Compact Electron Spin Rotator Design

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on behalf of

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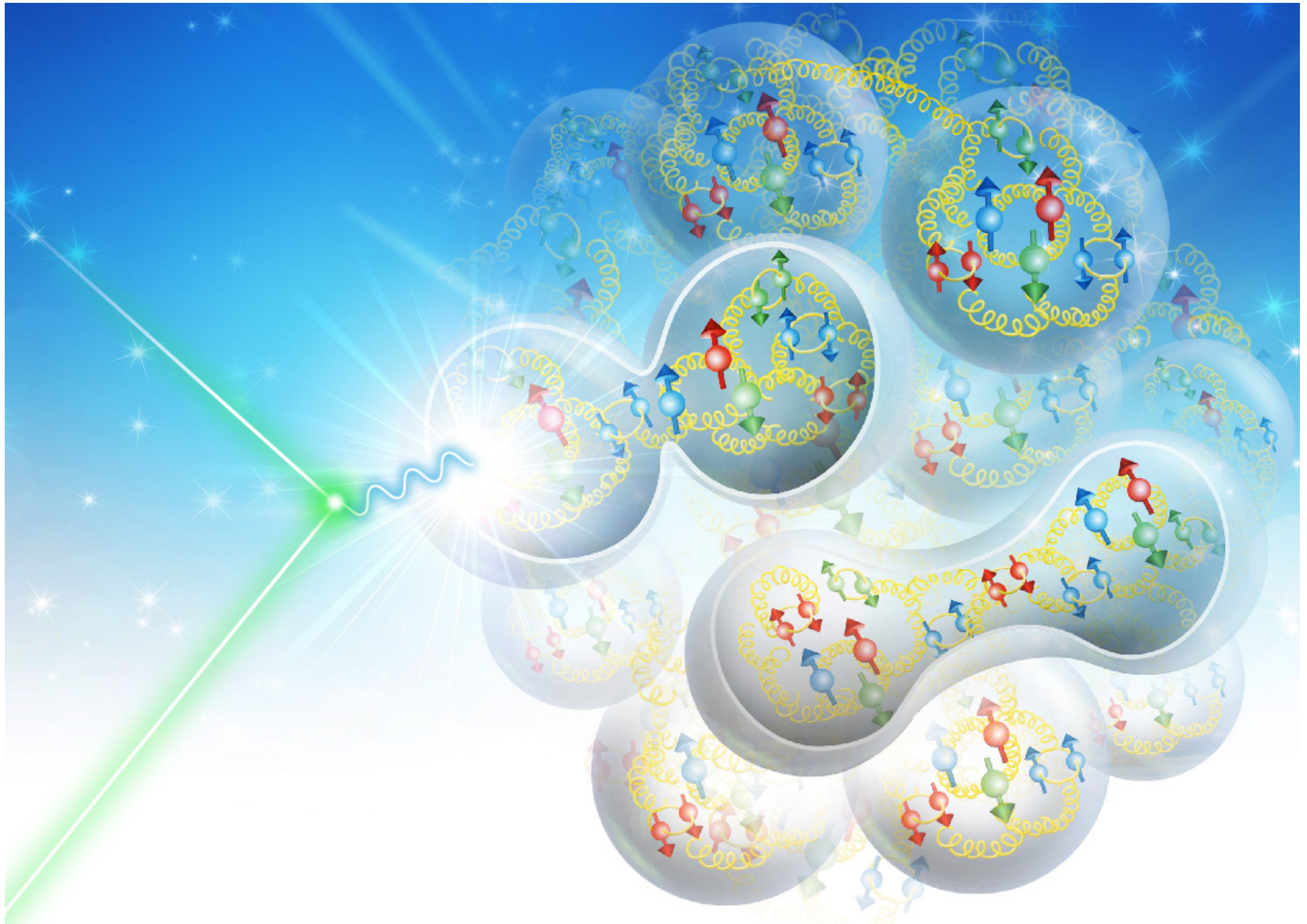

Outline:

- Introduction
- Compact Spin Rotator for EIC
- Summary and Outlook

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CFNS Workshop on Beam Polarization and Polarimetry at EIC
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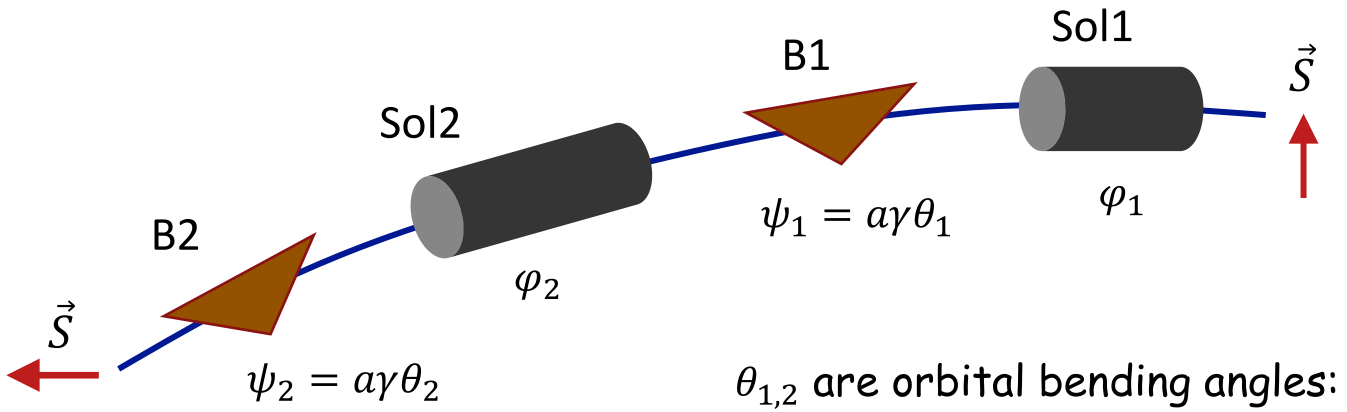
Electron Spin Rotator Design in the EIC



