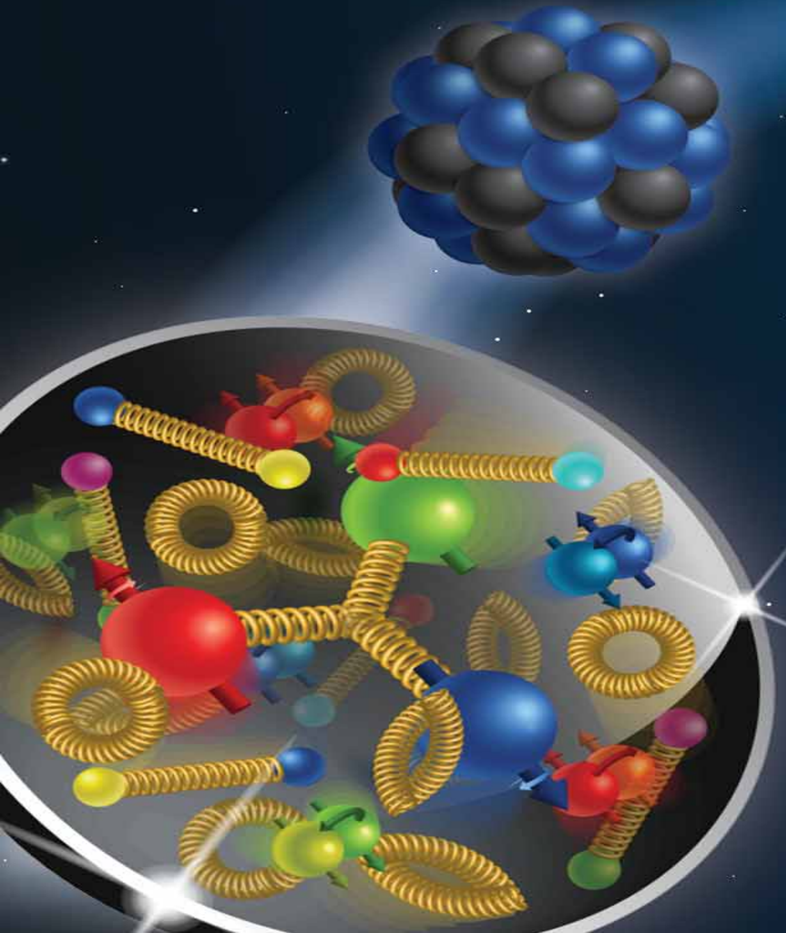
21st International Conference on Radio-Frequency Superconductivity (SRF 2023)



EIC Project Overview and Related SRF Technologies

Ed Daly, L2 RF Systems Manager
On behalf of the RF Systems Team

Electron-Ion Collider

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

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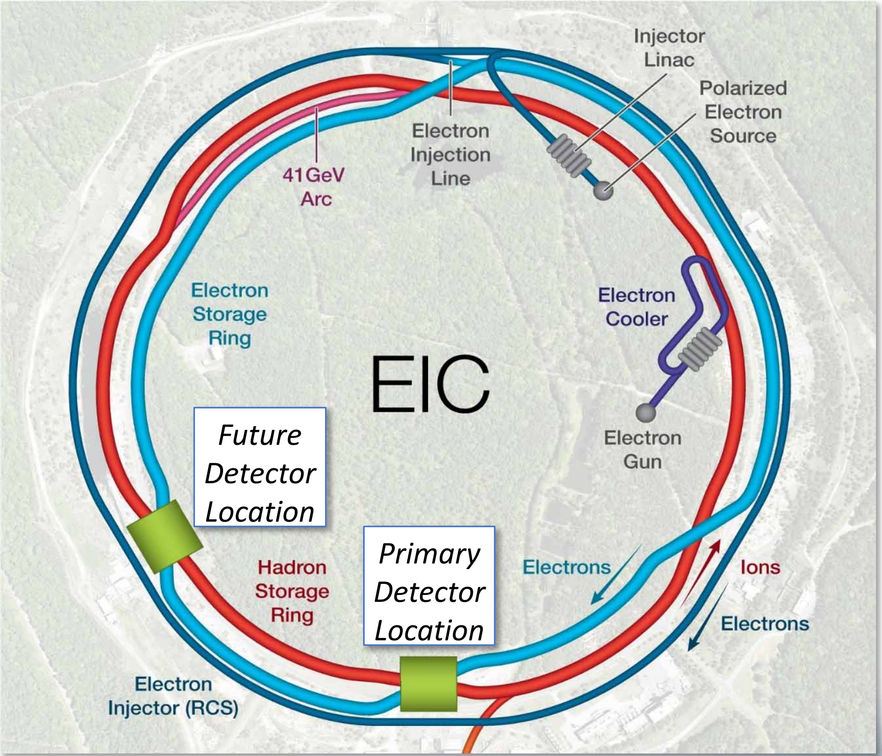
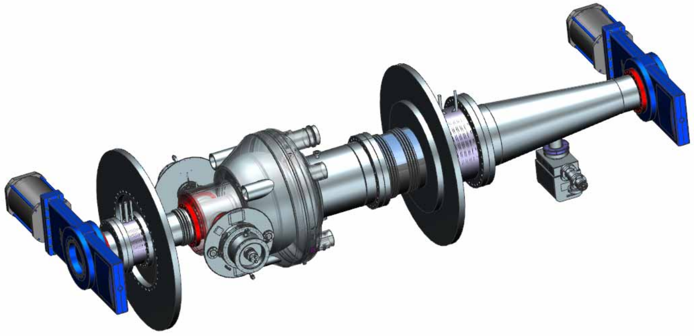
- *ODU – S. De Silva, J. Delayen*
- *SLAC – Z. Li*



Outline



- EIC Machine Overview
- ESR Elliptical cavity design
- High-power HOM power handling hardware
- Fundamental high-power coupler design & performance
- Crab cavity design
- Current status of prototypes
- Summary

EIC Science Requirements

System designs support the overall project design goals.

