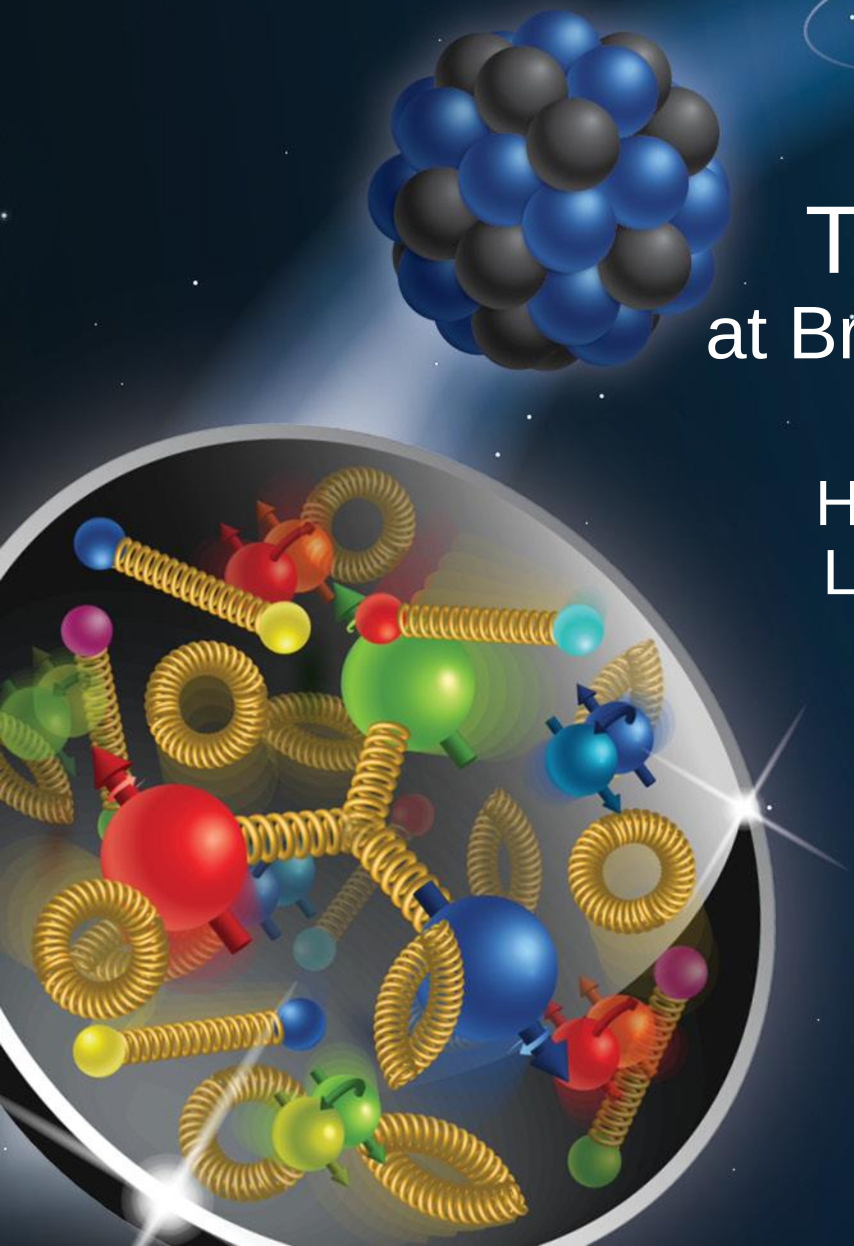


The Electron Ion Collider
at Brookhaven National Laboratory

Horizons in Particle Accelerators and
Laboratory Based Quantum Sensors

Bangalore, November 14-17, 2022

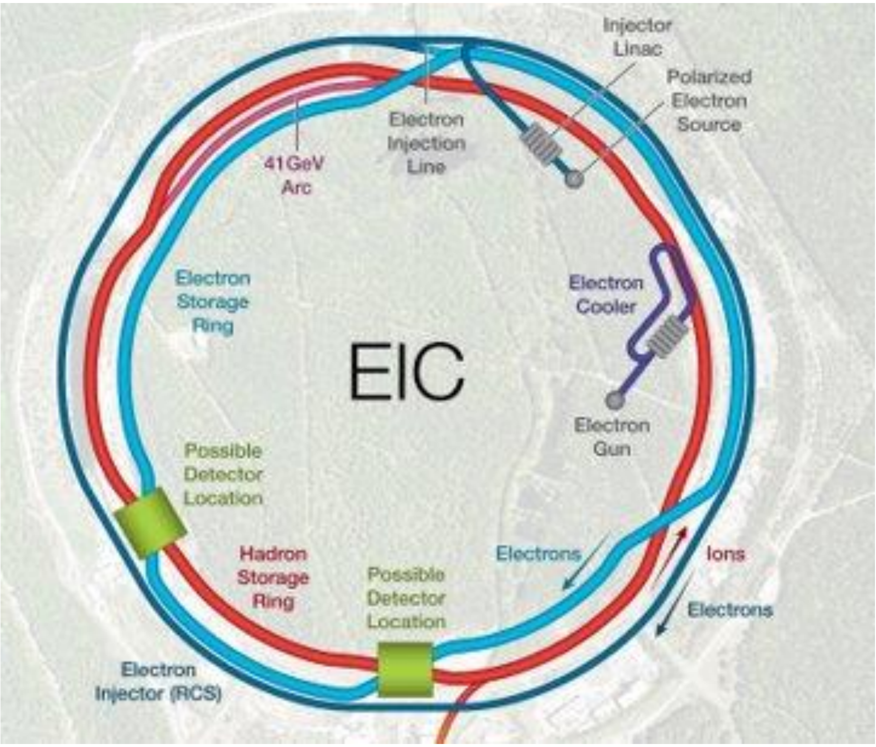
F. Willeke, BNL

Electron-Ion Collider

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

Outline

- The EIC Physics Case
- EIC Requirements
- EIC Design
- EIC Accelerator Challenges
  - High Luminosity
  - Beam Polarization
  - High Intensity Effects
  - High Energy Hadron Beam Cooling
  - Superconducting RF systems
- EIC Schedule
- EIC international Collaboration
- Summary



Electron Ion Collider Physics

Nuclear Physics Community compiled an EIC WHITE PAPER*) (2014/5):

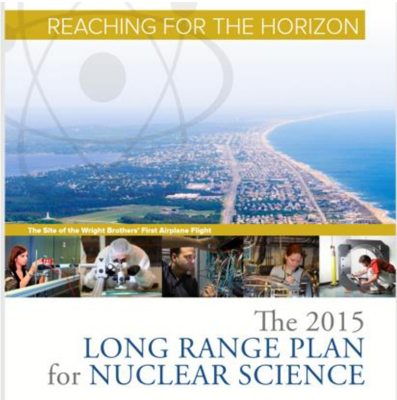
- How are quarks, gluons & their spins distributed in space & momentum in nucleus?
- How do nucleon properties emerge from quarks and gluons and their interactions?
- How do color-charged quarks, gluons & colorless jets, interact with a nuclear medium
- How do confined hadronic states emerge from quarks & gluons
- How do the quark-gluon interactions create nuclear binding?
- How does dense nuclear environment affect the quarks-gluons correlations & interactions?
- Does gluon density in nuclei saturate @ high energy

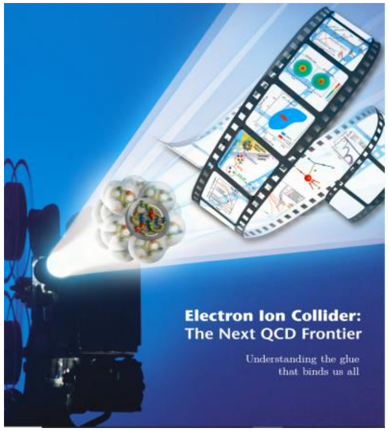
  result in gluonic matter with universal properties?

