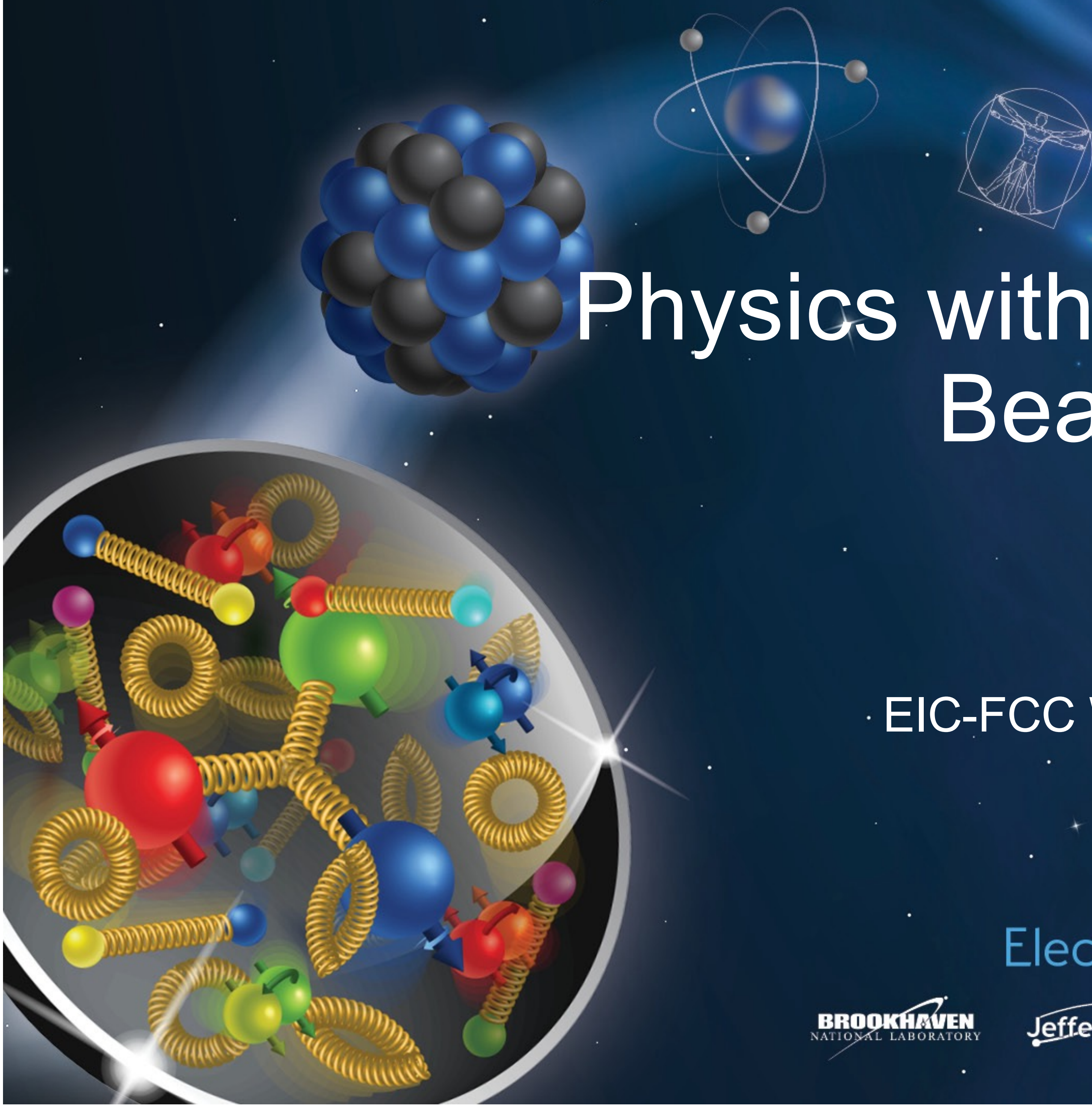

Physics with Polarized Beams in EIC

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EPOL 2022
EIC-FCC Working Meeting on e+e- polarization
September 20, 2022

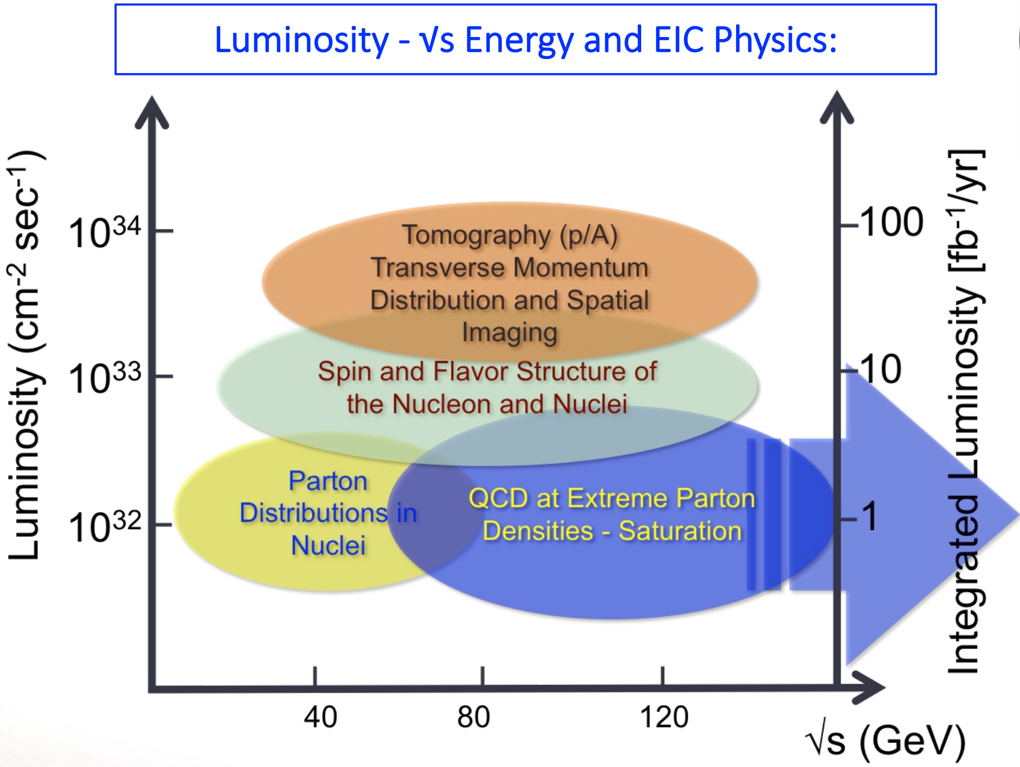
Electron-Ion Collider

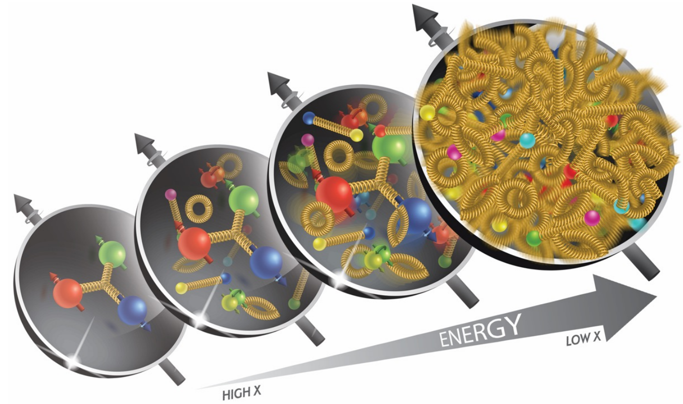
BROOKHAVEN NATIONAL LABORATORY · Jefferson Lab · U.S. DEPARTMENT OF ENERGY Office of Science

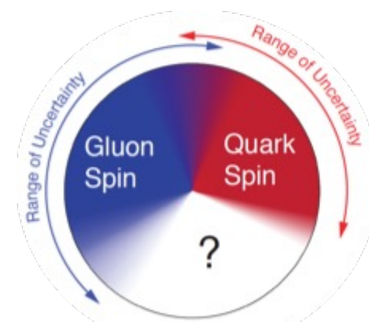
Outline

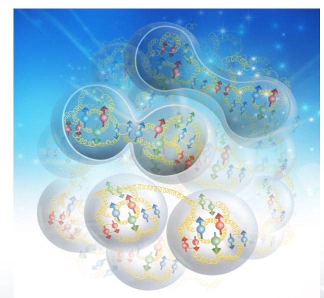
- Physics requirements on polarization in EIC
- Hadron (p, $^{3}He^{+2}$) polarization in EIC
- Hadron spin rotators
- Electron polarization setup in EIC
- Electron polarization in the source and RCS
- Spin rotators in electron storage ring
- Electron polarization challenges
- Conclusiions

What is needed experimentally?

