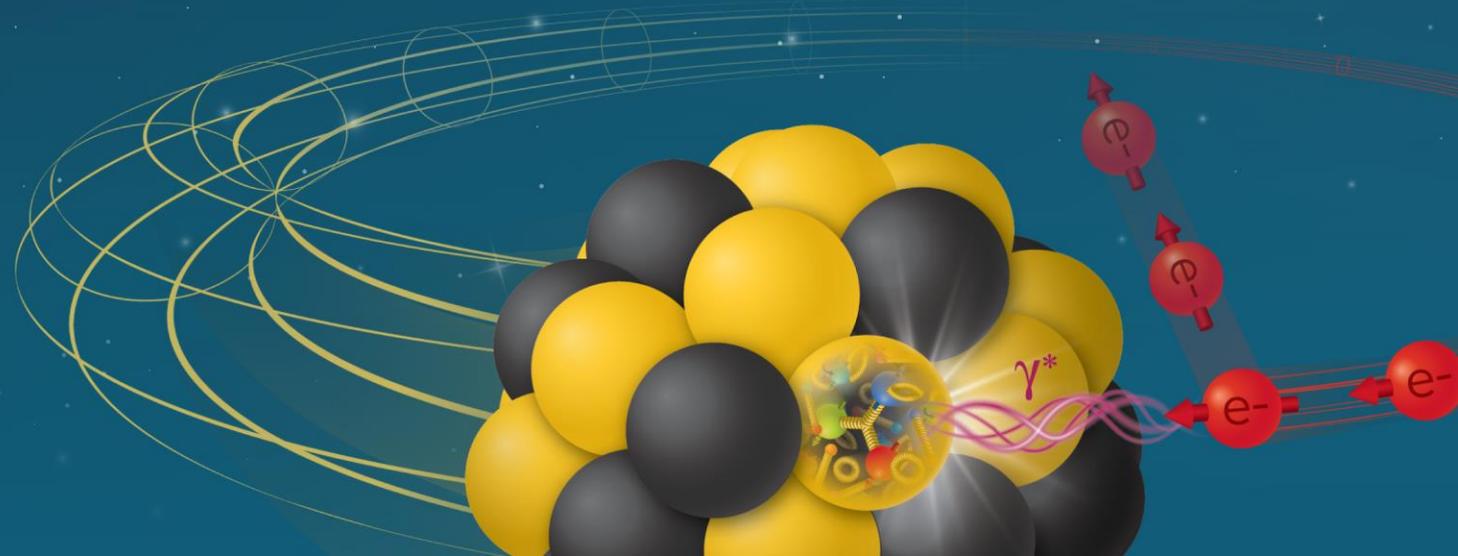


# Electron-Ion Collider

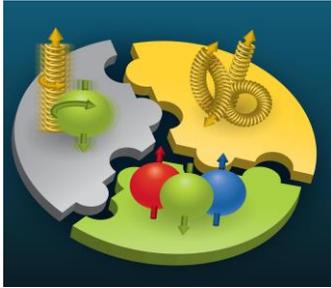
Sergei Nagaitsev  
EIC Technical Director

COOL25  
October 27, 2025

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.

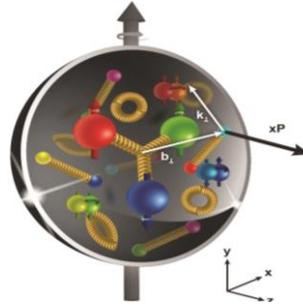
All elementary particles, but the Higgs, carry spin. Spin cannot be explained by a static picture, rather the interplay between the properties and interactions of quarks and gluons inside the proton.



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

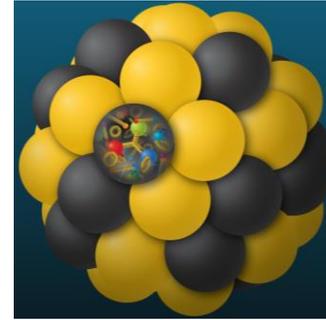
Atom: Binding/Mass = 0.00000001  
 Nucleus: Binding/Mass = 0.01  
 Proton: Binding/Mass = 100

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



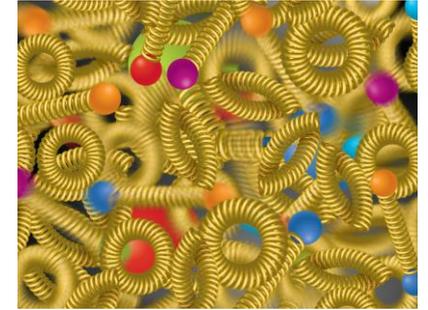
**How can we understand QCD dynamics and the relation to confinement?**

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.



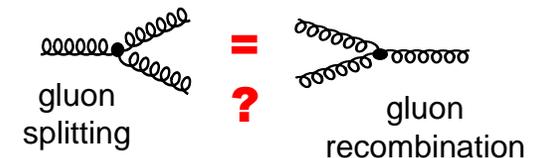
**How do quark-gluon interactions create nuclear binding?**

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?

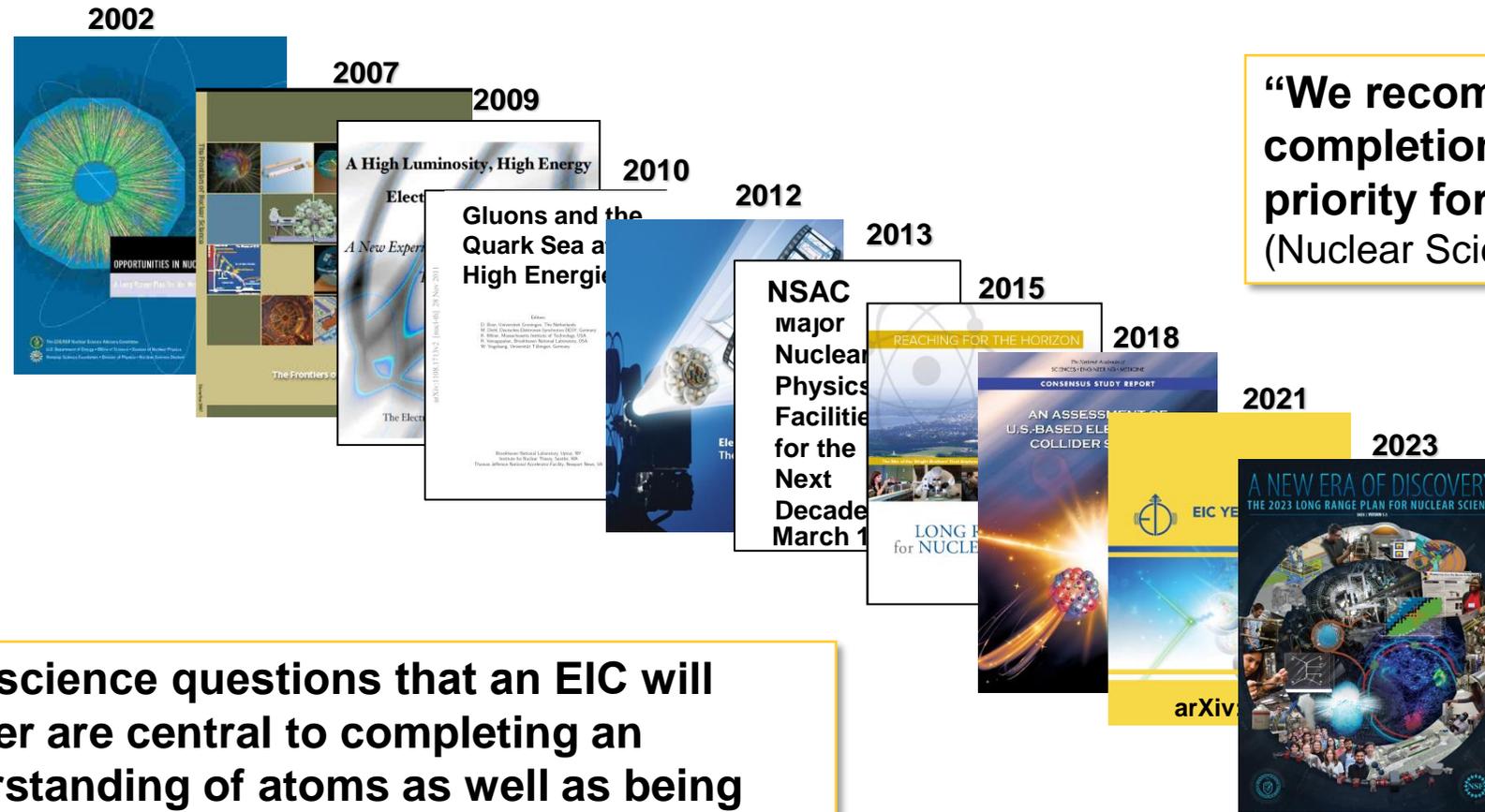


**Does gluon density in nuclei saturate at high energy?**

How many gluons can fit in a proton?  
 How does a dense nuclear environment affect the quarks and gluons, their correlations and interactions?



# EIC Scientific Case Built Over Decades

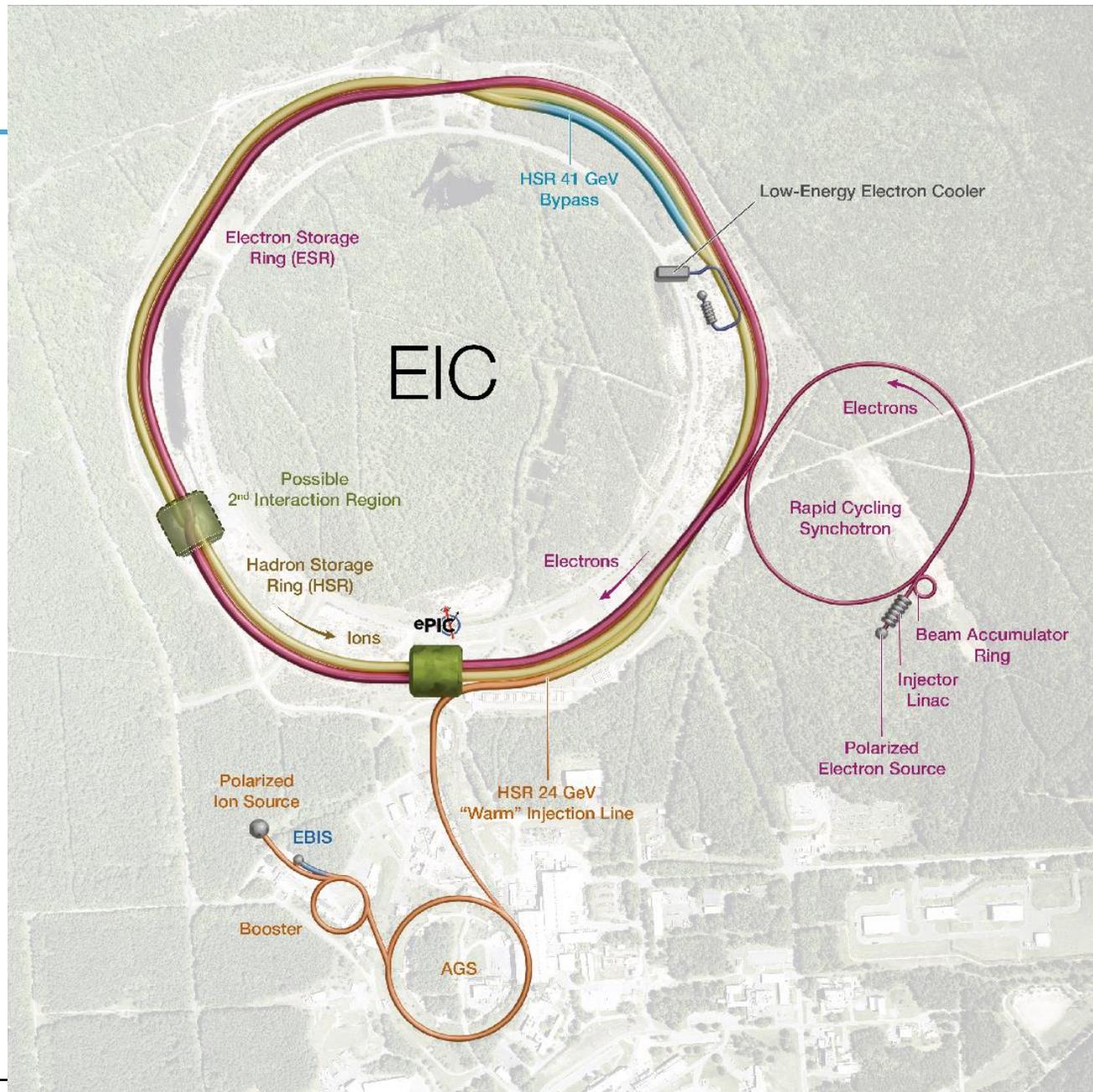


**“We recommend the expeditious completion of the EIC as the highest priority for facility construction.”**  
(Nuclear Science Advisory Committee, 2023)

