RF DIPOLE DESIGN

Suba De Silva

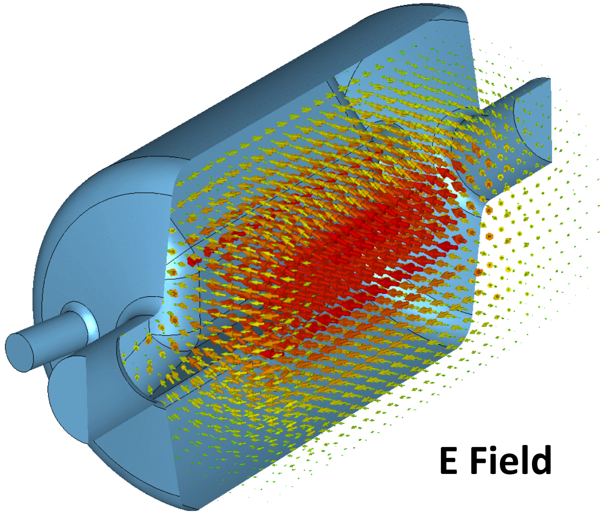
Jean Delayen, Bob Rimmer

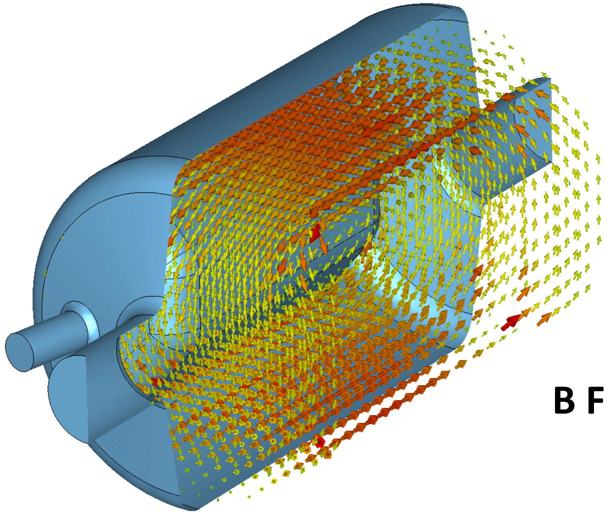
Center for Accelerator Science
Old Dominion University
and
Thomas Jefferson National Accelerator Facility

Outline

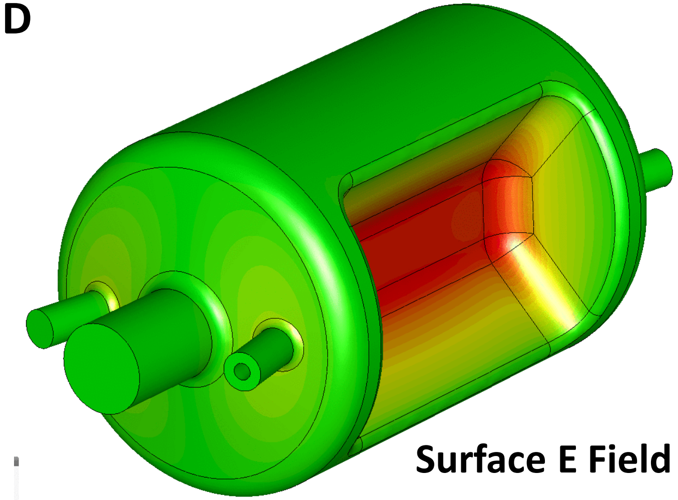
- Background
- RF Design
  - EM Design and RF Parameters
  - Higher order modes and impedances
  - Multipacting Analysis
  - Multipole Analysis
- Mechanical Analysis
  - Stress Analysis
  - Tuning Analysis
  - Pressure Sensitivity
  - Lorentz Detuning
- Conceptual cryomodule layouts
- Cavity fabrication
  - Fabrication options
  - Cavity processing plan
- Summary

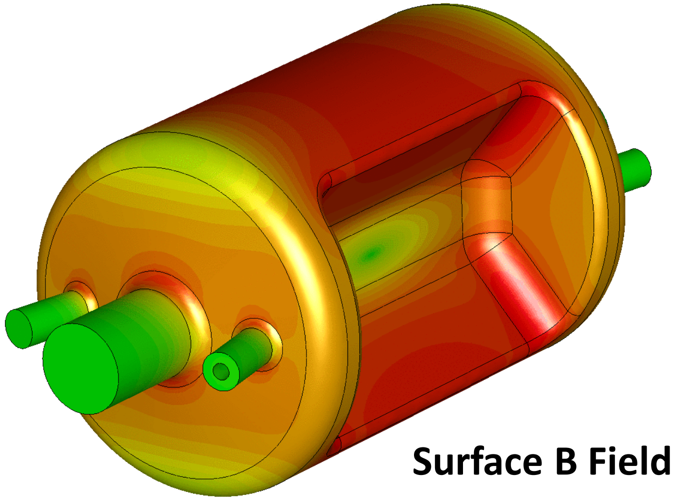
RF Field Profile of RF Dipole Cavity


E Field


B Field

Subashini De Silva PhD


Surface E Field


Surface B Field

S. U, De Silva and J. R. Delayen, “Design evolution and properties of superconducting parallel-bar rf-dipole deflecting and crabbing cavities”, PRSTAB 16, 012004 (2013)
S. U. De Silva and J. R. Delayen, “Cryogenic test of a proof-of-principle superconducting rf-dipole deflecting and crabbing cavity”, PRAB 16, 082001 (2013)