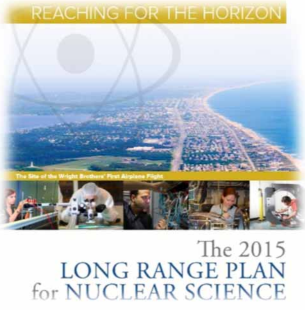
Project Design Goals

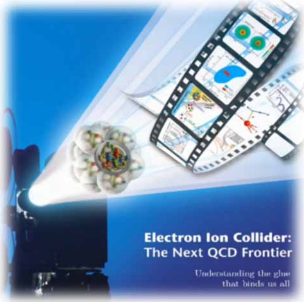
- High Luminosity: L= 10^{33} – 10^{34} $cm^{-2}s^{-1}$, 10 – 100 fb^{-1}/year
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: E_{cm} = 20 – 140 GeV
- Large Ion Species Range: Protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Accommodate a Second Interaction Region (IR)

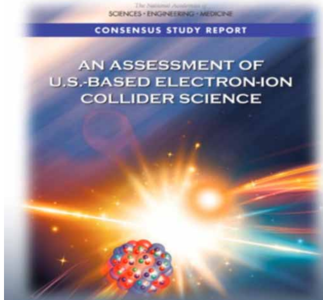
The EIC design meets or exceeds these goals,

But it is VERY challenging to achieve.

Conceptual design scope and expected performance meet or exceed NSAC Long Range Plan (2015) and the EIC White Paper requirements endorsed by NAS (2018)

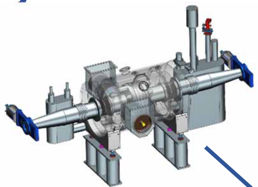




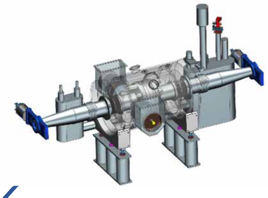


EIC RF Systems

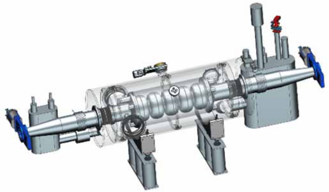
RF power and distribution 400kW×34 new SSAs for ESR 591MHz cavities, various power level for other cavities



Electron - 591 MHz electron storage cavity
17 CMs, IR10



Hadron - 591 MHz bunch compression cavity
3 to 5 CMs, IR10

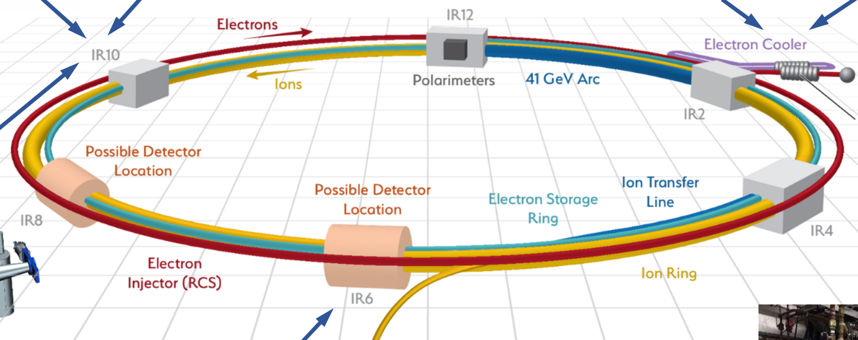


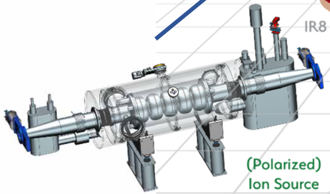
Hadron Cooling - 591 MHz acceleration cavity
10 CMs, Electron Cooler

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

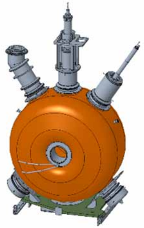
1773 MHz 3rd Harmonic (4) Cavities (Not shown)
1 CM, Electron Cooler

RCS injection harmonic RF kicker



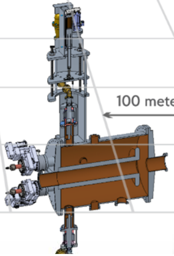


Rapid Cycling Synchrotron 591 MHz acceleration cavity
3 CMs, IR10

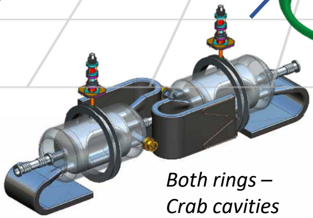


Hadron - 197 MHz bunch compression cavity

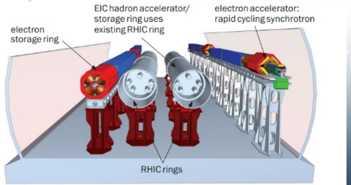
Hadron – 24.6 MHz acceleration cavity



Hadron – 49.2 MHz and 98.5 MHz bunch splitter cavity



Both rings – Crab cavities



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

EIC RF Systems – Function and Description

RF System	Sub System Functions	Freq [MHz]	Type	Location	# Cavities
Electron Storage Ring	*Accel / Store*	*591*	**SRF, 1-cell**	*IR-10*	*17*
Rapid Cycling Synchrotron	*Accel / Store*	*591*	**SRF, 5-cell**	*IR-10*	*3*
	Harmonic Kickers	*591*	**NCRF, QWR, 1-mode** **NCRF, QWR, 2-mode**	*IR-2 or IR-12*	*1* *1*
	Bunch Merge Type 1	*295*	**NCRF, Reentrant**	*IR-4*	*2*
	Bunch Merge Type 2	*148*	**NCRF, Reentrant**	*IR-4*	*1*
Hadron Storage Ring	*Capture / Accel*	*24.6*	**NCRF, QWR**	*IR-4*	*4*
	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*	*7*
	Store 2	*591*	**SRF, 1- or 2-cell**	*IR-10*	*5 or 3*
Strong Hadron Cooling / Energy Recovery Linac	*ERL Injector*	*197* *591*	**SRF, QWR** **SRF, 1-cell**	*IR-2*	*2* *1*
	ERL Low Energy Linac	*197* *591*	**SRF, QWR** **SRF, 1-cell**	*IR-2*	*4* *2*
	ERL Fundamental	*591*	**SRF, 5-cell**	*IR-2*	*10*
	ERL Third Harmonic	*1773*	**SRF, 5-cell**	*IR-2*	*4 (1 CM)*
Crab Cavities	*Hadron*	*197*	**SRF, RFD**	*IR-6*	*8 (4 CM)*
	Hadron/Electron	*394*	**SRF, RFD**	*IR-6*	*6*