**“The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today.”** (National Academies of Sciences, Medicine, and Engineering, 2018 Consensus Study Report)

**EIC will be the only operating particle collider in the U.S. in the next decades.**

# EIC at Brookhaven National Lab



# EIC Accelerator Performance Requirements

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

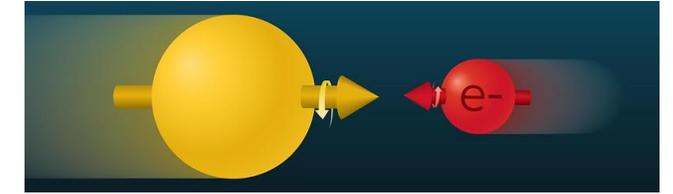
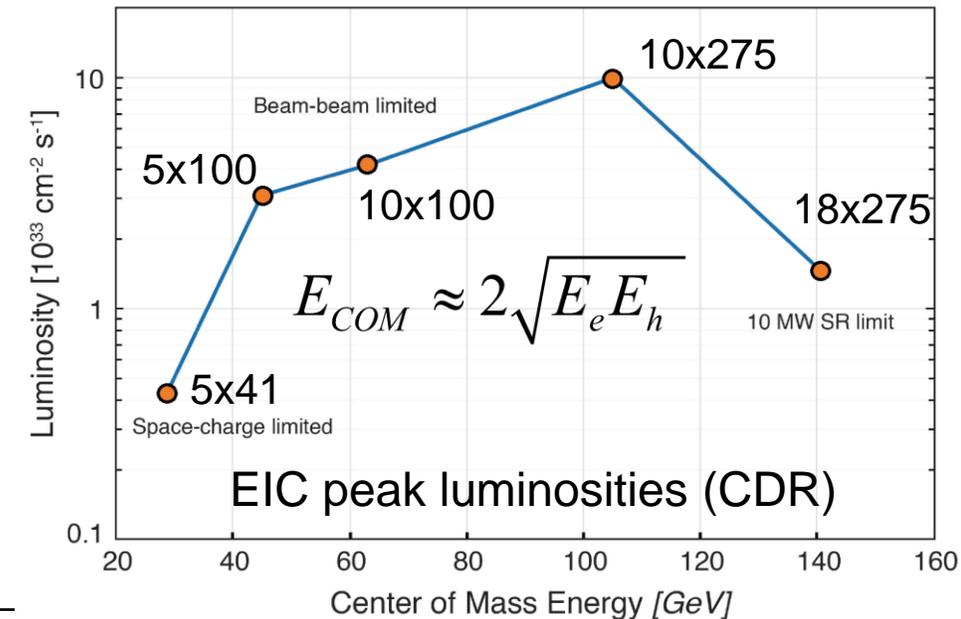


Figure of merit:  $LP^2$  to  $LP^4$

Based on the 2015 US NSAC Long-Range Plan

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

$$L = \frac{N_e N_p}{4\pi\sigma_h\sigma_v} N_b f_0 \approx 1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \quad N_b = 1160; f_0 = 78.3 \text{ kHz}$$



# EIC Accelerator Performance

wide center-of-mass energy  $\sqrt{s}$ : 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

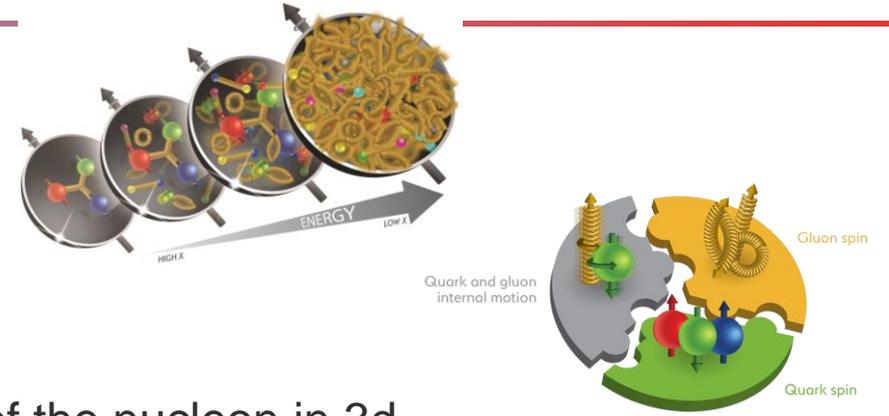
- accessing the highest gluon densities  $\rightarrow$  saturation
- quark and gluon interact with a nuclear medium

high luminosity  $10^{33}$ - $10^{34}$   $\text{cm}^{-2}\text{s}^{-1}$  :

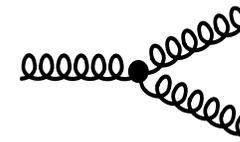
- mapping the spatial and momentum structure of nucleons and nuclei in 3d
- access to rare probes, i.e.  $W$ s

large acceptance (0.2 – 1.3 GeV) through forward focusing IR magnets

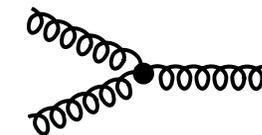
- spatial imaging of nucleons and nuclei



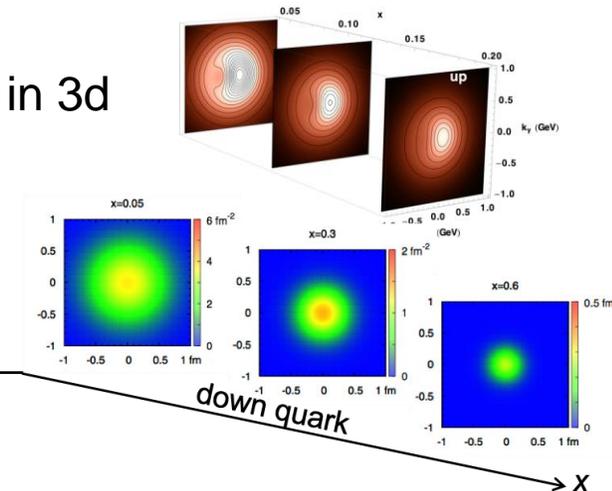
gluon emission



gluon recombination

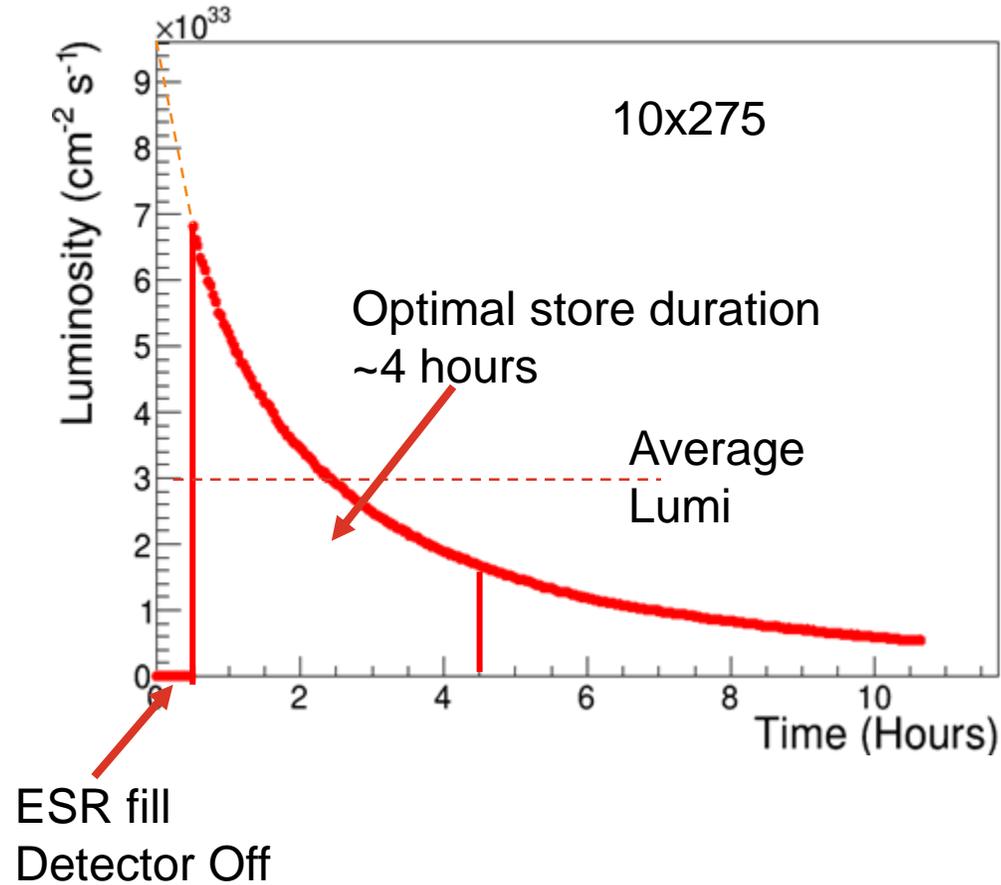


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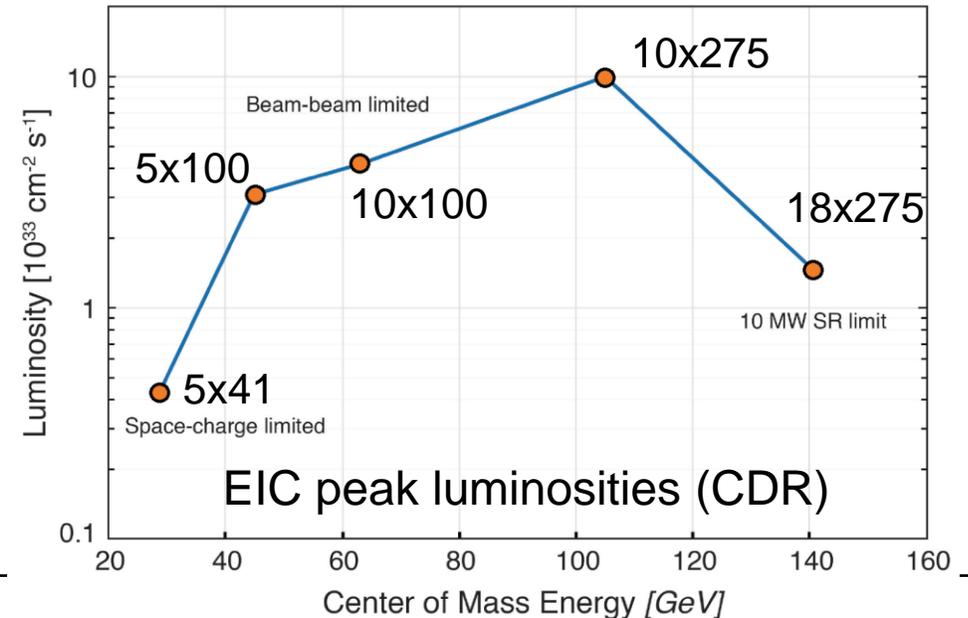


# Luminosity performance

“Flat” proton bunches allow for high initial luminosity



CoM Energy (GeV)	Average Lumi ( $\times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ ) (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:  $\sim 5 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$

- The EIC is an electron – ION collider (HERA was an e-p collider)
- Variable CoM energy (HERA was a fixed-energy collider)
- EIC beams are polarized, starting from the source (HERA was not)
- New modern particle detector
- EIC luminosity is a factor of  $\sim 200$  higher

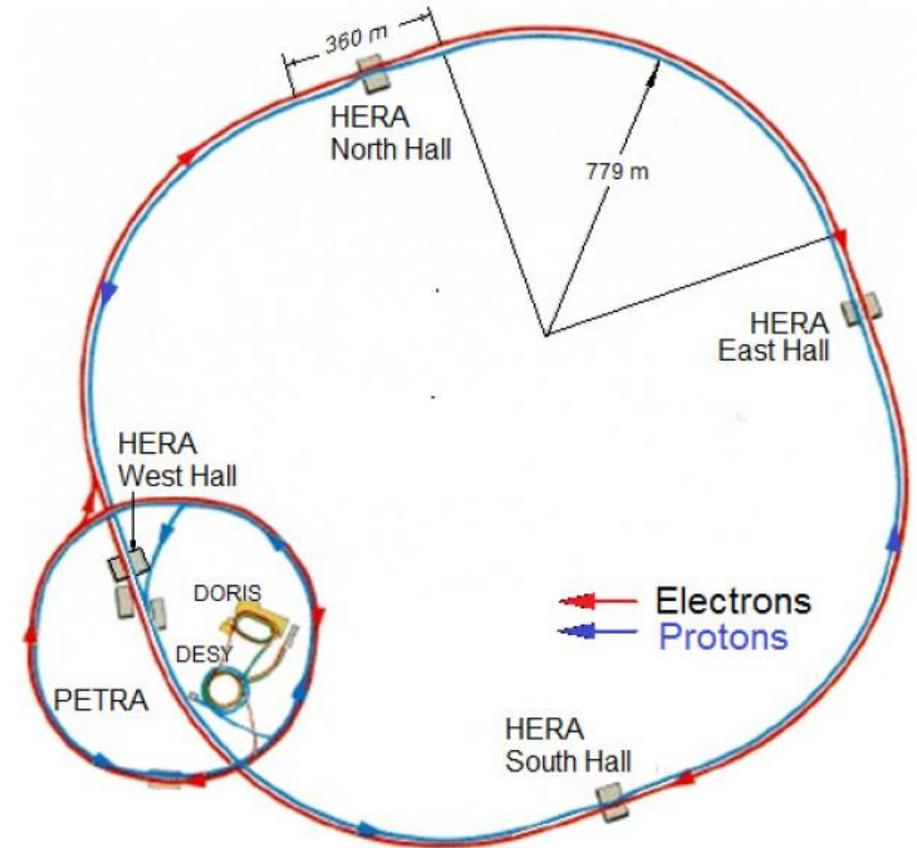


Fig. 1. HERA *ep* collider footprint.

