Making the EIC possible: machine perspectives

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Electron-Ion Collider

Compelling EIC Science Case

How do quarks, gluons, and orbital angular momentum contribute to proton spin?

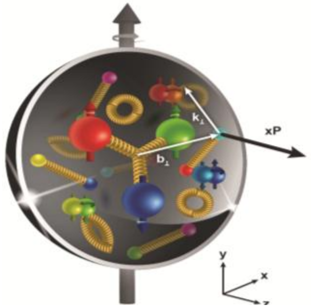
Spin is a fundamental property of matter.

All elementary particles, but the Higgs, carry spin. Spin cannot be explained by a static picture, rather the interplay between the properties and interactions of quarks and gluons inside the proton.

Does the mass of visible matter emerge from quark-gluon interactions?

Atom: Binding/Mass = 0.00000001
Nucleus: Binding/Mass = 0.01
Proton: Binding/Mass = 100

The EIC will determine an important term contributing to the proton mass, the so-called quantum chromodynamics (QCD) trace anomaly.



How can we understand QCD dynamics and the relation to confinement?

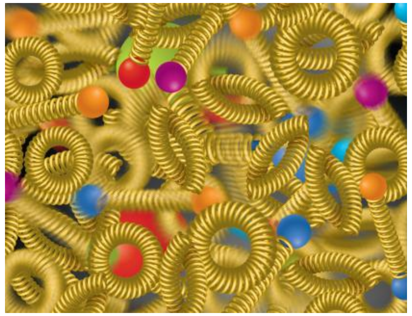
EIC will image quarks and gluons in 3D in space and momentum inside the nucleon and nuclei and uncover how the nucleon properties emerge from quarks and gluons and their interactions.

How do quark-gluon interactions create nuclear binding?

Is the structure of a free and bound nucleon the same?

How do quarks and gluons, interact with a nuclear medium?

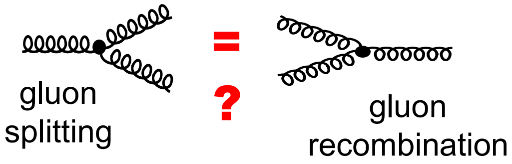
How do the confined hadronic states emerge from these quarks and gluons?



Does gluon density in nuclei saturate at high energy?

How many gluons can fit in a proton?

How does a dense nuclear environment affect the quarks and gluons, their correlations and interactions?

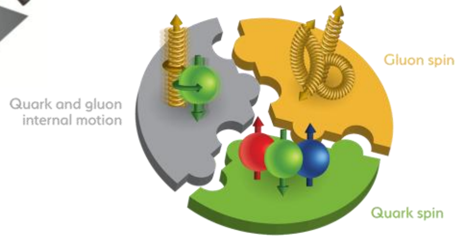


National Academies of Sciences, Medicine, and Engineering, 2018 Consensus Study Report)

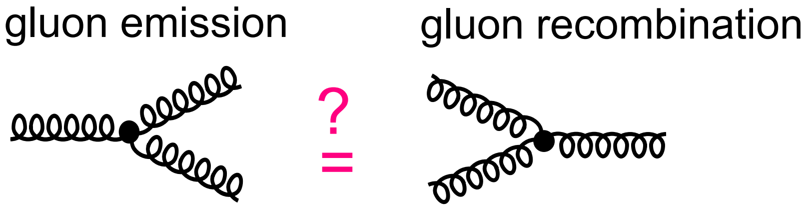
EIC Accelerator Performance

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

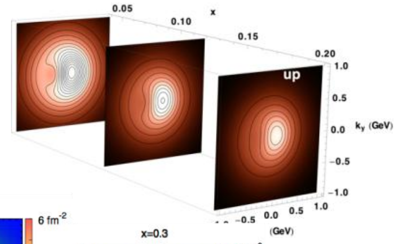
polarized electron and hadron (p, He-3) beams:
- ➢ access to spin structure of nucleons and nuclei
- ➢ Spin vehicle to access the spatial and momentum structure of the nucleon in 3d
- ➢ Full specification of initial and final states to probe q-g structure of NN and NNN interaction in light nuclei



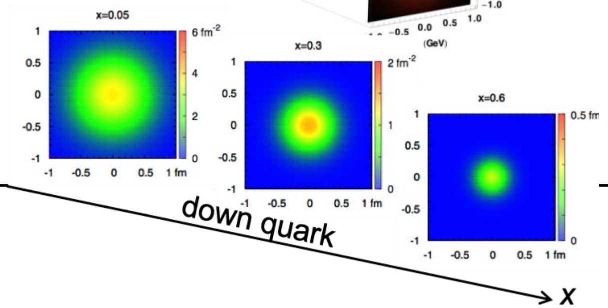
nuclear beams: p to Uranium
- ➢ accessing the highest gluon densities → saturation
- ➢ quark and gluon interact with a nuclear medium



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: E_{cm} = ~20 – 100 GeV (upgradeable to 140 GeV)
- High degree of beam polarization: ~70%
- Availability of ion beams: from proton to Uranium
- Luminosity: $10^{33} – 10^{34}$ $cm^{-2}sec^{-1}$
- Possibly more than one IR

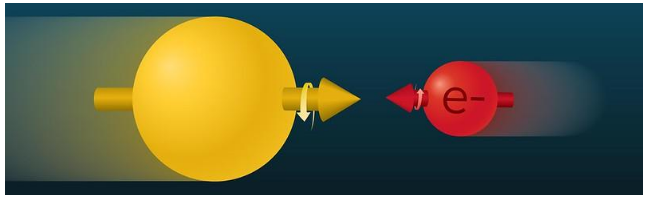
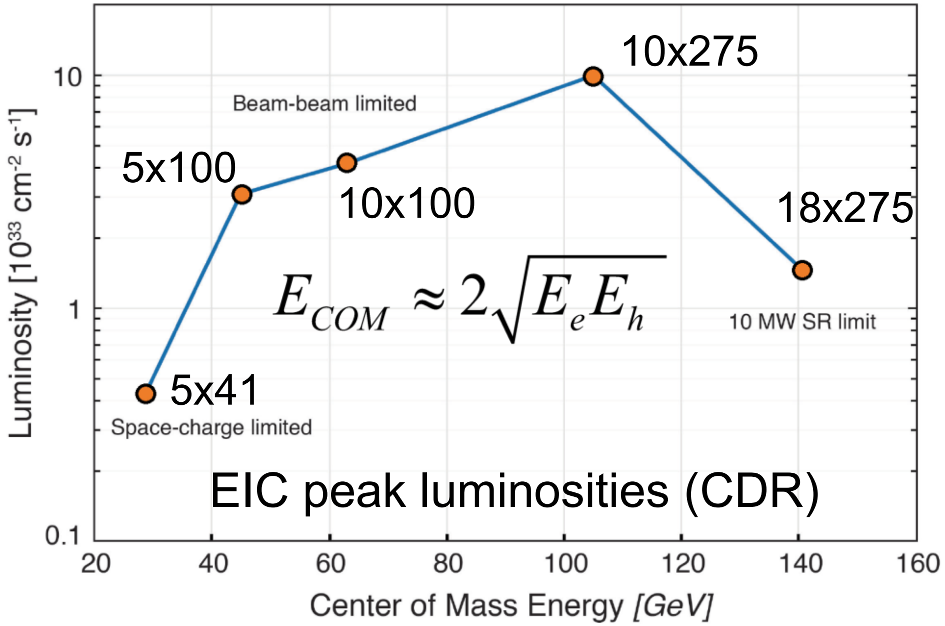


Figure of merit: LP^2 to LP^4

Based on the 2015 US NSAC Long-Range Plan

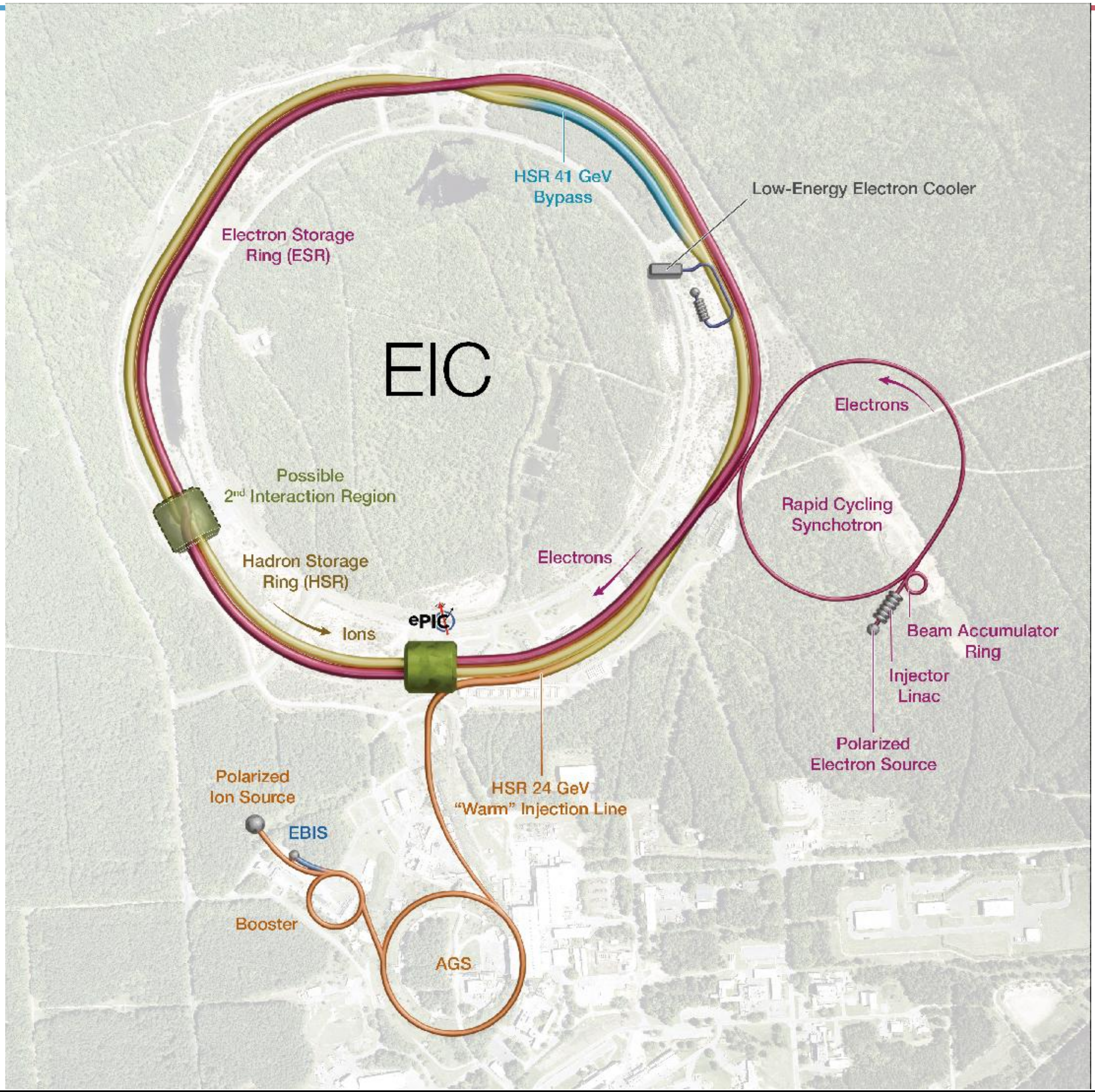
Bunch charges: 28 nC (10 GeV, e) and 11 nC (275 GeV, p)

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



EIC peak luminosities (CDR)

