# The Design and Status of the Electron Ion Collider at Brookhaven National Laboratory

International Conference on Heavy Ion Accelerator Technology 2022

Darmstadt 1July 22

F. Willeke, BNL

Electron-Ion Collider

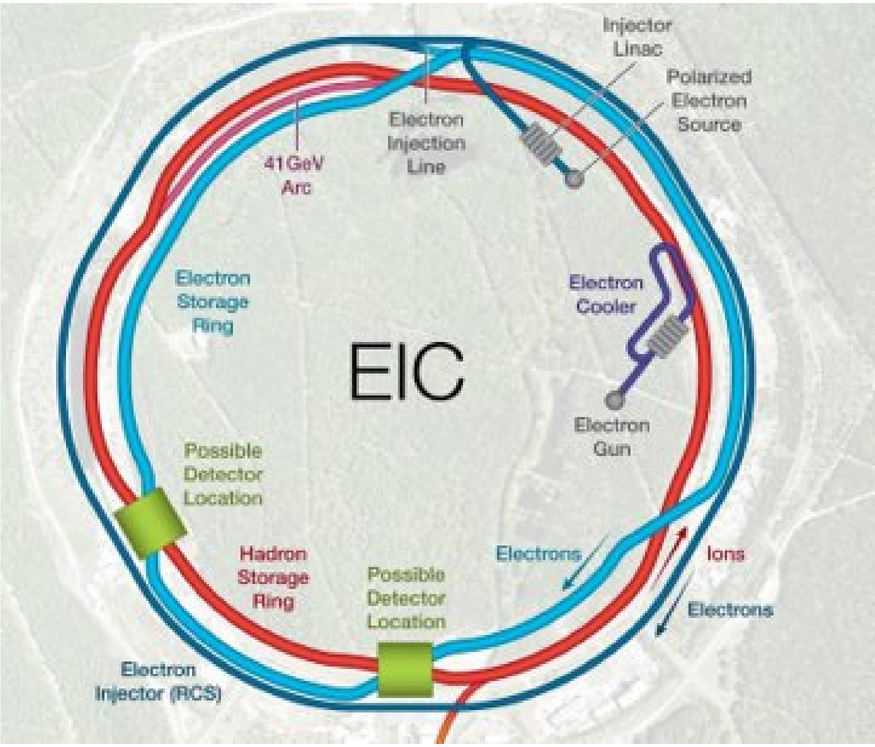
BROOKHAVEN NATIONAL LABORATORY

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

# Outline

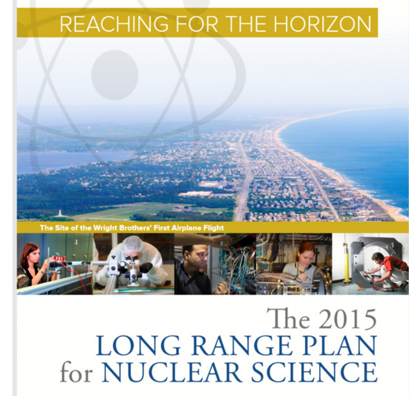
- Requirements
- Scope and design Overview
- Recent Progress on Accelerator
  Global accelerator design,
  beam interaction,
  polarization,
  strong hadron cooling
- Progress on accelerator R&D
  Vacuum, SC RF, SC IR magnets
- Summary

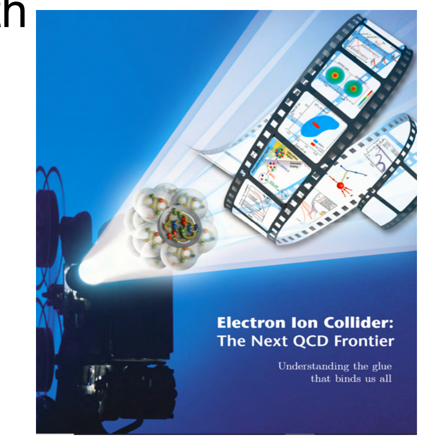


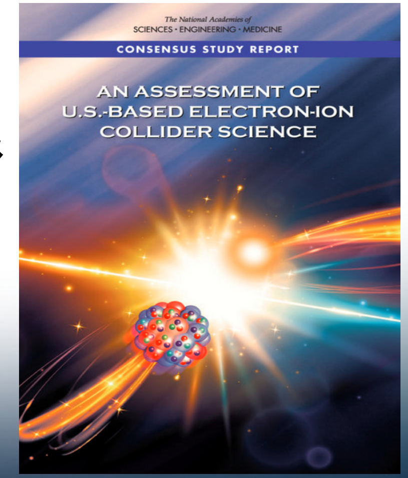
# Requirements

- EIC Design Goals
  - High Luminosity: $L=(0.1\text{-}1)\cdot10^{34}cm^{-2}sec^{-1}$, need 10 -100 $fb^{-1}$
  - Collisions of highly polarized e and p ( and 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