$\theta_{1,2}$ are orbital bending angles:
$\theta_1 = 76.89$ mrad, $\theta_2 = 38.45$ mrad

Spin rotation angles from solenoids and dipoles to rotate the spin from the vertical to the longitudinal satisfy:

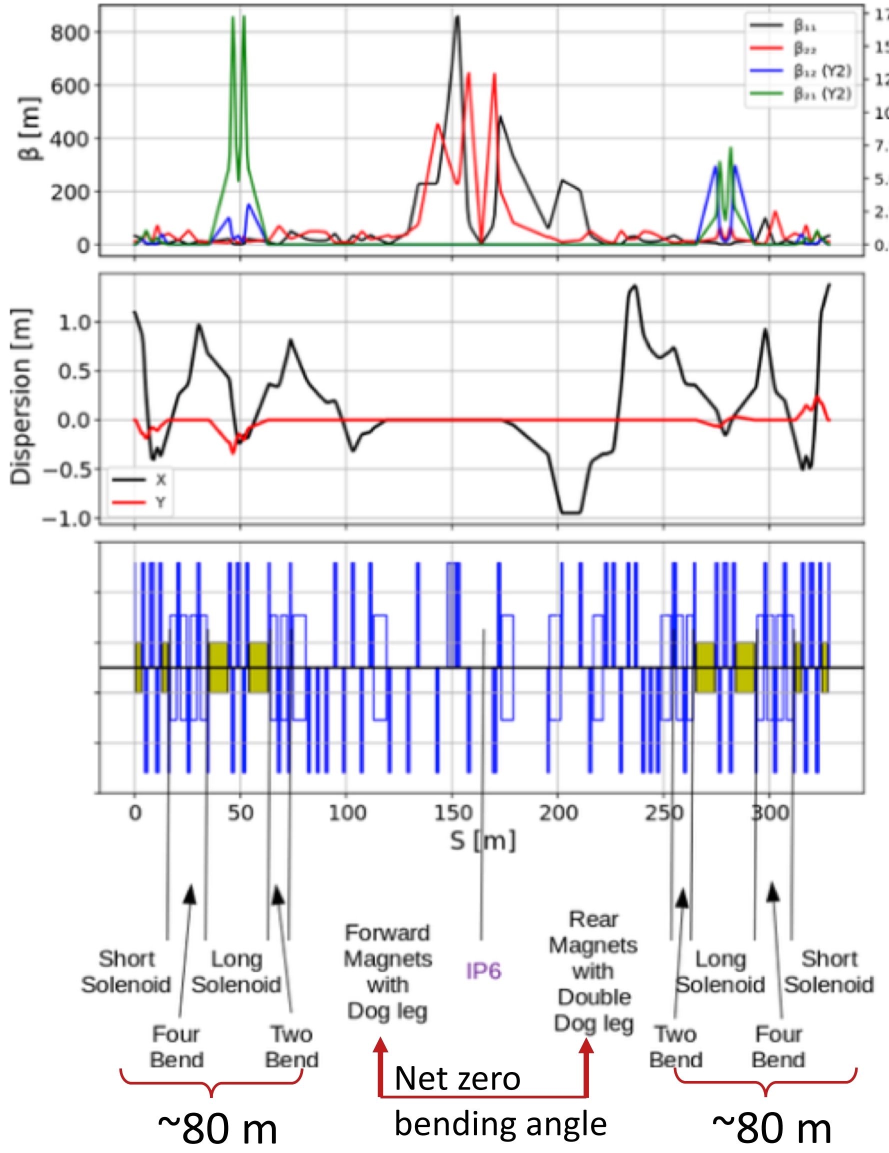
$$\tan\varphi_1 = \pm\frac{\cos\psi_2}{\sqrt{-\cos(\psi_1+\psi_2)\cos(\psi_1-\psi_2)}}$$

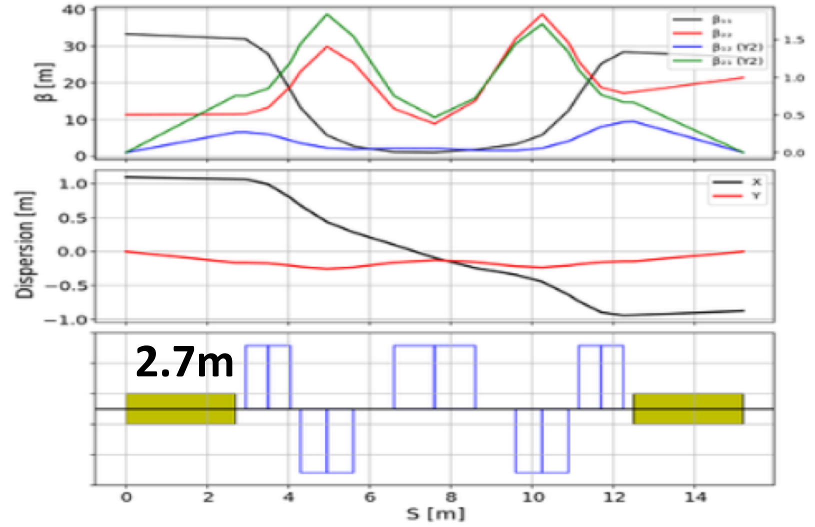
$$\cos\varphi_2 = \cot\psi_1\,\cot\psi_2$$

