RF DIPOLE DESIGN UPDATE

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Outline

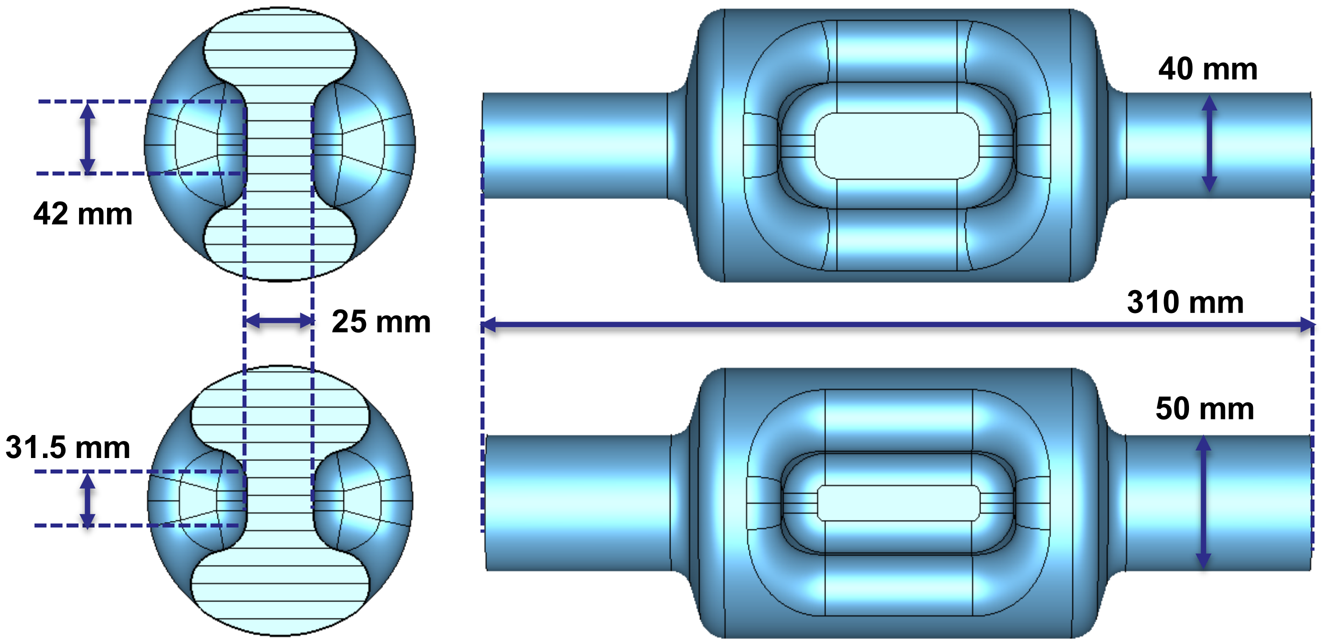
- Updated 1.3 GHz RFD crab cavity design for ILC
- Higher order modes and impedances
  - Transverse impedances
  - Loss factor for longitudinal modes
- Summary from Design Review #2
- Conceptual cryomodule layout
- Cavity fabrication sequence
- Summary

Main Goals of the Study

- Transverse voltage: 1.845 MV for 250 GeV and 7.4 MV for 1 TeV
- Cryostat length flange to flange < 3.80 m
  - *Focus on 1-cell RFD cavity with the increase in beam line space*
- Peak surface fields: E_p < 45 MV/m and B_p < 80 mT
- Total transverse impedance threshold:
  - Horizontal: 48.8 MΩ/m
  - Vertical: 61.7 MΩ/m
  - *Focus on achieving a well damped HOMs (up to 8 GHz)*

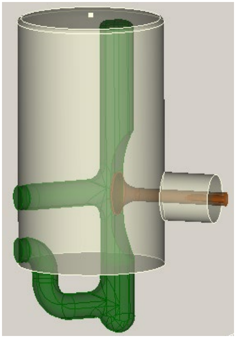
1.3 GHz RFD Cavity Design

- Pole separation – 25 mm
- Beam aperture increased – 40 mm → 50 mm
  - Large beam aperture allows better HOM extraction
- Optimized the pole shape (pole height and length):
  - To maintain maximum achievable V_t at 1.35 MV
  - While maintaining peak surface field requirements of E_p < 45 MV/m and B_p < 80 mT

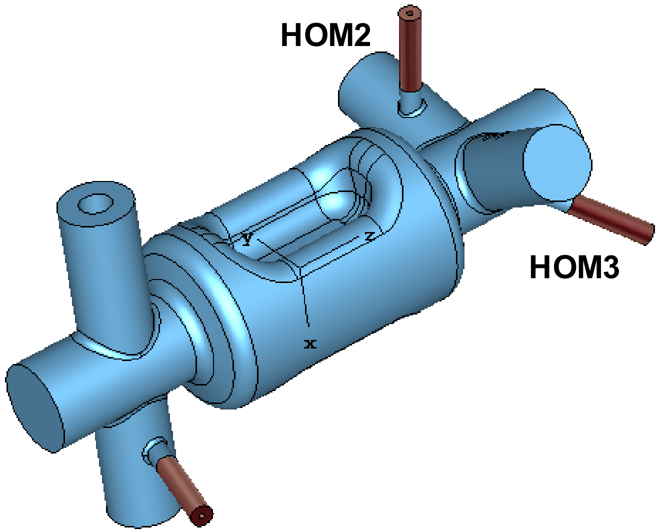


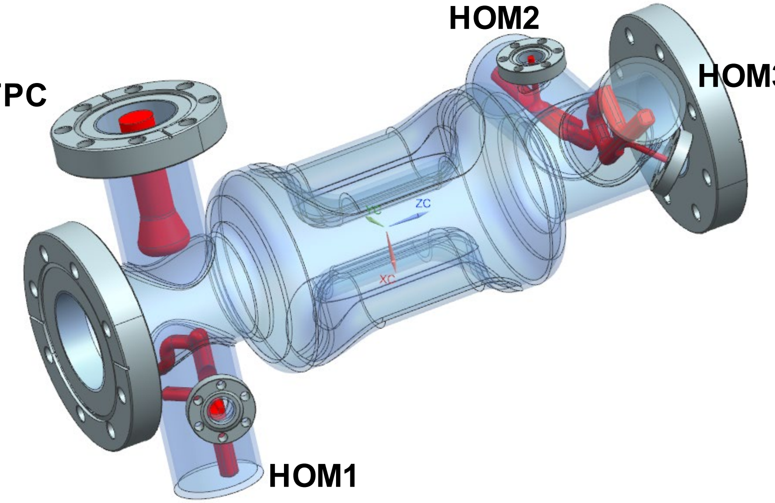
Property	1-cell	1-cell-new
Operating frequency [GHz]	1.3	1.3
1st HOM [GHz]	2.142	2.089
E_p/E_t^*	3.83	3.76
B_p/E_t^* [mT/(MV/m)]	6.84	6.80
B_p/E_p [mT/(MV/m)]	1.79	1.80
G [Ω]	129.9	129.54
R/Q [Ω] (V^2/P)	444.8	440.4
R_tR_s [Ω^2] (V^2/P)	5.78×10^4	5.70×10^4
*Reference length $V/E_t = \lambda/2$ [mm]	115.3	115.3
V_t [MV]	**1.35**	**1.35**
E_p [MV/m]	44.8	44.2
B_p [mT]	80.1	79.6
Pole separation [mm]	25	
Beam aperture [mm]	**40**	**50**
Cavity Length [mm] (flange-to-flange)	310	310
Cavity Diameter [mm]	100.3	99.4
Pole Length [mm]	80	85
Pole Height [mm]	42	31.5
Angle [deg]	22.5	22.5

