Brookhaven National Laboratory

Jefferson Lab

U.S. DEPARTMENT OF ENERGY

HOM Damping for Electron Ion Collider Crab Cavities

Binping Xiao

Brookhaven National Lab

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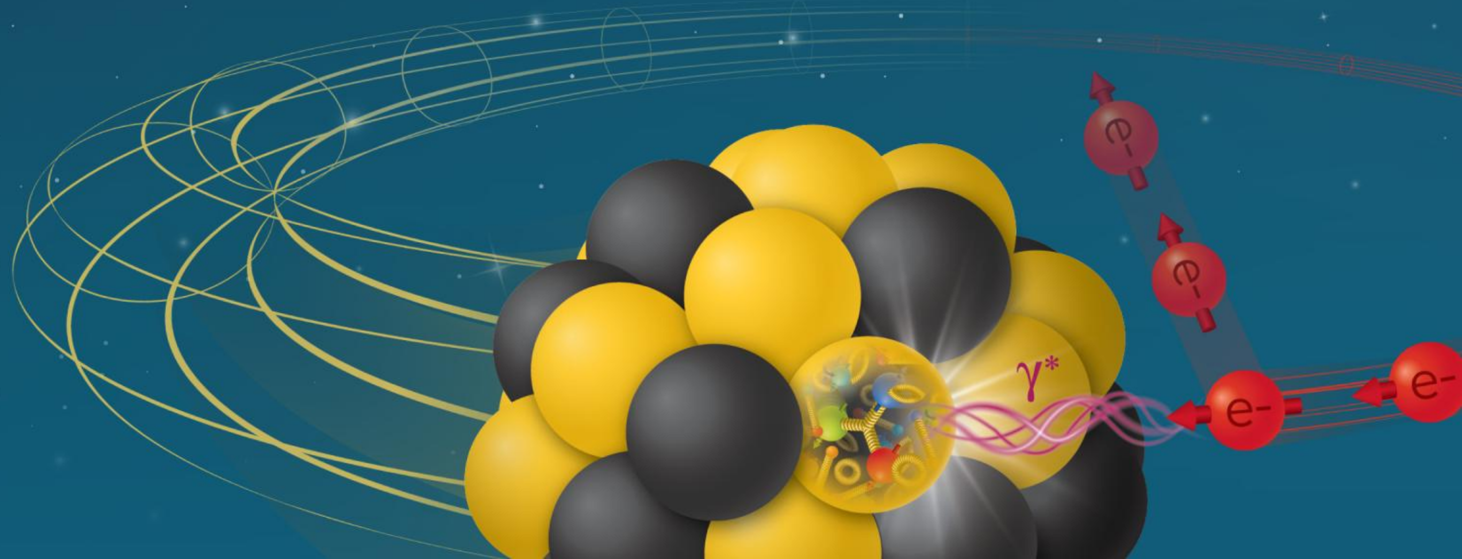
Electron-Ion Collider

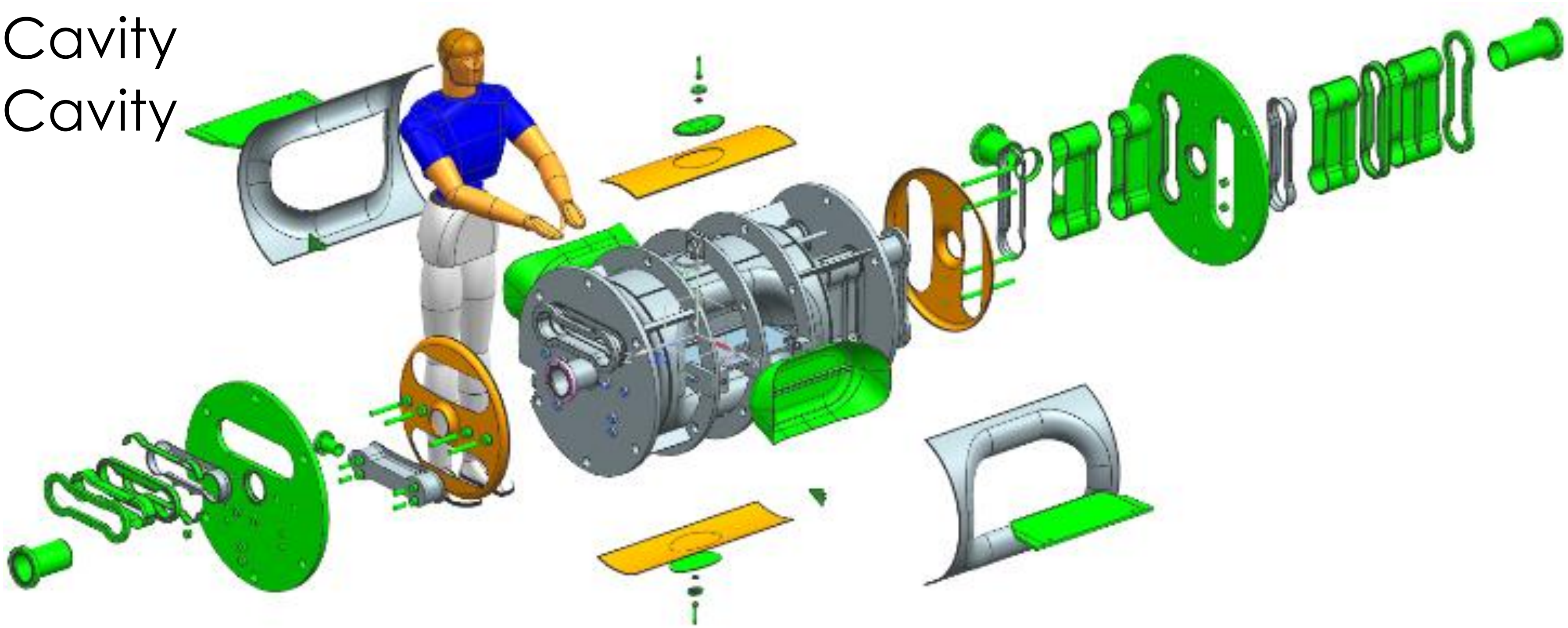


EIC Crab Cavity Team and Collaborators

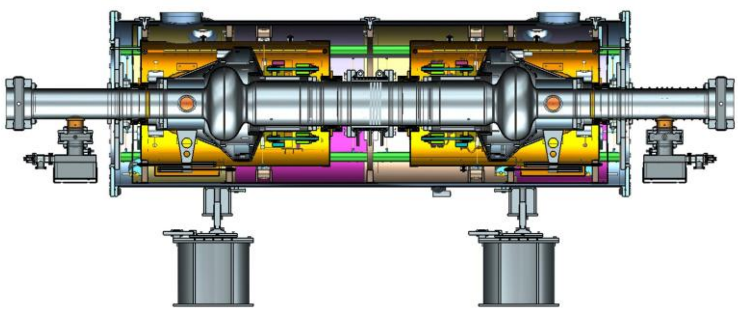
- BNL – B. Xiao, Q. Wu, G. Li, M. Blaskiewicz, W. Xu, J. Fite, D. Holmes, K. Smith, J. C. Brutus, S. Verdu-Andres, A. Zaltsman, D. Xu, Y. Luo, Y. Hao, S. Berg, G. Narayan, F. Severino, K. Mernick, K. Hamdi, and many more
- ODU – S. De Silva, J. Delayen
- JLAB – Naeem Huque, Chinmay Andhare, Gary Cheng, Alex Castilla, Jiquan Guo, Justine Cox, Eduard Drachuk, Paul Carrieri, John Buttles, Damon Rath, Ethan Senecal, Michelle Oast, Adam O'Brien, Greg Grose, Josh Armstrong, Zack Conway, S. Wang, H. Huang, G. Bamunuvita, and many more
- ANL – Mike Kelly, Ben Guilfoyle, Tom Reid
- SLAC – Z. Li
- Cal Poly - Themis Mastoridis
- 394 MHz Cavity Collaborators:
  - STFC – Nick Templeton, Graeme Burt, Edward Jordan
  - TRIUMF – R. Laxdal, P. Kolb, Z. Yao

