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Snakes for the Hadron Storage Ring

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Abstract

The Electron Ion Collider calls for collisions of polarized proton and polarized helion beams on polarized electron beams. To preserve polarization of these polarized hadron beams during acceleration, six full helical snakes will be installed. As there are currently 4 snakes in RHIC, the remaining two snakes will be made from existing rotator magnet coils. The existing snakes are made from only right-handed helices where the rotator magnets are made from both right handed and left handed helicity magnets. In order for a sufficient stock of spare coils, one snake will be made of left handed coils. Simulations using Opera field maps in zgoubi show the left handed snake has sufficient range to provide the desired snake precession axes for helions and protons with the existing power supplies. This is an overview of the right and left handed snake assemblies and their effects.

Introduction

The Electron Ion Collider (EIC) Hadron Storage Ring (HSR) will be primarily constructed using existing components from the Relativistic Heavy Ion Collider (RHIC). The HSR will have six snakes, each of which are comprised of four helical dipoles, to preserve polarization of protons and helions up to their maximum collision energies. The purpose of these snakes is to rotate the spin vector 180° at each of the snake locations. To produce the six snakes, four will be directly repurposed from RHIC, two from the RHIC yellow ring and two from the RHIC blue ring. The remaining two snakes will be modified from existing RHIC rotator magnets. The existing RHIC snakes are comprised of four right-handed helicity (RH) helical dipole coils. The existing rotators are comprised of four helical dipoles, however they alternate between left-handed helicity (LH) and RH. In addition, the coils in the rotators are rotated ninety degrees about the longitudinal axis relative to the coils found in the snakes. Additional details on the rotators and snake configurations are documented in [1]. To maximize the amount of spare coils, one of the remaining two snakes will be made of only LH helical dipoles [2]. This will allow for four spare LH coils and four spare RH coils. Each coil has a maximum supported field of 4 T which corresponds to 322 A in the power supply [3] with the excitation noted in Fig. 1.

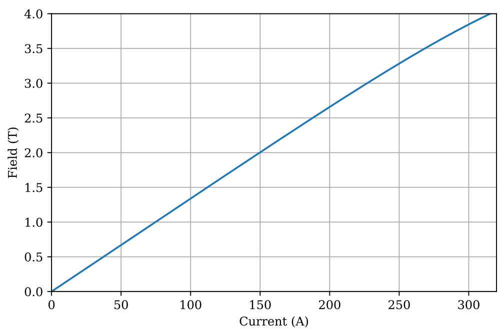

Figure 1: Excitation of the magnetic field in the snake coils as a function of current.

The helical dipoles have a period λ=2.4 m. The magnet period is defined as [4]

$$k = R\frac{2\pi}{\lambda} \tag{1}$$

with R being the helicity (that is -1 for LH and +1 for RH). The spin rotation from one coil is

$$\phi = \pi\sqrt{1+\chi^2} \tag{2}$$

where

$$\chi = (G + 1/\gamma)\frac{qB_o}{m\beta c|k|}. \tag{3}$$

with G being the anomalous gyromagnetic g-factor, q is the charge, m is the mass, B_o is the field amplitude, and c is the speed of light. This rotation occurs in the laboratory frame about the precession axis, defined as

$$u = [u_s, u_x, u_y]. \tag{4}$$

The precession axis for a single coil is defined as

$$u = \left[0, -\frac{R}{\sqrt{1+\chi^2}}, -\frac{\chi}{\sqrt{1+\chi^2}}\right]. \tag{5}$$

The total precession axis is a contribution from all four dipoles and can be defined as an angle in the horizontal plane, $\theta_{s,x}$. The axis as a function of $\theta_{s,x}$ is defined as

$$u = [\cos\theta_{s,x}, \sin\theta_{s,x}, 0]. \tag{6}$$

For a 180° rotation, the angle of the spin vector from the horizontal plane is $\theta_y = -90°$. These parameters are noted in Fig. 2.