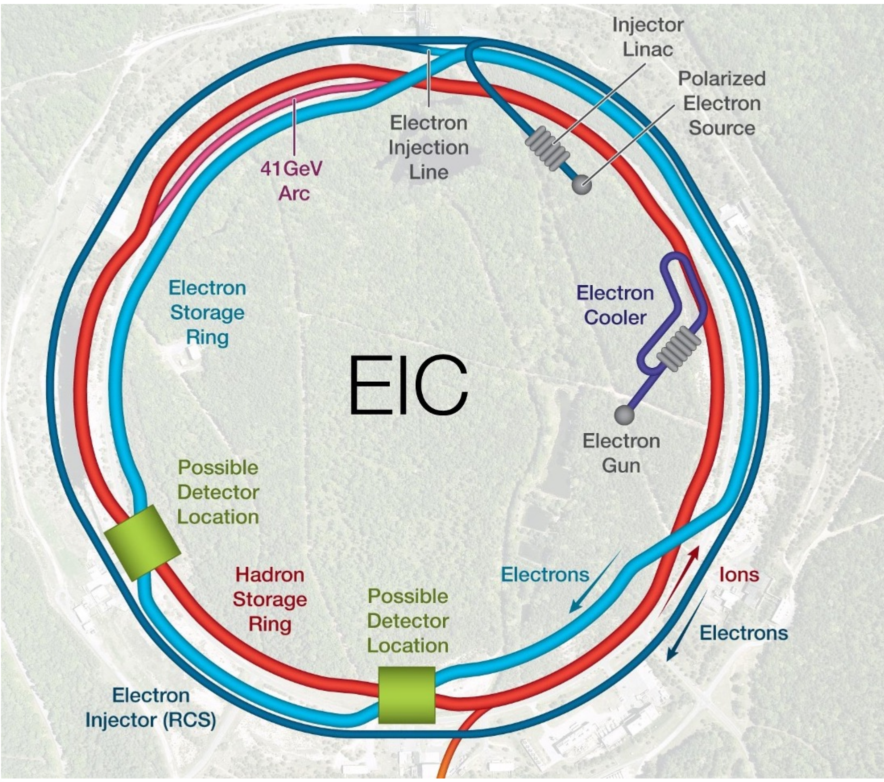






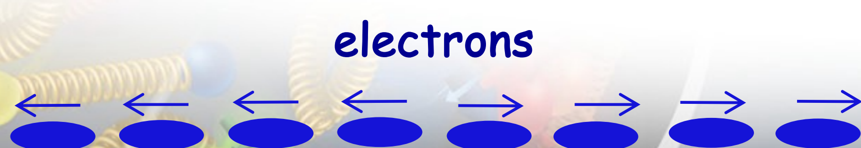


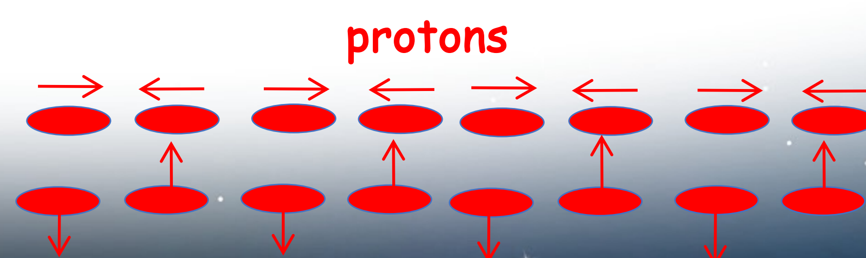
EIC Polarized Beam Requirements



- ❖ Highly polarized beams of:
  - Electrons
    (polarization goal: 70% average)
  - Proton, ^{3}He
    (polarization goal: 70%)

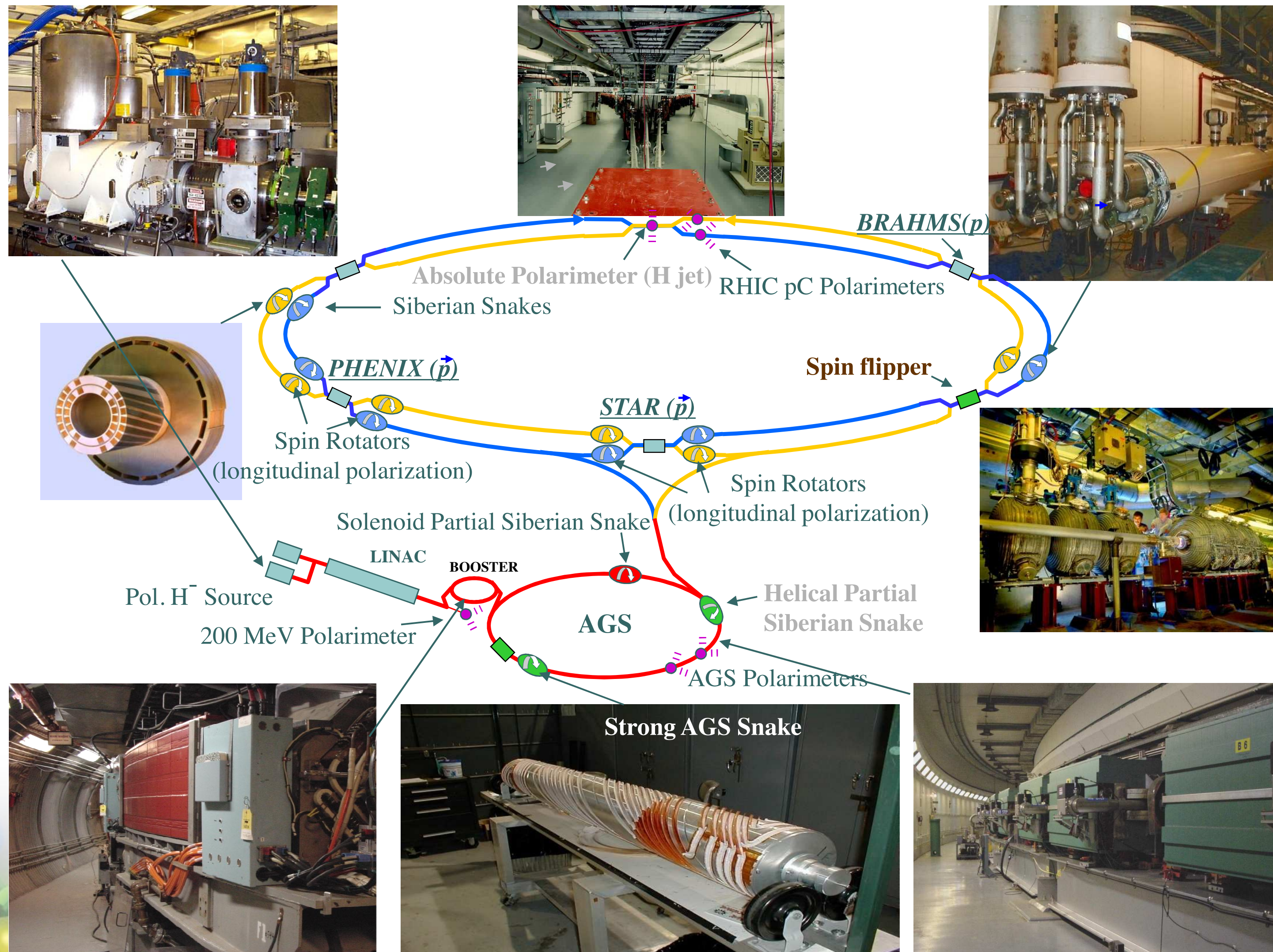
  Note: Polarized deuterons under discussion.
- ❖ Spin orientation at the collision point:
  1. Electrons: longitudinal
  2. Hadrons: longitudinal or vertical
- ❖ Using bunches with opposite spin orientation on the same fill





