MOPMB078

DESIGN AND PROTOTYPING OF THE ELECTRON ION COLLIDER ELECTRON STORAGE RING SRF CAVITY*

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Abstract

Among the numerous RF subsystems in the Electron Ion Collider (EIC), the electron storage ring's (ESR) 591 MHz fundamental RF system is one of the most challenging. Each cavity in the system will handle up to 2.5 A of beam current and supply up to 600 kW beam power under a wide range of voltage. The EIC R&D plan includes the design, fabrication and testing of such a cavity. In this paper, we will report the latest status and findings of the ongoing design and prototyping of this cavity, including the RF and mechanical/thermal design, fabrication design, and the progress of fabrication.

EIC ESR RF System Requirements

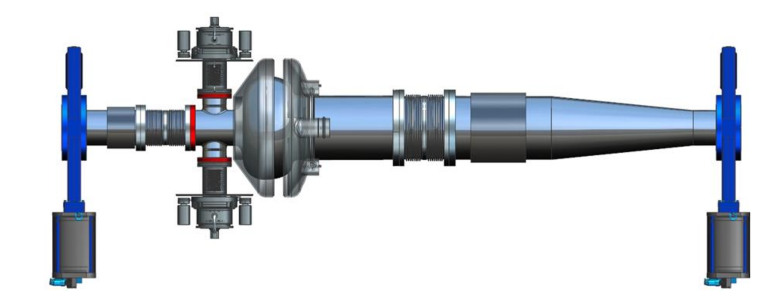
- EIC ESR is a high current electron storage ring required to operate at various beam energy (5-18GeV) and beam current (0.23-2.5A average, with one abort gap) [1, 2]
- Up to 10MW beam power will be provided by 17 SRF elliptical cavities, installed in single phase.
- Requires variable coupling, optimum Qext has up to factor of 20 range, or factor of ~10 if some reflection is allowed
- Low R/Q required for the ESR cavities to mitigate transient beam loading effect
- Proposed to reverse the RF phase (RPO) [3] of some cavities during low energy operations requiring lower total (vector sum) RF voltage, keeping the single cavity voltage close to maximum, reducing Qext tuning range and the transient beam loading

Case		18GeV 17 Cav	10GeV 17 Cav		5GeV 17 Cav	
Vtot (MV)		61.5	21.7		9.84	
Beam current (A, exc gap)		0.271	2.72		2.71	
Veff (SR+HOM loss, MV)		37.12	3.93		0.992	
Beam power/cav, (avg, SR+HOM) (kW)		546	578		201	
Beam power, avg, total, MW		9.28	9.83		3.41	
All Focus	Vcav (MV)	3.62	1.28		0.58	
	Qext per cav for opt power	2.90E5	3.41E4		2.02E4	
	Opt Pfwd/FPC(kW)	296	314		109	
	Qext per cav	2.0E5	6E4		2.5E4	
	Pfwd/FPC(kW)	307	340		110	
FD, Focus	Vcav (MV)		3.9		3.71	
	Qext		3.2E5	2.0E5	8.6E5	2.0E5
	Pfwd/FPC(kW)		316	333	105	171
FD, Defocus	Vcav (MV)		3.59		3.9	
	Qext		2.7E5	2.0E5	9.6E5	2.0E5
	Pfwd/FPC(kW)		316	323	105	183
	# of defocusing cav		6		7	

EIC ESR cavity Qext and power estimate for different operation scenarios

Beam power includes HOM loss
With RPO, it's possible to operate with fixed Qext
Calculated for peak power
Transient will increase the power level for the high beam current all focusing cases