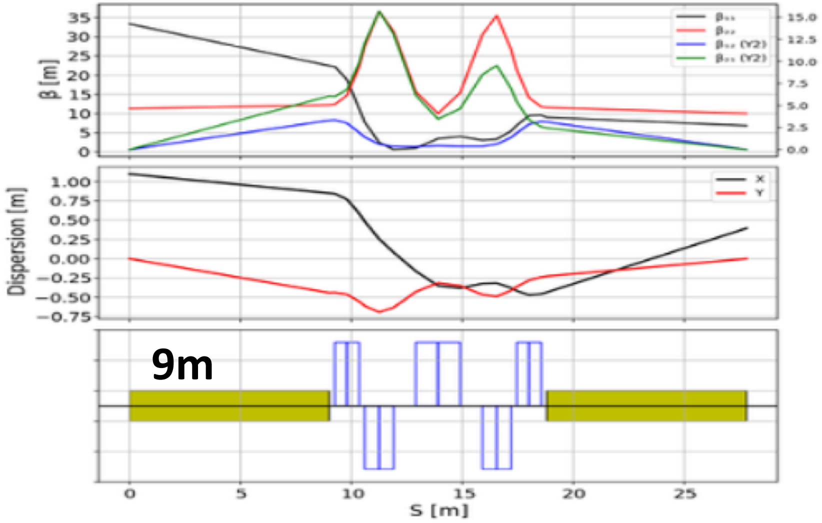
Parameter	Short solenoid module	Long solenoid module
Field integral range $[\mathrm{T}\cdot\mathrm{m}]$	20-34	4-122
Solenoid length [m]	5.4	18.
Solenoid spin rotation angle at 18 GeV	32°	116°
Location in the RHIC tunnel	RHIC dipole 9-10	RHIC dipole 6-8

Optimization of current spin rotator design is continued considering the coverage of energy range, strength of depolarization effect and spin matching to extend the polarization relaxation time. (see Vadim's talk)

Optics of Electron Spin Rotator Design







Some Comments on the Current Spin Rotator Design

- Spin rotators, composed of solenoids and dipoles, are utilized in the electron storage ring in the EIC energy range 5-18 GeV. The solenoid field in the rotator
  - Pros:
    - has no synchrotron radiation or synchrotron radiation easily under control,
    - has no or negligible contribution to the emittances,
  - Cons:
    - introduces transverse orbit coupling
      - compensated using normal or skew quadrupoles
    - may have strong solenoid fields at the high beam energies because the spin effect over the solenoid is inversely proportional to the beam energy
      - requiring relatively long solenoids

Relative long spin rotator ~80m

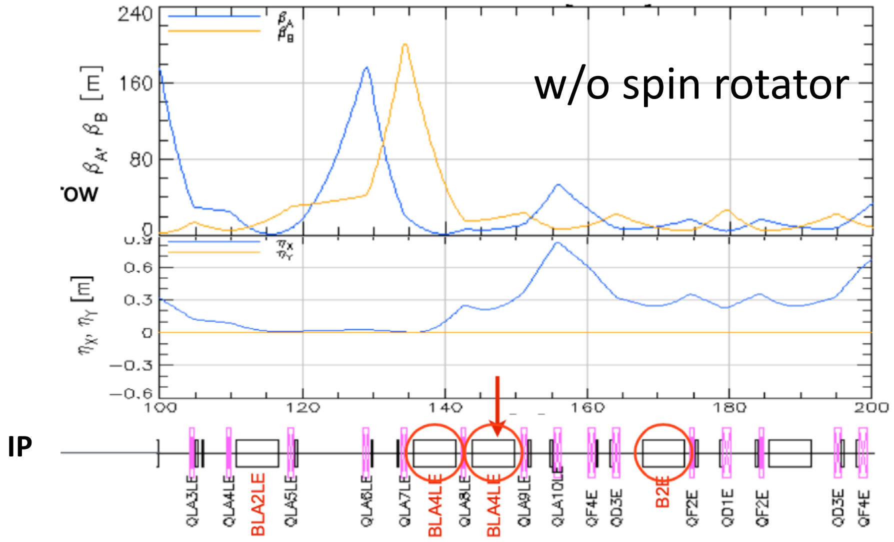
Q: Is there a way to make the spin rotator compact in the EIC ?

Origin of Compact Spin Rotator

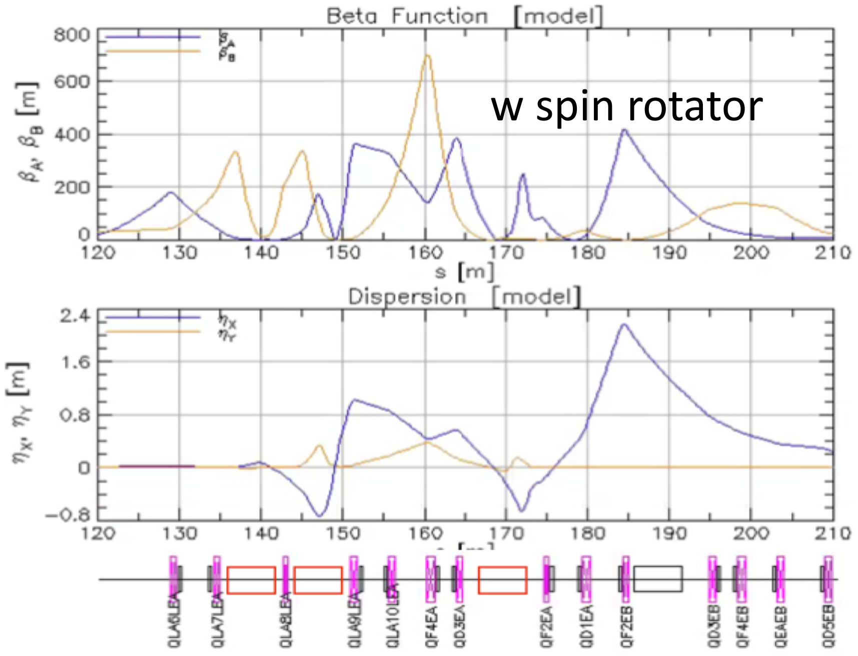
- An interest has arised to upgrade SuperKEKB to polarized electrons after the Hi-lumi program is complete.
- Question: "How do we get longitudinal polarization at the IP"?