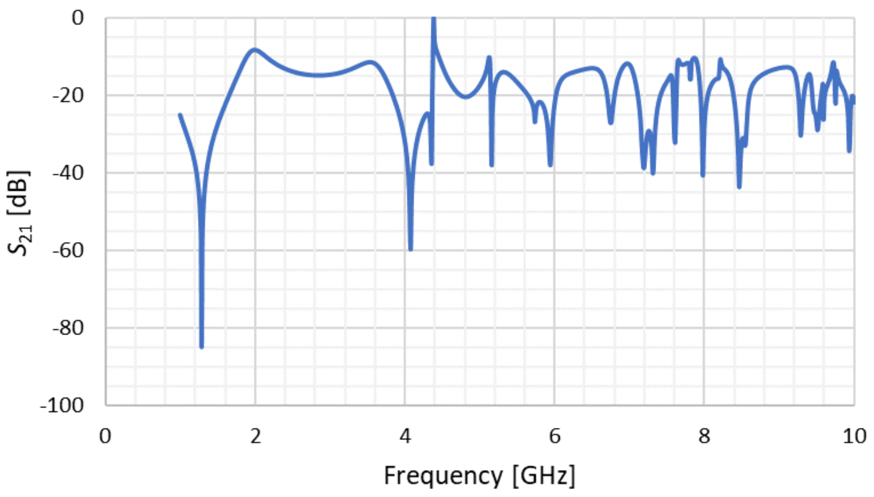
Higher Order Mode Damping



TESLA type
HOM coupler



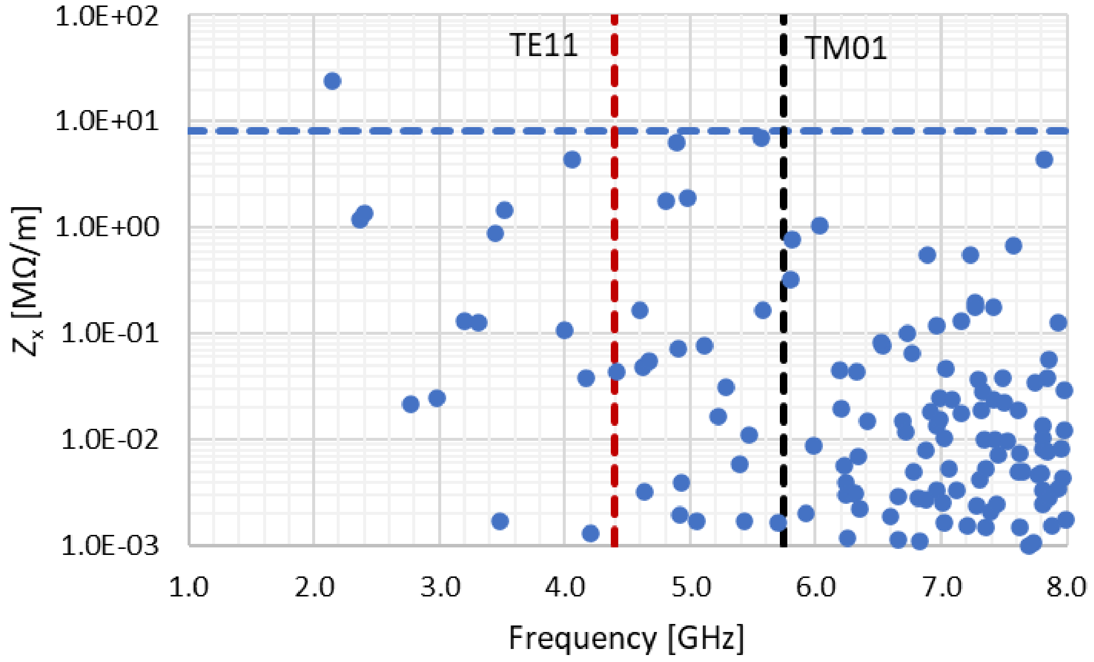


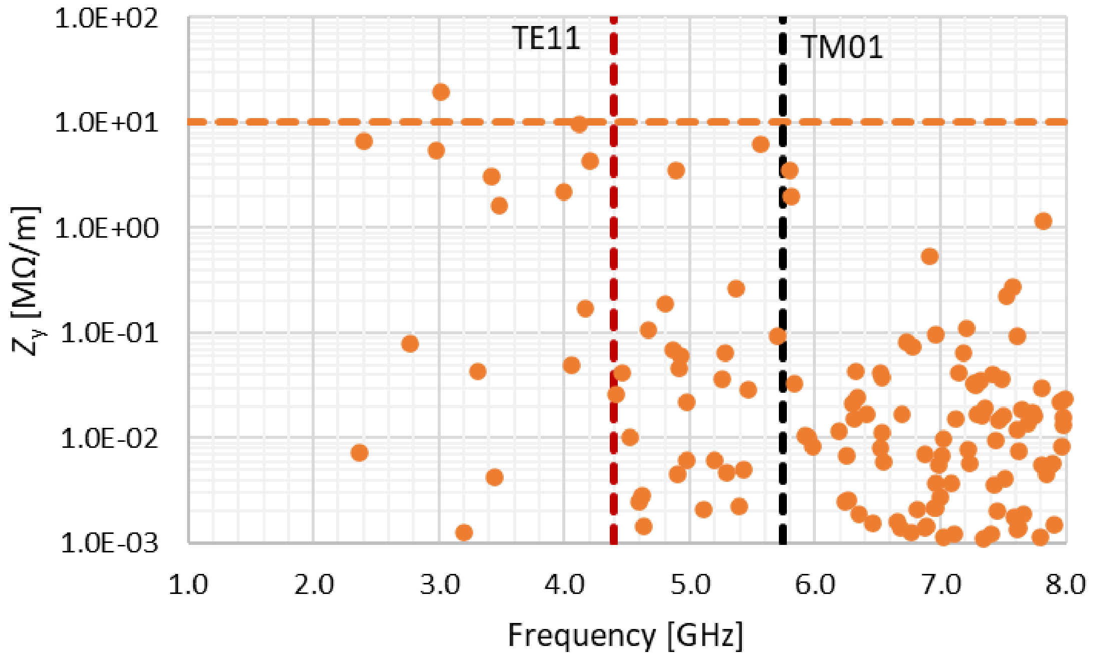


- TESLA HOM coupler with the notch at 1.3 GHz
  - A notch at 4.08 GHz
- Damping using 3 TESLA type HOM couplers
  - Damper design used in the LCLS II cavities
  - Compact damper design → Allows to place dampers on the beam pipes and suppress the HOMs

Transverse HOM Impedances – Design Review #2 (06/2022)

- Pole separation = 25 mm and beam aperture = 40 mm
- Total impedance threshold: Z_x = 48.8 MΩ/m and Z_y = 61.7 MΩ/m
- Impedance threshold per cavity: Z_x = 8.13 MΩ/m and Z_y = 10.28 MΩ/m (6 cavities)
- Two modes (2.142 GHz and 3.02 GHz) above impedance threshold

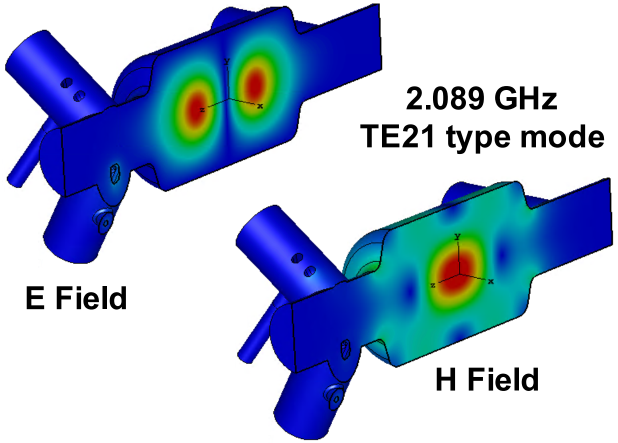


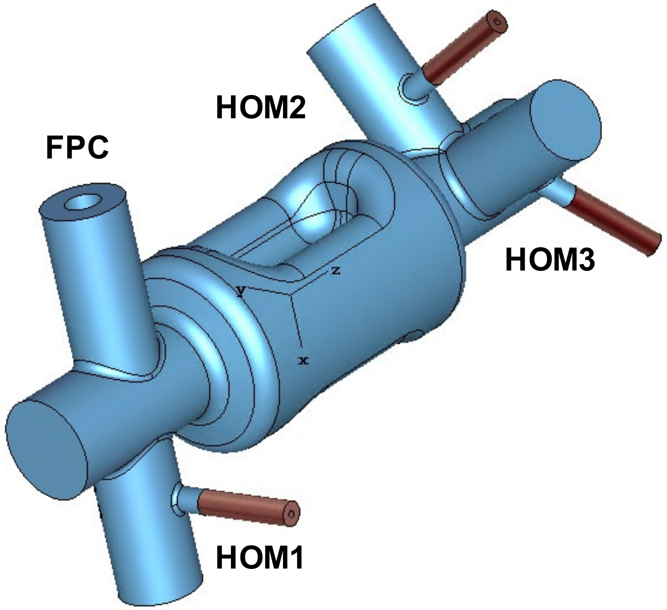


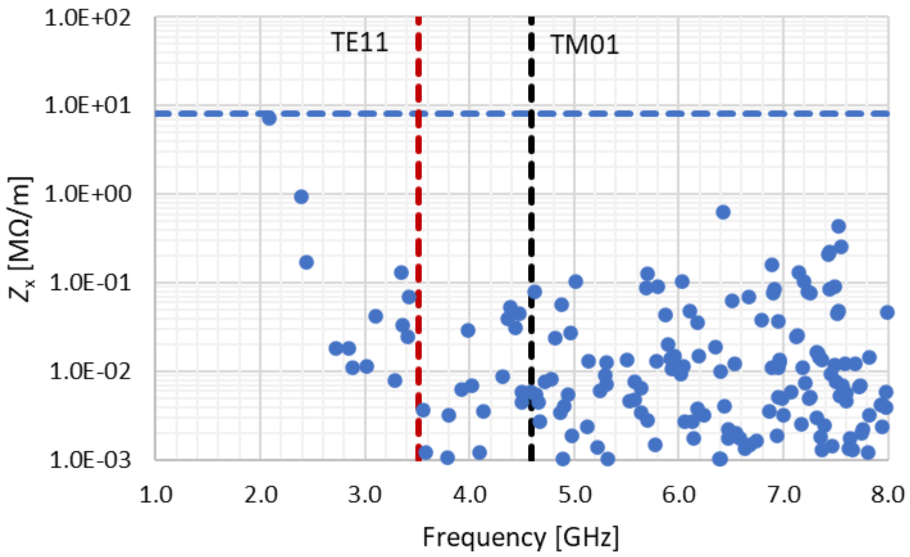
- Impedances calculated using circuit definition

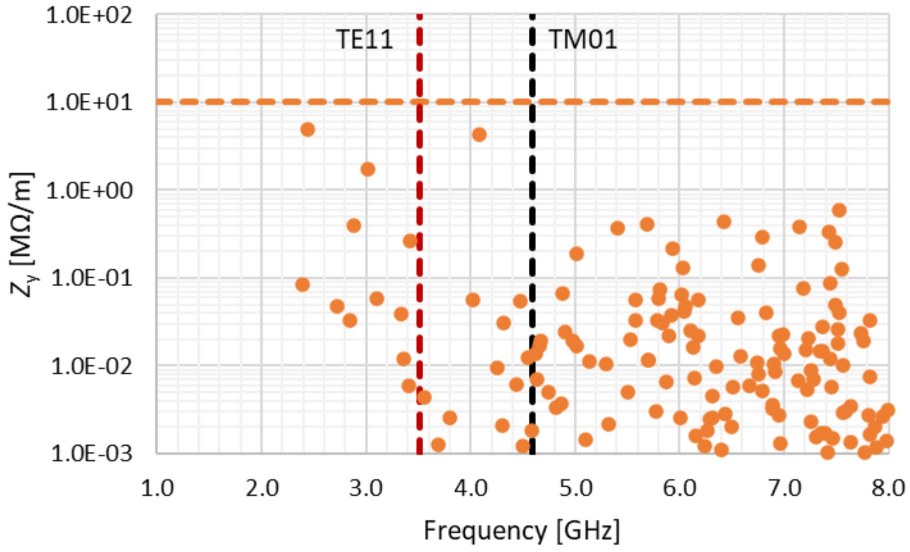
Transverse HOM Impedances – Design Option 1

- Pole separation = 25 mm and beam aperture = 50 mm
- Total impedance threshold: Z_x = 48.8 MΩ/m and Z_y = 61.7 MΩ/m
- Impedance threshold per cavity: Z_x = 8.13 MΩ/m and Z_y = 10.28 MΩ/m (6 cavities)
- Transverse-X mode at 2.089 GHz has very small margin from threshold
  - Limited rotation angle for HOM2 and HOM3 on the 50 mm beam pipe