Design of the ESR SRF cavity



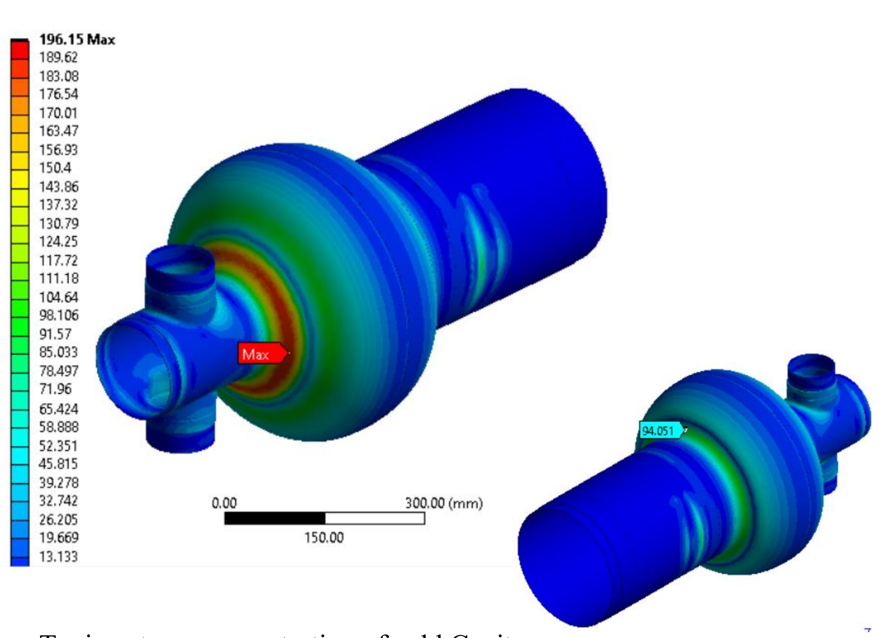
ESR cavity string, asymmetric design

R/Q (Circ. Def) (Ω)	38
Epk/Eacc	2.01
Bpk/Eacc (mT/(MV/m))	4.87
G (Ω)	307
Tip penetration for Qext ~2E5 (mm)	9
Loss factor (with FPC, 2 BLAs, exc FM, 7mm bunch, R75mm gate valve)	0.883 V/pC
Estimated total length (gate valve to gate valve, R75mm)	2.8m

- Adopted the asymmetric design
  - One large R137mm beampipe damping the lowest HOMs, one R75mm beampipe for FPCs – more room for warm-to-cold transition
- HOM damped by two beamline absorbers (BLA) using SiC with shrinkfit design
- Gate valve size limits the beampipe at the end of the cryomodules to R75mm
  - Considering to taper further to R36mm for reusing the APS quads
- Two coaxial FPCs per cavity, each powered by one 400kW SSA
- Uses external stubs to tune Qext; cavity Qext without tuning stubs is set at 2×10^5
- Single cavity cryomodule

Mechanical Analysis

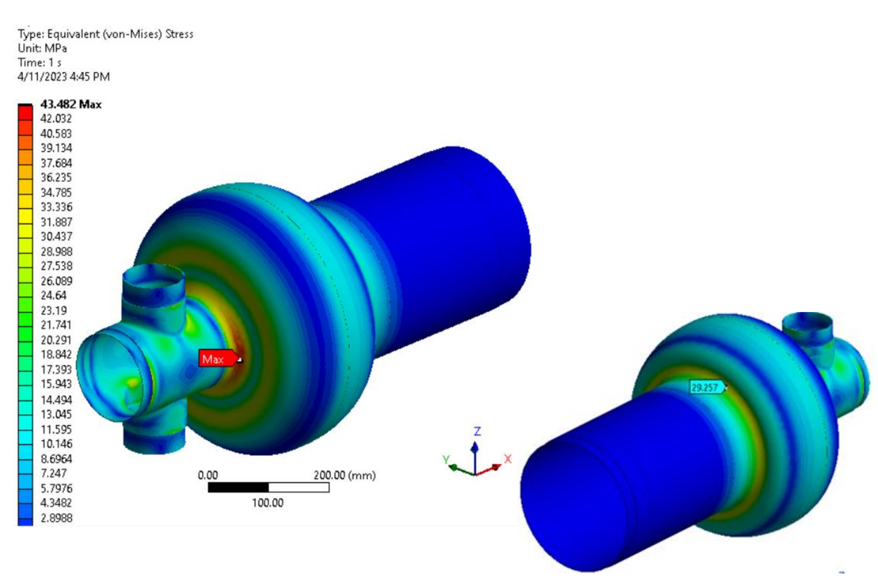
- Simulations have been conducted to ensure the dressed cavity will support both the pressure and tuning loads for the 4mm thick Nb
- An area of concern is the small beampipe iris for both the tuning and pressure forces



