Preliminary studies of systematics in a full spin frozen storage ring for deuteron

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Outline

- Brief reminder of storage ring based EDM search with frozen spin condition
  - Storage ring with spin frozen EB deflectors for deuterons, and source of main systematics

- Global full spin frozen storage ring for deuterons
  - MDM spin transparent quadrupole
  - The benefits and challenges
  - Preliminary tracking results with Bmad and PTC

- Summary

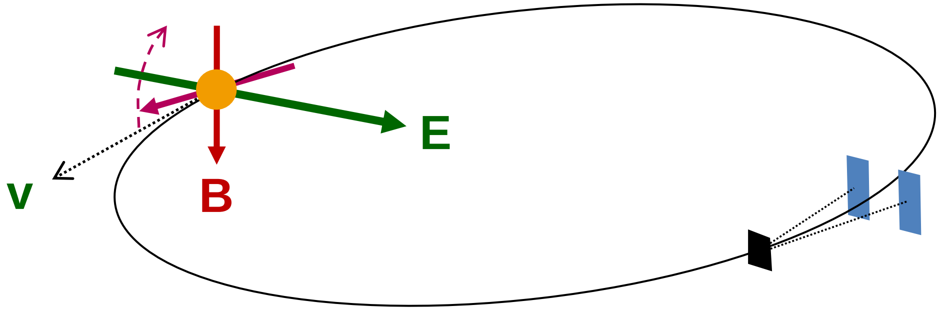
Storage ring based EDM search for deuterons

- In the presence of EDM

$$\frac{d\vec{S}}{dt} = \frac{e}{\gamma m}\vec{S} \times [(1+G\gamma)\vec{B}_{\perp} + (1+G)\vec{B}_{\parallel} + \left(G - \frac{\gamma}{\gamma^2-1}\right)\frac{\vec{E}\times\vec{\beta}}{c} + \boldsymbol{d}(\vec{\boldsymbol{E}} + \vec{\boldsymbol{\beta}} \times \vec{\boldsymbol{B}})]$$

- The spin motion due to MDM is Frozen along the particle velocity in the horizontal plane.
- Non zero EDM results in the vertical polarization buildup

$$\frac{d\vec{S}}{dt} = \frac{e}{\gamma m}\vec{S} \times [\boldsymbol{d}(\vec{\boldsymbol{E}} + \vec{\boldsymbol{\beta}} \times \vec{\boldsymbol{B}})]$$



courtesy of E. Stephenson

Spin frozen condition requirements

- For protons, G is positive and there exist a magic energy at which the proton spin vector precesses at the same rate as the velocity vector when using a pure radial electrostatic field. This energy is the magic momentum

$$p = m/\sqrt{G}$$

- For deuterons, G is negative and it is not possible to use a pure electrostatic ring to freeze the spin motion. It is necessary to use combined electrostatic and magnetic deflectors that satisfy

$$E = \frac{G\gamma cp}{1 + G\beta^2\gamma^2} B$$

Spin frozen condition requirements

	Bending radius[m]	Deflector E field strength	Deflector B field strength	CW/CCW same orbit/time
pEDM	52.3	8.017 MV/m	--	yes
dEDM	52.3	2.3 MV/m	0.07 Tesla	no
dEDM	26.4	4.54 MV/m	0.153 Tesla	no
pEDM	26.4	15 MV/m	--	yes

- For protons, it is possible to have CW and CCW beams simultaneously. However, high electrostatic fields are challenging.
- For deuterons, it is not possible to have CW and CCW beams at the same time. Hence, it is very important to have precise control of the systematics due to B field reversal.

Main systematics

pEDM ring, all electrostatic	dEDM ring, EB elements
Off-center vertical closed orbit through quadrupoles, which is mitigated by simultaneous CW/CCW beams	Off-center vertical closed orbit through quadrupoles, which is mitigated by CW/CCW beams assuming **the reversal of the fields** is perfect
Non zero $< B_r >$, that can be monitored by measuring the vertical split of the CW/CCW beams. High sensitive beam position monitor	Non zero $< E_y >$, can be mitigated by CW/CCW beams assuming **the reversal of the fields** is perfect
Polarimeter, mitigated by consecutive bunches of opposite helicity.	Polarimeter, various methods of mitigation.
fringe fields, E and B fields in RF cavity,Gravity	
Image current	Stern-Gerlach effect

[1] A Proposal to Measure the Proton Electric Dipole Moment with 10^{-29} e.cm Sensitivity, V. Anastassopoulos et al., October 2011.
[2] AGS Proposal: Search for a permanent electric dipole moment of the deuteron nucleus at the 10^{-29} e.cm level, D. Anastassopoulos et al.,