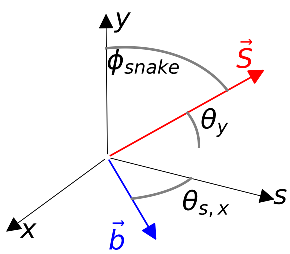

Figure 2: A visual of the snake coordinate system with relevant parameters shown.

An example 45° precession axis corresponds to =[0.707, 0.707, 0]. The notation for representing the sign of the field of the coil is denoted either (+) or (-). For the standard helix configuration of right handed helices and alternating the sign of B_o, it is labeled as R+R-R+R-. The two outer coils are powered together with current I_{out} and the two inner coils are powered with current I_{in}. The spin tune in the presence of full snakes is defined as

$$\nu_s = \frac{1}{\pi}\sum_{k=1}^{N_s}(-1)^k\phi_k. \tag{7}$$

where ϕ_k is the azimuthal location in the ring, and k is the snake number. For a nominal 6-snake configuration, example snake axes of ±15° and ±45° satisfy $\nu_s = n{+}0.5$, with n being an integer [5, 6]. These axes support ν_s=0.5 and $\nu_s = 1.5$, respectively. Relevant parameters for protons and helions are found in Tab. 1.

Table 1: Relevant parameters for protons and helions.

	G	q	m (GeV/c^2)
proton	1.7928474	1	0.93827209
helion	-4.1841536	2	2.80839148

It is convenient to define the maximum vertical orbit excursion, y_{max}, the vertical orbit match requirement, y_{match}, and the maximum supported β_y to provide zero clearance for a 6σ beam, $\beta_{y,max}$. An example vertical orbit is shown in with both y_{match} and y_{max} in Fig. 3.

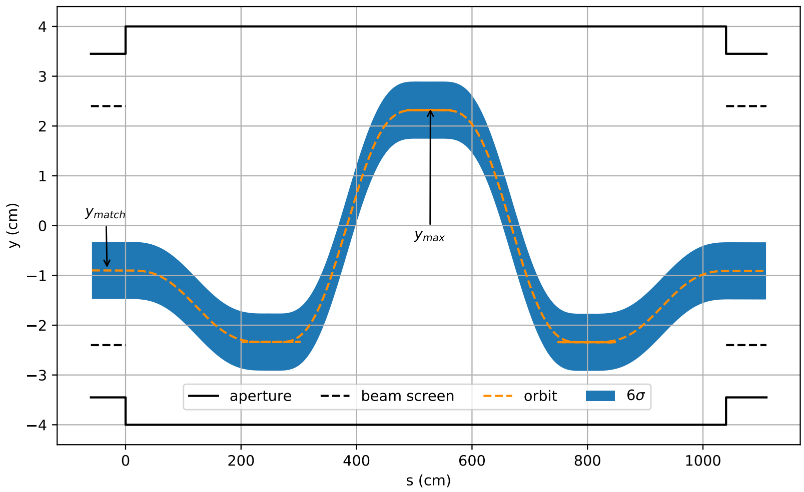

Figure 3: Example aperture diagram with the vertical orbit in the snake, the 6σ beam envelope, the physical aperture of the snake and beam screen, and y_{match} and y_{max} labelled.

Snakes

Proton Configurations

For the case of protons to rotate the spin vector 180° about a precession axis of 45°, the required currents are I_{out}=100 A and I_{in}=322 A. These currents are near the limit of the supply, leaving little to zero margin for tuning. Another caveat of being near the maximum current, the orbit excursion at injection would be large. The $\pm 15°$ has the benefit of a reduced total current, and the axis sits near the $I_{in} = 2I_{out}$ line (which results in zero orbit outside of the snake), reducing the orbit match requirements in the accelerator.

