1.3 GHz RF-Dipole Crabbing Cavity System for International Linear Collider

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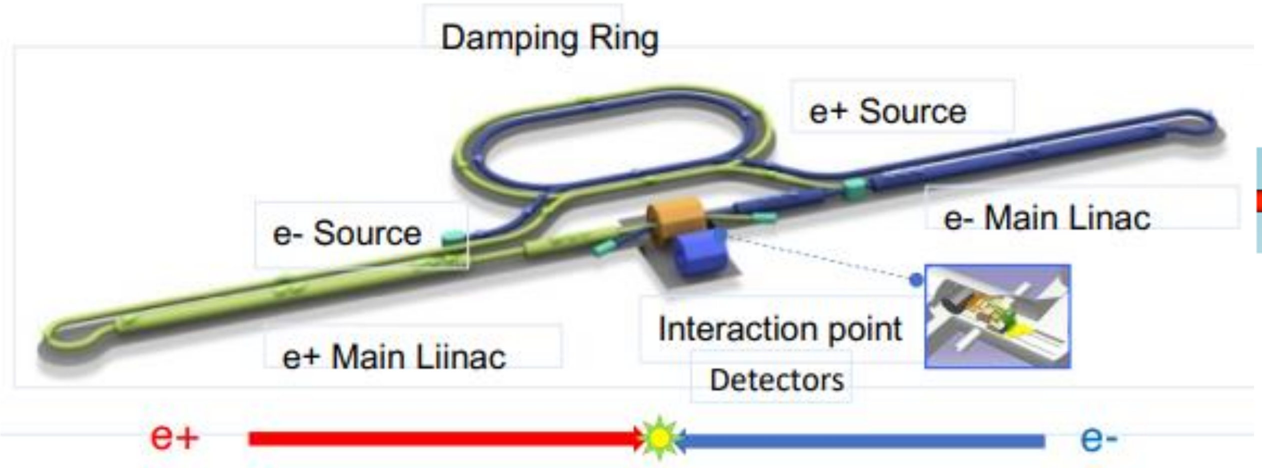
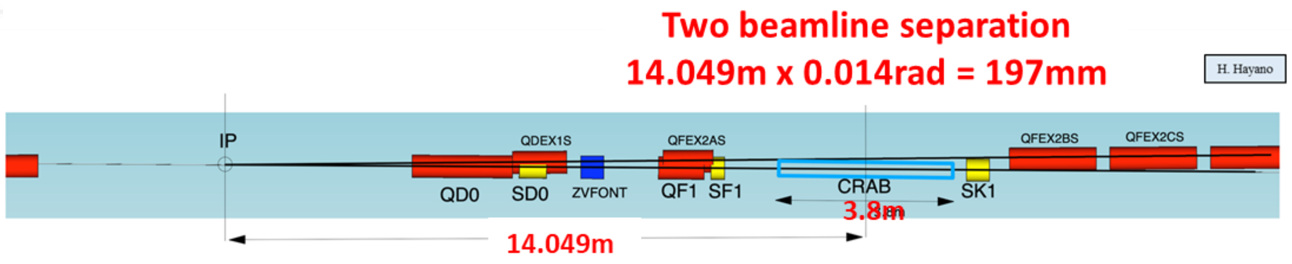
Outline

- Crabbing System for ILC
- ILC Crabbing System Specifications
- EM Design
  - RF Parameters
  - HOM Damping
- Mechanical Analysis
  - Stress Analysis
  - Tuning Sensitivity
- Fabrication Plan
- Cryomodule Layout
- Summary and Next Steps

Crabbing System for ILC





- Baseline design: $\sqrt{s}$ = 250 GeV with upgrade to 1 TeV
- Luminosity: $1.35/2.7\times10^{10}$ cm^2s^{-1}
- Crossing angle: 14 mrad
- Transverse voltage:

Beam Energy	250 GeV			1 TeV		
f_0 [GHz]	**1.3**	2.6	3.9	**1.3**	2.6	3.9
Tot. V_t [MV	**1.845**	0.923	0.615	**7.4**	3.7	2.5

ILC Technical Design Report

Parameter	Value
Center of mass energy [GeV]	250/1000
Crossing angle [mrad]	14.0
β_{cc} [m]	23.2
β_{IP} [mm]	13.0/22.6
RMS bunch length (σ_z) [mm]	0.3/0.25
RMS horizontal beam size (σ_x^*) [nm]	729.0/481.0

Requirements for ILC 1.3 GHz Crab Cavity

- Operating frequency – 1.3 GHz
  - Transverse voltage – 1.845 MV (125 GeV) and 7.4 MV (for 500 GeV)
- Maximum fields – E_p < 45 MV/m and B_p < 80 mT
- Total impedance threshold:
  - Z_x = 48.8 MΩ/m and Z_y = 61.7 MΩ/m
- Transverse kick factors:
  - $k_x < 1.6\times10^3$ V/pc/m and $k_y < 1.2\times10^2$ V/pc/m
- Tuning specifications – 100-180 kHz

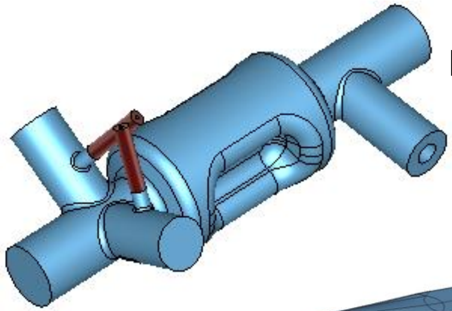
- Dimensional constraints:
  - Minimum beam aperture = 25 mm
  - Total cryomodule length < 3.8 mm
  - Parallel beam pipe separation = 197 mm

