RF DIPOLE DESIGN UPDATE

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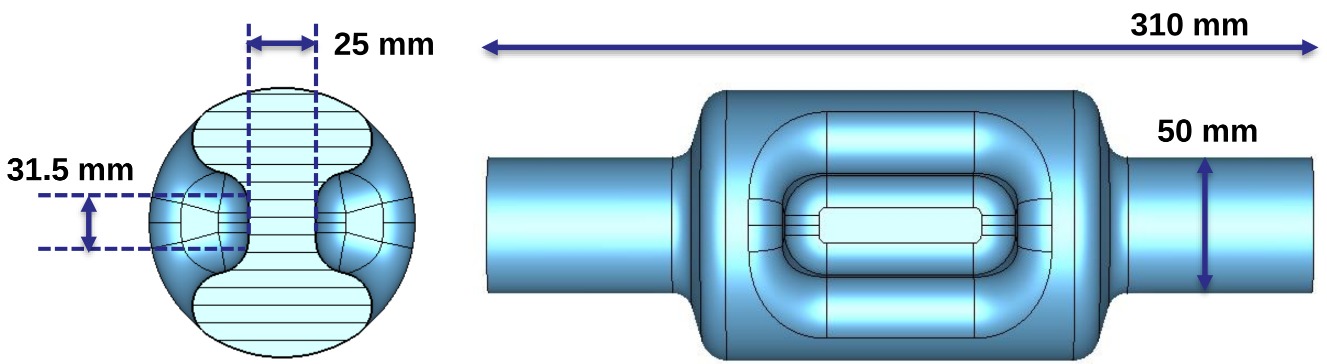
Outline

- Electromagnetic Design
  - RF Parameters
- Higher order modes and impedances
  - Transverse impedances
  - Longitudinal impedances and loss factor
- Multipole Analysis
- Stress Analysis
- Conceptual cryomodule layout
- Cavity fabrication sequence
- Summary

1.3 GHz RFD Cavity Design

- Optimized the pole shape (pole height and length):
  - To achieve peak surface field requirements of E_p < 45 MV/m and B_p < 80 mT

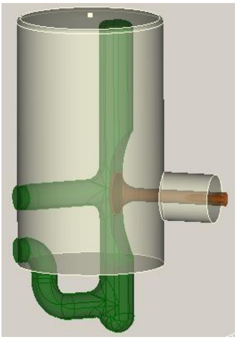


	250 GeV	1 TeV
Max V_t per cavity [MV]	1.35	1.35
Total V_t [MV]	1.845	7.4
Number of cavities	2	6
V_t per cavity [MV]	0.9225	1.234
$V_{t,max}$ / $V_{t,operational}$	1.46	1.09

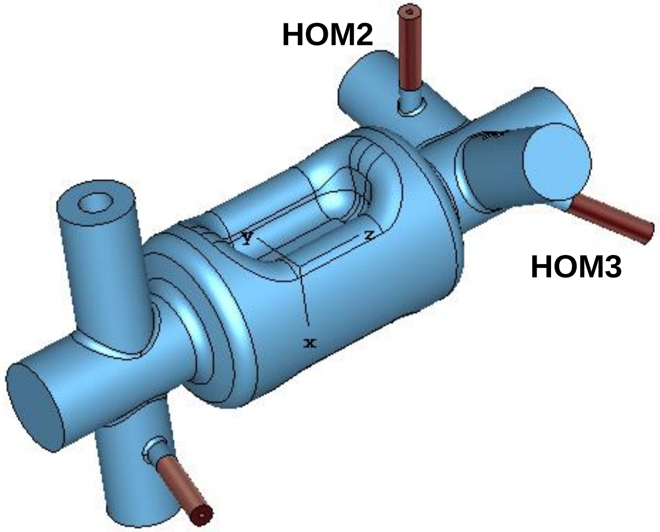
Cavity Dimensions (rf volume)	Value
Pole separation [mm]	25
Beam aperture [mm]	50
Cavity Length [mm] (flange-to-flange)	310
Cavity Diameter [mm]	99.4
Pole Length [mm]	85
Pole Height [mm]	31.5
Angle [deg]	22.5

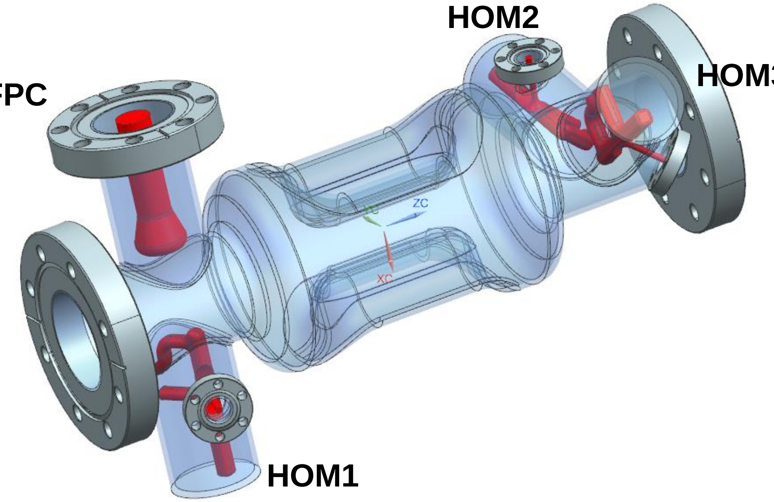
Property	Value
Operating frequency [GHz]	1.3
1st HOM [GHz]	2.089
E_p/E_t^*	3.76
B_p/E_t^* [mT/(MV/m)]	6.80
B_p/E_p [mT/(MV/m)]	1.80
G [Ω]	129.54
R/Q [Ω] (V^2/P)	440.4
R_tR_s [Ω^2] (V^2/P)	5.70×10^4
*Reference length $V/E_t = \lambda/2$ [mm]	115.3
V_t max per cavity [MV]	1.35
E_p [MV/m]	44.2
B_p [mT]	79.6
V_t per cavity [MV] (@ 125 GeV)	0.9225
Stored energy (U) [J]	0.125
P_{diss} [W] (for R_s = 30 nΩ)	0.45
Q_0 (for R_s = 30 nΩ)	4.3×10^9

