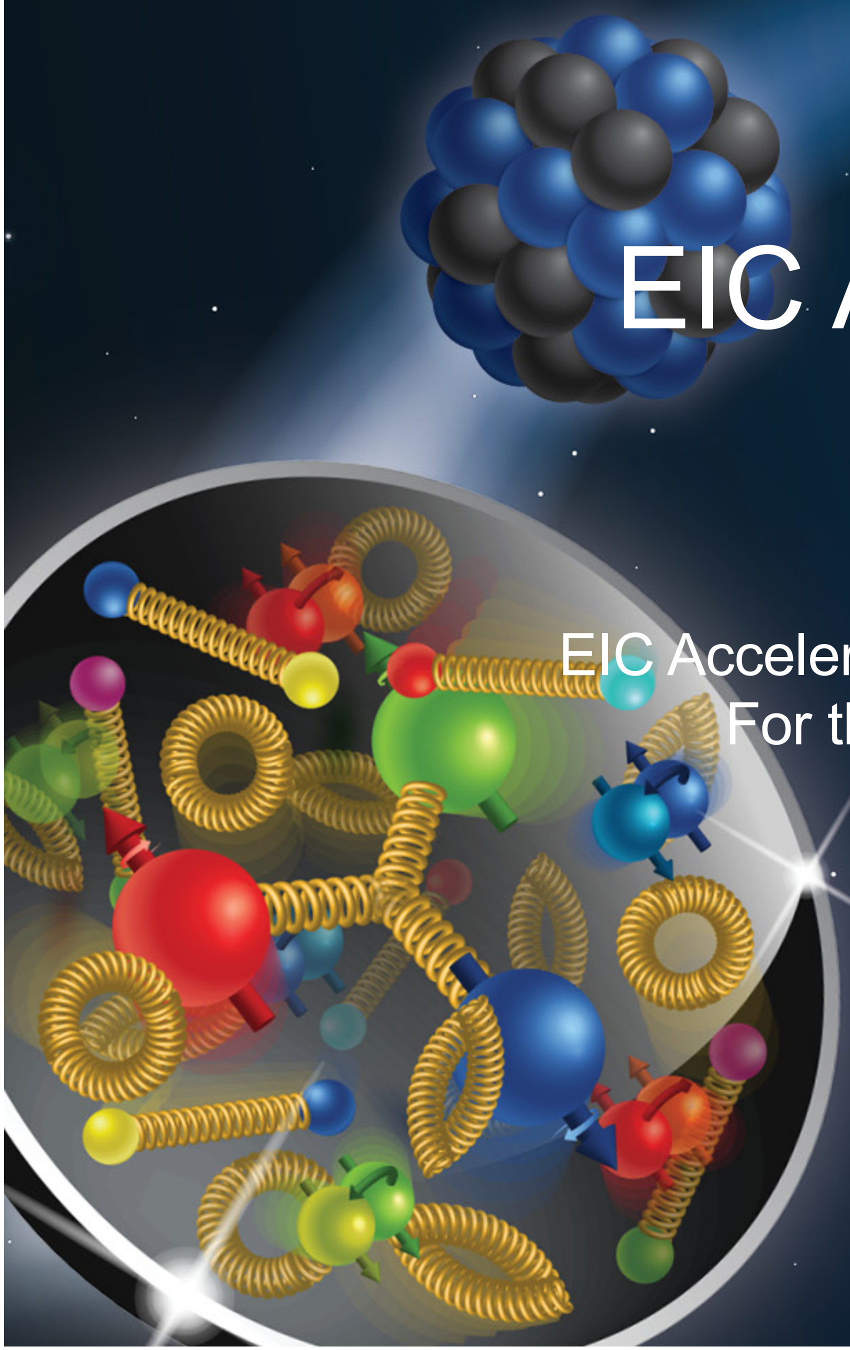


EIC Accelerator Status and Challenges

T. Satogata, JLab/ODU
EIC Accelerator Development/Pre-Operations L2 Deputy
For the EIC Accelerator Design/Engineering Team

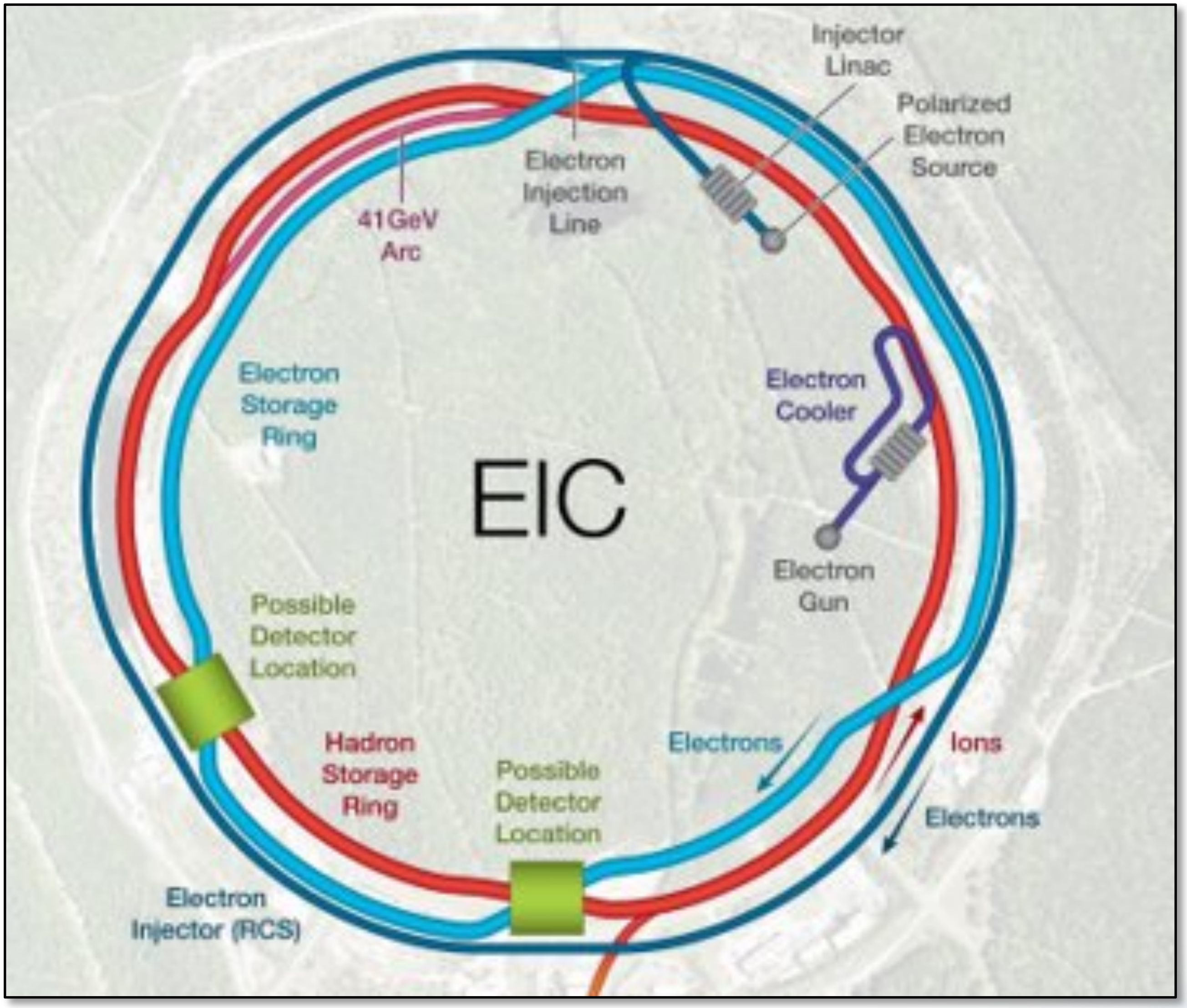
eeFACT'22 Workshop
12-16 September 2022

Electron-Ion Collider

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

Outline

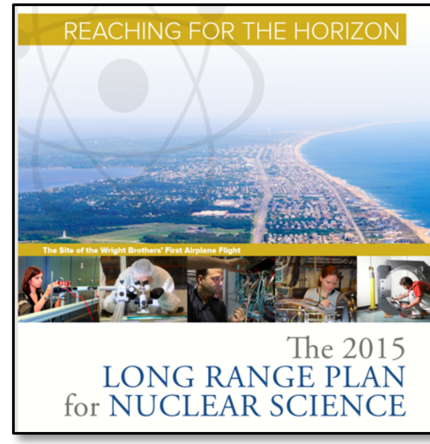
- Requirements
- Accelerator
    - Design overview
    - Design challenges
    - Beam dynamics
    - R&D progress
    - Engineering layout
    - Cooling
- Partnerships
- Summary

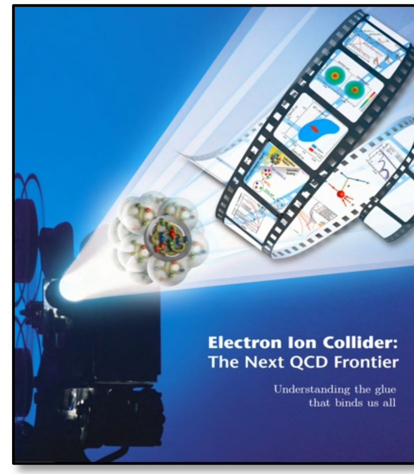


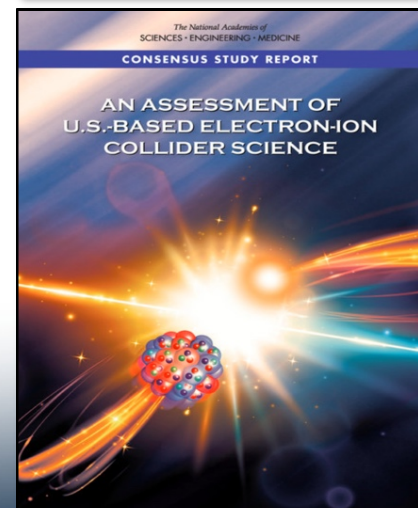
7 other EIC talks in 6 separate WG through the week

Requirements

- **EIC Design Goals**
  - **High Luminosity**: $L = (0.1\text{-}1)\cdot 10^{34}\ cm^{-2}s^{-1} \rightarrow 10\text{-}100\ fb^{-1}$
  - Collisions of **highly polarized** e and p (and light ion) beams with flexible bunch by bunch spin patterns : 70%
  - Large **range of CM 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
- The EIC design meets or exceeds goals and requirements

