Storage ring proton EDM experiment and systematic error studies

Physics of Fundamental Symmetries and Interactions
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Selcuk Haciomeroglu
On Behalf of the pEDM Collaboration

Center for Axion and Precision Physics
Institute for Basic Science
Korea

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Institute for Basic Science
기초과학연구원
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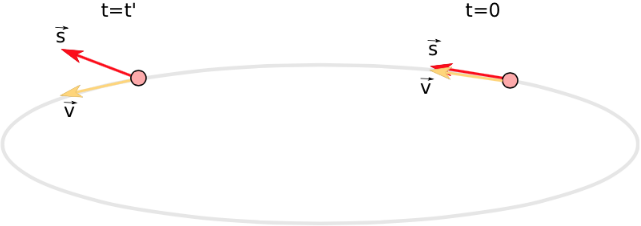
Center for Axion and Precision Physics Research

Experimental goal

Standard model	:	$< 10^{-30} - 10^{-31}$ e · cm
Experimental limit (n)	:	$< 7.9 \times 10^{-25}$ e · cm
pEDM experiment	:	$< 10^{-29}$e · cm

pEDM experiment

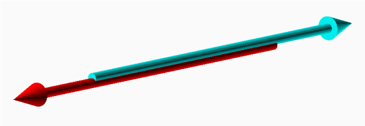
- Coupling between radial E-field and EDM $\longrightarrow$ out-of-plane spin precession.
- Polarized beams will be injected at magic momentum into the ring.
- Radial E-field will couple with the EDM to cause vertical spin precession.



Spin precession rate in the ideal case

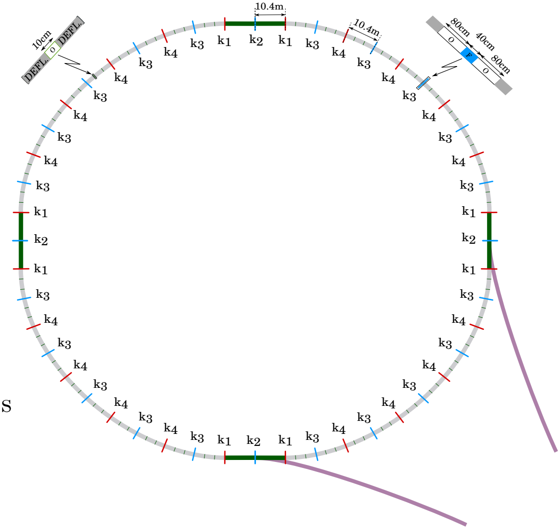
$$\frac{d\vec{s}}{dt} = \frac{e}{m}\frac{\eta}{2c}\vec{s} \times \vec{E}$$

- 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 $E_{\rm rad} = 8$MV/m).



pEDM ring

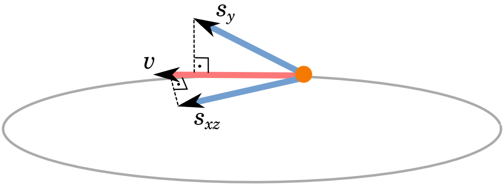
- We have working lattice
- 500m long electric ring
- No magnetic field
- 8MV/m gradient
- Quads in each drift
- Beam position monitors (BPMs) in some drifts
- Polarimeters in 4 long drifts



Frozen spin method

In the absence of magnetic field

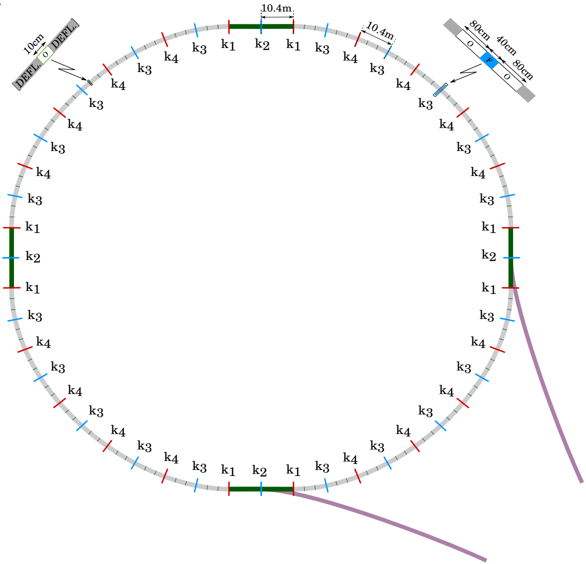
$$\frac{d\vec{s}}{dt} = \frac{e}{m}\vec{s} \times \left[\frac{\eta}{2c}\vec{E} - \left(a - \frac{m^2}{p^2}\right)\frac{\vec{\beta} \times \vec{E}}{c} \right]$$