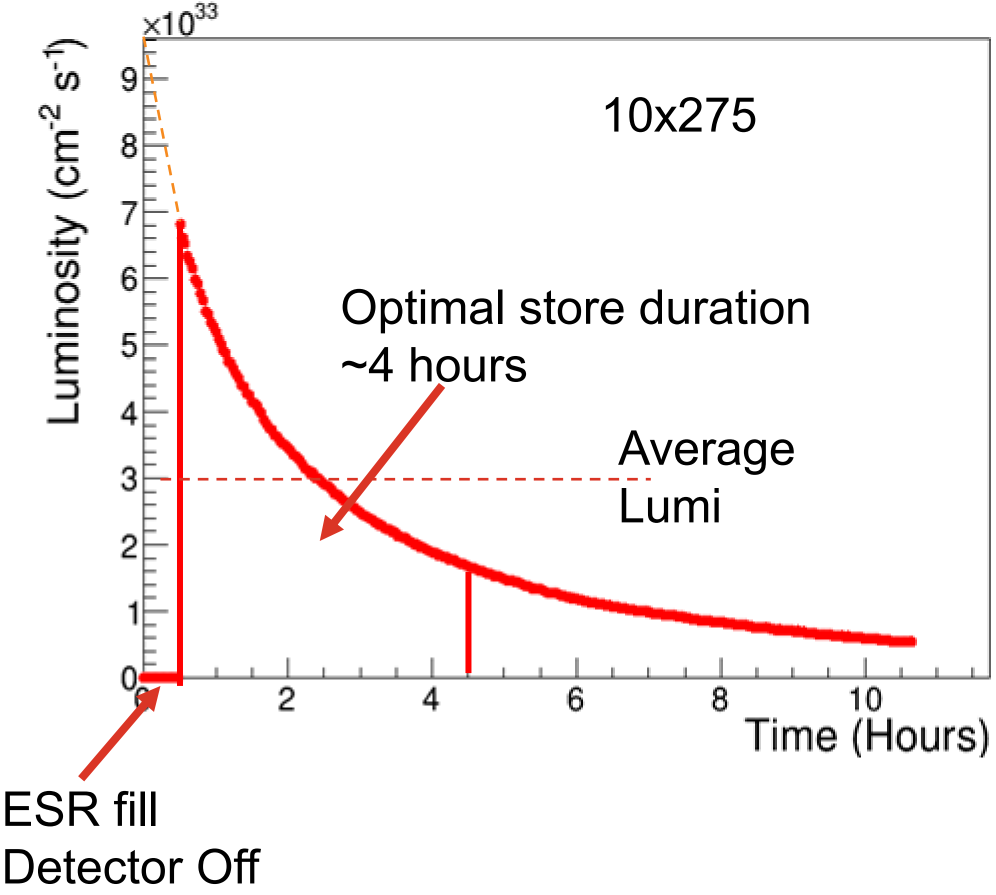
EIC concept



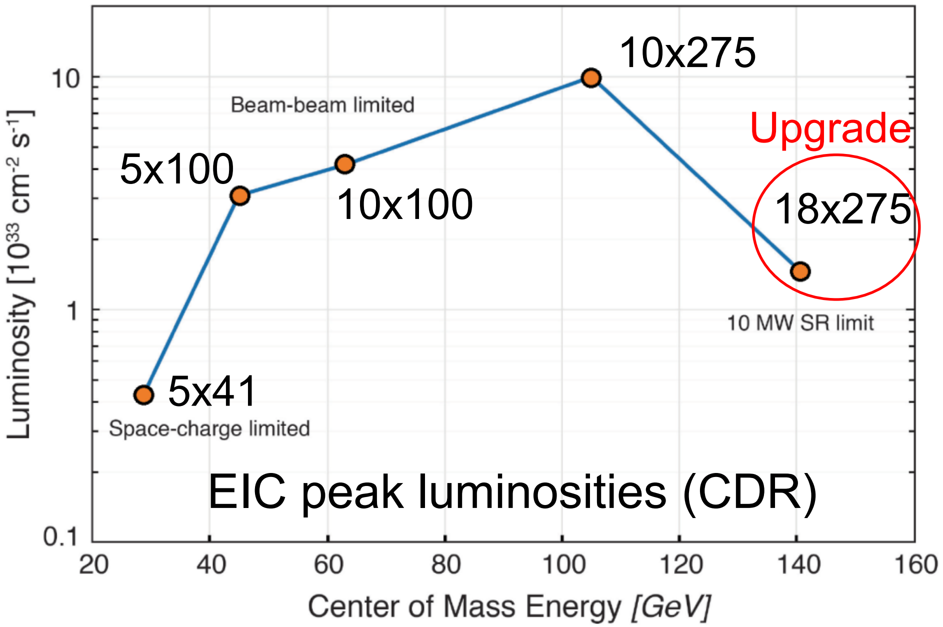
EIC
HSR 41 GeV
Bypass
Low-Energy Electron Cooler
Electron Storage
Ring (ESR)
Electrons
Rapid Cycling
Synchotron
Possible
2nd Interaction Region
Hadron Storage
Ring (HSR)
Electrons
Ions
ePIC
Beam Accumulator
Ring
Injector
Linac
Polarized
Electron Source
Polarized
Ion Source
HSR 24 GeV
"Warm" Injection Line
EBIS
Booster
AGS

Luminosity performance

"Flat" proton bunches allow for high initial luminosity



CoM Energy (GeV)	Average Lumi (x10^{33} cm^{-2}s^{-1}) (per 4-hour store)
105	3
63	1.2
45	1
140	0.44
29	0.13



HERA (1992 – 2007)

920 GeV protons (unpolarized)
27.5 GeV electrons (self-polarized by the Sokolov-Ternov effect)

HERA peak luminosity: ~5x10^{31} cm^{-2}s^{-1}
at E_{COM} = 318 GeV

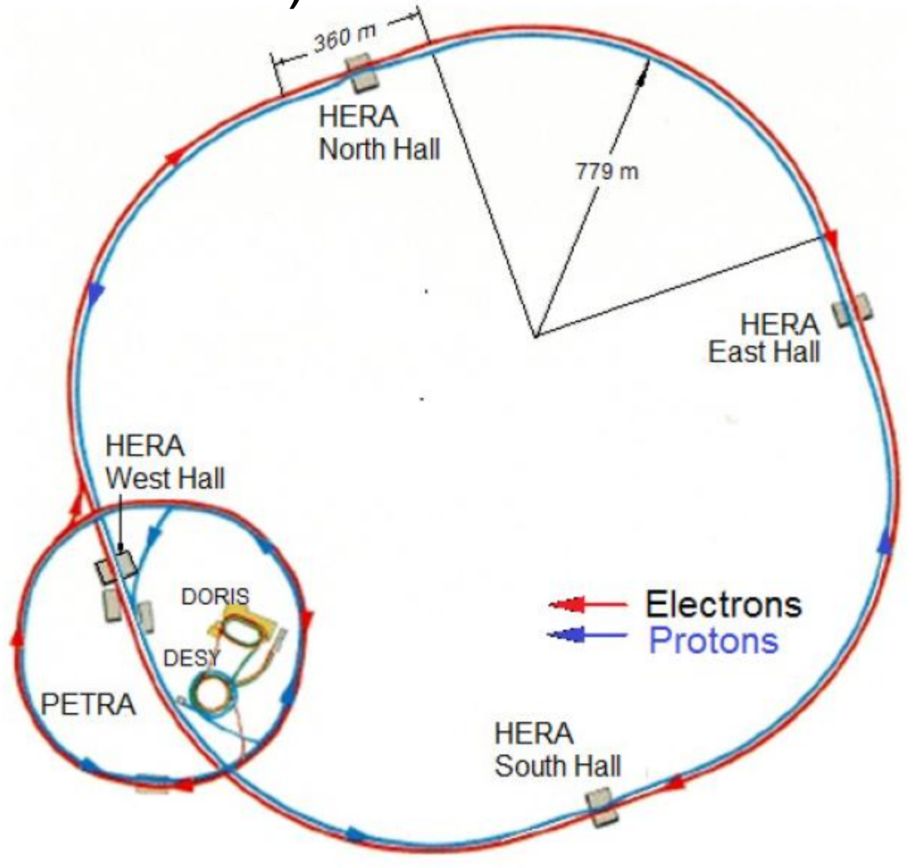


Fig. 1. HERA *ep* collider footprint.

- The EIC is an electron – ION collider (HERA was an e-p collider)
- Variable CoM energy
- EIC beams are polarized, starting from the source
- New modern particle detector
- EIC luminosity is a factor of ~200 higher

HERA vs EIC: key parameters

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

	HERA	EIC	FACTOR
Circumference (km)	6.3	3.8	1.7
Number of bunches	174	1160	6.7
Proton bunch charge (nC)	11.7	11	1
Electron bunch charge (nC)	5.3	28	5.3
Bunch length (cm), p/e	16/0.9	6/0.7	
Beta at IP (cm), proton H/V (cm)	245/18	80/7.2	
Beta at IP (cm), electron H/V (cm)	62/26	45/5.6	
Proton emittance, (nm, rms)	4/4	11/1	
Electron emittance, (nm, rms)	20/3	20/1.3	
Energy (COM), GeV	320	105	
Luminosity, x10^{31} $cm^{-2}s^{-1}$	5.3	1000	190

Bracketed factors (circumference through electron bunch charge): 60

Bracketed (beta at IP and emittance rows): ~3

Key EIC accelerator concepts

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

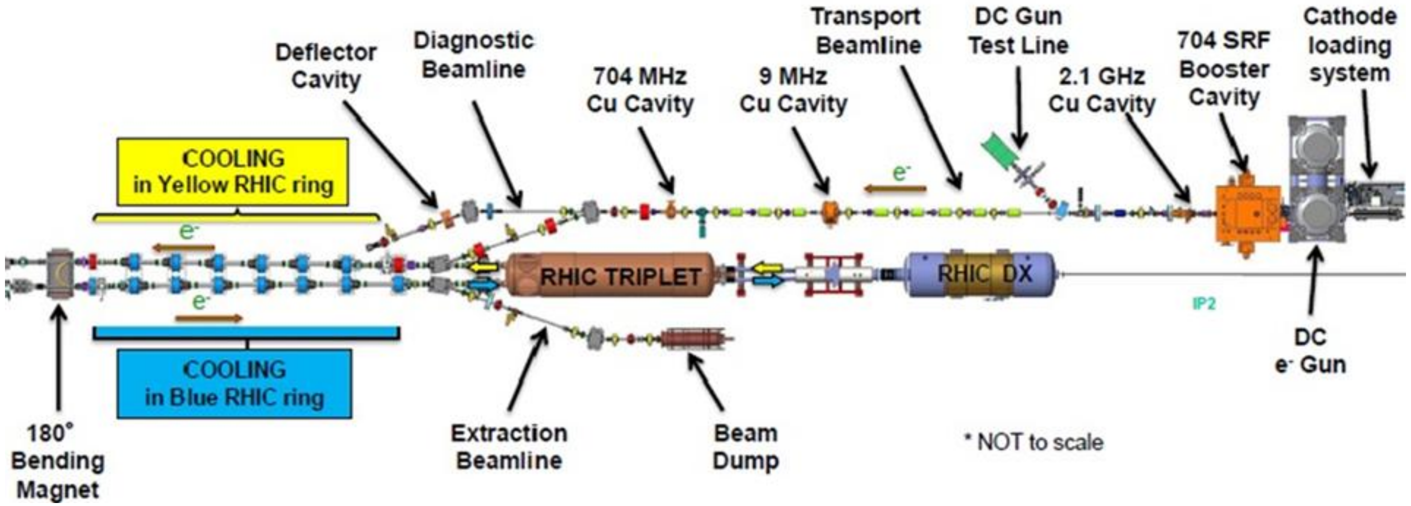
- Upgrade path: high-energy hadron cooling at collisions, 2nd detector

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

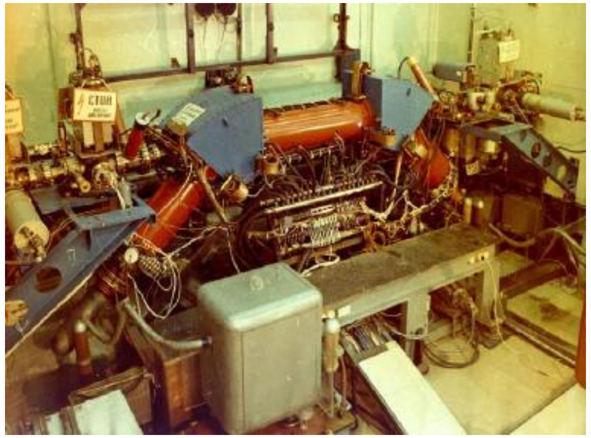
Key EIC Accelerator Technology Areas

- Hadron Beam Cooling
- Spin-transparent 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
- SRF (Crab and elliptical) cavities
  - Large-size, complex geometries;
  - High-power; HOMs
  - Very tight phase and amplitude noise requirements
- IR magnets (large aperture, one-of-a-kind SC magnets)
- Instability and impedance control;
  - Maintain low impedance budget for vacuum chambers, beam screens, kickers, SRF cavities

Hadron beam cooling

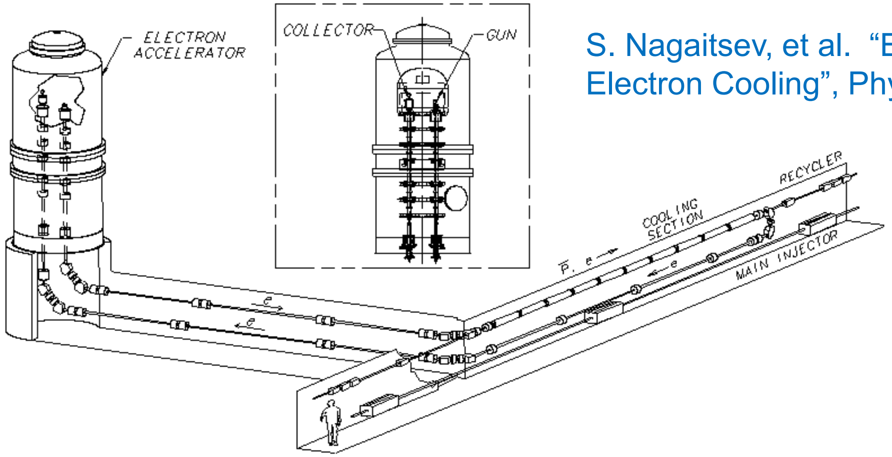


LEReC was designed to operate at electron energies up to 2.6 MeV (using single-cell SRF accelerating cavity).



