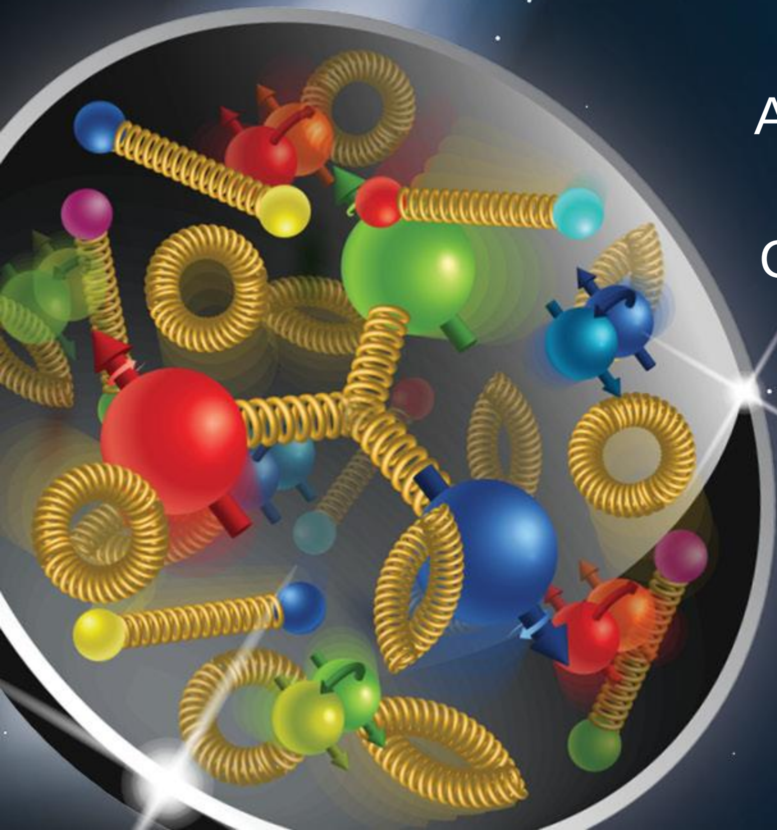
Overview of High Power RF for Electron-Ion Collider (EIC)



Alex Zaltsman, EIC High Power RF systems
On behalf of EIS RF team

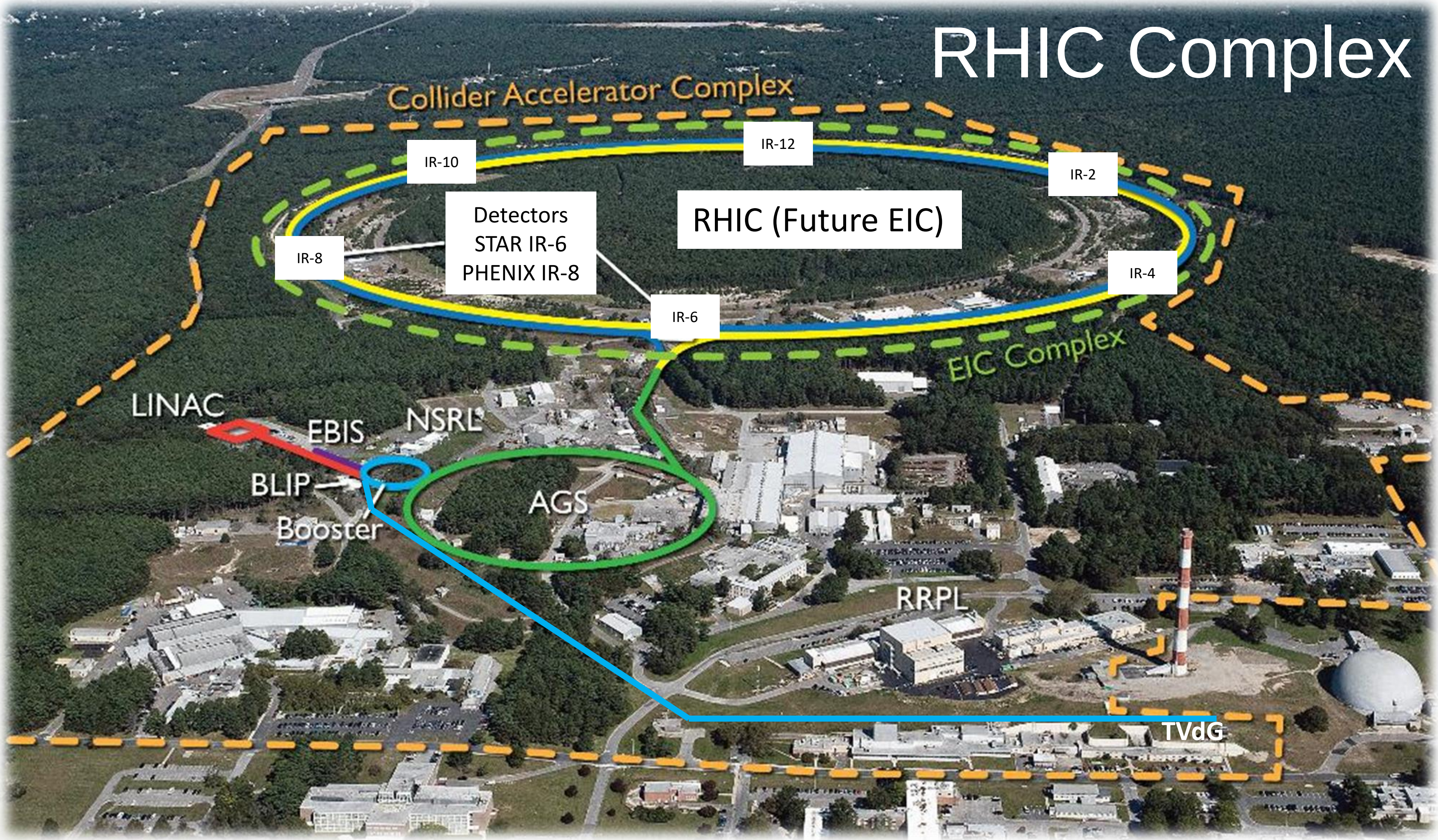
CW and High Average Power RF Workshop

September 2022

Electron-Ion Collider

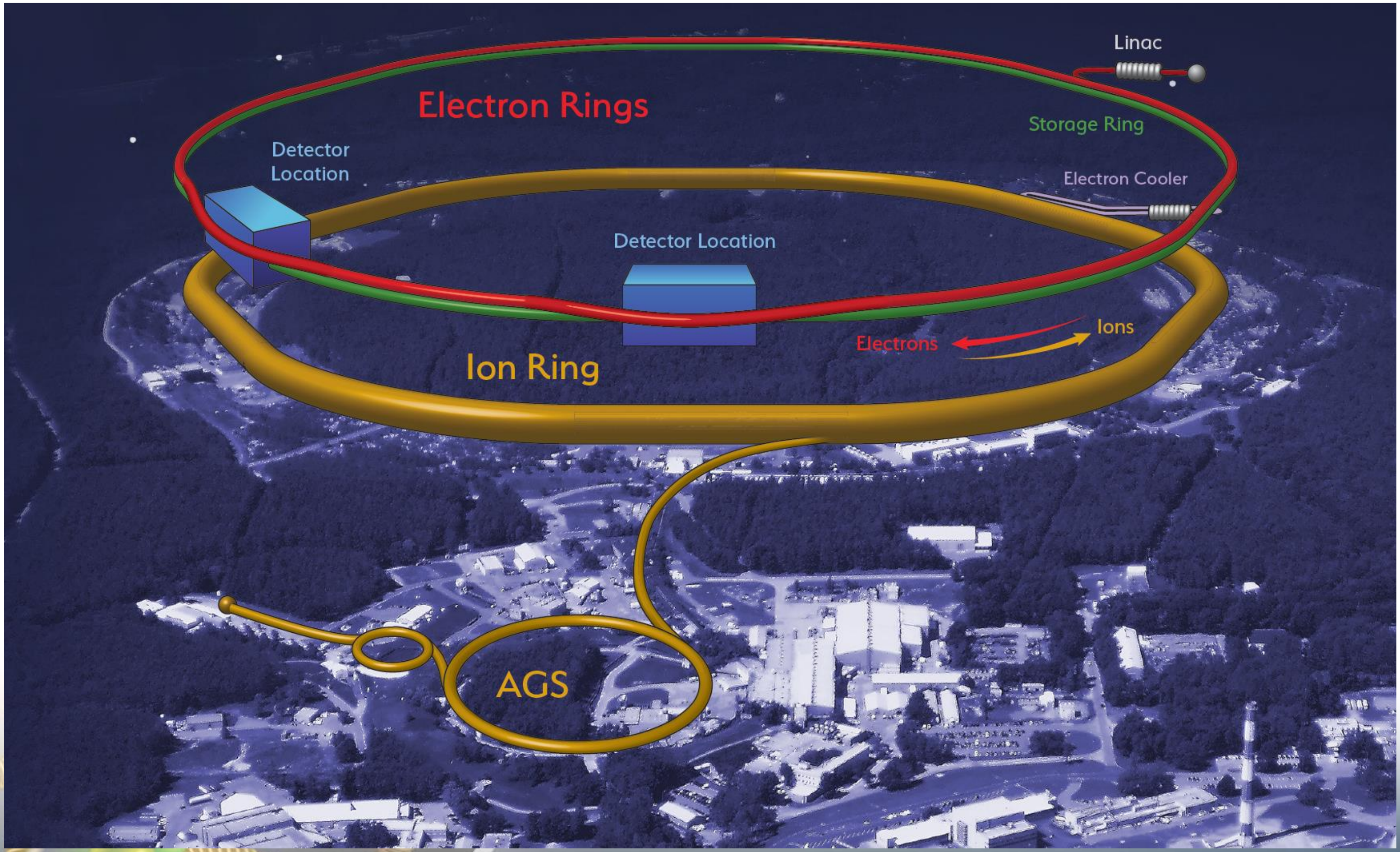
BROOKHAVEN NATIONAL LABORATORY   Jefferson Lab   U.S. DEPARTMENT OF ENERGY | Office of Science

RHIC Complex



- EIC leverages $B class investments and the highly successful RHIC program.

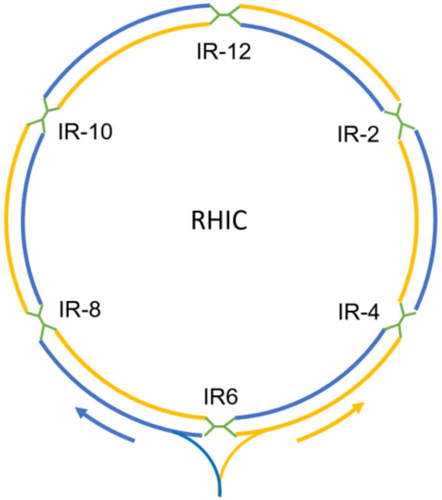
Electron Storage Ring (ESR), Rapid Cycling Synchrotron (RCS) and Detector

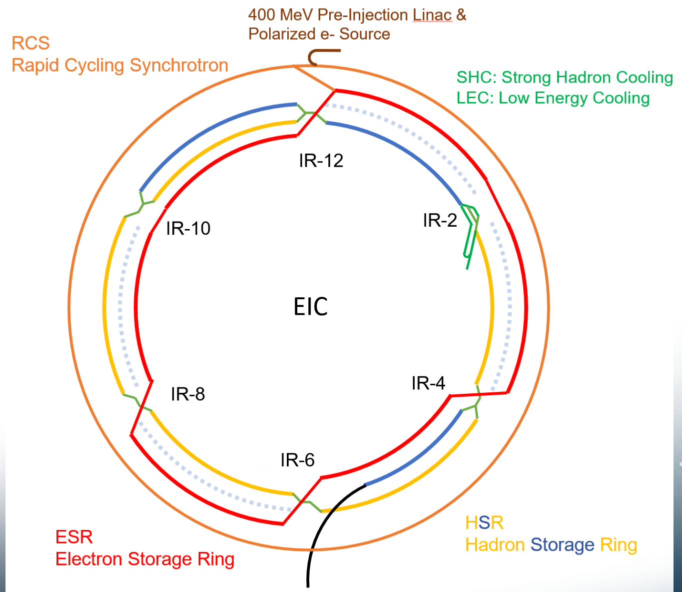


EIC Concept Based on a Ring-Ring Collider

Design leverages the **existing** RHIC and its injector complex.
RHIC is well maintained, operating at its peak performance (44x design Au luminosity).