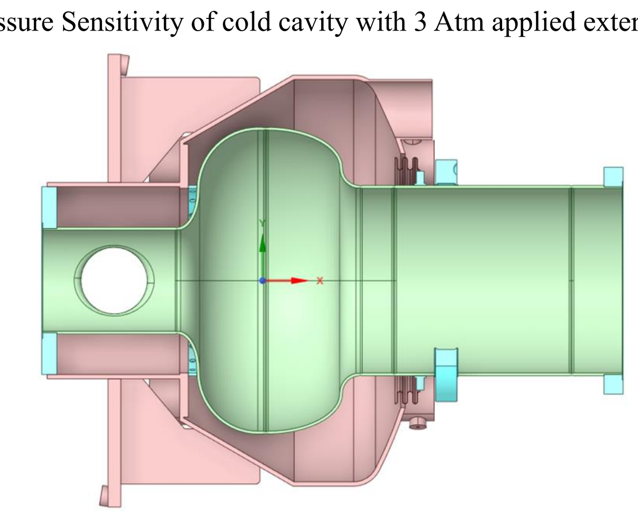
Tuning stress concentration of cold Cavity

Tuning sensitivity (kHz/mm)	Stiffness (N/mm)	Tuning force 600kHz (N)	Pressure Sensitivity (kHz/torr)	LFD (Hz/(MV/m)^2)
419.25	20,683	29,600	108.2	-4.46

Cavity Characteristics at 2K



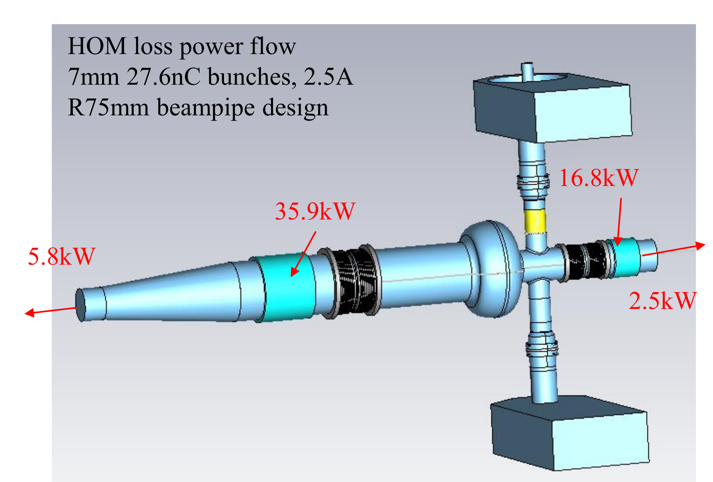
Pressure Sensitivity of cold cavity with 3 Atm applied external force



