Spin tracking studies for pEDM experiment

EDM Kickoff meeting @ CERN

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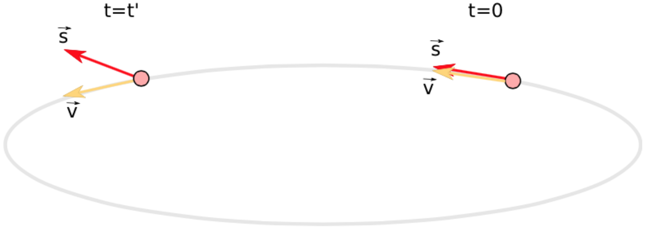
Where are we?

- We studied pEDM ring with a home-made Runge-Kutta tracking program
- The studies are still going on
- We understood and addressed the major issues including SCT and geometric phase
- This talk gives a brief overview of previous achievements and some of the current efforts

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.

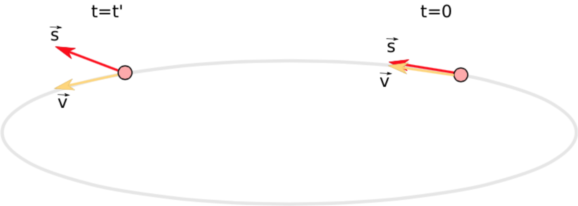


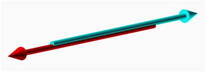
Spin precession rate in the ideal case

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

pEDM experiment

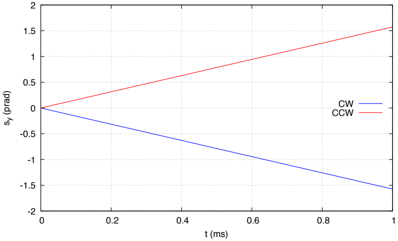
- Counter-rotating beams.
- These counter-rotating beams of a few cm^2 cross section (low luminuosity) will pass through each other continuously.
- They will be scraped continuously within 1000s for polarization measurement.
- The vertical rate of change in the polarization (ω_y) is proportional to the EDM value (estimated as a few nrad/s for $d_p = 10^{-29}$ and $E_{\mathrm{rad}} = 8\mathrm{MV/m}$).
- Ring parameters given at Review of Scientific Instruments 87, 115116 (2016)





EDM signal

- $\omega_y \equiv \frac{ds_y}{dt}$ = a few nrad/s for $10^{-29}\mathrm{e}\cdot\mathrm{cm}$
- ω_y's in opposite direction for counter-rotating particles if initially spin is in direction of momentum



T-BMT Equation

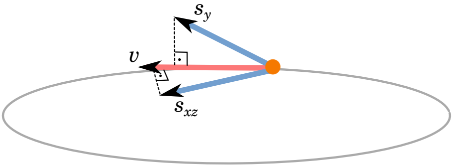
$$\vec{\omega} = \frac{e}{m}\vec{s} \times \left[\left(a\vec{B} - \frac{\gamma a}{\gamma + 1}\vec{\beta}(\vec{\beta} \cdot \vec{B}) - \left(a - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right) + \frac{\eta}{2c} \left(\vec{E} - \frac{\gamma}{\gamma + 1}\vec{\beta}(\vec{\beta}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

- B-field should be zero
- vertical spin precession comes from
  - EDM term
  - various configurations of $\vec{s} \times (\vec{\beta} \times \vec{E})$ (potential sys. error)

Frozen spin method

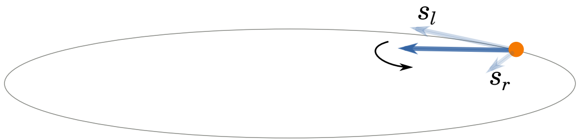
In the absence of magnetic field

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

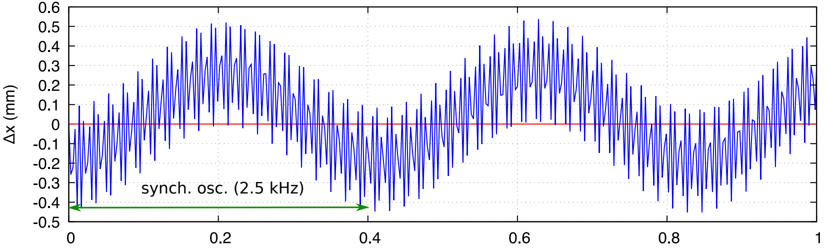


- The 2^{nd} term determines the horizontal spin component s_{xz} and it is cancelled at magic momentum: $p_m = m/\sqrt{a}$
- But not all the particles are at magic momentum
- The spread s_{xz} should not go beyond 90^0
- We call the time period satisfying this condition as spin coherence time