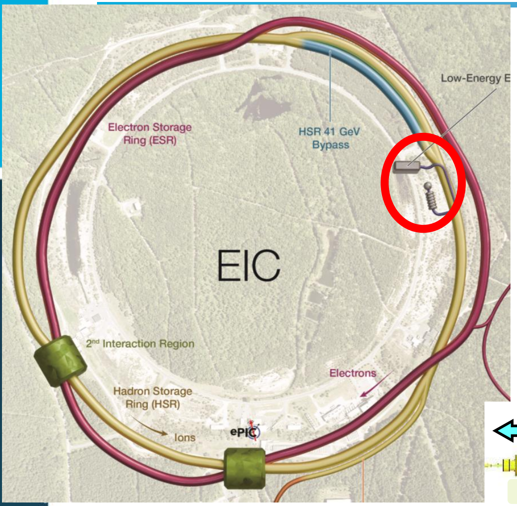
Experimental demonstration of electron cooling at NAP-M (Novosibirsk, 1974).

Similar to TARN-II ring, University of Tokyo



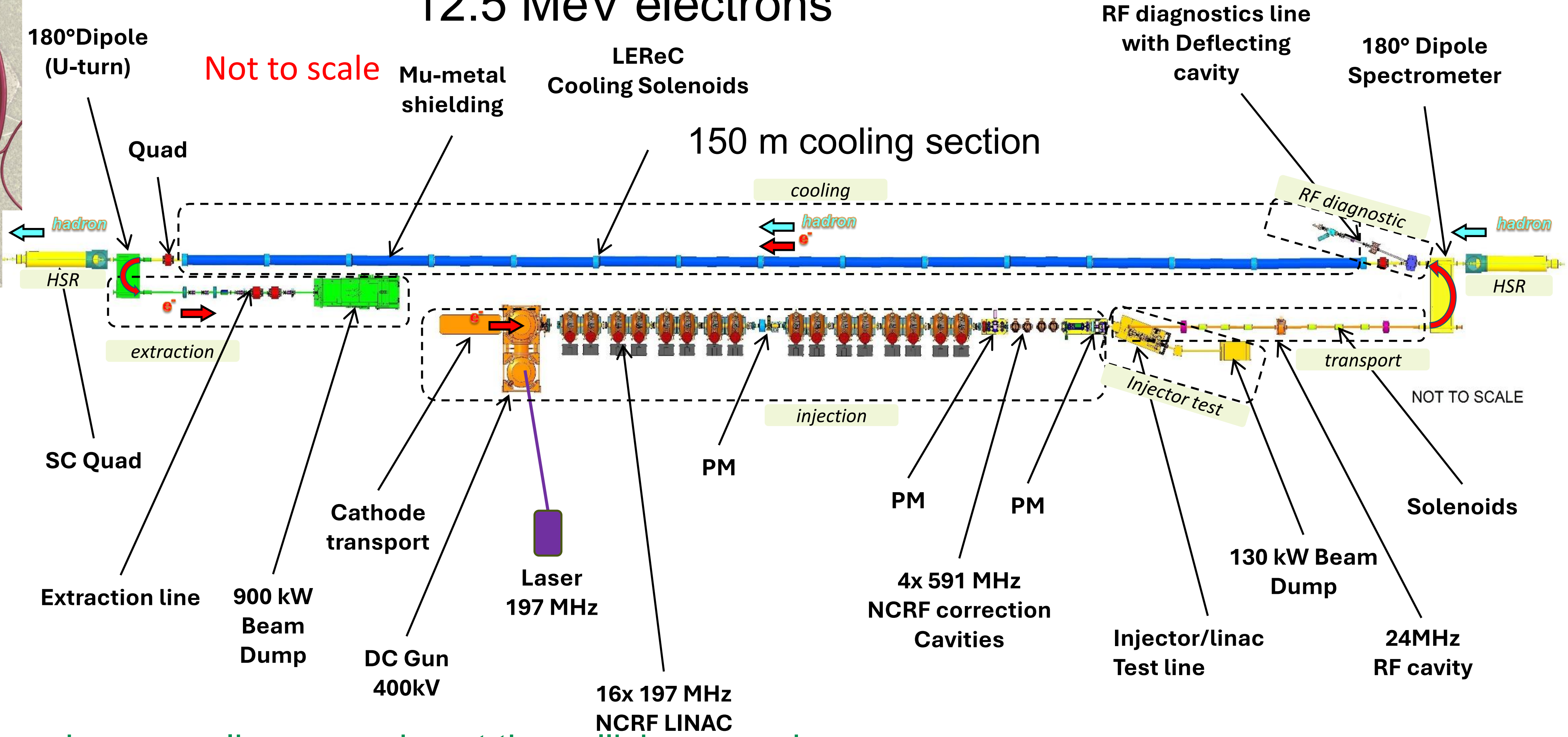
S. Nagaitsev, et al. "Experimental Demonstration of Relativistic Electron Cooling", Phys. Rev. Lett. 96, 044801 (2006)

Low-energy Cooler Concept



24 GeV protons
12.5 MeV electrons

Not to scale



IR2 layout (all within the existing RHIC Tunnel)

Compatible with future beam cooling upgrades at the collision energies

EIC Low Energy Cooler Parameters

	electrons	protons
Lorentz gamma factor	25.4	25.4
RHIC RF frequency, MHz	197	24.6
Cooling section length, m	168	168
Cooling sections beta function, m	150	100-200
Hadrons Dy, Dy’, m, rad		<1, <0.02
Total charge per proton bunch, nC	3	45
Electrons kinetic energy, MeV	12.46	
Electron average current, mA	74	
Normalized emittance, rms, um	<1.5	2
rms bunch length, cm	4	100
rms dp/p	<5e-4	6e-4
Angles in cooling section, urad	20-30	20

LEReC (2019-2025) key parameters for reference

electrons
4-5
704 MHz (9 MHz)
20 m
30 m
3 nC
1.6-2 MeV
30 (60 mA in tests)
<2 um
5 cm
<5e-4
<150 urad

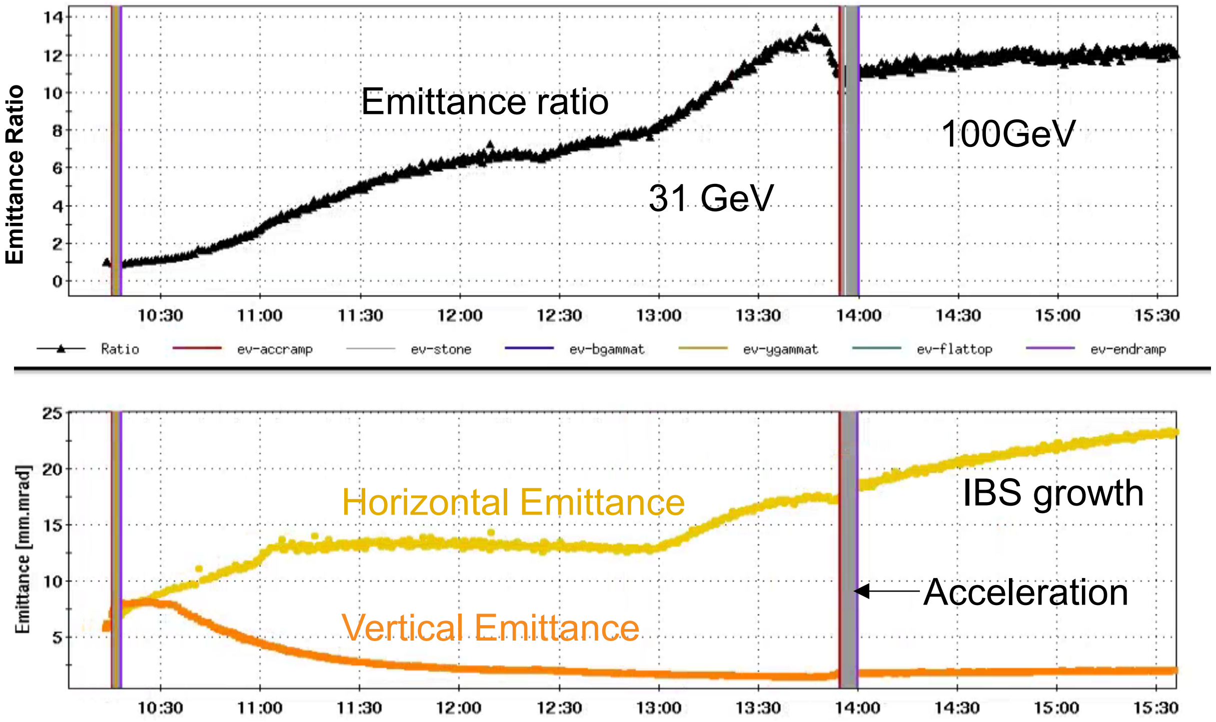
A. V. Fedotov et al., Phys. Rev. Lett. 124, 084801 (2020)

Flat Beam Acceleration Experiment in RHIC

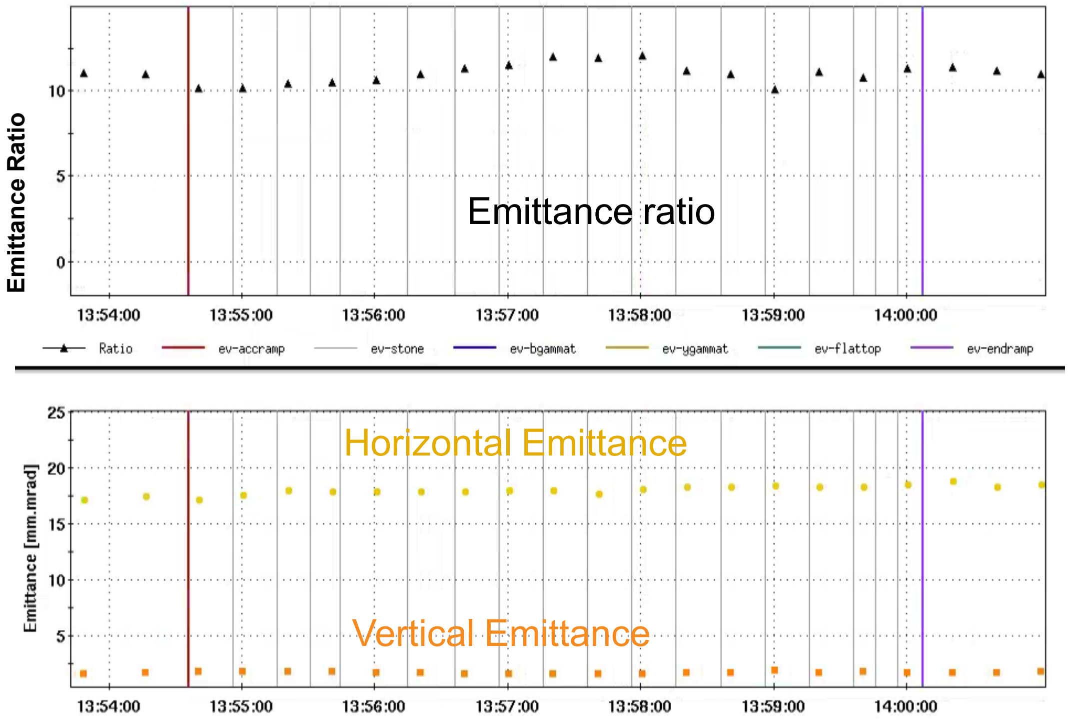
July 23, 2025

- Maximum transverse beam emittance ratio 13:1 was obtained with stochastic cooling at 31 GeV/nucleon
- Transverse emittance ratio 11:1 was well maintained during acceleration from 31 GeV/nucleon to 100 GeV/nucleon
- Flat beam was stored at 100 GeV/u with EIC/HSR tunes for ~2 hours, 11:1 emittance ratio was well maintained too

