Magnetic field cancellation in pEDM experiment

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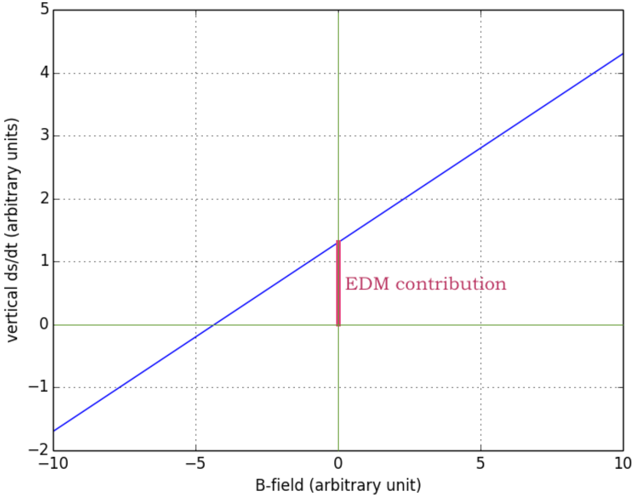
Magnetic field in pEDM ring

- A major source of systematic error for all EDM experiments
- We made analytical and numerical studies
- We have well defined procedures for cancellation of B-field components separately
- Thanks to the ring design, geometric phase is not an issue at all

EDM contribution

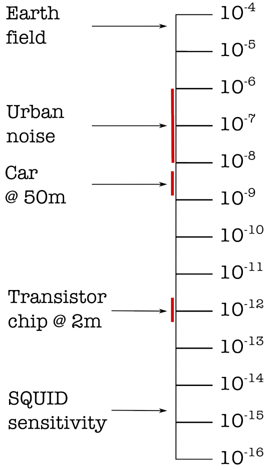
- ds_y/dt from polarimeter, B_r from BPM
- Reading at $B_r = 0$ corresponds to EDM



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 and vertical spin precession

- B-field leads to vertical spin precession just like the EDM effect.

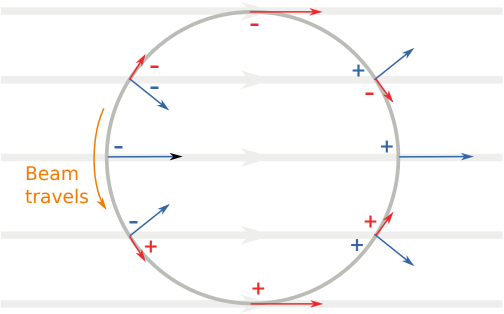
Vertical component of spin precession rate due to B-field

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

- 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 8 MV/m radial E-field lead to comparable vertical spin precessions

Static vs oscillating B-field

- With static, we mean static at the particle's rest frame.
- For instance earth's field is oscillating in particle's rest frame.
- This feature is very critical to understand the elimination of the effect of the earth's field
- We investigated the static and oscillating B-field scenarios separately.

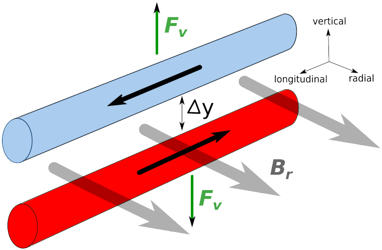


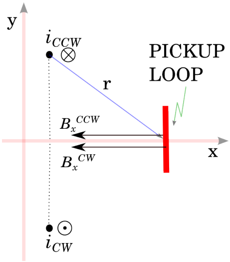
Static radial B-field

Beam split

- 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
2. Then, inverse magnetic field will be applied for compensation.