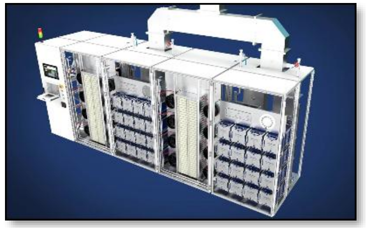
Outline

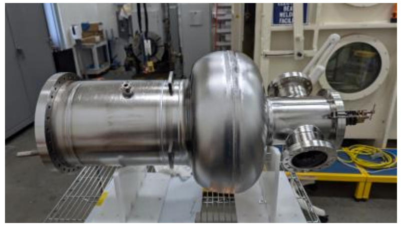
- EIC RF Systems Overview
- EIC Crab Systems
  - Overview
  - HOM Impedance Threshold
  - 197 MHz Crab Cavity
  - 394 MHz Crab Cavity
- Summary



EIC RF Systems Overview

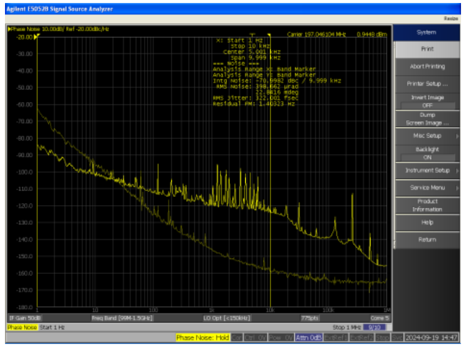




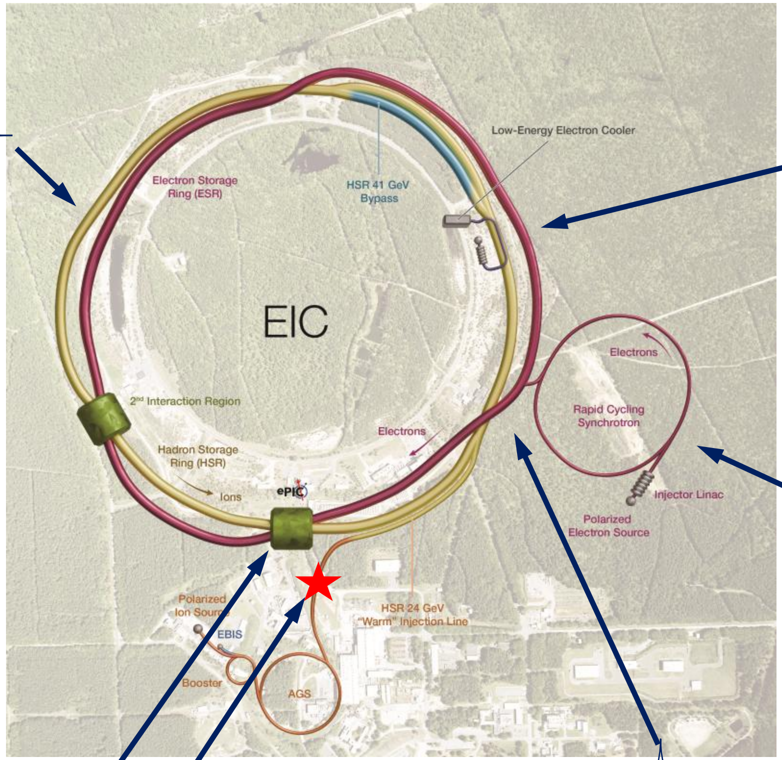


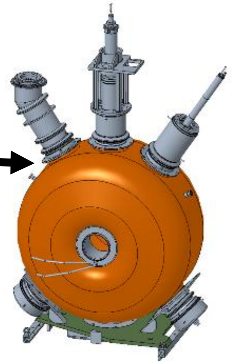
400 kW Amplifier

EIC LLRF DAC Clock for Crab Cavities

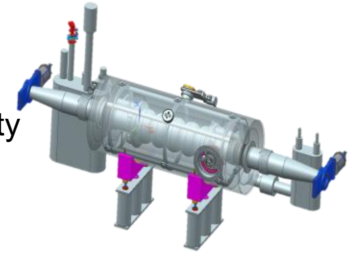


Electron Storage Ring & Hadron Storage Ring – IR10
591 MHz 800 kW 2 K
1-Cell Dula-Cavity
Cryomodules
ESR = 9 CMs
HSR = 3 CMs





Low-Energy Cooler, IR02 -
17 197 QWR NCRF,
4 591 NCRF,
1 24 MHz NCRF,
And **1** 591 MHz Deflecting Cavity



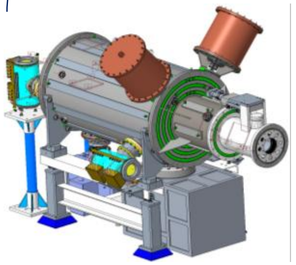
RCS
591 MHz 5-Cell Cavity
Cryomodules
8 CMs

IR06

EIC Scope Interface

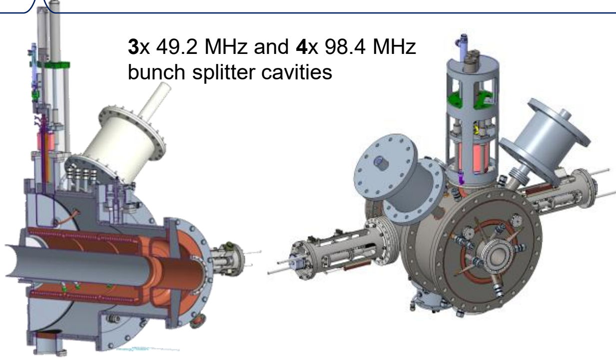
Crab Cavities (per IR)	HSR (Cavities/CMs)	ESR (Cavities/CMs)
197 MHz	8/4	–
394 MHz	4/4	2/2