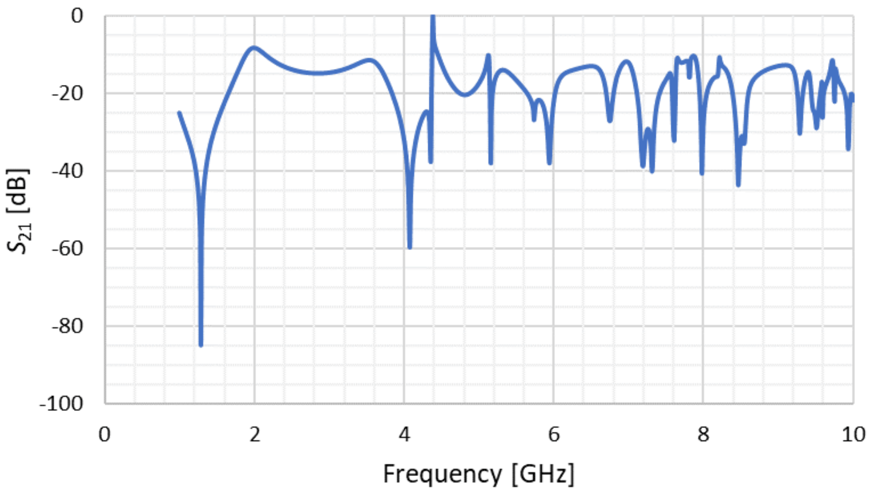
Higher Order Mode Damping



TESLA type
HOM coupler



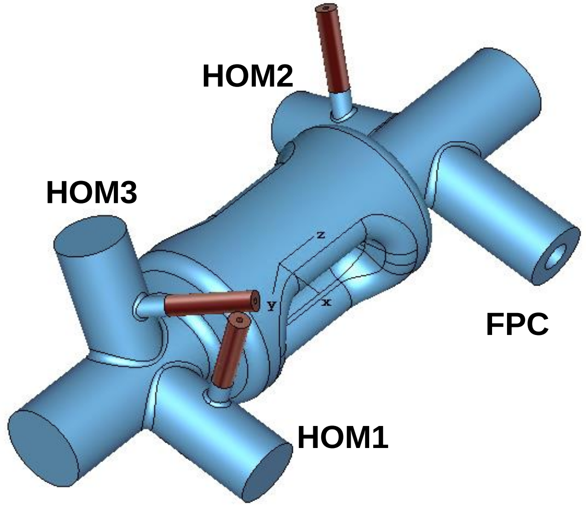


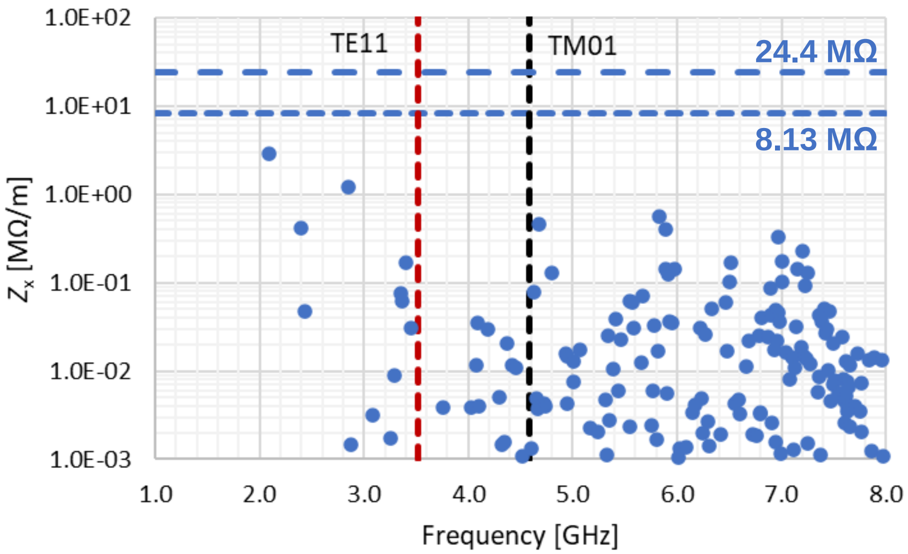


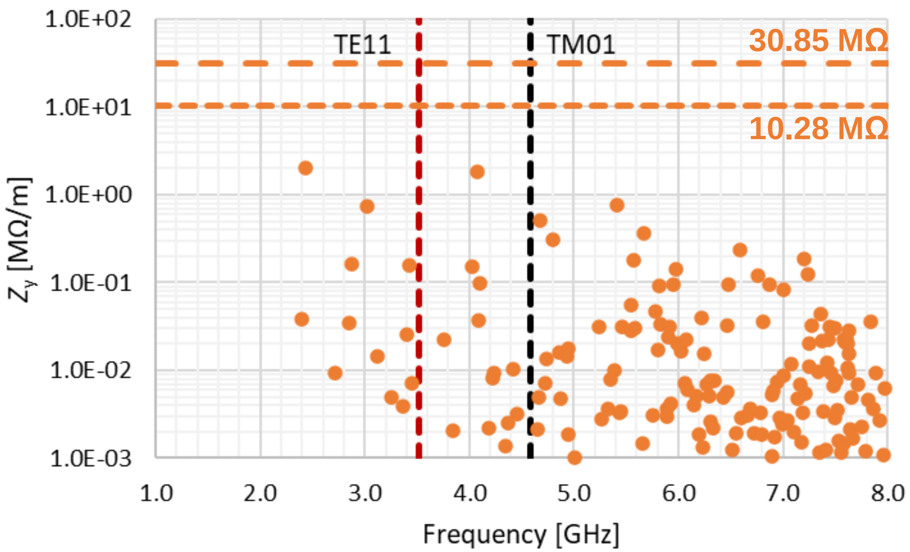
- TESLA HOM coupler with the notch at 1.3 GHz
  - A notch at 4.08 GHz
- Damping using 3 TESLA type HOM couplers
  - Damper design used in the LCLS II cavities
  - Compact damper design → Allows to place dampers on the beam pipes

Transverse HOM Impedances

- Pole separation = 25 mm and beam aperture = 50 mm
- Total impedance threshold (requirements): 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)
- Impedance threshold per cavity: Z_x = 24.4 MΩ/m and Z_y = 30.85 MΩ/m (2 cavities)
- Well damped HOMs with margin
  - Simulated with dummy coax absorbers
  - Since there is a large margin will explore damping with two HOM dampers