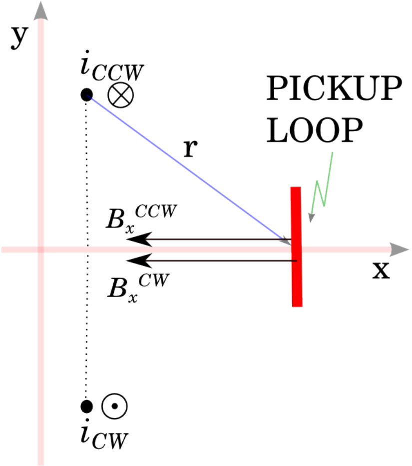




Static radial B-field

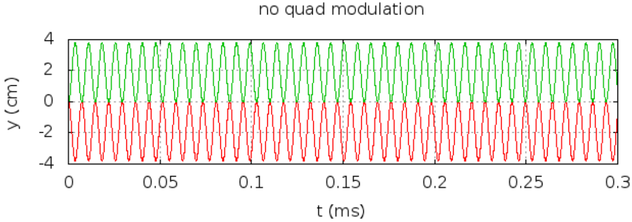
Measurement

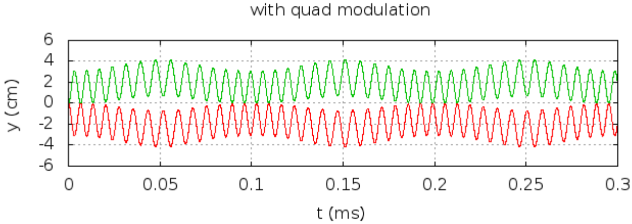
- Both CW & CCW beams induce horizontal B-field at the pickup location



Static radial B-field

Modulation of quads

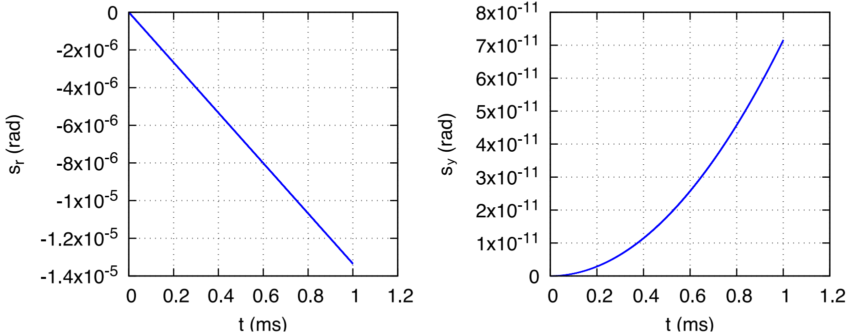




- The separation is proportional to the radial B-field
- The BPM will pick the signal at modulation frequency

Static longitudinal B-field

- Can emerge from currents inside the ring (25 mA → 1nT)
- Leads to s_y if there is on-plane spin precession
- 90° phase difference between EDM signal and this effect
- Can be identified from the polarimeter data and cancelled by Helmholtz coils
- Still, current should be avoided at the inner side of the ring
- Becomes much smaller with long SCT

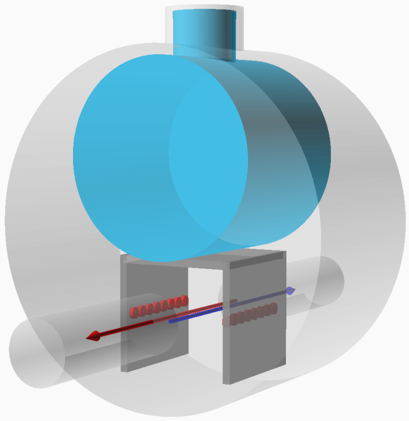


Static vertical B-fields

- Vertical B-field does not lead to out-of-plane spin precession.
- But it affects SCT.
- Therefore, it has indirect effect on s_y if there is also longitudinal B-field.