Drivers for Choice of SRF vs NCRF

- RF Voltage Requirements up to 3.7 MV per ESR SRF cavity
- CW Power Requirements up to ~800 kW per ESR SRF cavity
- Beam Impedance and HOM Power

Value Engineering Opportunities

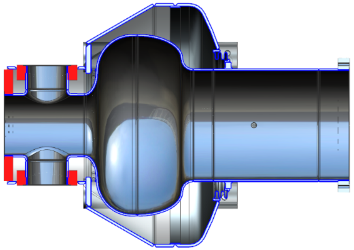
- Availability of Cryogenics (IR6, IR10, IR2)
  - Three satellite plants interface with a Central Helium Liquefier feeding SRF systems and Superconducting Magnets
- Existing NCRF Systems (IR4) suitable for use in HSR
  - Bunch compression (refurbish 197 MHz)
  - Acceleration (modify 28 MHz → 24.6 MHz)
- New NCRF systems meet requirements
  - Three bunch merge cavity systems (~0.7 MV)
  - Two harmonic kicker cavity systems

Existing 197MHz NCRF Cavity for Bunch Compression

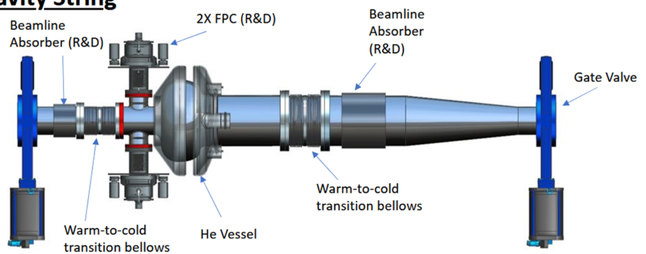
ESR Single Cell SRF System Function and Requirements

MOPMB078

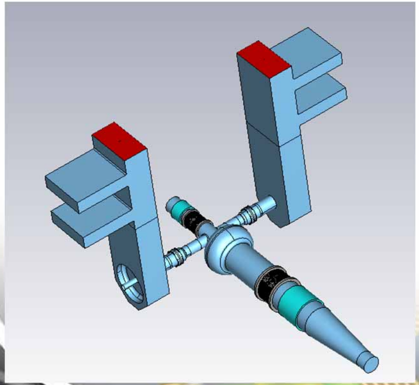
- Maintain ~7 mm bunch length over a wide range of beam energies (5 -18 GeV)
- To achieve the luminosity, system needs to provide up to 10 MW beam power (9 MW from SR power and 1 MW from HOM loss) with up to 2.5 A beam current and 28 nC bunches.
- Challenging HOM damping requirements
  - Beam power typical for HERs in B-factories like PEP-II and KEKB, maximum beam current and bunch charge similar to LERs
- Operates in a wide range of cavity voltage, beam current, beam phase with maximum beam power for 10-18 GeV
- 17 cavities in the system, all installed in one phase
  - Limited to 800 kW RF supply for each cavity, 400 kW per FPC
  - Low energy, High Current operation requires cavities installed



Asymmetric Cavity with Large Beampipe



First Article ESR 591 MHz CM



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

ESR Single Cell SRF Cavity Requirements

- Impact of wide range of cavity voltage and beam current
  - Broad range of cavity coupling is required for stable operation with affordable RF power
  - External Qext tuner is required
  - RF FODO operation is possible to eliminate the need for variable Qext

- Low R/Q to mitigate transient beam loading

- RF drive frequency 591.149 MHz, operation resonant frequency range 591.149 ± 220kHz

Major RF related parameters for selected ESR operation cases

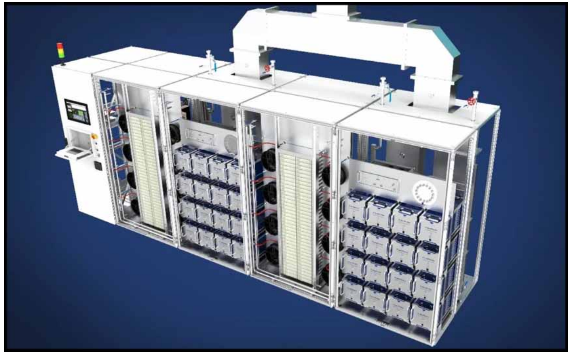
Case		**18GeV**	**10GeV**		**5GeV**	
Vtot (MV)		*61.5*	*21.7*		*9.84*	
Beam current (A, exc gap)		*0.271*	*2.72*		*2.71*	
Beam current (A, average)		*0.25*	*2.5*		*2.5*	
Veff (SR+HOM loss, MV)		*37.13*	*3.96*		*1.39*	
Beam power, avg, total, MW		*9.28*	*9.89*		*3.47*	
All Focusing scheme	*Vcav (MV)*	*3.42*	*1.21*		*0.55*	
	Optimal Qext per cav	*2.74E5*	*3.20E4*		*1.88E4*	
	Opt Pfwd/FPC (kW)	*280 (279)*	*299 (306)*		*105 (116)*	
	Qext per cav	*2.0E5*	*7.4E4*		*2.5E4*	
	Pfwd/FPC (kW)	*287 (287)*	*354 (376)*		*107 (196)*	
RF FODO scheme, Focusing Cav	*Vcav (MV)*		*3.73*		*3.9*	
	Qext		*3.07E5*	*2.0E5*	*9.55E5*	*2.0E5*
	Pfwd/FPC (kW)		*299*	*312*	*105*	*183*
RF FODO scheme, Defocusing Cav	*Vcav (MV)*		*3.9*		*3.65*	
	Qext		*3.35E5*	*2.0E5*	*8.36E5*	*2.0E5*
	Pfwd/FPC (kW)		*299*	*319*	*105*	*168*
	# of defocusing cav		*6*		*8*	

