Electron Ion Collider status: design and construction

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FCC Week 2024

Electron-Ion Collider

EIC Science Highlights

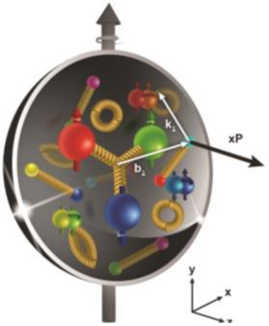
SPIN is one of the fundamental properties of matter.
All elementary particles, but the Higgs carry spin.
Spin cannot be explained by a static picture of the proton
It is the interplay between the intrinsic properties and interactions of quarks and gluons

The EIC will unravel the different contribution from the quarks, gluons and orbital angular momentum.

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

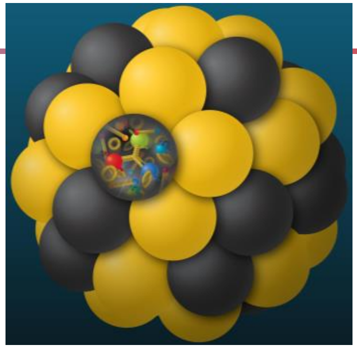
Atom: Binding/Mass = 0.00000001
Nucleus: Binding/Mass = 0.01
Proton: Binding/Mass = 100

For the proton the EIC will determine an important term contributing to the proton mass, the so-called “QCD trace anomaly



How are the quarks and gluon distributed in space and momentum inside the nucleon & nuclei?

How do the nucleon properties emerge from them and their interactions?
How can we understand their dynamical origin in QCD?
What is the relation to Confinement

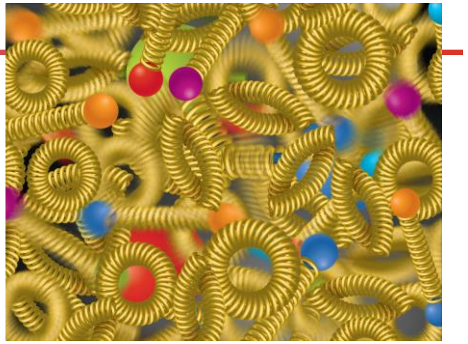


Is the structure of a free and bound nucleon the same?

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

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

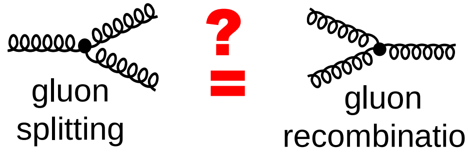
How do the quark-gluon interactions create nuclear binding?



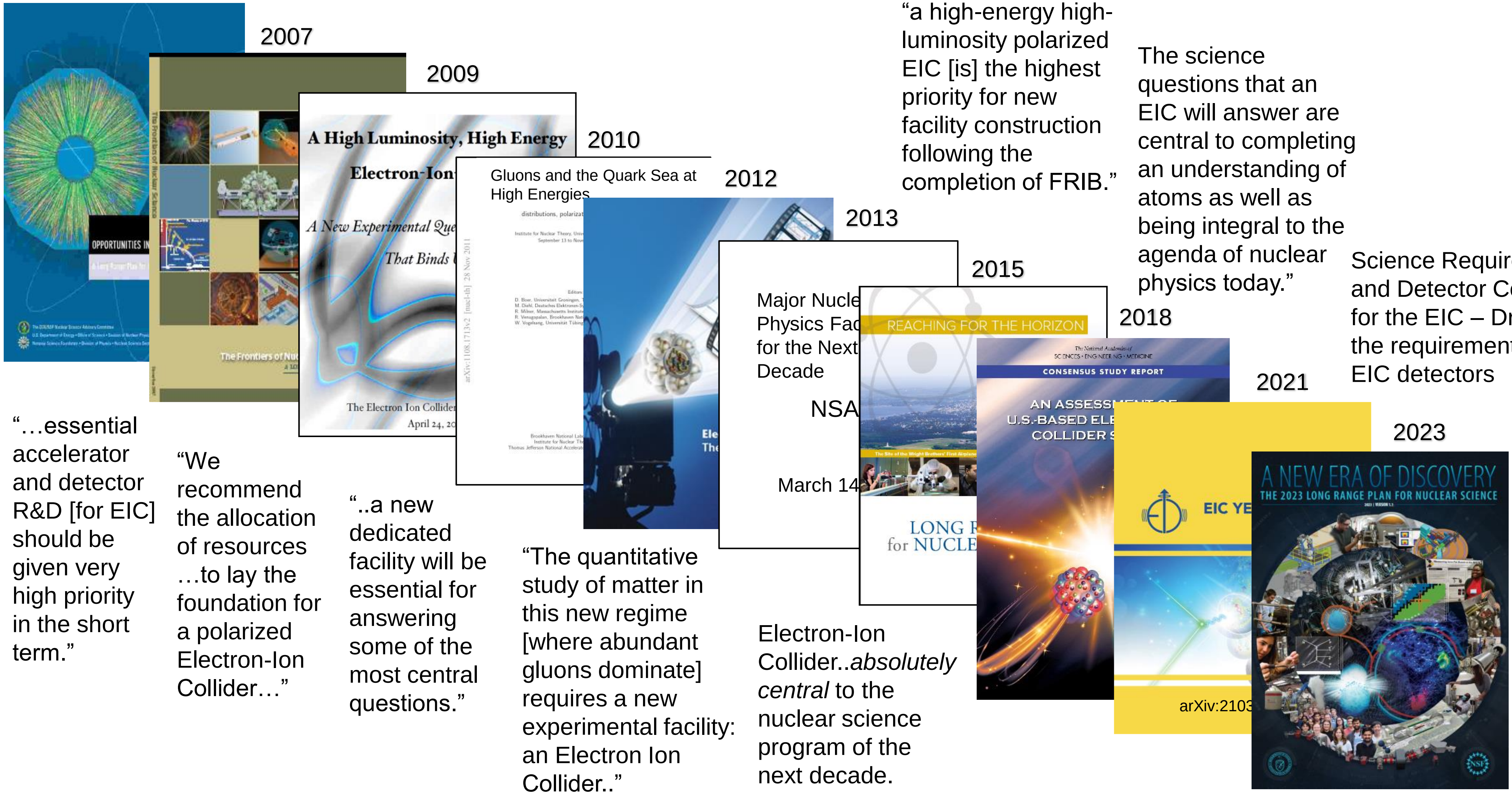
How many gluons can fit in a proton?

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

What happens to the gluon density in nuclei? Does it saturate at high energy?



The Scientific Foundation for an EIC was Built Over Two Decades



2002

2007

2009

2010

2012

2013

2015

2018

2021

2023

"…essential accelerator and detector R&D [for EIC] should be given very high priority in the short term."

"We recommend the allocation of resources …to lay the foundation for a polarized Electron-Ion Collider…"

"..a new dedicated facility will be essential for answering some of the most central questions."

"The quantitative study of matter in this new regime [where abundant gluons dominate] requires a new experimental facility: an Electron Ion Collider.."

Electron-Ion Collider..*absolutely central* to the nuclear science program of the next decade.

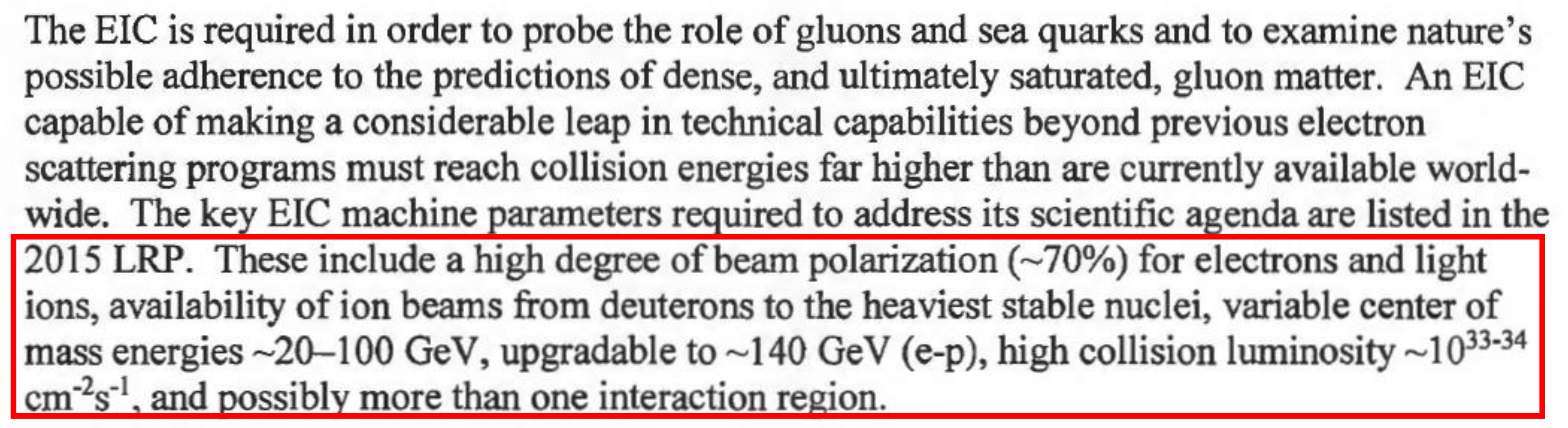
"a high-energy high-luminosity polarized EIC [is] the highest priority for new facility construction following the completion of FRIB."

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."

Science Requirements and Detector Concepts for the EIC – Drives the requirements of EIC detectors

We recommend the expeditious completion of the EIC as the highest priority for facility construction.

