Storage ring proton EDM experiment and systematic error studies

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Experimental goal

Standard model : $< 10^{-30} - 10^{-31} \text{ e} \cdot \text{cm}$
Experimental limit (n) : $< 7.9 \times 10^{-25} \text{ e} \cdot \text{cm}$
pEDM experiment : $< 10^{-29} \text{ e} \cdot \text{cm}$
Coupling between radial E-field and EDM $\rightarrow$ out-of-plane spin precession.

Polarized beams will be injected at magic momentum into the ring.

Radial E-field will couple with the EDM to cause vertical spin precession.

**Spin precession rate in the ideal case**

$$\frac{d\vec{s}}{dt} = \frac{e}{m} \frac{\eta}{2c} \vec{s} \times \vec{E}$$
Counter-rotating beams.

These counter-rotating beams of a few cm$^2$ cross section will pass through each other continuously.

They will be extracted continuously within 1000s for polarization measurement.

The rate of change in the polarization is proportional to the EDM value (estimated as a few nrad/s for $d_p = 10^{-29}$ and $E_{\text{rad}} = 8\text{MV/m}$).
We have working lattice
500m long electric ring
No magnetic field
8MV/m gradient
Quads in each drift
Beam position monitors (BPMs) in some drifts
Polarimeters in 4 long drifts
Frozen spin method

In the absence of magnetic field

\[
\frac{d\vec{s}}{dt} = \frac{e}{m} \vec{s} \times \left[ \frac{\eta}{2c} \vec{E} - \left( a - \frac{m^2}{p^2} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right]
\]

- The 2\textsuperscript{nd} term determines the horizontal spin component \(s_{xz}\) and it is cancelled at magic momentum: \(p = m/\sqrt{a}\)
- But not all the particles are at magic momentum
- The spread \(s_{xz}\) should not go beyond 90\(^0\)
- We call the time period satisfying this condition as spin coherence time
Spin coherence time (SCT)

- Spin coherence time gets down to ms if the ring is not designed carefully.
- We studied various all-electric ring lattice designs with our home-made high precision Runge-Kutta codes.
- Eventually found out that rings with quad-based alternating focusing give longer spin coherence time than we need.
- This can be further improved using RF cavity.
Ring elements

- **Deflectors**: Stores the beam and probes EDM
- **Quadrupoles**: Focuses the beam
- **RF cavity**: Improves the spin coherence time
- **BPM**: Indirectly measures the radial B-field
- **Polarimeter**: Measures the spin precession rate
- **Sextupoles**: Further improves the spin coherence time
Polarimeter

- Protons scattered by 6cm thick Carbon target
- Extraction will be made by slowly lowering vertical focusing strength
- 99% of the particles lose energy and leave the ring by Coulomb scattering
- 1% of the particles spin-dependent nuclear elastic scattering
- Vertical spin component leads to left-right asymmetry on the detector
- GEM, silicon, micro-megas and multi-resistive plate chambers under consideration

Handling magnetic field

- A major source of systematic error for all EDM experiments
- Most B-field effects cancelled due to the ring design
- The others require shielding, indirect B-field measurement and compensation
- Studies show that it is no more an issue in the pEDM experiment
Sources of B-field

3 major sources of environmental B-field are expected around the ring:

- **Mechanical movements nearby:** Generates a few nT. One-layer magnetic shielding would be sufficient to avoid it.

- **B-field distortions:** Due to magnetic materials nearby.

- **Earth’s field:** The beam sees it mainly as a sinusoidally oscillating field in the rest frame.
B-field leads to vertical spin precession just like the EDM effect.

Vertical component of spin precession rate due to B-field only

\[ \omega_y = \frac{e}{m} a \left[ (s_l B_r - s_r B_l) - \frac{\gamma}{\gamma + 1} (s_l B_{\beta,r} - s_r B_{\beta,l}) \right] \]

- \( r \) and \( l \) indicate radial and longitudinal respectively.
- Both longitudinal (\( s_l \)) and radial (\( s_r \)) spin components are nonzero during the storage.
- So, both \( B_r \) and \( B_l \) contribute the vertical spin precession
- Actually a net \( B_r \) is more critical, since aT level radial B-field and 10 MV/m radial E-field lead to the same vertical spin precession
With static, we mean static at the particle’s rest frame.

For instance earth’s field is oscillating field in the particle’s rest frame.

This feature is very critical to eliminate the effect of the earth’s field.

