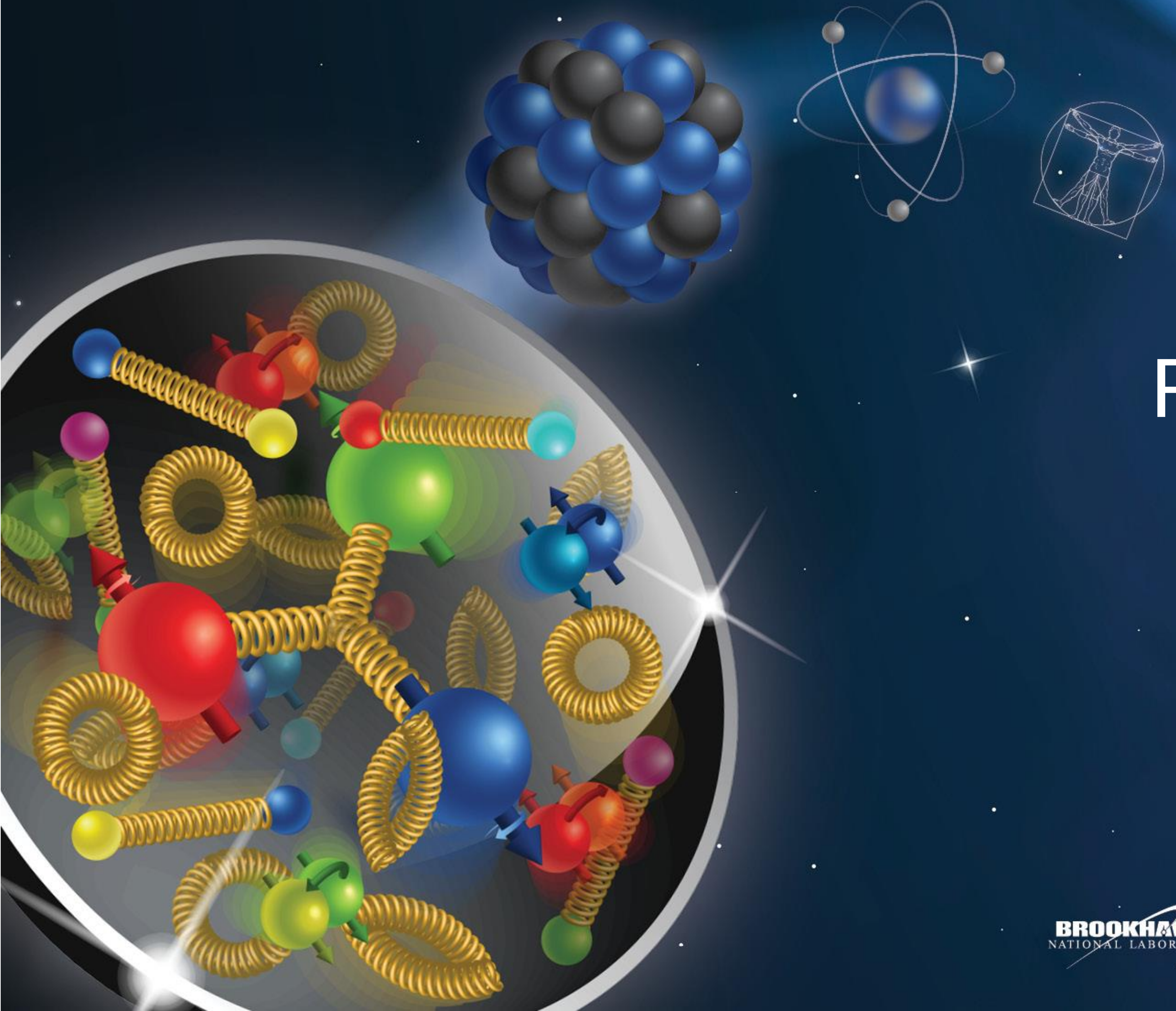


Report from the Accelerator

Christoph Montag, BNL

EICUG Meeting, Warsaw

July 21 - 31, 2023

Electron-Ion Collider

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

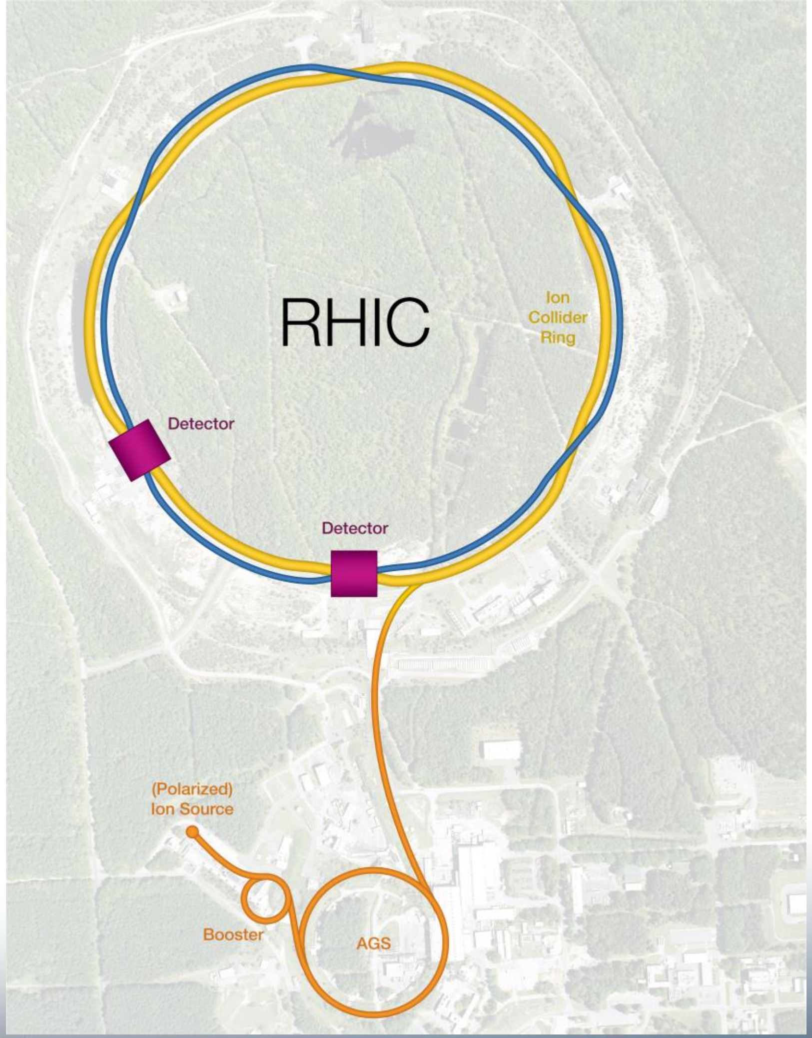
EIC Requirements

- 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}= 29 to 140 GeV
- Polarized beams with flexible spin patterns
- Favorable condition for detector acceptance such as p_T =200 MeV/c
- Large range of hadron species: protons ….Uranium
- Collisions of electrons with polarized protons and light ions (↑^{3}He, ↑d,…)

➔EIC meets or exceeds the requirements formulated in the White Paper

Relativistic Heavy Ion Collider (RHIC)

- Two superconducting storage rings
- 3.8km circumference
- Energy up to 255GeV protons, or 100GeV/n gold
- 110 bunches/beam
- Ion species from protons to uranium
- 60% proton polarization – world's only polarized proton collider
- Exceeded design luminosity by factor 44 - unprecedented
- 6 interaction regions, 2 detectors
- In operation since 2001



