Quad Misplacement studies for the pEDM rings

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Outline

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

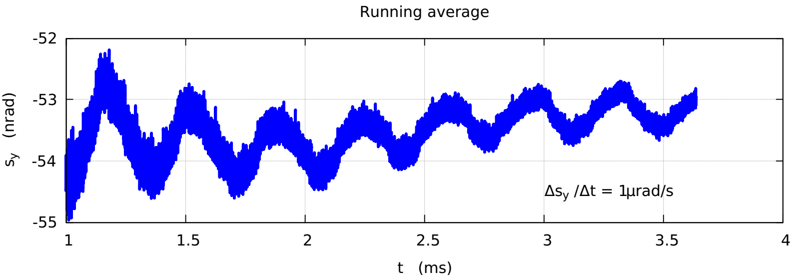
- We aim to measure the spin precession rate around radial axis (in other words, vertical spin component : s_y)
- There are several terms to change s_y
- $(\eta/2c)E_r$ is the EDM effect
- $s_l(G + 1/2)B_r$, $s_l\beta_l E_y$, $s_r\beta_y E_r$, etc. are all systematic error sources
- This work is about the ones with E-field term

Quadrupole misplacement

- A vertically misplaced quad (100μm) causes a vertical kick as well as a change in s_y because of $s_l \beta_l E_y$ and $s_r \beta_r E_y$.
- This effect was mentioned in several talks in the kick-off meeting (March 2017)
- In fact E_y has a direct effect only in case of geometrical phase, because if averages to zero.
- However, simulations with one vertically misplaced quad show accumulation of s_y. This is an indirect effect of E_y.

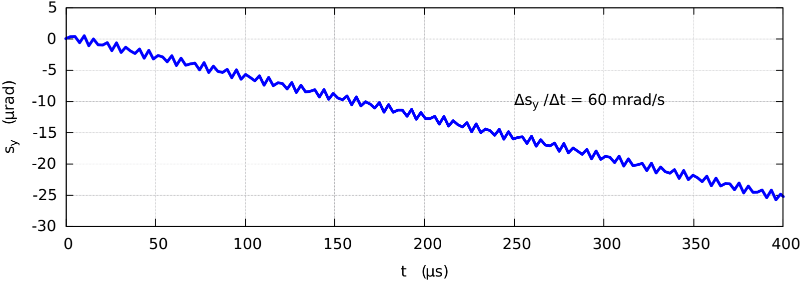
Simulations with pEDM prototype ring - 1

- Designed by Sig Martin
- FODO lattice with two long (≈ 25 m) straight sections
- One quad misplaced by 100 μm vertically.
- Initially spin is parallel to the momentum



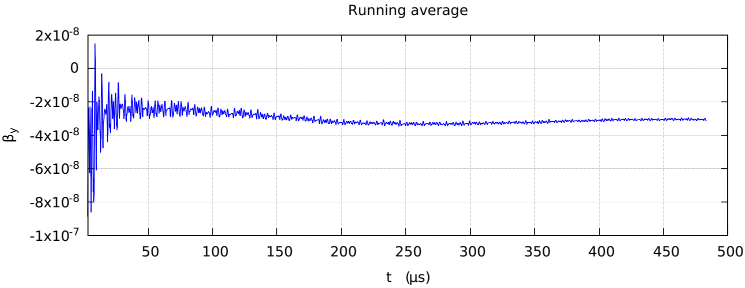
Simulations with pEDM prototype ring - 2

- s_y grows even faster if the spin has initial horizontal component



Simulations with pEDM prototype ring - 3

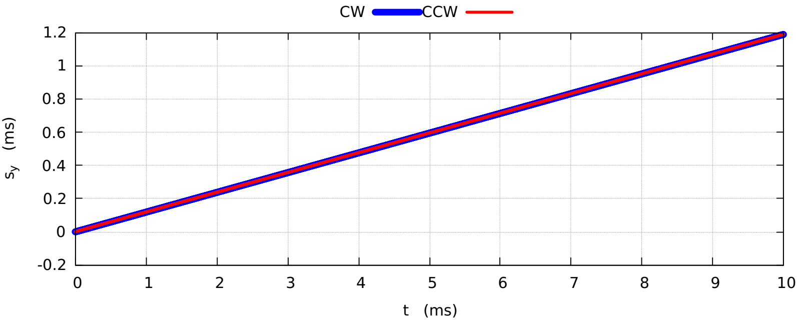
- It turns out that the effect comes from the deflectors: $s_r \beta_y E_r / c$



$$\frac{L_{def}}{L_{ring}} \frac{s_r \beta_y E_r}{c} \approx 0.57 \times \frac{0.5 \times 3.2 \times 10^{-8} \times 10^{7}}{3 \times 10^{8}} \approx 0.3nT$$

- 10^{-17} T → 2 nrad/s
  3×10^{-10} T → 60 mrad/s
- Consistent with spin tracking result

CW-CCW cancelation



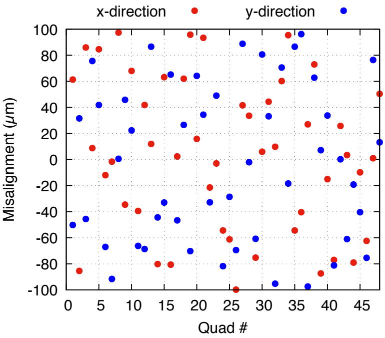
- CW-CCW particles cancel each other exactly.
- More can be done to decrease the growth of s_y.