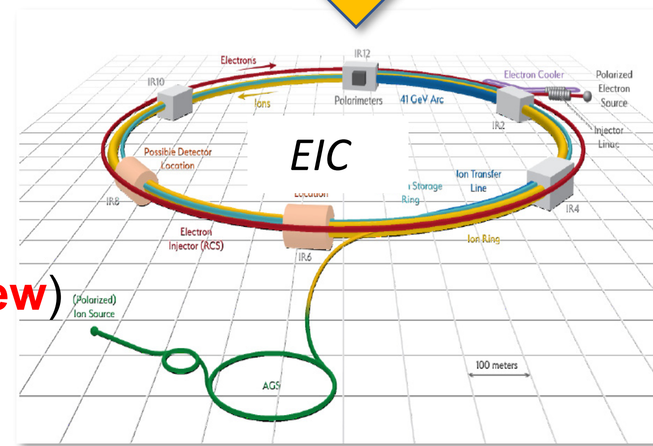



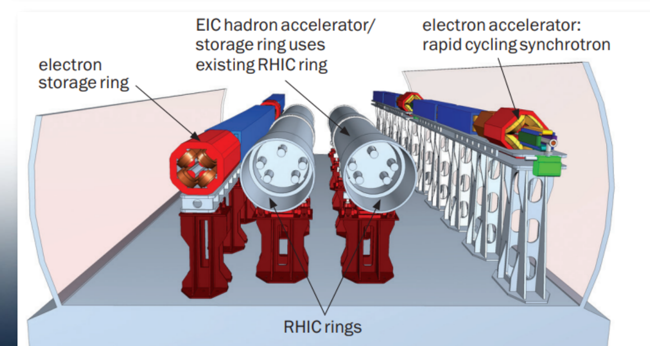



# EIC Design Overview

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

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



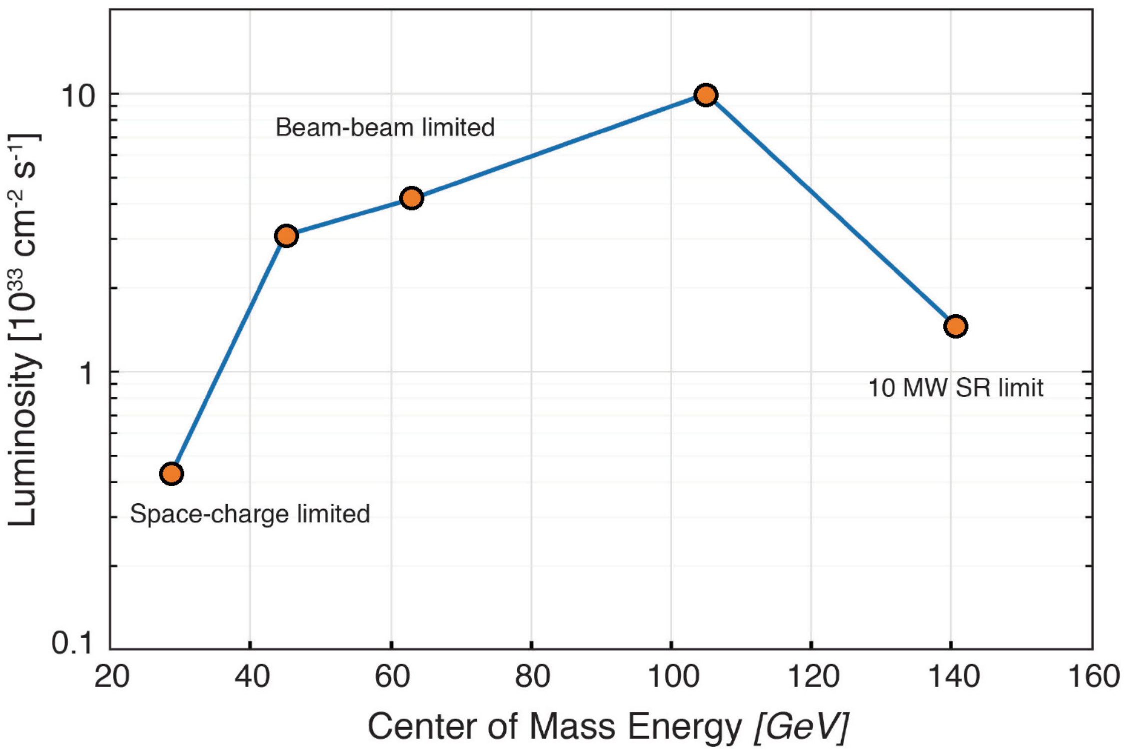



# EIC CDR Parameters for $E_{cm}$ and Luminosity

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

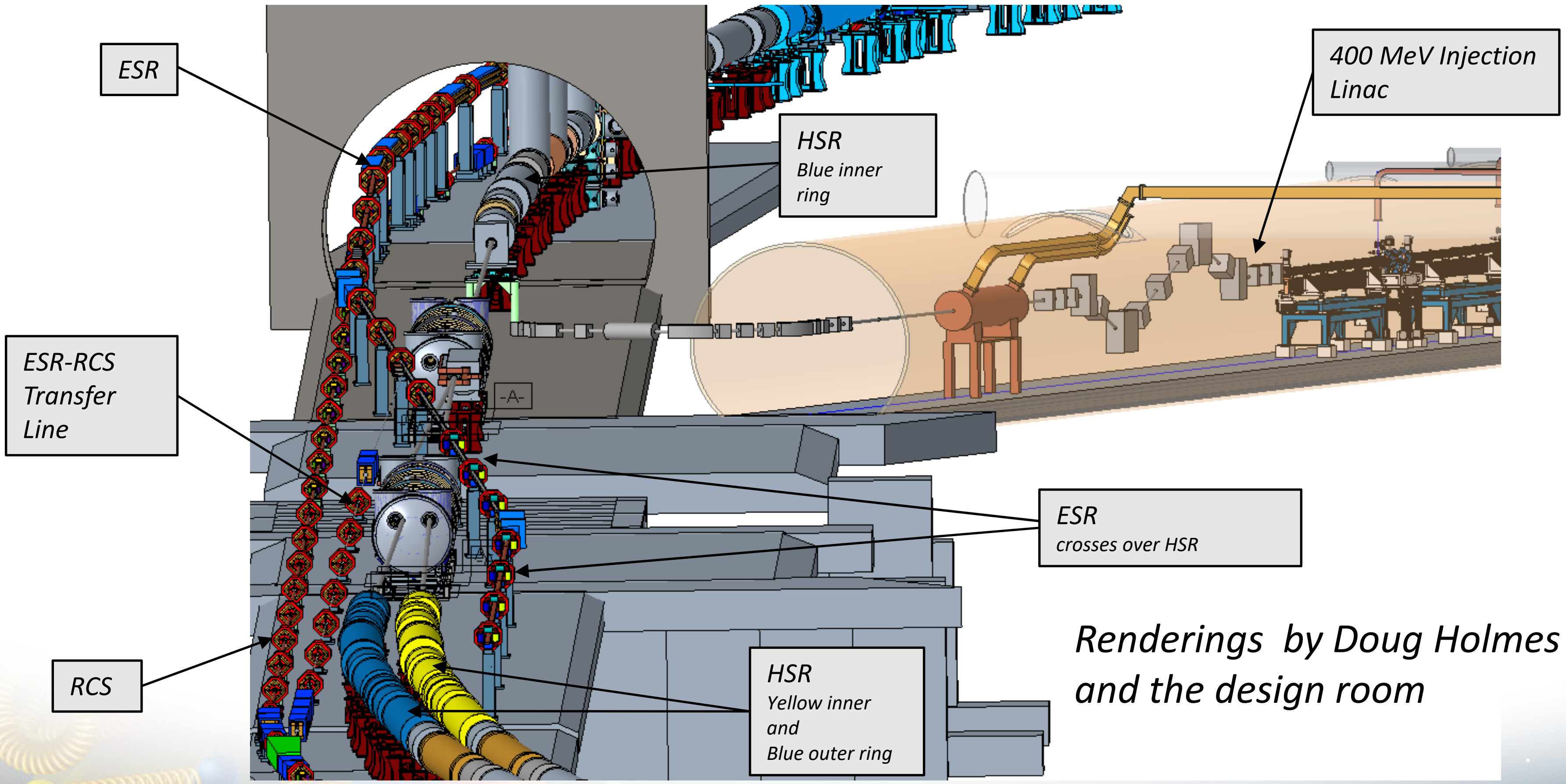
| | Electrons | Protons |
|---|---|---|
| Beam energies | 10 GeV | 275 GeV |
| Center of mass energy | $E_{cm}$ = 105 GeV | |
| number of bunches | nb =1160 | |
| crossing angle | 25 mrad | |
| Bunch Charge | $1.7 \cdot 10^{11}$e | $0.7 \cdot 10^{11}$e |
| Total beam current | 2.5 A | 1 A |
| Beam emittance,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

