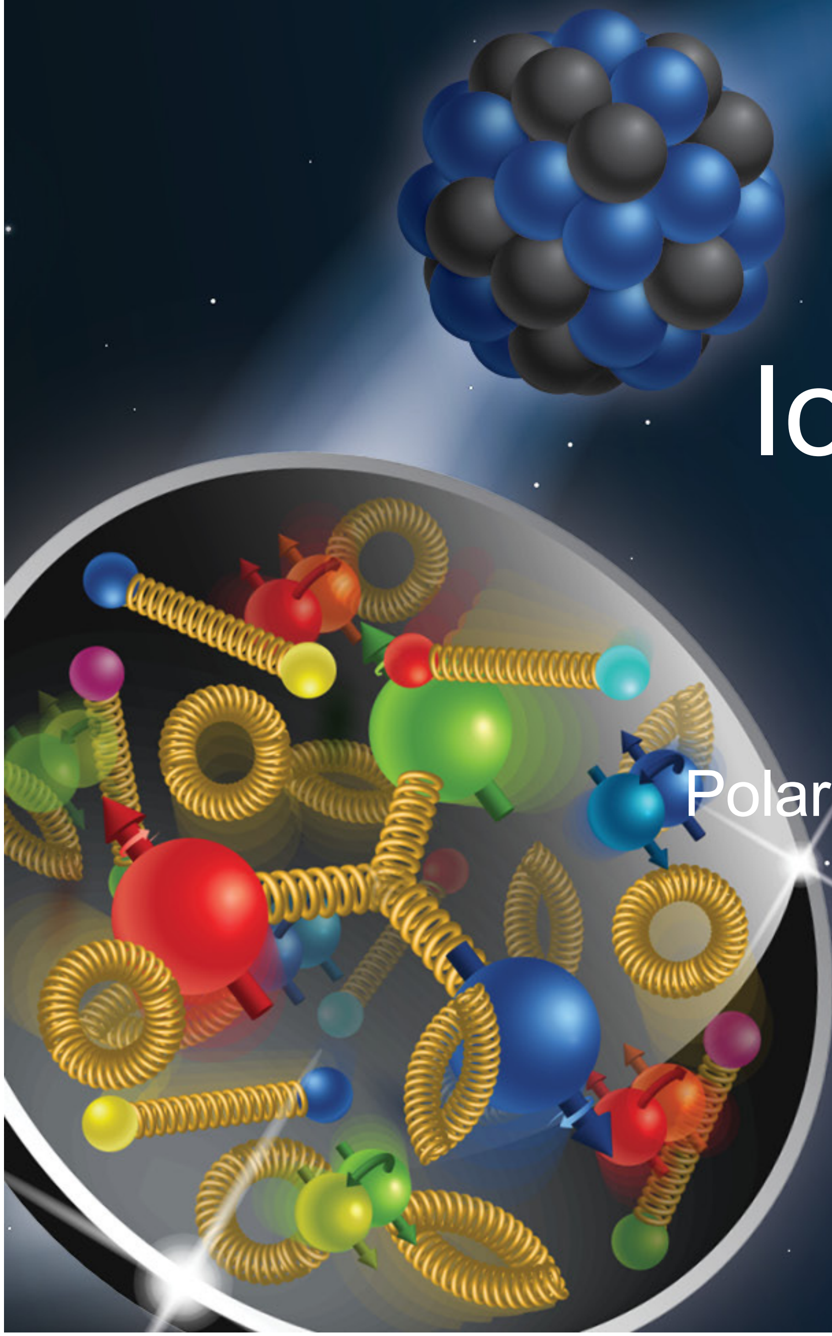

Ion Spin Rotation in IR

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Polarized Ion Sources and Beams in EIC, 2025
Workshop in SBU