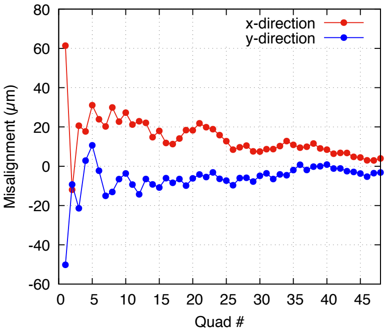
Randomly misaligned quads

- Random misalignment introduces geometric phase effects
- We studied Lebedev's lattice. Similar with Sig's prototype lattice, but with 4-fold symmetry and larger number of elements
- Some of the results are presented in last year's kick-off meeting
- More details can be found at arXiv:1709.01208

Misalignment of the quads

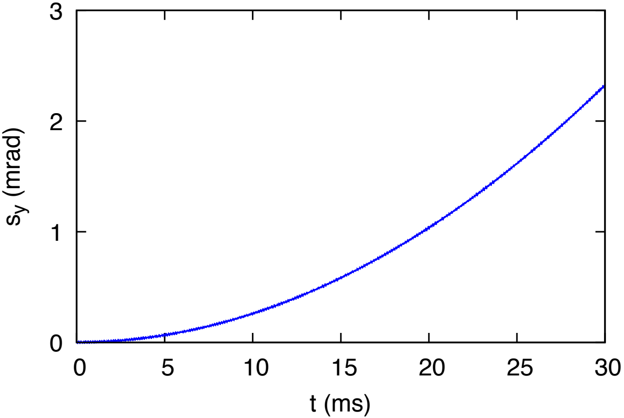
- All quads are misaligned within $\pm 100\mu m$
- The average along the ring is a few μm in both directions
- Unlike the previous case, this configuration leads to geometric phase effect





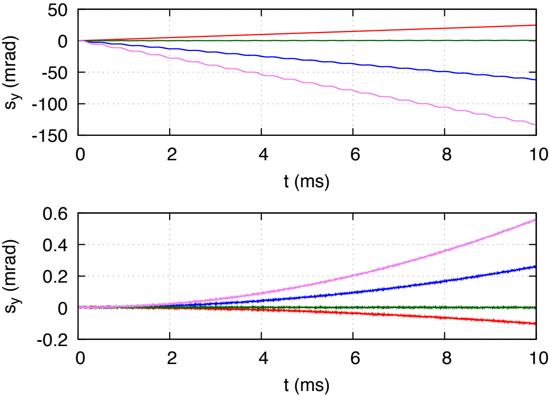
Growth of s_y

- s_y grows quadratically because of coupling with s_r, which grows linearly.
- We propose several methods to minimize the growth



Fixing the energy

- Misplaced quads shift the closed orbit, leading to off-magic momentum and growing s_r
- Simulations show that the RF cavity can be tuned to cross zero-growth
- Purple line represents the original RF configuration

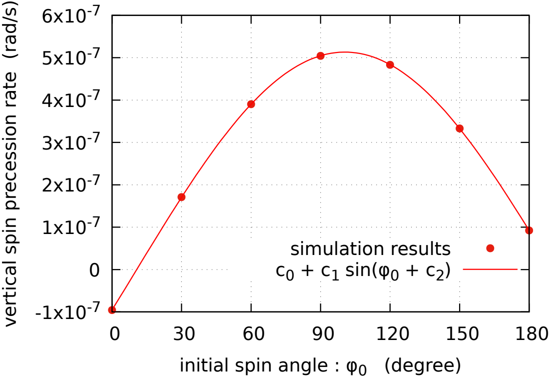


Correction quadrupoles - 1

- The effect becomes more sensitive with large horizontal spin component (s_r)
- We added a correction quadrupole with weaker strength.
- Then simulated particles with large initial s_r. This amplifies the effect of the quad misalignment.
- Then we tuned the quadrupole strength to minimize the growth of s_y.
- This method can be improved by using correction quadrupoles / dipoles on both sides of every quad

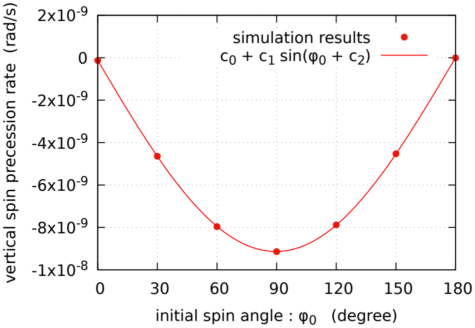
Correction quadrupoles - 2

- The spin precession rate after tuning the correction quadrupole (shifting by around 2.2cm)
- Note the strong dependence on the initial angle: c_1
- There is also a large phase c_2.