The attainable precession axis while remaining under the PS limits is seen in Fig. 4 where the symmetry between left (bottom) and right (top) handed helices is apparent. Here, the topography is calculated using the formulation

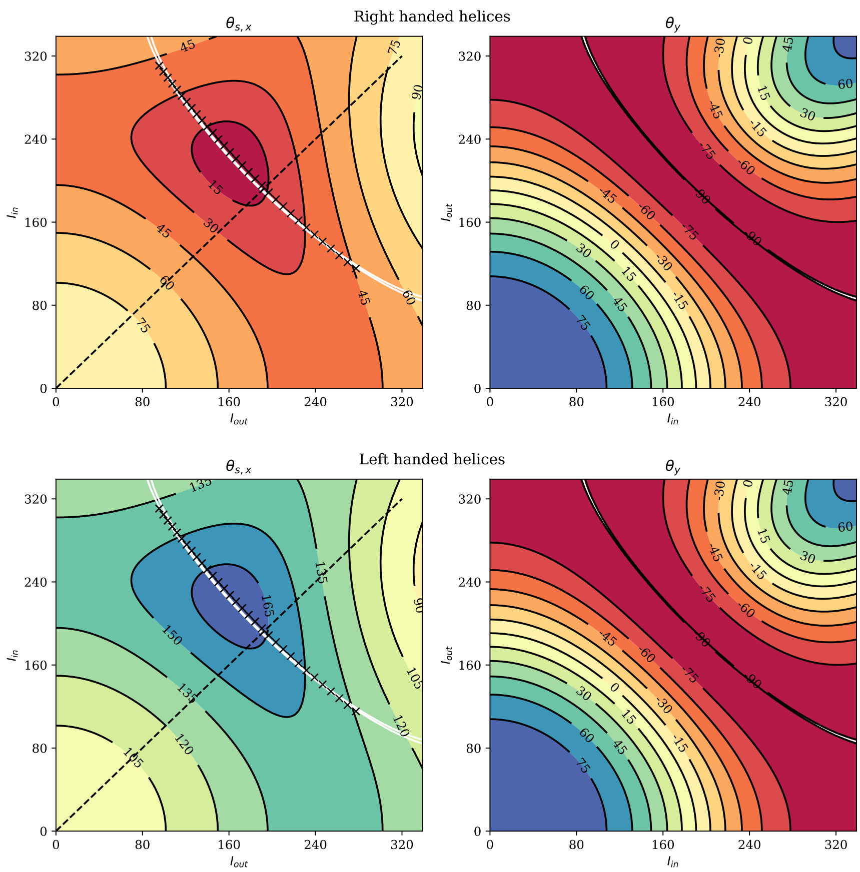

Figure 4: Attainable snake axes for protons, using right-handed (top) and left-handed (bottom) helices. The dashed line corresponds to $I_{out} = I_{in}$ to denote the region of a symmetric orbit. The 'x' marks correspond to calculations with field maps which agree closely with the numerical model.

of the Introduction, and the 'x' marks are from tracking using the field maps. This tracking has the constraints of θ_y=-90 and $\{\theta_{s,x} \in (-45, ..., 45)\}$, using zgoubi and its preinstalled fitting routine. The results of this tracking are also shown in Fig. 5. Relevant parameters are summarized in Tab. 2.

Table 2: Snake currents to achieve ±45° and ±15° and an evaluation at injection of the vetical orbit excursions, matching requirements, and the maximum supported β_y to provide zero clearance for a 6σ beam.

Angle	Species	I_{out}	I_{in}	y_{max} (cm)	y_{match} (cm)	$\beta_{y,max}$ (m)
±15	p	136	247	1.897	0.222	289.9
±45	p	100	322	2.331	0.888	182.6

Calculations using field maps of $\theta_{s,x}$ with respect to the inner and outer power supplies currents, with different field configurations (+-+- and -+-+), and with different handed helicities, is shown in Fig. 5. From this figure, it is apparent that only axes from $-45°$ to $+45°$ and 135° to 225° (by flipping the sign of B_o) can be achieved.