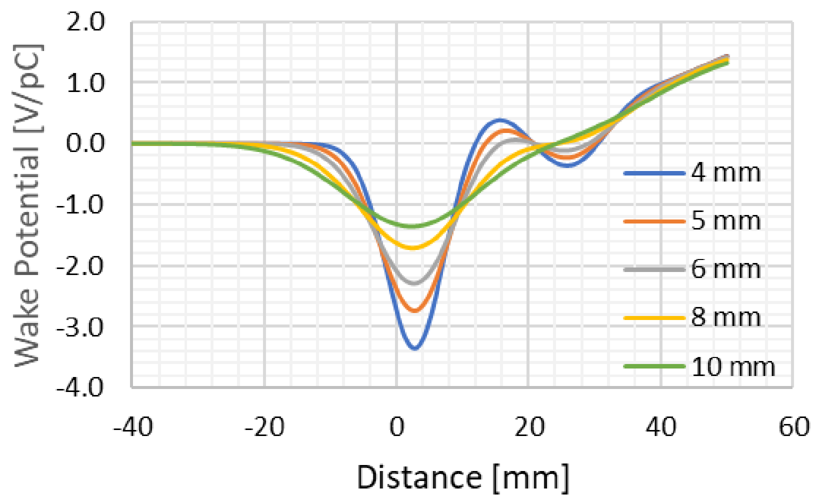


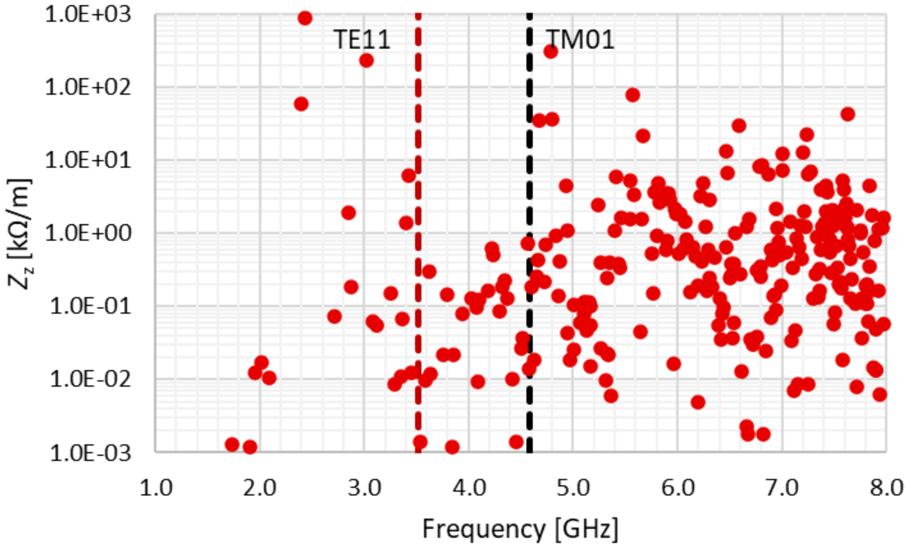


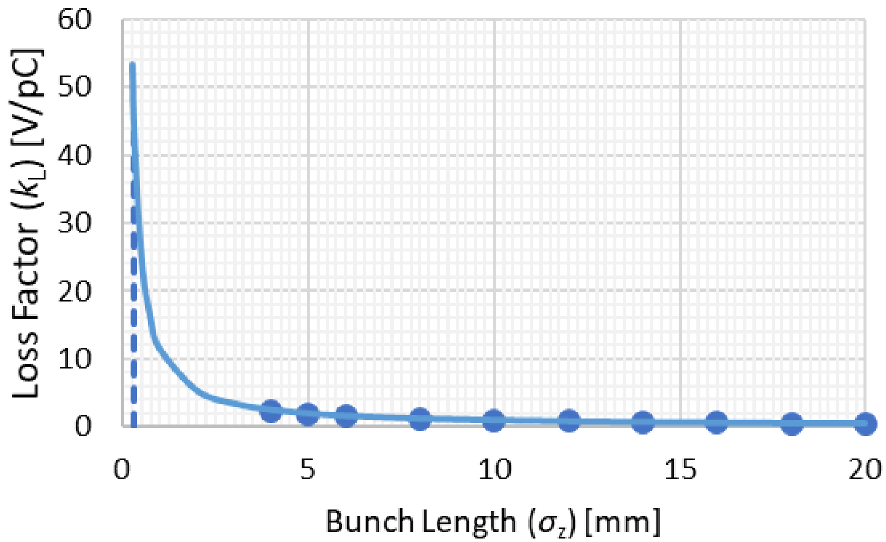
- Impedances calculated using circuit definition

Longitudinal Impedances and Loss Factor

- 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

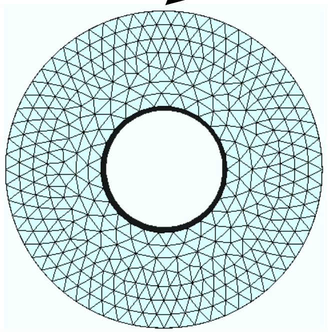


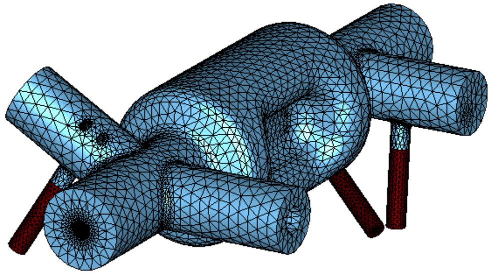




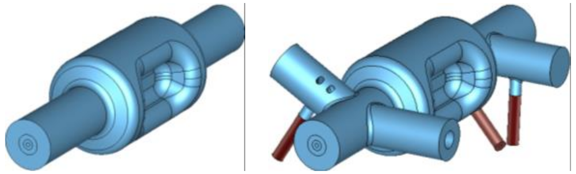
Multipole Components

- Higher order multipole components for the bare cavity and cavity with FPC and HOMs
- Multipole components normalized to V_t = 1 MV
- Calculated at a beam offset of 5 mm → To reduce noise
- # of mesh points on the 5 mm cylinder - 64



