Design Status Update of the Electron-Ion Collider

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IPAC'21

WEPAB006

Electron-Ion Collider

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

Requirements for the EIC

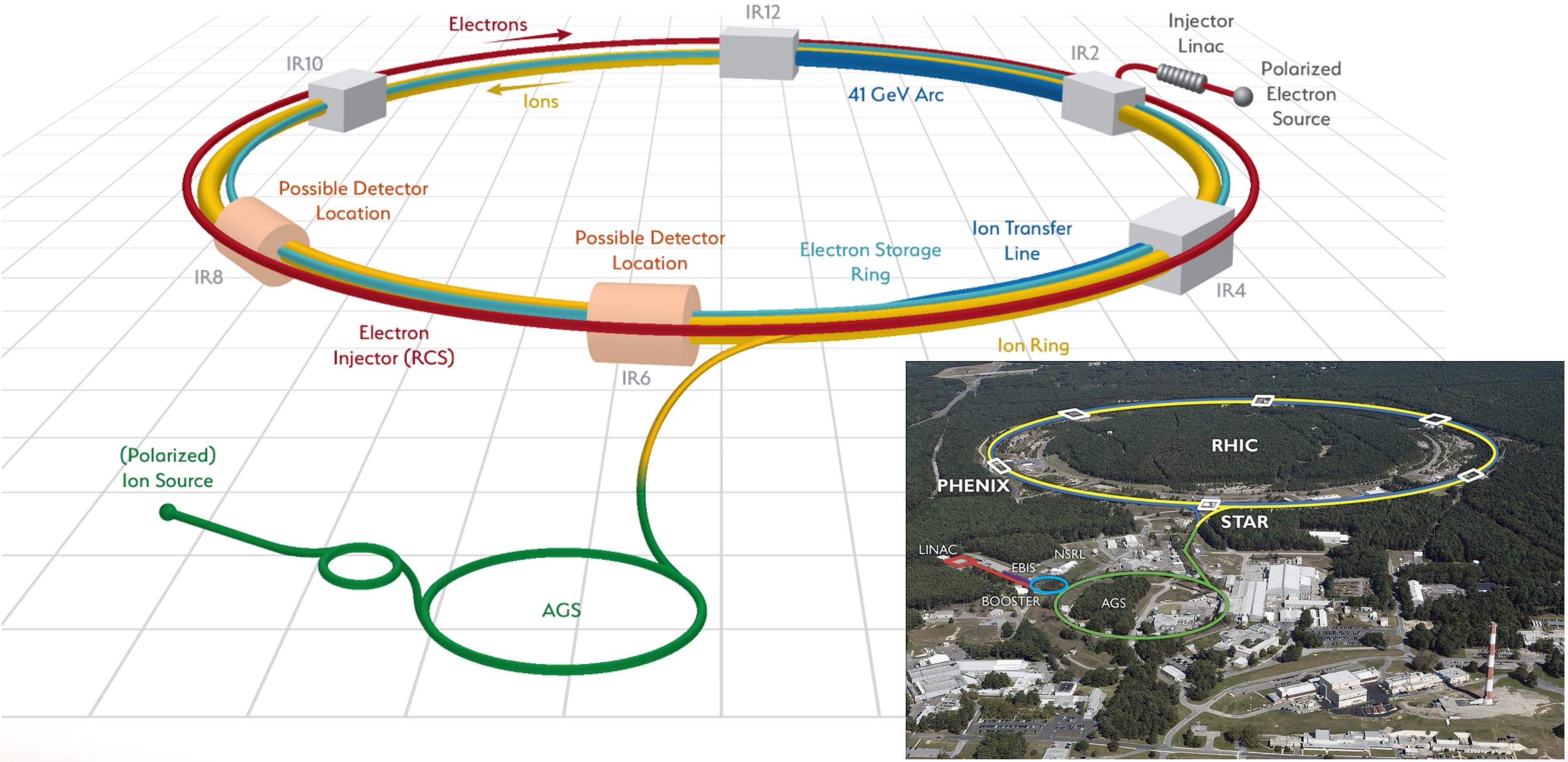
Requirements for an Electron-Ion Collider are defined in the White Paper:

- High luminosity: L = 10^{33} to 10^{34} $cm^{-2}sec^{-1}$ - factor 100 to 1000 beyond HERA
- Large range of center-of-mass energies E_{cm}= 20 to 140 GeV
- Polarized beams with flexible spin patterns
- Favorable condition for detector acceptance such as p_T =200 MeV
- Large range of hadron species: protons ….Uranium
- Collisions of electrons with polarized protons and light ions (↑^{3}He, ↑d,…)

EIC Design Concept (in a nutshell)

- Take one RHIC ring with its entire injector complex as the EIC hadron ring
- Add electron cooling to lower emittance and counteract IBS
- Modify the hadron ring to be suitable for EIC beam parameters
- Install an electron storage ring in the existing tunnel
- Use a spin-transparent rapid-cycling synchrotron as full-energy polarized electron injector for rapid bunch replacement to counteract depolarization
- Build a high luminosity interaction region that fulfills acceptance requirements

Facility layout



Electron complex to be installed in existing RHIC tunnel – cost effective

Parameters for Highest Luminosity

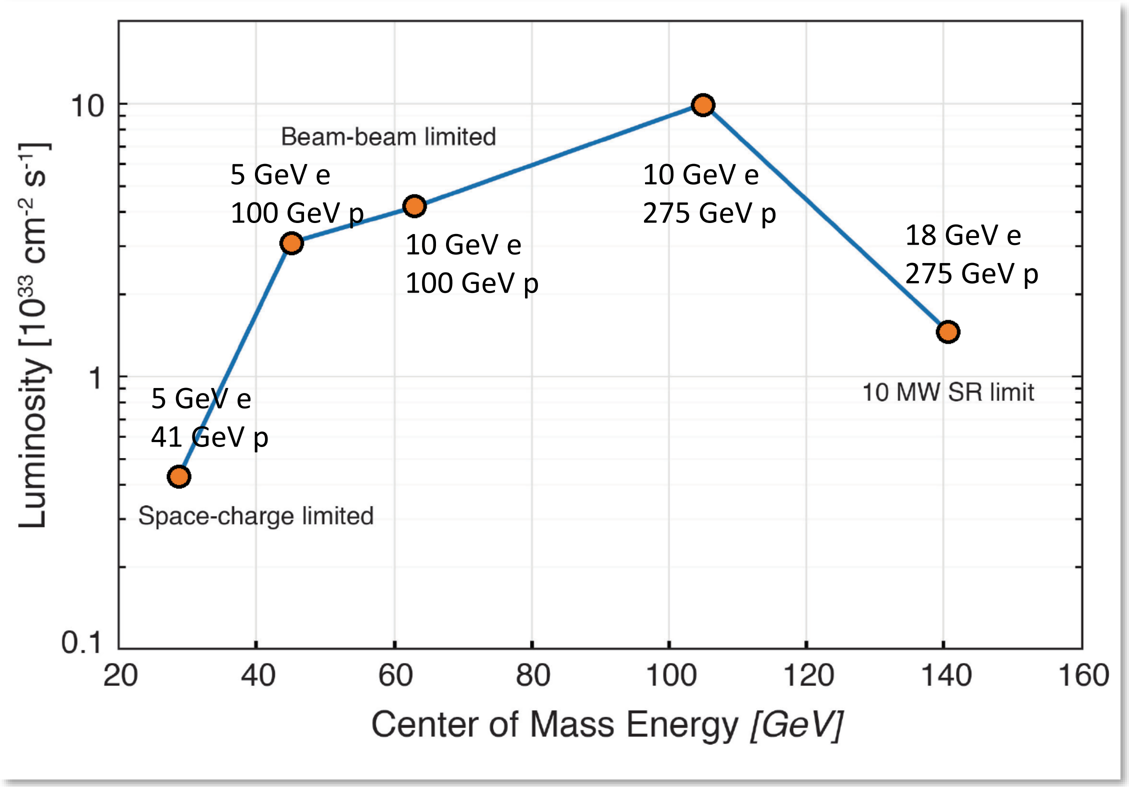
	proton	electron
no. of bunches	1160	
energy [GeV]	275	10
bunch intensity [10^{10}]	6.9	17.2
beam current [A]	1.0	2.5
ϵ_{RMS} hor./vert. [nm]	9.6/1.5	20.0/1.2
$\beta^*_{x,y}$ [cm]	90/4	43/5
b.-b. param. hor./vert.	0.014/0.007	0.073/0.100
σ_s [cm]	6	2
$\sigma_{dp/p}$ [10^{-4}]	6.8	5.8
τ_{IBS} long./transv. [h]	3.4/2.0	N/A
L [$10^{33}\,cm^{-2}sec^{-1}$]	10.05	

