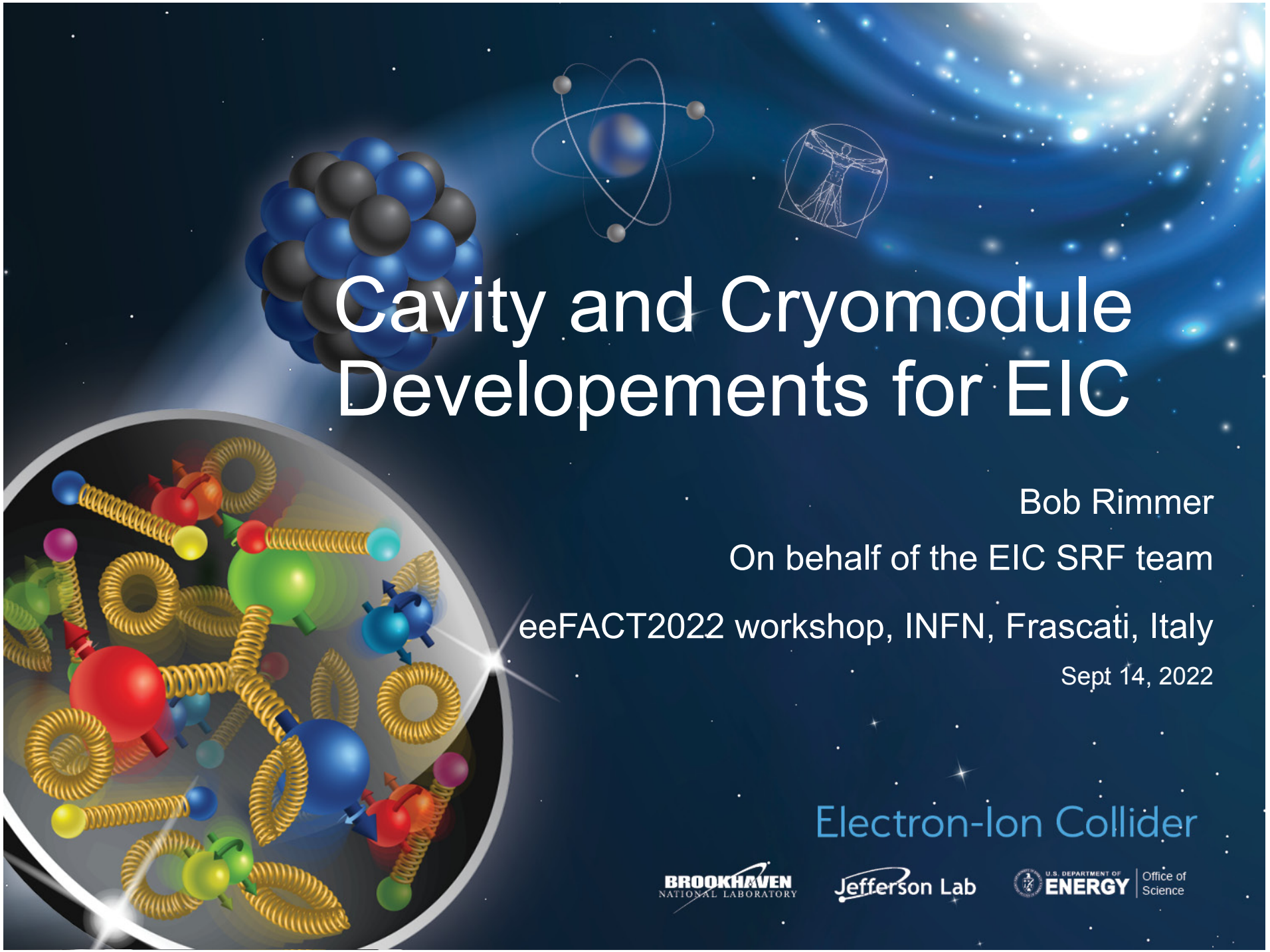
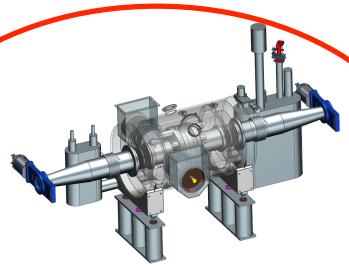

Cavity and Cryomodule Developements for EIC
Bob Rimmer
On behalf of the EIC SRF team
eeFACT2022 workshop, INFN, Frascati, Italy
Sept 14, 2022
Electron-Ion Collider
BROOKHAVEN NATIONAL LABORATORY
Jefferson Lab
U.S. DEPARTMENT OF ENERGY
Office of Science

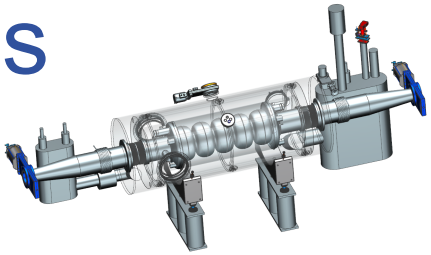
Outline

- Overview of EIC RF systems
- Details of SRF designs
  - **591 MHz ESR**
    - Asymmetric cavity
    - FPC thermal simulations
  - **197 MHz Crab**
    - Prototype RF design
    - Fabrication plan
    - HOM damper options
  - 394 MHz ESR crab first look
  - **FPC** and **BLA** progress
- Modular cryostat
- Summary

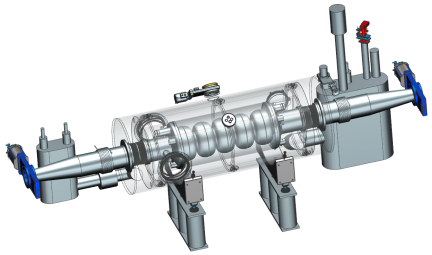
EIC RF systems



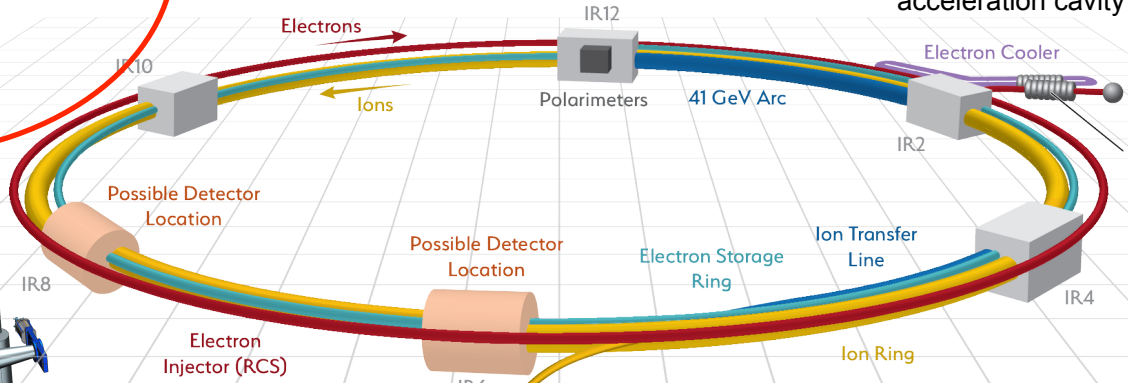
Electron - 591 MHz electron storage cavity