RF Dipole Cavity Properties

- 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

400 MHz Proof-of-Principle Cavity Test

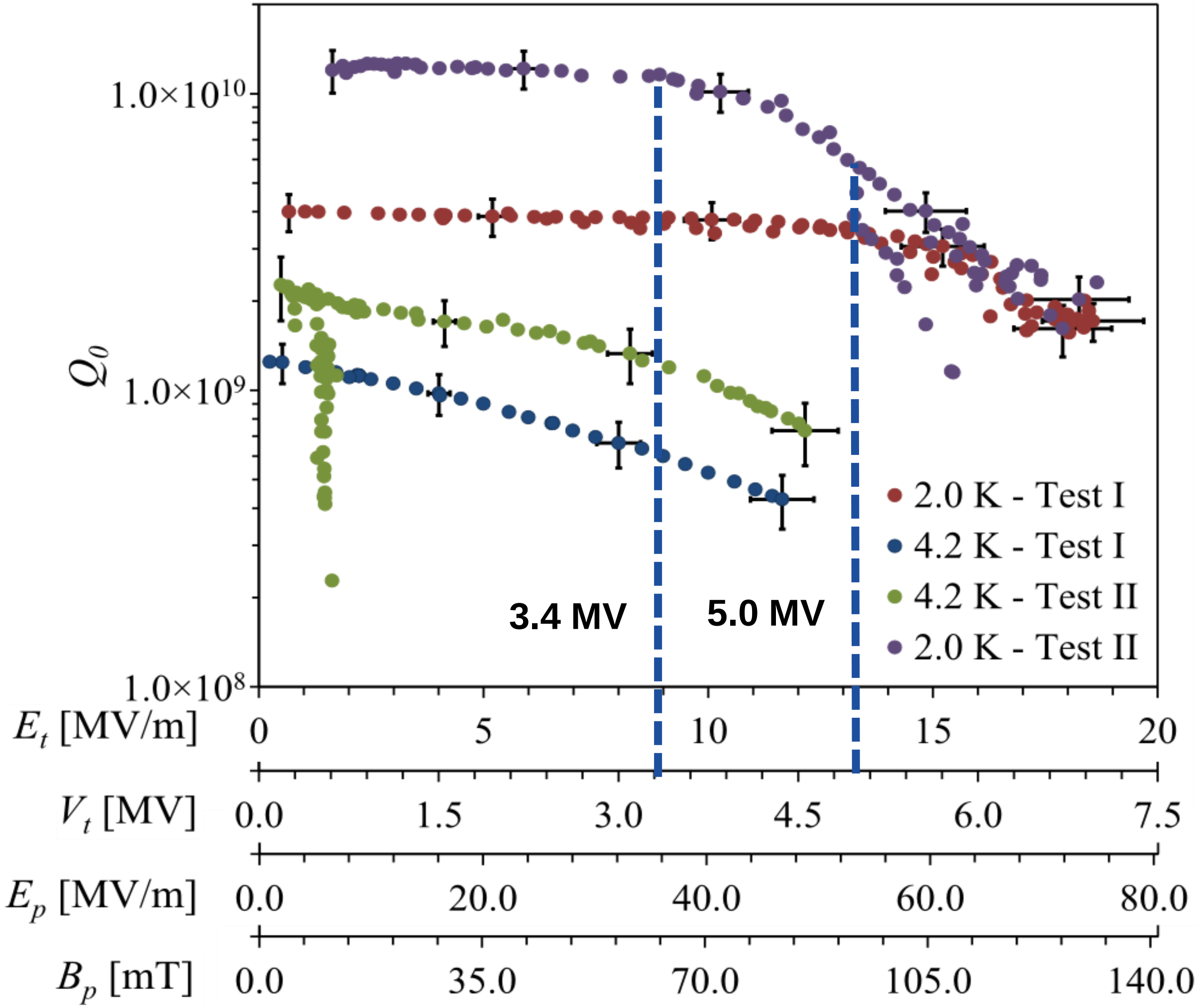
- Cavity reached a V_T of 7.0 MV
- Test II →
  - Cavity was retested with Nb coated flanges provided by CERN
  - Q_0 increased by a factor of 3 from 4×10^9 to 1.2×10^{10}
- Multipacting was processed easily and did not reoccur
- Results were confirmed by CERN

