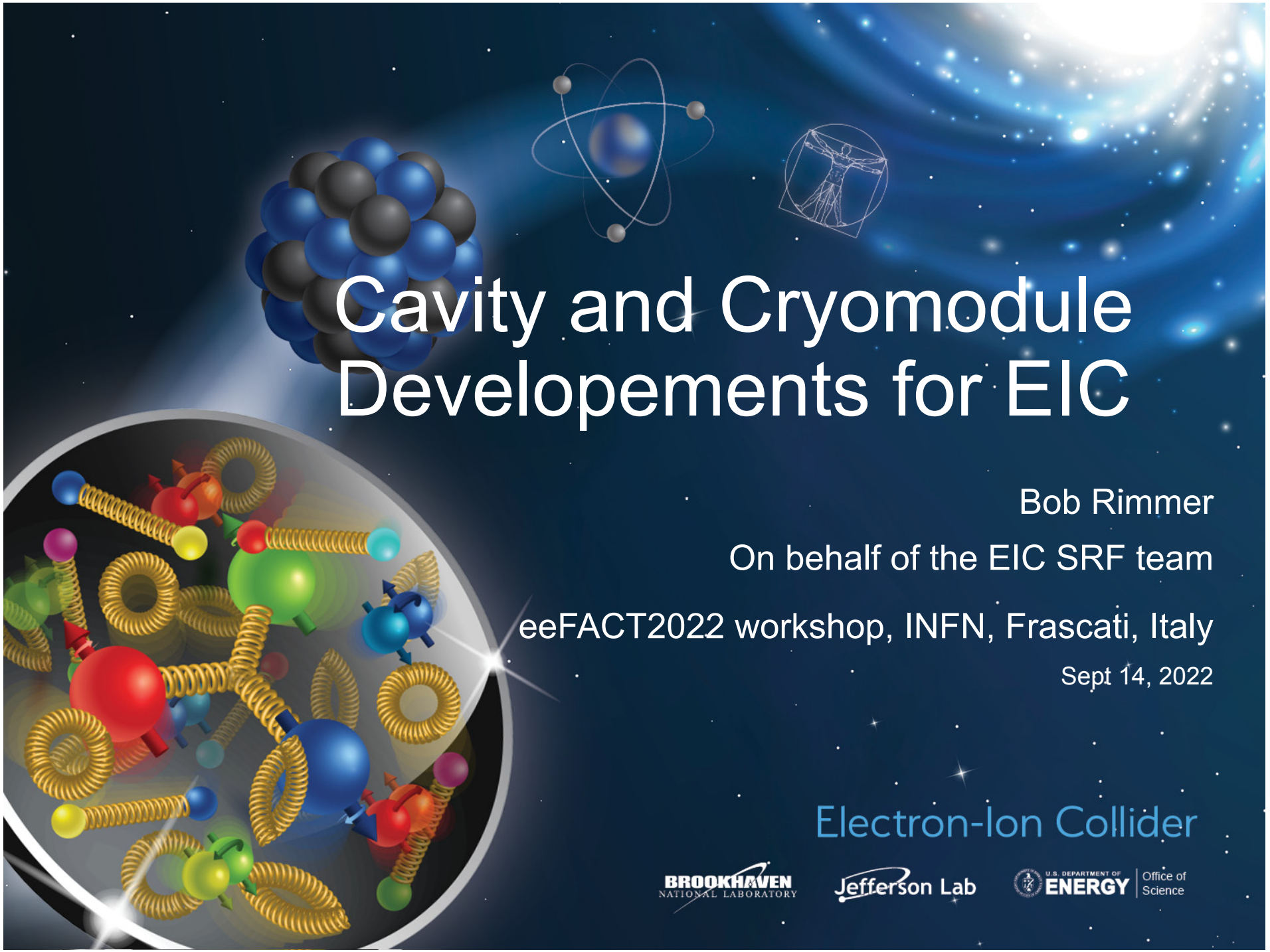
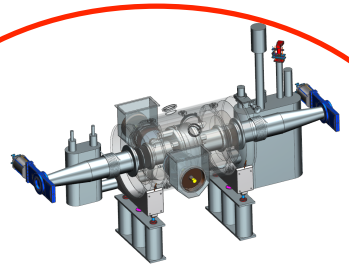

Cavity and Cryomodule Developements for EIC
Bob Rimmer
On behalf of the EIC SRF team
eeFACT2022 workshop, INFN, Frascati, Italy
Sept 14, 2022
Electron-Ion Collider
BROOKHAVEN NATIONAL LABORATORY
Jefferson Lab
U.S. DEPARTMENT OF ENERGY
Office of Science

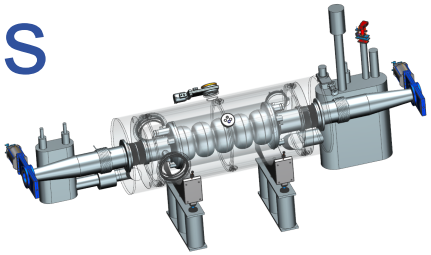
Outline

- 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

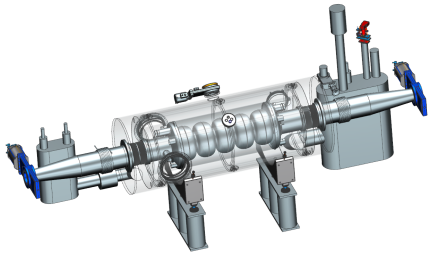
EIC RF systems



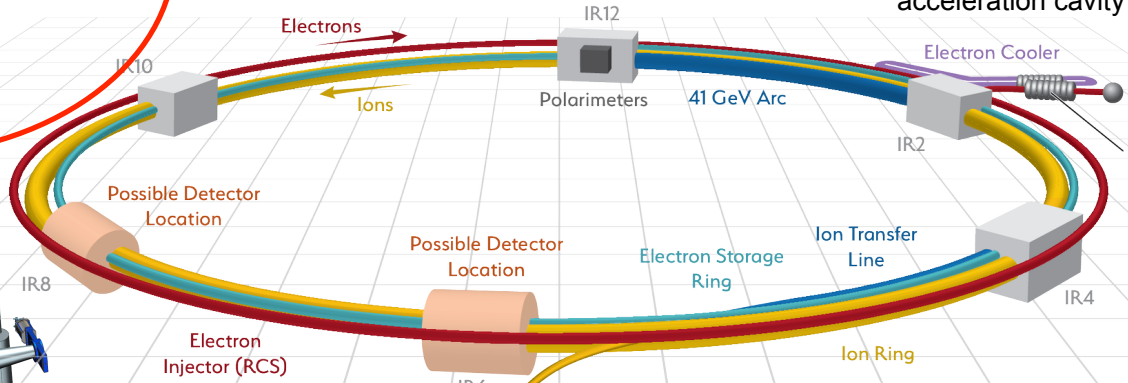
Electron - 591 MHz electron storage cavity

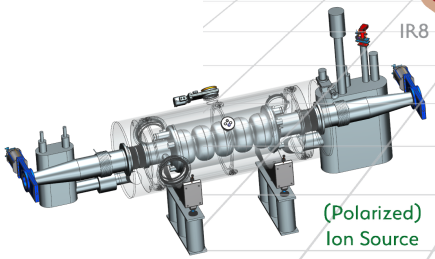


Hadron - 591 MHz bunch compression cavity

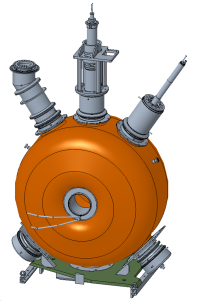


Hadron Cooling - 591 MHz acceleration cavity

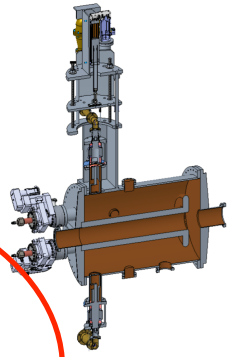


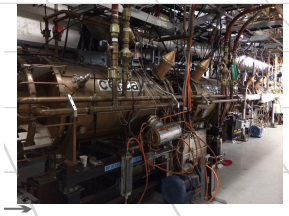


Rapid Cycling Synchrotron - 591 MHz acceleration cavity



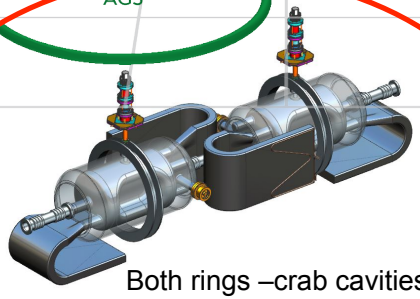
Hadron - 197 MHz bunch compression cavity





Hadron – 24.5 MHz acceleration cavity

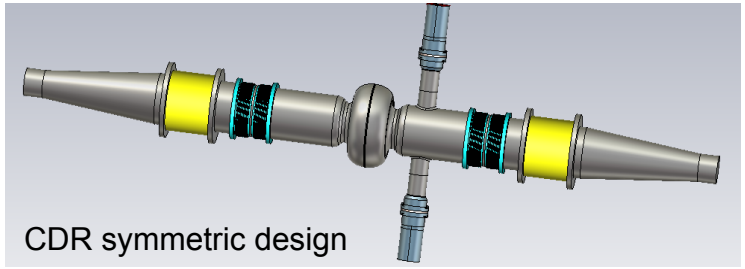
Hadron – 49.2 MHz and 98.5 MHz bunch splitter cavity