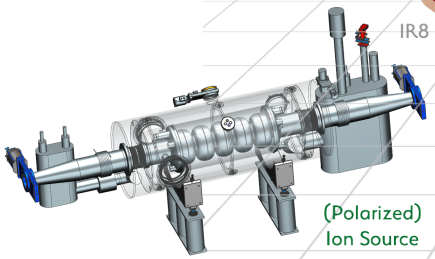


Hadron - 591 MHz bunch compression cavity

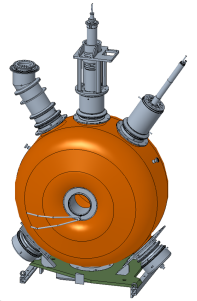


Hadron Cooling - 591 MHz acceleration cavity

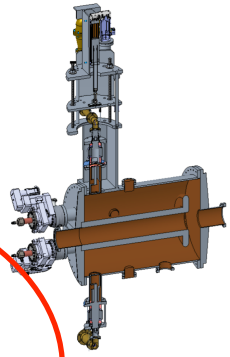


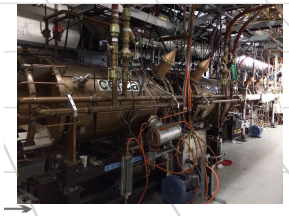


Rapid Cycling Synchrotron - 591 MHz acceleration cavity



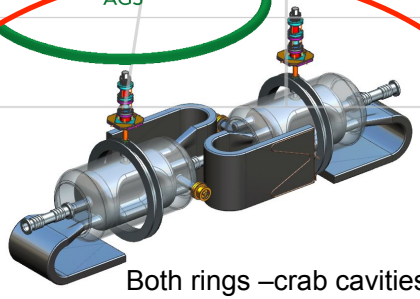
Hadron - 197 MHz bunch compression cavity





Hadron – 24.5 MHz acceleration cavity

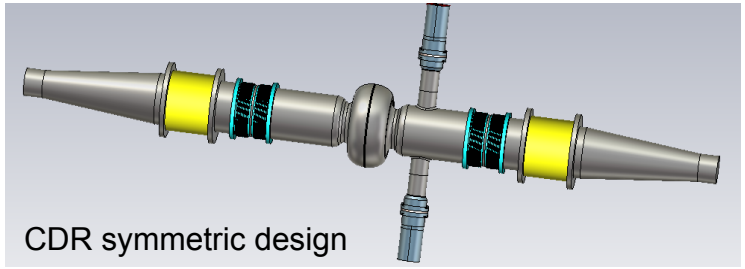
Hadron – 49.2 MHz and 98.5 MHz bunch splitter cavity



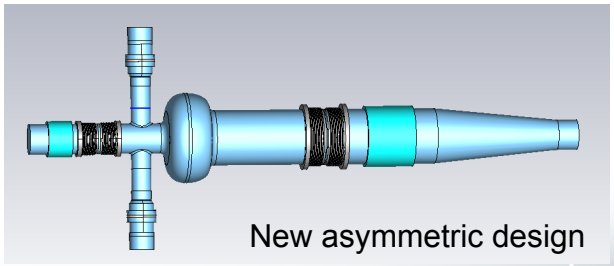
Both rings –crab cavities

ESR RF system

- Up to **68 MV** using 17 new **591 MHz** 1-cell SRF cavities
  - maintain 1% Bucket height from 5-18 GeV
  - Naturally short bunch length <1cm
  - **10MW** maximum beam power
  - **~40 kW** HOM power per cavity
  - **2.5A** maximum current


CDR symmetric design

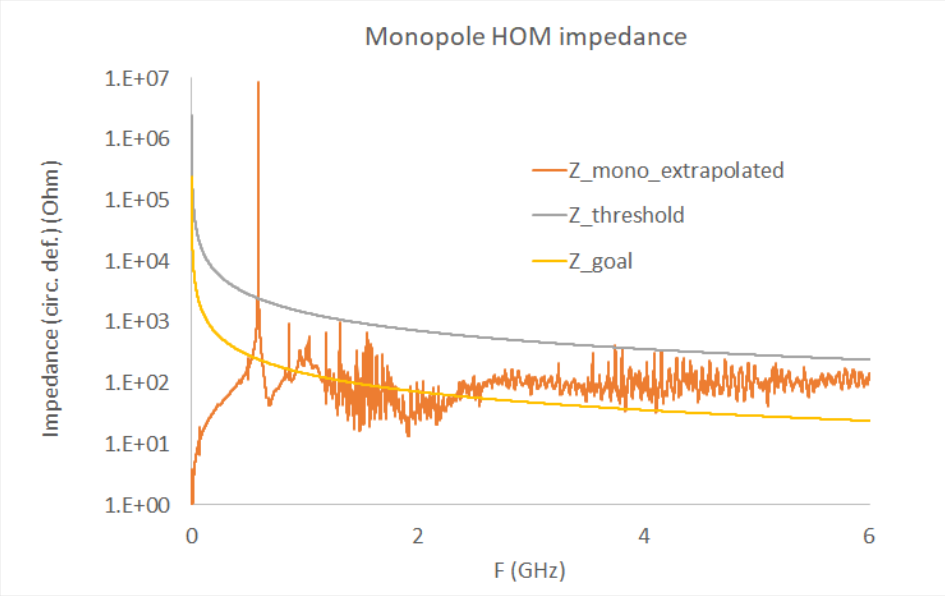
- Two fundamental power couplers per cavity, **~400kW** ea.
  - Thermal analysis under way
- Developed asymmetric option
  - 25% shorter, 11% lower loss factor, power to remaining large BLA up 13%
  - Eliminates one taper, more space for FPC
  - Fits better in IR10 available space.
- Preparing for prototype cavity fabrication
  - Nb sheet and die material in hand
  - Fabrication plan and die designs in progress

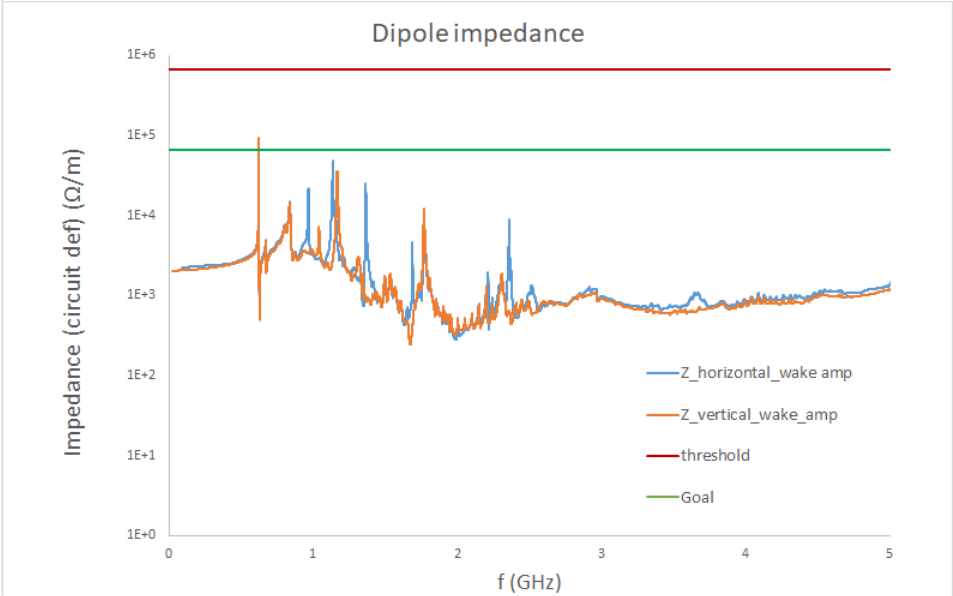

New asymmetric design

ESR1 baseline impedance

Longitudinal Impedance: Total for all cavities.
– Target Limit: 26 kΩ-GHz – Goal: 2.6 kΩ-GHz
  Limit: **1.53kΩ-GHz** per cavity for 17 cavities
Transverse Impedance: Total for all cavities.
– Target Limit: 12 MΩ/m– Goal: 1.2 MΩ/m
  Limit: **0.71** MΩ/m per cavity