FPC power estimated with DC beam loading, optimum detuning
FPC power in parenthesis are the simulated peaks with transient beam loading

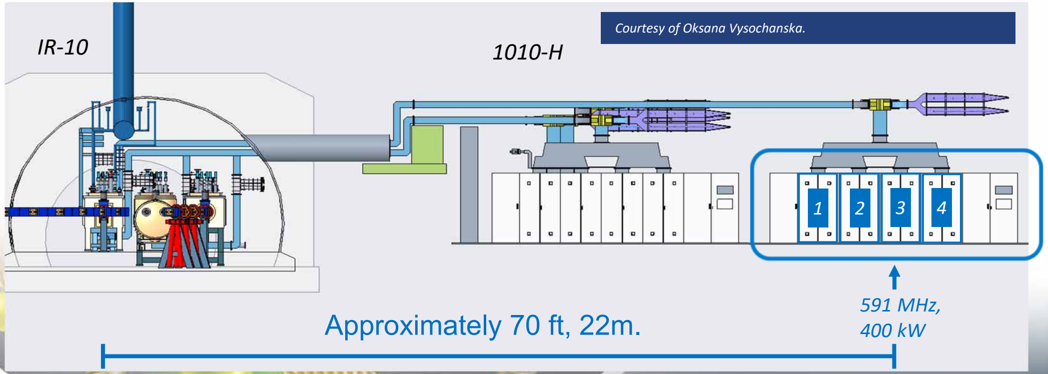
High Power SSAs:
Requirements and Conceptual Layout

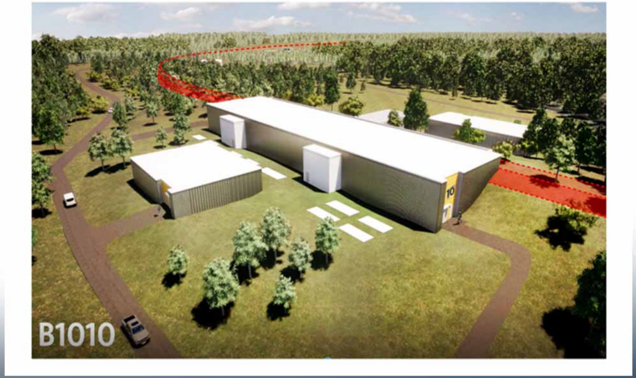
Project Requirements

- *ESR requires 17 591 MHz single cell cavity cryomodules (2 SSAs / CM)*
- *Design Validation - Full power and gradient testing of First Article CM*
- *Full power acceptance testing of all CMs prior to installation*
- *Testing requires 200 kW (full gradient) and 400 kW amps (full power)*
- *Assembly of First Article Cryomodule to start 09/2025*



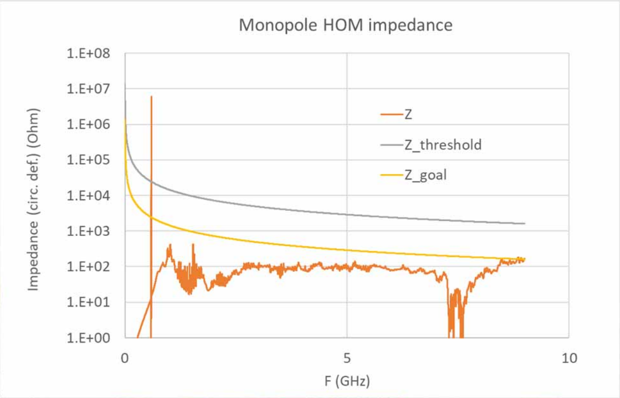
400 kW High Power Amplifier Conceptual Layout
(24' length x 5' width x > 10' height)

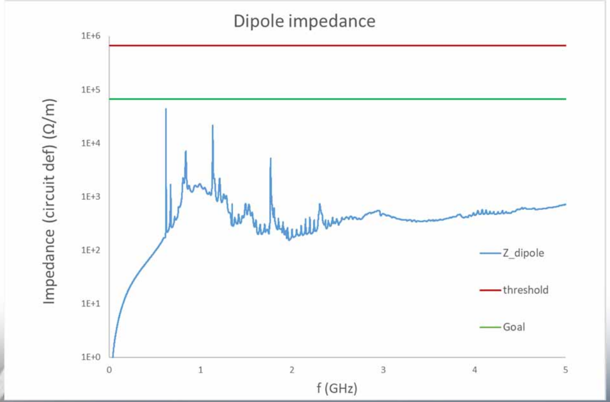


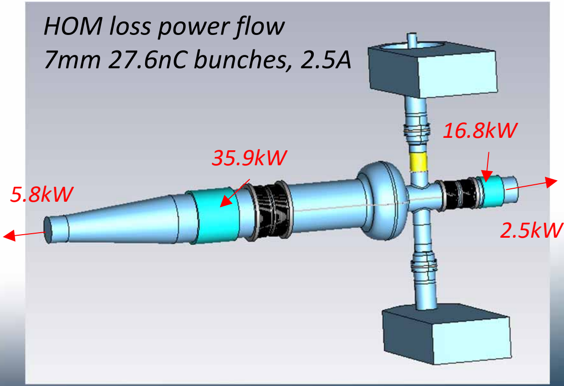


ESR Cavity HOM Absorbers

- HOM impedance analysis:
  - Long range wake simulation with the model including BLAs and the taper using CST
  - Meets stringent impedance goals (10x below threshold)
  - FPC/doorknob not included in the simulation shown
- HOM power flow:
  - Short range wake simulation with BLAs and FPCs using CST
  - **For the worst case, total HOM power per cavity is ~61 kW (RT water cooled)**
  - About 2/3 of the loss is on the large beampipe side and 1/3 on the small beampipe side
  - BLAs analysis shows significant self heating
- BLA design - Shrink fit SiC cylinder (APS-U style)