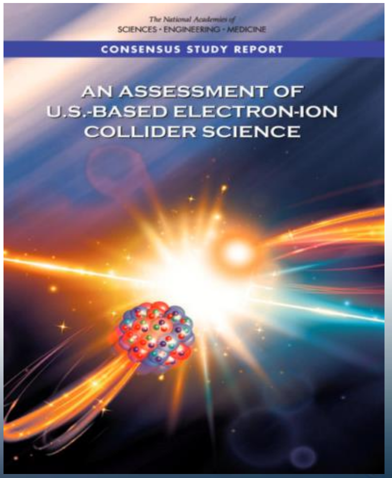
*) A. Accardi et al, Eur. Phys. J. A529:268 (2016)

Requirements

- EIC Design Goals
  - High Luminosity: $L=(0.1\text{-}1)\cdot 10^{34}cm^{-2}sec^{-1}$, need 10 -100 fb^{-1}
  - Collisions of highly polarized e and p (& light ion) beams with flexible bunch by bunch spin patterns : 70%
  - Large range of center of mass energies: E_{cm} = (20-140) GeV
  - Large range of Ion Species: Protons – Uranium
  - Ensure Accommodation of a second IR
  - Large detector acceptance
  - Good background conditions (hadron particle loss and synchrotron radiation in the IR)
- Goals match or exceed requirements of Long-Range Plan & EIC White Paper, endorsed by NAS
- EIC Design meets or exceeds goals and requirements



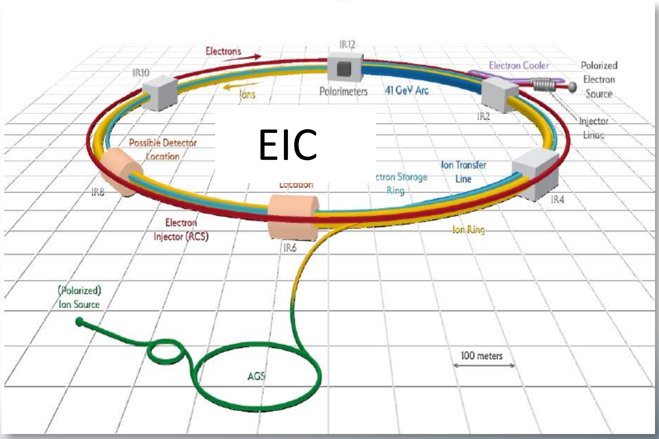




EIC Design Overview

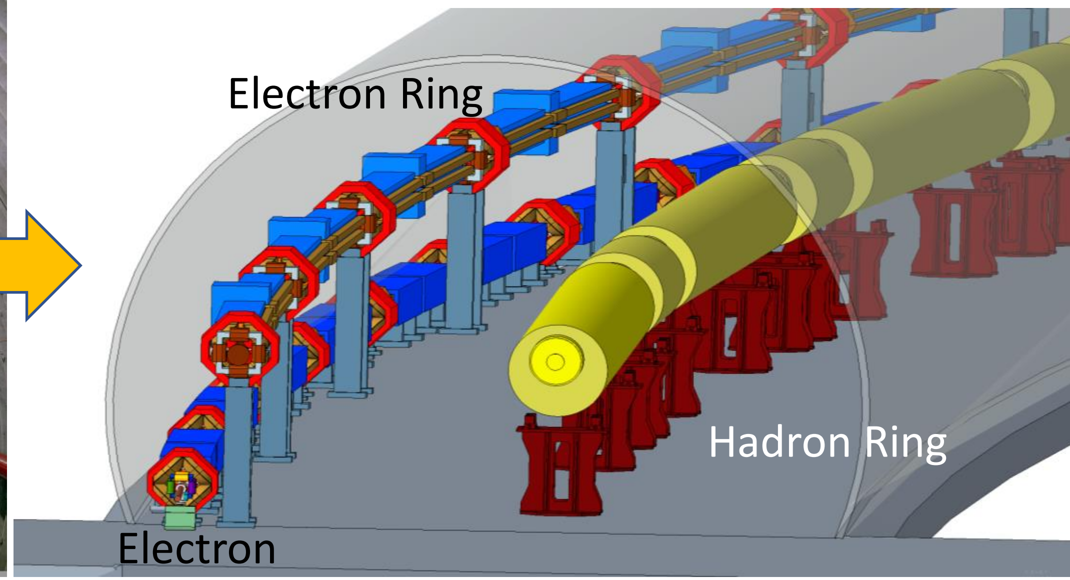
Design based on **existing RHIC Complex**
RHIC is well maintained, operating at its peak

EIC constructed in Collaboration with **JLab**



- **Hadron storage Ring (RHIC Rings) 40-275 GeV**
  - Superconducting magnets (existing)
  - 1160 bunches, 1A beam current (3x RHIC)
  - bright vertical beam emittance 1.5 nm (flat beam)
  - strong cooling (coherent electron cooling)
- **Electron storage ring 2.5–18 GeV**
  - many bunches,
  - large beam current, 2.5 A ➔ 9 MW S.R. power (10GeV)
  - S.C. RF cavities
  - Need to inject polarized bunches
- **Electron rapid cycling synchrotron 0.4- 18GeV**
  - 1-2 Hz
  - Spin transparent due to high periodicity
- **High luminosity interaction region(s)**
  - $L = 10^{34} cm^{-2} s^{-1}$
  - Superconducting magnets
  - 25 mrad Crossing angle with crab cavities
  - Spin Rotators (longitudinal spin)
  - Forward hadron instrumentation

RHIC to EIC

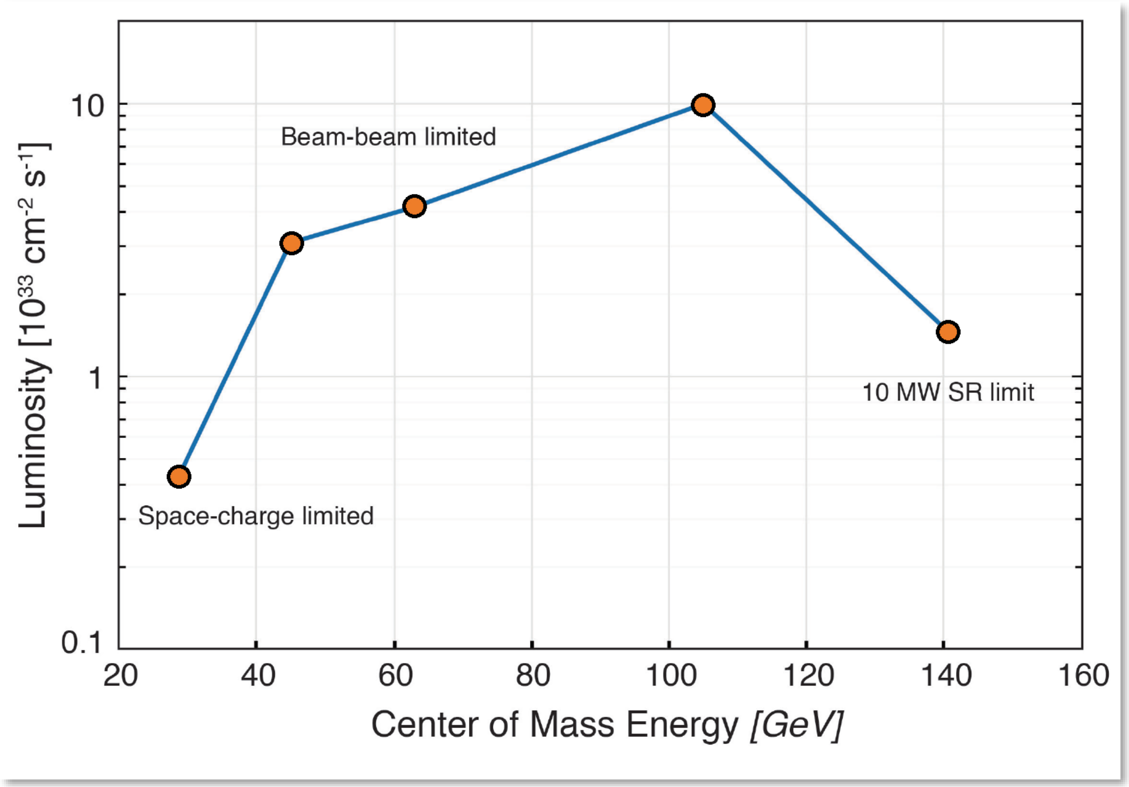


Parameters for Highest Luminosity @E_{cm}=100GeV

	Electrons	Protons
Beam energies	2.5 - 18 GeV	41- 275 GeV
Center of mass energy range	E_{cm} = 20-140 GeV	

	Electrons	Protons
Beam energies	10 GeV	275 GeV
Center of mass energy	E_{cm} = 105 GeV	
number of bunches	nb =1160	
crossing angle	25 mrad	
Bunch Charge	$1.7 \cdot 10^{11}$e	$0.7 \cdot 10^{11}$e
Total beam current	2.5 A	1 A
Beam emittance, horizontal	20 nm	9.5 nm
Beam emittance, vertical	1.2 nm	1.5 nm
β- function at IP, horizontal	43 cm	90 cm
β- function at IP, vertical	5 cm	4 cm
Beam-beam tuneshift, horizontal	0.073	0.014
Beam-beam tuneshift, vertical	0.1	0.007
Luminosity at E_{cm} = 105 Gev	$\mathbf{1 \cdot 10^{34} cm^{-2} s^{-1}}$	