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Electron-Ion Collider

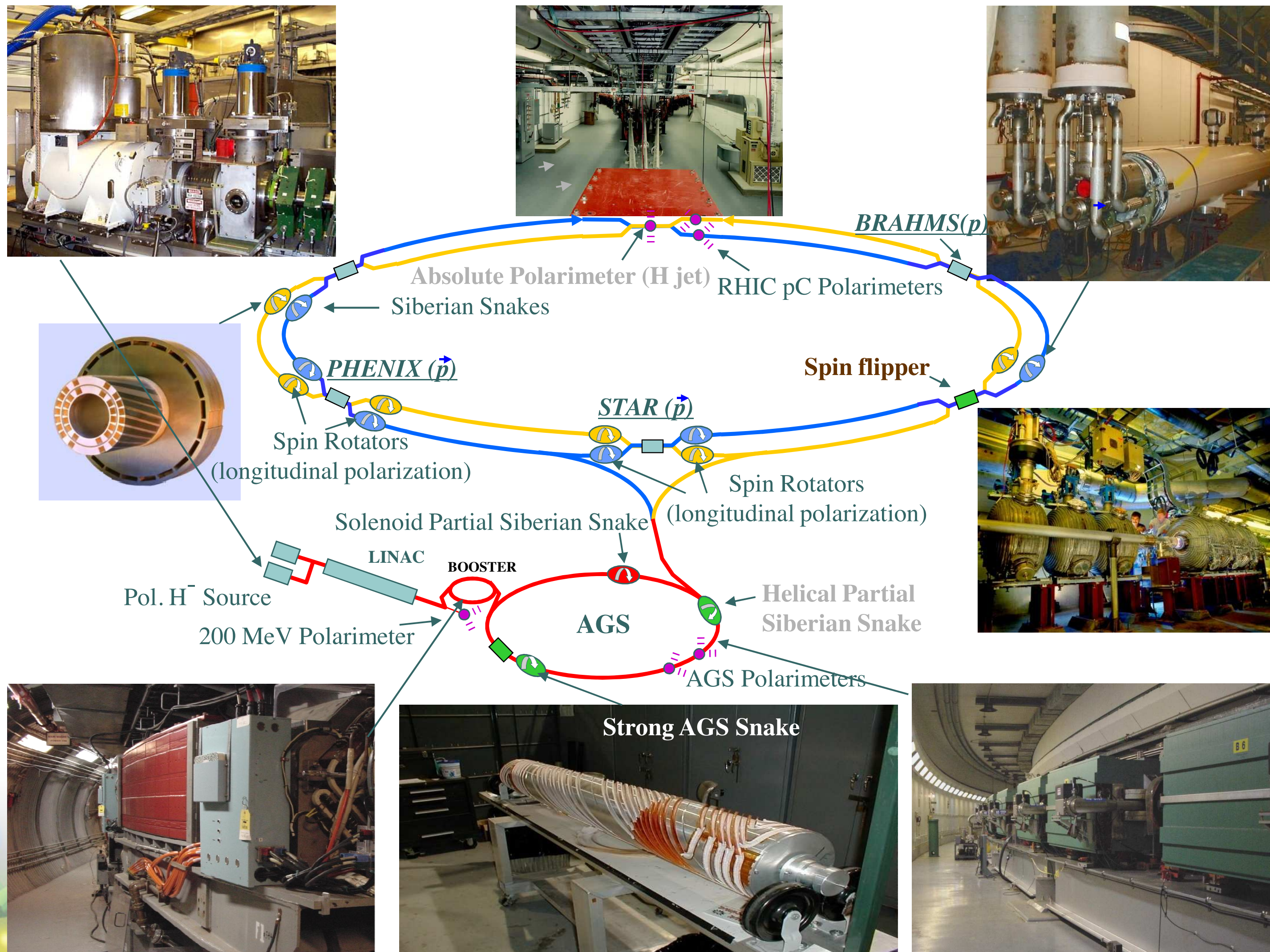
BROOKHAVEN NATIONAL LABORATORY
Jefferson Lab
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Helical dipole spin rotators in RHIC
- Spin rotators: difference in use between RHIC and HSR
- Energy operating range
- Spin tune shift
- Rotator parameters for He3 operation
- Longitudinal polarization for deuterons

RHIC Polarized Beam Complex

For more than 20 years provides polarized proton beam for physics experiments.