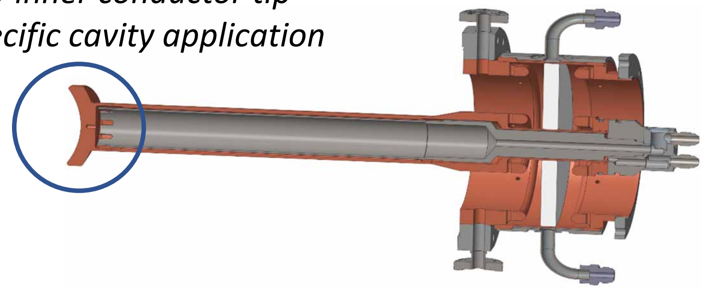




Common FPC Window Design

- *High power, broadband*
  - *Broadband: < -40 dB for frequencies below 591 MHz.*
  - *The peak field at the braze-joint is 367 kV/m.*
- *Mechanically robust for shipping*
- *Conservative thermal design*

Modify inner conductor tip for specific cavity application



	Requirement	FPC Design
Average RF power	*379 kW*	*1 MW, traveling wave* *500 kW, full reflection*
Peak Power	*1.5 MW, equivalent*	*2 MW, equivalent*
Frequency	*591 MHz*	*Broadband window design,* *for EIC cavities below 591 MHz*
Shock load	*5g*	*5g*
Modal frequency	*> 60 Hz*	*100 Hz*
IC length	*289 mm*	*425 mm*

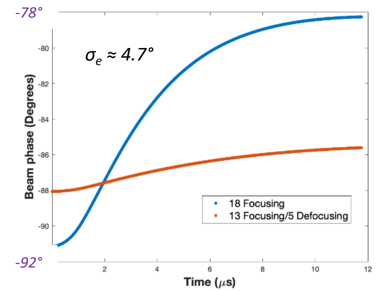
Brazing Development

EBW Development

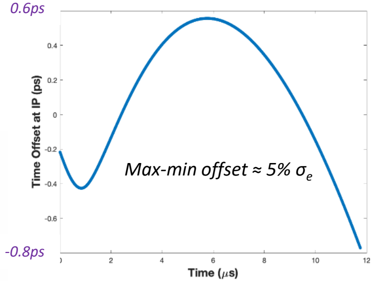
Challenge: Transient beam loading in eSR and HSR

- Cause:
  - Abort gap in the storage rings
  - Periodical change of beam induced voltage in the cavities
- Impacts:
  - Periodic phase shift of bunches, resulting luminosity loss
  - Different phase shift in eSR vs HSR, crab vs fundamental
  - Possible instabilities
- Possible mitigations
  - Low impedance cavity design - at the cost of efficiency
  - Reverse the phase of some cavities for low energy/low voltage operation (increase single cavity voltage, keep the voltage vector sum constant), aka RF FD (focusing-defocusing) – also reduces the range of Qext tuning, machine protection concerns not fully addressed yet
  - Direct feedback and comb loop LLRF (reduce effective impedance) – extra RF power
  - RF feed-forward
  - Matching the phase shift in two rings with RF reference modulation (need to adjust cavity R/Q of the two rings following beam current and voltage) Periodical detuning cavities with ultra-fast ferroelectric tuners

Controls and LLRF will play a significant role in mitigation strategies



eSR beam phase modulation, case of 10GeV 2.5A
~13° all focusing, ~2° RF FD (~1/2 σ_e)



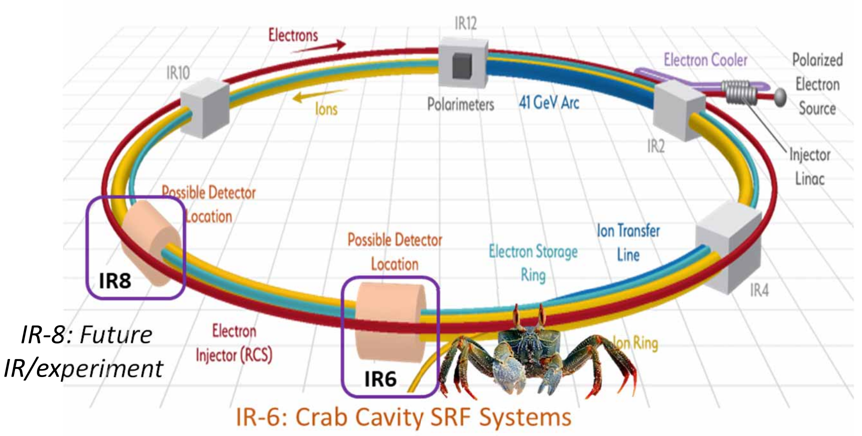
Phase modulation difference between eSR/HSR beam, RF FD with direct FB, eSR@10GeV 2.5A

J. Fox, "RF Beam loading, LLRF feedback applications in EIC storage rings", 2021 EIC Accelerator Partnership Workshop
T. Themis, "EIC LLRF studies", internal report
Also see T. Mastoridis et al., DOI:10.1103/PhysRevAccelBeams.23.101601