- Hadron beam parameters similar to present RHIC, but smaller vertical emittance and many more bunches
- 2 hour IBS growth time requires strong hadron cooling
- Electron beam parameters resemble a B-Factory

Parameters optimized for high luminosity at high energy

Alternative optimizations are possible, for example for high luminosity at low energy

Luminosity vs. CM Energy



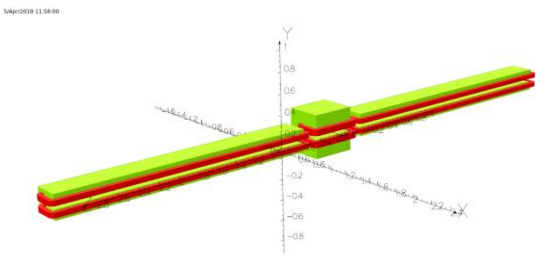
- Parameter and IR optimization at 105 GeV center-of-mass energy
- Optimization yields $10^{34} cm^{-2} sec^{-1}$ luminosity at 105 GeV

MOPAB385, TUPAB335, TUPAB212, TUPAB235, WEPAB035, THPAB034, THPAB238, WEPAB032, TUPAB253, TUPAB254, TUPAB258, TUPAB257

Electron Storage Ring

Composed of six FODO arcs with 60º /cell for 5 to 10 GeV

90º /cell for 18 GeV



Super-bends for 5 to 10 GeV for emittance control

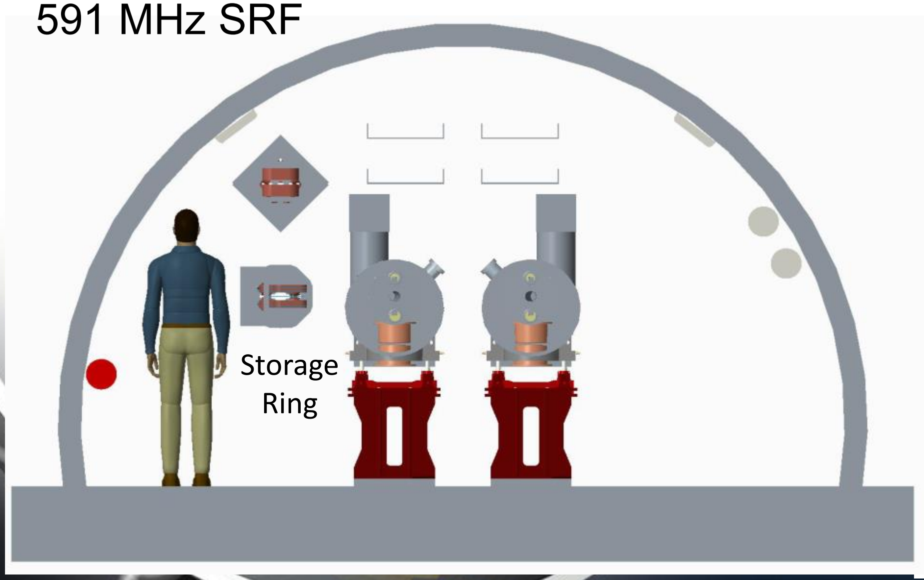
Straight sections with simple layout

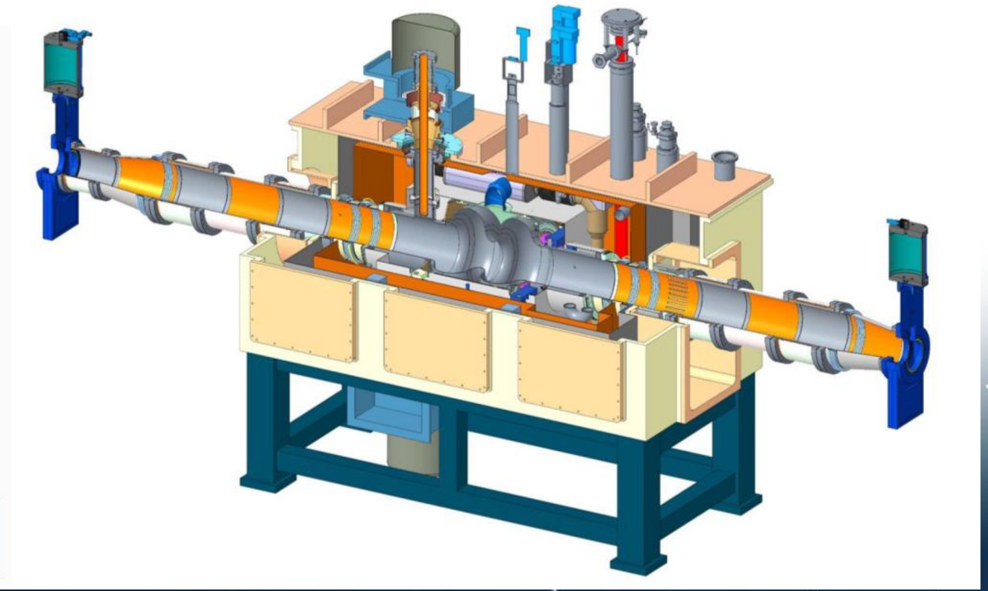
Up to two interaction regions