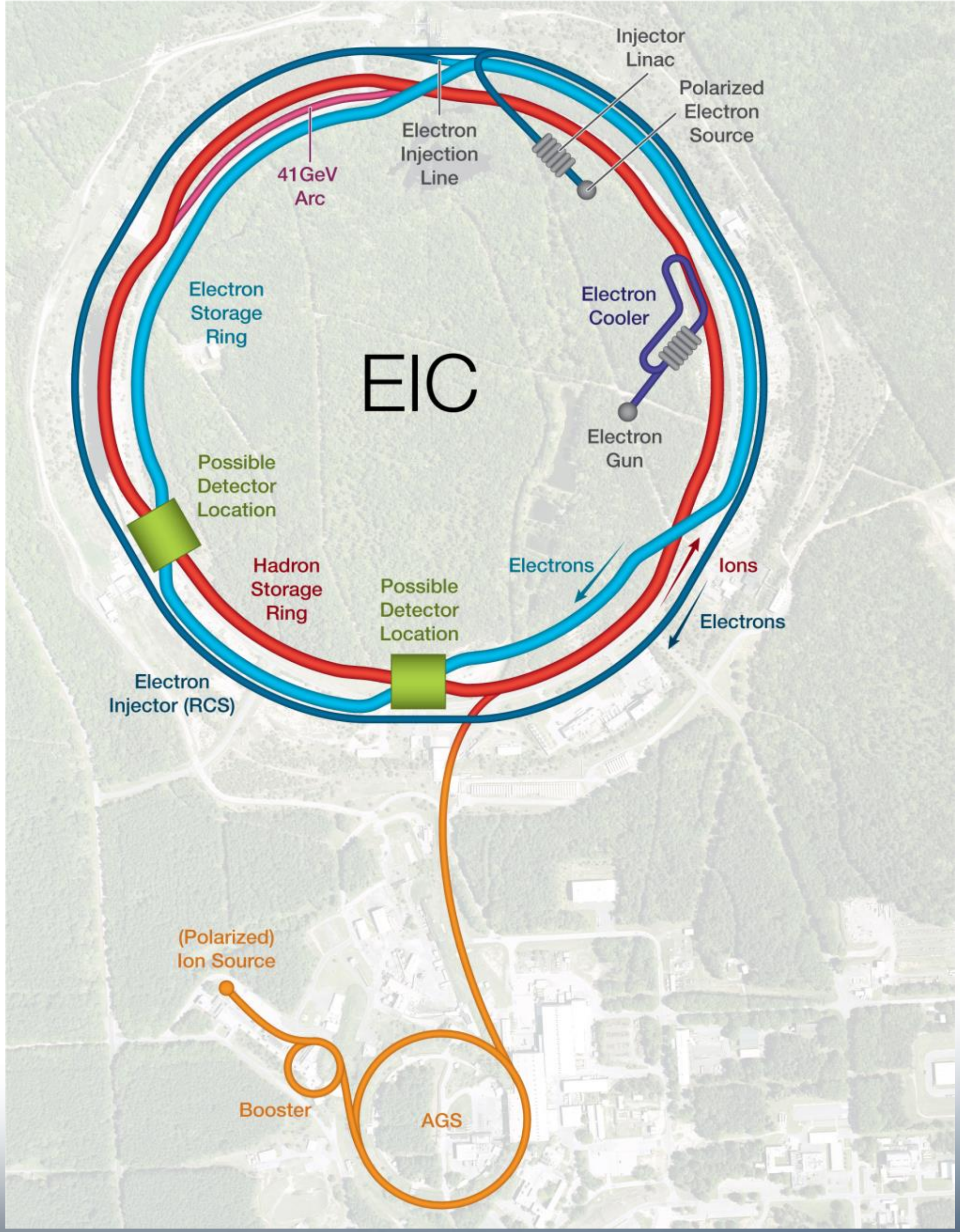
EIC is based on existing RHIC facility

EIC Design Concept

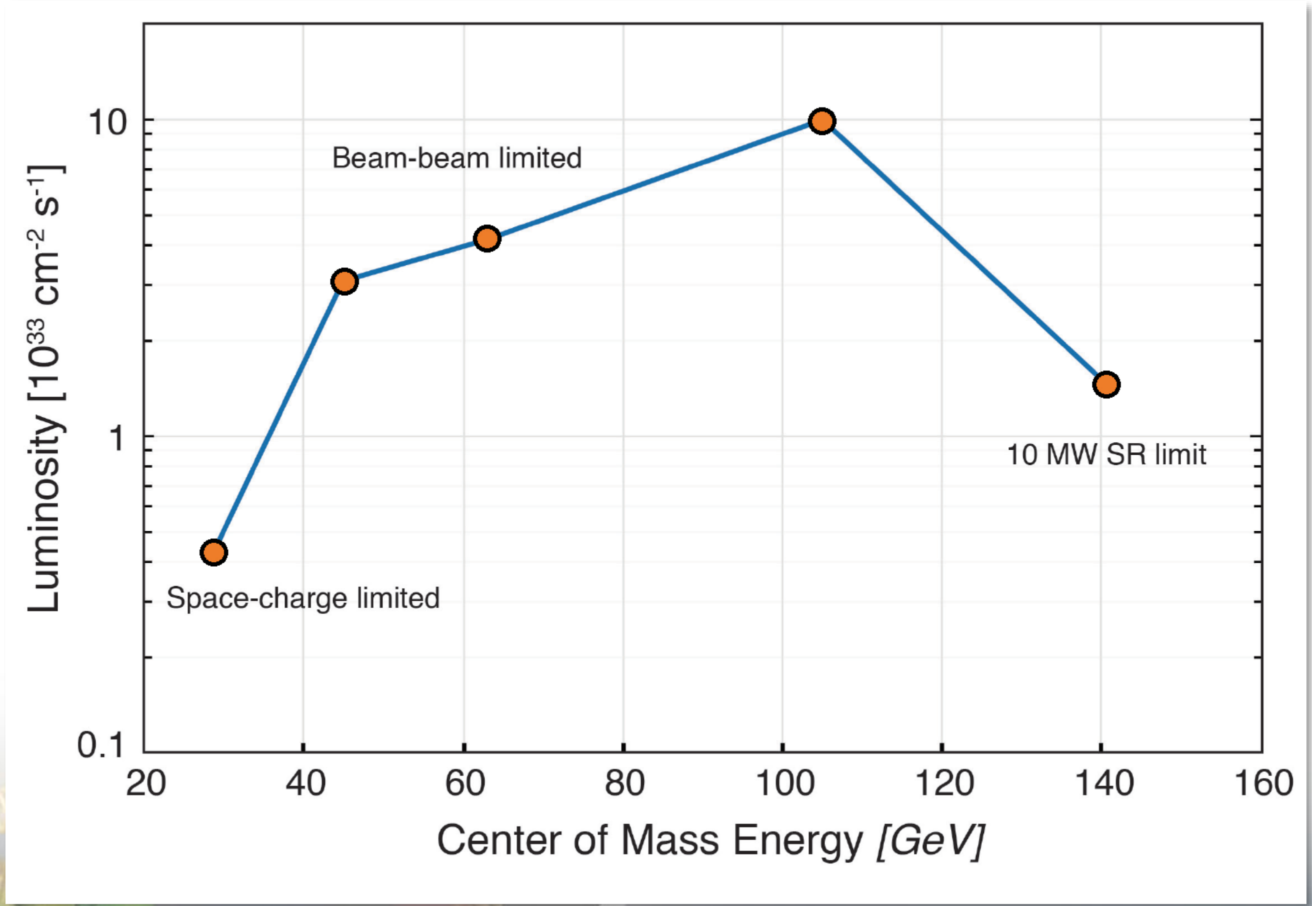
- EIC is based on the RHIC complex: Hadron Storage Ring (HSR), injectors, ion sources, infrastructure; needs only relatively few modifications and upgrades
- Today's RHIC beam parameters are close to what is required for EIC (except number of bunches, 3 times higher beam current, and vertical emittance)
- Add a 5 to18 GeV electron storage ring & its injector complex to the RHIC facility ➔ E_{cm} = 29-141 GeV
- Design and built a suitable interaction region

Facility layout