The DOE CD0 Mission-Need 2019



The EIC is required in order to probe the role of gluons and sea quarks and to examine nature's possible adherence to the predictions of dense, and ultimately saturated, gluon matter. An EIC capable of making a considerable leap in technical capabilities beyond previous electron scattering programs must reach collision energies far higher than are currently available world-wide. The key EIC machine parameters required to address its scientific agenda are listed in the 2015 LRP. These include a high degree of beam polarization (~70%) for electrons and light ions, availability of ion beams from deuterons to the heaviest stable nuclei, variable center of mass energies ~20–100 GeV, upgradable to ~140 GeV (e-p), high collision luminosity ~$10^{33\text{-}34}$ cm^{-2}s^{-1}, and possibly more than one interaction region.

$$E_{COM} \approx 2\sqrt{E_e E_h}$$

$$E_e = 5\text{ GeV} \quad E_p = 40\text{ GeV} \quad E_{COM} \approx 28\text{ GeV}$$

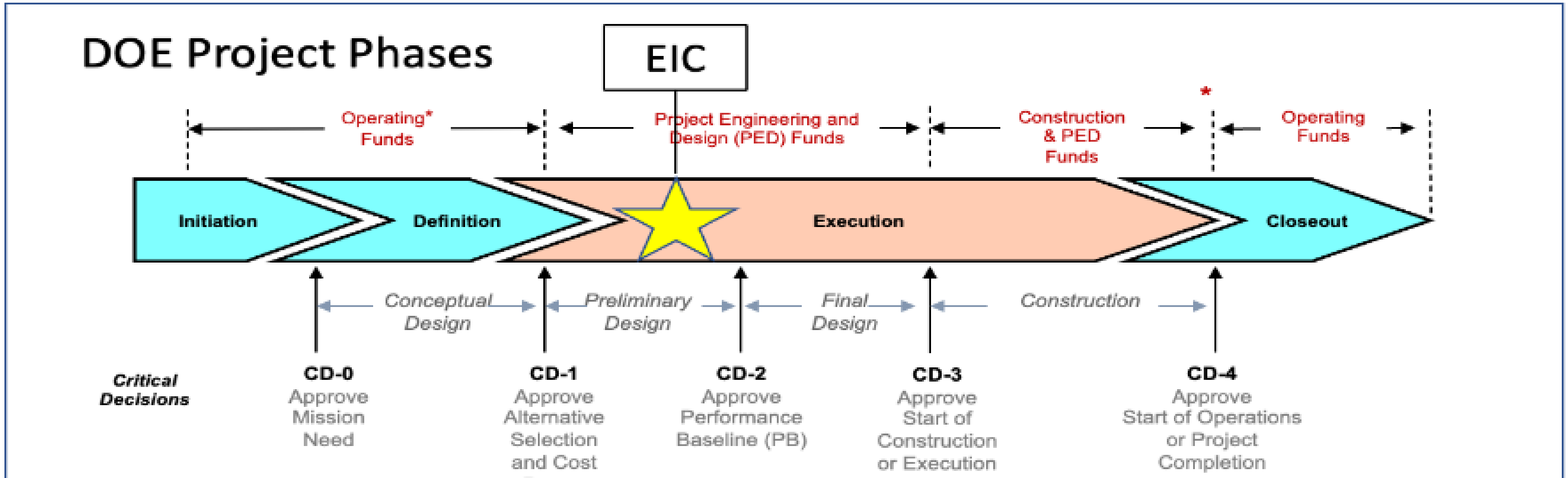
$$E_e = 5\text{ GeV} \quad E_p = 100\text{ GeV} \quad E_{COM} \approx 45\text{ GeV}$$

$$E_e = 10\text{ GeV} \quad E_p = 275\text{ GeV} \quad E_{COM} \approx 100\text{ GeV}$$

$$E_e = 18\text{ GeV} \quad E_p = 275\text{ GeV} \quad E_{COM} \approx 140\text{ GeV}$$

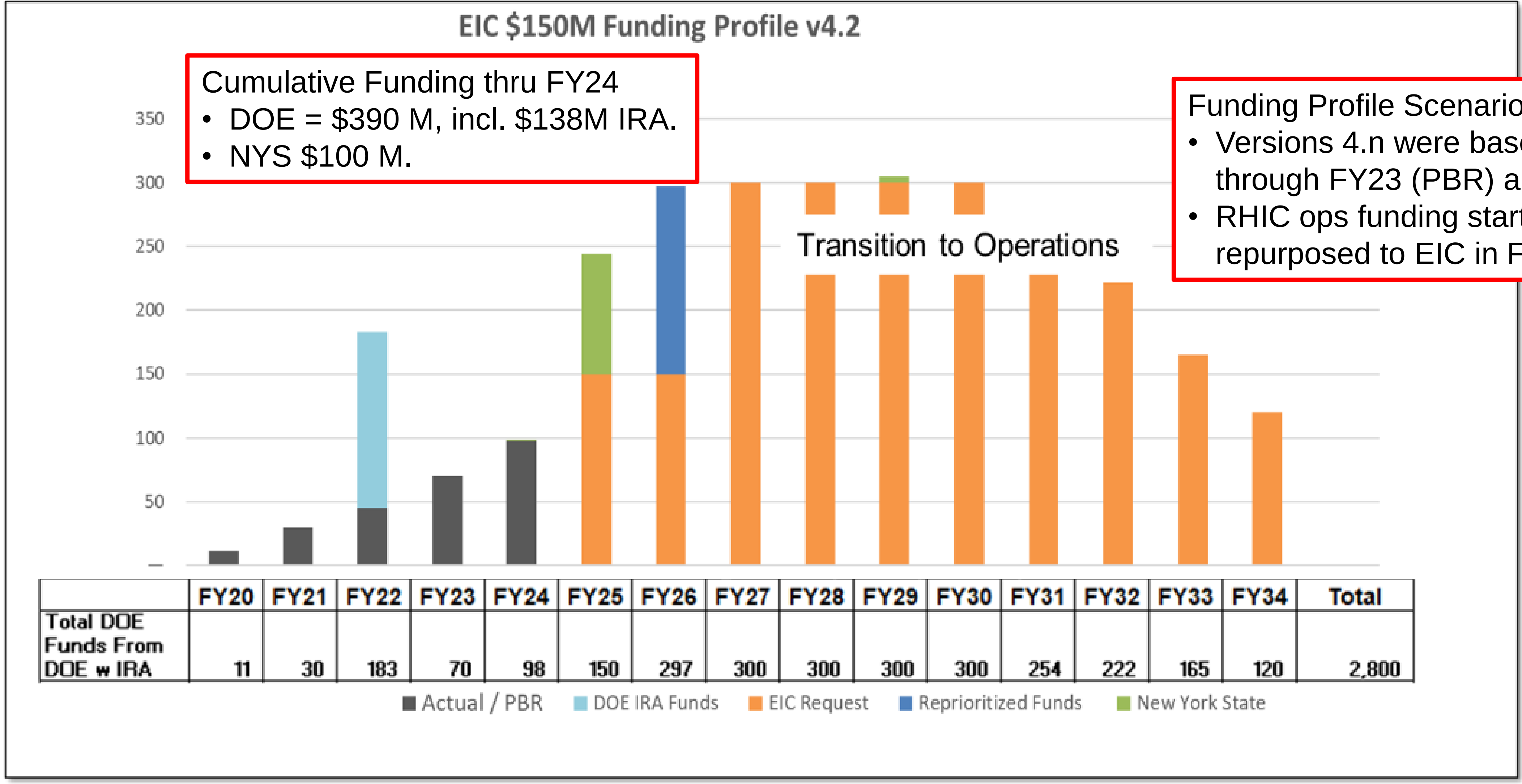
EIC Project Critical Decisions and Plans

CD-0, Mission Need Approved	December 2019
DOE Site Selection Announced	January 2020
CD-1, Alternative Selection and Cost Range Approved	June 2021
CD-3A, Long-Lead Procurement Approved	**March 2024**
CD-3B, Long-Lead Procurement Planned Approval	**March 2025**
CD-2/3, Performance Baseline/Construction Start Plan	**End 2025**



DOE Independent Project Review for CD-3B and Project Status on Jan 7-9, 2025.

Reference Funding Profile Prior to 2025 PBR



	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	FY31	FY32	FY33	FY34	Total
Total DOE Funds From DOE w IRA	11	30	183	70	98	150	297	300	300	300	300	254	222	165	120	2,800

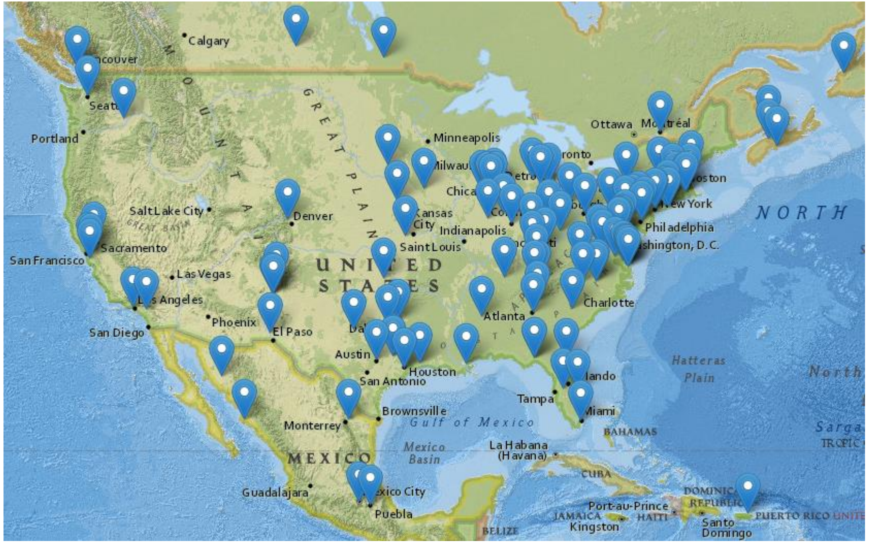
Cumulative Funding thru FY24
- DOE = $390 M, incl. $138M IRA.
- NYS $100 M.

Funding Profile Scenarios
- Versions 4.n were based on actuals through FY23 (PBR) and forecasts.
- RHIC ops funding starts to be repurposed to EIC in FY26.