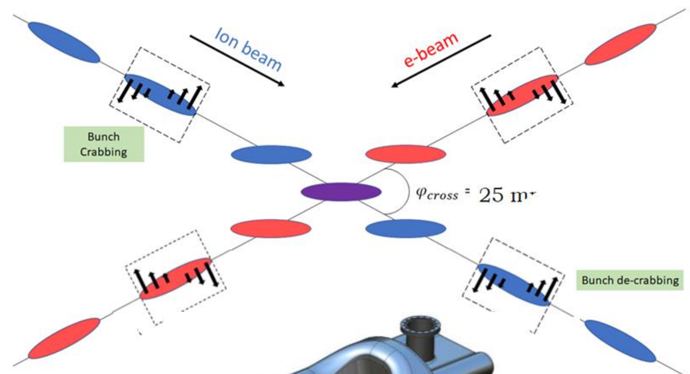
Luminosity vs. CM Energy

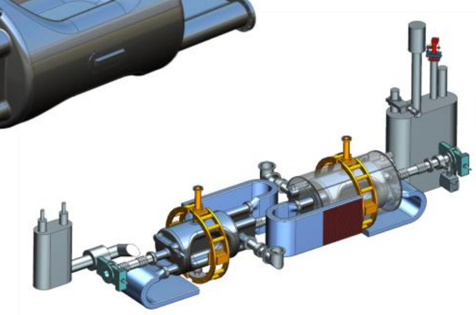


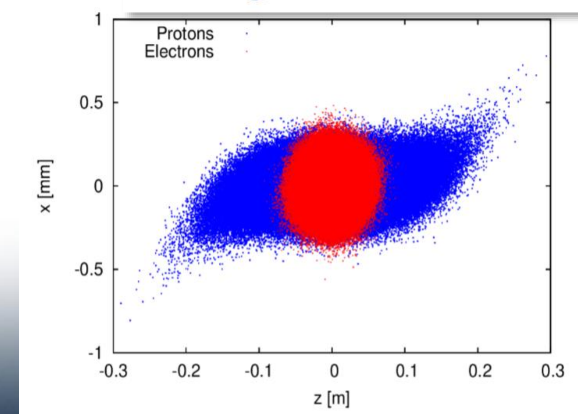
- Parameter and IR optimization at 105 GeV center-of-mass energy
- Optimization yields $10^{34} cm^{-2} sec^{-1}$ luminosity at 105 GeV

Beam-Beam Interactions & Crossing Angle

- 1160 bunches must collide only at the IP
  - ➔ need 25 mrad crossing angle
- Uncompensated, crossing angle dramatically reduces luminosity
  - ➔ need "crab" rf deflectors parallel beam orientation
- Complicates beam-beam interaction, source of hadron emittance blow-up ➔ **2nd harm crab**
- Once hadron beam size is blown up, electron re-shrink and the blow-up accelerated (mismatch)
- Crab Phase noise: Fluctuating beam-beam offset causes rapid emittance growth many ➔ extremely small tolerances

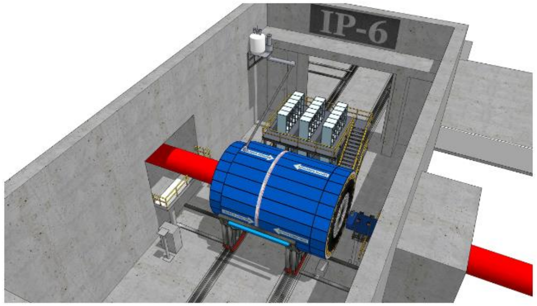


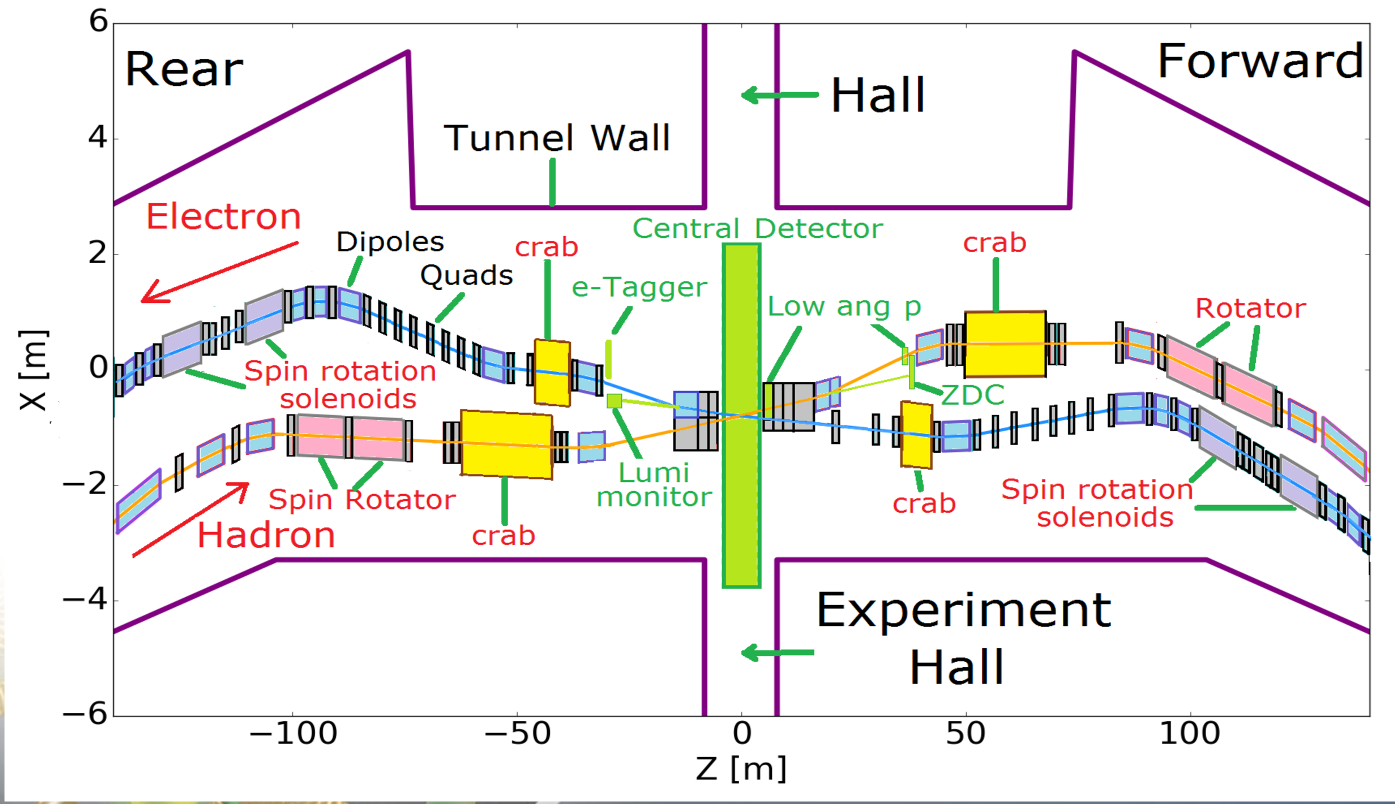




Interaction Region

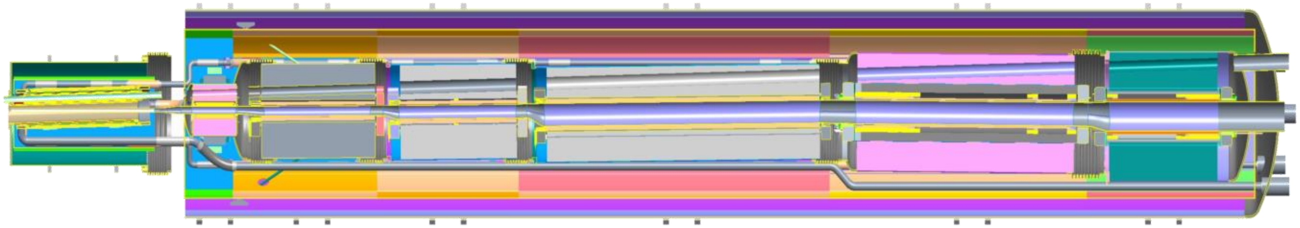
- 25 mrad crossing angle (acceptance)
- Superconducting final focus magnets
- Crab cavities
- Spin rotators
- Large acceptance for forward scattered hadrons



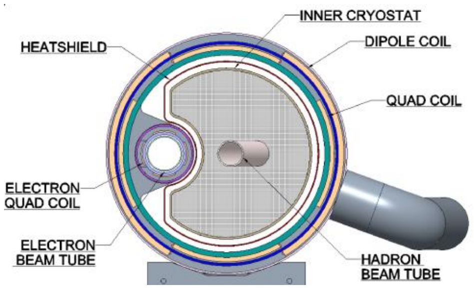


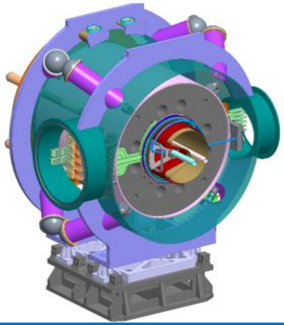
Electron-Ion Collider

IR Superconducting Magnets

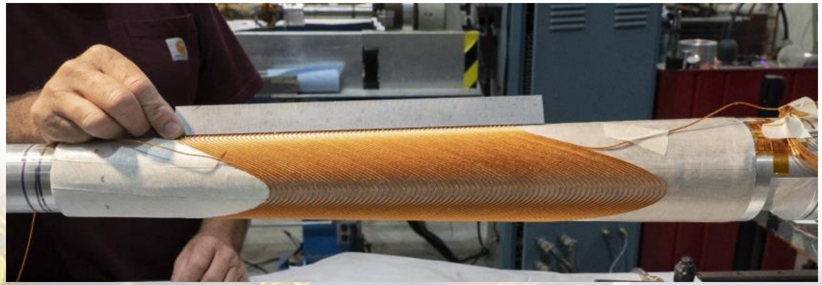


Highly integrated superconducting hadron and electron magnets, some operated at 2K