Impedances are in circuit definition
CB feedback will give additional margin

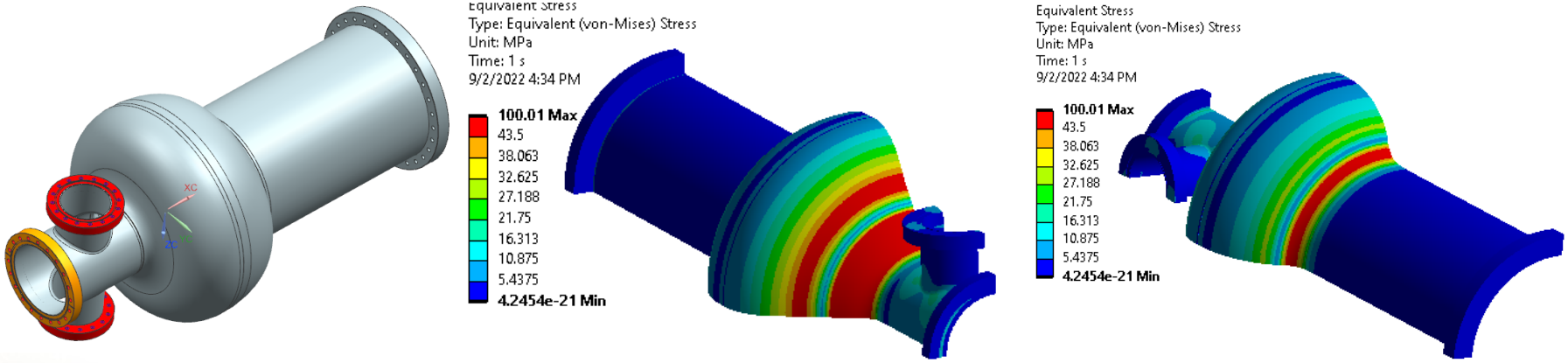




Tuning Sensitivity of Un-stiffened warm cavity

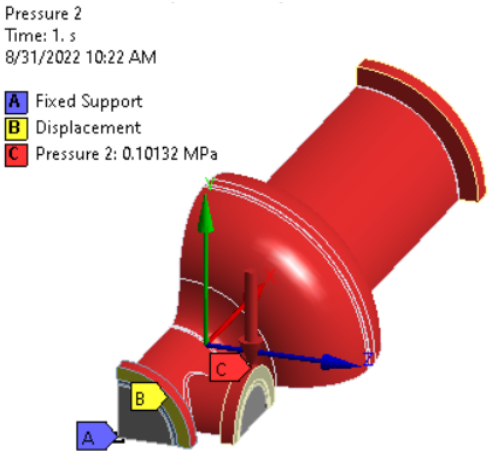
- Bare cavity modeled with 1 mm displacement, no stiffeners

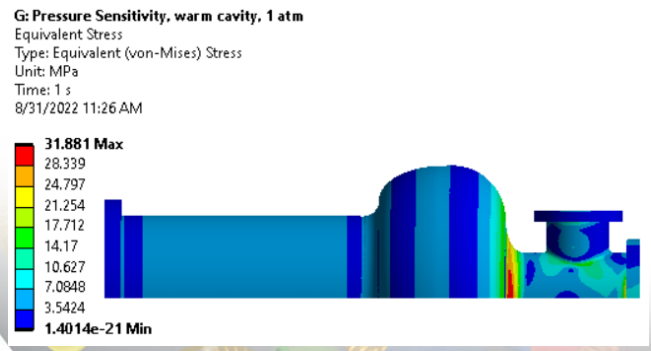
Model	Freq (MHz)	Tuning Sensitivity (KHz/ mm), 1mm	Stiffness (N/mm)	von Mises (MPa)	Elastic tuning range (mm)	Force to Yield (N)
No Stiffeners	590.83	447.05	14,258	100.01	0.435	6,200



Pressure Sensitivity for bare cavity

- Tuning analysis was performed with a surface pressure and no displacement applied.
- The cavity is fixed on one end and free on the opposite end.



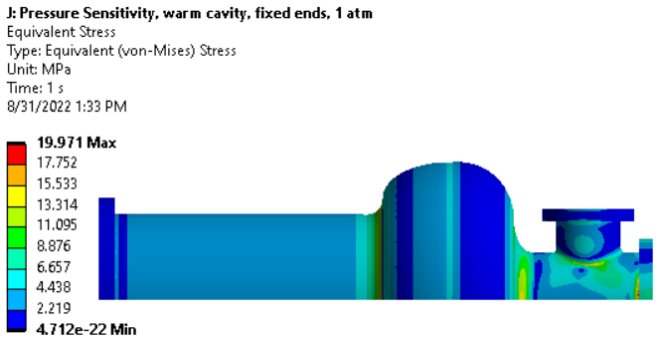


Pressure (atm), **295.15K**	Pressure sensitivity (Hz/ atm)	Stress (MPa)	Safe?
1	121,065	31.88	Yes
2	120,800	63.76	No
3	120,540	95.64	No

Pressure (atm), **4K**	Pressure sensitivity (Hz/ atm)	Stress (MPa)	Safe?
1	82,107	32.07	Yes
2	81,986	64.13	Yes
3	81,865	96.20	Yes

Pressure Sensitivity for both ends fixed

- Tuning analysis was performed with a surface pressure and no displacement applied.
- The cavity is constrained on both ends (e.g. by tuner)



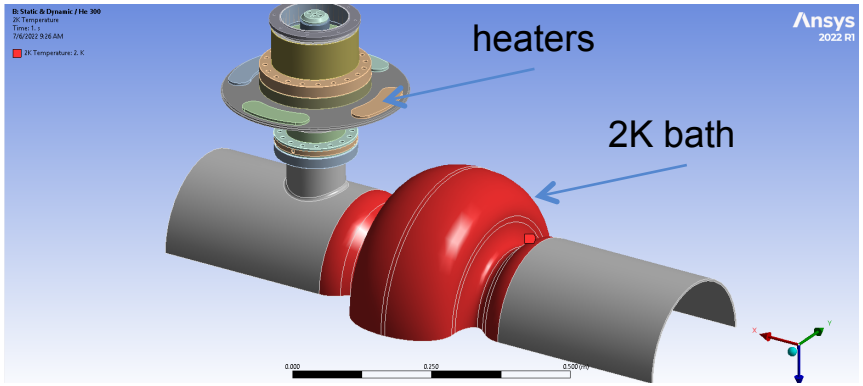
Pressure (atm), **295.15K**	Pressure sensitivity (Hz/ atm)	Stress (MPa)	Safe?
1	12,028	19.97	Yes
2	12,003	39.94	Yes
3	11,979	59.91	No

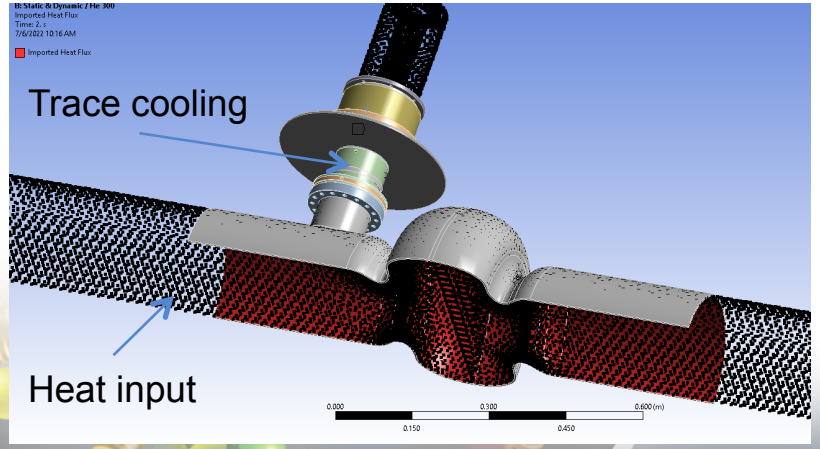
Pressure (atm), **4K**	Pressure sensitivity (Hz/ atm)	Stress (MPa)	Safe?
1	8,038	20.73	Yes
2	8,027	41.45	Yes
3	8,016	62.18	Yes