The EIC Users Group – a vibrant community

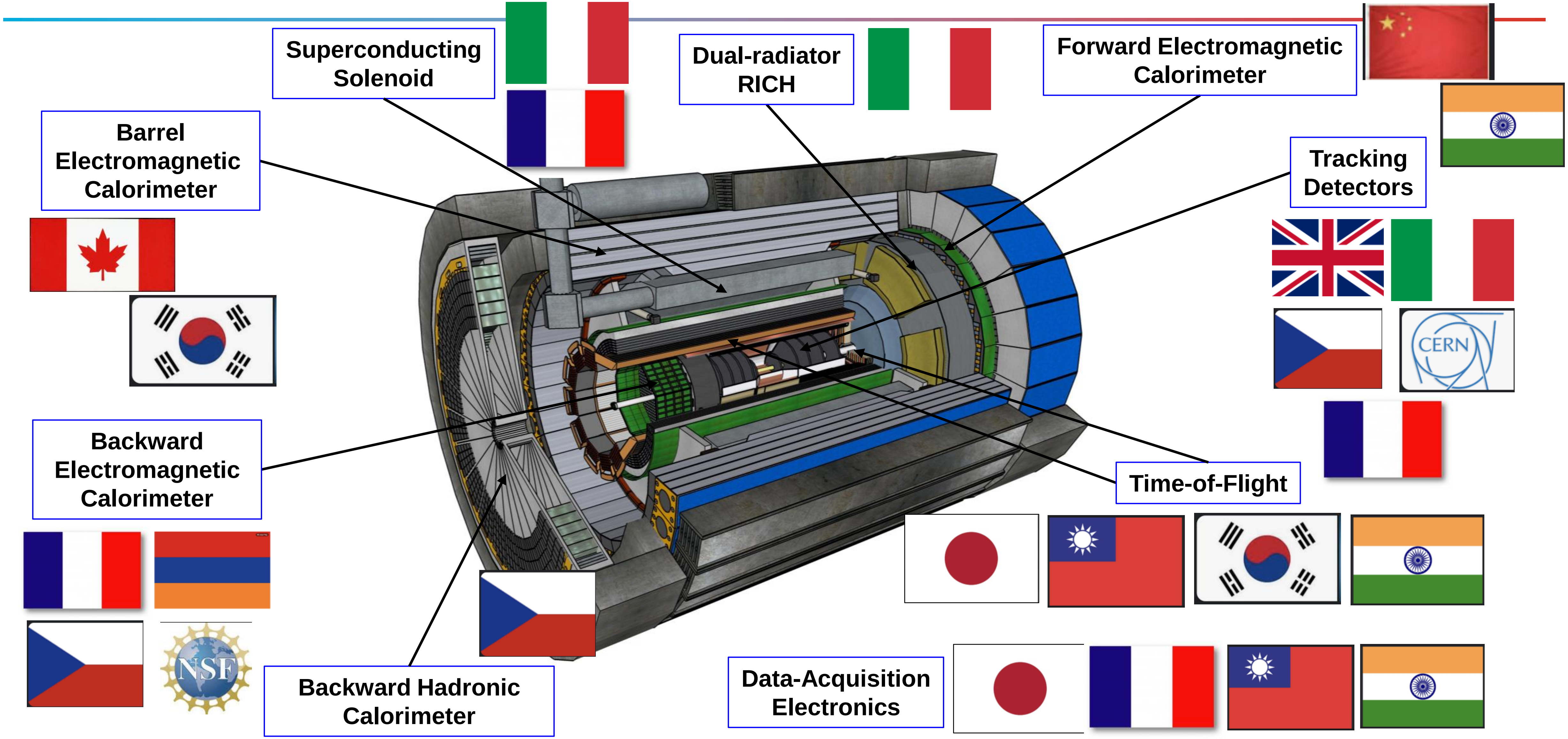
- Nine national labs and 99 U.S. universities and institutions, as well as 139 international partners, will participate in the EIC.

- The EIC Users Group has been growing rapidly—more than 1,400 scientists from more than 296 institutions in 40 countries around the world.
- UK EIC funding was announced on Mar 27, 2024
- Ongoing discussions with France, Italy, Canada, Brazil, Korea, Japan, CERN, and others



The EIC will maintain U.S. leadership at the frontiers of nuclear physics and accelerator science technology for decades to come.

ePIC detector collaboration



Superconducting Solenoid

Dual-radiator RICH

Forward Electromagnetic Calorimeter

Barrel Electromagnetic Calorimeter

Tracking Detectors

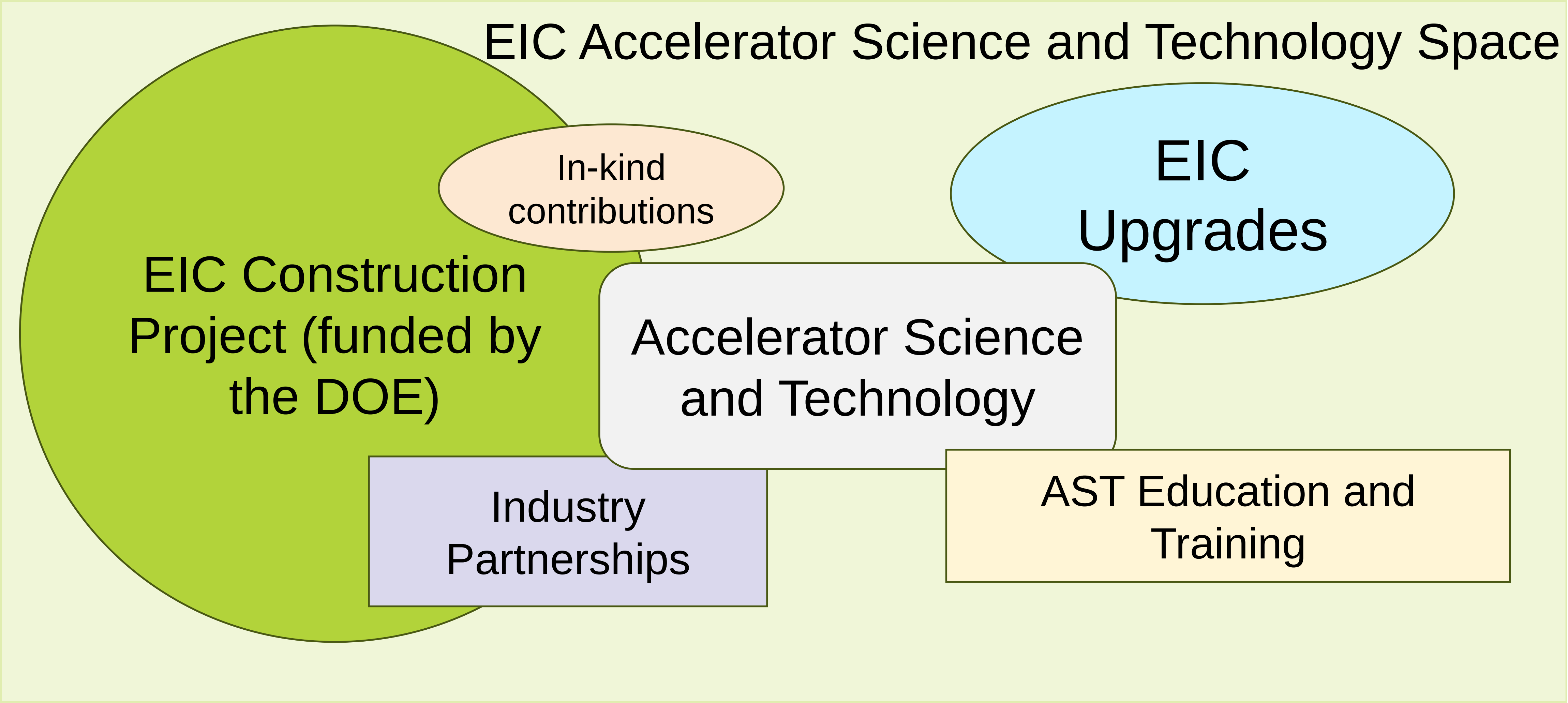
Backward Electromagnetic Calorimeter

Time-of-Flight

Backward Hadronic Calorimeter

Data-Acquisition Electronics

EIC Accelerator Collaboration?



EIC Accelerator Science and Technology Space

In-kind contributions

EIC Upgrades

EIC Construction Project (funded by the DOE)