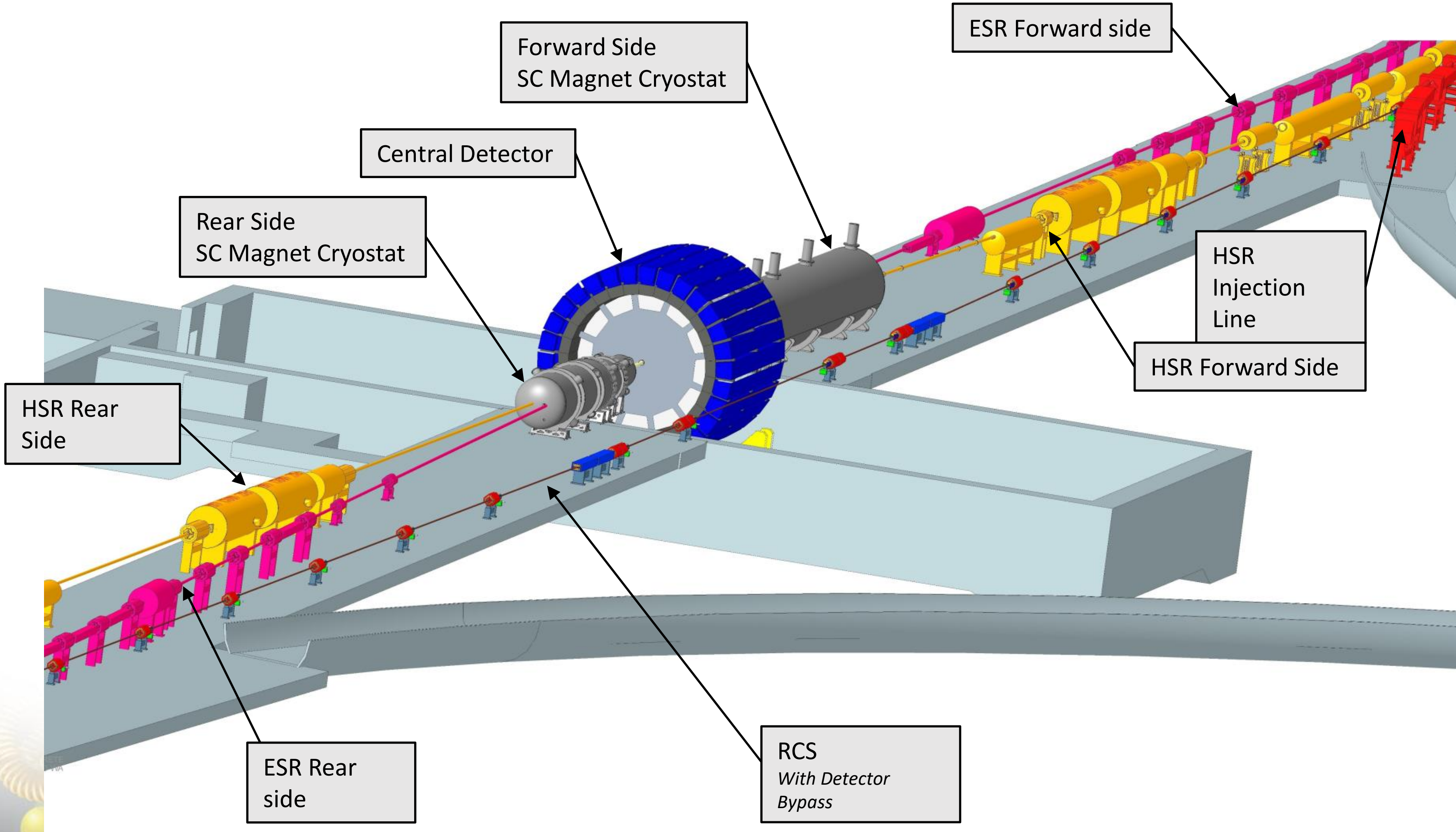


Spectrometer magnet including hadron and electron beam pipe

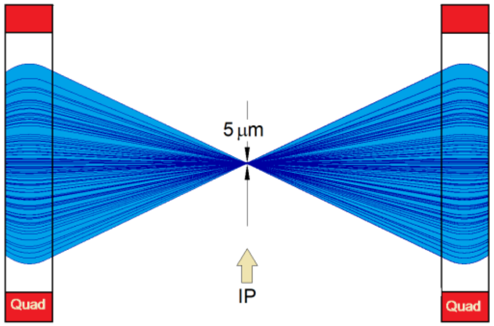


Direct wind technology

IR-6


Forward Side
SC Magnet Cryostat
ESR Forward side
Central Detector
Rear Side
SC Magnet Cryostat
HSR
Injection
Line
HSR Forward Side
HSR Rear
Side
ESR Rear
side
RCS
With Detector
Bypass

Dynamic Aperture



- Luminosity requires small beam size at collision point, implies large beam divergence
- Particles with slightly different beam energies experience weaker/stronger focusing ("chromaticity") ➔beam optics distortions ➔must be corrected to store beam
- Need compensation by nonlinear sextupole magnets in the arcs
- Contributions from IR where beam size is large and final focus quadrupoles a strong dominate➔ strong nonlinear sextupoles
- Strong nonlinear sextupoles limit betatron oscillations amplitudes (@beam size)
- As the electrons beam size generated by from synchrotron radiation effects we must
  - limit the focusing (affects beam size at IP and luminosity)
  - Optimize distribution of nonlinear sextupole fields around the machine to keep the beam stable.

- ➔ sophisticated linear and nonlinear lattice design

High Beam Intensity

- Large amount of synchrotron radiation from the electron beam:

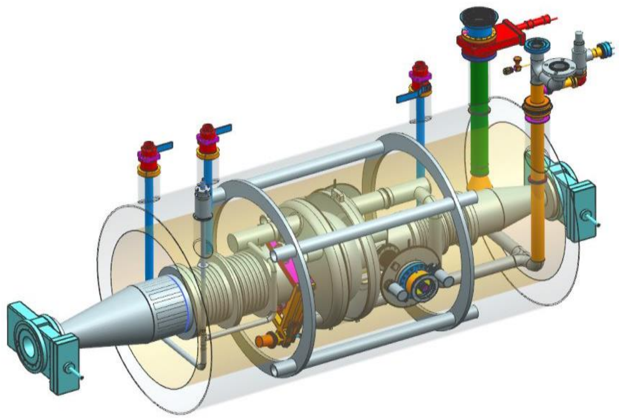
9 MW, need 64 MV for 18 GeV electrons

➔superconducting cavities driven by solid state RF amplifiers

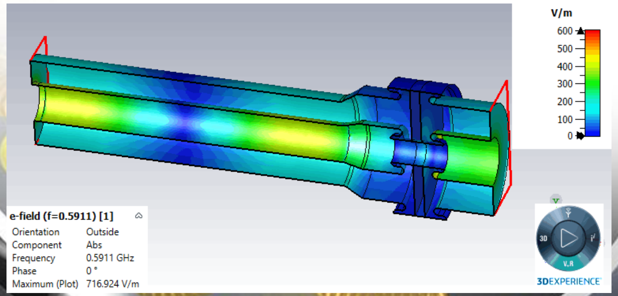
- High electron bunch charge 28 nC, careful low impedance vacuum design (tapers, shielded bellow, single-mode cavity design, effective higher order mode damping by SiC beampipe HOM absorbers)
- RHIC cold beam pipe is stainless steel, large resistive heating by 1 A beam current, large cryogenic losses
- Hadron beam suffers from clouds of electrons produced by ionization of rest-gas and amplified by secondary emissions

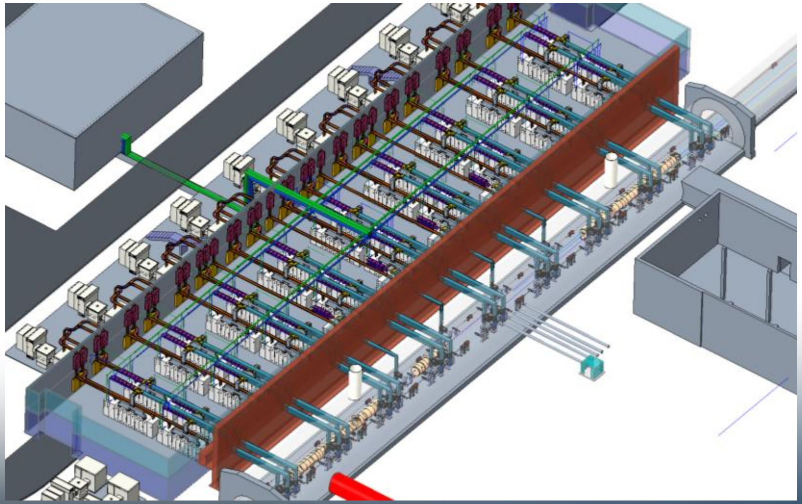
➔Need to insert a Cu and aC coated screen to reduce cryogenic load and suppress electron cloud by low SEY