Subashini De Silva PhD

400 MHz Proof-of-Principle Cavity Test

JLab

CERN

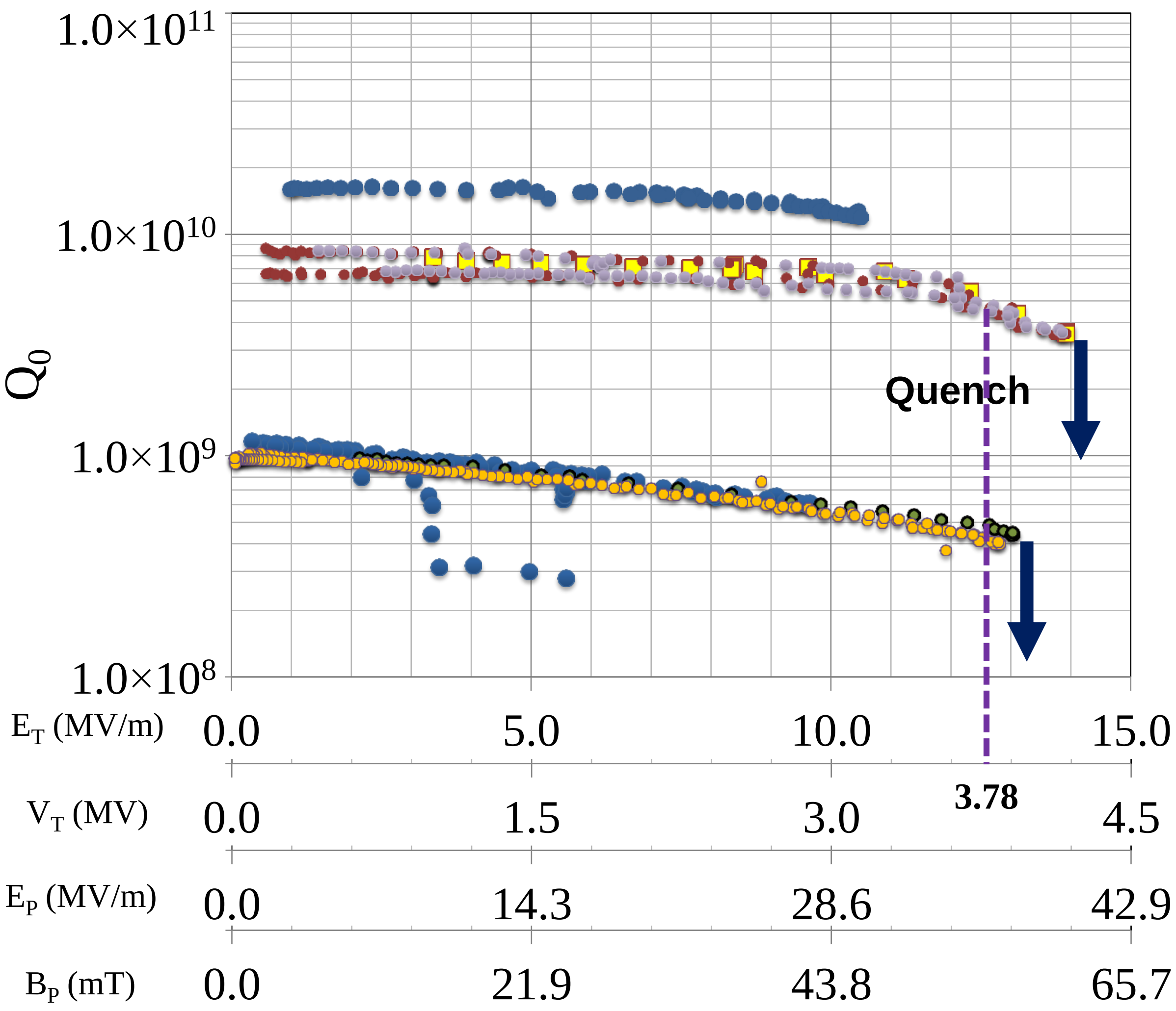


499 MHz Deflecting Cavity for JLab

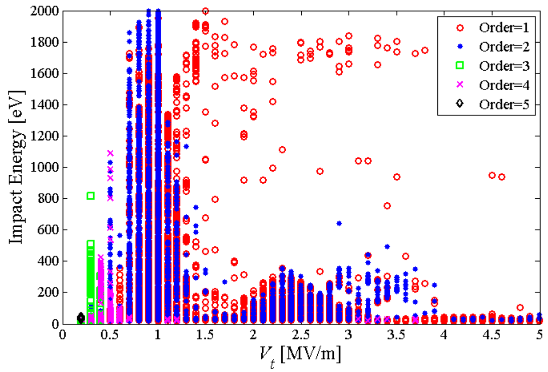
S. De Silva, H. Park

Frequency	**499.0**	**MHz**
Aperture Diameter (d)	40.0	mm
Nearest HOM	777.0	MHz
E_p^*	2.86	MV/m
B_p^*	4.38	mT
B_p^*/E_p^*	1.53	mT/ (MV/m)
$[R/Q]_T$	982.5	Ω
Geometrical Factor (G)	105.9	Ω
R_TR_S	1.0×10^5	Ω^2
At E_T^* = 1 MV/m		

499 MHz RF-Dipole Cavity



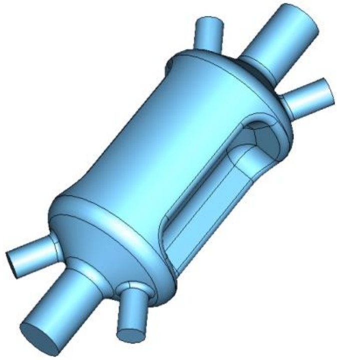
- Multipacting was easily processed during the 4.2 K rf test



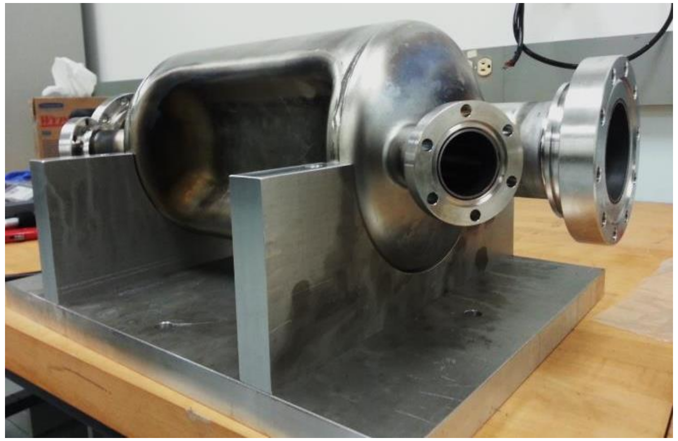
- No multipacting levels were observed in the reprocessed cavity
- Design requirement of 3.78 MV can be achieved with 1 cavity
- Achieved fields at 2.0 K
  - E_T = 14 MV/m
  - V_T = 4.2 MV
  - E_P = 40 MV/m
  - B_P = 61.3 mT

750 MHz Crabbing Cavity

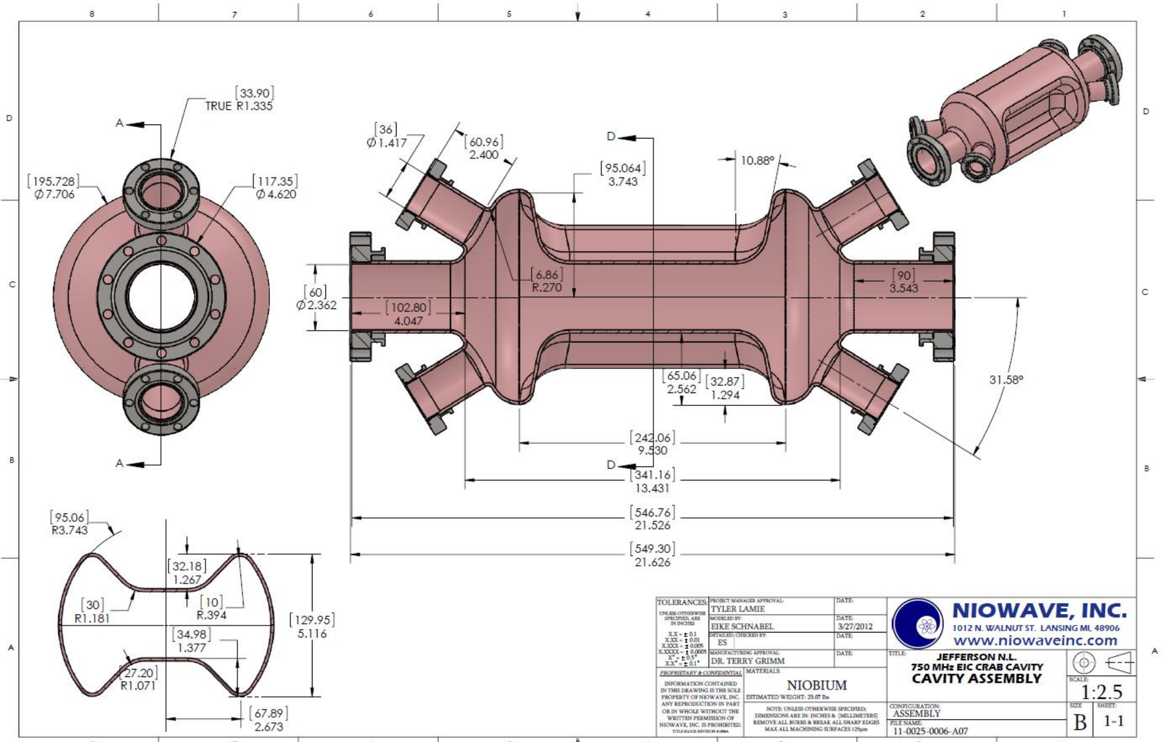
- Crabbing cavity for proposed Medium-Energy Electron-Ion Collider (MEIC)
- Desired net deflection
  - e^- beam: 1.5 MV
  - p beam: 8 MV