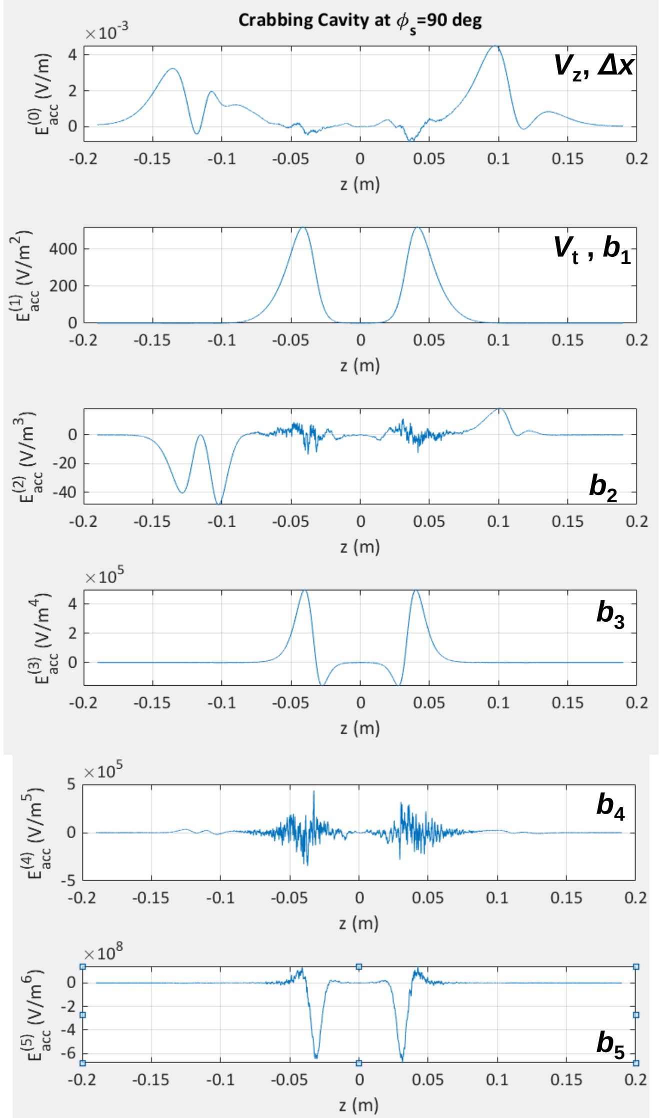


2.45M mesh cells



Component	No FPC &HOMs	With FPC & HOMs
V_t [MV]	1.0	
b_0 [mT/m²]	0.0	0.0
b_1 [mT/m]	3.34	3.34
b_2 [mT]	-1.0×10^{-3}	-0.24
b_3 [mT m]	**4377.3**	**4372.2**
b_4 [mT m²]	80.07	633.51
b_5 [mT m³]	**5.39×10^{6}**	**5.47×10^{6}**
V_z [V]	-7.0×10^{-4}	-159.4
Δx [µm]	-1.7×10^{-4}	-38.7

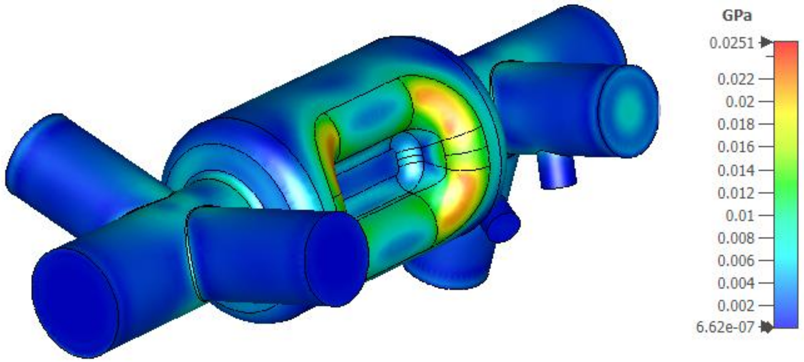
- No impact on b_3 and b_5 due to FPC & HOM dampers on the beam pipe
- FPC & HOM dampers impact the shift in electrical center

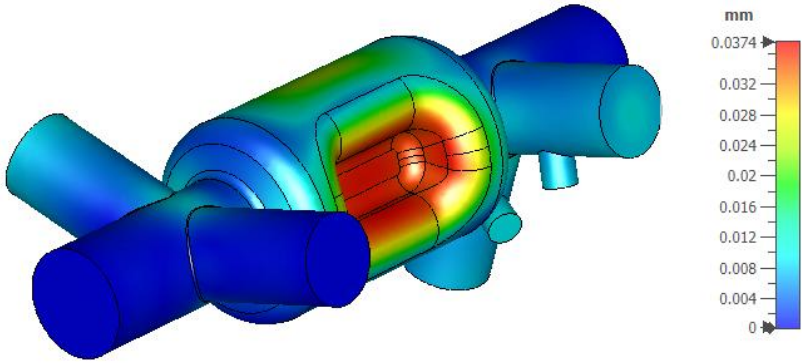


Stress Analysis

- Analysis at 2.2 atm external pressure
- Nb material properties at room temperature
  - **Reference – 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 is 25.1 MPa
- Initial analysis shows cavity doesn't require stiffening
- Cavity can be machined with varying thickness

Cavity Thickness [mm]	Max. Stress [MPa]
2.5 mm	32.6
3.0 mm	25.1

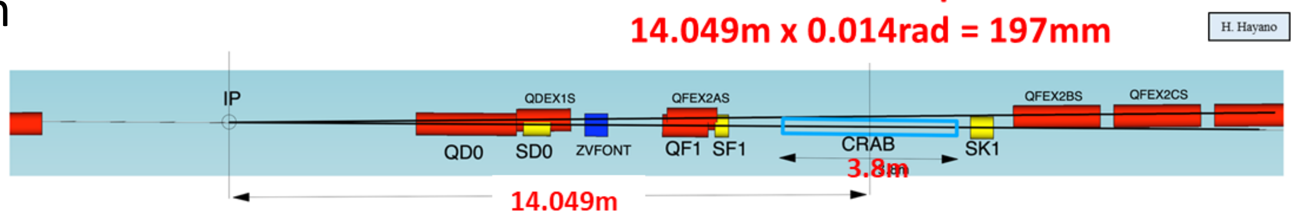


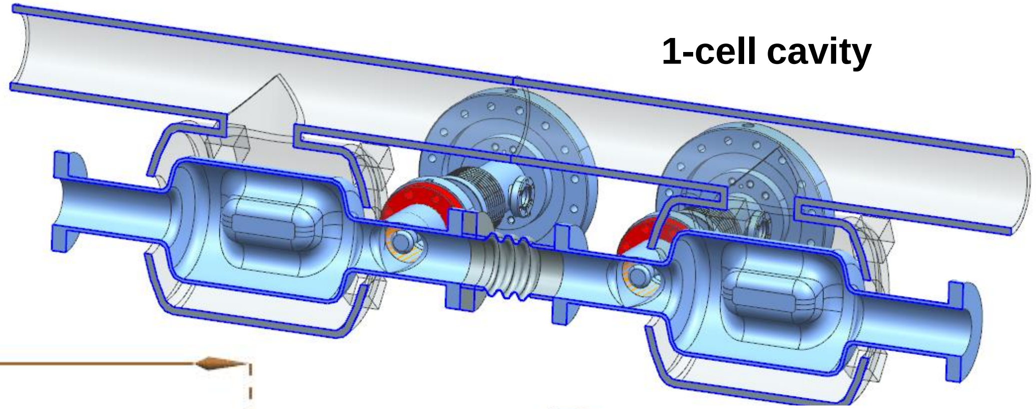


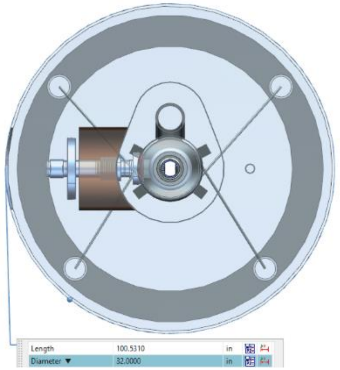
Conceptual He Vessel and Cryomodule Design