We investigated the static and oscillating B-field scenarios separately.
Magnetic field simulations

- We studied vertical, longitudinal and radial field configurations.
- Radial and longitudinal B-fields lead to vertical spin precession rate $\omega_y$ just like the EDM signal.
- aT radial B-field is comparable to EDM signal.
- We studied the static and oscillating B-fields with 4th order Runge-Kutta tracking.
- The static field requires continuous measurement and compensation during the storage.
- On the other hand, oscillating B-field is not a problem if we can shield the ring with nT residual field.
  - In some configurations, the CW-CCW design helps avoiding the geometric phase effect.
  - In other configurations the average out-of-plane spin precession is just negligible.
Static radial B-field

- Static radial B-fields lead the CW and CCW beams split vertically.
- This split will lead to net B-field proportional to the field causing it.
- Then, this static B-field will be eliminated in two steps:

1. The beam position monitors (BPM) will measure the field proportional to the split of the beams (SNR $\approx 20$ for $10^{-29}\text{e} \cdot \text{cm}$).
2. Then, inverse magnetic field will be applied for compensation.
SQUID-based BPMs

- Being developed by KRISS (Korea Research Institute of Standards and Science)
- Radial aT B-field can be measured by averaging with \(3\text{fT}/\sqrt{\text{Hz}}\) SQUIDs.
- Should be shielded to nT level.
- The volume is roughly 1m\(^3\).
- Will be delivered by the end of this year.
\[ \omega_a = -13.5 \text{ mrad/s leads to } s_y \approx 70 \text{ prad after 1ms} \]

- \( s_y \) by 50pT longitudinal and vertical DC B-field is much bigger than EDM effect, but there is \( 90^\circ \) phase difference between them:

\[
s_{y}^{EDM} \propto \sin(\omega_a t) \quad ; \quad s_{y}^{BL\&BV} \propto \cos \omega_a t - 1
\]

- So, this effect can be identified from the polarimeter data and cancelled by Helmholtz coils.

- Still, vertical B-field should be kept smaller for longer SPT
Static vertical B-fields

- Vertical B-field does not lead to out-of-plane spin precession.
- But it affects $\omega_a$.
- Therefore, it has indirect effect on $s_y$ if there is also longitudinal B-field.
4 classes of geometric phase effect

- All combinations of perpendicular B-field couples were studied.
- In all simulations the B-field has one oscillation around the ring.
- Running average of $s_y$ falls into one of four classes depending on
  - which perpendicular B-field couples are involved
  - the phase between the perpendicular B-field components
- CW-CCW design solves many systematic errors. It also helps for some geometrical phase cases.
- $B_V = B_L = 1 \text{ nT}$ with $90^\circ$ phase difference.
- $\omega_y > 20 \text{ nrad/s}$, an order of magnitude bigger than the EDM signal.
- The sum of CW and CCW cancels, unlike the EDM signal.
CW an CCW do not cancel this time.

But it oscillates to average out below 50 prad/s in 0.1 s.
• Vertical B-field splits the CW and CCW particles slightly on the horizontal plane.
• Difference in their momentum causes tiny difference in $s_r$, hence $s_y$. This will actually oscillate.
• This effect causes phase difference between CW and CCW. So, the total signal does not cancel immediately, but averages out to $< 50$ prad/s in 0.1s.
Similar to the earlier case, $B_V$ splits the particles
But $\omega_y$ is much less because $B_L$ couples very weakly with $s_r$.
CW and CCW don’t cancel.
Total B-field has negligible linear term
The quadratic term is comparable to the EDM signal at the end of the storage.
Still, the quadratic term can be separated from the linear term in the polarimeter data.
The Storage Ring EDM Collaboration designed an experiment for searching for the proton EDM with $10^{-29}$ e·cm sensitivity.

The critical systematic errors are well understood and addressed.

We are developing prototypes for the BPM, magnetic shielding, polarimeter (at COSY in Germany and CAPP/IBS in Korea), etc.

We are also developing software for handling high precision spin and beam dynamics for many particles in parallel.

Geometric phase is not an issue at all.

A possible EDM measurement will shed light on new physics beyond SM.
Thank you for your attention...
Magnetic shielding

\[ SF = \frac{\text{B-field without shield}}{\text{B-field with shield}} \]

- Characterized by shielding factor (SF) and residual field.
- SF is determined by several parameters
  - Relative permeability (\( \mu \))
  - Material thickness
  - Size
  - Number of layers
  - Separation between the layers
- SF depends on frequency.
- Residual field originates from the shielding material itself.
- Residual field is closely related to degaussing process.
Magnetic shielding

Degaussing

- Magnetic domains orient themselves in the direction of the external field.
- Therefore the magnetic material gets magnetized by earth’s field.
- This orientation can be eliminated by degaussing.
- It is based on applying sinusoidal B-field on the material with a decreasing amplitude.
- This has an effect like shaking the magnetic domains.
- Smooth degaussing signal is essential for small residual field.
Magnetic shielding
Magnetic equilibration

- Degaussing process reorients the magnetic domains in the shielding material in such a way that they oppose the constant external field.
- This effect is called equilibration and cancels the constant field inside.
- After proper degaussing, two-layer shield easily cancels the earth’s field to less than 1nT.
- One-layer shield could also be sufficient for this equilibration. We need to study it.
Magnetic shielding
Prototype

- Two layers of 1mm thickness. 2.25m long, 60 and 65 cm inner diameters.
- Cylinder inside, octagonal outside
- High permeability annealed mu-metal
- Low-noise power amplifier, 16 bit DAC to avoid bit-size effects and a transformer for smooth and DC-free degaussing signal.
Magnetic shielding
Shielding factor measurements

\[ SF = \frac{\text{B-field without shield}}{\text{B-field with shield}} \]