Parameter	750 MHz	Unit
Nearest mode to π mode	1062.5	MHz
Deflecting voltage (V_T^*)	0.2	MV
Peak electric field (E_P^*)	4.29	MV/m
Peak magnetic field (B_P^*)	9.3	mT
Geometrical factor ($G = QR_S$)	136.0	Ω
$[R/Q]_T$	125.0	Ω
At $E_T^* = 1$ MV/m		

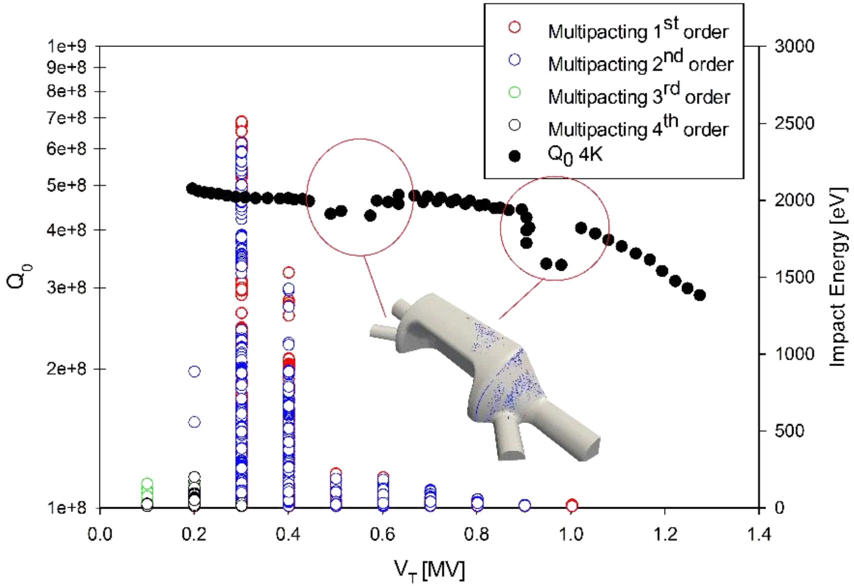


PhD project Alejandro Castilla

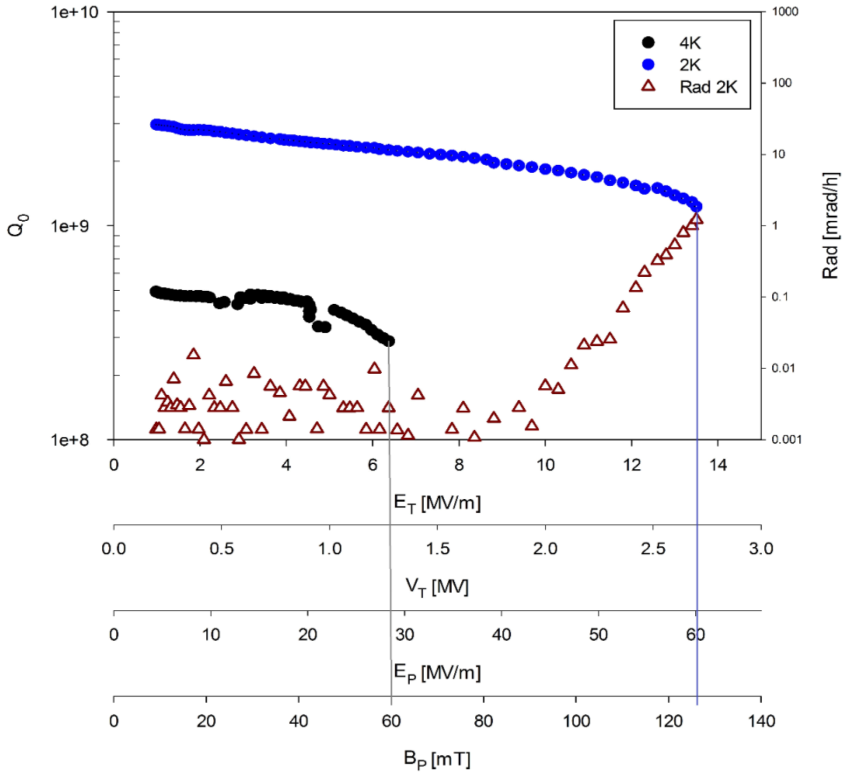


750 MHz Crabbing Cavity for JLab MEIC

Multipacting



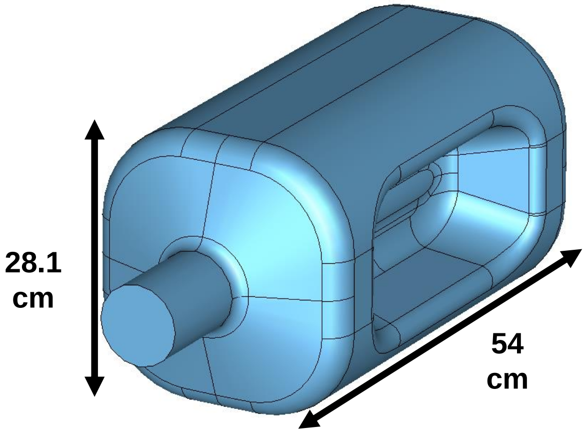
Cryogenic Tests

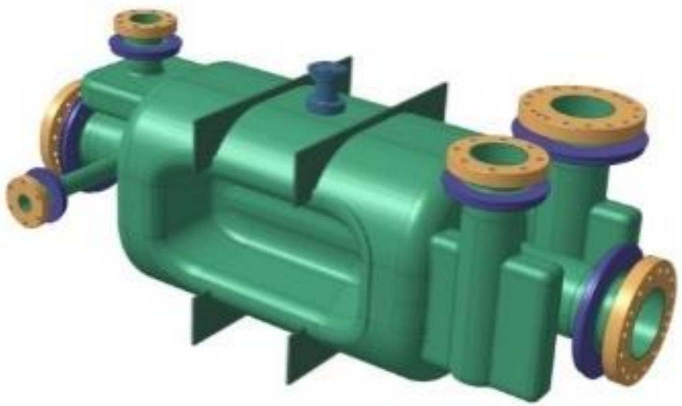


$$E_T = 13.5\ MV/m$$
$$V_T = 2.7\ MV$$
$$E_P = 60\ MV/m$$
$$B_P = 126\ mT$$

400 MHz Prototype RF Dipole Design

Prototype design has improved rf-properties

