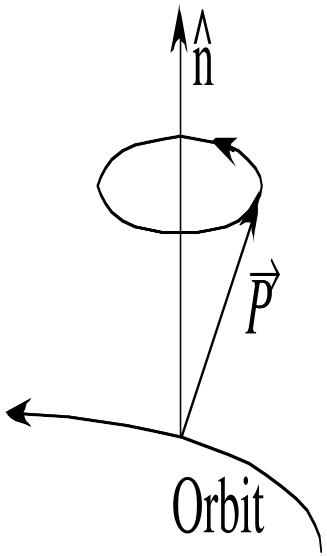
A Compact Spin Rotator



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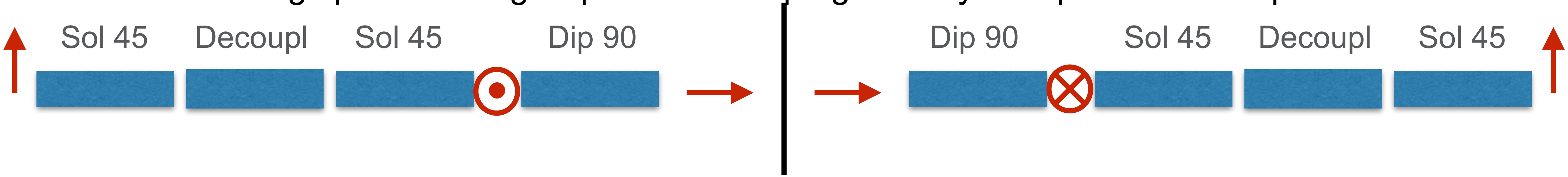
Motivation/Context

- There is interest by a group of physicists (led by U. of Victoria, CDN) to upgrade SuperKEKB to polarized electrons after the hi-lumi program is complete.
- Many immediate questions, one of them being “How do we get longitudinal polarization at the IP?”
  - Spin rotators (cf. HERA) up-and downstream of the IP.
  - A practical solution should not disturb the geometry of the lattice
  - Any practical solution cannot affect emittance and beam dynamics too much.
  - Highly desirable to be able to restore the present lattice by turning off the spin rotators.
  - Electron ring is 7 GeV (High Energy Ring). 4 GeV posi’s in LER remain unpolarized.
- Since EIC is planning polarization capability, this work may be of interest.

Spin Rotators

- Simplest rotator: Richter-Schwitters vertical-dipole rotator.
  - large excursion tilt the detector, no way to fit into an existing machine.
- HERA used interleaved horizontal and vertical dipoles. To change helicity, they mechanically moved (by maybe 20-40 cm).
  - still large excursions and quite long. vertical dipoles enlarge vertical emittance.
- Solenoid-dipole rotators with decoupling section(s)
  - use solenoids to rotate polarization vector into plane, ring dipoles to orient longitudinally.
  - in simplest form require specific bending to IP; decoupling quadrupole section (≥ 5 quads)
  - Note: Strong spin matching requires “S” shape geometry: Not possible in SuperKEKB



Compact Rotator

- S/C technology allows building of multi-function magnets,
  - Can we overlay solenoid, dipole and the decoupling quadrupoles in one magnet??
  - (inspired by BNL "Direct Winding" technique)
- Q: What is the spin-rotation of a combined-function solenoid and dipole?
- Ans (spinor matrix):