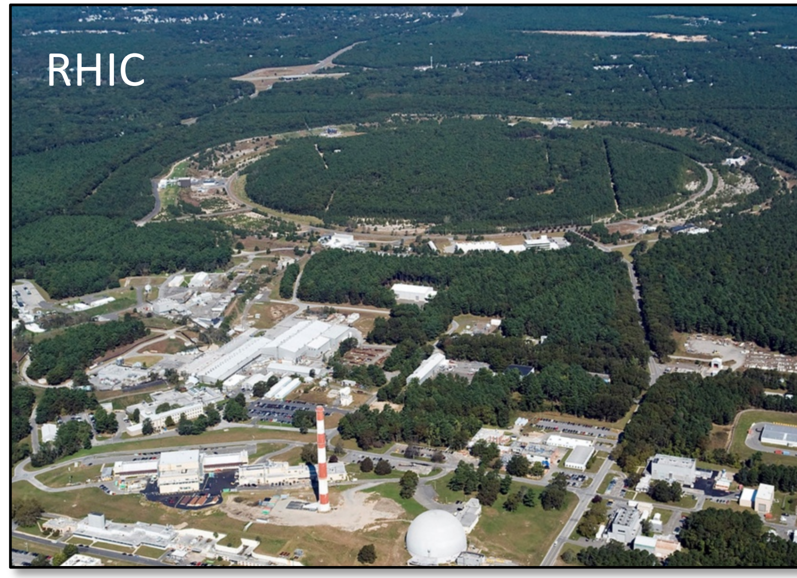




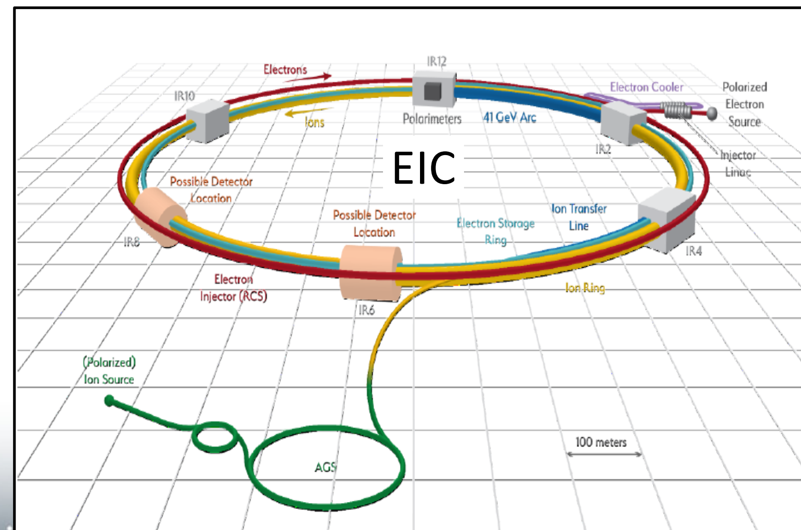


EIC Design Overview

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



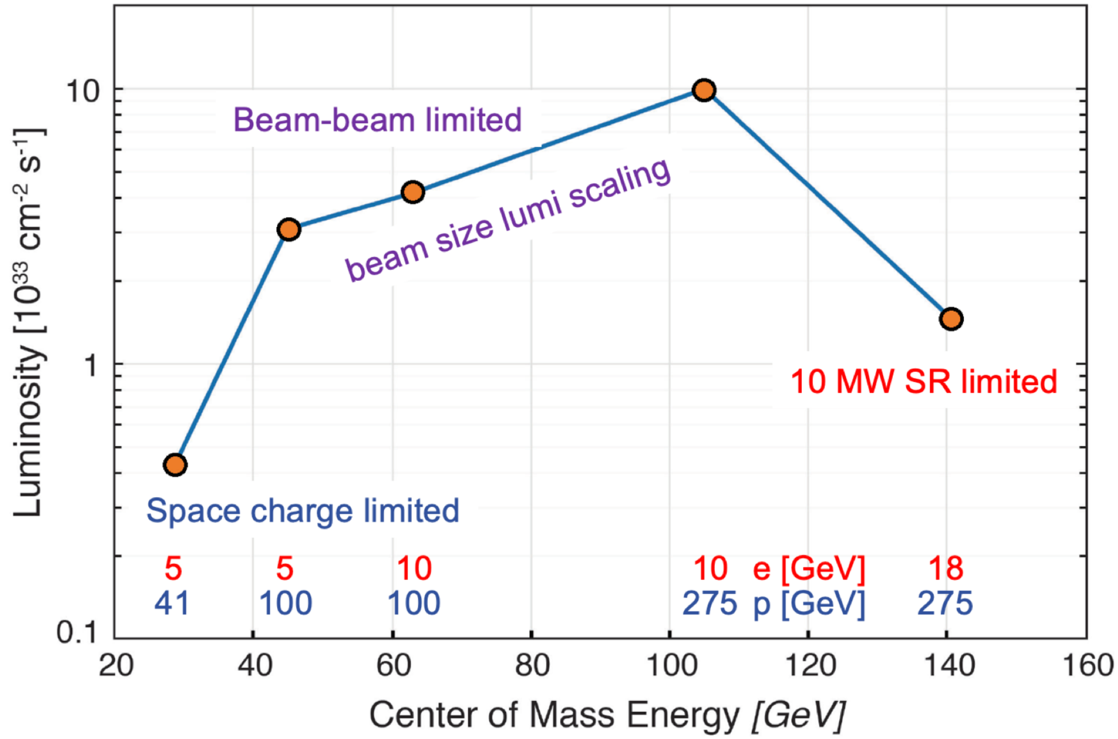
- **Hadron storage ring (HSR): 40-275 GeV** (existing)
    - up to 1160 bunches, **1 A** (3x RHIC)
    - bright vertical beam emittance 1.5 nm
    - **strong cooling** (coherent electron cooling, ERL)
- **Electron storage ring (ESR): 5–18 GeV** (new)
    - up to 1160 polarized bunches
        - high polarization by **continual reinjection** from RCS
    - **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 up to 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



EIC Luminosity Optimization

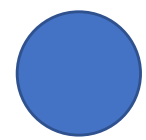
	Electrons	Protons
Beam energies	2.5 - 18 GeV	41- 275 GeV
Center of mass energy range	E_{cm} = 20-140 GeV	

	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	**$1 \cdot 10^{34} cm^{-2} s^{-1}$**	



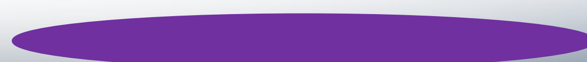
electrons: flat

hadrons: round



SuperKEKB: 10 um x 50 nm, 200:1

EIC optimization: ~11:1 transverse IP aspect ratio



(Some) EIC Challenges (e, p, collider)

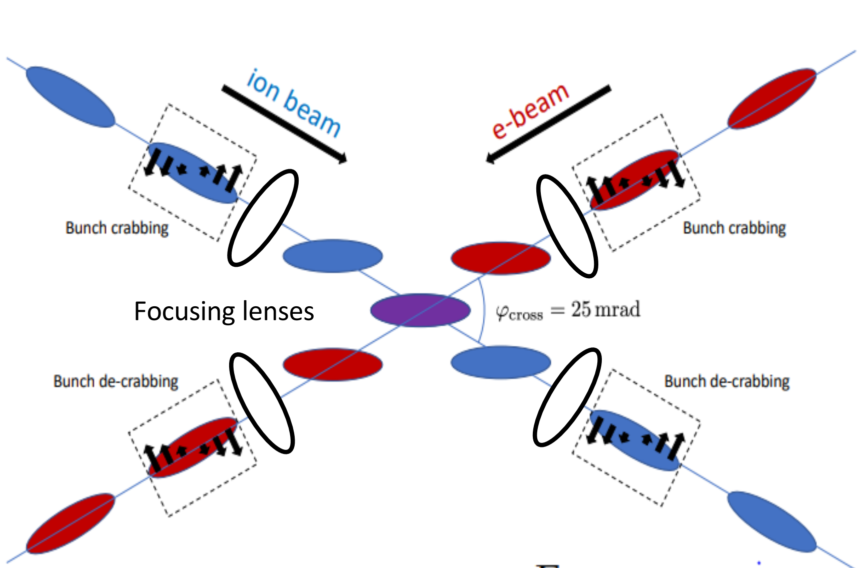
- **Design**
  - Beam-beam
  - Hadron crabbing
  - Crabbing phase noise
  - Hadron cooling
  - Hadron high current
  - Electron polarization
  - Electron high current
  - IR optimization
- **Technology**
  - Coupling/cooling control, reinjection, crab closure, solenoid compensation
  - Crab cavities, diagnostics
  - Crab RF feedback
  - High-power ERL, alignment, operability
  - Cu/aC coated screens
  - Compact spin rotators, coupling/orbit control, polarimetry, reinjection
  - Gap transient RF feedback
  - IR magnets, vacuum

e polarimetry: D. Gaskell WG8 17:25 Tue e polarization: V. Ranjbar WG8 18:40 Tue
Also overlap with CERN FCC-ee EPOL workshop in late September

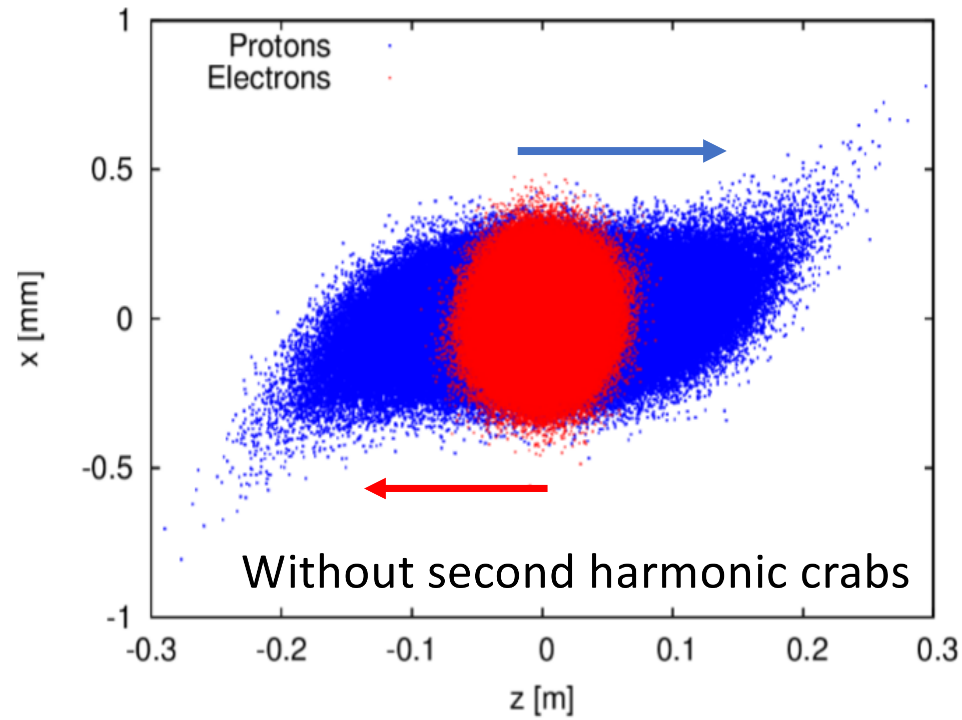
Progress in Beam Dynamics

- **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 sextupole distribution (4 families/arc; collab. with SLAC, IPAC'22 WEPOPT043)
- **Collective effects and beam-vacuum vessel interaction**
    - Assessed: no issues from excessive heating by 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**

Crossing Angle Collision



$$\hat{V}_{\text{RF}} = -\frac{cE_s}{4\pi f_{\text{RF}}\sqrt{\beta_x^* \beta_{cc}}}\theta_c.$$

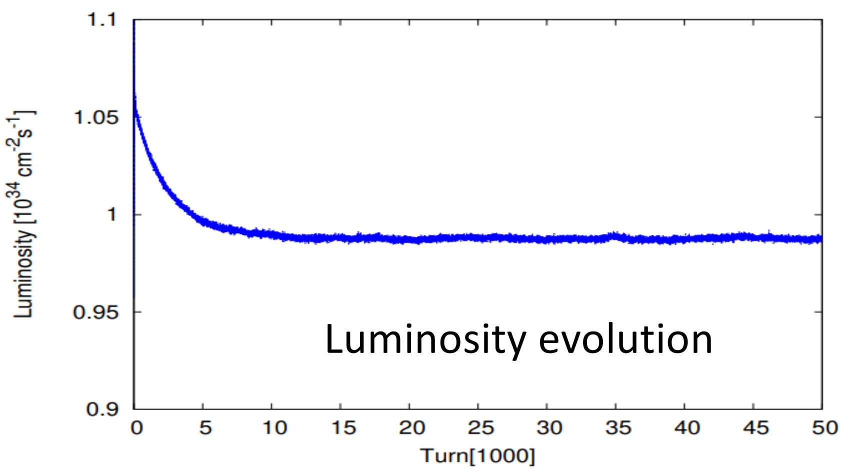


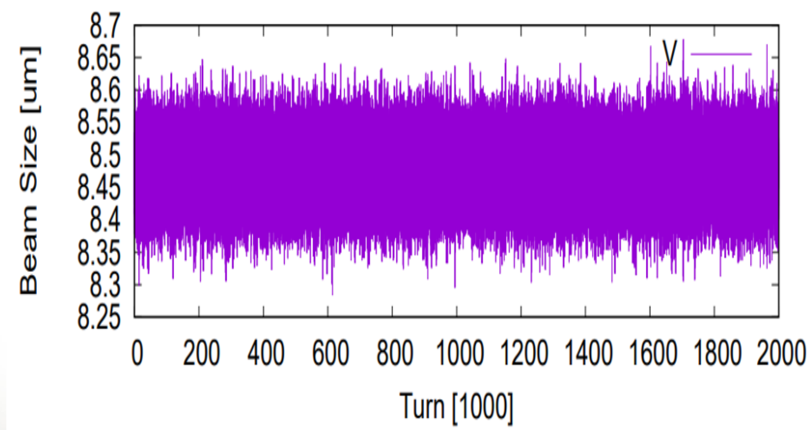
- **Local (semi-)closed crabbing scheme** adopted in both HSR and ESR
  - Bump closure/solenoid coupling effects/corrections under study
- Hadron head/tail offset beam-beam ➔ proton emittance growth
  - **Second harmonic crab cavities** added in HSR to minimize synchrobetatron resonances.

