Electron-Ion Collider Design Status

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EIC Technical Director

ePIC Collaboration Meeting
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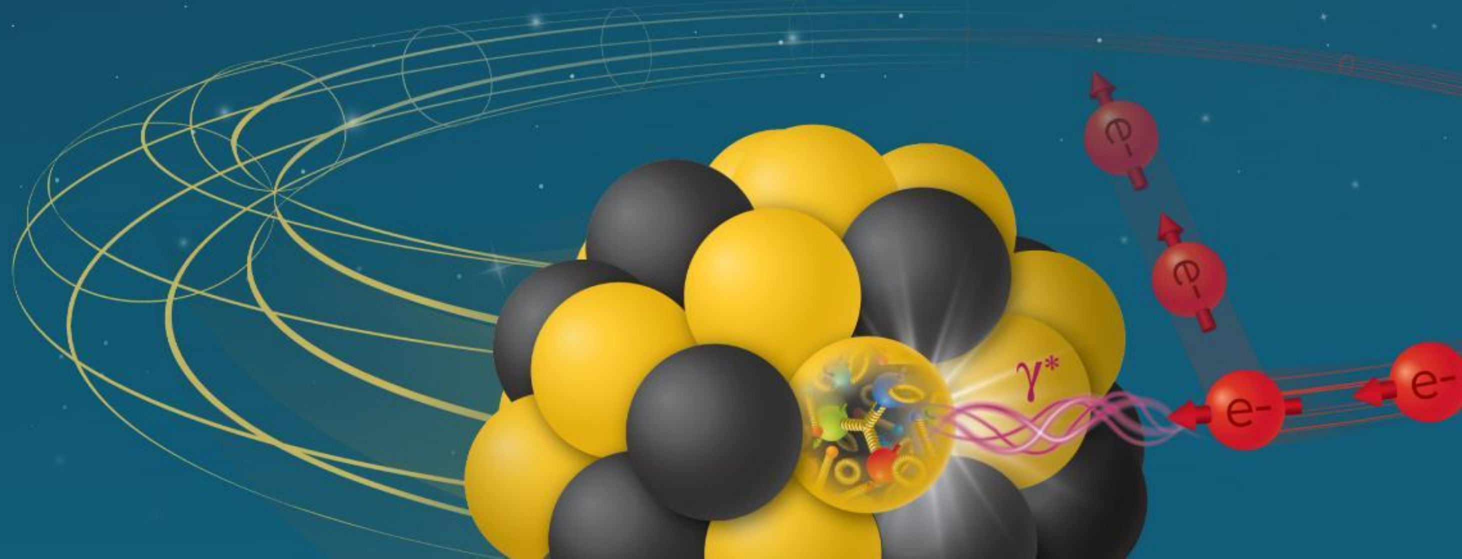
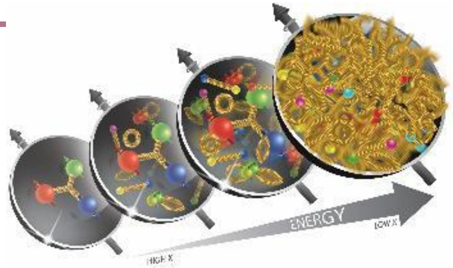
Electron-Ion Collider



Outline

- Requirements
- Design changes
- Present concept
- Summary

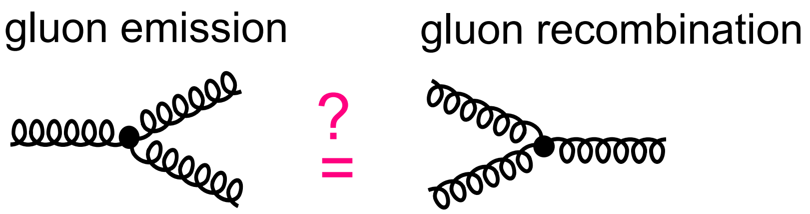
EIC Accelerator Performance Drivers



wide center-of-mass energy √s: 20 – 140 GeV :
- map the out nucleon and nuclei structure from high to low x

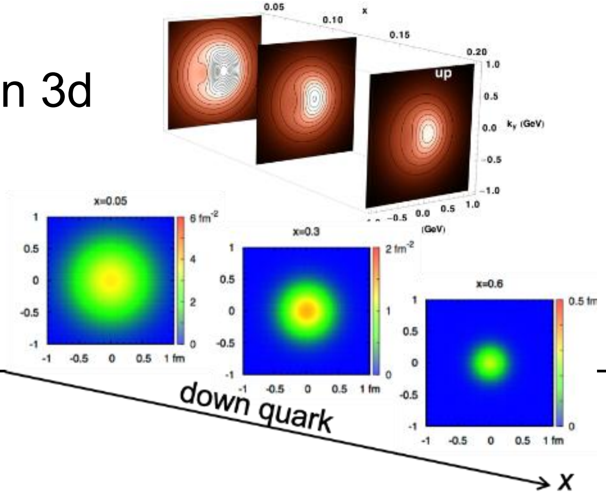
polarized electron and hadron (p, He-3) beams:
- access to spin structure of nucleons and nuclei
- Spin vehicle to access the spatial and momentum structure of the nucleon in 3d
- Full specification of initial and final states to probe q-g structure of NN and NNN interaction in light nuclei

nuclear beams: d to Pb
- accessing the highest gluon densities → saturation
- quark and gluon interact with a nuclear medium



high luminosity 10^{33}-10^{34} $cm^{-2}s^{-1}$:
- mapping the spatial and momentum structure of nucleons and nuclei in 3d
- access to rare probes, i.e. Ws

large acceptance (0.2 – 1.3 GeV) through forward focusing IR magnets
- spatial imaging of nucleons and nuclei



EIC Accelerator Performance Requirements

- Center-of-mass energies: ~20 to ~140 GeV (e-p)
- High degree of beam polarization *(P):* ~70%
- Availability of ion beams: from proton to Pb
- Luminosity *(L):* 10^{33} – 10^{34} $cm^{-2}sec^{-1}$
- Possibly more than one IR

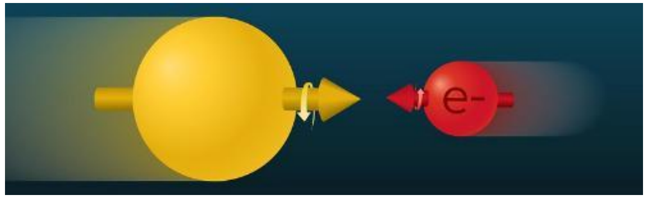
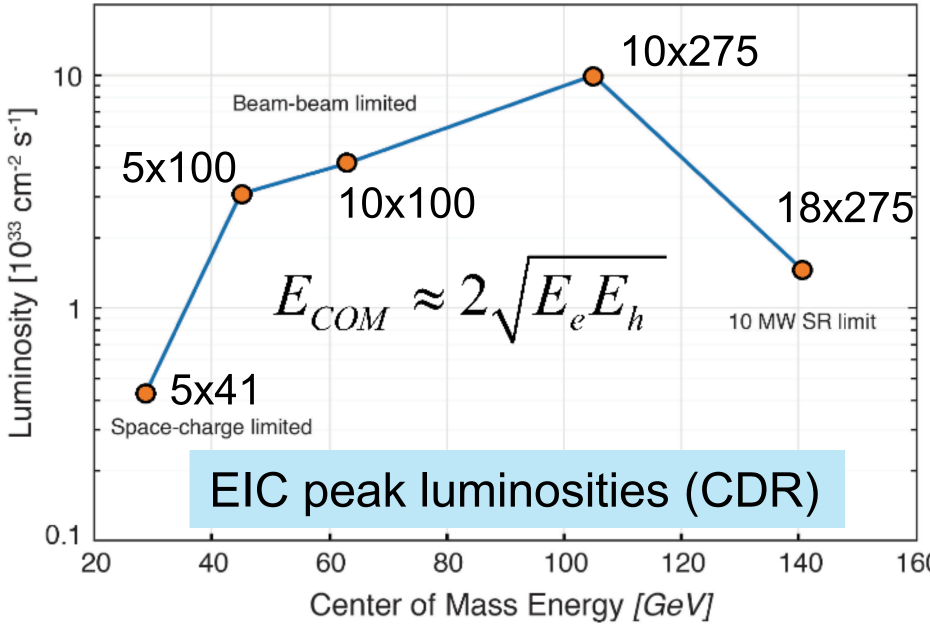


Figure of merit: LP^2 to LP^4

Bunch charges: 28 nC (10 GeV, e) and 11 nC (275 GeV, p)

$$L = \frac{N_e N_p}{4\pi\sigma_h\sigma_v} N_b f_0 \approx 1\times10^{34}\ \text{cm}^{-2}\text{s}^{-1} \qquad N_b = 1160;\ f_0 = 78.3\ \text{kHz}$$



The EIC design and performance parameters address the requirements established by the U.S. Nuclear Science Advisory Committee (NSAC) Long Range Plans (2015 & 2023)

Key EIC Accelerator Concepts, Proposed in the CDR

- Ribbon-like (flat) hadron beam (11:1 transverse emittance & beam size ratio)
- Large crossing angle (25 mrad)
- Beam-beam limits for both beams (0.1 e/ 0.01 p)
- Spin preservation from source to collisions (protons and electrons)
- Very high bunch intensities and circulating beam currents (1 A (p), 2.5 A (e))

- Possible upgrade path: 18 GeV electron capability, high-energy hadron cooling at collisions

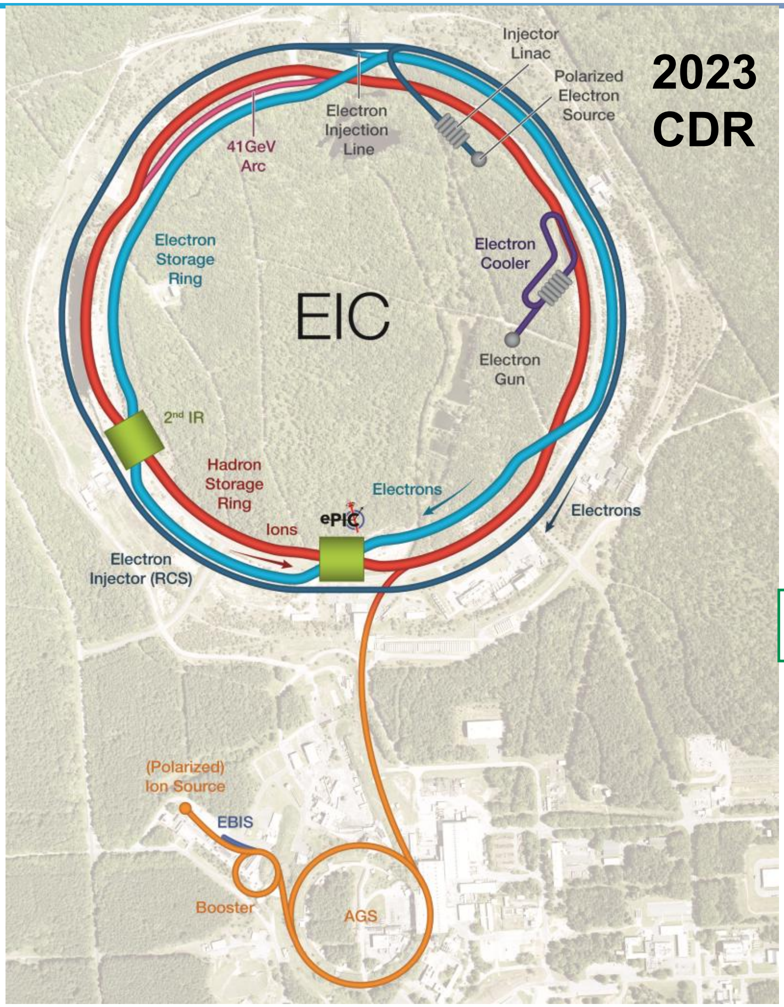
These are the key concepts that allow to attain peak luminosity of ~10^{34} $cm^{-2}s^{-1}$ and to maintain high polarization at collisions over a broad range of CoM energies

