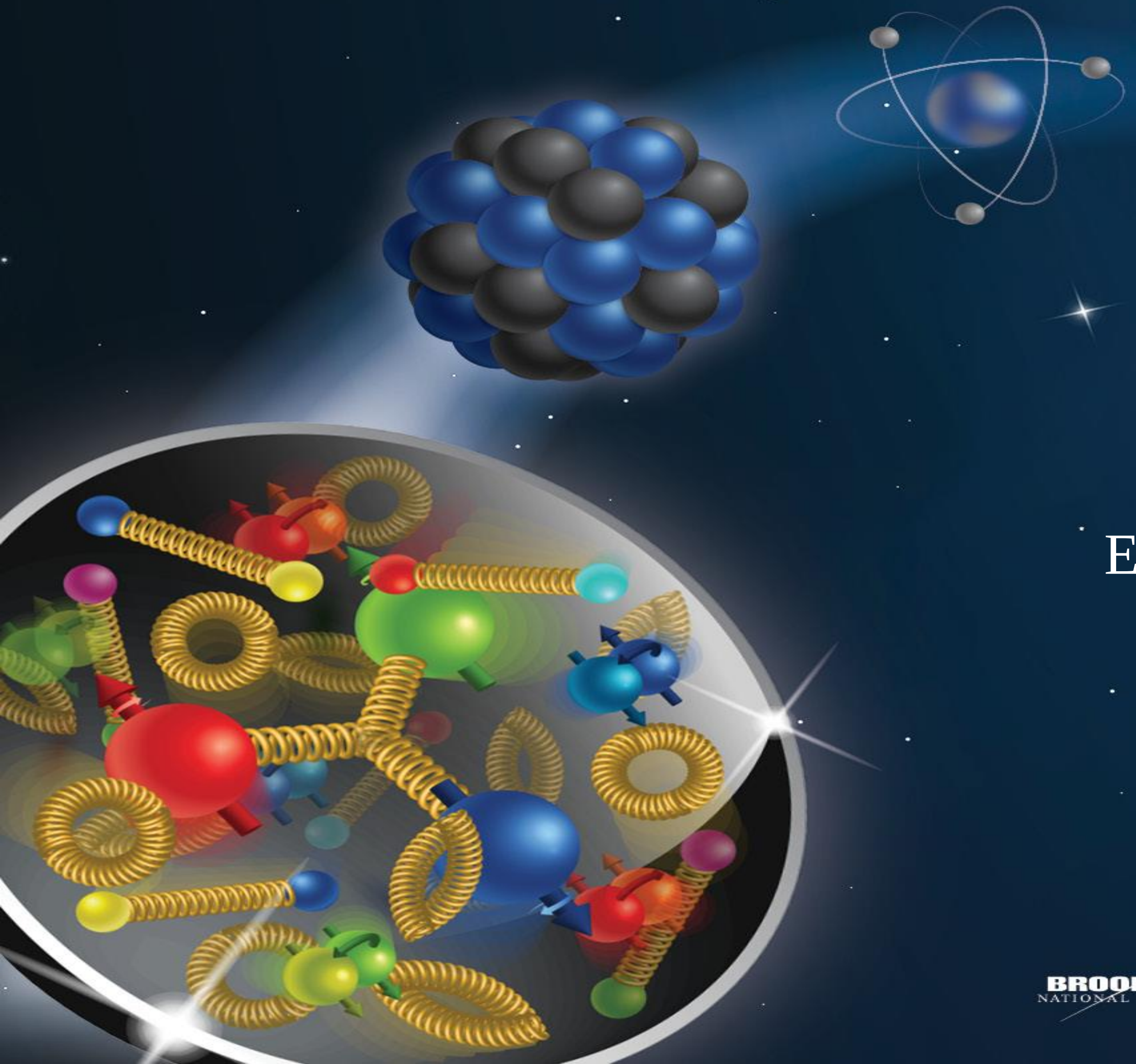


EIC 591MHz SRF cavity progress

Jiquan Guo, Jefferson Lab
For the EIC RF team
FCC Week, San Francisco, 2024

Electron-Ion Collider

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

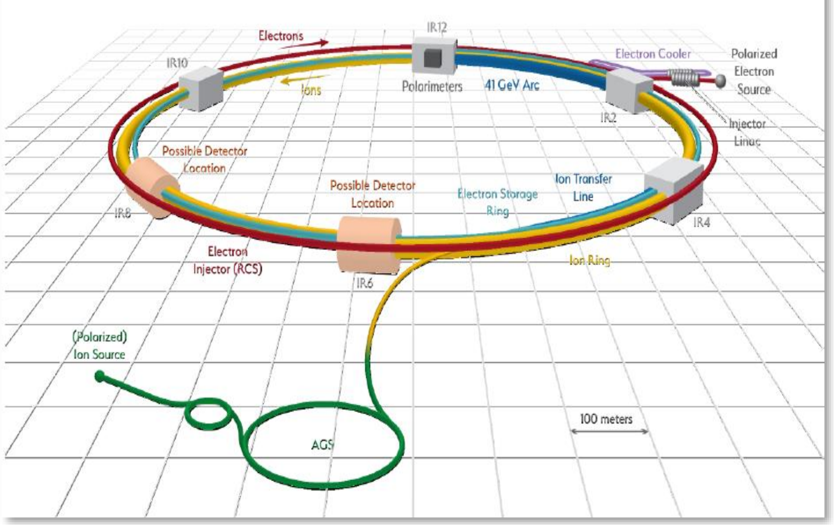
Outline

- Introduction: Overview of EIC and its RF systems
- EIC single cell 591 MHz cavity
  - Requirements
  - ESR single cell cavity string design
  - Cavity prototype progress
  - HOM damping and beamline absorber (BLA) development
  - Fundamental power coupler (FPC)
  - Beampipe warm-to-cold transition (WTC) bellows
- Summary