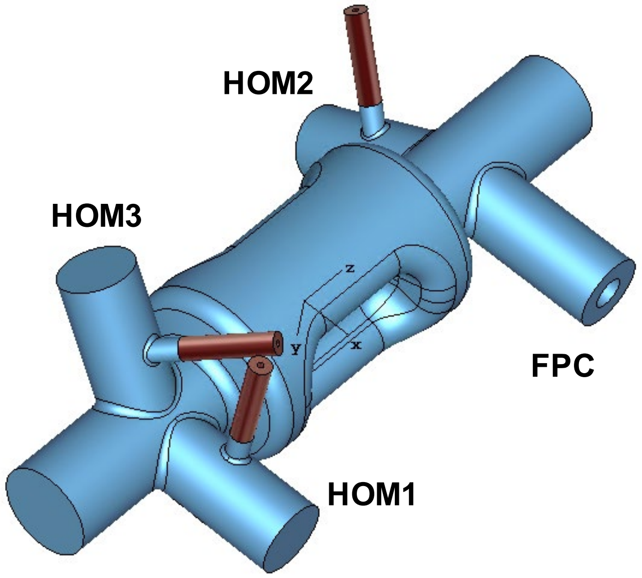


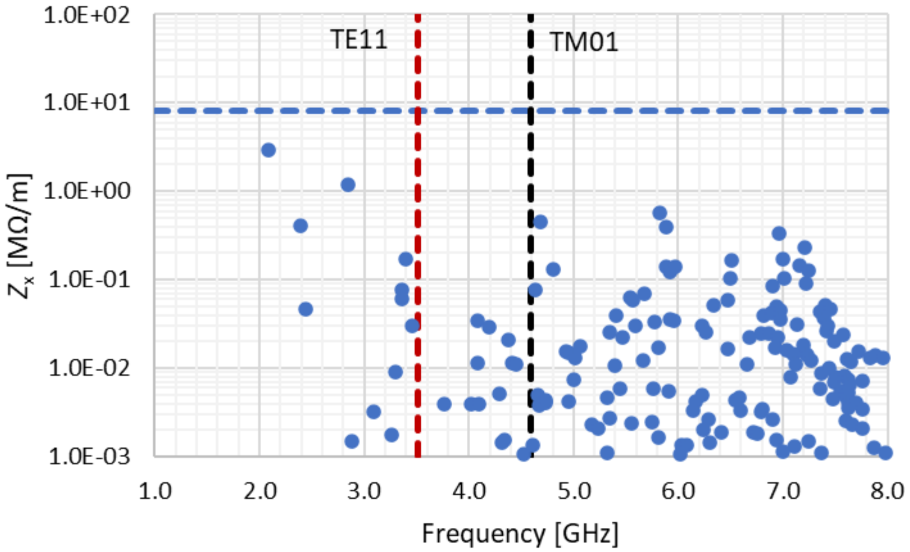


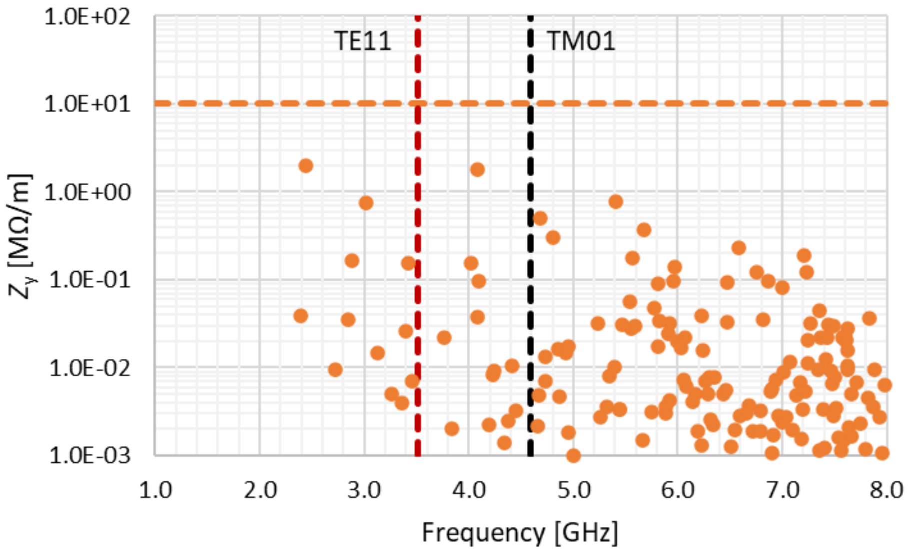
- Impedances calculated using circuit definition

Transverse HOM Impedances – Design Option 2

- Pole separation = 25 mm and beam aperture = 50 mm
- Total impedance threshold: Z_x = 48.8 MΩ/m and Z_y = 61.7 MΩ/m
- Impedance threshold per cavity: Z_x = 8.13 MΩ/m and Z_y = 10.28 MΩ/m (6 cavities)
- Rearranged HOM dampers on the beam pipes → More rotation angle for HOM2 and HOM3
- Well damped HOMs with margin



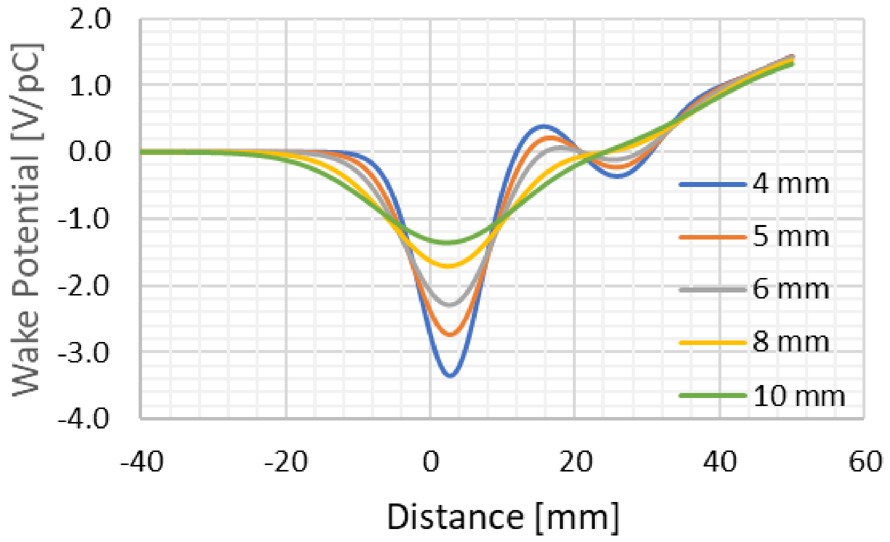


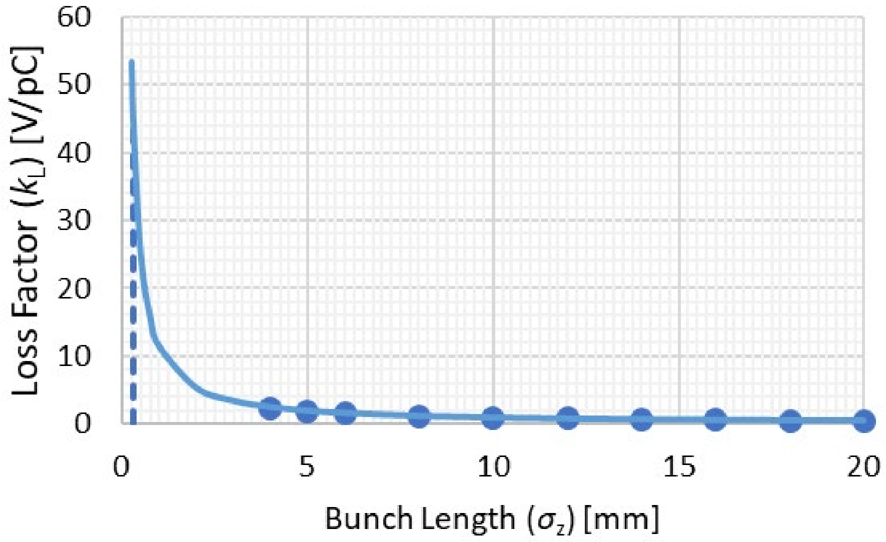


- Impedances calculated using circuit definition

Loss Factor for Longitudinal HOMs

- Longitudinal wakefield for a short-range wake of 50 mm for several bunch lengths
- Simulated with CST
- Extrapolated loss factor for the ILC bunch length σ_z = 0.3 mm → 44 V/pC

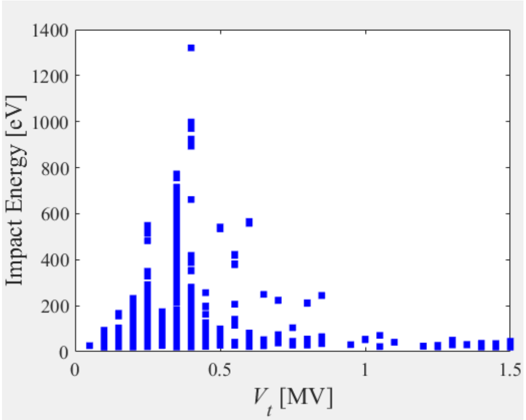


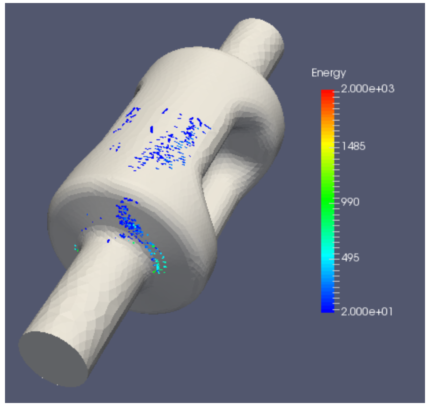


- Need to verify with Gdfidl
- Is this acceptable?

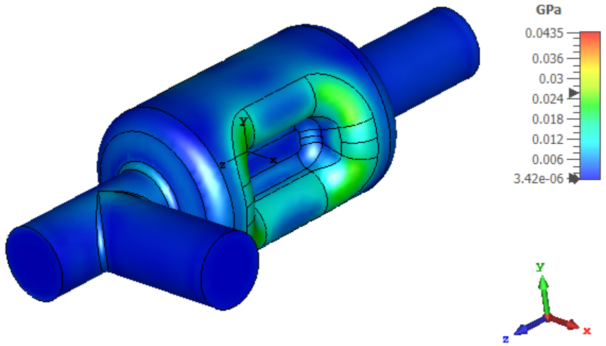
Summary from Design Review #2 (06/2022)

- **Multipacting Analysis** – Completed for bare cavities
  - Need to complete the analysis for full cavity including FPC and HOMs





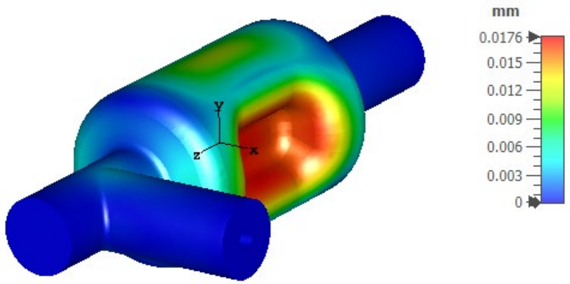
- **Stress Analysis** – At 2 K
  - Well within allowable maximum stress of 43.5 Pa
  - For cavity thickness of 2.5 mm

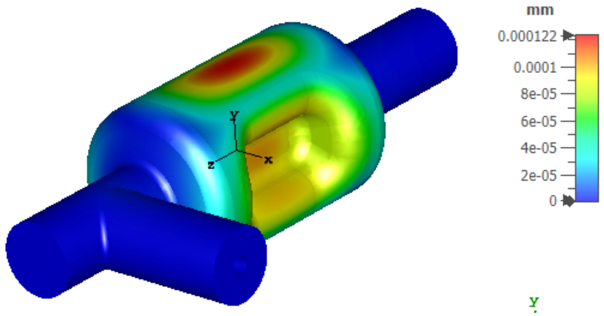


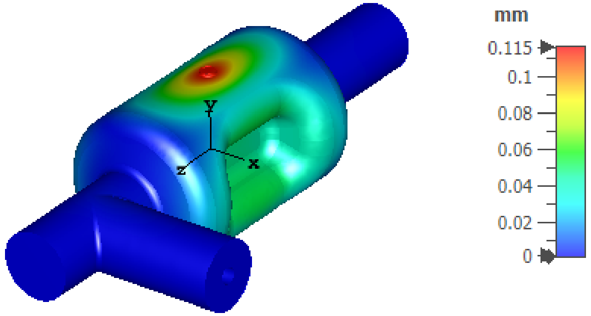
- **Tuning Sensitivity** – At 2 K
  - Tuning range ≈ 1.96 MHz
  - 8.5 MHz/mm at 1.6 kN and 0.23 mm displacement per side