  Answer: spin rotators up- and downstream of the IP
- Constraints:
  - A practical solution should not disturb the geometry of the lattice
  - Any practical solution cannot affect the emittance and beam dynamics too much
  - Highly desirable to be able to restore the present lattice by turning off the spin rotators
  - Spin rotators are placed in the High Energy Ring for polarized electrons only
- The concept of a compact spin rotator was explored and presented by Uli Wienands in the EIC Accelerator Collaboration meeting in 2019.
- If it works, such a compact spin rotator will make the geometric layout much easier and more flexible in the EIC design.

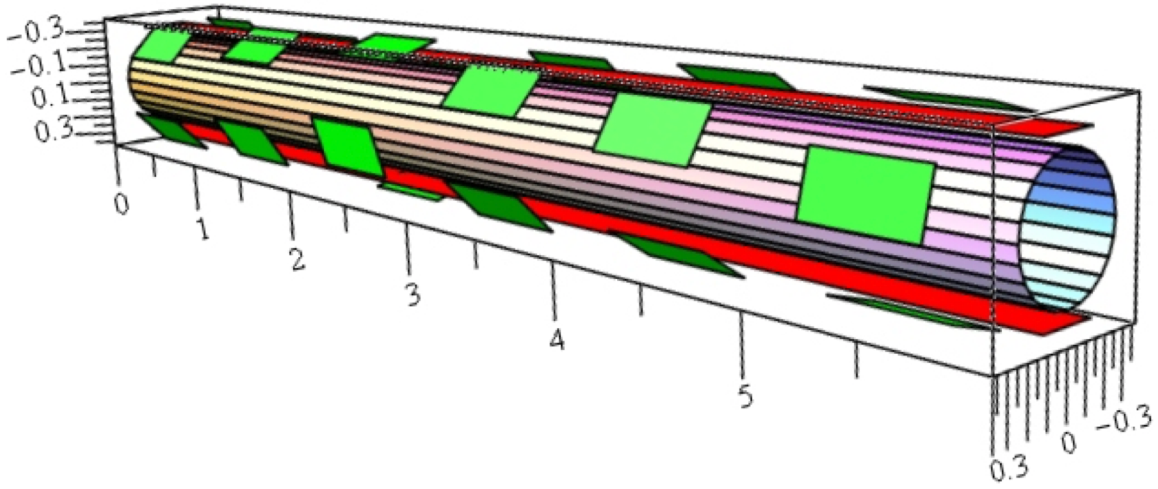
SuperKEKB Spin Rotator



Using Bmad (David Sagan (Cornell))



- Three of these make up the whole rotation
  - Solenoid strengths: two 26.37 Tm, one 5.27 Tm
  - With solenoids and 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



- Solenoid $\leq$ 4.45 T, dipole 0.28 T, quads $\leq$ 35 T/m

Overall Effects of SuperKEKB Spin Rotator

- Some noticeable effect on emittances
- Not acceptable chromaticity growth
  - 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}

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A Compact Spin Rotator in the EIC ?

- Idea:
  - It is a compact solenoid-dipole field spin rotator
  - The combined-function magnets with solenoid, dipole and/or quadrupole fields may reduce the physical length, taking advantage of the superconducting technology (BNL "Direct Winding" technique)
    - Spin rotation from solenoid and dipole fields
    - Decoupling of transverse motions by (skew) quadrupoles

- Constrains
  - Rotate the spin between vertical and longitudinal directions in the EIC energy range
  - Keep the geometry fixed
  - Maximum solenoid field 7 T