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



e-p Luminosity versus Center-of-Mass Energy



Electron-nucleon luminosities in e-A collisions are similar within a factor of 2 to 3

Parameters for Highest e-p 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
$\sigma_{\mathrm{d}p/p}$ [10^{-4}]	6.8	5.8
τ_{IBS} long./transv. [h]	3.4/2.0	N/A
L [$10^{33}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$]	10.05	

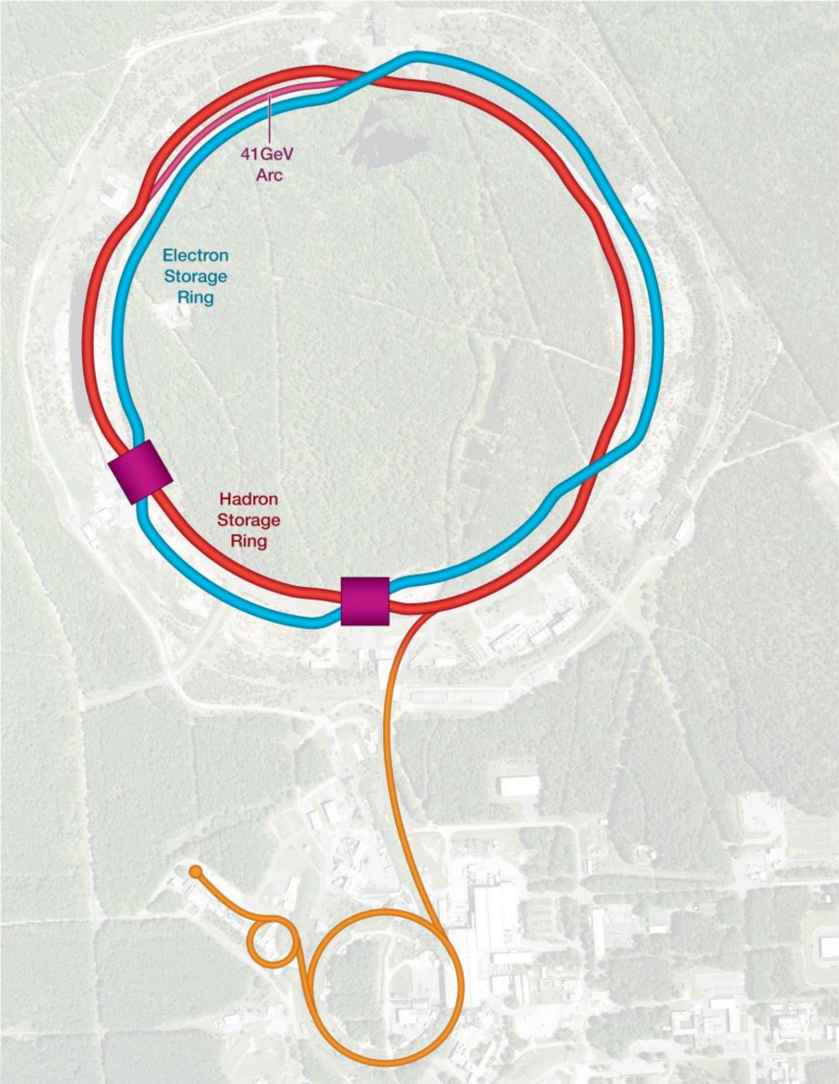
- Hadron beam parameters similar to present RHIC, but smaller vertical emittance and many more bunches
- 2 hour IBS growth time requires strong hadron cooling
- Electron beam parameters resemble a B-Factory