- **Pressure Sensitivity** – At RT
  - d*f*/d*P* ≈ 730 Hz/mbar for 2.5 mm cavity thickness

- **Lorentz Detuning** – At 2 K
  - $k_L \approx -7.44$ [kHz/(MV)^2] for 2.5 mm cavity thickness

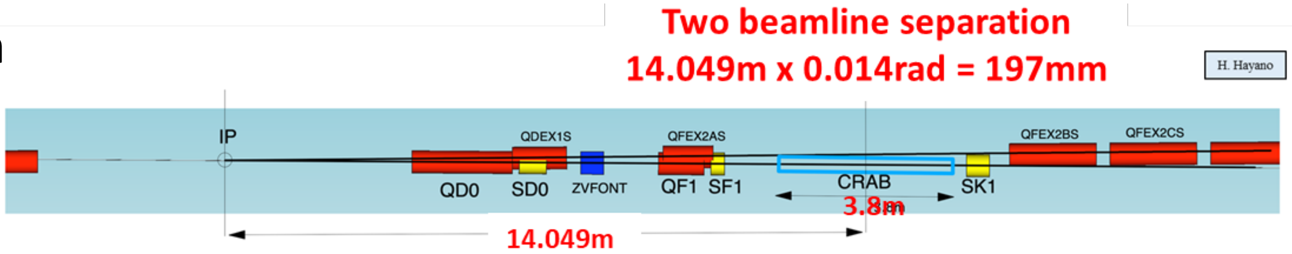


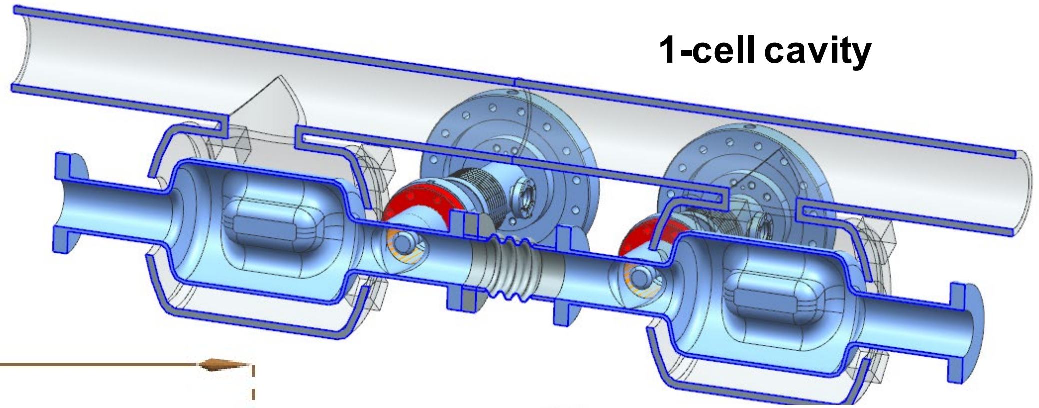


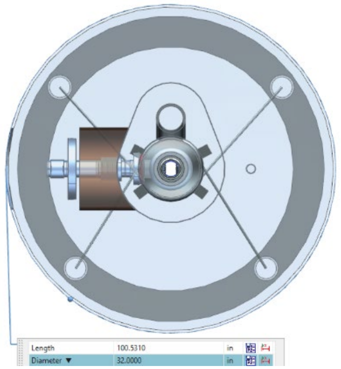


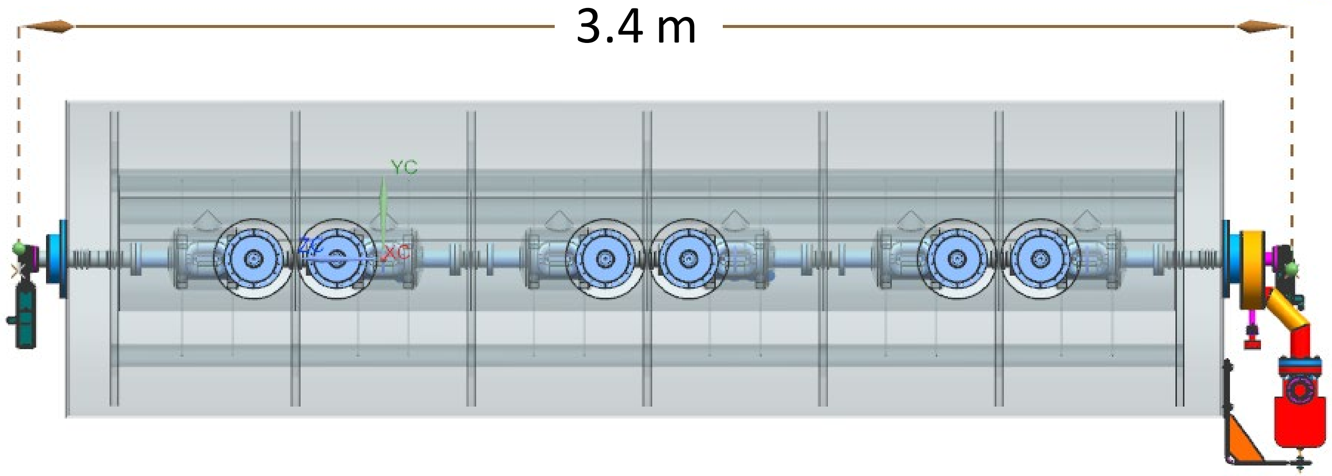
Conceptual He Vessel and Cryomodule Design

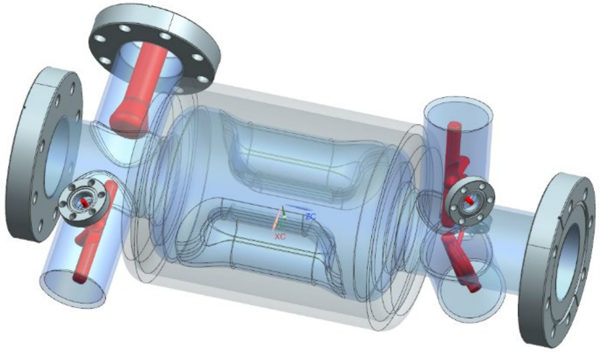
- At 1 TeV – Cryomodule required to fit in within 3.8 m
- 1-cell cavity
  - 6 cavities in a single cryomodule
  - Second beam pipe – 20 mm beam pipe
  - Total achievable – 8.1 MV (1.24 MV V_t per cavity)
  - ~10% extra margin
- Design concept follows JLab C100 cryomodule
- Cryomodule length = 3.4 m
- Cryomodule diameter = 0.82 m





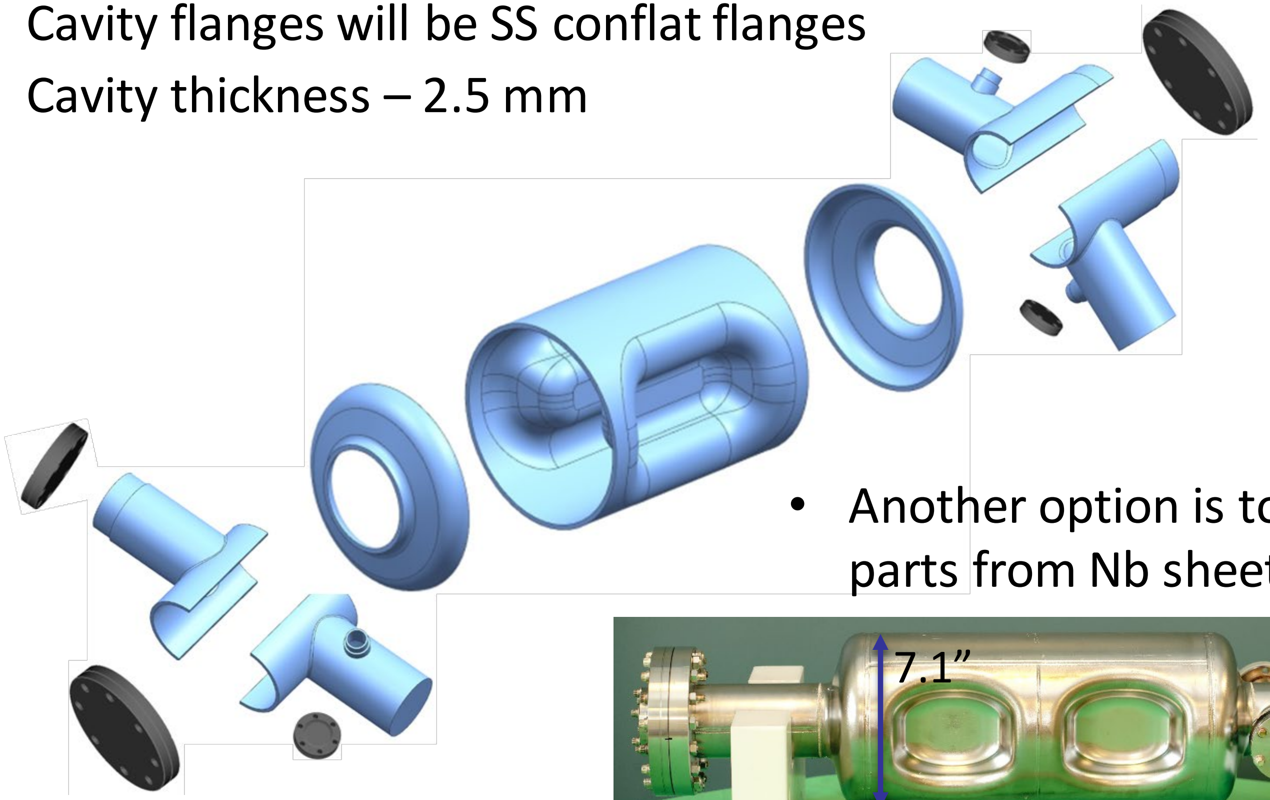




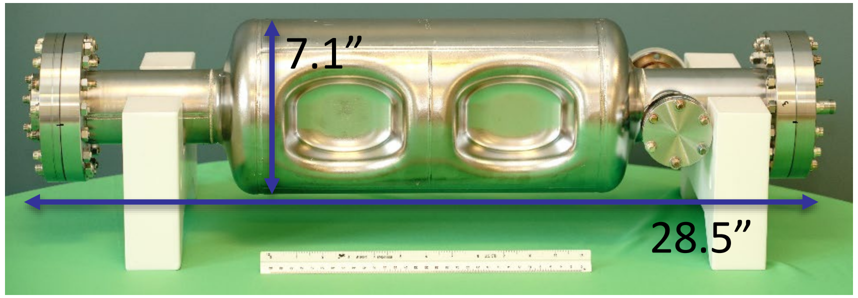


Cavity Fabrication Sequence

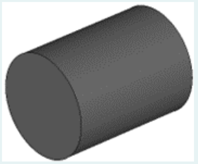
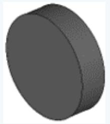
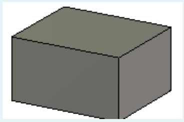
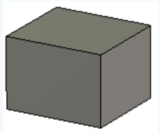
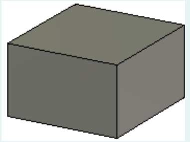
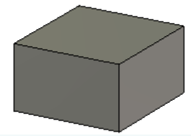
- Center body and end caps will be machined out of Nb ingots
  - Additional material included to add varying thickness
- Cavity flanges will be SS conflat flanges
- Cavity thickness – 2.5 mm