- 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

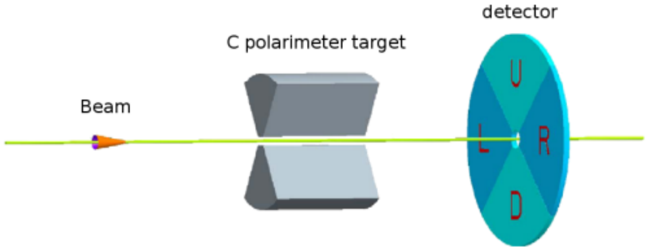


Ring elements

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



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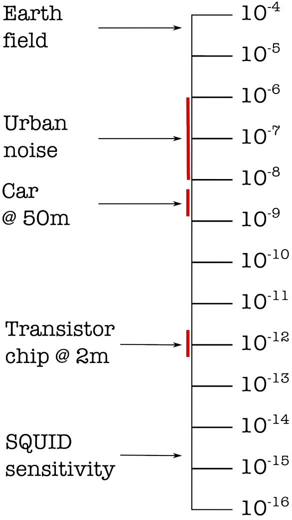
Handling magnetic field

- 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 and vertical spin precession

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

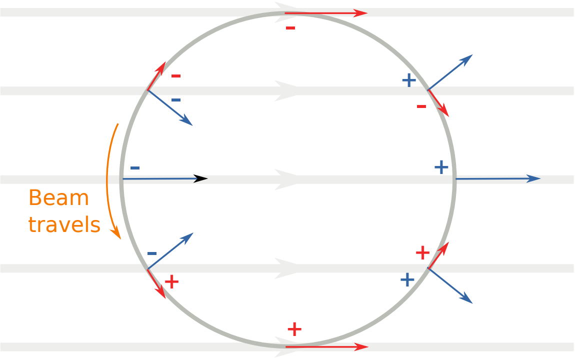
Vertical component of spin precession rate due to B-field only

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

- 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

Static vs oscillating B-field

- 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.



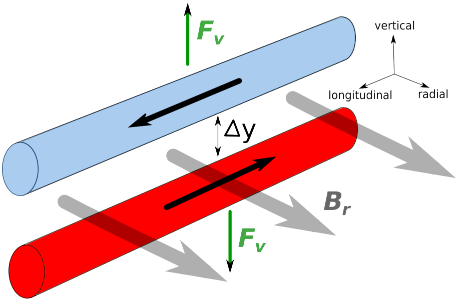
Magnetic field simulations

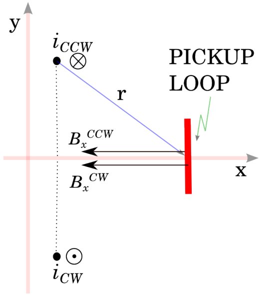
- We studied vertical, longitudinal and radial field configurations
- Radial and longitudinal B-fields lead to vertical spin precession rate ω_y just like the EDM signal.
- aT radial B-field is comparable to EDM signal
- We studied the static and oscillating B-fields with 4^{th} order Runge-Kutta tracking.
- 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:

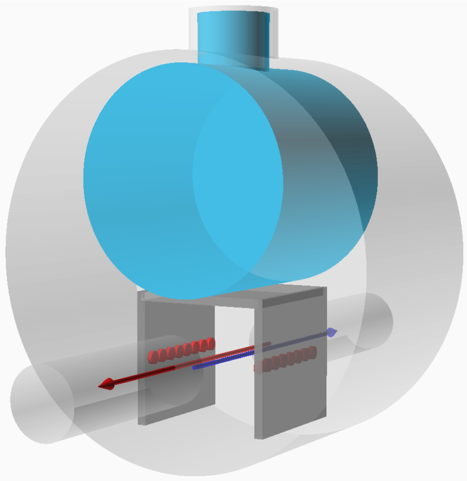
1. The beam position monitors (BPM) will measure the field proportional to the split of the beams (SNR ≈ 20 for 10^{-29}e·cm)
2. Then, inverse magnetic field will be applied for compensation.