SQUID-based BPMs

- For radial and vertical B-field components
- Vertical one doesn't need to be too sensitive
- For radial, 10 stations (each with 8 sensors) yield ≈ 20 SNR over 10^7 seconds
- Will be delivered soon
- More details in Andrei Matlashov's talk



Geometric phase effect

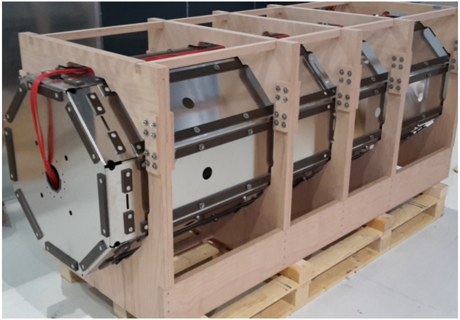
- Simulations show 4 classes of geometric phase effect (Details in spin tracking talk)
- In all cases the effect is negligible:
  1. average out
  2. CW & CCW cancel
  3. negligible linear rate
- Shielding requirement is no stricter than a few nT

- Geometric phase is not an issue

Magnetic shielding

Prototype

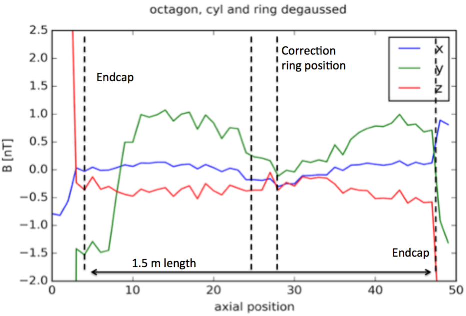
- Designed by Peter Fierlinger from TUM
- Two layers of 1mm thickness. 2.25m long, 60 and 65 cm inner diameters.
- Cylinder inside, octagonal outside
- High permeability annealed mu-metal
- More details in Peter Fierlinger's talk



Magnetic shielding

Residual field

- Originates from the shielding material itself
- Can be minimized by degaussing
- < 0.5 nT and < 2 nT/m achieved in transverse directions
- The coil distribution on the outer layer is not that important.
- But it should be evenly distributed inside.



Summary

- We made analytical and numerical studies on B-field
- The issues with B-field are well understood and addressed
- Most B-field effects cancelled thanks to the ring design
- The others require shielding to a few nT level and further compensation with Helmholtz coils inside the vacuum chamber.
- Studies show that geometric phase is not an issue in the pEDM experiment
- We are currently working on BPM development integrated with a magnetic shield for pEDM ring

Thank you for your attention...

Additional slides

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
- $v = 1.8\text{x}10^8$ m/s
- $Q_y = 0.4$
- $B_r = 6$ aT

Beam separation should be $\Delta y < 4$ pm

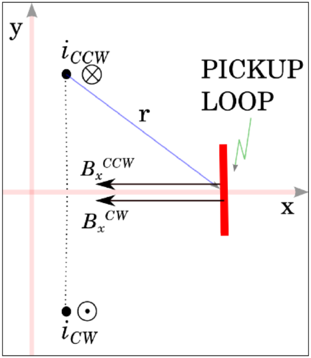
B-field induced by the beams

B-field sensitivity

Δy = 4pm beam separation

- 2.5 mA current,
- at r=2cm from the pickup loop
- modulated at about ω_m=1 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

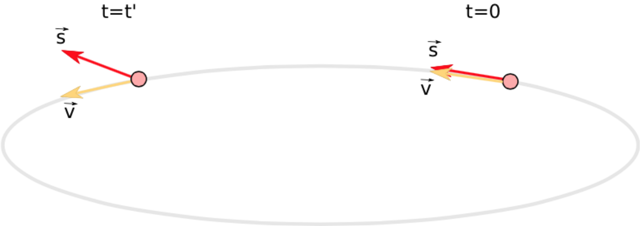
$B_x = 2.5$ aT induced at the pickup coil

- 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 x10^{-2} aT
  → S/N > 25

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

pEDM experiment

- Coupling between radial E-field and EDM $\longrightarrow$ 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.