Note: HERA(1992-2007) peak luminosity: ~$5x10^{31}$ $cm^{-2}s^{-1}$

Key EIC Accelerator Technology Areas Contributing to MNS

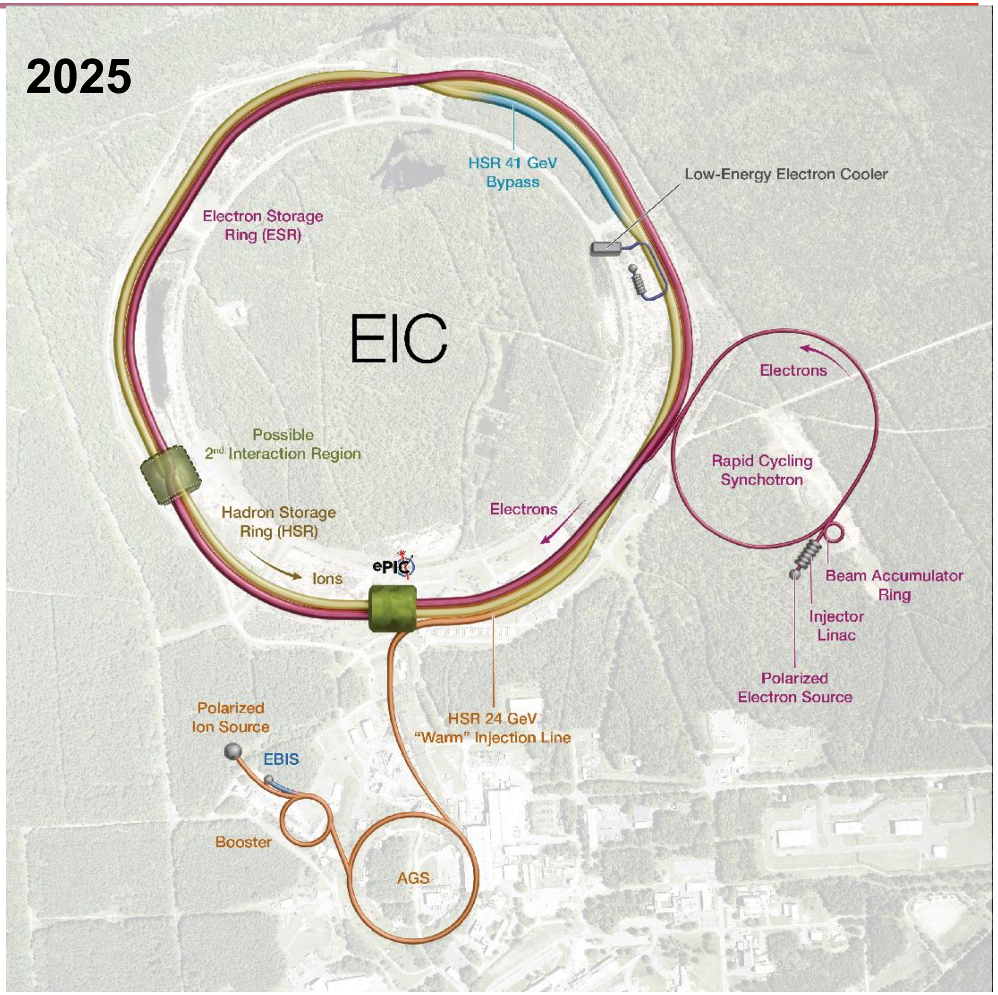
- Hadron Beam Cooling
- Spin-preserving beam optics
  - High polarization for both beams from source to collisions
  - Swap-out injection for electron bunches (at 1 Hz) to maintain high polarization in the ESR
- Crab cavities
  - Large-size, complex geometries;
  - Very tight phase and amplitude noise requirements
- IR magnets
  - Large aperture, One of a kind SC magnets
- Beam instability and impedance control
  - Vacuum chambers, beam screens, kickers, SRF cavities

EIC Design has converged. Stable since Jan 2025



Protons: ~40 – 275 GeV
Electrons: 5 – 18 GeV
E_{CM} = 29 – 140 GeV

MNS ✓



Design changes addressed technical uncertainties and risks, and did not change the performance and cost objectives.

Preparing the Accelerator Design for Performance Baseline in 2026

Date	Milestone/Progress
2019	DOE EIC Mission Need Statement (MSN)
2021	EIC Conceptual Design Report
2023	EIC Global Requirements
2023-2024	Design changes reviewed by Machine Advisory Committee and documented by TCCB, CCB, RoDs, System Requirements
2025	Design Converged • EIC Global Parameters List (draft) – now under version control
2026	Draft Preliminary Design Report posted for August 2025 IPR • Final version will be released by Summer 2026

The EIC Accelerator design is stable.

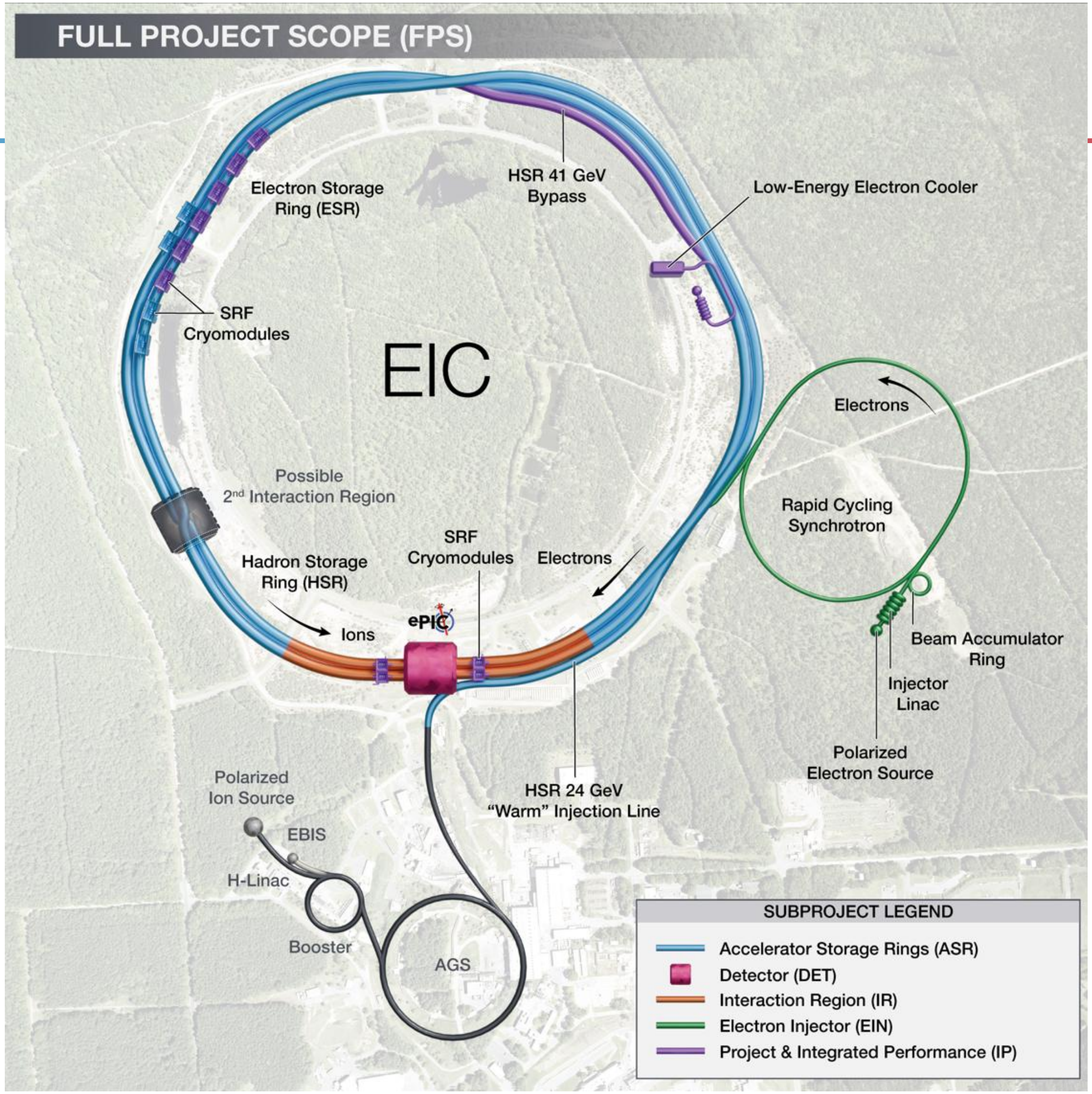
We have a well-defined vision of what is required to build the EIC!

Sub-projects

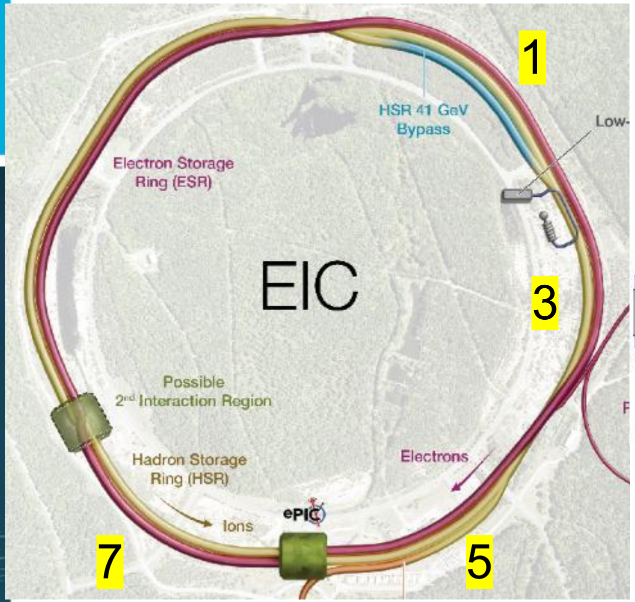
CD-3A, CD-3B, and NYS	Baselined (CD3A). NYS Secure.
Accelerator Storage Rings (ASR)	**High design maturity. Low risk.**
Electron Injector Complex (EIN)	Medium design maturity. Low risk.
Interaction Region (IR)	Medium design maturity. High risk.
Detector (DET)	High design maturity and cost risk*.
Project & Integrated Performance (IP)	Medium design maturity. Low risk.

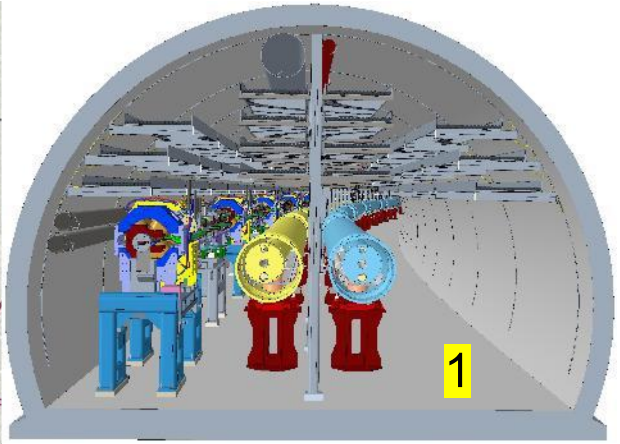
Stability of overall EIC design allowed for an efficient scope split into sub-projects

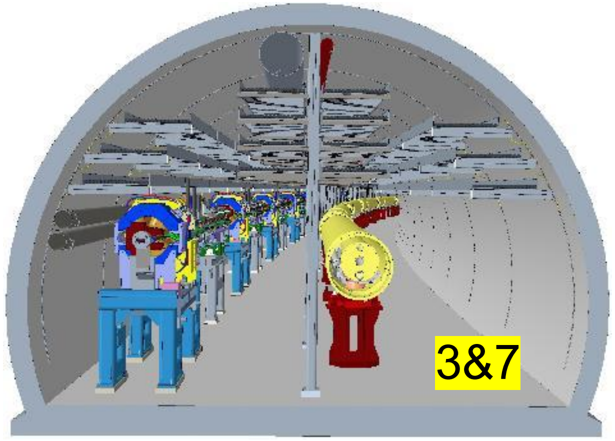
* due to large in-kind contributions, which need to be formalized

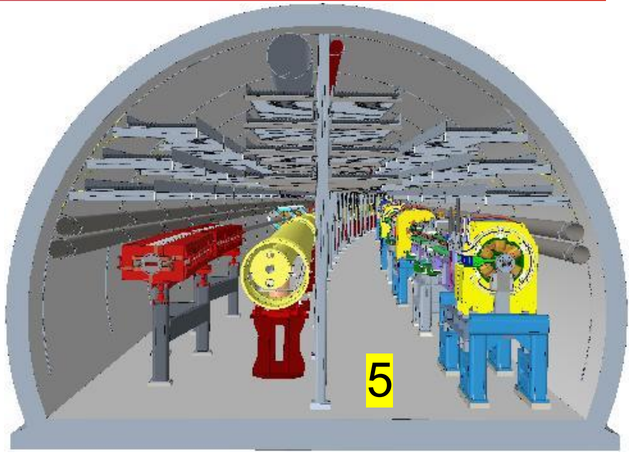

FULL PROJECT SCOPE (FPS)
Electron Storage Ring (ESR)
HSR 41 GeV Bypass
Low-Energy Electron Cooler
SRF Cryomodules
EIC
Electrons
Possible 2nd Interaction Region
Rapid Cycling Synchrotron
SRF Cryomodules
Electrons
Hadron Storage Ring (HSR)
Ions
ePIC
Beam Accumulator Ring
Injector Linac
Polarized Electron Source
HSR 24 GeV "Warm" Injection Line
Polarized Ion Source
EBIS
H-Linac
Booster
AGS
SUBPROJECT LEGEND
Accelerator Storage Rings (ASR)
Detector (DET)
Interaction Region (IR)
Electron Injector (EIN)
Project & Integrated Performance (IP)