# HERA vs EIC: key parameters

$$L = \frac{N_e N_p}{4\pi\sigma_h\sigma_v} N_b f_0 \approx 1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$$

	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	
<b>Luminosity, <math>\times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}</math></b>	<b>5.3</b>	<b>1000</b>	<b>190</b>

} 60 (for Circumference, Number of bunches, Proton bunch charge, Electron bunch charge)

} ~3 (for Beta at IP, Proton emittance, Electron emittance)

# Key EIC accelerator concepts

---

- Ribbon-like (flat) hadron beam (11:1 transverse emittance/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))
- 
- Upgrade path: high-energy hadron cooling at collisions

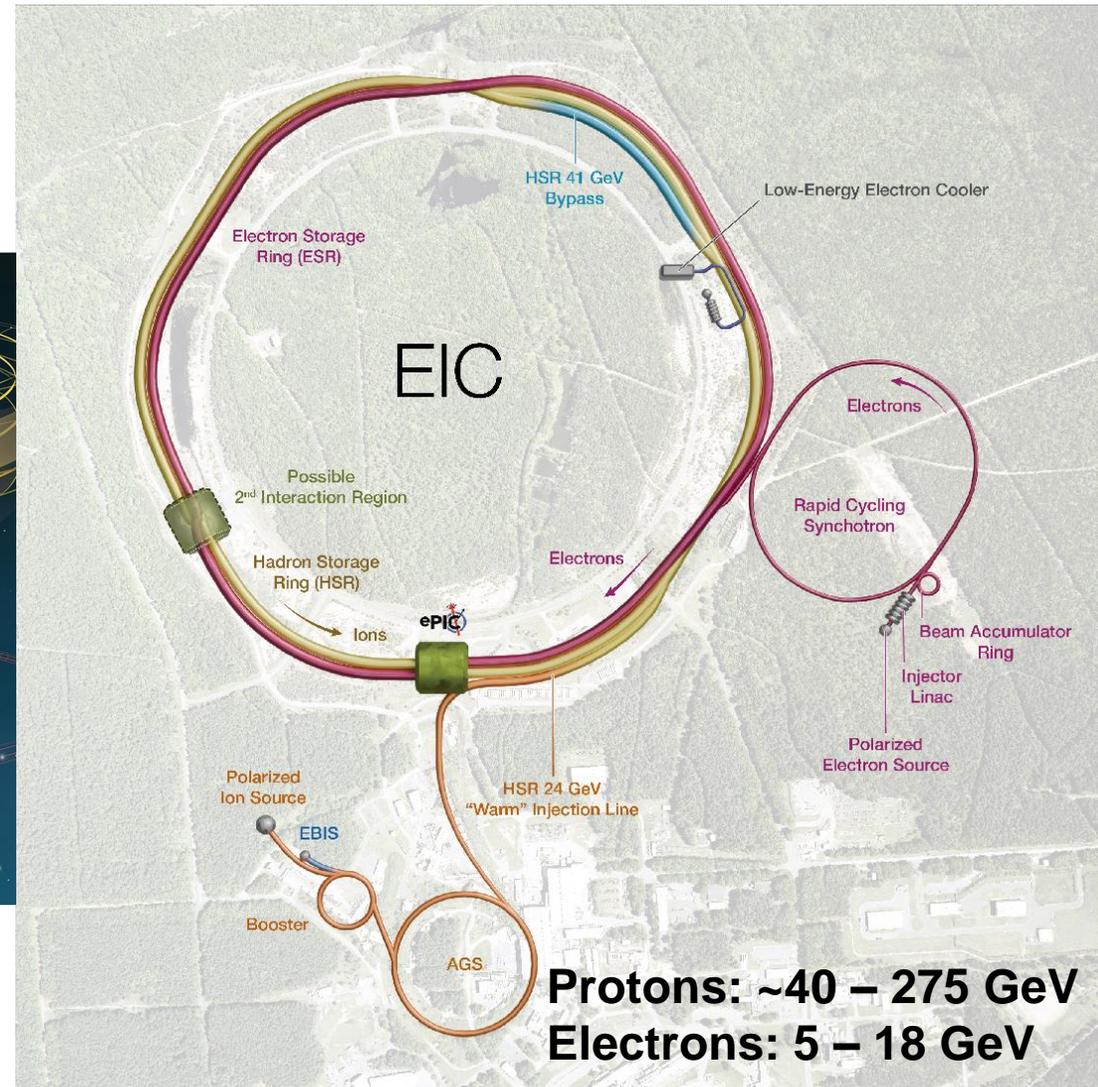
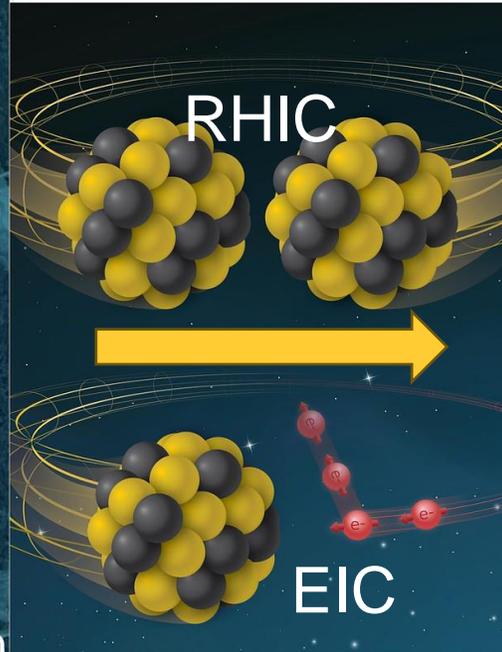
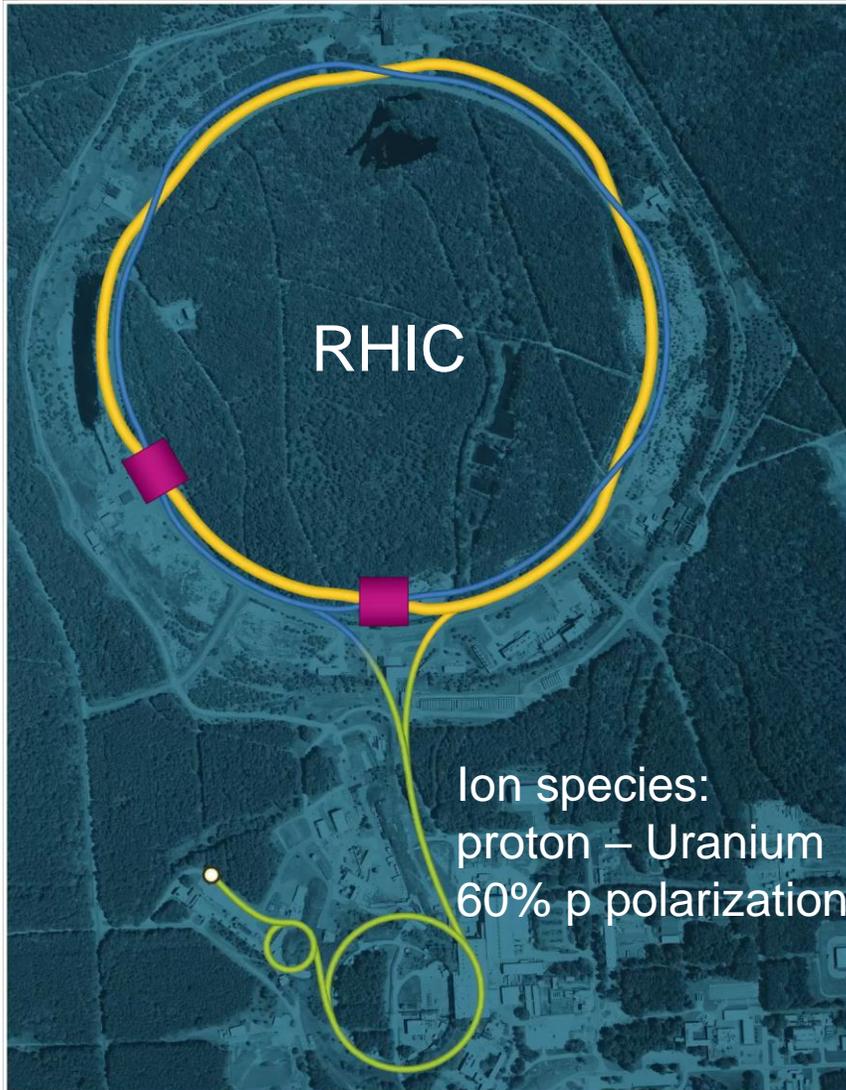
These are the key concepts that allow to attain luminosity of  $\sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  and maintain high polarization at collisions over a broad range of CoM energies

