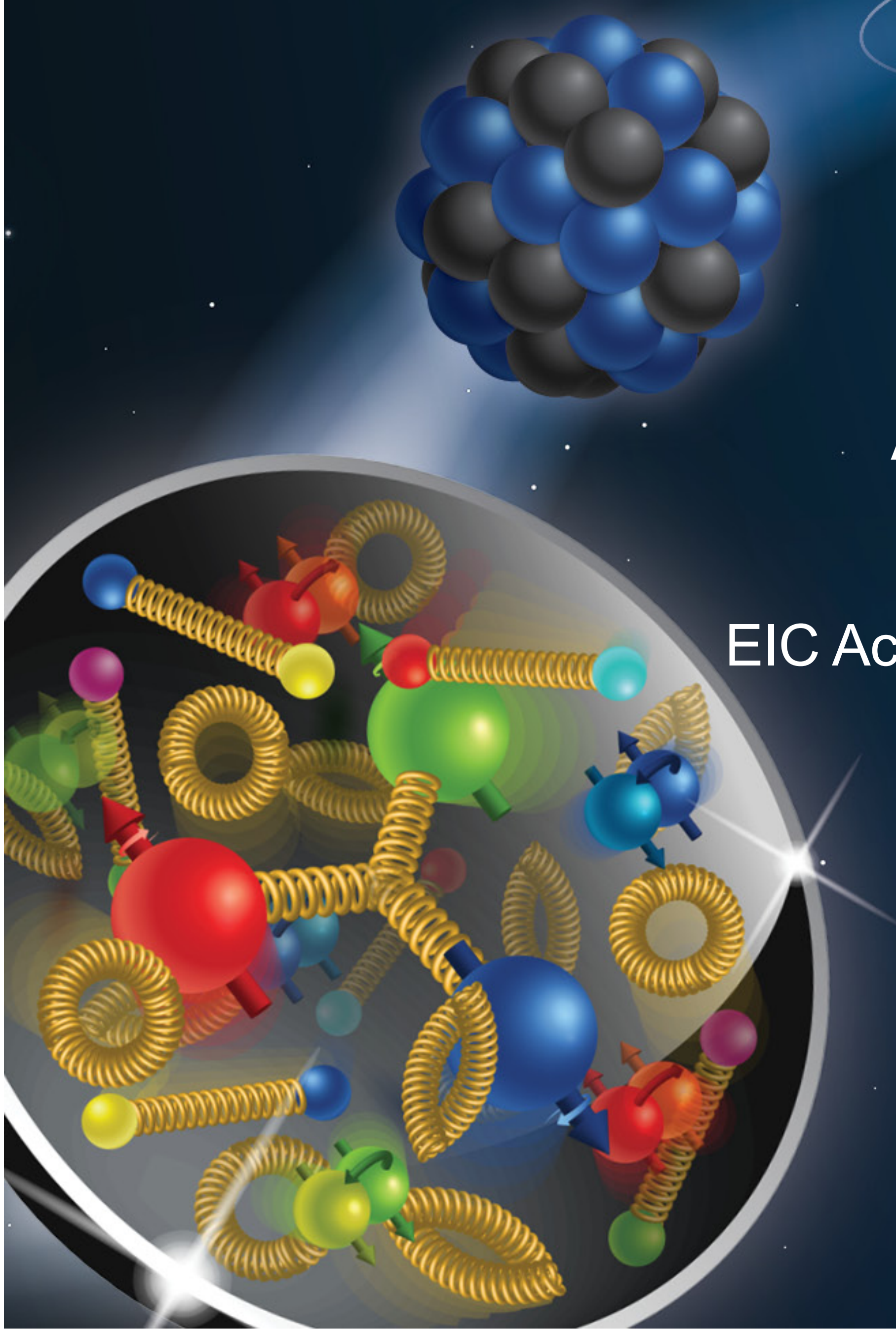


Accelerator Overview

T. Satogata, JLab/ODU
EIC Accelerator Development/Pre-Ops L2 Deputy
EIC Partner Project Associate Manager

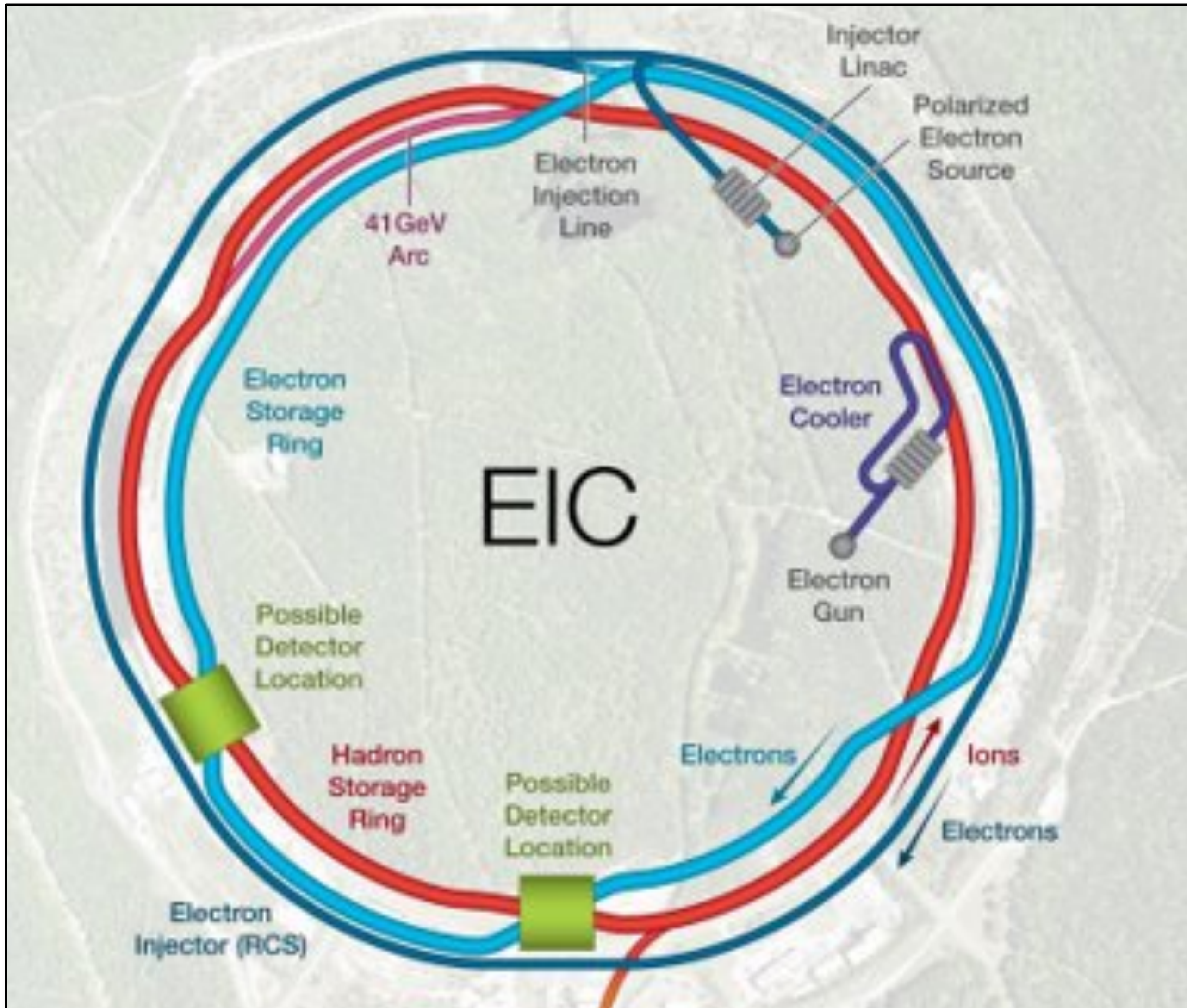
EIC User's Group Meeting
July 26-29 2022

Electron-Ion Collider

Brookhaven National Laboratory · Jefferson Lab · U.S. Department of Energy Office of Science

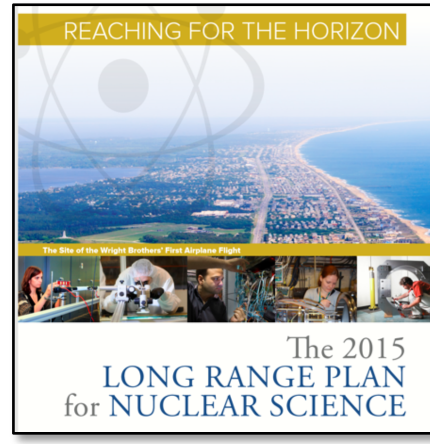
Outline

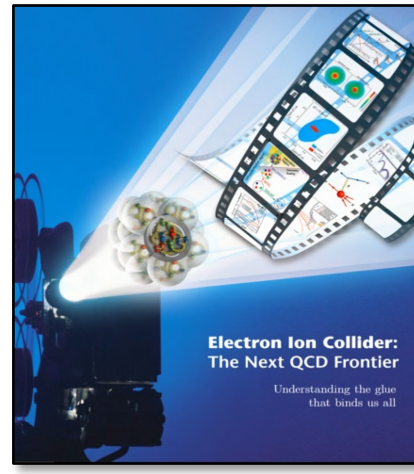
- Requirements
- Accelerator
  - Design overview
  - Design progress
  - Engineering layout
  - Beam dynamics
  - R&D progress
  - Cooling
- Partnerships
- Summary

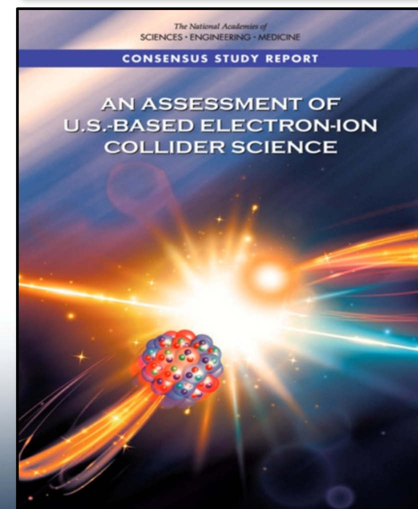


Requirements

- EIC Design Goals
  - High Luminosity: $L = (0.1\text{-}1)\cdot10^{34}\ cm^{-2}s^{-1} \rightarrow 10\text{-}100\ fb^{-1}$
  - 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
    - acceptable 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



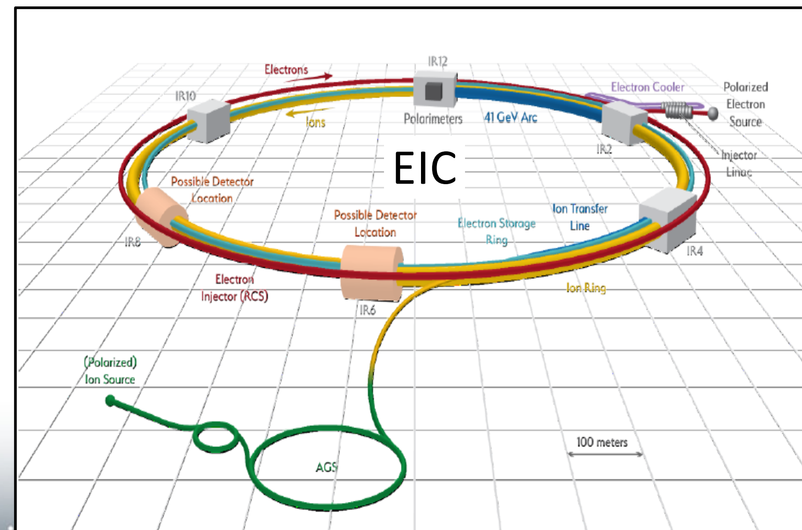




EIC Design Overview

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

- **Hadron storage ring (HSR): 40-275 GeV** (existing)
  - up to 1160 bunches, 1A beam current (3x RHIC)
  - bright vertical beam emittance 1.5 nm
  - strong cooling (coherent electron cooling, ERL)
- **Electron storage ring (ESR): 2.5–18 GeV** (**new**)
  - up to 1160 polarized bunches
    - high polarization by continual reinjection from RCS
  - large beam current (2.5 A) ➔ 9 MW SR power
  - superconducting RF cavities
- **Rapid cycling synchrotron (RCS): 0.4-18 GeV** (**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 (produce longitudinal spin at IP)
  - forward hadron instrumentation



Progress on Accelerator Design

- Since the last user's group meeting, we have **advanced and matured** the accelerator lattices and resolve corresponding design issues.
- The **design fundamentals have not changed significantly** in the past year.
- Designs are now **very robust** and provide a solid base for the engineering design of accelerator hardware components.