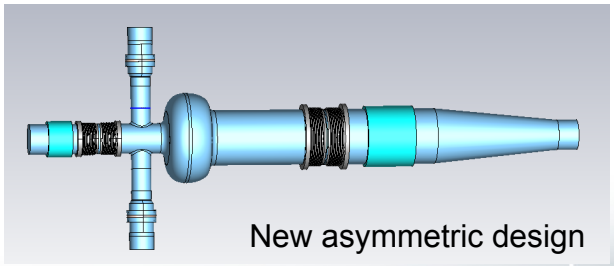
Both rings –crab cavities

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

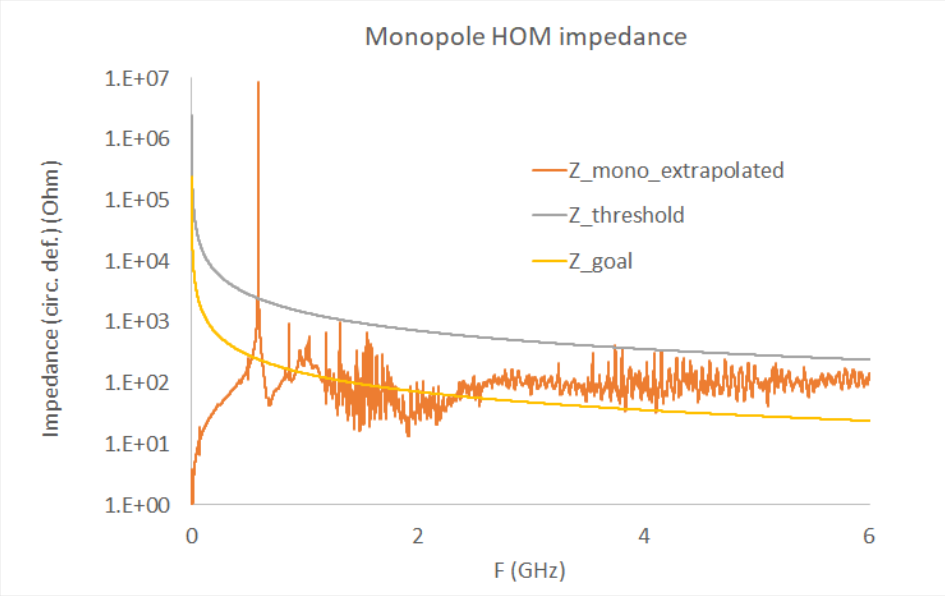
- Two fundamental power couplers per cavity, **~400kW** ea.
  - Thermal analysis under way
- Developed asymmetric option
  - 25% shorter, 11% lower loss factor, power to remaining large BLA up 13%
  - Eliminates one taper, more space for FPC
  - Fits better in IR10 available space.
- Preparing for prototype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

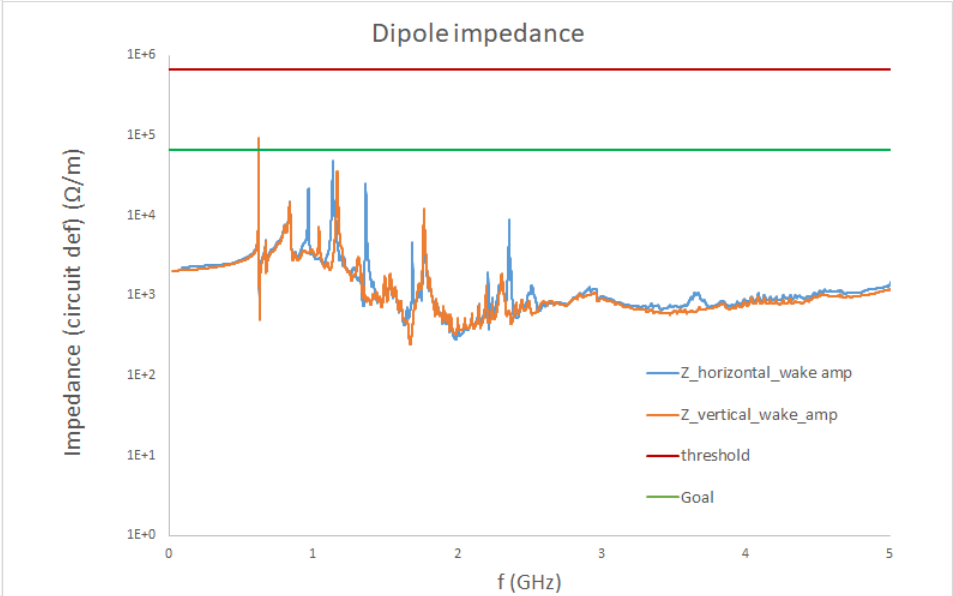

New asymmetric design

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

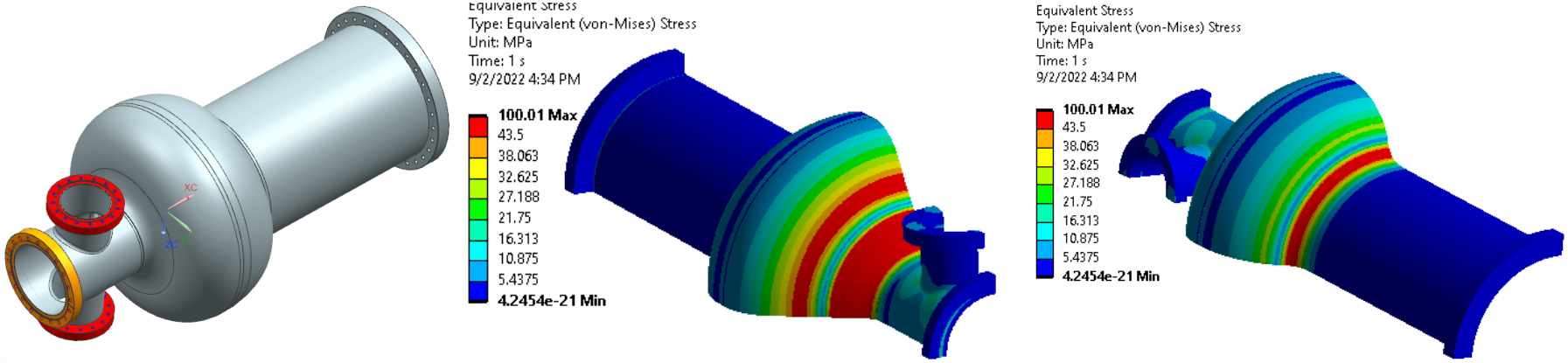




Tuning Sensitivity of Un-stiffened warm cavity

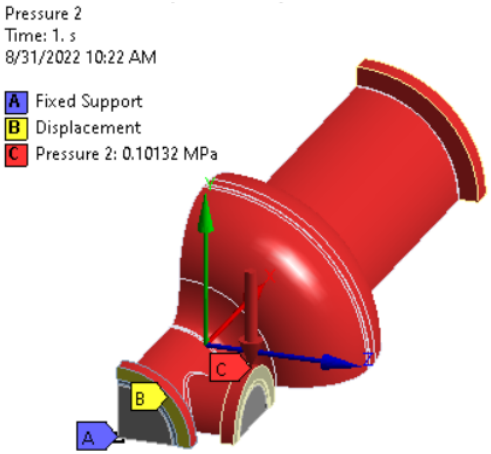
- Bare cavity modeled with 1 mm displacement, no stiffeners

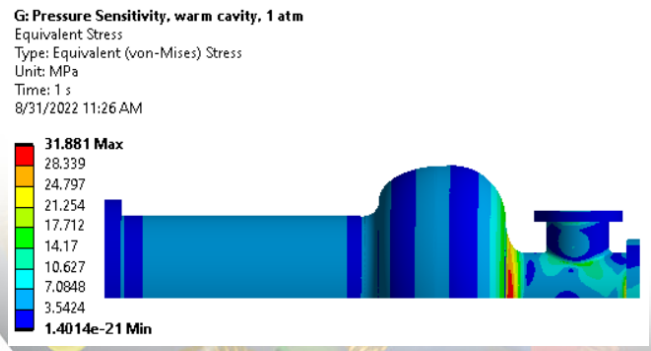
Model	Freq (MHz)	Tuning Sensitivity (KHz/ mm), 1mm	Stiffness (N/mm)	von Mises (MPa)	Elastic tuning range (mm)	Force to Yield (N)
No Stiffeners	590.83	447.05	14,258	100.01	0.435	6,200



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.