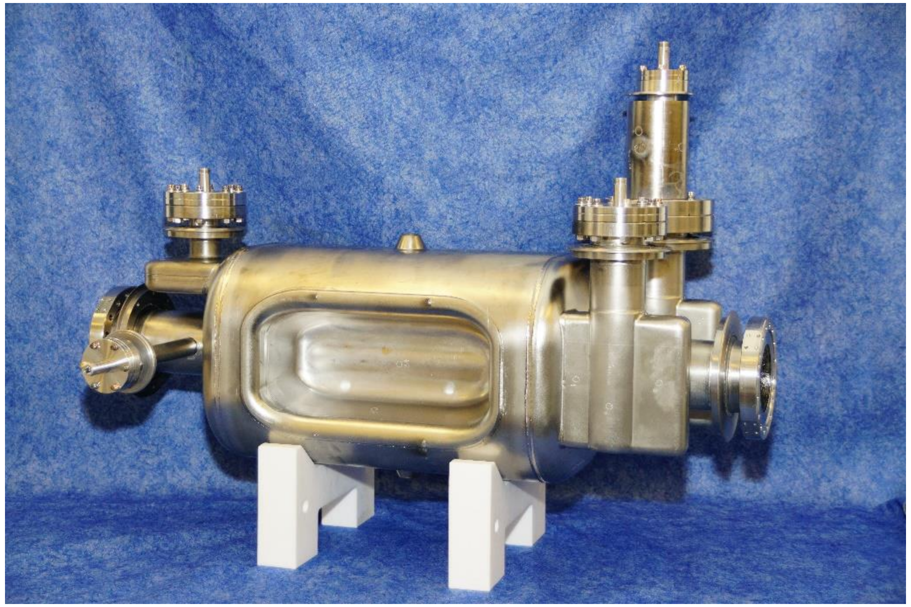


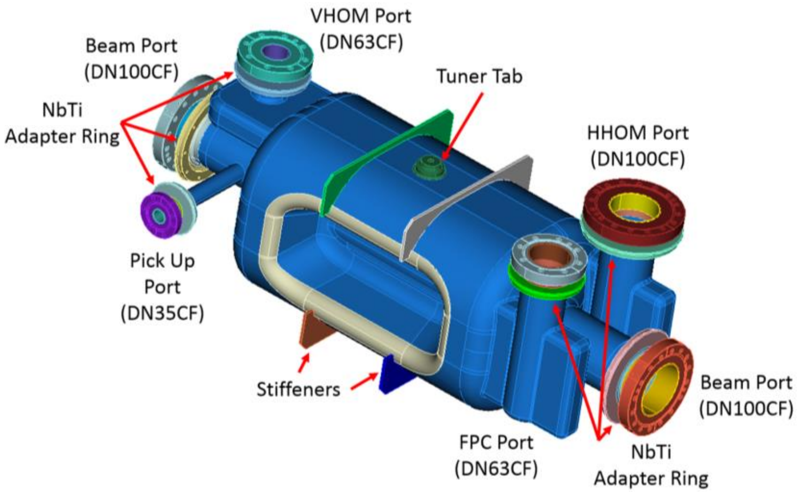


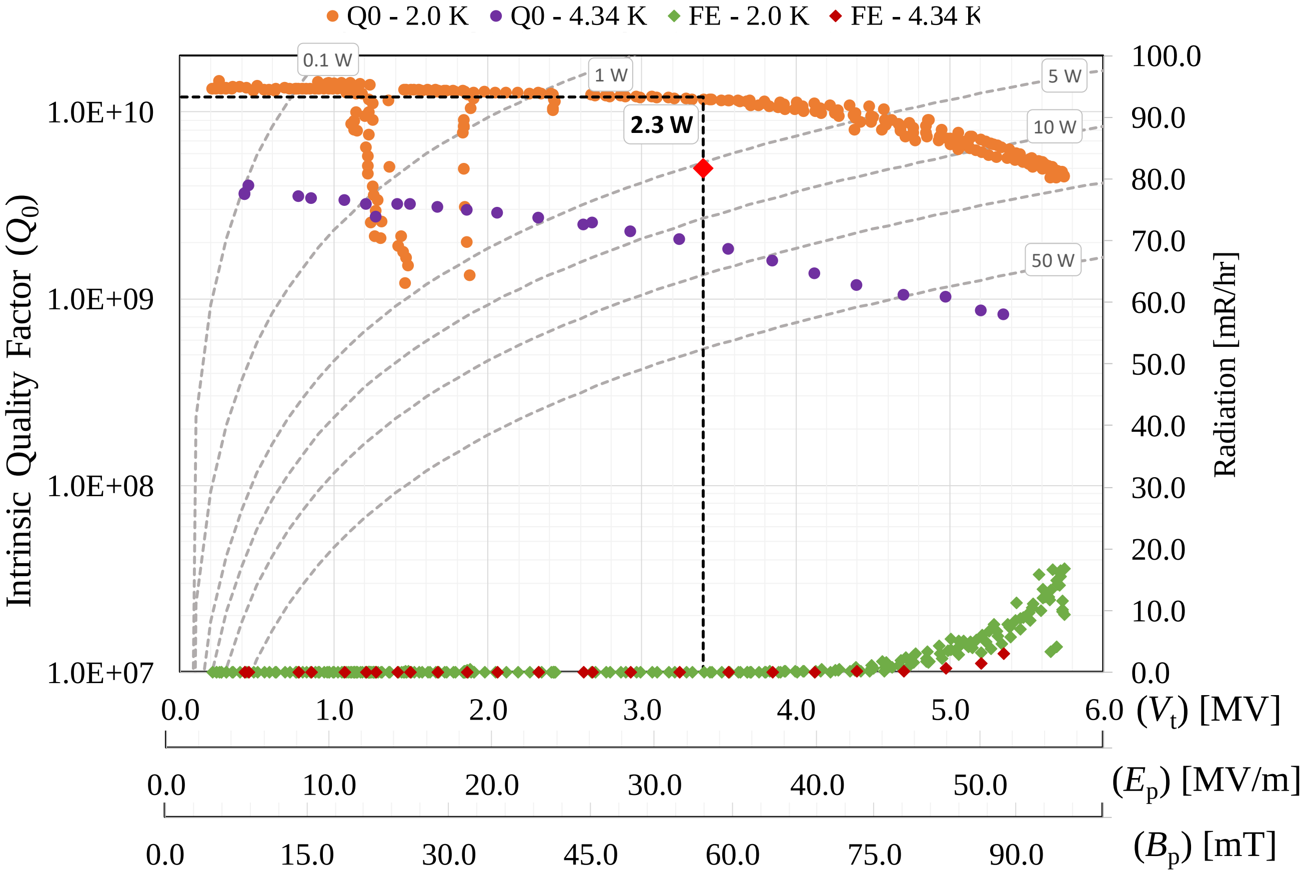
Parameters	Prototype	P-o-P	Units
Frequency of fundamental	400	400	MHz
Frequency of 1st HOM	632	590	MHz
Deflecting Voltage (V_T^*)	0.375	0.375	MV
Peak Electric Field (E_p^*)	3.65	4.02	MV/m
Peak Magnetic Field (B_p^*)	6.22	7.06	mT
Peak Electric Field (E_p^{**})	32.6	35.9	MV/m
Peak Magnetic Field (B_p^{**})	55.6	63.1	mT
B_p/E_p	1.71	1.76	mT/(MV/m)
Stored Energy (U^*)	0.13	0.195	J
$[R/Q]_T$	427.4	287.0	Ω
Geometrical Factor (G)	106.7	140.9	Ω
$R_T R_S$	4.6×10^4	4.0×10^4	Ω^2
*At E_T = 1 MV/m ** At V_T = 3.35 MV			