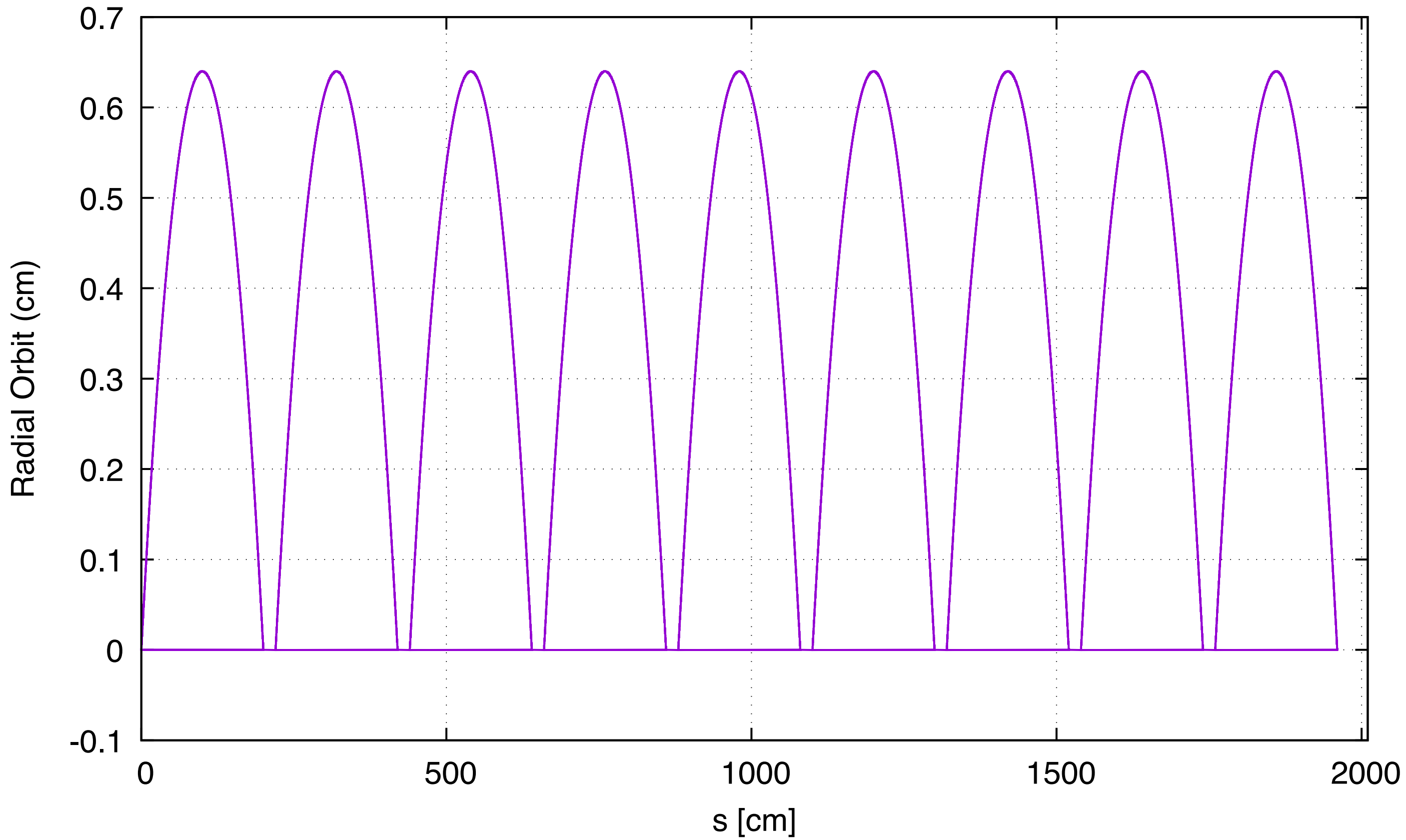
Simulation Environments

- Tools: ZGOUBI + tune (external optimizer)
- Procedure:
  - Code ZGOUBI is used to generate a combined-function magnet composed of solenoid and dipole fields and track the orbital and spin motions.
  - Code tune is utilized to optimize solenoid and/or dipole field components in the combined-function magnet to achieve the desired spin rotation between vertical and longitudinal directions.

Examination of Orbit in Pure Dipole Magnets

Six 2m-long dipoles (with 20 cm drifts between them)

Three 2m-long dipoles (with 20 cm drifts between them)