# 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;
  - Vacuum chambers, beam screens, kickers, SRF cavities

# From RHIC to EIC



# From RHIC (yellow ring) to EIC HSR

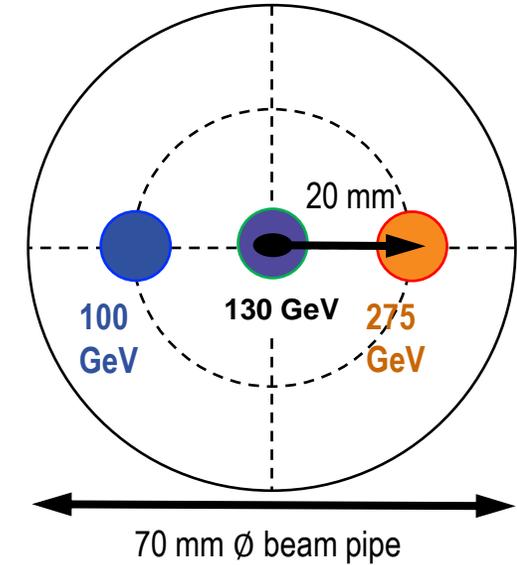
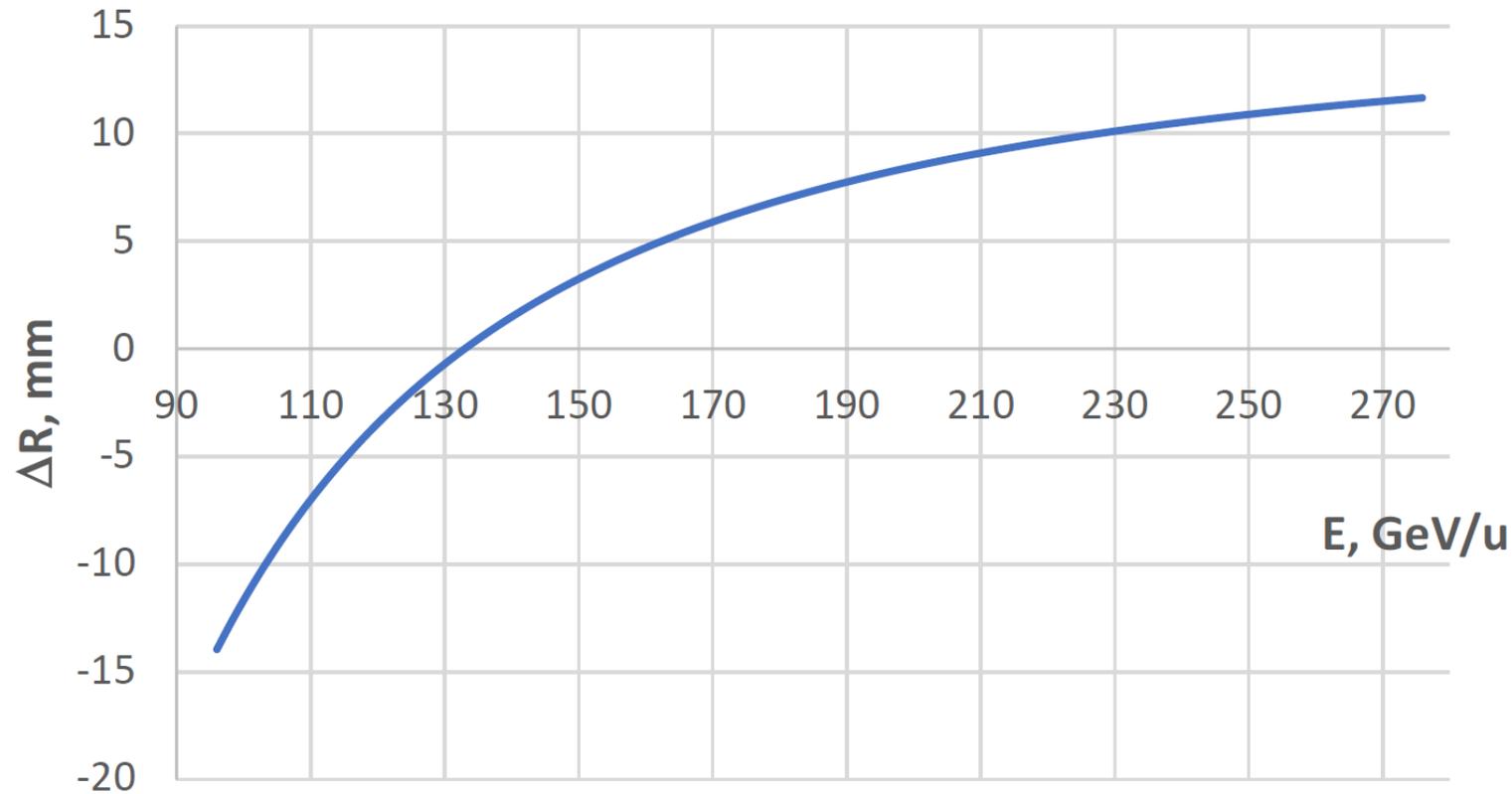
Tripled beam current, shorter bunch length, shorter bunch distance, 'flat' beams with small vertical emittance

- 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



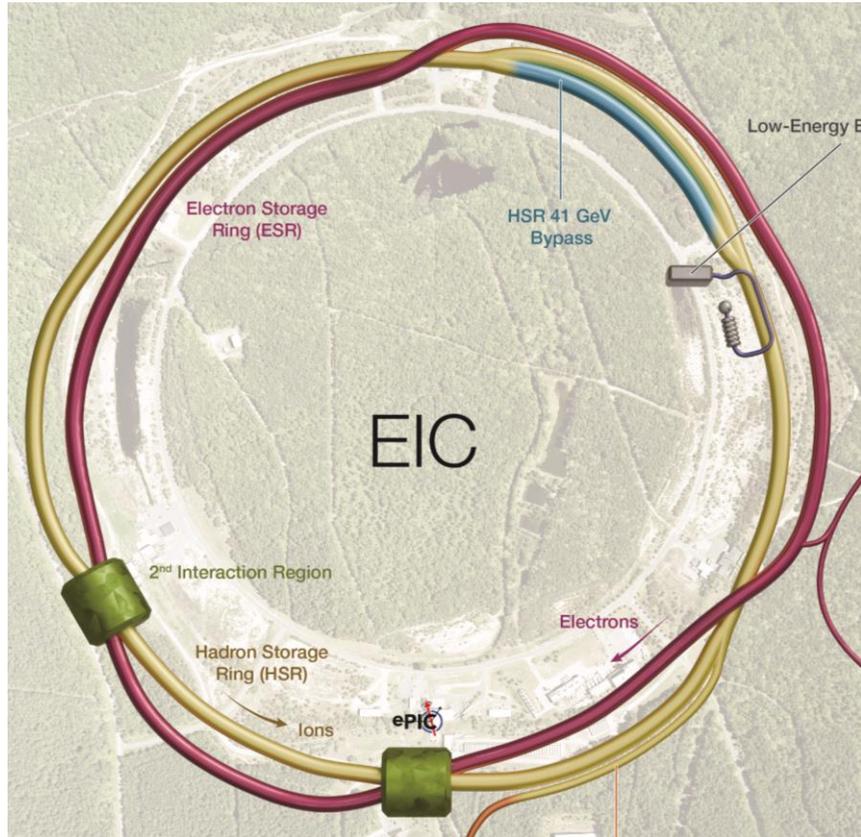
# Beam Energy and Average Orbit Radius in the HSR



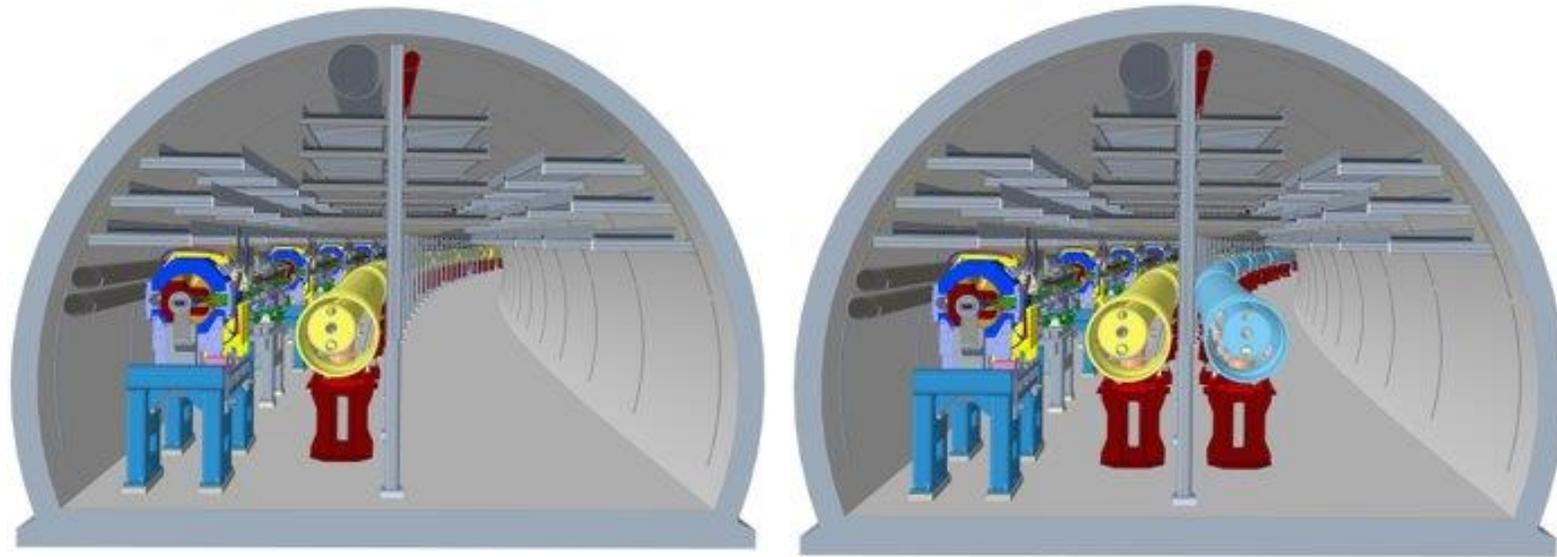
Since the electron revolution frequency is fixed, the hadron orbit must be adjusted with energy to keep the collisions in sync.

# 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 hadron beam cooling

- **Low-energy cooling (LEC):**

The goal of cooling at proton injection energy is to obtain initial proton parameters by **cooling the vertical emittance from  $\sim 2 \mu\text{m}$  to  $0.3\text{-}0.5 \mu\text{m}$**  (rms normalized).

Cooling at **injection energy of protons** (24 GeV) requires a 13 MeV electron beam.

**Our present design concept is similar to the existing RHIC LEReC system**

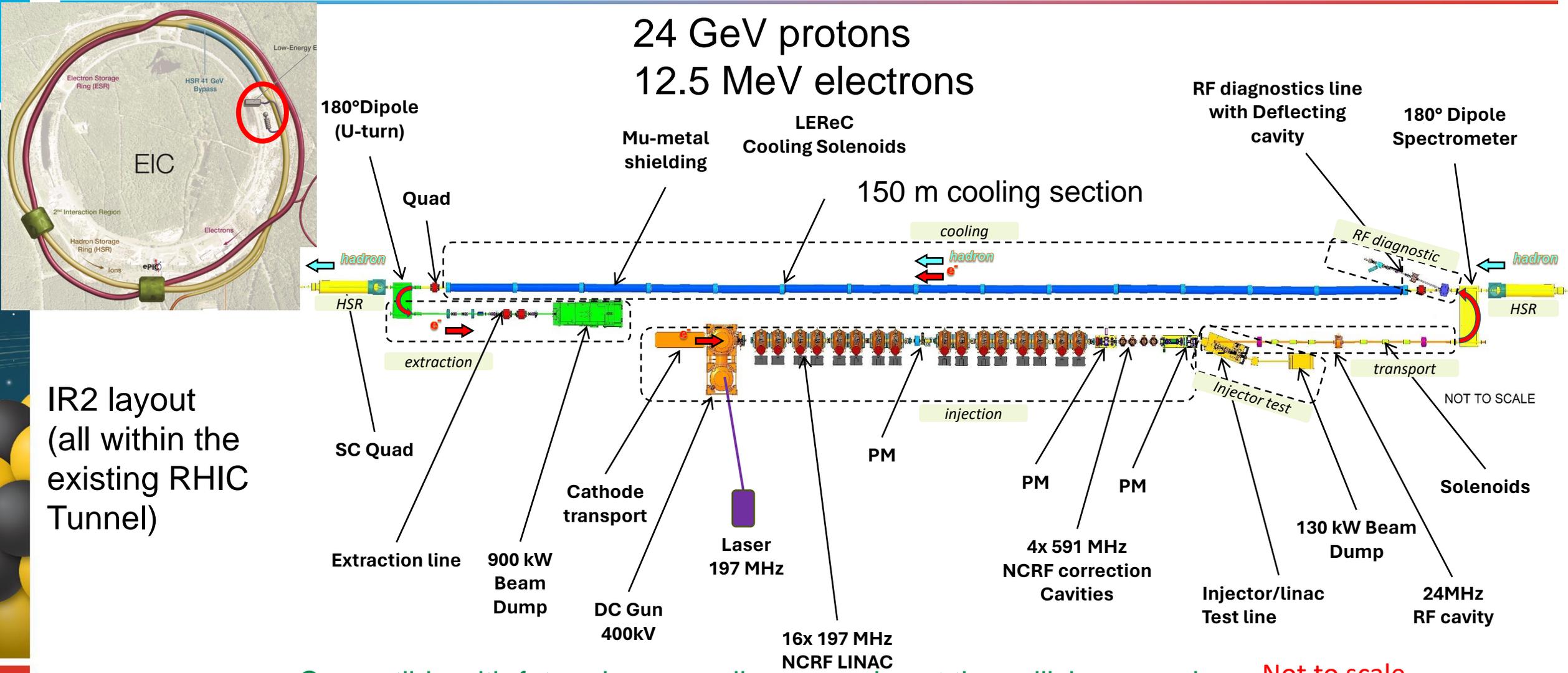
A. V. Fedotov et al. "Experimental Demonstration of Hadron Beam Cooling Using Radio-Frequency Accelerated Electron Bunches", Phys. Rev. Lett. 124, 084801 (2020)

- **High-energy proton cooling at collisions** (possible future upgrade)

The goal of cooling at EIC proton collision energies of 41, 100 -- 275 GeV is to **counteract the longitudinal and transverse emittance growth and to maintain the 'flat' proton beam**. Several candidate concepts are being considered.