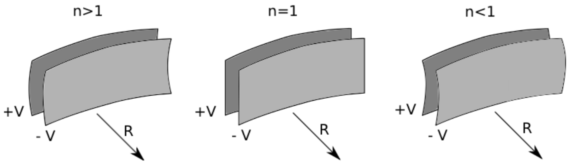
Spin coherence time (SCT)



- Almost no particle will be at p_m
- But SCT should be OK if they oscillate around p_m
- That is, the beam should oscillate around the design orbit
- This is closely related to focusing
- Enhanced with RF cavity

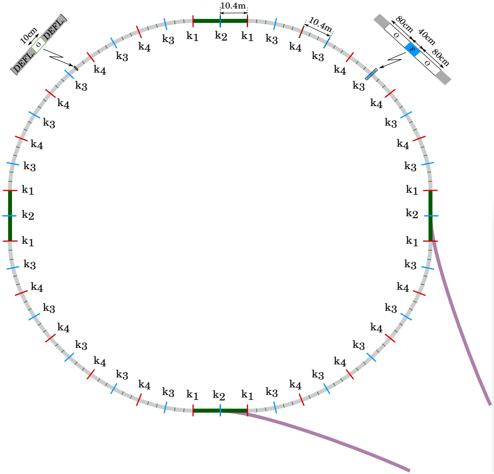


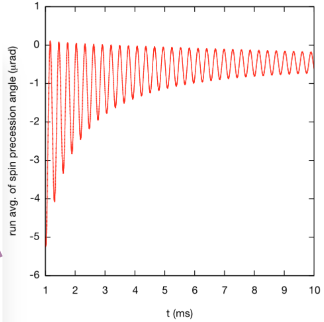
Focusing



- Weak focusing ring
  - Field index is determined by shape of plates
  - Hard to manufacture plates with small field index
  - Simulations yielded ≈ 100 s SCT with RF cavity
  - SCT improves by using deflectors with alternating field indices
- Alternating gradient ring
  - Flat cylindrical plates with with quadrupoles in between
  - Quadrupoles change sign in consequent sections
  - High SCT

Alternating gradient ring





SCT becomes > 10^4 with relatively weak quads

Working lattice

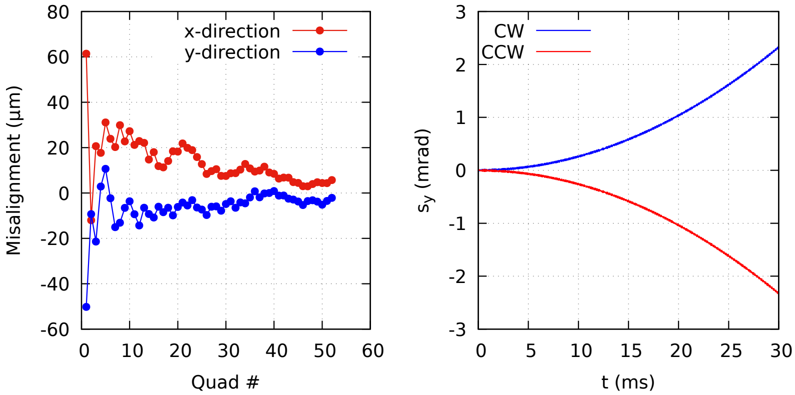
V. Lebedev from Fermilab designed a working lattice with alternating gradient design

Main parameters

Beam energy	232.792 MeV
Circumference	500 m
Qx/Qy	2.42/0.44
Number of super-periods	4
FODO sells per super period	6
FODO sell length	20.83333 m
Number of arcs	4
Sells per arc	5
Number of straights	4
Sells per straight	1
Bends per half cell	3
Bending radius	52.3089
Gap	3 cm
Bending voltage	±120 kV
Slip-factor, $\eta = \alpha - 1/\gamma^2$	-0.192