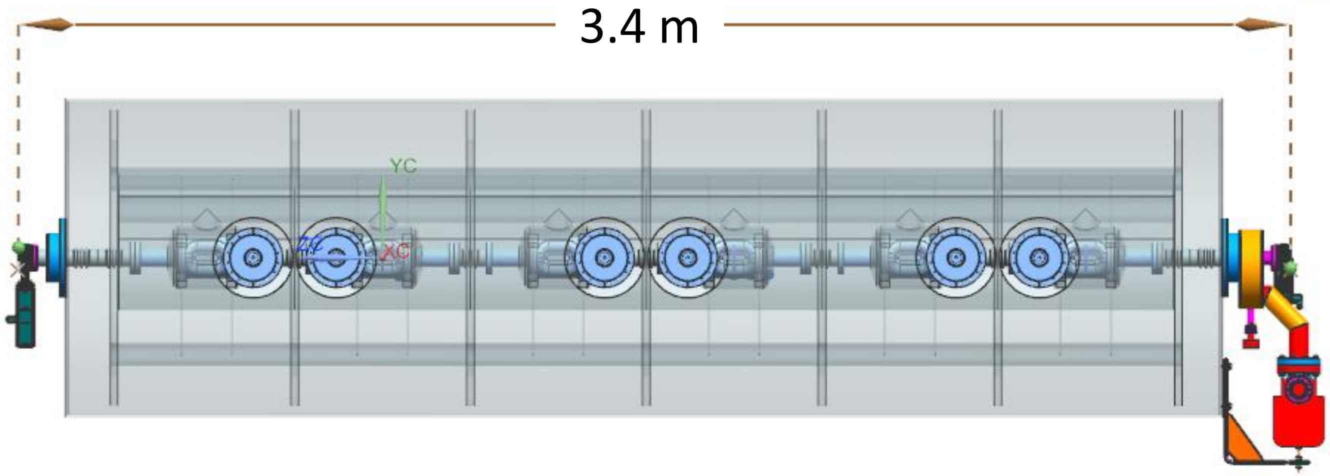
- At 1 TeV – Cryomodule required to fit in within 3.8 m
- 1-cell cavity
  - 6 cavities in a single cryomodule
  - Second beam pipe – 20 mm beam pipe
  - Total achievable – 8.1 MV (1.24 MV V_t per cavity)
  - ~10% extra margin
- Design concept follows JLab C100 cryomodule
- Cryomodule length = 3.4 m
-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

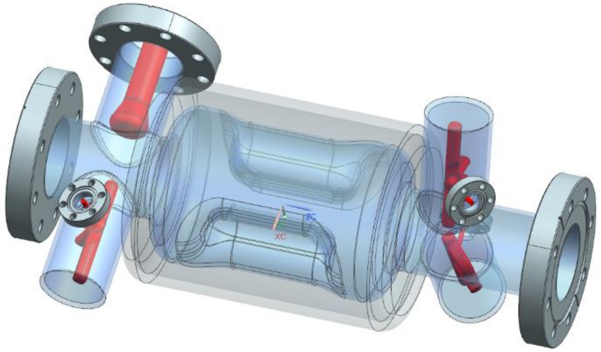
Two beamline separation
14.049m x 0.014rad = 197mm