- Another option is to stamp parts from Nb sheets



952 MHz 2-cell JLEIC crab cavity

Cavity Parts (Nb)		Dimensions [in]	Qty	Weight
Center body		Ø 4.5” × 5.6”	1	12.6 kg
End caps		Ø 4.5” × 1.2”	2	5.4 kg
Beam tube with FPC		4.0” × 2.2” × 3.4”	1	4.2 kg
Beam tube with HOM1		3.7” × 2.6” × 3.4”	1	4.6 kg
Beam tube with HOM2		4.1” × 2.5” × 4.4”	1	6.3 kg
Beam tube with HOM3		4.1” × 2.4” × 4.4”	1	6.1 kg
Total				**39.2 kg**

Summary

- Updated 1-cell cavity design: 25 mm pole separation with increased beam aperture of 50 mm
  - Increased beam aperture allows better HOM extraction
- 1-cell cavity meets current specifications in:
  - Dimensional requirements, peak surface fields with required transverse voltage
  - Preliminary mechanical analysis is completed
- HOM damping with the rearranged HOM dampers on the beam pipes
  - Improved transverse impedances with sufficient margin
  - Need to verify longitudinal effects with a secondary simulation on Gdfidl or other code
- Initial cavity design is completed with FPC and HOM damping scheme
  - Need to do multipacting analysis on the full cavity including FPC and HOMs

Summary

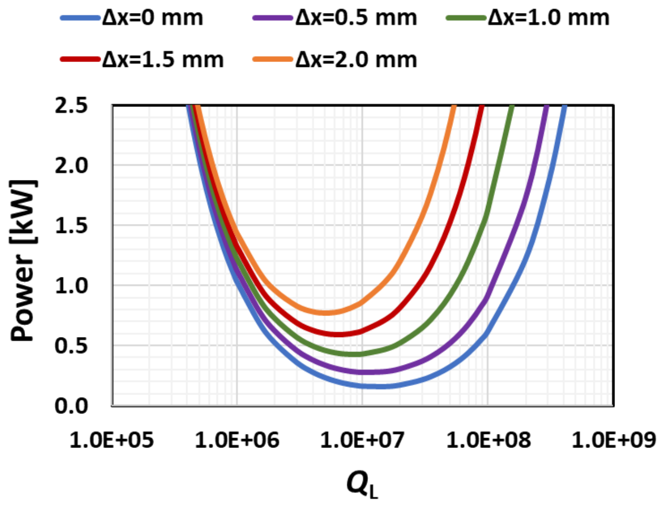
- Cryomodule design
  - For 250 GeV → Requires 2 1-cell cavities
  - For 1 TeV → Requires 6 1-cell cavities → Fits within beam line space of 3.8 m
- The design can be extended to 2-cell cavity for 1 TeV high energy
  - To achieve compact cryomodule design
- Need to further improve the cavity geometry considering
  - Fabrication feasibility
  - He jacket design
  - Tuner design

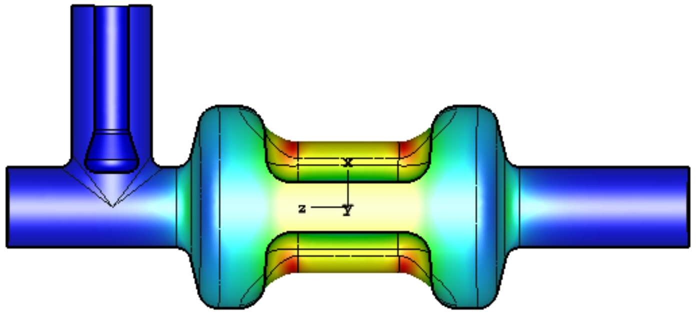
Back Up Slides

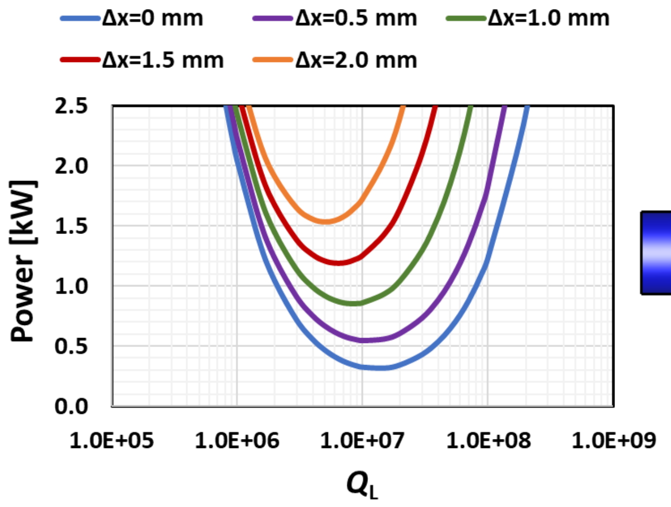
1.3 GHz RFD Cavity for ILC

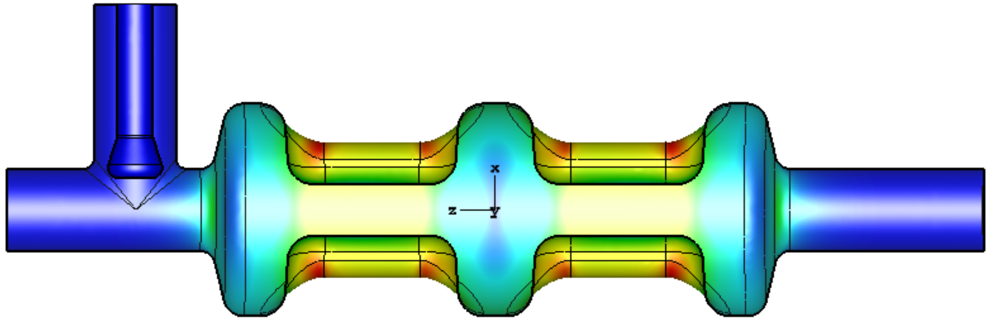
	250 GeV	1 TeV
Max V_t per cavity [MV]	1.35	1.35
Total V_t [MV]	1.845	7.4
Number of cavities	2	6
V_t per cavity [MV]	0.9225	1.234
Extra margin per cavity [MV]	0.43	0.12