Beam-beam Simulations

- Both **strong-strong** and **weak-strong** simulation methods have been used for EIC BB studies.
- There is **no coherent beam-beam instability** with design parameters.
- Strong-strong simulations show emittance growth from numerical effects. We continue to investigate whether the actual design can be validated in the appropriate limit.
- Comprehensive parameter scans were performed to optimize the design.
- Both weak-strong and dynamic aperture calculations have confirmed the design parameters.
- Machine and lattice errors were studied
  - effects of detector solenoid, tilted ESR plane, crab dispersion tolerances at IP, phase noise of crab cavities, …
- **Design beam-beam parameters are achievable**
- c.f. IPAC'22 WEPOPT036-42...

Max ξ_{xy} = $(0.1, 0.1)_e$ $(0.015,0.009)_p$

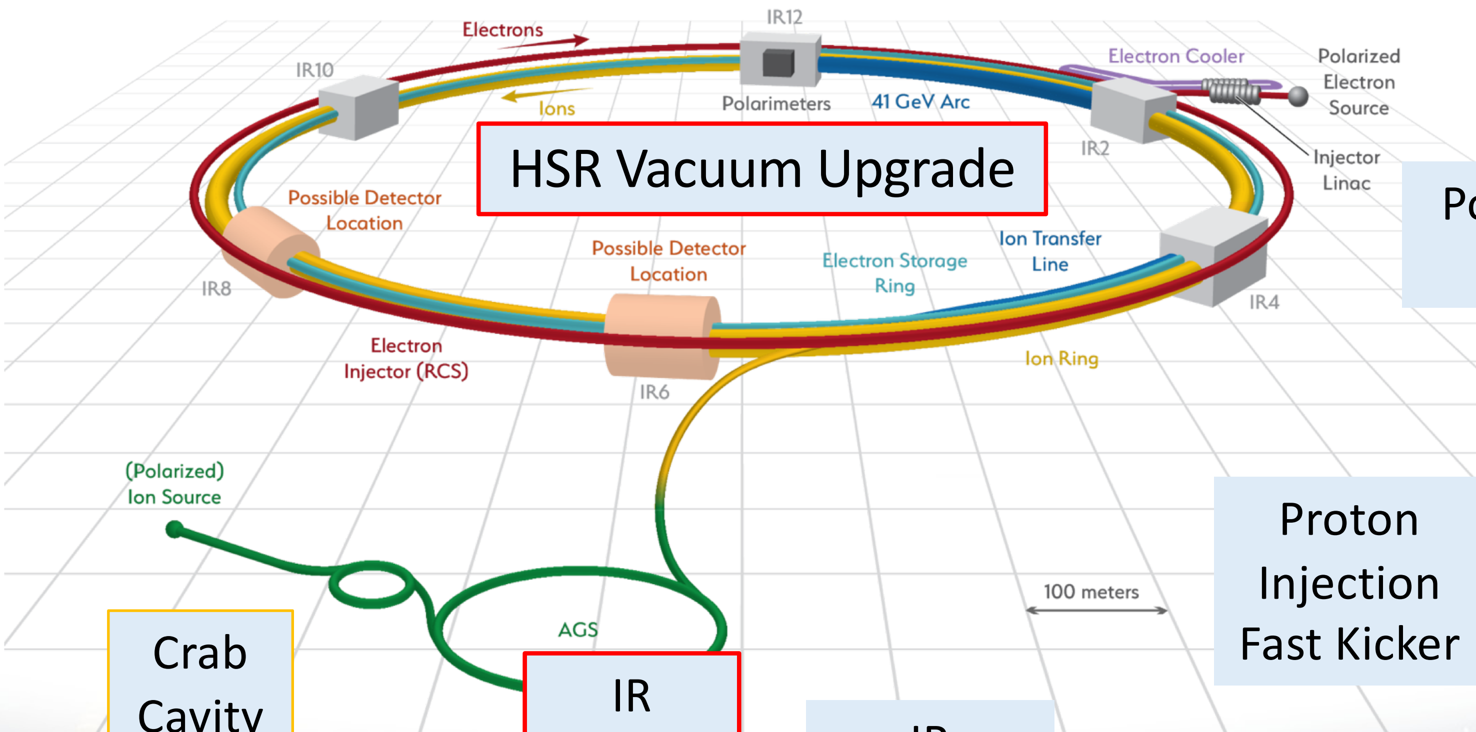




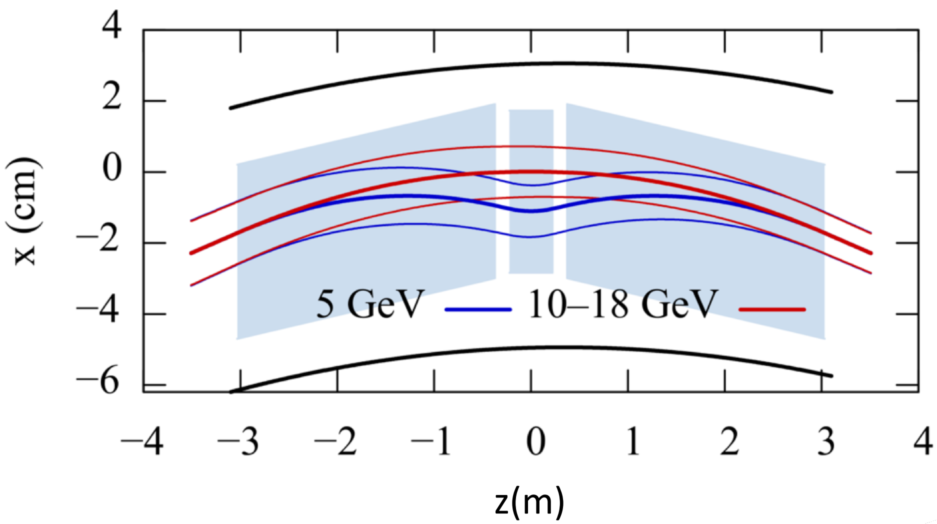
Proton vertical beam size from weak-strong simulation

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



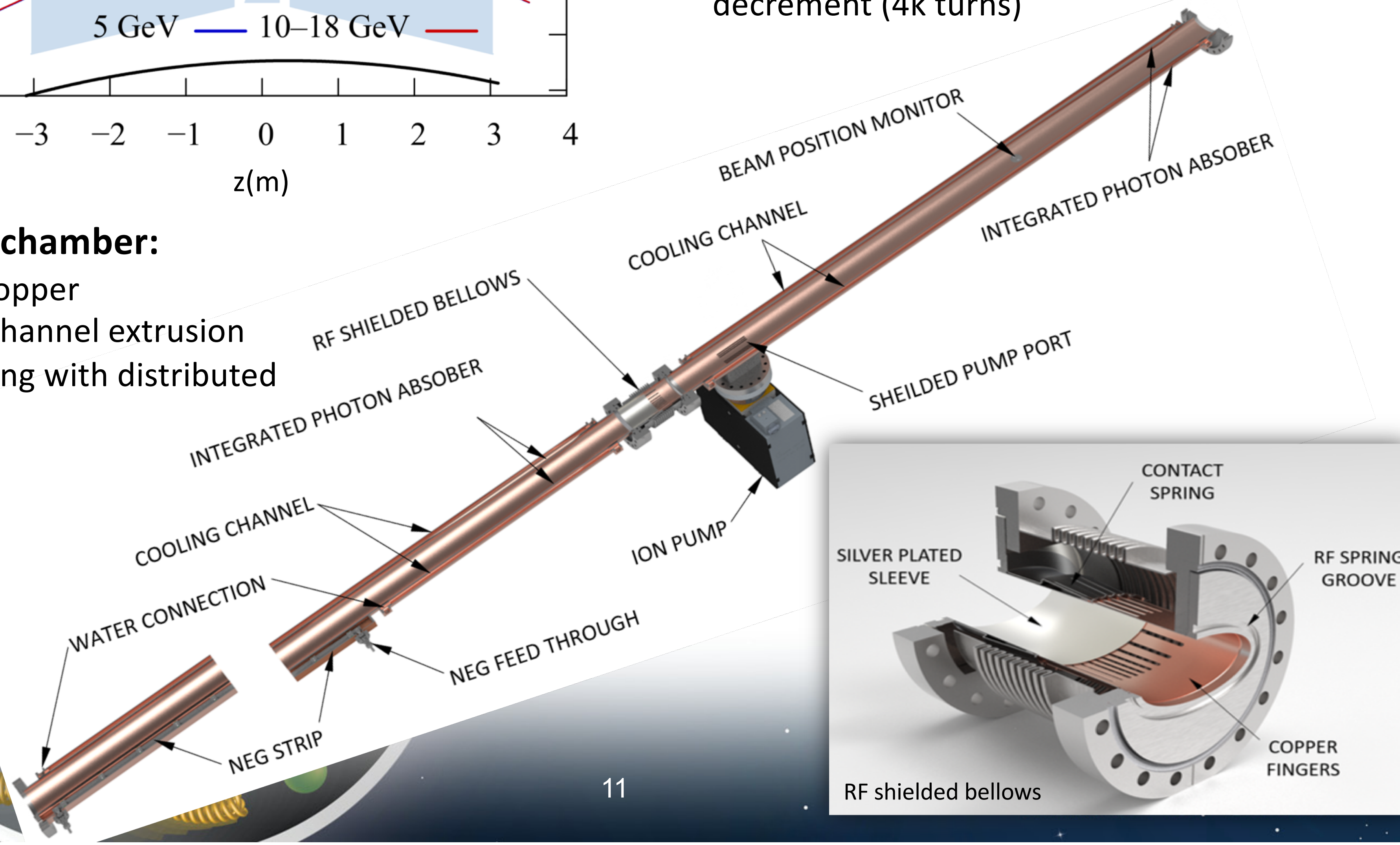
Electron Storage Ring



- 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 (4k turns)

Vacuum chamber:

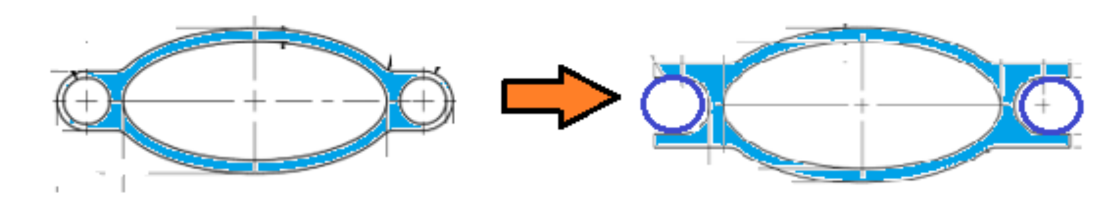
- OFE Copper
- Multichannel extrusion
- Pumping with distributed NEG



RF shielded bellows

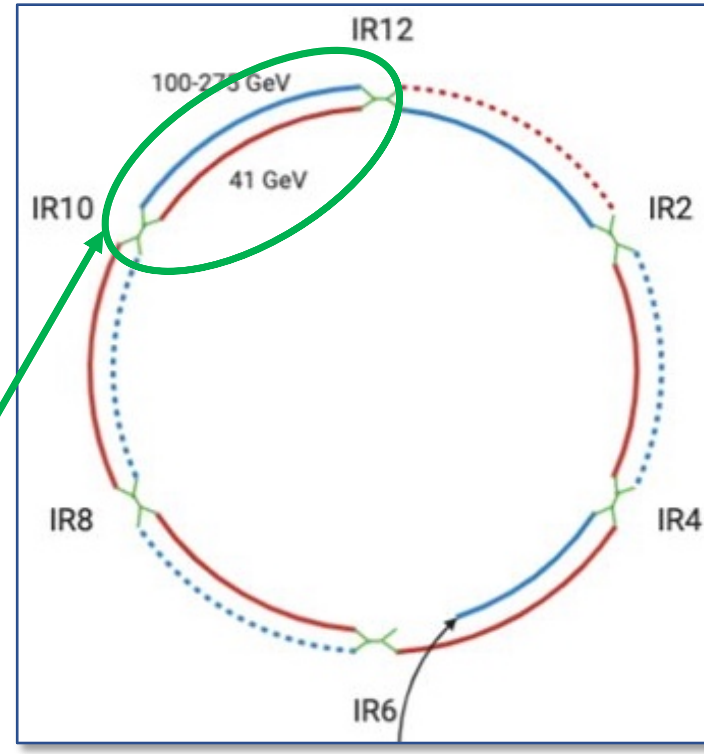
ESR Engineering, Vacuum R&D

- **ESR and RCS Normal Conducting Magnets**
  - Single turn coils changed to multi-turn coils
  - RCS dipoles split into two (cost saving; manufacturing simplification)
  - Engaged with magnet vendors and possible DOE lab collaborations (ANL)
  - Evaluating possible reuse of HERA magnets for ESR
- **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