MDM spin transparent quadrupole

- Similar to the condition for freezing spin in a dipole, it is possible to make the MDM part of the spin motion to be transparent in a quadrupole as well.

$$E_x - iE_y = (b_{e1} + ia_{e1})\frac{x+iy}{r_0} \qquad B_y + iB_x = (b_1 + ia_1)(x+iy)$$

- Only using normal components b_1 and b_{e1}.
- It is necessary that electric and magnetic fields remain perpendicular $\vec{B}\cdot\vec{E} = 0.$
- We get a relation between magnetic and electric components

$$b_1 = \left[1 - \frac{1}{(\gamma+1)(1+G\gamma)}\right]\frac{\beta b_{e1}}{r_0 c}$$

M. Bai, Y. Dutheil, D. Sagan, **arXiv:1611.04992, 2016**

MDM spin transparent quadrupole

- Or expressed in terms of fields

$$B_x = -\left[1 - \frac{1}{(\gamma+1)(1+G\gamma)}\right]\frac{\beta E_y}{c} \qquad B_y = \left[1 - \frac{1}{(\gamma+1)(1+G\gamma)}\right]\frac{\beta E_x}{c}.$$

- The equivalent field gradient of such a quadrupole is

$$k_1 = \left[\left[1 - \frac{1}{(\gamma+1)(1+G\gamma)}\right]\frac{\beta}{c} + \frac{1}{\beta c}\right]\frac{b_{e1}}{r_0}$$

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Benefits

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- Spin precession due to the average non zero vertical electric field, with regular magnetic quadrupole [1]

$$\omega_{E_v} = (G+1)\frac{e}{mc}\frac{\langle E_v\rangle}{\beta^2\gamma^2}$$

  - for deuteron ring at p=1GeV/c we have $\omega_{E_v} = 2.0\frac{e}{mc}\langle E_v\rangle$

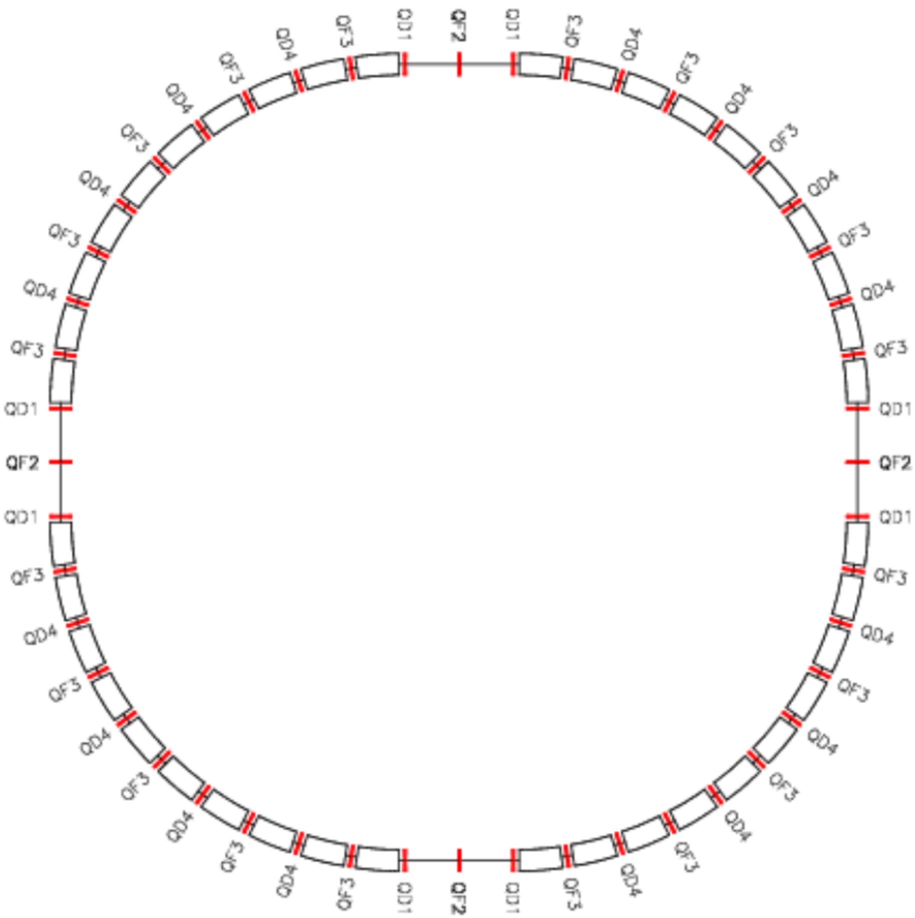
- Spin precession due to the average non zero vertical electric field, with MDM spin