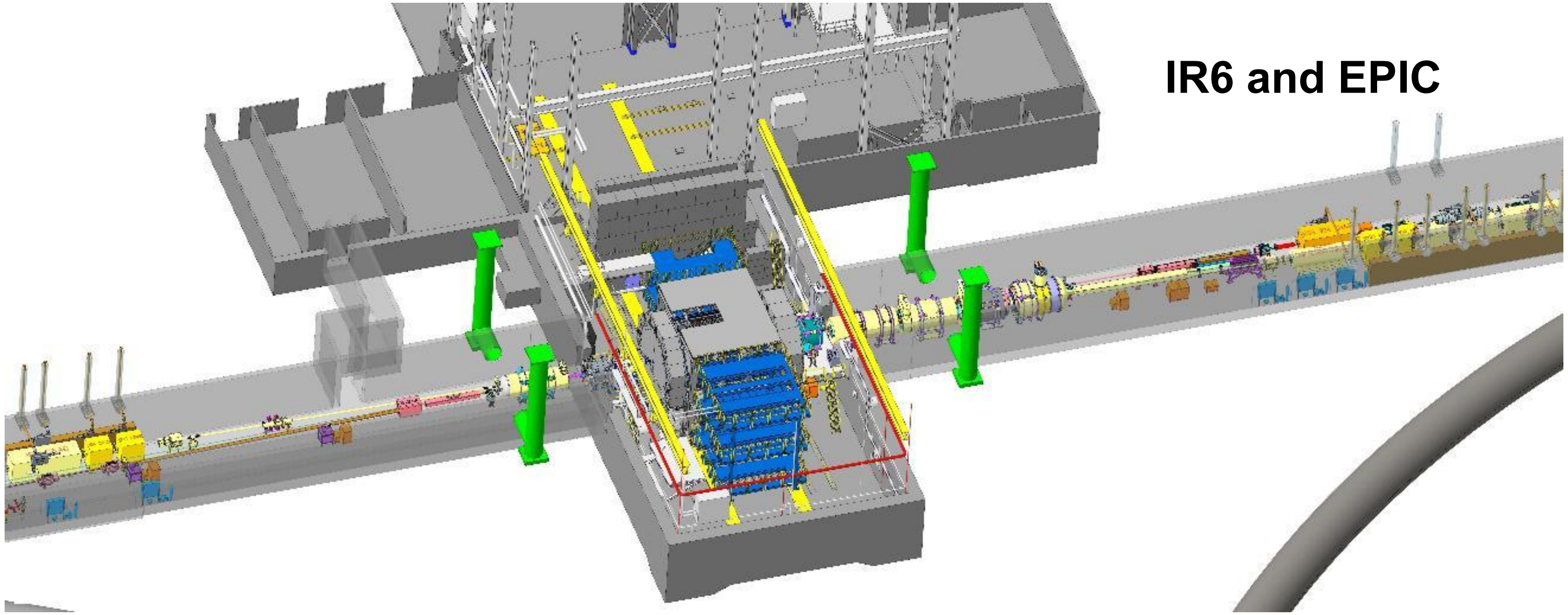
Collider Layout



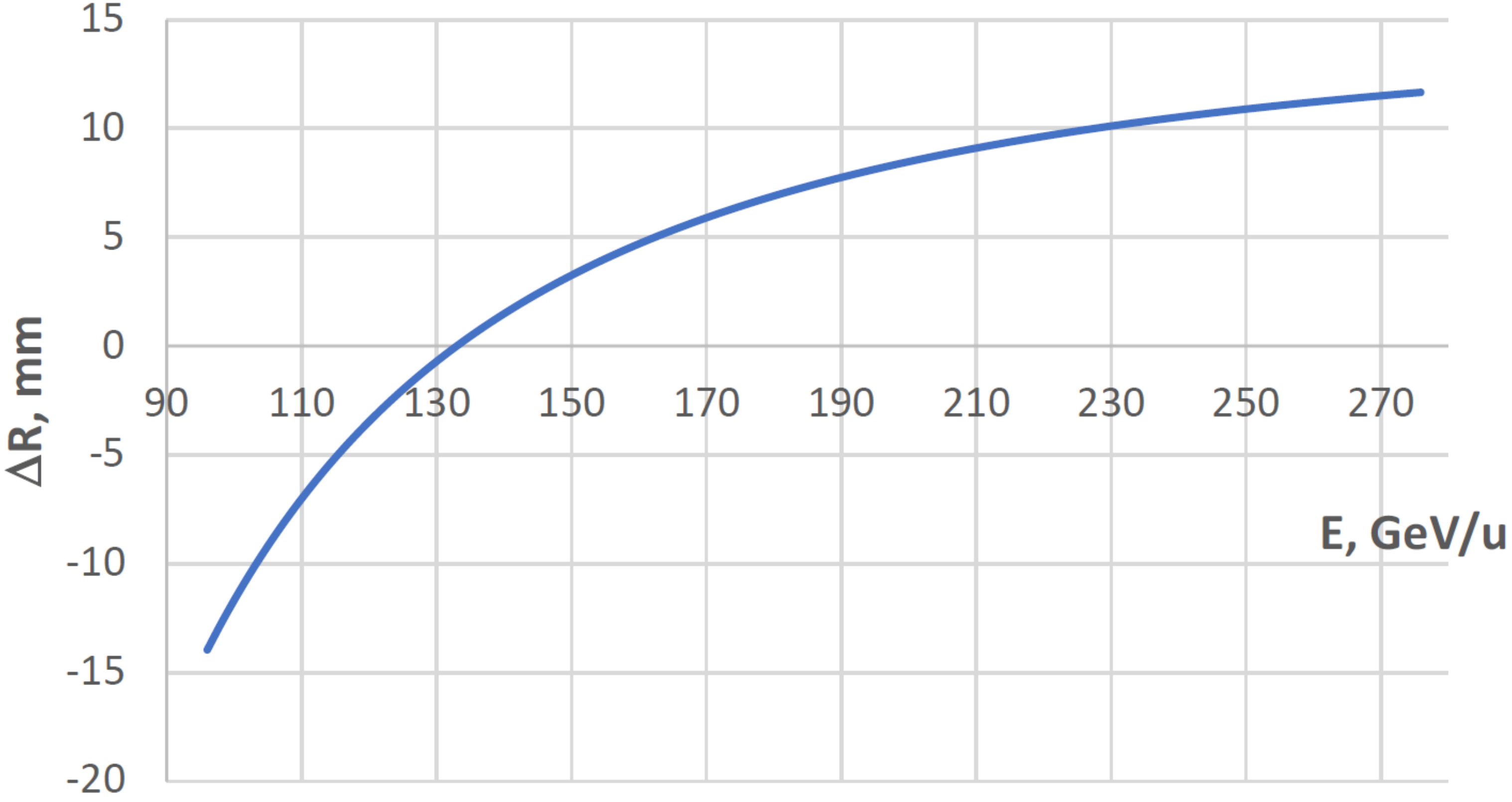


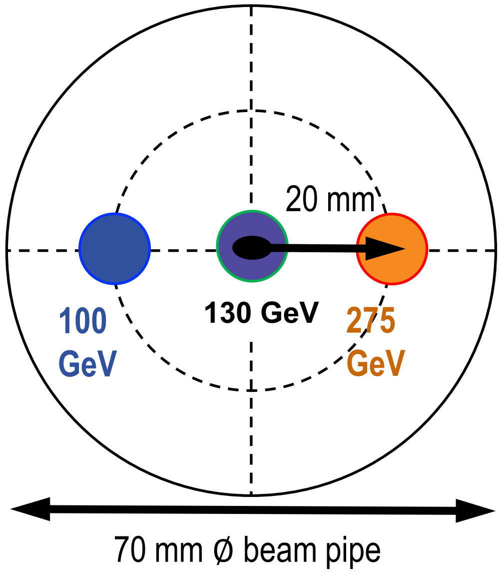






Beam Energy and Average Orbit Radius in the HSR



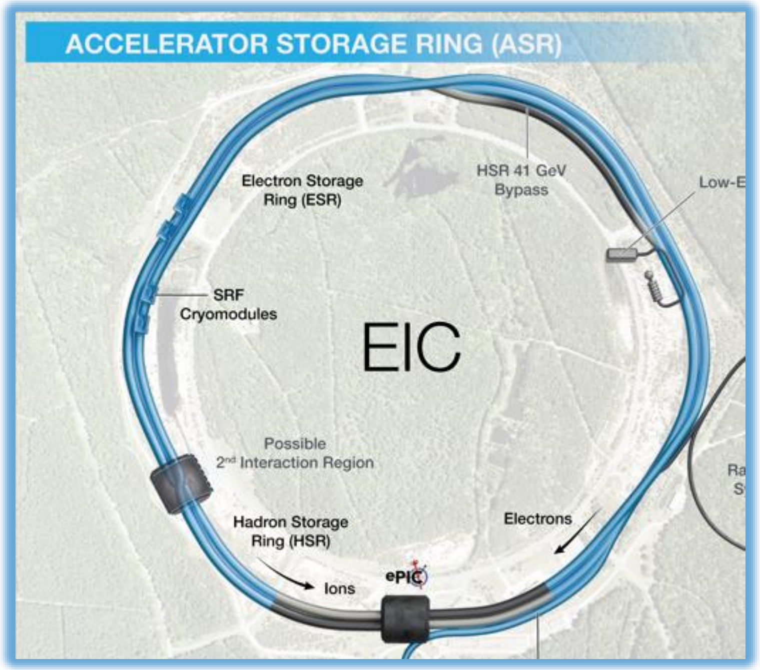


Since the electron revolution frequency is fixed, the hadron orbit must be adjusted with energy to keep the collisions in sync.

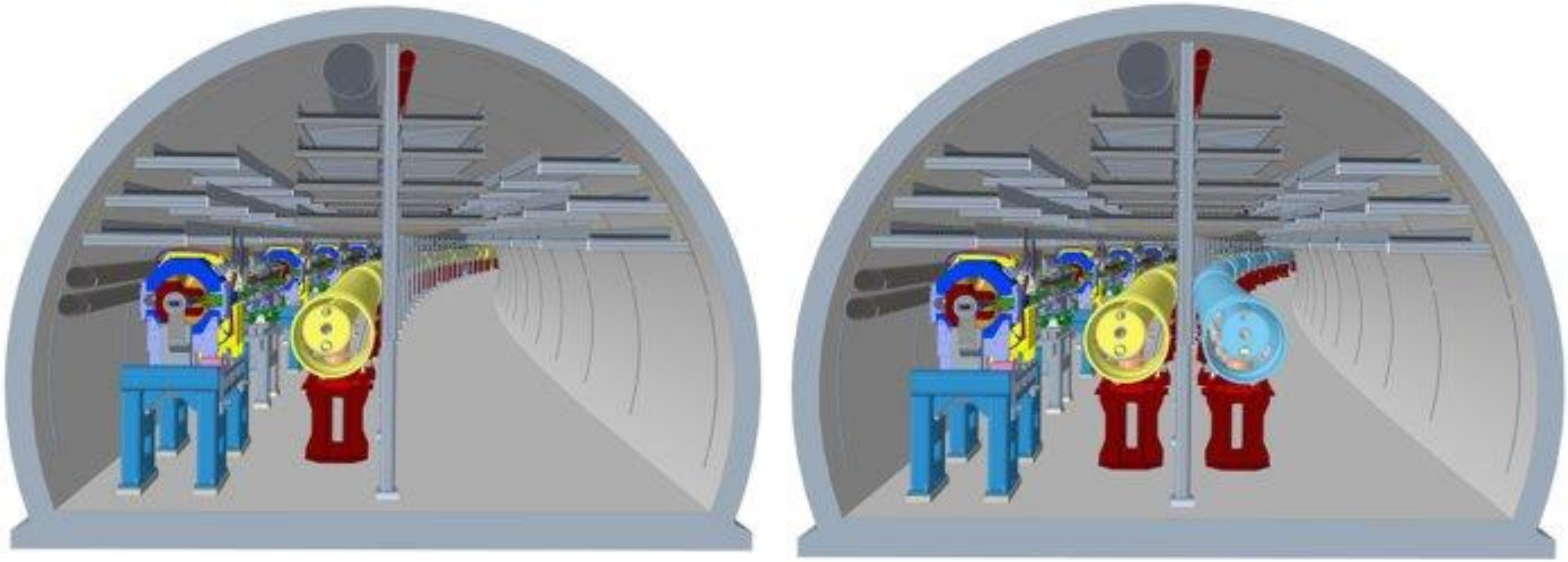
The 41-GeV ‘bypass’