- **Ion beam cooling at collisions:** Conventional microwave stochastic cooling

# Low-energy Cooler Concept



IR2 layout  
(all within the existing RHIC Tunnel)

Compatible with future beam cooling upgrades at the collision energies **Not to scale**

# EIC Low Energy Cooler Parameters

LEReC key parameters for reference

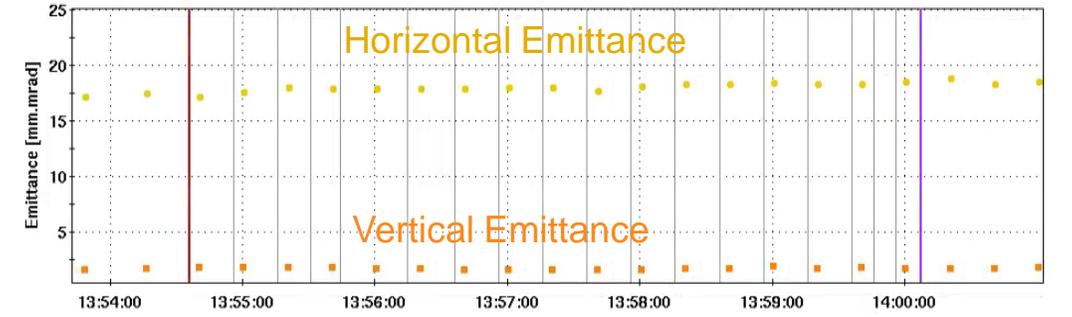
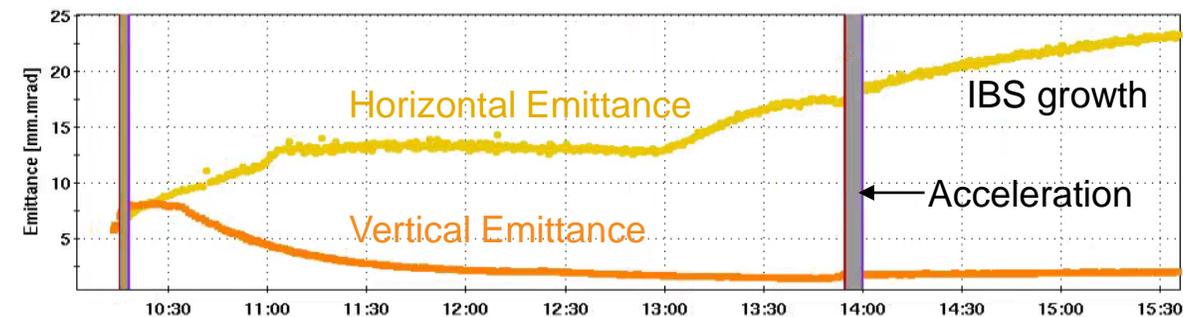
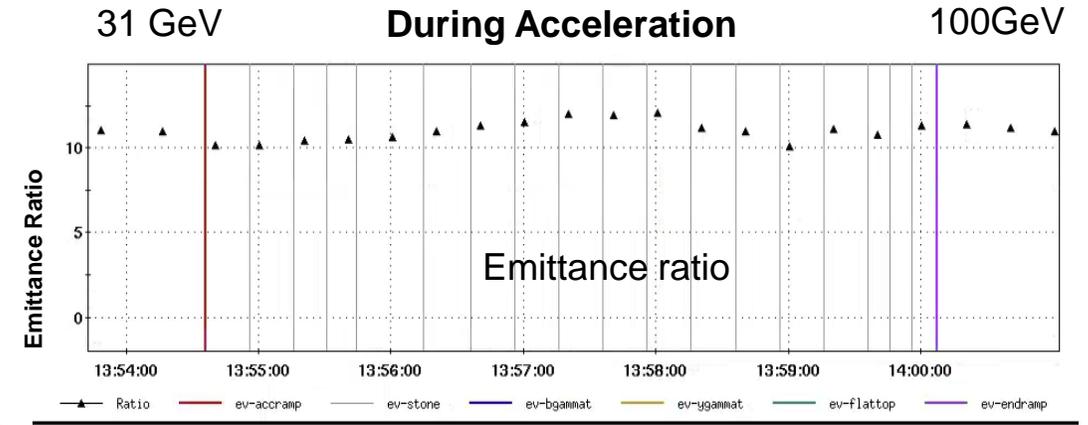
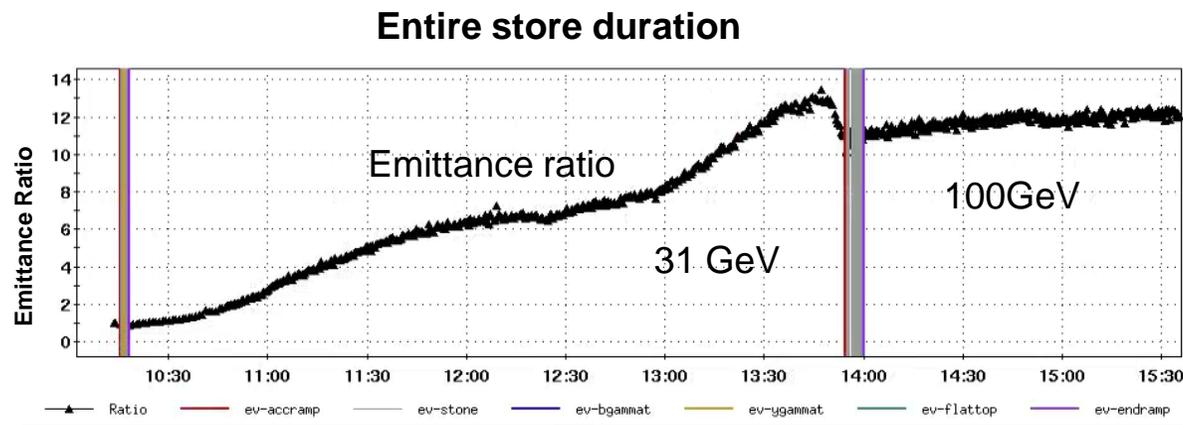
	electrons	protons
gamma	25.4	25.4
RHIC RF frequency, MHz	197	24.6
Cooling section length, m	168	168
Cooling sections beta function, m	150	100-200
Hadrons $D_y$ , $D_y'$ , m, rad		<1, <0.02
Total charge per proton bunch, nC	3	45
Electrons kinetic energy, MeV	12.46	
Electron average current, mA	<b>74</b>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

electrons
4-5
704 MHz (9 MHz)
20 m
30 m
3 nC
1.6-2 MeV
<b>30 (60 mA in tests)</b>
<2 $\mu\text{m}$
5 cm
<5e-4
<b>&lt;150 <math>\mu\text{rad}</math></b>

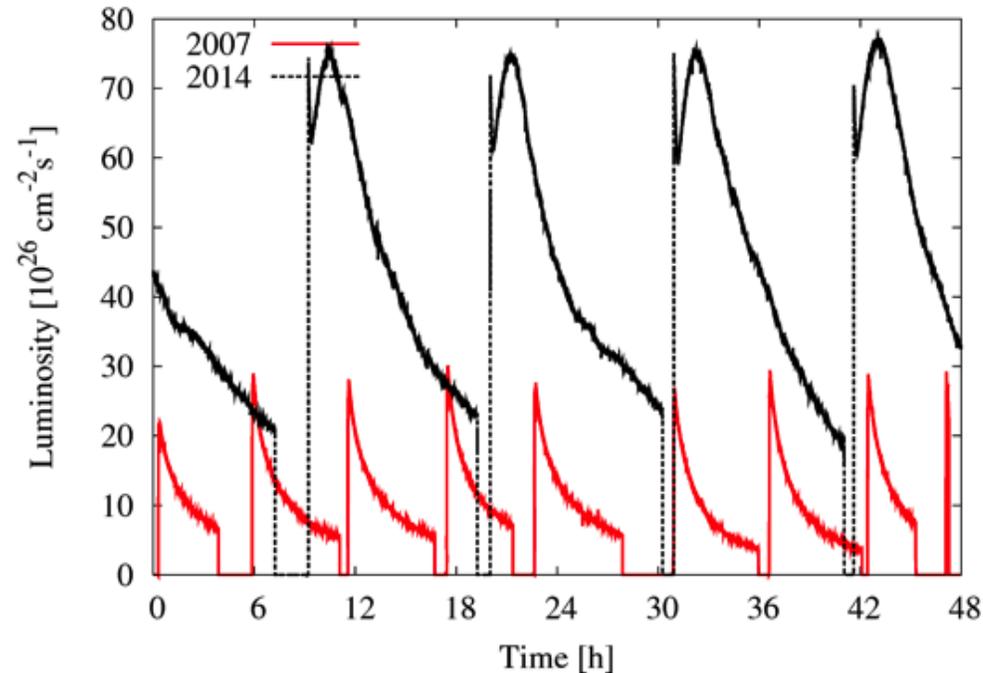
# Flat Beam Acceleration Experiment in RHIC

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



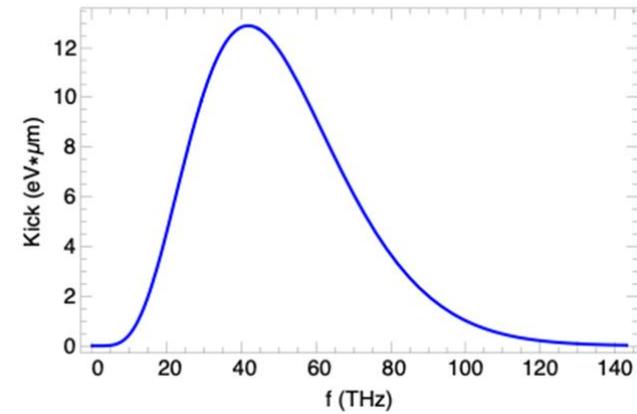
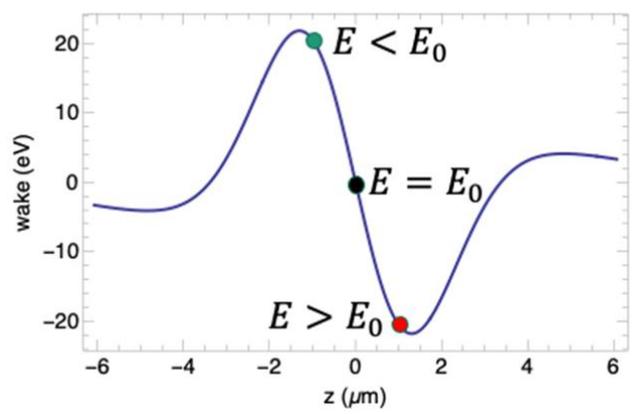
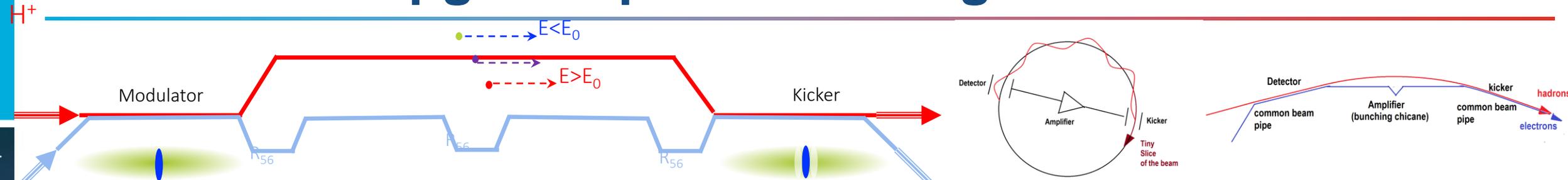
# Conventional stochastic cooling at collisions



RHIC luminosity

- 3-D stochastic cooling (5-9 GHz).
- $\sim 5x$  U-U and  $\sim 4x$  Au-Au luminosity improvements.
- Cooling led to first increase of instantaneous luminosity and smallest emittance ever in a hadron collider.
- Is not adequate for the EIC (protons), but will work with ions (after some upgrades)

# Possible EIC upgrade: proton cooling at collisions

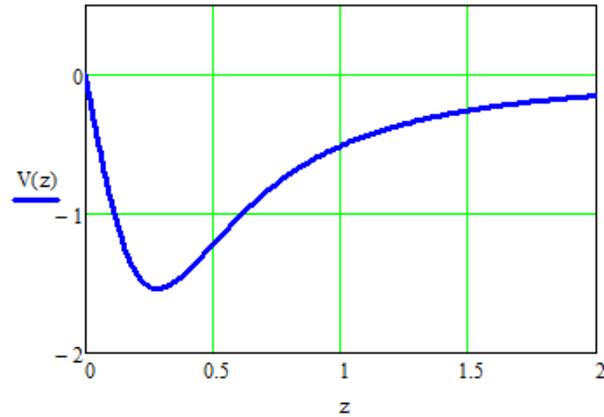


Case	100 GeV	275 GeV
Proton Bunch Length (cm)	7	6
Electron Normalized Emittance (x/y) (mm-mrad)	2.8 / 2.8	2.8 / 2.8
Electron Bunch Charge (nC)	1	1
Electron Bunch Length (mm)	14	7
Electron Fractional Energy Spread	1e-4	1e-4
Modulator/Kicker Length (m)	39 / 39	39 / 39
Amplifier Drift Lengths (m)	43	43
Proton Horizontal Dispersion in Modulator & Kicker (m)	1.108	1.36
Horizontal / Longitudinal IBS Times (hours)	2.0 / 2.5	2.0 / 2.9
Horizontal / Longitudinal Cooling Times (hours)	1.8 / 2.3	1.9 / 3.0

- The primary concept in the 2021 EIC CDR was based on coherent electron cooling with microbunching amplification
  - It's a type of stochastic cooling based on transit time between the modulator and the kicker. Typical bandwidth of ~40 THz, compared to ~10 GHz (conventional SC).
  - **This is a longitudinal-only cooling scheme.** Cooling in x and y requires coupling/sharing of cooling.
  - Pre-cooling at injection energy is still required.