$$\begin{bmatrix} \dfrac{\mathrm{I}\, a_v e^{-\frac{\sqrt{-a_l^2-a_v^2}}{2}} - \mathrm{I}\, a_v e^{\frac{\sqrt{-a_l^2-a_v^2}}{2}} + e^{-\frac{\sqrt{-a_l^2-a_v^2}}{2}}\sqrt{-a_l^2-a_v^2} + e^{\frac{\sqrt{-a_l^2-a_v^2}}{2}}\sqrt{-a_l^2-a_v^2}}{2\sqrt{-a_l^2-a_v^2}} & \dfrac{a_l e^{-\frac{\sqrt{-a_l^2-a_v^2}}{2}} - a_l e^{\frac{\sqrt{-a_l^2-a_v^2}}{2}}}{2\sqrt{-a_l^2-a_v^2}} \\ \dfrac{-a_l e^{-\frac{\sqrt{-a_l^2-a_v^2}}{2}} + a_l e^{\frac{\sqrt{-a_l^2-a_v^2}}{2}}}{2\sqrt{-a_l^2-a_v^2}} & \dfrac{-\mathrm{I}\, a_v e^{-\frac{\sqrt{-a_l^2-a_v^2}}{2}} + \mathrm{I}\, a_v e^{\frac{\sqrt{-a_l^2-a_v^2}}{2}} + e^{-\frac{\sqrt{-a_l^2-a_v^2}}{2}}\sqrt{-a_l^2-a_v^2} + e^{\frac{\sqrt{-a_l^2-a_v^2}}{2}}\sqrt{-a_l^2-a_v^2}}{2\sqrt{-a_l^2-a_v^2}} \end{bmatrix}$$

a_l is spin prec. angle in solenoid, a_v is spin prec. angle in dipole (full angle)

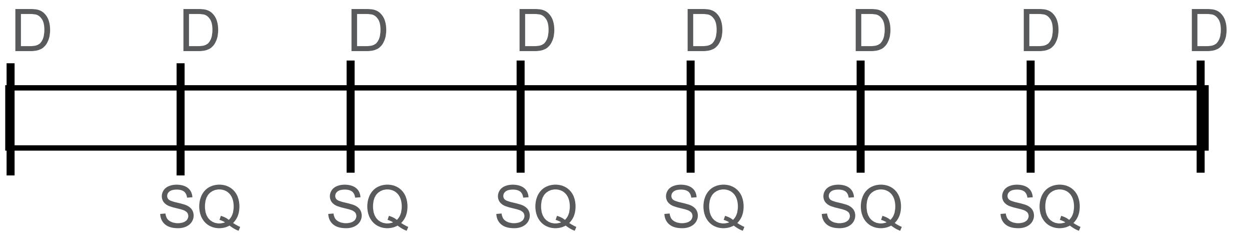
- This model is exact with no approximations beyond those inherent in 1st order spin matrices.

Decoupling

- Overlaying 6 skew quadrupoles at various skew angles allows decoupling of such a rotator at least in principle:
  - A.A. Zholents, V.N. Litvinenko, “On the Compensation of Solenoid Field Effect by quadrupole Lenses“, (I. Schulz-Dahlen, Trans), BINP-81-80 (1984)