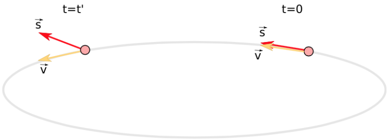


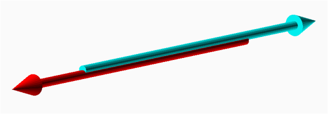
Spin precession rate in the ideal case

$$\frac{d\vec{s}}{dt} = \frac{e}{m}\frac{\eta}{2c}\vec{s} \times \vec{E}$$

pEDM experiment

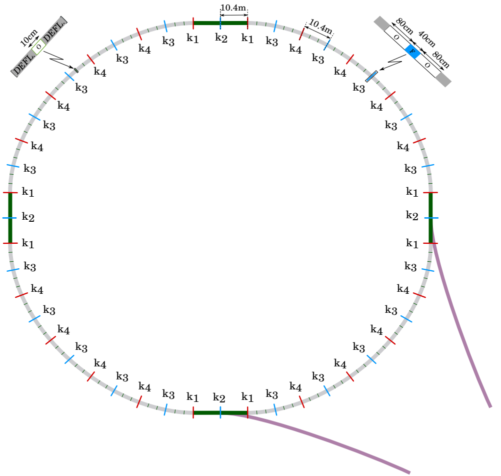
- Counter-rotating beams.
- These counter-rotating beams of a few cm^2 cross section will pass through each other continuously.
- They will be extracted continuously within 1000s for polarization measurement.
- The rate of change in the polarization is proportional to the EDM value (estimated as a few nrad/s for $d_p = 10^{-29}$ and $E_{\text{rad}} = 8\text{MV/m}$).





pEDM ring

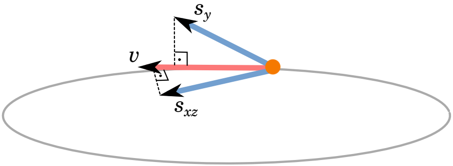
- We have working lattice
- 500m long electric ring
- No magnetic field
- 8MV/m gradient
- Quads in each drift
- Beam position monitors (BPMs) in some drifts
- Polarimeters in 4 long drifts



Frozen spin method

In the absence of magnetic field

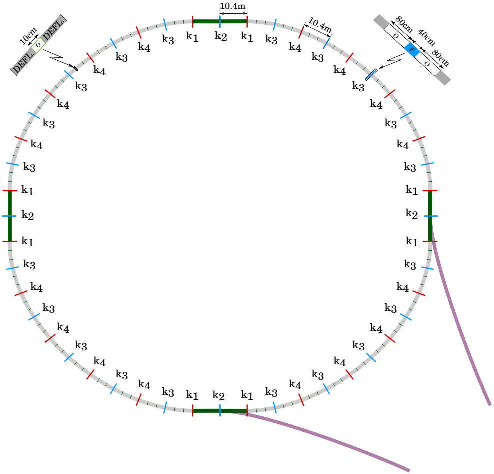
$$\frac{d\vec{s}}{dt} = \frac{e}{m}\vec{s} \times \left[\frac{\eta}{2c}\vec{E} - \left(a - \frac{m^2}{p^2}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right]$$



- The 2nd 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)

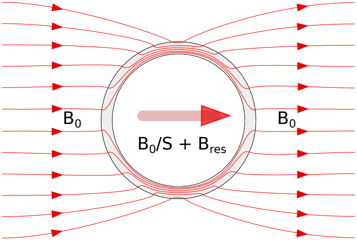
- Spin coherence time gets down to ms if the ring is not designed carefully
- We studied various all-electric ring lattice designs with our home-made high precision Runge-Kutta codes
- Eventually found out that rings with quad-based alternating focusing give longer spin coherence time than we need
-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



Magnetic shielding

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

- Characterized by shielding factor (SF) and residual field.
- SF is determined by several parameters
  - Relative permeability (μ)
  - Material thickness
  - Size
  - Number of layers
  - Separation between the layers