Luminosity Sharing with two IRs

- Both electrons and hadrons are at the beam-beam limit with one collision point – they would not “survive” a second IR
- To enable two collision points, both electron and hadron bunch intensity would have to be reduced by a factor two – resulting luminosity at each IR would be factor 4 smaller
- Instead, we modify the fill pattern such that half the bunches collide in IR6, while the other half collides in IR8
- As a result, total luminosity is preserved, and each detector gets half of the total

Collision Synchronization

- HSR needs to operate over a wide energy range
- Changing the beam energy in the HSR causes a significant velocity change
- To keep the two beams in collision, they have to be synchronized so bunches arrive at the detector(s) at the same time
- Synchronization accomplished by path length change
- Between 100 and 275 GeV (protons), this can be done by a small radial shift – there is enough room in the beampipe
- For lower energies, use an inner instead of an outer arc as a shortcut. 90 cm path length difference corresponds to 41 GeV proton beam energy



Emittance Control in the ESR

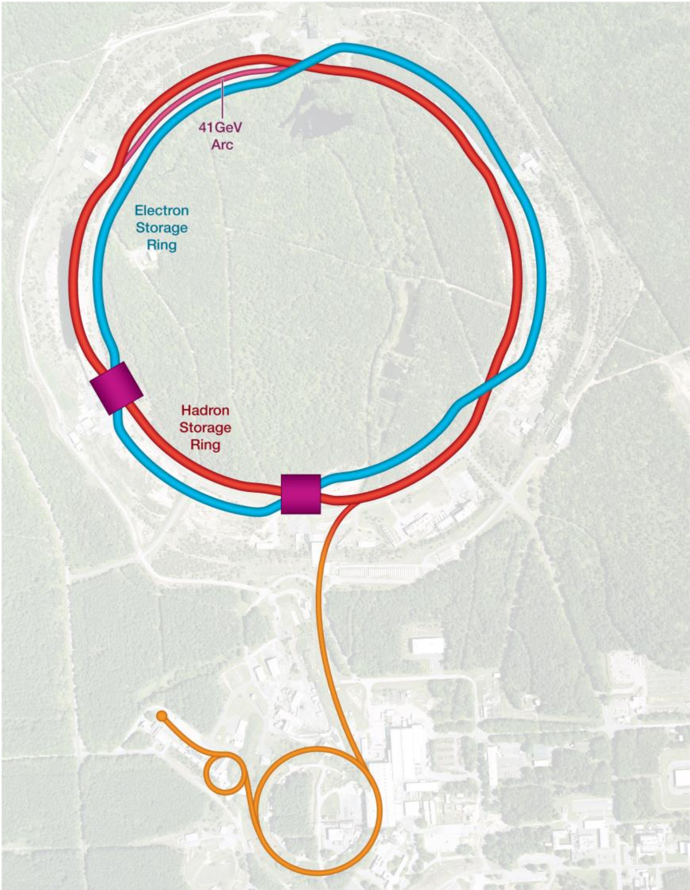
- EIC needs 24 nm emittance from 5 to 18 GeV for optimum luminosity, but equilibrium emittance in an electron storage ring depends on beam energy:

$$\epsilon_x = C_q \frac{\gamma^2}{J_x}\frac{I_5}{I_2}, \qquad \text{with} \quad C_q = \frac{55}{32\sqrt{3}}\frac{\hbar c}{mc^2}$$

- Betatron phase advance μ per FODO cell is the "knob" to adjust the emittance
- 60 degrees at 10 GeV and 90 degrees at 18 GeV both yield ~24 nm
- "super-bends" for emittance generation below 10 GeV

Beam Energies

- γ range for hadrons:
  - γ = 43.7 through “41 GeV arc”
  - 107 < γ < 293 with radial shift
- Maximum hadron energy:
  - E [eV] < 916*c [m/sec]*Z/A
- Electron energies:
  - 5 to 10 GeV, with 60 degree lattice and super-bends
  - 18 GeV, with 90 degree lattice
  - Energies between 10 and 18 GeV are feasible, but at somewhat reduced luminosity due to non-optimum emittance, scaling as γ^2



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_∞
- At 18 GeV, every bunch is replaced (on average) after 2.2 min with RCS cycling rate of 2Hz