Subashini De Silva, Zenghai Li

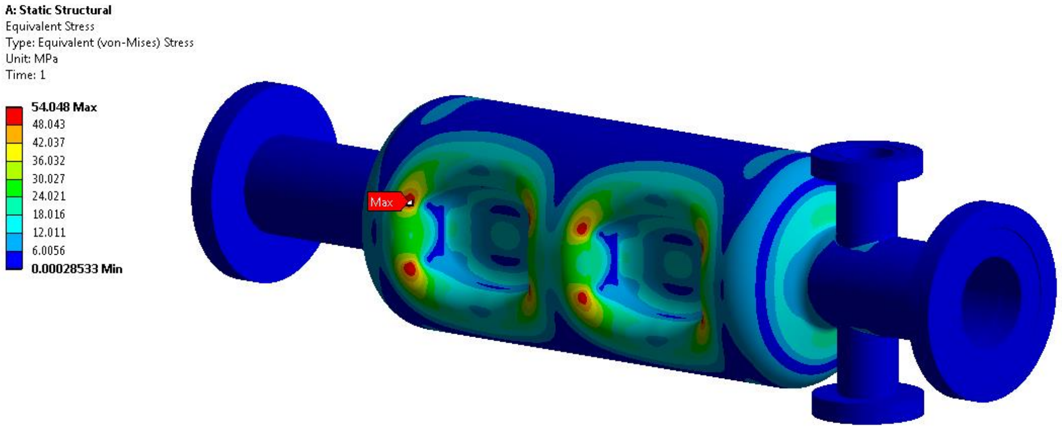
400 MHz Prototype RF Dipole Design for LHC