This bypass provides access to the lowest HSR energy, 41 GeV

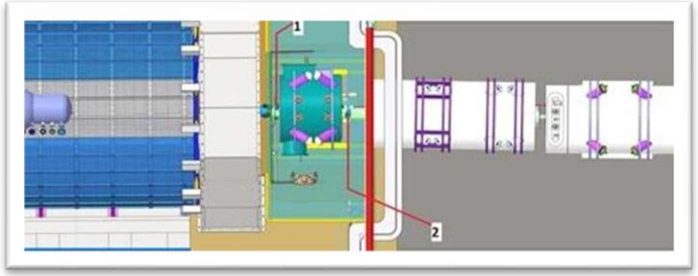
MNS: ✓

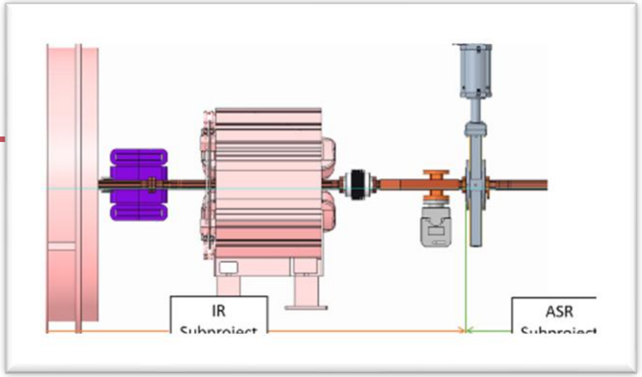


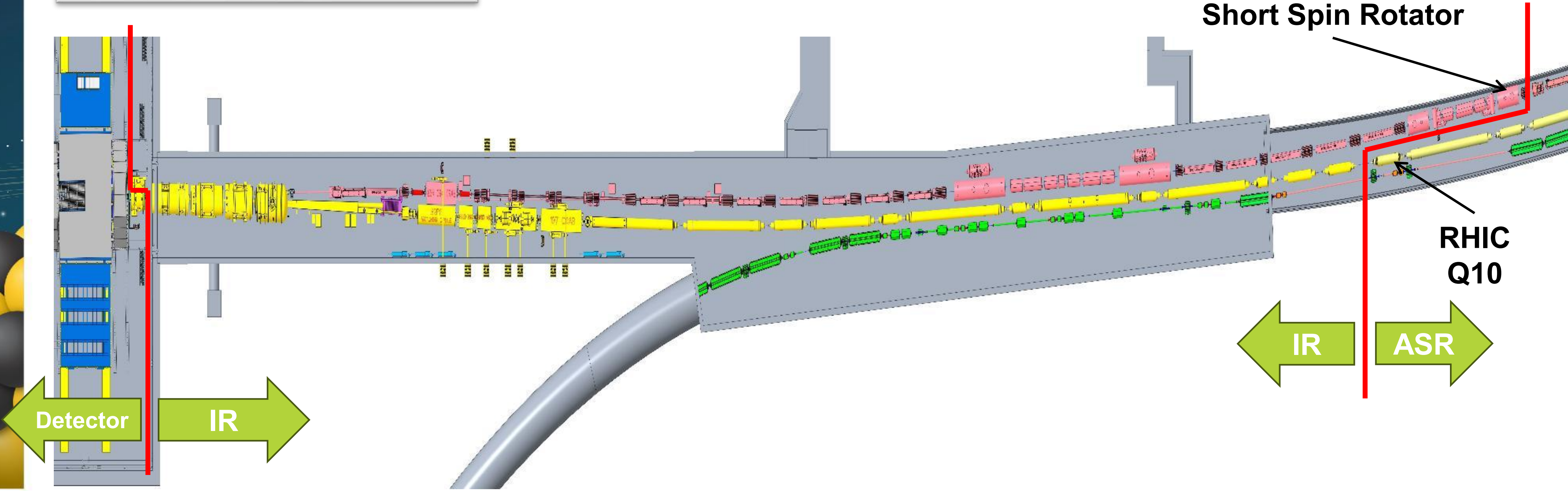
Sector 1 without and with the 41-GeV bypass line



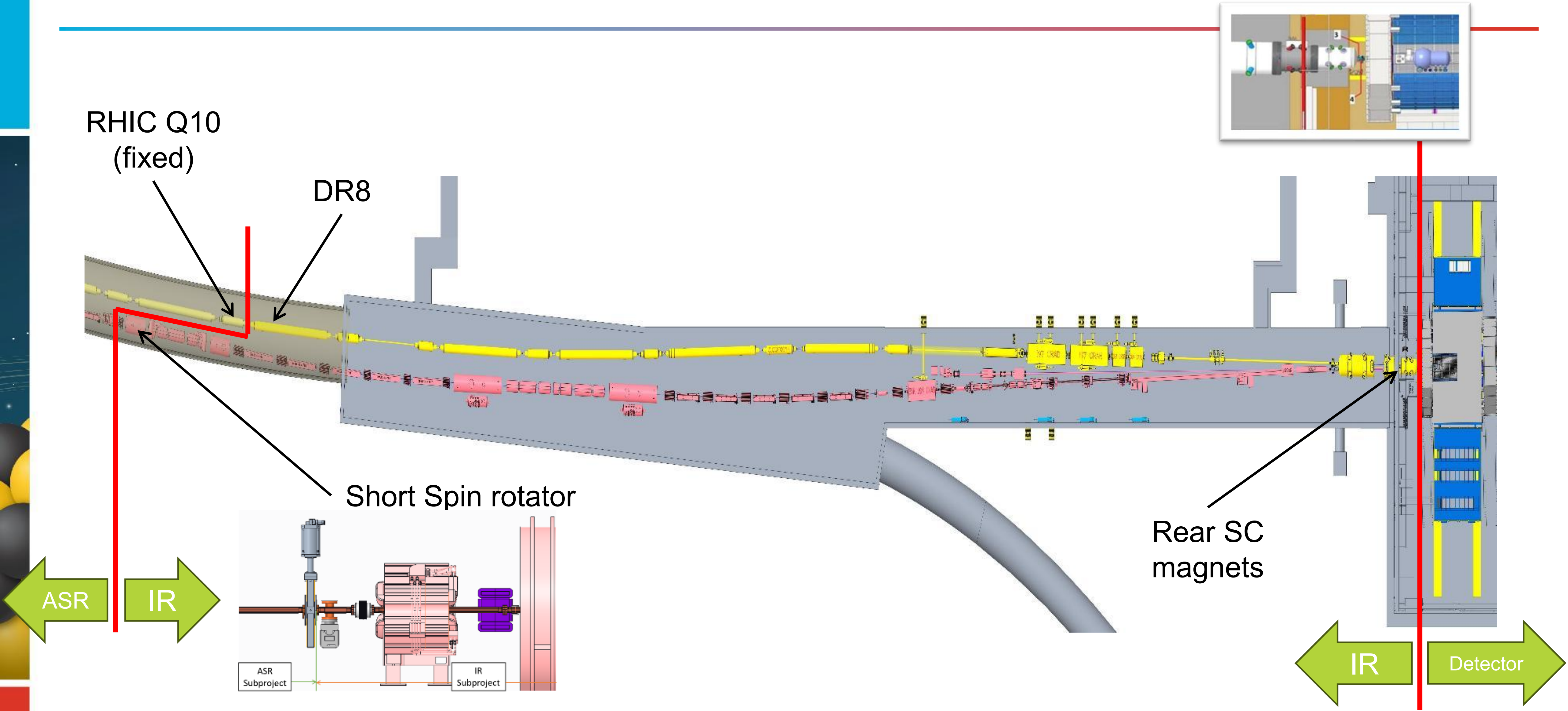
ePIC Interfaces in Sector 5







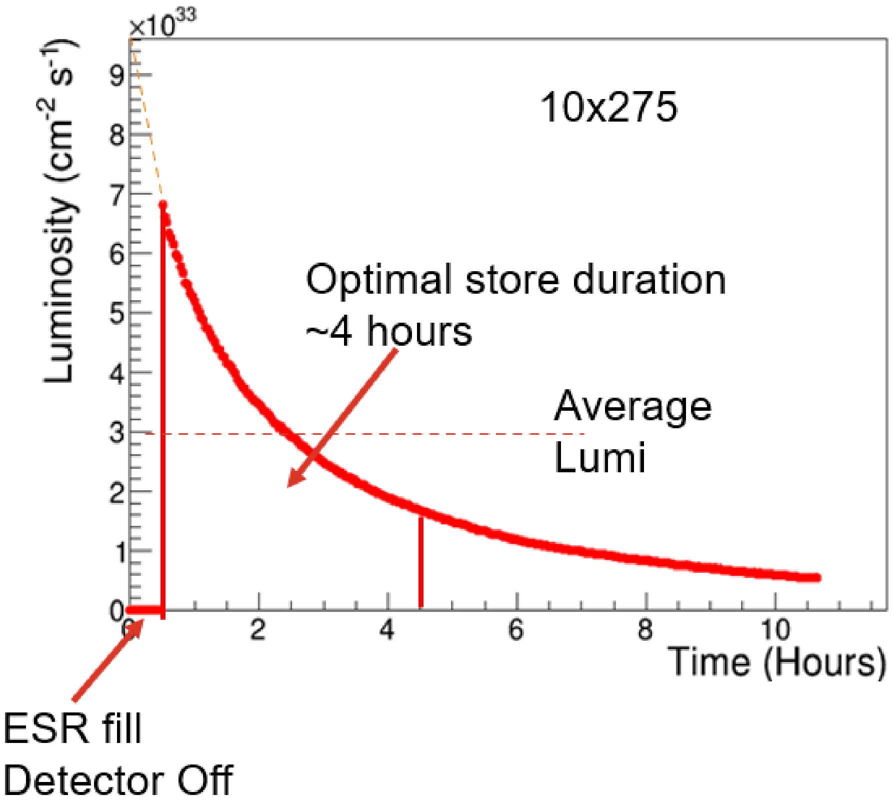
ePIC Interfaces in Sector 7

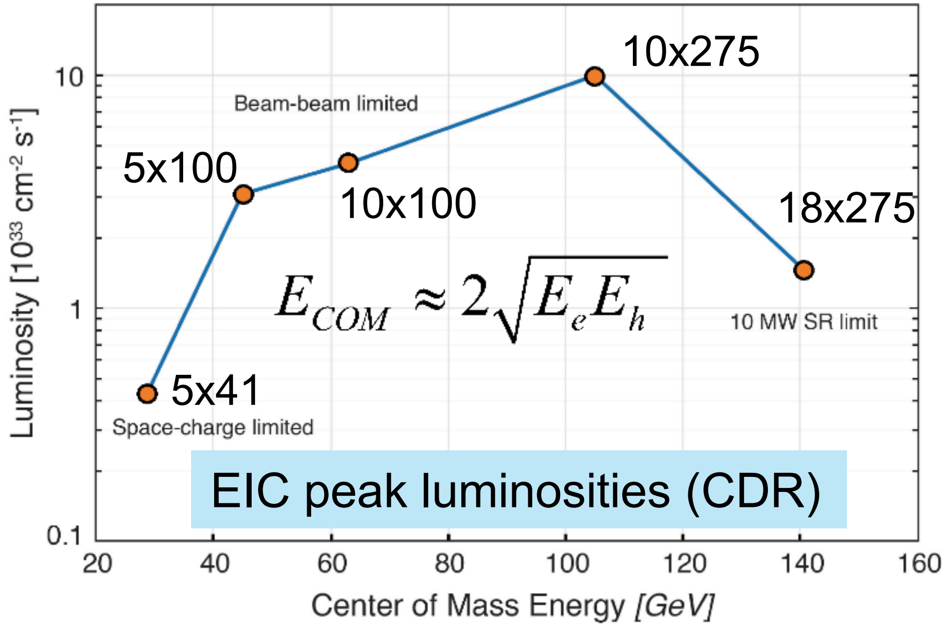


Luminosity Performance Meets the Established Requirements

"Flat" proton bunches allow for high initial luminosity.

CoM Energy (GeV)	Average Lumi ($\times10^{33}$ $cm^{-2}s^{-1}$) (per 4-hour store)
105	3
63	1.2
45	1
140	0.44
29	0.13





EIC peak luminosities (CDR)

Polarization Performance Meets the Established Requirements

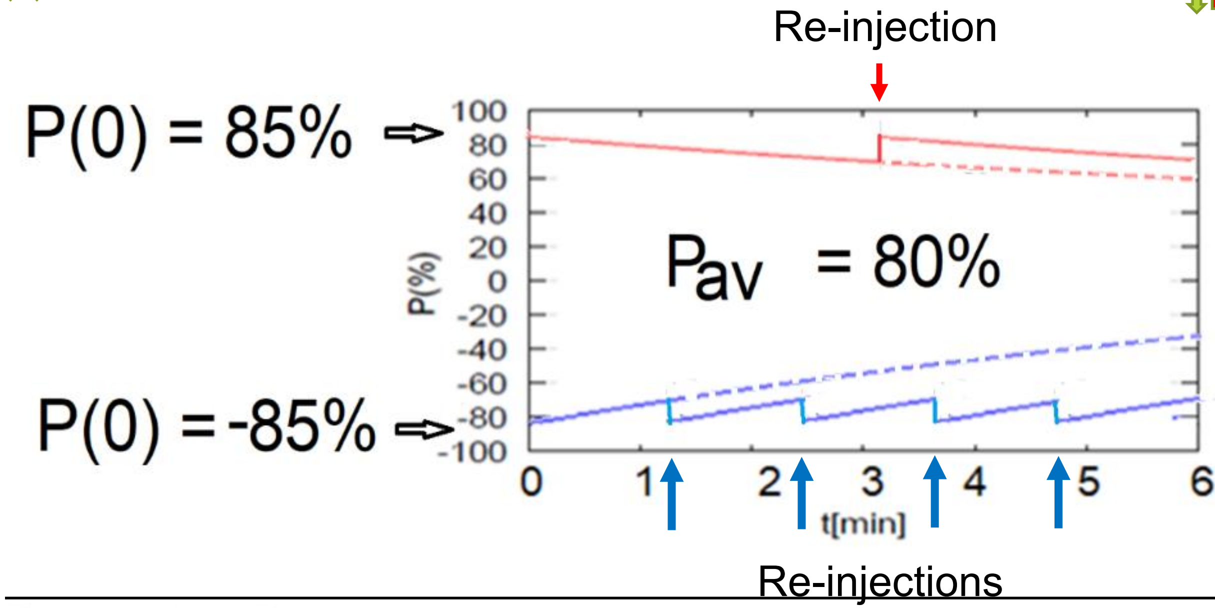
- Frequent swap-out injection of bunches with high initial polarization of 85%
  - Bunch spacing is ~10 ns
- Initial polarization decays towards P_∞
- At 18 GeV, every bunch is replaced (on average) after 2.2 min with RCS cycling rate of 1Hz