RHIC Polarized Beam Complex

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



RHIC Polarization: current status

- Provided polarized protons for experiments in energy range from 31 Gev to 255 GeV.
- Polarization 60% at 255 GeV has been delivered
- Two full Siberian Snakes are used in each of the two present RHIC rings to maintain polarization
- Feedback during acceleration – on the betatron tune, coupling, and orbit – is crucial for polarization preservation.
- EIC polarization goal: 70% at 275 GeV.
  Also, polarized ^{3}He will be used.

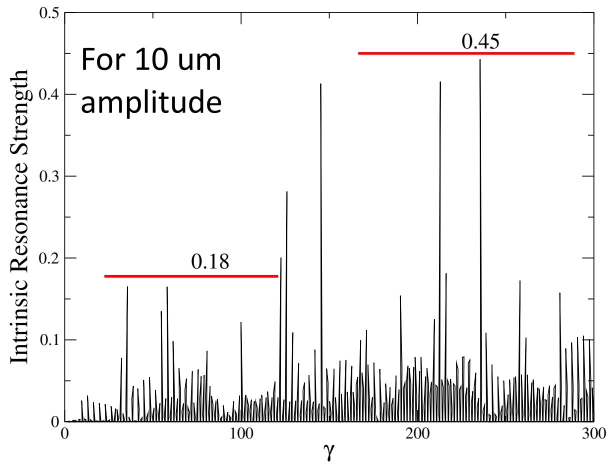
RHIC Siberian Snakes

➢To overcome spin resonances during acceleration in RHIC Siberian Snakes are used (two per ring)

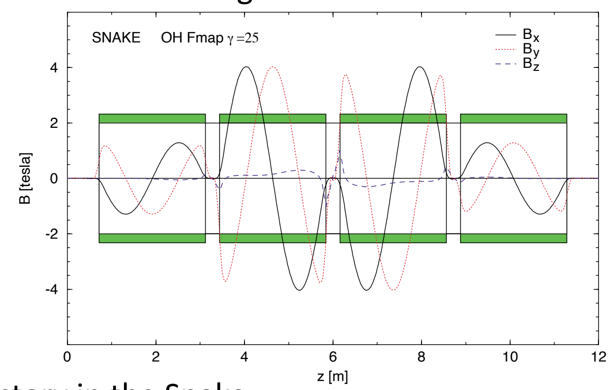
➢Siberian Snake produces spin rotation by 180 degree around a rotation axis in horizontal plane

➢Proper located Snakes produce the spin tune at constant value (1/2) avoiding spin resonances

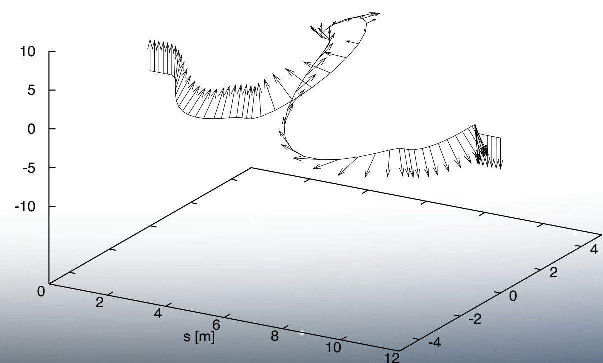
➢Each Siberian Snake: 4 SC helical dipoles, up to 4 T, each 2.4 m long and full 360° twist



Magnetic field of the Snake



Particle orbit and spin trajectory in the Snake



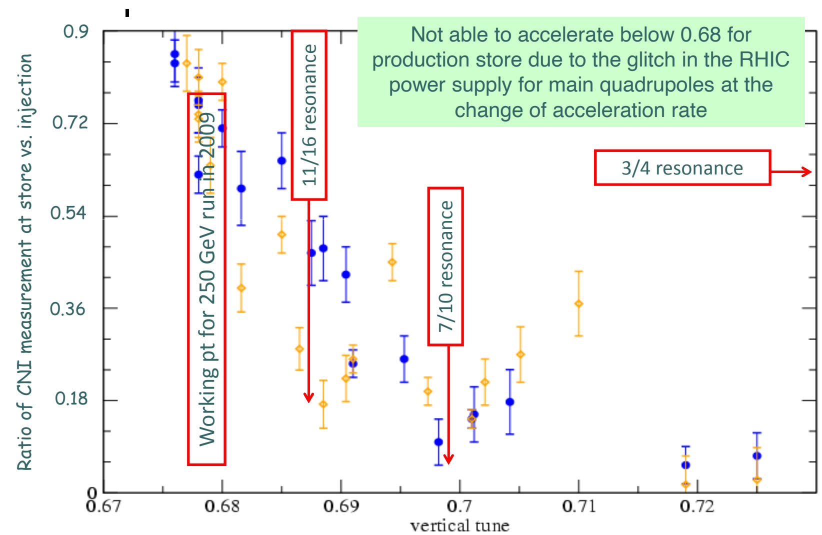
Snake Resonances in RHIC

- Depolarization can still happen at certain vertical betatron tunes due to higher order resonances (n>1):

  $\frac{1}{2} = m \pm nQ_y$

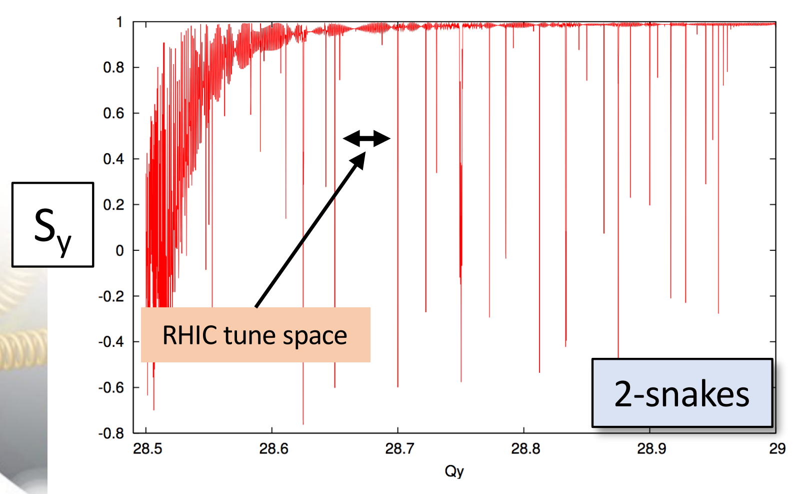
- Far more tune space available in six snake configuration
  - Important for flexibility in the face of complicated beam dynamics (high peak currents, interaction with coolers, etc)