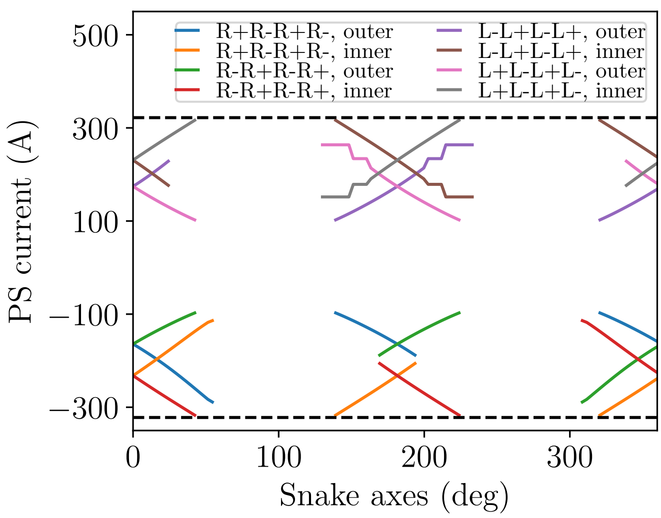

Figure 5: Proton case of inner and outer PS currents required to achieve the specified precession axis for RH and LH helices and different B_o.

Fig. 6 shows a comparison of the horizontal (top) and vertical (bottom) orbits for the ±15° (left) and the ±45° (right) precession axes. As noted in Tab. 2, the orbit requirement for the ±15° axis to match with the accelerator is minimal when having the orbit centered in the snake. As noted in Tab. 2, $y_{match}(\pm 15°) = 0.222$ cm and $y_{match}(\pm 45°) = 0.888$ cm.

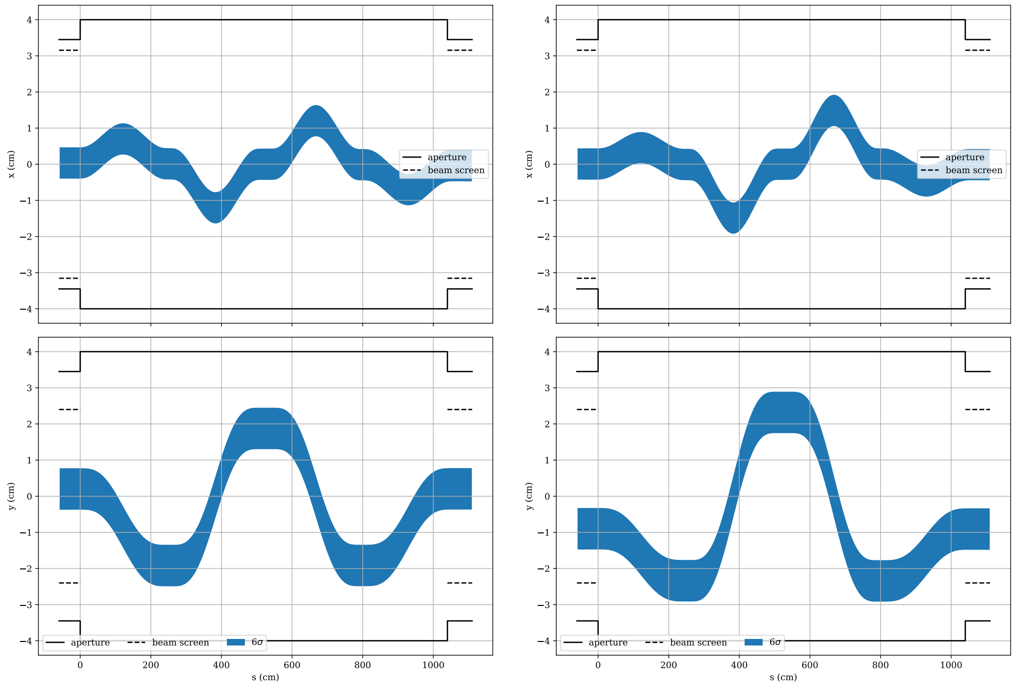

Figure 6: Proton orbits in a 15° snake (left) and a 45° snake (right).

Helion Configurations

For the case of helion, $G = -4.1842$ with the equivalent configuration as protons to rotate the spin vector for protons 180° with a precession axis of 45° in the horizontal plane is to have the outer coils powered at I_{out}=65.5 A, and the inner coils at I_{in}=211 A. For powering an equivalent magnet that is only made of left handed coils rotates the spin vector about a precession axis of 135°, equivalent to a -45° rotation. Due to the higher G of helions compared to protons, the snakes are able to satisfy almost all possible snake precession axes. The precession axes are seen in Fig. 7 where the symmetry between left and right handed helices is apparent. Note that nearly the full array from 0 to 360° can be satisfied while remaining under PS limits.