B P

Refilled every 1.2 minutes

B P

Refilled every 3.2 minutes

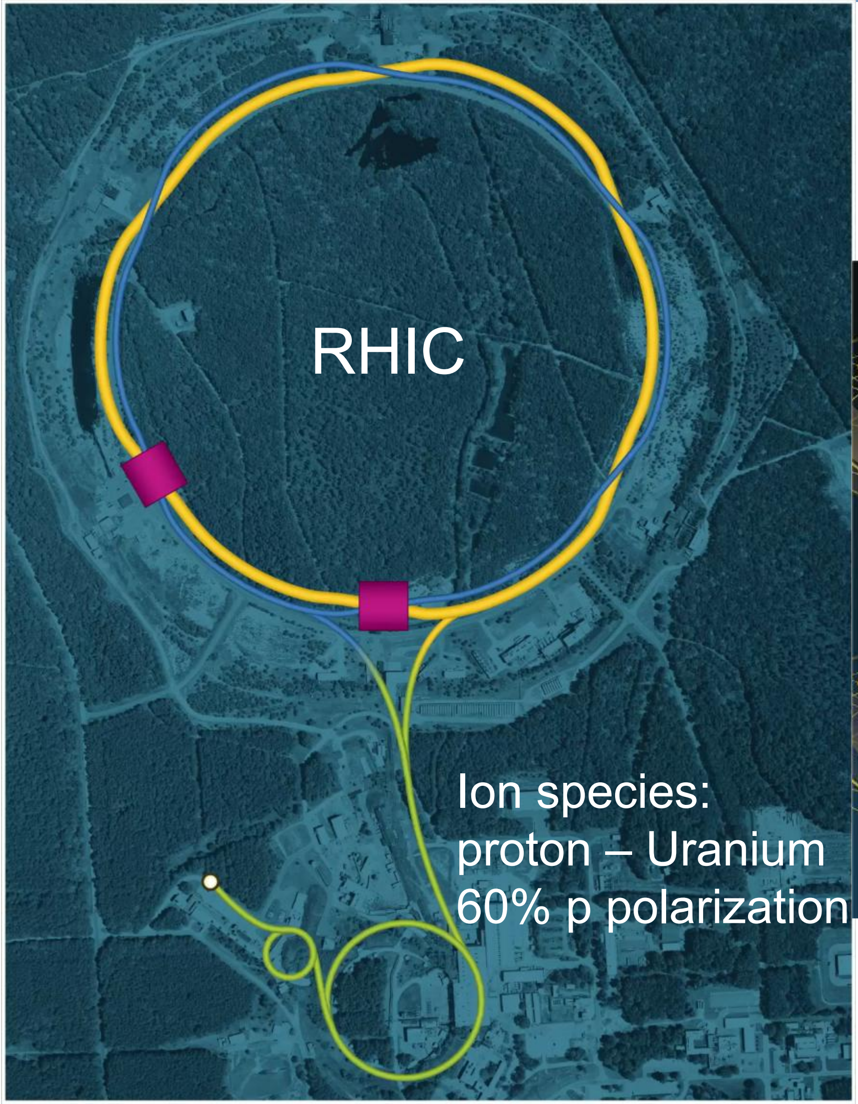


P_∞= 30% (conservative)

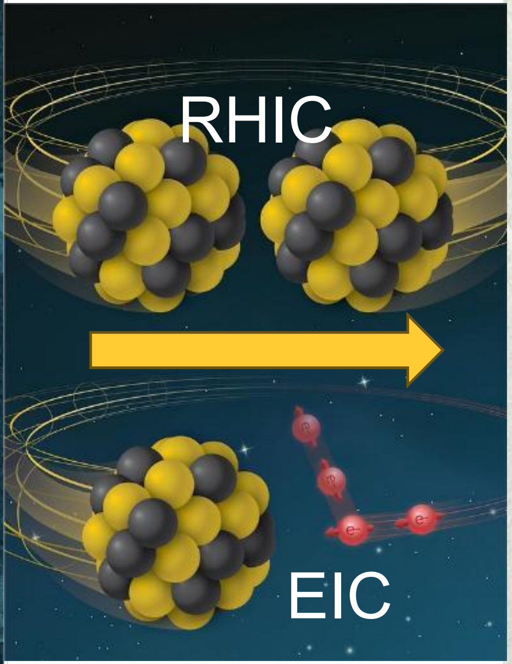
HSR proton polarization performance also meets the requirements.

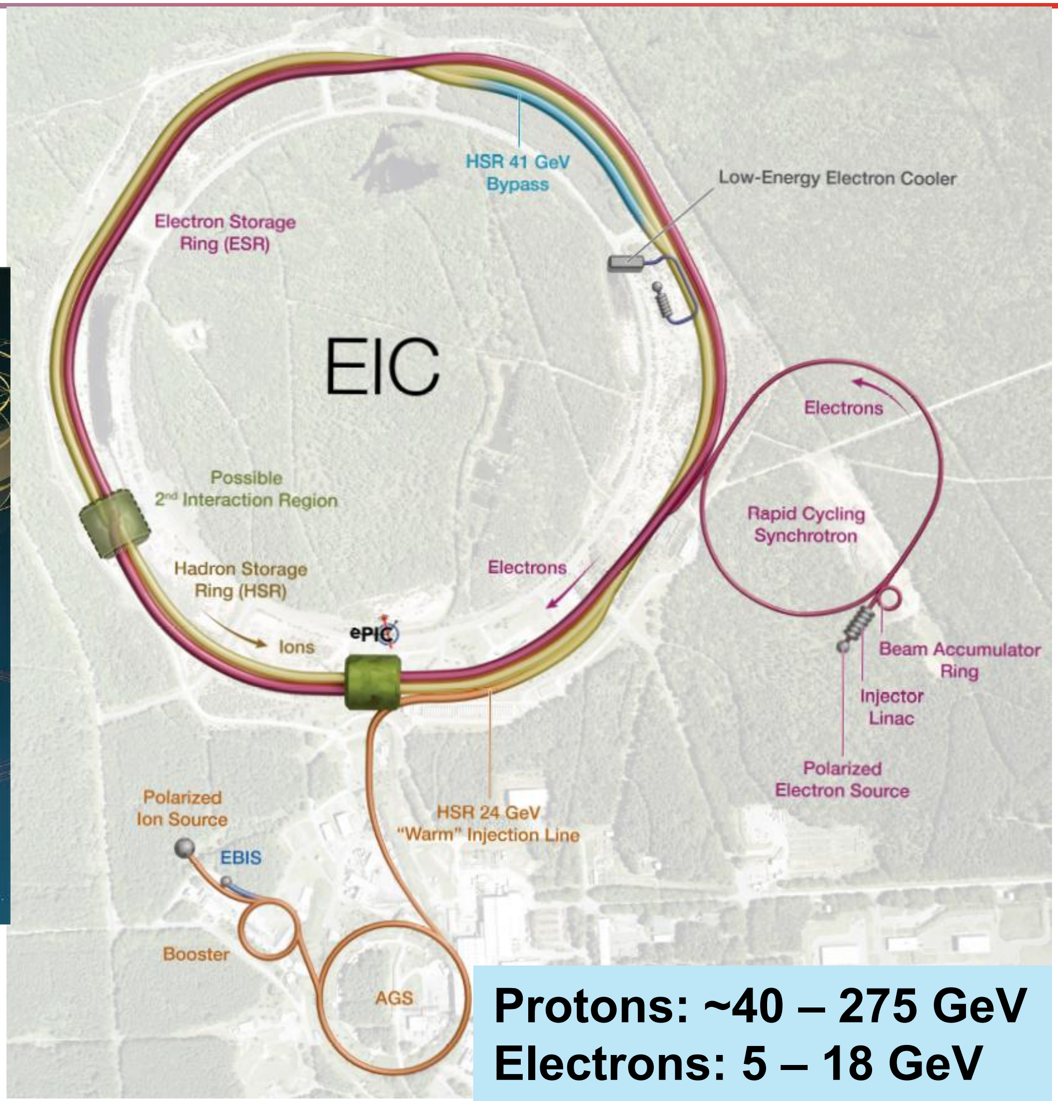
Present RHIC proton polarization is 60%

From RHIC to EIC



Ion species:
proton – Uranium
60% p polarization



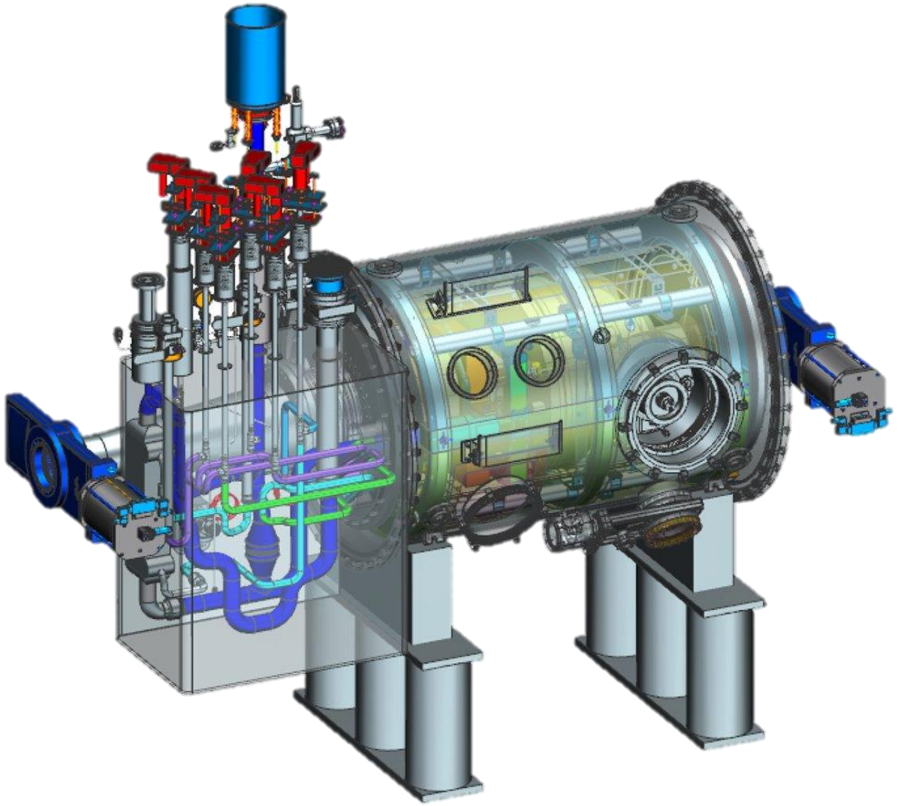


Protons: ~40 – 275 GeV
Electrons: 5 – 18 GeV

From RHIC (Yellow Ring) to EIC HSR

Tripled beam current, shorter bunch length, shorter bunch distance, ‘flat’ beams with small vertical emittance

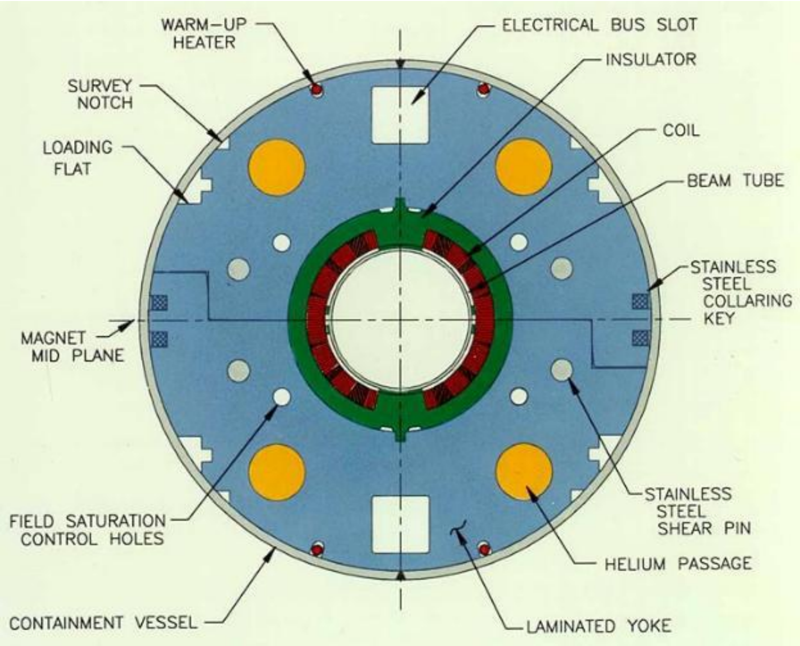
- EIC HSR to be composed of existing arcs of the Yellow RHIC ring (remove unused magnets)
- Insert sleeves coated with copper and amorphous carbon into superconducting magnet beam pipes to improve conductivity and reduce secondary electron yield (-> electron cloud)
- Add new RF cavities
- Add hadron cooling to create flat beam
- Add crab cavities, new IR SC magnets
- Add a collimation system
- Add extra ‘snakes’ for spin control