Fundamental Power Coupler







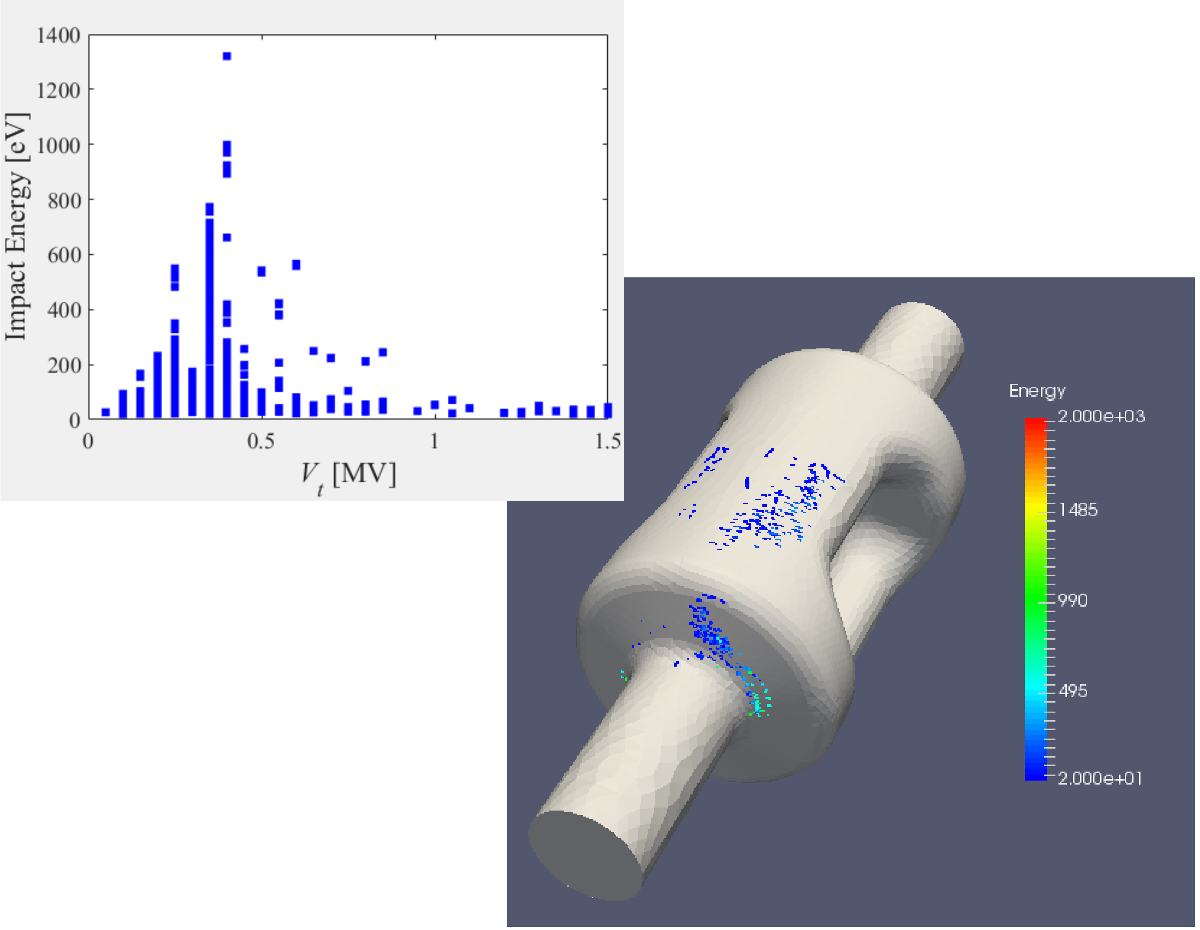


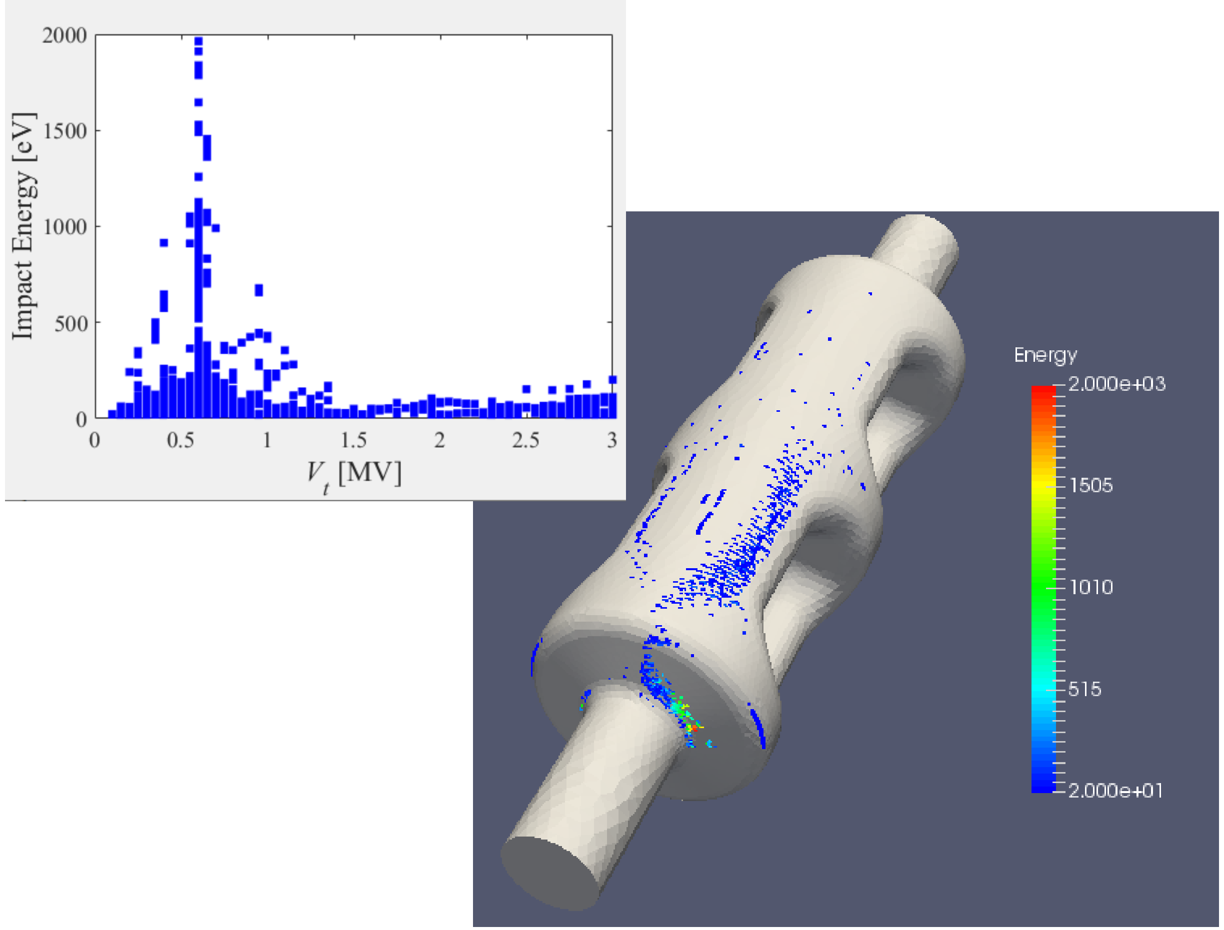
- Coupling using coaxial antenna
  - Similar to LCLS II power coupler
- Beam current: I_b = 10 mA
- Beam offset: Δx = 0.5 mm
- Microphonics: δf = 50 Hz
- Cavity parameters:

	1-cell	2-cell
R/Q [Ω]	444.8	895.6
V_t per cavity [MV]	1.35	2.7
Q_{ext}	1.5×10^7	
RF Power at the cavity [W]	300	600
RF heating at Cu probe [W]	1.2	2.22

Multipacting Analysis

- Resonant particles traced for 50 rf cycles with impact energy 20-2000 eV
- Simulated for a 1/8th surface area

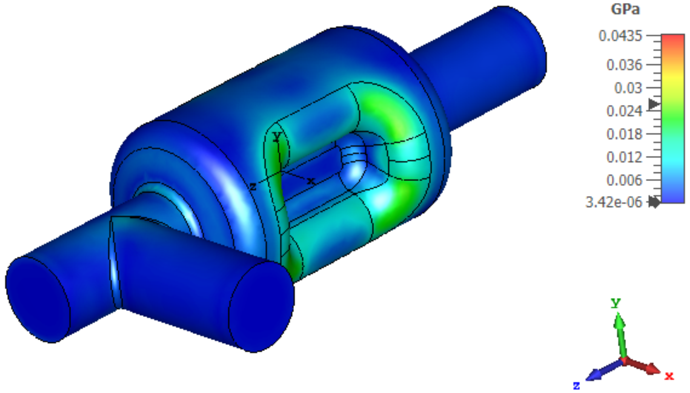


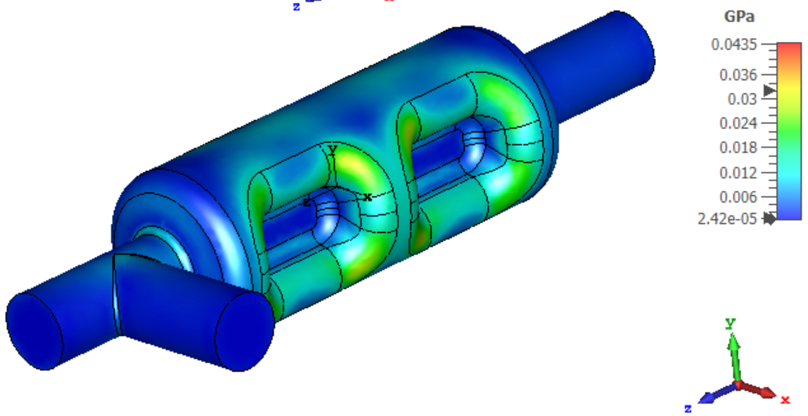


Stress Analysis

- Analysis at 2.2 atm external pressure
- Nb material properties at room temperature
  - (JLAB-TN-09-002 – C100 Cryomodule Niobium Cavity Structural Analysis)
  - Young's modulus – 82.7 GPa (1.2×10^7 psi)
  - Poisson's ratio – 0.38
- Cavity thickness – 3 mm
- Boundary conditions – Cavity constrained at beam pipes and FPC
- Allowable stress < 43.5 MPa
- Maximum stress
- Initial analysis shows cavity doesn't require stiffening
- Cavity can be machined with varying thickness

Cavity Type	Max. Stress [MPa]
1-cell	25
2-cell	32

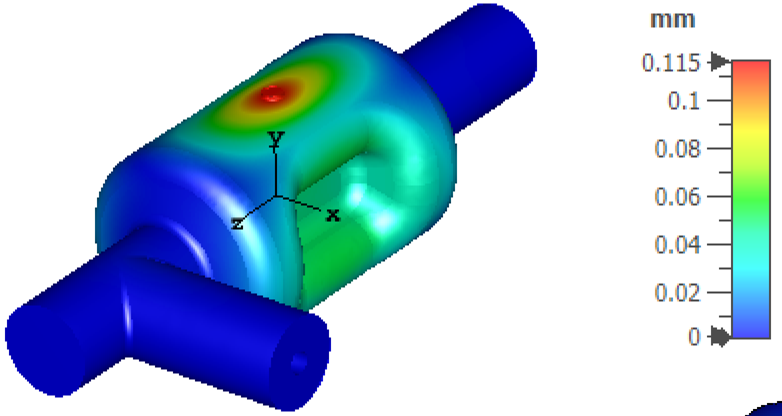


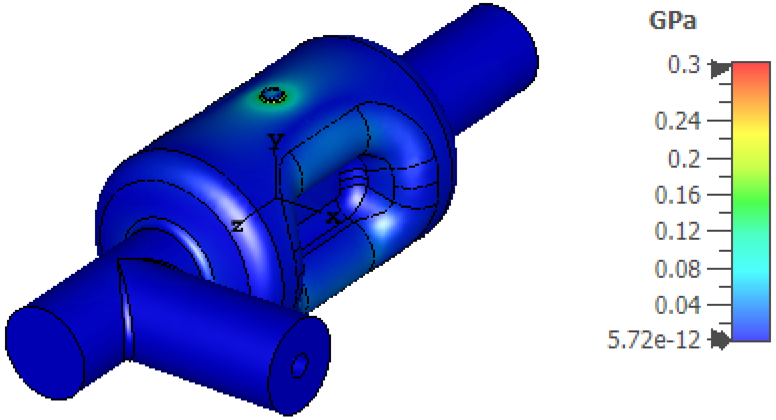


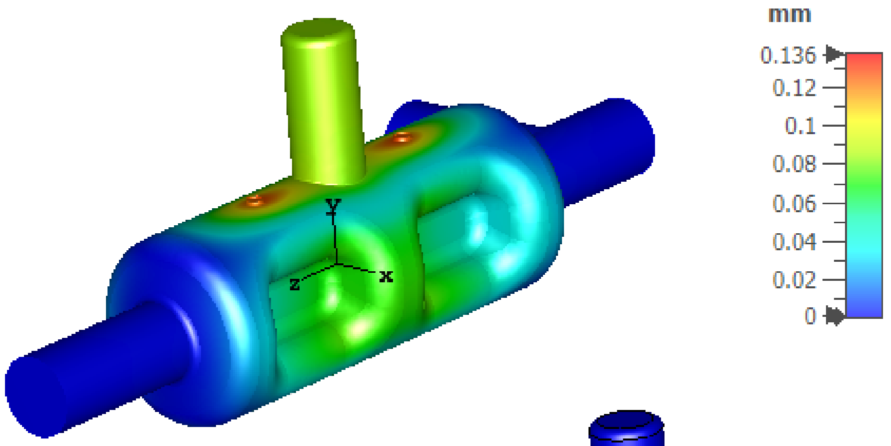
Tuning Sensitivity

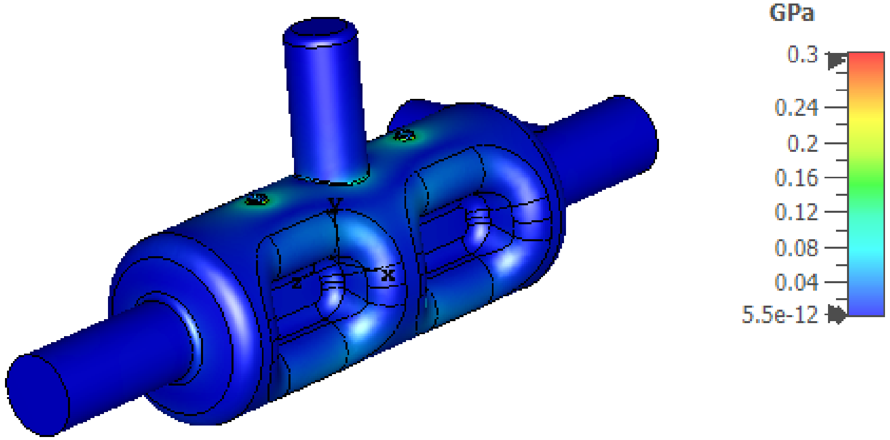
- Nb material properties at cryo temperature
  - Young's modulus – 123 GPa (1.79×10^7 psi)
- Cavity thickness – 3mm
- Cavity constrained at beam pipe ports and FPC