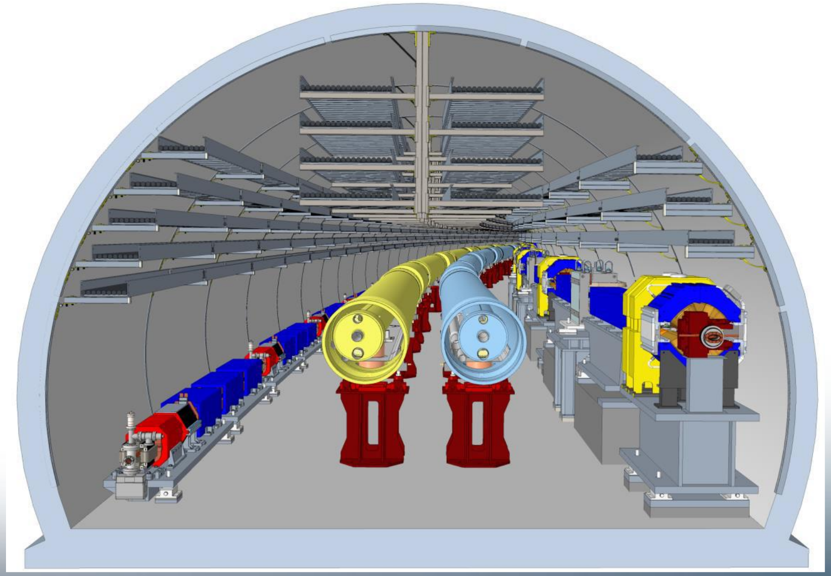
Overview of EIC

- The future Electron-Ion Collider
  - DOE CD-0 (mission need) approved in Dec. 2019
  - To be constructed at BNL, partnership with JLab
  - CD-3A (long-lead procurement) approved in Mar. 2024
  - The project is pre-CD2 (performance baseline) and in design phase
- Design highlights
  - High luminosity 10^{33} -10^{34} cm^{-2} s^{-1}, high polarization, high intensity beam
  - Wide energy range, CMS 20-140 GeV
  - Based on the existing, well-performing Relativistic Heavy Ion Collider (RHIC)
  - Hadron complex reuses the RHIC arcs (41-275 GeV) as the hadron storage ring (HSR), and reuses the RHIC injection chain (AGS); high beam current (1A) and bunch number (1160) with new bunch splitting RF system; new hadron cooling ERLs (strong cooler at collision, pre-cooler at injection)
  - Add new electron storage ring (ESR) in the RHIC tunnel, 5-18 GeV, up to 2.5 A, 10 MW beam power
  - Add new electron rapid cycling synchrotron (RCS) in the RHIC tunnel, 0.4-18 GeV 1 Hz
    - Currently this part of accelerator design is under major revision
  - High luminosity interaction regions (IR), one IR in the design, 2nd as upgrade; large crossing angle with full crabbing

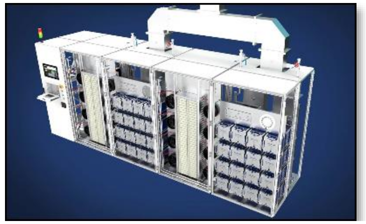
Layout of EIC



EIC tunnel cross-section



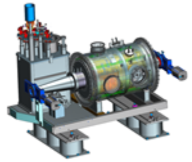
EIC RF systems



RF power and distribution
400kW×34 new SSAs for ESR 591MHz cavities, various power level for other cavities

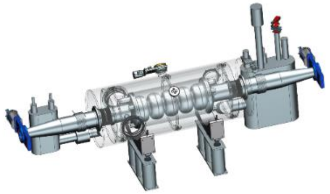
The ESR 591 MHz 1-cell and the HSR 197 MHz crab cavities being prototyped

CD3-A approved the ESR 591 MHz 1-cell first article cryomodule procurement

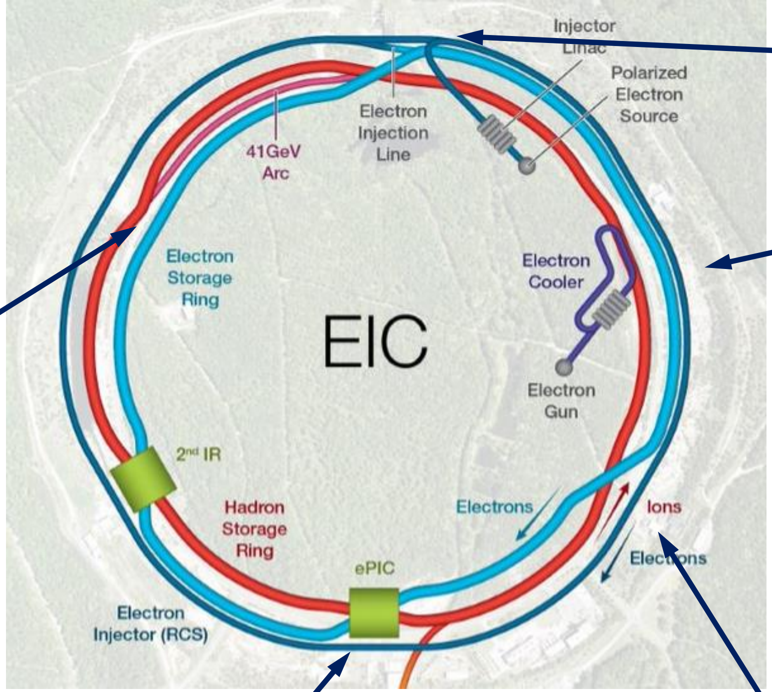


Hadron Storage Ring
591 MHz bunch compression cavity
5 CMs, IR10

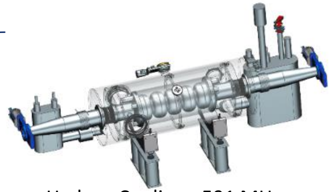
Electron Storage Ring
591 MHz Single Cell Cavity Cryomodule
17 CMs, IR10



Rapid Cycling Synchrotron
591 MHz Five-Cell Acceleration Cavity Cryomodule
4 CMs, IR10



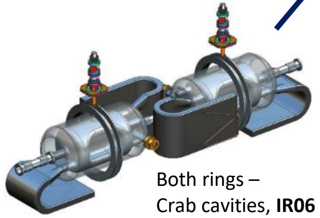
RCS injection harmonic RF kicker, **IR12**