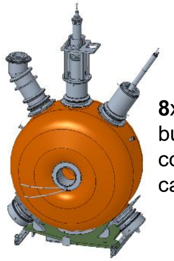
HSR NCRF – IR04



4x 24.6 MHz Accelerating Cavity

3x 49.2 MHz and **4**x 98.4 MHz bunch splitter cavities

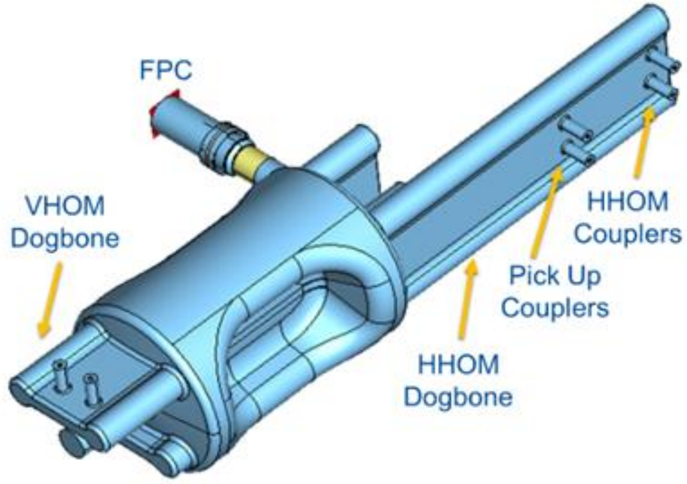




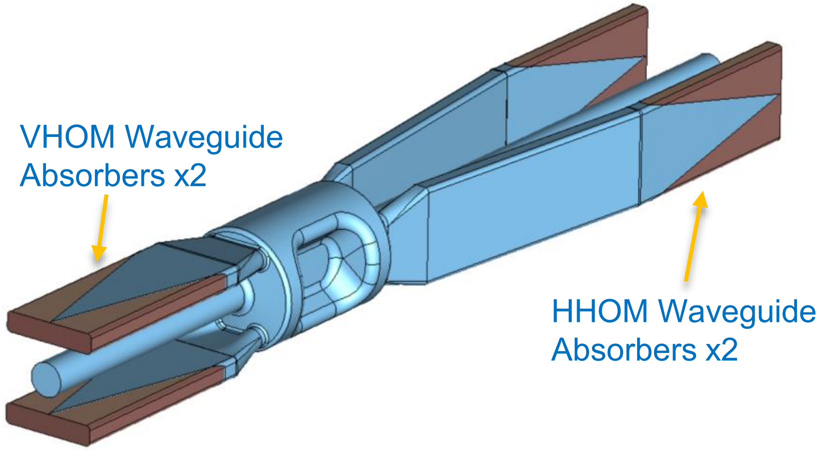
8x 197 MHz bunch compression cavity

EIC Crab Systems Overview

197 MHz with coaxial absorbers

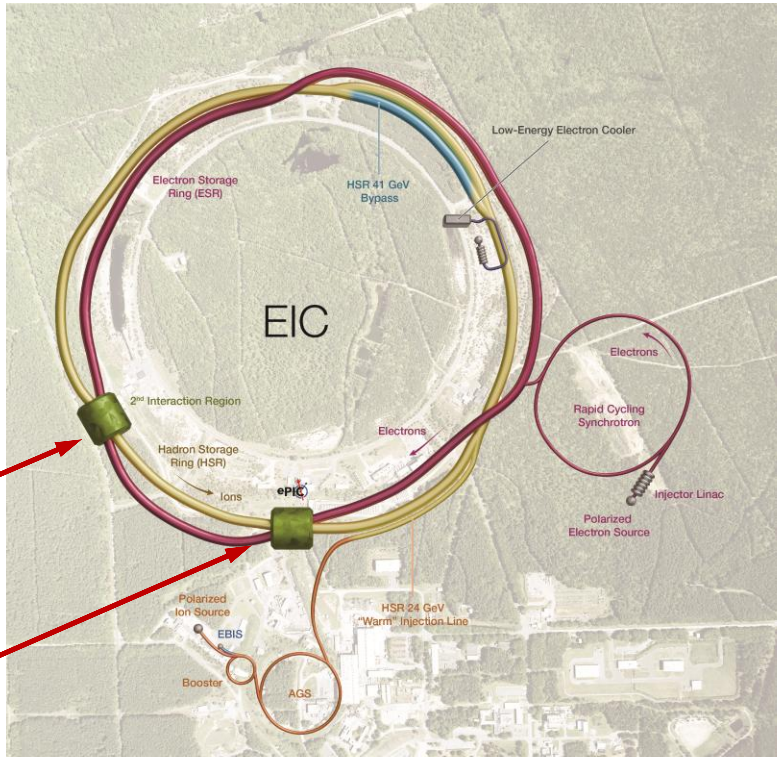


394 MHz with waveguide absorbers



	HSR		ESR
Crossing angle [mrad]	25		
Freq [MHz]	197	394	394
V_t [MV]*	33.83	4.75	2.90
Number of Cavities/CMs	8/4	4/4	2/2
V_t per cavity [MV]	8.5	2.4	1.5
Space allocation – longitudinal [m]*	15		4.5

50% more



*per side of the IP

2nd IP needs 1.5x cavity numbers comparing with 1st IP due to higher crossing angle, NOT in the baseline

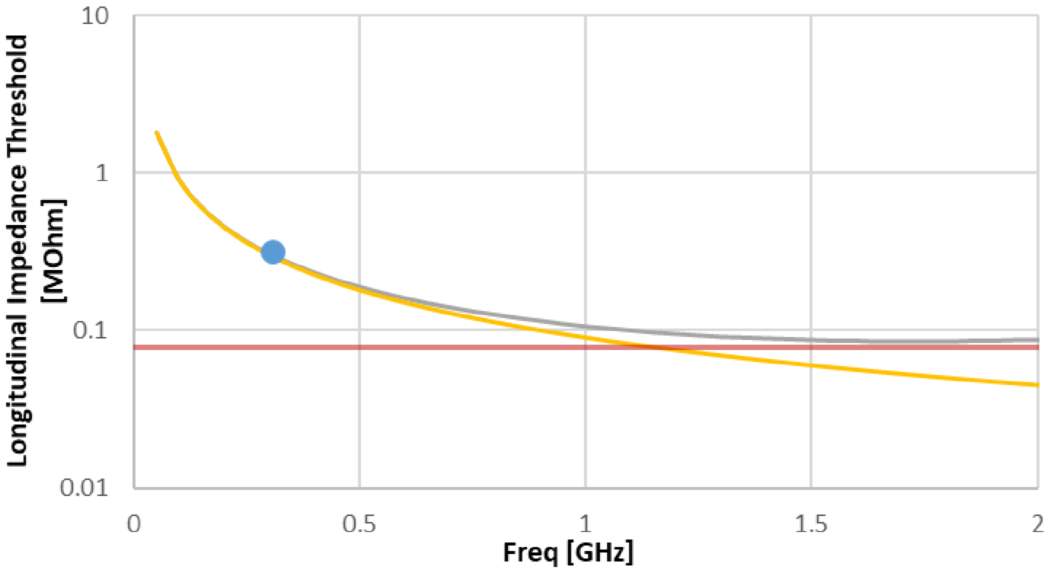
HOM Impedance Threshold - Overall

	HSR		ESR
Total			
Longitudinal	80 kΩ		26 kΩ-GHz
Transverse × β function [MΩ]	3432		288
Number of Cavities/CMs for IR6	8/4		2/2
Per Cavity			
Freq [MHz]	197	394	394
Number of Cavities/CMs	8/4	4/4	2/2
Longitudinal	10 kΩ	20 kΩ	4.33 kΩ-GHz
Horizontal β function [m]	1300		150
Horizontal	0.132	0.66	0.16
Vertical β function [m]	260		30
Vertical	0.66	3.3	0.8