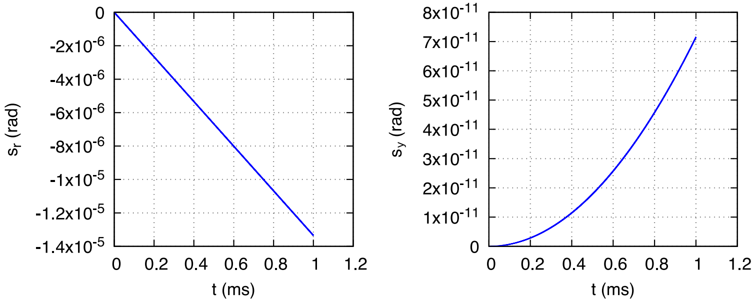


SQUID-based BPMs

- Being developed by KRISS (Korea Research Institute of Standards and Science)
- Radial aT B-field can be measured by averaging with $3fT/\sqrt{Hz}$ SQUIDs.
- Should be shielded to nT level.
- The volume is roughly $1m^3$.
- Will be delivered by the end of this year.



Static longitudinal B-field



- $\omega_a = -13.5$ mrad/s leads to $s_y \approx 70$ prad after 1ms
- s_y by 50pT longitudinal and vertical DC B-field is much bigger than EDM effect, but there is 90^0 phase difference between them:

$$s_y^{EDM} \propto \sin(\omega_a t) \qquad ; \qquad s_y^{B_L \& B_V} \propto \cos\omega_a t - 1$$

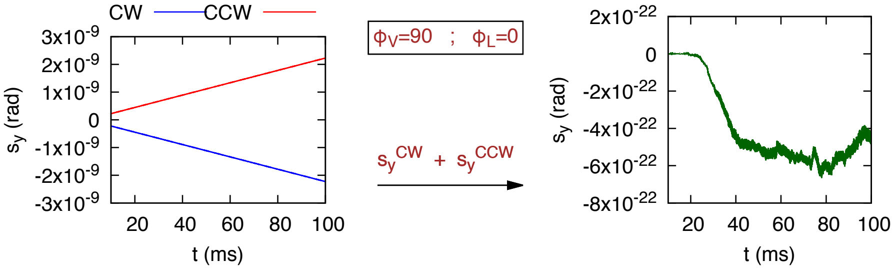
- So, this effect can be identified from the polarimeter data and cancelled by Helmholtz coils.
- Still, vertical B-field should be kept smaller for longer SPT

Static vertical B-fields

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

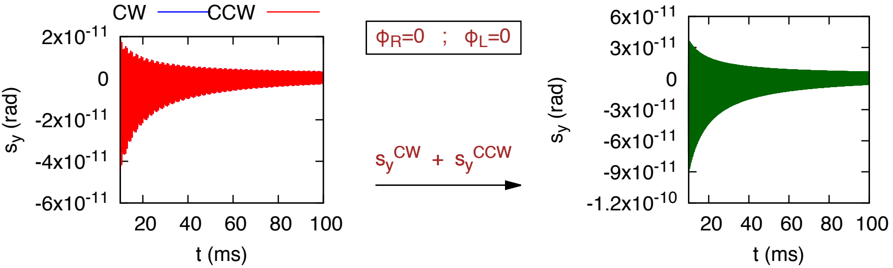
4 classes of geometric phase effect

- 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.

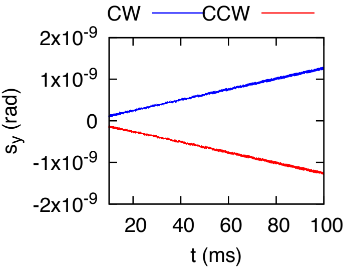


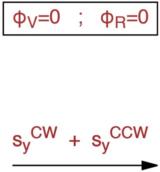
- $B_V = B_L = 1$ nT with 90^0 phase difference.
- $\omega_y > 20$ nrad/s, an order of magnitude bigger than the EDM signal.
- The sum of CW and CCW cancels, unlike the EDM signal.