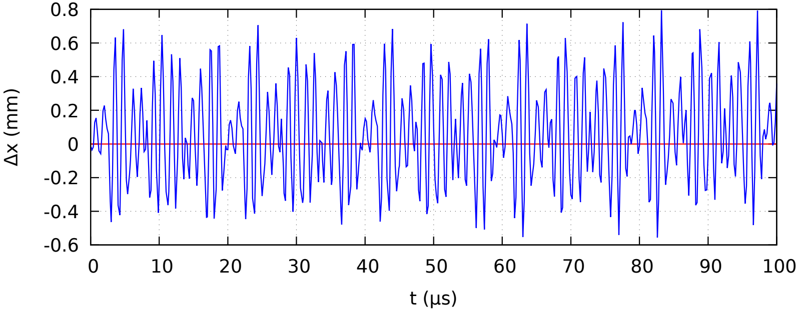
Quad misalignment - random case

- All quads are misaligned by a random amount ($< 100\mu$m)
- Average misalignment is not zero. It is $\approx 5\mu$m in both directions
- Approximately equivalent to all quads misaligned by 5μm
- This shifts the particle from the design orbit considerably



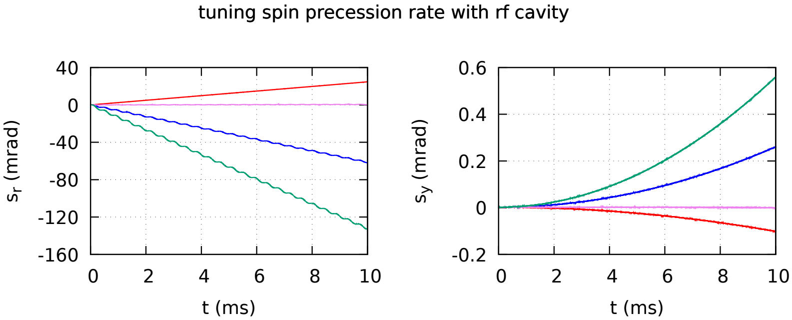
Quad misalignment - random case

- The main source of this vertical spin precession is essentially the radial offset w.r.t the design orbit
- $\Delta x \quad \rightarrow \quad \Delta p/p_m \quad \rightarrow \quad \omega_a \quad \rightarrow \quad s_y$



Quad misalignment - random case

- $\Delta p/p_m$ can be fixed by tuning RF cavity

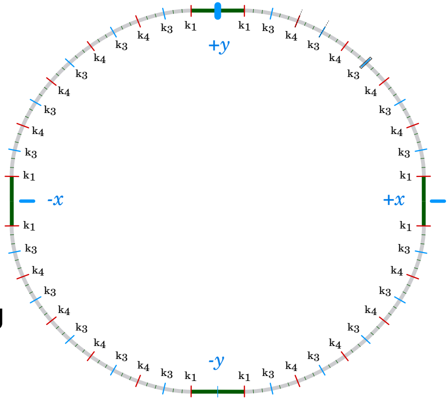


Quad misalignment - random case

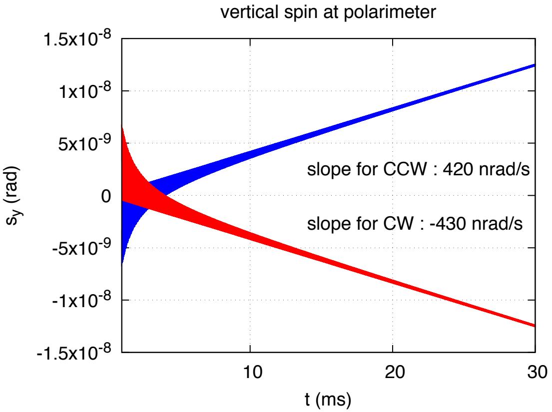
- The effect also changes quadratically with quad offset.
- They may be corrected by using beam-based alignment

Quad misalignment - geometric phase effect

- The average quad misalignment is zero
- But there is an accumulative effect due to non-commutation
- 90^0 configuration gives the biggest effect
- The four quads are misaligned by 100μm

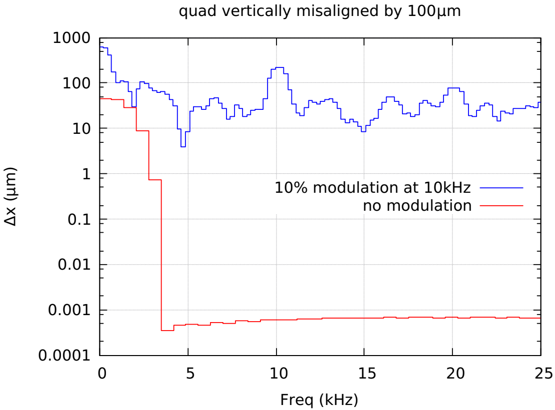


Quad misalignment - geometric phase effect



- The spin precession rate is similar to the EDM signal, 2 orders of magnitude bigger !
- Quadratically depends on quad strength
- Beam-based alignment may solve the issue