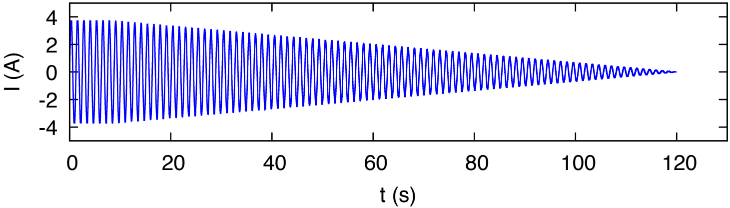


- SF depends on frequency.
- Residual field originates from the shielding material itself.
- Residual field is closely related to degaussing process.

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

Shielding factor measurements

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

- Depends on frequency
  - SF>600 @ 1mHz
  - SF>700 @ 10mHz

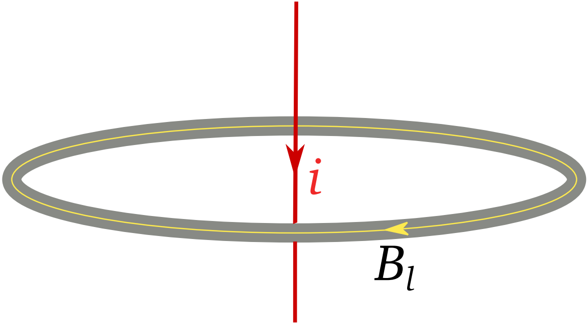
Magnetic shielding

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 2cm 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 symmetic 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 → 1nT). It is easy to get, and apparently easy to avoid.
- Static radial field is more difficult to achive, but EDM experiment requires it to be as low as aT level.



T-BMT equation

$$\vec{\omega} = \frac{e}{m}\vec{s} \times \left[\left(a\vec{B} - \frac{\gamma a}{\gamma + 1}\vec{\beta}(\vec{\beta} \cdot \vec{B}) - \left(a - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right) \right.$$
$$\left. + \frac{\eta}{2c} \left(\vec{E} - \frac{\gamma}{\gamma + 1}\vec{\beta}(\vec{\beta} \cdot \vec{E}) + c\vec{\beta} \times \vec{B} \right) \right]$$

Static radial B-field

Radial B-field mimics the radial E-field

$$B_r \approx \frac{1}{a}\frac{\eta}{2c}E_r = \frac{1}{1.8} \times \frac{2 \times 10^{-15}}{2 \times 3 \times 10^{8}} \times 10.5 \times 10^{6} \approx 2 \times 10^{-17}\ \mathrm{T}$$

- Average B_r along the ring should be kept at aT level
- We will do this by continuously measuring the field by means of vertical beam split and cancel by Helmholtz coils.

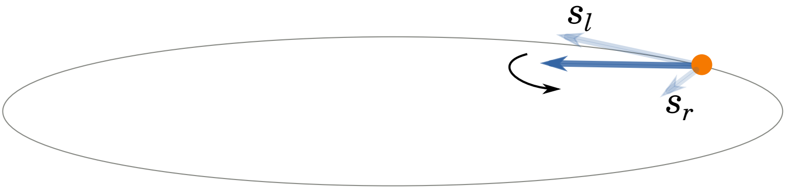
Static longitudinal B-field (1)

Neglecting B_r;

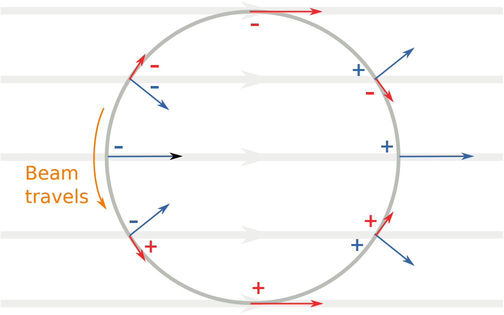
Vertical spin component

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

- s_y is mainly determined by ω_a
- ω_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.



Oscillating B-field



- 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

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.