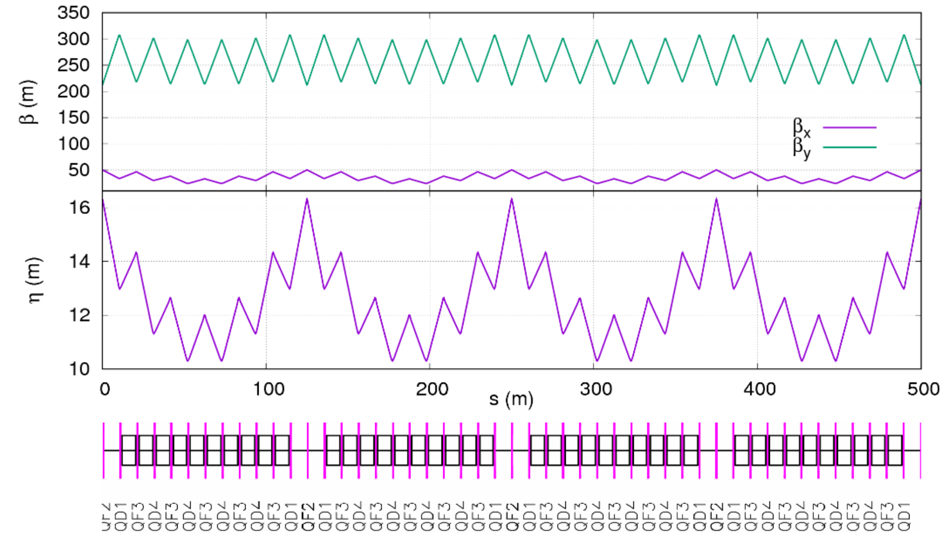
$$\omega_{E_v} = \frac{e}{mc}(G + \frac{1}{\gamma+1})\langle E_v\rangle\beta$$

  - for deuteron ring at p=1GeV/c we have $\omega_{E_v} = 0.2\frac{e}{mc}\langle E_v\rangle$ about an order of magnitude better than with magnetic quadrupole.

[1] Y. Semertzidis, W. M. Morse et al, https://www.bnl.gov/edm/files/pdf/deuteron proposal 080423 final.pdf, 2008
[2] M. Bai, Y. Dutheil, D. Sagan, arXiv:1611.04992, 2016

EDM deuteron storage ring





Lattice parameters

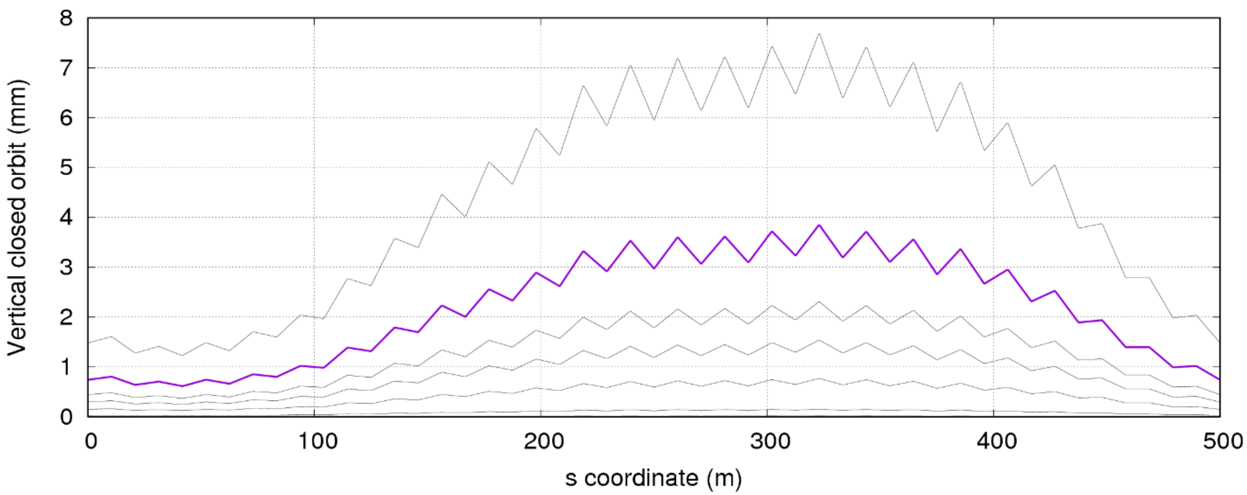
- Deuteron momentum 1GeV/c
- Bending radius 52.3 m
- Circumference 500 m
- Qx, Qy 2.31, 0.312
- Radial electric field 1.9 MV/m
- Vertical magnetic field 770 G

- Lattice developed in [1] for proton EDM and using here combined EB deflector.