Progress on Accelerator Design

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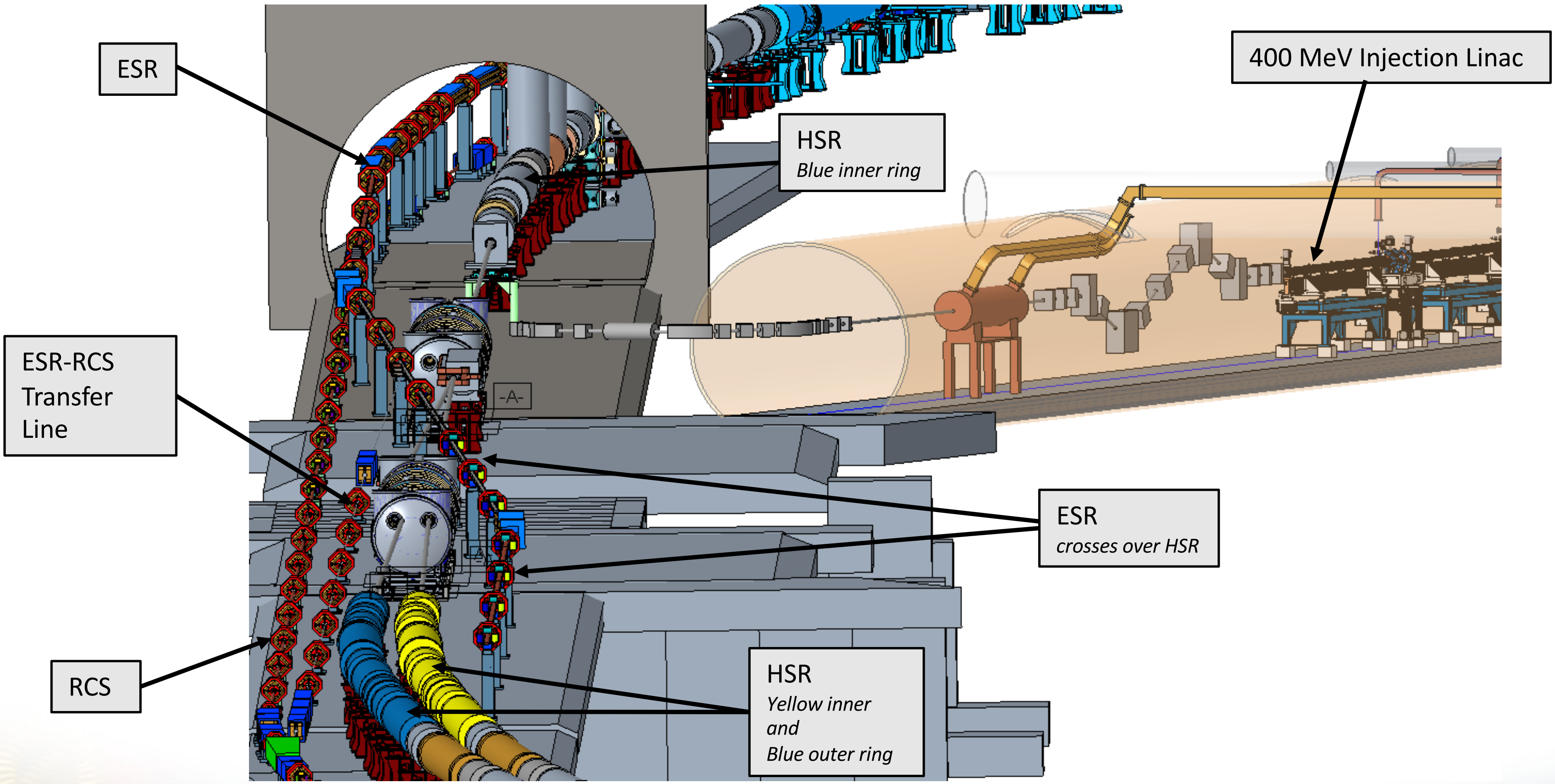
E
- **Electron injection** moved from IR2 to IR12
- **RCS accelerator lattice design** complete
- **Electron injection into ESR** modified: Eliminated slow bumps, slow residual effects on global orbit/IR steering. Now using stronger fast kickers, investigating nonlinear injection.
- **ESR accelerator lattice design** is nearly complete

I
- **Strong Hadron Cooling ERL** moved from ring outside to ring inside, decoupled from injector
- **Hadron straight sections**: beam transport uses now normal conducting dipoles instead of superconducting dipoles
- Many details on **HSR lattice** resolved; "closed" lattice available for tracking
- **Low energy HSR bypass** was moved from sector 2-12 to sector 12-10, now use 4 sextants from the yellow ring and two sextants from the blue ring for the HSR

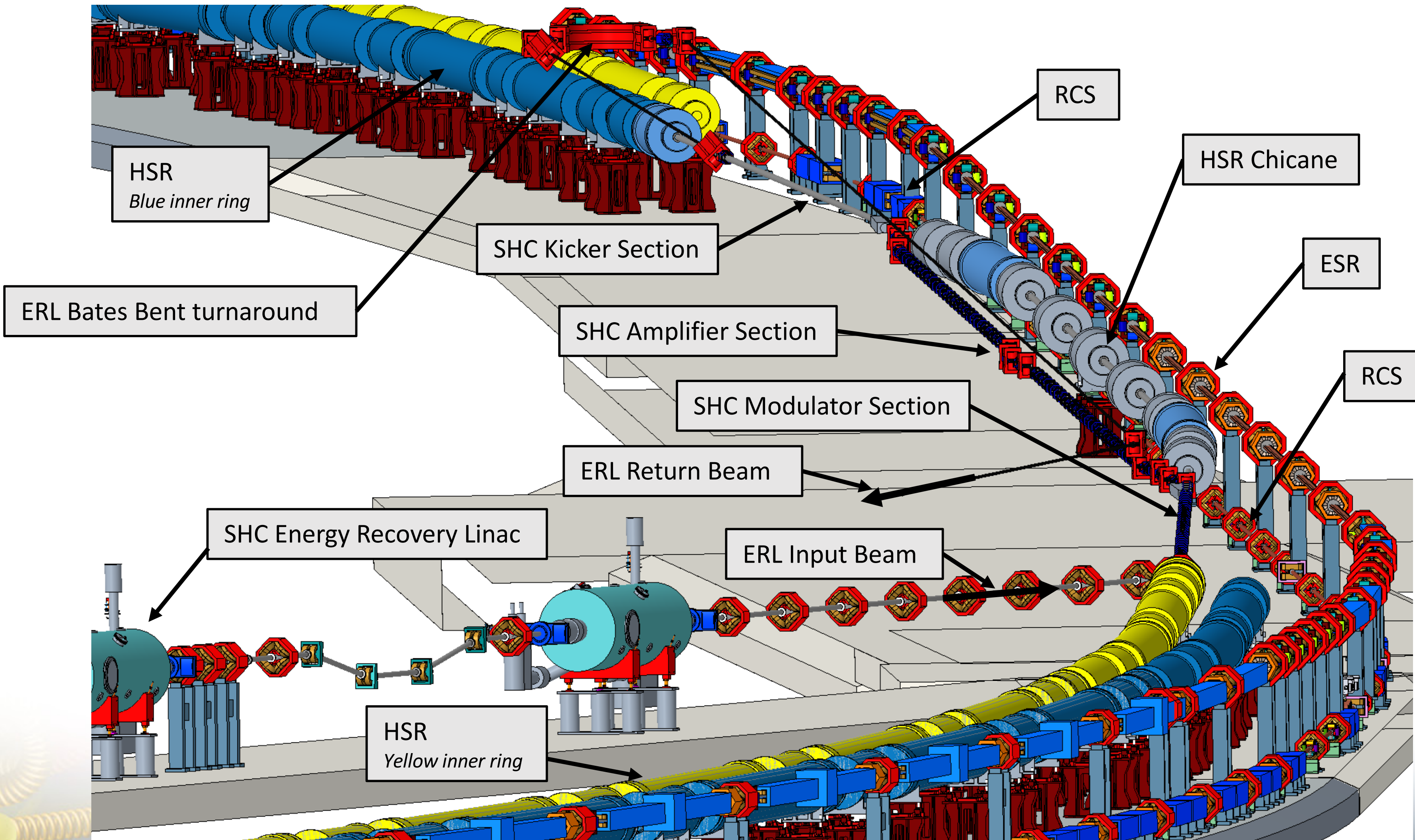
C
- **Interaction region further matured:** lattice stable, synchrotron radiation masking laid out, collimation design in progress

IR12

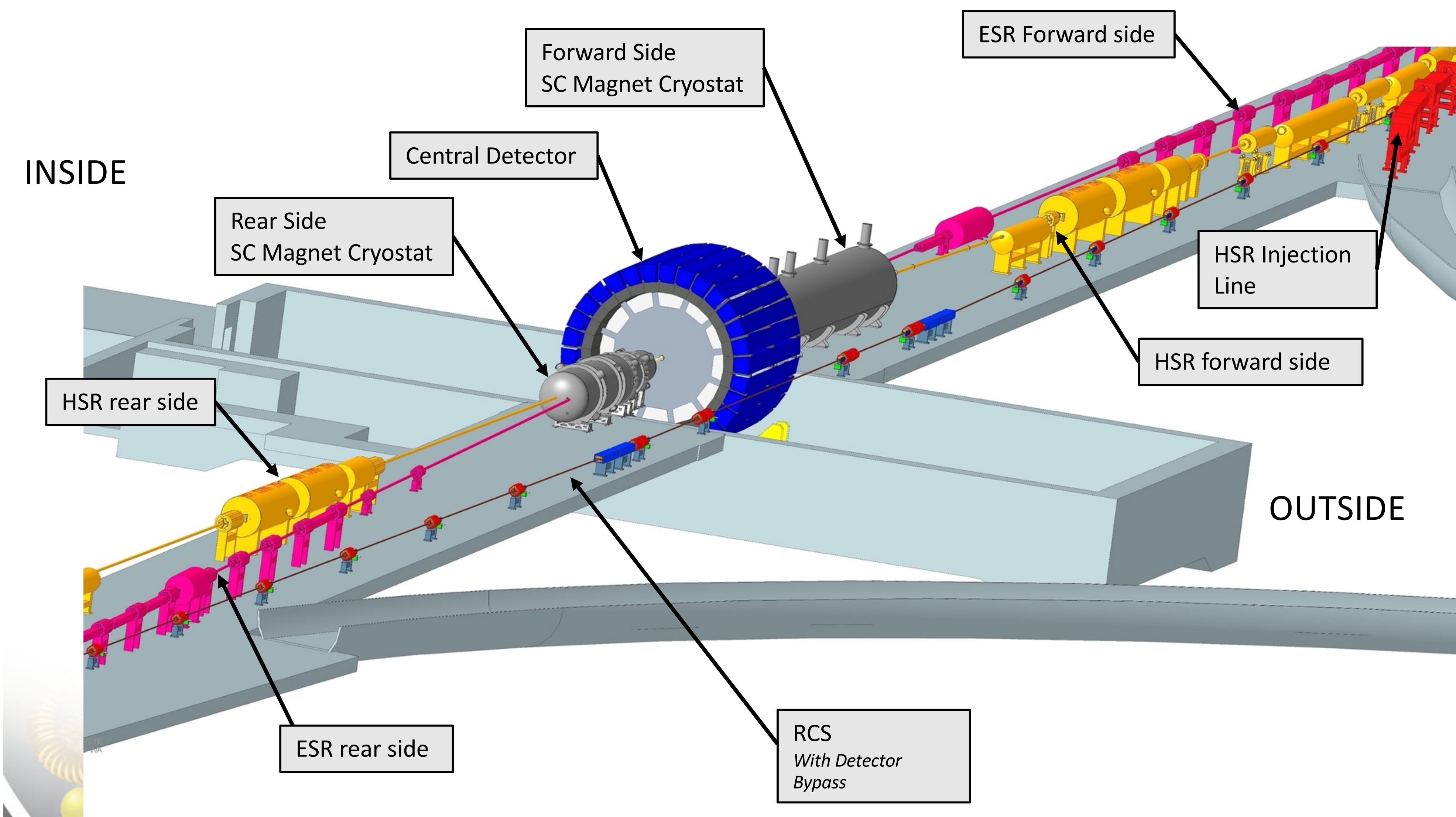


ESR
400 MeV Injection Linac
HSR
Blue inner ring
ESR-RCS
Transfer
Line
ESR
crosses over HSR
RCS
HSR
Yellow inner
and
Blue outer ring