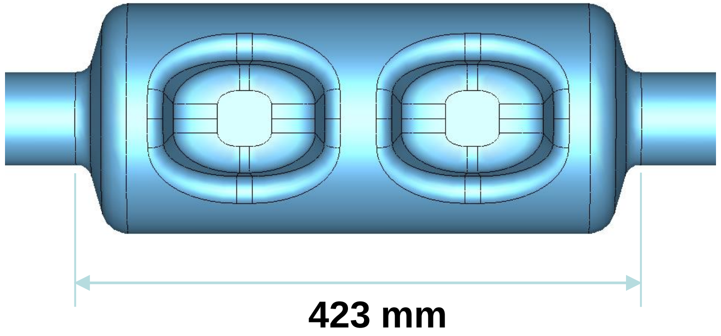


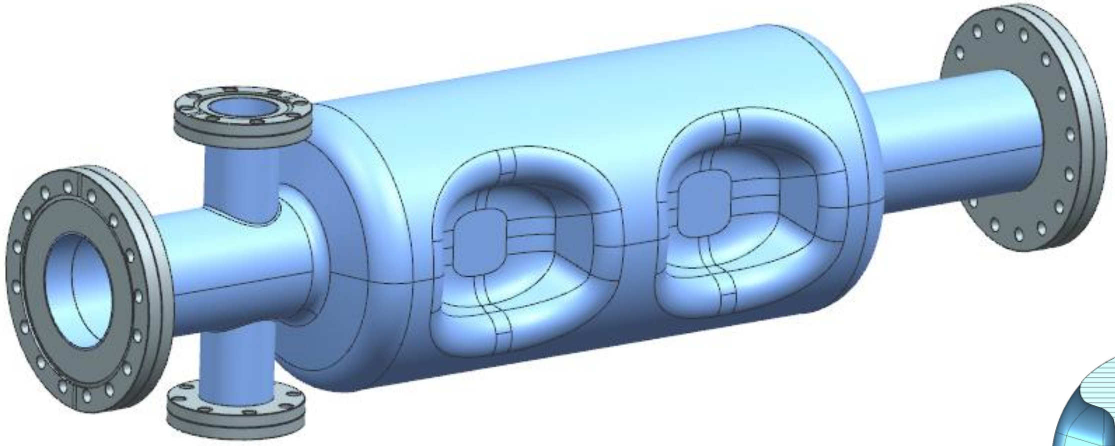


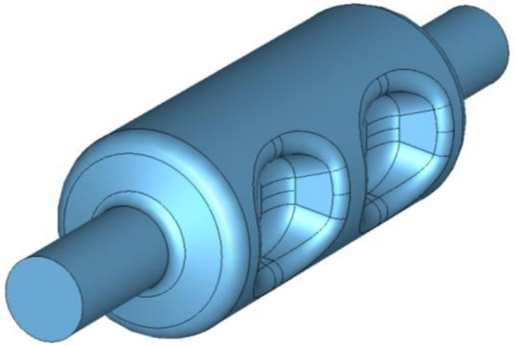


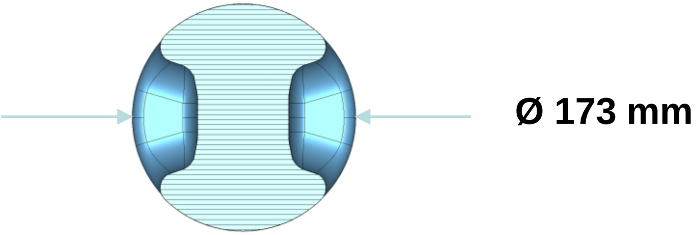
952 MHz 2-cell RFD











Subashini De Silva, HyeKyoung Park

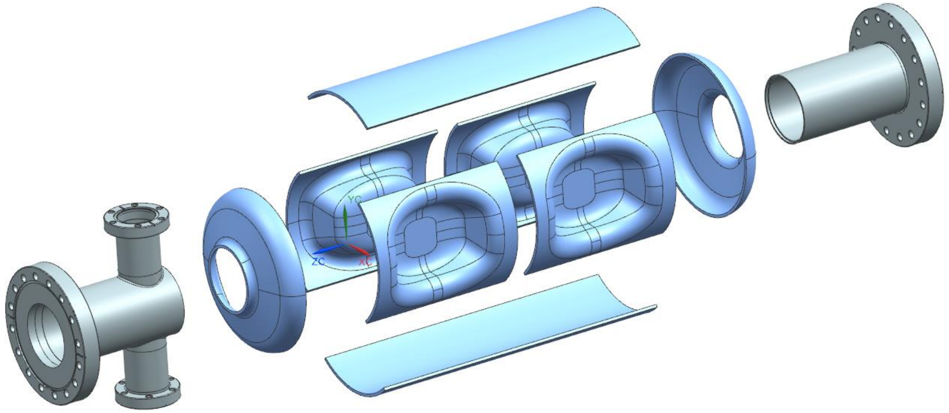
**Supported by grant from the
state of Virginia through SURA**

952 MHz 2-cell RFD

- 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 welds only – high production yield
- Strategy relevant to final cavity with HOM dampers

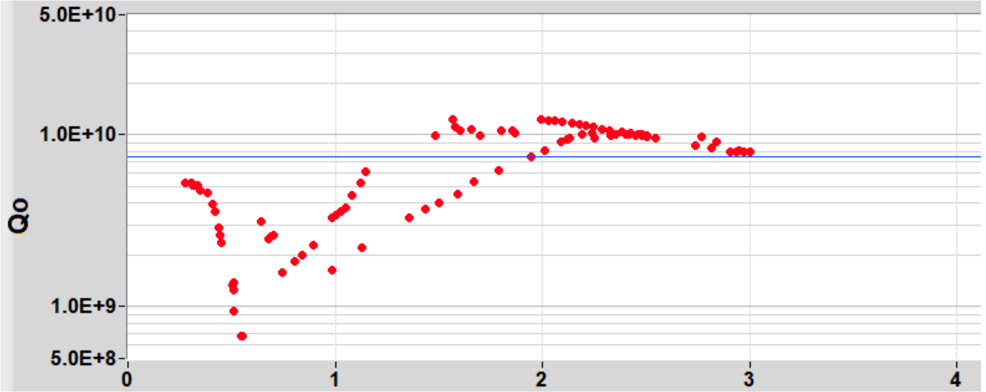
Subashini De Silva, HyeKyoung Park

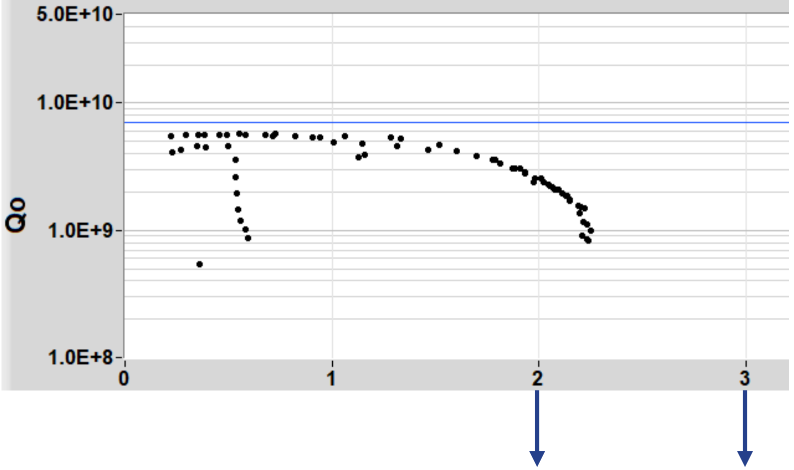
Supported by grant from the state of Virginia through SURA



952 MHz 2-cell RF Dipole

Frequency	2-cell Cavity	MHz
Aperture Diameter (d)	70.0	mm
LOM	849.7	MHz
Nearest HOM	1380.0	MHz
E_p^*	5.71	MV/m
B_p^*	11.71	mT
B_p^*/E_p^*	2.05	mT/(MV/m)
$[R/Q]_T$	149.9	Ω
Geometrical Factor (G)	171.1	Ω
$R_T R_S$	2.56×10^4	Ω^2
At $E_T^* = 1$ MV/m		