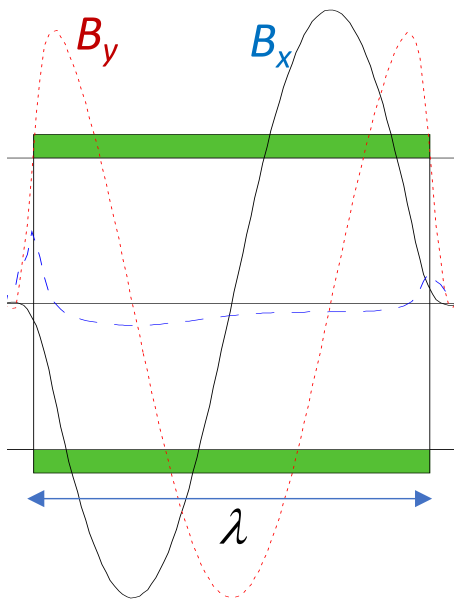
RHIS Spin Rotators

- Spin rotator use helical dipole magnets.
  Exactly, the same magnets as in the Snakes.
  Maximum field is 4T.
  But, unlike the Snakes, the orientation of the magnetic field in the center of the helical magnet is horizontal.

Main parameters of the spin rotators in RHIC

Number of helical magnets				4	
Total length				10.56 m	
Magnet bore				100 mm	
Helical Magnets					
	Length (effective)	Field helicity	Field orientation at entrance/exit	Field (25 GeV)	Field (250 GeV)
1	2.40 m	right-handed	Horizontal	2.1 T	3.5 T
2	2.40 m	left-handed	Horizontal	2.8 T	3.1 T
3	2.40 m	right-handed	Horizontal	2.8 T	3.1 T
4	2.40 m	left-handed	Horizontal	2.1 T	3.5 T
Max. orbit excursion (hor./ver.)			(25 GeV)	25 mm / 10 mm	
Total field integral				23 T-m	
Orbit lengthening			(25 GeV)	1.4 mm	

Spin Rotation: Helical Dipole



Paraxial helical dipole field (without magnet edges):

$$B_y = B_0 \cos ks, \qquad B_x = B_0 \sin ks$$

$$k = R\frac{2\pi}{\lambda}$$

Compared with common dipole the helical dipole has an additional parameter, Helicity R, which can be +1 or -1

Actual helical field is intrinsically nonlinear, as well as contains longitudinal off-axis component:

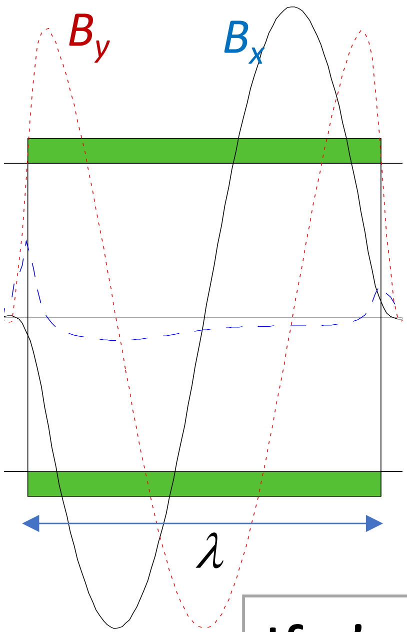
$$B_x \simeq -B_0 \left\{ \left[1 + \frac{k^2}{8}(3x^2 + y^2) \right] \sin(ks) - \frac{k^2}{4} xy \cos(ks) \right\}$$

$$B_y \simeq \quad B_0 \left\{ \left[1 + \frac{k^2}{8}(x^2 + 3y^2) \right] \cos(ks) - \frac{k^2}{4} xy \sin(ks) \right\}$$

$$B_s \simeq -B_0 k \left\{ 1 + \frac{k^2}{8}(x^2 + y^2) \right\} [x \cos(ks) + y \sin(ks)].$$

But, for initial evaluation of the spin and particle motion near the helical magnet axis, the <u>paraxial helical field is a good approximation.</u>

Orbit Motion in Helical dipole



Solution of the orbital motion in the paraxial approximation:

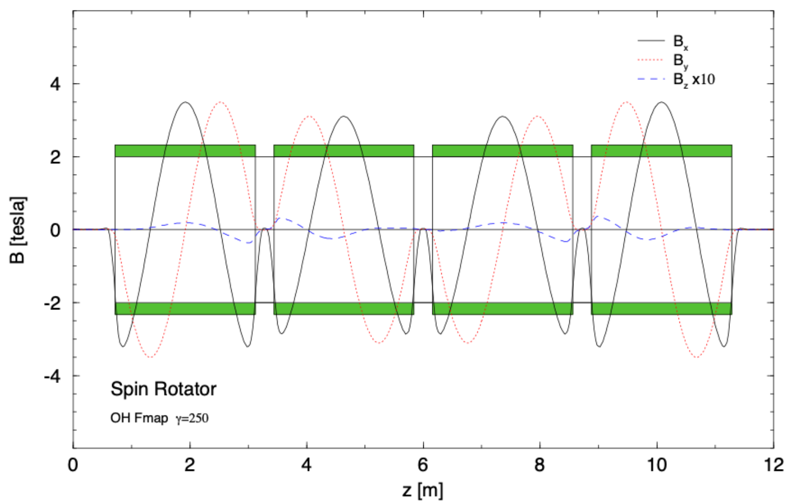
$$x(s) = -r(1-\cos(ks)) + x_0 + x'_0 s,$$
$$y(s) = -r\sin(ks) + y_0 + (y'_0 + kr)s$$
$$r = \frac{eB_0}{k^2 p}$$

If x'_0 and y'_0 the orbit shift after one helix period is just
$\Delta y = 2\pi R\, r$

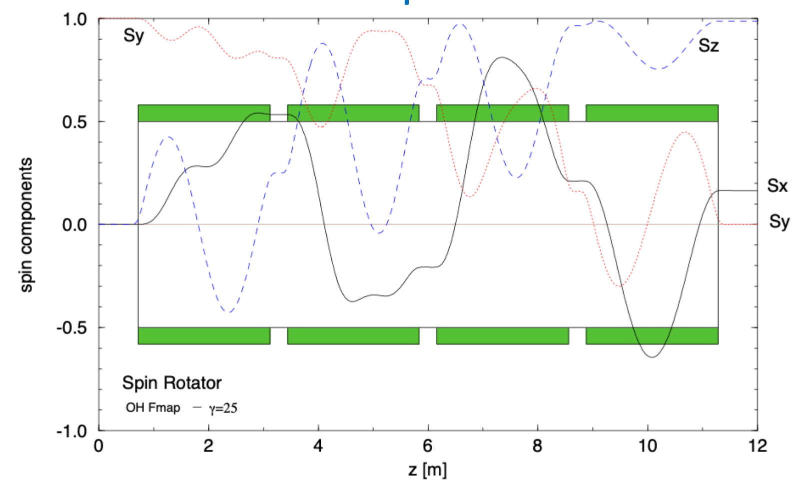
Simultaneous switching the sign of field and helicity produces does not change the orbit shift

RHIC Spin Rotators(2)