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 'TOSCA'
0  0
10.  1.00000000E+00  1.00000000E+00  1.00000000E+00
HEADER 8
3 3 3  15.2  0.7684765  0.0
dipole.txt
solenoid1.txt
0 0 0 0
2
.1
1   0.00000000E+00  0.00000000E+00  0.0
 'CHANGREF'
ZR -0.733353357
```

- "CHANGREF" is set correctly in the "TOSCA"
- Short dipoles are chosen to have a small sagitta, which may help to have a relatively small magnet aperture.
- Dipole length and bending angle should be optimized for a reasonably large synchrotron radiation density

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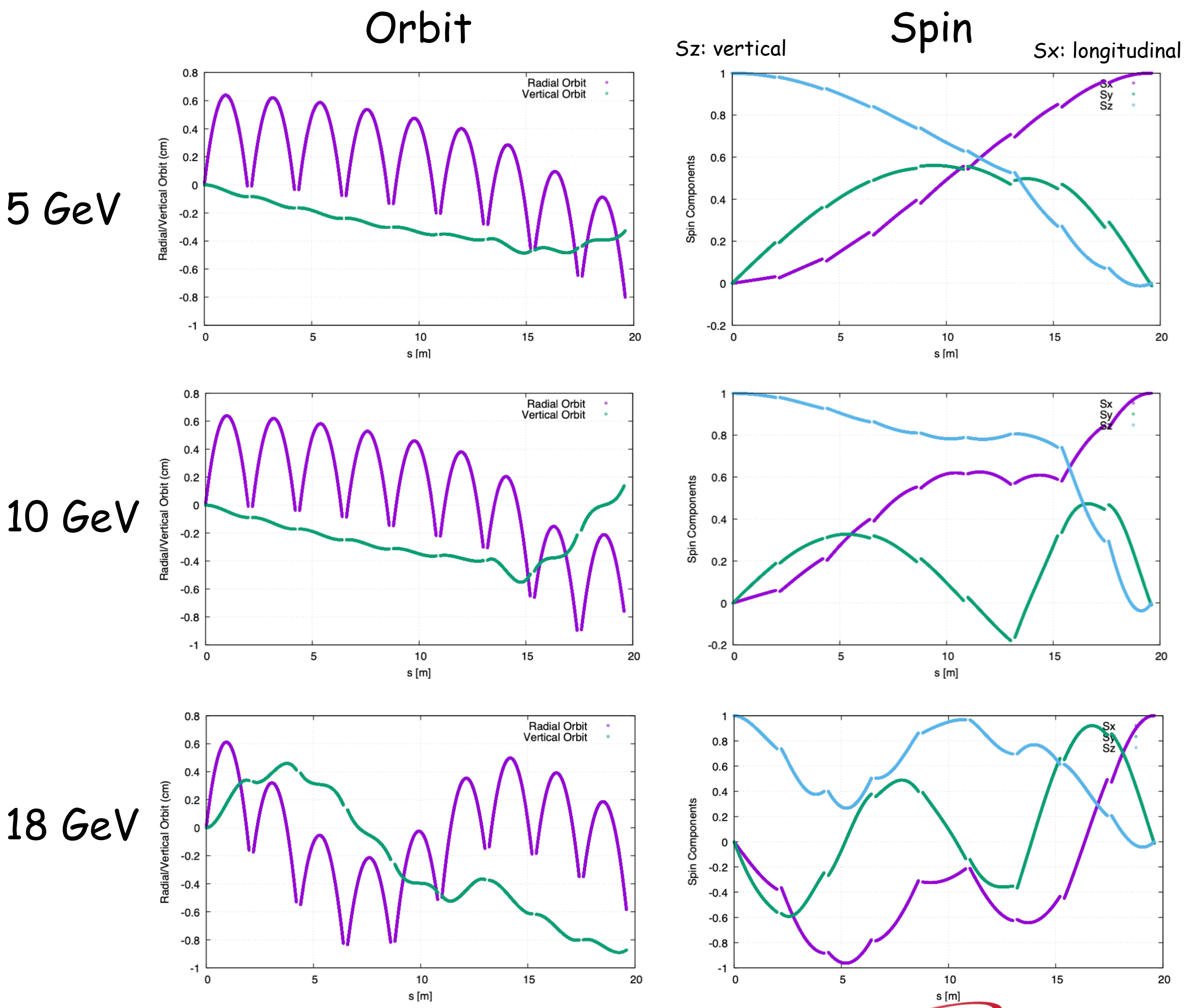
Solution with Scaled Dipole Field + Two Solenoid Fields

energy (GeV)	5	10	18
number of combined-function magnet 1	6		
dipole field (T)	0.21	0.43	0.77
dipole length (m)	2		
dipole radius (m)	78.13		
Sol1 (T)	**1.65**	**3.47**	**-26.67**
number of combined-function magnet 2	3		
dipole field (T)	0.21	0.43	0.77
dipole length (m)	2		
dipole radius (m)	78.13		
Sol2 (T)	**4.50**	**18.14**	**15.81**



- Conclusion:
  – solenoid fields are too strong when scaling the dipole fields with the beam energy

⇩

- Try to vary the dipole field, in addition to solenoid fields