ILC Crab Cavity Specifications (V19) – P. McIntosh

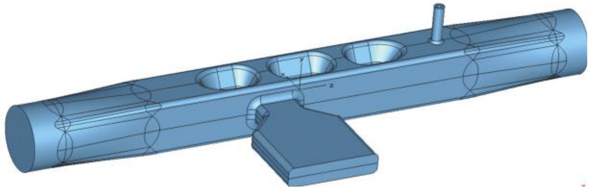
Parameter	Post-TDR Specification		10Hz Upgrade[1,2]	1 TeV CoM Spec[2]		
Beam Energy (GeV) e-	125			500		
Crossing Angle (mrad)	14					
Installation site (m from IP)	14					
RF Repetition Rate (Hz)	5		10	4		
Number of bunches	1312		2625	2450		
Bunch Train Length (ms)	727		961	897		
Bunch Spacing (ns)	554		366			
Beam current (mA)	5.8		8.75	7.6		
Operating Temp (K)	2					
Cryomodule installation length (m)	3.8 (incorporating gate valves)					
Horizontal beam-pipe separation (m)	0.1967 (centre) ±0.0266 (each end of installation length)					
Cavity Frequency (GHz)	3.9	2.6	1.3	3.9	2.6	1.3
Total Kick Voltage (MV)	0.615	0.923	1.845	2.5	3.7	7.4
Max Ep (MV/m)	45					
Max Bp (mT)	80					
Amplitude regulation/cavity (% rms)	3.5 (for 2% luminosity drop)					
Relative RF Phase Jitter (deg rms)	0.069					
Timing Jitter (fs rms)	49 (for 2% luminosity drop)					
Max Detuning (kHz)	240	170	100 - 180	240	170	100 - 180
Longitudinal impedance threshold (Ohm)	Cavity wakefield dependent					
Trasverse impedance threshold (MOhm/m) (X,Y)	48.8, 61.7					
Cavity field rotation tolerance/cavity (mrad rms)	5.2 (for 2% luminosity drop)					
Beam tilt tolerance (H and V) (mrad rms and urad rms)	0.35, 7.4 (for 2% luminosity drop)					
Minimum CC beam-pipe aperture size (mm)	>25 (same as FD magnets)					
Minimum Exraction beam-pipe aperture size (mm)	20					
Beam size at CC location (X, Y,Z) (mm,um,um)	0.97, 66, 300					
Beta function at CC location (X, Y) (m,m)	23200, 15400					
Horizonal kick factor (kx) (V/pC/m)	<< 1.6×10^3					
Vertical kick factor (ky) (V/pC/m)	<< 1.2×10^2					
CC System operation	assume CW-mode operation					

ILC Crab Cavity Designs

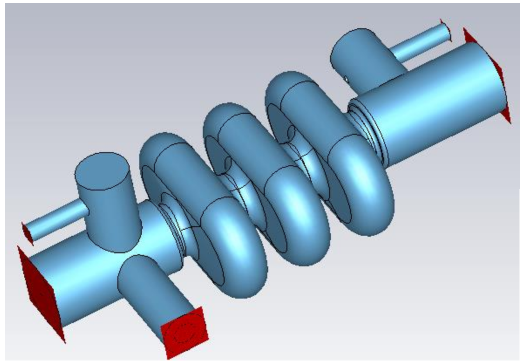
- Several crab cavity designs have been proposed
- Down Selection Review on Crab Cavity Design – April 4-6, 2023 – KEK, Japan
  - Two crab cavity designs were down selected
- 2 Final Designs
  - RF-Dipole Cavity (RFD) [1.3 GHz] from ODU/JLab
  - Quasi-waveguide Multi-cell Resonator (QMiR) [2.6 GHz] from Fermilab
- 2 selected designs will go into prototype production in the 18 month Pre-Lab phase



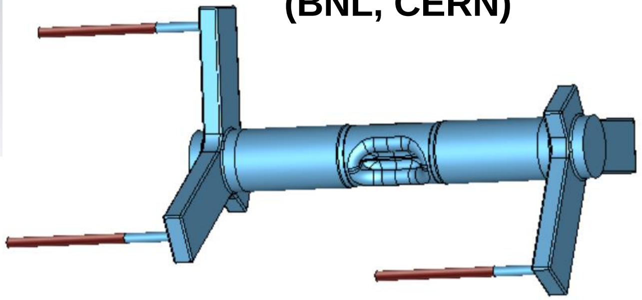
RFD 1.3 GHz (ODU/JLAB)



QMIR 2.6 GHz (FERMILAB)



RACETRACK 3.9 GHz (LANCASTER UNIV. /COCKTROFT)

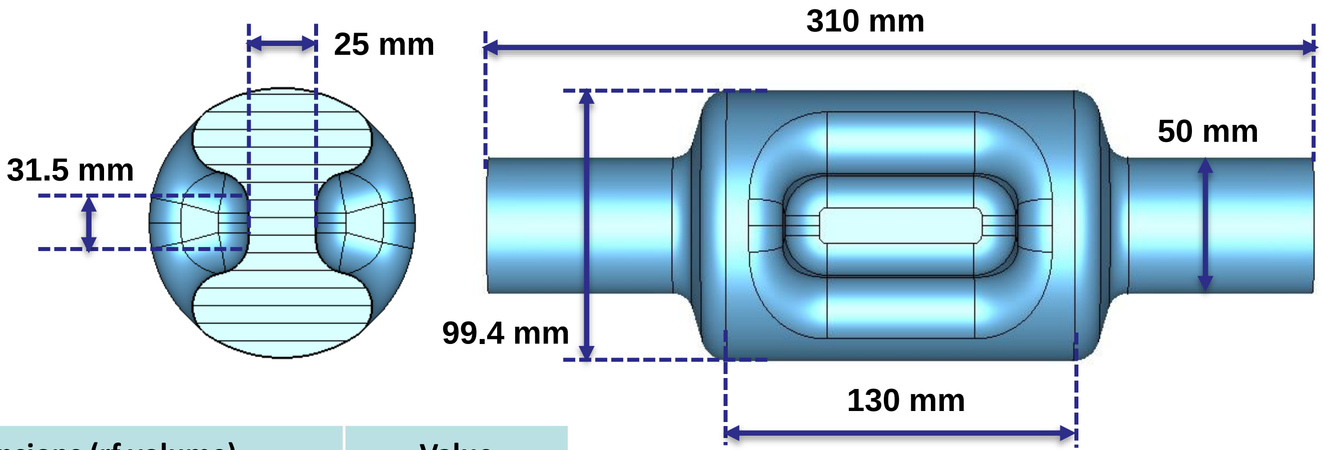


WOW 1.3 GHz (BNL, CERN)

DQW 1.3 GHz (BNL, CERN)