Experimental observation of Snake Resonances in RHIC M.Bai

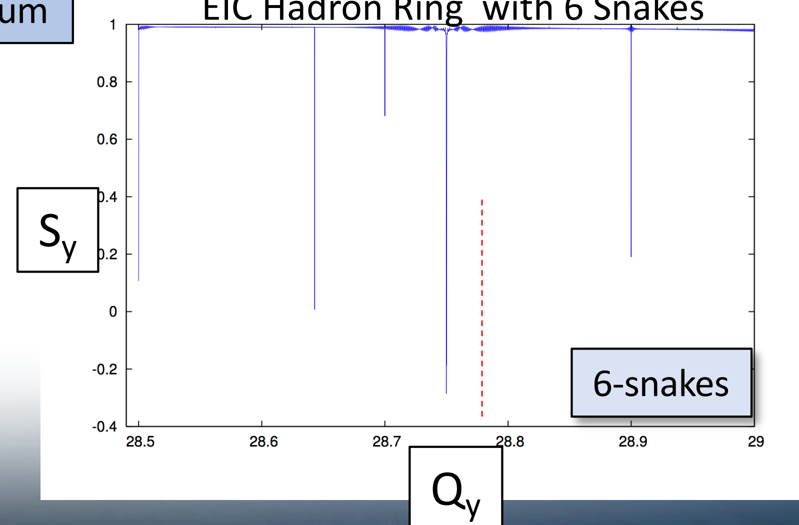


Snake resonance spectrum

RHIC with 2 Snakes

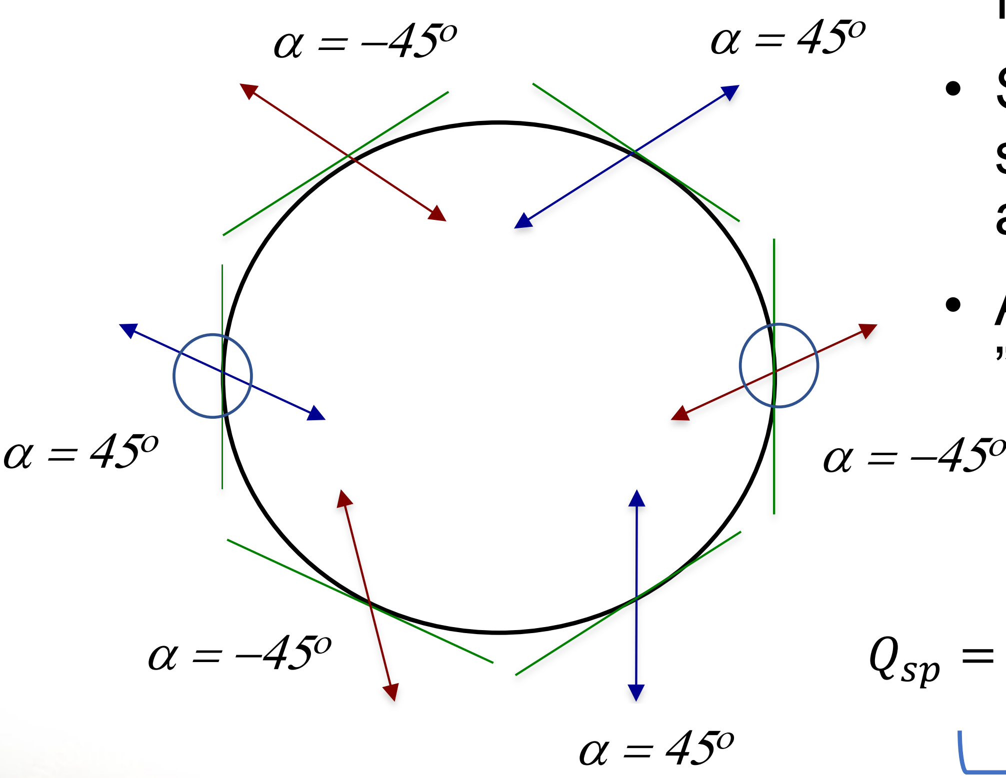


EIC Hadron Ring with 6 Snakes



Six snakes in EIC hadron ring

- Number of Snakes will be increased from 2 to 6
- Snake arrangement is perfectly symmetric with 60 degree bending angle between Snakes.
- Additional Snakes are put in DU7 ”dummy” sections, free of magnets.



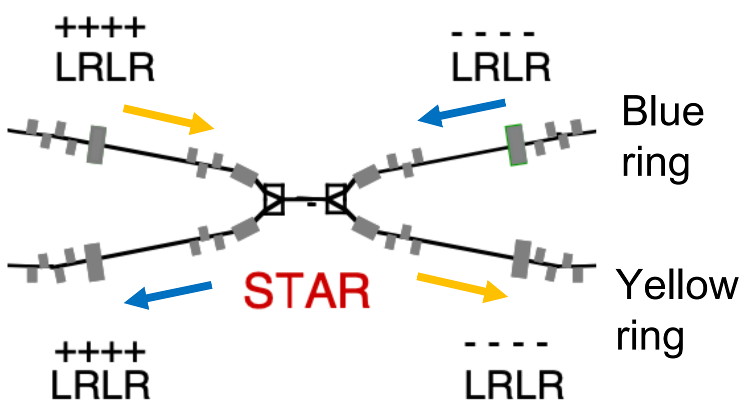
$$Q_{sp} = \frac{1}{\pi}\sum_{k=1}^{6}(-1)^{k+1}\alpha_k + \frac{G\gamma}{2\pi}\sum_{1}^{6}(-1)^{k+1}\theta_{k,k+1}$$

Snake axes selected to give $Q_{sp} = 3/2$

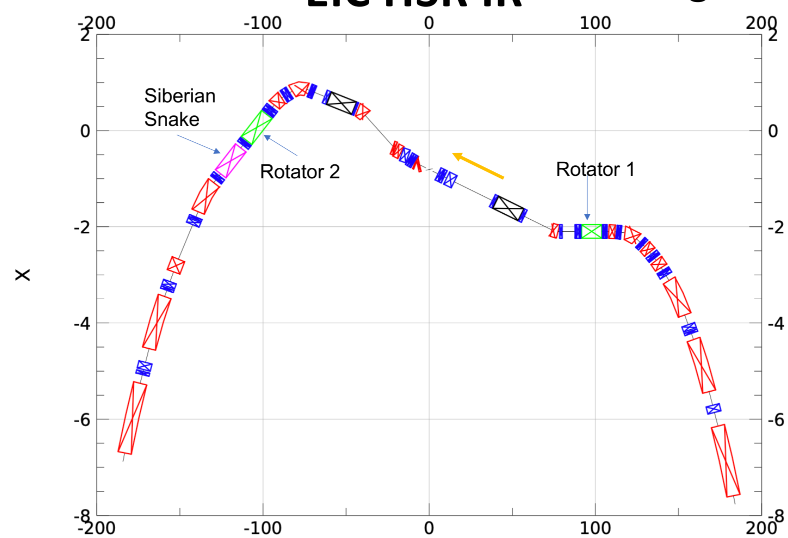
Nullified due to symmetric snake arrangement

EIC Spin Rotators

RHIC IR6



EIC HSR IR S.Berg



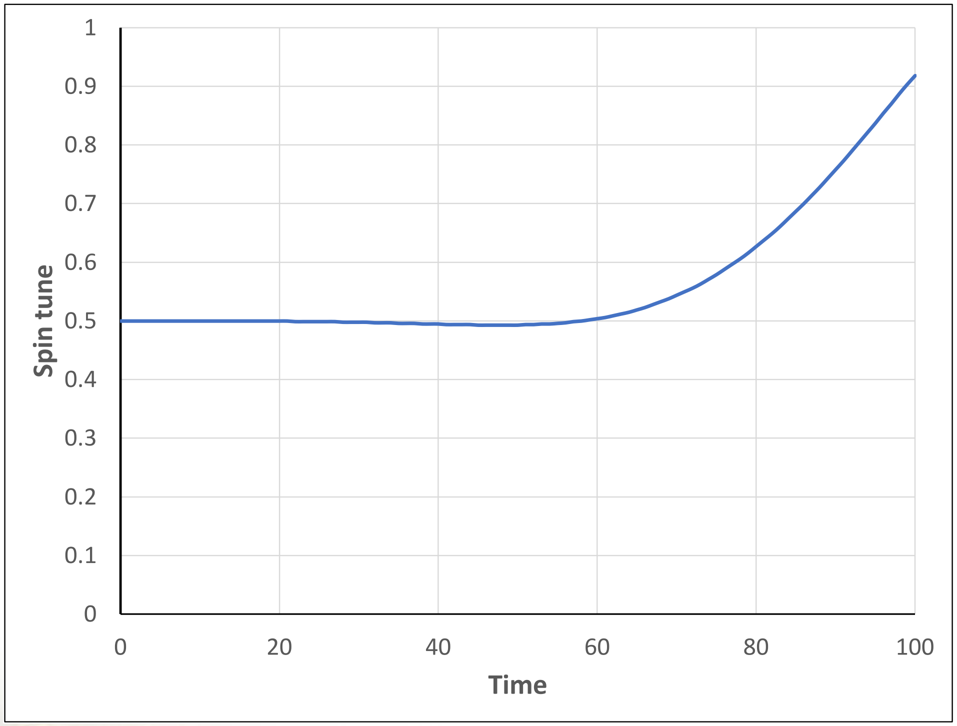
The Hadron Storage Ring spin rotators:

- The spin rotators used presently in RHIC will be re-used in the EIC HSR.
- The locations of the spin rotators in the HSR differ considerably from their RHIC locations The net bending angle between HSR spin rotators is non-zero.

	Distance from IP	Bending angle from IP
RHIC Rotator 1	61.4 m	3.675 mrad
RHIC Rotator 2	61.4 m	-3.675 mrad
HSR Rotator 1	97.8 m	-17 mrad
HSR Rotator 2	103.8 m	61.35 mrad

Spin rotator turn on

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

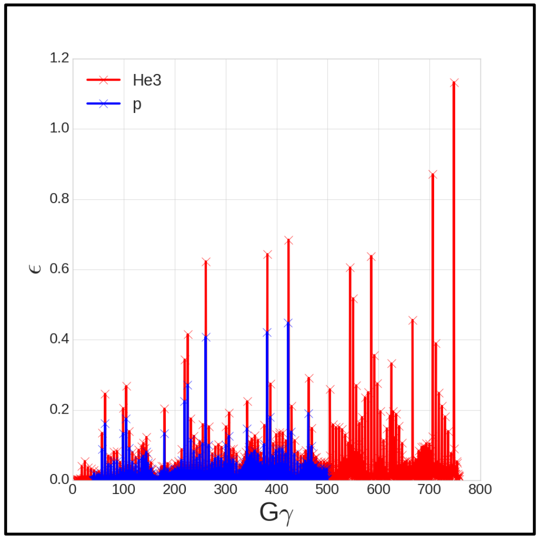


This spin tune shift can be mitigated by simultaneous adjustment of spin rotation axes in Snakes:

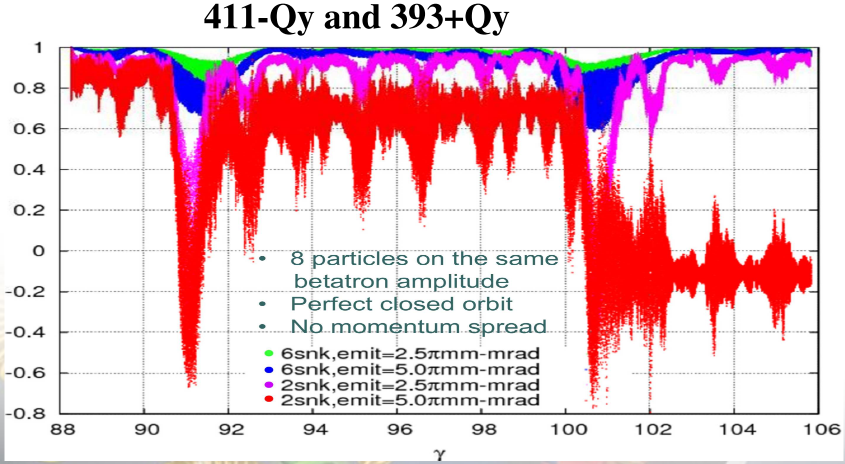
$$\nu_{sp} = \frac{1}{\pi}\sum_{i=1}^{3}(\alpha_{s,2i} - \alpha_{s,2i-1})$$

Polarized ^{3}He Acceleration in EIC HSR

	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*



Crossing strongest spin resonance with 2 and 6 Snakes

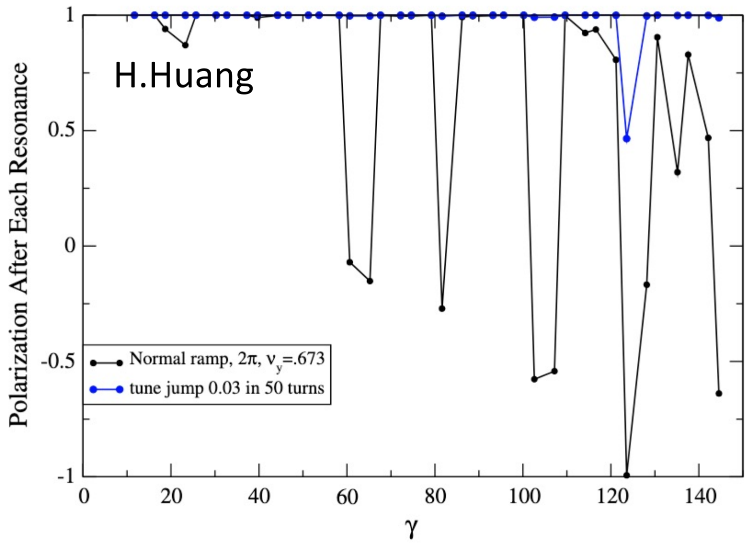


- RHIC Siberian snakes and spin rotators can be used for the spin control, with less orbit excursions than with protons.
- More spin resonances. Larger resonance strength.
- **6 Snakes are necessary to preserve ^{3}He polarization at acceleration**

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

D polarization at acceleration with and without tune jumps



- Polarized deuteron possibility in EIC has been explored.
- The imperfection resonances can be overcome by partial snakes on the base of the planned detector solenoid(s).
- The intrinsic resonance can be overcome with modest tune jump.
- At Gγ =3n (3, 6, 9, 12, 15, 18), longitudinal polarization can be reached at both 6 o'clock and 8 o'clock IRs. 22.5 GeV interval.
- **The deuteron polarimetry presents a serious challenge.**

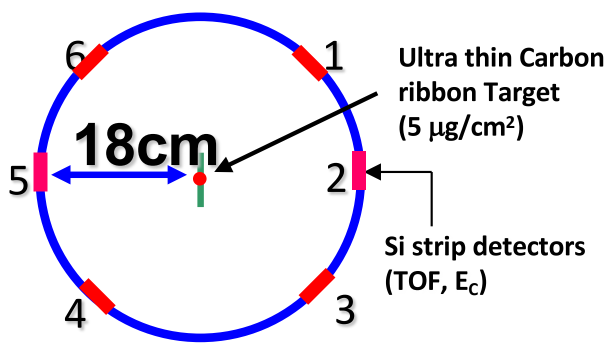
Other topics for hadron polarization

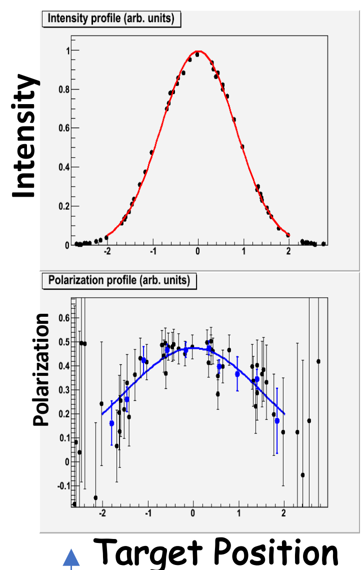
- Space charge effect on the polarization.
  Although the depolarizing resonances are weaker at lower energies, the betatron tune spread is large.
  Studies found no serious issues with polarization lifetime at 41 GeV operation (space charge tune spread ~0.05).
- Effect of IBS and Cooling on the polarization during the stores.
  Depolarization mechanism similar to stochastic depolarization by SR for electrons has been studied. Depolarizing function (dn/dgamma) was evaluated. Found depolarization was very week.
- Effect of crab cavities. RMS spin spread in the IP was evaluated to be ~0.01 rad.