# 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*

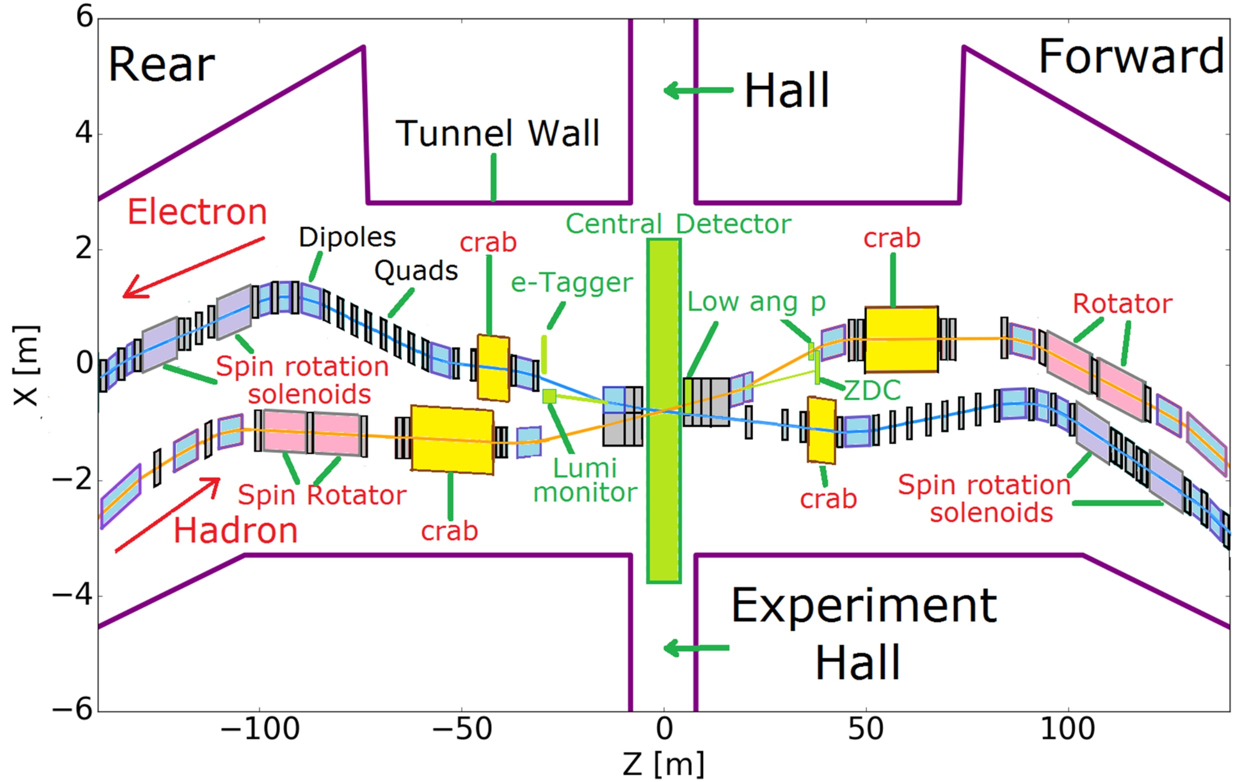
# IR-12

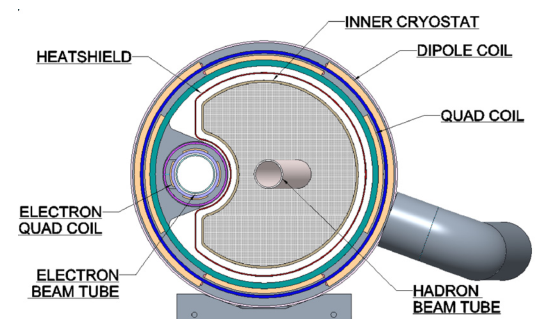


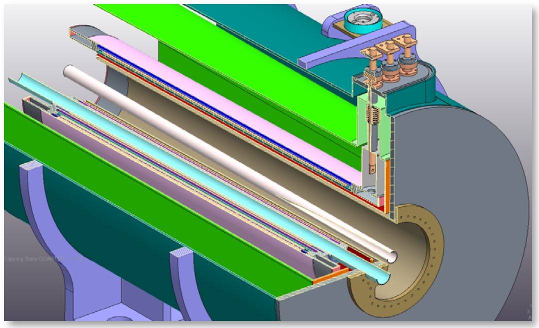

*Renderings by Doug Holmes and the design room*

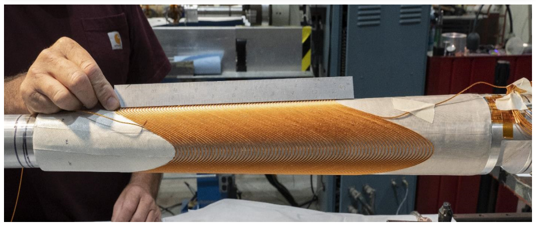
# Interaction Region

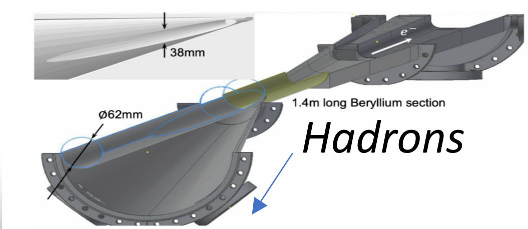
- *25 mrad crossing angle*
- *Superconducting  final focus magnets*
- *Crab cavities*
- *Spin rotators*
- *Large acceptance for forward scattered hadrons*