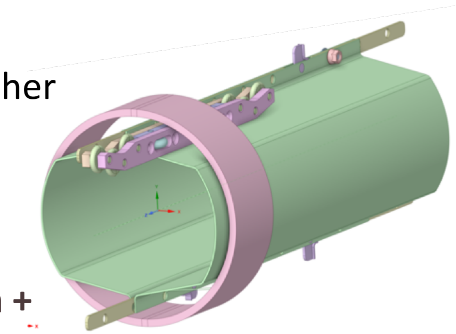
Hadron Storage Ring

- 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



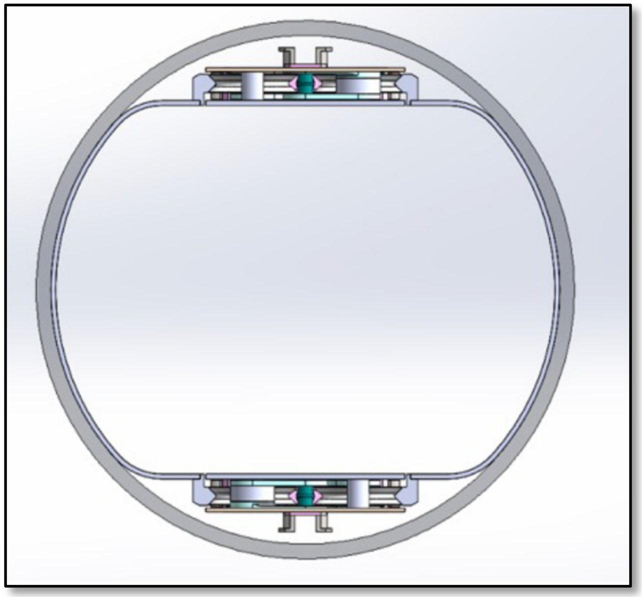
Hadron Ring Vacuum chamber upgrade

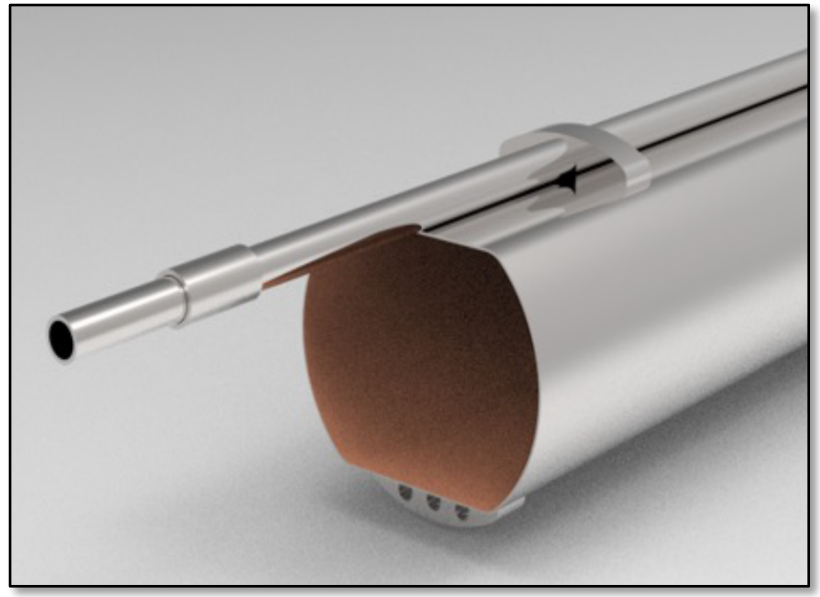
- Two main concerns towards existing RHIC vacuum pipes during EIC operation with higher current and shorter bunch length:
  - Resistive-wall impedance
  - e-cloud buildup
- Solution: **copper-clad stainless-steel screen + amorphous Carbon (aC) thin film**
  - *Cu significantly reduces surface resistivity,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

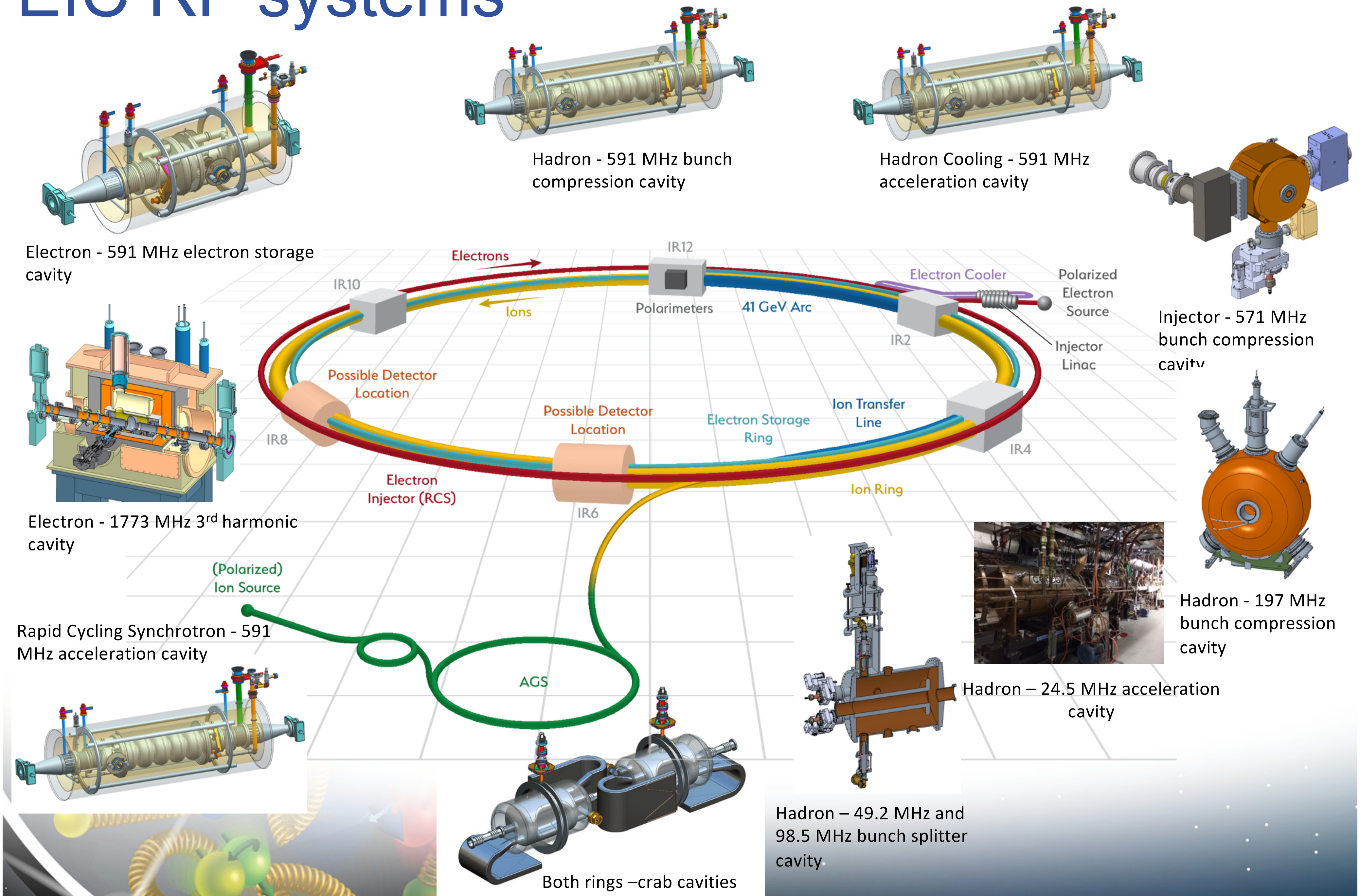




- HSR vacuum liner cooling changed from passively cooled (contact with RHIC beam pipe) to actively cooled

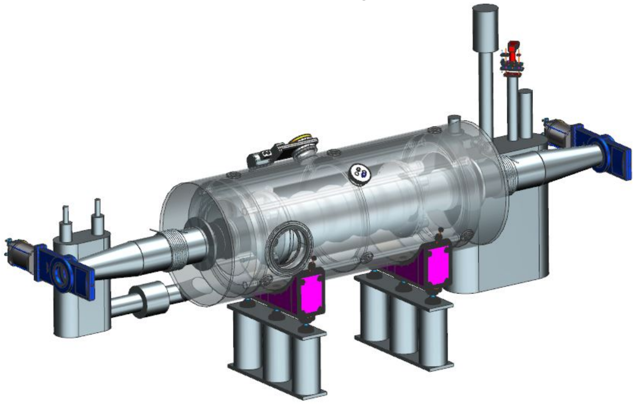
More on EIC vacuum systems in Charlie Hetzel's talk WG9 11:15 Thu

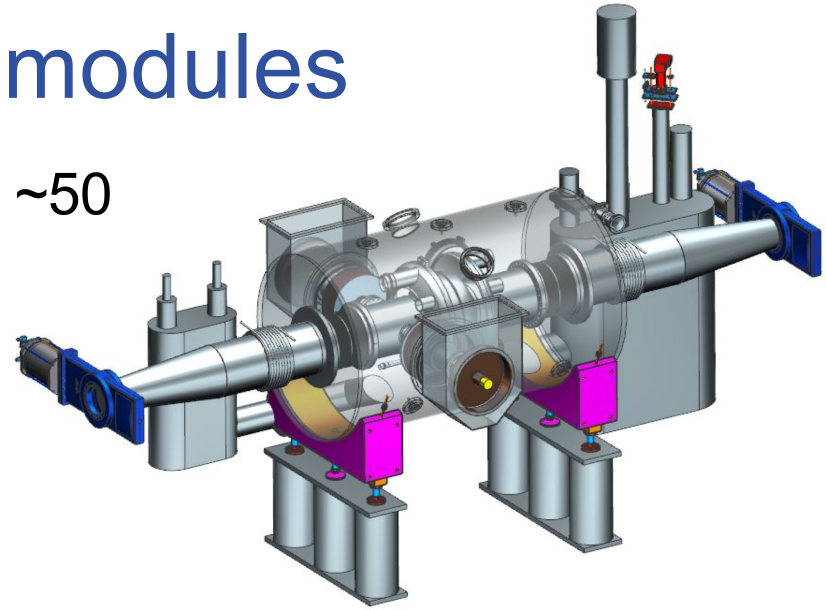
EIC RF systems

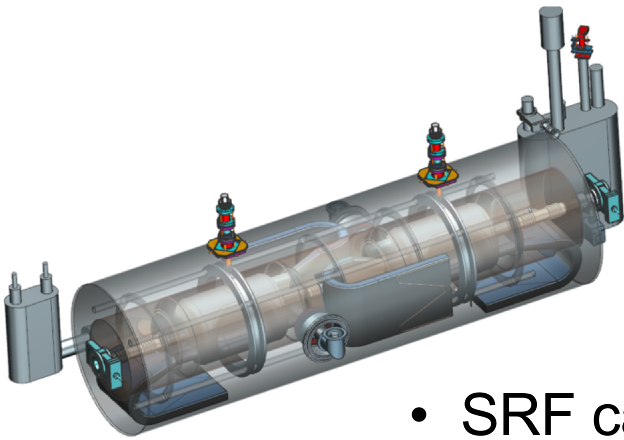


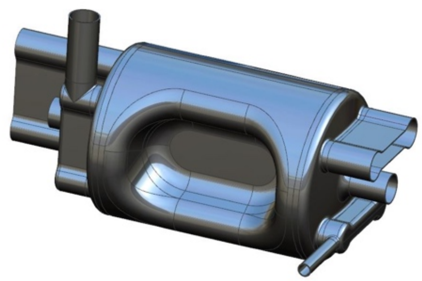
EIC SRF Cavities & Cryomodules

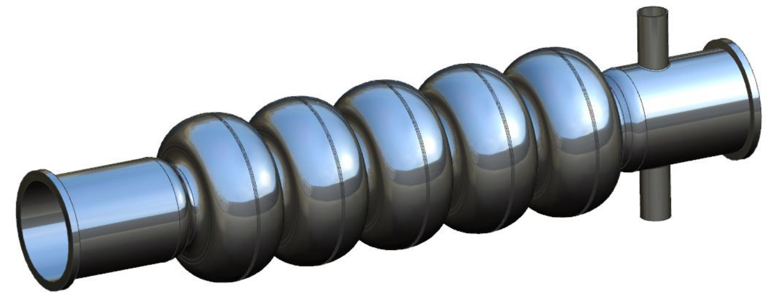
- Several cryomodule types required, total ~50