Cavity Type	Total Displacement	Tuning Sensitivity	Tuning Range
1-cell	0.23 mm	8.5 MHz/mm	1.96 MHz
2-cell	0.27 mm	4.1 MHz/mm	2.23 MHz







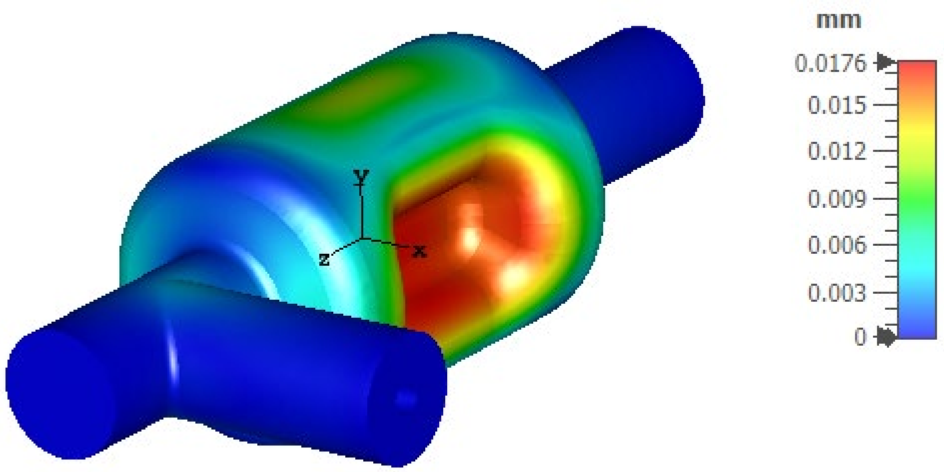


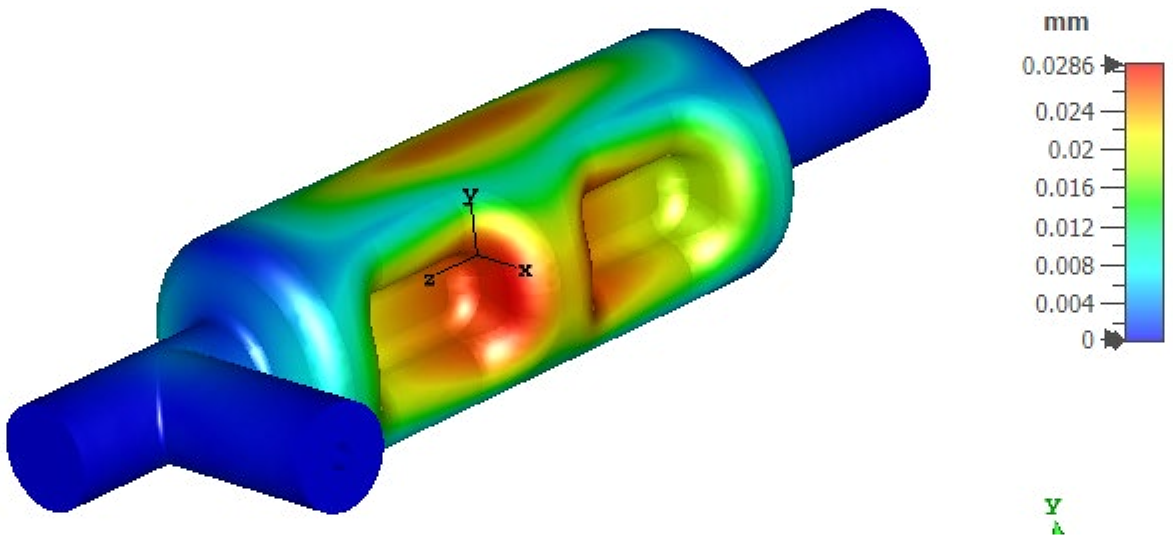
Pressure Sensitivity

- Nb material properties at room temperature
  - Young's modulus – 82.7 GPa (1.2×10^7 psi)
  - Poisson's ratio – 0.38
- Cavity thickness – 3mm
- Cavity constrained at beam pipe ports and FPC
- Stiffening at poles can reduce pressure sensitivity

Cavity Type	d*f*/d*P* [Hz/mbar]
1-cell	561.3
2-cell	751.5

- Stiffening at poles can reduce pressure sensitivity

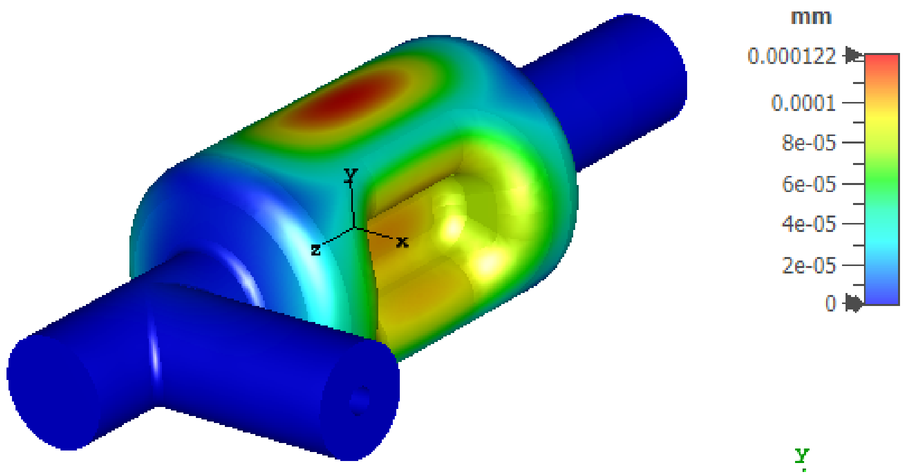


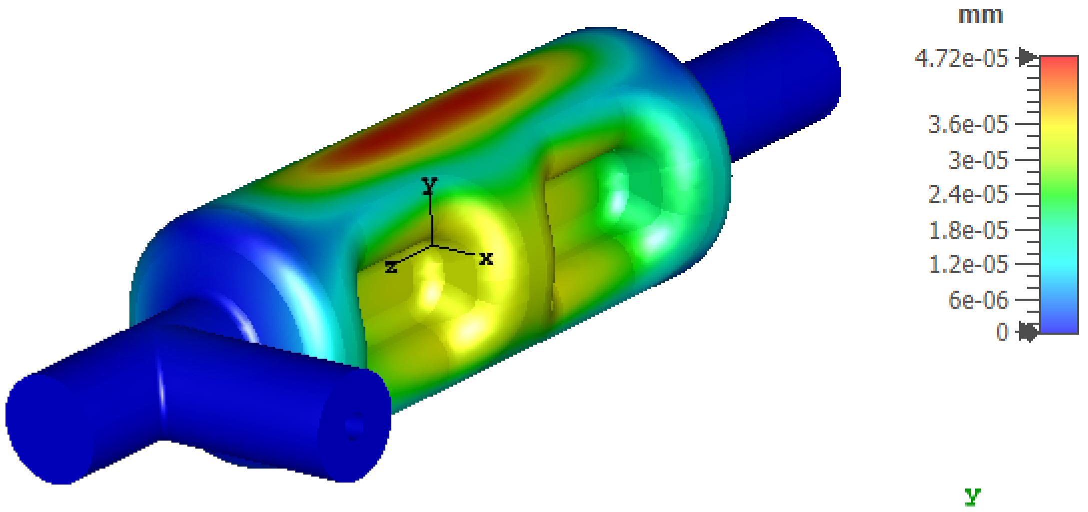


Lorentz Detuning

- Nb material properties at cryo temperature
  - Young's modulus – 123 GPa (1.79×10^7 psi)
  - Poisson's ratio – 0.38
- Cavity thickness – 3mm
- Cavity constrained at beam pipe ports and FPC
- Lorentz detuning can be reduced by tuner
  - Tuning by push/pull at top and bottom of the cavity

Cavity Type	k_L [kHz/(MV)^2]	Vt [MV]	Δf [kHz]
1-cell	-3.67	1.35	6.7
2-cell	-1.11	2.7	8.1