# “Cooling” force for a proton at the center of the electron beam

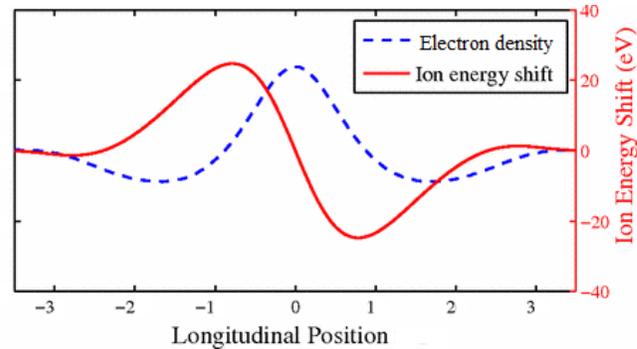
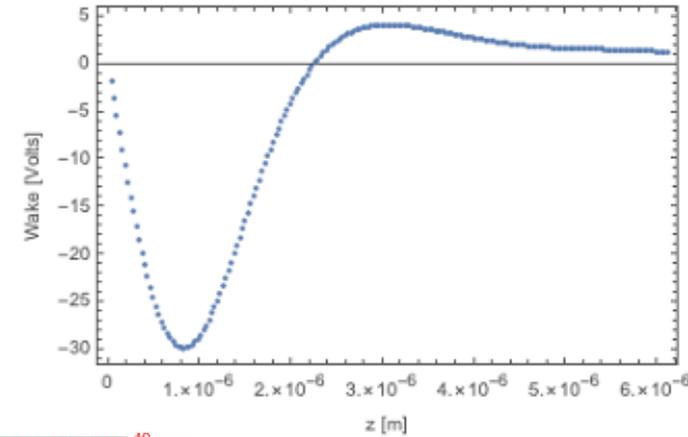
Initial modulation after “Modulator”



Amplification with some limited BW



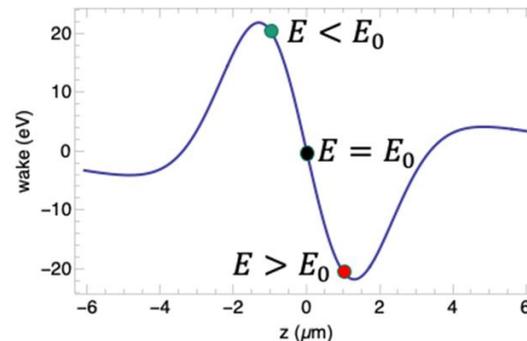
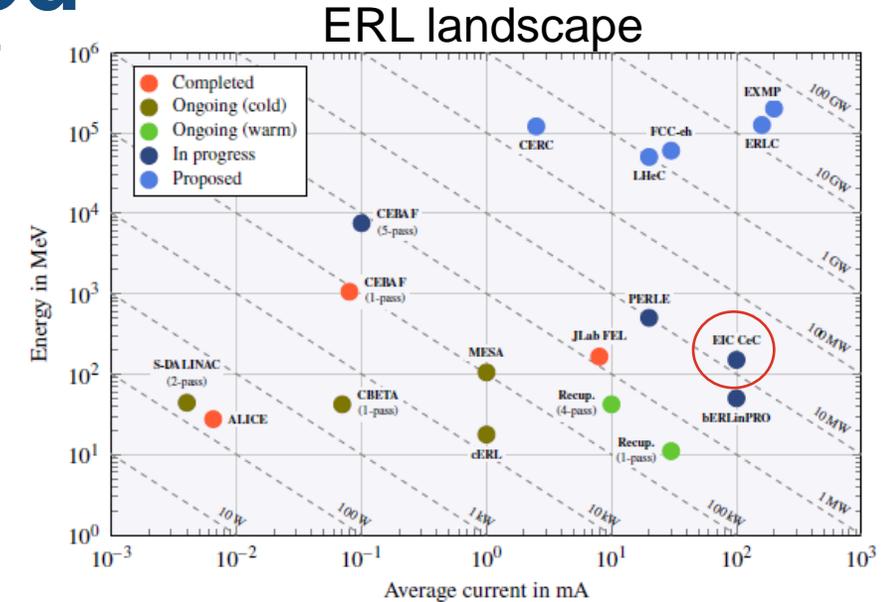
Kick in the “Kicker” section



Predicted cooling times of about 1 hour for 275 GeV protons

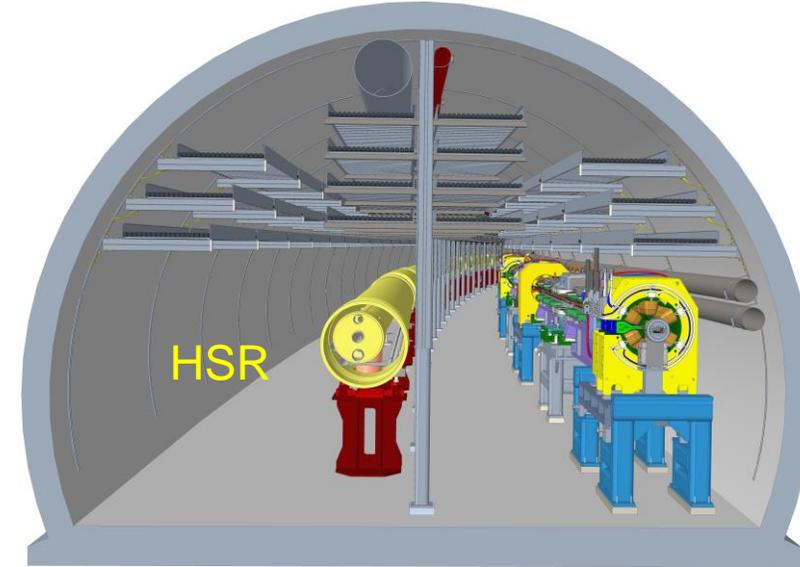
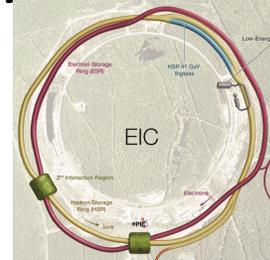
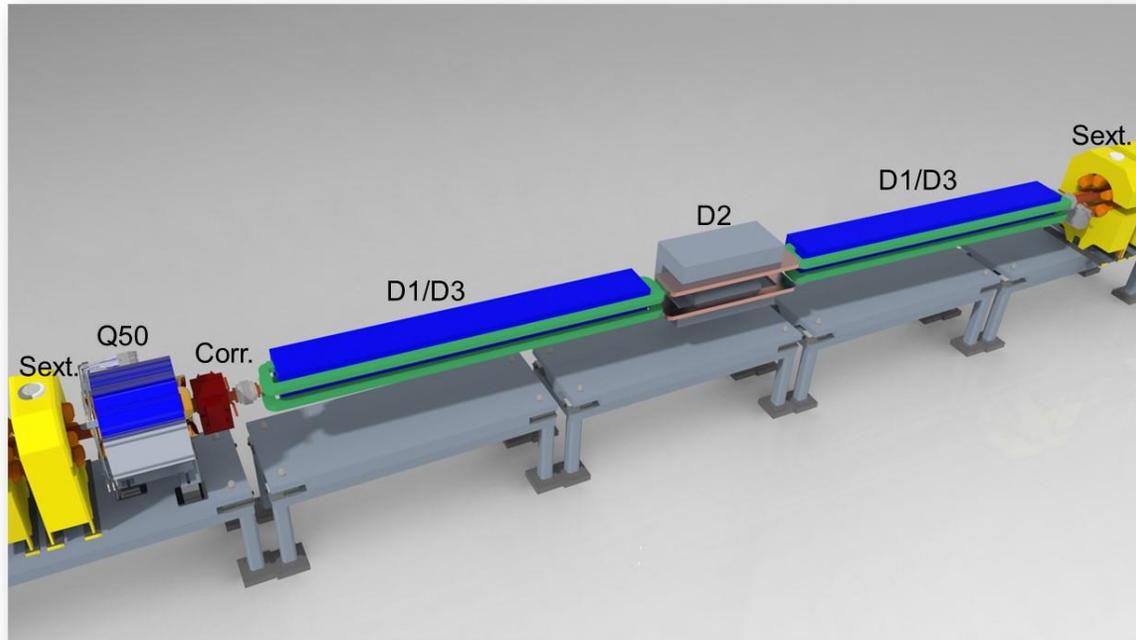
# Main challenges of the CEC method

- High-current SCRF ERL
  - <https://arxiv.org/abs/2207.02095>
- Low-noise electron beam
  - On-going experiments at BNL/SBU, Fermilab
- Controlled broad-band amplification of density fluctuations
  - Some experience at FELs (narrow band) and CeC (BNL/SBU)
- Longitudinal alignment of e-p beams to better than 100 nm over 100 m distance
  - No clear solution yet...



# 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  $\sim 2.5$  A and the synchrotron radiation power of  $\sim 10$  MW



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.

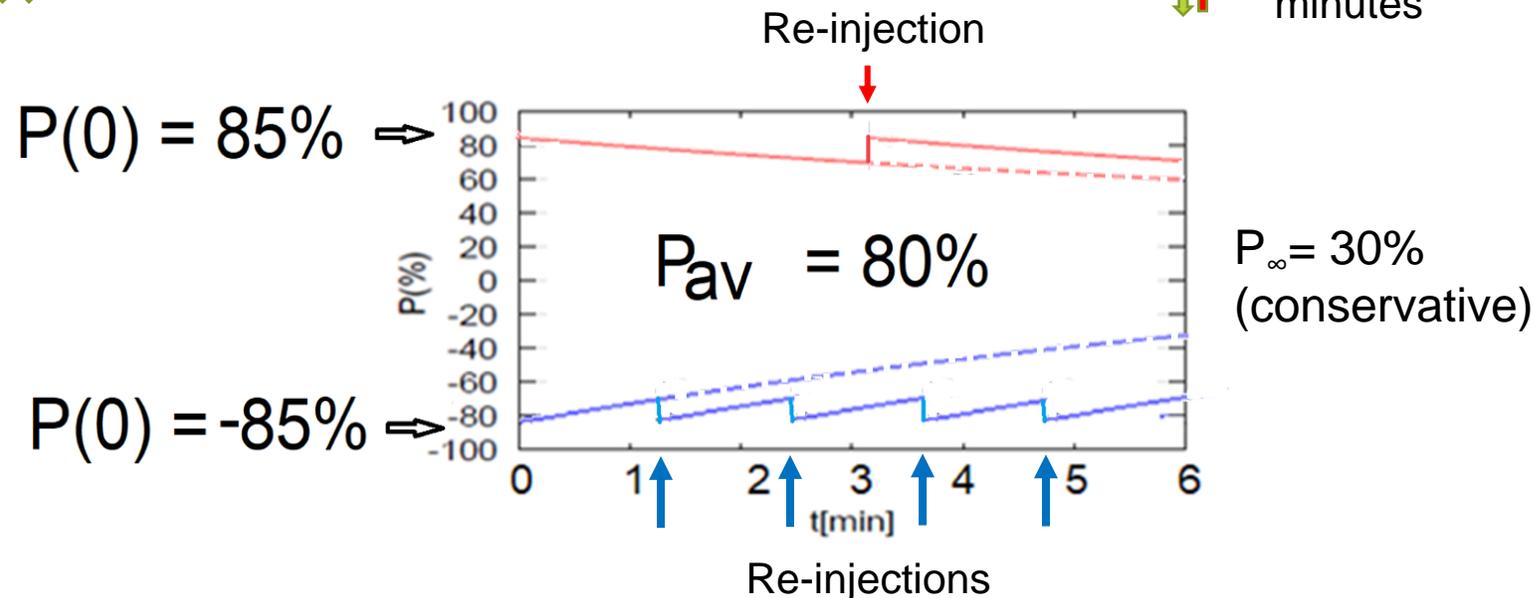
We will use 'super bends' (reverse bends) for emittance control below 10 GeV