Impedances in circuit definition
*HOM impedance thresholds per cavity considered the possible 2nd IR8, except for 197 MHz longitudinal

HOM Impedance Threshold – HSR Longitudinal

- Together with Shaoheng Wang (JLab) and Qiong Wu, CERN's method has been used to estimate the longitudinal HOM impedance threshold, grey line
- Longitudinal HOM impedance using simplified model with 90kΩ-GHz threshold, yellow line
- Single point checked by Mike Blaskiewicz, blue dot
- The above three results agree well at low frequency, CERN method gives higher threshold at high frequency
- **80kΩ** is used regardless the frequency, red line



References:

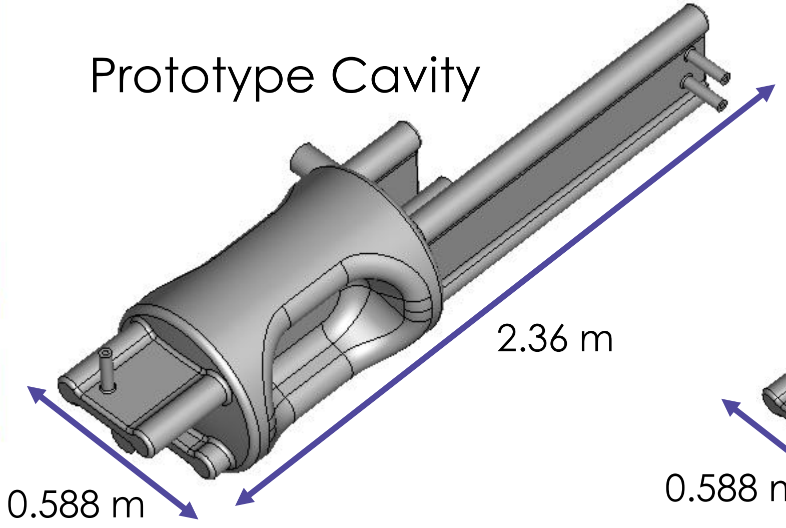
Balbekov, V. I., and S. V. Ivanov. "Longitudinal instability threshold of bunched beams in proton synchrotrons." Sov. At. Energy (Engl. Transl.);(United States) 60.1 (1986).

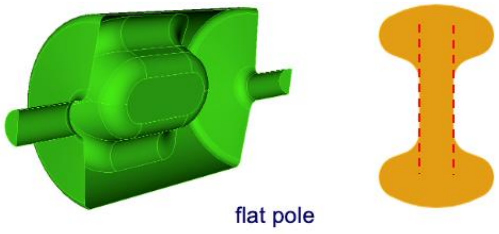
Karpov, I., Argyropoulos, T., & Shaposhnikova, E. (2021). Thresholds for loss of Landau damping in longitudinal plane. PRAB, 24(1), 011002.

197 MHz Crab Cavity

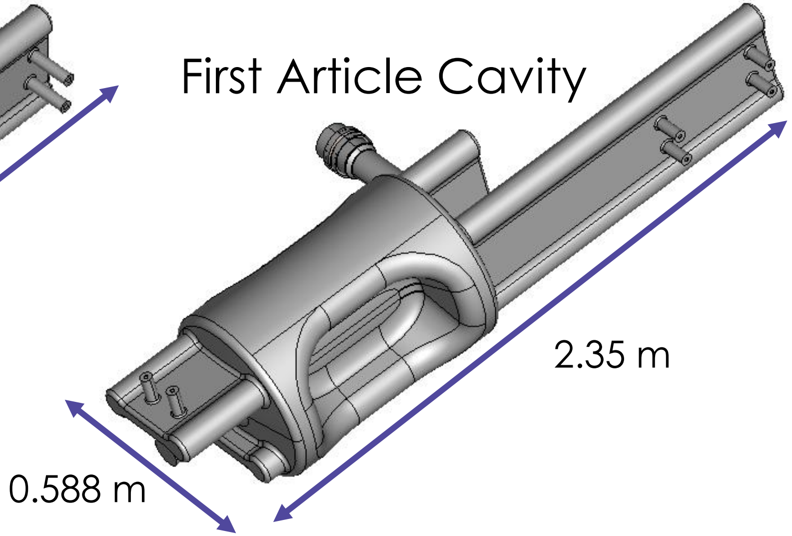
- RF-Dipole (RFD) design is chosen over Double Quarter Wave (DQW)
- Coax absorber design is chosen over waveguide absorber
- Reasonable peak surface fields

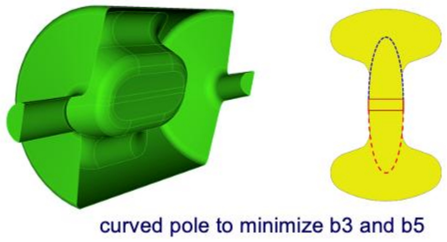
Prototype Cavity





First Article Cavity





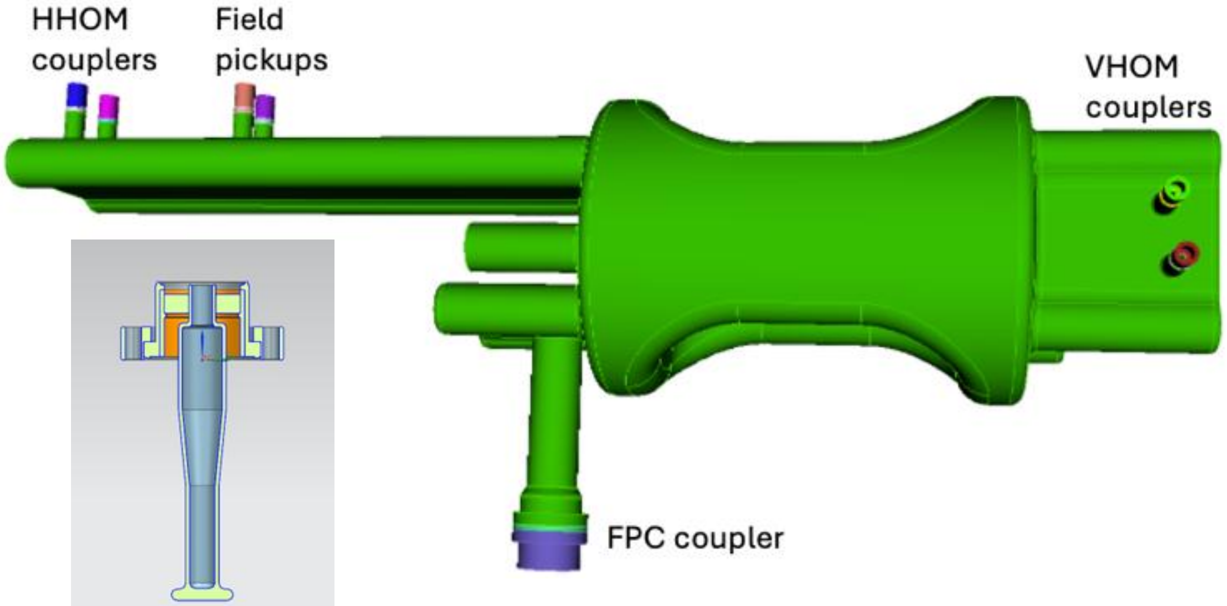
RF Property	Prototype Cavity	FA Cavity
V_t [MV]	8.5/11.5	8.5/11.5
E_p [MV/m]	33.2/44.9	32.3/43.7
B_p [mT]	60.1/81.3	59.3/80.2
G [Ω]	97.2	94.6
R/Q [Ω]	1161	1034