Accelerator Science and Technology

Industry Partnerships

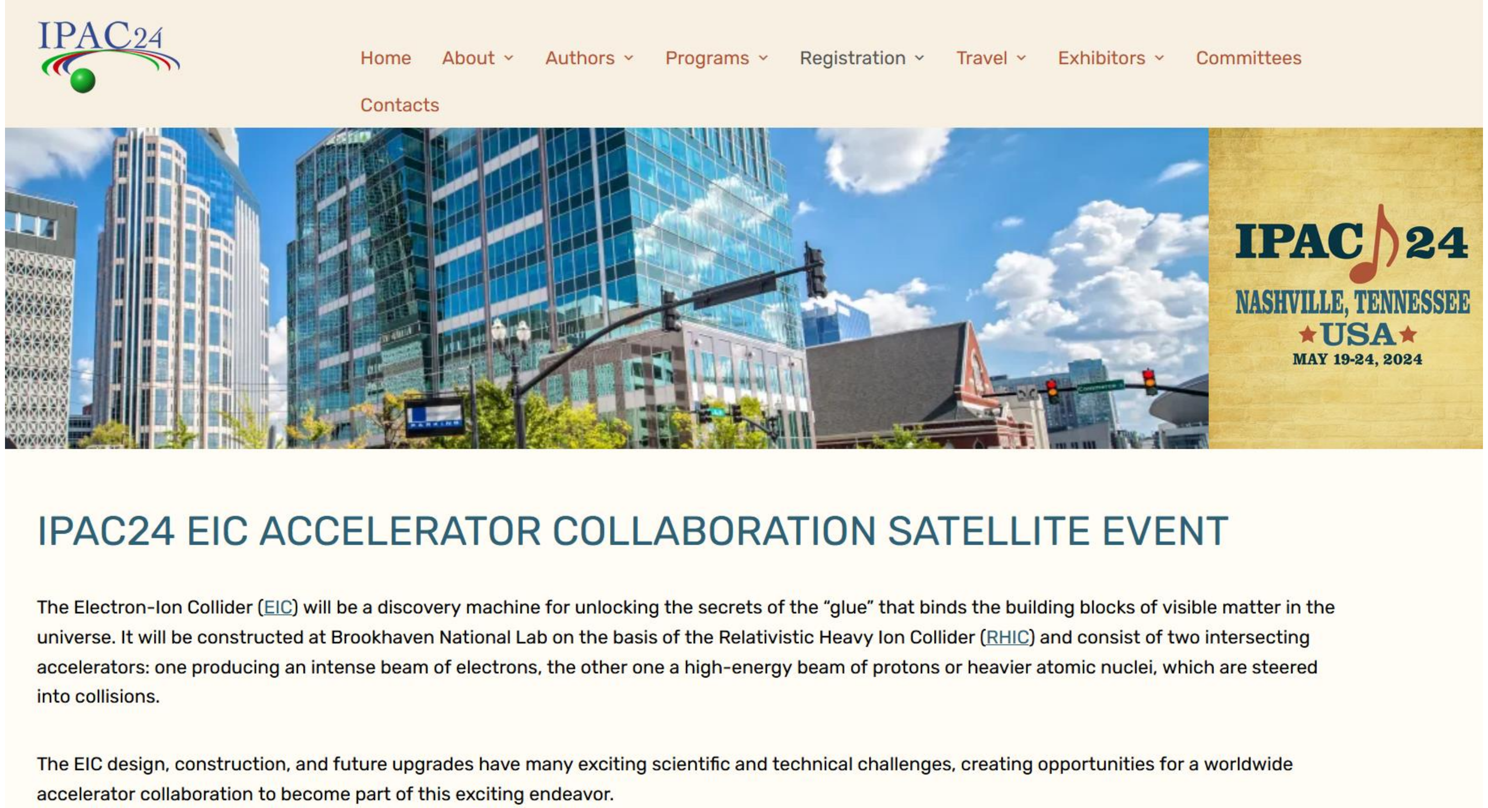
AST Education and Training

EIC Accelerator Collaboration kick-off mtg@IPAC

- Our proposal and our goal is to form an EIC Accelerator Collaboration with the following missions:
  - Provide a discussion forum and a collaboration vehicle for the EIC accelerator-related working groups and topics;
  - Identify and create opportunities for US institutions to contribute to the EIC construction project;
  - Identify and create opportunities for In-Kind contributions to the EIC project and to future upgrades;
  - Identify and develop future EIC facility upgrades;
  - Identify and provide accelerator research and development topics and opportunities;
  - Communicate to EIC stakeholders on behalf of the accelerator R&D community;
  - Communicate to various long-range planning panels.

- The EIC Accelerator Collaboration will enhance the long-term evolution and performance of the EIC, and should also help us construct the EIC more efficiently.

EIC Accelerator Collaboration @ IPAC



IPAC24 EIC ACCELERATOR COLLABORATION SATELLITE EVENT

The Electron-Ion Collider (EIC) will be a discovery machine for unlocking the secrets of the "glue" that binds the building blocks of visible matter in the universe. It will be constructed at Brookhaven National Lab on the basis of the Relativistic Heavy Ion Collider (RHIC) and consist of two intersecting accelerators: one producing an intense beam of electrons, the other one a high-energy beam of protons or heavier atomic nuclei, which are steered into collisions.

The EIC design, construction, and future upgrades have many exciting scientific and technical challenges, creating opportunities for a worldwide accelerator collaboration to become part of this exciting endeavor.

https://ipac24.org/ipac24-eic-collaboration-satellite-event/

https://indico.jlab.org/event/834/

Tuesday 21 May 2024,
18:00 → 20:30

18:00 → 18:05
Welcome, JoAnne Hewett (BNL)
18:05 → 18:30
Electron-Ion Collider Status
Sergei Nagaitsev (BNL)
18:30 → 18:55
EIC Accelerator Collaboration
Carsten Welsch (University of Liverpool/Cockcroft Institute, UK)
18:55 → 19:10
Open Microphone Session
19:10 → 20:30
Networking Reception

EIC Collaboration Working Groups (examples)

As presented at IPAC

1. Beam dynamics, beam optics
2. Beam-beam effects ← Group launched
3. Beam cooling at collisions
4. Beam polarization generation, preservation and diagnostics ← Being launched
5. Second IR
6. EIC commissioning
7. EIC upgrades
8. In-kind accelerator contributions
9. Synergies with other projects (e.g. FCC, MC)

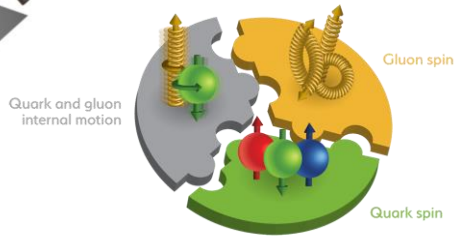
Also suggested: EIC Industrial Forum

If you are interested in these topics, please contact co-chairs of EIC Accelerator Collaboration Andrei Seryi, Jefferson Lab, and Carsten Welsch, Univ. Liverpool, Cockcroft Institute, UK

Accelerator Performance Needs

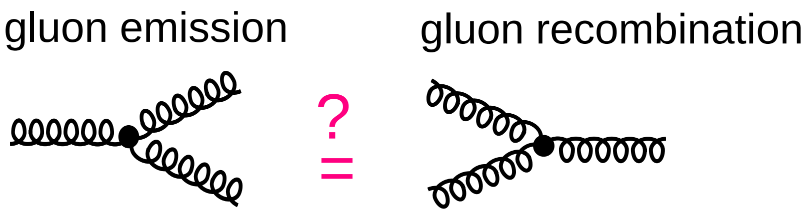
wide center-of-mass energy √s: 20 – 140 GeV :

- ➢ 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

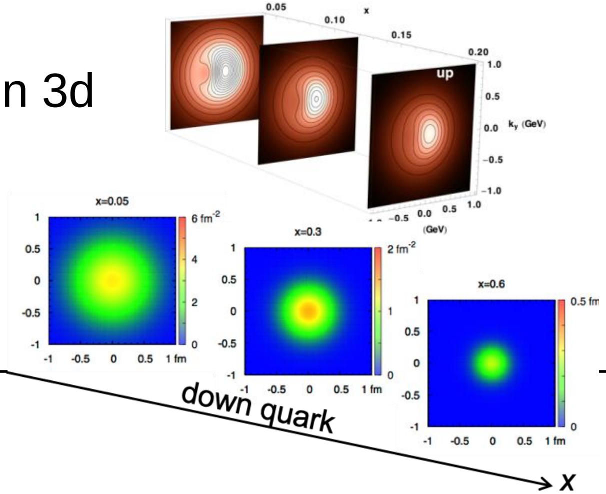


nuclear beams: d to Pb

- ➢ 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

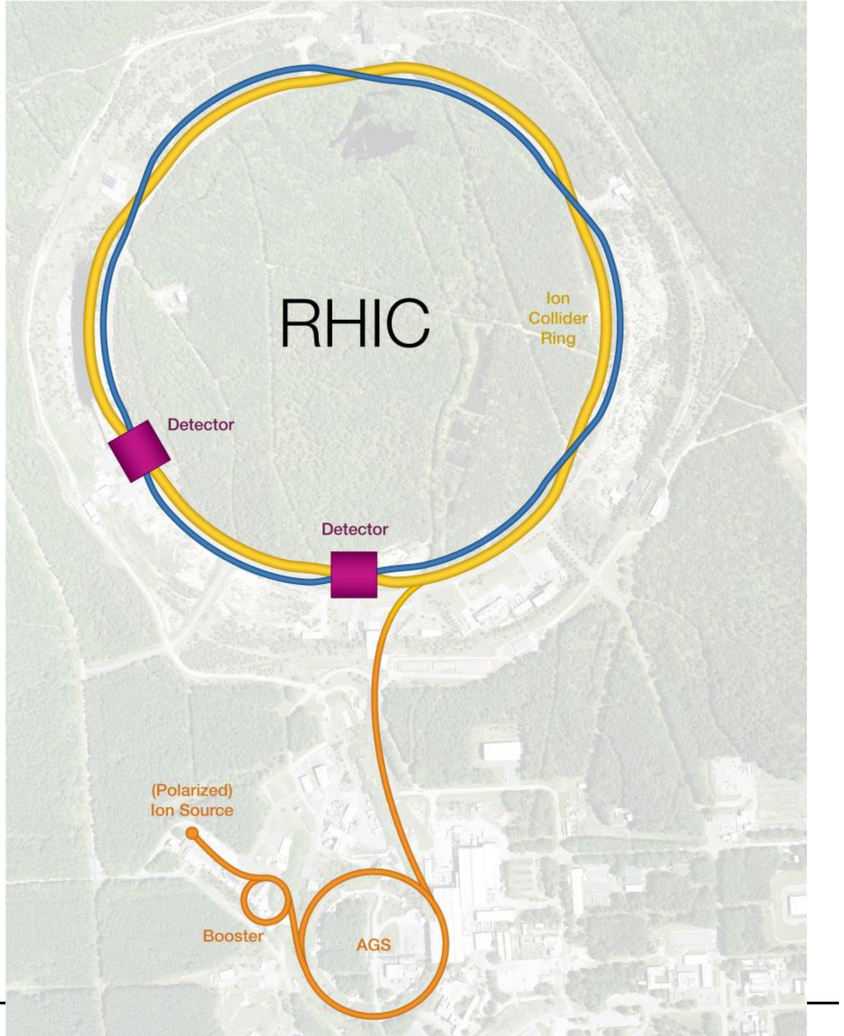
- ➢ spatial imaging of nucleons and nuclei

Relativistic Heavy Ion Collider (RHIC)

- Existing tunnel and infrastructure
- 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 a factor of 44
- 6 interaction regions, 2 detectors
- In operation since 2001; operations will end in 2025

EIC is based on the existing RHIC facility



EIC Accelerator Design Progress

EIC accelerators are based on the **existing, well-performing RHIC**

Hadron storage Ring will reuse RHIC arcs: 40-275 GeV

- Superconducting magnets (existing)
- 1160 bunches, 1A beam current (3x RHIC)
- Bright vertical beam emittance 1.5 nm (“flat beams”)
  - See Phys Rev Lett 132, 205001 (2024)
- Hadron cooling at collisions; pre-cooler at injection
  - Can start science with pre-cooler only.