Hadron Cooling - 591 MHz acceleration cavity
10 CMs, Electron Cooler, IR02

6 ea 197 QWR, 3 ea 591 SC Cavities (Not shown)
3 CMs, ERL Injector / Linac, IR02

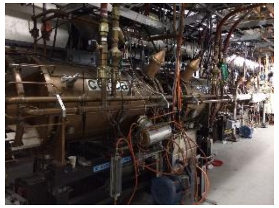
1773 MHz 3rd Harmonic (4) Cavities (Not shown)
1 CM, Electron Cooler, IR02



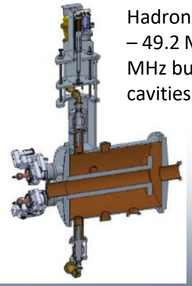
Both rings –
Crab cavities, **IR06**

Crab Cavities (per IR)	HSR (Cavities/CMs)	ESR (Cavities/CMs)
197 MHz	8/4	–
394 MHz	4/4	2/2

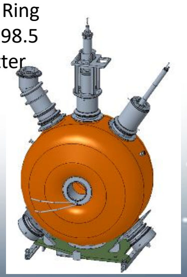
RCS – 148MHz and 296MHz bunch merger cavities **IR04**



Hadron Storage Ring – 24.6 MHz acceleration cavity **IR04**



Hadron Storage Ring – 49.2 MHz and 98.5 MHz bunch splitter cavities **IR04**



Hadron Storage Ring - 197 MHz bunch compression cavity **IR04**

EIC ESR 591 MHz 1-cell SRF system function and requirements

- Provide the RF voltage to maintain ~7mm bunch length and replenish the beam power loss from synchrotron radiation and HOM at different beam energy/current
- Suppress the HOM from the high current/high bunch charge and different fill pattern
  - fills 290, 580 or 1160 bunches out of the 7560 buckets in ESR, bunch reprate of 24.6/48.3/98.5MHz, 27.6 nC per bunch, with a gap of ~1μs matching the HSR abort gap
- 17 SRF cavities will be installed in a single phase. Each cavity provides up to ~600kW average beam power (~640 kW excluding the gap) with 2×400kW SSA (400kW per FPC), 2×200kW installed in the initial phase
  - Requiring variable coupling if each cavity operates at the same voltage and phase with full power
  - During low energy operation, the phase of some cavities can be reversed to keep the cavity voltage close to 4 MV while the vector sum lowered to 9.8 MV, allowing fixed coupling. Demonstrated at SuperKEKB

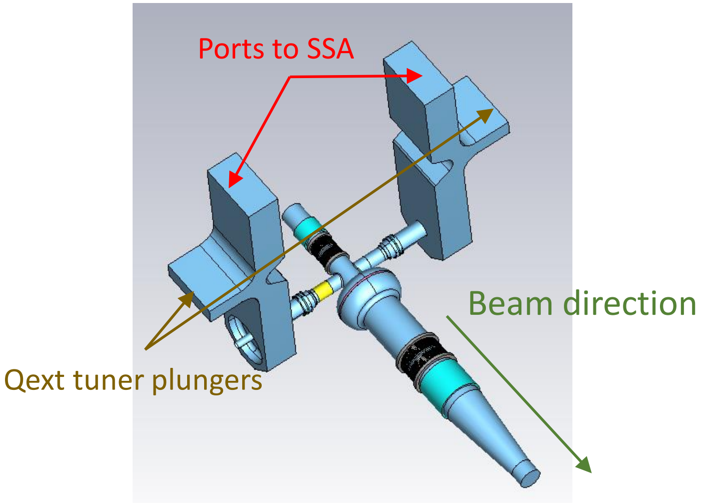
EIC HSR will use 5 ESR cavities to provide up to 20 MV of RF voltage
~60 kW RF power per cavity to compensate reactive beam loading and transient
Single FPC per cavity

EIC ESR RF system parameters

Beam energy (GeV)	18	10	5
Total RF voltage (MV)	61.5	21.7	9.84
Beam current (A, exc gap)	0.272	2.72	2.72
Beam current (A, average)	0.25	2.5	2.5
Veff (SR+HOM loss, MV)	37.14	4.02	1.45
Beam power, avg, total, MW	9.28	10.04	3.62
Beam power, avg, per cav, kW	546	591	213

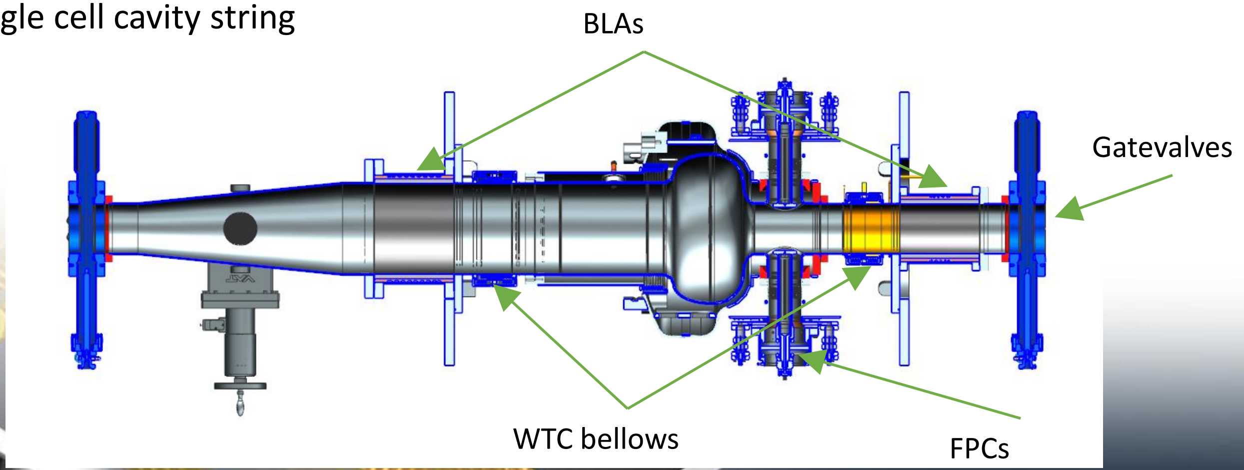
ESR single cell cavity string design

- Strong high order modes (HOM) excitation from the high beam current and short bunches, damped by two BLAs
- Asymmetric design with R75mm beampipe on one side (matching the largest possible gatevalve under the geometry constraints); R137mm on the other side to damp the lowest dipole HOM and lower the fundamental mode R/Q, but needs to be tapered to R75mm
  - Low R/Q mitigates the transient beam loading and other instabilities
  - High stiffness due to the large beampipe iris in combination of 4mm Nb thickness
- Qext can be tuned by Tee stubs terminated with plungers
  - Intrinsic Qext optimized to 2×10^5 for the highest voltage case
  - Can be factor of ~10 lower than the intrinsic Qext with strong standing wave