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



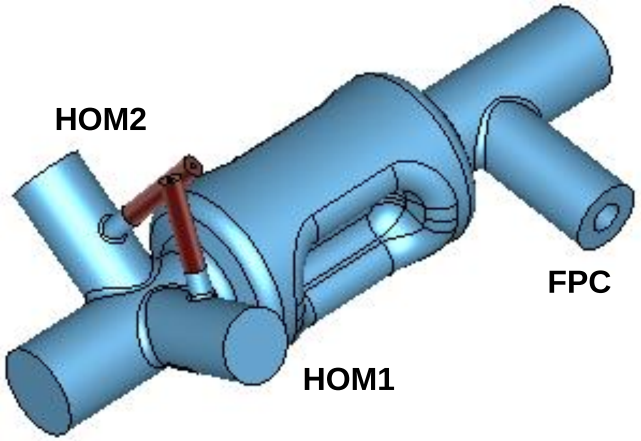
Cavity Dimensions (rf volume)	Value
Pole separation [mm]	25
Beam aperture [mm]	50
Cavity Length [mm] (flange-to-flange)	310
Cavity Diameter [mm]	99.4
Pole Length [mm]	85
Pole Height [mm]	31.5
Angle [deg]	22.5

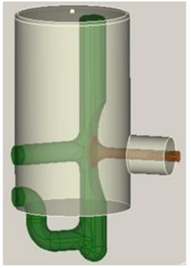
	250 GeV	1 TeV
Max V_t per cavity [MV]	1.36	1.36
Total V_t [MV]	1.845	7.4
Number of cavities	2	6
V_t per cavity [MV]	0.9225	1.234
$V_{t,max}$ / $V_{t,operational}$	1.47	1.10

Property	Value
Operating frequency [GHz]	1.3
1st HOM [GHz]	2.089
E_p/E_t^*	3.81
B_p/E_t^* [mT/(MV/m)]	6.78
B_p/E_p [mT/(MV/m)]	1.78
G [Ω]	129.88
R/Q [Ω] (V^2/P)	439.51
R_tR_s [Ω²] (V^2/P)	5.71×10^4
*Reference length $V/E_t = \lambda/2$ [mm]	115.3
V_t max per cavity [MV]	1.36
E_p [MV/m]	44.94
B_p [mT]	79.96
V_t per cavity [MV] (@ 125 GeV)	0.9225
Stored energy (U) [J]	0.237
P_{diss} [W] (for R_s = 30 nΩ)	0.45
Q_0 (for R_s = 30 nΩ)	4.33×10^9

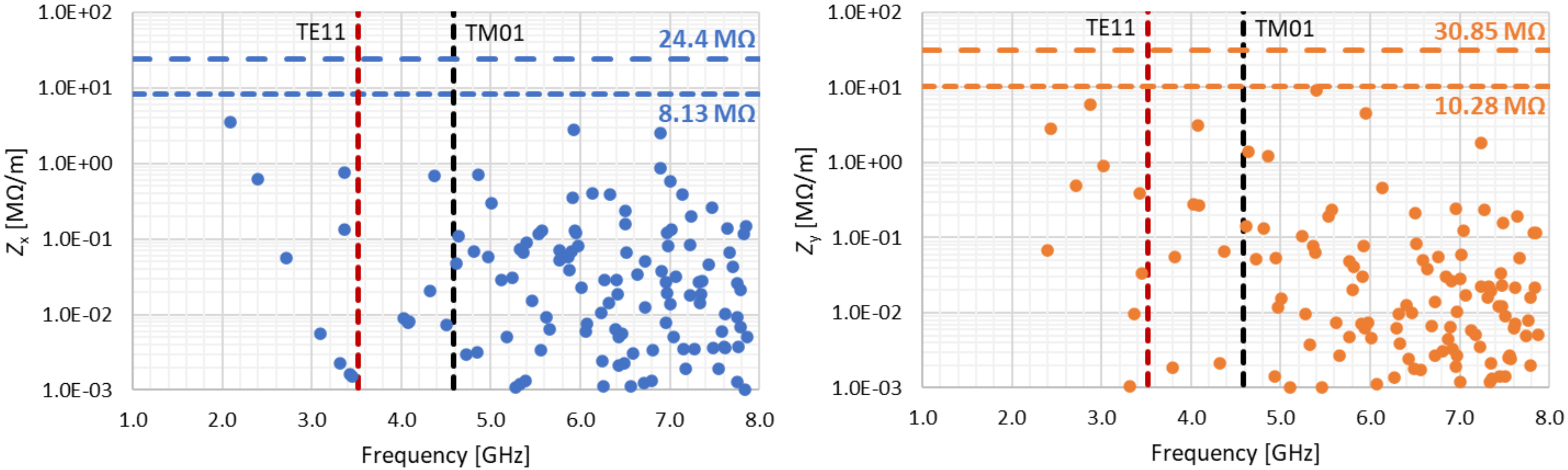
HOM Impedances

- Damping using 2 TESLA type HOM couplers
- 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)
- Dampers placed on one end of the cavity: no interference with the FPC