Crabbing Systems for EIC

- *Primary interaction point is IR6*

	HSR		ESR
Cavity frequency [MHz]	*197*	*394*	*394*
Crossing angle [mrad]	*25.0*	*25.0*	*25.0*
β_{cc} [m]	*1300*	*1300*	*150*
β_{IP} [m]	*0.8*	*0.8*	*0.45*
Piwinski angle [rad]	*7.9*	*7.9*	*2.4*
Crabbing voltage [MV]	*33.83*	*–4.75*	*2.9*



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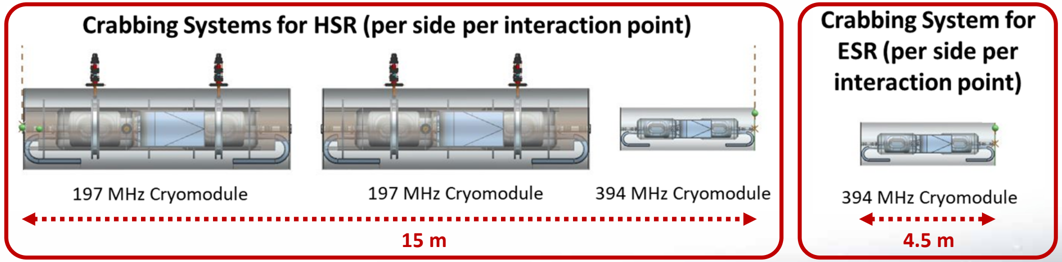
FRIBA03

- *EIC requires several crabbing systems per side*

	V_t [MV]		No. of cavities	
System	**HSR**	**ESR**	**HSR**	**ESR**
197 MHz	*33.83*	*–*	*4*	*–*
394 MHz	*4.75*	*2.90*	*2*	*1*

Schematic of Crabbing Systems

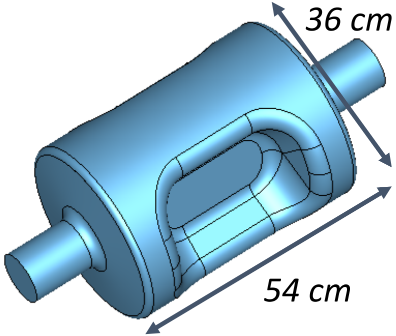


197 MHz crabbing cavity is identified as one of the two R&D cavities to be prototyped for EIC

ESR 394 MHz RFD Crab Cavity

MOPMB054

- *394 MHz cavities will be installed on both HSR and ESR*
  - *197 MHz crabbing system is the primary crabbing system at HSR*
  - *Second harmonic crabbing system operating at 394 MHz will be installed at HSR to linearize the kick for the 6-7 cm long proton bunches*
- *Specifications:*
  - *Beam aperture = 100 mm*
  - *Total impedance budget: $Z_z = 2.6\times10^4$ Ω-GHz and $Z_t = 0.96\times10^6$ Ω/m*
  - *Per cavity: $Z_z = 6.5\times10^3$ Ω-GHz and $Z_t = 0.24\times10^6$ Ω/m*
    - *For 4 cavities considering the two IPs*
    - *394 MHz design for the ESR has tighter impedance budget*
- *394 MHz crab cavities will be designed as a single cavity cryomodule to be similar for both HSR and ESR*



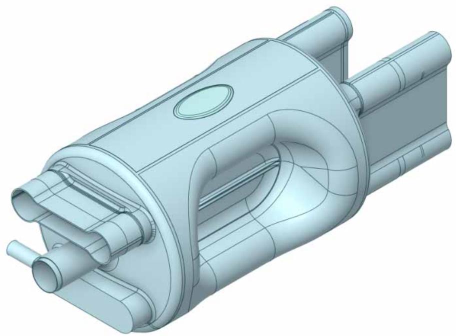
Property		
Operating frequency	*394.0*	
1st HOM [MHz]	*537*	
E_p/E_t^*	*3.87*	
B_p/E_t^* [mT/(MV/m)]	*8.08*	
B_p/E_p [mT/(MV/m)]	*2.09*	
G [Ω]	*125.4*	
R/Q [Ω]	*308.6*	
R_tR_s [Ω²]	*3.9×10^4*	
Max V_t [MV] per cavity	*2.9*	
E_p [MV/m]	*29.5*	
B_p [mT]	*61.56*	
Total V_t [MV]	*2.9*	*4.75*
No. of cavities	*1*	*2*