Entire store duration



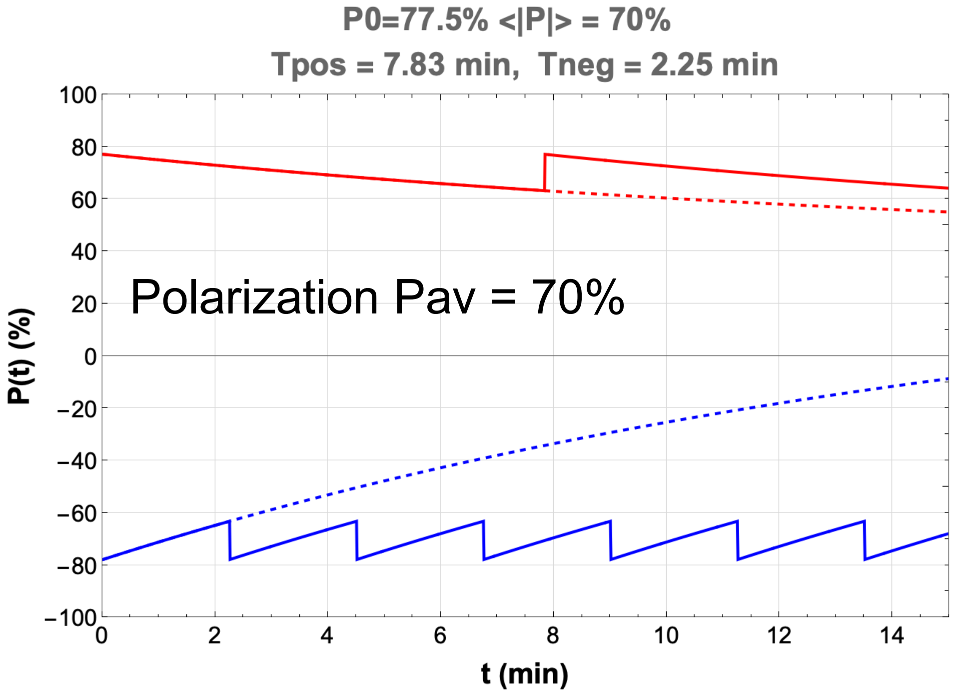
31 GeV **During Acceleration** 100GeV



Electron beam polarization

Electron polarization loss in the ESR

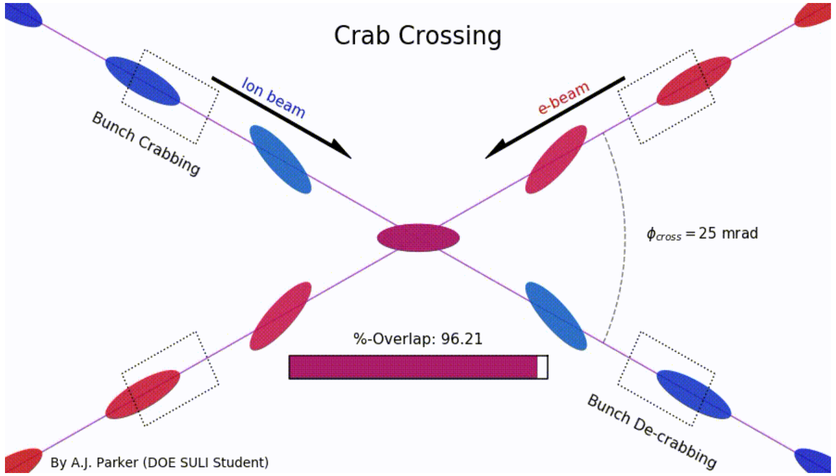
- Frequent swap-out injection of bunches with high initial polarization of 85%
  - Bunch spacing is ~10 ns
- Initial polarization decays towards P_∞
- At 18 GeV, every bunch is replaced (on average) after 2.2 min with RCS cycling rate of 1Hz



The HSR will also have polarized protons and light ions; RHIC experience will be key to polarization performance.

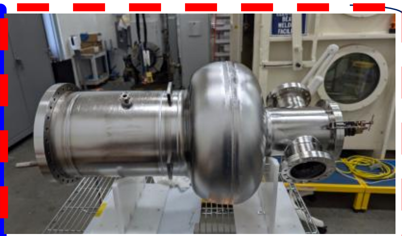
SRF cavities

Hadron bunch length (rms): 6 cm
Electron bunch length (rms): 6 mm

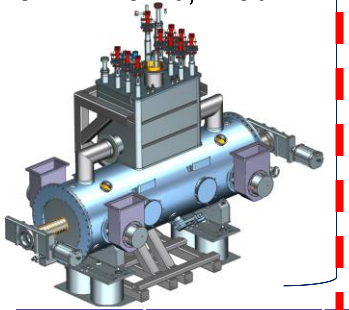


EIC - RF Systems

The Project is pre-CD2 and in the design phase. Many systems are still developing.

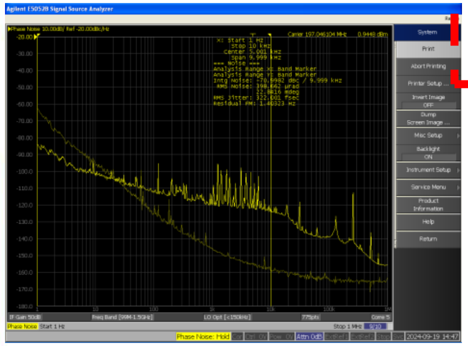


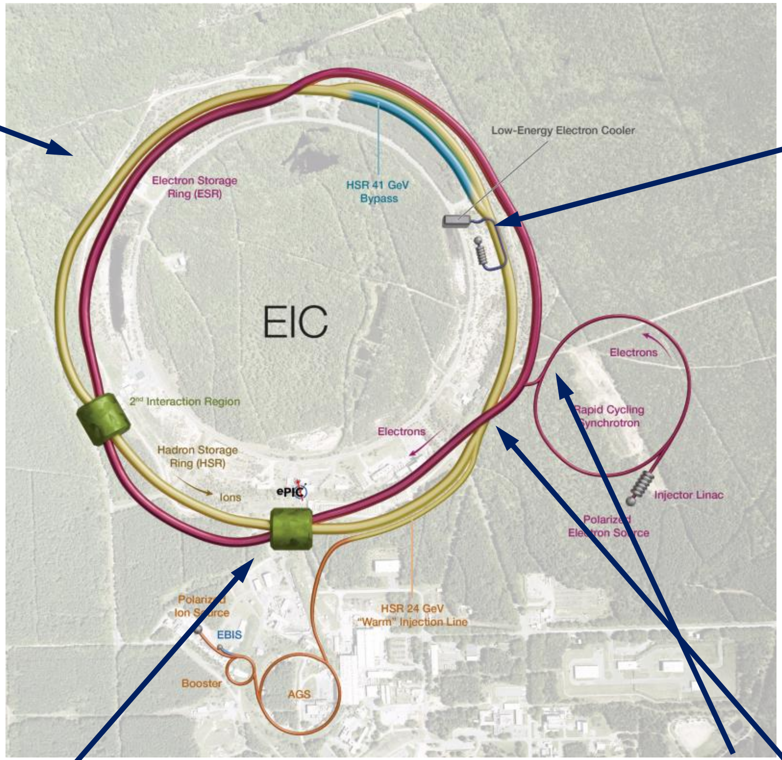
Electron Storage Ring & Hadron Storage Ring – IR10
591 MHz 800 kW 2 K
1-Cell Cavity Cryomodules
ESR = 8 CMs, 16 Cav
HSR = 2 CMs, 4 Cav



400 kW Solid State Amplifier

EIC LLRF DAC Clock for Crab Cavities

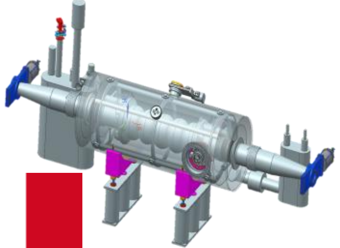




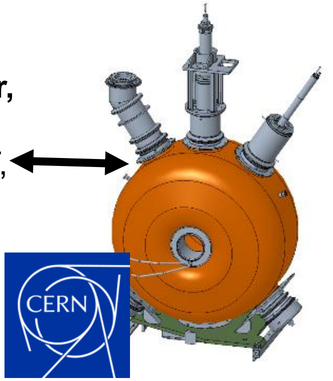
IR06

Crab Cavities (per IR)	HSR (Cavities/CMs)	ESR (Cavities/CMs)
197 MHz	8/4	–
394 MHz	4/4	2/2

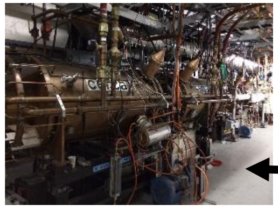
RCS
591 MHz 5-Cell Cavity Cryomodules
2 CMs



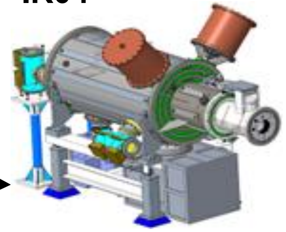
Low-Energy Cooler, IR02 -
16 197 QWR NCRF,
4 591 NCRF,
1 24 MHz NCRF,
And **1** 591 MHz Deflecting Cavity



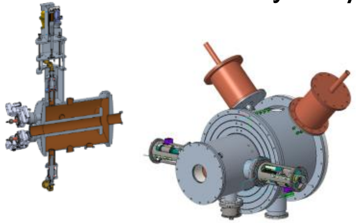
HSR NCRF – IR04



RHIC – 28 MHz acceleration cavity

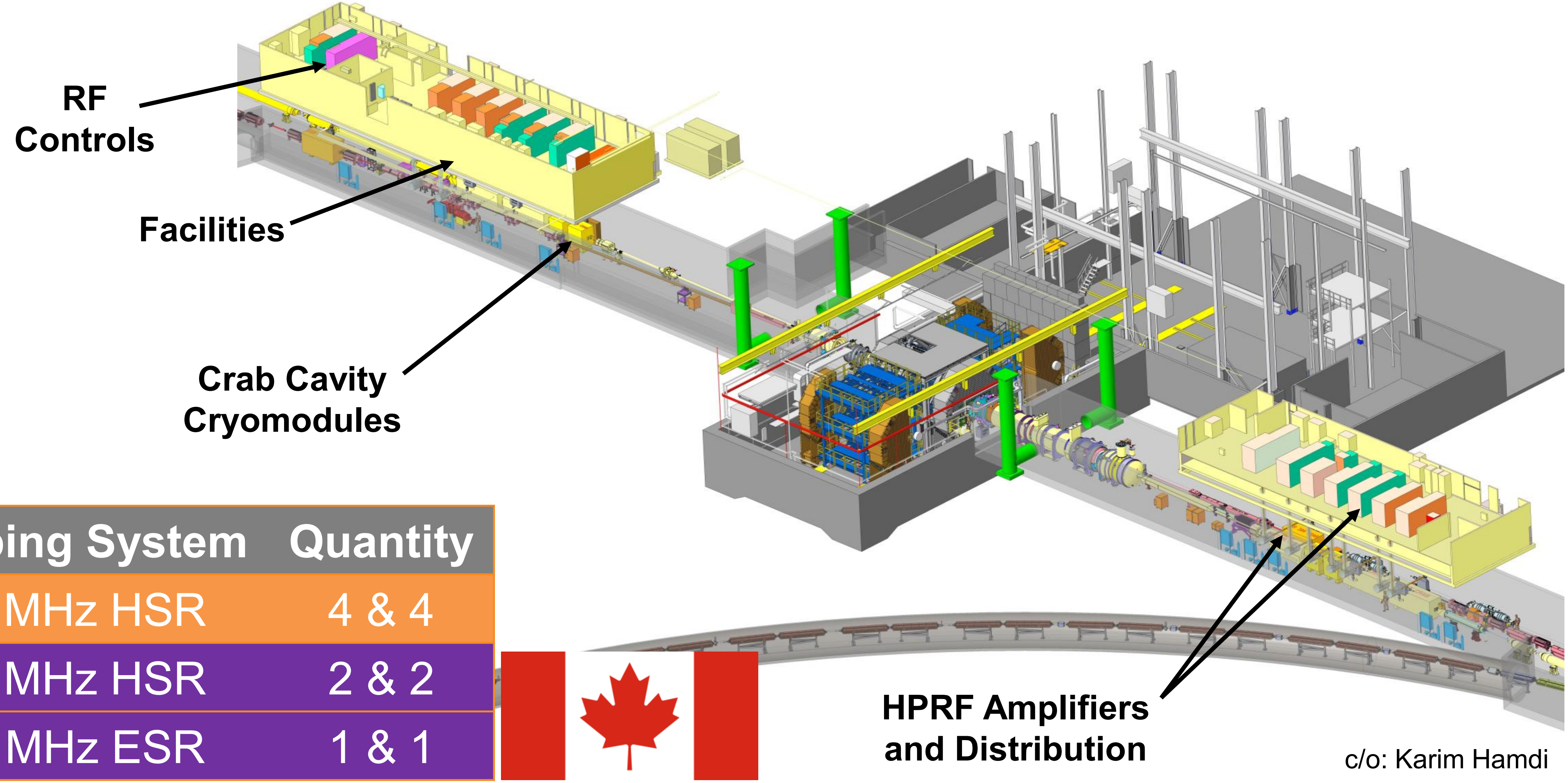


4 24.6 MHz Capture & Accel Cavity, IR04



Bunch Splitting
3 49.2 MHz NCRF
4 98.5 MHz NCRF
Capture & Accel
8 197 MHz NCRF

IR6 (Crab Cavities)