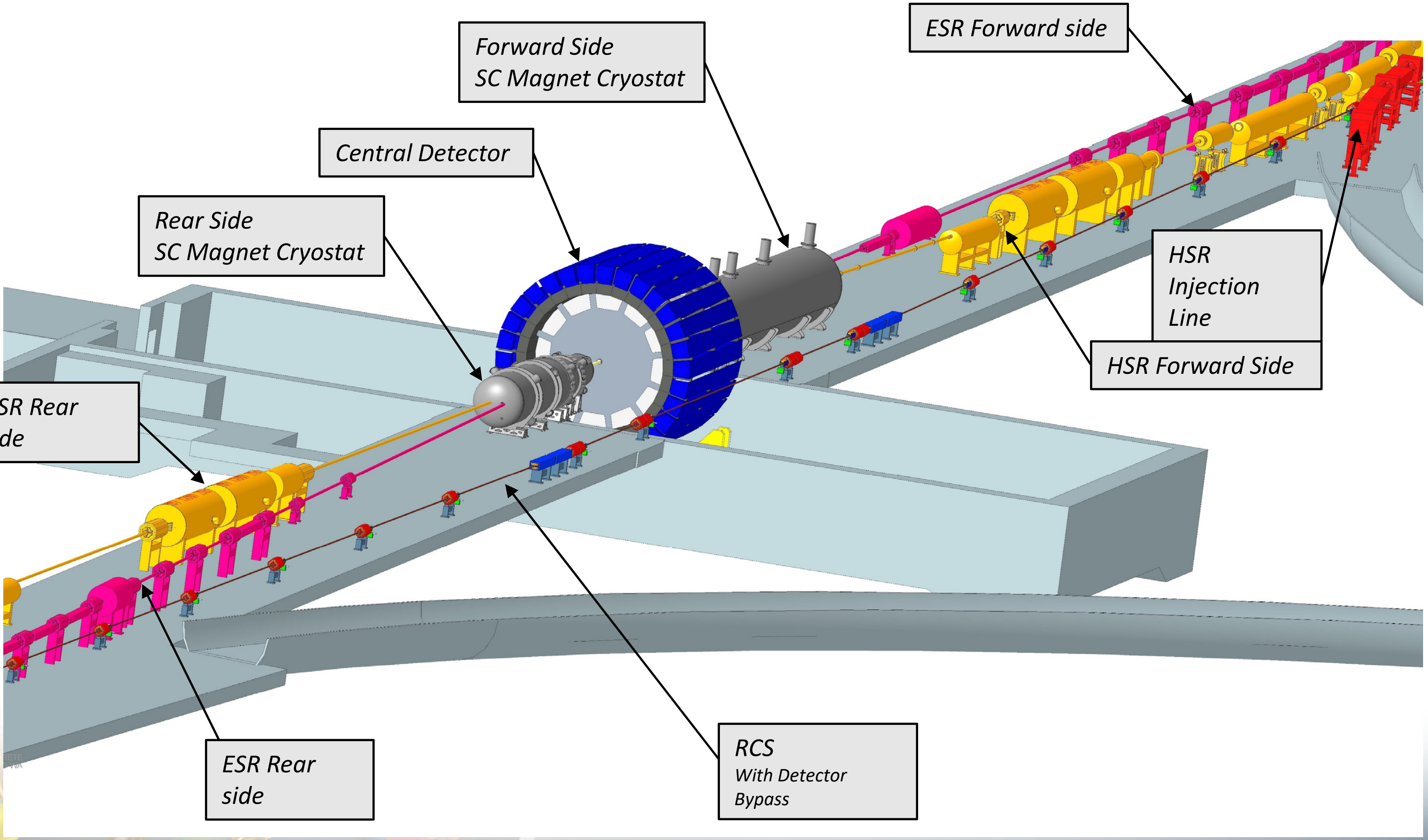






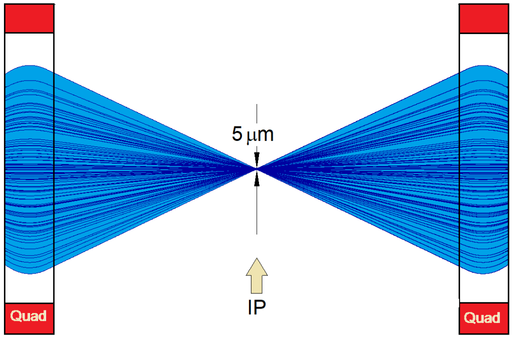

Electron-Ion Collider

# 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 divergence




- Particles with slightly different beam energies experience weaker/stronger focusing ("chromaticity") ➔ beam optics distortions: must be corrected to store a beam
- Need nonlinear sextupole magnets to compensate
- Contributions from IR where beam size is large and final focus quadrupoles a strong dominate➔ strong nonlinear sextupoles
- Strong sextupoles limit betatron oscillations (@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

# ESR polarization

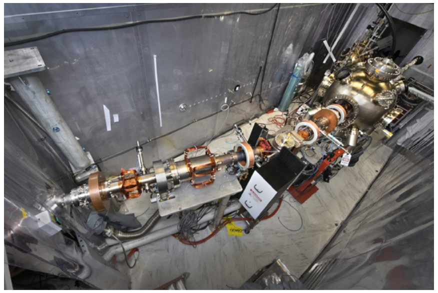
- In ESR, synchrotron radiation helps building up polarization slowly
- but there are counteracting effects that destroy polarization

➔ Equilibrium polarization is only 30%-60% in ESR, but need we 70-80%

- Buildup would work only for upward direction

➔ Electron polarization electrons created by polarized source

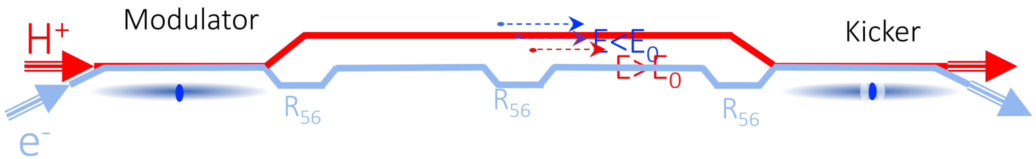
- and preserved during acceleration in the RCS (quite tricky)
- In ESR, long list of effects that destroy injected polarization



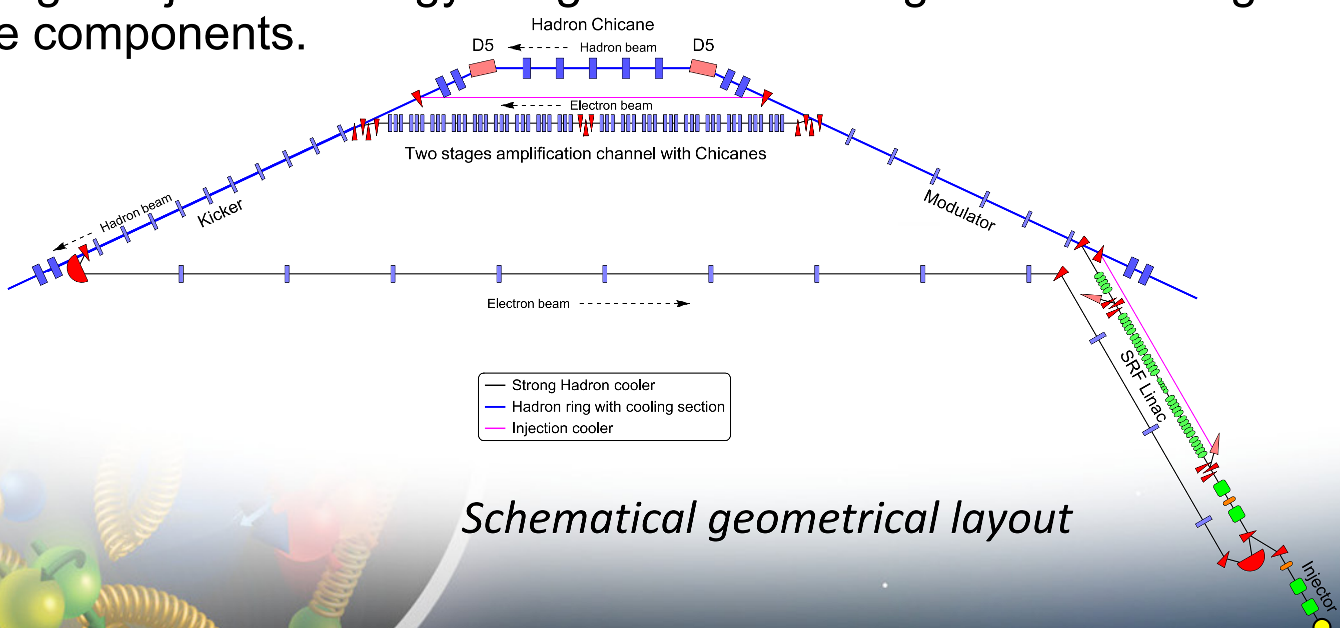
➔ need

  - Extremely careful orbit control (microns)
  - Extremely careful compensation of cross coupling between transverse planes
  - Very careful choice of tunes hor, vert, long, and spin
  - Careful compensation of detector solenoid by rotated quadrupoles

# Strong Hadron Cooling Design




- Cooling Concept unch 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.