** $E_t = V_t/(\lambda/2)$*

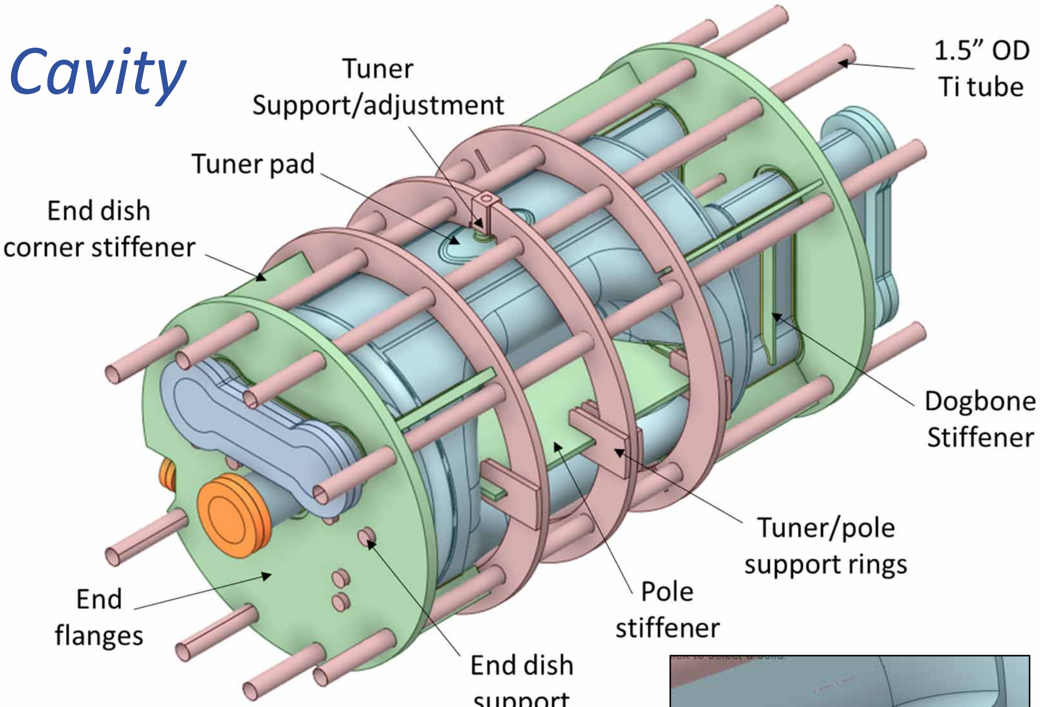
Challenge: RF Control for Crab Cavities

- Beam dynamic study on the instabilities showed that
  - High gain feedback: $Q_{ext\_cav}/Q_{ext\_effective}$ = 1.75E6/300
  - Short feedback delay (~380 nS)
  - Transverse dampers are also needed during injection and ramping
  - Otherwise, FMDs are required for hadron
- Emittance growth due to crab cavity phase and amplitude noise was studied.
  - Phase noise should be a factor of 2-7 lower than that of HiLumi-LHC
  - A low frequency feedback system with precise pickup measurement is needed

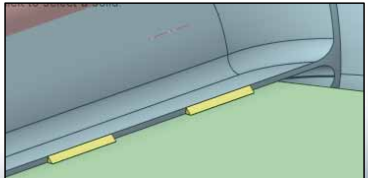
197 MHz Prototype Crab Cavity



	Nb
	NbTi
	Ti
	SS
	Weld



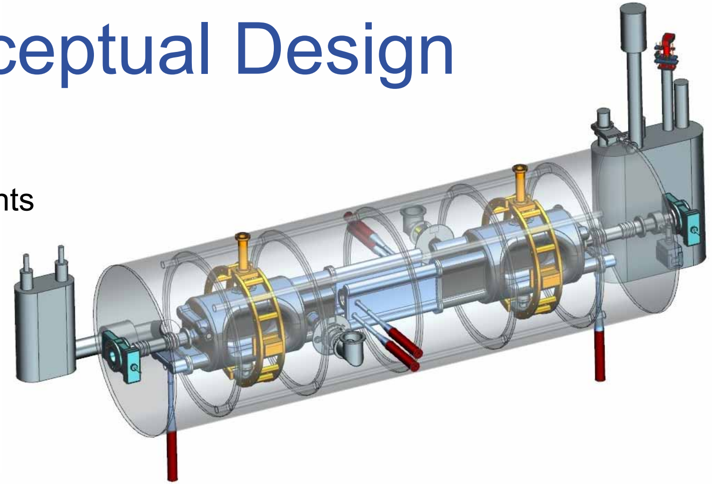
- Cavity body is comprised of 4 mm Nb with some regions thicker than 4 mm
- Stiffeners are needed to maintain stress at acceptable level

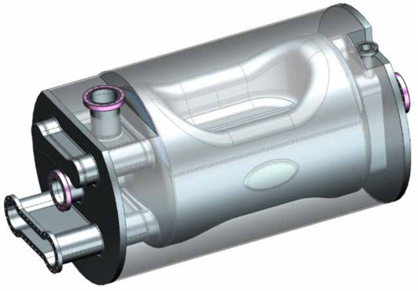


Welds modeled at all NbTi to Nb joints

First Article Crab Cavity CM Conceptual Design

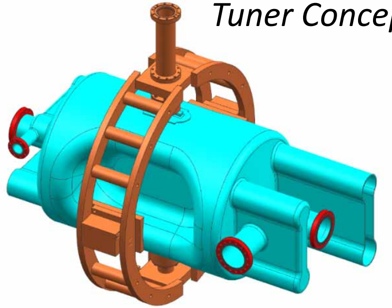
- Cryomodule with 2 ea 197 MHz crab cavities
  - Cavity geometry with curved poles to suppress multipole components
- Cryomodule architecture will be similar to SNS cryomodule
- Information from prototype cavity fabrication and test performance will be incorporated into FA cavity

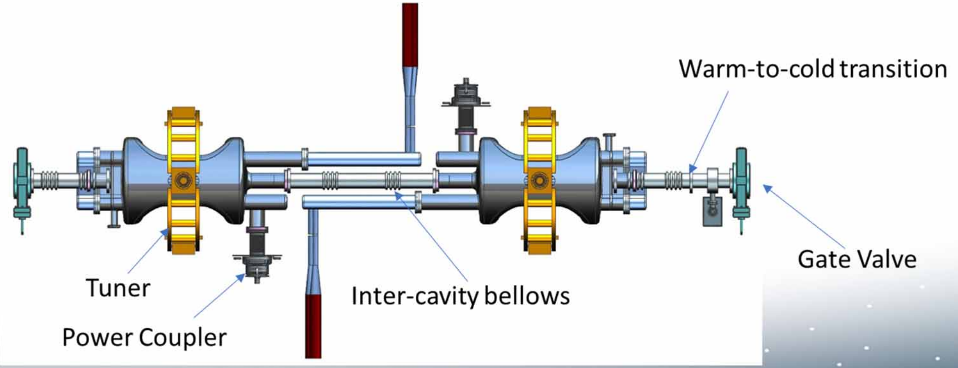




Jacketed Cavity

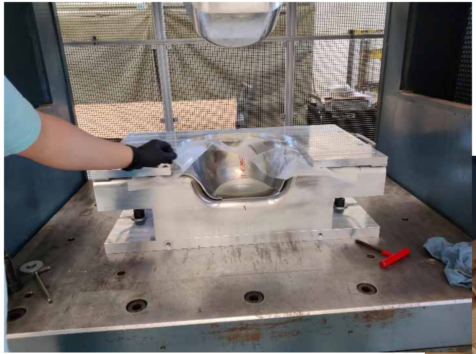
Tuner Concept





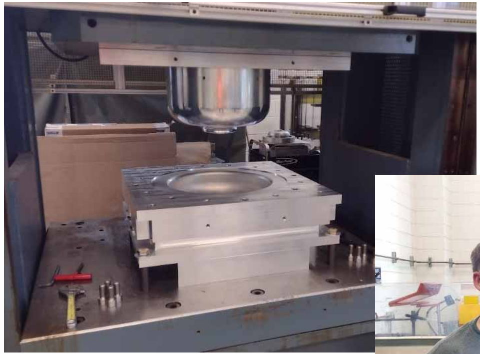
R&D Pressing of Prototypes: 197 Crab / 591 Single Cell Cavities