Electron Storage Ring 5–18 GeV

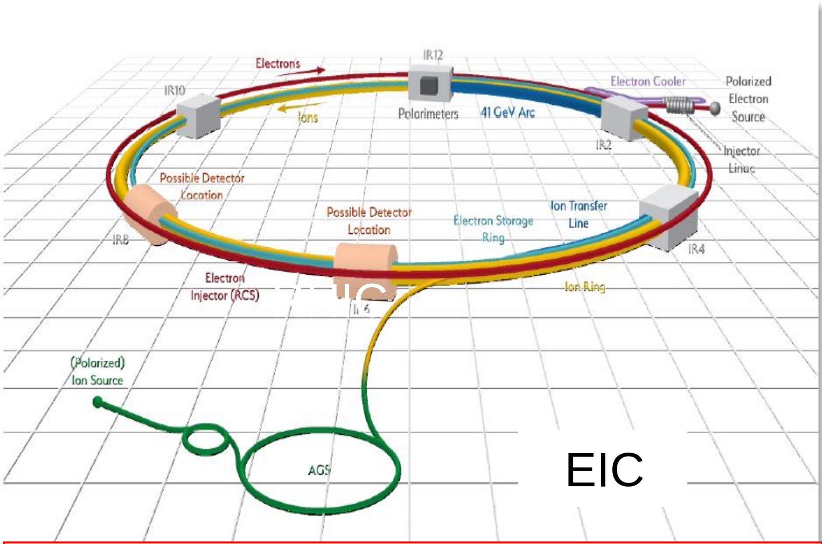
- New electron ring added to the RHIC tunnel;
- Using Synch Light community experience; re-using APS magnets

Electron rapid cycling synchrotron, 1Hz, (0.4 -> 18) GeV

- New electron synchrotron in the RHIC tunnel;
- Presently, this is an area of accelerator design focus;
- Identified several technical risks: low magnetic fields and high bunch charges;
  - Engaged with the NSLS-II team to help mitigate risks, while controlling costs

High luminosity Interaction Region(s) – one IR in the design; 2nd IR is an upgrade

- Superconducting final focus magnets; large crossing angle with crab cavities
- Spin Rotators (longitudinal spin)

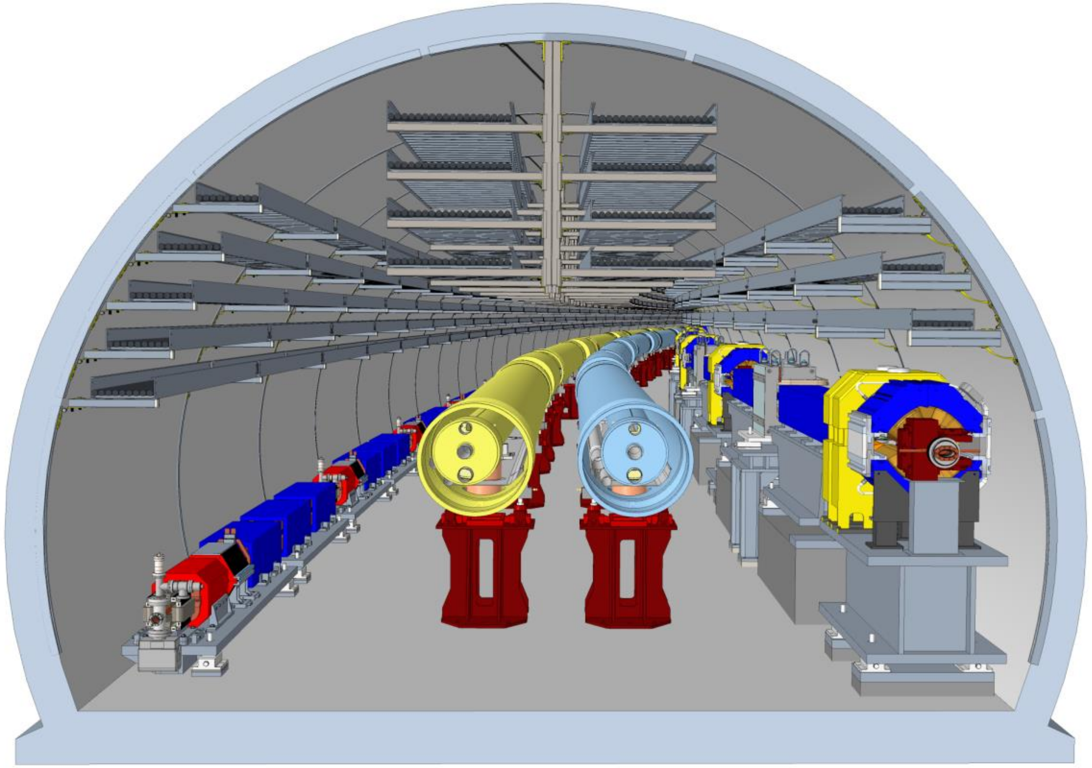


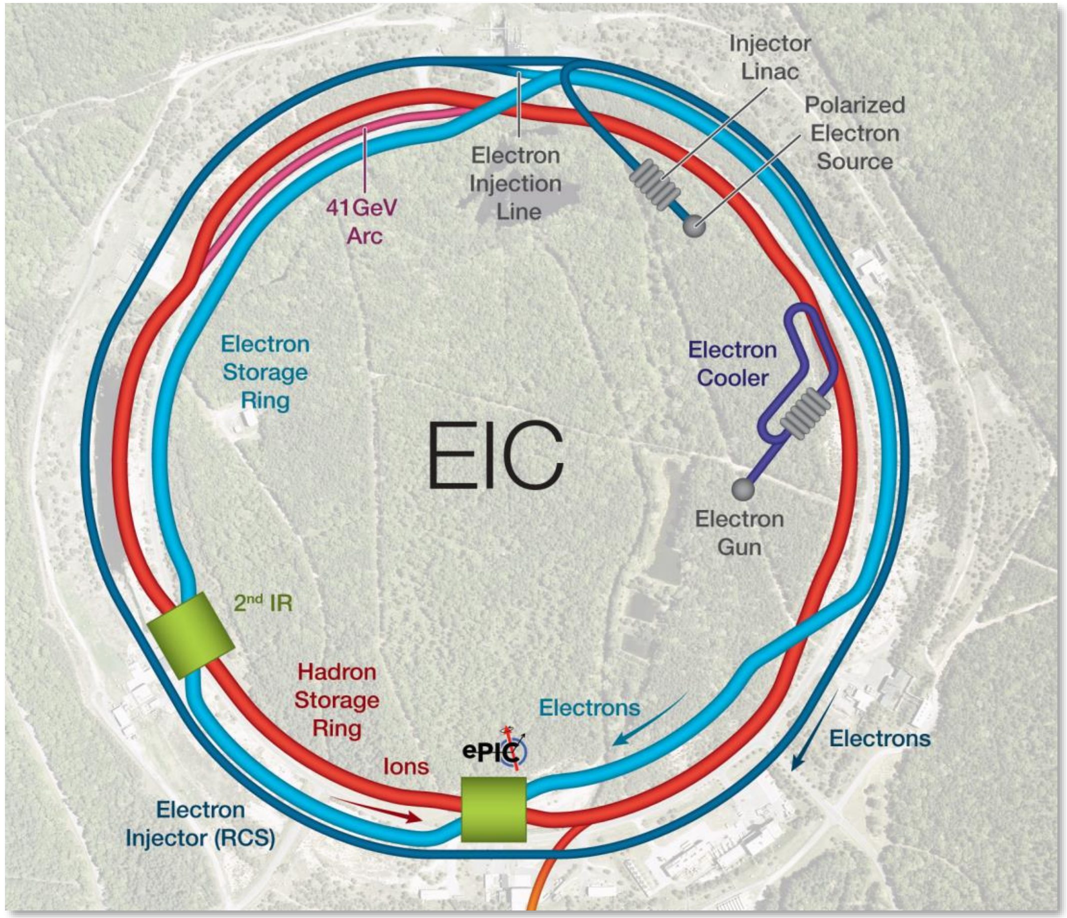
Many areas for partner contributions and collaborations exist. Engaged with France, UK, Canada, Italy, CERN

EIC Accelerator Design Challenges

- Very high beam currents (2.5A e, 1A h)
- Very high bunch intensities ($1.7 \cdot 10^{11}$e (28 nC), $1 \cdot 10^{11}$ p (16 nC))
- Strong beam-beam interaction (ξ_e=0.1, ξ_p =0.015)
- 25 mrad crossing angle, compensated by crab cavities
- Large center-of-mass energy range that implies operating hadrons with up to 15 mm off-center
- Cu clad and aC coated Beam screen to suppress SEY that causes eddy current problems
- Highly polarized electron and hadron beams, including novel polarized He3+ beams
- Spin matched electron ring beam optics 5 GeV, 10 GeV, 18 GeV
- Electron cooling at injection to create flat beams with flatness being preserved during collisions
- Hadron cooling at collisions to maintain hadron beam brightness
- Challenging dynamic aperture issues
- Complex beam optics in the IRs including detector solenoid coupling compensation, spin rotation
- Maintaining an option for the 2nd IR …

Tunnel View



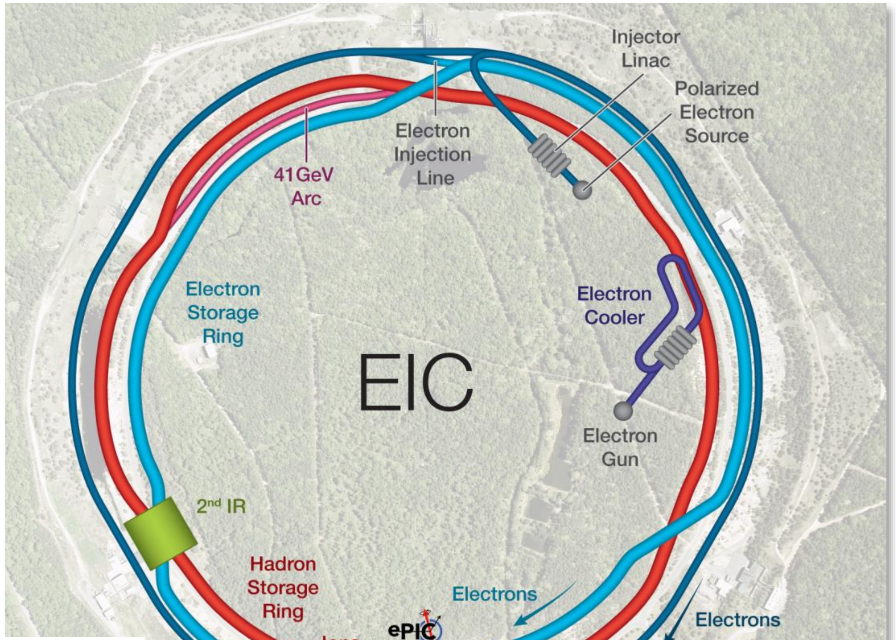

Injector
Linac
Polarized
Electron
Source
Electron
Injection
Line
41GeV
Arc
Electron
Storage
Ring
Electron
Cooler
EIC
Electron
Gun
2nd IR
Hadron
Storage
Ring
Electrons
Electrons
ePIC
Ions
Electron
Injector (RCS)