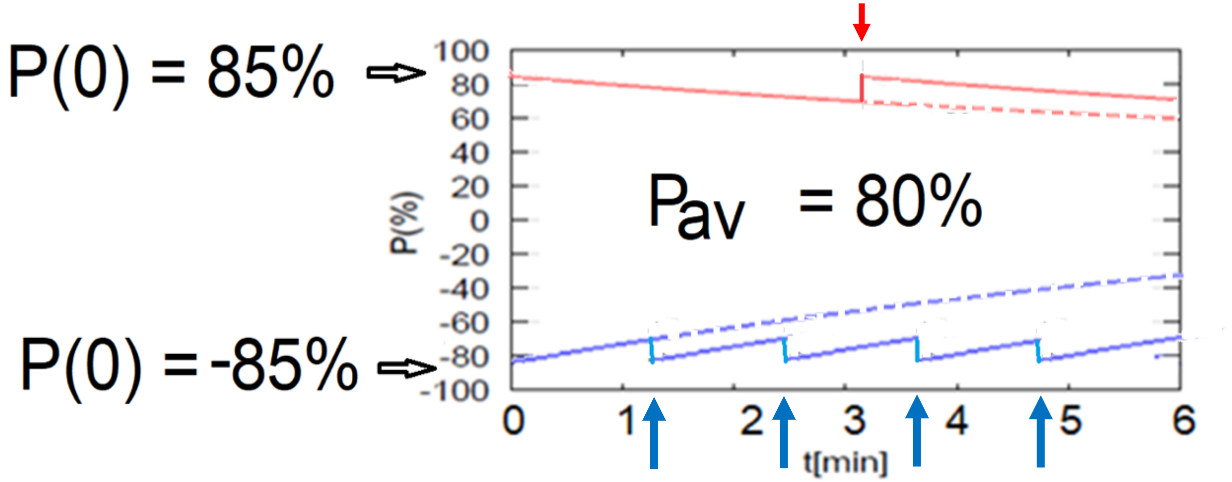
B P

Refilled every 1.2 minutes

B P

Refilled every 3.2 minutes

Re-injection



P_∞ = 30% (conservative)

Re-injections

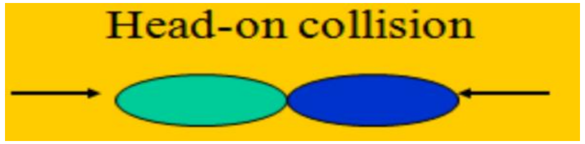
Spin Rotators

- Both electrons and protons will have longitudinal polarization at the IP
- Hadron spin rotators will be taken from present RHIC (helical dipoles)
- Electron spin rotators are based on solenoid magnets with subsequent dipole – large chunk of beamline with fixed geometry, challenging to fit into existing tunnel

Crossing Angle and Luminosity

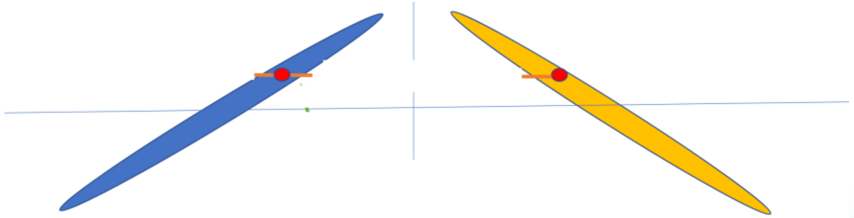
- EIC interaction region is based on a 25 mrad crossing angle for beam separation and luminosity maximization

- In head-on collisions, every beam particle in one beam can potentially interact with every particle in the other beam



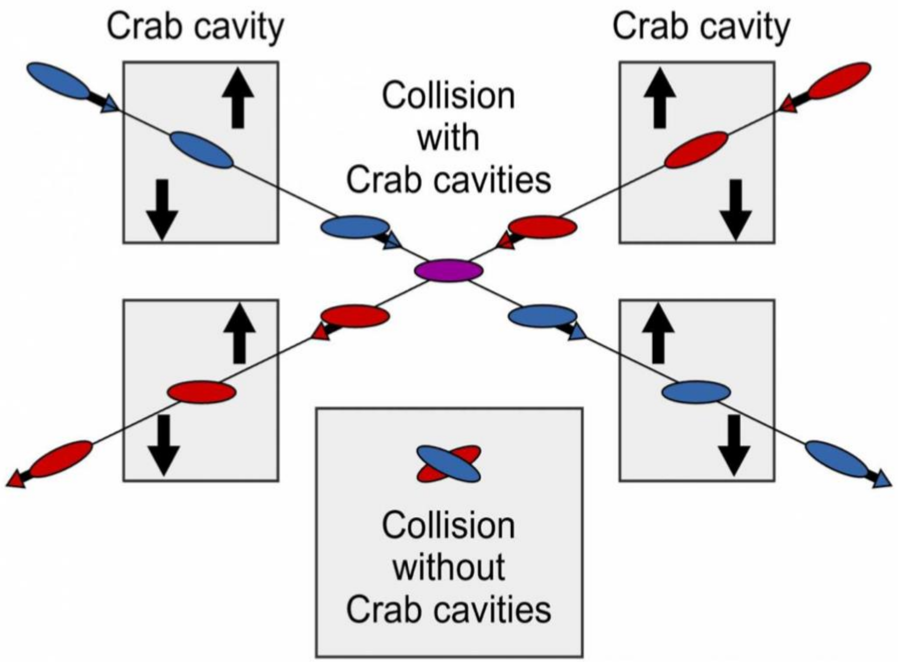
- Long (~+/-6 cm), skinny (100 um) bunches colliding at an angle have very little overlap

- With 25 mrad crossing angle, each electron can only interact with a thin slice of the +/-6 cm long oncoming hadron bunch

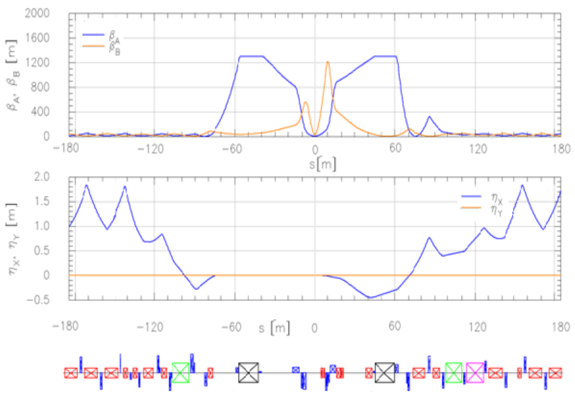


Crab Crossing

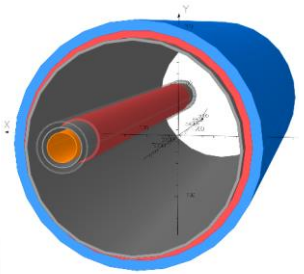
- Head-on collision geometry is restored by rotating the bunches before colliding ("crab crossing")
- Bunch rotation ("crabbing") is accomplished by transversely deflecting RF resonators ("crab cavities")
- Actual collision point moves laterally during bunch interaction