Multipole components at 33.8 MV per side

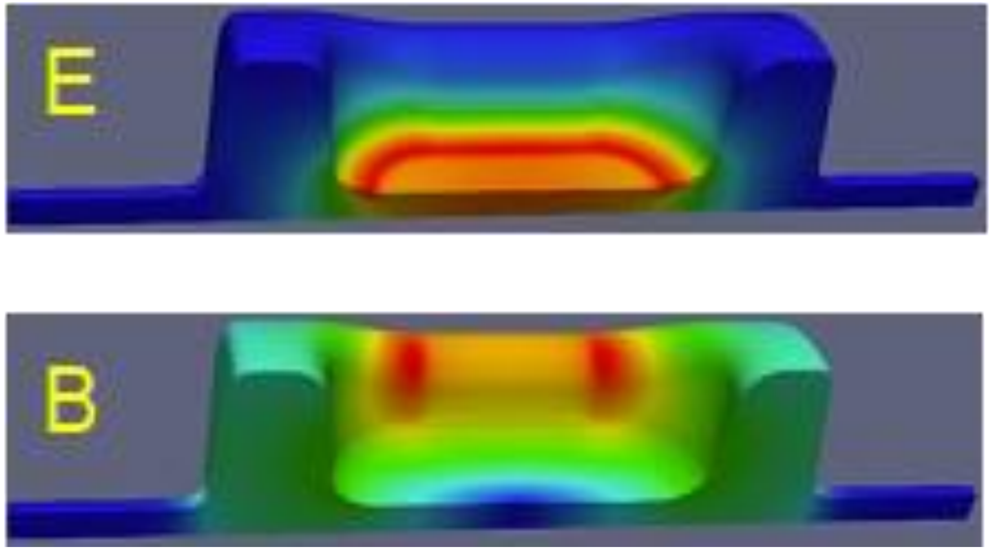
Component	Value	Requirement	Unit
b_2	0.0004	0.008	T
b_3	0.043	0.16	T/m
b_4	0.01	7.6	T/m^2
b_5	101	410	T/m^3

197 MHz Crab Cavity Ports

- Four waveguides: two on each side, 90 degree rotation between two sides, one for FPC, one for HHOM and field probes, one for VHOM, and one to balance the field
- Four HOM coax couplers: two on each HHOM and VHOM, thermal simulations done
- Two field probes as required by LLRF
- One FPC port
- Coax Port ID: HOM & Field probes 40mm, FPC 100mm, all E type probe