IR2

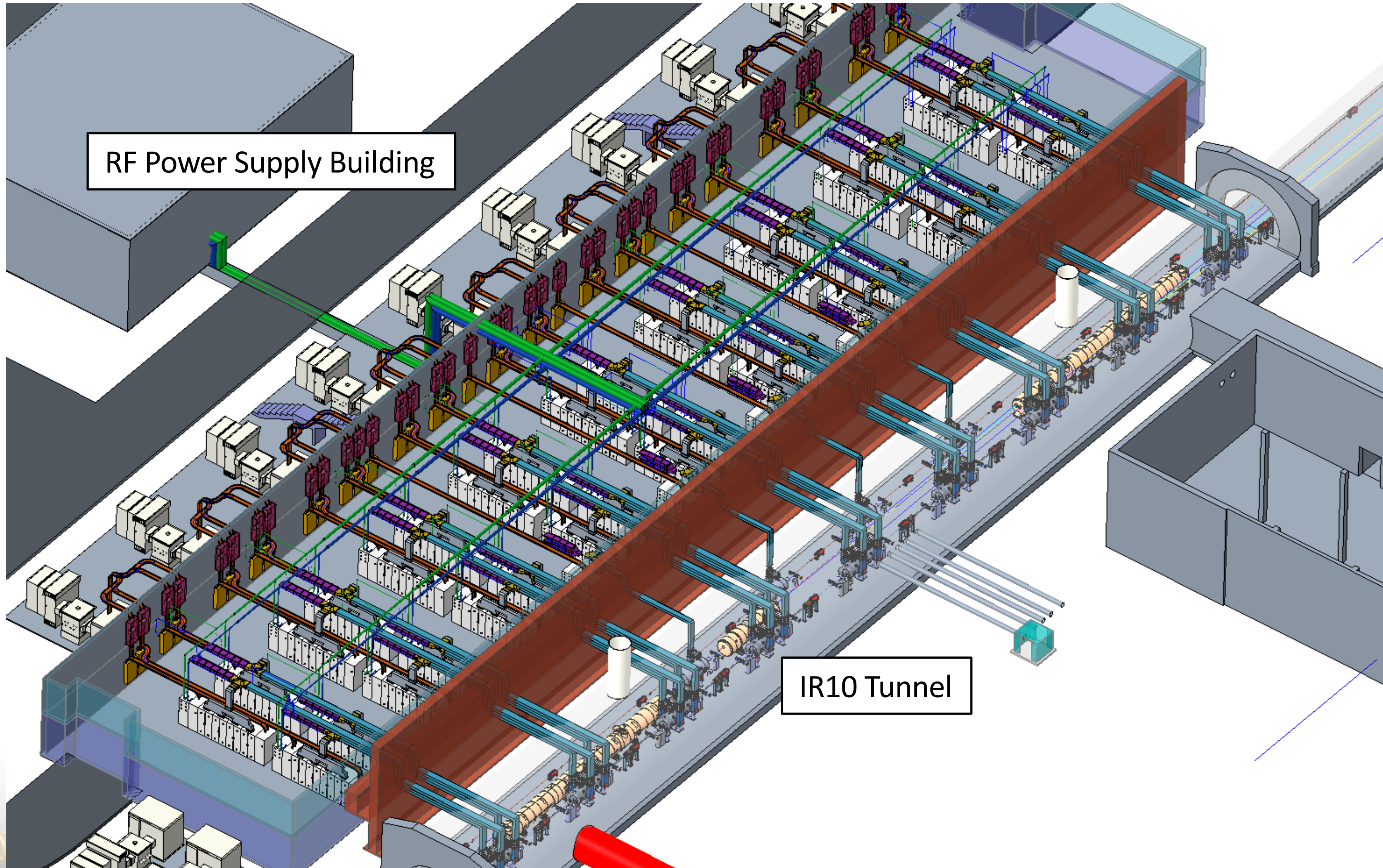

HSR
Blue inner ring
ERL Bates Bent turnaround
SHC Kicker Section
RCS
HSR Chicane
ESR
SHC Amplifier Section
SHC Modulator Section
RCS
ERL Return Beam
SHC Energy Recovery Linac
ERL Input Beam
HSR
Yellow inner ring

IR6



INSIDE
OUTSIDE
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

IR10



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**
    - Ensures sufficient dynamic aperture with 2 IRs at 18 GeV including magnet imperfections; sophisticated distribution of sextupole-magnets.
- **Collective effects and beam-vacuum vessel interaction**
    - Assessed, with no issues from excessive heating by the beam or instabilities.
- **ESR Impedance**
    - Budget 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.
- **Crab cavity phase noise tolerances**
    - Very tight; require strong direct feedback to suppress fundamental mode driven transverse instability.
    - **Requirements:** Install RF power and controls on the accelerator tunnel berm, close to the cavities, fabrication modifications to correct crab cavity nonlinear sextupole fields