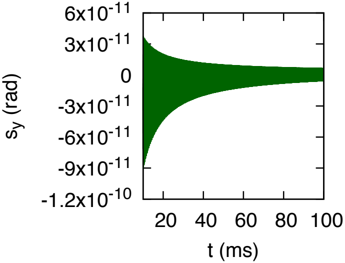
Class II



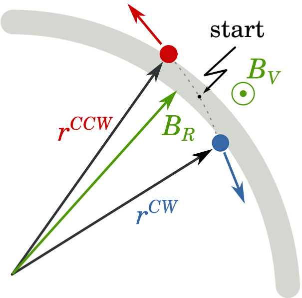
- CW an CCW do not cancel this time.
- But it oscillates to average out below 50 prad/s in 0.1 s.



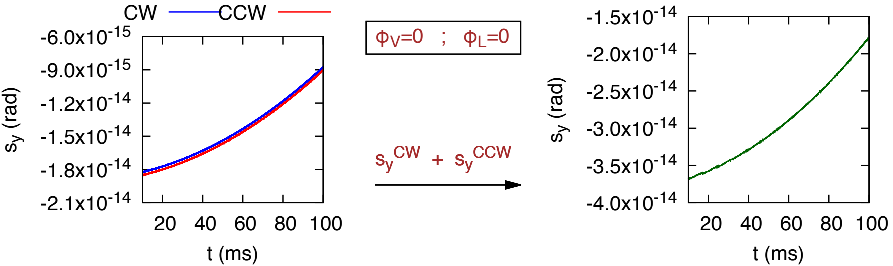




- Vertical B-field splits the CW and CCW particles slightly on the horizontal plane.
- Difference in their momentum causes tiny difference in s_r, hence s_y. This will actually oscillate.
- This effect causes phase difference between CW and CCW. So, the total signal does not cancel immediately, but averages out to < 50 prad/s in 0.1s .



Class IV



- Similar to the earlier case, B_V splits the particles
- But ω_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.

Summary

- 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.

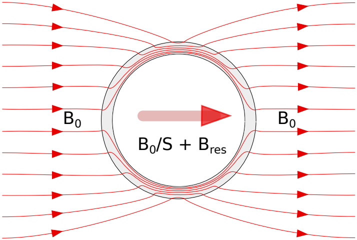
Thank you for your attention...

Additional slides

Magnetic shielding

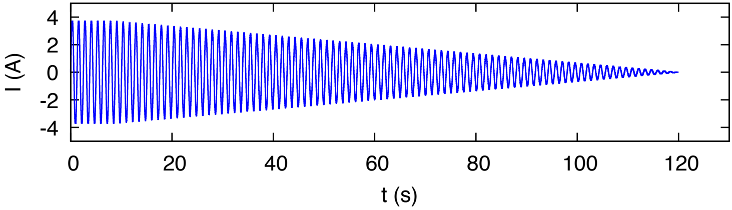
$$\text{SF} = \frac{\text{B-field without shield}}{\text{B-field with shield}}$$

- 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 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.

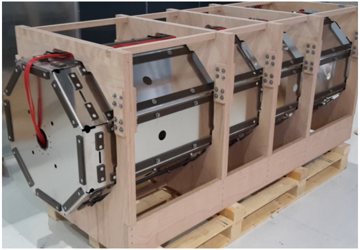


- Degaussing process reorients the magnetic domains in the shielding material in such a way that they oppose the constant external field.
- This effect is called equilibration and cancels the constant field inside.
- After proper degaussing, two-layer shield easily cancels the earth's field to less than 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.



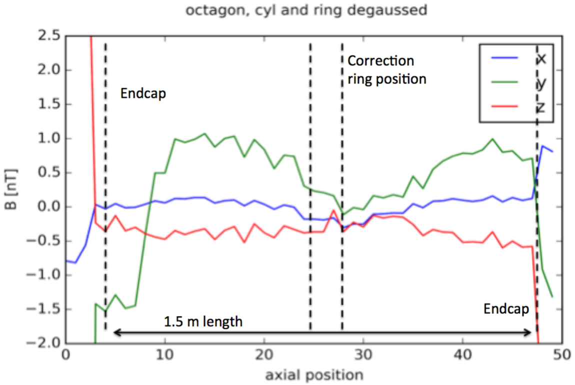
$$\mathrm{SF} = \frac{\text{B-field without shield}}{\text{B-field with shield}}$$

- 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.