- **High Luminosity Interaction Region(s) (IR-6)**
  - $L = 10^{34} cm^{-2} s^{-1}$
- **Hadron Storage Ring 40-275 GeV (Existing)**
  - Reuse parts of RHIC Yellow and Blue Rings
  - 1160 bunches via bunch splitting, up to 1A beam current
  - Beam Screen (Cu + Amorphous Carbon) - Installation In-Situ
  - Injection at IR-4
  - Need strong cooling at store - likely injection cooling too.
- **Electron Storage Ring (2.5–18 GeV, New)**
  - 1160 bunches, up to 2.5A beam current
  - Up to 10 MW S.R. power
  - Simultaneous Swap Out/In of Replacement Bunches, 1 Hz
- **Rapid Cycling Synchrotron (New)**
  - 1 Hz rep rate, 100ms ramp
  - **400 MeV Polarized e- Injector**





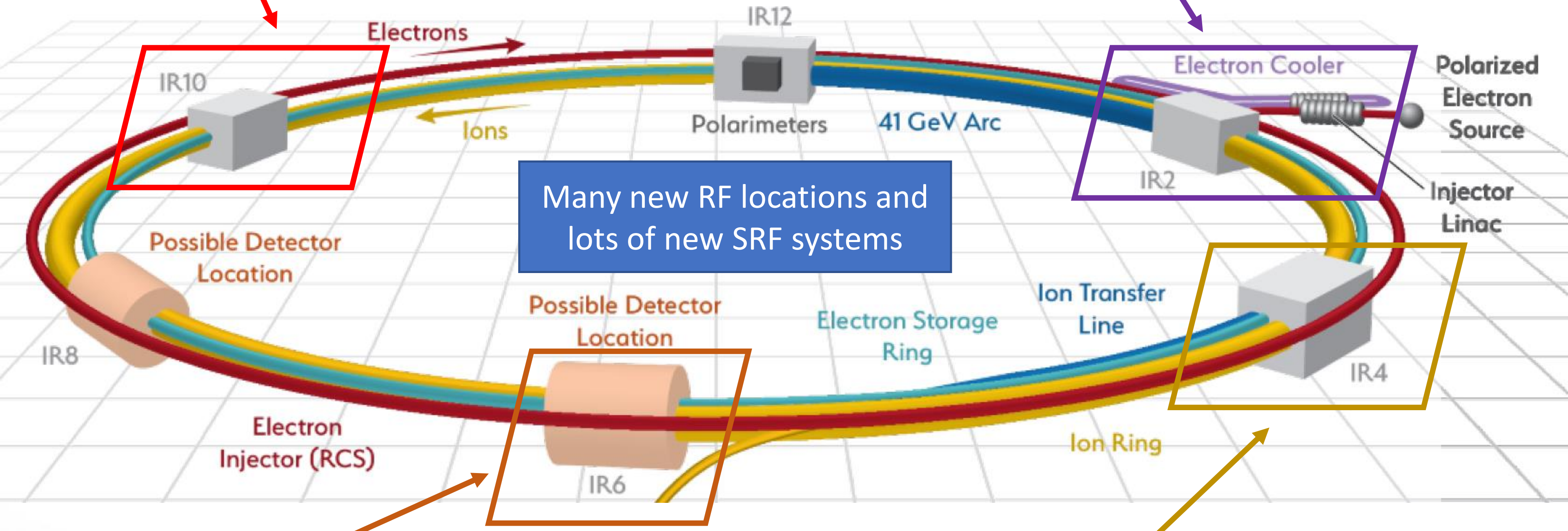
EIC Big Picture – RF Systems

IR-10: SRF Systems

RCS SRF
Electron Storage Ring SRF
Hadron Ring SRF

IR-2: Strong Hadron Cooling

Energy Recovery Linac (ERL)



Many new RF locations and lots of new SRF systems

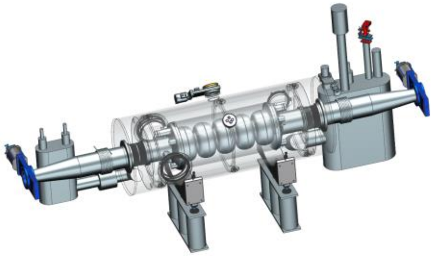
IR-6: Crab Cavity SRF Systems

197 MHz and 394 MHz Hadron Crab Cavity Systems
394 MHz Electron Crab Cavity Systems

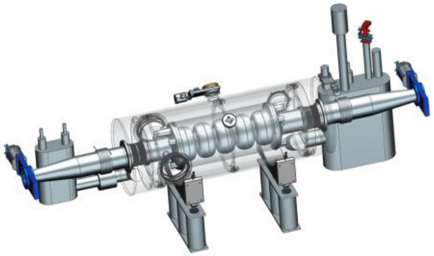
IR-4: Warm RF Systems

Current location for all RHIC RF systems
Hadron RF Systems (Hadron SRF at IR-10)
RCS Warm RF Systems (Bunch Merging)

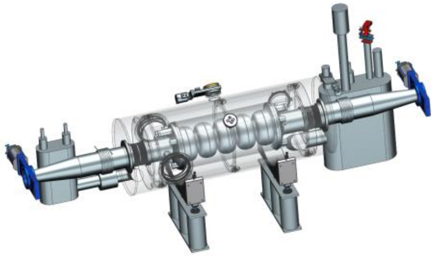
SRF and NCRF Cavities



RCS - 591 MHz 5-Cell Cavity
Acceleration Cavity

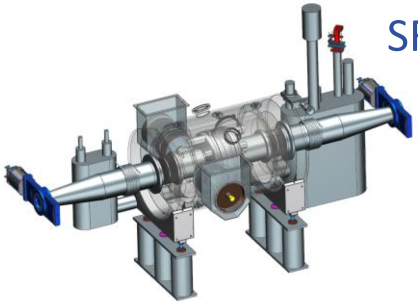


HSR - 591 MHz 5-Cell Cavity
Bunch Compression

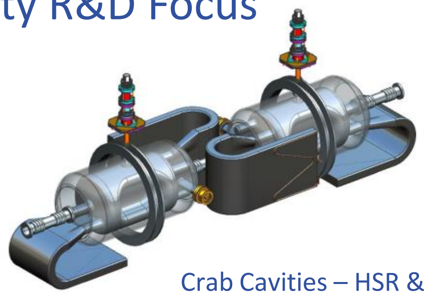


SHC- 591 MHz 5-Cell and
1773 MHz 5-Cell ERL Cavities

SRF Cavity R&D Focus

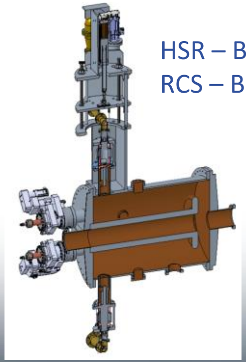


591 MHz ESR 1-Cell Cavity



Crab Cavities – HSR & ESR

HSR – 24.5 MHz Capture & Acceleration
Reuse with Modifications

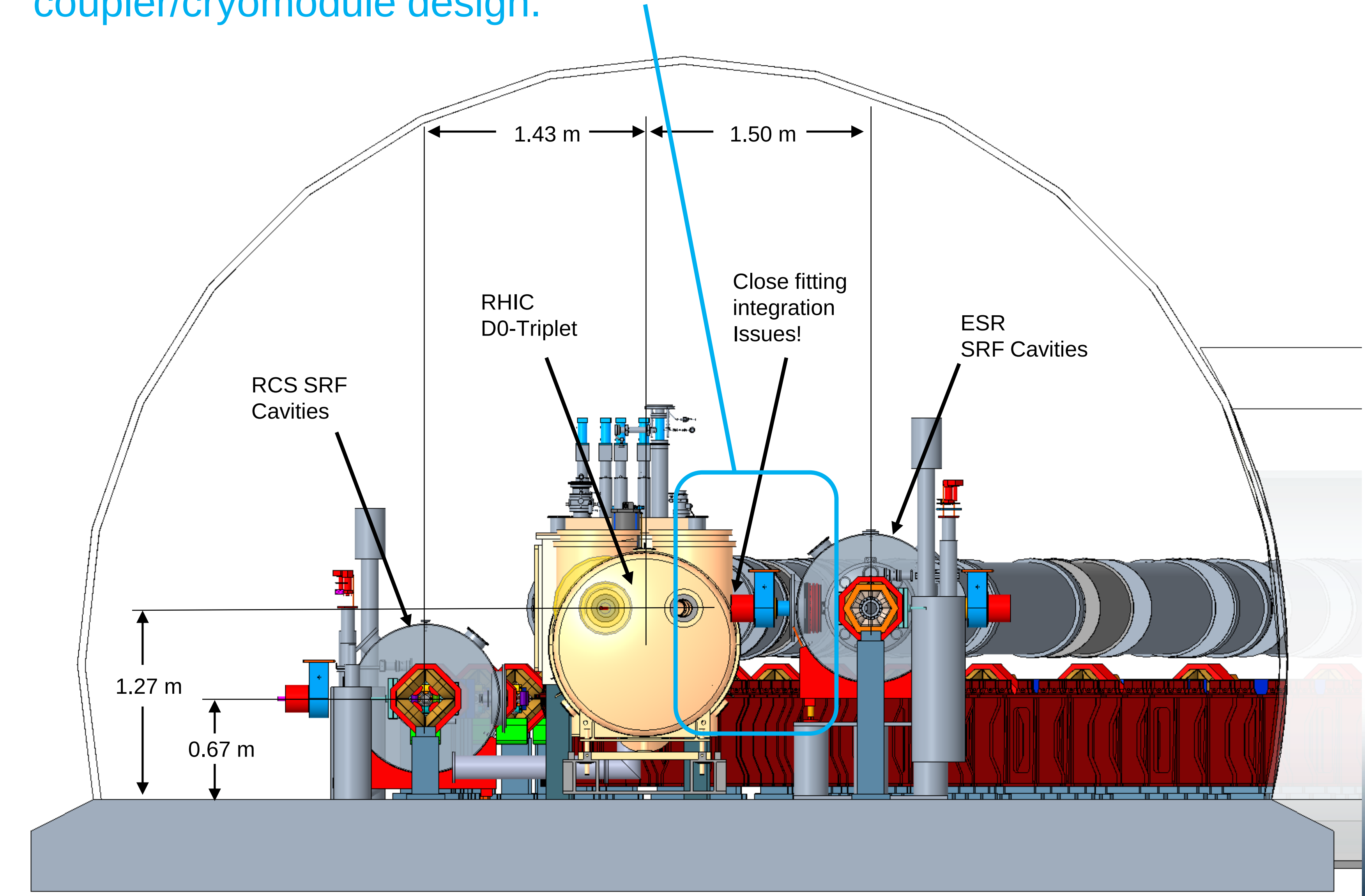


HSR – Bunch Splitting (New)
RCS – Bunch Merging (New)