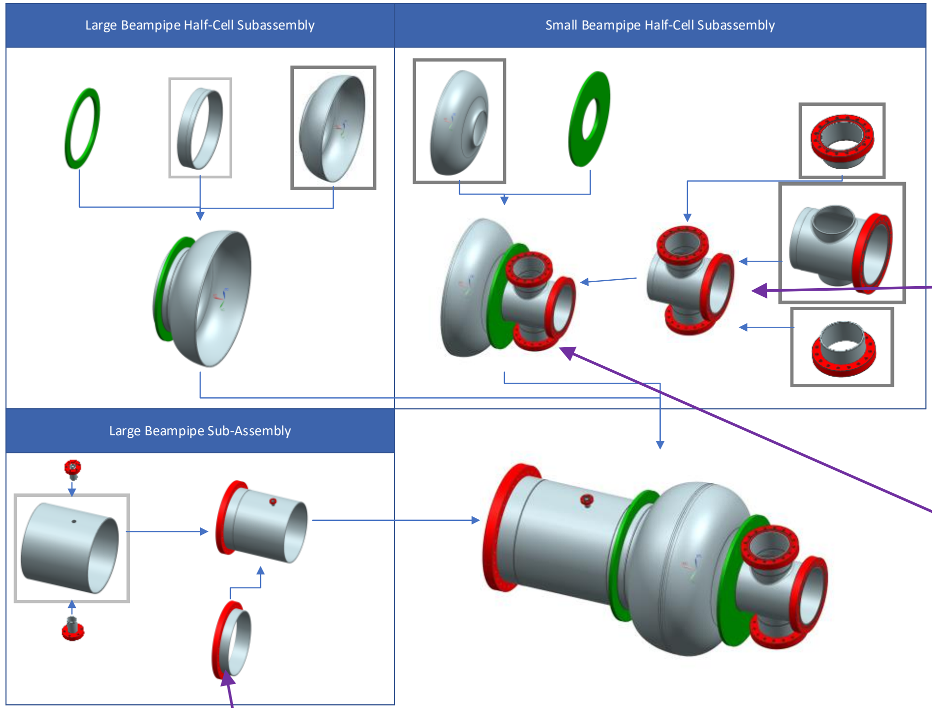
Parameters	Value
R/Q (Circ. Def) (Ω)	38
Epk/Eacc	2.01
Bpk/Eacc (mT/(MV/m))	4.87
G (Ω)	307
Intrinsic Qext (no tuning network)	2×10^5
FPC tip penetration for Qext ~2×10^5 (mm)	9
Tuning sensitivity (kHz/mm)	419
Stiffness (N/mm)	20683
Lorentz force detuning (LFD) (Hz/(MV/m)^2)	-4.46

ESR single cell cavity string

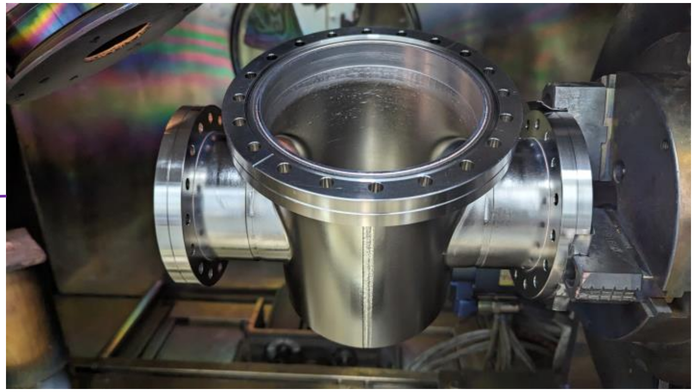


591MHz 1-cell cavity prototype at JLab

Cavity Fabrication Plan



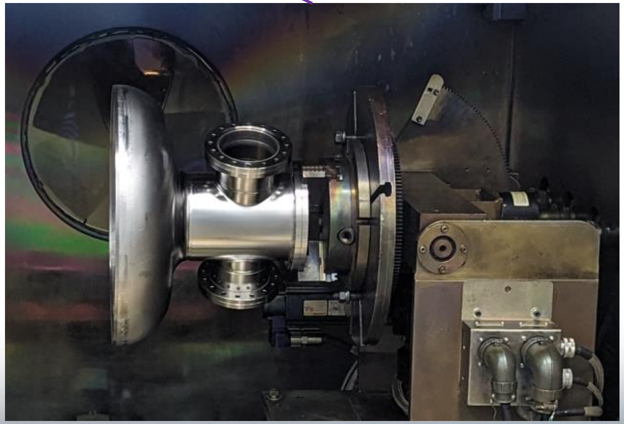
R75mm beampipe with flanges brazed, FPC ports e-beam welded



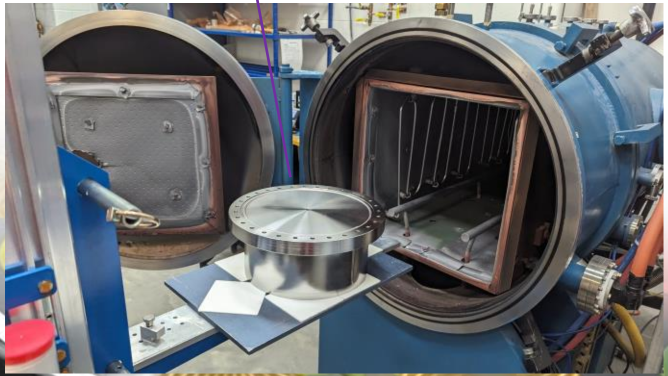
Nb small beampipe with pulled FPC ports

Cavity subassemblies stacked together (some welds pending)