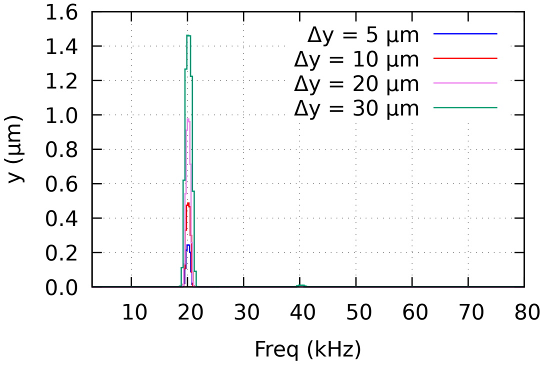
Quad strength

Quadrupole	Lattice-1	Lattice-2
k_1 (V/m^2)	-3.4×10^7	0
k_2 (V/m^2)	4.2×10^7	10^5
k_3 (V/m^2)	3.7×10^7	-2×10^5
k_4 (V/m^2)	-3.2×10^7	0



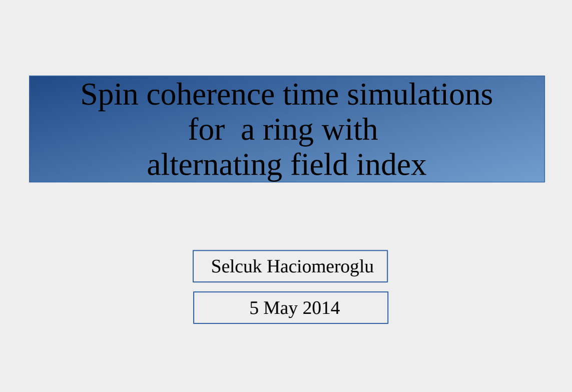
Beam-based alignment

- We simulated a ring with one quad modulated by 3%.
- The vertical motion shows a peak at that frequency.
- One can actuate the quadrupoles to minimize the peak.
- JEDI group recently made beam-based alignment at the order of 10μm without modulation



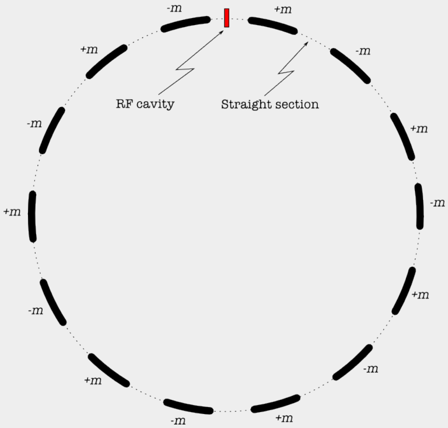
Lattice with alternating field index – 1

- Switching back to the quad-free weak focusing lattice may be another solution because of the weak vertical field.
- In previous studies we have shown that a lattice with weak focusing, alternating field index also fits the requirements of pEDM experiment.
- https://npvm2.ceem.indiana.edu/elog1/scratch/177



Ring Design

- The ring has 14 bending and straight sections
- Ring radius is 40m
- Each straight section is 1m
- One of the straight sections have RF cavity



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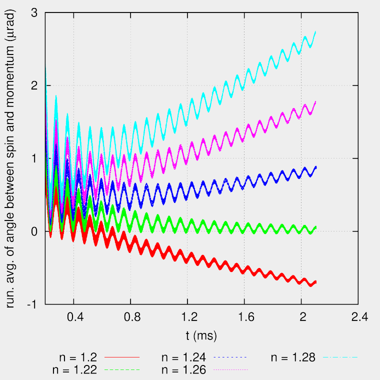
Lattice with alternating field index – 3

Results – Spin Coherence Time

Field index n = (1+m)	Approx. SCT (s)
1.2	1333
1.22	20000
1.24	1333
1.26	645
1.28	408



- Initial Δp/p=2e-4
- SCT values increased by more than an order of magnitude w.r.t.case of constant field index
- Average angle changes sign at a specific field index (around n=1.22), leading infinite SCT

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Summary

- We have studied quad misplacement and it turns out that we have several tools to suppress the false EDM signals.
- Trim quadrupoles can decrease the false EDM signal by several orders of magnitude.
- Most efficient way of tuning the trim quadrupoles is to use them with horizontally polarized beams. Softer focusing also helps since the effect is proportional to vertical field.
- We can also consider the lattice with alternating index.