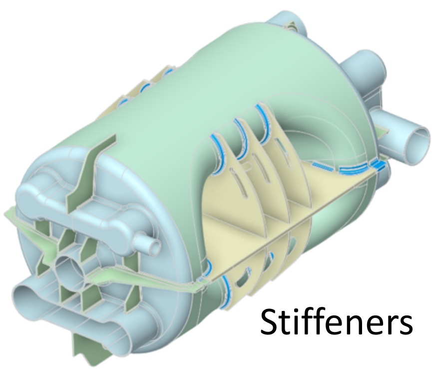


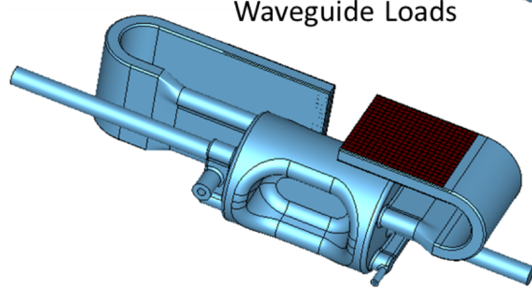
- SRF cavities, 197-1773 MHz
  - High RRR, fine grain, Niobium sheet cavities
  - 5 types, 3 elliptical and 2 non-elliptical, quantities ~ 4-20

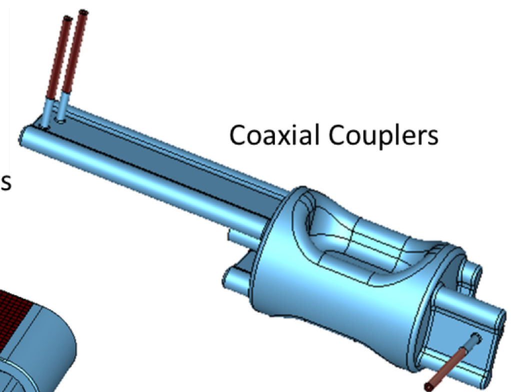
More on RF systems in Bob Rimmer's talk WG11 09:00 Weds

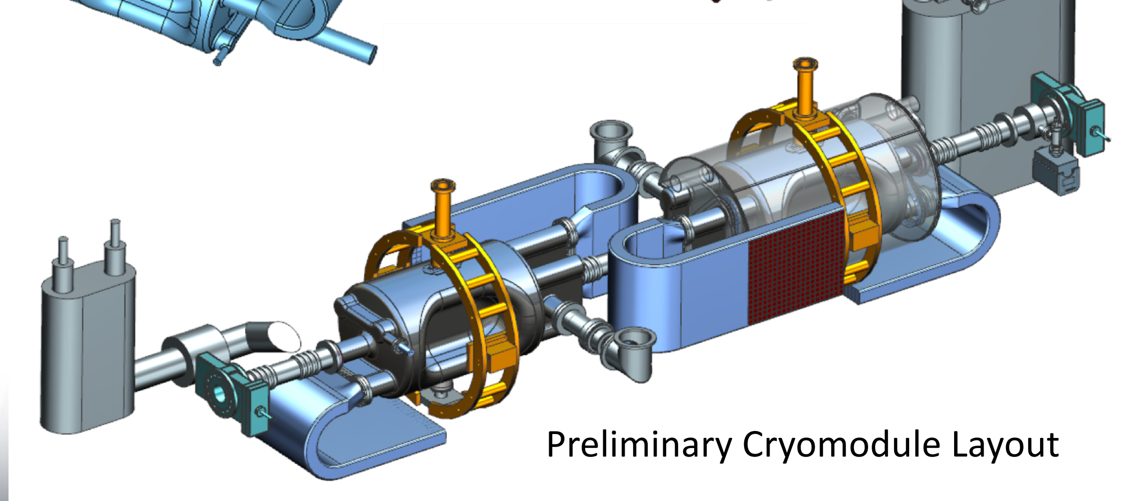
197 MHz Crab Cavity

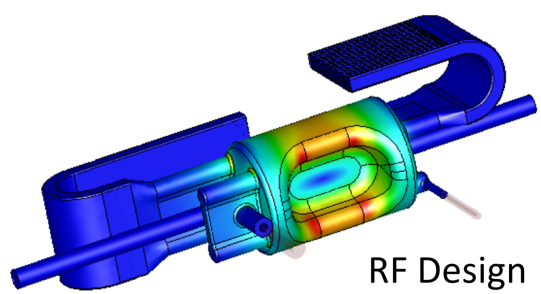
- 197 MHz HSR crab cavity is one of the cavities that will be prototyped first
- Bare cavity RF design is complete
    - Including HOM damping, FPC design
    - Two possible HOM damping schemes: Waveguide loaded and coaxial couplers
    - Developing final RF multipole specifications
- Stress analysis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



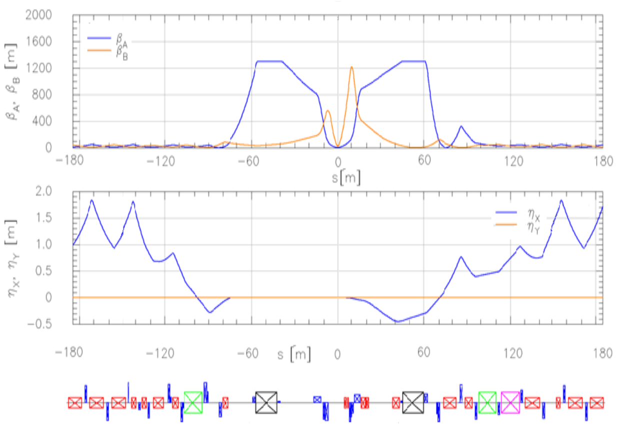




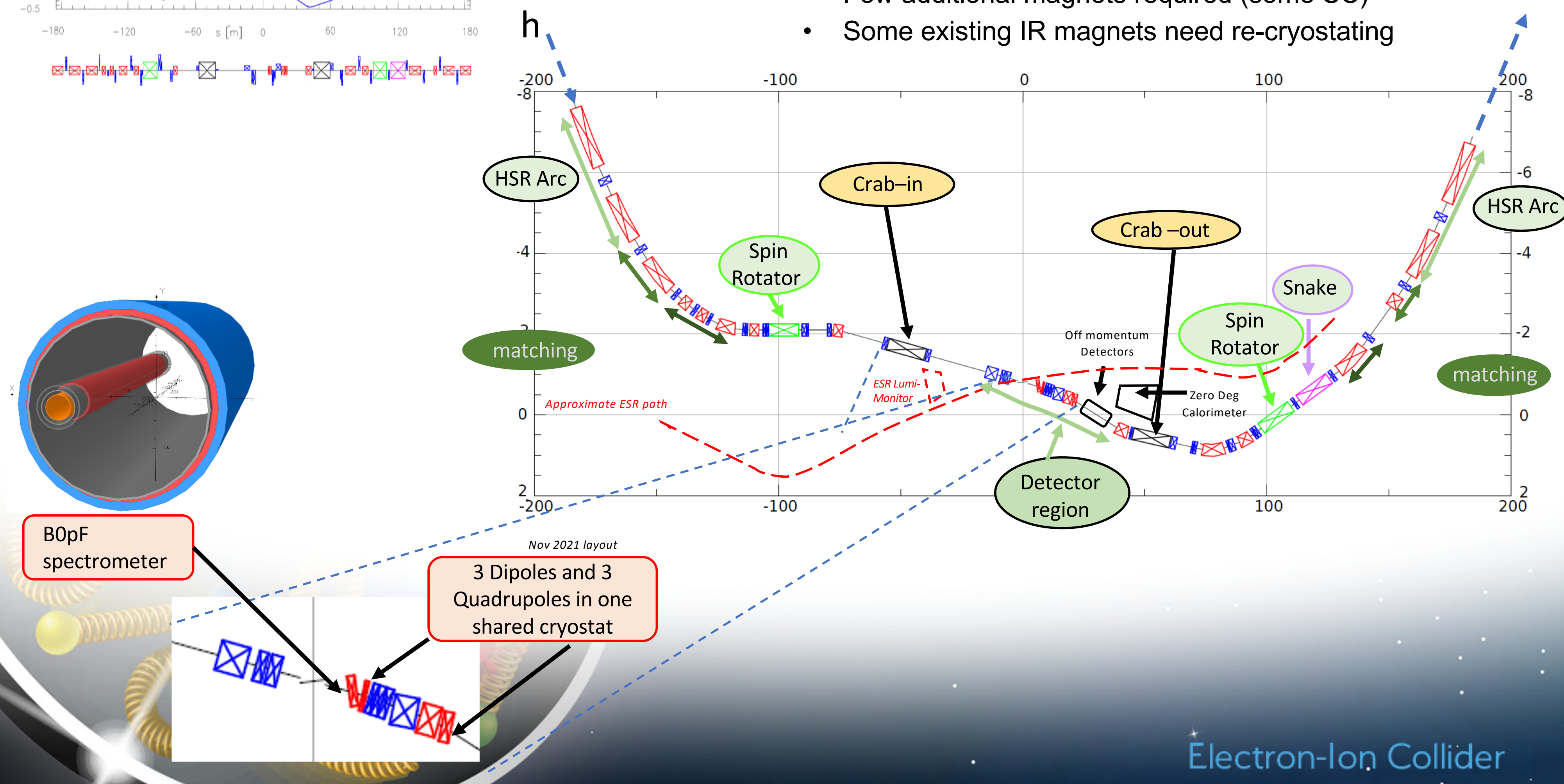




HSR layout in IR6

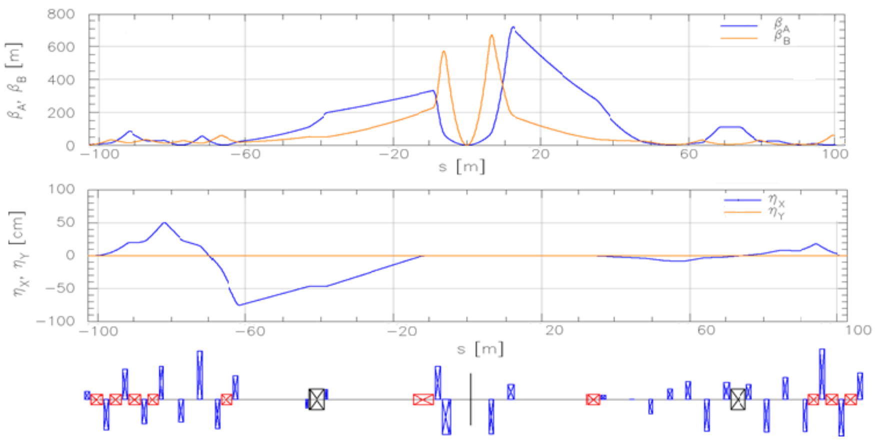


- HSR IR lattice matched into RHIC
  - Snake at correct global angle for polarization
  - β_x=1300 m at crab cavities
    - Compromise with forward tagging
  - Matching Magnets
    - Mostly repurposed RHIC magnets
    - Few additional magnets required (some SC)
    - Some existing IR magnets need re-cryostating