Beam-based alignment

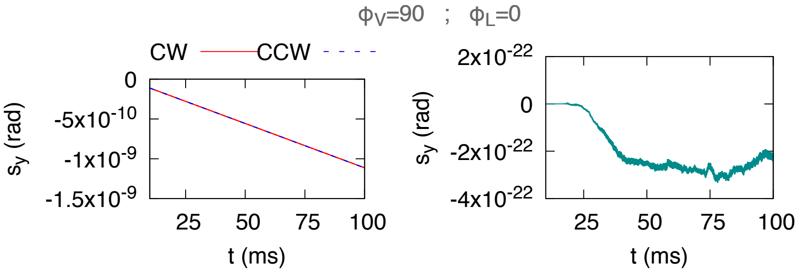


- One of the quads is modulated at 10kHz
- Peak shows up at the radial position data
- The achievable precision should be investigated

4 classes of geometric phase effect

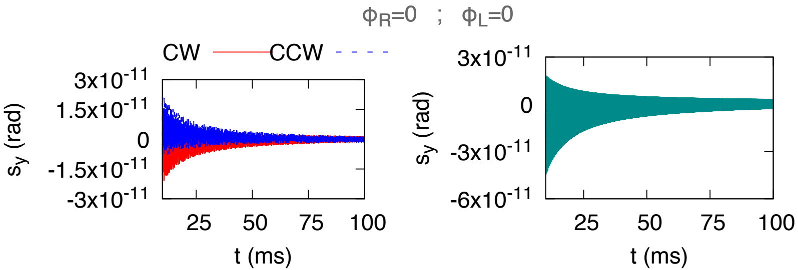
- All combinations of perpendicular B-field couples were studied.
- In all simulations the B-field has one oscillation around the ring
- Running average of s_y falls into one of four classes depending on
  - which perpendicular B-field couples are involved
  - the phase between the perpendicular B-field components
- As with many systematic errors, CW-CCW design also helps for some geometrical phase cases.

Class I



- $B_V = B_L = 1$ 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.

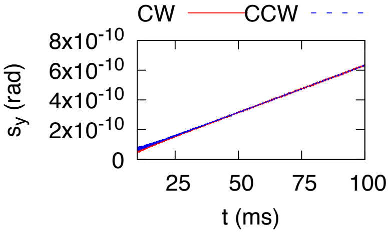
Class II

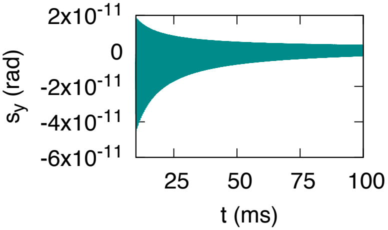


- CW an CCW do not cancel this time.
- But it oscillates to average out below 50 prad/s in 0.1 s.

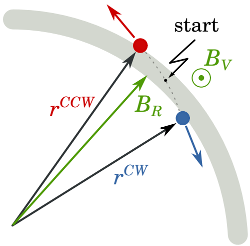
Class III

$\phi_V=0 \;\; ; \;\; \phi_R=0$

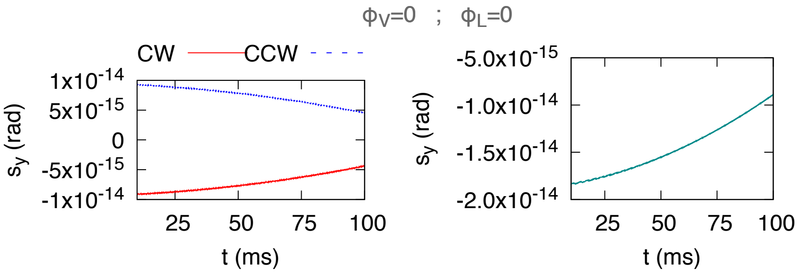




- Vertical B-field splits the CW and CCW particles slightly on the horizontal plane.
- Difference in their momentum causes tiny difference in s_r, hence s_y. This will actually oscillate.
- This effect causes phase difference between CW and CCW. So, the total signal does not cancel immediately, but averages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



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

- Long SCT is achievable with certain lattice designs
- Quad misalignment seems to be solvable
- Geometric phase of magnetic field is not an issue