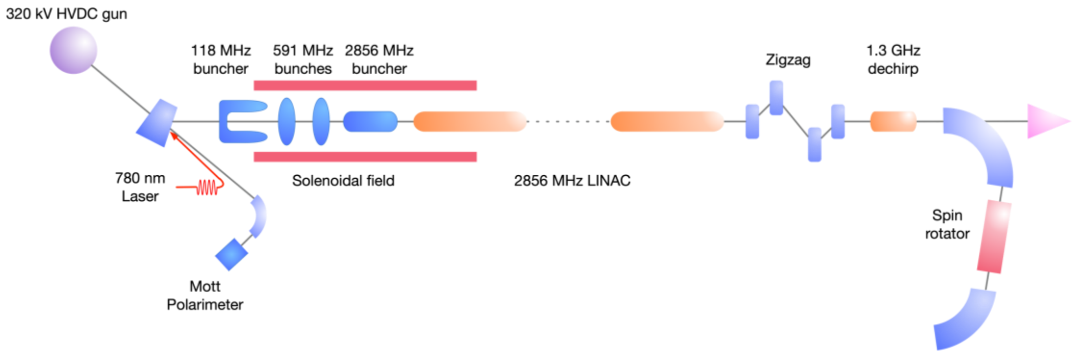
From RHIC to HSR

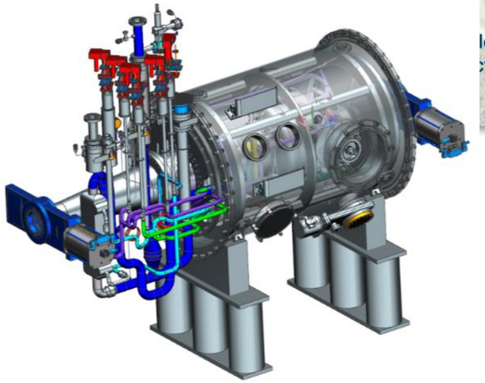
- EIC Hadron Storage Ring (HSR) to be composed of existing arcs of the two RHIC rings (remove unused magnets)
- Insert sleeves coated with copper and amorphous carbon into superconducting magnet beam pipes to improve conductivity and reduce secondary electron yield (-> electron cloud)
- Add hadron cooling to counteract intra-beam scattering
- Add crab cavities, new IR SC magnets

Adding an electron source and a storage ring

- The ESR at the same height as RHIC, tilted by 200 urad around axis through IPs 6 and 8 to simplify cross-overs in IRs 4 and 12
- The RCS is at ~60 cm above tunnel floor, underneath ESR in three arcs.
- The electron source is capable of producing polarized electron bunches of up to 10 nC



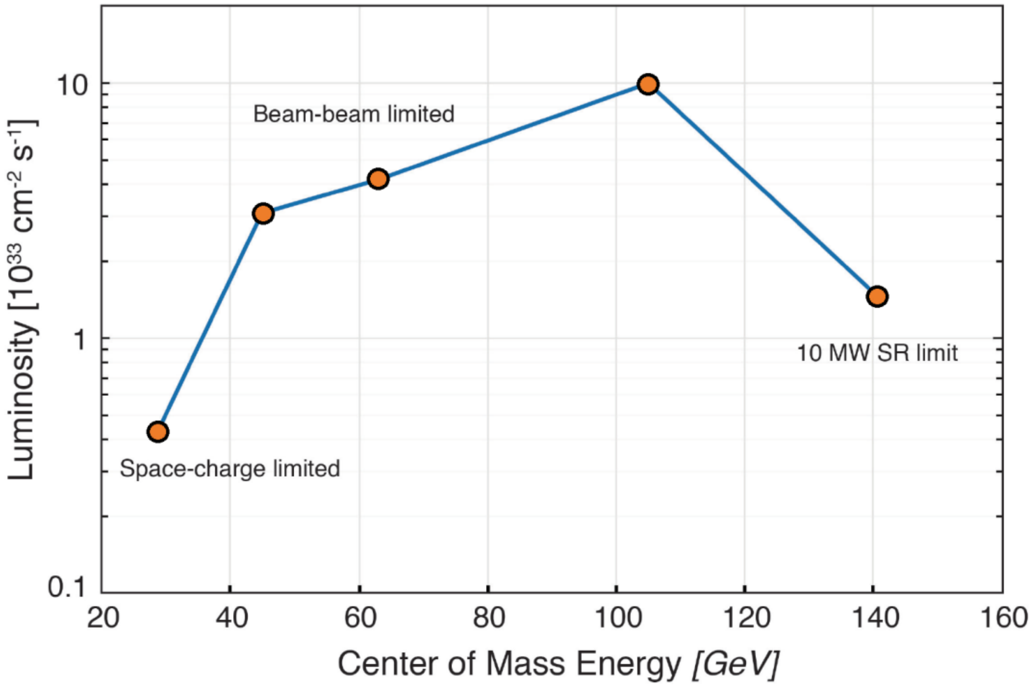




591 MHz Single Cell ESR Cryomodule

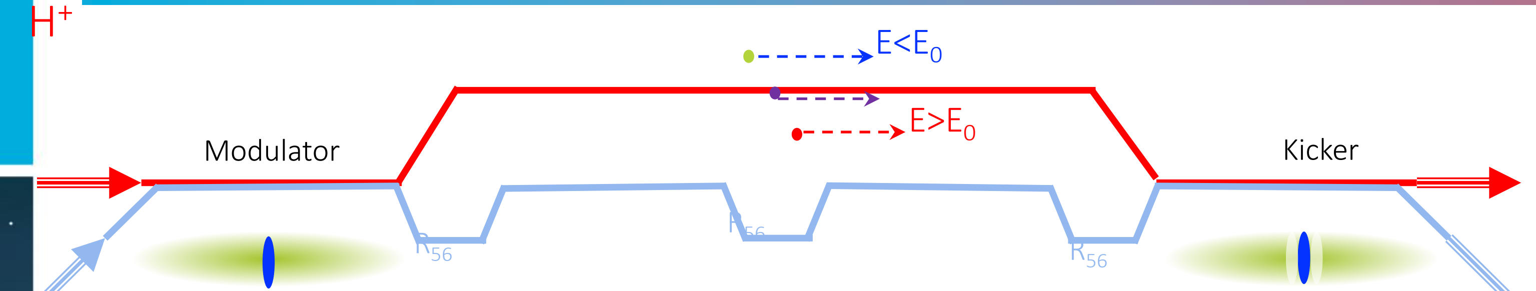
High Luminosity and Hadron Cooling

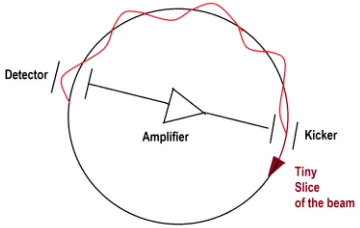
- The luminosity of lepton-hadron colliders in the energy range of the EIC benefits strongly from cooling the hadron’s transverse and longitudinal beam emittance
- IBS longitudinal and transverse(h) growth time is 2-3 hours. Beam-beam growth time(v) is > 5 hours. The cooling time shall be equal to or less than the diffusion growth time from all sources.

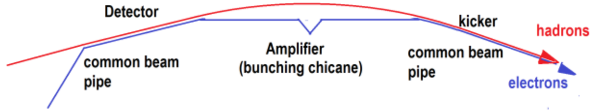


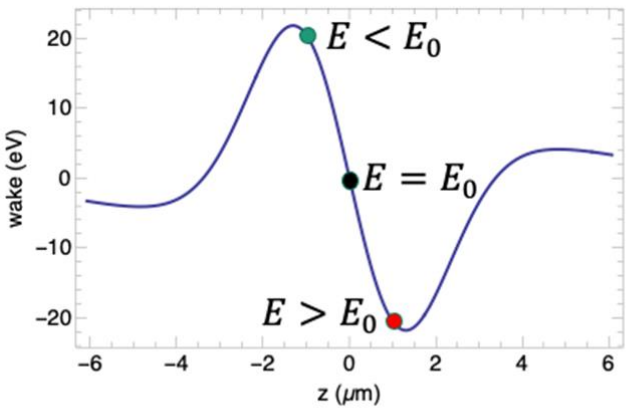
Cooling at collisions is essential for maintaining high integrated luminosity, while precooling is essential for peak luminosity

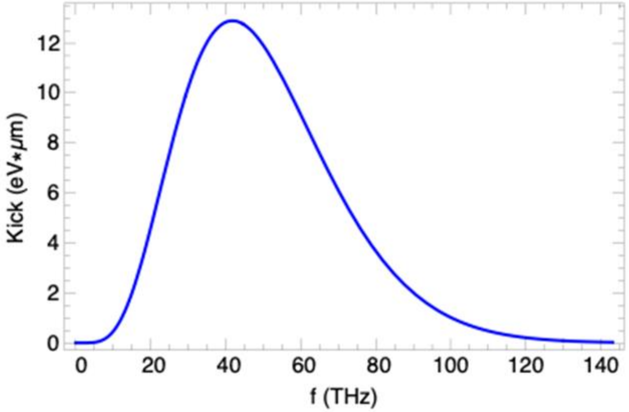
Cooling at collisions (100 GeV & 275 GeV)