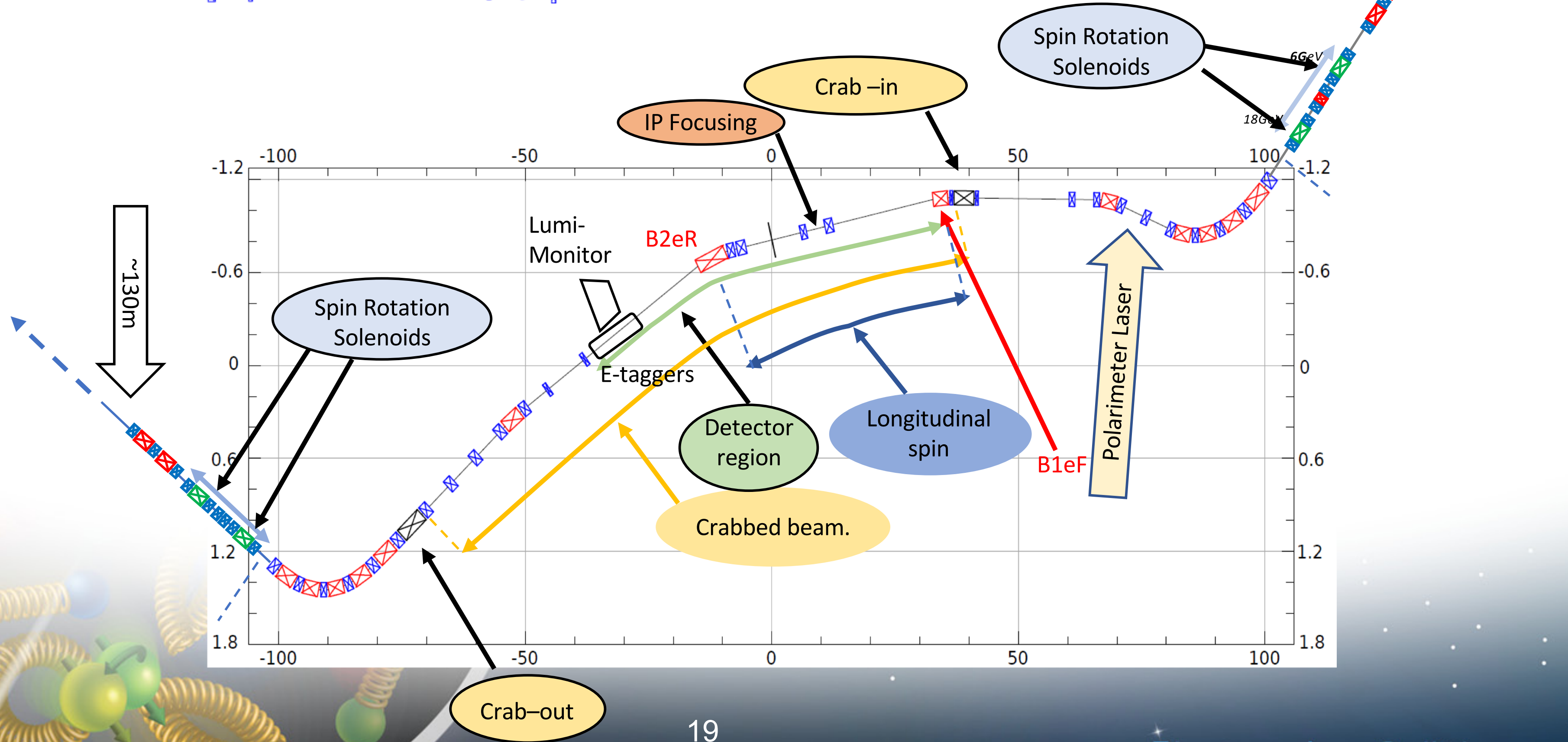
Electron-Ion Collider

ESR layout in IR6



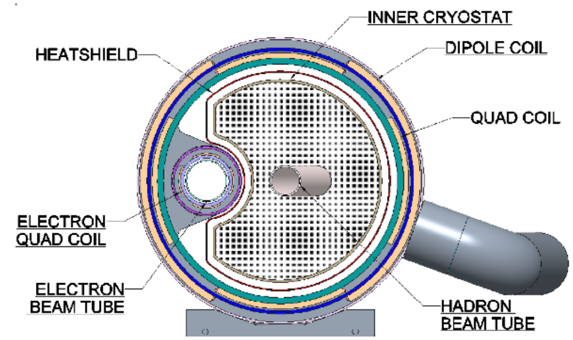
Design to:

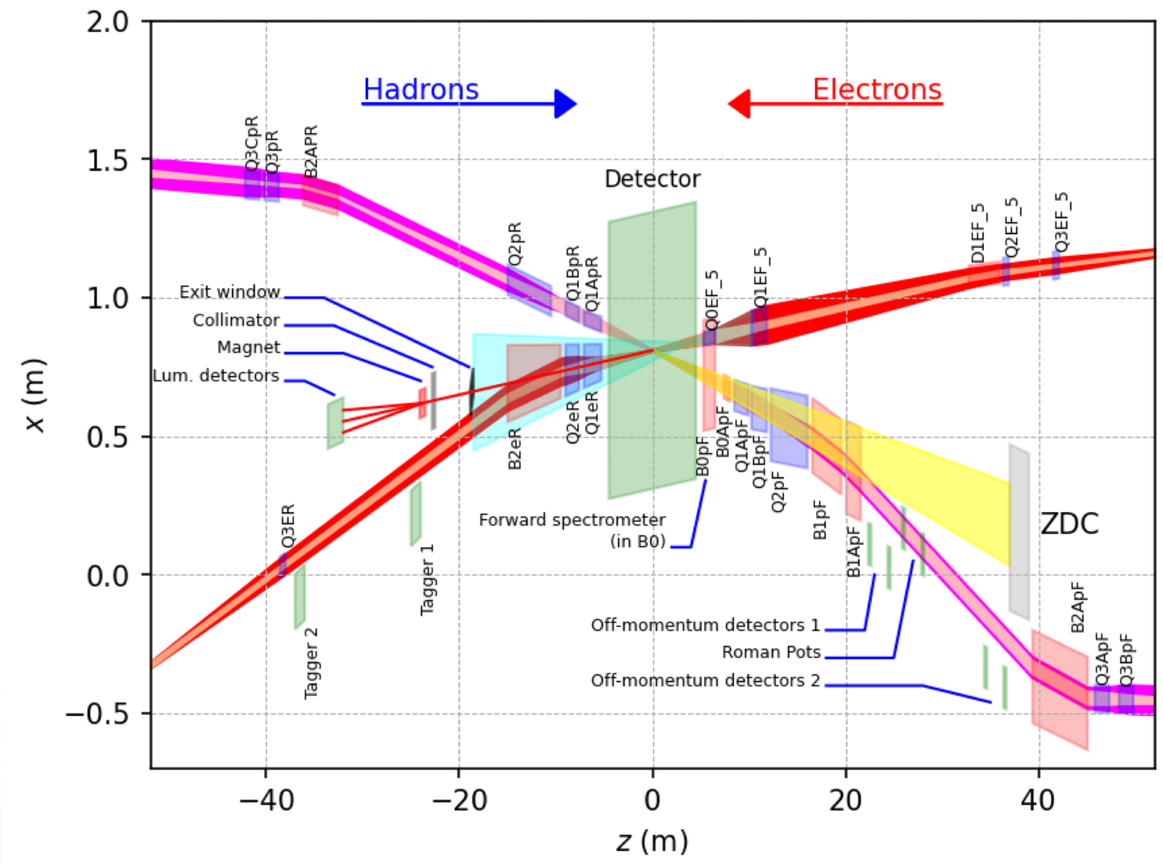
- Provide room for detector components
- Mitigate synchrotron radiation issues
- Provide longitudinal spin (new spin rotators)
- Match into the arcs
- Provide conditions for crabbing
- Allow 3 rings and beam elements

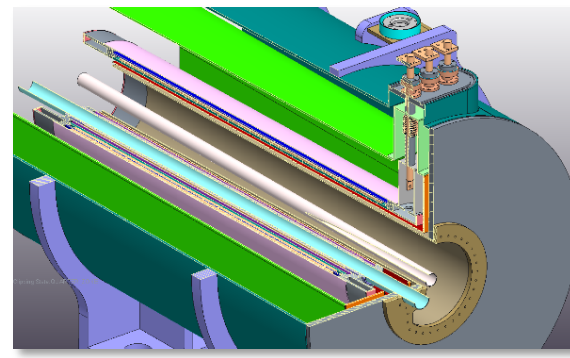


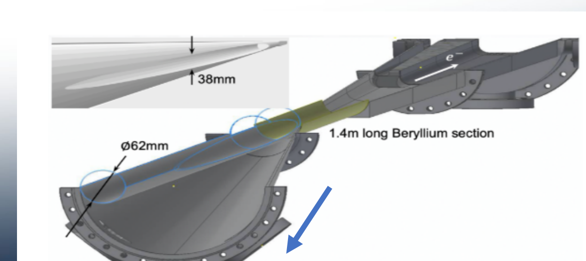
Interaction Region

- Beam focused to $\beta_y \le 5$ cm @ $\sigma_y = 5\ \mu$m, => $L = 10^{34}\ \mathrm{cm^{-2}\,s^{-1}}$
- 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