Electron Beam RF System



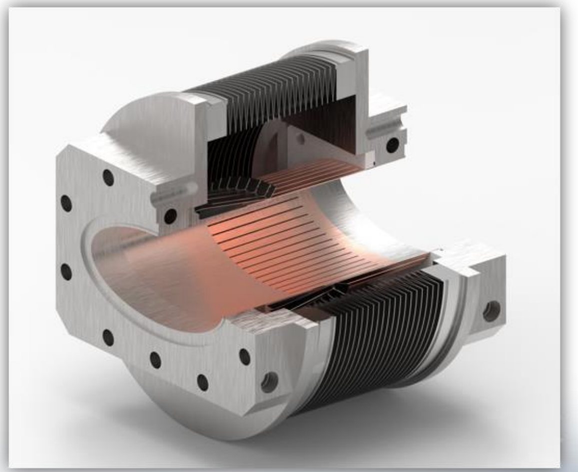
- 18 single cell “single mode” superconducting cavities
- SiC higher order mode absorbers integrated in th beam pipe
- Each with two 400 kW forward power couplers with variable coupling
- Each powered by a 800 kW two stage solid state RF amplifier





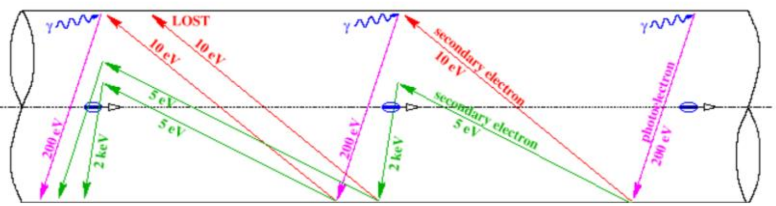
Electron Ring Vacuum system

- OFE Cu beam pipe with integrated NEG pumping (NEG stripes)
- Carefully optimized shielded bellow derived from NSLS-II design

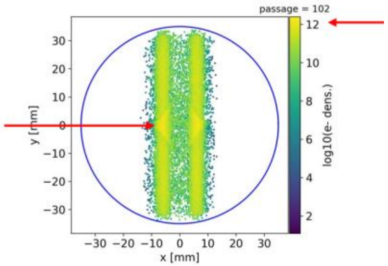


HSR Vacuum Cu/aC Coated Beam Screen

- The resistive losses of the 1A proton beam current leads to an unacceptable cryogenic load ➔ need a **Cu coated surface**
- Build up of electron cloud by ionization of rest gas amplified by secondary emission from stainless steel beam pipe



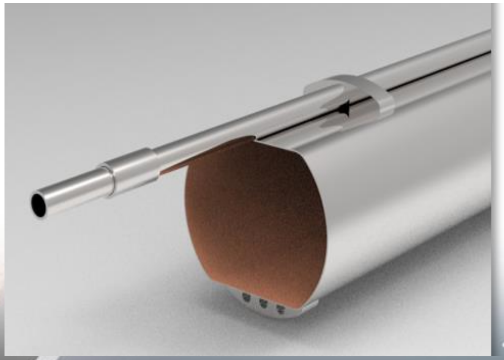
30 ns, dipole, 35 mm



- Need increase conductivity of RHIC cold SS beampipe, suppress electron cloud with SEY ~1

➔In situ insertion of a **Cu and aC coated screen**

- An actively gas cooled screen is the only feasible solution (unfortunately also the most expensive one



Electron Spin Polarization

In ESR, synchrotron radiation would build up polarization slowly

- Equilibrium polarization is only 30%-60% in ESR, but need 70-80%
- Buildup for polarization is very slow (hrs)
- Buildup would work only for spin up direction but need spin down also

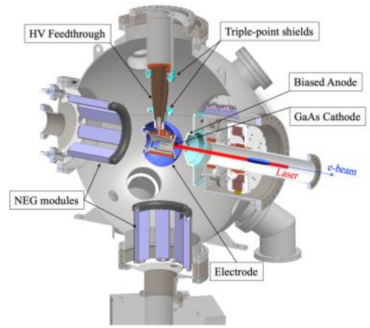
➔

- Electron polarization electrons created by polarized source
- preserved during acceleration in the RCS (quite tricky)
- Need to compensate many effects that may destroy injected polarization

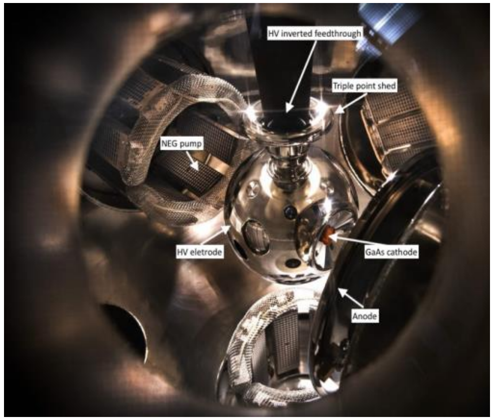
➔ need

- Extremely careful orbit control (microns)
- Extremely careful compensation of coupling between transverse planes of oscillations
- Careful choice of tunes: horizontal, vertical, longitudinal, and spin
- Careful compensation of detector solenoid by rotated quadrupoles

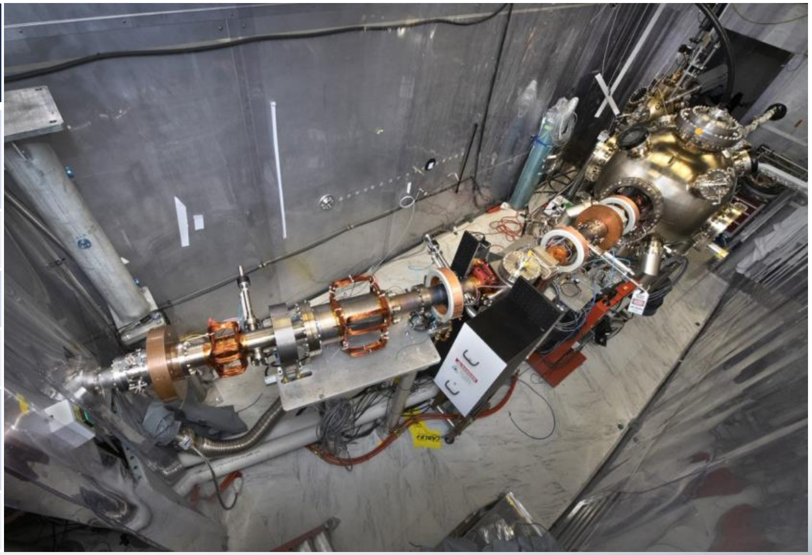
Polarized Electron Source



Finally assembled



	EIC	Achieved in stable operation	R&D deliverable
Bunch charge [nC]	7	7.5 (12)	Y
Peak current [A]	3.8	4.8 (No SCL)	Y
Frequency [Hz]	1 (8 bunches)	1 (9000 bunches)	Y/N*
Voltage [kV]	300	300	Y
Average Current	56 nA	76.5 uA	Y
Polarization [%]	> 85%	Bulk (~35%)	Y/N**



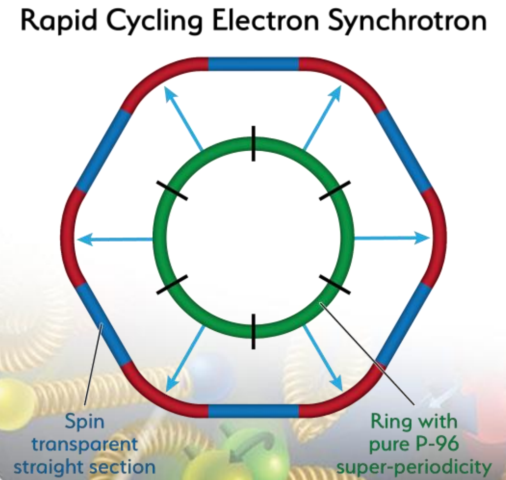
85% polarization will be achieved with strained lattice GaAs cathode

18 GeV Rapid Cycling Synchrotron enables high electron polarization in the electron storage ring

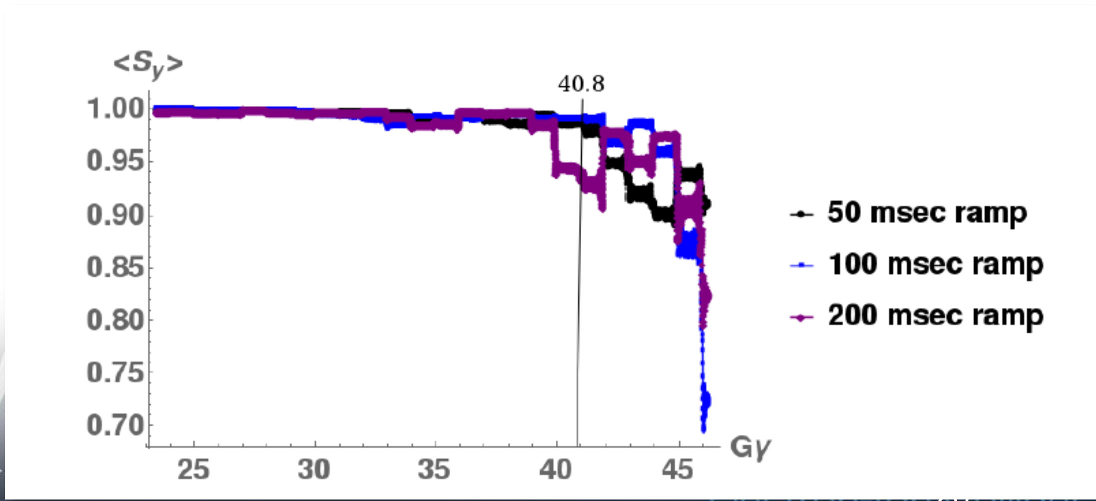
- Depolarizing resonances at acceleration (350MeV) threaten to destroy polarization
- AGS experience confirms depolarization suppressed by lattice periodicity
- Ingenious optical design with high quasi-periodicity arcs and unity transformations in the straights suppresses all systematic depolarizing resonances up to E >18 GeV
- Good orbit control $y_{cl.o.}$< 0.5 mm; good reproducibility suppresses depolarization by imperfection resonances.