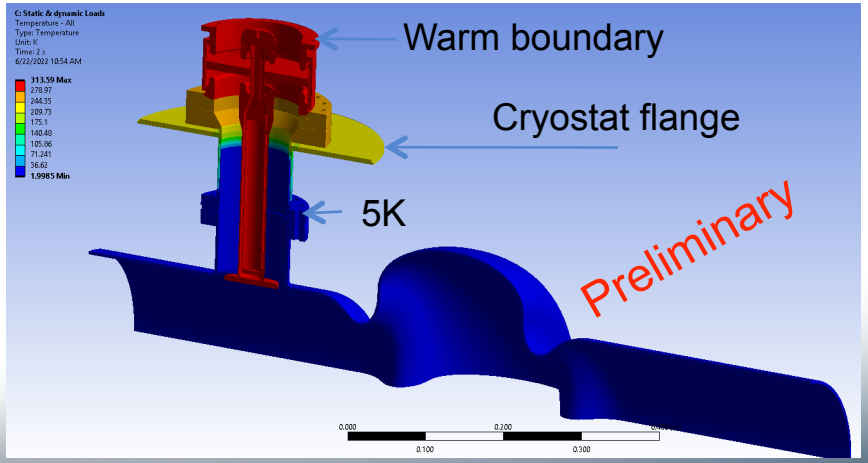
FPC transition thermal analysis

Thermal analysis is under way

- Heat loads from CST
- Non-linear thermal analysis in ANSYS
- 5K intercept
- He “trace cooling” of outer conductor
- Water cooling of window and center conductor
- 300K warm boundary, optional heaters
- Preliminary result: Cryostat flange is too cold, need better isolation



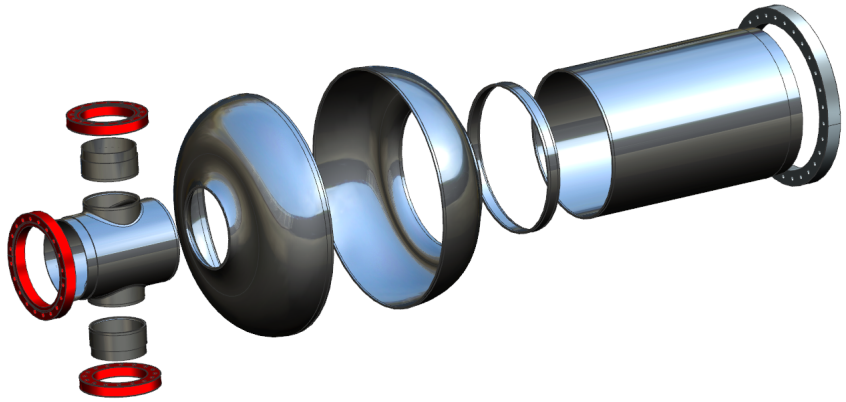


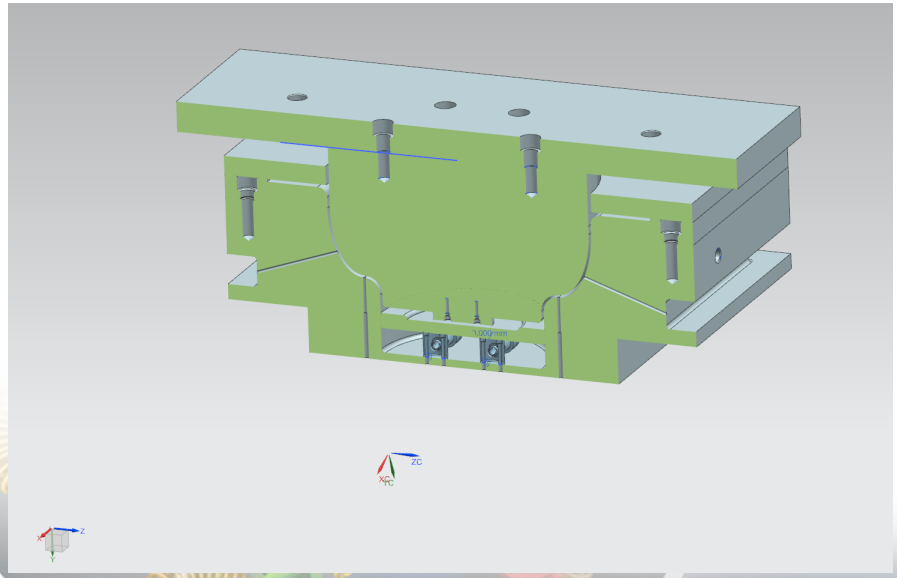


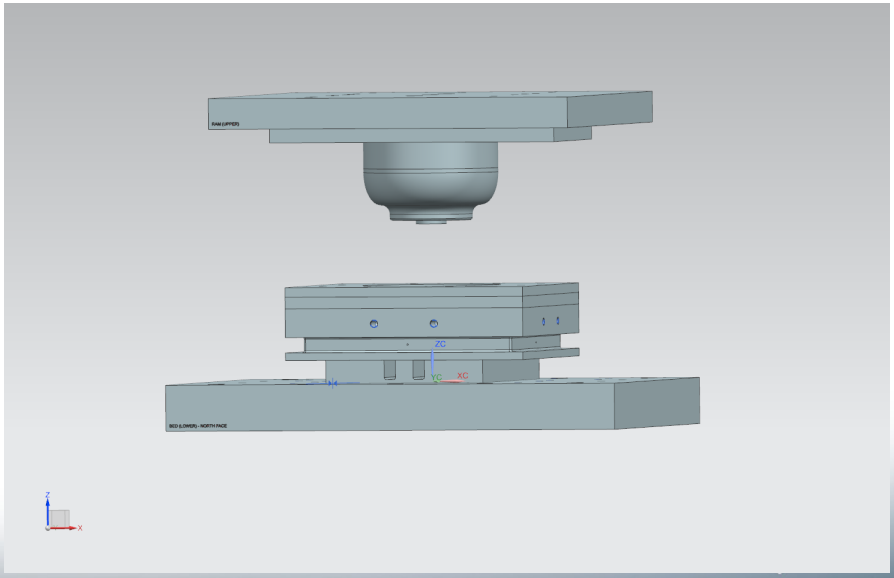
ESR 591 MHz single cell fabrication and deep drawing dies

Conventional fabrication

- Deep draw cells
- Rolled or formed tubes
- Brazed Conflat flanges
- e-beam welding