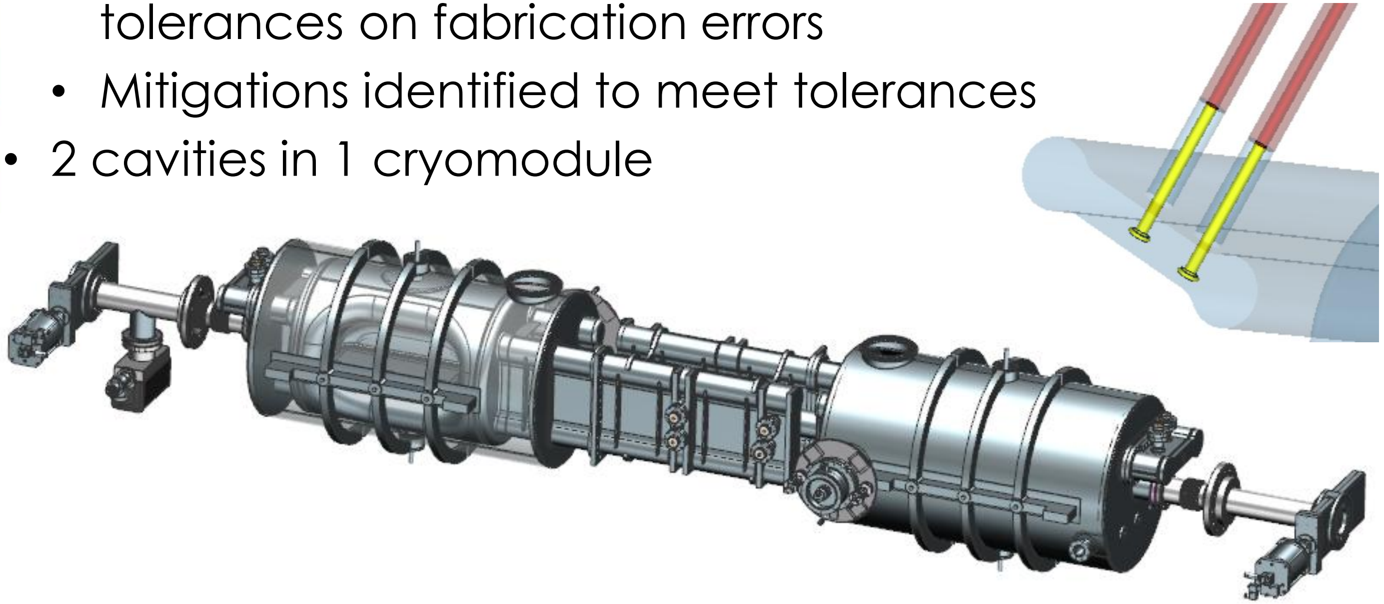


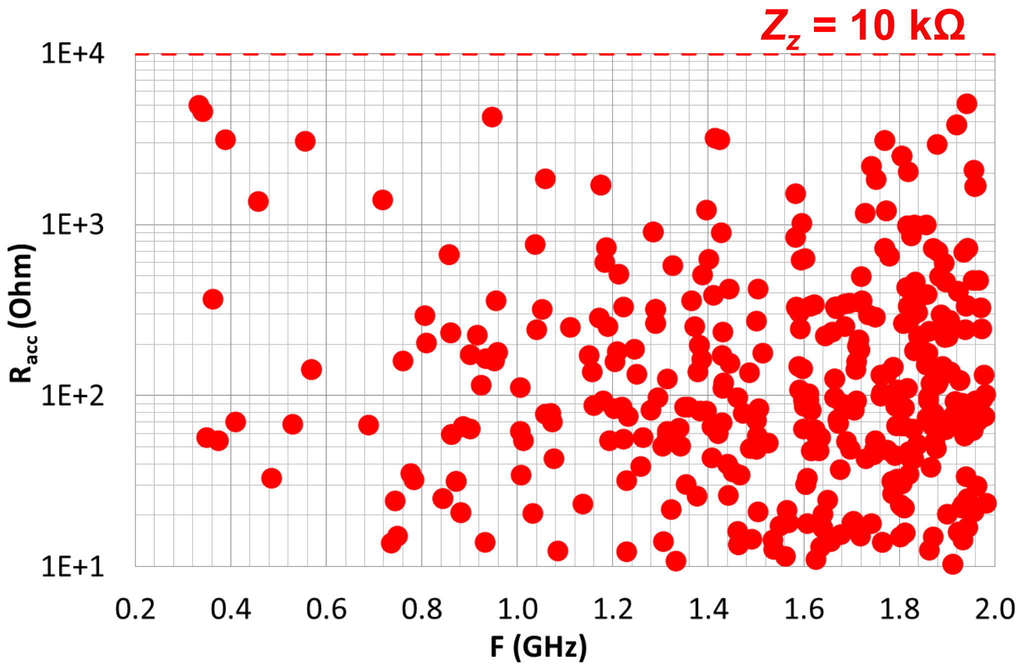
HOM Coaxial Antenna

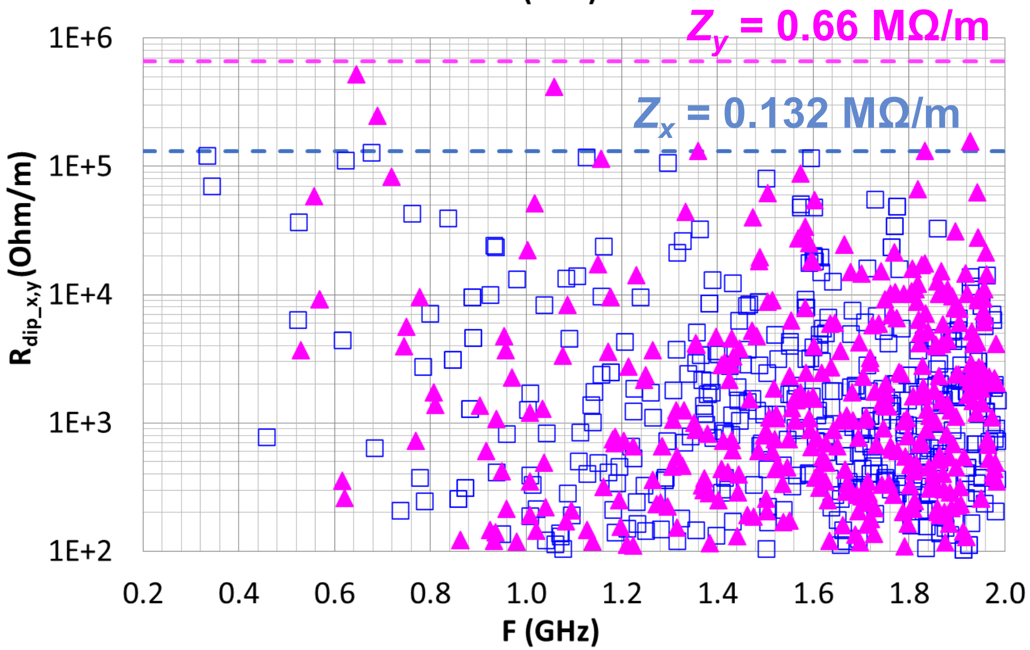


Coaxial HOM Couplers

- Identical coaxial antennas in all 4 couplers
- No more than 2.3kW each port
- Simulated with RF window designed for ILC crab cavities
- Simulated with coax absorbers with VSWR of the off-the-shelf product
- All longitudinal and vertical dipole modes are well damped
  - Sensitivity study on end dish, pole, cavity radius, waveguide, tuning deformation, etc., suggested tight tolerances on fabrication errors
  - Mitigations identified to meet tolerances
- 2 cavities in 1 cryomodule