Superconducting Radio Frequency Cavity

RHIC magnets conversion to EIC

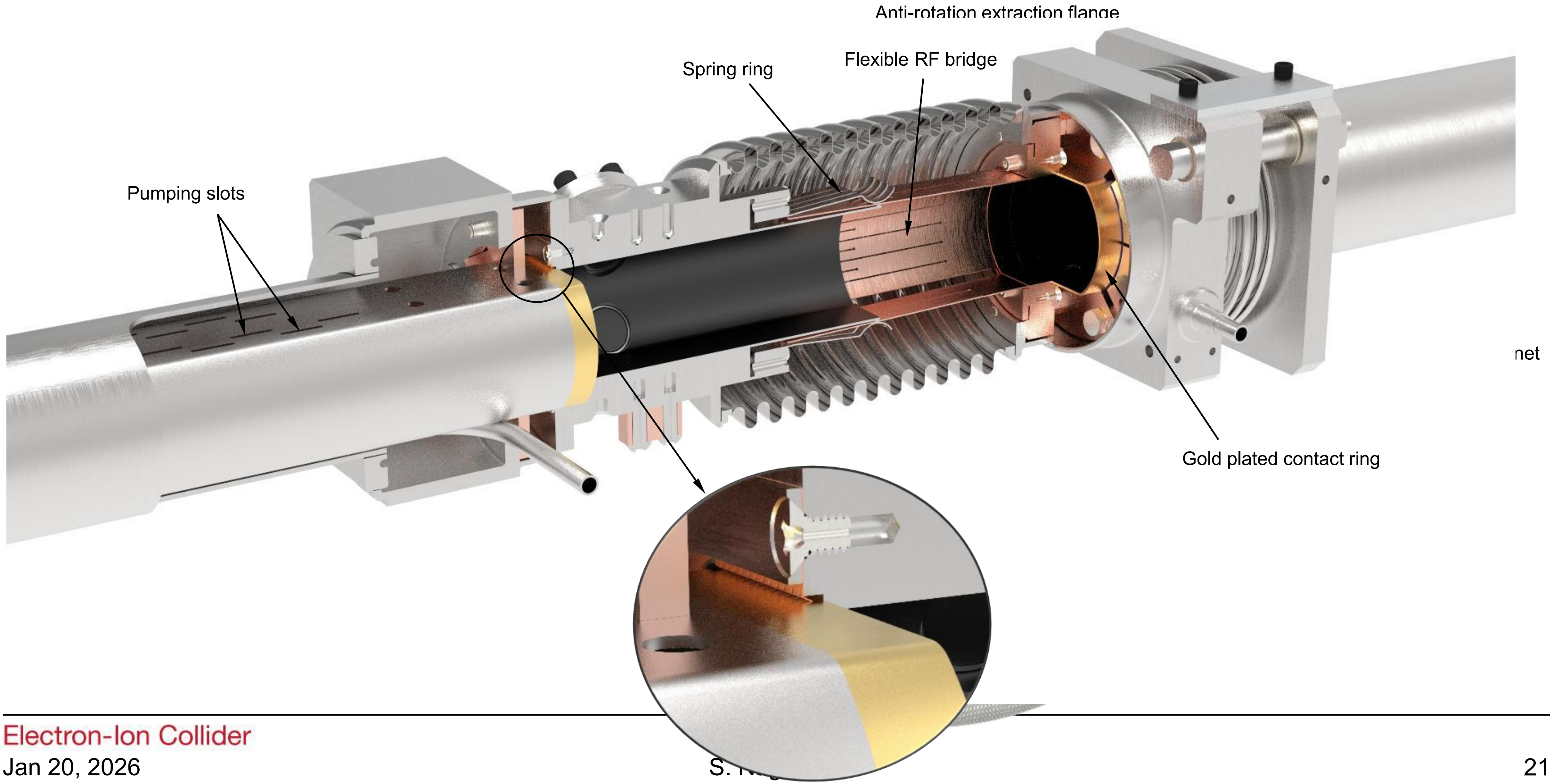
- Existing RHIC cold bore beam pipes are stainless steel
  - High surface resistance -> Excessive resistive wall heating
  - High secondary electron yield (SEY) -> Electron cloud formation
- New parameters required for EIC
  - High stored beam current (.72 A vs .27 A)
  - Reduced bunch length (60 cm vs 600 cm)
  - Short bunch spacing (10 ns vs 108 ns)
  - High bunch charge (1.2x10^{11} ppb)



Actively Cooled Beam Screen

CD3A procurement

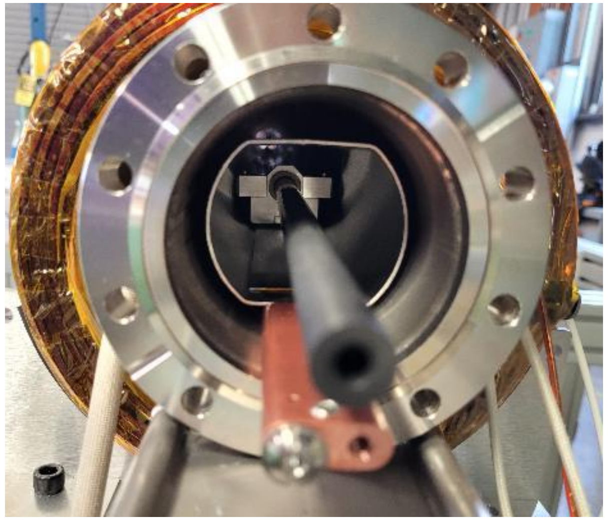
Magnet Interconnect Assembly

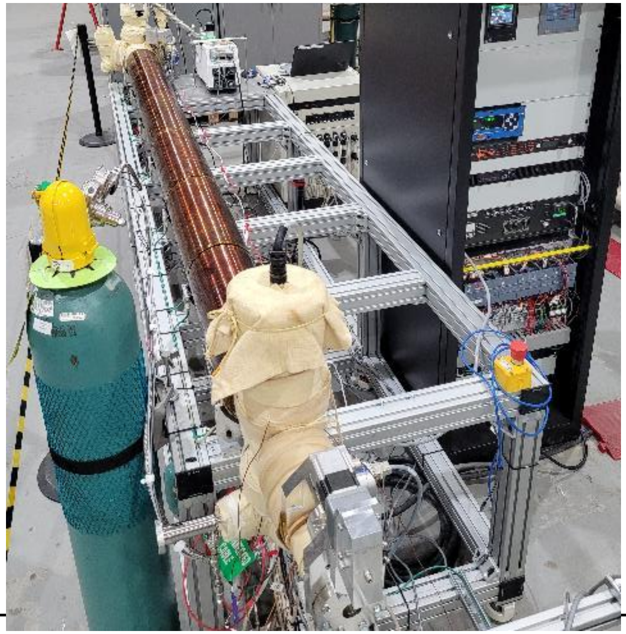


a-Carbon Coating

- Proof of principle coating system
  - Cycle time meets production requirements
- Design of full length (11m) system completed
  - Assembly in process
- Clean tent area for production nearing completion
- Ultrasonic cleaning equipment (11m) commissioned


Cleaning facility

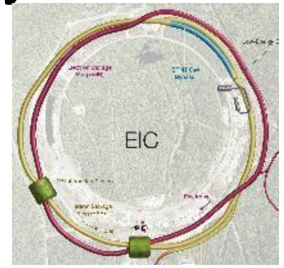

Graphite target inside beam screen

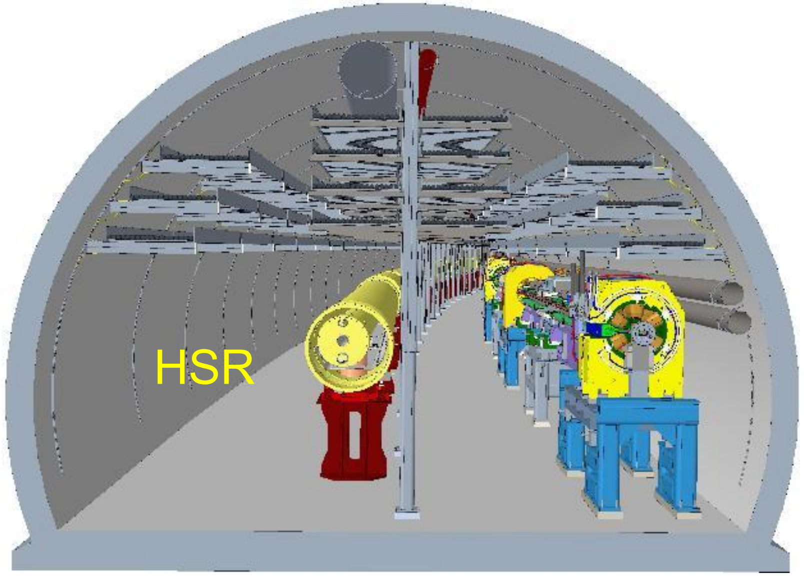

POP horizontal coating system

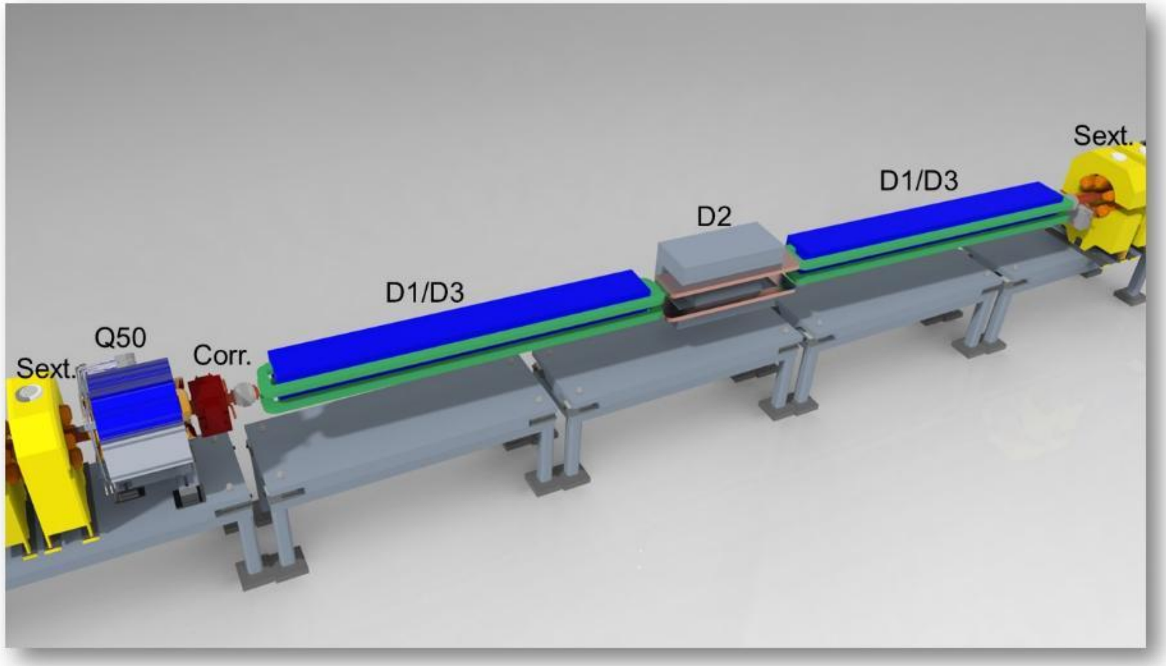

Coating Facility

EIC Electron Storage Ring

- Electron Storage Ring (ESR) consists of six FODO-cell arcs, and six straight sections (IRs)
- High-intensity (28 nC), short (7 mm) bunches add many interesting accelerator challenges
- Circulating beam current ~2.5 A and the synchrotron radiation power of ~10MW





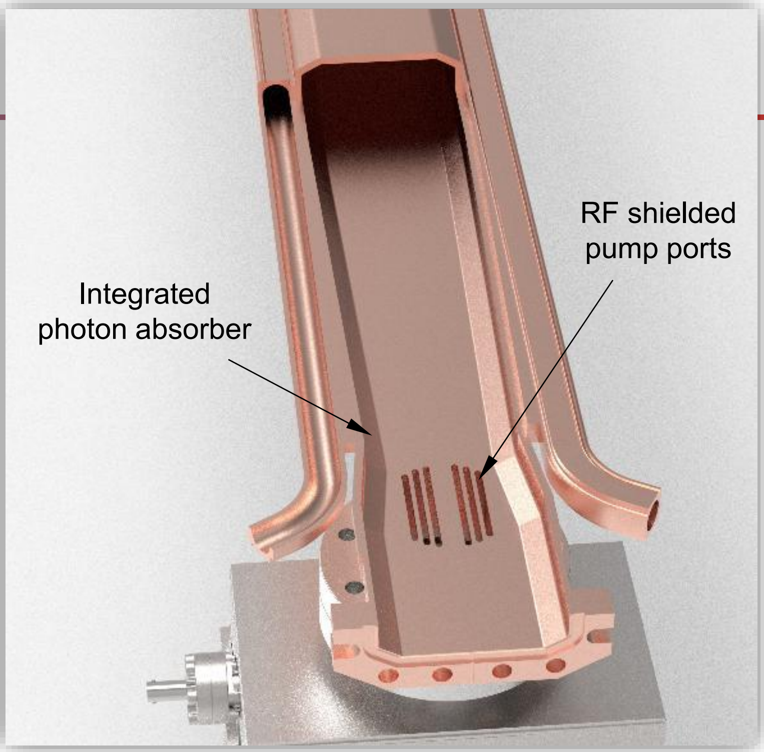


EIC needs nearly constant (20 to 24 nm) emittance from 5 to 18 GeV for optimum luminosity, but equilibrium emittance in an electron storage ring depends on beam energy.

