \times 10^6$</td>
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<td>$6.0 \times 10^{-31}$</td>
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<tr>
<td>0.38</td>
<td>0.9473</td>
<td>$10^4$</td>
<td>$8.65 \times 10^6$</td>
<td>$4.27 \times 10^7$</td>
<td>$1.9 \times 10^{-30}$</td>
<td></td>
</tr>
<tr>
<td>0.38</td>
<td>0.988</td>
<td>$10^5$</td>
<td>$7.05 \times 10^6$</td>
<td>$4.60 \times 10^7$</td>
<td>$5.5 \times 10^{-30}$</td>
<td>$1.8 \times 10^{-31}$</td>
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<td>0.38</td>
<td>1.035</td>
<td>$2 \times 10^5$</td>
<td>$5.06 \times 10^6$</td>
<td>$5.00 \times 10^7$</td>
<td>$7.2 \times 10^{-30}$</td>
<td></td>
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<tr>
<td>0.38</td>
<td>1.133</td>
<td>$4 \times 10^5$</td>
<td>$3.47 \times 10^6$</td>
<td>$5.86 \times 10^7$</td>
<td>$8.7 \times 10^{-30}$</td>
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<tr>
<td>0.38</td>
<td>1.239</td>
<td>$6 \times 10^5$</td>
<td>$-5.47 \times 10^6$</td>
<td>$6.83 \times 10^7$</td>
<td>$9.1 \times 10^{-30}$</td>
<td></td>
</tr>
<tr>
<td>0.38</td>
<td>1.355</td>
<td>$8 \times 10^5$</td>
<td>$-1.26 \times 10^7$</td>
<td>$7.93 \times 10^7$</td>
<td>$9.1 \times 10^{-30}$</td>
<td></td>
</tr>
<tr>
<td>0.38</td>
<td>1.484</td>
<td>$10^6$</td>
<td>$-2.14 \times 10^7$</td>
<td>$9.21 \times 10^7$</td>
<td>$8.8 \times 10^{-30}$</td>
<td></td>
</tr>
<tr>
<td>0.38</td>
<td>2.513</td>
<td>$10^6$</td>
<td>$-9.13 \times 10^6$</td>
<td>$2.01 \times 10^8$</td>
<td>$4.0 \times 10^{-30}$</td>
<td></td>
</tr>
<tr>
<td>0.80</td>
<td></td>
<td>$10^6$</td>
<td>$0$</td>
<td>$2.28 \times 10^8$</td>
<td>$3.5 \times 10^{-30}$</td>
<td>E ring</td>
</tr>
<tr>
<td>0.9198</td>
<td>2.7574</td>
<td>$10^6$</td>
<td>$0$</td>
<td>$2.75 \times 10^9$</td>
<td>$9.3 \times 10^{-31}$</td>
<td></td>
</tr>
<tr>
<td>9.1977</td>
<td>27.574</td>
<td>$10^7$</td>
<td>$0$</td>
<td>$3.5 \times 10^{-30}$</td>
<td>$9.3 \times 10^{-31}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$b$</td>
<td></td>
</tr>
</tbody>
</table>

**a:** Axion $Q = 10^6$, Polarimeter Efficiency = 0.02, Initial polarization = 0.8, Analyzing power $A = 0.36$, $SCT = 10^4$ s.

**b:** Axion $Q = 10^{10}$, Polarimeter Efficiency = 0.02, Initial polarization = 0.8, Analyzing power $A = 0.36$, $SCT = 10^4$ s.
Table 2: Examples of experiment parameters for frequency tuning and results of sensitivity calculation (Proton). The analyzing power used for E/B combined ring was $A = 0.6$ and $A = 0.25$ was used for B field only ring.

<table>
<thead>
<tr>
<th>B (T)</th>
<th>P (GeV/c)</th>
<th>$f_{g-2}$ (Hz)</th>
<th>$E_r$ (V/m)</th>
<th>$E^*$ (V/m)</th>
<th>Sensitivity (e·cm)</th>
<th>Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>a</td>
<td></td>
</tr>
<tr>
<td>0.00010</td>
<td>0.6984</td>
<td>$10^2$</td>
<td>$-8.00 \times 10^6$</td>
<td>$8.02 \times 10^6$</td>
<td>$1.0 \times 10^{-30}$</td>
<td></td>
</tr>
<tr>
<td>0.00008</td>
<td>0.6982</td>
<td>$10^3$</td>
<td>$-8.00 \times 10^6$</td>
<td>$8.01 \times 10^6$</td>
<td>$3.2 \times 10^{-30}$</td>
<td></td>
</tr>
<tr>
<td>-0.00017</td>
<td>0.6964</td>
<td>$10^4$</td>
<td>$-8.00 \times 10^6$</td>
<td>$7.97 \times 10^6$</td>
<td>$1.0 \times 10^{-29}$</td>
<td></td>
</tr>
<tr>
<td>-0.00243</td>
<td>0.6747</td>
<td>$10^5$</td>
<td>$-8.00 \times 10^6$</td>
<td>$7.57 \times 10^6$</td>
<td>$3.4 \times 10^{-29}$</td>
<td></td>
</tr>
<tr>
<td>-0.00495</td>
<td>0.6519</td>
<td>$2 \times 10^5$</td>
<td>$-8.00 \times 10^6$</td>
<td>$7.15 \times 10^6$</td>
<td>$5.0 \times 10^{-29}$</td>
<td></td>
</tr>
<tr>
<td>-0.01523</td>
<td>0.7103</td>
<td>$4 \times 10^5$</td>
<td>$-1.10 \times 10^7$</td>
<td>$8.24 \times 10^6$</td>
<td>$6.2 \times 10^{-29}$</td>
<td></td>
</tr>
<tr>
<td>-0.02002</td>
<td>0.6711</td>
<td>$6 \times 10^5$</td>
<td>$-1.10 \times 10^7$</td>
<td>$7.51 \times 10^6$</td>
<td>$8.3 \times 10^{-29}$</td>
<td></td>
</tr>
<tr>
<td>-0.02666</td>
<td>0.6643</td>
<td>$8 \times 10^5$</td>
<td>$-1.20 \times 10^7$</td>
<td>$7.38 \times 10^6$</td>
<td>$9.8 \times 10^{-29}$</td>
<td></td>
</tr>
<tr>
<td>-0.03327</td>
<td>0.6583</td>
<td>$10^6$</td>
<td>$-1.30 \times 10^7$</td>
<td>$7.27 \times 10^6$</td>
<td>$1.1 \times 10^{-28}$</td>
<td></td>
</tr>
<tr>
<td>0.36587</td>
<td>1.0968</td>
<td>$10^7$</td>
<td>0</td>
<td>$8.33 \times 10^7$</td>
<td>$3.1 \times 10^{-29}$</td>
<td></td>
</tr>
<tr>
<td>3.65868</td>
<td>10.9684</td>
<td>$10^8$</td>
<td>0</td>
<td>$1.09 \times 10^9$</td>
<td>$7.4 \times 10^{-30}$</td>
<td></td>
</tr>
</tbody>
</table>