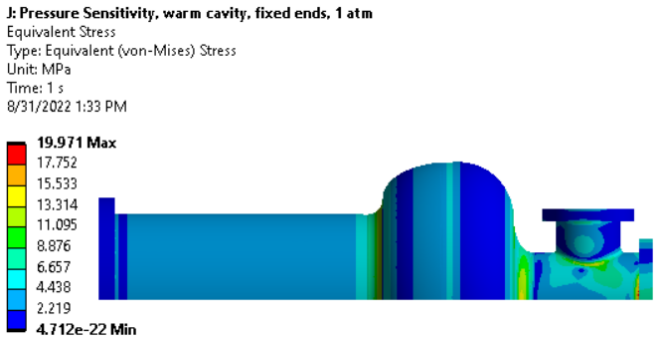


Pressure (atm), **295.15K**	Pressure sensitivity (Hz/ atm)	Stress (MPa)	Safe?
1	121,065	31.88	Yes
2	120,800	63.76	No
3	120,540	95.64	No

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)



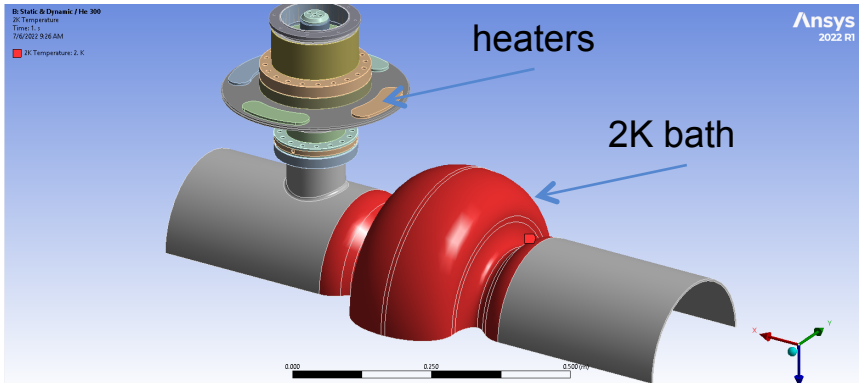
Pressure (atm), **295.15K**	Pressure sensitivity (Hz/ atm)	Stress (MPa)	Safe?
1	12,028	19.97	Yes
2	12,003	39.94	Yes
3	11,979	59.91	No

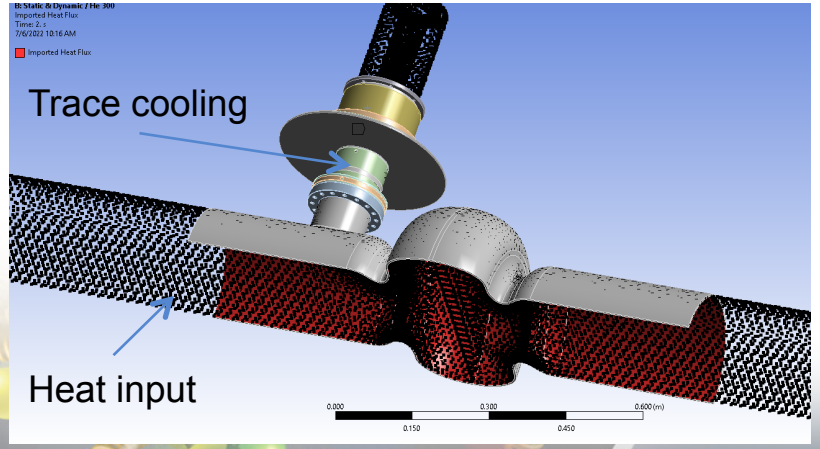
Pressure (atm), **4K**	Pressure sensitivity (Hz/ atm)	Stress (MPa)	Safe?
1	8,038	20.73	Yes
2	8,027	41.45	Yes
3	8,016	62.18	Yes

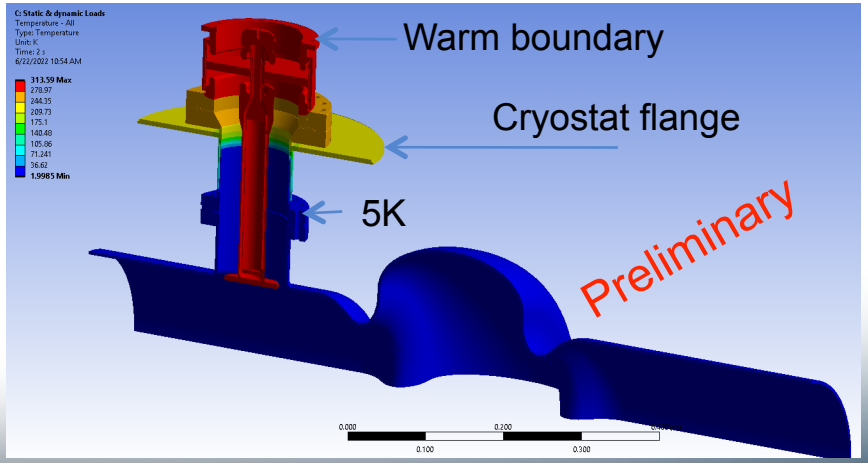
FPC transition thermal analysis

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



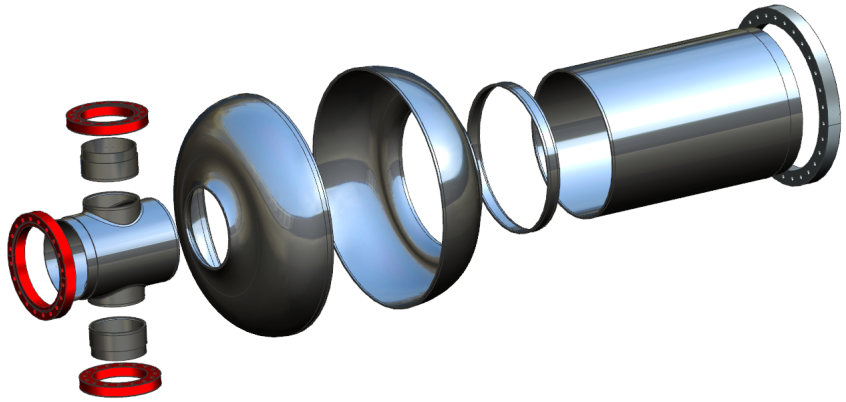


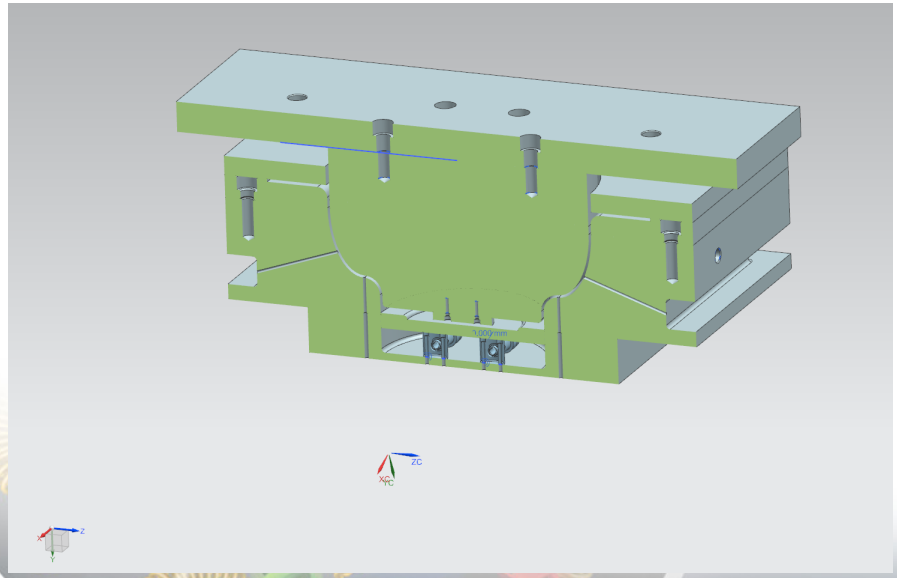


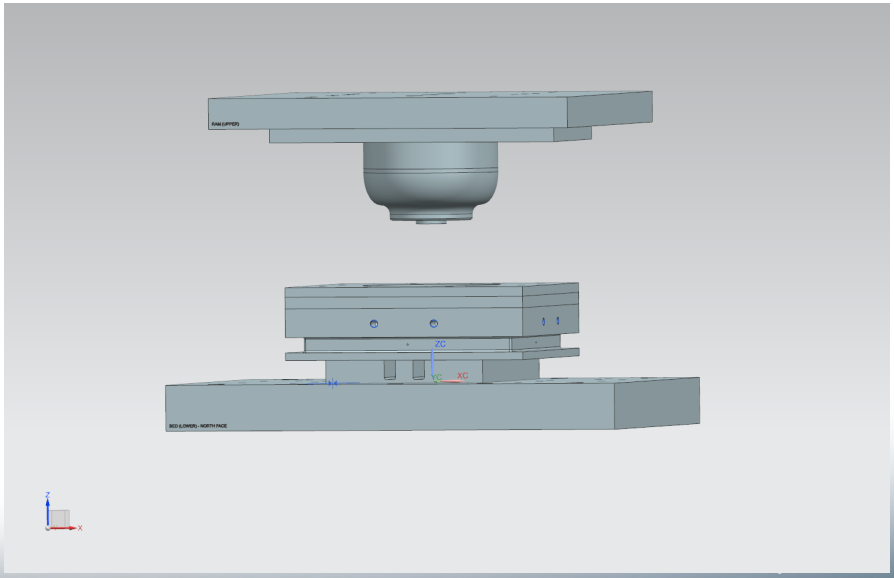
ESR 591 MHz single cell fabrication and deep drawing dies