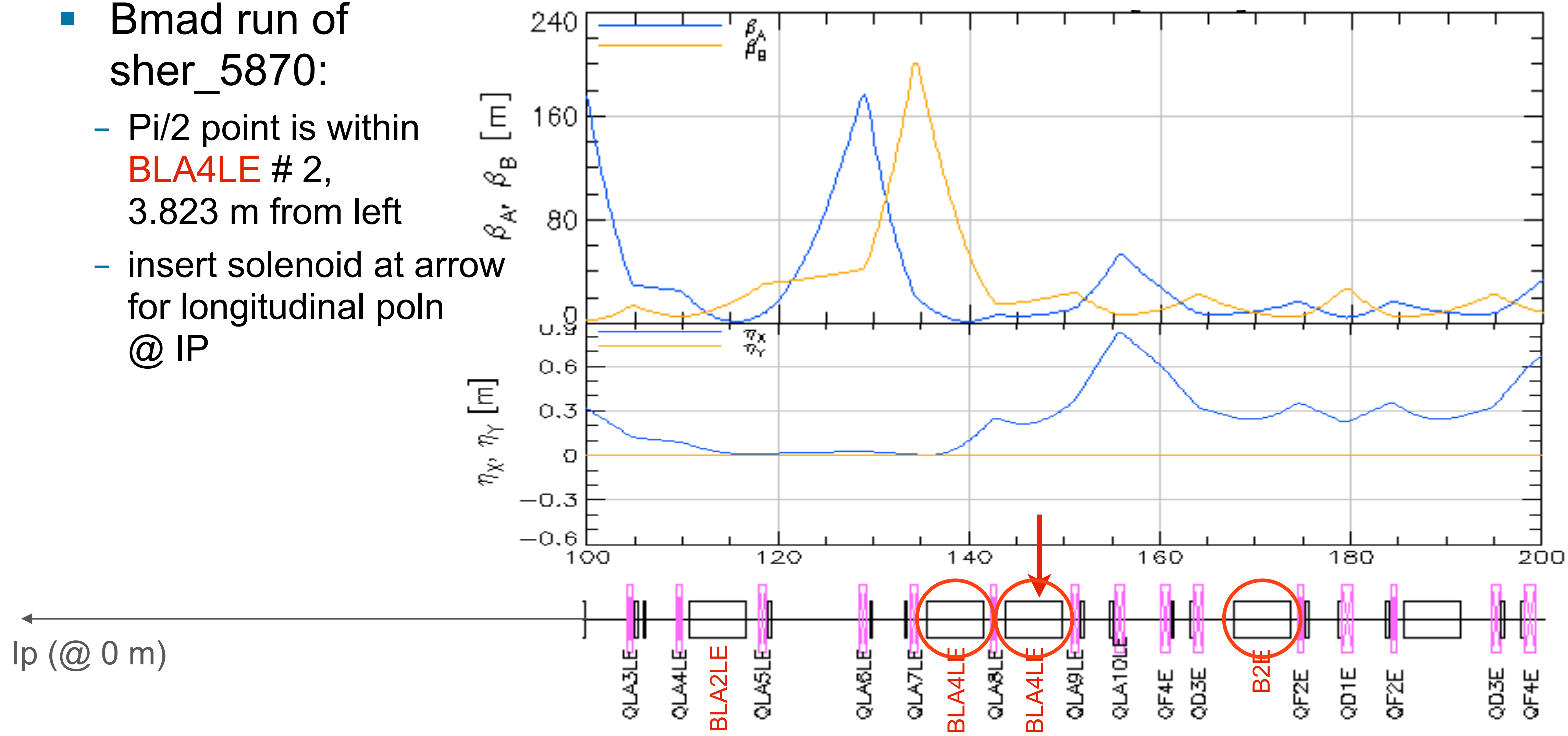
$$\begin{bmatrix} -0.822977812463494 & -0.436845511853400 & 4.62516442853445\ 10^{-9} & 1.17755177608814\ 10^{-7} & 0. & 0.0471444197606779 \\ -0.472803001176467 & -1.46606852673593 & -4.41649958214871\ 10^{-7} & -0.000001371450664868 78 & 0. & 0.00318556574183547 \\ 8.58055902398444\ 10^{-8} & -4.76578634028835\ 10^{-7} & 4.19153915993413 & 13.8109689336249 & 0. & -0.000165272595730890 \\ 1.17541419729361\ 10^{-7} & -1.20672154782508\ 10^{-7} & 1.48037621498376 & 5.11636157910899 & 0. & 0.000455843360788200 \\ -0.0196683732844376 & -0.0677253496881336 & -0.00215537175331314 & -0.00714129788468482 & 1. & -0.00181434222845887 \\ 0. & 0. & 0. & 0. & 0. & 1. \end{bmatrix}$$

- This was done with a slice model:



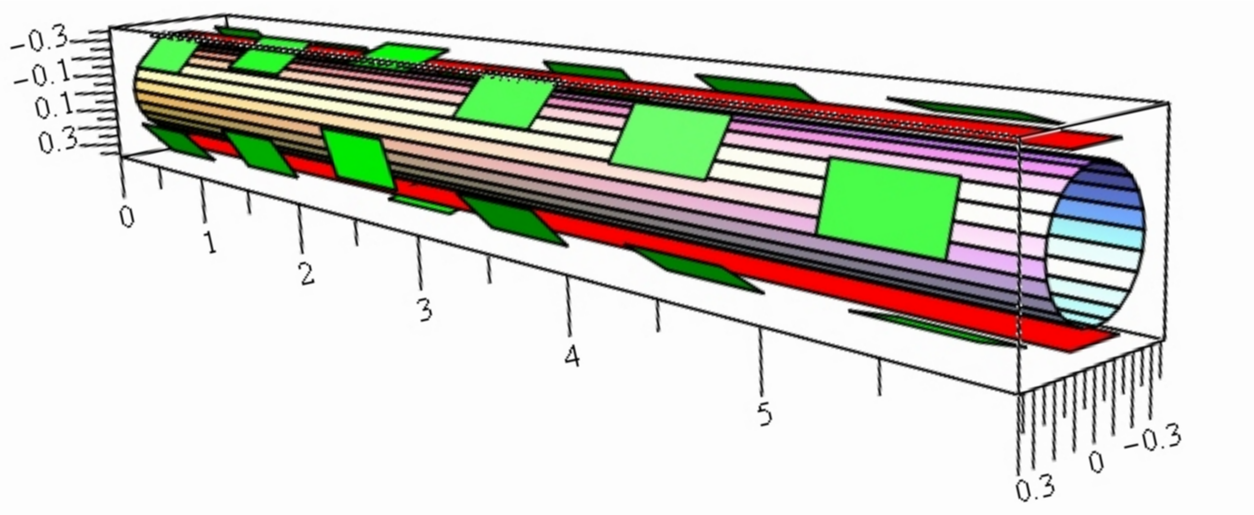
Lattice Locations for Spin Rotator Solenoid(s)

- Bmad run of sher_5870:
  - Pi/2 point is within BLA4LE # 2, 3.823 m from left
  - insert solenoid at arrow for longitudinal poln @ IP



SuperKEKB Rotator

- Three of these make up the whole rotation;
  - solenoid strengths: 0.095734, 0.095734, 0.02077 m^{-1}
  - 4.47 T, 5.9 m ea: 26.37 Tm for two (BLA4LE); the 3rd one (B2E) is about 1/5. of the others.
  - With the solenoids & skew quads off the rotators reduce to pure dipoles.
- The ring magnets make up the horizontal rotation.
- It turns out the three solenoids give flexibility in the rotator location as well as ability to tune the spin angle at the IP.
- Sketch of rotator magnet (1 of 3):