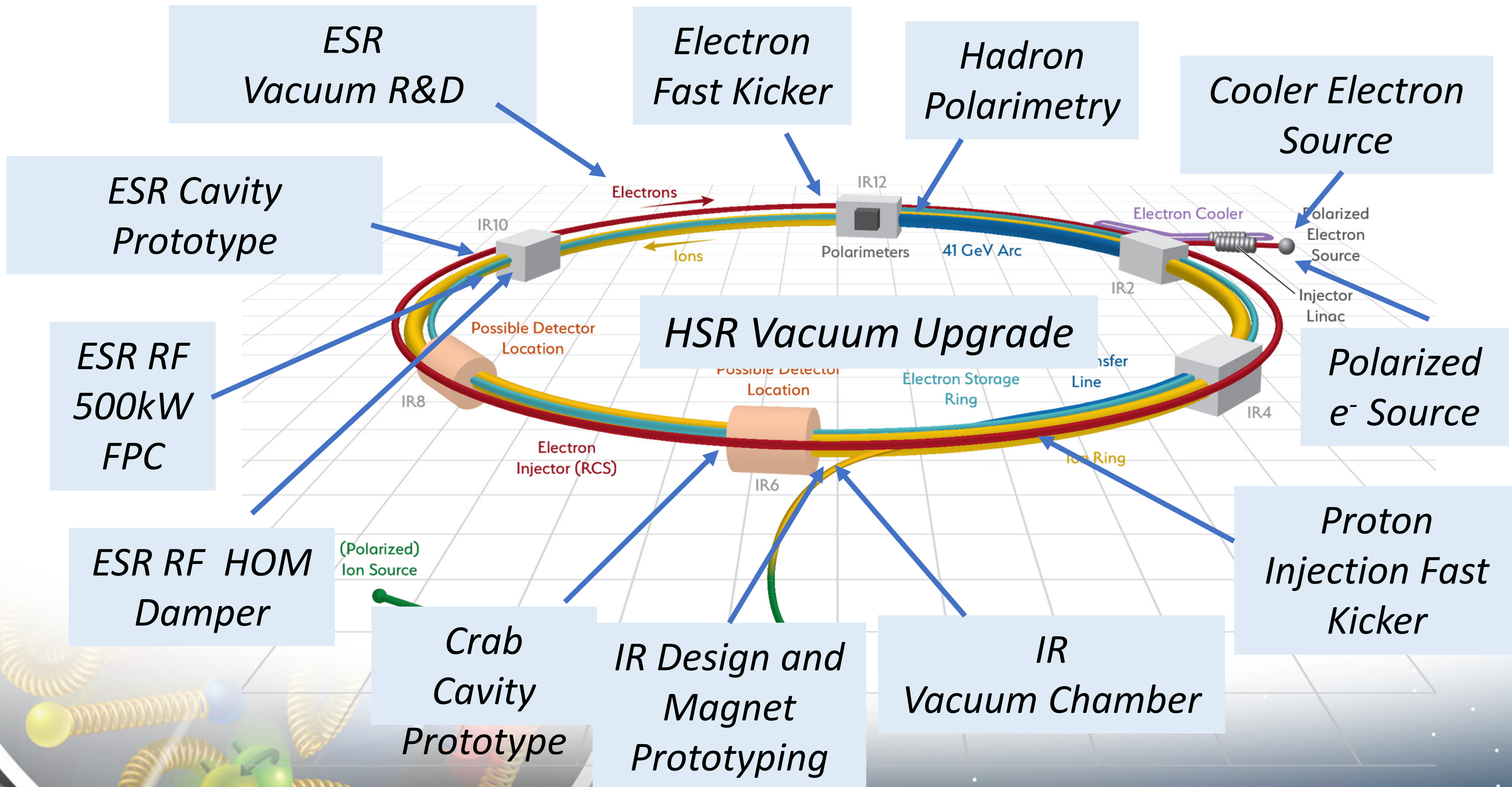

*Schematical geometrical layout*

# Progress in Beam Dynamics

- **Beam-Beam interaction:** Comprehensive simulations and studies investigating numerous effects. Simulations confirm feasibility of EIC beam-beam performance parameters.
- **ESR dynamic aperture**
  Now ensures sufficient dynamic aperture with 2 IRs @ 18GeV including magnet imperfections, sophisticated distribution of sextupole-magnets.
- **Collective effects and beam-vacuum vessel interaction** assessed and there are no issues with excessive heating by the beam or instabilities.
- **ESR Impedance** budget is complete with assessment of all vacuum hardware components.
- **Electron Beam Polarization:** Achieving required level of electron spin polarization up to 18 GeV with the vertical beam size required for stable beam-beam interaction resolved by “spin-matching” ESR beam optics.
- **Tolerance studies** for magnets, alignments, strength of correctors well underway.
- **Tolerances for crab cavity phase noise** worked out – very tight, also require strong direct feedback to suppress fundamental mode driven transverse instability. Requirement: Install RF power and controls on the accelerator tunnel berm, close to the cavities.

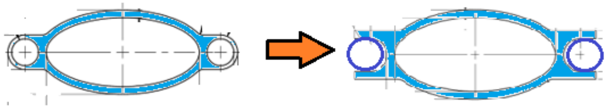
# Accelerator R&D Overview

EIC R&D is prototyping of novel, challenging, or critical components to obtain confidence for final design and production of the components in industry or in-house



# Progress in PED and R&D

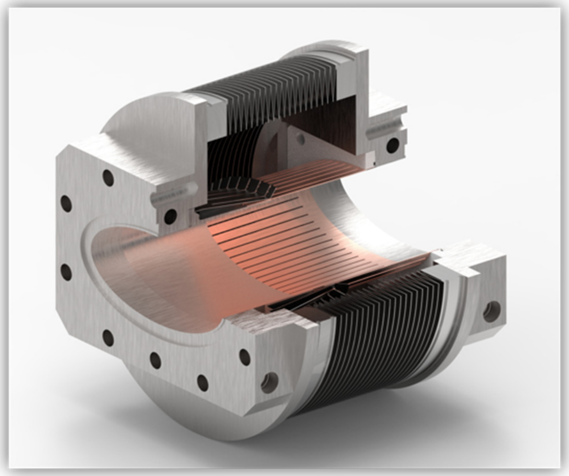
- **ESR and RCS Magnets** (WBS 6.04.02, 6.04.03, 6.03.02.01,6.03.02.02):
  - Value engineering efforts: Single turn coils changed to multi-turn coils (change request pending), RCS dipoles split into two (cost saving and manufacturing simplification)
  - Specifications for RFI developed, RFI published, 16 of 24 vendors responded positively.
- **ESR Vacuum** (WBS 6.04.05)
  - Vacuum chamber profile optimized for better manufacturability (extruded ➔ attached cooling chamber )



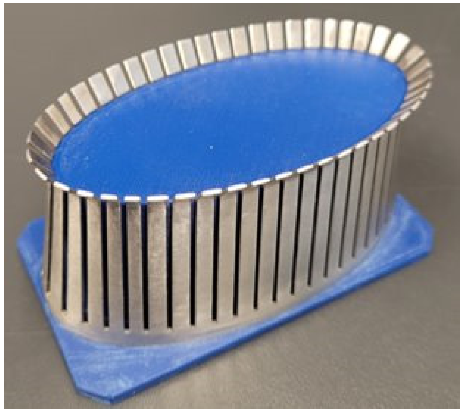
  - Shielded bellows: Fabrication of prototype in progress.
  - Novel self-supporting NEG strip design, greatly simplifies installation and activation