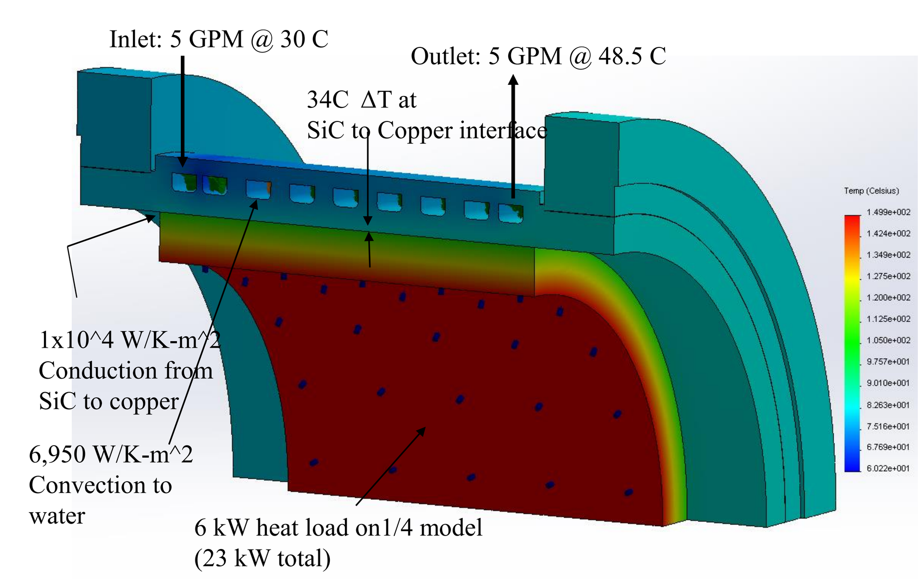
Possible Helium Vessel Design

HOM and BLA Thermal Analysis

- Monopole and dipole impedance of the R75mm beampipe design analyzed with CST long range wakefield solver and meets the design goal.
- Monopole HOM total loss factor calculated from long range wake impedance and excitation spectrum from beam pattern matches short range simulation result.
- Short range simulation also provides a breakdown of HOM power to different locations
  - ~61 kW total for 7mm 2.5A beam
  - up to 22.6kW in the small R75mm BLA, challenging power density of 0.4 W/cm^2
- R36mm beampipe option under analysis, with ~20% more loss expected if taper ratio is kept constant, but the portion goes to the small BLA might be smaller