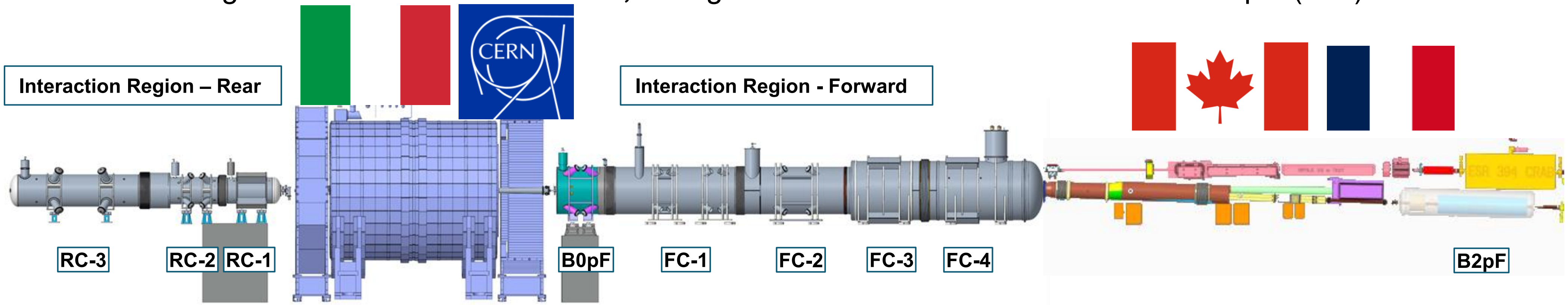


Crabbing System	Quantity
197 MHz HSR	4 & 4
394 MHz HSR	2 & 2
394 MHz ESR	1 & 1

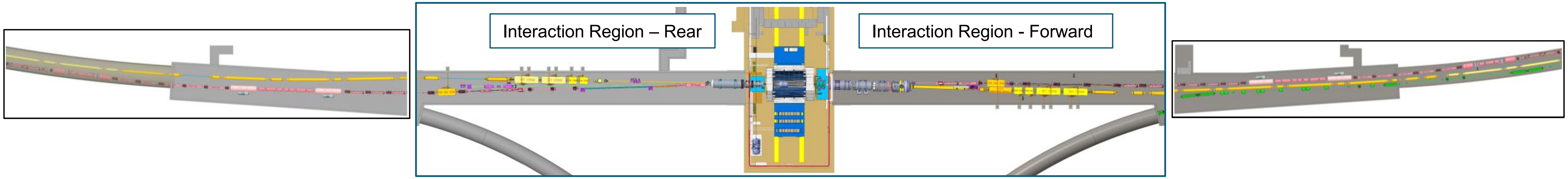
c/o: Karim Hamdi

EIC IR layout

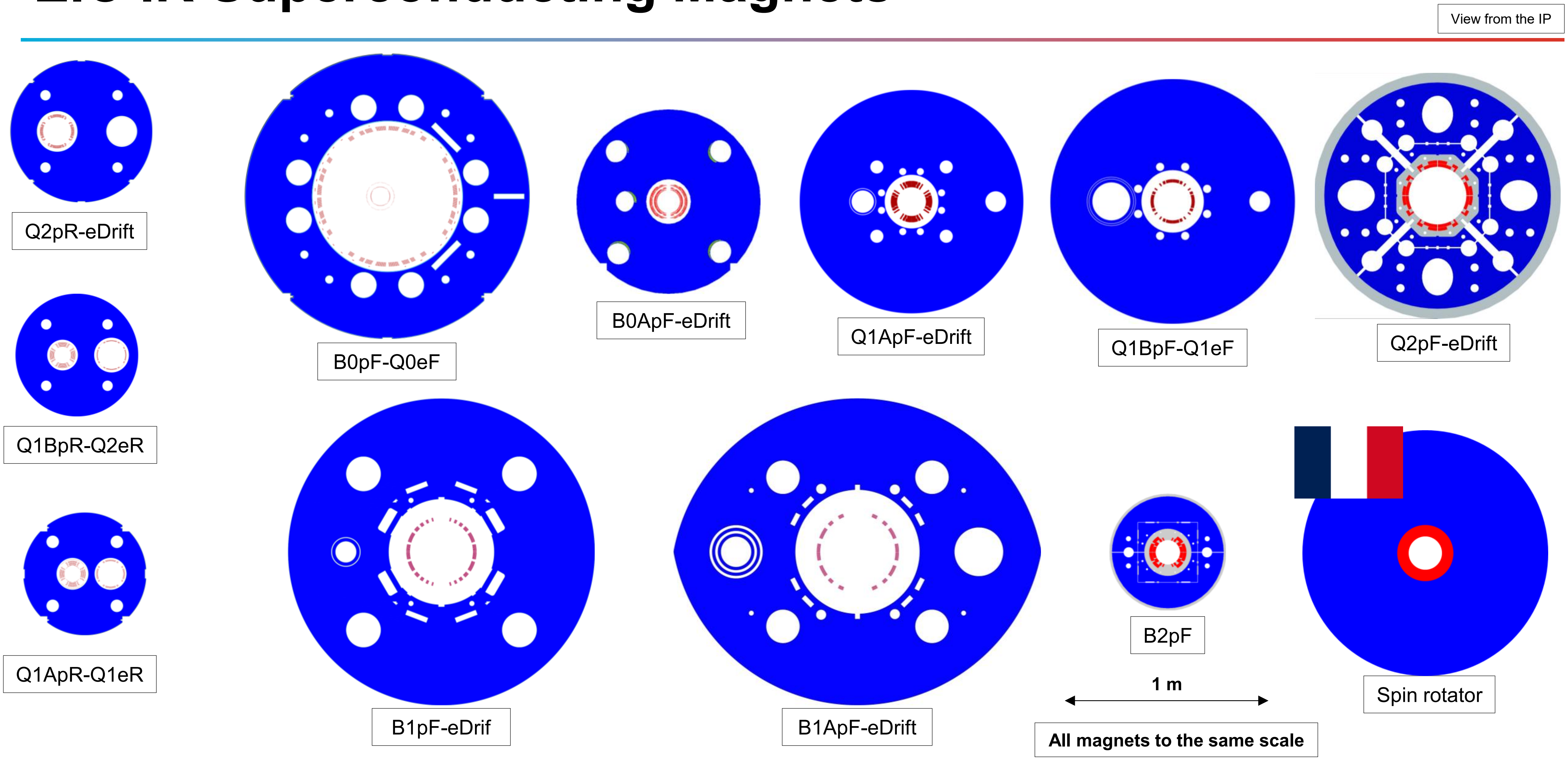
- **9 cryostats** housing **11 cold masses (2 K)**
  - **15 magnets** (dipole, quadrupole, and combined-function)
    - **6** “cos-theta” magnets with **Rutherford cables, 9** magnets fabricated with Direct Wind technique (**DW**)



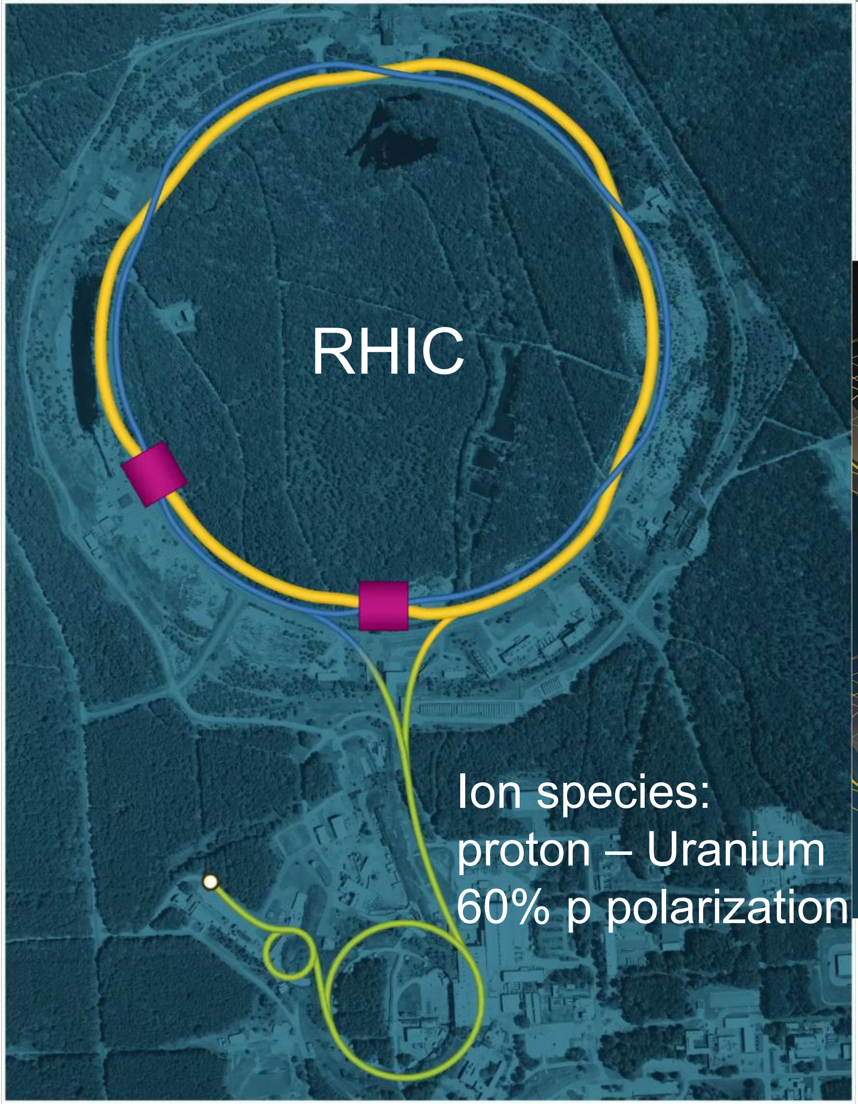
- **8 cryostats** (4 per side) which contain the **spin rotators** (solenoids 8.5 T, 2K)
  - 2 long and 2 short per side