TESLA type HOM coupler



Impedances calculated using circuit definition

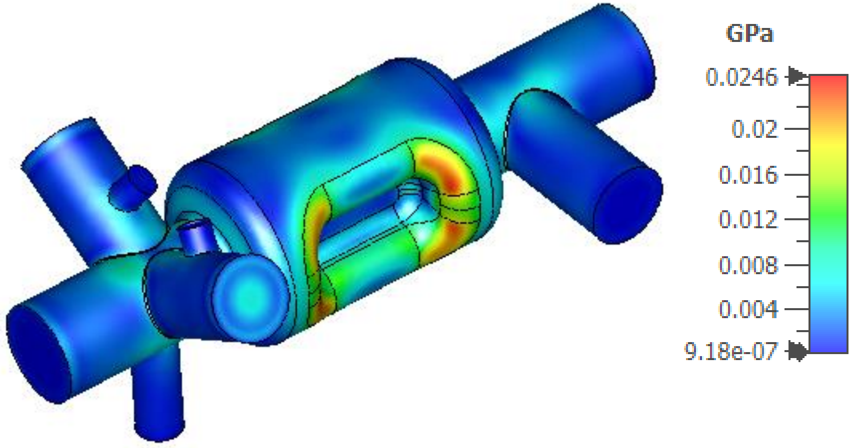
Stress Analysis

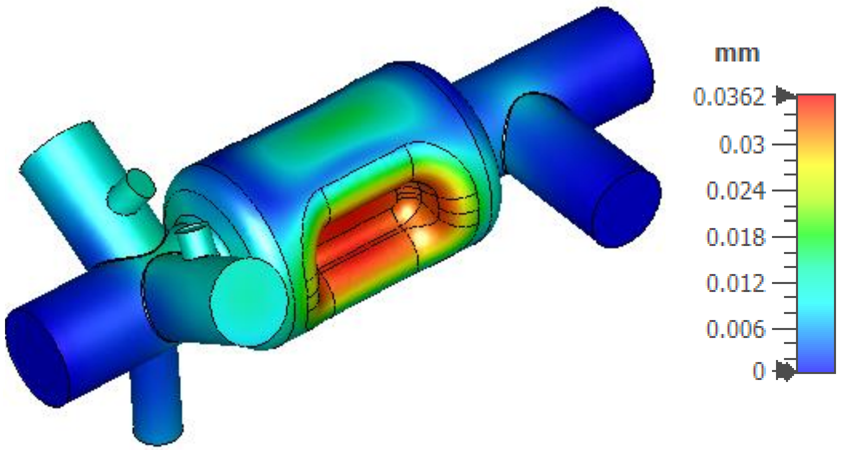
- Analysis at 2.2 atm external pressure
- Nb material properties at room temperature for MG
  - Young’s modulus – 88.7 GPa
  - Poisson’s ratio – 0.38
- Cavity thickness – 3 mm
- Allowable stress < 39 MPa (For MG)
  - Maximum stress is 24.6 MPa

New Nb Material for Cost Saving, A. Yamamoto (Tuesday,11.30 am)

ATI MG Nb Specimens

Temperature [K]	Sample Processing	Young’s Modulus [GPa]	0.2% Proof Strength [MPa]	Tensile Strength [MPa]	Elongation [%]
300	Annealed	$88.7^{\pm 9*}$	$39^{\pm 2}$	$123^{\pm 5}$	$25.3^{\pm 3}$
300	ASR	$89.7^{\pm 6}$	$43^{\pm 4}$	$145^{\pm 7}$	$23.9^{\pm 4}$
4.2	Annealed	$114.0^{\pm 11}$	$283^{\pm 34}$	$651^{\pm 60}$	$7.5^{\pm 2}$
4.2	ASR	$115.4^{\pm 14}$	$284^{\pm 22}$	$351^{\pm 28}$	$1.8^{\pm 1}$





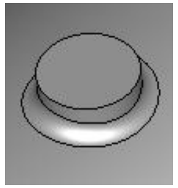
Case	Max. Stress [MPa]
Cavity with HOMs	24.6
+ Tuner – Pull	23.8
+ Tuner – Push	29.2

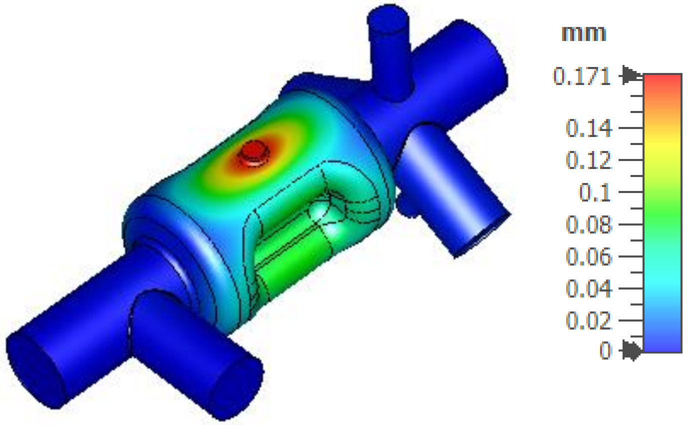
Tuning Sensitivity Analysis

- Nb material properties at cryo temperature for annealed MG
  - Young's modulus – 114 GPa (1.65×10^7 psi)
  - Allowable stress < 283 MPa (For MG)
- Required tuning range – 100-180 kHz

Total Displacement	Tuning Sensitivity	Max. Tuning Range
0.34 mm	9.5 MHz/mm	±3.24 MHz

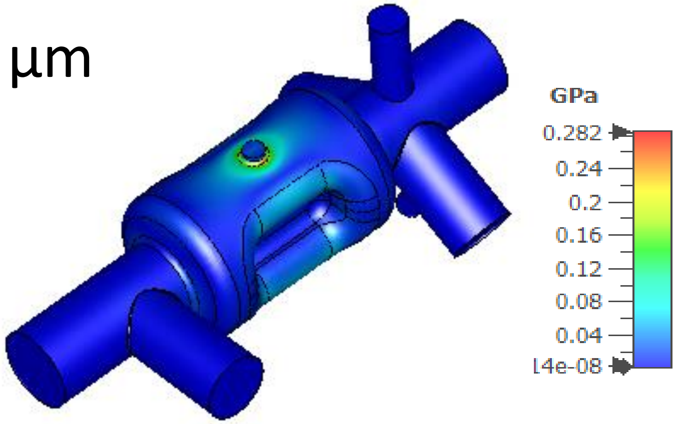
Tuner Adapter
Ø 1.5 cm





- Sensitivity: 9.5 Hz/nm
- Tuning range of 200 kHz corresponds to a total displacement of 22 µm
- Loaded bandwidth of 87 Hz ($Q_L = 1.5\times10^7$) corresponds to a total displacement of 9.2 nm
- Tuning force (for 200 kHz) per side – 175 N