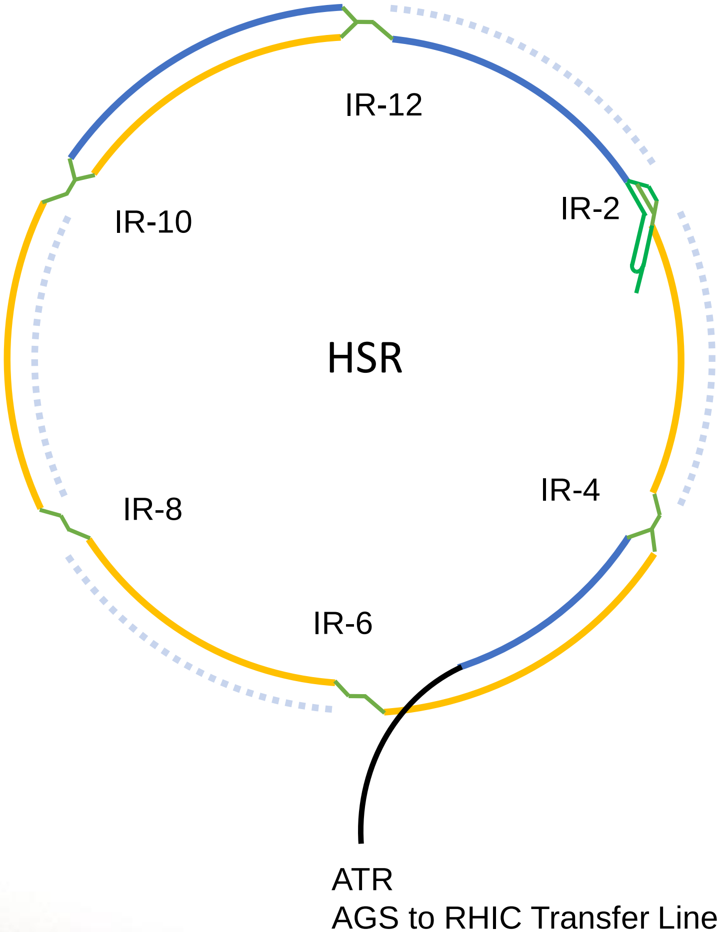
HSR - 197 MHz Bunch Compression
Reuse with Modifications

IR-10 Tunnel: Cryomodule Space Allocation

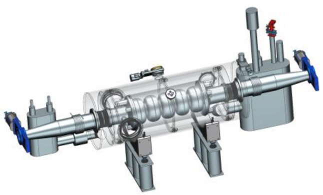
- Space constraints will contribute to the challenge for the integrated coupler/cryomodule design.



Proton (Hadron) Store for Collisions



- Depending on operating mode, may require up to a 1:2:4 bunch splitting.
  - Thus, the h=630 (49 MHz) and h=1260 (98 MHz) RF systems.
- After bunch splitting, need to compress bunches to desired store bunch length.
  - 5x shorter than RHIC.
  - Adiabatic compression first with h=2520 (197 MHz) and then with h=7560 (591 MHz).
- Then fill the ESR.

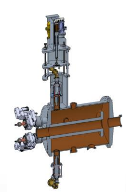
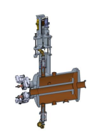


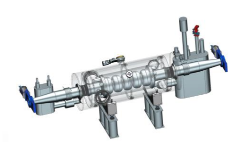
Proton (Hadron) RF System Summary

Table 6.67: EIC Hadron Ring RF System Parameters.

Parameter	Capture & Acceleration	Bunch Split 1	Bunch Split 2	Store 1	Store 2
Harmonic number	315	630	1260	2520	7560
RF nrequency [MHz]	24.6	49.3	98.5	197.1	591.1
Installed voltage [MV]	0.6	0.6	0.6	6.0	20.0
Number of cavities	2	2	2	6	1
Voltage per cavity [MV]	0.3	0.3	0.3	1.0	20.0
Cavity type	NCRF	NCRF	NCRF	NCRF	SRF
Cavity geometry [a]	QWR	QWR	QWR	Reentrant	Elliptical
Cavity $R/Q\,[\Omega_{ckt}]$	61	65	65	162	251
Cavity Q_0	16E3	19E3	14E3	44E3	2.3E10

[a] QWR = Quarter Wave Resonator



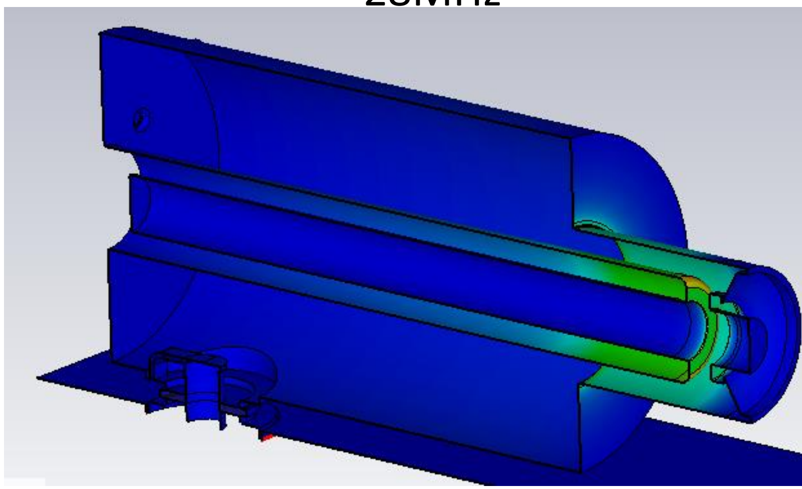
Proton (Hadron) RF System Summary

- Cavities & Cryomodule
  - Capture and Acceleration: 2x 24.6 MHz Cavities
    - Reuse (modify) RHIC 28 MHz Cu ¼ wave cavities, 300 kV each.
  - 1:2:4 Bunch Splitting: 2x 49.2 MHz and 2x 98.5 MHz Cavities
    - New Cu bunch splitter cavities
  - Store 1 Bunch Compression: 6x 197 MHz Cavities
    - Reuse RHIC 197 MHz Cu re-entrant style cavities, up to 1 MV each.
  - Store 2 Bunch Compression: 591 MHz SRF 5-cell Elliptical Cavity Cryomodules with SiC Beam Line Absorbers (BLAs)
    - Standard Toshiba 70 kW power coupler we have experience with.
    - Second highest HOM power (~3 kW) after ESR (~40kW)

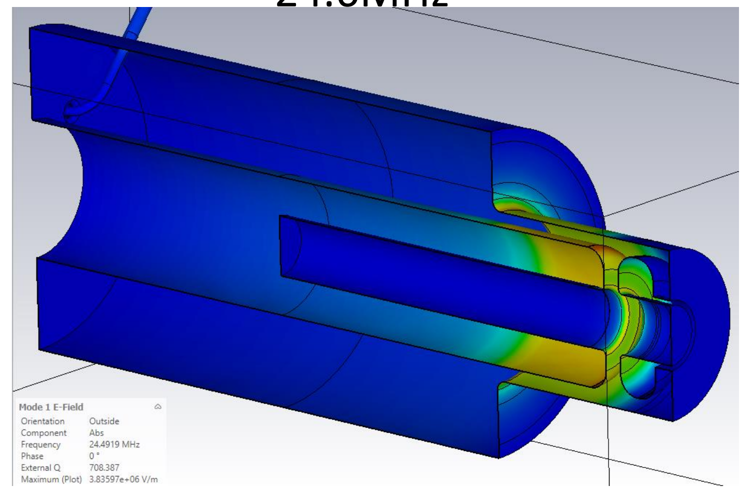
- High Power Amplifiers
  - 591 MHz: 75 kW Solid State Amplifiers (same modular unit type as ESR)
  - Hadron RF systems historically use strong, direct RF feedback. Likely to continue.
    - Solid state amplifiers in the ring – we have experience with this (at least with hadron secondaries).

28MHz Cavity & Amplifier Upgrades

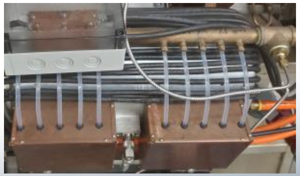
28MHz



24.6MHz



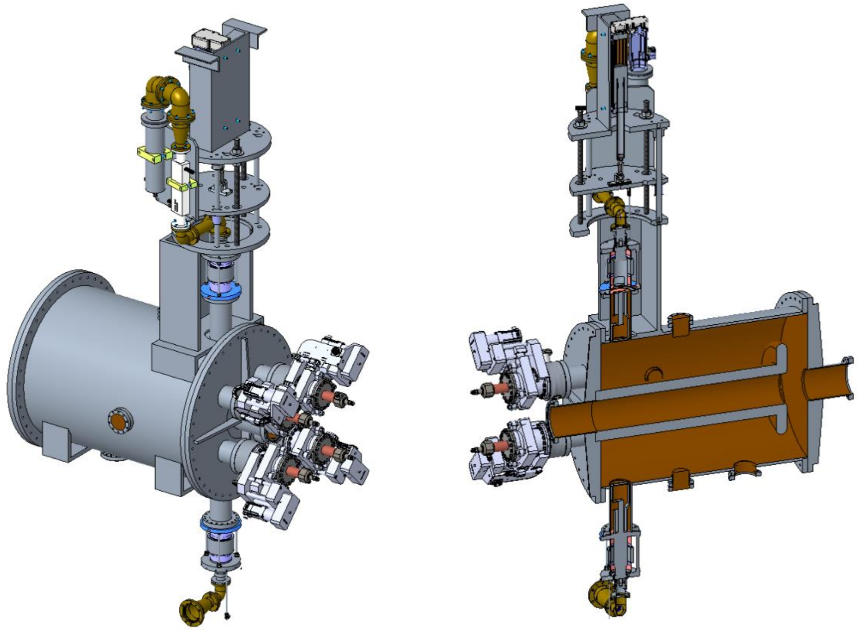
- Adjust critical cavity parameters (primarily for R/Q)
- Increase high order mode damper load power handling
- Upgrade fundamental power coupler
- Design a new ferroelectric tuner or upgrade the current ferrite tuner’s range
- Refurbish critical Power Amplifiers (PA) components
- Replace drive chain with new Rad-Hard GaN amplifier platform



HSR bunch splitter

- QWRs that split 290 bunches in HSR into 580 and finally 1160 bunches. H=315 + abort gap
- The 49.2MHz cavity produces as much as 7kW HOM power, and for 98.5MHz it is 20kW.
- Minimum detune required: 10.4kHz for 49.2MHz cavity, and 18.2kHz for 98.5MHz cavity.