Comparing Fig. 4 with Fig. 7 it is obvious that polarized helions have a much broader range of available precession axes that the snakes can satisfy. The primary set of axes that are of interest are ±15°, ±45° and $0, 90°$. The current requirements, and orbit evaluation at injection is summarized in Tab. 3. Here it is important to note that the 90° axes requires large current with $I_{out} > I_{in}$, resulting in a large orbit match requirement. In this case, the orbit matching requirement is outside of the beam screen aperture of 2.4 cm.

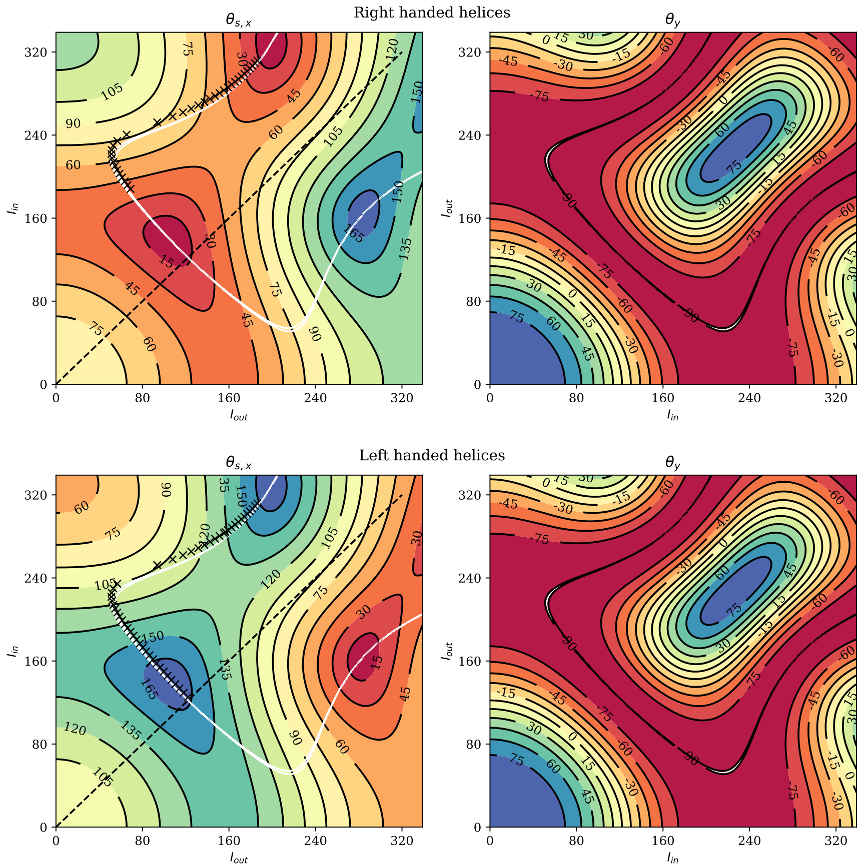

Figure 7: Attainable snake axes for helions, using right-handed (top) and left-handed (bottom) helices. The dashed line corresponds to $I_{out} = I_{in}$ to denote the region preferential for minimal orbit excursions, $I_{out} < Iin$. The 'x' marks correspond to calculations with field maps which agree closely with the numerical model.

Table 3: Snake currents to achieve 90°, ±45°, ±15°, and 0°, and an evaluation at injection of the vetical orbit excursions, matching requirements, and the maximum supported β_y to provide zero clearance for a 6σ beam.