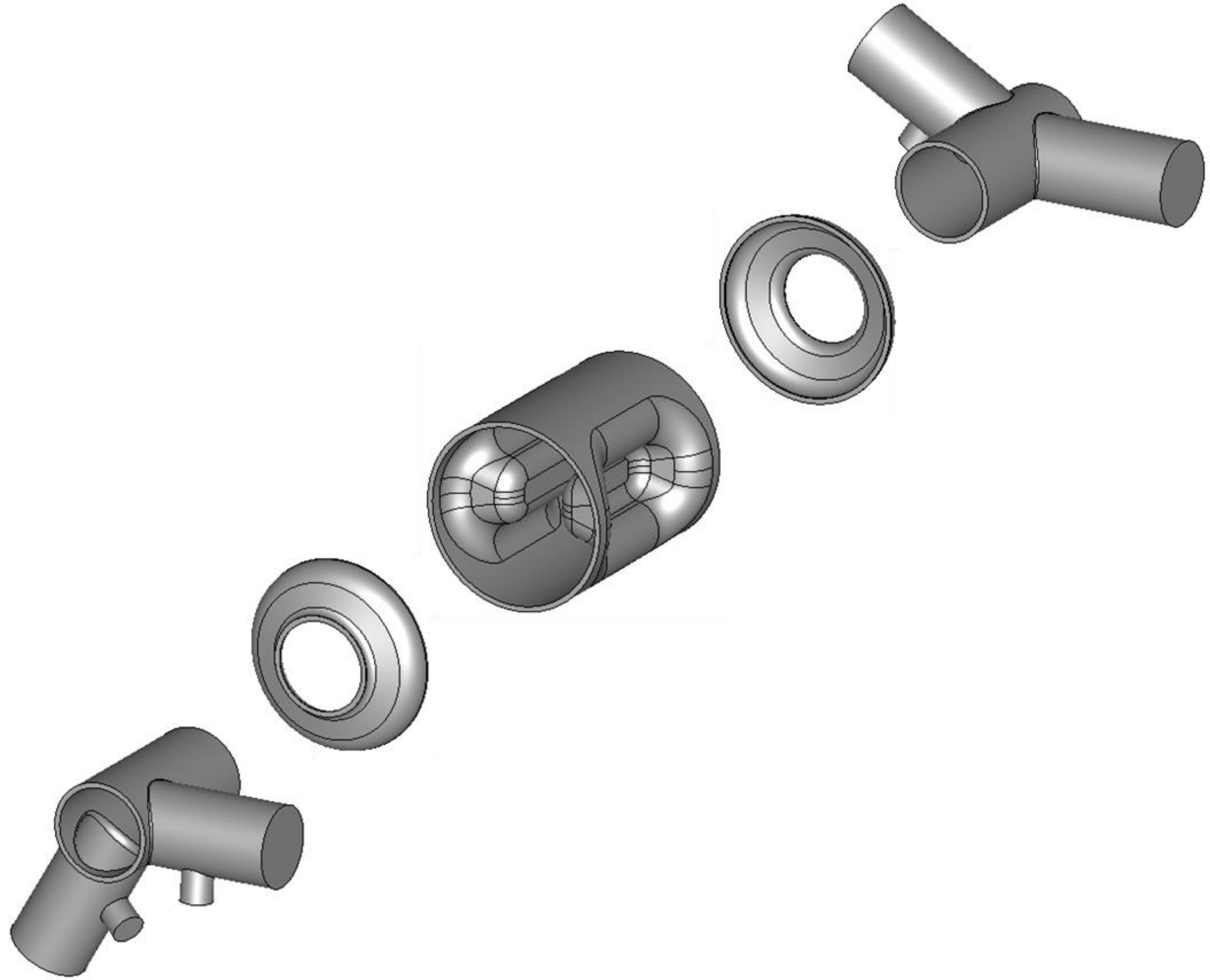






Cavity Fabrication Sequence

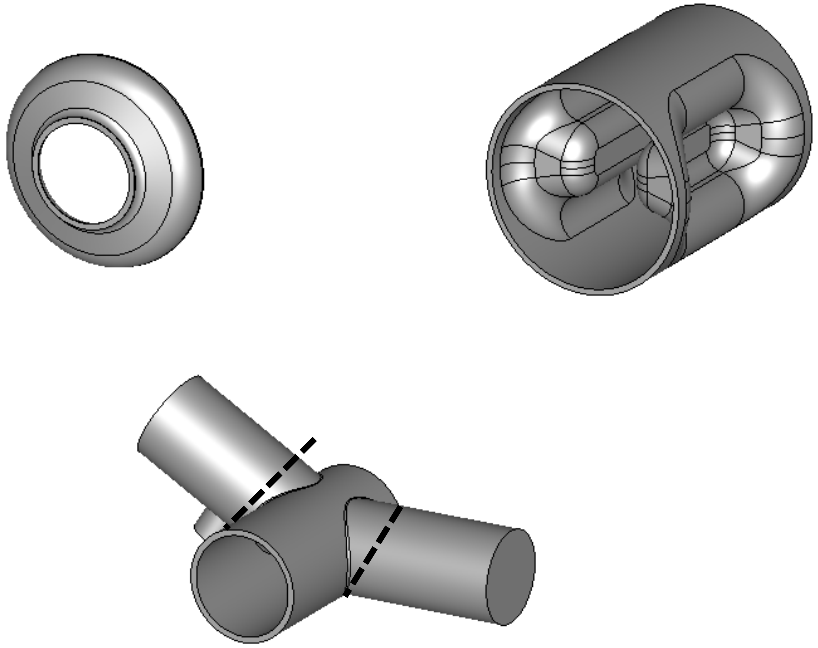
- Two fabrication options:
  - Machining out of Nb ingots
    - Better control over dimensions and tolerances
    - Reduced number of welds
    - Allows for variable thickness
  - Stamping and forming using Nb sheets
    - Well understood technology
    - Requires forming and machining dies
    - Also requires more fixturing to achieve tolerances



Option 1 – Machining Out of Nb Ingots

- Center body and end caps will be machined out of Nb ingots
- Beam pipe and HOM cans will be machined out of Nb tubes
- Parts of HOM dampers (Nb hook and probes) can be machined out of left over material from center body

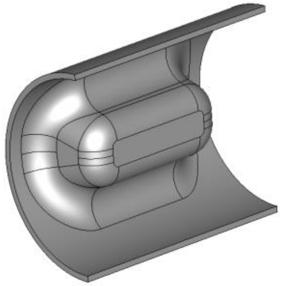
Cavity Parts (Nb)	Dimensions [in]	Qty	Weight
Center body (tube)	Ø 4.5” × 5.6”	1	12.6 kg
End caps	Ø 4.5” × 1.2”	2	5.4 kg
Beam tube including HOM transitions	ID = 1.9” OD = 3.1” L = 4.5”	2	6.1 kg
HOM cans	ID = 1.5” OD = 1.85” L = 3.0”	3	1.8 kg
Total			**25.9 kg**



Option 2 – Forming Out of Nb Sheets

- All parts will be stamped using Nb sheets of 3 mm thickness
- Center body will be formed in two halves
- Sheet dimensions include additional length of 0.5”

Cavity Parts (Nb)	Sheet type	Dimensions [in]	Qty	Weight
Center body	Sheet	7.6” × 7.4”	2	1.9 kg
End caps	Disc	Ø 6.1”	2	1.0 kg
Beam tubes	Sheet	4.6” × 7.5”	2	1.2 kg
HOM cans	Sheet	4.0” × 6.2”	3	1.4 kg
HOM coupler and probes	Ingot	ID = 1.5” OD = 1.85” L = 3.0”	3	1.8 kg
Total				**7.3 kg**