R75mm beampipe welded to half cell

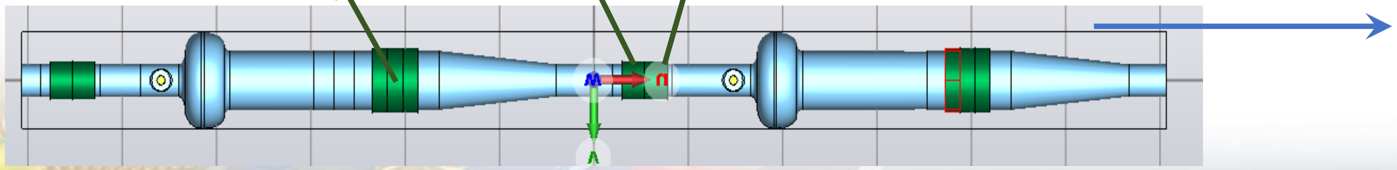


R137mm beampipe stub brazed to a flange

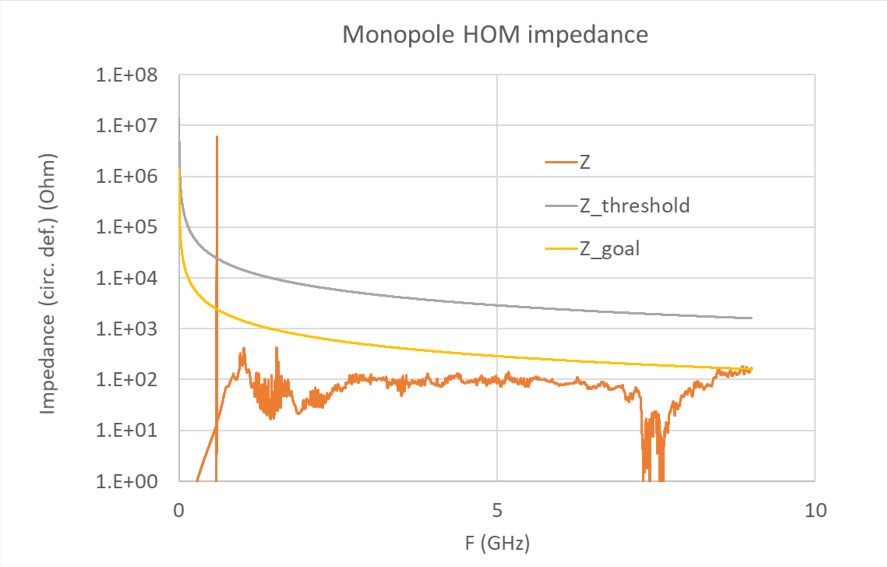


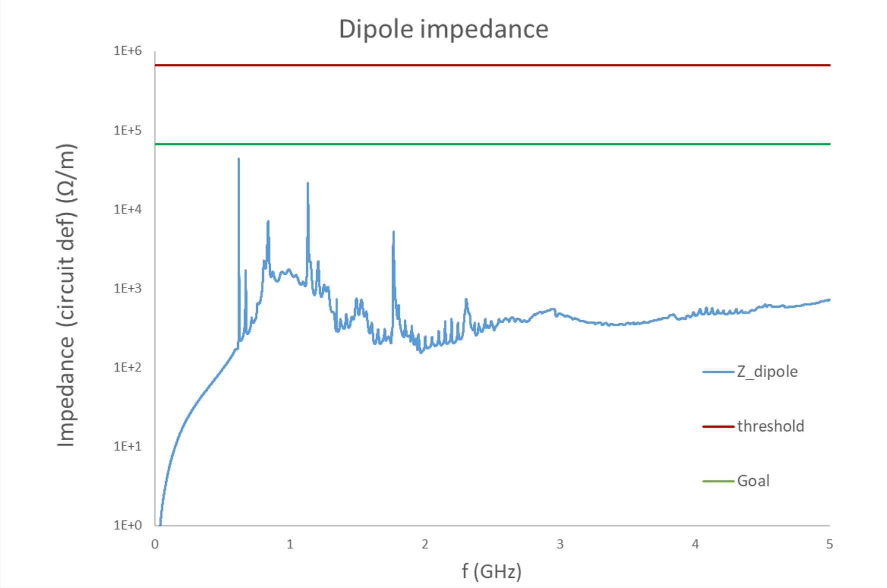
HOM damping and BLA heat load

- HOM damped by two 24cm long BLAs, one large (R137mm) and one small (R75mm)
- HOM impedance well damped under the goals (simulated with earlier assumption of 12cm R75mm BLA using CST)
- Total HOM loss up to 73kW per cavity
  - Strong self heating with the small radius BLA
  - Loss density up to 0.39W/mm^2 in the left half of the small BLA (lowered from 0.47W/mm^2 with 12cm R75mm BLA)