EIC Accelerator R&D Scope

ESR (arc) Vacuum Chamber

Electron Fast Kicker

Cooler Electron Source

Cooler SRF

ESR Cavity

500kW FPC

HOM Damper

HSR Vacuum Upgrade

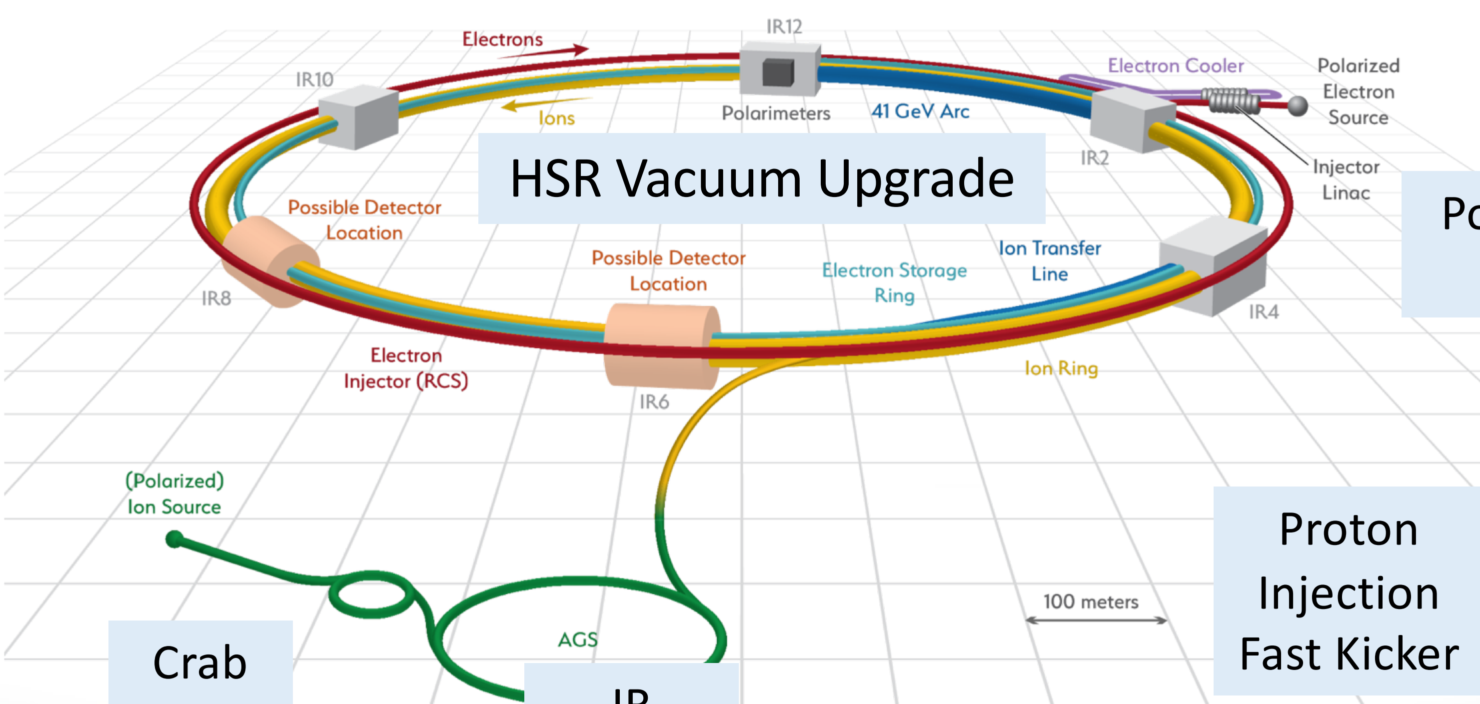
Polarized e$^-$ Source

Proton Injection Fast Kicker

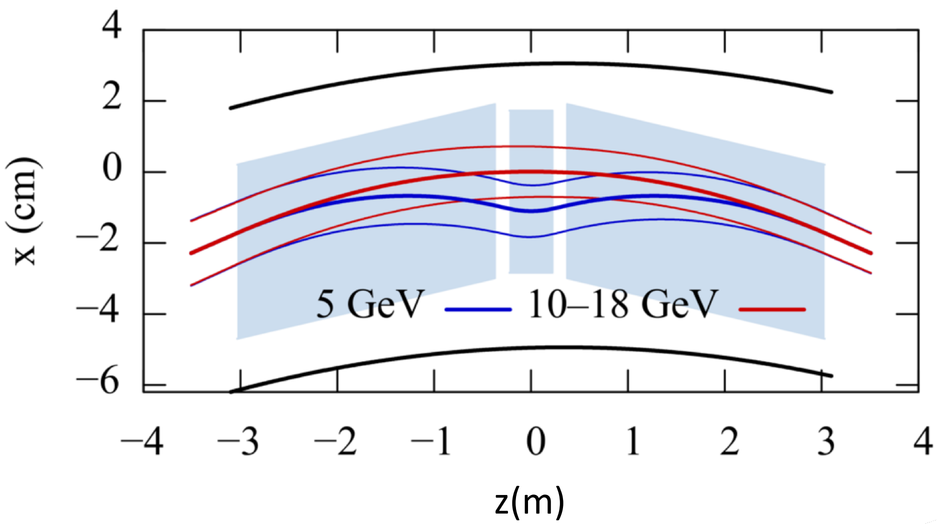
Crab Cavity

IR Magnet

IR Vacuum Chamber



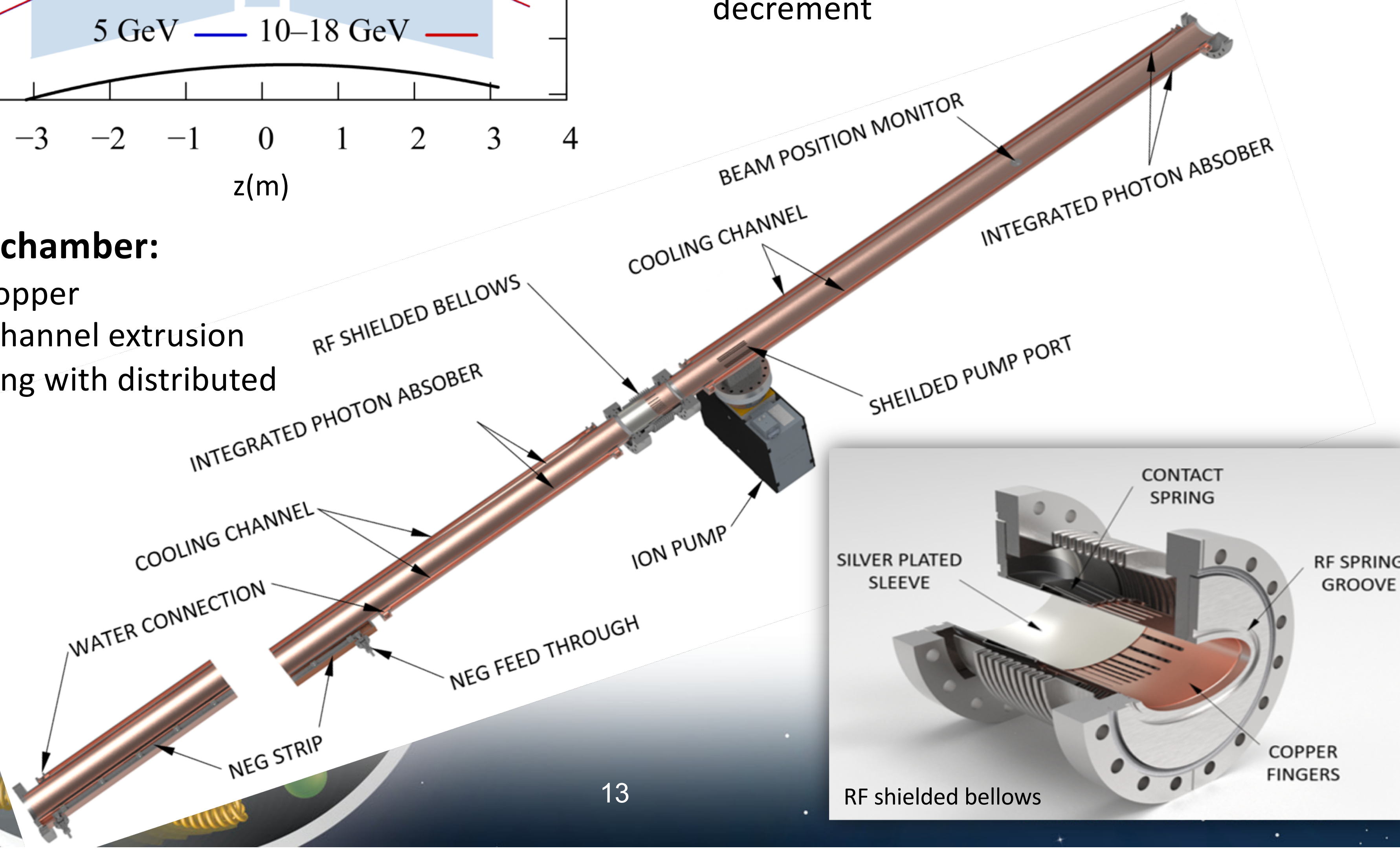
Electron Storage Ring



- Above 10 GeV, all segments powered uniformly to reduce SR power
- At 5 GeV, short center dipole provides a reverse bend to increase damping decrement

Vacuum chamber:

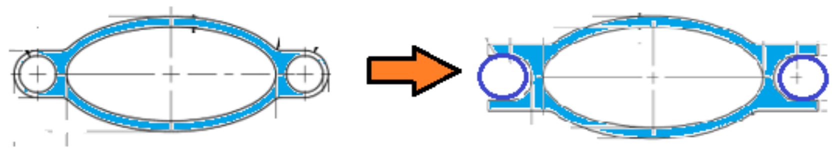
- OFE Copper
- Multichannel extrusion
- Pumping with distributed NEG



RF shielded bellows

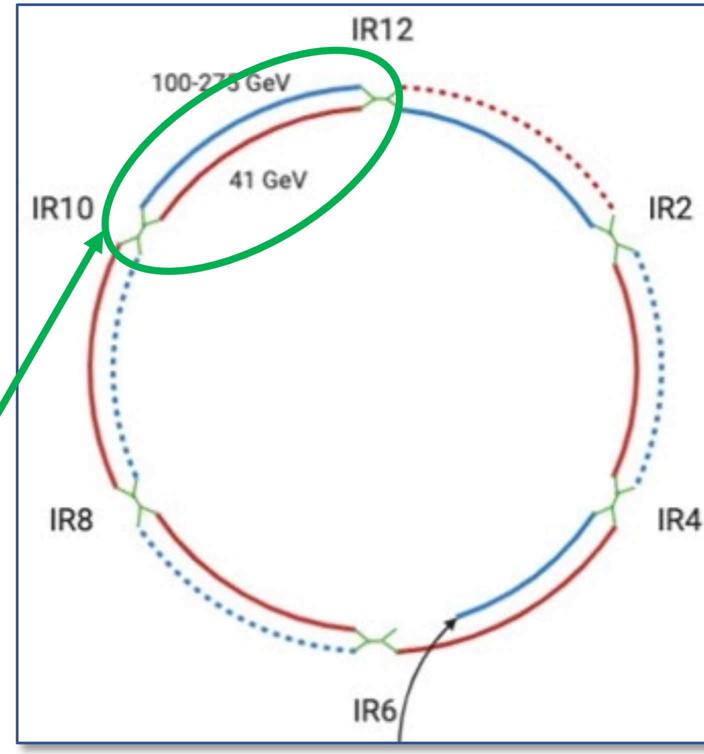
ESR Engineering, Vacuum R&D

- **ESR and RCS Magnets**
  - Single turn coils changed to multi-turn coils (change request pending)
  - RCS dipoles split into two (cost saving and manufacturing simplification)
  - Engagement with magnet vendors and possible DOE lab collaborations
- **ESR Vacuum**
  - Vacuum chamber profile optimized for better manufacturability (extruded ➔ attached cooling chamber)



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

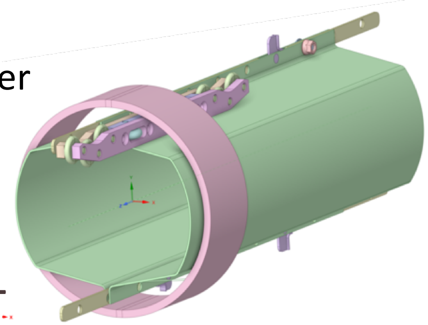
Hadron Storage Ring



- Existing RHIC with superconducting magnets supports E_p = 41 - 275 GeV
- HSR pathlength must be reduced for 41 GeV ops to maintain f_{rev} and collision synchronism
  - Accomplished by using one RHIC blue ring arc as a pathlength adjustment bypass
  - Requires reversing one arc of quench protection diodes
  - Other hadron pathlength adjustments feasible with arc radial shifts

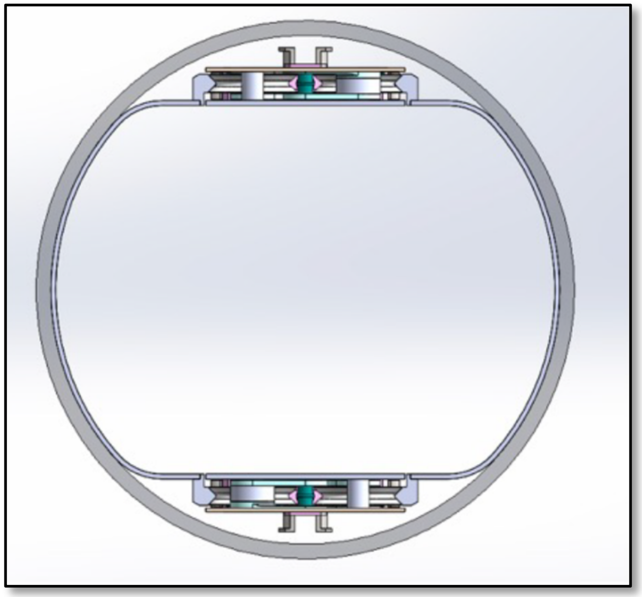
Hadron Ring Vacuum chamber upgrade

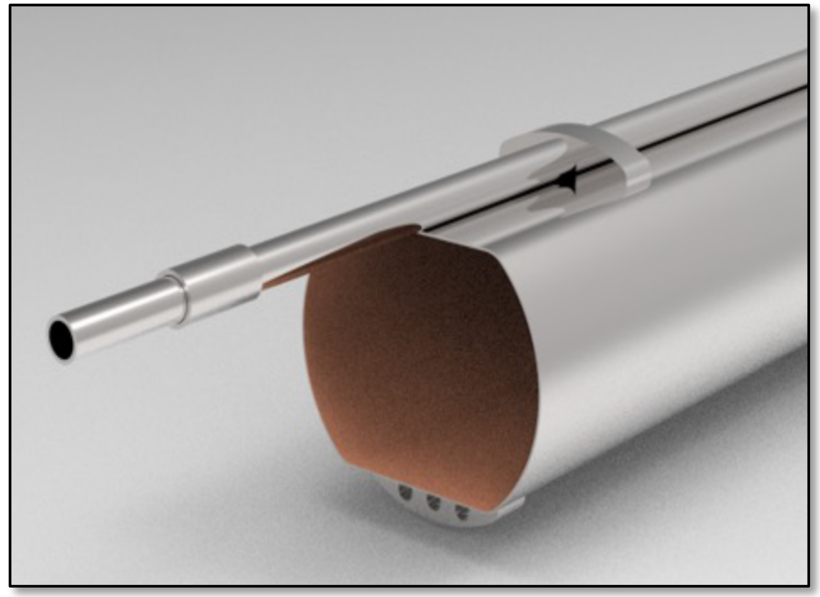
- Two main concerns towards existing RHIC vacuum pipes during EIC operation with higher current and shorter bunch length:
  - Resistive-wall impedance
  - e-cloud buildup
- Solution: **copper-clad stainless-steel screen + amorphous Carbon (aC) thin film**
  - *Cu significantly reduces surface resistivity, especially at cryo temps*
  - *aC reduces secondary electron yield*