Conventional fabrication

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

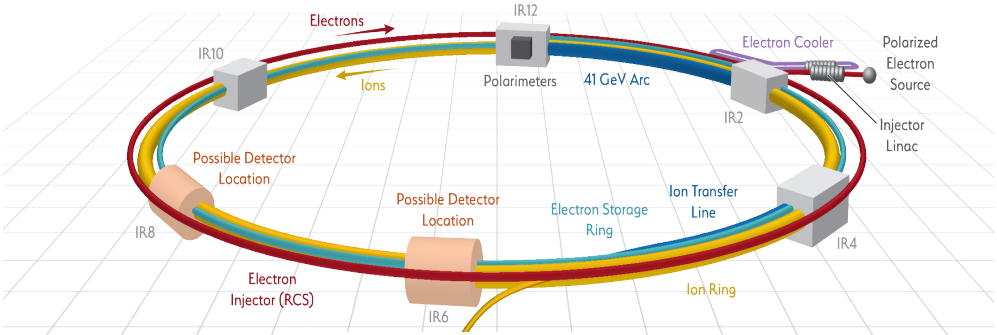






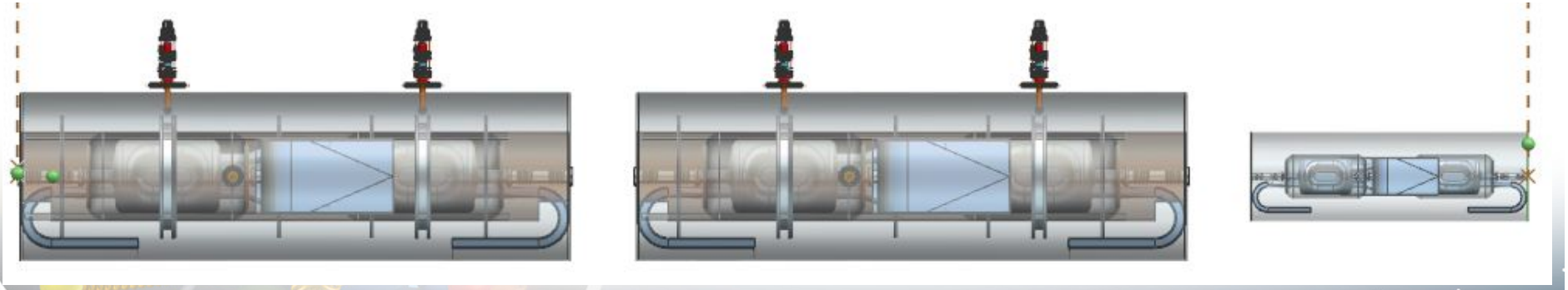
EIC Crab Cavity Systems

	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



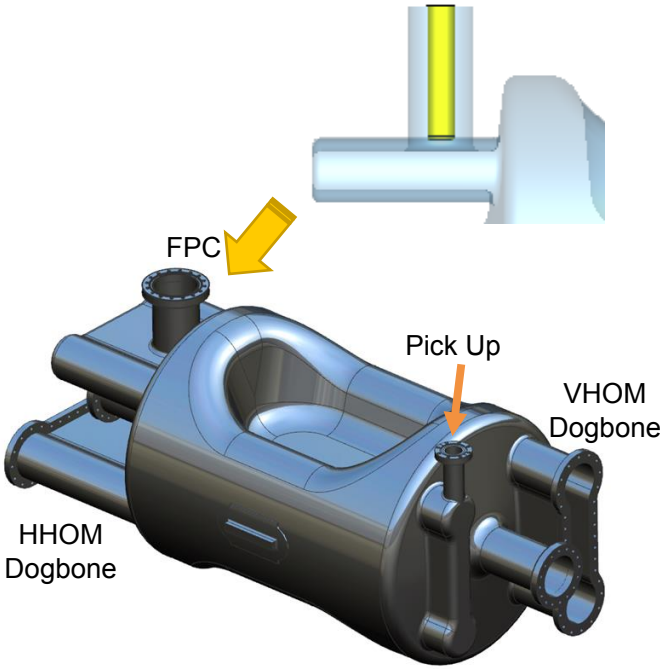
IR-6: Crab Cavity SRF Systems

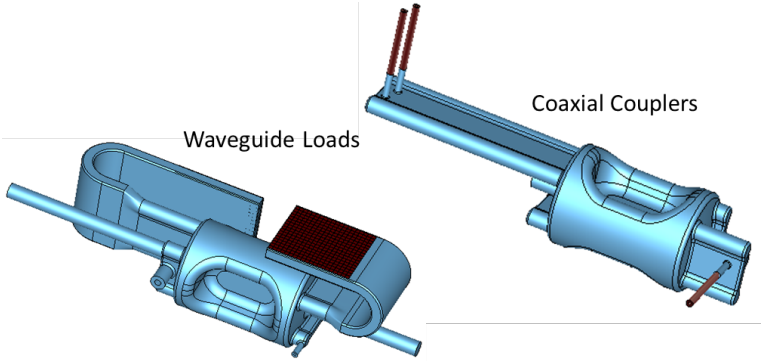
- HSR will be installed with two 197 MHz RFD cryomodules and one 394 MHz cryomodule each side of the IP Total length < **12.5 m**
- ESR requires only one 394 MHz cavity each side of the IP
- Impedance budget allows for second IP
- *197 MHz crab cavity is identified as one of first RF cavities to be prototyped*