# Electron polarization loss in the ESR

- Frequent swap-out injection of bunches with high initial polarization of 85%
  - Bunch spacing is  $\sim 10$  ns
- Initial polarization decays towards  $P_\infty$
- 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



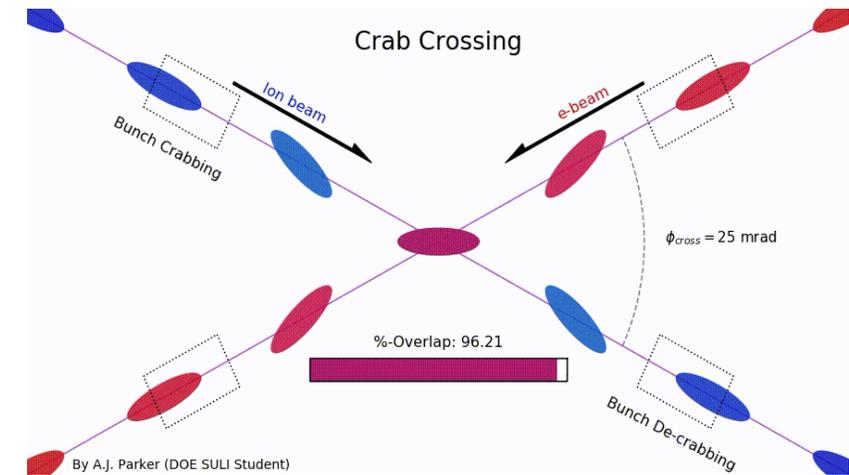
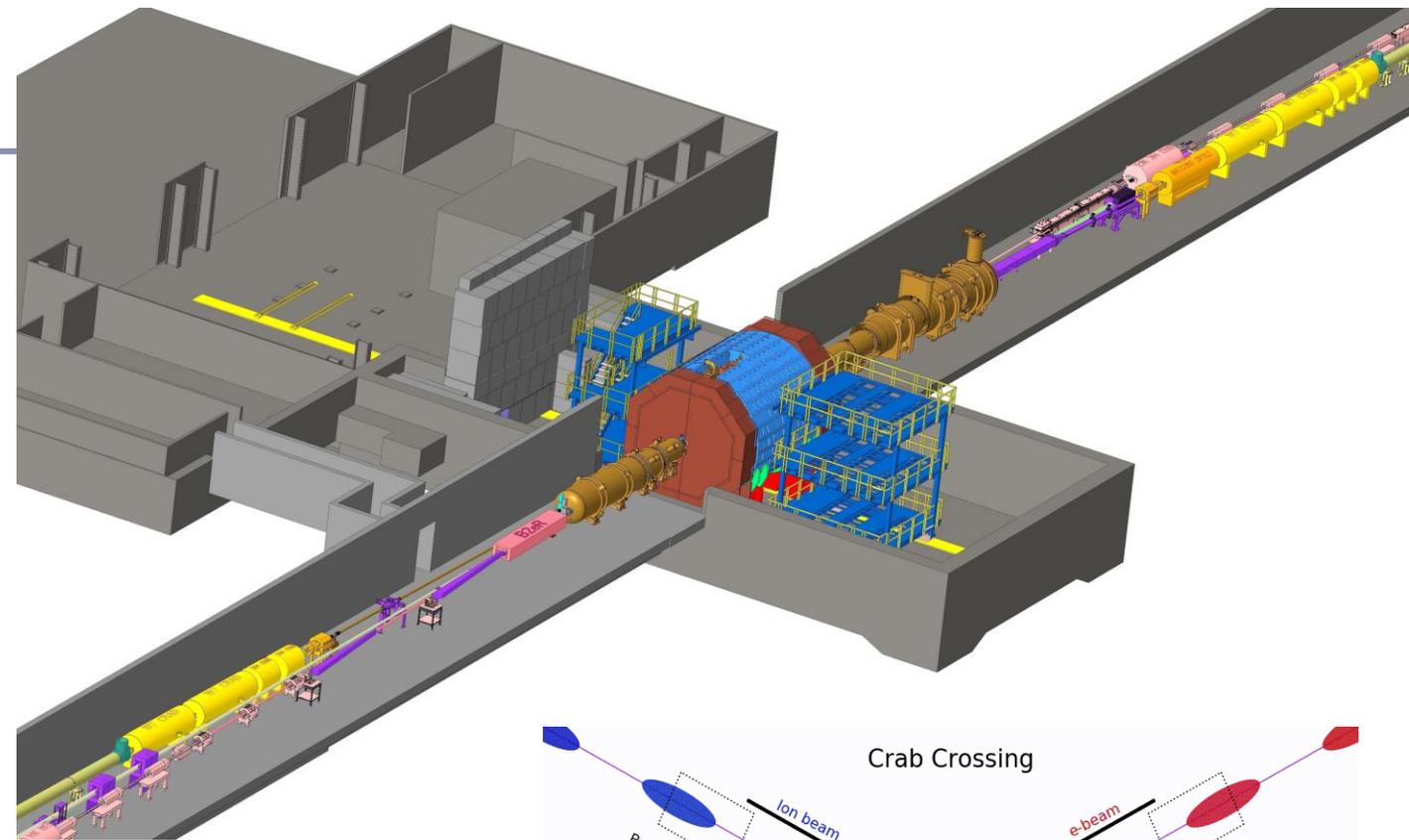
# EIC IR Layout

## High Luminosity:

- 25 mrad crossing angle
- Small  $\beta^*$  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”

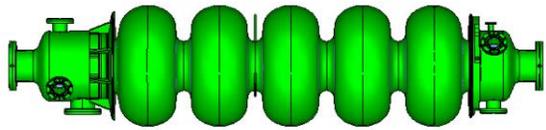




# Electron Injector

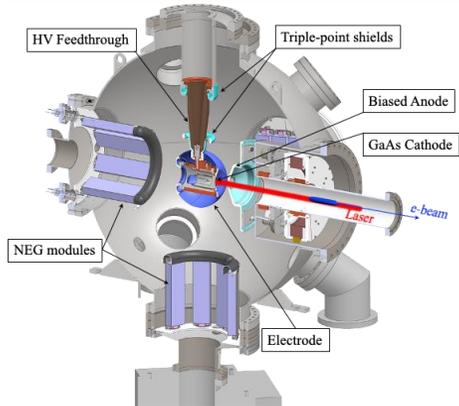
Concept modeled after the ANL APS-U injector

**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 SRF Cavity, 591 MHz

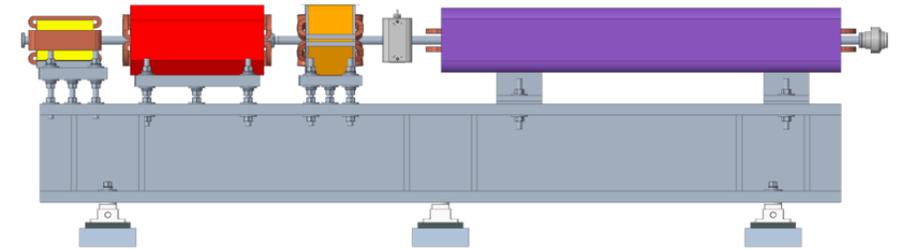
RESEARCH ARTICLE | JUNE 17 2024  
**High-intensity polarized electron gun featuring distributed Bragg reflector GaAs photocathode**  
Erdong Wang, Omer Rahman, Jyoti Biswas, John Skarika, Patrick Inacker, Wei Liu, Ronald Napoli, Matthew Paniccia



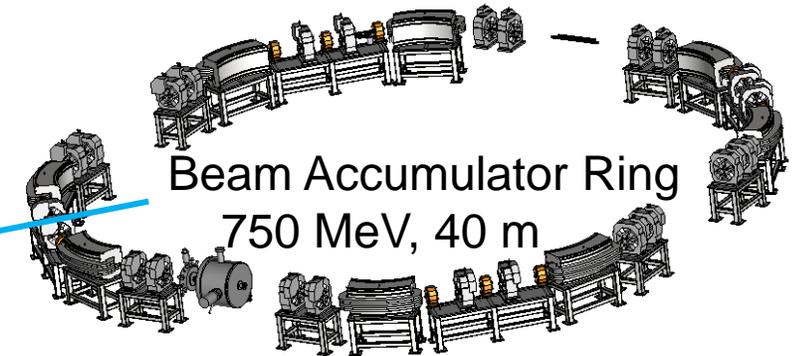
Polarized Electron Gun  
1-nC, 30 Hz



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



RCS magnet assembly  
Vacuum chamber: stainless steel, copper coated (50  $\mu$ m)



Beam Accumulator Ring  
750 MeV, 40 m

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

# Present EIC Concept (2025)

## Ultimate EIC Performance Parameters:

- High Luminosity:  $L = 10^{33} - 10^{34} \text{cm}^{-2}\text{sec}^{-1}$
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range:  $E_{\text{cm}} = 28 - 140 \text{ GeV}$
- 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

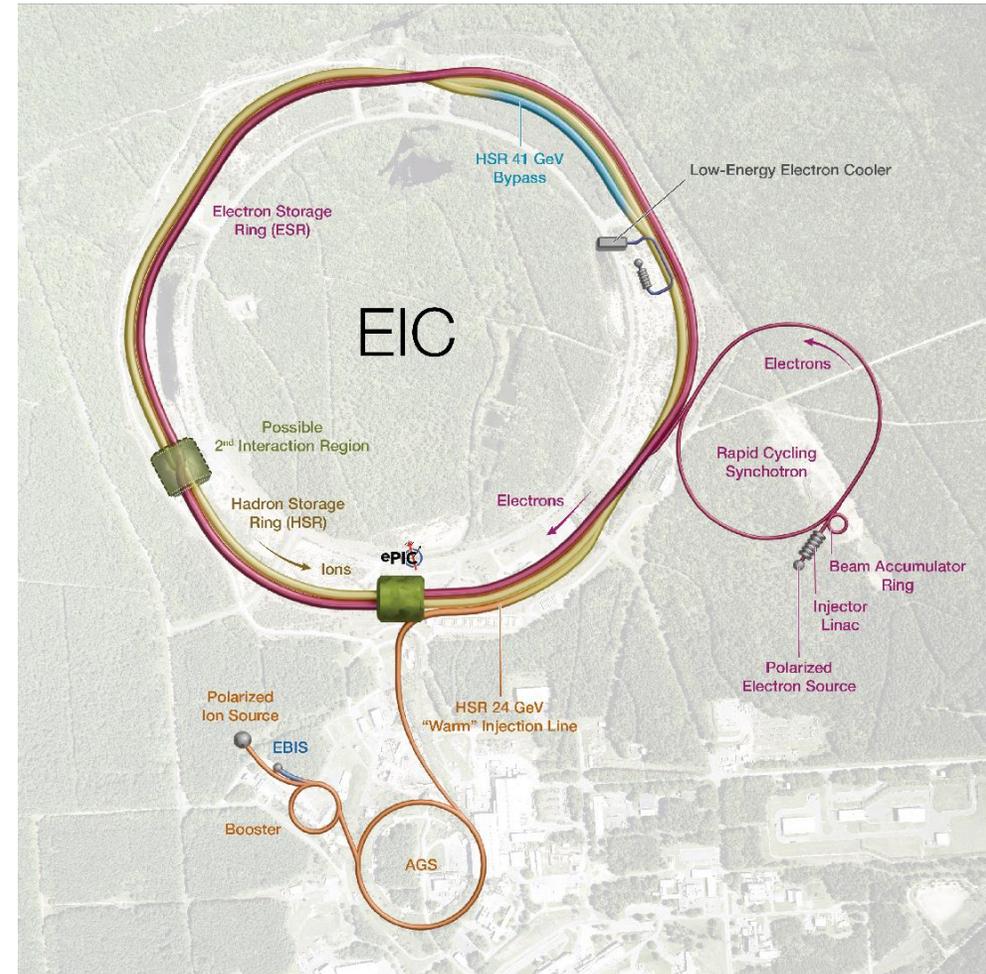
**NEW** Electron Storage Ring (5 GeV – 18 GeV) – ESR