HOM heat in different parts of the BLAs

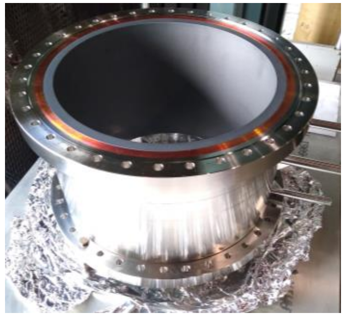




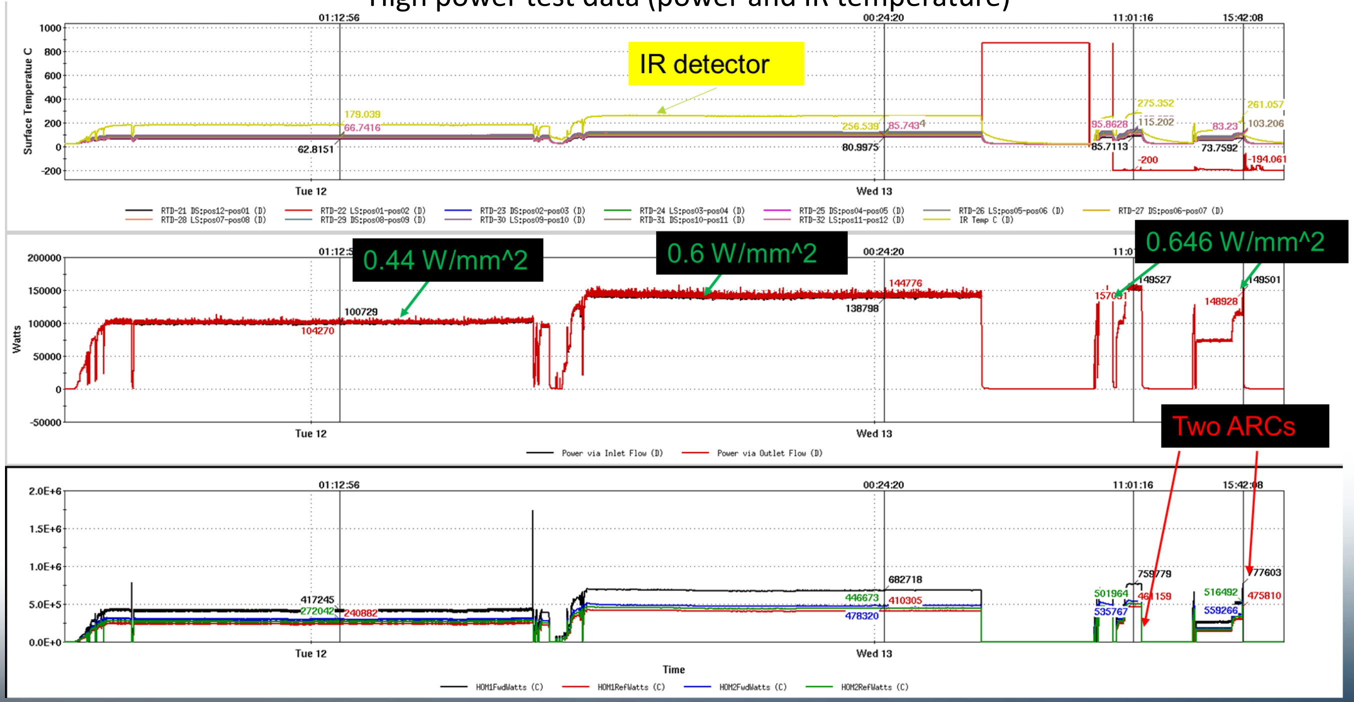
BLA design and prototype

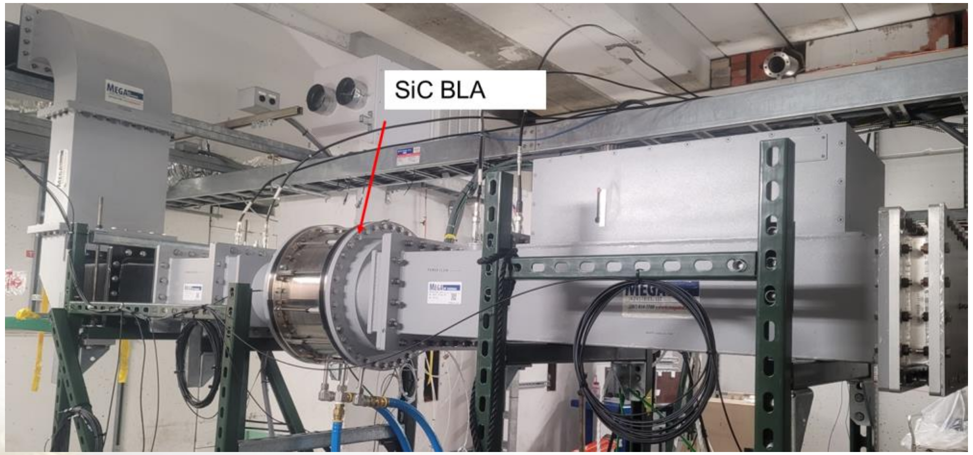
- Shrink-fit SiC cylinder BLA design (APS-U style)
- An R154mm prototype developed at BNL under LDRD program
- Recently high power tested
  - Survived with estimated 103kW total absorbed RF power (0.44W/mm^2)
  - Arcing and visible damage after 0.65W/mm^2 test

R154mm shrink fit BLA



High power test data (power and IR temperature)



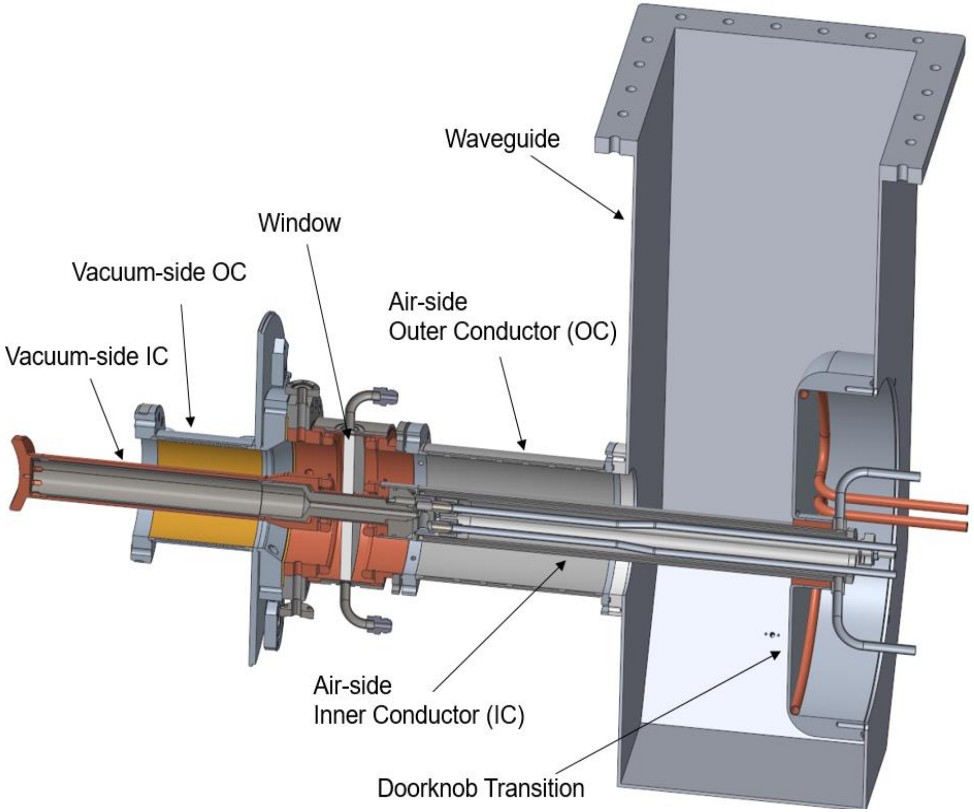


High power test setup with 704MHz 1MW CW klystron
Standing wave with short plate

W. Xu et al., WEPS13, IPAC2024

FPC development

- EIC ESR FPC is required to handle at least 400 kW forward power and strong standing wave
- The design is a variation of KEKB/Tristan/SNS/BNL BeO high power window, replaced with 99.5% Al_2O_3.
- Broadband match
- Will be the common window for EIC SRF systems
- Prototyping ongoing at BNL. Target for high power testing (600kW klystron) in summer 2025