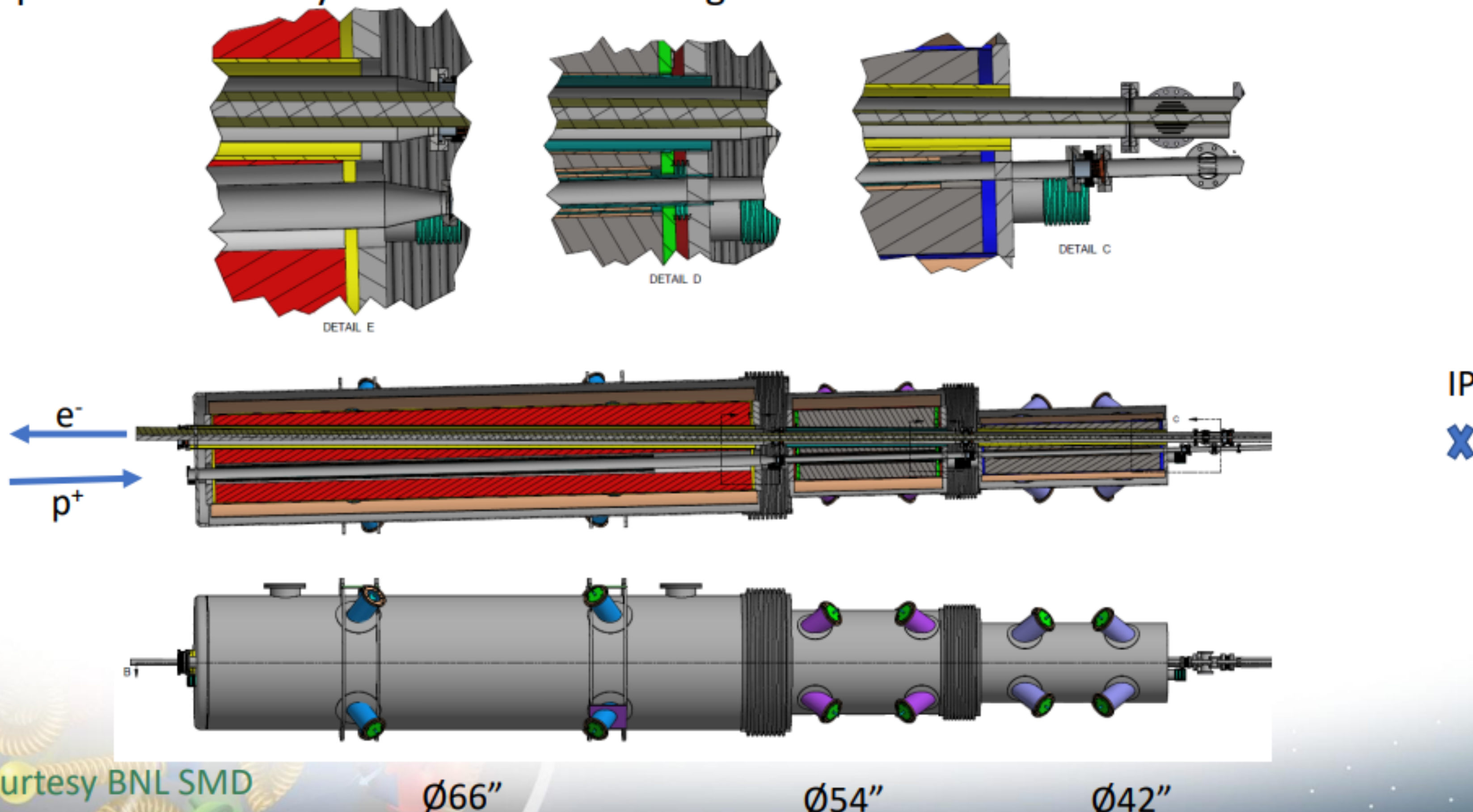


Superconducting IR Magnets

Rear Side Integration / Beampipe

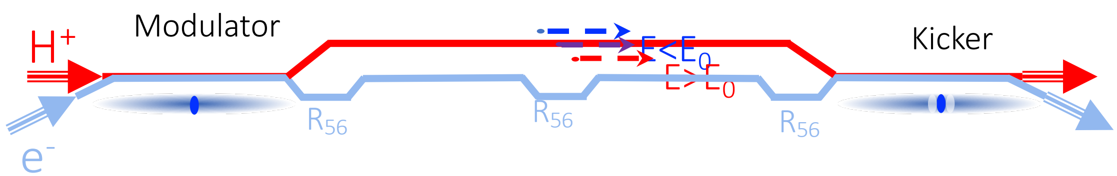
Separate cold masses - helium vessels

Separate circular cryostats with decreasing OD's toward IP

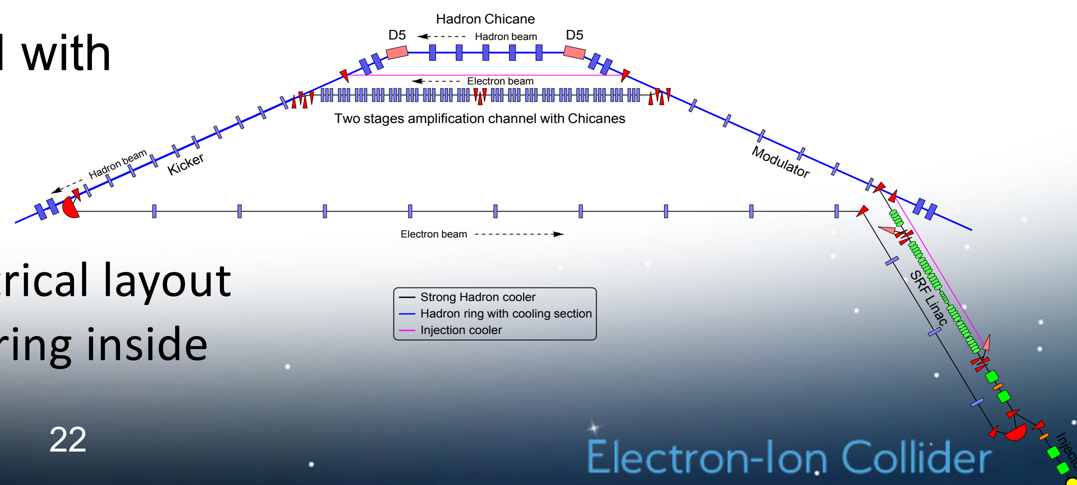


More on EIC MDR/IR Magnets: Holger Witte 18:00 Tue 13 Sep, Brett Parker 18:05 Wed 14 Sep

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

Progress on Accelerator Design

- The EIC design team has **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.

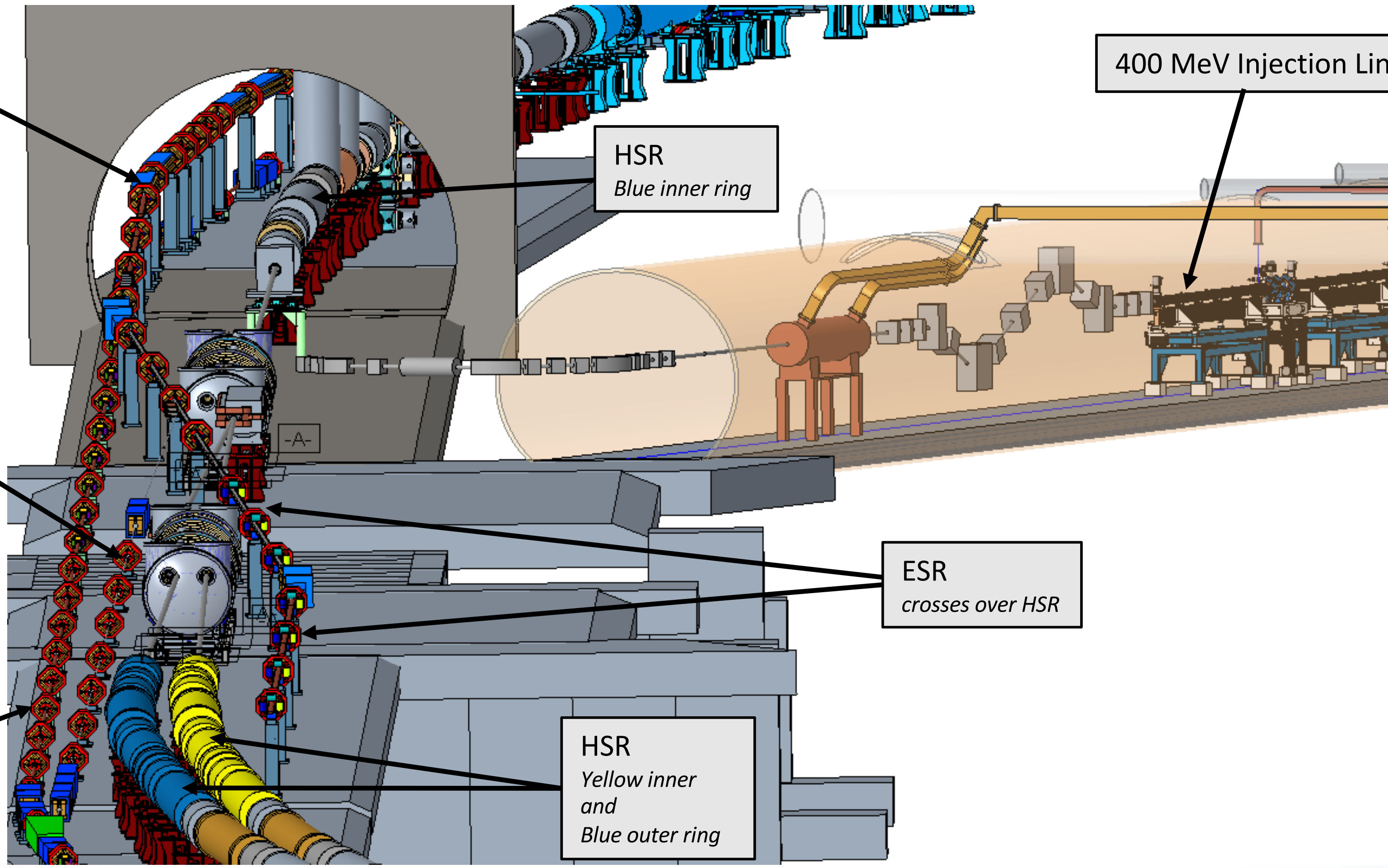
E
- **Electron injection** moved from IR2 to IR12
- **RCS accelerator lattice design** complete
- **Electron injection into ESR** modified: Eliminated slow bumps, slow residual effects on global orbit/IR steering. Now using stronger fast kickers, investigating nonlinear injection.
- **ESR accelerator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

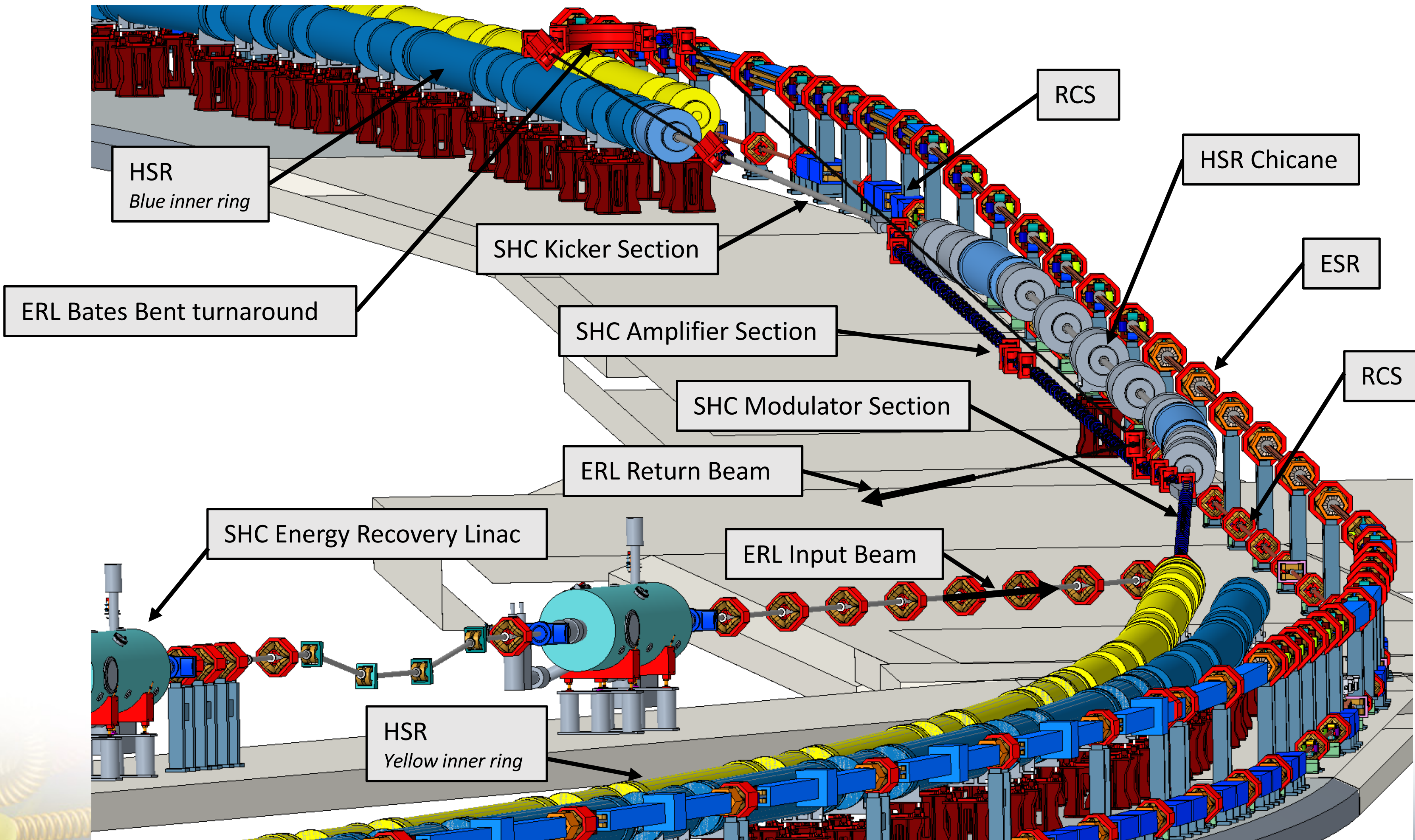
C
- **Interaction region further matured:** lattice stable, synchrotron radiation masking laid out, **collimation design in progress**