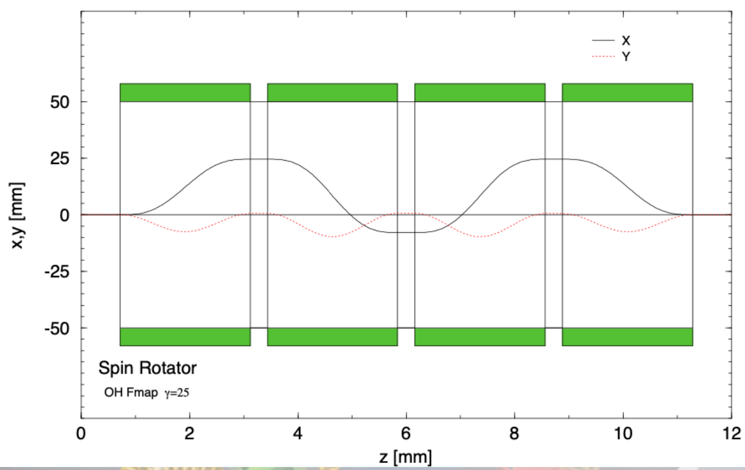
Magnetic Field



Spin



Orbit



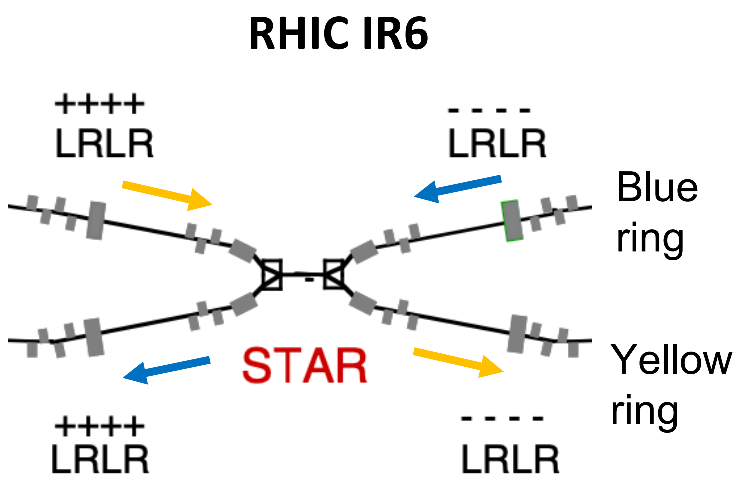
- Since there are dipole magnets (D0,DX) between the rotator and the IP, spin direction is not longitudinal after the rotator. The required spin direction varies with the beam energy.

- Due to large orbit excursion at the injection the spin rotators are turned on at the store energy.

From RHIC to HSR Spin Rotators

- EIC Hadron Storage Ring (HSR) will re-use the RHIC spin rotators.
- The rotators will be disassembled.
  The vacuum pipe will be replaced with a new pipe coated with copper and amorphous carbon layers to mitigate the effects of resistive heating and electron cloud.
  New BPM will be installed at the center of the rotator .
- In RHIC: total of 8 spin rotators
  In HSR : initially 2 spin rotators, then 4
  Helical modules off remaining spin rotators will be used to construct additional Snakes for the HSR

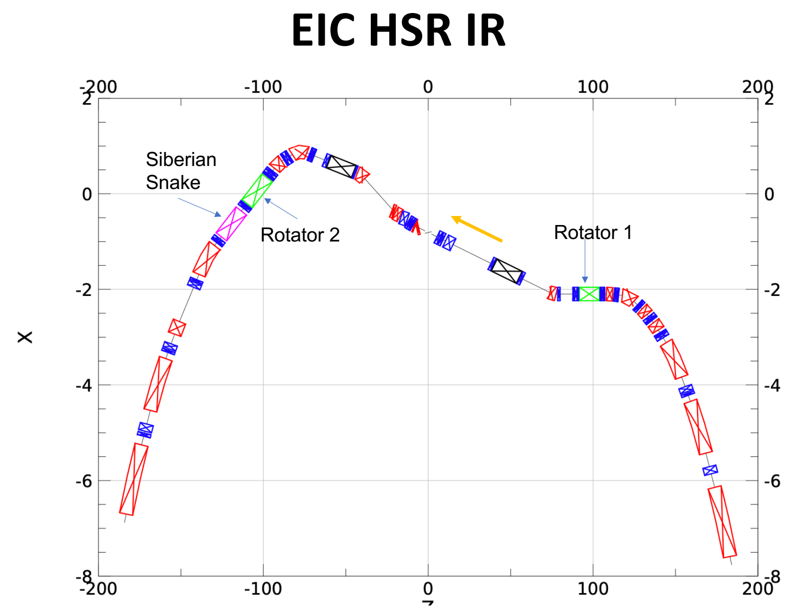
RHIC Spin Rotator are in symmetrical location



L/R –is the helicity of magnet
+/- is the sign of magnetic field

- The rotator are placed in 61.4 m from the IP
- The bending angle from the IP to rotators is +- 3.675 mrad
- The net bending angle between the RHIC spin rotators is zero
- When the rotators are turned on at the store the spin motion around the ring is not affected

EIC HSR Spin Rotators



- The EIC interaction region is much more complicated than in RHIC
- The rotator can only be placed further from the IP, and not symmetrically: at 97.8m and 107.8m
- The bending angles from the IP to rotators are also not symmetrical: -17 mrad and 61.35 mrad
- The net bending angle between the RHIC spin rotators is not equal to zero

HSR Rotator Operating Energy Range

The plot shows relation between rotator fields and the spin orientation after the rotator for protons