- Can be implemented with a piezo tuner



RF-Dipole Crabbing Cavities

400 MHz

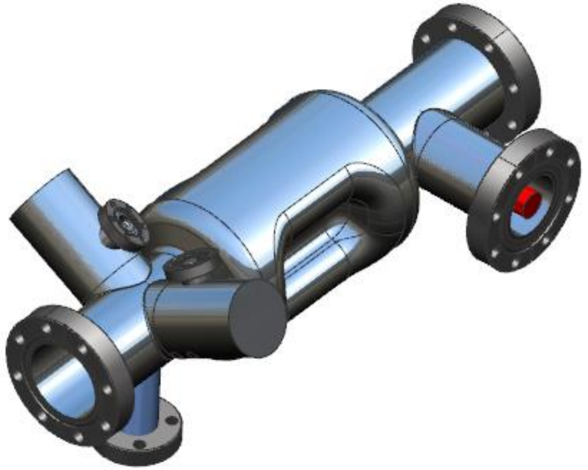
499 MHz

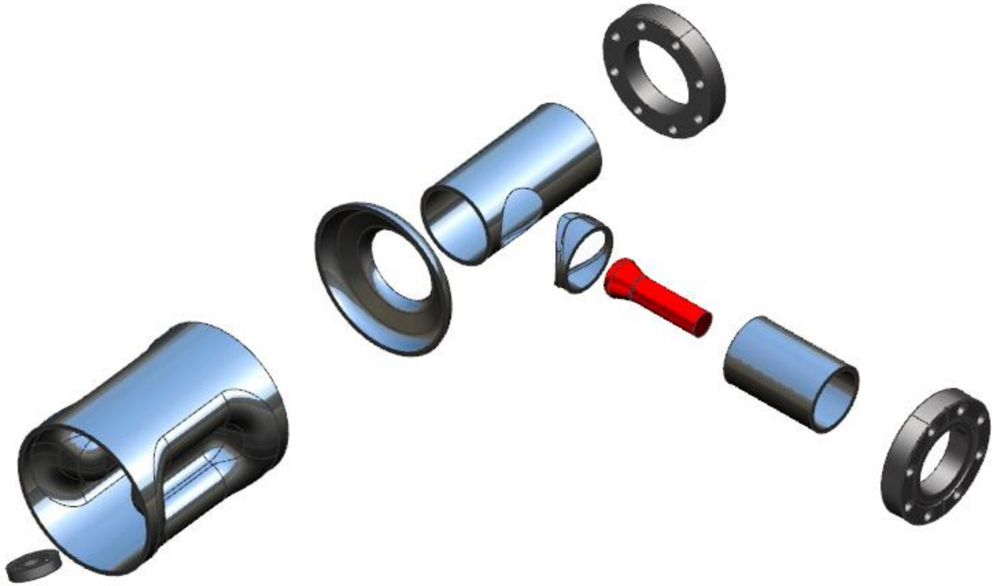
750 MHz

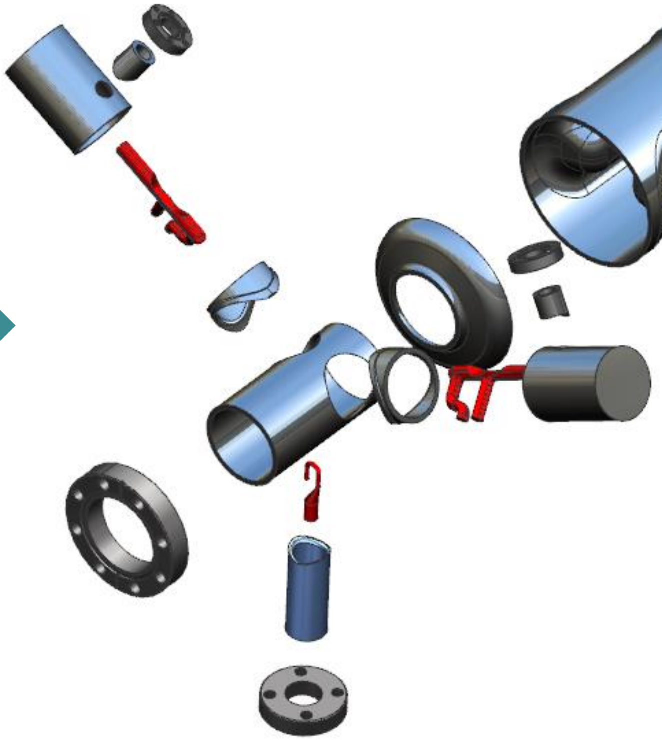
960 MHz

Cavity Fabrication

- Cavity body thickness - 3mm
- Thickness of beam pipes, HOM cans – 2 mm
- HOM hooks and probes – Nb
- FPC and FP probes – Cu
- Cavity flanges – SS 316LN with Cu gaskets







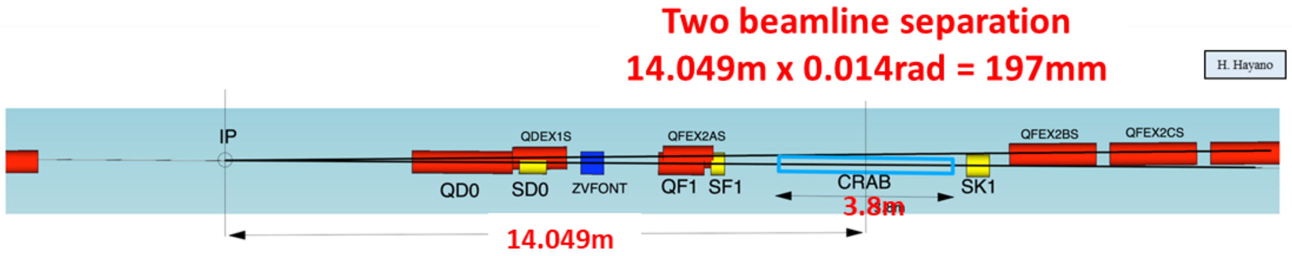
- HOM coupler fabrication
  - TESLA HOM couplers used in XFEL, LCLS-II, CEBAF-C100, and ILC
  - Well understood fabrication process