Angle	Species	I_{out}	I_{in}	y_{max} (cm)	y_{match} (cm)	$\beta_{y,max}$ (m)
0	h	103	137	1.540	-0.785	396.6
±15	h	86	156	1.751	-0.198	331.5
±45	h	59	193	2.237	0.979	203.6
90	h	229	62	2.534*	2.534*	0

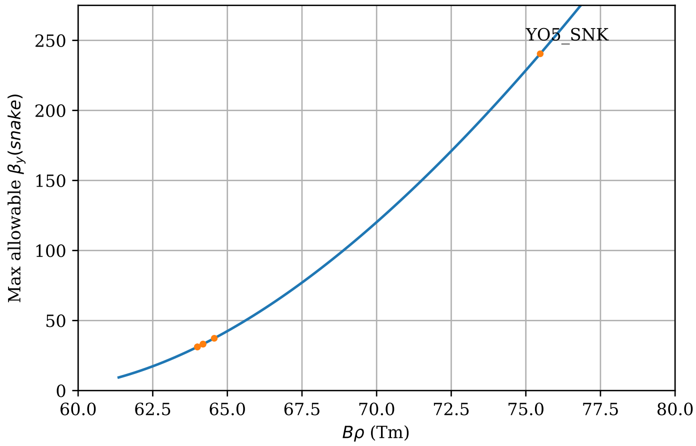

Figure 8: The maximum supported β_y as a function of $B\rho$ at a 90° snake for polarized helions, with existing snakes marked in orange.

At injection $|G\gamma| = 49.5$, $B\rho$=55.2 Tm which is significantly lower than that of protons at $G\gamma = 45.5$ ($B\rho$=79.4 Tm). This lower rigidity results in larger orbit excursions, which reduces the available axes due to aperture constraints. The maximum supported β_y as a function of $B\rho$, taking into account the reduction in beam size and the reduced orbit excursion with increased energy, is shown in Fig. 8. At a minimum, $B\rho$=61.35 Tm ($|G\gamma| = 54.96$) would be needed to achieve the 90° axis. This involves crossing the very strong $|G\gamma| = 60 - \nu_y$ in the Alternating Gradient Synchrotron. This also assumes zero clearance when considering actual beam sizes with 2 μm assumed for injection. Simulations in the AGS show that it is possible to cross the $|G\gamma| = 60 - \nu_y$ resonance in the AGS with two cold snakes, each with a strength of 25% [7]. The yo5 snake, labelled as "YO5_SNK" in Fig. 8, is located in the low beta insertions of IR6, resulting in a larger β_y which would required an even larger injection $B\rho$. It is possible for this snake to operate at 0° in the 0, 90° snake scheme which would eliminate this requirement.

A comparison of the orbits at injection ($|G\gamma| = 49.5$) with a 45° and a 90° is shown in Fig. 11. Although the total orbit excursion of the two are similar, the 45° requires a matched orbit amplitude of 9.8 mm to have the orbit centered, whereas for 90° the matched orbit is 25.3 mm. Due to 0° being near the symmetry line in Fig. 7, the matched orbit amplitude will be minimal.

The current on the power supplies for the inner and outer currents, with different field configurations, and with different helicities, is shown in Fig. 10. This figure also shows that the snakes with polarized helions can support