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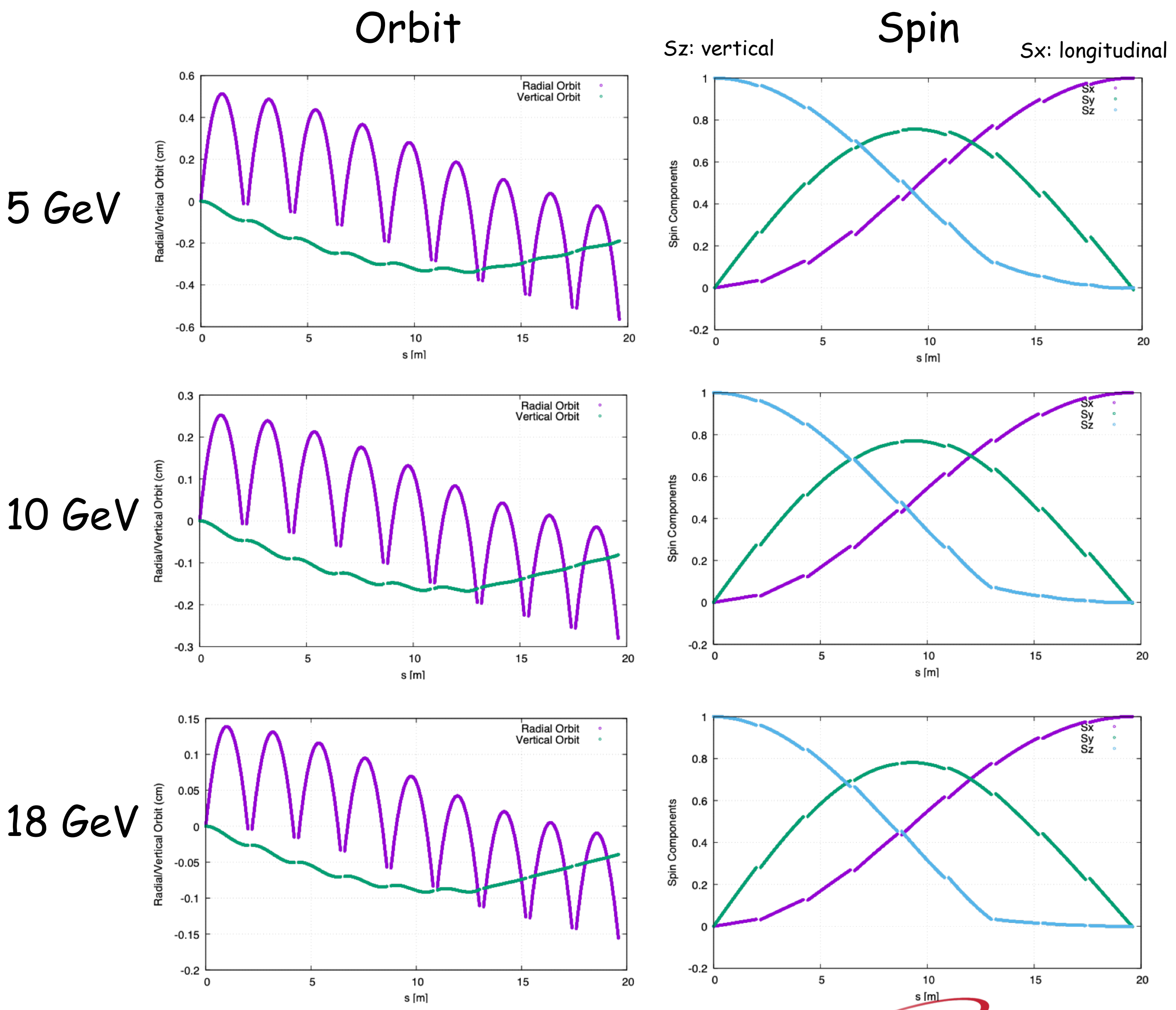
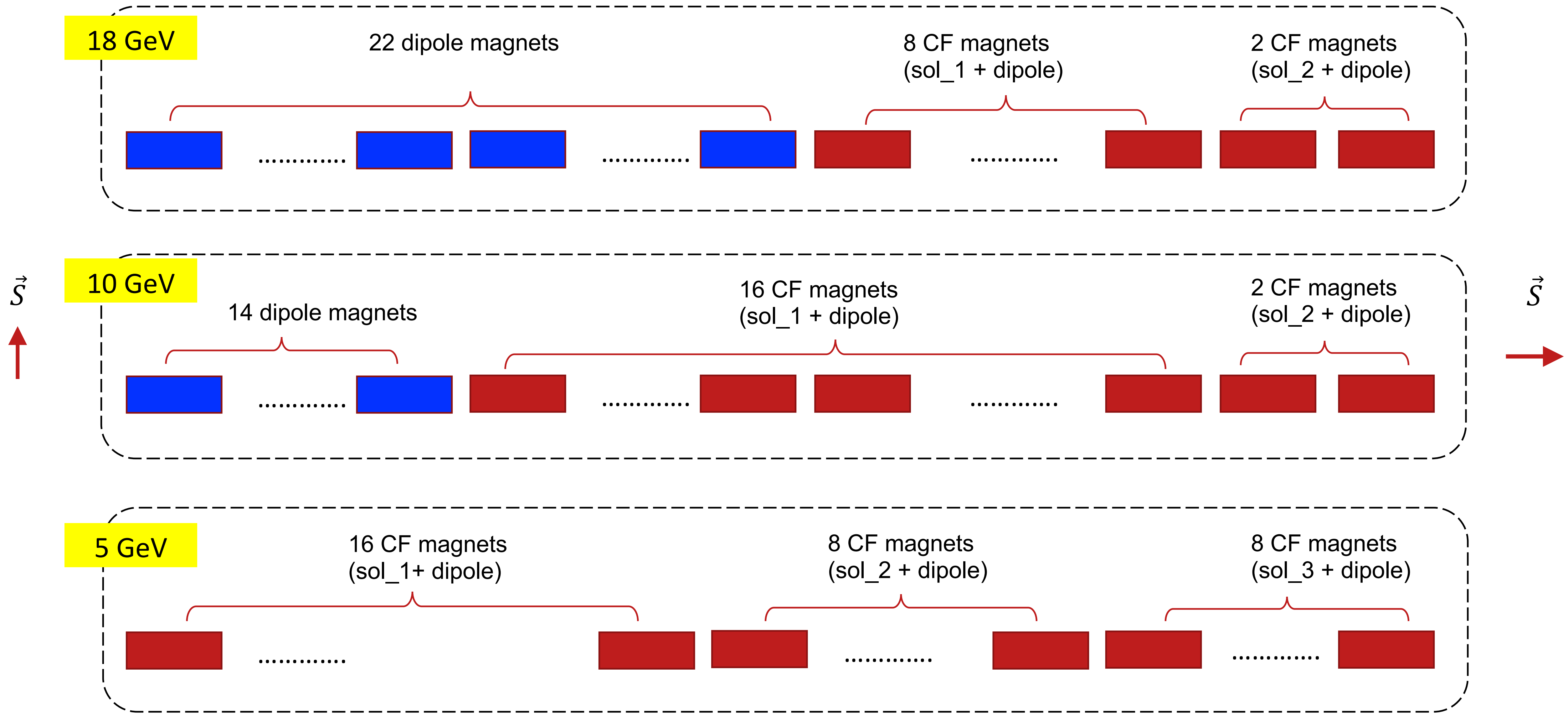
Solution with One Dipole and Two Solenoid Fields

energy (GeV)	5	10	18
number of combined-function magnet 1	6		
dipole field (T)	**0.172**	**0.169**	**0.167**
dipole length (m)	2		
dipole radius (m)	97.12	197.16	358.57
dipole 1 bending angle (deg)	1.17	0.58	0.32
Sol1 (T)	**2.27**	**4.68**	**8.63**
number of combined-function magnet 2	3		
dipole field (T)	**0.172**	**0.169**	**0.167**
dipole length (m)	2		
dipole radius (m)	97.12	197.16	358.57
Sol2 (T)	**1.01**	**1.19**	**1.01**



- Conclusion:
  - Dipole Dipole fields are almost constant in the whole energy range. This leads to
    - total bending angle is inversely proportional to the energy
    - either change the geometry to keep small orbit excursion in the magnets (shown on the orbit plots), or keep a fixed geometry but with large orbit excursions up to ~1m in the magnets
  - The first solenoid fields are almost proportional to the energy

Configuration of Spin Rotator with a Fixed Geometry



Solution with A Fixed Geometry and Three Solenoid Fields