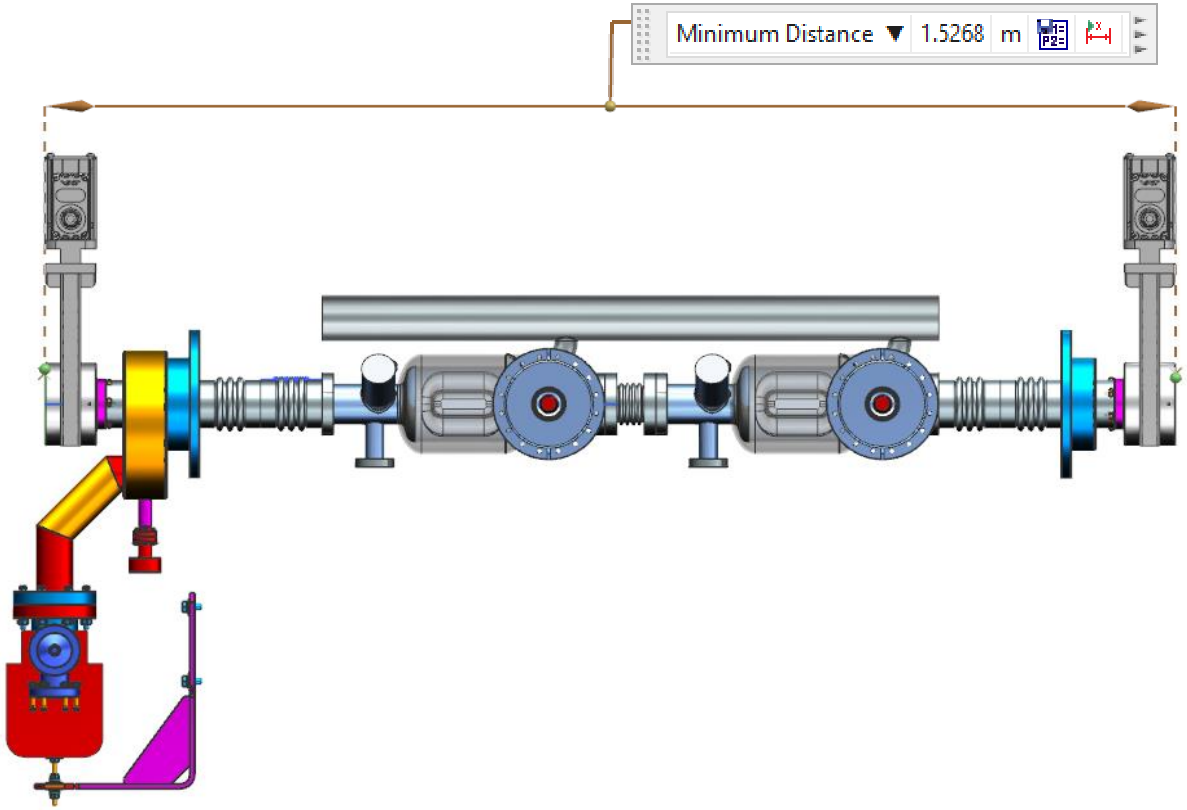
Center body will be machined and EDM out of Nb ingot

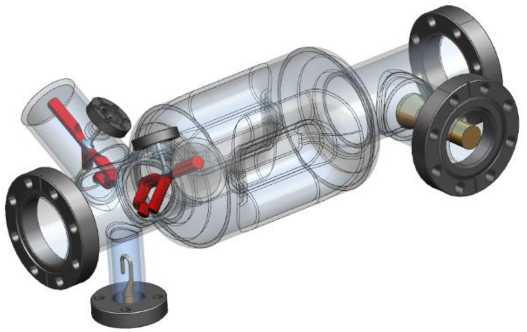
- Better control over dimensions and tolerances
- Reduced number of welds
- Reduces number of dies and fixturing
- Allows for variable thickness

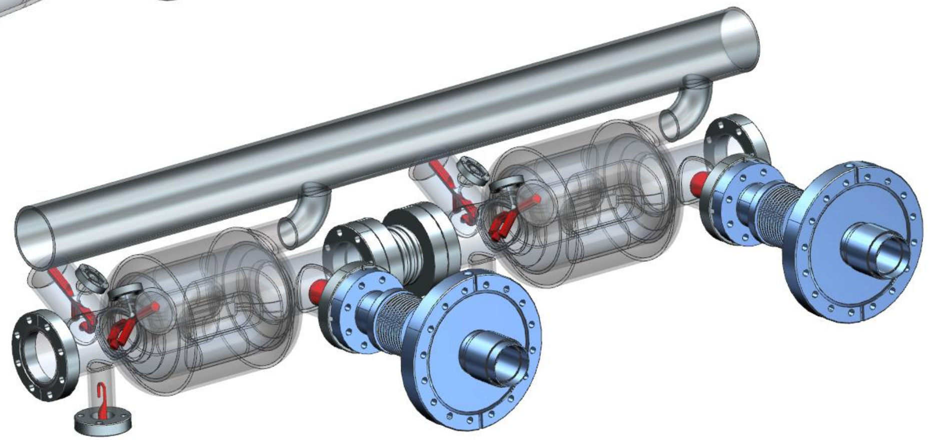
Conceptual He Vessel and Cryomodule Design

- 2 cavities in a single cryomodule
  - Second beam pipe – 20 mm beam pipe
  - Total achievable – 2.72 MV (1.36 MV V_t per cavity)
- Design concept follows JLab C100 cryomodule
- FPC, HOM couplers can be placed outside the He vessel
- Cryomodule length ~1.5 m and diameter < 1 m









Summary and Next Steps

- RFD cavity was down selected as one of the two cavities to be prototyped in the next phase of crabbing cavity development for ILC

- Basic design is completed; will do detailed analysis to finalize the cavity dimensions
  - Wakefield analysis
  - Multipacting analysis with HOM dampers
- Full engineering design and develop a detailed fabrication plan
- Fabrication of the prototype cavity with HOM dampers

- We have had great collaborations with LHC HiLumi and EIC with SLAC, BNL, Fermilab, CERN, TRIUMF
- Looking forward to collaborations on developing the ILC crabbing systems

THANK YOU !!!