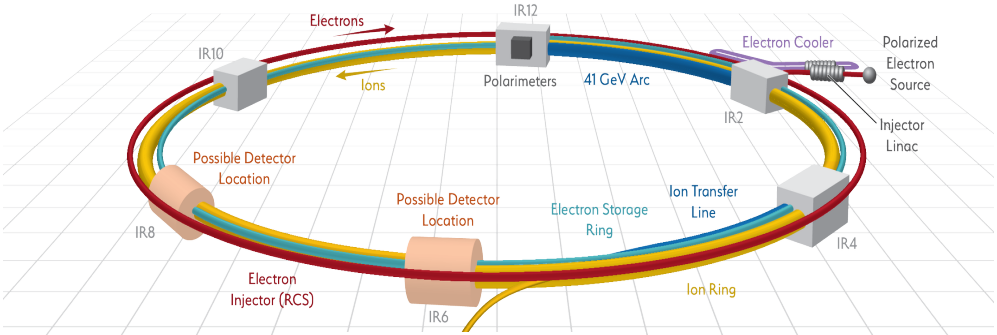






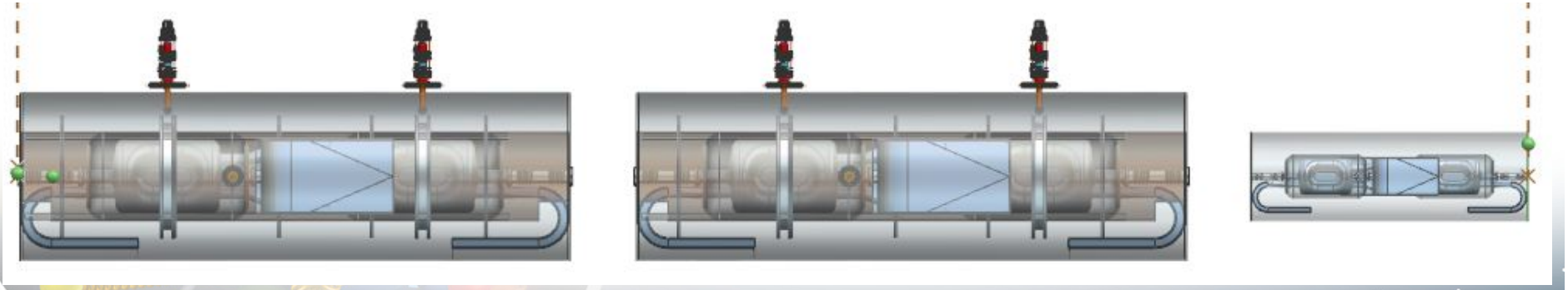
EIC Crab Cavity Systems

	V_t [MV]		No. of cavities (per IP)	
System	**HSR**	**ESR**	**HSR**	**ESR**
197 MHz	33.83	–	8	–
394 MHz	4.75	2.90	4	2



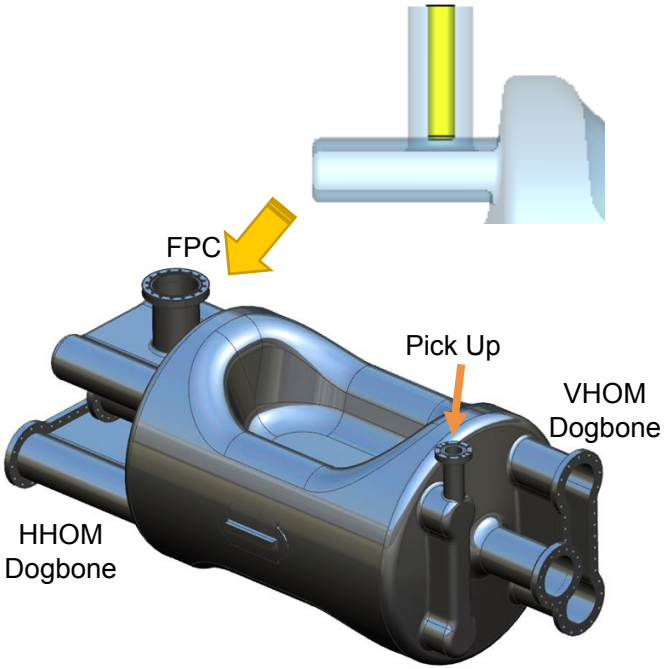
IR-6: Crab Cavity SRF Systems

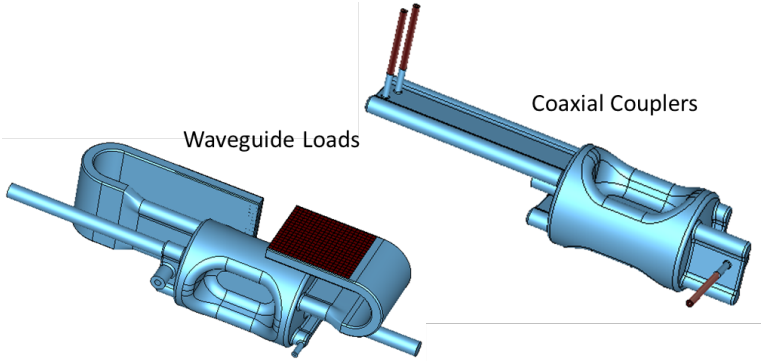
- HSR will be installed with two 197 MHz RFD cryomodules and one 394 MHz cryomodule each side of the IP Total length < **12.5 m**
- ESR requires only one 394 MHz cavity each side of the IP
- Impedance budget allows for second IP
- *197 MHz crab cavity is identified as one of first RF cavities to be prototyped*



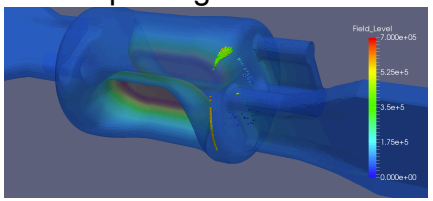
197 MHz Crab Cavity for HSR

- Cavity design frozen:
  - Peak surface fields: E_p < 45 MV/m and B_p < 80 mT at 11.5 MV
  - Longitudinal and transverse impedance thresholds
  - FPC: Coaxial antenna of Q_{ext} = 1.75×10^6 at 0.6 mm beam offset and 50 Hz microphonics
- Two HOM damping schemes are currently being studied – Common bare cavity design