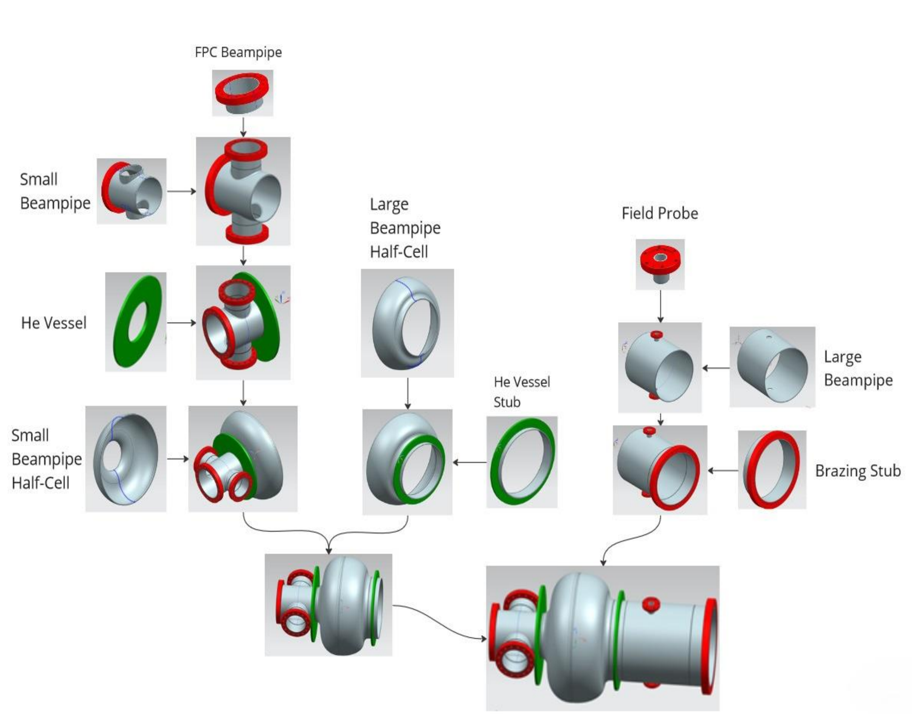
HOM power flow



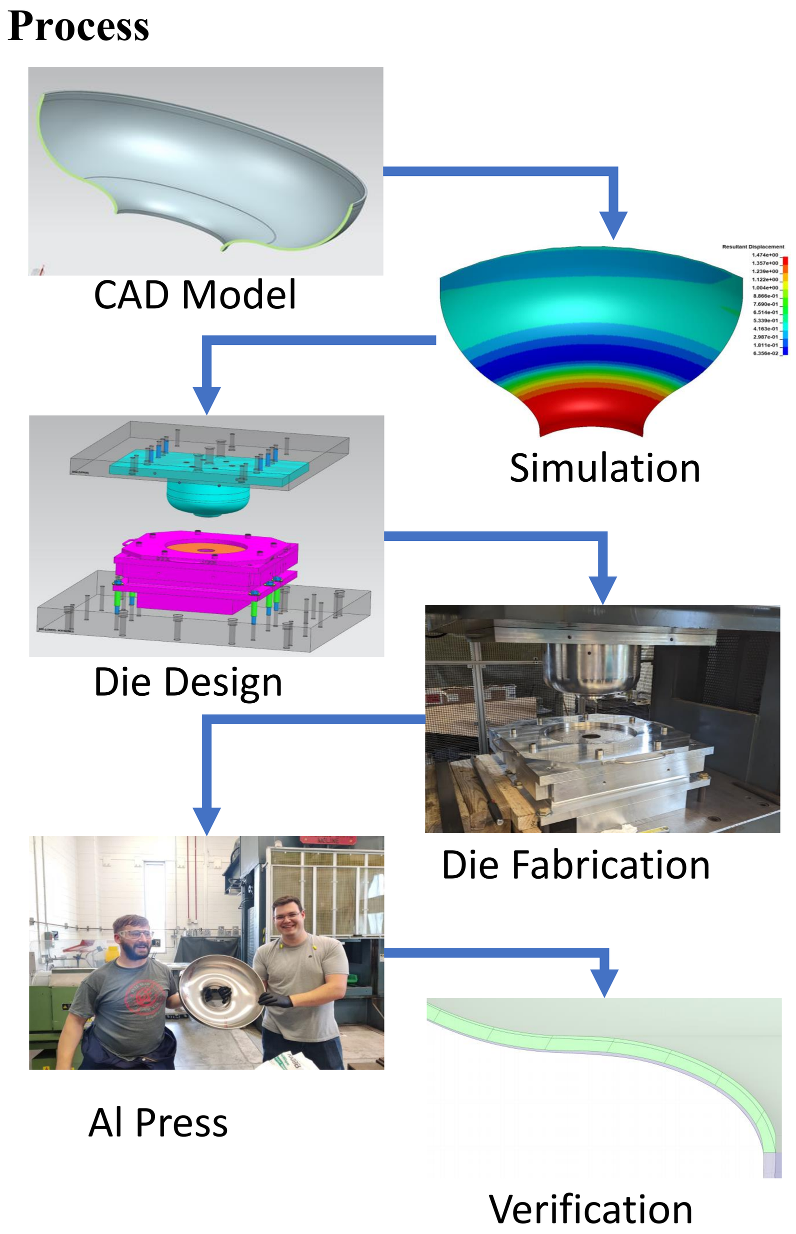
R75mm BLA thermal analysis

Fabrication Process

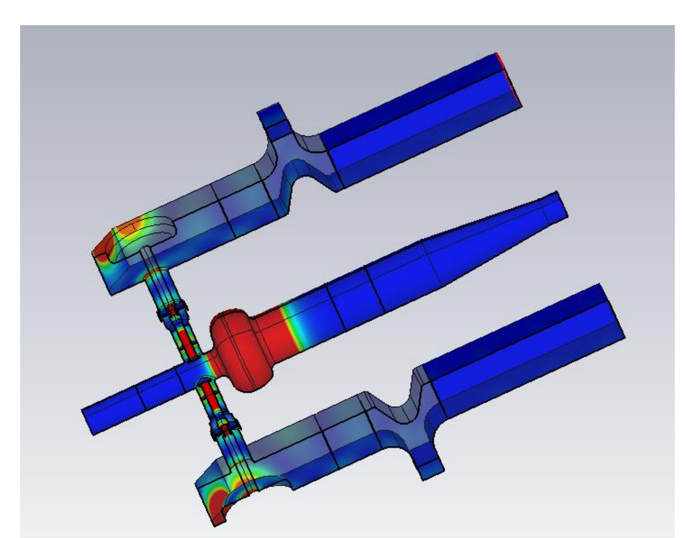
- Bulk of fabrication tooling has been received
- Al pressing has begun on small beampipe half-cell
- Spring-back compensation of half-cell dies yields positive results (<0.5mm error from RF Shape)