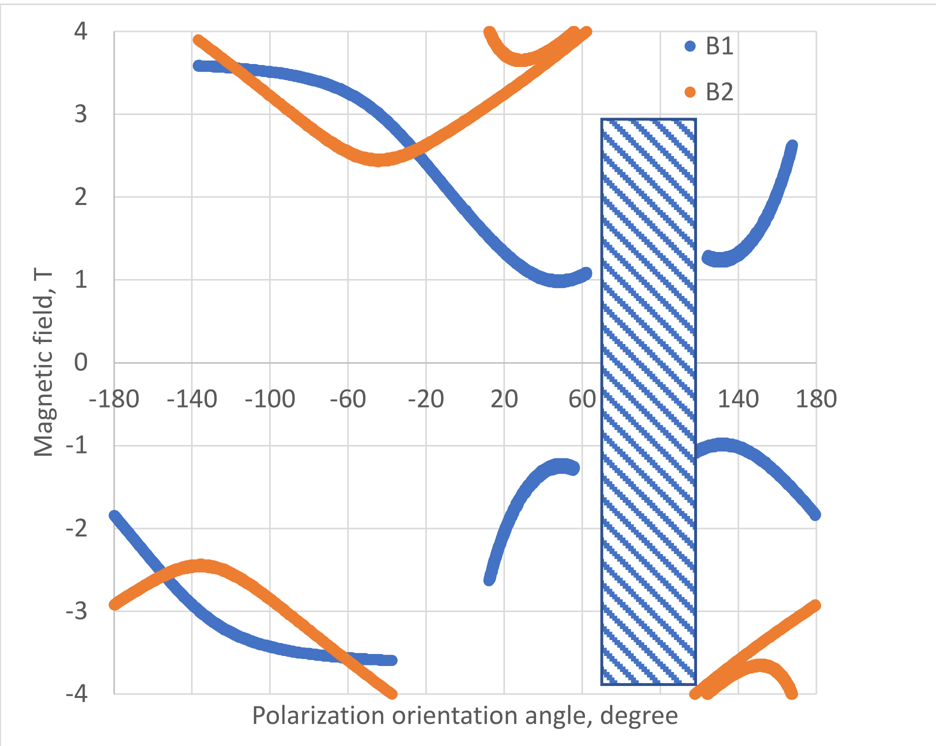


Table 2: The Proton Beam Energies Where the Longitudinal Polarization Can Not Be Realized

2nd rotator helicity configuration	Energies (GeV)
(L,R,L,R)	36-44, 250-257

The HSR main proton operating energies are 41 GeV, 100 GeV and 275 GeV.

HSR Rotator Operating Energy Range

The plot shows relation between rotator fields
and the spin orientation after the rotator for protons

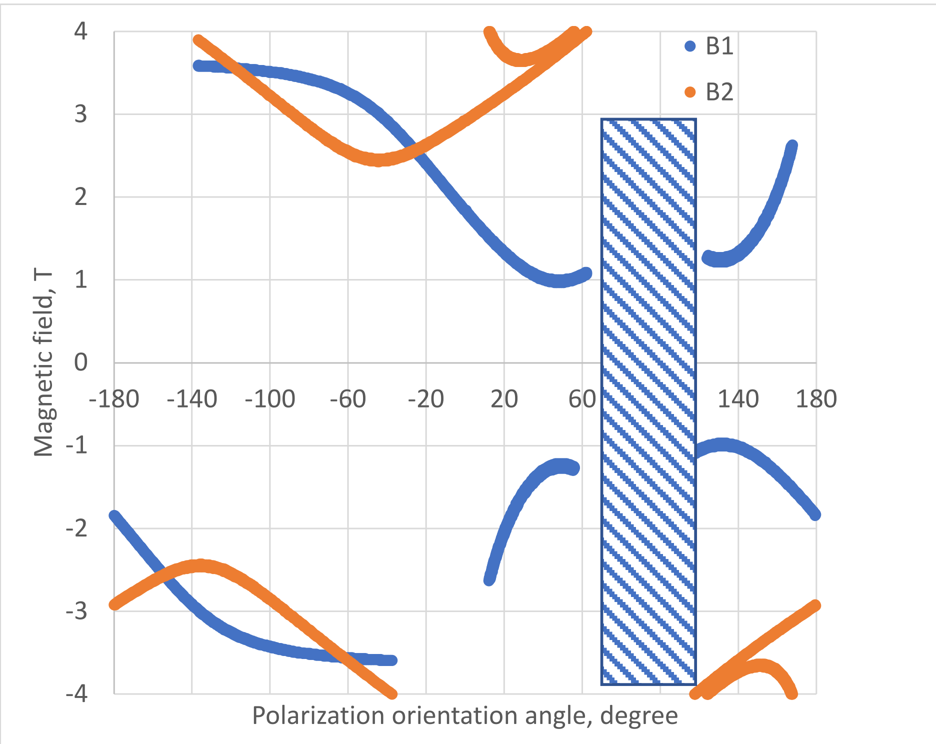


Table 2: The Proton Beam Energies Where the Longitudinal Polarization Can Not Be Realized