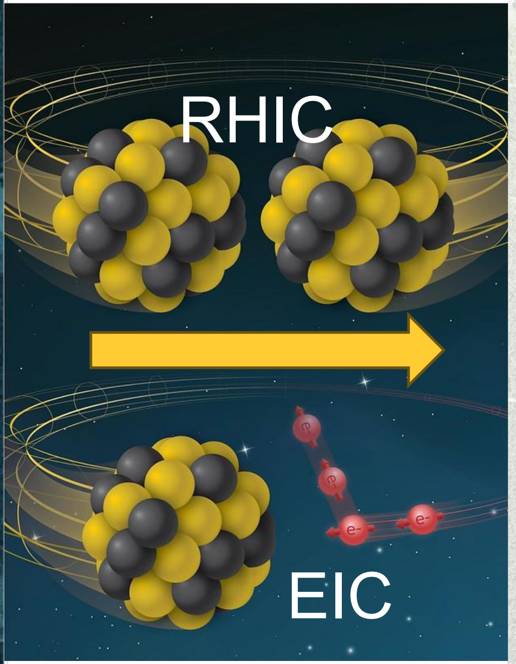


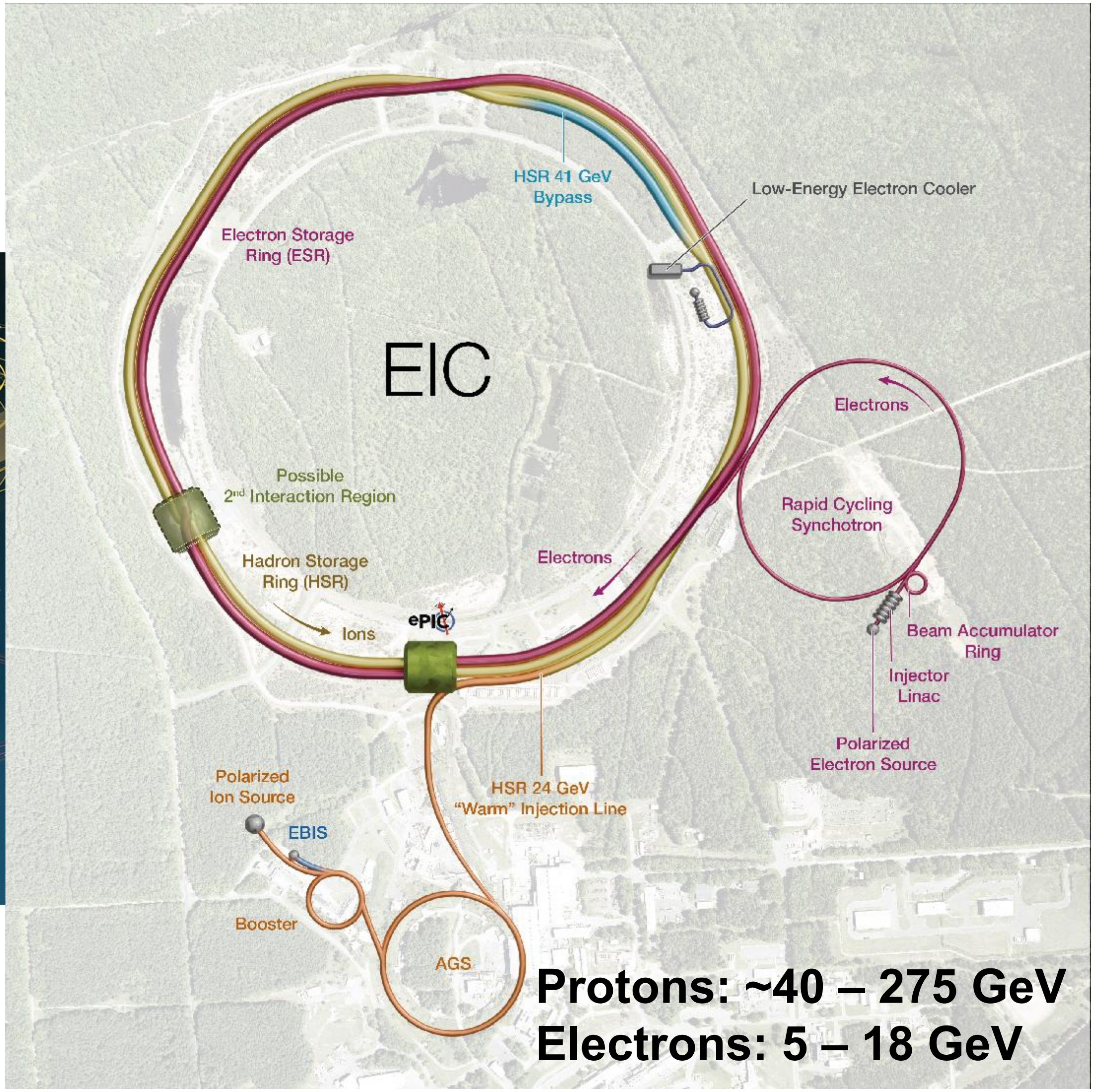
EIC IR Superconducting Magnets



From RHIC to EIC





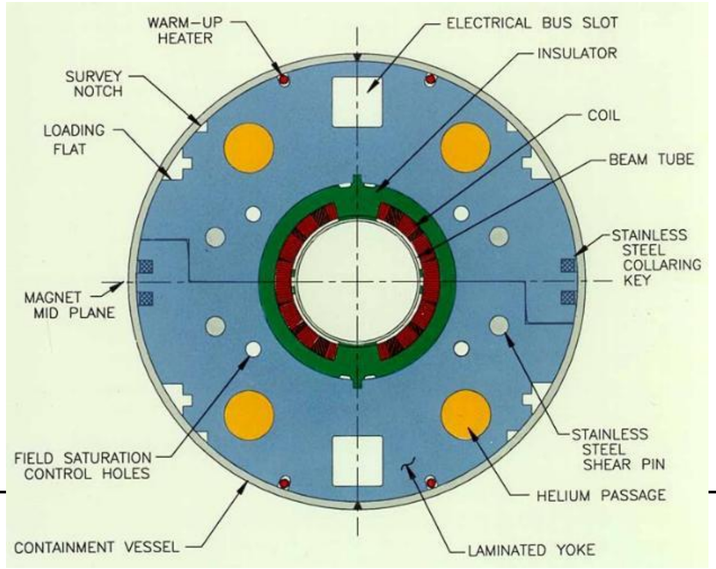


From RHIC (yellow ring) to EIC HSR

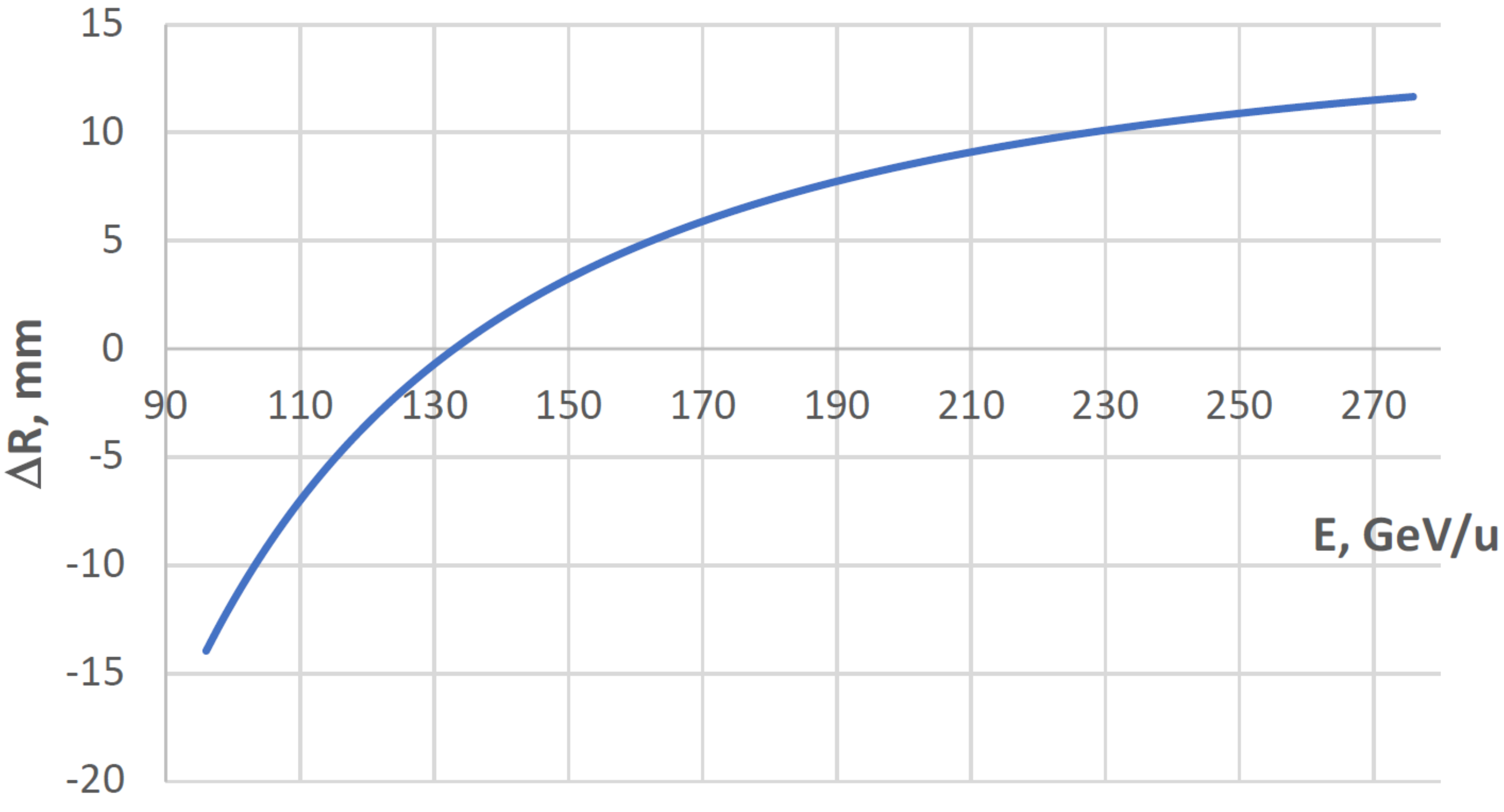
Tripled beam current, shorter bunch length, shorter bunch distance, 'flat' beams with small vertical emittance

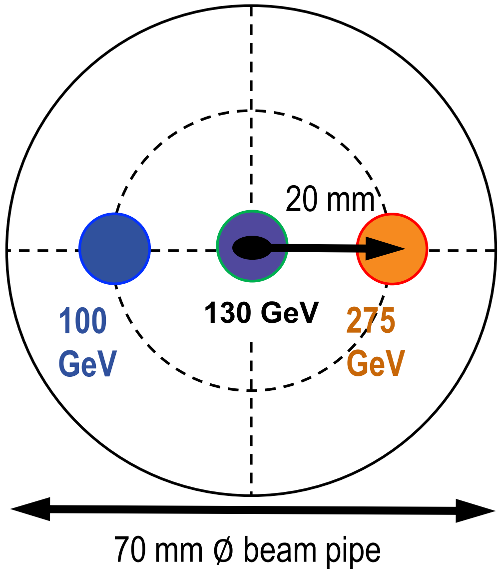
- EIC HSR to be composed of existing arcs of the Yellow RHIC ring (remove unused magnets)
- Insert sleeves coated with copper and amorphous carbon into superconducting magnet beam pipes to improve conductivity and reduce secondary electron yield (-> electron cloud)
- Add new RF cavities
- Add hadron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

Actively Cooled Beam Screen Material procurement



Beam Energy and Average Orbit Radius in the HSR

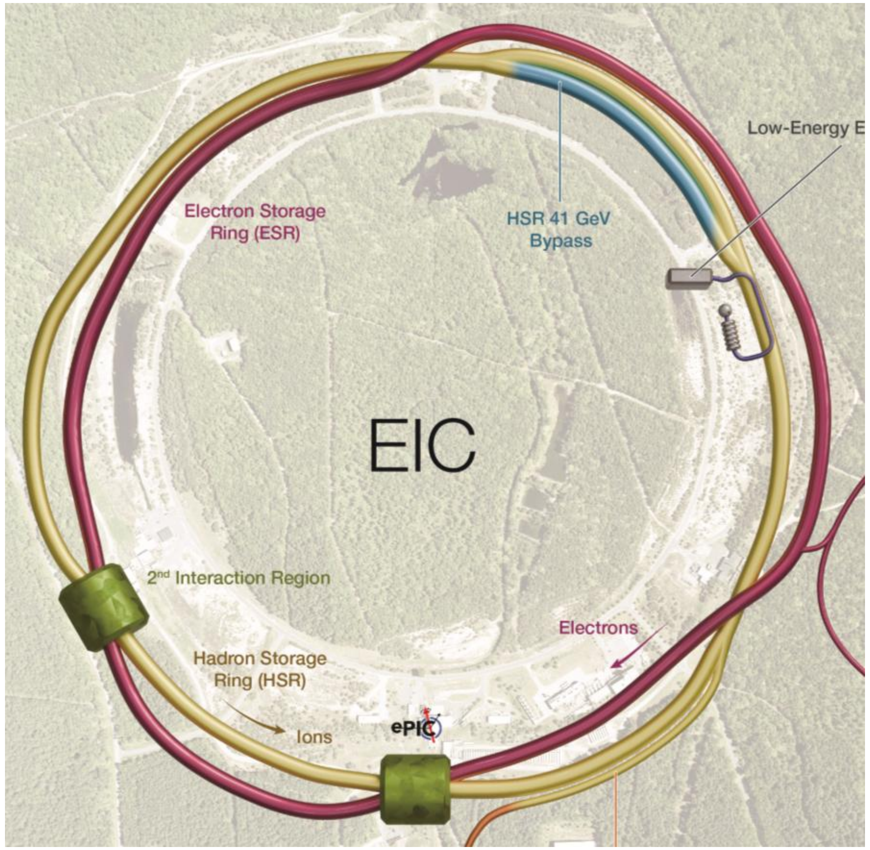




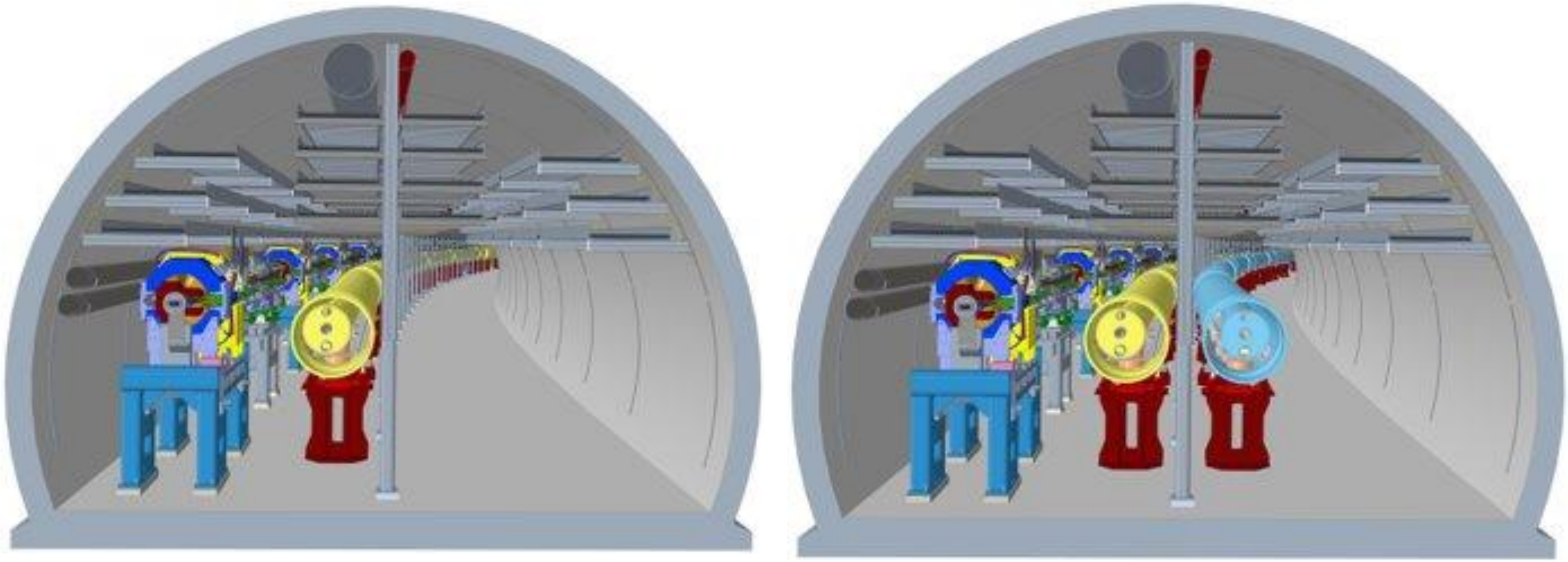
Since the electron revolution frequency is fixed, the hadron orbit must be adjusted with energy to keep the collisions in sync.