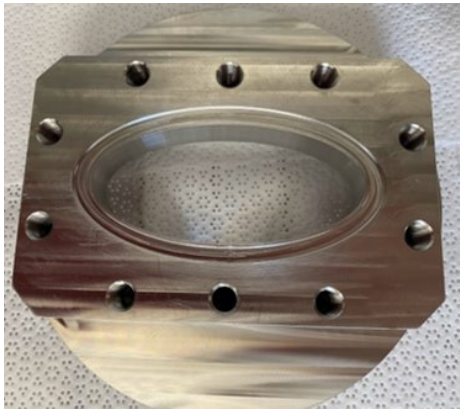
# ESR Vacuum: Shielded Bellows

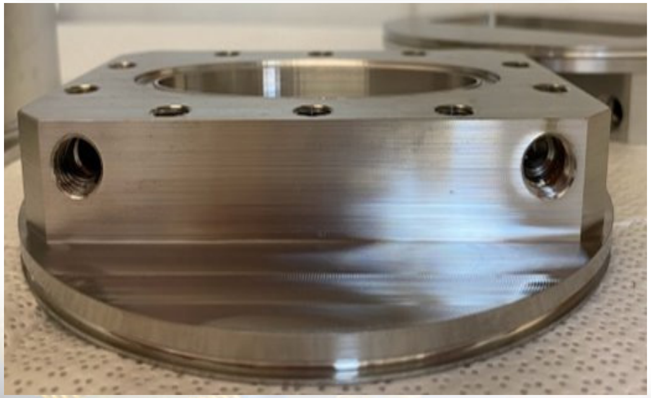
*Prototype Design*



*Manufactured parts for a prototype*





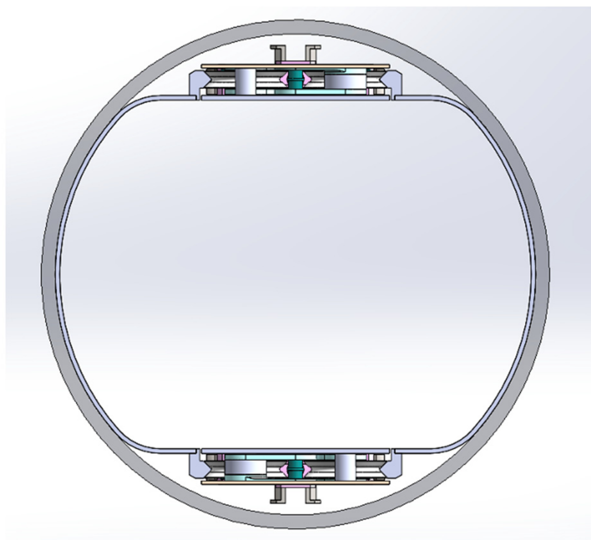


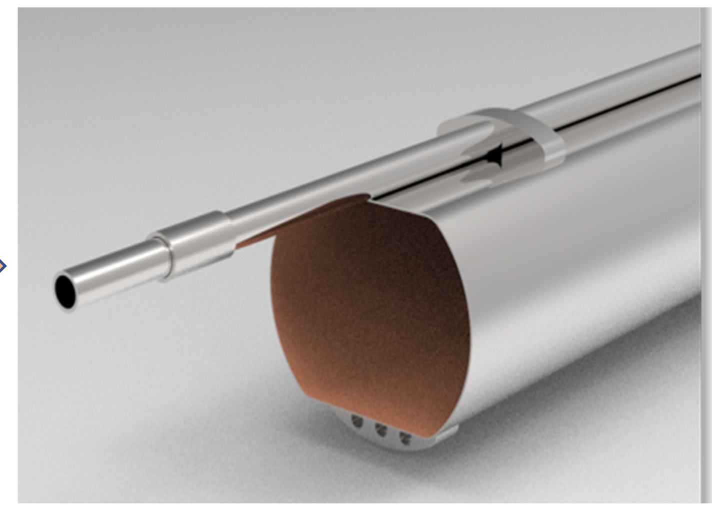
*Plans for lifetime testing*

# HSR Vacuum Cu/aC Coated Beam Screen

## WBS 6.05.04, 6.02.03.04

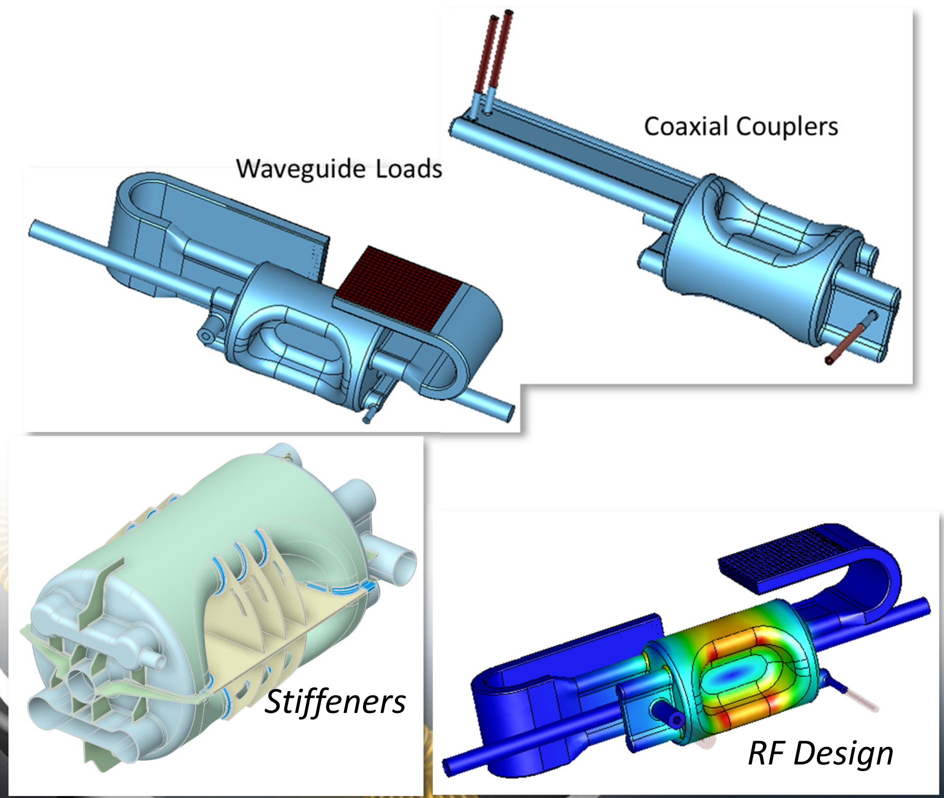
*HSR vacuum beam screen design change from passively cooled conduction cooling to actively cooled.*