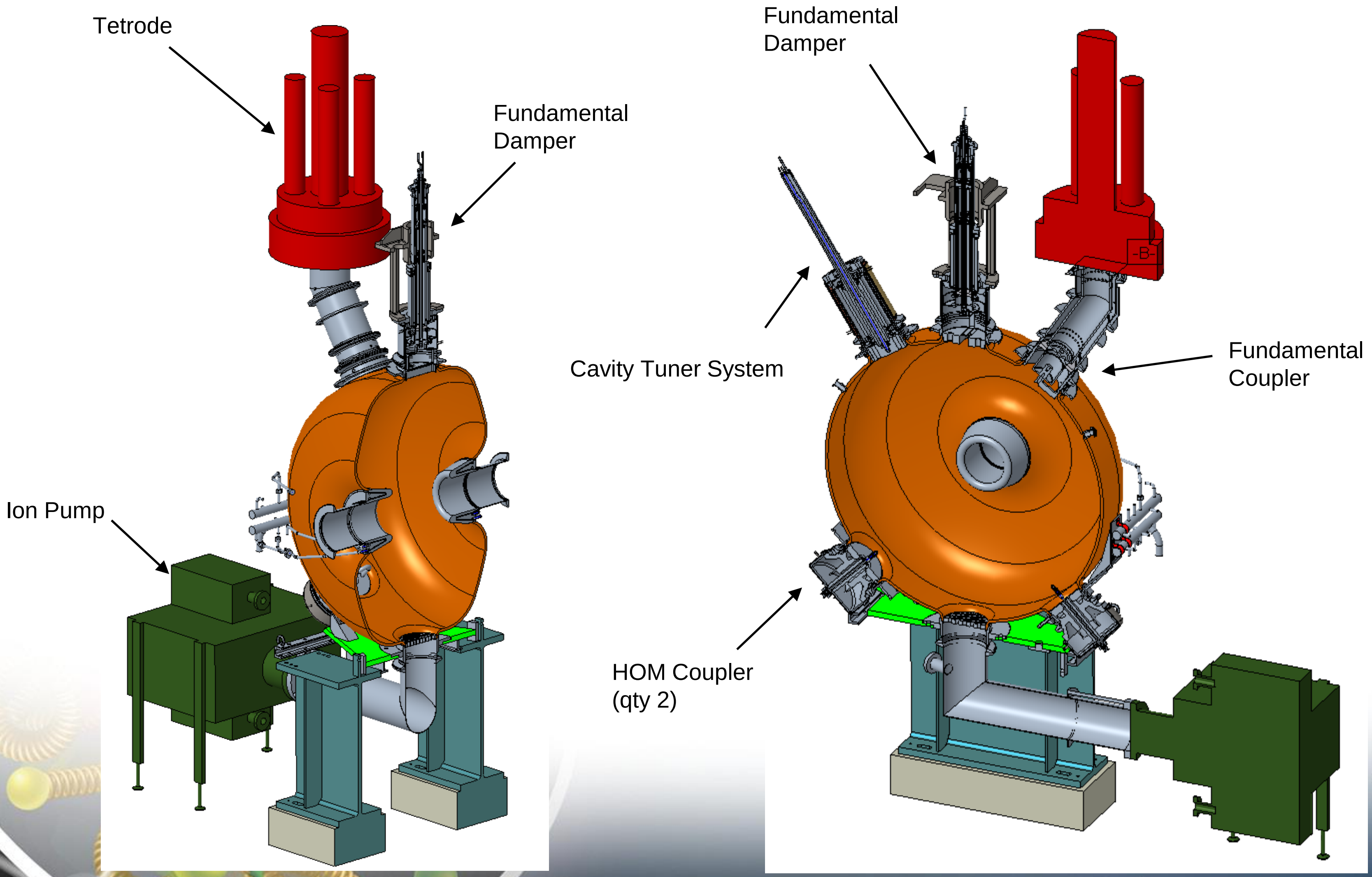
The conceptual design view of 49.2MHz splitter cavity. The 98.5MHz cavity will be a direct scale from the 49.2MHz cavity.



Design parameters of the 49.2MHz and 98.5MHz cavities.

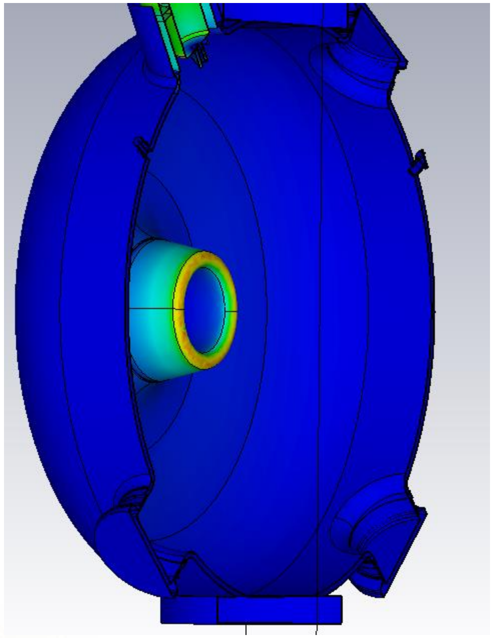
Parameter	49.2 MHz Cavity	98.5 MHz Cavity
Diameter [mm]	800	400
Length [mm]	1600	800
Gap [mm]	117	58.5
Beampipe radius [mm]	85	42.5
Thickness of nose cone [mm]	55.8	27.9
Radius of capacitor disk [mm]	253.2	126.6
Thickness of capacitor disk [mm]	50	25
Radius of corner blending [mm]	10	5
Frequency [MHz]	49.2	98.5
R/Q [Acc. Def.]	130.7	130.7
E_{acc} [MV/m]	2.6 @ 300 kV	6.0 @ 350 kV
E_{max} [MV/m]	4.5 @ 300 kV	10.4 @ 350 kV
Q_0	1.9×10^4	1.36×10^4
R_{sh} [Ω]	2.48×10^6	1.77×10^6
RF power loss [kW]	36 @ 300 kV	70 @ 350 kV

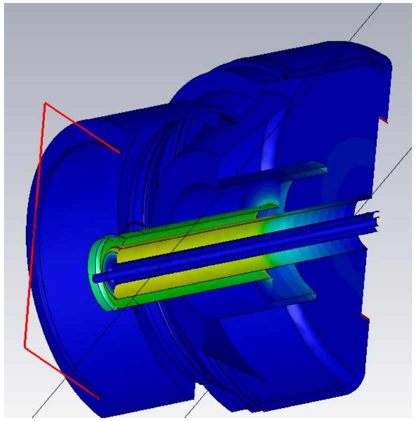
Hadron 197 MHz RF Cavity System Assembly



197MHz Cavity & Amplifier Upgrades

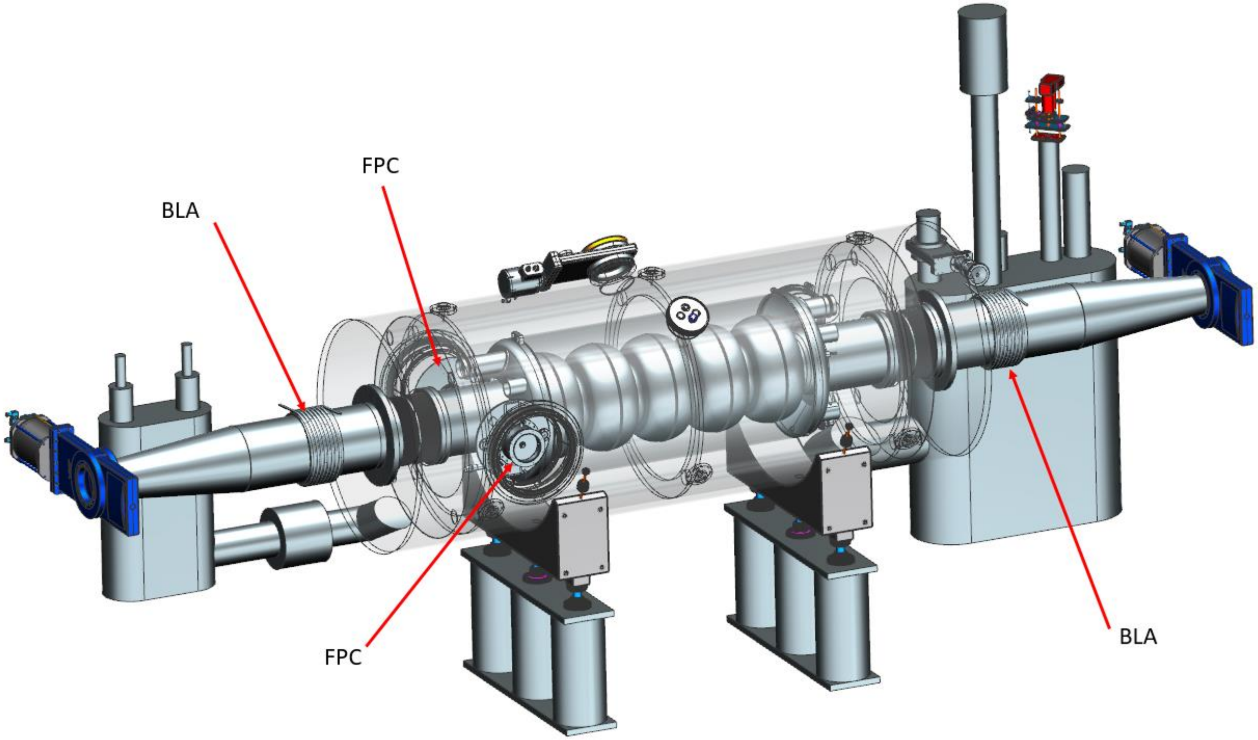
- Increase high order mode damper load power handling
- Upgrade fundamental power coupler windows
- Refurbish critical PA components
- Replace drive chain with new Rad-Hard GaN amplifier platform



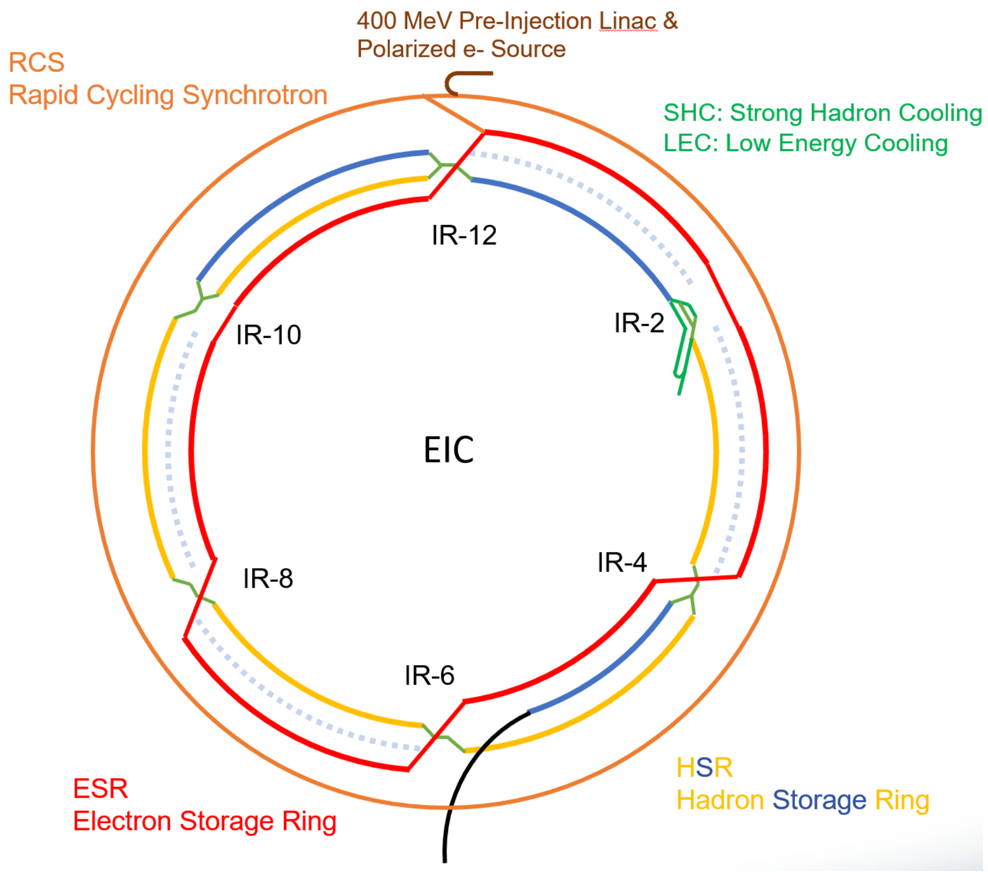


591 MHz SRF 5-cell Elliptical Cavity Cryomodules with SiC BLAs

70 kW solid state amplifier



RCS


400 MeV Pre-Injection Linac &
Polarized e- Source
RCS
Rapid Cycling Synchrotron
SHC: Strong Hadron Cooling
LEC: Low Energy Cooling
IR-12
IR-10
IR-2
EIC
IR-8
IR-4
IR-6
ESR
Electron Storage Ring
HSR
Hadron Storage Ring