|       |           |                |             |             | b                 |      |
| 0.00010 | 0.6984   | $10^2$        | $-8.00 \times 10^6$ | $8.02 \times 10^6$ | $1.0 \times 10^{-30}$ |      |
| 0.00008 | 0.6982   | $10^3$        | $-8.00 \times 10^6$ | $8.01 \times 10^6$ | $3.2 \times 10^{-30}$ |      |
| -0.00017 | 0.6964   | $10^4$        | $-8.00 \times 10^6$ | $7.97 \times 10^6$ | $1.0 \times 10^{-29}$ |      |
| -0.00243 | 0.6747   | $10^5$        | $-8.00 \times 10^6$ | $7.57 \times 10^6$ | $3.4 \times 10^{-29}$ |      |
| -0.00495 | 0.6519   | $2 \times 10^5$ | $-8.00 \times 10^6$ | $7.15 \times 10^6$ | $5.0 \times 10^{-29}$ |      |
| -0.01523 | 0.7103   | $4 \times 10^5$ | $-1.10 \times 10^7$ | $8.24 \times 10^6$ | $6.2 \times 10^{-29}$ |      |
| -0.02002 | 0.6711   | $6 \times 10^5$ | $-1.10 \times 10^7$ | $7.51 \times 10^6$ | $8.3 \times 10^{-29}$ |      |
| -0.02666 | 0.6643   | $8 \times 10^5$ | $-1.20 \times 10^7$ | $7.38 \times 10^6$ | $9.8 \times 10^{-29}$ |      |
| -0.03327 | 0.6583   | $10^6$        | $-1.30 \times 10^7$ | $7.27 \times 10^6$ | $1.1 \times 10^{-28}$ |      |
| 0.36587 | 1.0968   | $10^7$        | 0          | $8.33 \times 10^7$ | $3.1 \times 10^{-29}$ |      |
| 3.65868 | 10.9684  | $10^8$        | 0          | $1.09 \times 10^9$ | $7.4 \times 10^{-30}$ |      |

a: Axion $Q = 10^6$, Polarimeter Efficiency = 0.02, Initial polarization = 0.8, SCT = $10^4$ s.
b: Axion $Q = 10^{10}$, Polarimeter Efficiency = 0.02, Initial polarization = 0.8, SCT = $10^4$ s.

Analyzing power $A$: $A = 0.6$ for E/B ring, $A = 0.25$ for B ring.
History/Status of nEDM@SNS

- **2011:** NSAC Neutron Subcommittee
- **2013:** Critical R&D successfully demonstrated
- **2014-2017:** Critical Component Demonstration (CCD) phase begun
  - Build working, full-scale, prototypes of technically-challenging subsystems (use these in the full experiment)
  - 4yr NSF proposal for 6.5M$ CCD funded
  - DOE commitment of $\approx 1.8M$/yr for CCD
- **2018-2020:** Large scale Integration and Conventional Component Procurement
- **2021:** Begin Commissioning and Data-taking
A charged particle between Electric Field plates would be lost right away...
Proton storage ring EDM experiment is combination of beam + a trap
The Electric Dipole Moment precesses in an Electric field

\[ \frac{\overrightarrow{ds}}{dt} = \overrightarrow{d} \times \overrightarrow{E} \]
Stored beam: The radial E-field force is balanced by the centrifugal force.
The proton EDM uses an **ALL-ELECTRIC** ring: spin is aligned with the momentum vector at the magic momentum

\[
 p = \frac{mc}{\sqrt{a}} = 0.7 \ \text{GeV/c}
\]

\[
 p = \frac{mc}{\sqrt{a}} = 15 \text{MeV/c}
\]

for electrons!

\[
\vec{d} \times \vec{E} = \vec{d} \times \vec{E}
\]

\[
\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}
\]
Magnetometer Design

Andrei Matlashov, IBS/CAPP