Beam parameters require careful study of collective effects

Radiate approx. 10 MW for maximum luminosity parameters at 10GeV

591 MHz SRF





EIC Electron Polarization

- Physics program requires bunches with spin "up" and spin "down" (in the arcs) to be stored simultaneously
- Sokolov-Ternov self-polarization would produce only polarization anti-parallel to the main dipole field
- Only way to achieve required spin patterns is by injecting bunches with desired spin orientation at full collision energy
- Sokolov-Ternov will over time re-orient all spins to be anti-parallel to main dipole field
- Spin diffusion reduces equilibrium polarization
- Need frequent bunch replacement to overcome Sokolov-Ternov and spin diffusion

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 with RCS cycling rate of 2Hz

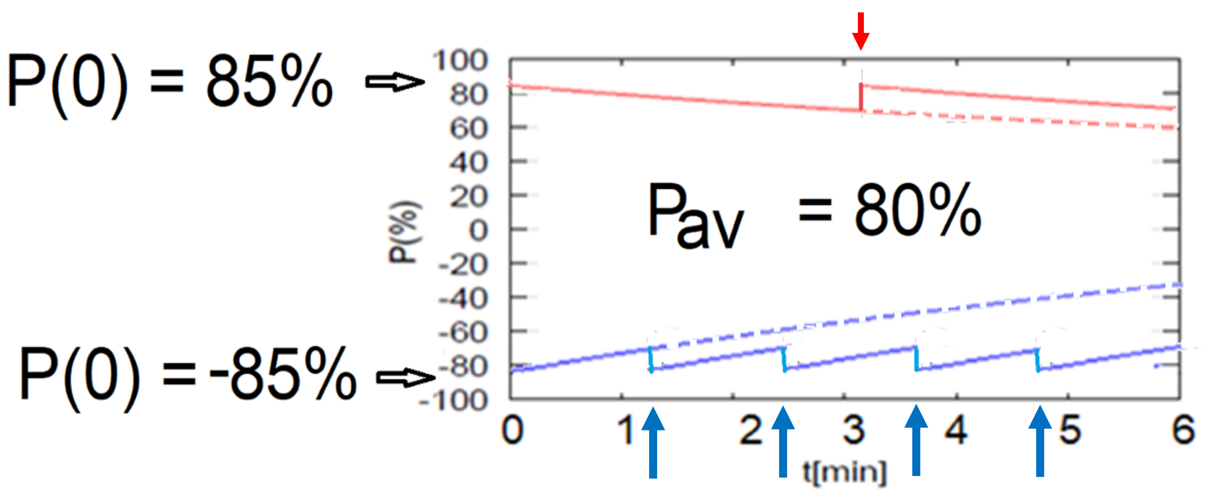
B P

Refilled every 1.2 minutes

B P

Refilled every 3.2 minutes

Re-injection



P_∞= 30%
(conservative)