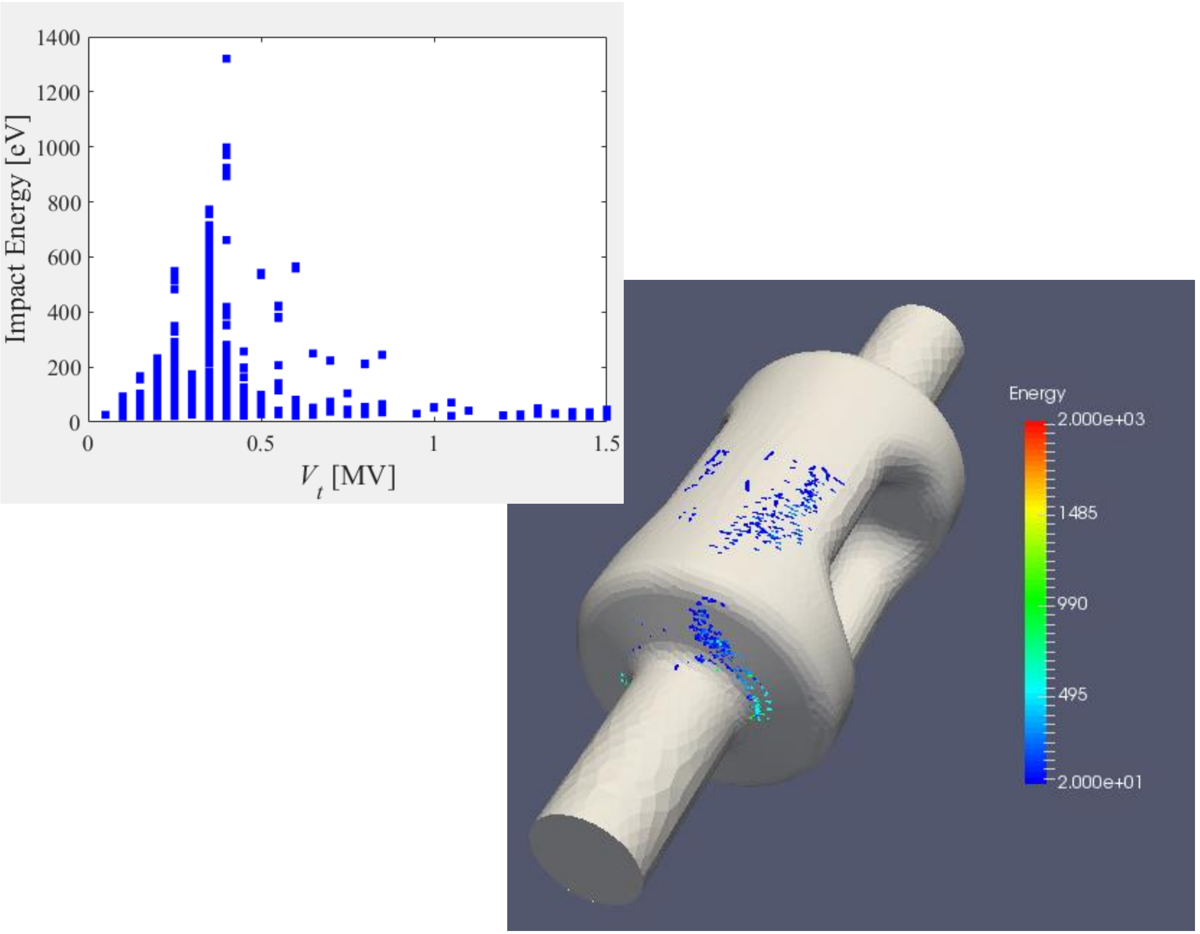
Summary

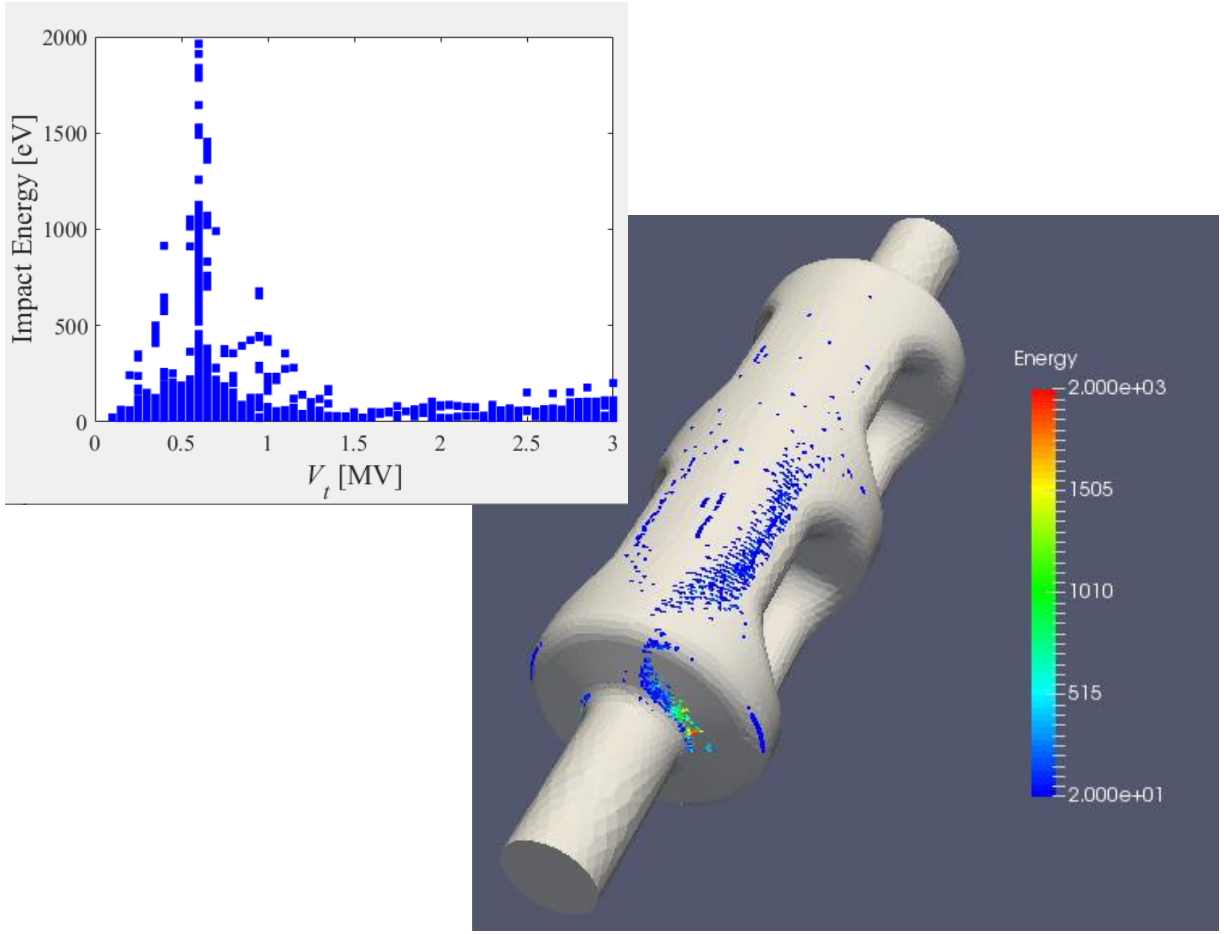
- 1-cell cavity meets current specifications in:
  - Dimensional requirements, peak surface fields with required transverse voltage
  - Preliminary mechanical analysis is completed
- HOM damping:
  - Meets transverse impedance thresholds with wide margin
  - Further calculations on loss factor and transverse kick factors pending
- Initial cavity design is completed with FPC and HOM damping scheme
  - Next steps: Multipacting analysis on the full cavity including FPC and HOMs
- Remaining work for cavity prototyping
  - Full engineering analysis
  - Manufacturing plan