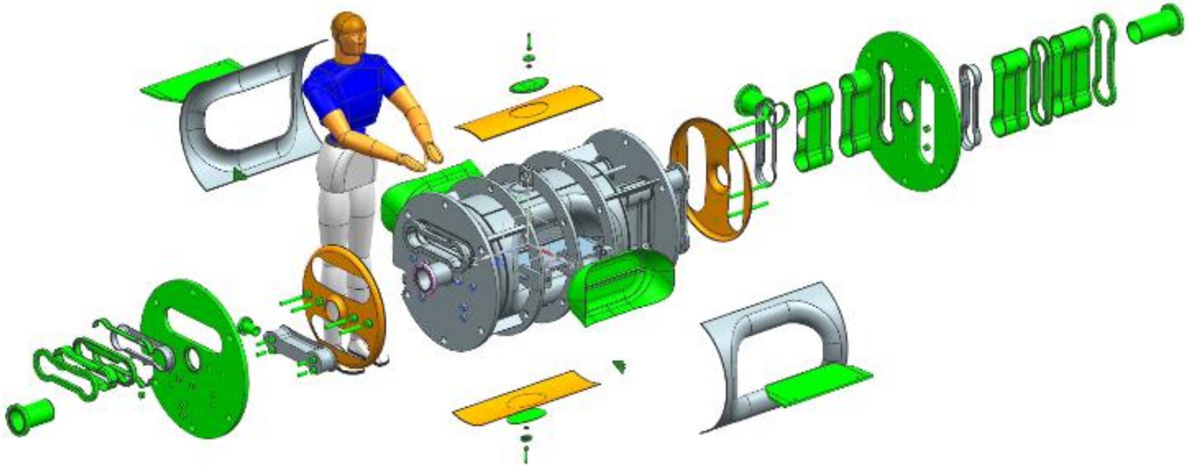


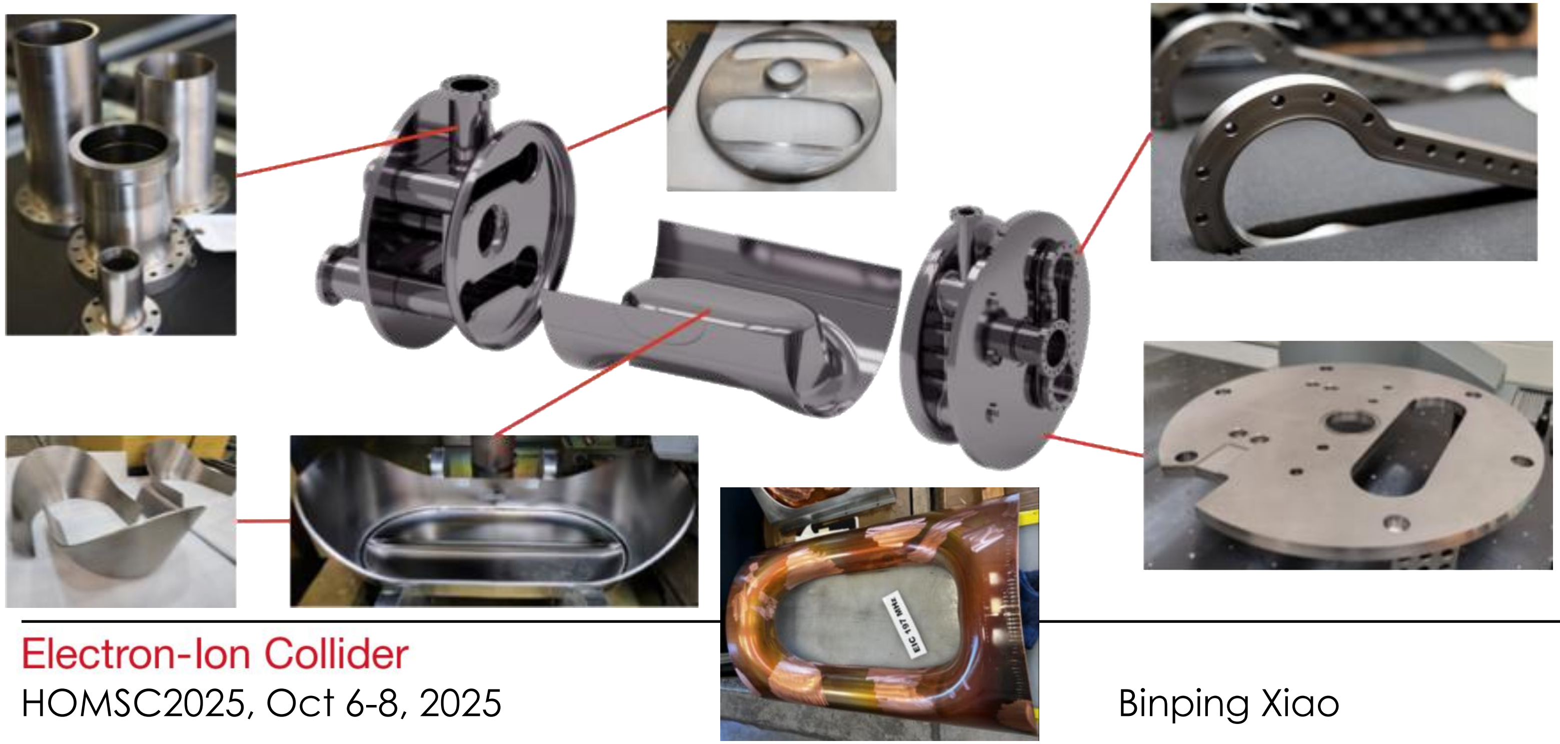


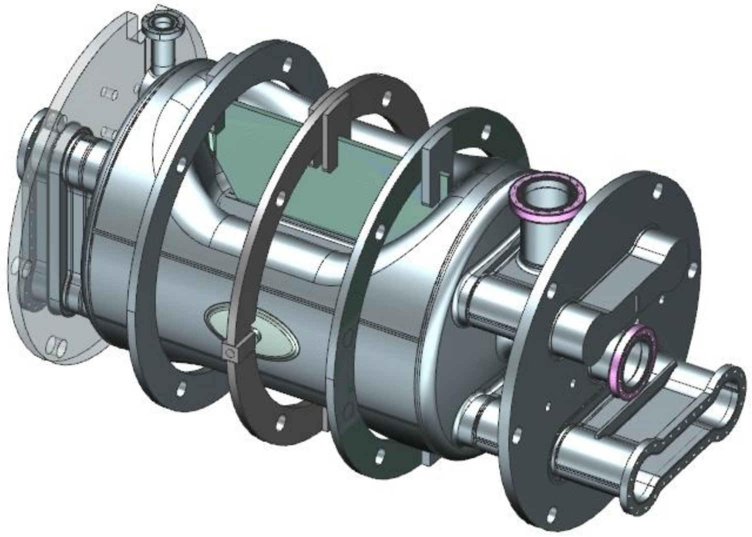
Design Verification Component

N. Huque

- A prototype (DVC) cavity is being fabricated in-house at Jlab
- Cavity is expected to be built and tested at JLab by late 2026
  - Processing will be done at ANL
  - Leveraging recent experience with CERN HL-LHC 400 MHz crab cavity