energy (GeV)	5	10	18
dipole field (T)	0.044	0.088	0.167
dipole radius (m)	380		
dipole bending angle (deg)	0.3		
Sol1 (T)	**1.23**	**2.16**	**6.99**
Sol2 (T)	**-0.93**	**-3.61**	**1.73**
Sol3 (T)	**-0.45**	**0**	**0**
Number of pure dipole magnets	0	14	22
Number of combined function magnets	32	18	10

- Conclusion:
  - Dipole fields are scaled with the beam energy, so the geometry is fixed
  - Orbit excursion in the magnets < 2 mm
  - Maximum solenoid field < 7 T
- IF the spin rotator covers spin rotation in the whole energy range, the effective length may not be too compact.

Orbit

Spin

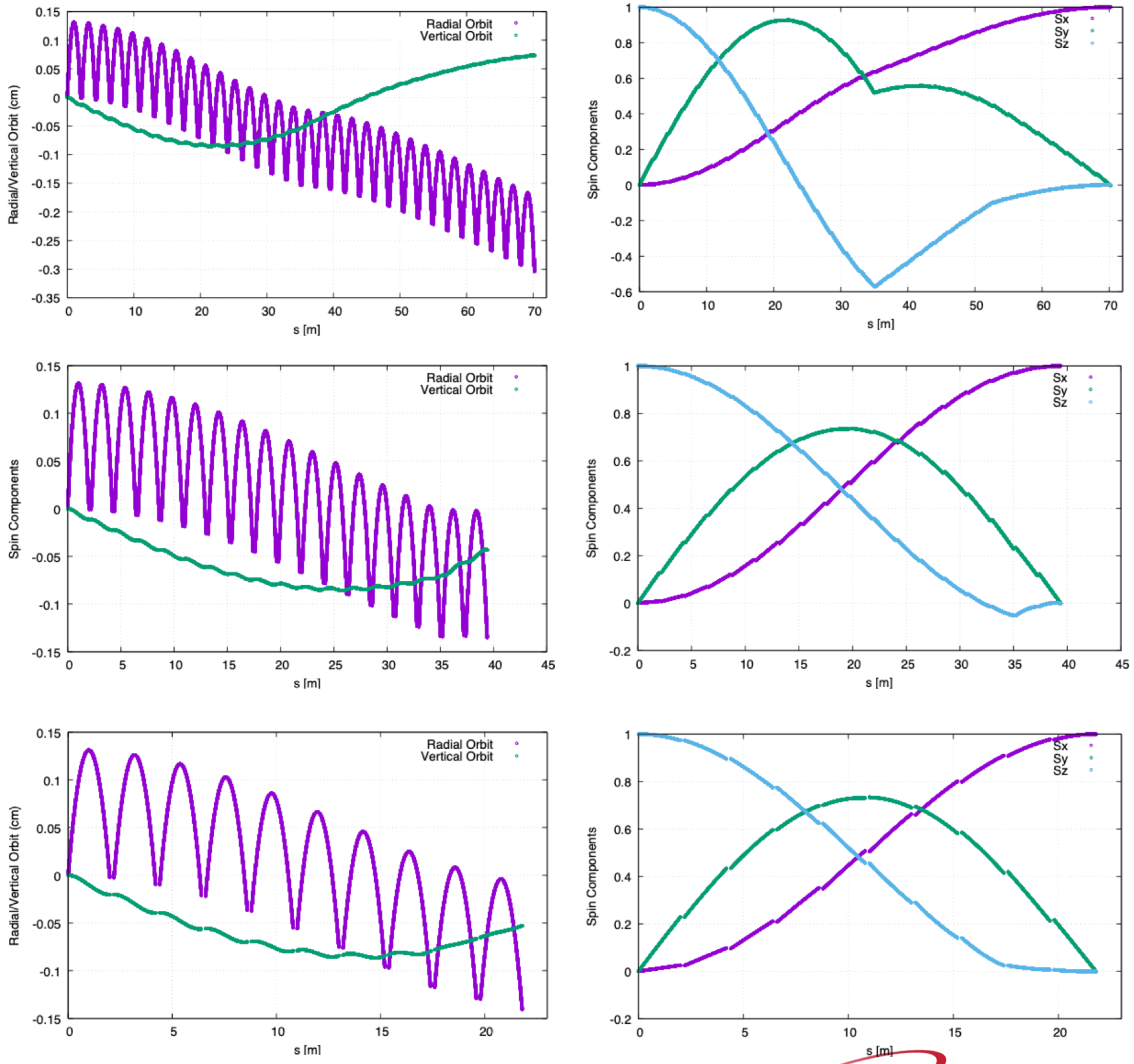
Sz: vertical

Sx: longitudinal

5 GeV

10 GeV

18 GeV



Summary and Outlook

- Study of the feasibility of a compact spin rotator in the EIC is carried out
- A few design scenarios have been explored considering the orbit and spin motions and applicability at different beam energies
- Future work
  - continue the optimization in the design to reduce the length of the spin rotator
  - consider to include radial dipole fields while control the vertical emittance contribution

Thank You for Your Attention !