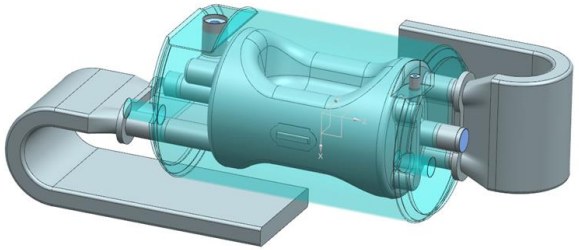




Multipacting Resonances



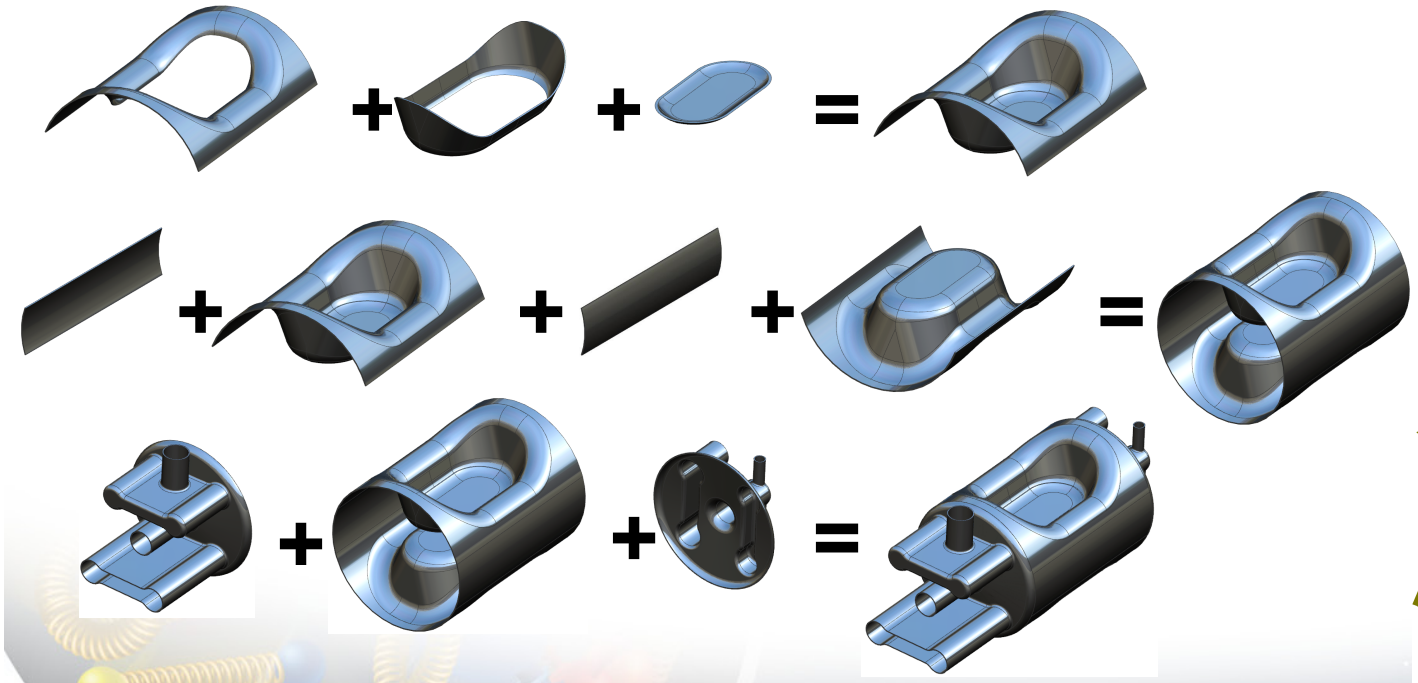
Cavity with He jacket

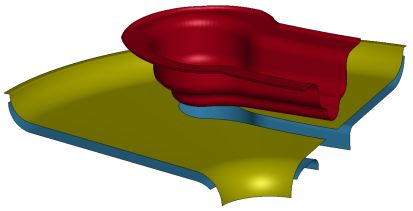


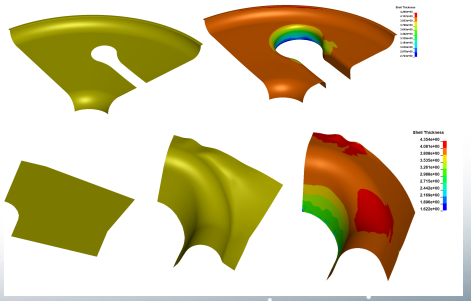
- Multipacting resonances on the cavity and HOMs will be processable.
- Will proceed with prototyping the bare cavity
- HOM choice will be based on cost and design maturity

Fabrication Overview

- Fabrication steps of the prototype cavity
- Frequency tuning will be done at the final step with the 3 sub assemblies
- Working on stiffening scheme, tuner attachments and helium vessel
- Investigating deep drawing by simulation

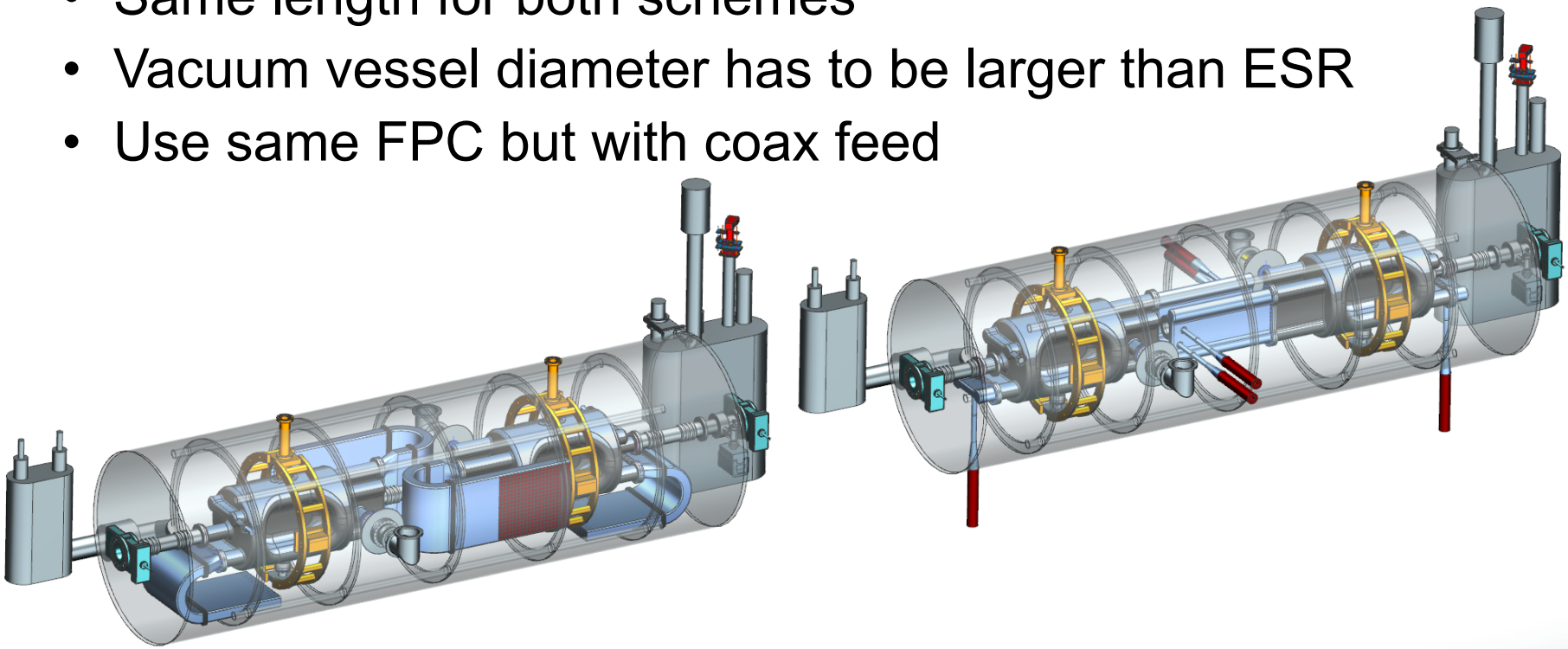






Preliminary Cryomodule Layout

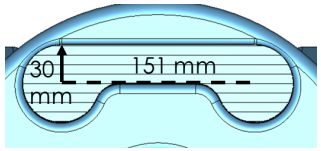
- Layouts for the two HOM damping schemes
- Total length ~ 5 m
- Same length for both schemes
- Vacuum vessel diameter has to be larger than ESR
- Use same FPC but with coax feed

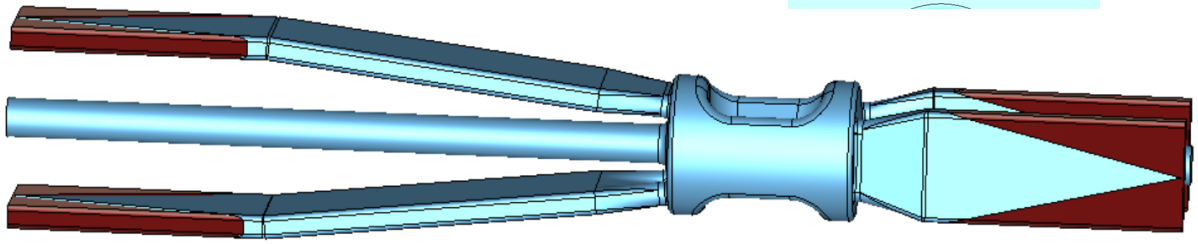


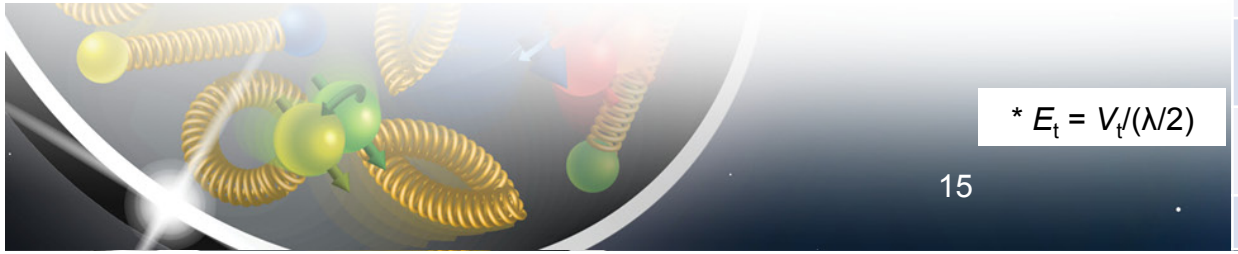
ESR 394 MHz RFD Crab Cavity

- Beam aperture = 100 mm
- 394 MHz design for the ESR has tighter impedance budget
- Total impedance budget: Z_z = 2.6×10^4 Ω-GHz and Z_t = 0.96×10^6 Ω/m
- Per cavity: Z_z = 6.5×10^3 Ω-GHz and Z_t = 0.24×10^6 Ω/m (For 4 cavities considering the two IPs) With increased crossing angle at the second IP, no of cavities may need to be increased to 8
  - Will reduce the impedance threshold per cavity
- WOW type crab cavity as the backup plan