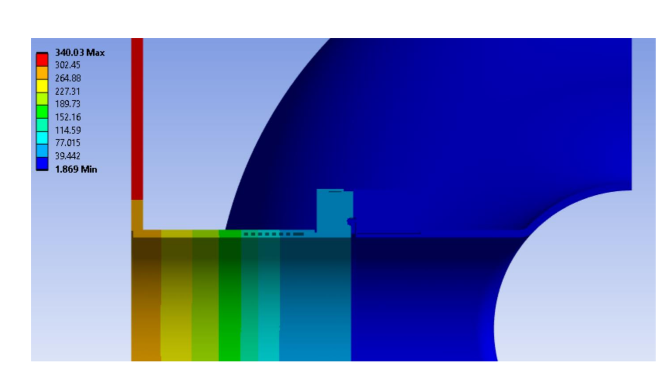
Cavity Fabrication Plan



Qext Tuning and FPC Thermal Optimization



Surface current with Qext tuned to Qe=6×10^4, for the case of 10 GeV 2.5 A avg beam loading (2.71A peak) operation with 18 all focusing cavities



Temperature and heat flow for the FPC warm to cold transition with He trace cooling (100mg/s)

Boundary Condition		4 heaters, 11W
2K	-10.2	
300K	10	45% helix
Air	-7.6	
Water	-1150	
Helium	-70.7	
Temperatures (K)		
At extent of Nb	6.5	
Transition Start	45.8	
Transition End	285.7	
Inner Bell Flange	290.1	
Outer Bell Flange	325.3	

- In this analysis, Qext of the cavity is tuned by one stub on a matched T for each FPC.
  - A matched T provides linear phase response and smoother S11/S21 change, resulting a smooth Qext tuning curve. It also minimizes heating in the 3rd arm of the T.
- Strong standing wave in the FPC and doorknob transition when the Qext is tuned
  - Choose intrinsic Qe=2×10^5 to minimize the heat load for the extreme cases, eliminate the need of Qext tuning for the RPO cases.
  - The worst FPC heating case will be the 10GeV 2.5A with 18 all focusing cavity, requires tuning to Qe=6×10^4 with max beam power 600kW (but lower Vacc of 1.2MV). Other cases also explored
- RF simulation includes 600kW beam loading and 710kW forward power (3kHz off optimum detuning)
- With helium trace cooling in the FPC warm to cold transition, one FPC will generate 10-14W 2K heat load plus 50-70W heat load in the helium gas for this worst case.

Summary

- The EIC ESR single cell bare cavity prototype design is complete and meets the requirements.
- Prototype fabrication is on going, with the first Al half cell pressed and got green light for Nb half cell stamping.
- Cavity string design and analysis continues to mature. The RF/thermal optimization of beampipe tapers, BLAs, shielded bellows, Qext tuners and FPC is still ongoing.

References:

1. Brookhaven National Lab, "Electron-Ion Collider Conceptual Design Report"
2. C. Montag et al., WEPOPT044, IPAC 2022
3. Y. Morita, "Reverse phase mode operation of the RF", EIC Workshop – Promoting Collaboration on the Electron-Ion Collider, Cockcroft Institute, Oct. 2020
4. J. Guo et al., TUPOTK040, IPAC 2022

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