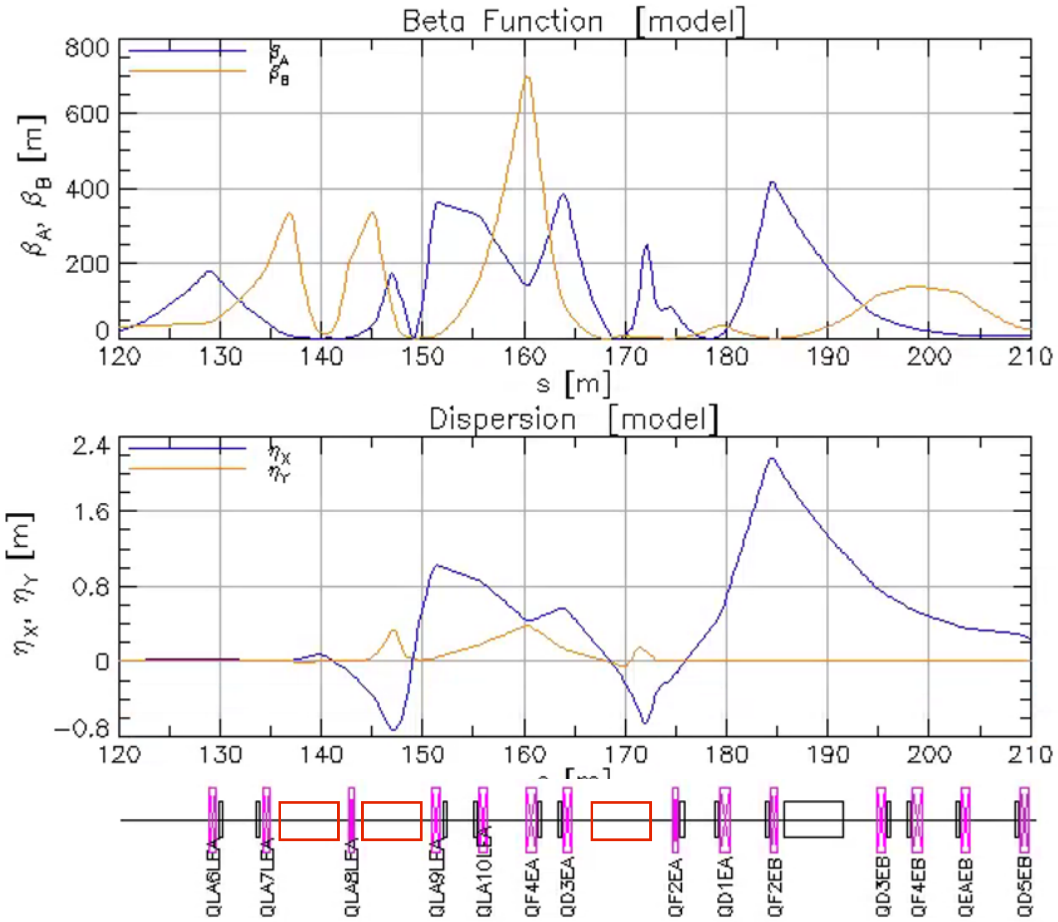


Bmad Calculation

- For accurate parameters and optics matching: Bmad (Sagan et al.).
  - Bmad does spin tracking as well.
  - sol_quad element can model the combined-function magnets
    - dipole modeled as kicks, need patch elements to fix orbit, but dispersion & spin ok.
- Overall R matrix:

$$\begin{bmatrix} 11.33 & -0.3086 & -3.098\times10^{-5} & -4.25\times10^{-6} & 0 & 0.2377 \\ 1.096 & 0.05839 & -2.69\times10^{-6} & -4.4\times10^{-7} & 0 & -0.04210 \\ -6.65\times10^{-6} & 7.01\times10^{-6} & -18.82 & -0.08484 & 0 & -0.06507 \\ 4.50\times10^{-6} & -5.07\times10^{-6} & 13.24 & 6.549\times10^{-3} & 0 & 0.00378 \\ 0.7377 & 8.929\times10^{-4} & -0.7904 & -1.057\times10^{-4} & 1 & -0.05413 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

  - not too bad, vertical dispersion may be issue
- Solenoid: ≤ 4.45 T; quads ≤ 35 T/m; Dipole 0.28 T



Overall Effect of Rotator

- Some noticeable effect on emittances needs to be assessed
- Chromaticities are clearly not acceptable;
  - turns out there are sextupoles within the rotator that need retuning.

Parameter	Without Rotator	With Rotator
Emittance_x	4.44×10^{-9}	5.42×10^{-9}
Emittance_y	1.88×10^{-12}	9.70×10^{-12}
Alpha Damp_x	1.79×10^{-4}	2.54×10^{-4}
Alpha Damp_y	1.79×10^{-4}	1.81×10^{-4}
Damping Partition x	0.999667	1.420164
Damping Partition y	1.001851	1.013181
Chromaticity_x	3.953515	-82.933671
Chromaticity_x	6.595477	-17.182644
Momentum Compaction	4.54×10^{-4}	4.58×10^{-4}

Magnet Properties

- The magnet will have to be warm-bore to accommodate cooling and X-ray shielding
  - needs significant extra aperture.
- The quadrupole strength is a concern
  - for the magnet coils: need to limit at or below 3T at coil
  - for beam dynamics: chromaticity, aberrations.
    - Maybe enforcing (anti-) symmetry helps?
- Tunability of skew-quadrupole angle
  - splitting the quadrupole coil into upright and skew would help; at the expense of # circuits.
- Vertical dispersion and decoupling seem to be somewhat anti-correlated.
  - that trade-off needs exploring.
- Bmad model needs refinement

Summary

- A compact spin-rotator arrangement has been found that fulfills some of the requirements:
  - fits into machine geometry; optical match can be found; field parameters not crazy.
  - spin-rotation angle and rotation axis can be tuned. Rotator can be turned off to restore original optics.
  - effect on lattice noticeable, remains to be assessed and optimized.
  - 2^{nd} spin rotator and tracking remain to be done.

- Maybe has promise for the EIC designs?

- David Sagan answered numerous naïve questions by Yours Truly and updated the code for us.
- Brett Parker looked at an earlier version of the magnet and gave valuable advise on what is doable and the parameter limits.