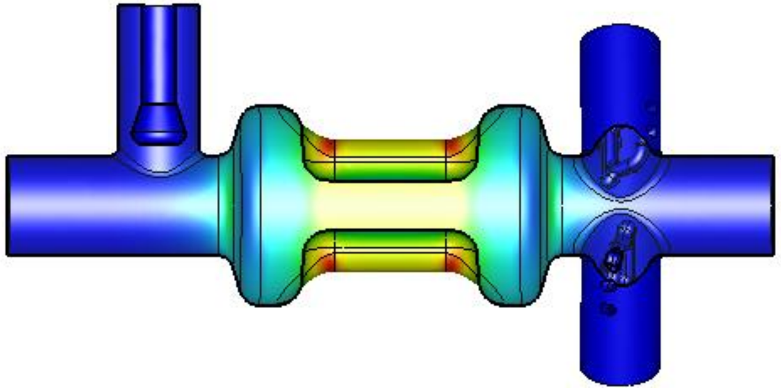
Features of RF-Dipole Cavities

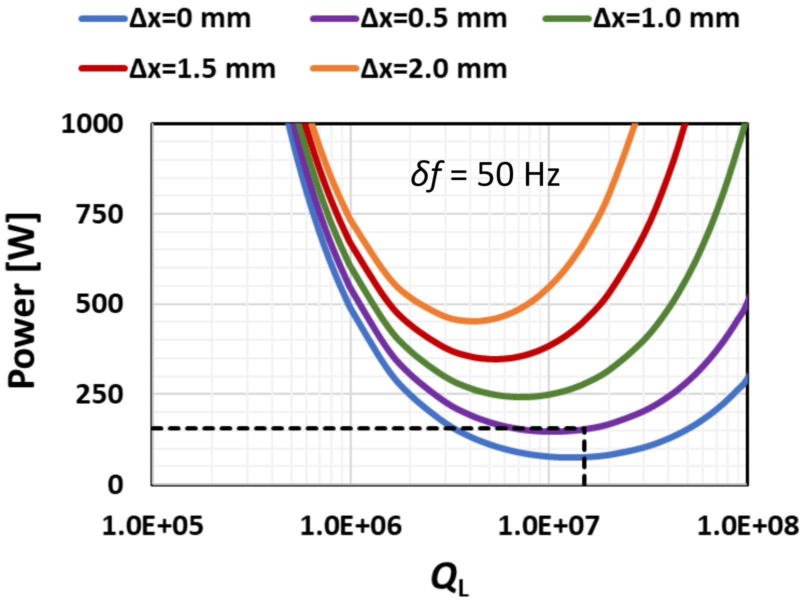
- Compact design
- Fundamental deflecting/crabbing mode has the lowest frequency
  - No LOMs, no need for notch filter in HOM coupler for LOM
  - Nearest HOM widely separated (> 1.5 fundamental)
- Low surface fields and high shunt impedance
- Good balance between peak surface electric and magnetic field
- Good uniformity of deflecting field due to high degree symmetry
- Multipole components can be managed by shaping the geometry of the poles.
- HOM couplers located in area of low field in fundamental mode

Fundamental Power Coupler

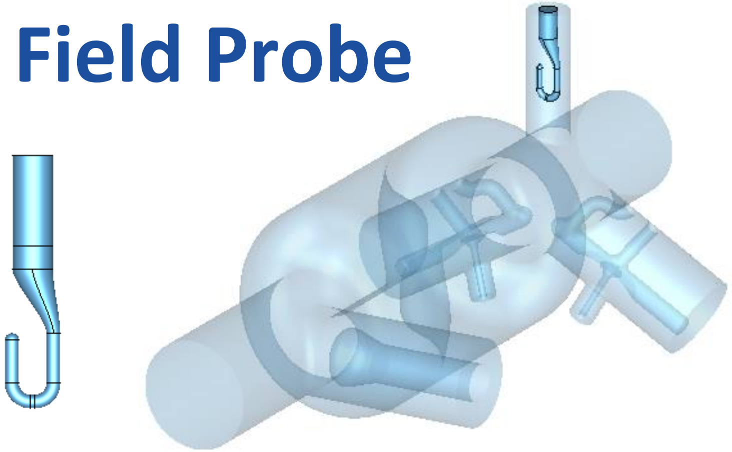
- Coupling using coaxial antenna
  - Similar to LCLS II power coupler
- Beam current: I_b = 8.75 mA
- Design parameters:
  - Beam offset: Δx = 0.5 mm
  - Microphonics: δf = 50 Hz
- Cavity parameters:
  - R/Q (V^2/P_{diss})= 444.8 [Ω]
  - Total V_t for 125 GeV = 1.845 [MV]
  - V_t per cavity = 0.9225 [MV]
- FPC Coupling:

Parameter	Value
Q_{ext}	1.5×10^7
RF Power at the cavity [W]	154
RF heating at Cu probe [W]	0.65





Field Probe

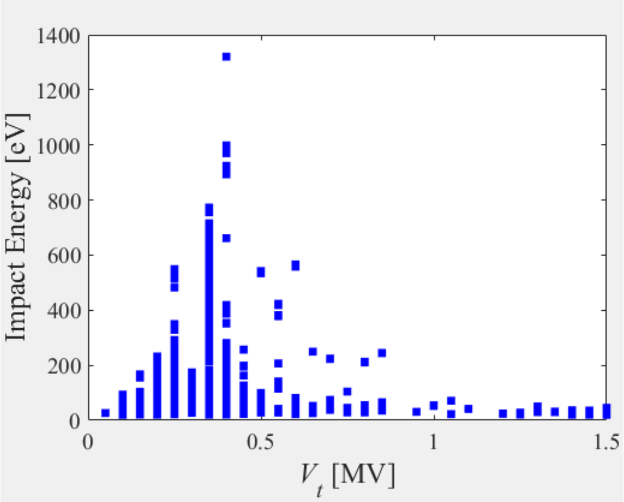


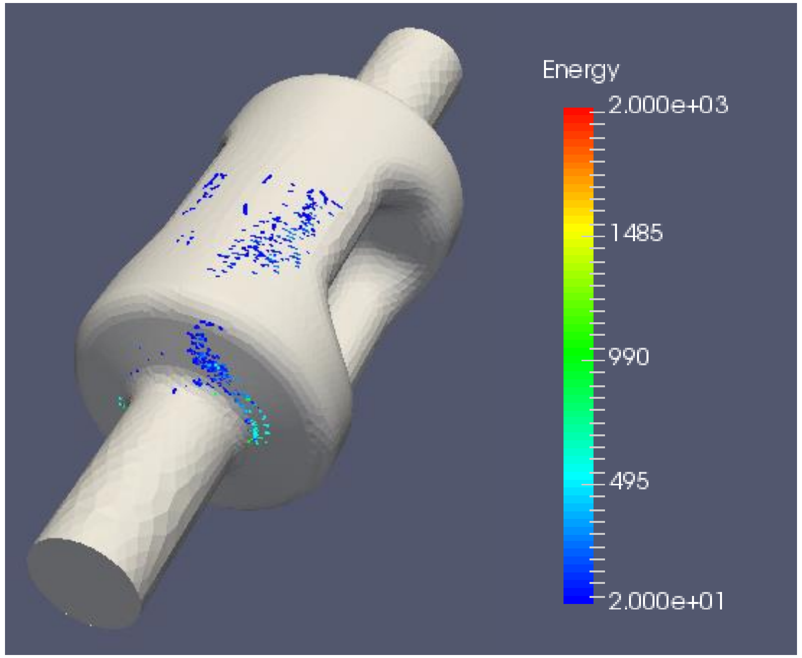
- Coupling using hook coupler
- Field probe:
  - $Q_{ext} < 1.0\times10^{10}$
  - Extract ~200 mW at 0.9225 MV