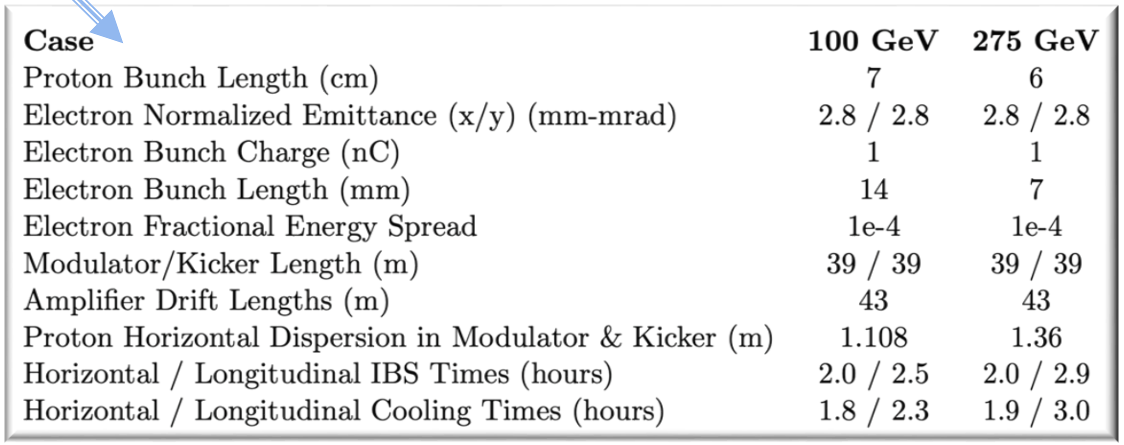










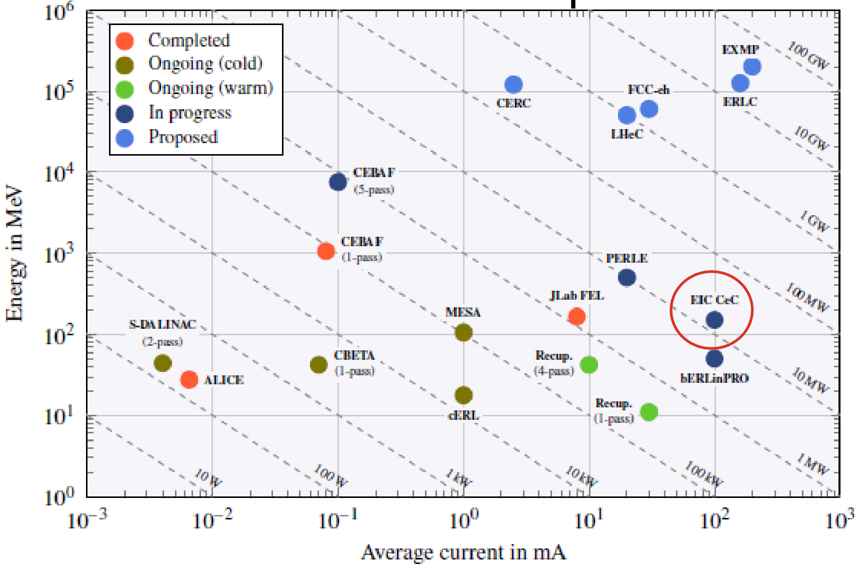


Case	**100 GeV**	**275 GeV**
Proton Bunch Length (cm)	7	6
Electron Normalized Emittance (x/y) (mm-mrad)	2.8 / 2.8	2.8 / 2.8
Electron Bunch Charge (nC)	1	1
Electron Bunch Length (mm)	14	7
Electron Fractional Energy Spread	1e-4	1e-4
Modulator/Kicker Length (m)	39 / 39	39 / 39
Amplifier Drift Lengths (m)	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 is 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.
  - ERL-based, pre-cooling at injection energy can be integrated into strong hadron cooling, sharing many hardware components.

Main challenges of the CEC method

- High-current SCRF ERL
    - https://arxiv.org/abs/2207.02095

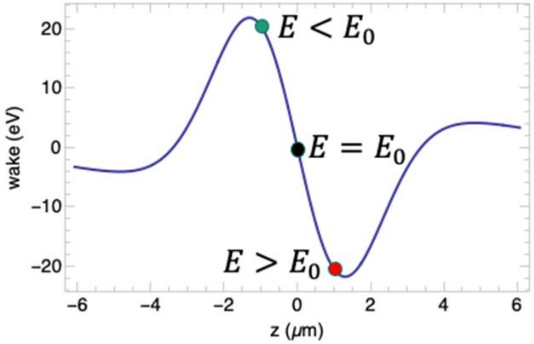


ERL landscape

- Low-noise electron beam

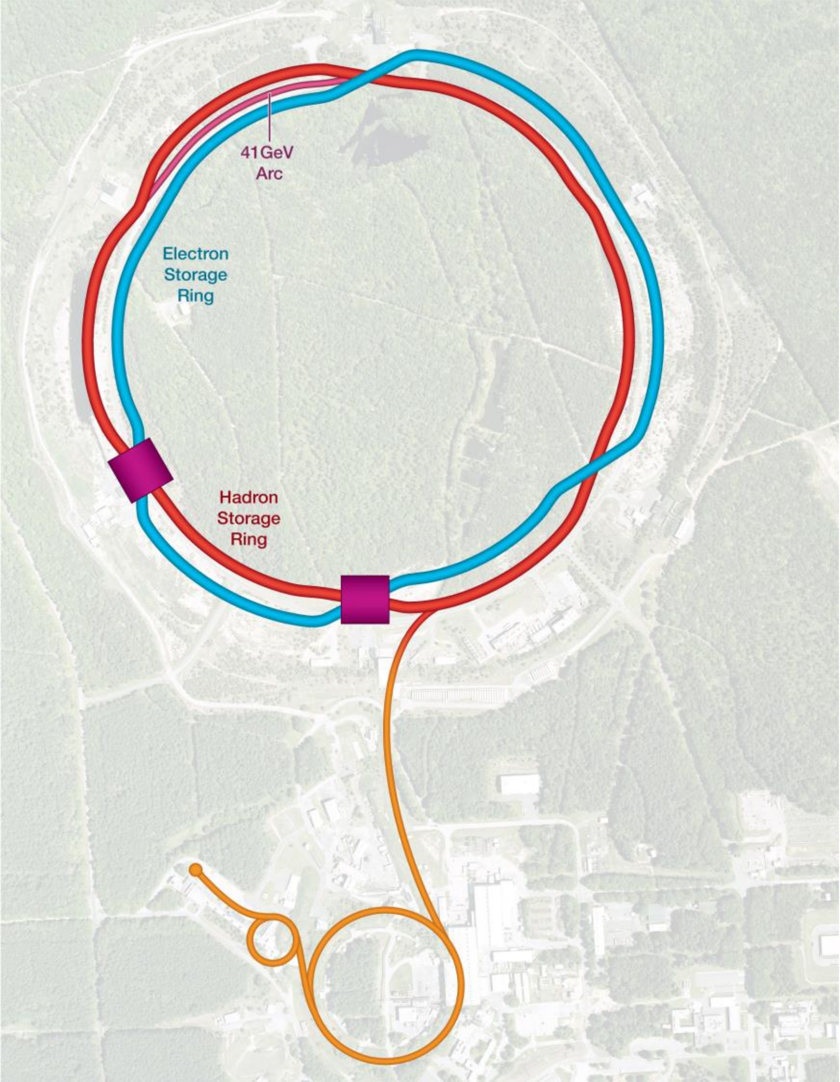
- Controlled broad-band amplification of density fluctuations
    - Some experience at FELs (narrow band)

- Longitudinal alignment of e-p beams to better than 100 nm over 100 m distance



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

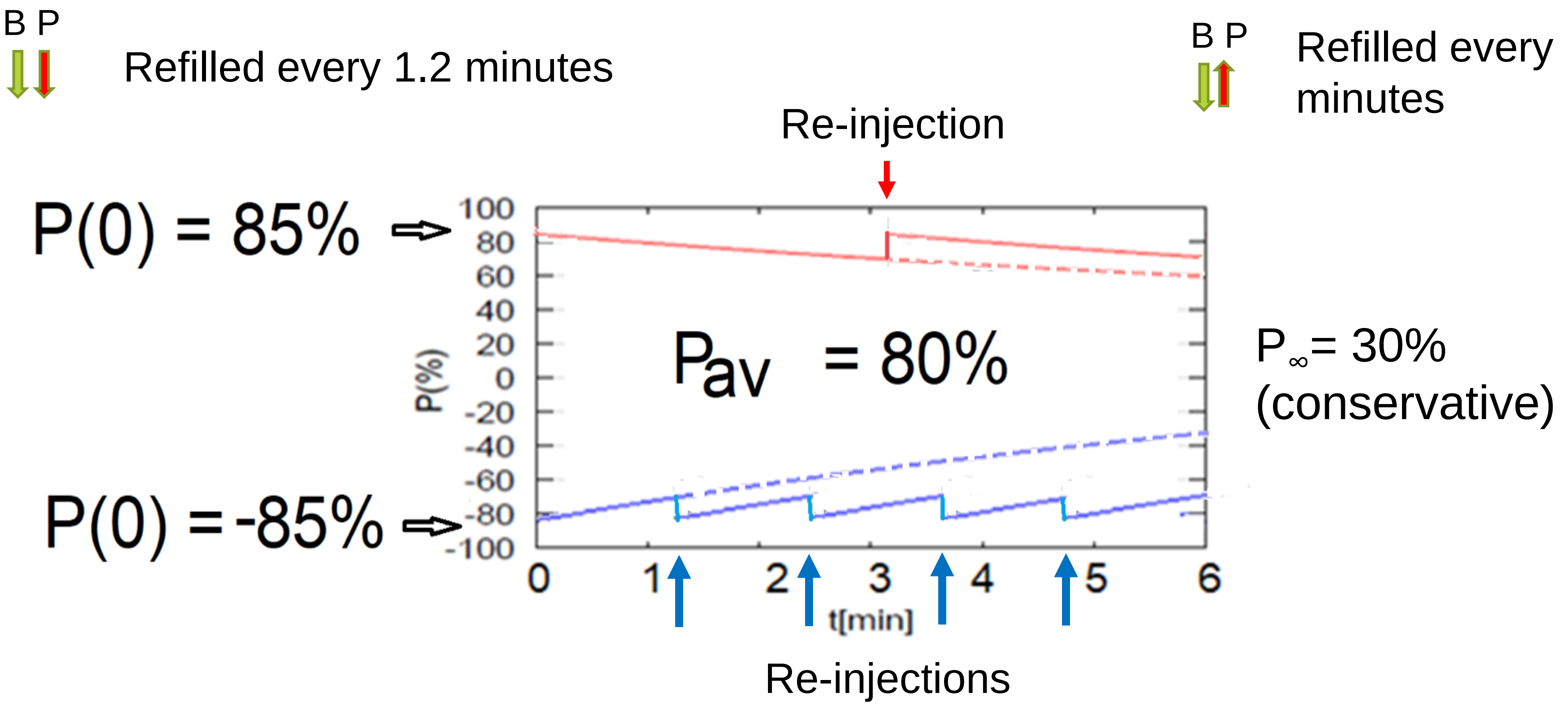


EIC Electron Polarization

- 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
  - However, the asymptotic polarization is quite low, ~30%
- The 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