➔ No depolarizing resonances during acceleration 0.4-18 GeV
no loss of polarization on the entire ramp up to 18 GeV (100 ms ramp time, 2 Hz)

RCS Design

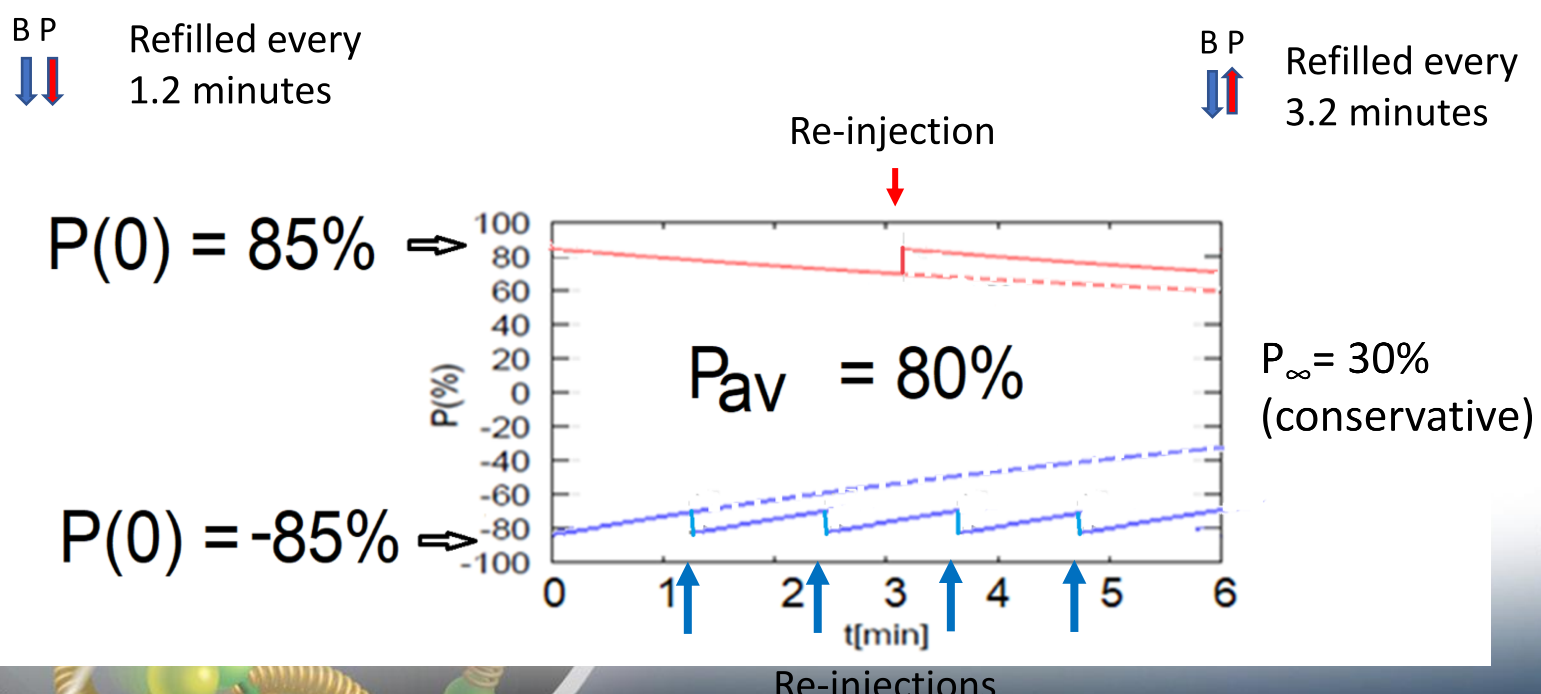


RCS Polarization Performance confirmed by extensive simulations



High average polarization at electron storage ring of 80% by

- Frequent injection of bunches on energy with high initial polarization of 85%
- Initial polarization decays towards P_∞ < ~50%
  (equilibrium of self-polarization and stochastic excitation)
- At 18 GeV, every bunch is refreshed within minutes with RCS cycling rate of 2Hz.
- Need both polarization directions present at the same time



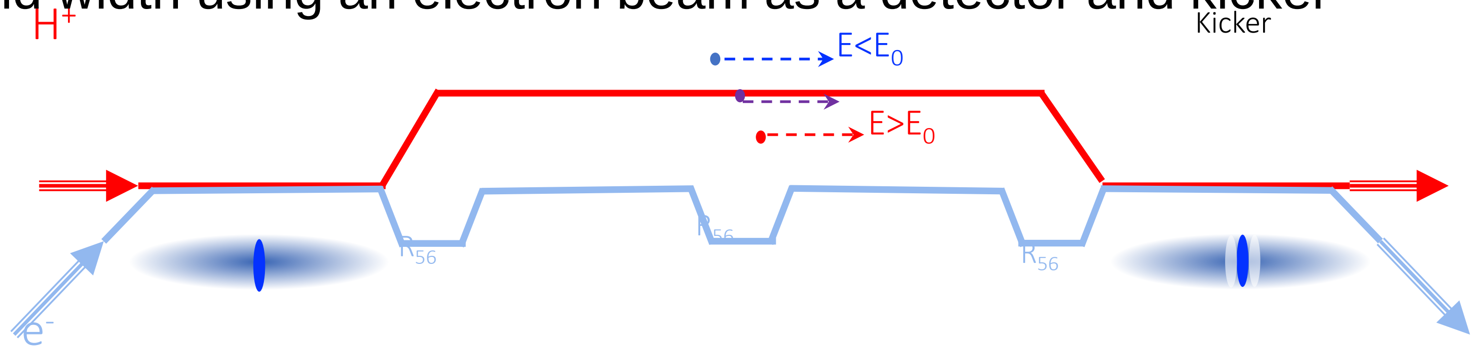
EIC Hadron Polarization

- Existing p Polarization in RHIC achieved with "Siberian snakes" P=60%
- Additional "snakes" will increase proton polarization in RHIC from 60% to 80%.
- ^{3}He polarization of >80% measured in source
- 80% polarized ^{3}He in EIC will be achieved with six "snakes",
- Acceleration of polarized Deuterons in EIC 100% spin transparent
- Need tune jumps in the hadron booster synchrotron