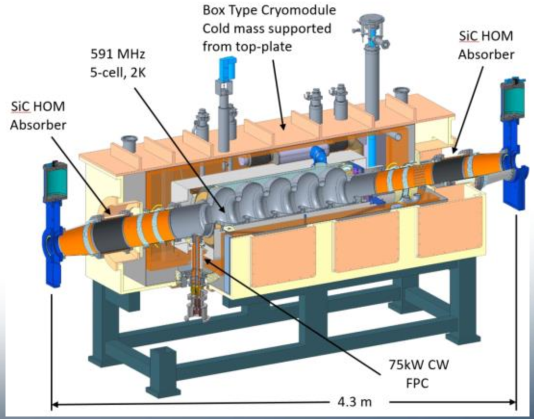
RCS RF Systems

- 3 Cryomodules
  - 591 MHz, 2K, 5-cell elliptical cavity, single cavity cryomodule with SiC BLAs.
  - Standard Toshiba 70 kW power coupler we have experience with.

- 3 High Power Amplifiers
  - 2x 28nC bunches @ (2MV/turn (accel) 38 MeV/turn (SR) = 175 kW to the beam.
  - 75 kW modular SSPA
    - Utilizes a single cabinet of the much larger ESR high power amplifier type – configured with fewer modules for lower power requirement.

- 3 NCRF Bunch Merging Cavities (4 => 2 => 1 Bunch Merge at 400 MeV injection or 1 GeV porch)
  - 296 MHz: 2x reentrant style @ 650 kV. PA 70 kW
  - 148 MHz: 1x reentrant style @ 700 kV. PA 70 kW

- Nx (N >= 1) NCRF Multi-Harmonic QWR Injection Kicker



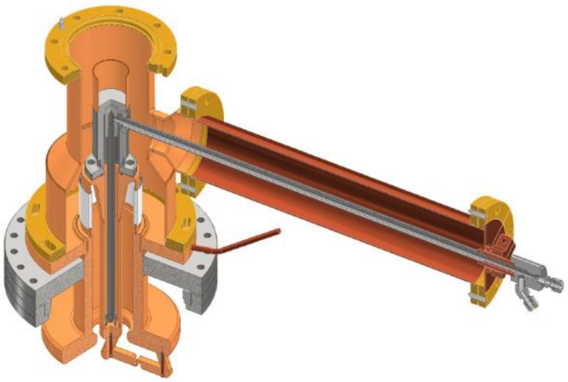
RCS Parameters

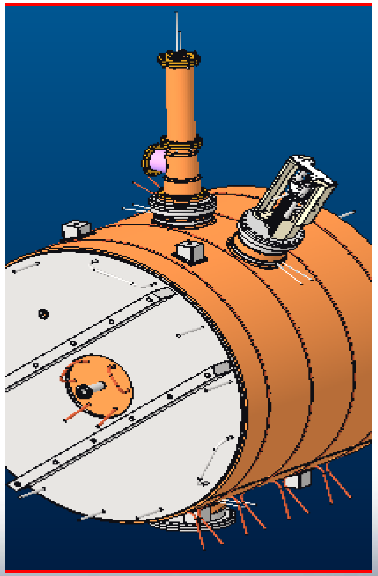
RCS Bunch Merge RF

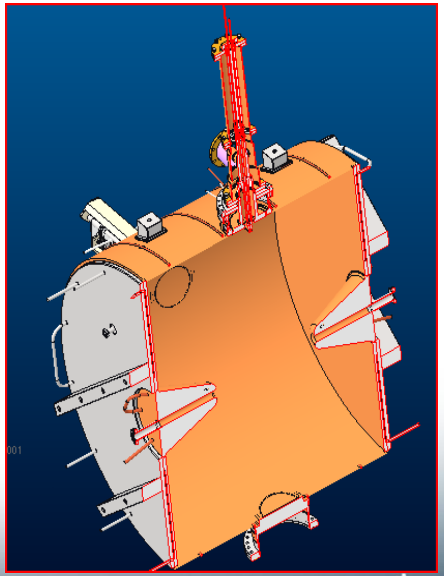
Table 6.66: Operating Parameters for the NCRF Bunch Merging Cavities.

Parameter	Bunch Merge 1	Bunch Merge 2
RF frequency [MHz]	295.5	147.8
Harmonic number	3780	1890
Installed voltage [MV]	1.3	0.7
Number of cavities	2	1
Cavity R/Q	170	170
Cavity Q_0	41000	50000
Maximum cavity voltage [MV]	0.65	0.7
Cavity power dissipation [kW]	30.3	28.8
Coupling Beta	1	1
Coupling Q_{ext}	41000	50000
Cavity loaded half bandwidth [kHz]	7.2	3.0

RCS Fundamental RF





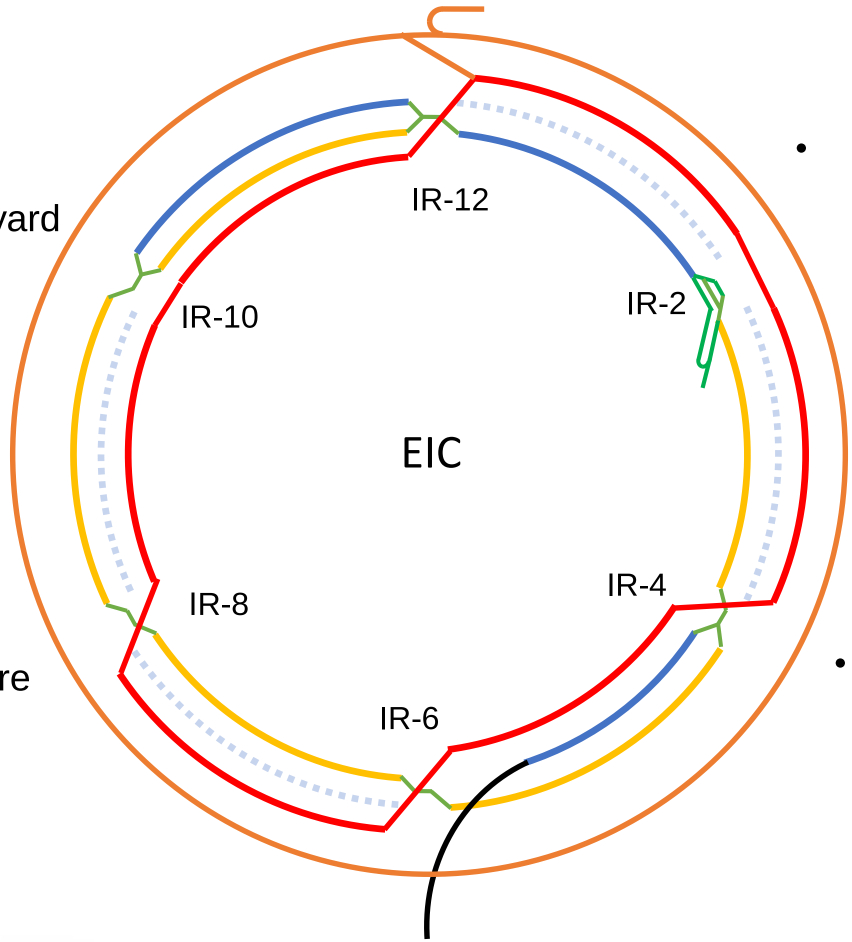


From RHIC to EIC

- IR-12
  - 400 MeV Polarized e- Injector
  - RCS/ESR Swap In/Out Transfer
  - 41/100 GeV Switchyard

- IR-10
  - Ring SRF Systems (RCS, ESR, HSR)
  - 41/100 GeV Switchyard
  - HSR Abort System

- IR-2
  - Strong Hadron Cooling / Injection Cooling
  - ERL and ERL Injector SRF systems



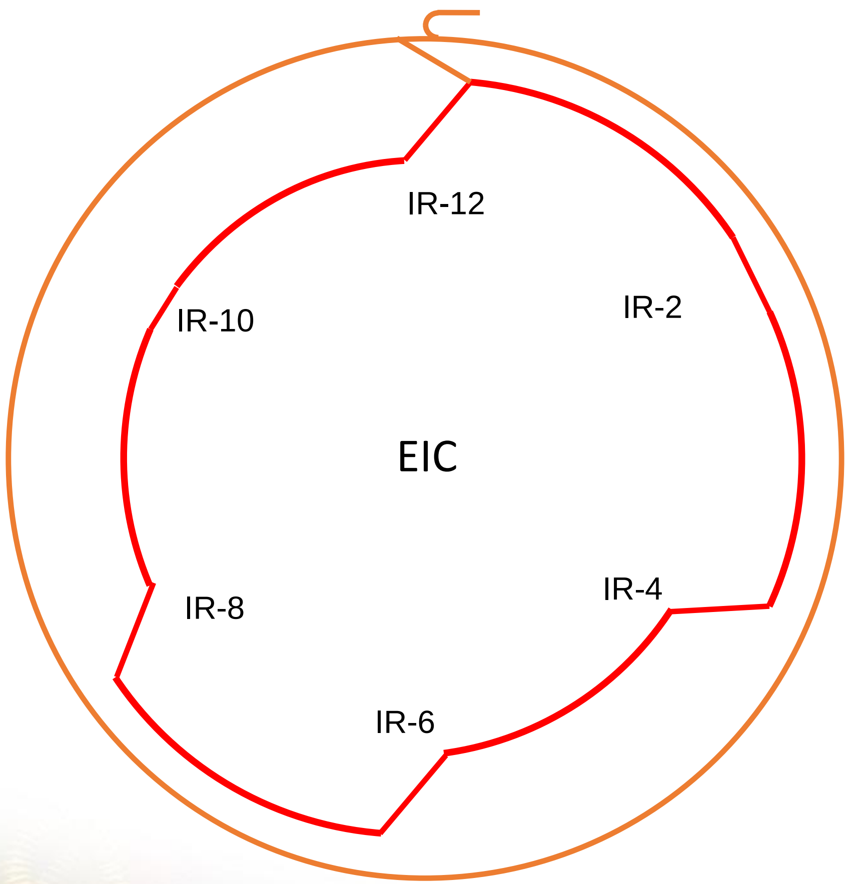
- IR-8
  - Reserve space and accommodate a future second detector.
  - Not on project.