- Depends on frequency
  - \( SF > 600 \) @ 1mHz
  - \( SF > 700 \) @ 10mHz
Magnetic shielding

Residual field

- Originates from the shielding material itself
- Can be minimized by degaussing
- $<0.5$ nT achieved in transverse directions
- The coil distribution on the outer layer is not that important.
- But it should be evenly distributed inside.
Magnetic shielding
Field gradient

- We aim 0.1 nT/m
- The measurement inside could be taken at \( \approx 20 \) cm
- For a rough gradient calculation one can take measurement with 2 cm steps.
- Then, the measurements should be with \( \approx 20 \) pT sensitivity.
- The environment was too noisy for this sensitivity. So we need a magnetic shielding room (MSR).
- Currently we are in construction process of the MSR.
Static B-field

- Static field is symmetric w.r.t. the azimuthal angle.
- For instance one can achieve longitudinal static B-field by having current at the center of the ring (25mA $\rightarrow$ 1nT). It is easy to get, and apparently easy to avoid.
- Static radial field is more difficult to achieve, but EDM experiment requires it to be as low as aT level.
Magnetically Shielded Room

MSR is required for:
- Pretest measurements
- BPM measurements for pEDM
- BPM measurements for g-2/EDM
- Integrated current transformer

It will be used for 2 years.
\[ \vec{\omega} = \frac{e}{m} \vec{s} \times \left[ \left( a \vec{B} - \frac{\gamma a}{\gamma + 1} \vec{\beta}(\vec{\beta} \cdot \vec{B}) - \left( a - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right) ight. \\
\left. + \frac{\eta}{2c} \left( \vec{E} - \frac{\gamma}{\gamma + 1} \vec{\beta}(\vec{\beta} \cdot \vec{E}) + c \vec{\beta} \times \vec{B} \right) \right] \]
Static radial B-field

Radial B-field mimics the radial E-field

\[ B_r \approx \frac{1}{\alpha} \frac{\eta}{2c} E_r = \frac{1}{1.8} \times \frac{2 \times 10^{-15}}{2 \times 3 \times 10^8} \times 10.5 \times 10^6 \approx 2 \times 10^{-17} \text{ T} \]

- Average \( B_r \) along the ring should be kept at \( \alpha T \) level
- We will do this by continuously measuring the field by means of vertical beam split and cancel by Helmholtz coils.
Neglecting $B_r$;

Vertical spin component

\[ s_y(t) = \frac{eaB_l}{m\omega_a} \left( 1 - \frac{\gamma \beta^2}{\gamma + 1} \right) \left( \cos(\omega_a t) - 1 \right) \]

- $s_y$ is mainly determined by $\omega_a$
- $\omega_a$ is related to the spin coherence time (SCT) and determined by ring design, particle momentum and vertical B-field
- We are aiming $\omega_a < 1$ mrad/s.
There could be many sources of oscillating B-field. Earth’s field is one of them.

The particle sees the earth’s field as longitudinal (red) and radial (blue) components.

Both components make one oscillation around the ring in the particle’s rest frame. And it averages to zero after one revolution.

There may be phase difference between the perpendicular field components.
Geometric phase effect

- At first glance alternating B-field seems harmless since it averages to zero.
- But some B-field configurations lead to geometric phase effect.
- In those cases, the residual amount of $s_y$ in each cycle accumulates to mimic the EDM effect.
- Conceptually this resembles to the Rubick’s cube.
- All the simulations in this section were made with 1nT B-fields.
Amount of the vertical split

Beam separation due to the radial DC B-field

\[ \Delta y(\theta) = 2 \sum_{N=0}^{\infty} \frac{\beta c R_0 B_{rN}}{E_r (Q_y^2 - N^2)} \cos(N \theta + \varphi_N) \]

- \( N = 0 \) (DC B-field)
- \( R_0 = 96 \) m
- \( E_r = 3.5 \) MV/m
- \( v = 1.8 \times 10^8 \) m/s
- \( Q_y = 0.4 \)
- \( B_r = 6 \) aT

Beam separation should be \( \Delta y < 4 \) pm
B-field induced by the beams

B-field sensitivity

\[ \Delta y = 4 \text{pm beam separation} \]

- 2.5 mA current,
- at \( r = 2 \text{cm} \) from the pickup loop
- modulated at about \( \omega_m = 1 \text{ kHz} \)
  with modulation amplitude \( A = 0.1 \)

\[
B_x(r, \omega_m) = \frac{2 \mu_0 I \Delta y A \cos(\omega_m t)}{\pi r^2} \approx 2.5 \cos(\omega_m t) \text{ aT}
\]
**Average measurement**

Measurement of induced B-field using SQUID gradiometer

\[ B_x = 2.5 \text{ aT induced at the pickup coil} \]

- SQUIDs can measure about 3 fT/√Hz.
- 100 BPMs → noise = 0.3 fT.
- \(10^3\) s for storage → 9.5 aT
- \(10^4\) injections → 9.5 \(\times 10^{-2}\) aT
  → S/N > 25

So, the SQUIDs measure the DC component and Helmholtz coils compensate.