Single ridged waveguide cross section







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

Property	Bare Cavity	
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 [Ω^2]	3.9×10^4	
V_t [MV]	2.9	1.45
E_p [MV/m]	29.5	14.75
B_p [mT]	61.56	30.78
Total V_t [MV]	2.9	
No. of cavities	1	2
Cavity Length [mm] (iris-to-iris)	535.6	
Cavity Diameter [mm]	356.3	
Pole Length [mm]	300	

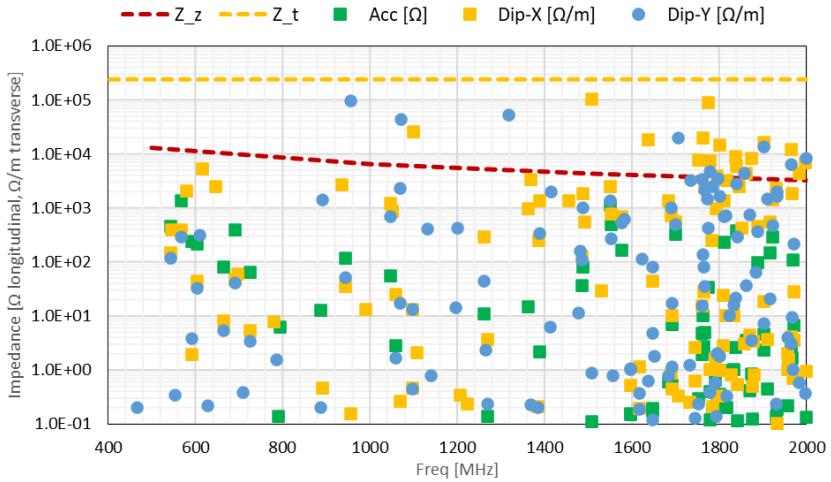
ESR 394 MHz RFD Crab Cavity Impedances

- HOMs are suppressed with 4 waveguide dampers
- Tilted ridged waveguide allows more space between the beam pipe and waveguide for flanges

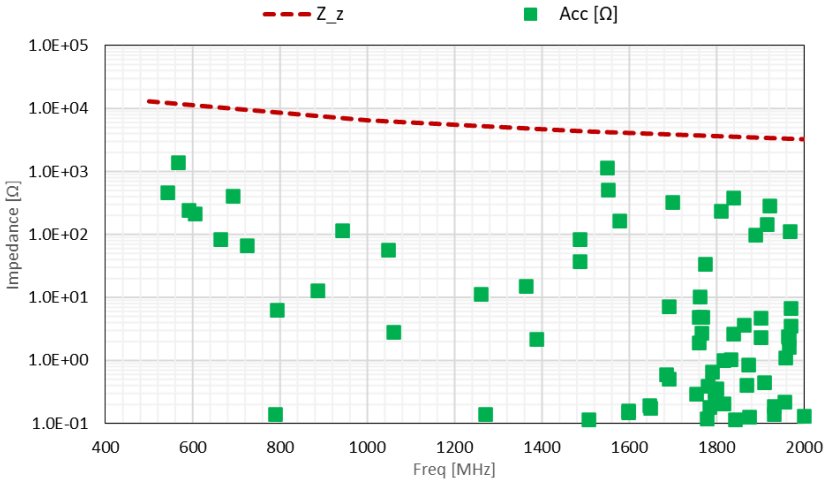
- Maximum Z_t at 1506.4MHz with 0.106MΩ/m and 2400 loaded Q
- Maximum Z_z at 1549.9MHz with 1.77kΩ-GHz and 271 loaded Q
- HOM power estimates up to 20 GHz are ongoing

- Up to 8 cavities can be incorporated in ESR without going beyond the impedance budget for the two IPs