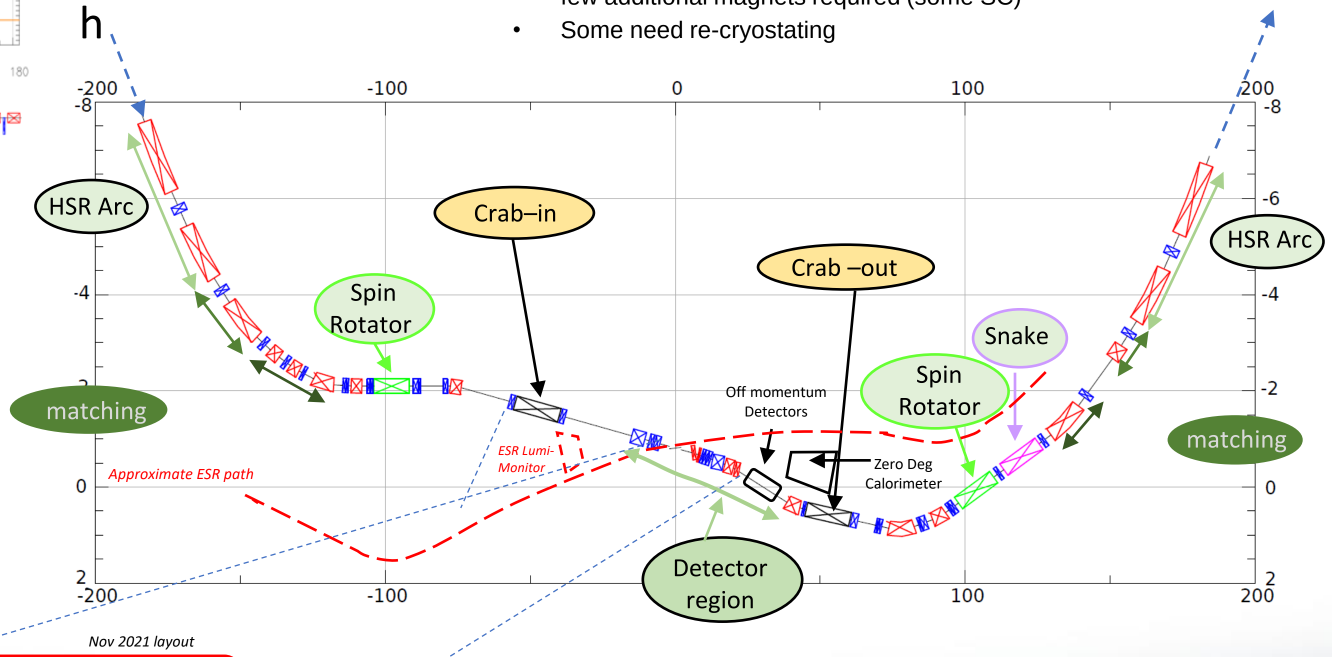


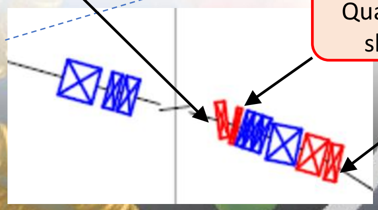
HSR layout in IR6



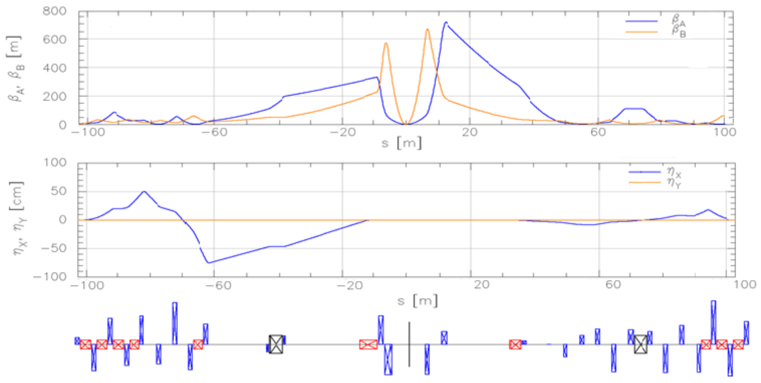
- Forward and rear hadron lattice matched into RHIC
  - Snake at correct angle
  - Beta = 1300m at crab cavities
    - Hor. phase advance 90º
  - Matching Magnets
    - Mostly repurposed RHIC magnets
    - few additional magnets required (some SC)
    - Some need re-cryostating