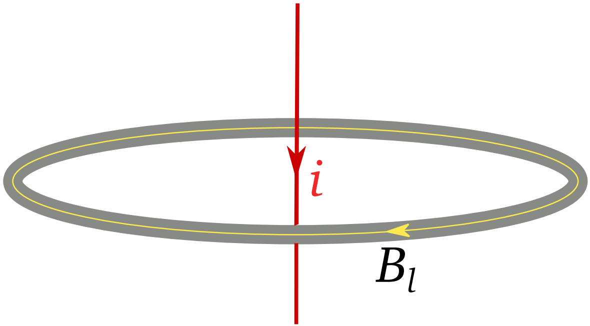
Magnetic shielding

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 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 $\rightarrow$ 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.

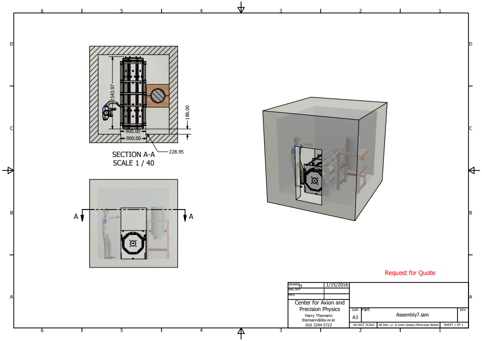


Magnetically Shielded Room

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.



T-BMT equation

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

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.

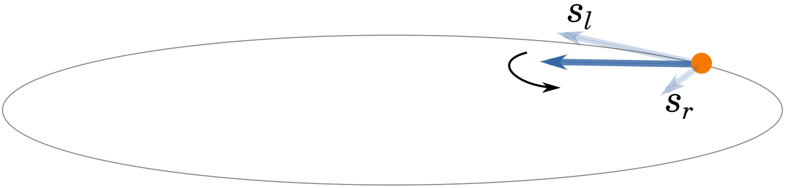
Static longitudinal B-field (1)

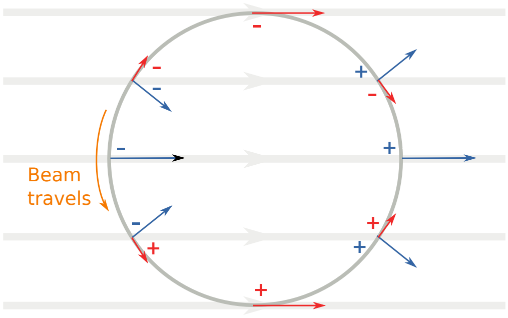
Neglecting B_r;

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.

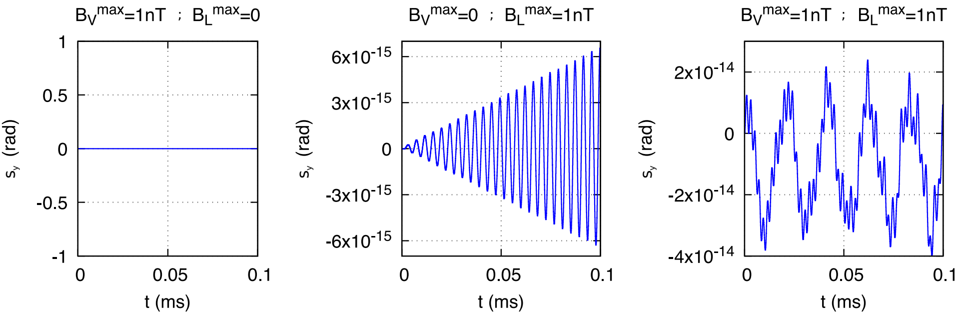




- There could be many sources of oscillating B-field. Earth's field is one of them.
- The particle sees the earth's field as longitudinal (red) and radial (blue) components.
- Both components make one oscillation around the ring in the particle's rest frame. And it averages to zero after one revolution.
- 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
- $v = 1.8\text{x}10^8$ m/s
- $Q_y = 0.4$
- $B_r = 6$ aT

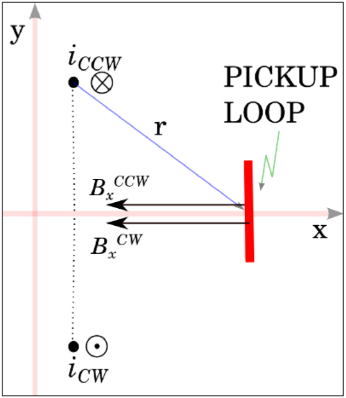
Beam separation should be $\Delta y < 4$ pm

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.