2nd rotator helicity configuration	Energies (GeV)
(L,R,L,R)	36-44, 250-257
(R,L,R,L)	143-151, 226-232

(R,L,R,L) configuration must be used to produce the longitudinal polarization at 41 GeV.

The sequence of the helical magnets in the 2nd rotator must be changed!

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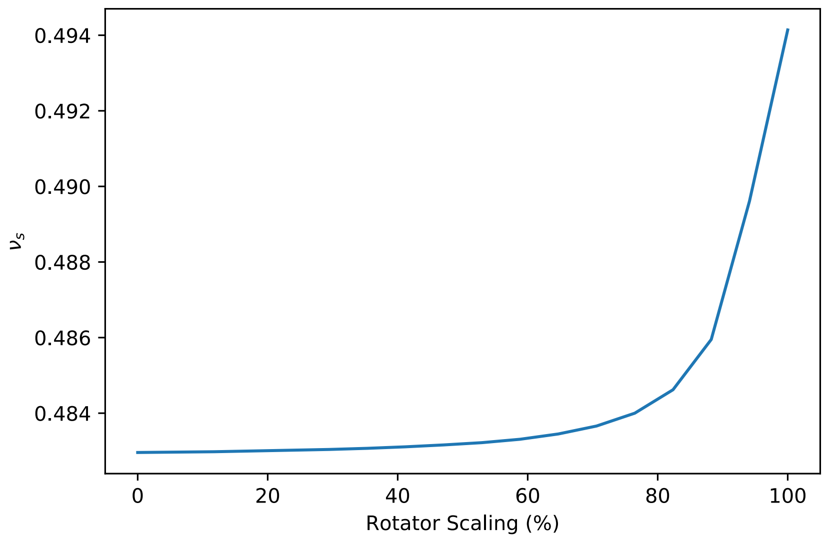
HSR Spin rotator turn on

The rotators are turned on at the store energy

Non-symmetric rotator arrangement results in the spin tune shift when the rotators are turned on the rotator turn-on.

@K.Hock

Spin tune shift ~0.01
when turning on the rotators at 275 GeV



Note: the spin tune is not exactly 0.5
with the rotators off because of a small alignment error in IR6
present during this calculation

This small spin tune shift can be mitigated by simultaneous adjustment of spin rotation axes in Snakes:

$$\nu_{sp} = \frac{1}{\pi} \sum_{i=1}^{3} (\alpha_{s,2i} - \alpha_{s,2i-1})$$

Helion longitudinal polarization

	p	$^3He^{+2}$
m, GeV	0.938	2.808
G	1.79	-4.18
E/u, GeV	24-275	16-183
$\|G\gamma\|$	46.5-525.5	72.6-819.4

- Due to considerably larger G the coupling of the spin to magnetic field is strong:
  - Smaller spin rotator field are required to realize the longitudinal spin
  - Smaller orbit excursion inside the rotators