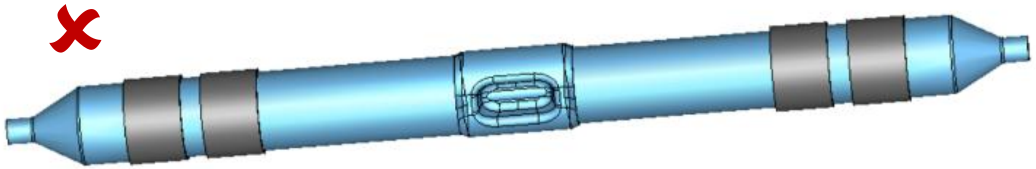


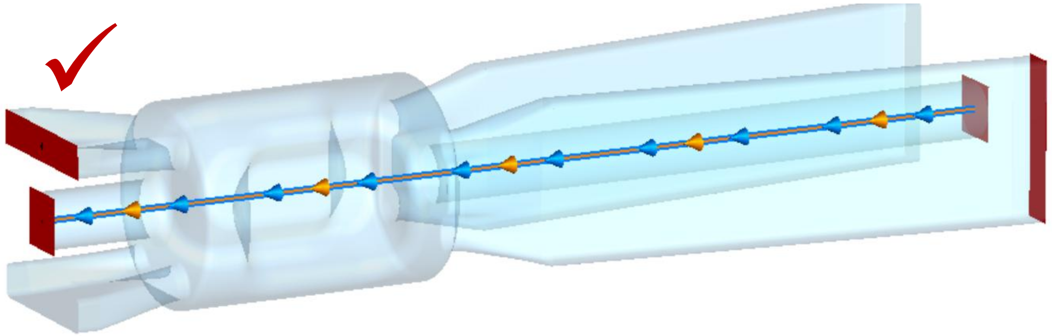


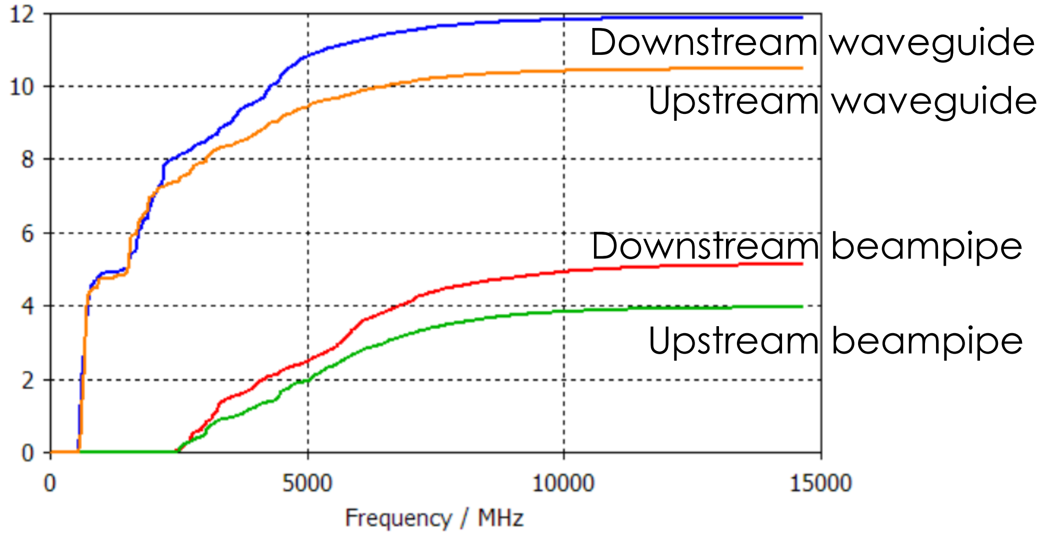


394 MHz Cavity Consideration

- Why not use wide-open-waveguide (WOW) type with beamline absorbers?
  - Bare WOW type cavity produces 69kW HOM power. With transitions and SiC absorbers, it will produce more HOM power at 179kW.
    - Crab cavity behaves like 2-cell cavity considering longitudinal modes and HOM power
    - Lengthening the cavity or using multicell will increase the HOM power, not preferred
- RFD cavity with 4 waveguide absorbers, the HOM power is around 55kW, with
  - each beampipe ~5kW, more on downstream
  - each waveguide absorber ~10kW upstream of the beam
  - each VHOM waveguide absorber ~12kW downstream of the beam
  - Yes, the beam direction matters



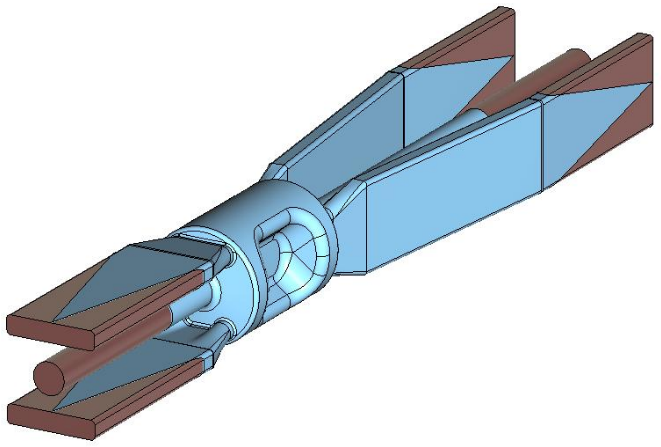


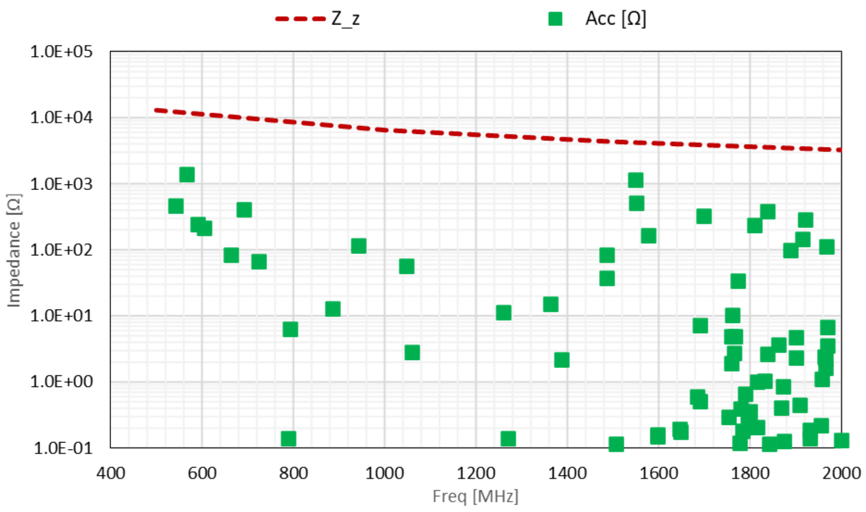


HOM power [kW] on each port

394 MHz Cavity Design

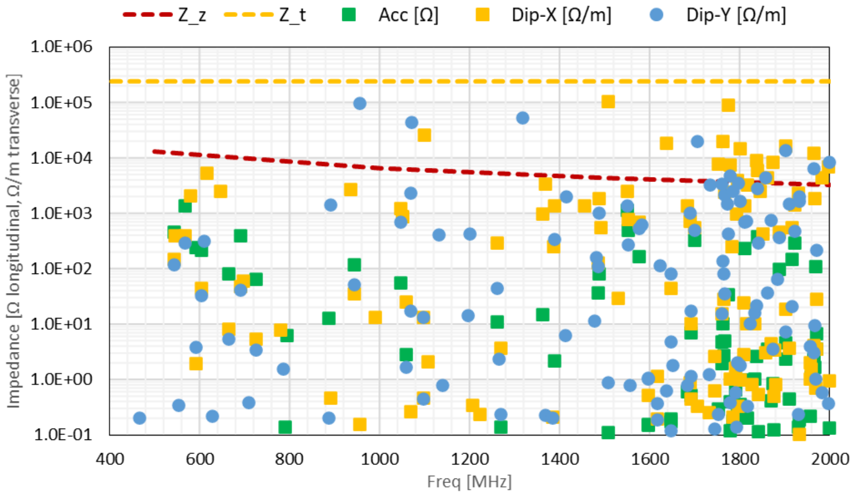
- 394 MHz cavities are installed at both ESR and HSR
- Preliminary RF design is complete
  - Optimized cavity flat poles
  - Reasonable peak surface fields at operating voltages
- Tight HOM impedance thresholds due to ESR impedance limits
- Requires 4 HOM waveguides
- HOM power:
  - Up to 12kW per waveguide
- Cavity geometry may require curved poles depending on the multipole component requirements
- In-kind contribution expected from international collaboration





RF Property	Value*
V_t [MV]	2.9/3.5
E_p [MV/m]	28.5/34.3
B_p [mT]	59.5/71.8
G [Ω]	125.4
R/Q [Ω]	308.6

*Operational / Design



Summary

- Challenges
  - Large crabbing angle → high crabbing voltage
  - Tight impedance threshold → better damping
  - High current short bunch → high HOM power
  - Low frequency → large cavity size
  - Tight space
  - Tight multipoles → pole shape
- Solutions
  - On-cell waveguide ports to provide better damping
    - Advanced 197MHz design: waveguide to coaxial design to avoid large waveguide damper; 2 cavities in 1 cryomodule to save longitudinal space
    - Preliminary 394 MHz design: waveguide absorber design to handle high HOM power
  - Curved pole (machine from ingot Nb) for multipoles specs
  - Tolerance studies are ongoing to assess impacts of imperfections on HOM damping and multipole fields
  - Engineering challenges arise from the large cavity size (138 kg, 182 liter), tight tolerances, and fabrication complexity, requiring custom tooling and infrastructure upgrades
  - Prototype cavity is continuing fabrication and testing; lessons learned will guide FA cavity production
  - 394 MHz second harmonic cavity is advancing through global collaboration, with ongoing RF and HOM optimization

Thank you!

Questions?