The 41-GeV ‘bypass’

This bypass provides access to the lowest EIC CoM energy, 29 GeV

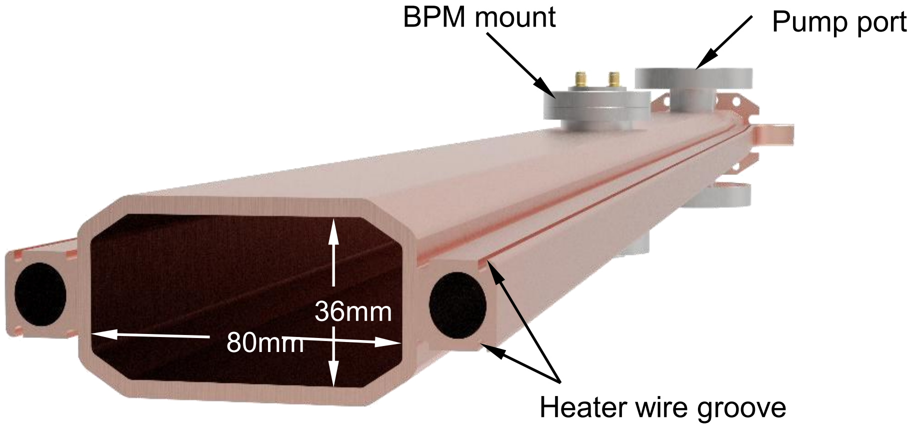


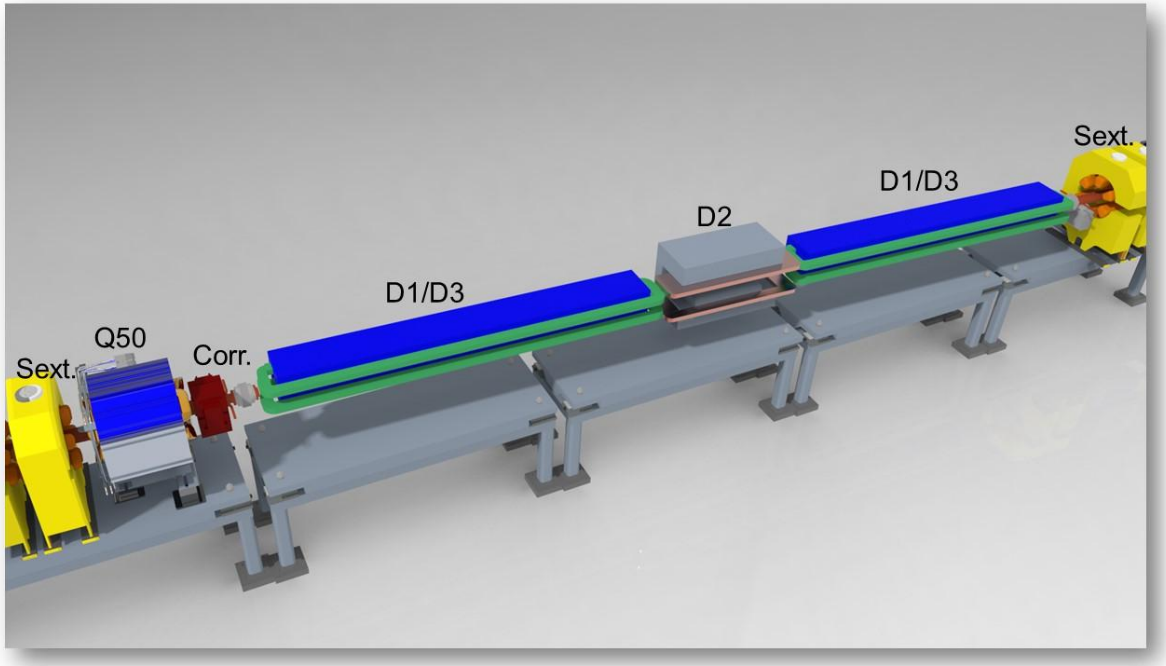
Sector 1 without and with the 41-GeV bypass line



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

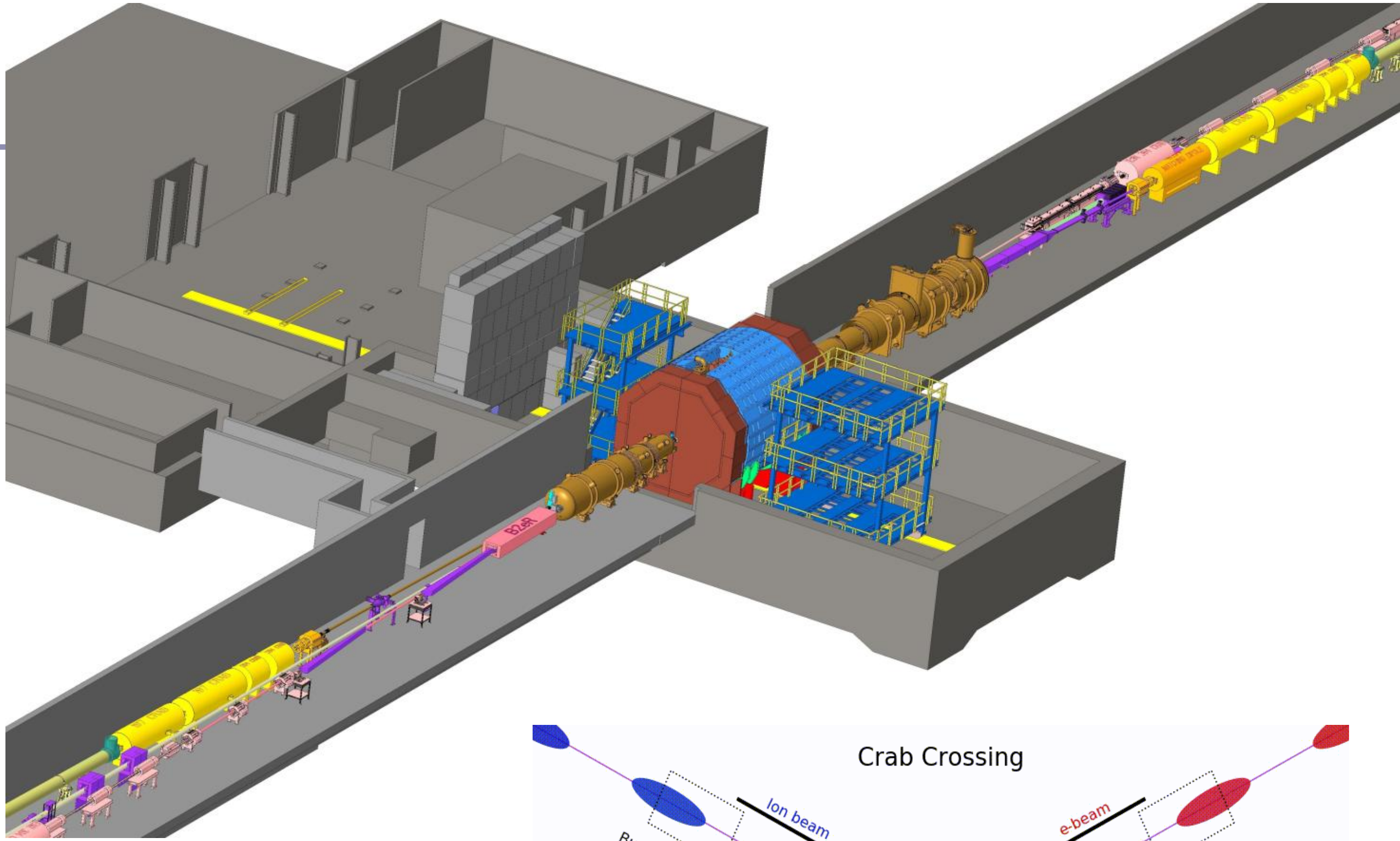




EIC needs nearly constant (20 to 24 nm) emittance from 5 to 18 GeV for optimum luminosity, but equilibrium emittance in an electron storage ring depends on beam energy.

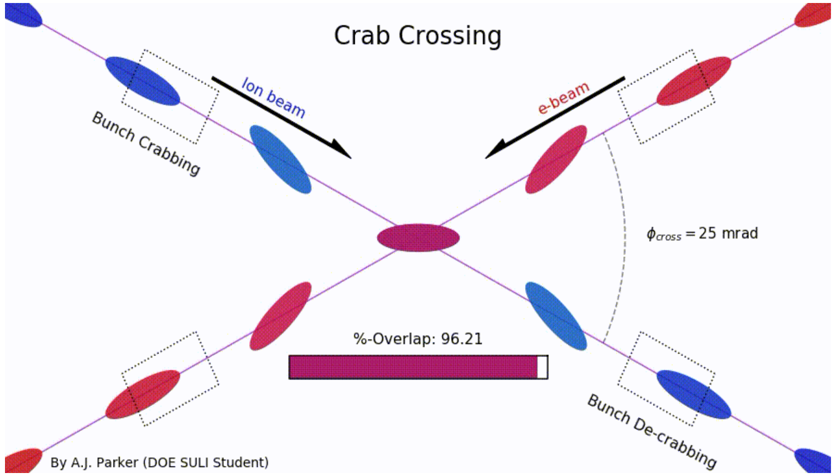
We will use ‘super bends’ (reverse bends) for emittance control below 10 GeV