Electron beam ion source EBIS with polarized ^{3}He extension

Strong Hadron Cooling Design

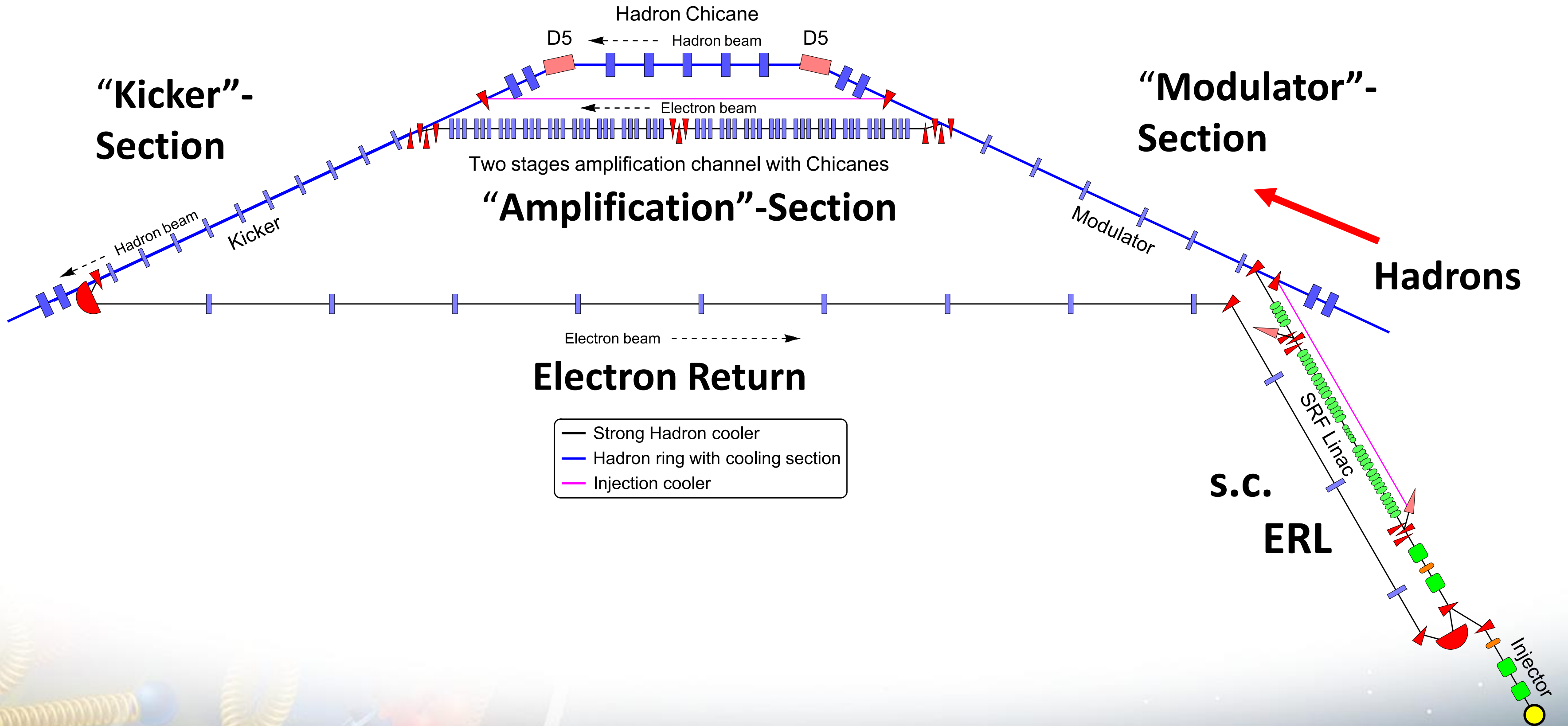
Intra beam scattering will blow up hadron emittance➔ need cooling
Method: Coherent Electron cooling, a cousin of stochastic cooling, detecting fluctuations of the hadron density along the bunch with high band width using an electron beam as a detector and kicker



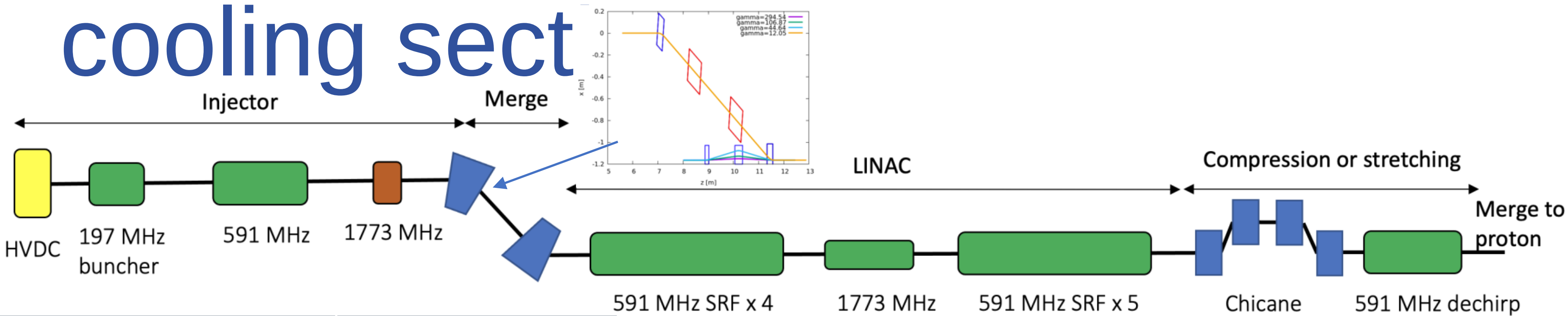
Cooling times of 2-3 hrs

- Coherent electron cooling with microbunching amplification
- Cooling process and amplification process supported by extensive simulations 1-D and 3-D simulations show slightly reduced cooling rates
- Challenging beam diagnostic tasks: beams have to remain synchronous across the cooling section on the micron level
- Pre-cooling at injection energy integrated into strong hadron cooling sharing many hardware components.

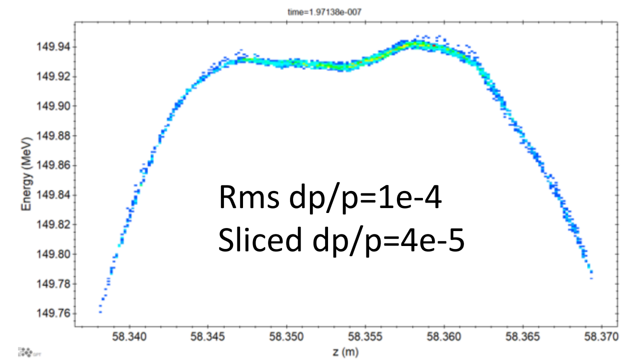
Schematic Layout of the cooling facility

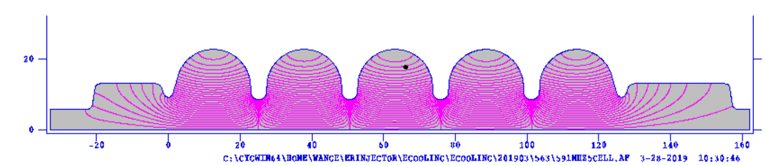


e-beam quality before entering cooling sect



	parameter
Bunch charge	1 nC
Peak current	8.5-34 A
RMS Bunch length	14-3.4 mm
RMS Normalized emittance	3 mm-mrad
Energy	150 MeV
RMS dp/p	<1 e-4



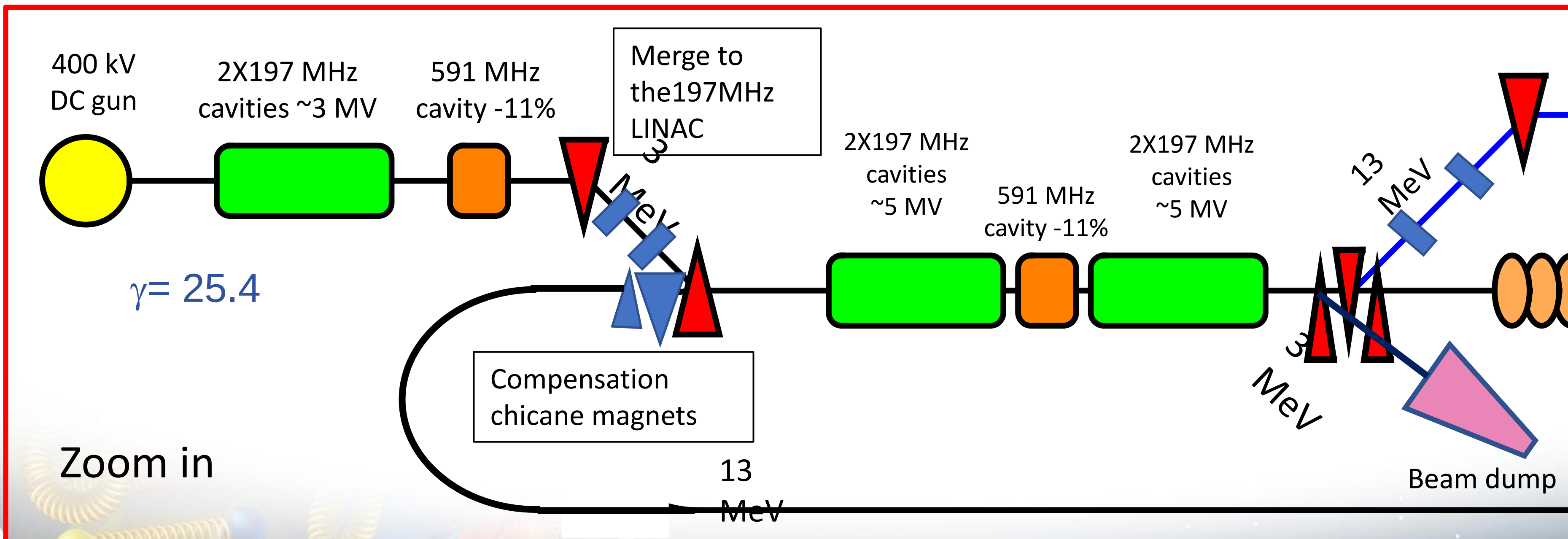


Injector and Linac up to cooling section are simulated by advanced 3D space charge code GPT 3.4, including CSR (Wakefield yet to be included).