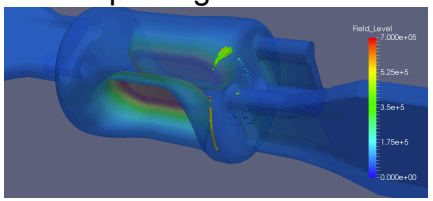
197 MHz Crab Cavity for HSR

- 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

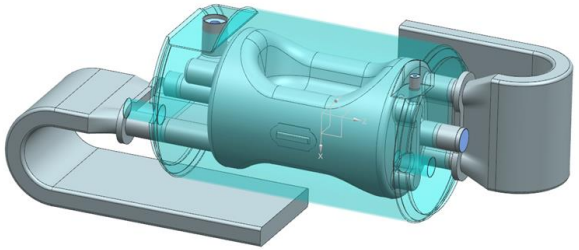




Multipacting Resonances



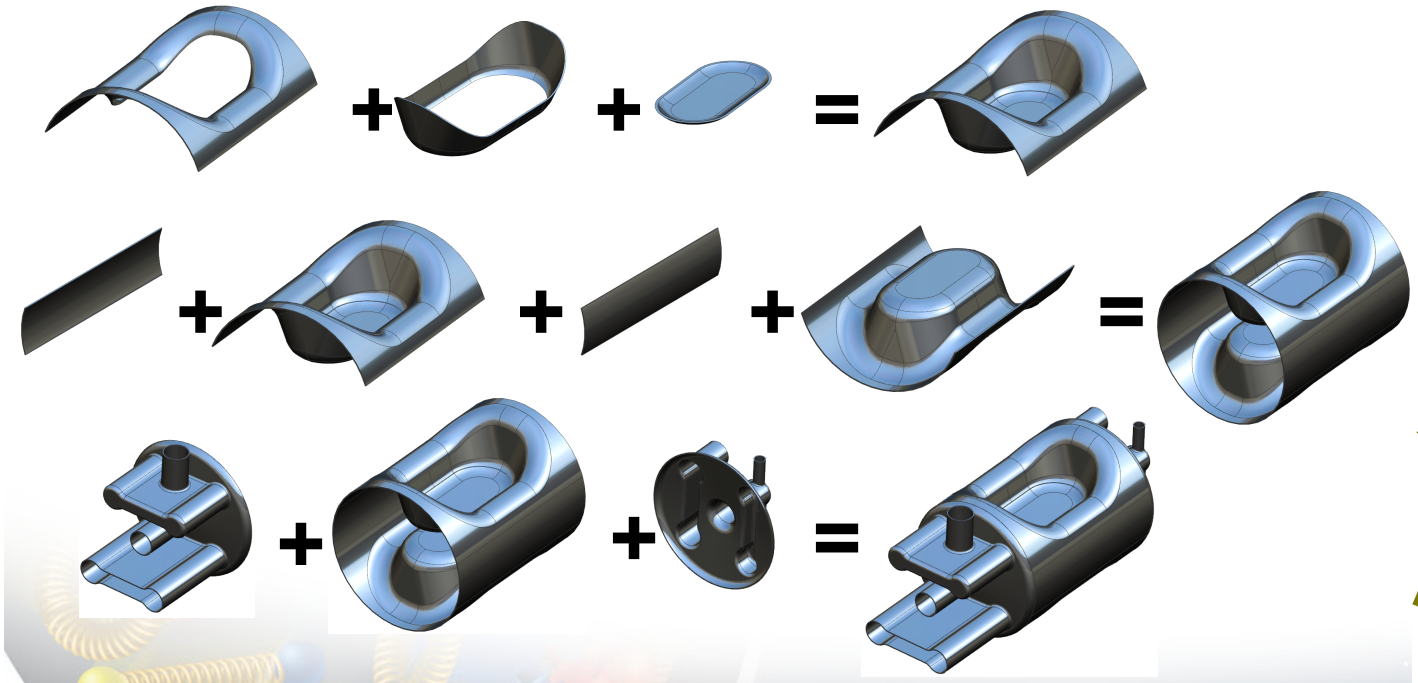
Cavity with He jacket

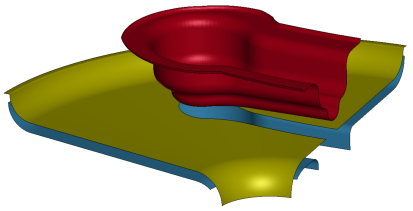


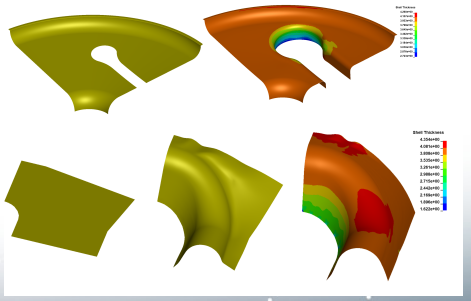
- Multipacting resonances on the cavity and HOMs will be processable.
- Will proceed with prototyping the bare cavity
- HOM choice will be based on cost and design maturity

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

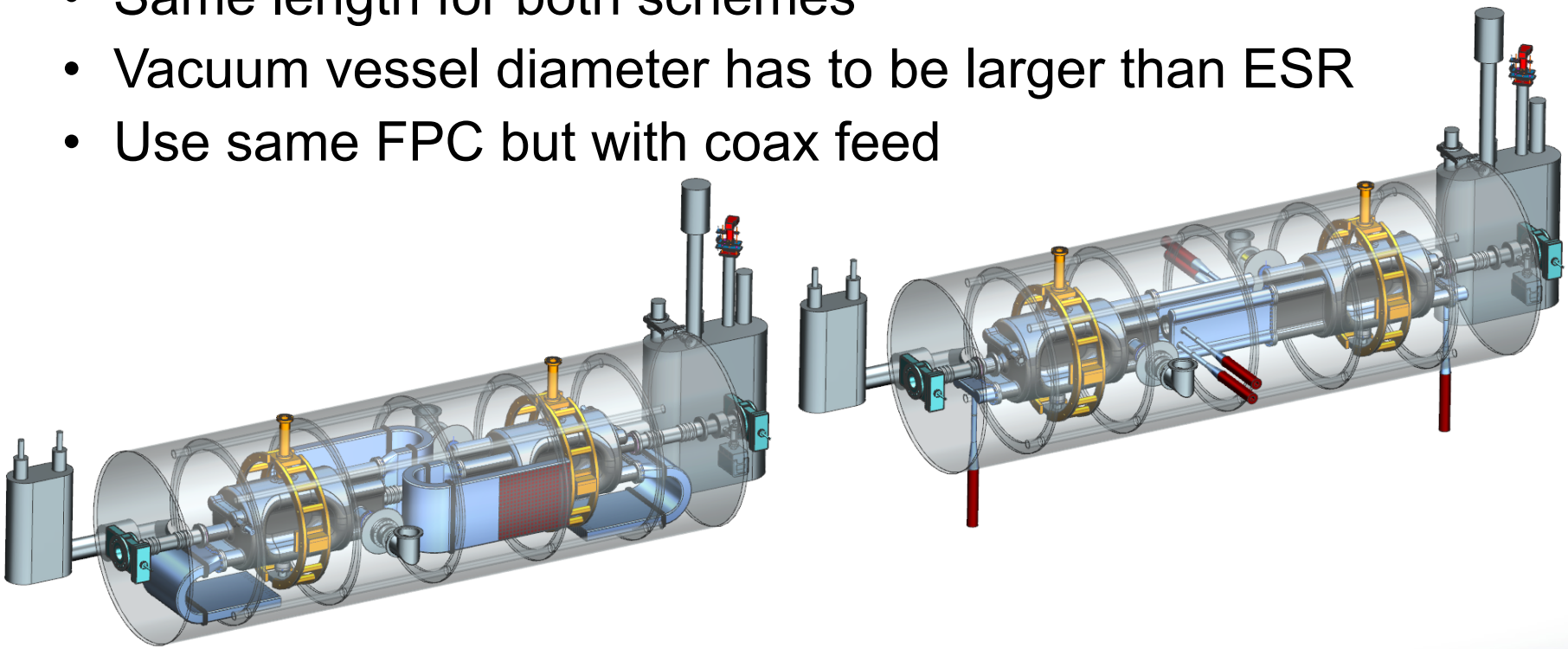






Preliminary Cryomodule Layout

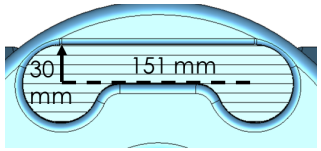
- Layouts for the two HOM damping schemes
- Total length ~ 5 m
- Same length for both schemes
- Vacuum vessel diameter has to be larger than ESR
- Use same FPC but with coax feed

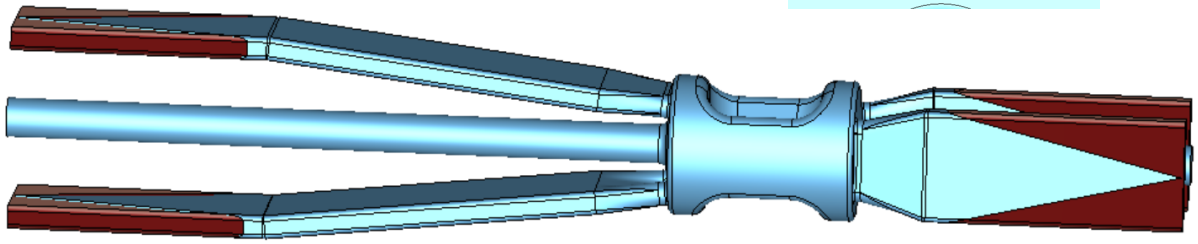


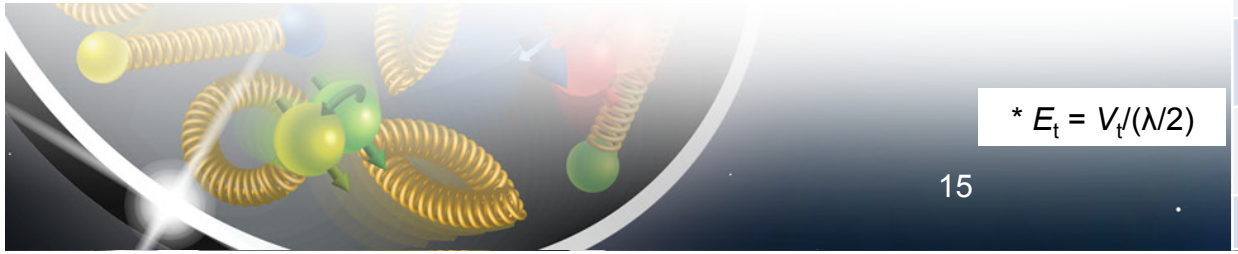
ESR 394 MHz RFD Crab Cavity

- 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	

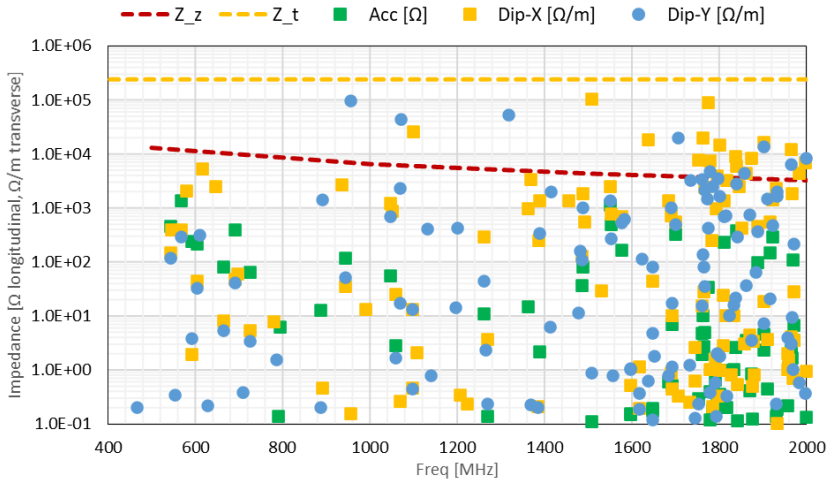
ESR 394 MHz RFD Crab Cavity Impedances

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

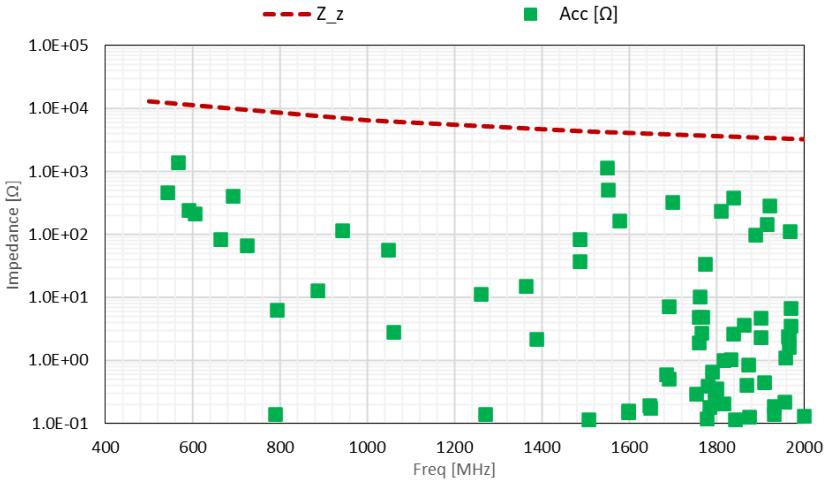
- Maximum Z_t at 1506.4MHz with 0.106MΩ/m and 2400 loaded Q
- Maximum Z_z at 1549.9MHz with 1.77kΩ-GHz and 271 loaded Q
- HOM power estimates up to 20 GHz are ongoing