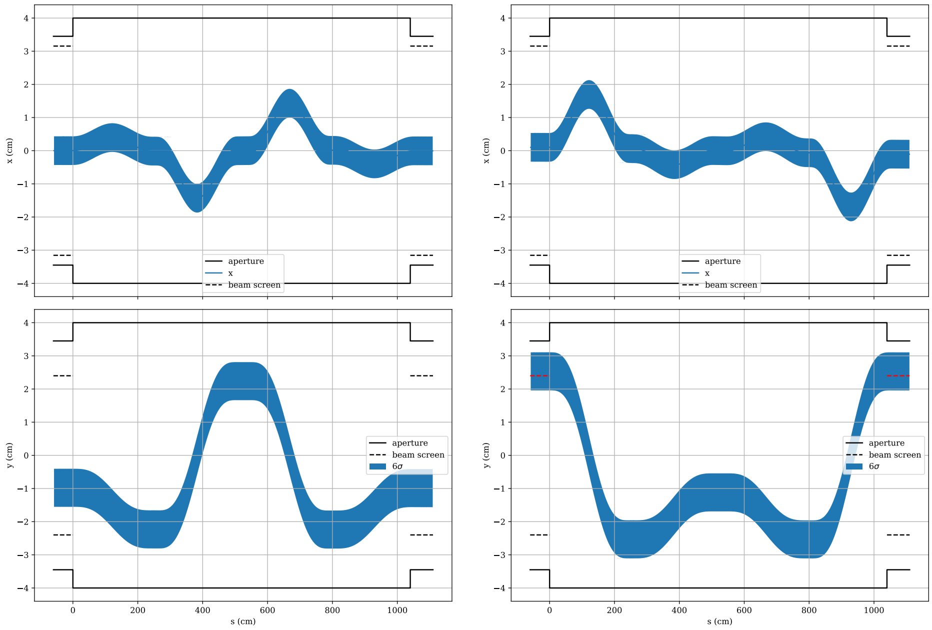

Figure 9: Helion orbits in a 45° snake (left) and a 90° snake (right).

almost all snake axes.

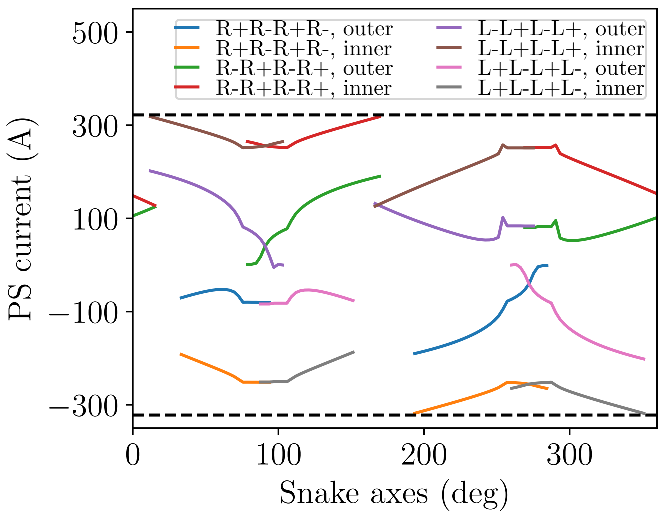

Figure 10: Helion case of inner and outer PS currents required to achieve the specified precession axis for RH and LH helices and different B_o.

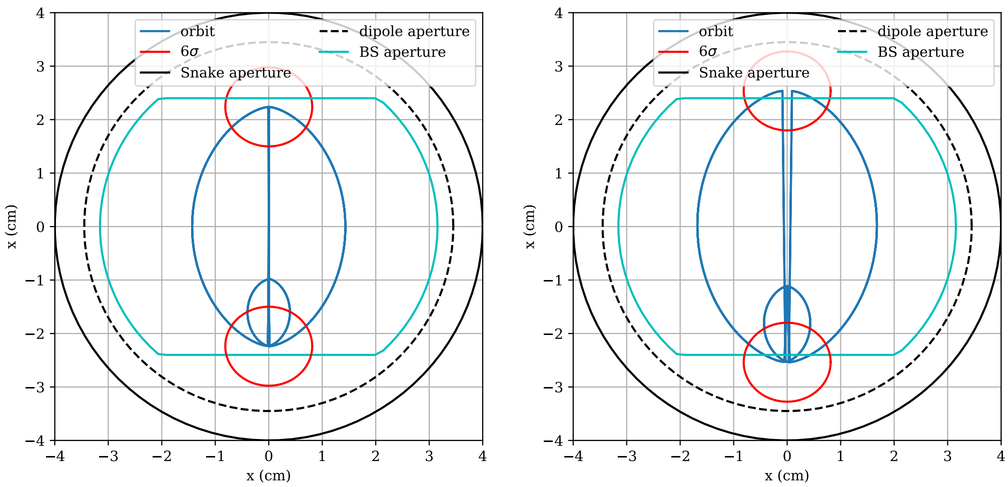

Figure 11: Orbits of helions through the snakes with physical apertures and the 6σ envelopes for a snake axis of 45° (left) and 90° (right).

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Snake ramp diagrams for RHIC

The snake ramp rates and currents as documented in [8].