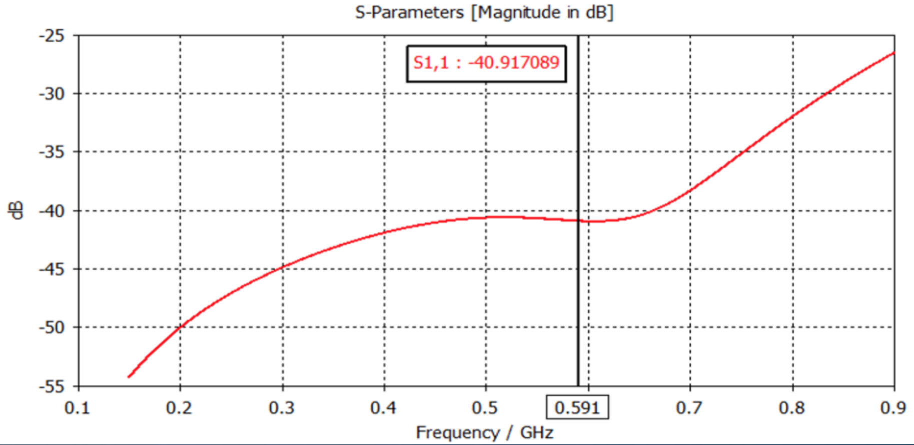


First window brazing

Inner conductor test braze

W. Xu et al., WEPS14, IPAC2024

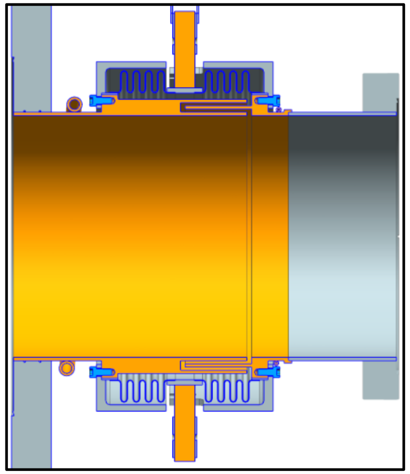
FPC pringles



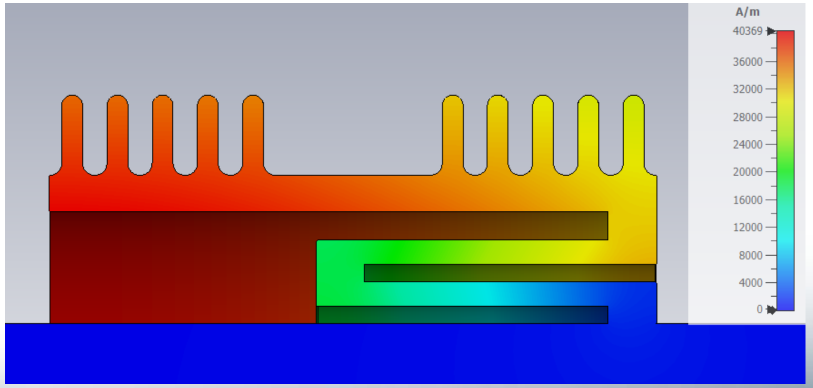
Beampipe warm to cold transition bellows

- Cavity string beampipe WTC bellows will provide thermal isolation, as well as the mechanical compliance for tuning, cavity cooldown, and fabrication tolerance
  - Withstand the 2.5A beam current and various fill pattern (as low as 24.6MHz reprate)
  - RF shieleded for both aspects of beam instability and RF heating
  - <u>Avoid sliding contact in the RF shield for cleanliness</u>
- Choke shielded bellows design in progress for both R75mm and R137mm versions
  - Effectively shields the short range wake
  - The coaxial like monopole modes below beampipe cutoff has considerably high R/Q, but the structures are optimized so that
    - Only one trapped mode in each version of design
    - Trapped modes avoid all the 24.6MHz harmonics
    - The R137mm version has ~12mm longitudinal deformation range with trapped mode frequency change of 13MHz
    - The R75mm version has ~3mm allowable longitudinal deformation range
  - Trapped mode heat can be concentrated on the warm side

EIC ESR choke shielded WTC bellows



H-field of the trapped monopole mode (260 MHz) in the 137 mm radius shielded bellows



Summary

- EIC requires a large variety of SRF/NCRF system. The ESR 1-cell cavity has some unique challenges
- The ESR 1-cell prototype cavity is close to complete, with vertical testing expected in a few months. Cavity string components design is being finalized, with FPC/BLA prototype ongoing. The first article cryomodule is funded and scheduled to complete is about 2 years.
- Lot of synergy between EIC and FCC-ee SRF systems. The EIC SRF experience and lessons learned will be beneficial for FCC-ee.

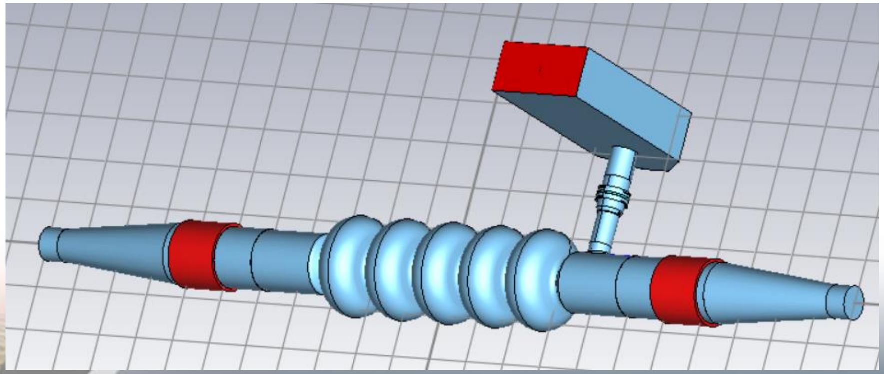
Acknowledgements

- The author needs to thank the whole EIC team as well as external experts from various institutes for the collaborative work.