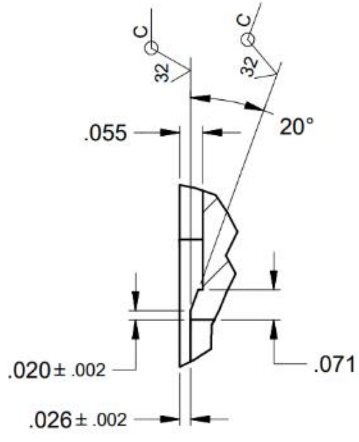
We will use 'super bends' (reverse bends) for emittance control below 10 GeV

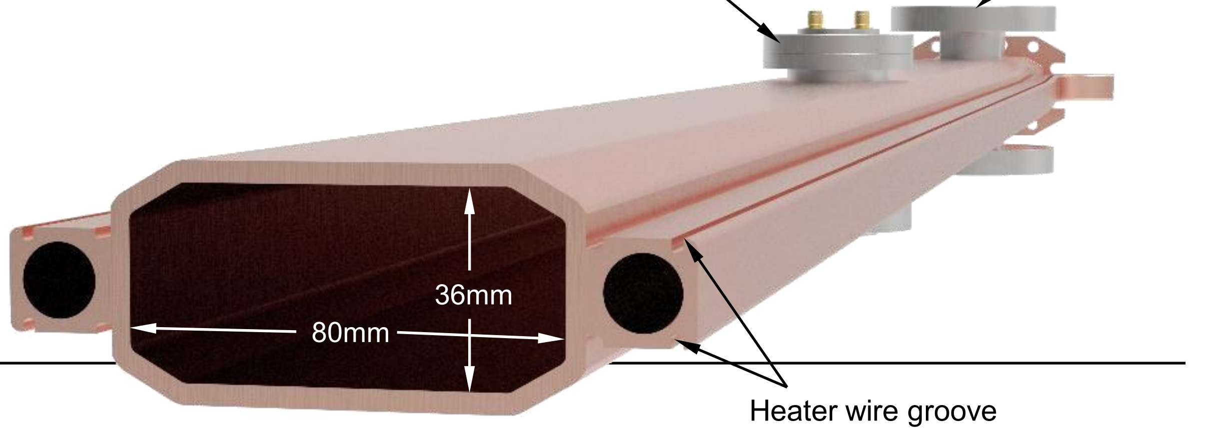
ESR Chamber Detail

- Beam channel 80mm x 36mm [3.15” x 1.42”]
- Chamber material: OFS copper (C10700)
- Water cooling channels joined by e-beam or laser welding
- Internal surfaces are NEG coated
- Photon absorber formed at end of chambers
- CuCrZr flanges with combination RF-vacuum seal