Hadron Polarimetry

EIC will use the same polarimetry techniques as presently used in RHIC.

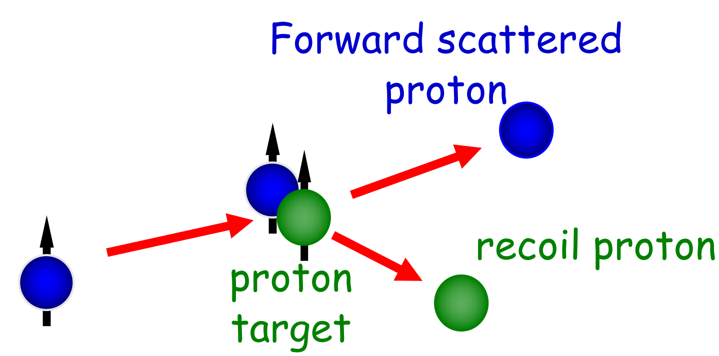
p-C polarimeter





- Fast polarization measurement
- Polarization profile measurements
- Analyzing power can not be analytically calculated: needs calibration

H-jet polarimeter



- Both recoil and forward scattered protons are detected
- Absolute polarization measurement
- But measurements are slow
- Provides calibration for p-C

Main challenge for EIC: higher beam current and bunch repetition rate (background issue)

EIC Electron Polarization

- Physics program requires bunches with spin “up” and spin “down” to be stored simultaneously
- The wanted spin patterns is produced by injecting bunches with desired spin orientation at full collision energy
- Since stored bunch polarization decays due to Sokolov-Ternov and stochastic depolarization processes.
- Frequent bunch replacement is used to replace bunches with lower polarization with new highly polarizied bunches.

High Average Electron Polarization

- Frequent injection of bunches with high initial polarization of 85%
- Initial polarization decays towards P_∞ < ~50%
- At 18 GeV, every bunch is replaced (on average) after 2.2 min

B P

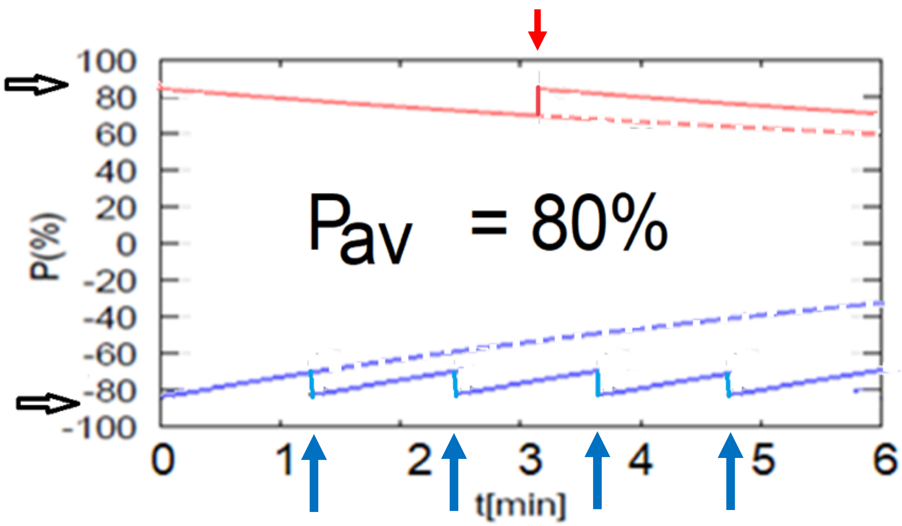
Refilled every 1.2 minutes

B P

Refilled every 3.2 minutes

Re-injection

P(0) = 85%

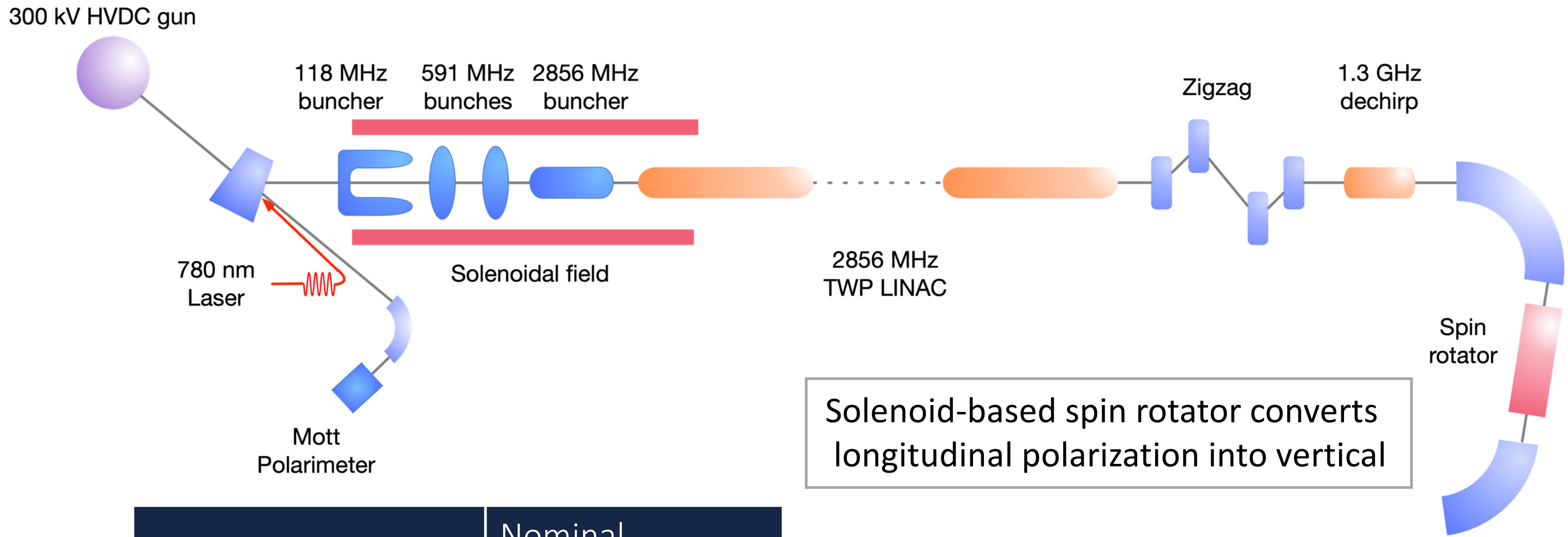


P(0) = -85%

P_∞= 30%
(conservative)

Re-injections

Pre-injector beam line set up



	Nominal
Bunch charge [nC]	7
Bunch length [ps]	40
Energy spread dp/p	2.5e-3
Frequency [Hz]	1Hz w 8 bunches
Energy [MeV]	400
Polarization [%]	85%
Lifetime	>2 weeks

- 2.856 GHz Buncher and Linac (6-8 tanks)
- 2 x 591 MHz Buncher
- 118 MHz Buncher
- Need R56 rotates the bunch in longitudinal phase space to reduce energy spread
- 1300 MHz dechirp cavities

Rapid Cycling Synchrotron is based on resonance free lattice

- RCS must preserve polarization at acceleration from 400 MeV to 18 GeV.
  Spin tune range: **$0.907 < \gamma a < 41$.**