See detail in S.Benson's talk

Pre-Cooling

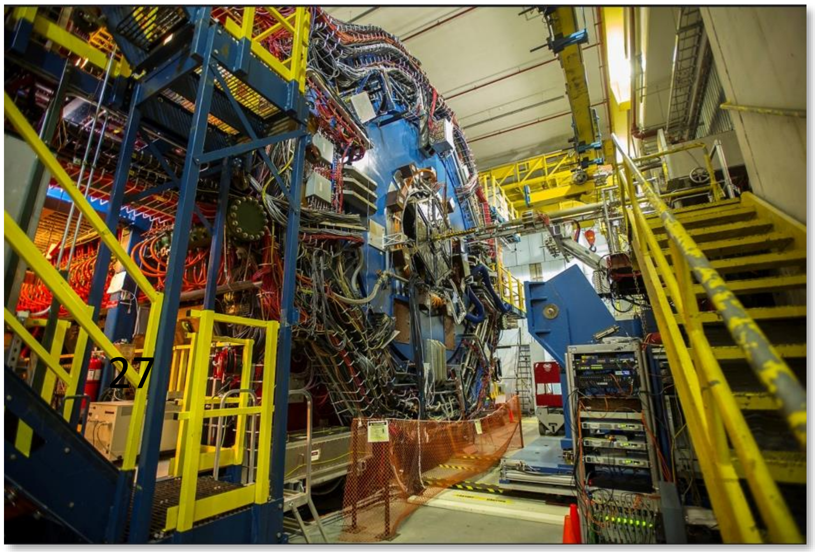
Achieving required beam parameters quickly requires pre-cooling of hadron at injection energy using bunched beam (incoherent) electron cooling.
The low energy cooler shares electron source, pre-injector and beam transport with the Strong Hadron Cooler and is highly integrated into the SHC facility



The EIC will benefit from two large existing detector halls in IR 6 and IR 8

- Both halls are **large** and **fully equipped** with infrastructure such as power, water, overhead crane, ….

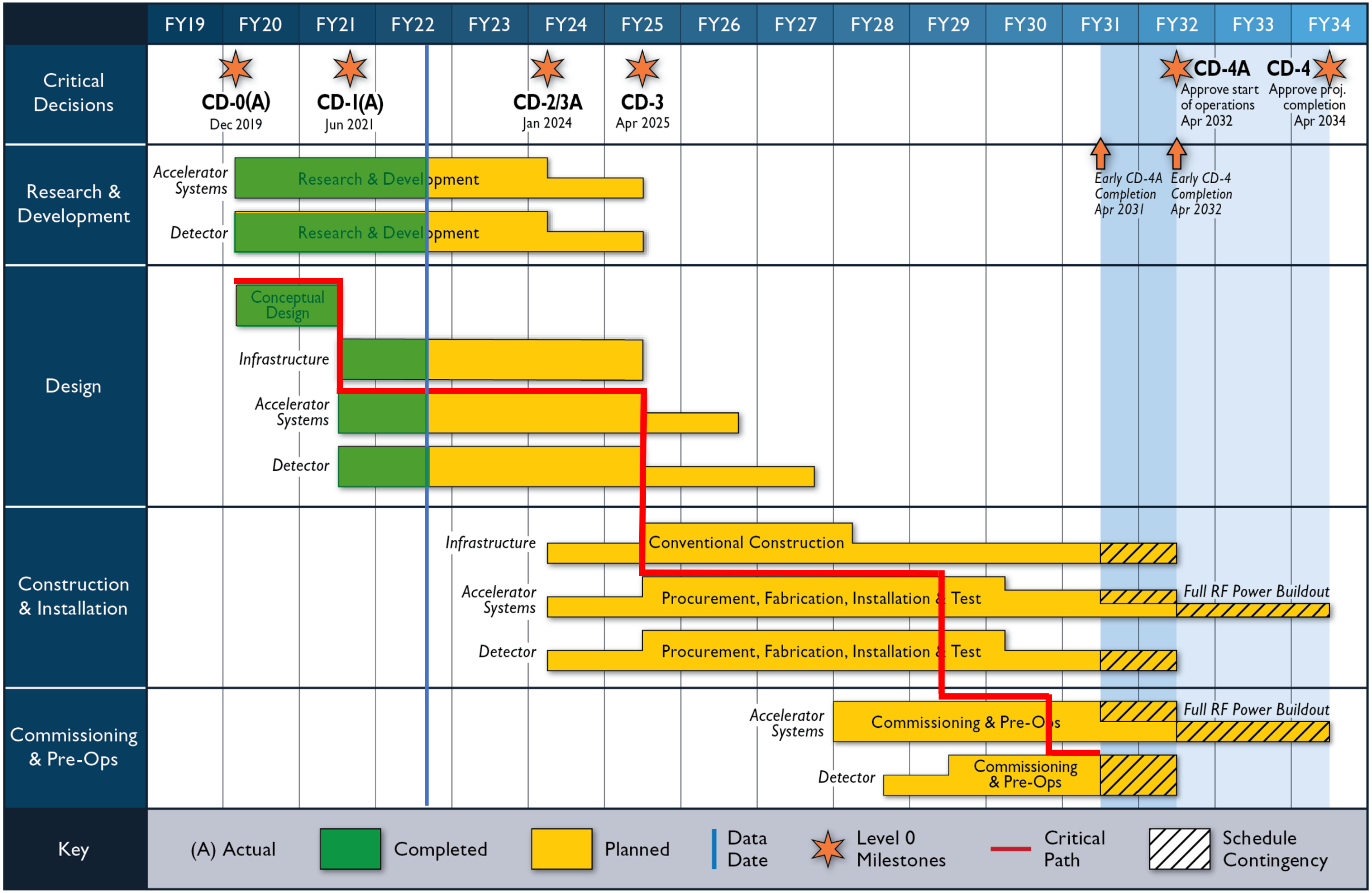
IR 8 detector hall with PHENIX detector (transitioning to sPHENIX)



IR 6 detector hall with STAR detector

- Both IRs can be implemented simultaneously in the EIC lattice and be accommodated within beam dynamics envelope
- 2 IR's: laid out <u>identically</u> or <u>optimized for maximum luminosity at different</u> E_{CM}

EIC Schedule



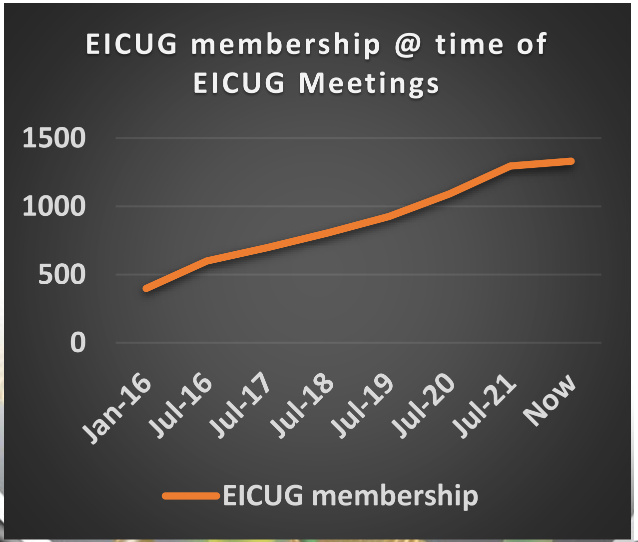
Worldwide Interest in EIC

The EIC Users Group:
https://eicug.github.io/

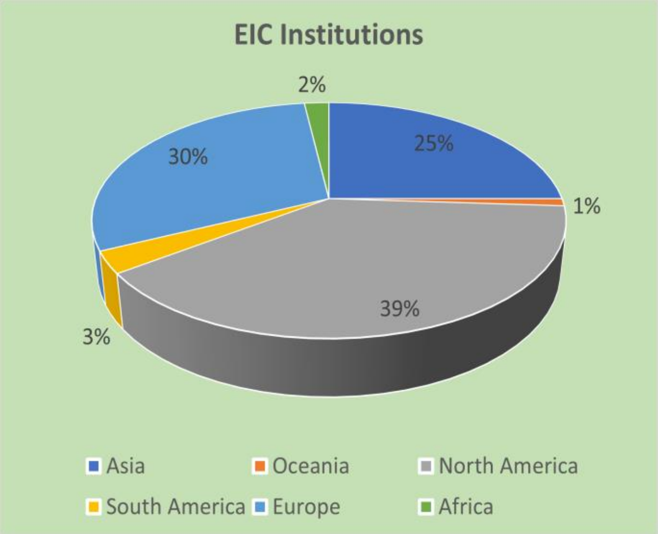
Formed 2016 –

- **1331 collaborators,**
- **36 countries,**
- **266 institutions as of June 07, 2022.**

Strong and Growing International Participation.



Annual EICUG meeting
2016 UC Berkeley, CA
2016 Argonne, IL
2017 Trieste, Italy
2018 Washington, DC
2019 Paris, France
2020 Miami, FL
2021 VUU, VA & UCR, CA
2022 Stony Brook U, NY
2023 Warsaw, Poland



Summary

- The EIC is one of the most complex colliders because of several performance requirements that all are require reaching at or beyond state of the art
- The challenging accelerator science questions of the EIC have all been addressed and remaining open question will only have a minor impact of EIC performance
- Accelerator global design is close to be completed and designs are now stable to serve a base for engineering design
- R&D made good progress in all areas that did not require large material expenses
- Engineering of components has started
- The project seeks to will collaborate with scientists and science institutions world-wide
- Scientists and Engineers contributing to EIC are developing into a strong competent team that will deliver the EIC project.