[1] V. Anastassopulos et al, https://arxiv.org/abs/1502.04317

Simulation results

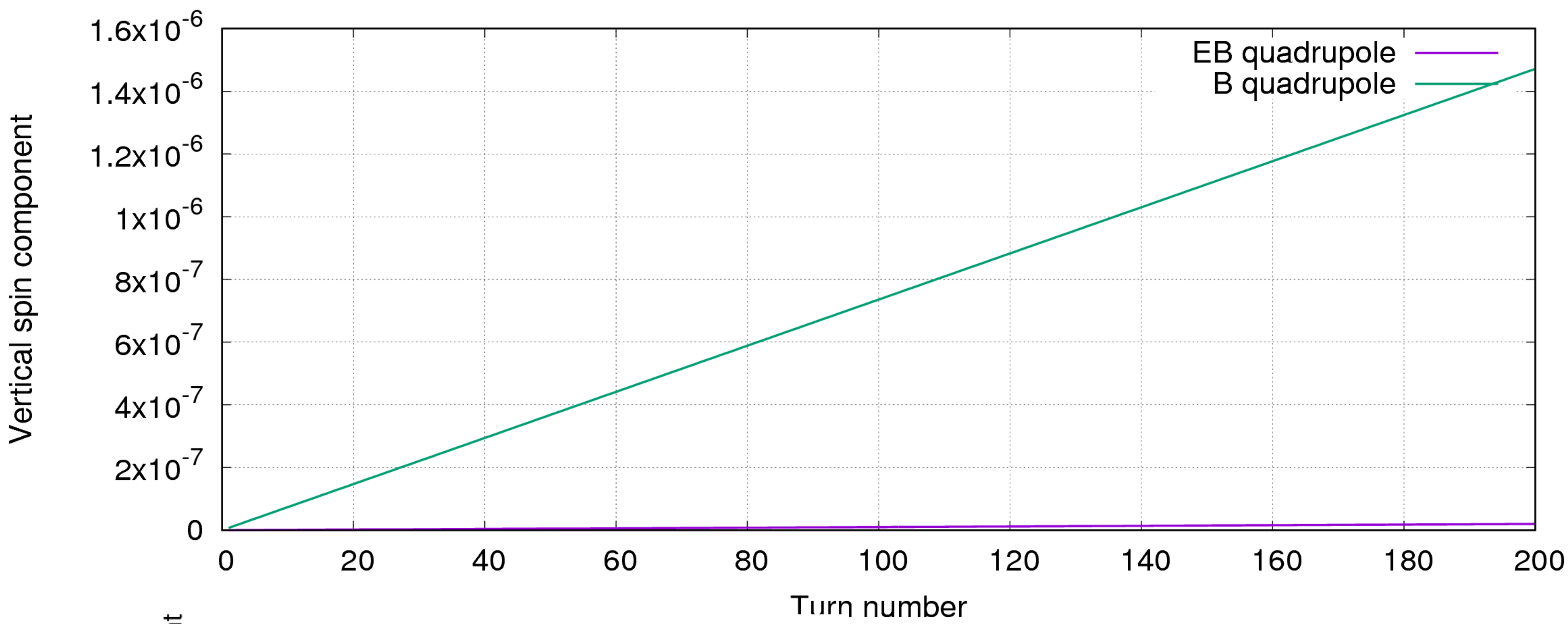
- We use the BMAD[1] library and the PTC tracker[2].
  - In details we use SBEND to model the deflectors with the PTC exact model and vertically pure multipole corrections.
- We use two lattices, one with pure magnetic quadrupoles and the other with MDM spin transparent quadrupoles (EB quadrupoles). The optics are strictly the same for the two lattices.
- The first systematics we investigated is by vertical random misalignments of the quadrupoles.

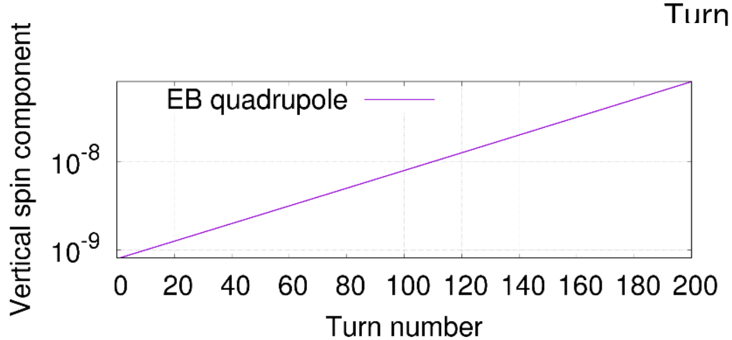


Here the vertical orbit in purple is 1.06mm RMS

Simulation results

- The buildup of the vertical spin component is here only caused by the vertical orbit as the EDM is deactivated. This is the main source of systematics for this machine.