Re-injections

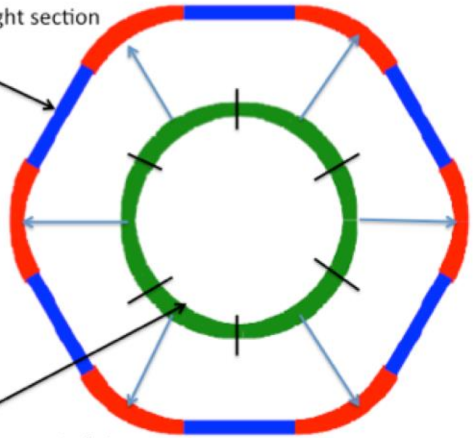
WEXA04, TUPAB037, WEPAB019

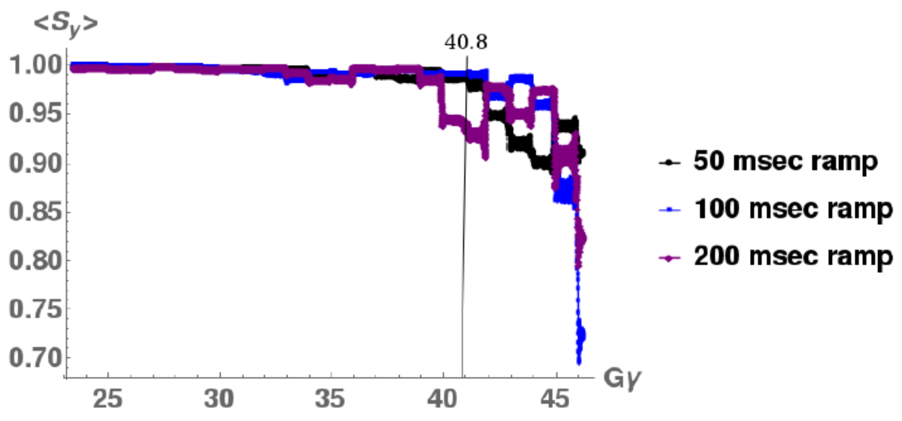
Rapid Cycling Synchrotron as Full Energy Polarized Injector

- Both the strong intrinsic and imperfection resonances occur at spin tunes:
  - **$G\Upsilon$** = nP +/- Qy
  - **$G\Upsilon$** = nP +/- [Qy] (integer part of tune)
- To accelerate from 400 MeV to 18 GeV requires the spin tune ramping from
  - **$0.907 < G\Upsilon < 41$.**
- If we use a periodicity of P=96 and a tune Qy with an integer value of 50 then our first two intrinsic resonances will occur outside of the RCS energy range:
  - **$G\Upsilon$**1 = $50+\nu_y$ (ν_y is the fractional part of the tune)
  - **$G\Upsilon$**2 = 96 – $(50+\nu_y) = 46-\nu_y$
  - Imperfection resonances will follow suit with the first major one occurring at **$G\Upsilon$**2 = 96 – 50 = 46

Spin Tracking in the Rapid-Cycling Synchrotron

High quasi-symmetry, with identity transformation in straight sections
➔ Good spin transparency properties