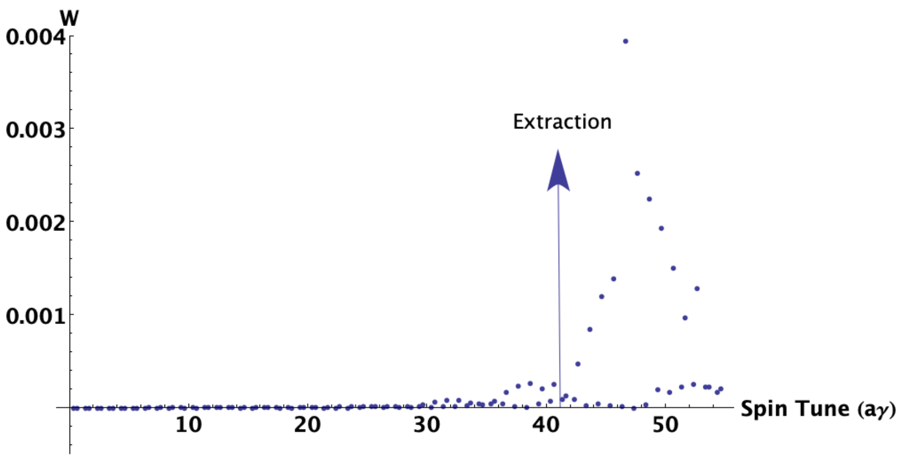
- Both the strong intrinsic and imperfection resonances occur at spin tunes:
  - $\gamma a = nP \pm Qy$
  - $\gamma a = nP \pm [Qy]$ (integer part of tune)

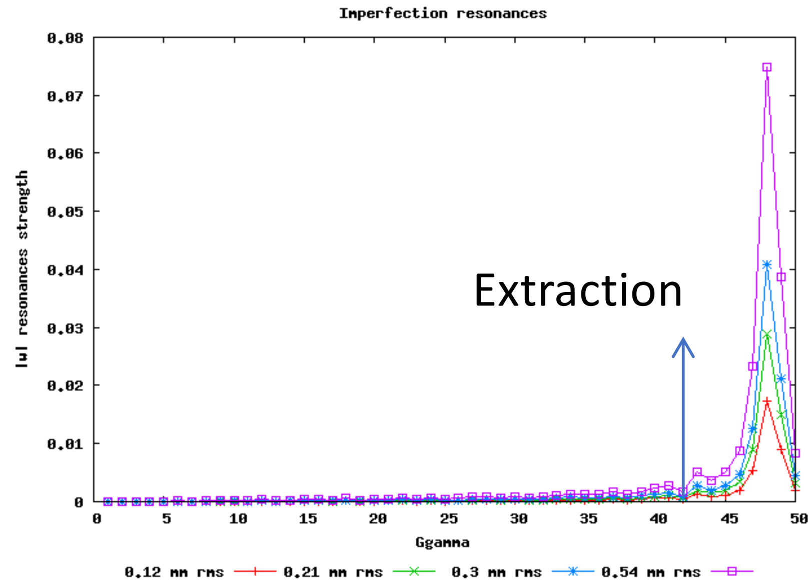
- By selecting proper P and Qy one can move strong intrinsic resonances out of the RCS energy range.
  P=96 and a tune Qy with an integer value of 50.

- Imperfection resonances follow suit with the first major one occurring at γa = 96 – 50 = 46

RCS Spin Resonances

See talk by V. Ranjbar in WG1 for further details





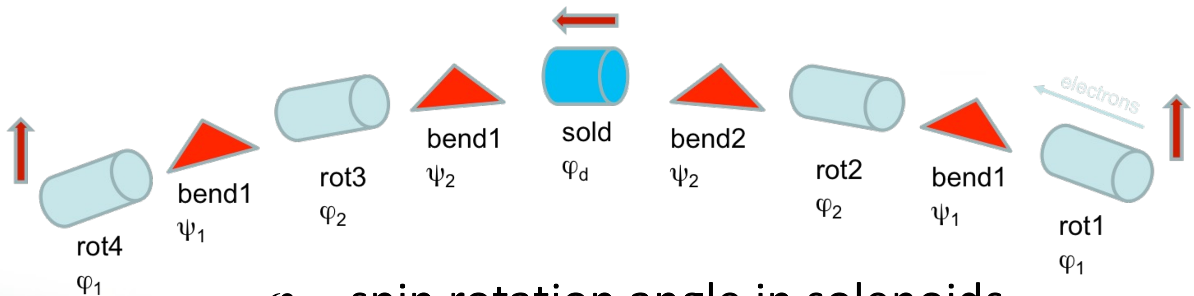
- No polarization loss from cumulative effects of intrinsic spin resonances for distributions with RMS normalized emittance > 1000 mm-rad (100 msec ramp rate).
- At 200 mm-mrad RMS normalized emittance, we can tolerate beyond 2% field errors and still maintain above 95% polarization transmission.
- Issue to control: Imperfection spin resonances ~ vertical RMS orbit 0.5 mm to keep losses < 5%.

Electron storage ring spin rotators

- Goal electron energy range: 6-18 GeV
- A HERA-type rotator (based on sequence of vertical and horizontal bend) creates meter scale orbit excursion at lower energies.
- The rotator design capable to operate in all energy range is based on the combination of solenoidal and horizontal bending magnets.

EIC spin rotator

C-type bending configuration



φ_j – spin rotation angle in solenoids

ψ_i – spin rotation angle in bends

$\psi_1 = \nu_0 \theta_1$

$\psi_2 = \nu_0 \theta_2$

$\nu_0 = \gamma a$

$\theta_{1,2}$ – bending angles

Spin matching conditions for solenoidal rotators

In order to minimize stochastic depolarization the rotator insertion optics has to satisfy special set of spin matching conditions:

$$\sum_{rot:j=1,4} H_j\left(f_I\right) = 0\,; \quad \sum_{rot:j=1,4} H_j\left(f_I^*\right) = 0\,;$$

Betatron motion conditions

$$a\gamma \sum_{rot:j=1,4} H_j\left(D\right) + \sum_{rot:j=1,4} \varphi_j k_{sj} - \sum_{bends:i=1,4} \psi_j k_{yi} = 0$$

Off-momentum condition

where:

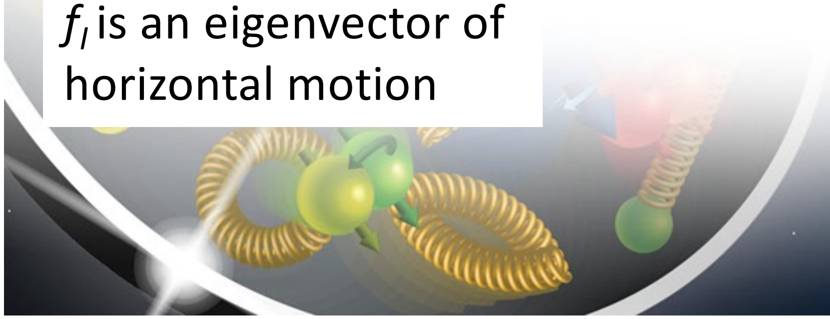
$$H_j\left(F\right) = \frac{\varphi_j}{2}\left[\left(k_x\left(F_x' + \frac{K_s}{2}F_y\right) + k_y\left(F_y' - \frac{K_s}{2}F_x\right)\right)_{j,entrance} + \left(k_x\left(F_x' + \frac{K_s}{2}F_y\right) + k_y\left(F_y' - \frac{K_s}{2}F_x\right)\right)_{j,exit}\right]$$