- Crab Cavity die and Al test parts



WPEWB051

- Single Cell cavity die and Al test pieces



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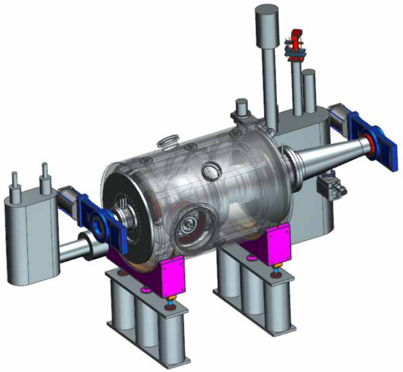
Path to Production Cryomodules

Design Iterations

- Prototype Cavities
  - 591 MHz single cell
  - 197 MHz Crab
- First Article Cryomodules
  - 591 – Elliptical Family
  - 197 – Crab Family
- Production Cryomodules
  - Elliptical : 591 single-cell, 591 5-cell, 1773 5-cell, ERL inj.
  - Crab : 197, 394

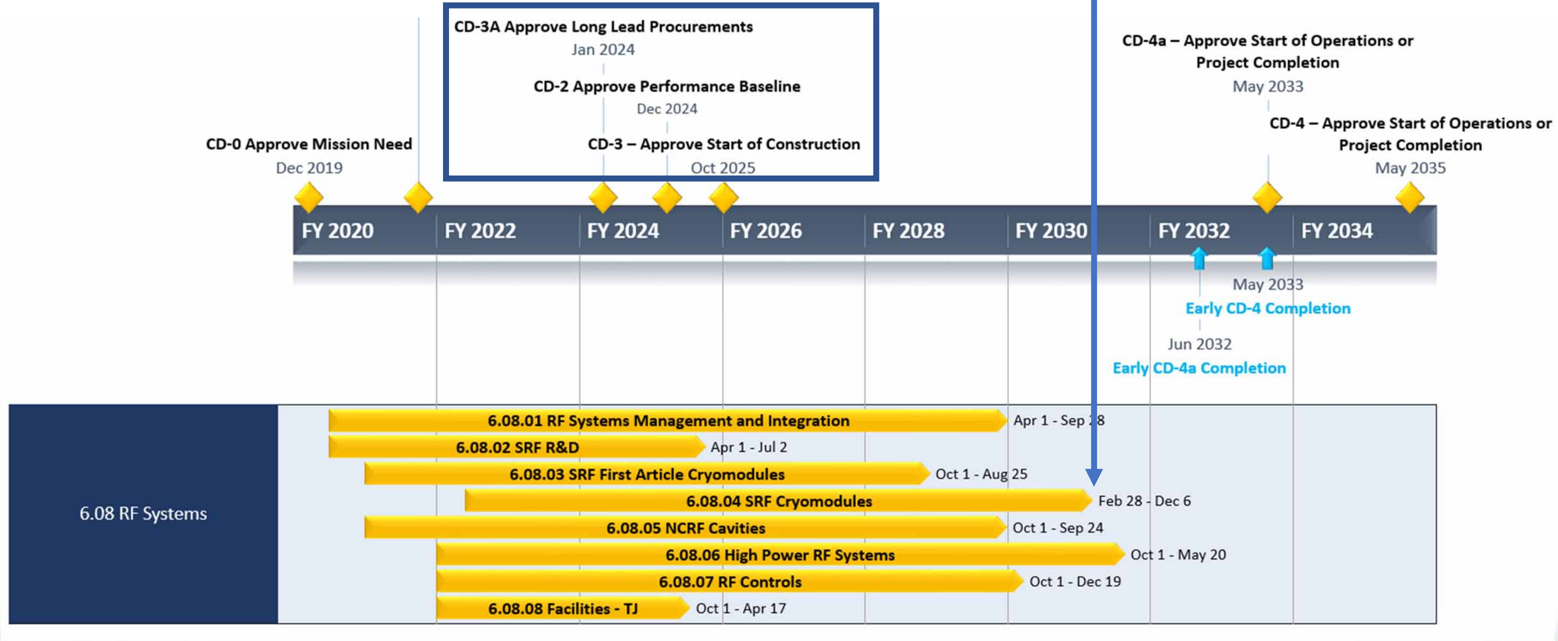
Lessons Learned
- *Cavity fabrication*
- *Vertical test*



ESR 591 MHz First Article Single Cell Cavity Cryomodule to be tested utilizing the SSA EDUs

Lessons Learned
- *Cavity fabrication*
- *Component analysis & design*
- *Component procurement*
- *Tooling*
- *Cryomodule Assembly*
- *Horizontal test*

Current plan consists of 60 cavities and 47 cryomodules – last units installed by 2031



Summary

- Very good progress on RF Systems requirements and design
- 400 kW SSAs provide power for ESR cavities
- FPC and HOM development efforts – FA hardware in progress
- Significant progress on First Article cavity and cryomodule designs
- ESR and Crab Cavity Prototype work on-going
- Project focused on Critical Decisions planned within next two years

Thanks for your attention!