conceptual design (being updated to active cooling) see next slide

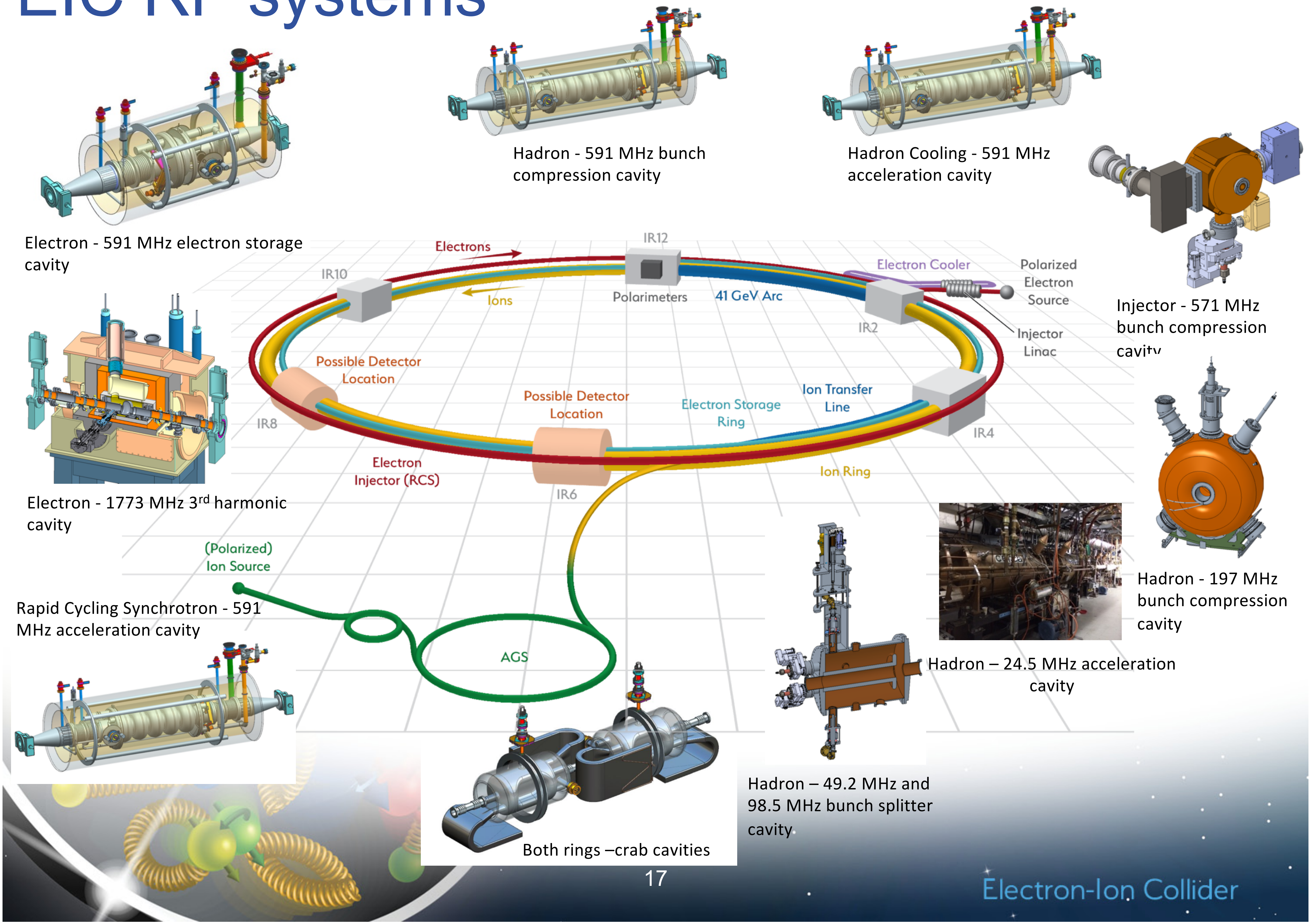
HSR Vacuum Cu/aC Coated Screen





- HSR vacuum liner cooling changed from passively cooled (contact with RHIC beam pipe) to actively cooled

EIC RF systems



Electron - 591 MHz electron storage cavity

Hadron - 591 MHz bunch compression cavity

Hadron Cooling - 591 MHz acceleration cavity

Injector - 571 MHz bunch compression cavity

Electron - 1773 MHz 3rd harmonic cavity

Hadron - 197 MHz bunch compression cavity

Rapid Cycling Synchrotron - 591 MHz acceleration cavity

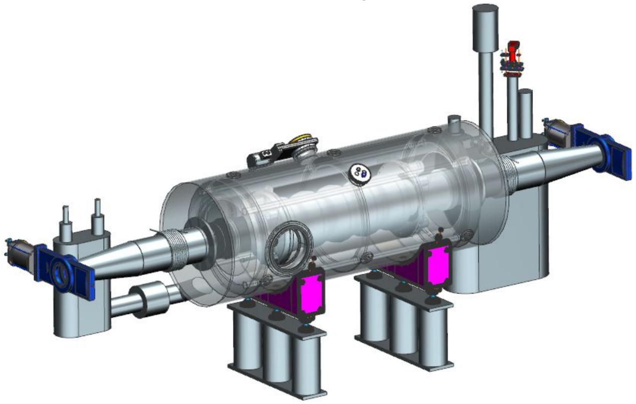
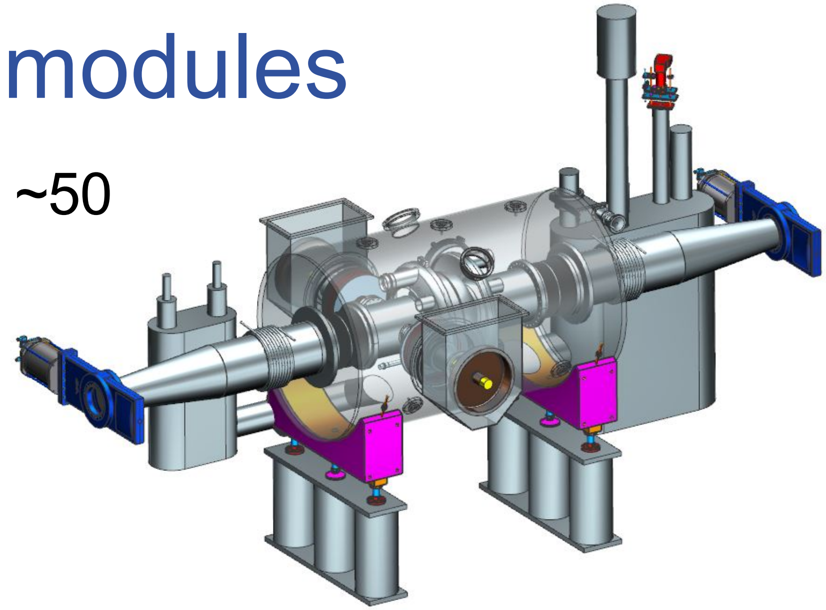
Hadron – 24.5 MHz acceleration cavity

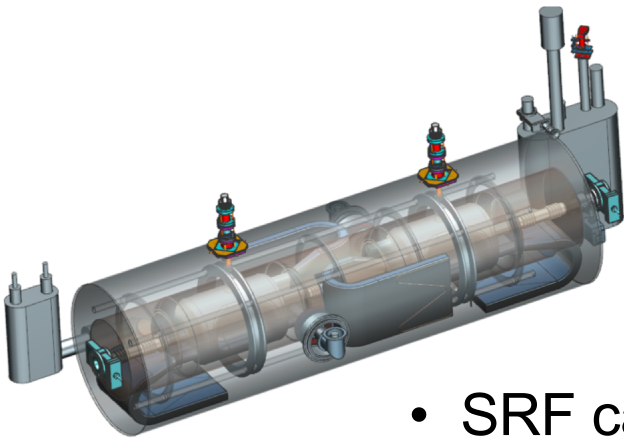
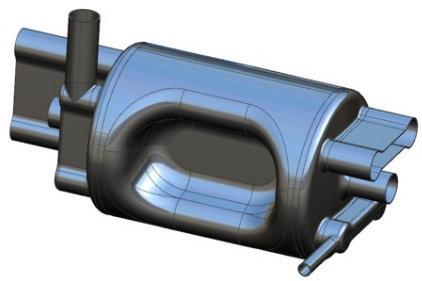
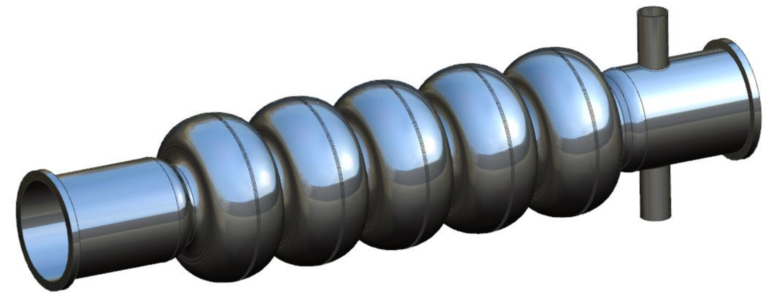
Hadron – 49.2 MHz and 98.5 MHz bunch splitter cavity

Both rings –crab cavities

EIC SRF Cavities & Cryomodules

- Several cryomodule types required, total ~50

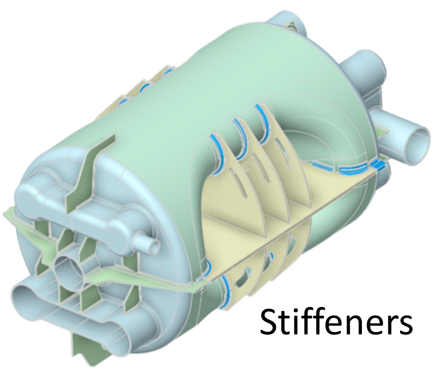



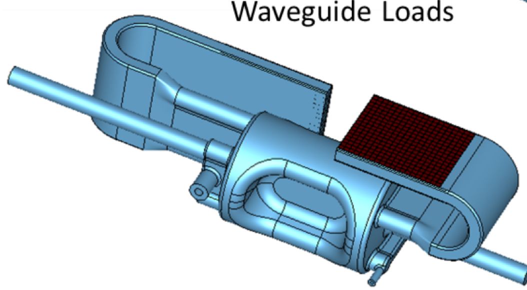




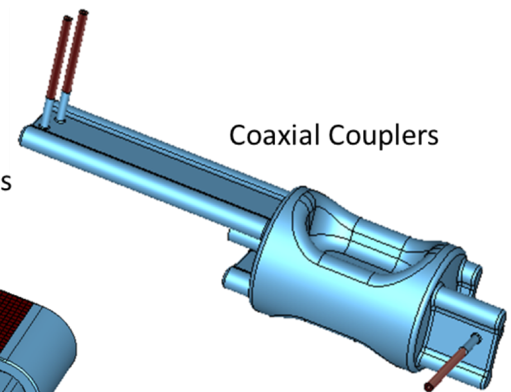
- SRF cavities, 197-1773 MHz
  - High RRR, fine grain, Niobium sheet cavities
  - 5 types, 3 elliptical and 2 non-elliptical, quantities ~ 4-20

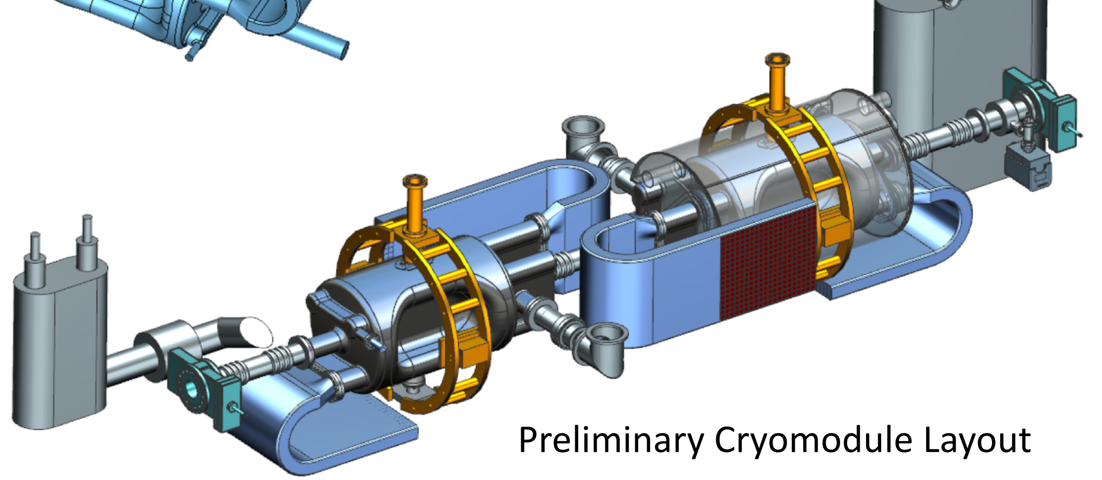
197 MHz Crab Cavity

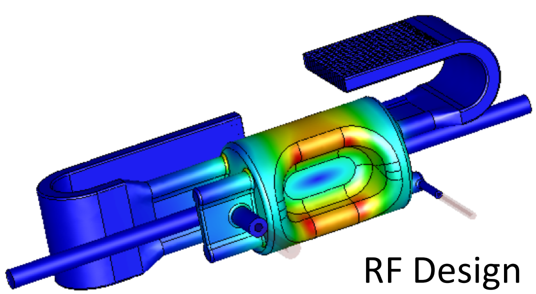
- 197 MHz HSR crab cavity is one of the cavities that will be prototyped first
- Bare cavity RF design is complete
  - Including HOM damping, FPC design
  - Two possible HOM damping schemes: Waveguide loaded and coaxial couplers
  - Developing final RF multipole specifications
- Stress analysis is near completion
- Preliminary fabrication plan is completed