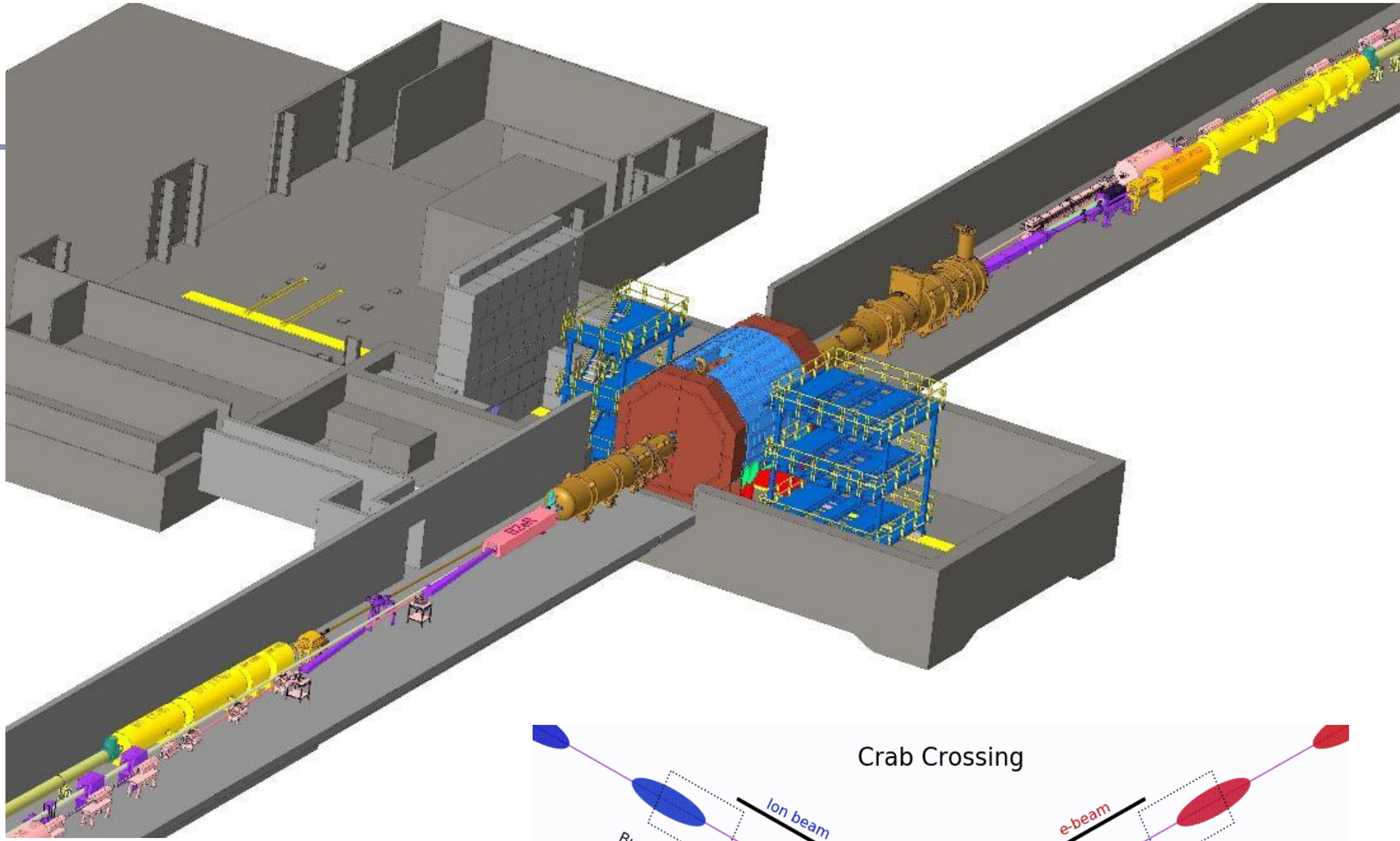



CuCrZr flange



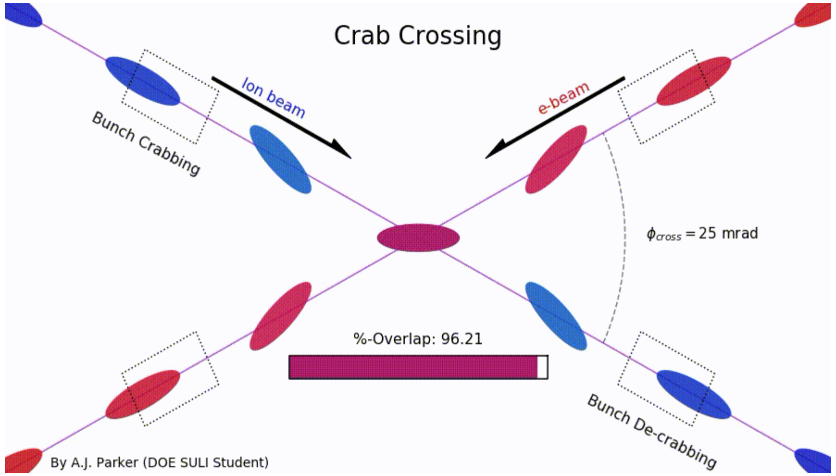


EIC IR Layout

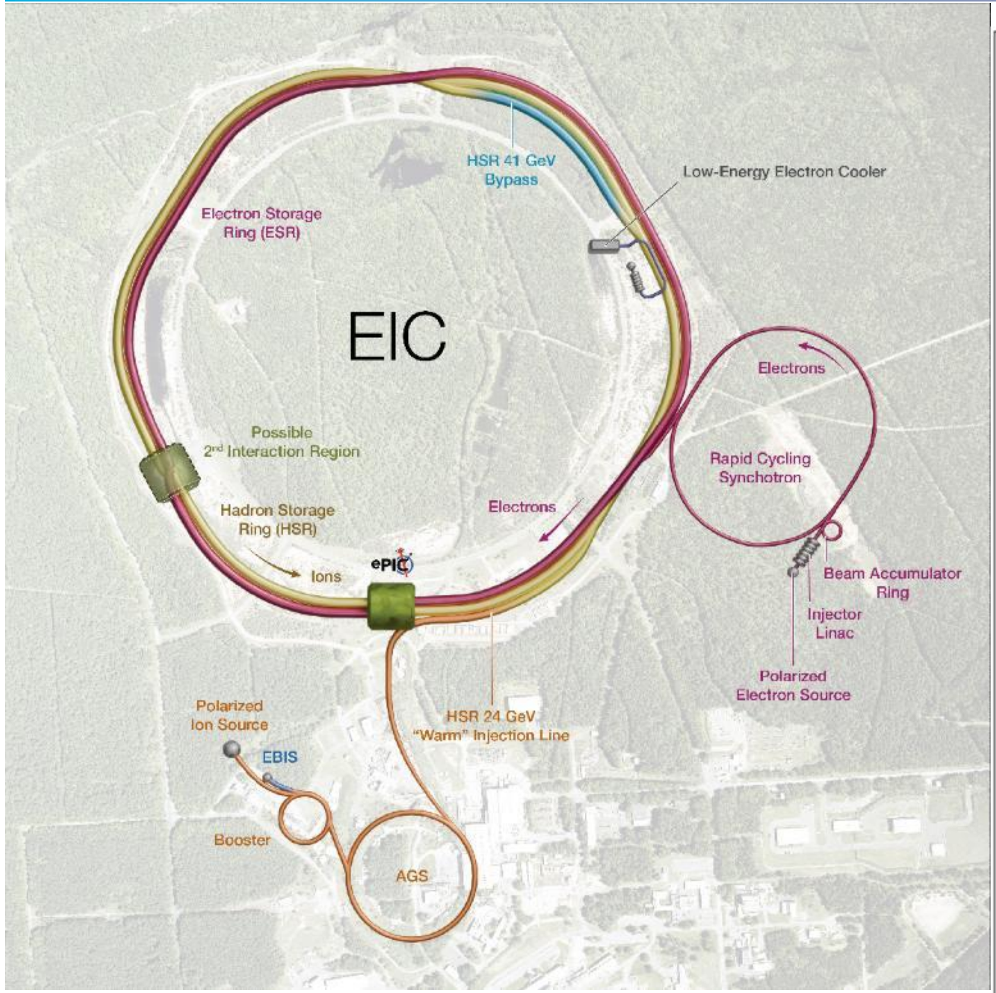


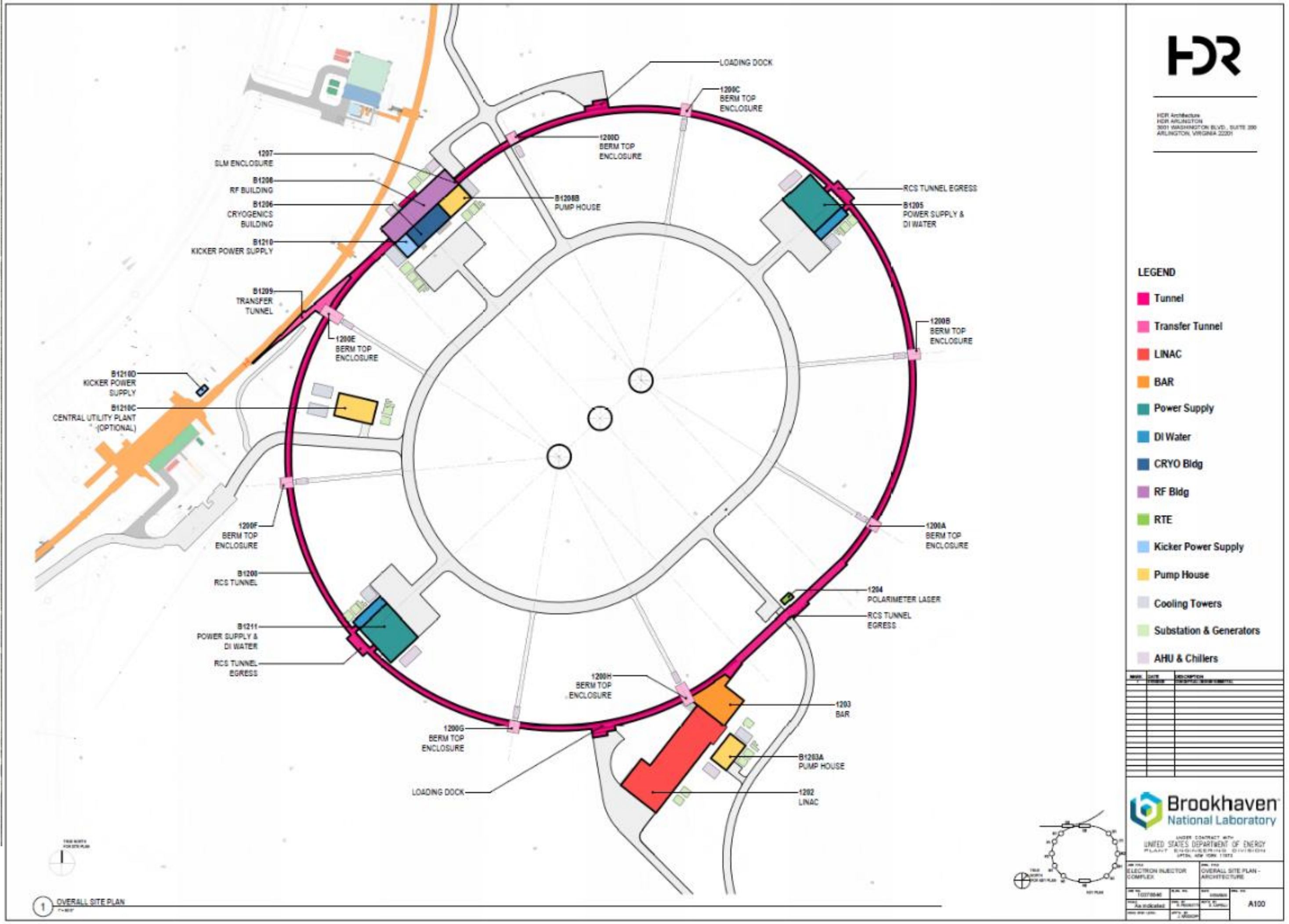
High Luminosity:
- 25 mrad crossing angle
- Small β* for high luminosity with limited IR chromaticity contributions
- Large final focus quadrupole aperture

Machine Detector Interface
- Large detector acceptance
- Forward spectrometer
- No magnets within - 4.5 / +5 m from IP
- Space for luminosity detector, neutron detector, "Roman Pots"



Electron Injector

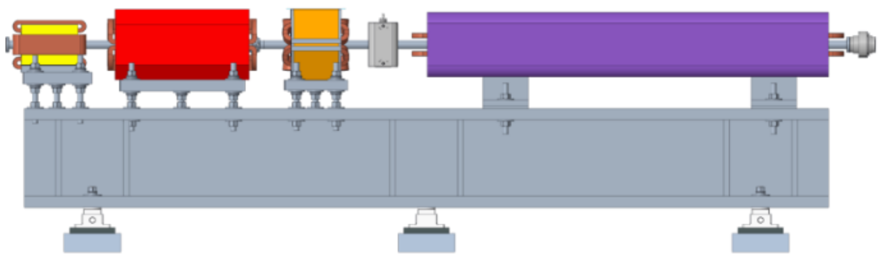




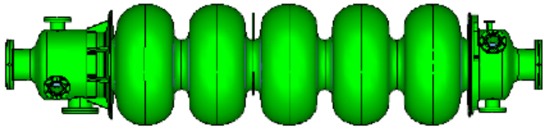
Electron Injector

Concept modeled after the ANL APS-U injector

Function: Deliver electron bunches of up to 28 nC at a 1 Hz repetition rate for injection into the ESR at various energies of 5 – 18 GeV.



RCS magnet assembly
Vacuum chamber: stainless steel, copper coated (50 um)



RCS SRF Cavity, 591 MHz

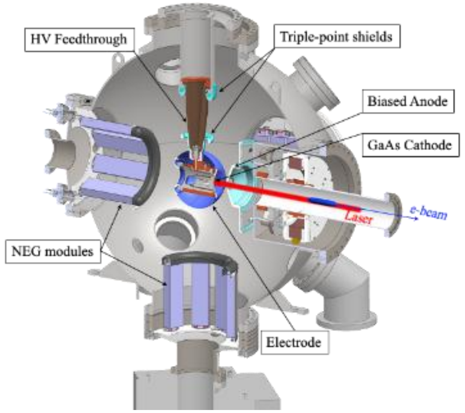

RESEARCH ARTICLE | JUNE 17 2024

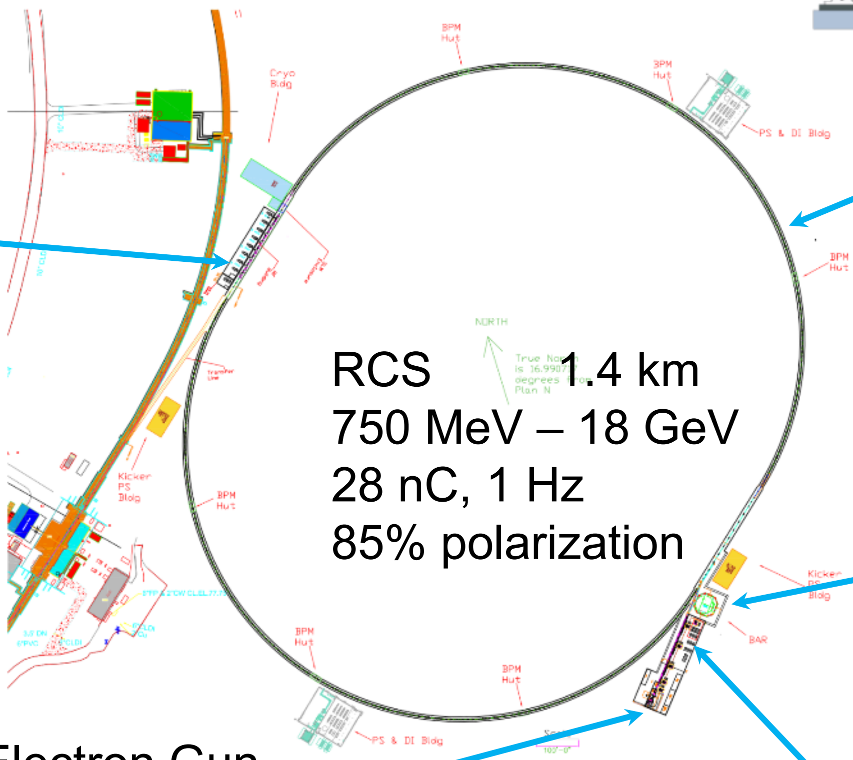
High-intensity polarized electron gun featuring distributed Bragg reflector GaAs photocathode

Erdong Wang; Omer Rahman; Jyoti Biswas; John Skaritka; Patrick Inacker; Wei Liu; Ronald Napoli; Matthew Paniccia

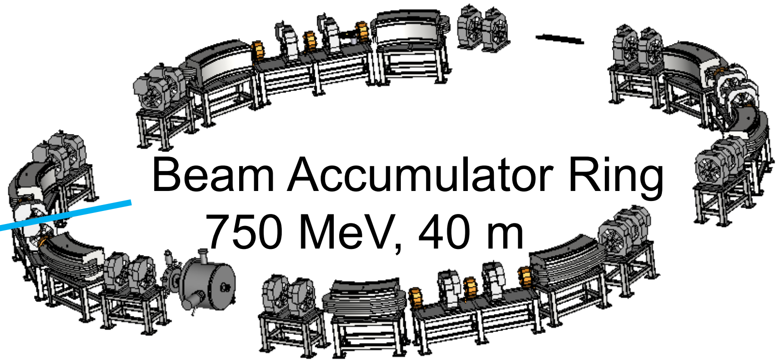
Check for updates

Appl. Phys. Lett. 124, 254101 (2024)
https://doi.org/10.1063/5.0216694





RCS 1.4 km
750 MeV – 18 GeV
28 nC, 1 Hz
85% polarization



Beam Accumulator Ring
750 MeV, 40 m

Polarized Electron Gun
1-nC, 30 Hz

S-band linac, 750 MeV, 30 Hz, 1 nC single bunch

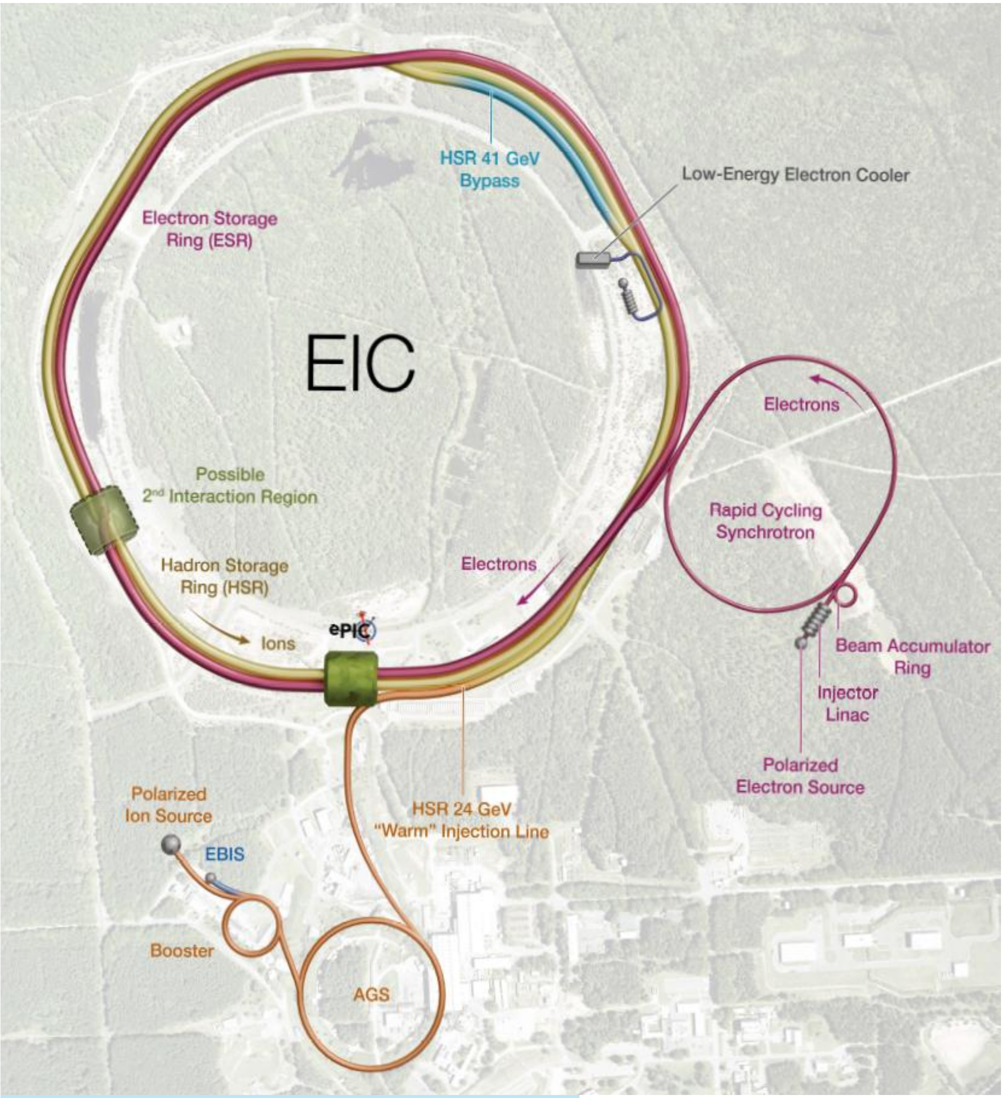
Present EIC Concept (2026)

Ultimate EIC Performance Parameters:

- High Luminosity: L= 10^{33} – 10^{34} $cm^{-2}sec^{-1}$
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: Ecm = 28 – 140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Forward Acceptance and Low-Background Conditions
- Possibility to Implement a Second Interaction Region (IR)

Accelerator Status at a glance:

- ✓ Polarized ion/proton source
- ✓ Ion injection and initial acceleration systems – Linac (200 MeV), Booster (1.5 GeV), AGS (25 GeV)
- UPGRADE Hadron Storage Ring (40-275 GeV) – HSR
- NEW Electron Pre-Injector (750 MeV linac)
- NEW Beam Accumulation Ring (750 MeV) – BAR
- NEW Electron Rapid Cycling Synchrotron (0.75 GeV – top energy) – RCS
- NEW Electron Storage Ring (5 GeV – 18 GeV) – ESR
- NEW Interaction Region(s) – IR
- NEW Hadron Cooling System



Protons: ~40 – 275 GeV
Electrons: 5 – 18 GeV

Summary

- EIC is a unique, high-energy, high-luminosity, polarized beam collider that will be one of the most challenging and exciting accelerator complexes ever built – the only new collider in the next decades.
- Since the publication of the 2021 CDR, the project has implemented several design changes to advance design maturity and reduce risk, without affecting the established preliminary performance and cost objectives.
- The EIC design is stable and complete.
- Subproject scope is well developed, designs are mature, Long-lead procurements are in execution since 2024.

We now have a well-defined vision of what is required to build the EIC!