Backup

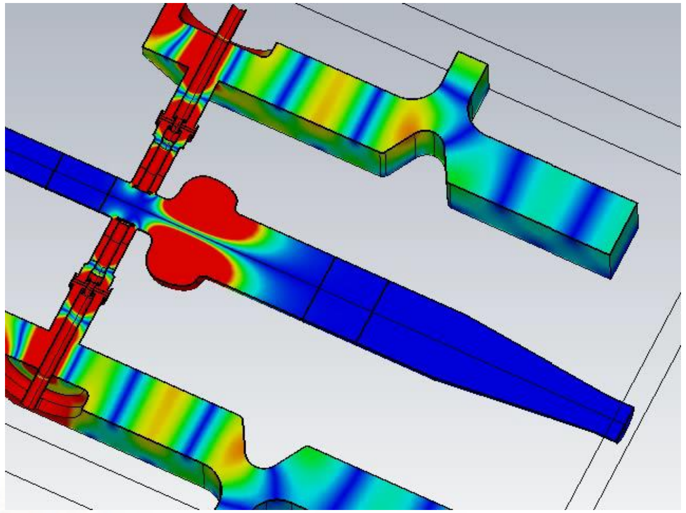
EIC 591MHz 5-cell cavity

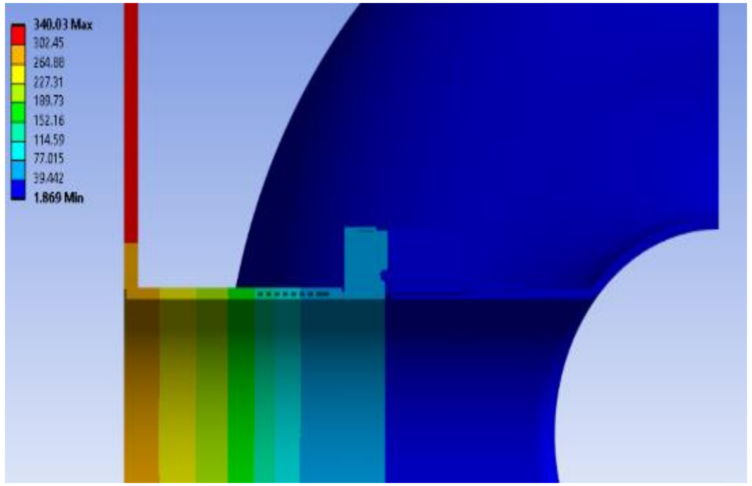
- Currently plan to use the scaled BNL 650 MHz 5-cell ERL cavity design (was well optimized), with beampipe transition redesigned to R137mm beampipe
- RCS application requires 4 cavities of ~64MV total:
  - Fast ramping of voltage in ~6000 revolutions or ~80ms
    - Fast tuner (piezo or fast reactive tuner) to compensate ~300Hz of LFD and microphonics
    - π mode Qext ~7×10^6 optimizes the required peak RF power to <70kW
  - Low passband impedance. Worst in π/5 mode, ~210KΩ (circ. def.)
    - Close to the reference design budget. Budget might be relaxed with revamped accelerator design; impedance can be lowered further with lower fundamental Qext at the cost of more power
- Strong cooler ERL application: dipole HOM impedance well damped



Qext tuning and FPC WTC

- Stub tuners capable to tune Qext from 2E5 (intrinsic) to ~2E4
  - Enhanced standing wave and heating in FPC
- RF/thermal analysis made under different operation scenario
  - 10 GeV 2.5A operation with all focusing, Qext=60000 is the worst case for FPC heat load, but low on Nb heat.
- FPC WTC trace cooled with 4K gas
  - ~20W in 2K load and ~140W in 5K helium gas load for the worst case





ESR 1-cell cross-section FPC RF magnetic field (left) and WTC temperature (right) for the worst heat load case

List of EIC RF/SRF cavities

RF System	Sub System	Freq [MHz]	Type	Location	# Cavities	# FPC/cavity	FPC power (kW)
Electron Storage Ring	Accel / Store	591	**SRF, 1-cell**	IR-10	17	2	400
Rapid Cycling Synchrotron (RCS) The whole electron injection chain design under revision. The pre-injectors (linac and the potential booster) not included.	Accel / Store	591	**SRF, 5-cell**	IR-10	3	1	70
	Harmonic Kickers	295 148/443	**NCRF, QWR, 1-mode** **NCRF, QWR, 2-mode**	IR-2 or IR-12	1 1	1	1 5
	Bunch Merge 1	295	**NCRF, Reentrant**	IR-4	2	1	70
	Bunch Merge 2	148	**NCRF, Reentrant**	IR-4	1	1	70
Hadron Storage Ring	Capture / Accel	24.6	**NCRF, QWR**	IR-4	4	1	100
	Bunch Split 1	49.2	**NCRF, QWR**	IR-4	2	1	200
	Bunch Split 2	98.5	**NCRF, QWR**	IR-4	2	1	200
	Store 1	197	**NCRF, Reentrant**	IR-4	7	1	100
	Store 2	591	**SRF, 1-cell**	IR-10	5	1	60
Hadron Cooling ERL (combination of pre-cooler and strong hadron cooler) ERL design and requirements are still evolving	ERL Injector	197 591	**SRF, QWR** **SRF, 1-cell**	IR-2	2 1	2 1	200 10
	ERL Low Energy Linac	197 591	**SRF, QWR** **SRF, 1-cell**	IR-2	4 2	2 1	200 10
	ERL Fundamental	591	**SRF, 5-cell**	IR-2	10	1	60
	ERL Third Harmonic	1773	**SRF, 5-cell**	IR-2	4 (1 CM)	1	5
Crab Cavities (2^{nd} IR not included)	Hadron	197	**SRF, RFD**	IR-6	8 (4 CM)	1	70
	Hadron/Electron	394	**SRF, RFD**	IR-6	6	1	50