EIC IR Layout

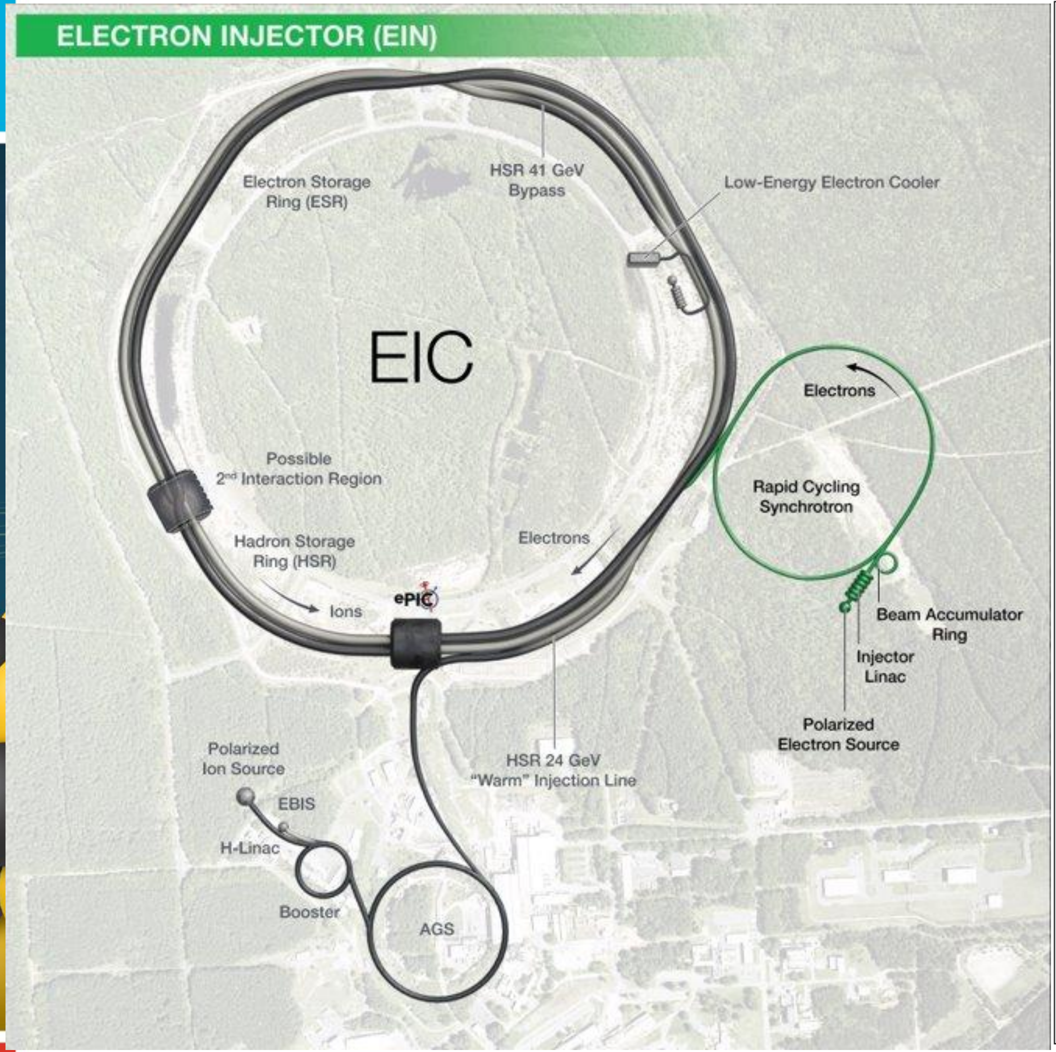


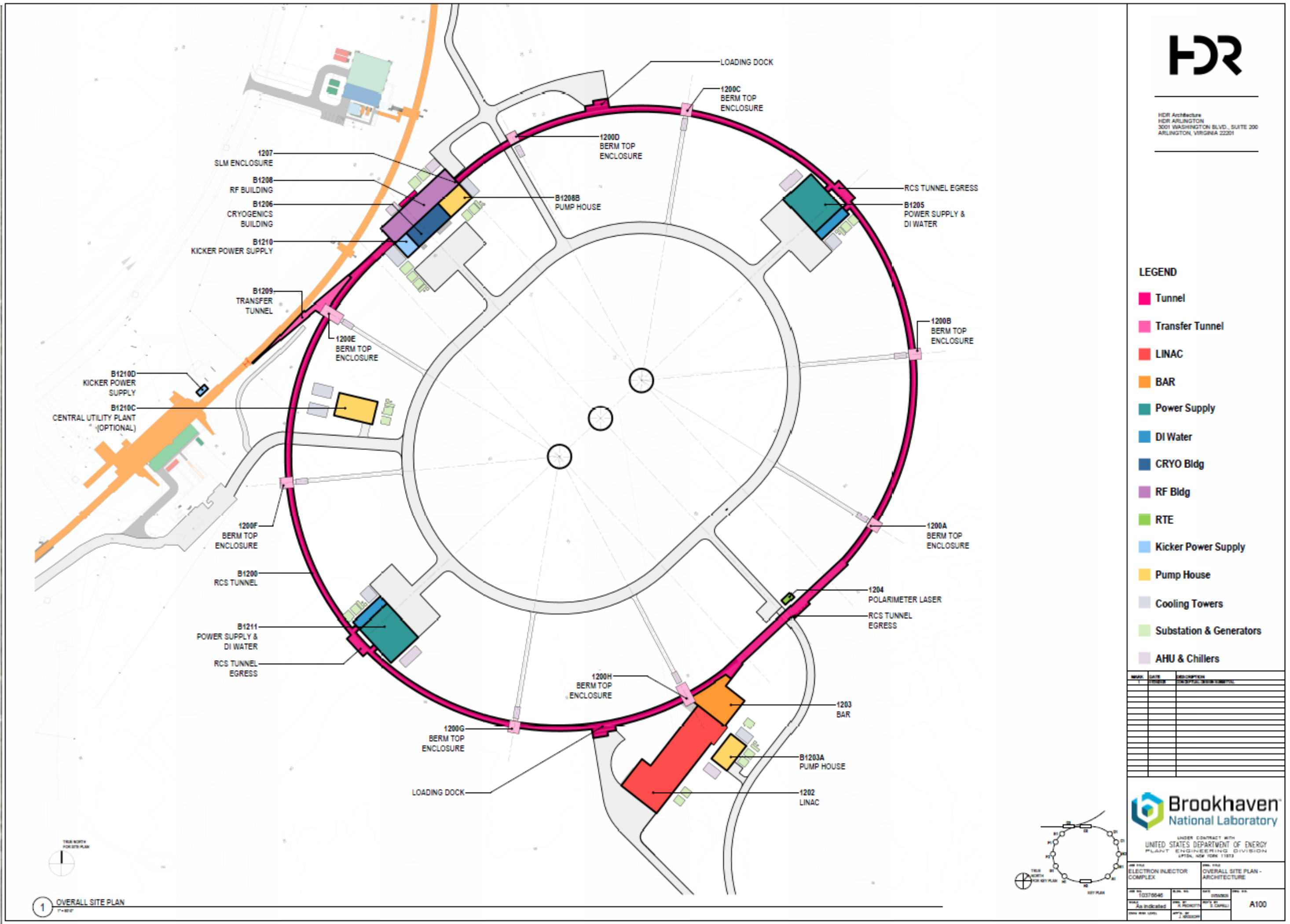
High Luminosity:
- 25 mrad crossing angle
- Small β* for high luminosity with limited IR chromaticity contributions
- Large final focus quadrupole aperture

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

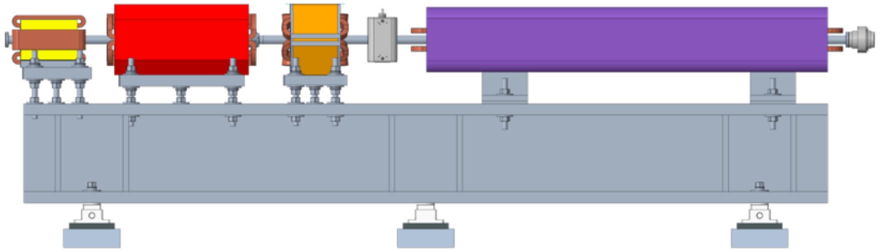




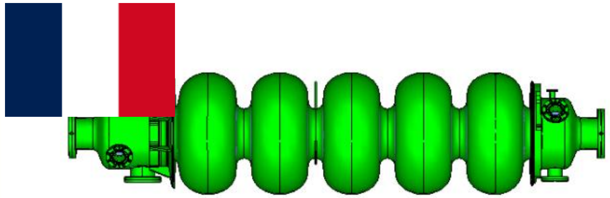
Electron Injector

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 – 10 GeV (upgradeable to 18 GeV).



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



RCS SRF Cavity, 591 MHz


RESEARCH ARTICLE | JUNE 17 2024

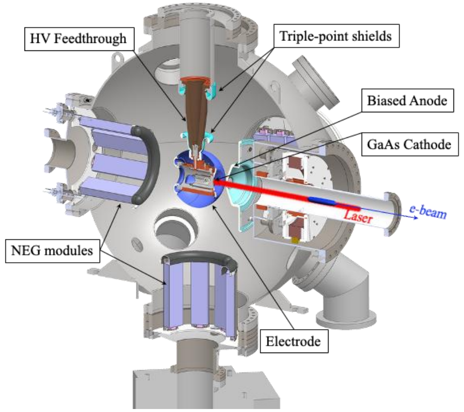
High-intensity polarized electron gun featuring distributed Bragg reflector GaAs photocathode

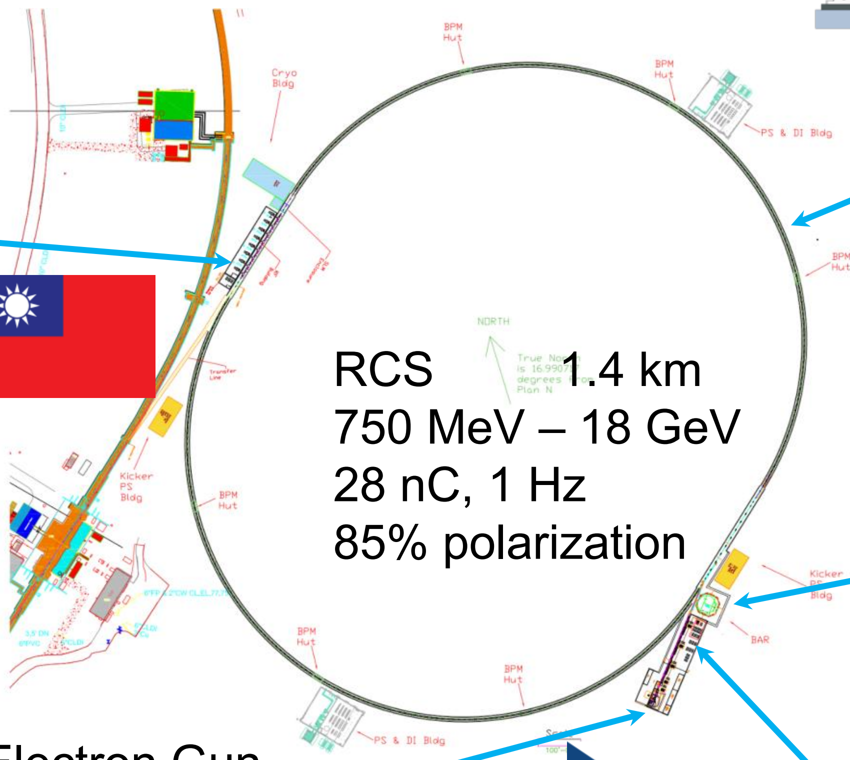
Erdong Wang; Omer Rahman; Jyoti Biswas; John Skaritka; Patrick Inacker; Wei Liu; Ronald Napoli; Matthew Panicia

Check for updates

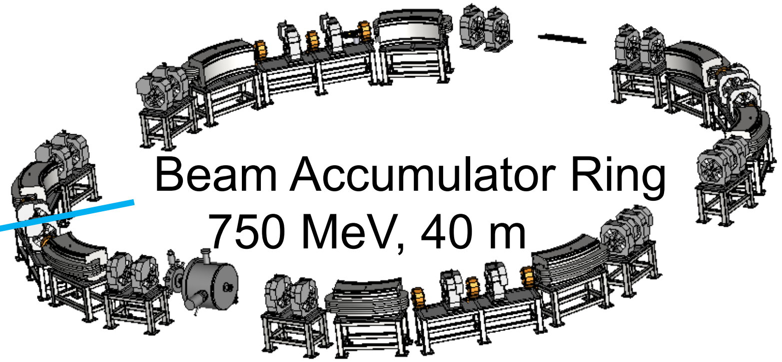
Appl. Phys. Lett. 124, 254101 (2024)

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)

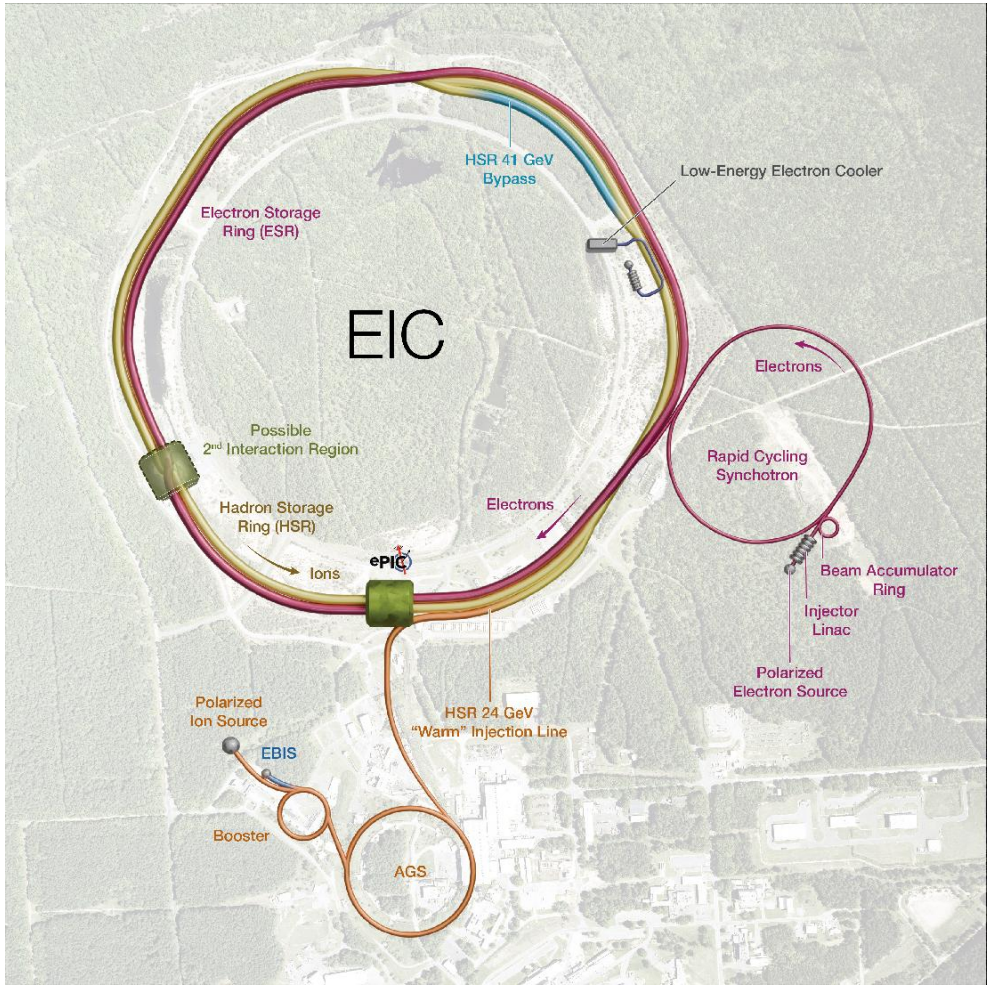
NEW Beam Accumulation Ring (750 MeV) – BAR

NEW Electron Rapid Cycling Synchrotron (0.75 GeV – top energy) – RCS

NEW Electron Storage Ring (5 GeV – 10 GeV) – ESR

NEW Interaction Region(s) – IR

NEW Hadron Cooling System



Protons: ~40 – 275 GeV
Electrons: 5 – 10 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.
- EIC design has converged. The EIC scope is stable and supports the Global Requirements and the DOE Mission Need Statement.
- **Some project scope** is well developed, designs are mature, **and is being executed as Long-lead procurements (DOE CD3A and CD3B)**

- We understand what we need to build to deliver the EIC!

Opportunities for collaborations

- Polarized electron injector, linac, and the RCS
- The electron cooling system
- SC magnets
- SRF cavities
- AI/ML: virtual EIC accelerator, polarization preservation, luminosity optimization
- Beam dynamics
- Collimation and Machine Protection