F is either f_I or *D*

entrance of first part of solenoid

exit of second half of solenoid

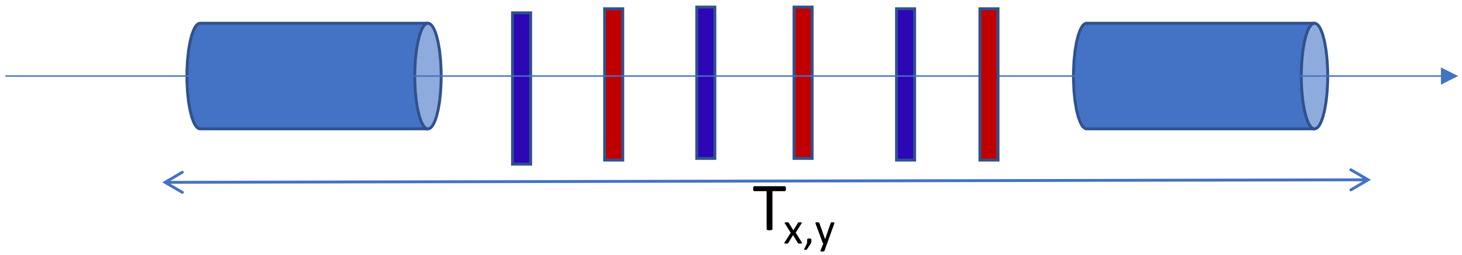
f_I is an eigenvector of horizontal motion



Solenoidal insertion with betatron spin matching

Spin matching conditions related with betatron motion can be satisfied for each individual solenoidal insertion, using two solenoid halves and (at least 6) quadrupoles between them.

That is for each j : $H_j(f_I) = 0$ and $H_j(f_I^*) = 0$



ESR lattice task force made further lattice optimization finding a compromise between spin matching and dynamic aperture.

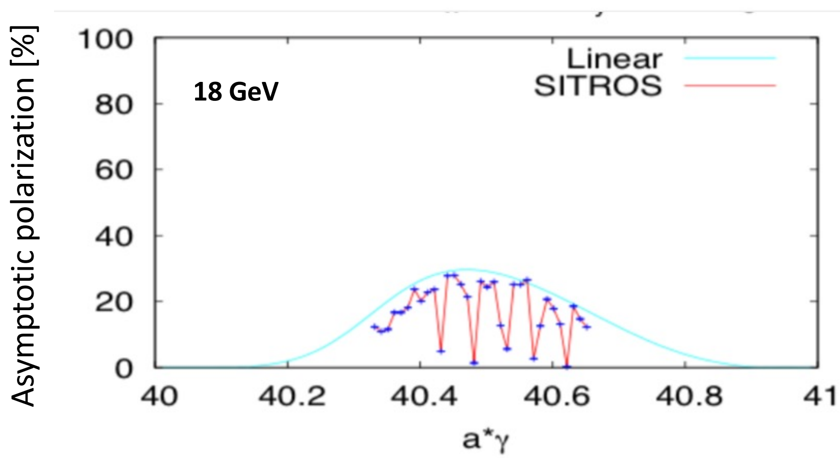
L

Polarization simulation studies

Used codes: SITROS, BMAD, Zgoubi

SITROS simulations studies with machine errors done at 10 and 18 GeV established required degree of orbit and coupling control in the ESR.

E. Gianfelice-Wendt, SITROS/SITF



Assumed quadrupole RMS misalignments

horizontal offset	δx^Q	200 μm
vertical offset	δy^Q	200 μm
roll angle	$\delta \psi^Q$	200 μrad

Orbit corrected to rms: ~0.150 mm, coupling corrected to below 0.005. SITROS includes nonlinear sextupole fields and quantum excitation

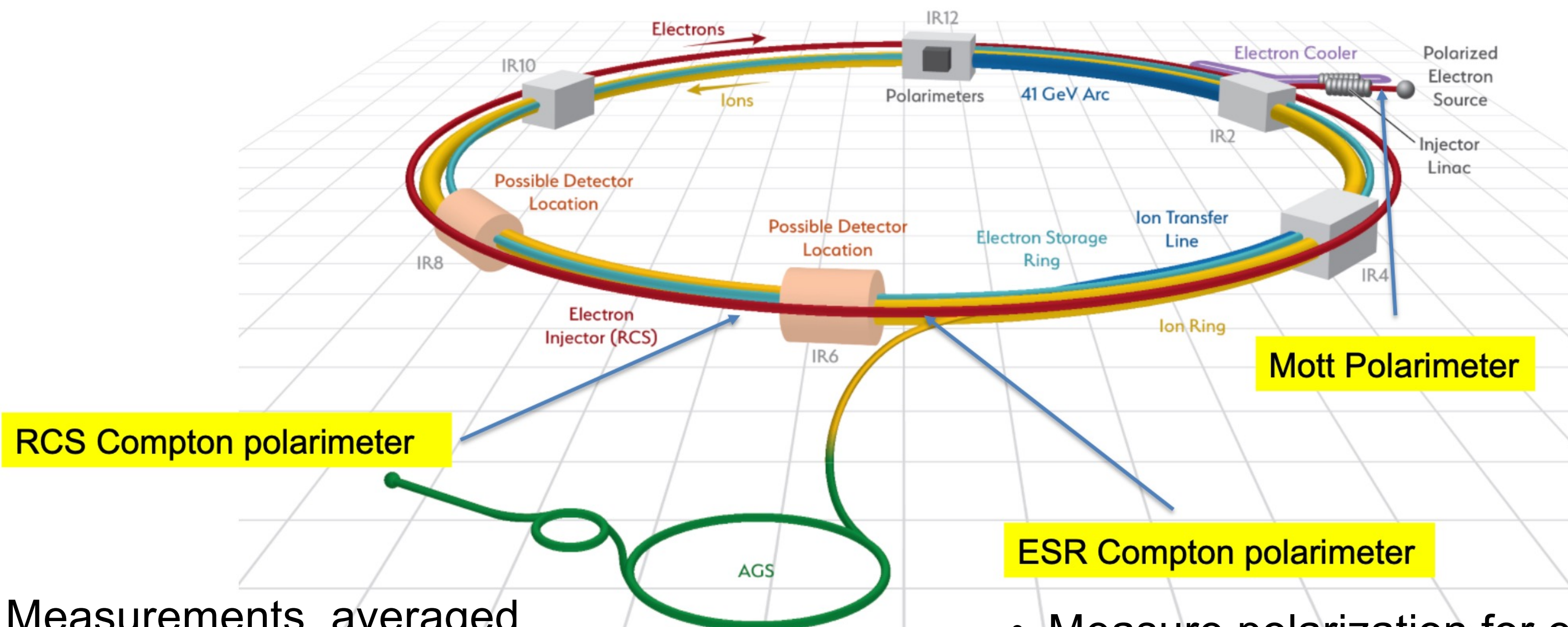
At 18 GeV with 2.5min refill time:
16% asymptotic polarization corresponds to ~70% average polarization

See talks by E.Gianfelice-Wendt, M.Signorelli, F.Meot in WG1 for further details

On-going ESR polarization studies

- Completing machine error tolerance studies
- Evaluating beam-beam effect on polarization
- Verifying detector solenoid compensation
- Maximizing polarization with two detectors
- Operational knobs for polarization tuning

Electron Polarimetry



- Measurements averaged over several bunches
- Vertical polarization
- Requires measurement in multiphoton mode (~1000 backscattered photons/crossing)

- Measure polarization for each bunch
- Requirements on measurement time due to lifetime in ring
- Measure longitudinal and transverse polarization

See talk by C.Gal in WG3 for further details

Summary

- EIC will use highly polarized beams of electrons, protons and ^3He ions.
- Spin rotators are used for both electrons (solenoidal insertions) and hadrons (helical dipoles) to create longitudinal polarization at the IP.
- For hadrons number of Snakes will be increased to 6 to ensure high polarization transmission on the acceleration ramp.
- Electron RCS free-resonance lattice preserve polarization up to 18 GeV
- For electron storage ring the lattice has been optimized to incorporate spin matching conditions in the solenoidal insertions.
- Electron spin simulations studies are very important for defining machine error tolerances and machine operational behavior and tuning.

Thank You
for your attention!