- 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



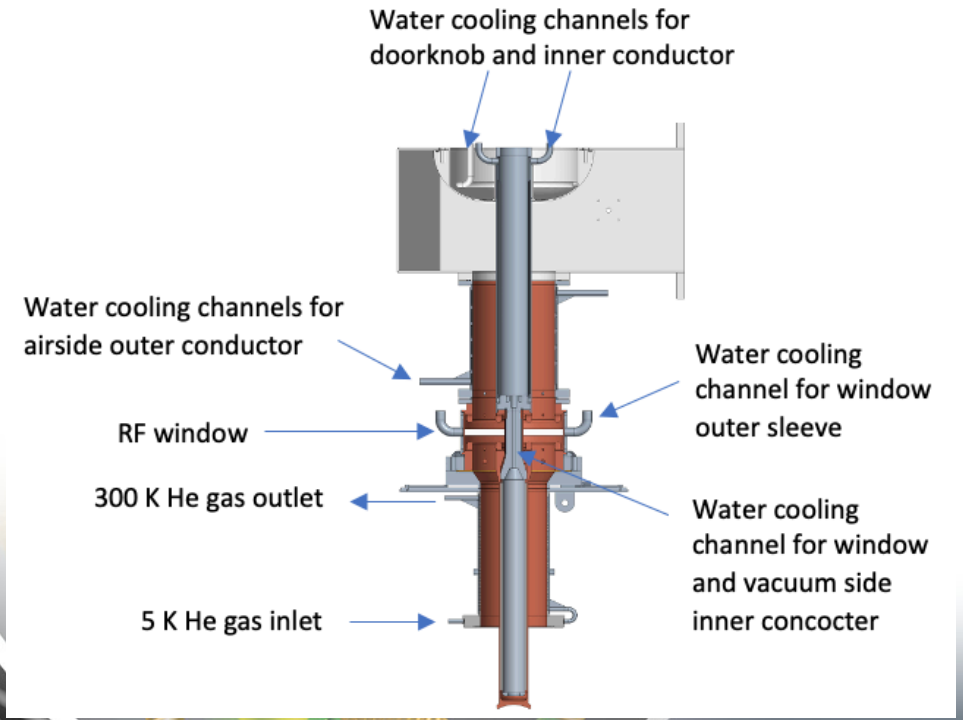
$Z_z = 6.5\times10^3$ Ω-GHz

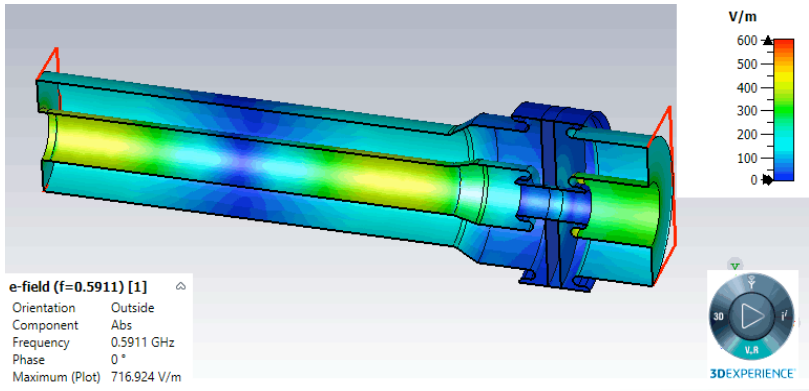


- Impedances are in circuit definition and includes 0.5 factor

High power FPC Status

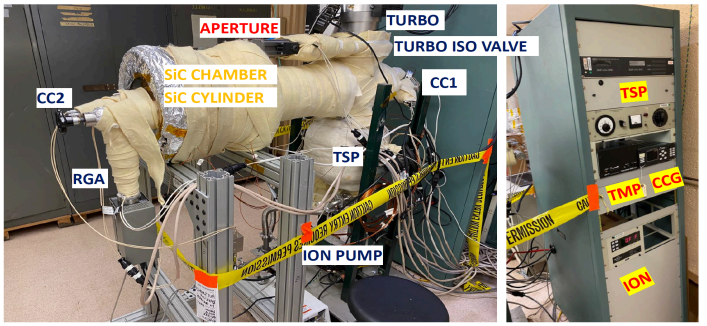
- A high power (CW 500 kW standing wave) alumina window FPC was designed for EIC ESR SRF cavity.
- The design was reviewed by an international technical review committee in June 2021.
- The review committee stated their “support moving forward with this design into prototype stage”.
- Detailed engineering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