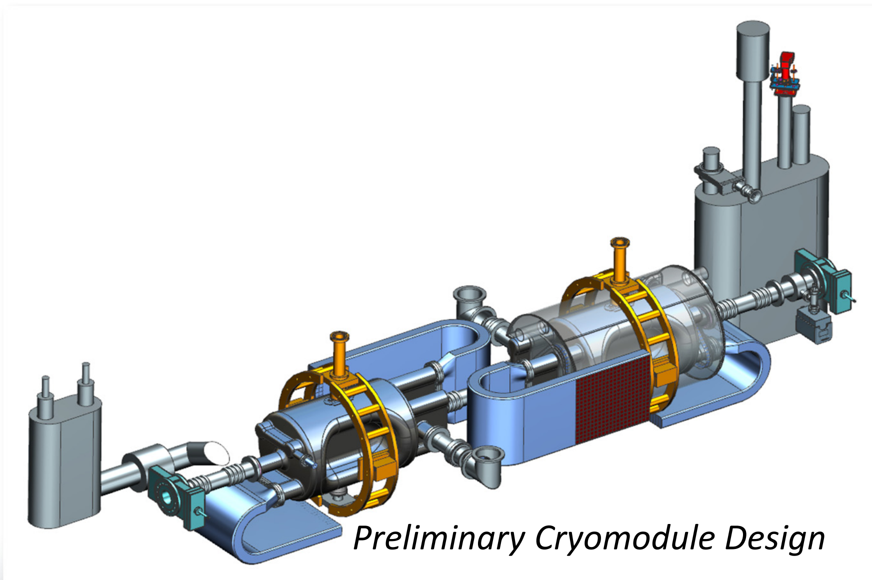




# 197 MHz Crab Cavity Status WBS 6.08.02.01

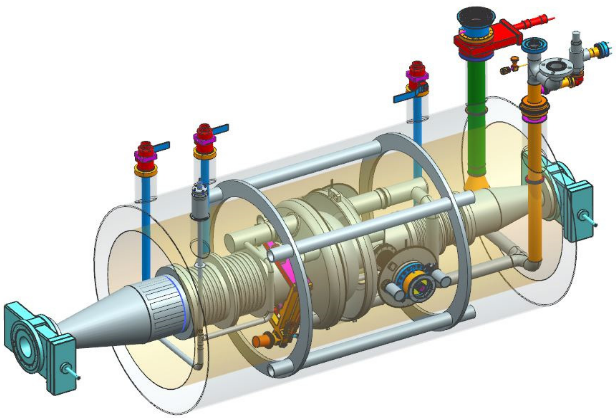
- 197 MHz HSR crab cavity is one of the cavities that will be prototyped first
- Bare cavity rf design is complete
  - Including HOM damping, FPC design
  - Two possible HOM damping schemes: Waveguide loaded and coaxial couplers
  - Waiting for final rf multipole specifications and are not considered in the current design
- Stress analysis is near completion
- Preliminary fabrication plan is completed



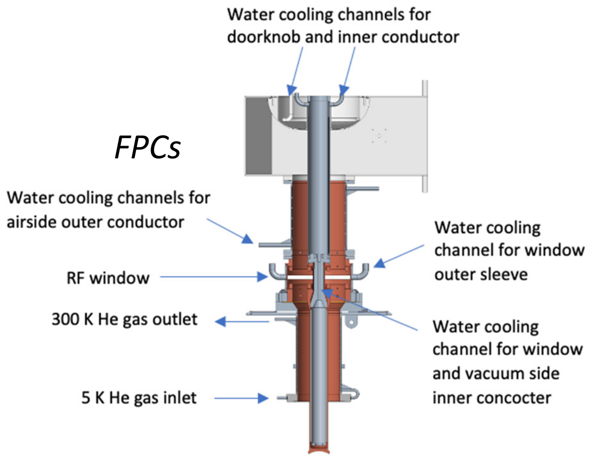



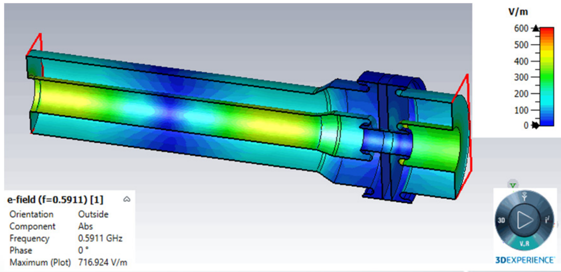
# R&D on High power FPC Status

- A high power ( CW 500 kW standing wave) alumina window FPC was designed for EIC ESR SRF cavity.
- The design was reviewed by an international technical review committee in June 2021.
- The review committee stated their “support moving forward with this design into prototype stage”.
- Detailed engineering design for window and vacuum side has been finalized and in the process of prototyping.
- FPC airside is almost finalized and getting ready to purchase materials for fabrication.