Helion Spin Rotator Settings

@K.Hock

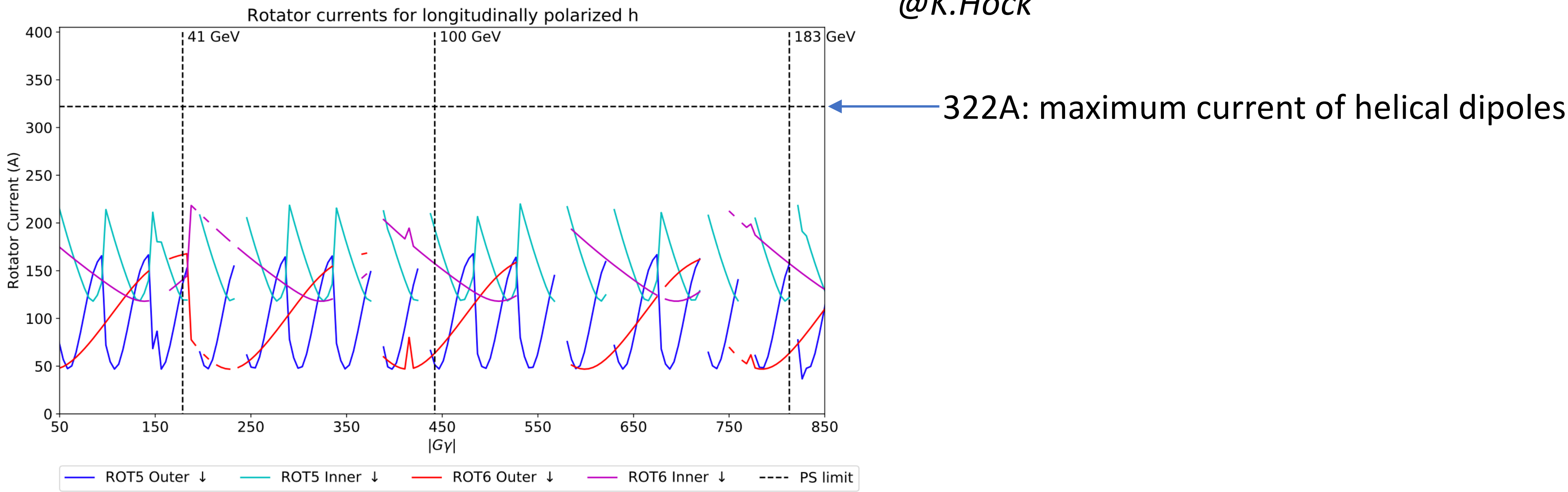


Table of power supply currents for the sector 5 (Rot5) and sector 6 (Rot6) at 41, 100, and 183 GeV.

Energy (GeV)	Rot5		Rot6	
	Outer	Inner	Outer	Inner
41	152.6	119.3	167.8	144.5
100	47.1	178.5	68.4	153.9
183	160.7	126.1	65.4	156.0

Polarized deuterons

	p	d
m, GeV	0.938	1.876
G	1.79	-0.143
E/u, GeV	24-275	12-137
$\|G\gamma\|$	46.5-525.5	1.6-20.9

- Polarization deuterons are not officially in the EIC Physics program.
  But they may become part of the program included in the future
- Deuteron G is order of magnitude less than for protons: stronger field is required for spin rotation
- Spin resonances are weaker and not so numerous.
  Deuteron polarization preservation during acceleration can be done applying the same techniques as in AGS (partial snake, tune jumps).
- But what about longitudinal polarization: helical spin rotators would require unreasonably large field (~300 T*m)

Deuteron longitudinal polarization

- Approach: use the beam energy which is close to an integer spin tune.

That is somewhat similar to Figure-8 approach (using small fields for deuteron polarization control) but works at particular deuteron energies
($G\gamma$ = int):

E_d *(GeV) = 131.5, 124.9, 118.4, 111.8, ... and so on*

ΔE *= 6.58 GeV at one detector operation*
ΔE *= 19.74 GeV at two detector operation (with the detectors in IR6 and IR8)*

- The spin direction control is defined by the combination of effects from the detector solenoid field and the artificial vertical orbit bumps introduced in the arcs:
  - The spin tune spread: $G\gamma*(\Delta p/p)_{rms}$ = 0.007
  - The vertical orbit bumps with ~5-6 mm amplitude is needed to overcome the spin tune spread and ensure the polarization is in transverse plane.

Summary

- HSR will re-use the RHIC spin rotators which are based on helical dipole magnets.
- Beam pipe and BPM of spin rotators will be upgraded
- The locations of spin rotators in the HSR are not symmetric, thus the area between spin rotators is not fully spin-transparent
- Sequence of helical magnets in 2nd rotator should be changed to produce longitudinal polarization at 41 GeV
- The spin tune during the rotator turn-on is ~0.01 and can be compensated by adjustment of Snake rotation axes.
- Spin rotator operation with 3He is simpler. Less field required.
- Longitudinal polarization of deuteron beam can be arranged near certain energies ($G\gamma$ ~ integer)

Thank You
for your attention!