Stiffeners


Waveguide Loads

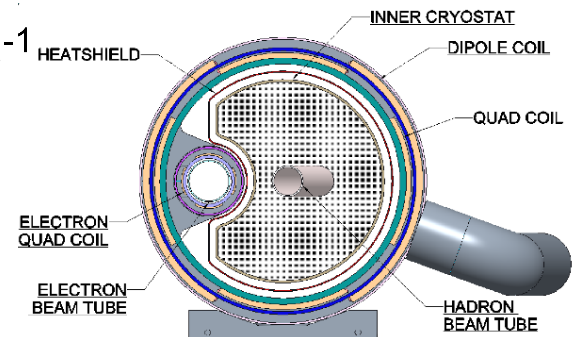

Coaxial Couplers

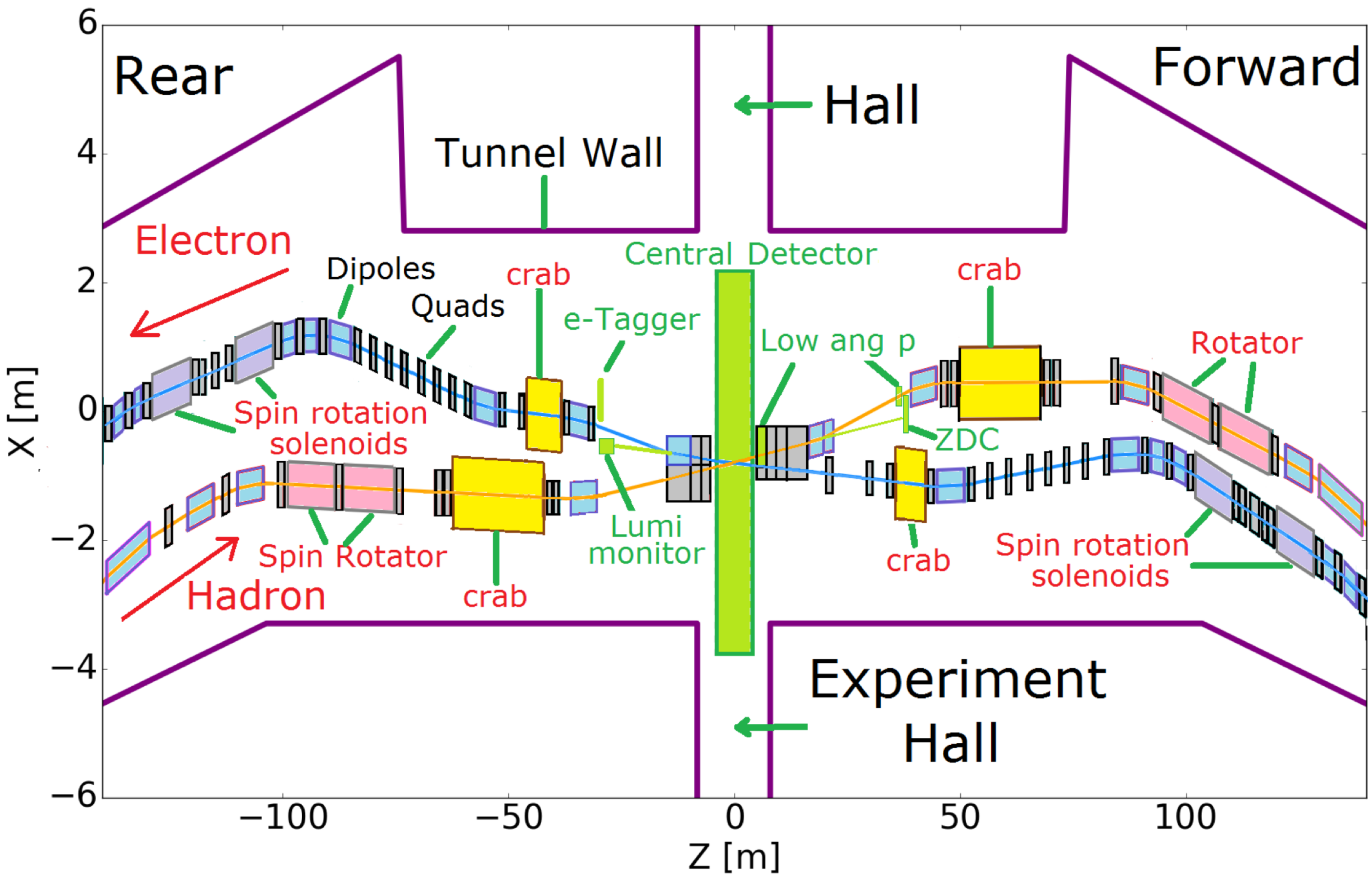

Preliminary Cryomodule Layout

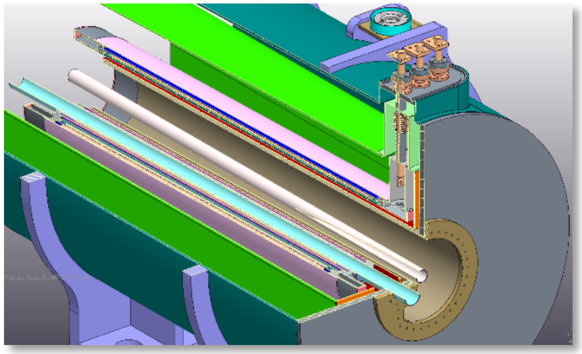

RF Design

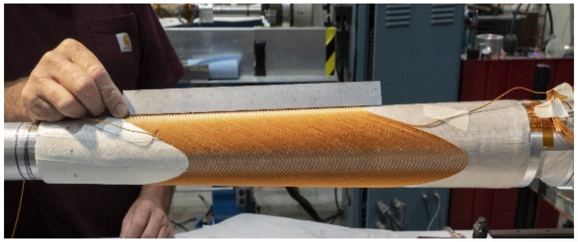
Interaction Region

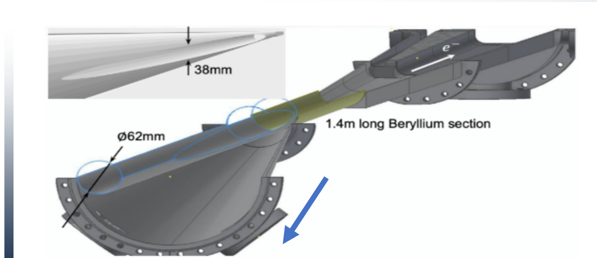
- Beam focused to $\beta_y \leq 5$ cm @ $\sigma_y = 5\ \mu$m, => $L=10^{34}\ cm^{-2}\ s^{-1}$
- Manageable IR chromaticity and sufficient DA
- Full acceptance for the colliding beam detector
- Accommodates crab cavities and spin rotators
- Synchrotron radiation and impedance manageable
- Conventional NbTi SC magnets, collared & direct wind