$Z_t = 0.24\times10^6$ Ω/m



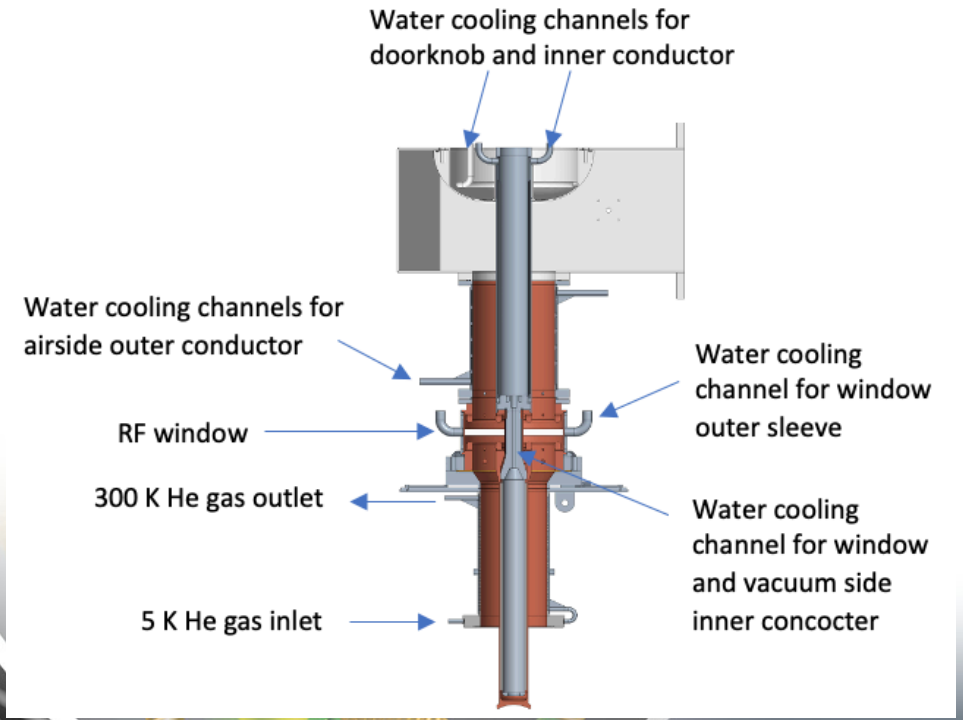
$Z_z = 6.5\times10^3$ Ω-GHz

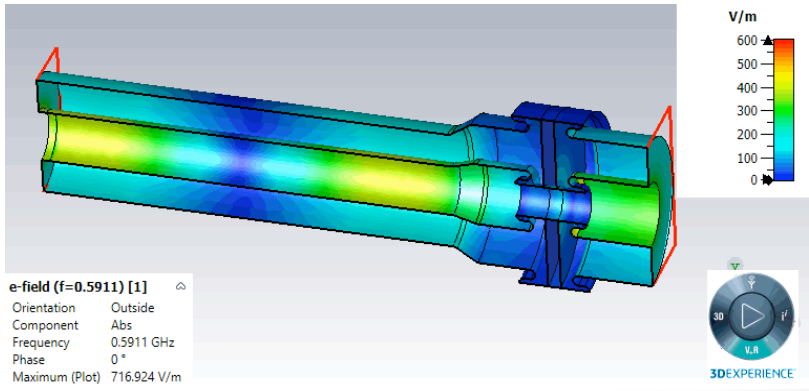


- Impedances are in circuit definition and includes 0.5 factor

High power FPC Status

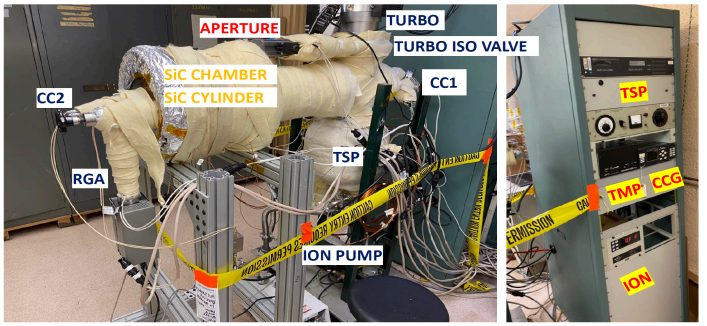
- A high power (CW 500 kW standing wave) alumina window FPC was designed for EIC ESR SRF cavity.
- The design was reviewed by an international technical review committee in June 2021.
- The review committee stated their “support moving forward with this design into prototype stage”.
- Detailed engineering design for window and vacuum side has been finalized and in the process of prototyping.
- FPC airside is almost finalized, purchasing materials for fabrication.

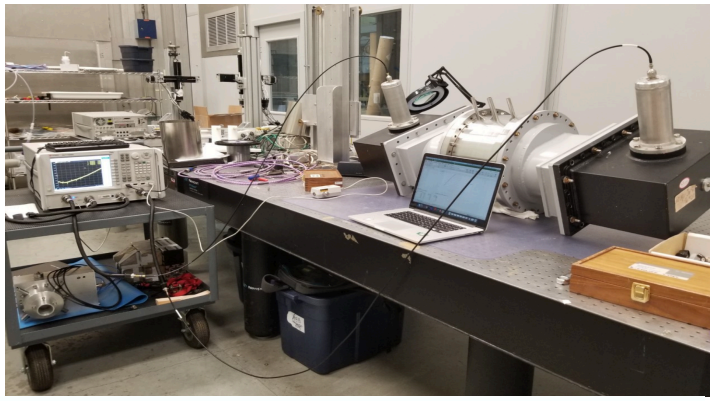


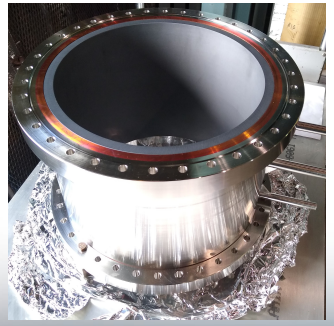


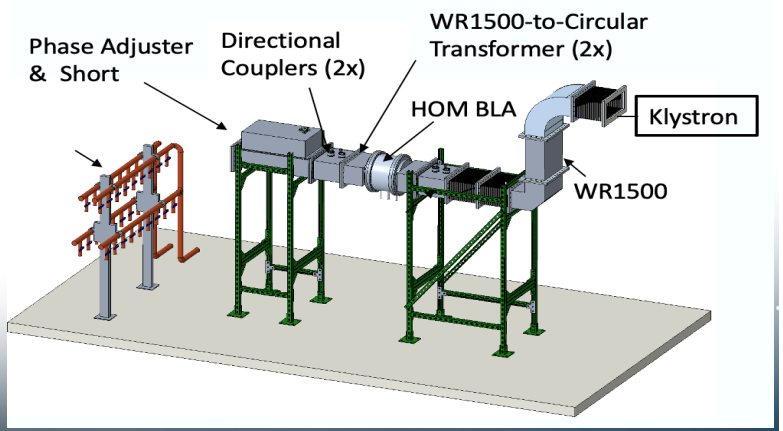
HOM damper R&D status

- First outgassing test were completed with solid SiC HOM damper.
- Low power measurement on solid SiC HOM damper, result is close to expectation.
- SiC samples were ordered and RF properties measurements ares ongoing
- Back up segmented design being developed via SBIR



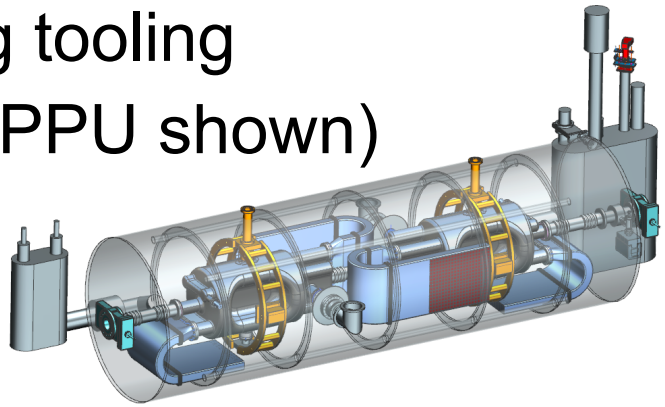






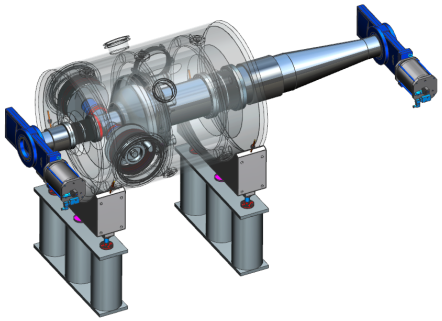
Modular cryostat

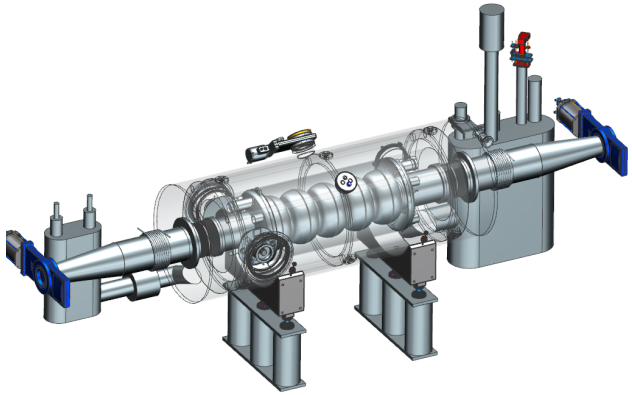
- Based on SNS cryostat dimensions
- High degree of commonality of components
- Takes advantage of much existing tooling
- Cryogenic distribution TBD (SNS PPU shown)



HSR 197 MHz crab

ESR 591 MHz 1-cell





HSR 591 MHz 5-cell
Also RCS and ERL

And others!
394 MHz crab
197 MHz QWR
1773 MHz elliptical
Cooler injector

Summary

- Continuing to build on CDR designs
- ESR 591 MHz compact cavity meets requirements
  - FPC thermal studies are under way
  - Preparing to start prototype cavity
  - 591 MHz 5-cells will be developed later from the 1-cell
- 197 MHz Crabbing mode optimization complete
  - RF design “frozen”
  - HOM damping meets requirements with 2 load options
  - Fabrication plan well advanced
  - 394 MHz RF design starting, not just a simple scaling
- FPC and BLA R&D progressing according to plan
- Modular cryostat
  - Will speed up development
  - Minimizes total design effort

Thank You

References:

EIC Conceptual Design Report, 2021, https://www.bnl.gov/ec/files/EIC_CDR_Final.pdf

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HOM damper design for BNL EIC 197MHz crab cavity, Binping Xiao et. al. Proc IPAC21, Brazil