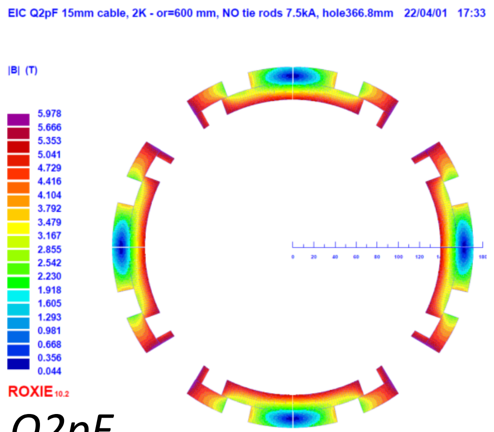


*Preliminary Cryomodule Design*

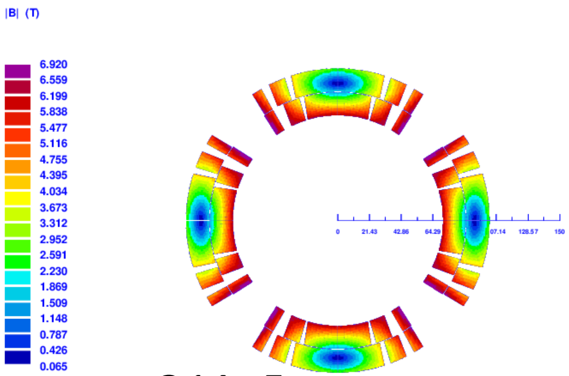


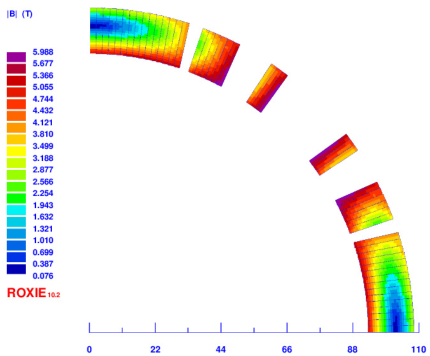
# SC IR Magnet R&D



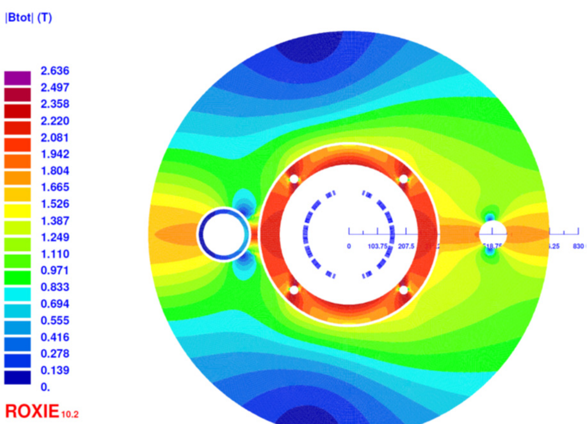

*Q2pF*



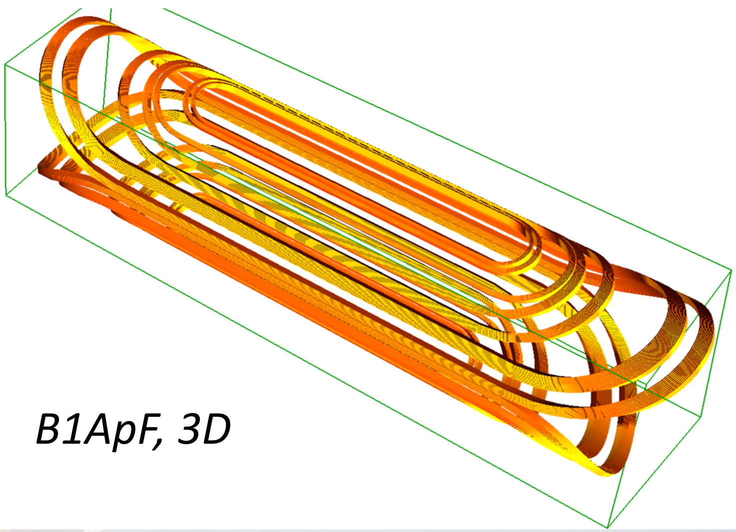

*Q1ApF*




*Q1BpF*

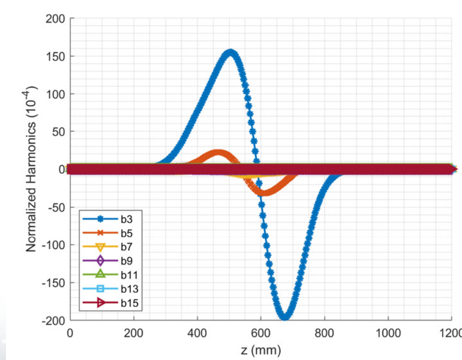



*B1pF*

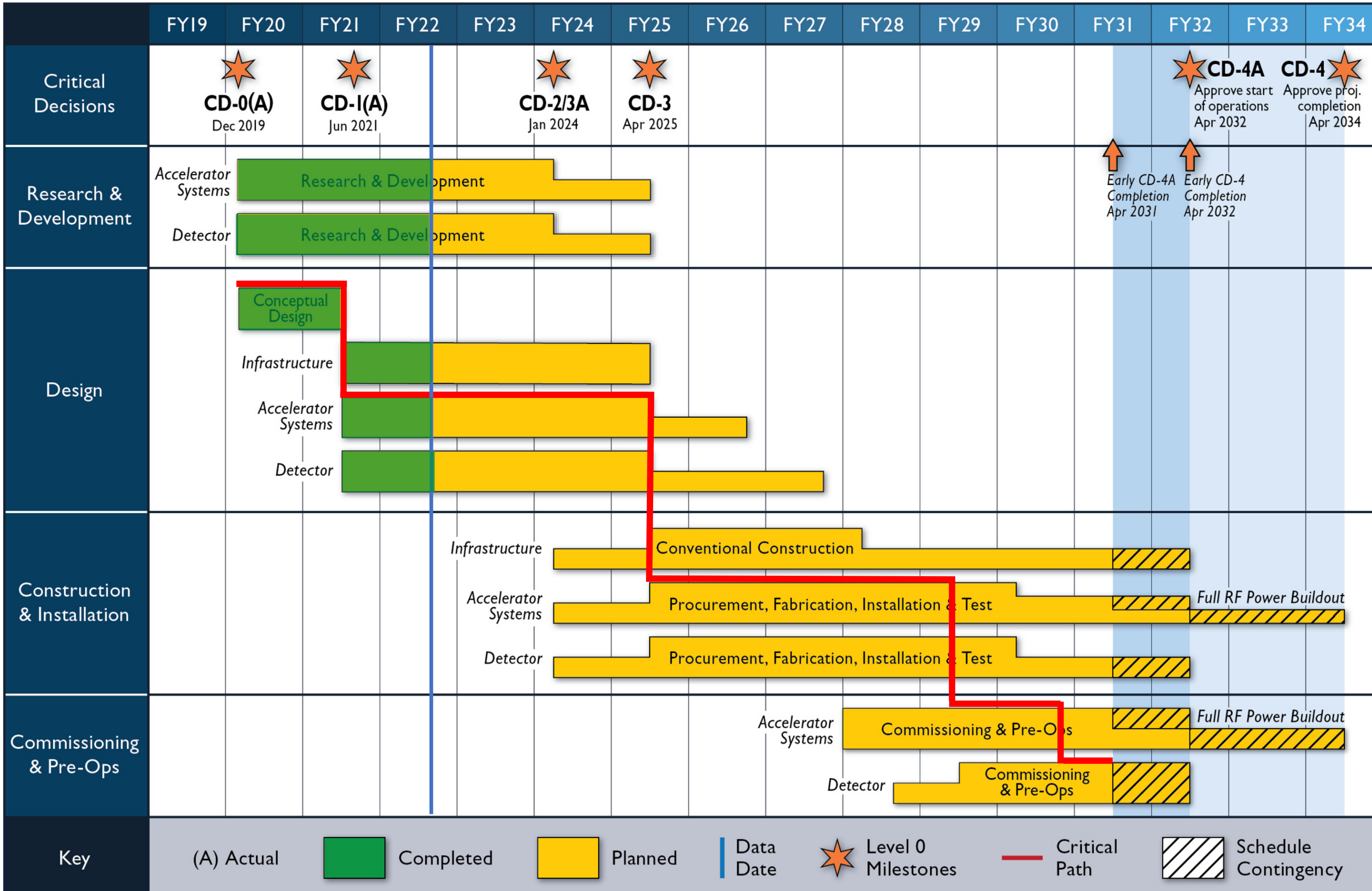


*B1ApF, 3D*

*B1ApF, end harmonic optimization*



# EIC Schedule

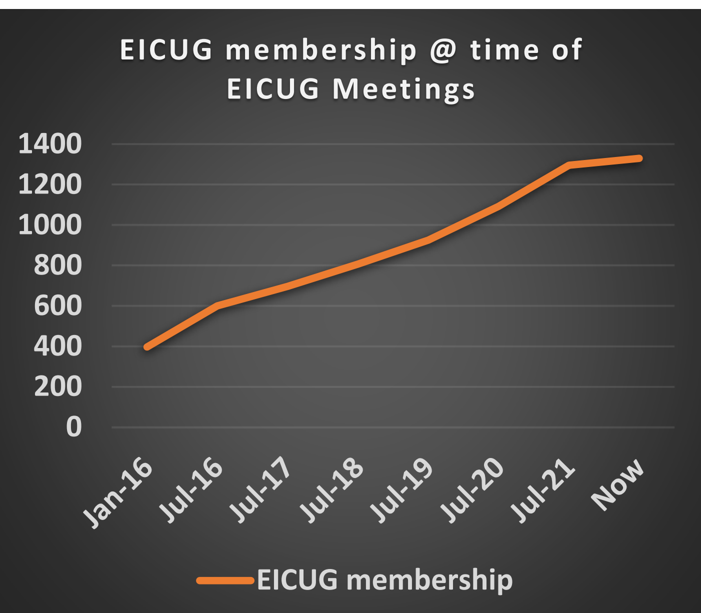


# Worldwide Interest in EIC

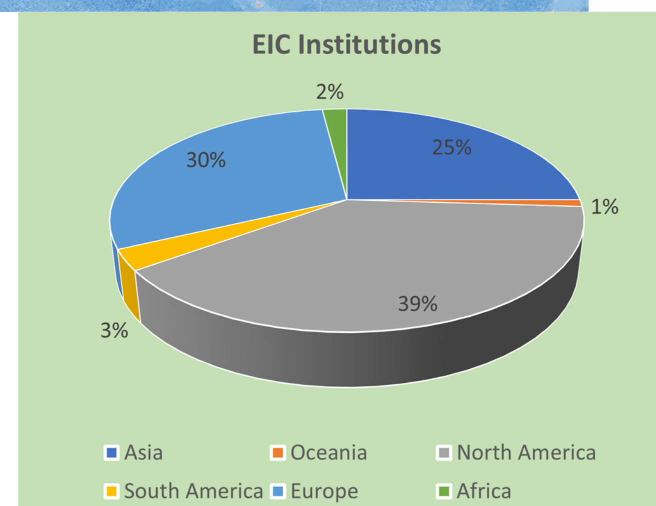
**The EIC Users Group:**
**https://eicug.github.io/**

**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 is still in an early stage
- The project will increase collaboration with other DOE laboratories to deliver the EIC scope.
- Scientists and Engineers contributing to EIC are developing into a strong competent team that will deliver the EIC project.