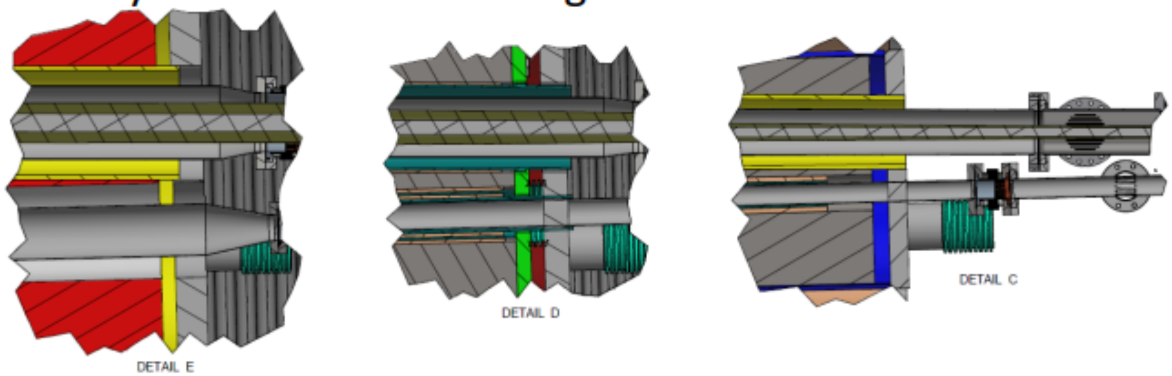


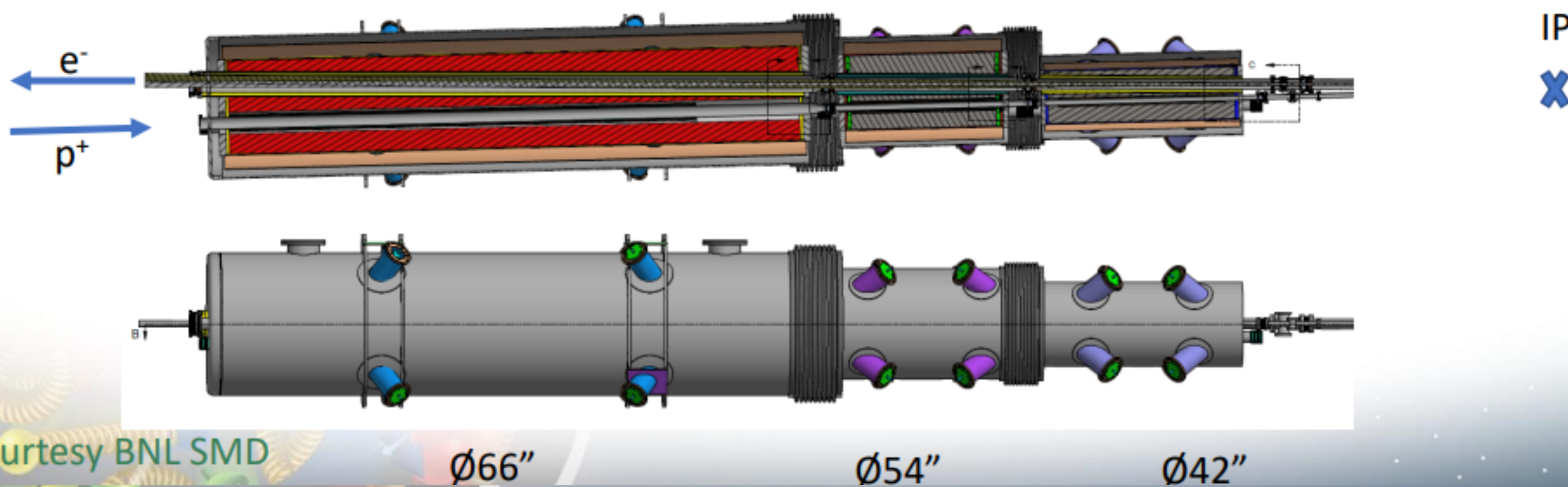
Superconducting IR Magnets

Rear Side Integration / Beampipe

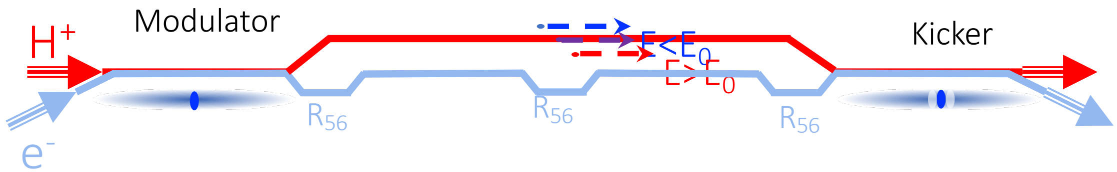
Separate cold masses - helium vessels

Separate circular cryostats with decreasing OD's toward IP

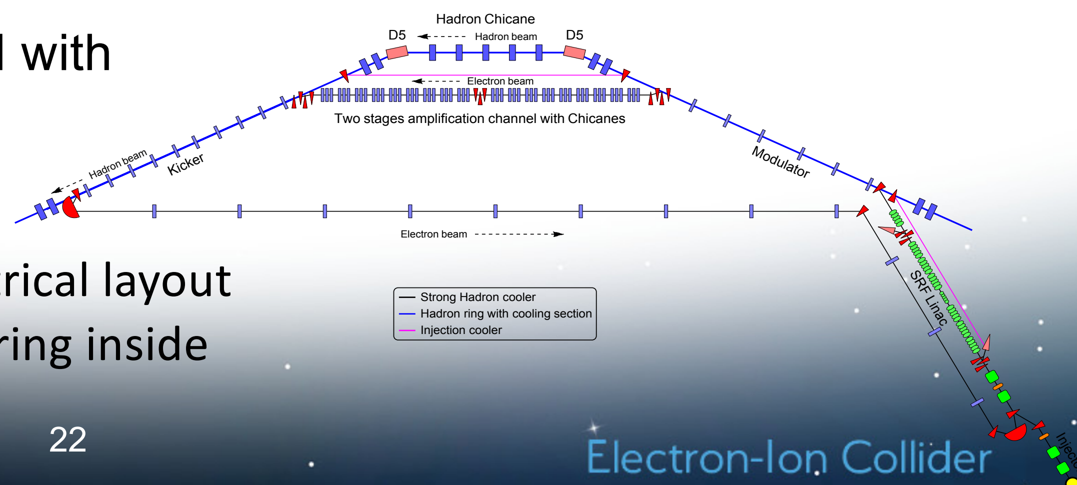




Strong Hadron Cooling Design Update



- **Cooling concept unchanged**: Coherent electron cooling with microbunching amplification
- First 3D simulations showed slightly reduced cooling rates (10-20%)
- Margin of cooling performance addressed by geometry changes: **increased modulator and cooler lengths**
- **Pre-cooling at injection energy** integrated into strong hadron cooling sharing many hardware components. Needed to avoid long initial cool down. Not part of the reference design, cost and schedule yet. **Decision pending.**
- Detailed cooling road map developed with milestones and decision points.



New geometrical layout with ERL on ring inside

EIC Accelerator Collaborations

Existing accelerator collaborations with DOE laboratories

- SLAC: dynamic aperture optimization for the ESR, Strong hadron cooling theory, RF cavity design, low level RF design
- Fermilab: Optimization of electron spin polarization in the ESR
- LBNL: beam-beam interactions
- ANL: normal conducting magnet design, fast ESR injection kicker development, SHC
- ORNL: beam dynamics and lattice design

Existing accelerator collaborations with universities

- Cornell, MSU, ODU, Cal Poly, Stonybrook

Other collaborations envisioned

- e.g. superconducting collared magnets to engage strengths of DOE magnet expertise

International Engagement - Accelerator

- Active engagement ramped up last summer through meetings with DOE and funding agency reps, Accelerator Workshops, and dialogue with potential partners
- Collaborations contributing to both design and hardware that cover a broad range of WBS items are in development
- Bi-lateral meetings now expand from EIC L1 management to L2 & L3 EIC experts for detailed technical discussion of possible in-kind scope
  - Examples: **Crab Cavity** system information exchange meeting w/UK and Canada, meetings w/INFN-Accelerator collaboration on **HSR vac. system**, w/CERN on **ESR vac. sys.**, etc.

	Armenia	Australia	Austria	Belgium	Brazil	Canada	Czechia	France	Germany	India	Italy	Japan	Korea, Republic of	Mexico	Netherlands	New Zealand	Poland	Senegal	South Africa	Spain	Sweden	Switzerland	Thailand	Ukraine	United Kingdom
Contact / Attend EIC Accelerator Partnership Workshop 2020	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Presentation at EIC Accelerator Partnership Workshop 2020		■			■	■		■	■		■	■	■	■			■		■			■	■		■
Bi-lateral meetings with L1 management to explore interests		■			■	■		■	■		■			■			■			■		■			■
Bi-lateral meetings with L2 & L3 experts on concrete scope						■		■			■											■			■
Scope proposal ready for DOE & funding agencies																									

Potential Accelerator Contributions

- Italy, INFN
  - HSR vacuum chamber inserts
- Canada, TRIUMF
  - SC Crab Cavity system
  - Pulsed systems
- UK, ASTEC & Cockcroft Inst.
  - ERL components
- France, IJCLab
  - SHC ERL diagnostics
- France, CEA Saclay
  - IR SC magnets
  - SC spin rotators
- CERN, Switzerland
  - ESR SC cryomodules joint design
  - ESR high current elements joint design
- Japan, KEK
  - ESR collimation system

High level readiness of technical status
Possibly, first case for use of seed funds

High level readiness of technical status

Project is developing possibility of "Seed" funds for EIC international collaboration that can enable early start of EIC accelerator design efforts in partner countries

- Recent & tentative:
- Israel, SARAF
  - RF power amplifiers, collimators, controls
- Sweden, Uppsala Uni.
  - SSPA

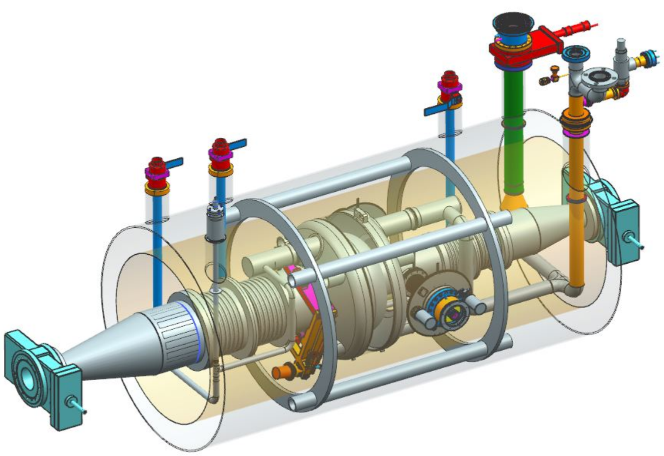
Summary

- Accelerator global design is close to be completed and designs are now stable to serve a base for engineering design
- The challenging accelerator science questions of the EIC are identified and well-understood, with strategies to address each in place
- Accelerator science and engineering R&D are making good progress in all areas
- The project is highly collaborative with US and international laboratories and universities
- Scientists and engineers contributing to EIC have developed into a strong competent team that will deliver the EIC project

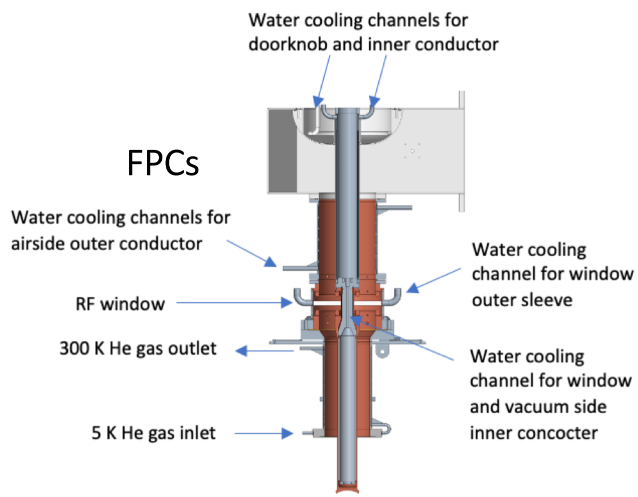
Backup slides

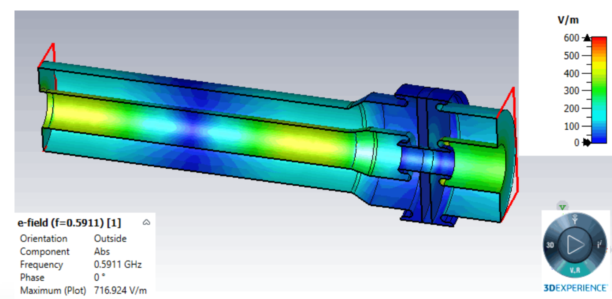
R&D on High power FPC Status

- 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

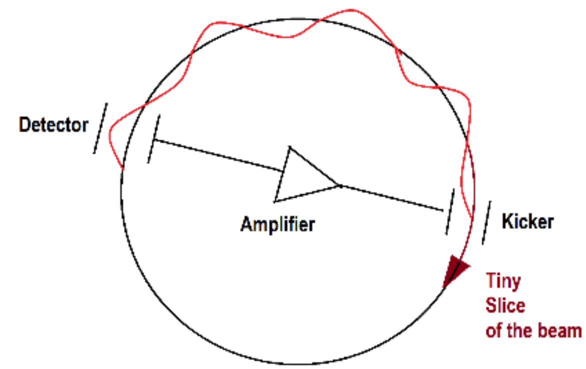




Coherent Electron Cooling (CEC)

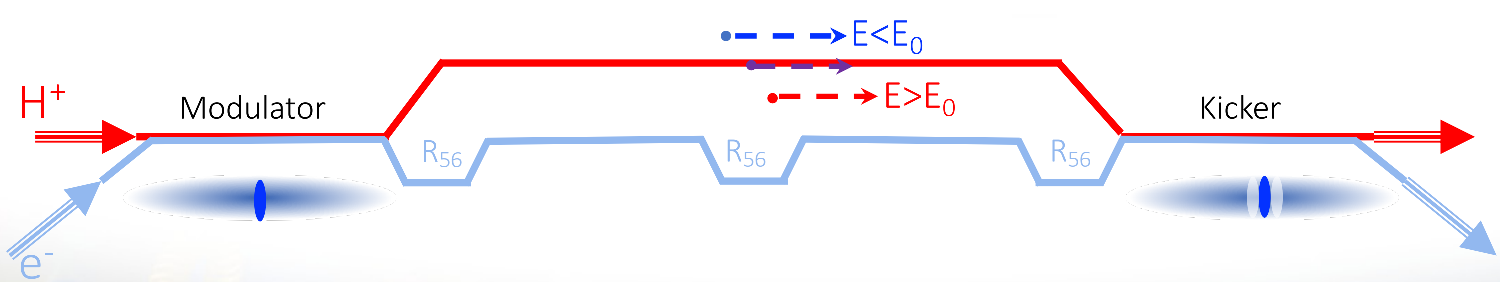
Like in stochastic cooling, tiny fluctuations in the hadron beam distribution (which are associated with larger emittance) are detected, amplified and fed back to the hadrons thereby reducing the emittance in tiny steps on each turn of the hadron beam

- High bandwidth (small slice size)
- Detector, amplifiers and kickers



For high energy protons, a large bandwidth (tens of THz) is required:
➔ Using an electron beam to detect fluctuations, to amplify and to kick.