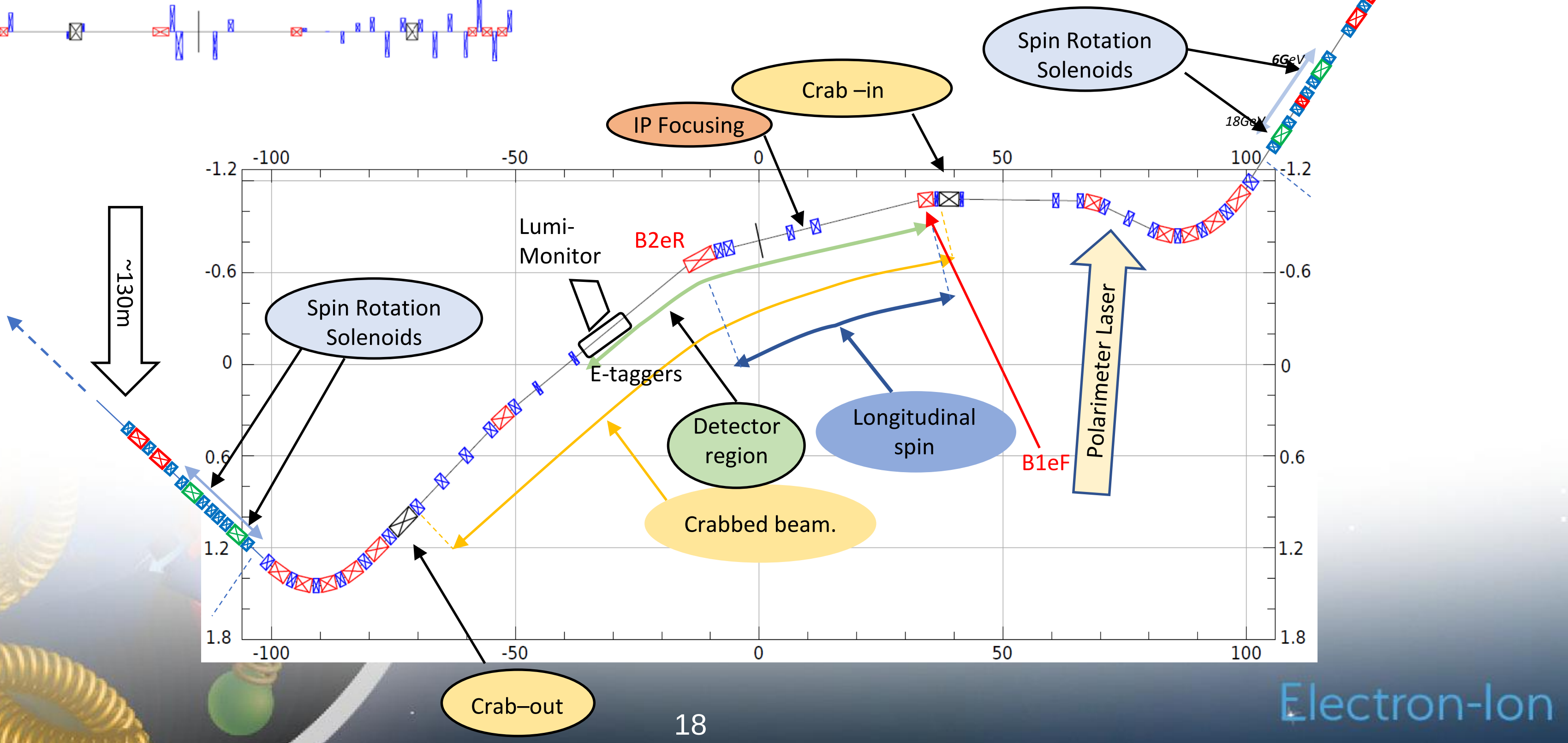


ESR layout in IR6



Design to:

- Provide room for detector components
- Mitigate synchrotron radiation issues
- Provide longitudinal spin (new spin rotators)
- Match into the arcs
- Provide conditions for crabbing
- Allow 3 rings and beam elements



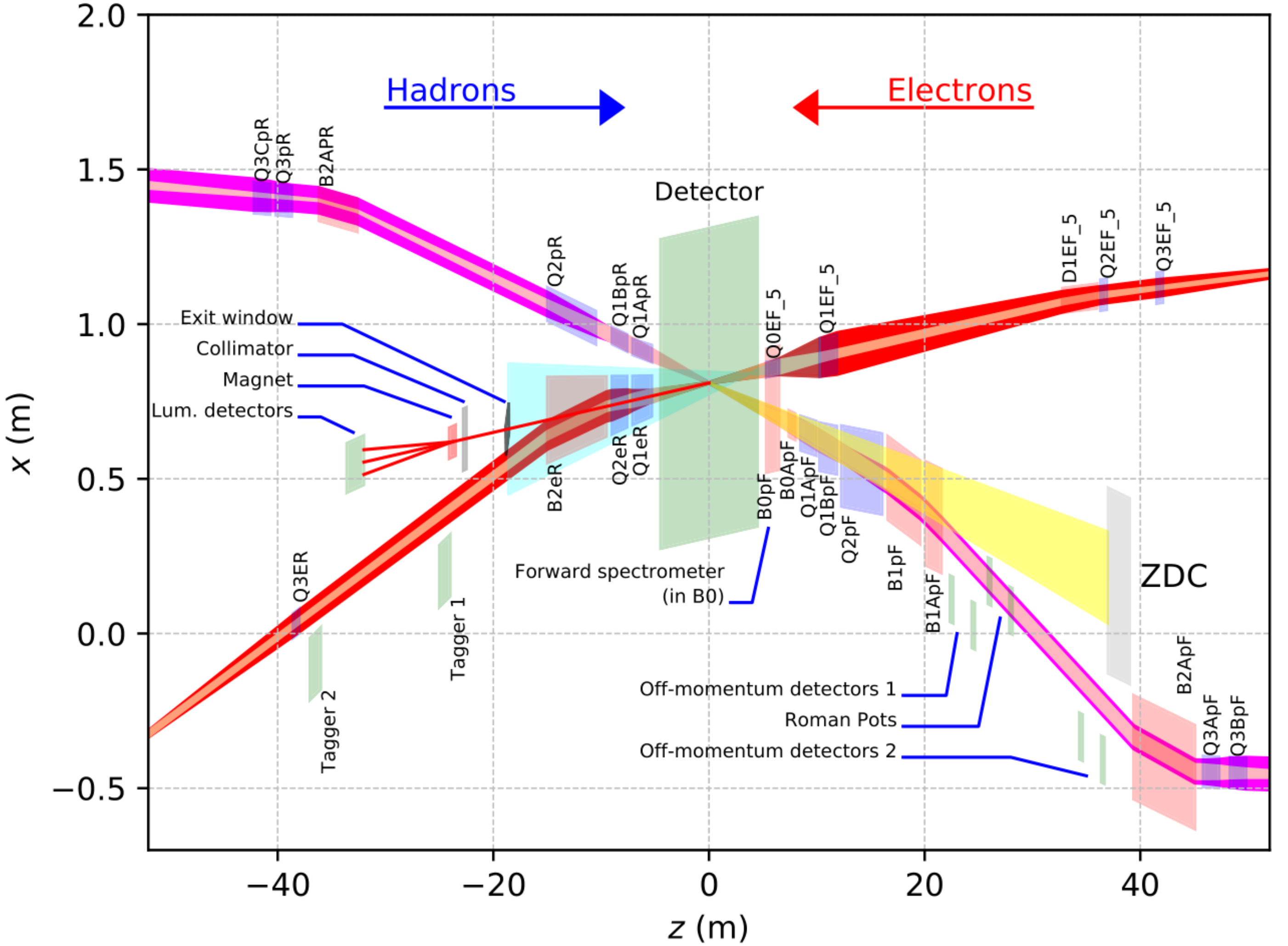
EIC IR Layout

High luminosity:

- Small β* for high luminosity
- Limited IR chromaticity contributions
- Large final focus quadrupole aperture

Physics requirements:

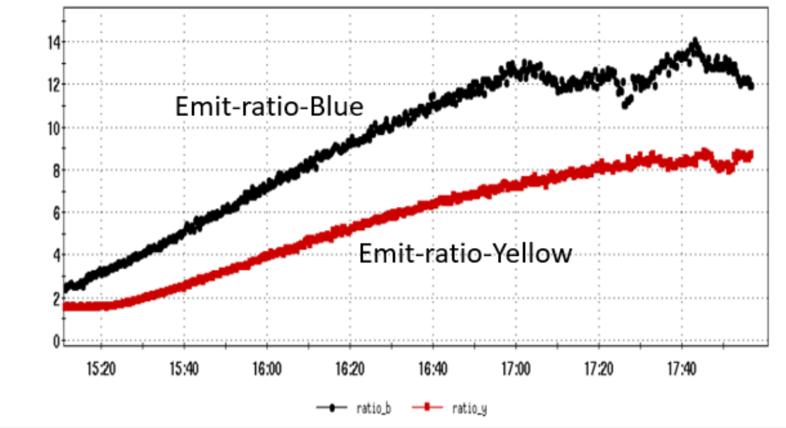
- Large detector acceptance
- Forward spectrometer
- No machine elements within +/- 4.5m from the IP
- Space for luminosity detector, neutron detector, "Roman Pots"

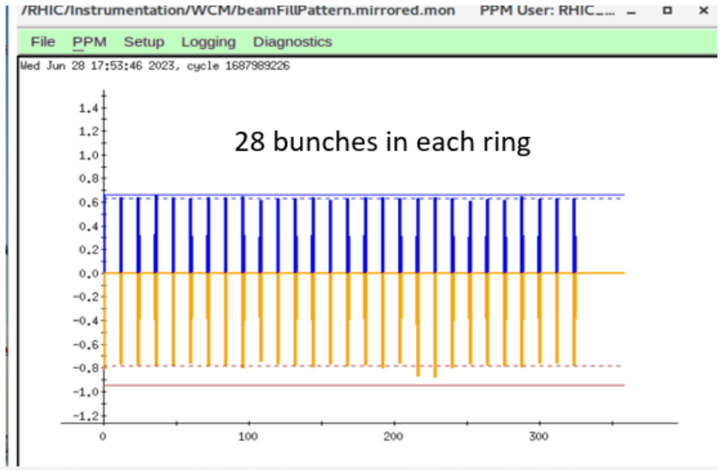


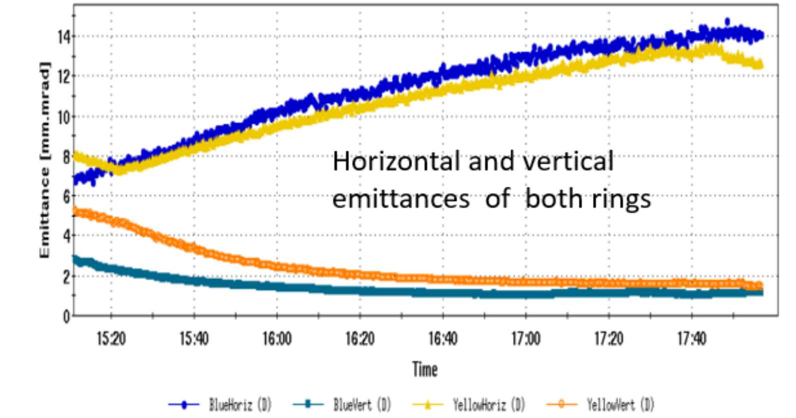
Multi-stage separation:

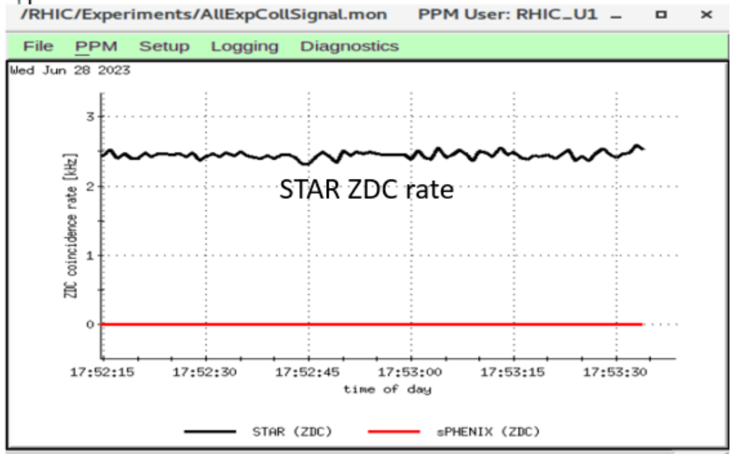
- Electrons from protons
- Protons from neutrons
- Electrons from Bethe-Heitler photons (luminosity monitor)

Latest Highlight #1 – Flat Hadron Beam Collisions









Latest Highlight #2 – Magnets for the ESR

- 400 Quadrupoles and 280 Sextupoles from the Advanced Photon Source at ANL to be repurposed for ESR
- > $10M cost savings
- Magnet shipment to start 7/31

Summary

- The EIC will be the next large nuclear physics facility, starting operations ~2031
- It fulfills all the requirements listed in the White Paper, facilitating a rich physics program
- These requirements make it a very challenging machine – high beam currents, polarization, novel hadron cooling technique, large energy range, …