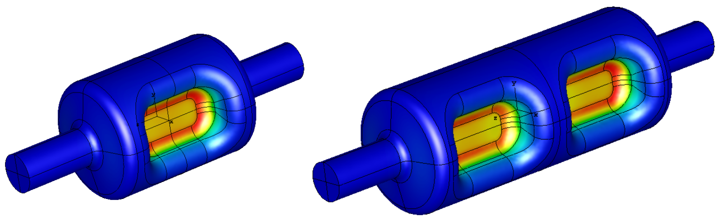


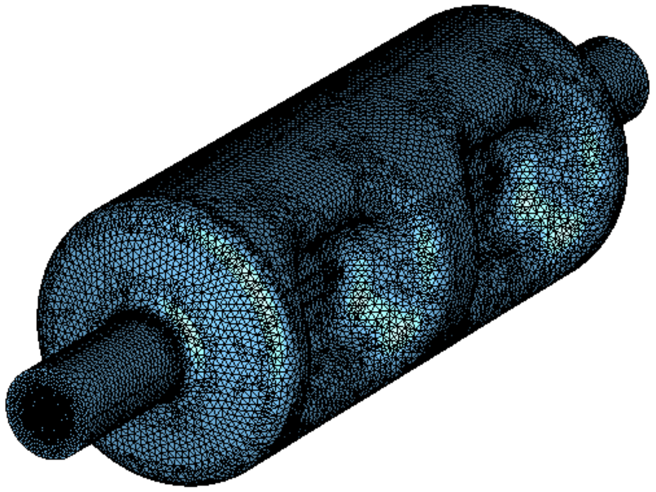


Multipole Components

- Higher order multipole components for the bare cavity

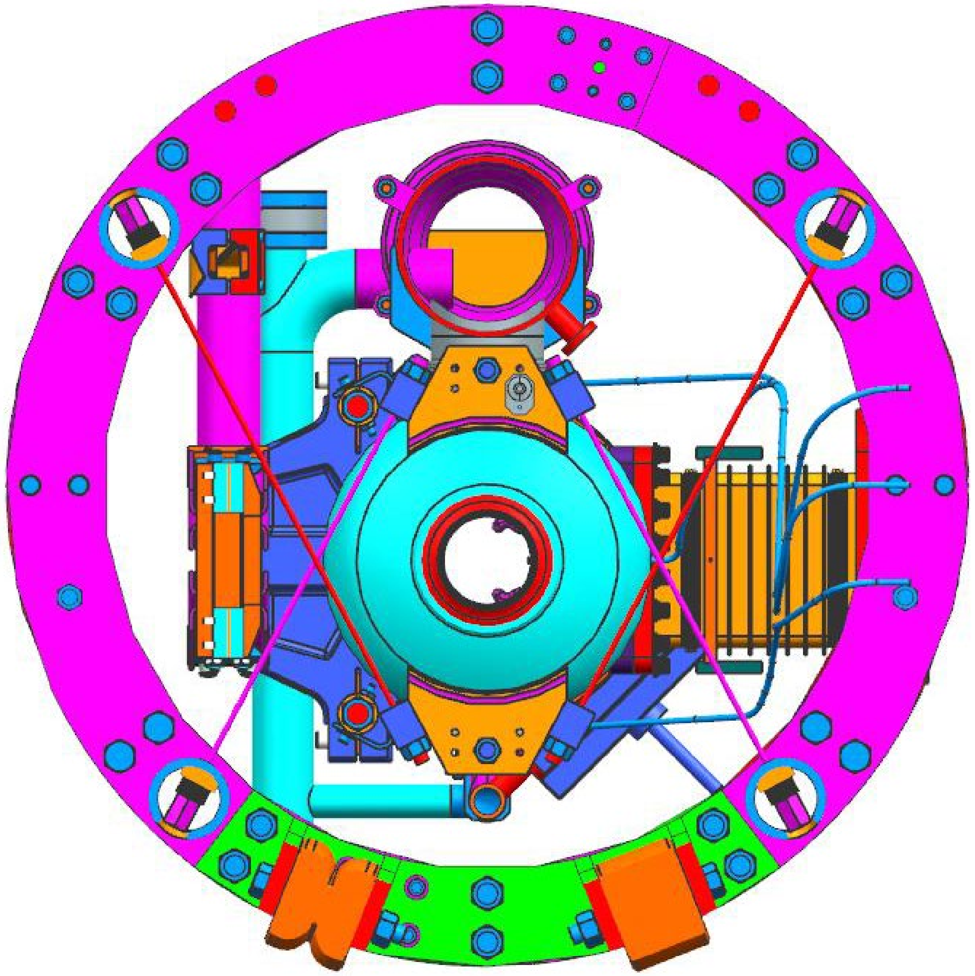
- Requires a finer mesh along the beam center



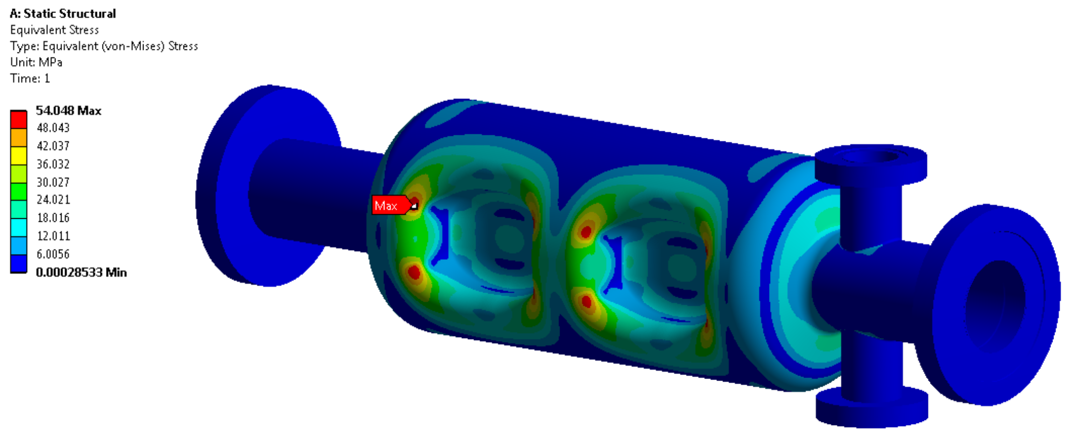


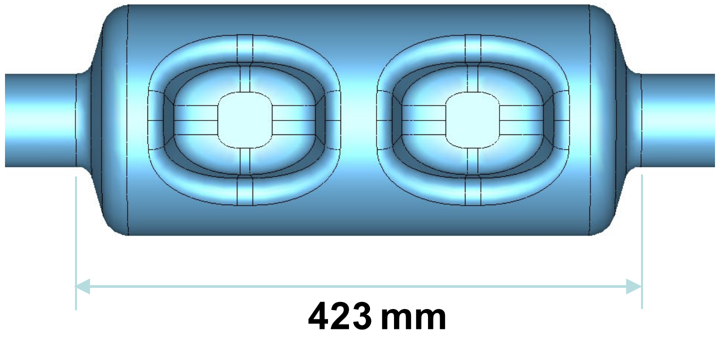
Component	Units	1-cell	2-cell
V_z	[V]	0.575	-77.25
V_t	[V]	1.0E+06	1.0E+06
b_0	[mT/m²]	0	0
b_1	[mT/m]	3.3	3.3
b_2	[mT]	-0.0013	-0.00045
b_3	[mT m]	2275.8	2106.6
b_4	[mT m²]	9.2	3.2
b_5	[mT m³]	-1.39E+6	-1.43E+6
b_6	[mT m⁴]	-4.83E+4	-1.68E+4
b_7	[mT m⁵]	-1.97E+9	-1.89E+9

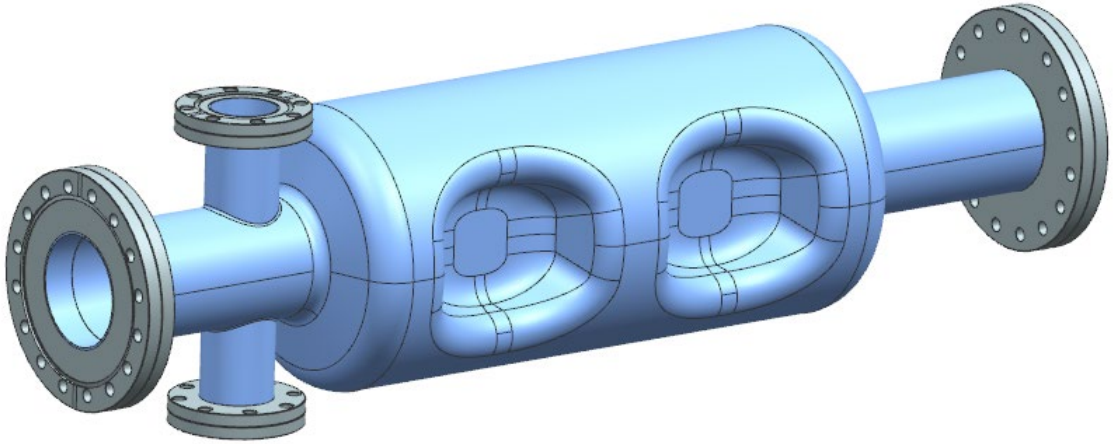
C100 Cryomodule Design

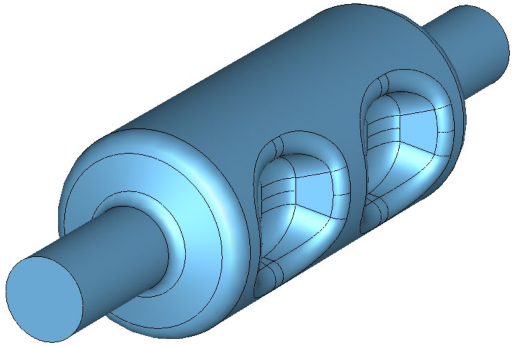


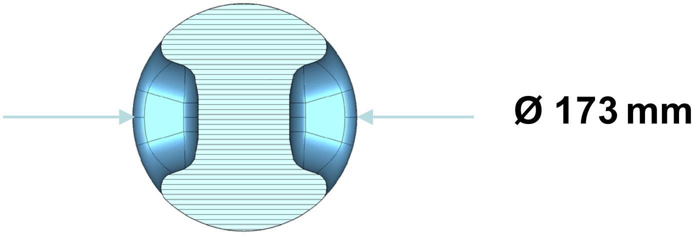
Final Design for JLEIC Crabbing System - 952 MHz 2-cell RFD











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952 MHz RFD - Fabrication in Progress

- Material cost – sheet Nb forming instead of machining
- Avoid weld seams at high mechanical stress area and high surface magnetic field area
- Use of simple weld only – high production yield
- Strategy relevant to final cavity with HOM dampers

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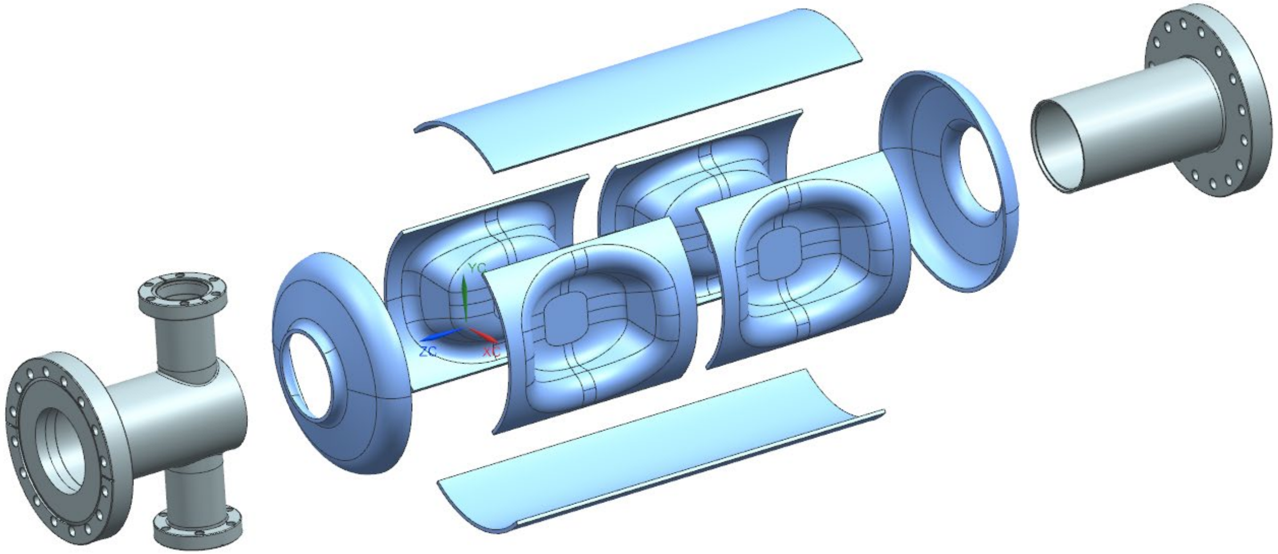

Summary

- Further HOM damping schemes to be explored
  - LHC-RFD HOM coupler option
  - Waveguide damping option
- Final choice will be decided based on
  - RF properties including HOM power
  - Engineering and manufacturing complexity