More on EIC diagnostics/instrumentation in Dave Gassner’s talk WG7 18:15 Wed

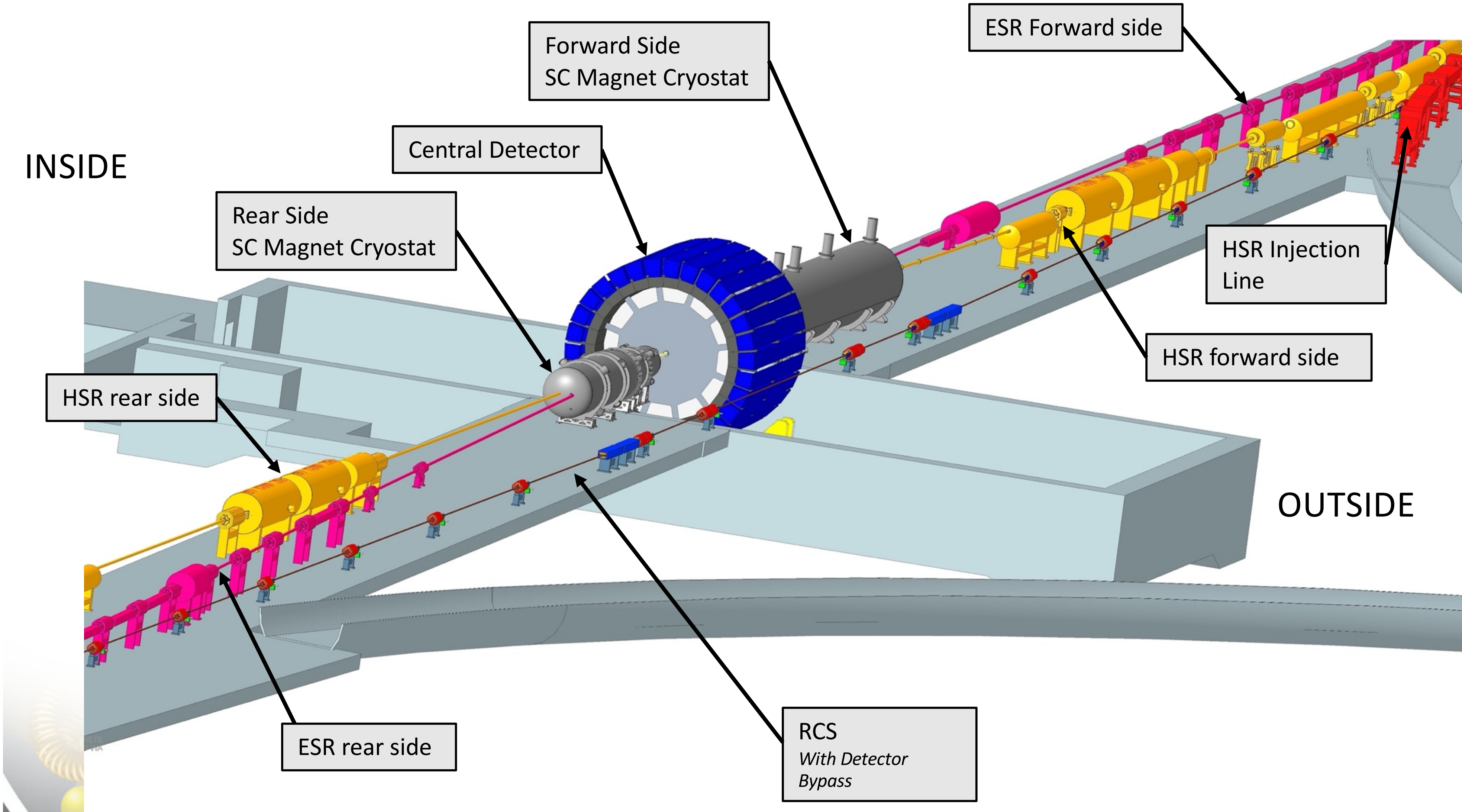
IR12


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

IR2

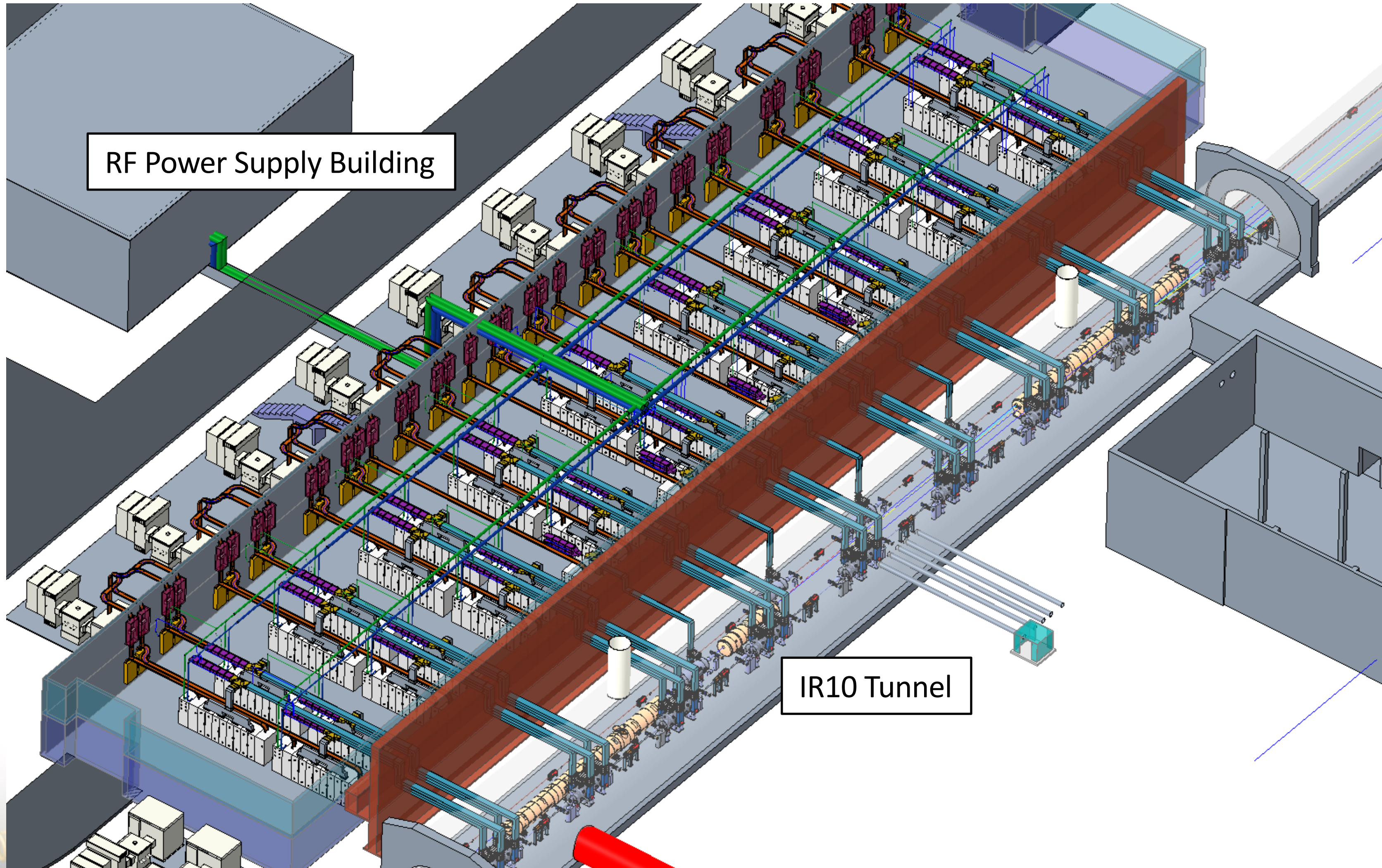

HSR
Blue inner ring
ERL Bates Bent turnaround
SHC Kicker Section
RCS
HSR Chicane
ESR
SHC Amplifier Section
RCS
SHC Modulator Section
ERL Return Beam
SHC Energy Recovery Linac
ERL Input Beam
HSR
Yellow inner ring

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



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 are now expanding from EIC management to 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

- The EIC is a challenging world-class facility
  - Dynamics and technology challenges are abundant and tractable
- Accelerator global design is close to be completed
  - Designs are now stable to serve a base for engineering design
- 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

CDR Parameters: High Divergence e-p

Table 3.3: EIC beam parameters for different center-of-mass energies $\sqrt{s}$, with strong hadron cooling. High divergence configuration.

Species	proton	electron	proton	electron	proton	electron	proton	electron	proton	electron
Energy [GeV]	275	18	275	10	100	10	100	5	41	5
CM energy [GeV]	140.7		104.9		63.2		44.7		28.6	
Bunch intensity [10^{10}]	19.1	6.2	6.9	17.2	6.9	17.2	4.8	17.2	2.6	13.3
No. of bunches	290		1160		1160		1160		1160	
Beam current [A]	0.69	0.227	1	2.5	1	2.5	0.69	2.5	0.38	1.93
RMS norm. emit., h/v [μm]	5.2/0.47	845/71	3.3/0.3	391/26	3.2/0.29	391/26	2.7/0.25	196/18	1.9/0.45	196/34
RMS emittance, h/v [nm]	18/1.6	24/2.0	11.3/1.0	20/1.3	30/2.7	20/1.3	26/2.3	20/1.8	44/10	20/3.5
β^*, h/v [cm]]	80/7.1	59/5.7	80/7.2	45/5.6	63/5.7	96/12	61/5.5	78/7.1	90/7.1	196/21.0
IP RMS beam size, h/v [μm]	119/11		95/8.5		138/12		125/11		198/27	
K_x	11.1		11.1		11.1		11.1		7.3	
RMS $\Delta\theta$, h/v [μrad]	150/150	202/187	119/119	211/152	220/220	145/105	206/206	160/160	220/380	101/129
BB parameter, h/v [10^{-3}]	3/3	93/100	12/12	72/100	12/12	72/100	14/14	100/100	15/9	53/42
RMS long. emittance [10^{-3}, eV·s]	36		36		21		21		11	
RMS bunch length [cm]	6	0.9	6	0.7	7	0.7	7	0.7	7.5	0.7
RMS $\Delta p/p$ [10^{-4}]	6.8	10.9	6.8	5.8	9.7	5.8	9.7	6.8	10.3	6.8
Max. space charge	0.007	neglig.	0.004	neglig.	0.026	neglig.	0.021	neglig.	0.05	neglig.
Piwinski angle [rad]	6.3	2.1	7.9	2.4	6.3	1.8	7.0	2.0	4.2	1.1
Long. IBS time [h]	2.0		2.9		2.5		3.1		3.8	
Transv. IBS time [h]	2.0		2		2.0/4.0		2.0/4.0		3.4/2.1	
Hourglass factor H	0.91		0.94		0.90		0.88		0.93	
Luminosity [10^{33}cm^{-2}s^{-1}]	1.54		10.00		4.48		3.68		0.44	

CDR Parameters: High Acceptance e-p

Table 3.4: EIC beam parameters for different center-of-mass energies $\sqrt{s}$, with strong hadron cooling. High acceptance configuration.

Species	proton	electron	proton	electron	proton	electron	proton	electron	proton	electron
Energy [GeV]	275	18	275	10	100	10	100	5	41	5
CM energy [GeV]	140.7		104.9		63.2		44.7		28.6	
Bunch intensity [10^{10}]	18.9	6.2	6.9	17.2	6.9	17.2	4.8	17.2	2.6	13.3
No. of bunches	290		1160		1160		1160		1160	
Beam current [A]	0.69	0.227	1	2.5	1	2.5	0.69	2.5	0.38	1.93
RMS norm. emit., h/v [μm]	5.2/0.46	845/70	3.3/0.3	391/26	3.2/0.29	391/26	2.7/0.25	196/18	1.9/0.45	196/34
RMS emittance, h/v [nm]	17.6/1.6	24.0/2.0	11/1.0	20/1.3	30/2.7	20/1.3	26/2.3	20/1.8	44/10	20/3.5
β^*, h/v [cm]]	417/38	306/30	265/24	149/19	94/8.5	143/18	80/7.2	103/9.2	90/7.1	196/21
IP RMS beam size, h/v [μm]	271/24		172/16		169/15		143/13		198/27	
K_x	11.1		11.1		11.1		11.1		7.3	
RMS $\Delta\theta$, h/v [μrad]	65/65	89/82	65/65	116/84	180/180	118/86	180/180	140/140	220/380	101/129
BB parameter, h/v [10^{-3}]	3/3	92/100	12/12	72/100	12/12	72/100	14/14	100/100	15/9	53/42
RMS long. emittance [10^{-3}, eV·s]	36		36		21		21		11	
RMS bunch length [cm]	6	0.9	6	0.7	7	0.7	7	0.7	7.5	0.7
RMS $\Delta p/p$ [10^{-4}]	6.8	10.9	6.8	5.8	9.7	5.8	9.7	6.8	10.3	6.8
Max. space charge	0.007	neglig.	0.004	neglig.	0.026	neglig.	0.021	neglig.	0.05	neglig.
Piwinski angle [rad]	2.8	0.9	4.3	1.4	5.2	1.5	6.1	1.7	4.2	1.1
Long. IBS time [h]	2.0		3.2		2.5		3.1		3.8	
Transv. IBS time [h]	2.0		2.0		2.0/4.0		2.0/4.0		3.4/2.1	
Hourglass factor H	0.99		0.98		0.94		0.91		0.93	
Luminosity [10^{33}cm^{-2}s^{-1}]	0.32		3.14		3.14		2.92		0.44	