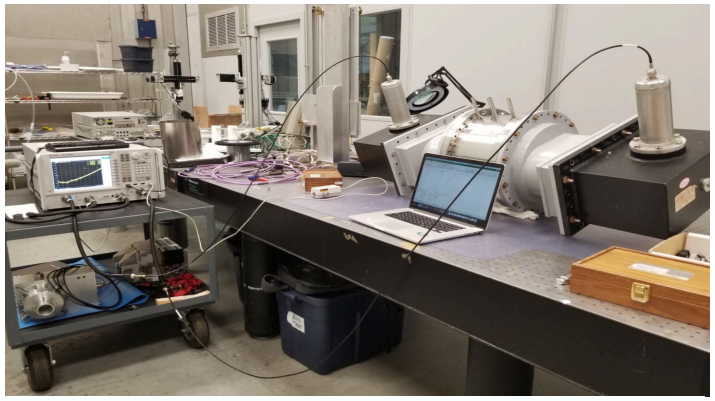


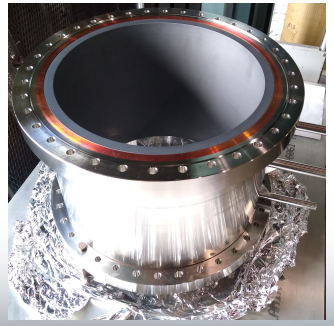


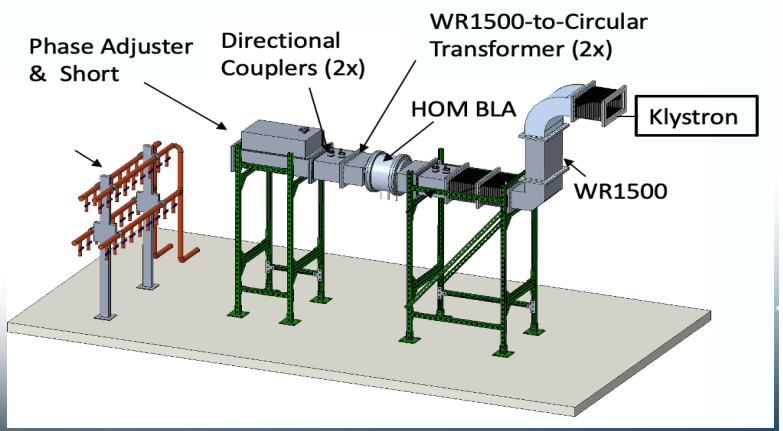
HOM damper R&D status

- 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



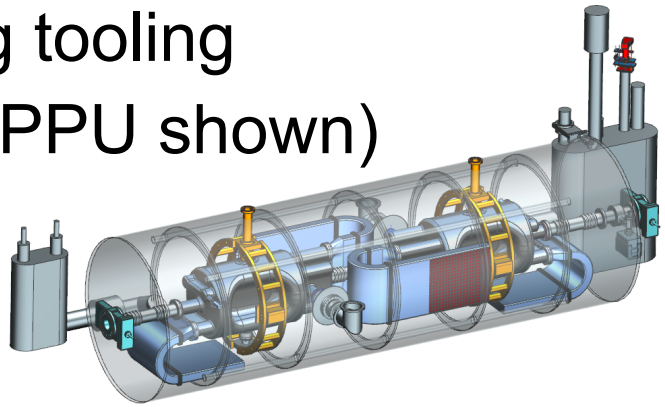






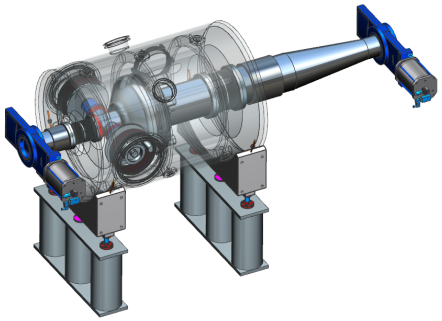
Modular cryostat

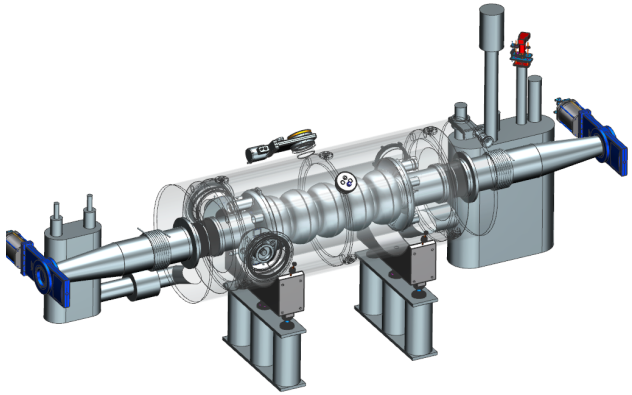
- Based on SNS cryostat dimensions
- High degree of commonality of components
- Takes advantage of much existing tooling
- Cryogenic distribution TBD (SNS PPU shown)



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

Design of the Electron Ion Collider Electron Storage Ring SRF cavity, J. Guo et. Al., Proc. IPAC22

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

Back ups

ESR cavity parameters

- HOM power distribution:
- 64% large BLA
- 28% small BLA
- 7% tapered beam pipe
- 1% small beam pipe

Table 1: Basic parameters of the ESR cavity designs

Parameters	Sym	Asym
R/Q (Circ. Def) (Ω)	37	38
Epk/Eacc	2.13	2.01
Bpk/Eacc (mT/(MV/m))	4.87	4.87
G (Ohm)	293	307
FPC tip penetration (Qext~3.5E5)	1 mm	3 mm
Approximate total length (gate valve to gate valve)	3.75 m	2.8 m

Table 2: Loss factor (V/pC) of two ESR cavity designs, 20 mm Gaussian bunch, excluding the fundamental mode.

Cases	Sym	Asym
Bare cavity, tapered to 150 mm diameter	0.128	0.097
Bare cavity with 2 BLAs, tapered	0.276	0.238
FPCs with Qext=3.5E5, doorknobs, tapers, 2 BLAs	0.283	0.252
Estimated total HOM power for 2.5A, 7mm bunch	~40 kW	~35 kW

Tuning Sensitivity of Warm Cavity

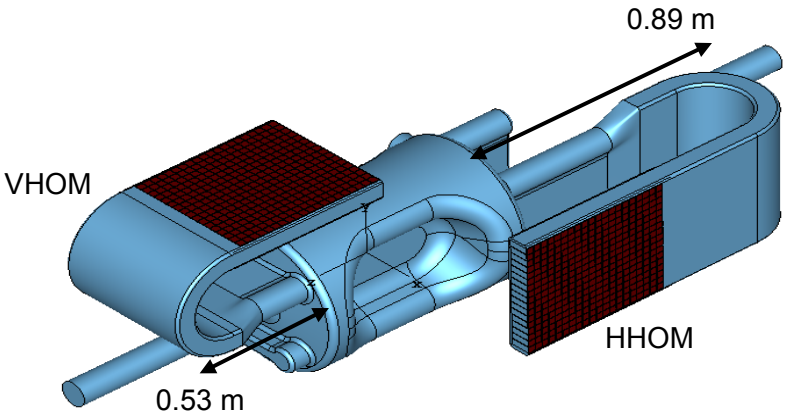
- To understand how the cavity will deform during tuning, the displacement was varied from 1 to 3 mm. No pressure was considered.
- The elastic tuning range shows that the cavity will yield for less than 1mm.
- The 1st table shows tensile displacements while the 2nd is for compression.

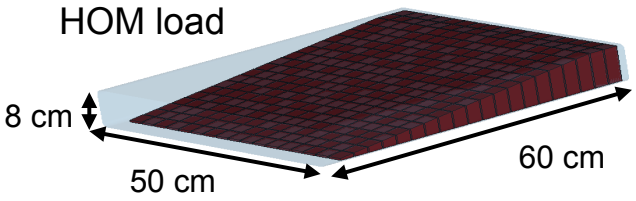
Tensile Displacement (mm)	Freq (MHz)	Tuning Sensitivity (KHz/ mm), 1mm	Stiffness (N/mm)	von Mises (MPa)	Elastic tuning range (mm)
1	590.83	447.05	14,258	100.01	0.435
2	590.83	443.48	14,258	200.02	
3	590.83	439.94	14,259	300.02	

Compressive Tuning Disp. (mm)	Freq (MHz)	Tuning Sensitivity (KHz/ mm), 1mm	Stiffness (N/mm)	von Mises (MPa)
1	590.83	454.27	14,258	100.01
2	590.83	457.92	14,257	200.02
3	590.83	461.60	14,257	300.02

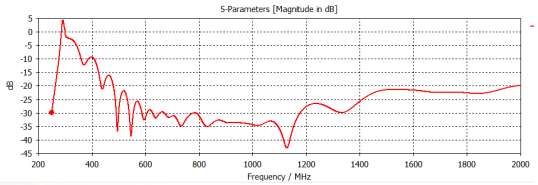
197 MHz Crab Cavity with Waveguide Dampers

- Two HOM waveguide dampers (HHOM and VHOM) to damp modes up to 2 GHz
- Total HOM power < 5 kW
- Current HOM load material – AlN-SiC composite
  - Alternative load material (SC-35) is being studied to reduce number of tiles and lower manufacturing cost

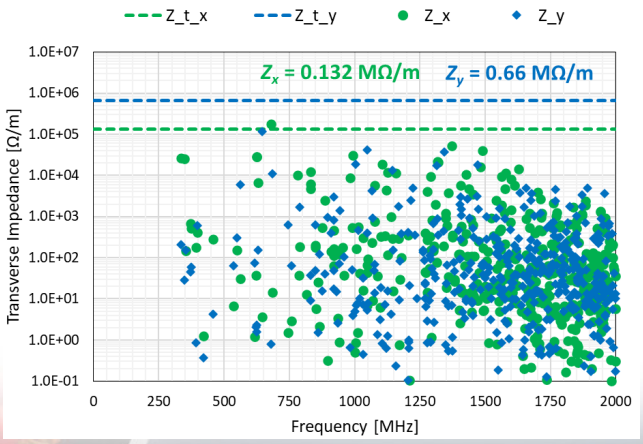


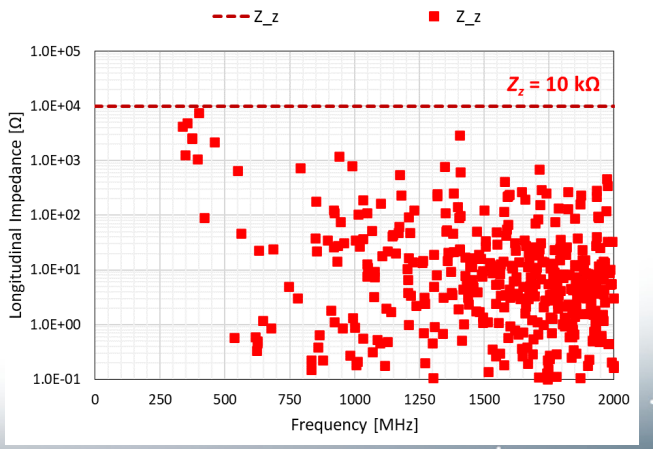


S_{11} at load start face



$Z_x = 0.132\times10^6\ \Omega/m,\ Z_y = 0.66\times10^6\ \Omega/m$

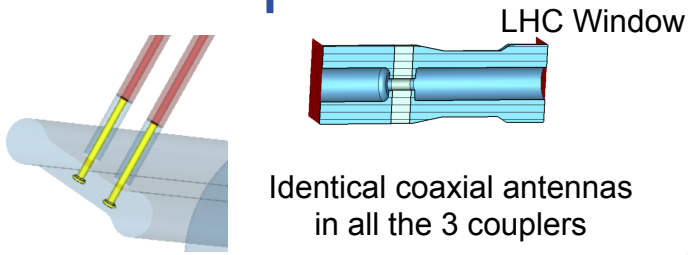


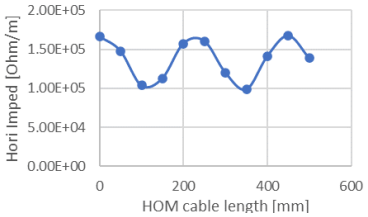


- Impedances are in circuit definition and includes 0.5 factor

197 MHz Crab Cavity with Coaxial Couplers

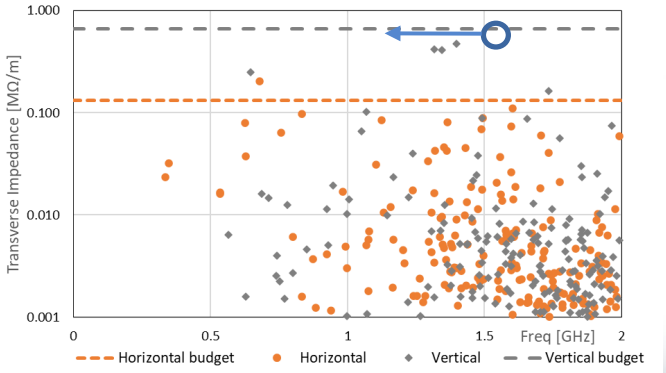
- Bird 8726 coax loads, 500MHz to 2000MHz, 1.25 max VSWR, 5kW.
- LHC DQW HOM windows are used.
- Total HOM power is 5.66 kW, 16.3% from the transverse modes (290 buckets ON 25 buckets OFF)
- HOM power for each port:
  - Port V = 2.06 kW
  - Port H1 = 2.25 kW
  - Port H2 = 1.35 kW
- More simulations with detailed FPC design will follow.