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 1Hz


B P

Refilled every 1.2 minutes

B P

Refilled every 3.2 minutes

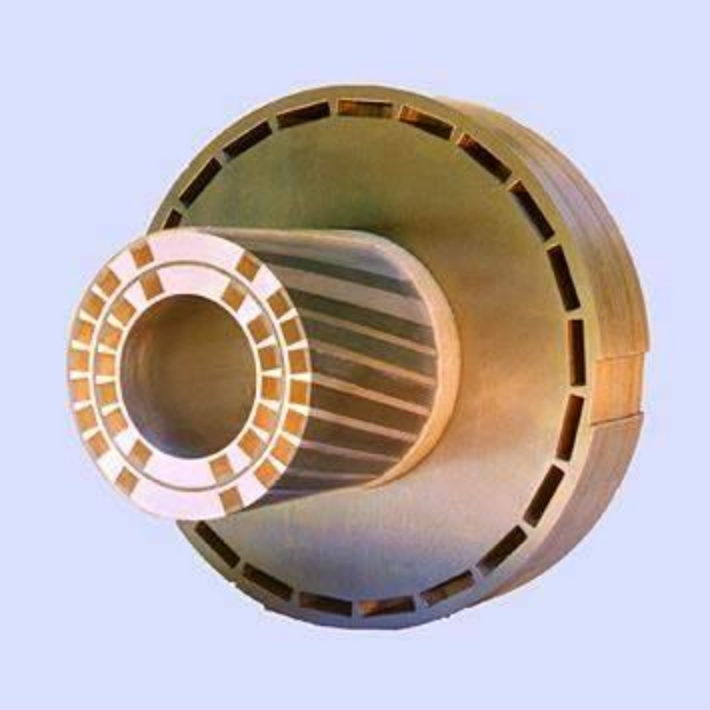
Re-injection

P_∞= 30% (conservative)

Re-injections

Spin Rotators

- Both electrons and protons will need longitudinal polarization at the IP
- Hadron spin rotators will be taken from present RHIC (helical dipoles)

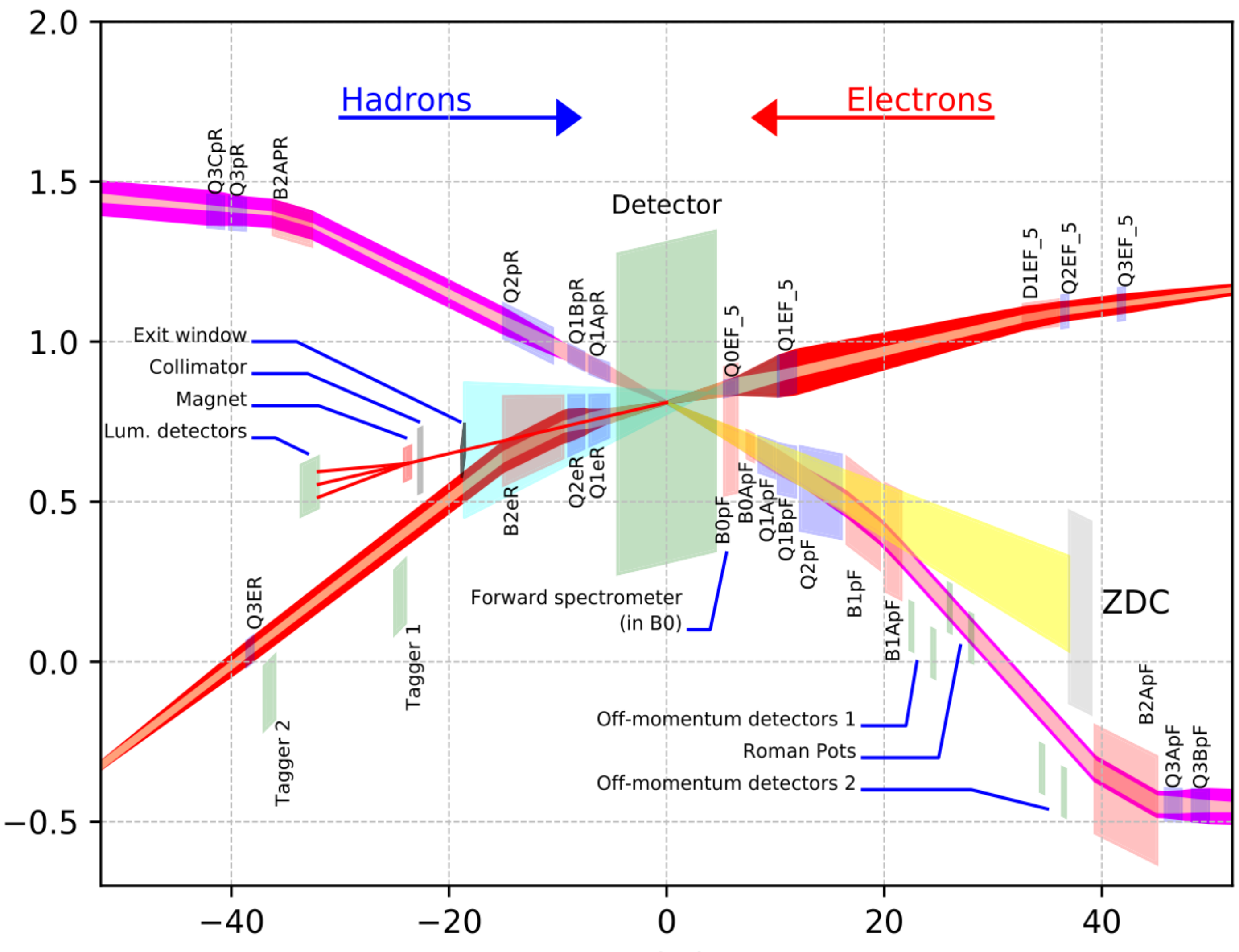


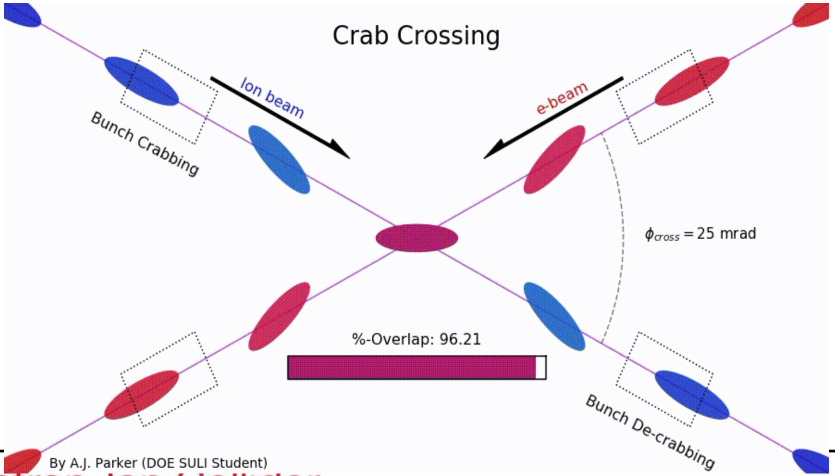
- Electron spin rotators are based on solenoid magnets with subsequent dipole

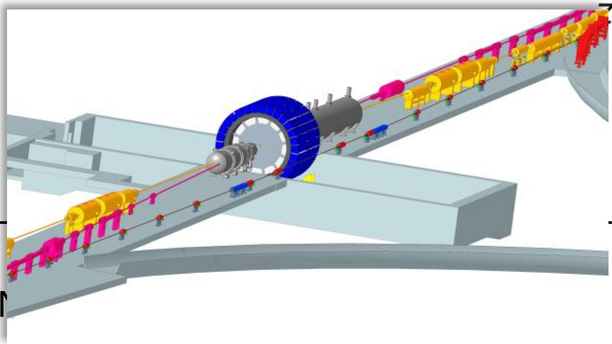
EIC IR Layout

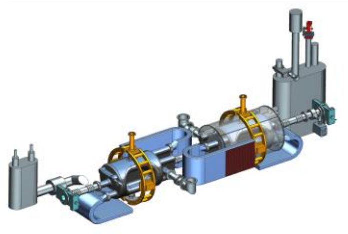
High luminosity:
- 25 mrad crossing angle
- Small β* for high luminosity
  with limited IR chromaticity contributions
- Large final focus quadrupole aperture

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”









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 can modify the fill pattern such that half the bunches collide in IR6, while the other half collides in IR8
- As a result, the total luminosity is preserved, and each detector gets half of the total

What is still ‘at play’ in the EIC Design and Construction?

- Attaining high electron bunch charge (28 nC) for a ‘swap-out’ injection
- Understanding of beam-beam interactions (ξ_e=0.1, ξ_p =0.015)
- Full understanding of a 25-mrad crossing angle, compensated by crab cavities
- Highly polarized electron and hadron beams, including novel polarized He3+ beams
- Spin matched electron ring beam optics at 5 GeV, 10 GeV, 18 GeV
- Hadron cooling at collisions to maintain hadron beam brightness
- Dynamic aperture optimizations

Science

- Maintaining an option for the 2nd IR
- Large number of NC magnets for synchrotrons and beam lines
- Design and fabrication of IR SC magnets
- Design and fabrication of SCRF cavities and cryomodules
- Cu-clad and aC coated Beam screen to suppress SEY that causes eddy current problems
- Modern control system and instrumentation

Technology

Summary

- The EIC will be the next large international collider facility, starting operations ~2032

- The design fulfills all the requirements listed in the White Paper and LRPs, facilitating a rich physics program

- These requirements make it a very challenging machine – high beam currents, polarized beams, novel hadron cooling technique, large energy range, crab crossing

- We welcome the US and the international accelerator community to join the EIC Accelerator Collaboration, to face the EIC challenges and to deliver this exciting machine.
- We are looking forward to work with FCC on the areas of mutual interests