Back Up Slides

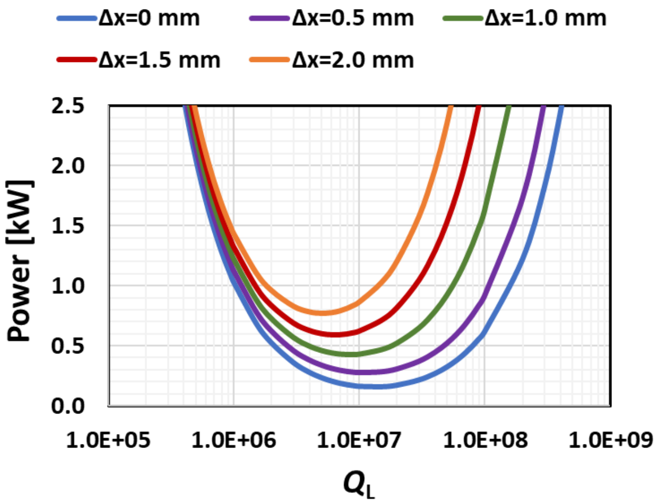
Multipacting Analysis

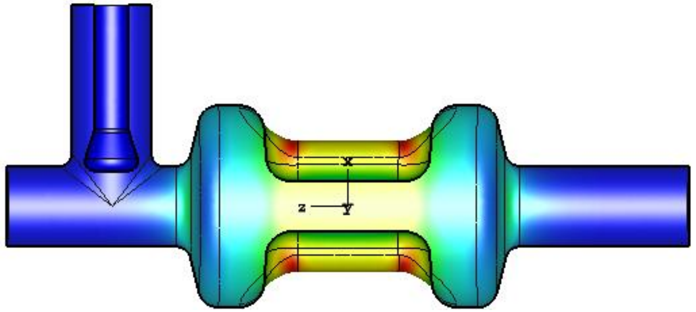
- Resonant particles traced for 50 rf cycles with impact energy 20-2000 eV
- Simulated for a 1/8th surface area

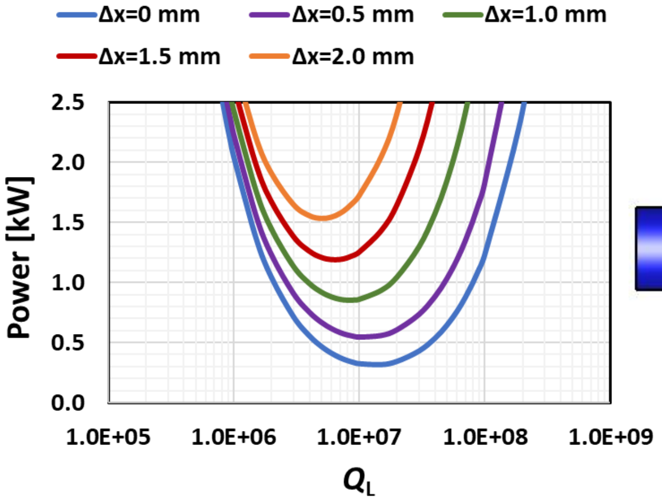


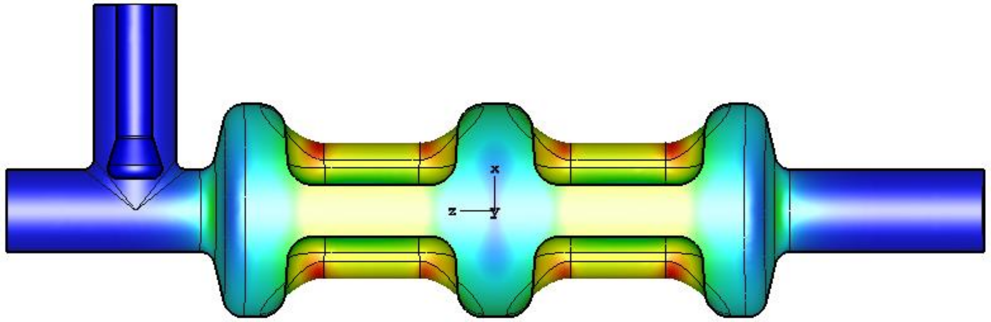


Fundamental Power Coupler







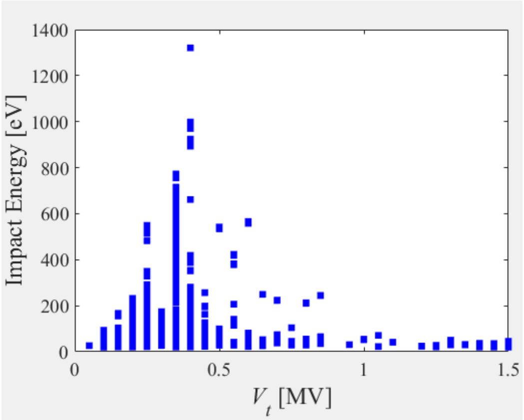


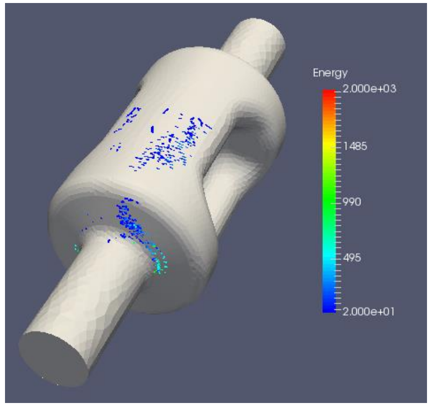
- Coupling using coaxial antenna
  - Similar to LCLS II power coupler
- Beam current: I_b = 10 mA
- Beam offset: Δx = 0.5 mm
- Microphonics: δf = 50 Hz
- Cavity parameters:

	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

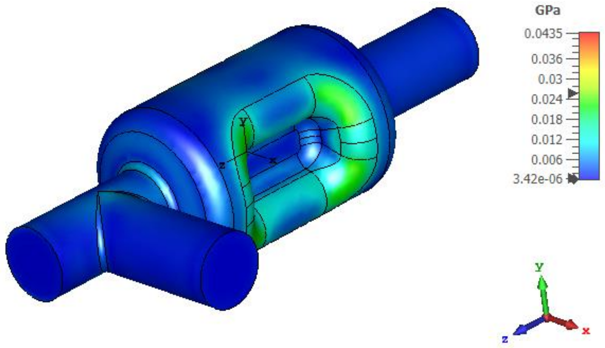
Summary from Design Review #2 (06/2022)

- **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 ≈ – 7.44 [kHz/(MV)^2] for 2.5 mm cavity thickness