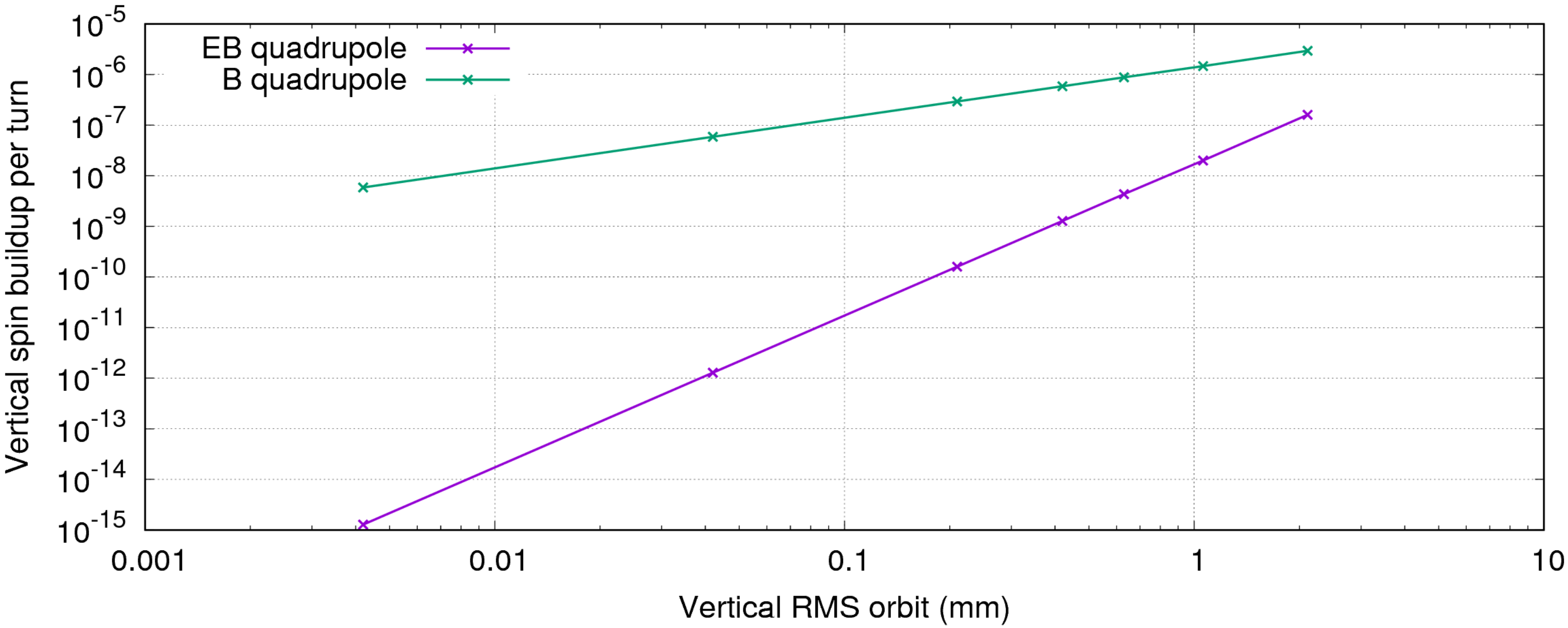




The MDM spin transparent quadrupole is much less sensitive to vertical orbit.

Simulation results

- Comparing the vertical spin buildup without EDM as a function of the amplitude of the vertical orbit.



- The MDM spin transparent quadrupole considerably reduces the effect of misaligned vertical orbit onto the vertical buildup.

Summary

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- For deuteron, frozen spin condition requires combined EB deflectors. However, the spin frozen condition for deflector is not satisfied by the magnetic quadrupoles.
- We recently explored the idea of global full frozen using MDM spin transparent quadrupole.
  - Our preliminary study so far has shown that this concept can help to mitigate the first order systematics by an order of magnitude.
  - Our latest preliminary study of the effect of the non-zero vertical orbit on fake vertical spin buildup has been very encouraging.
- We continue to :
  - explore the systematics via spin tracking with Bmad and PTC, w/wo MDM spin transparent quadrupoles to make sure this idea works.
  - Will take a look the engineering design of this kind of element.
  - Investigate the options of different optics choices of full spin frozen storage ring lattices.