- IR-4
  - New HSR injection point
  - HSR and RCS NCRF systems

- IR-6
  - Experimental Detector location
  - VERY, VERY different from RHIC
  - New and Complex SC Magnets
  - Crab SRF systems on both sides

RF

High Average RF Power - ESR Synchrotron Radiation

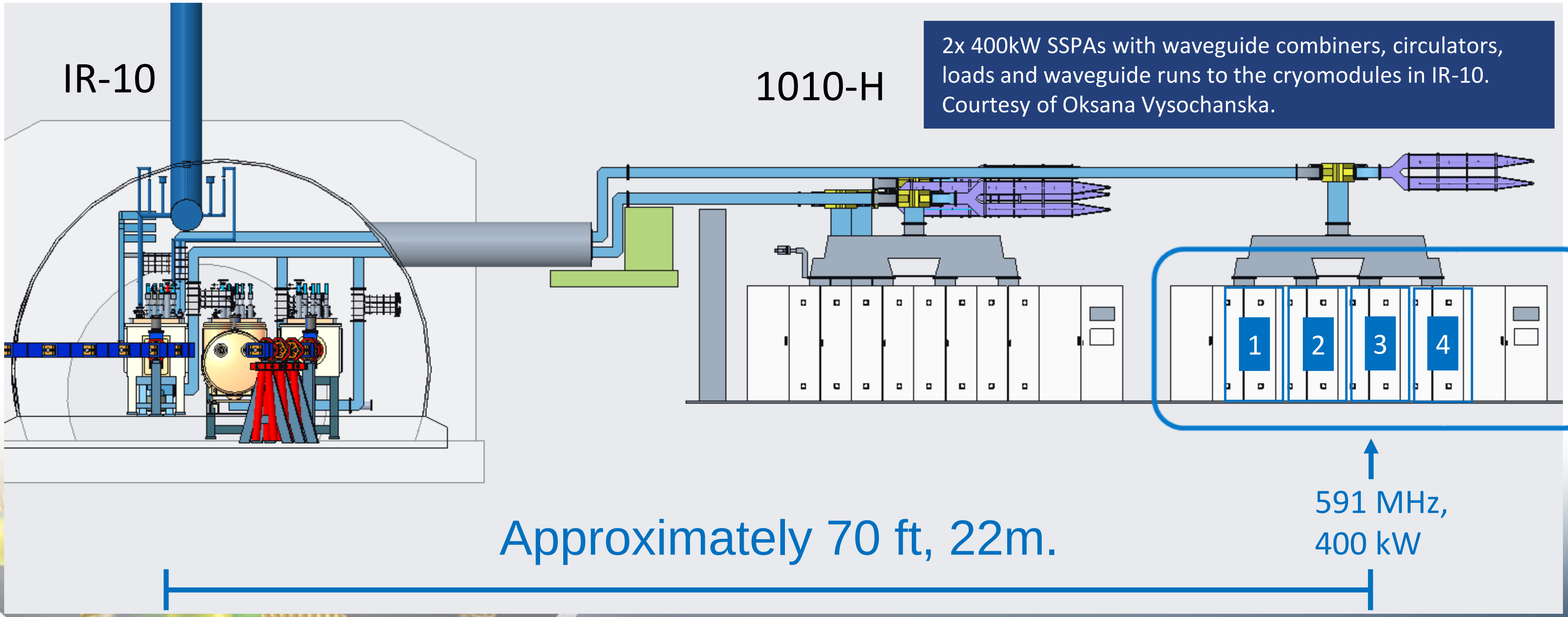


- ESR
  - Very high beam current up to 2.5A DC.
    - 18 GeV: 0.225 A
    - 5-10 GeV: 2.5 A
  - Very high synchrotron radiation loss:
    - 18 GeV: 36.95 MeV per turn
    - 10 GeV: 3.52 MeV per turn
    - 5 GeV: 0.95 MeV per turn
  - Very high synchrotron radiation power:
    - 18 GeV: 8.3 MW
    - 10 GeV: 8.8 MW
    - 5 GeV: 2.4 MW
  - Design for 10 MW maximum
  - Plus:
    - Cavity HOM power: 600kW – 800kW
    - Ring Resistive Wall and Geometric Impedance: 500 kW – 1MW
    - A little overhead power would be nice.
  - 14 MW installed power.
    - Very large SSA installation.

Electron Storage Ring RF Power

- 34 High Power RF Amplifiers
  - 13.6 MW total installed power - 400kW solid state amplifiers (4x cabinets of 100kW ea. + DC power + controls)
  - Solid state has become competitive on cost, power density, space.
  - Additional advantages w.r.t. safety (low voltage), modularity, commonality, future proofing.

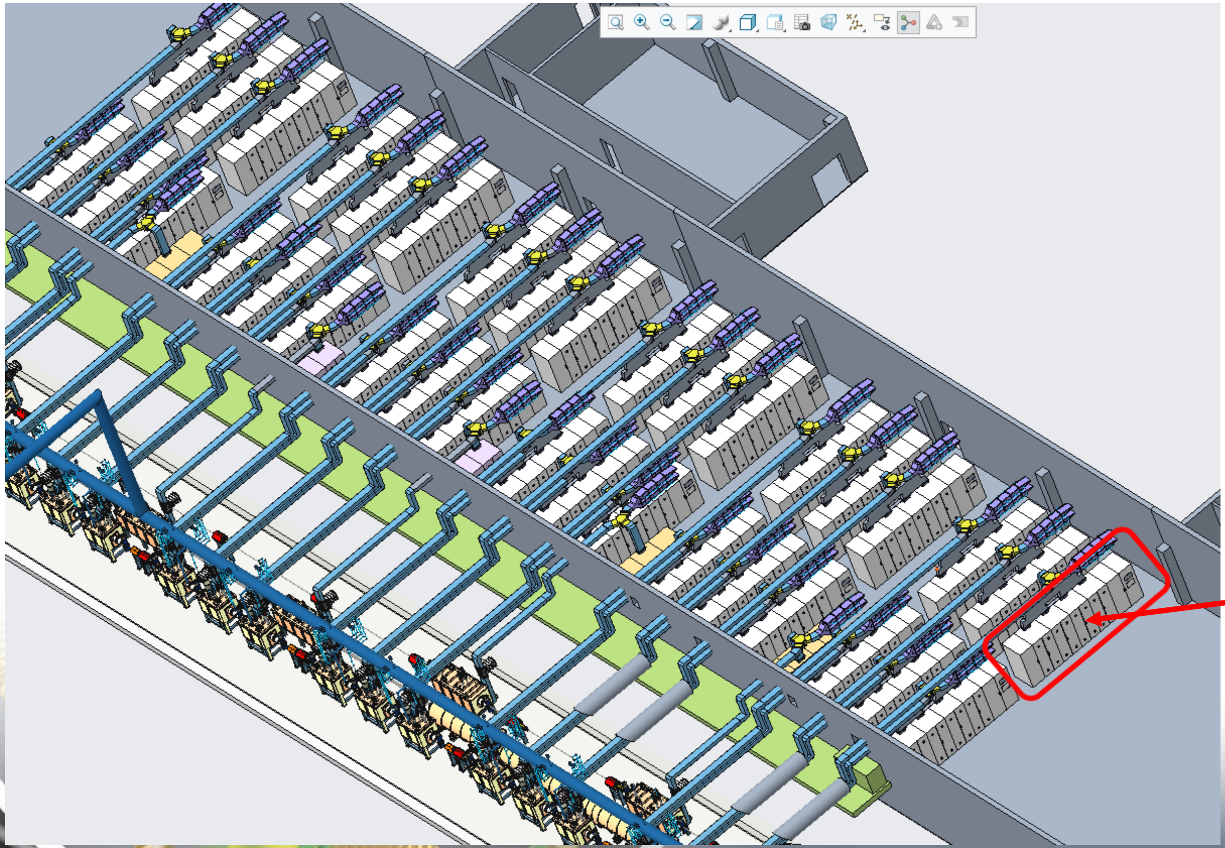
- Cavities have dual 400 kW CW FPCs



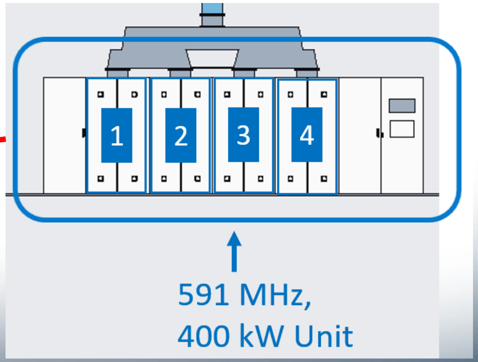
ESR RF System.

RF1010 Support Building with ~14 MW total SSA based high power RF, interface to IR-10 and IR-10 cryomodule layout.**

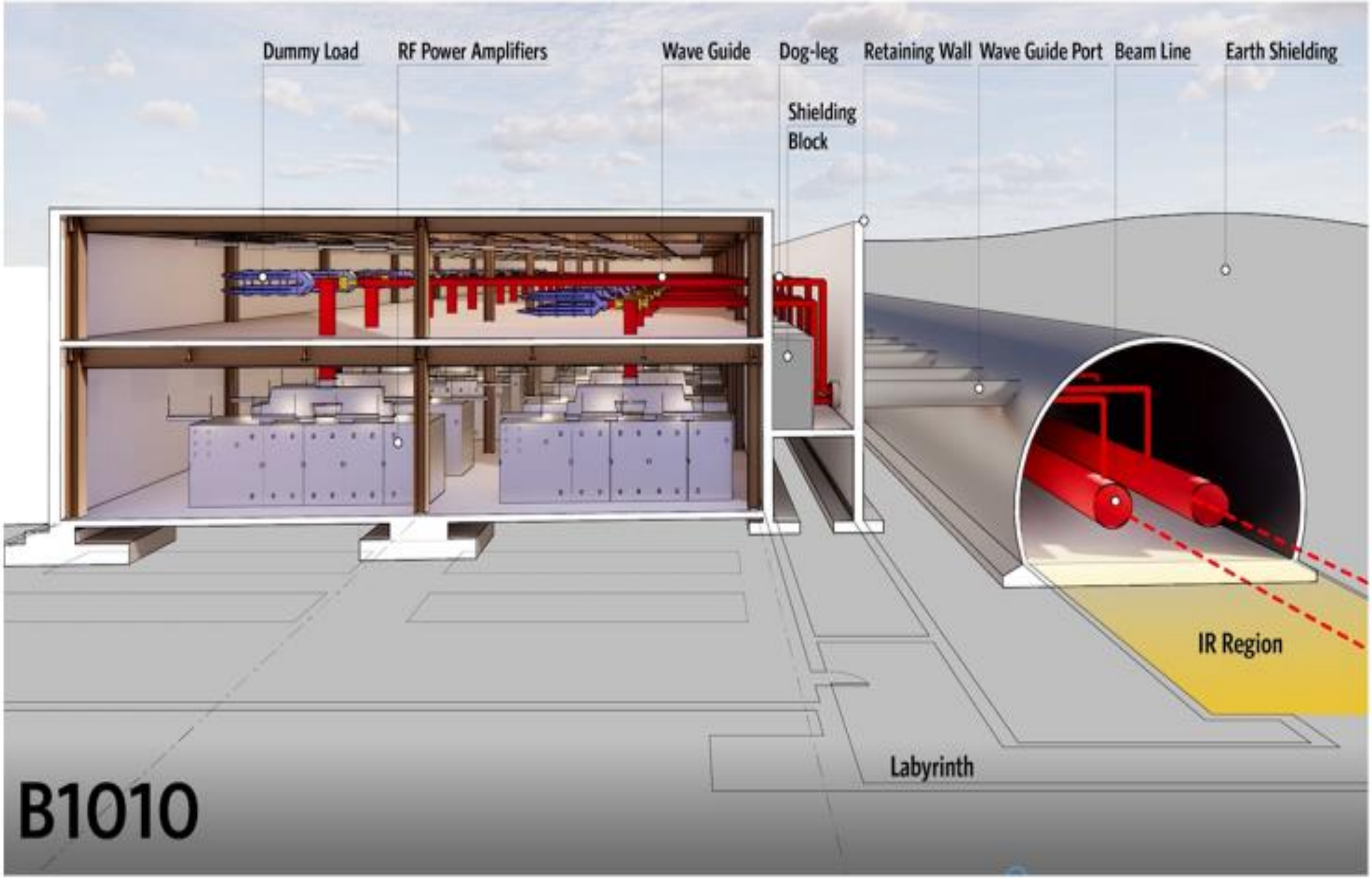
- Remarkable power densities becoming realistic for solid state power across the digital TV broadcast frequencies.