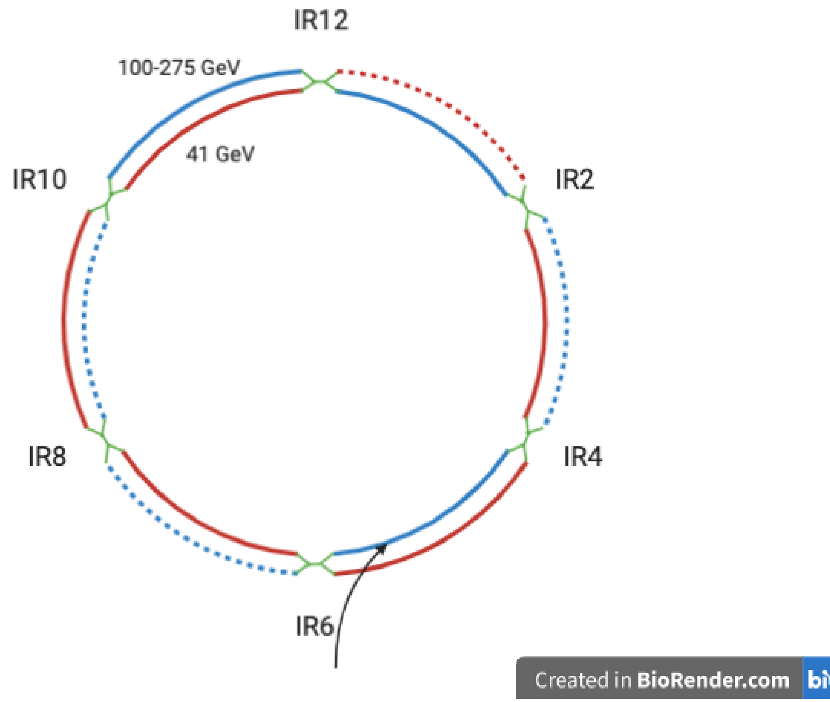




- Requires well aligned quadrupoles, rms orbit ≤ 0.5 mm, and good reproducibility
- Well within the present state of the art of orbit control
- Orbit stability routinely achieved by NSLS-II Booster synchrotron

WEPAB193, WEPAB194, THPAB019, THPAB006, TUPAB042, TUPAB036, TUPAB179, TUPAB180, THPAB141

Hadron Ring



- Existing RHIC facility will be re-purposed as EIC hadron storage ring
- Beam parameters are similar to RHIC, except number of bunches and vertical emittance
- Need strong hadron cooling at store energy to counteract IBS

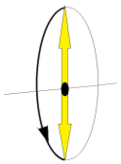
Hadron Storage Ring Modifications

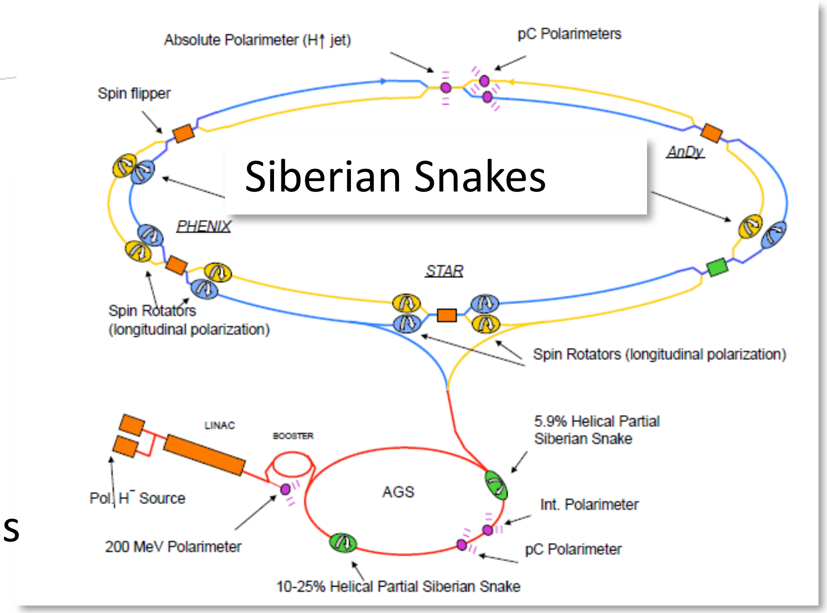
- Insertion of pre-coated sleeves improve conductivity and reduce SEY
- Rebuild injection area with faster kickers to accommodate shorter bunch spacing
- Remove energy-limiting DX separator dipoles
- Inner arc between IRs 10 and 12 for circumference matching during 41 GeV low-energy operation
- (Energy range from 100 to 275 GeV can be covered by radial shift)

EIC Hadron Polarization

MOPAB015, MOPAB180

EIC will fully benefit from present RHIC polarization and near future upgrades





Measured RHIC Results with Siberian Snakes:

- Proton Source Polarization 83 %
- Polarization at extraction from AGS 70%
- Polarization at RHIC collision energy 60%

Planned near term improvements:

AGS: Stronger snake, skew quadrupoles, increased injection energy

➔expect 80% at extraction of AGS

RHIC: Add 4 snakes to 2 existing, no polarization loss

➔ expect 80% polarization in RHIC and eRHIC

Expected results obtained from simulations which are benchmarked by RHIC operations