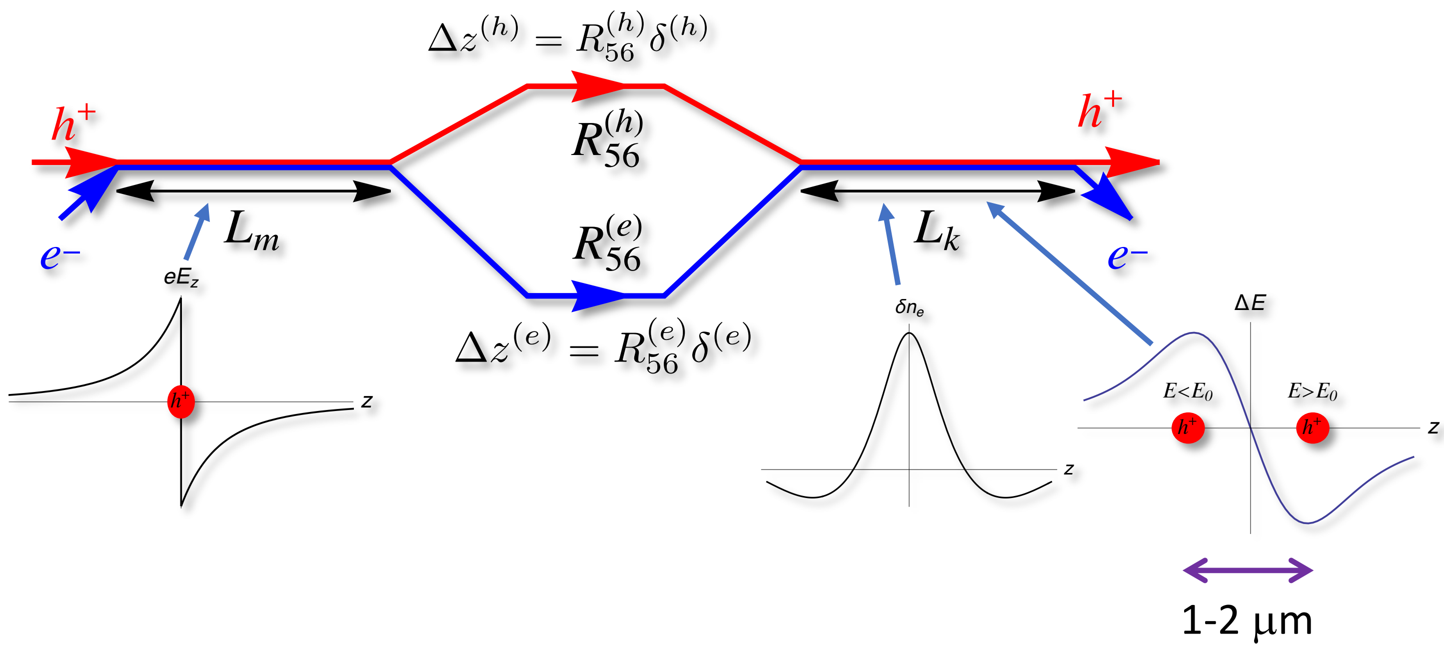
CDR baseline Amplification: micro-bunched amplifier (MBEC)



We acknowledge there are other three amplification schemes

CeC pickup(modulator) and kicker

Coherent electron cooling is a variant of the stochastic cooling with the operational frequency range raised from ~GHz to tens of THz [Ref].

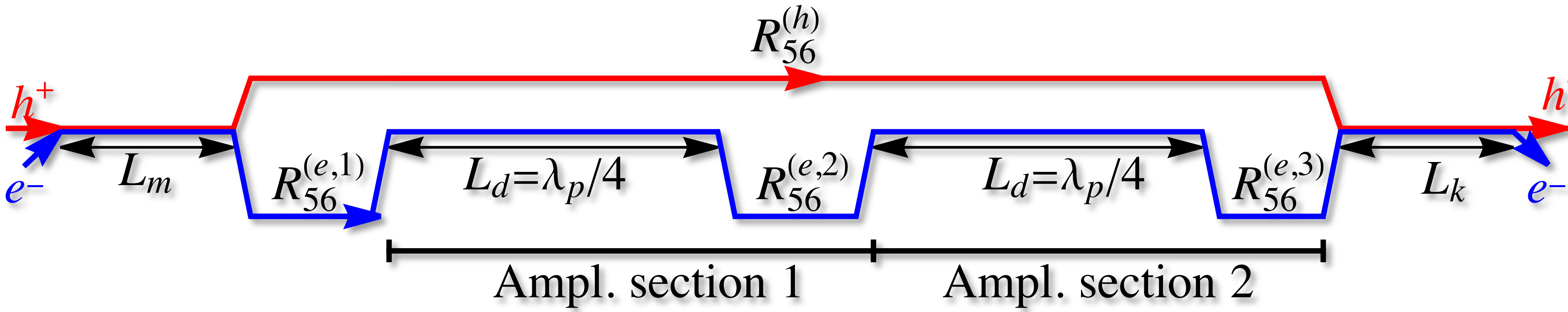


- The pickup and the kicker are implemented via the Coulomb interaction of the hadrons and electrons, $\gamma_e = \gamma_h$. Without amplification, the cooling rate is too small - the signal (the imprint in the e-beam) should be amplified.
- The extent of the longitudinal wake is 1-2 microns – sets requirement on the path length match when e and p bunches are merged in the kicker

Ref: Derbenev, AIP Conf. Proc. **253**, 103 (1992); Litvinenko, Derbenev. PRL, **102**, 114801 (2009)

CeC amplification

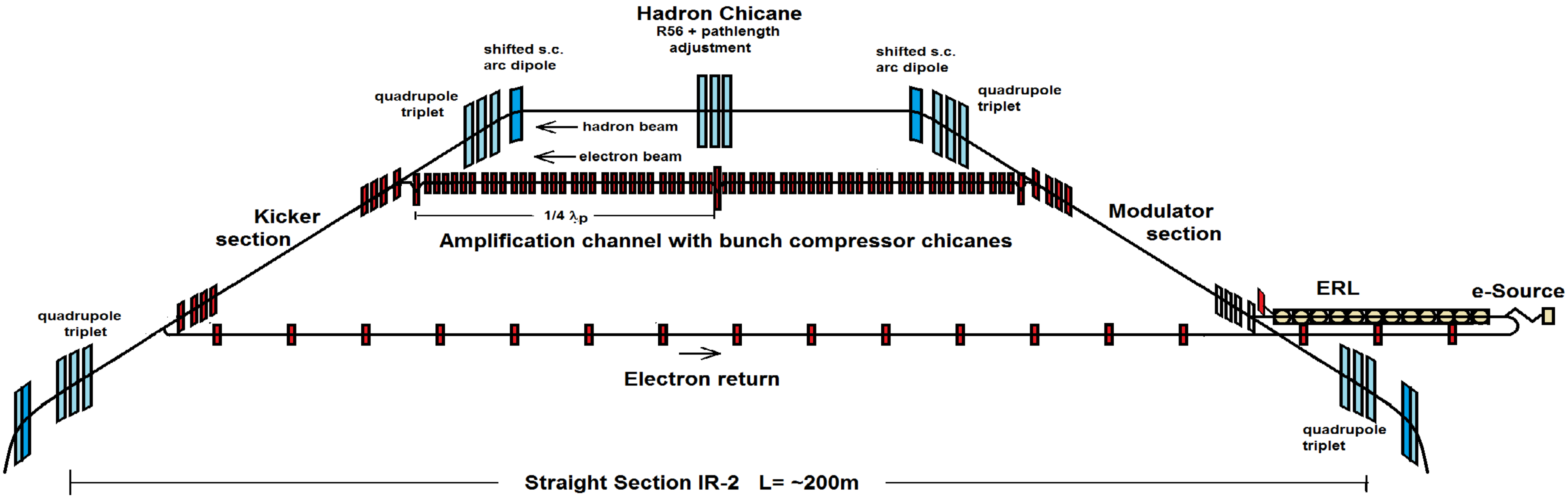
Micro-bunched amplification (well known from FELs) is the effect selected for CeC amplification - MBEC (micro-bunched electron cooling)



One stage of amplification is achieved through a combination of a drift of length=$\frac{1}{4}$ plasma oscillation length followed by a chicane. For the nominal EIC parameters, one stage amplification gain $G \approx \sigma_\delta^{-1}\sqrt{I_e/\gamma I_A} \approx 10-20$. The effective bandwidth of this amplifier is tens of THz.

EIC Strong Hadron Cooling

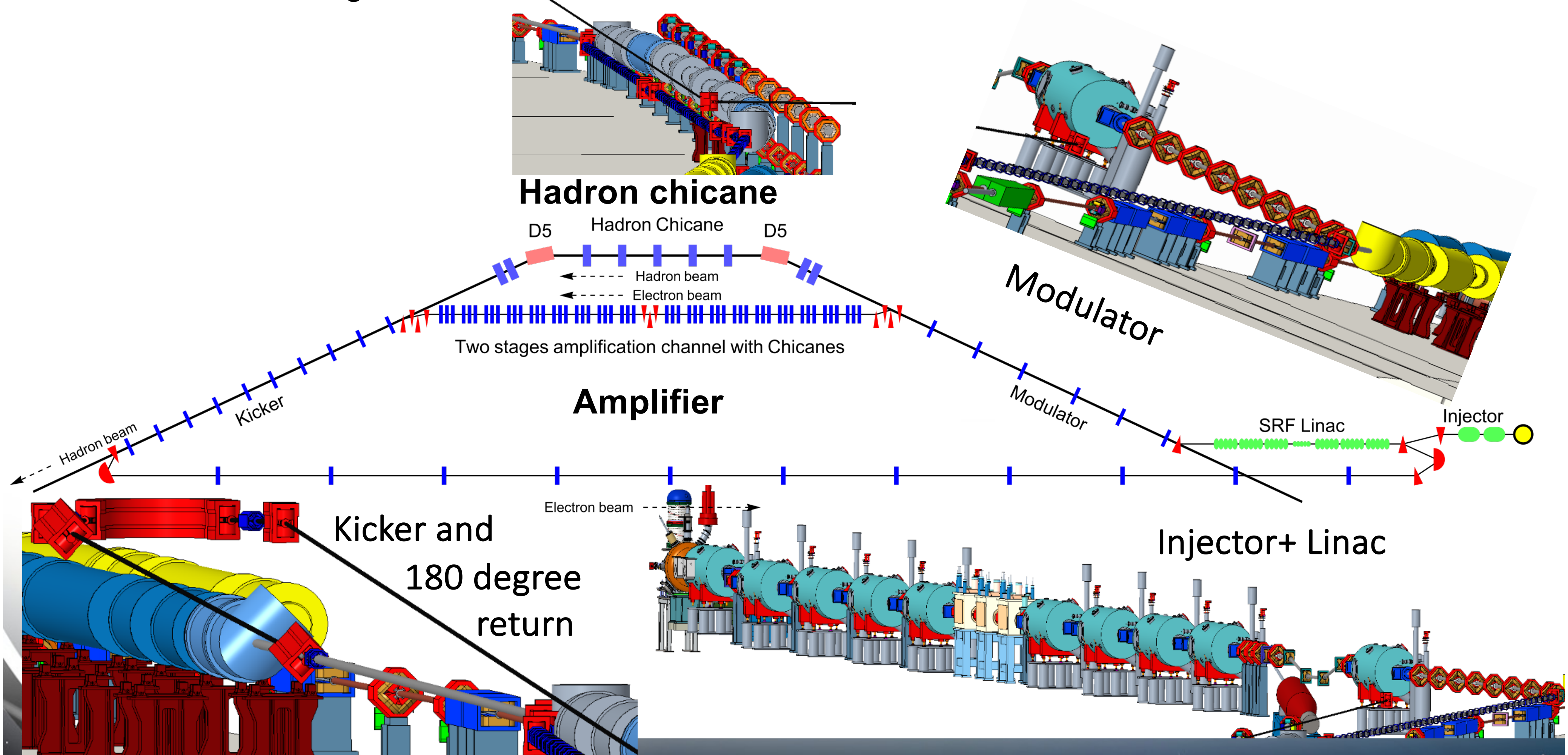
Coherent Electron Cooling with μ-bunching amplification



- The EIC cooler requires up to 150 MeV electron beams with average electron beam current of ~100 mA => 15 MW
  - Requires use/design of a world-class SRF **energy-recovery linac** (ERL)
- Electron/hadron beams separate and rejoin each other
  - Wake extent 1-2 μm => path length accuracy and stability must be sub-micron
- Electron beam must be **extremely "quiet"** (less than twice the shot noise)
  - Avoid amplification of "shot noise", no substructure in electron beam

EIC Strong Hadron Cooling

- Cooling theory and simulations, from 1D models to 3D models and simulations
- Good progress in electron acceleration, beam-transport
- Started studies of SHC integration with low energy pre-cooler (LEReC type)
- CeC Proof of Principle experiment in progress, a lot of valuable knowledge gained, giving us confidence in design of SHC beamlines



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