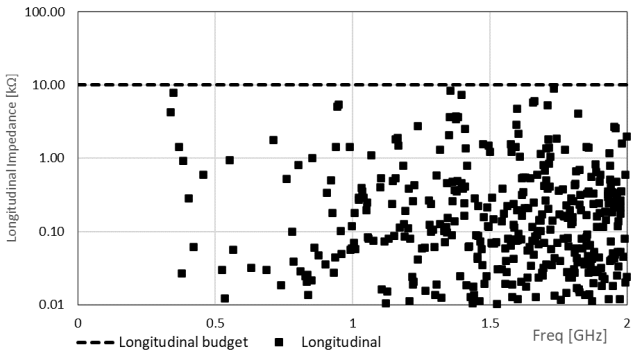


Carefully choose the cable length between HOM window and load help reducing the impedance of 680MHz mode

$Z_x = 0.132\times10^6\ \Omega/m$, $Z_y = 0.66\times10^6\ \Omega/m$



$Z_z = 10^4\ \Omega$

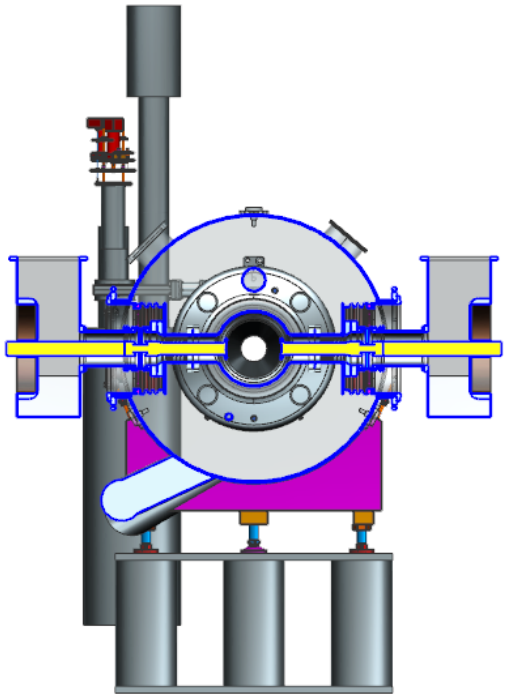


- Impedances are in circuit definition and includes 0.5 factor

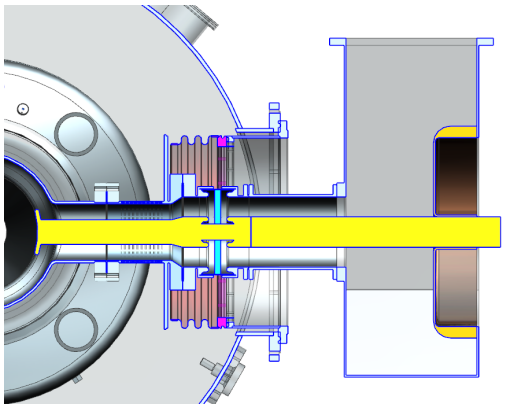
ESR Cavity/Cryomodule Concept with 500 kW Fixed Coupler

- Coupler is an evolution from the KEK / SNS / BNL high power fixed coupler design
- Goals: High power, broadband and physically robust window

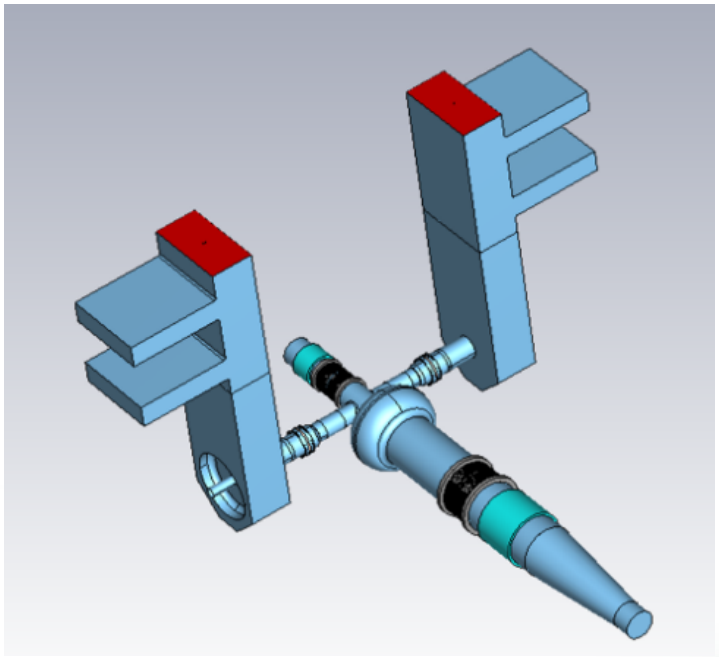
End view of the cryomodule, cut on the mid-plane of the couplers. Courtesy: Jim Henry.



Zoom of one coupler. Pringle position set for minimum Q_{ext}. Ceramic in detuned-short position.
Courtesy: Jim Henry.

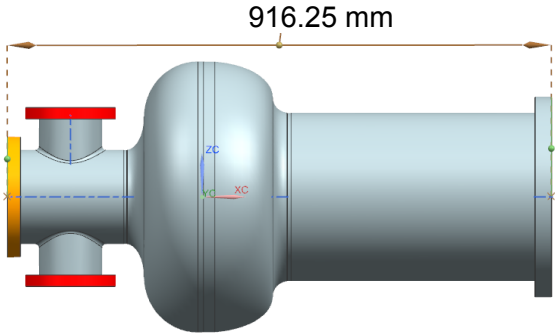


Matching stubs for external Qext adjustment

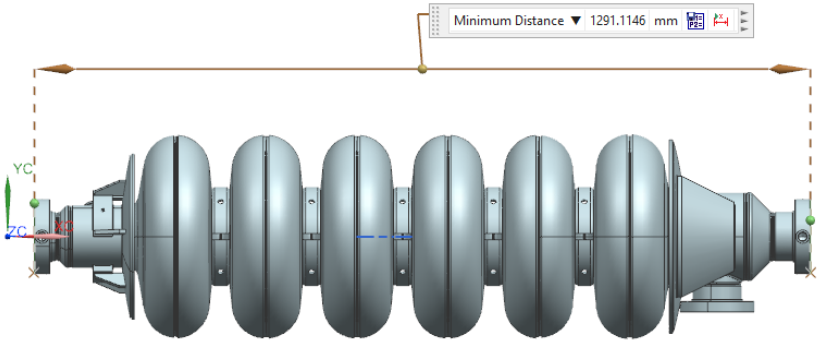


Comparison of Different Cavities

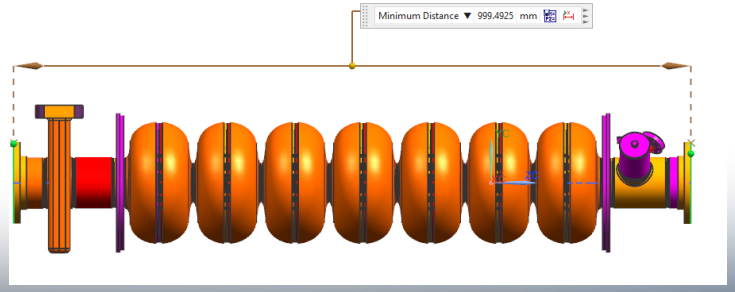
Asymmetric
591 MHz



SNS



C100



Comparison of Different Cavities

Cavity	Current (asym 591MHz)	SNS (high beta)*	C100**
Fundamental Frequency (MHz)	591	805	1,497
Length (mm)	916.25	1291.11	999.49
# Cells	1	6	7
Tuning Sensitivity (KHz/ mm)	447	261	492
Warm cavity Stiffness (N/ mm)	14,258	3,047.8	1,156.5
Cold cavity stiffness (N/ mm)	21,019 (at 4K)	----	1,725.2 (at 2K)
Warm Pressure Sensitivity (KHz/atm) unrestrained cavity	121.06	30 (?)	----
Cold Pressure Sensitivity (KHz/atm) unrestrained cavity	82.11	----	----