Polarized ^{3}He in EIC with six snakes

Achieved ~85% polarization in 3He ion source

Benchmarked simulations:

Polarization preserved with 6 snakes, at twice the design emittance

Polarized Deuterons in EIC:

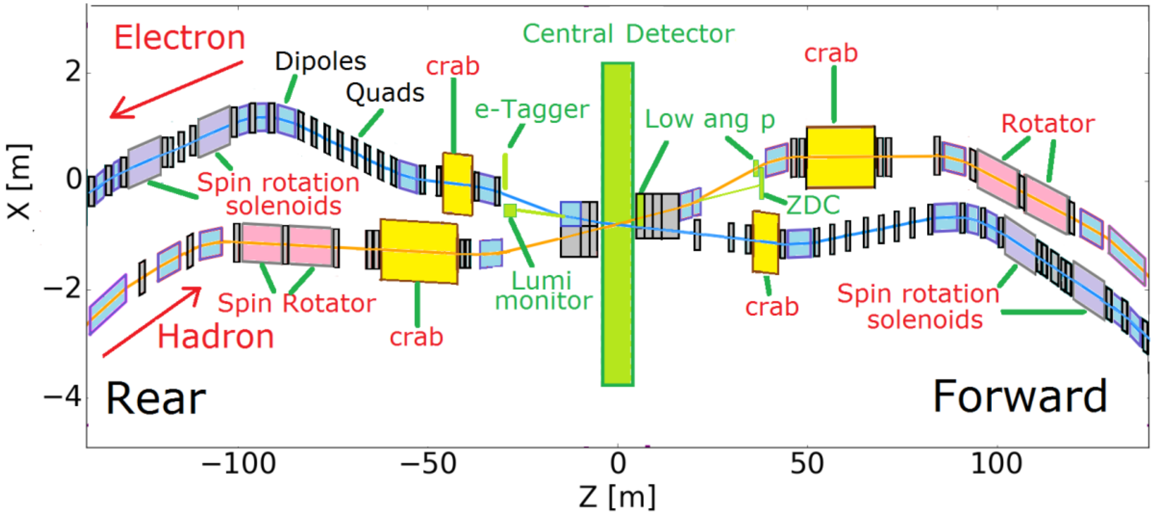
Requires tune jumps in RHIC to overcome few intrinsic resonances

Benchmarked simulation shows 100% spin transparency

No polarization **loss** expected in the EIC hadron ring

Interaction Region

WEPAB002, WEPAB003, WEPAB006, THPAB239, WEPAB340, TUPAB041, TUPAB040



- +/- 4.5 m machine-element free space for central detector
- 25 mrad total crossing angle, crab crossing
- Transverse momentum acceptance down to 200 MeV/c
- Peak magnetic fields below 6T (NbTi sufficient)
- Most magnets direct-wind; few collared magnets

Spin Rotators

Longitudinal polarization is provided by pairs of spin rotators around the IR:

- Helical dipole rotators for hadrons (same as in present RHIC)
- Solenoid-based rotators for electrons
- Compact electron spin rotator would ease geometric layout in the tunnel

Rotators are included in spin matching to avoid polarization loss

Beam-beam

THPAB028, WEPAB010, WEPAB008, WEPAB009, THPAB015, WEPAB252

- Electrons and protons operate at beam-beam limit, ξ_e=0.1, $\xi_p = 0.015$
- Crab crossing of long proton bunches requires second harmonic crab cavities
- Studied effect of electron bunch replacement on proton emittance
- Performed extensive weak-strong and strong-strong simulations to optimize design parameters

Summary

- The EIC is designed to collide highly polarized electron and light ion (p, d, h) beams, as well as unpolarized heavy ions
- EIC reaches a peak electron-proton luminosity of

$$\mathbf{L = 1.05 \cdot 10^{34} cm^{-2} s^{-1}}$$

  at 105 GeV center-of-mass energy
- Arbitrary spin patterns (“up” and “down”) in both beams are provided by injectors
- Ingenious design of the rapid cycling electron synchrotron (RCS) allows polarization preservation all the way up to 18 GeV
- Frequent electron bunch replacement allows short lifetime (1 to 2 h) in ESR
- Strong hadron cooling to reduce and preserve emittance will result in very long hadron beam lifetimes