** This layout is a conceptual layout to explore the space requirements for up to 18x single cell 591 MHz ESR cryomodules. Up to 18 cryomodules fit in the available IR space. The SSA power density leads to reduced building space needs.

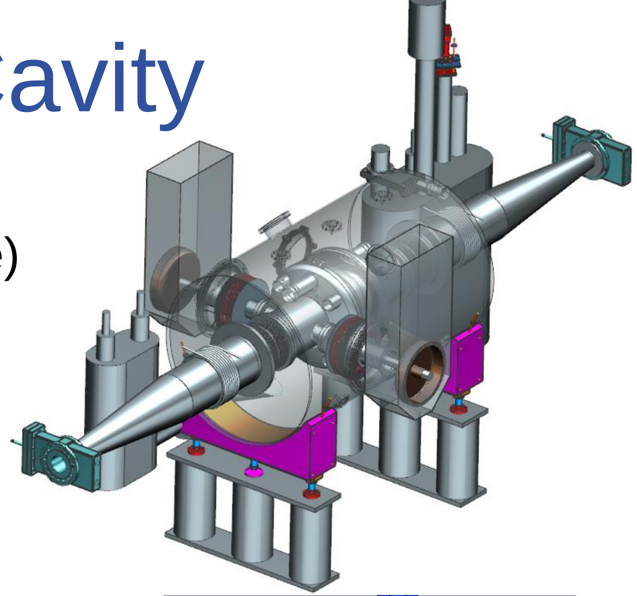


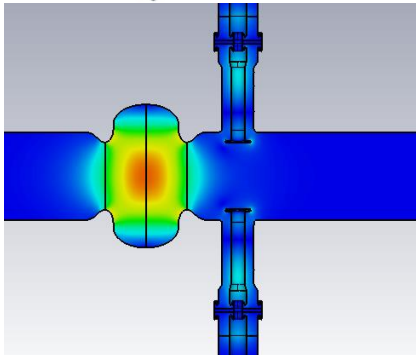
Electron-Ion Collider Buildings - RF B1010

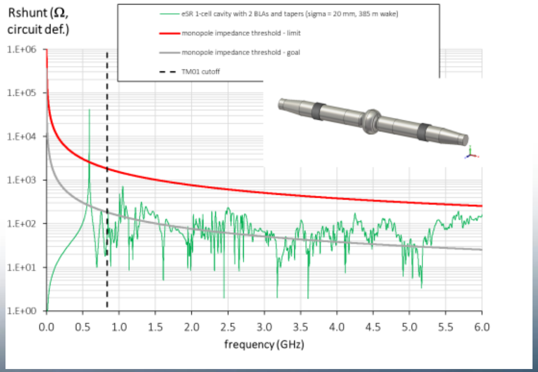


ESR 591 MHz Single Cell Cavity

- 591 MHz Single Cell Cavity for ESR (Design Baseline)
  - 68MV, 17 Cav, 2.5A Beam, 10 MW SyncRad
  - Baseline symmetric cavity EM optimization completed
    - Low R/Q
    - Strong coupling
    - Strong HOM damping
  - Alternative asymmetric design under optimization
    - Space saving, possible lower impedance
  - Thermal-mechanical analysis ongoing
    - Large tuning range, 2x400kW FPC

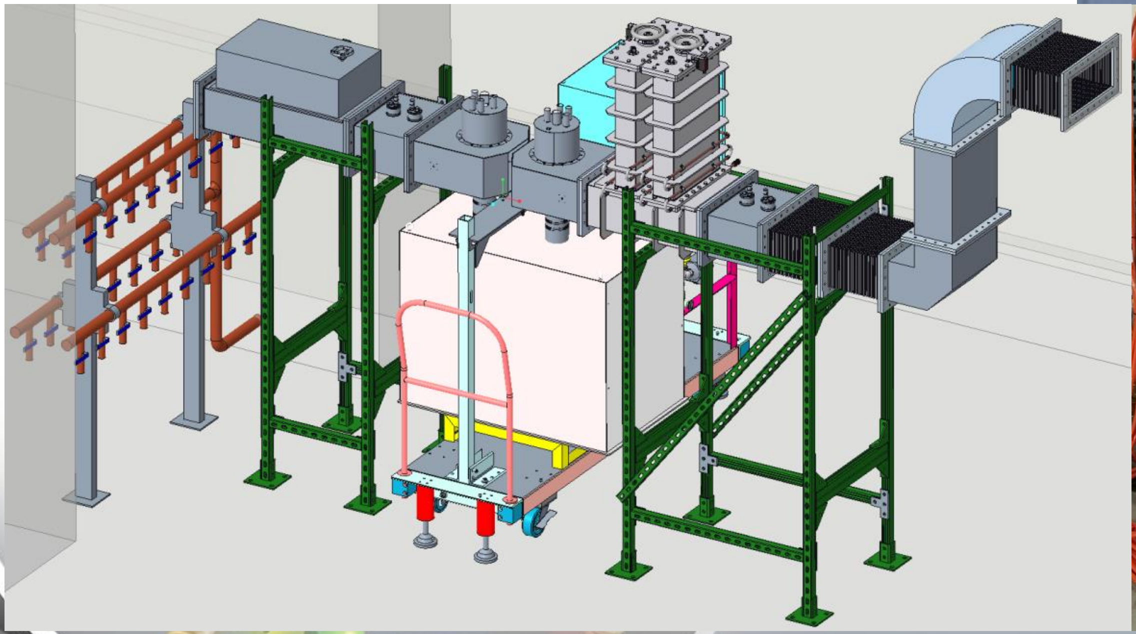






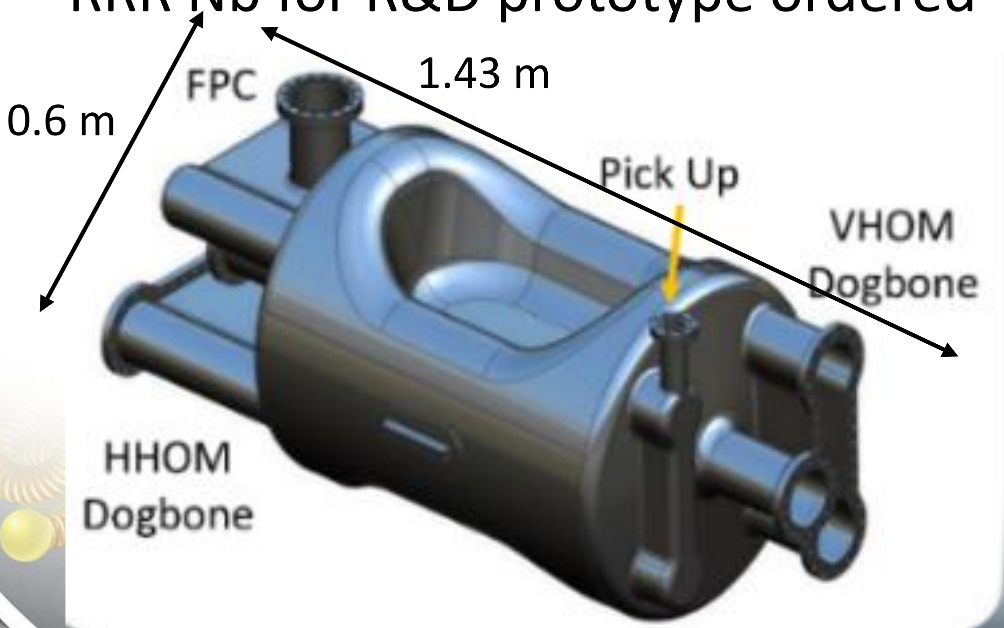
500 kW CW, Variable Qext Couplers

- Use fixed 500 kW CW coupler design.(25% safety margin)
- Vary Q_{ext} using waveguide tuner section.
- High Power FPC Review June 2021