**NEW** Interaction Region(s) – IR

**NEW** Hadron Cooling System

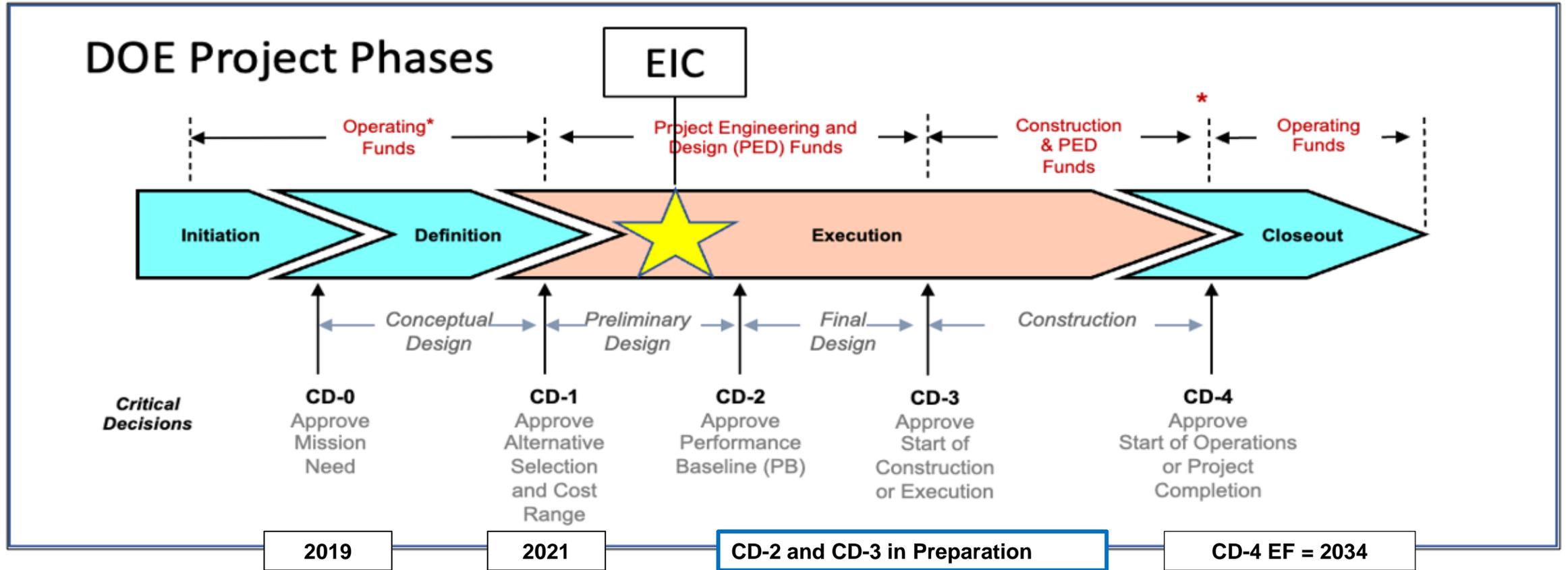
Electron-Ion Collider

Oct 27, 2025



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

# EIC Project: Critical Decisions and Plans



- CD-3A, Long-Lead Procurement, approved March 2024. Excellent use of IRA funding.
- CD-3B, Long-Lead Procurement, approval planned for 2025.

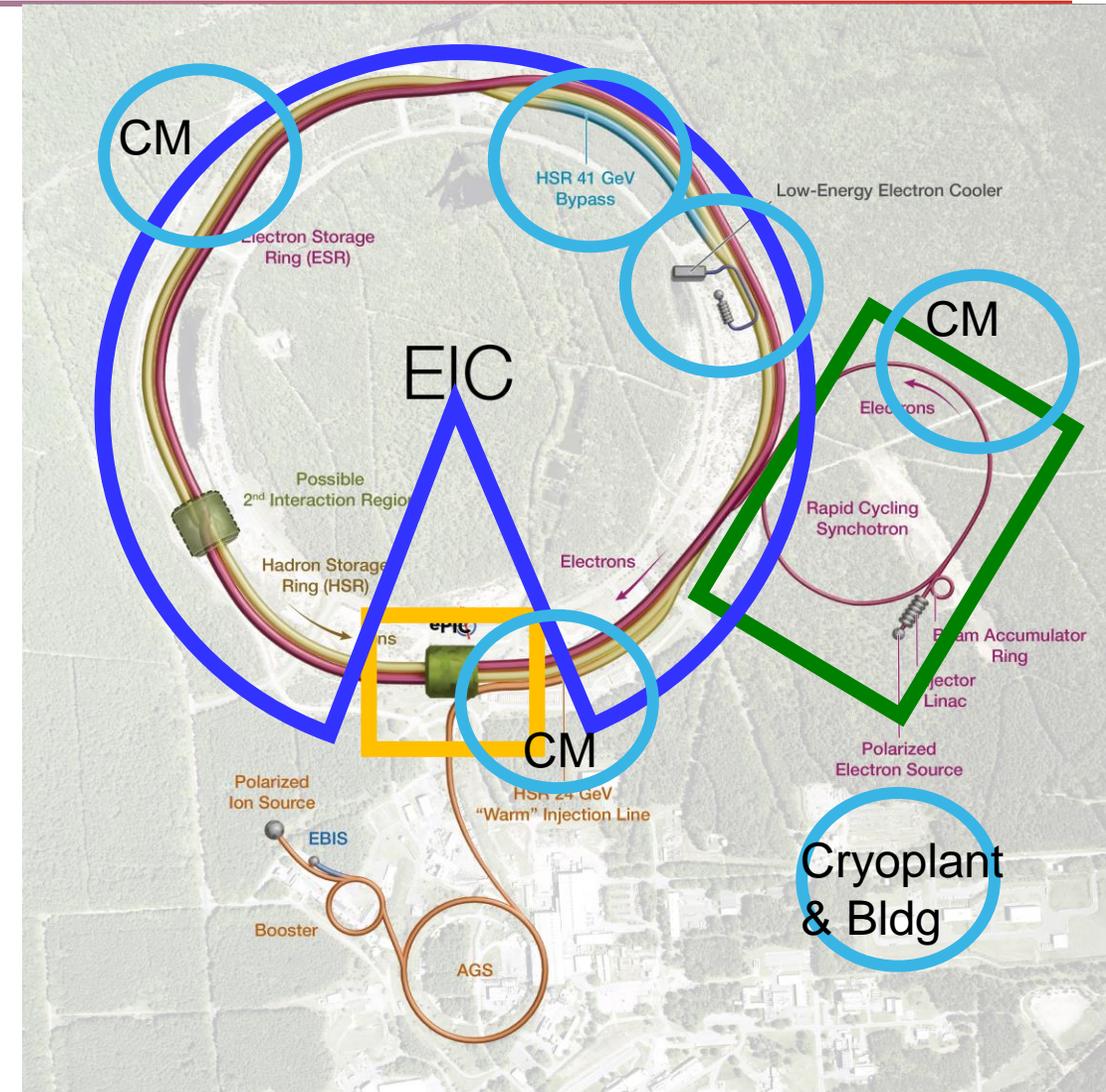
# Subproject Strategy

Subproject strategy follows the maturity status

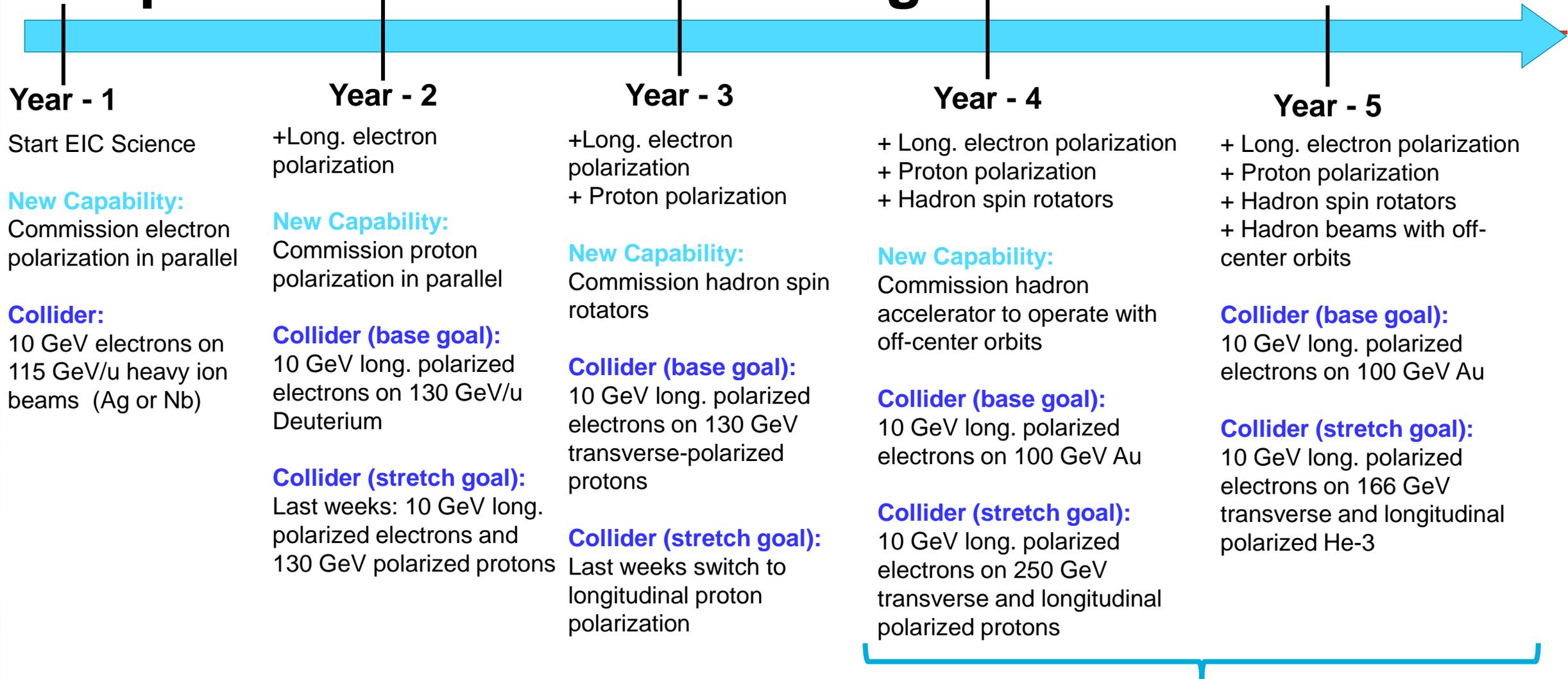
- Accelerator Storage Rings (lowest risk)
  - Detector
  - IR
  - Electron Injector
- • **Start Science Program**
- Energy and Luminosity Ramp-up
  - Integrated Project Office and Global Commissioning

Subprojects minimize dependencies, create well-defined interfaces, and well-defined physical boundaries.

The roll-up of subproject scope progressively elaborate a complete EIC facility.



# Proposal for EIC Science Program in the First Years



Time to construct the ELR subproject

# Strong Support from Partners & Collaborators

- **New York State** committed **\$100M** toward construction of EIC buildings and infrastructure.
- **EIC Accelerator Collaboration** kicked off at IPAC'24 with over 150 participants expressing interest in contributing to the global EIC effort.
- **UK** announced £58 million (**\$75M**) for the EIC.



- **EIC Resource Review Board** Meetings in Rome in May 2024 and at BNL in Oct. 2024. Strong participation from **Canada, Czech Republic, France, India, Israel, Italy, Japan, Poland, South Korea, United Kingdom, and Taiwan**. Recent meeting held in Prague in June 2025.

**In-kind contribution goals represent ~30% of the Detector and ~5% of the Accelerator**

# Summary

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- 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.
- **All EIC design elements are progressing well!**
- **Some project scope** is well developed, designs are mature, **ready to be executed as Long-lead procurements**
  - **Implementing sub-projects as our scope delivery strategy**
- We made several project design decisions to increase the design maturity and decrease risks.
  - There is no change to the current preliminary performance parameters and no change to the EIC cost objective.
- **We understand what we need to build in order to deliver the EIC!**