Multipacting Analysis

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

- Multipacting barrier at ~0.35 MV is similar to other barriers seen in other RFD cavities, and is fully processable
  - Doesn't reappear after fully processed





Final location of the resonant particles after 50 rf cycles

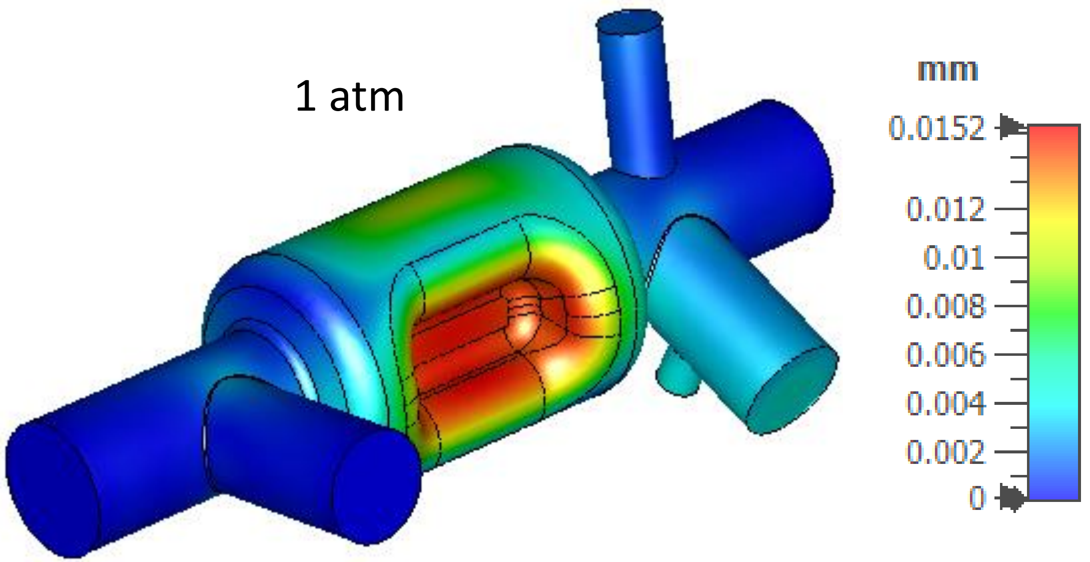
- Multipacting analysis including couplers remains to be done

Pressure Sensitivity

- Nb material properties at room temperature for MG
  - Young's modulus – 88.7 GPa (1.29×10^7 psi)
  - Poisson's ratio – 0.38
- Cavity thickness – 3mm
- Cavity constrained at beam pipe ports and FPC
- Stiffening at poles can reduce pressure sensitivity
  - Or with variable thickness at the poles
- Frequency shift at 2 K (24 torr) = -15.7 kHz

Cavity Type	d*f*/d*P* [Hz/torr]
1-cell	– 652.45

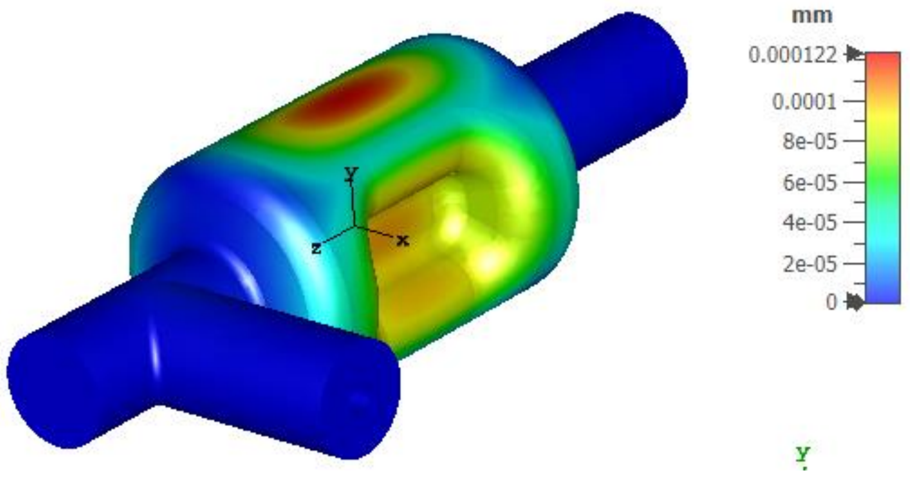
1 atm



Lorentz Detuning

- Nb material properties at cryo temperature for annealed MG
  - Young's modulus – 114 GPa (1.65×10^7 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]	V_t [MV]	Δf [kHz]
1-cell	-3.67	1.35	6.7



List of Nb Material

Cavity Parts (Nb)	Material Type	Dimensions [mm]	Qty	Weight [kg]
Center body	MG forged ingot	Ø 110 mm × 140 mm	1	11.4
End caps	Disc	Ø 130 mm × 3 mm	2	0.7
Beam tubes	Sheets	115 mm × 180 mm × 2 mm	2	0.8
HOM cans	Sheets	65 mm × 148 mm × 2 mm Ø 45 mm × 2 mm	2	0.4
FPC tube	Sheets	84 mm × 148 mm × 2 mm	1	0.3
FP tube	Rod	Ø 25 mm × 70 mm	1	0.3
FPC & HOM transitions	MG forged ingot	Machined from remaining material of the center body	3	0
HOM hooks and probes	MG forged ingot		2	0
Total				**13.9**