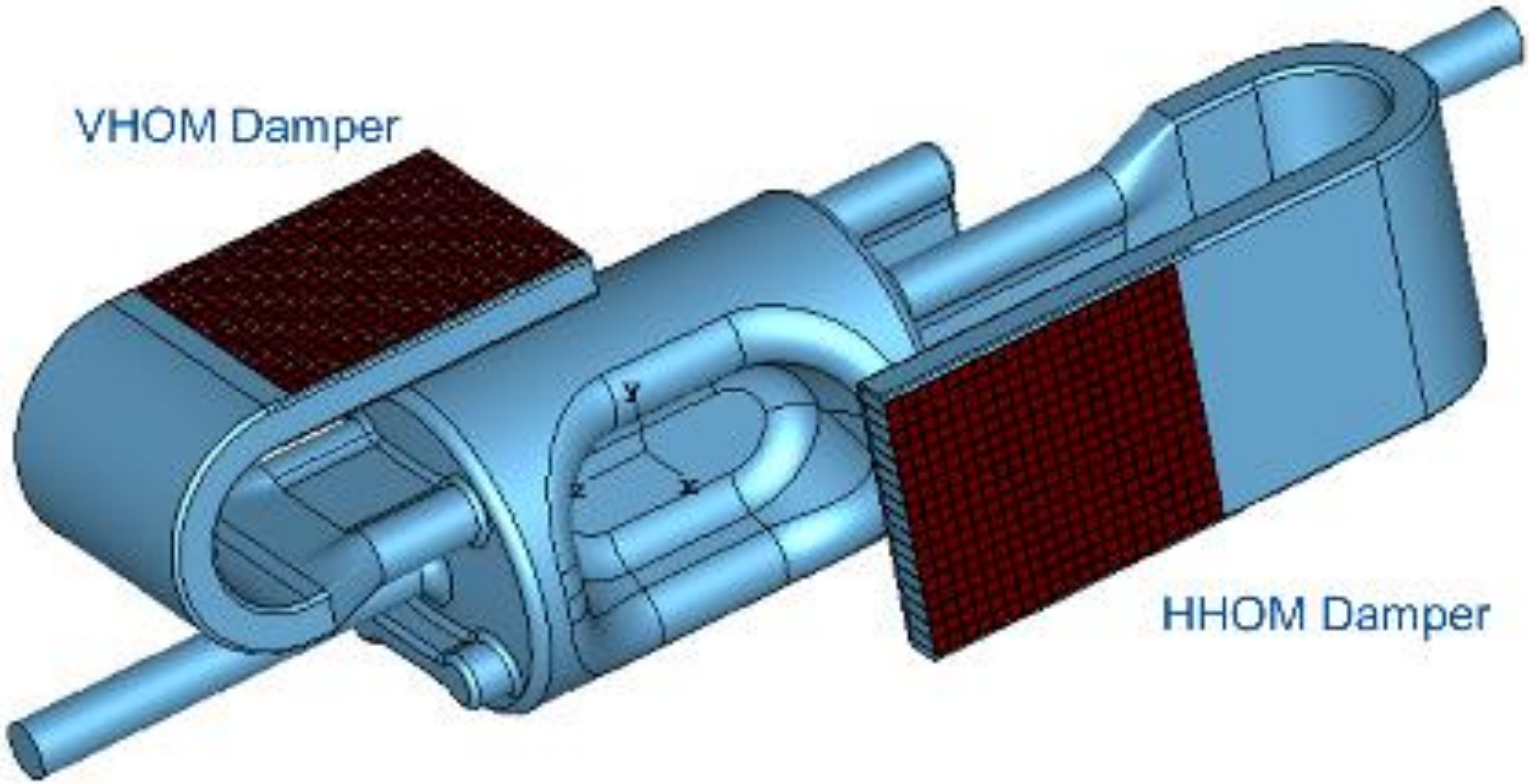
HSR 197 MHz RFD Crab Cavity

- Down-selected to RFD after Critical Decision 1 (CD-1).
  - Alternative design was DQW.
- 197 MHz Cavity EM design optimization complete
- 394 MHz cavity EM design optimization underway (not a simple scaling)
- RRR Nb for R&D prototype ordered



Property	Bare Cavity	
Operating frequency	197.0	
1st HOM [MHz]	347	
E_p/E_t^*	2.87	
B_p/E_t^* [mT/(MV/m)]	5.19	
B_p/E_p [mT/(MV/m)]	1.81	
G [Ω]	97.2	
R/Q [Ω]	1161.4	
R_tR_s [Ω^2]	1.13×10^5	
V_t [MV]	8.5	11.5
E_p [MV/m]	32.1	43.4
B_p [mT]	58.0	78.4
Total V_t [MV]	34	
No. of cavities	4	3
Cavity Length [mm] (iris-to-iris)	912	
Cavity Diameter [mm]	588.7	
Pole Length [mm]	520	

197 MHz Crab Cavity with Waveguide Dampers



Crab cavities

The transverse impedance of the fundamental mode in the 197MHz HSR crab cavities is high. (33.6 GΩ/m with 1.75e6 FPC Q_{ext})

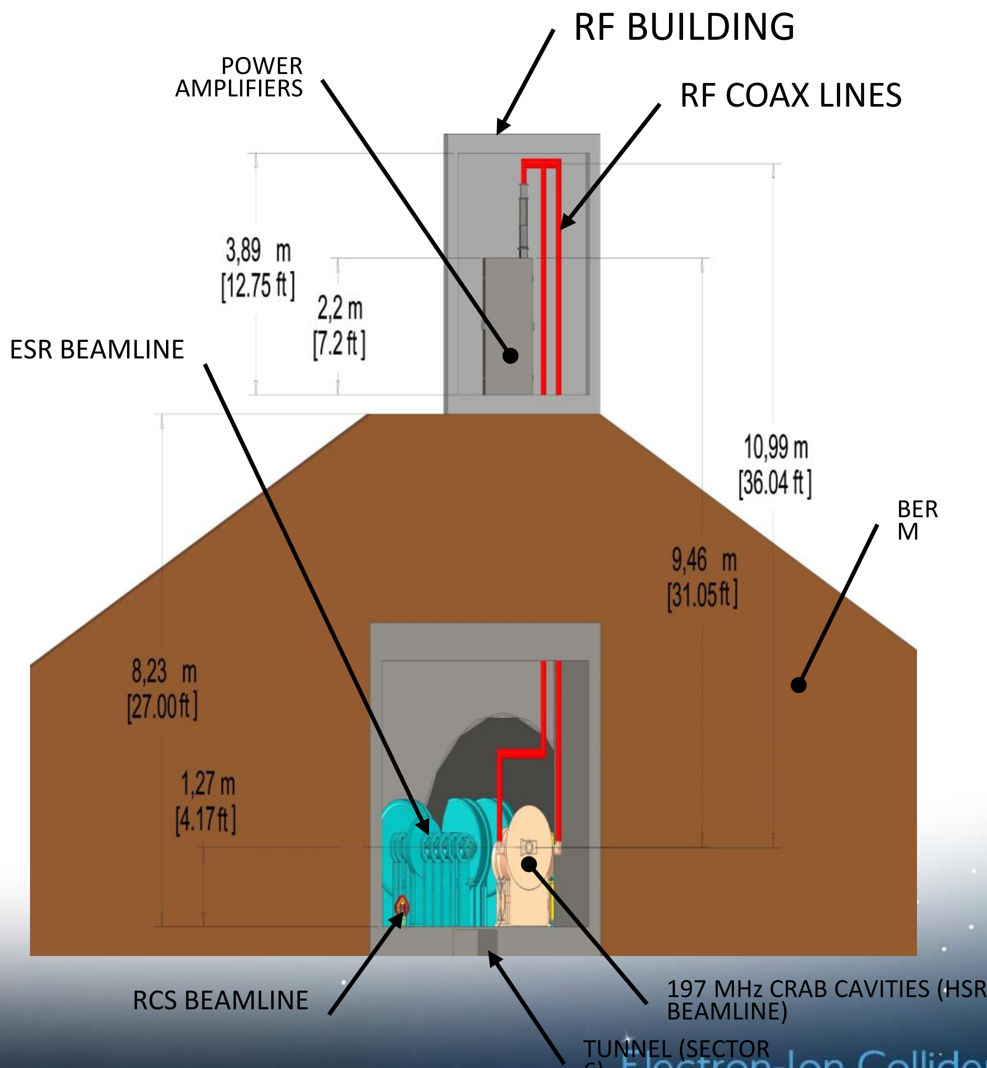
A high gain (~300 effective quality factor) low delay (~380ns) RF feedback is needed to suppress the instabilities driven by this mode.

Power amplifiers are placed in the RF building right on top of the ring for low delay, high feedback gain is also needed.

Solid state, RAD hardened, low group delay amplifier to place in the ring???

Possible?

6 o'clock IR



RCS, HSR and SHC ERL RF Systems

- Different RF systems which nonetheless provide opportunity to leverage design commonality.

- Systems all require high installed voltage.
  - HSR with 6cm bunch length requires minimum 20MV.
  - RCS with 100ms ramp (~2 MeV/turn) and high sync energy loss per turn (~38 MeV at 18 GeV).
  - ERL at 150 MeV – minimize required linac tunnel length.

- Systems all require strong HOM damping.
  - HSR with up to 1A beam and 6cm rms bunch length – hadrons have no intrinsic damping, avoid coupled bunch instabilities.
  - RCS with only two bunches, but 28nC per bunch – still must control long range wakes.
  - ERL with 100 mA beam, 1nC per bunch – maintain dE/E = 1E-4 and maximize BBU threshold.

EIC RF Systems (By Type & Number)

RF System	Sub System	Freq [MHz]	Type	Location	# Cavities
Electron Storage Ring	Fundamental	591	SRF, 1-cell	IR-10	17
Rapid Cycling Synchrotron	Fundamental	591	SRF, 5-cell	IR-10	3
	Bunch Merge 1	295	NCRF, Reentrant	IR-4 or IR-10	2
	Bunch Merge 2	148	NCRF, Reentrant	IR-4 or IR-10	1
Hadron Ring	Capture / Accel	24.6	NCRF, QWR	IR-4	2
	Bunch Split 1	49.2	NCRF, QWR	IR-4	2
	Bunch Split 2	98.5	NCRF, QWR	IR-4	2
	Store 1	197	NCRF, Reentrant	IR-4	6
	Store 2	591	SRF, 5-cell	IR-10	1
Strong Hadron Cooling	Inj. Bunch Comp.	197	NCRF, Reentrant	IR-2	1
	Inj. Booster	197	NCRF, Reentrant	IR-2	6
	Inj. Linearization	591	NCRF, Reentrant	IR-2	1
	ERL Fundamental	591	SRF, 5-cell	IR-2	8
	ERL Third Harmonic	1773	SRF, 5-cell	IR-2	3
Crab Cavity	Hadron	197	SRF, DQW/RFD	IR-6	8 (4 CM)
	Hadron/Electron	394	SRF, DQW/RFD	IR-6	6

EIC SRF Cryomodules and NCRF Cavities for CD-1 Estimate											
WBS Name	Location	Frequency (MHz)	SRF/NCRF	Type	Cavity Voltage (MV)	Cavity Total Qty	FPCs per Cavity	FPCs per System	SSAs per System	FPC Rated Power (kW)	SSA Power (kW)
RCS RF Systems											
RCS H1 RF System	IR-10	591	SRF	Elliptical, 5-cell	20.0	3	1	3	3	75	75
RCS Bunch Merge 1 RF System	IR-4	295	NCRF	Reentrant	0.7	2	1	2	2	75	40
RCS Bunch Merge 2 RF System	IR-4	148	NCRF	Reentrant	0.7	1	1	1	1	75	40
Electron Storage Ring RF Systems											
eSR H1 RF System	IR-10	591	SRF	Elliptical, 1-cell	4.0	17	2	34	34	500	400
Hadron RF Systems											
HR Capture and Acceleration RF System	IR-4	24.5	NCRF	QWR	0.3	2	1	2	2	Tetrode/Loop	150
HR Bunch Split 1 RF System	IR-4	49	NCRF	QWR	0.3	2	1	2	2	75	75
HR Bunch Split 2 RF System	IR-4	98	NCRF	QWR	0.3	2	1	2	2	75	75
HR Storage 2 RF System	IR-4	197	NCRF	Reentrant	1.0	7	1	7	7	Tetrode/Loop	90
HR Storage 2 RF System	IR-10	591	SRF	Elliptical, 5-cell	20.0	1	1	1	1	75	75
Crab Cavity Systems											
Crab Cavity HSR H1 RF System	IR-6	197	SRF	RFD		8	1	8	8	75	75
Crab cavity HSR H2 RF System	IR-6	394	SRF	RFD or WOW		4	1	4	4	75	75
Crab cavity ESR RF System	IR-6	394	SRF	RFD or WOW		2	1	2	2	75	75
Energy Recovery Linac (ERL)											
ERL H1 Cryomodule	IR-2	591	SRF	Elliptical, 5-cell	20.0	8	2	16	16	75	50
ERL H3 Cryomodule	IR-2	1773	SRF	Elliptical, 5-cell	7.0	3	2	6	6	10	20
ERL Injector H1	IR-2	197	NCRF	Reentrant	0.9	7	1	7	7	Tetrode/Loop	90
ERL Injector H3	IR-2	591	NCRF	Reentrant	0.6	1	1	1	1	75	50
						70		98	98		
						46		74	74		
						24		24	24		

Summary

- Over 100 solid state amplifiers
- Over 15 MW of RF power
- Wide range of power levels
- Majority is 591 MHz
- Possibility of developing radiation hardened solid state amplifier to place next to crab cavities in the tunnel
- Very challenging project helped with very close collaboration with JLAB that is working great.