$E_p = 36.3$ MV/m
$B_p = 74.5$ mT

$E_p = 54.4$ MV/m
$B_p = 111.7$ mT

ODU/JLab RF Dipole Zoo

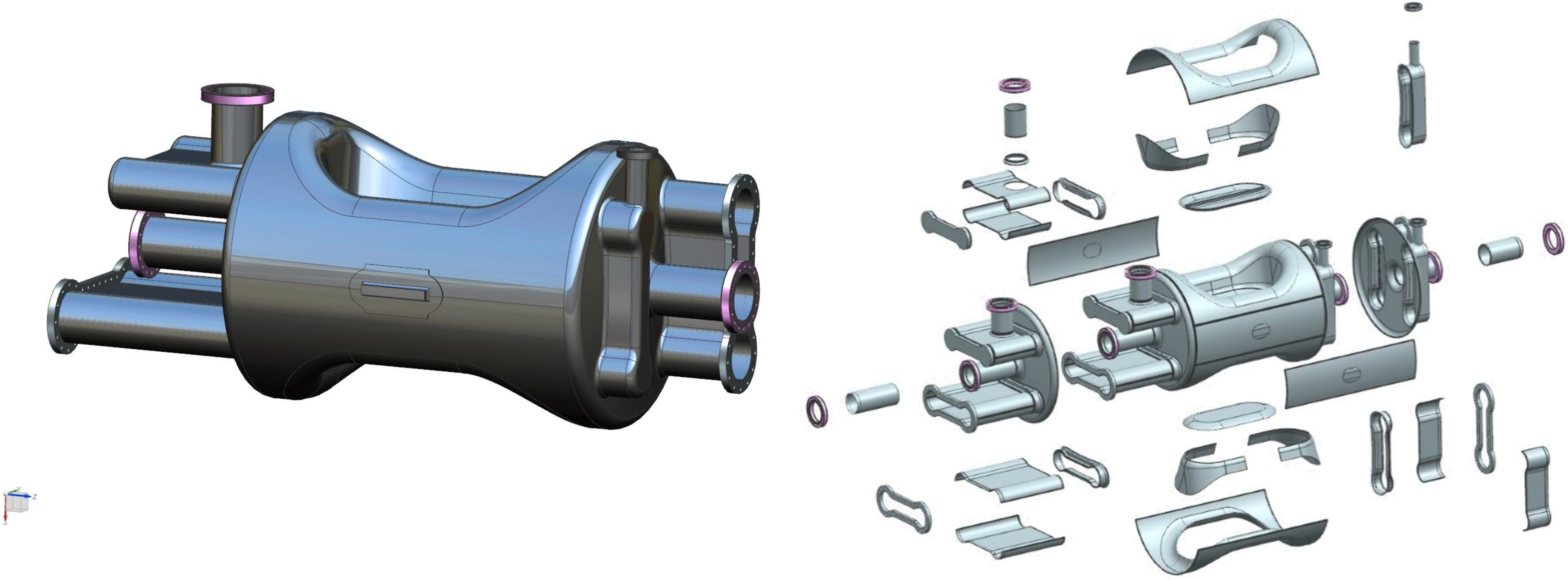
400 MHz

499 MHz

750 MHz

960 MHz

197 MHz for EIC



Requirements for ILC 1.3 GHz Crab Cavity

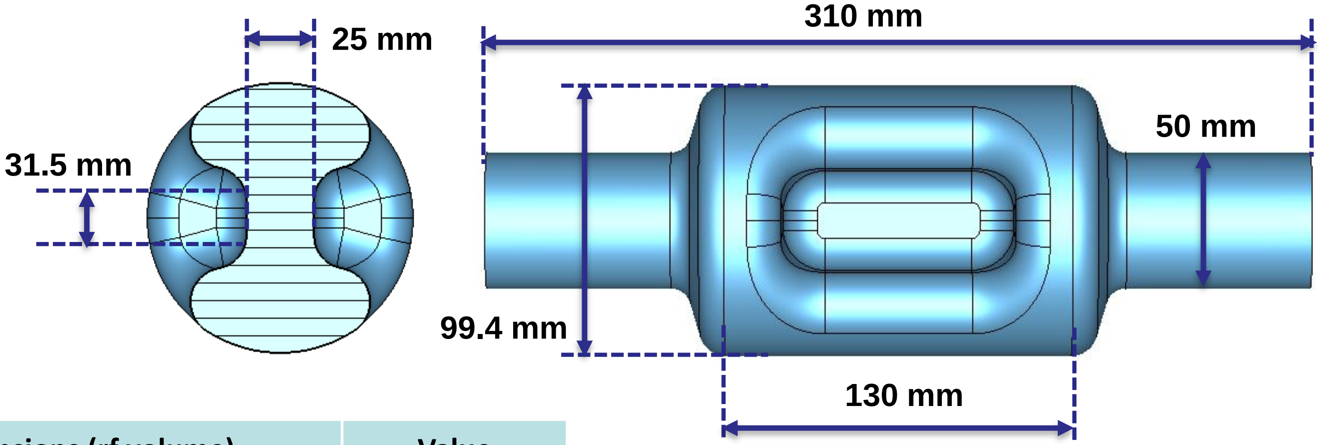
- Operating frequency – 1.3 GHz
- Transverse voltage – 1.845 MV (125 GeV) and 7.4 MV (for 500 GeV)
- Maximum fields – $E_p < 45$ MV/m and $B_p < 80$ mT
- Total impedance threshold (requirements):
  - $Z_x = 48.8$ MΩ/m and $Z_y = 61.7$ MΩ/m

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

Parameter	Post-TDR Specification		10Hz Upgrade[1,2]	1 TeV CoM Spec [2]		
Beam Energy (GeV) e-	125			500		
Crossing Angle (mrad)	14					
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					
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)	$\ll 1.6 \times 10^3$					
Vertical kick factor (ky) (V/pC/m)	$\ll 1.2 \times 10^2$					
CC System operation	assume CW-mode operation					

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



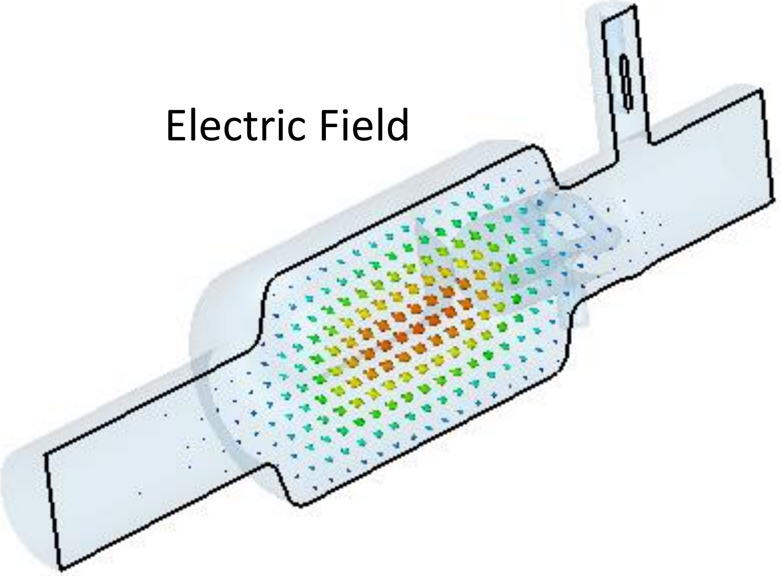
Cavity Dimensions (rf volume)	Value
Pole separation [mm]	25
Beam aperture [mm]	50
Cavity Length [mm] (flange-to-flange)	310
Cavity Diameter [mm]	99.4
Pole Length [mm]	85
Pole Height [mm]	31.5
Angle [deg]	22.5

	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

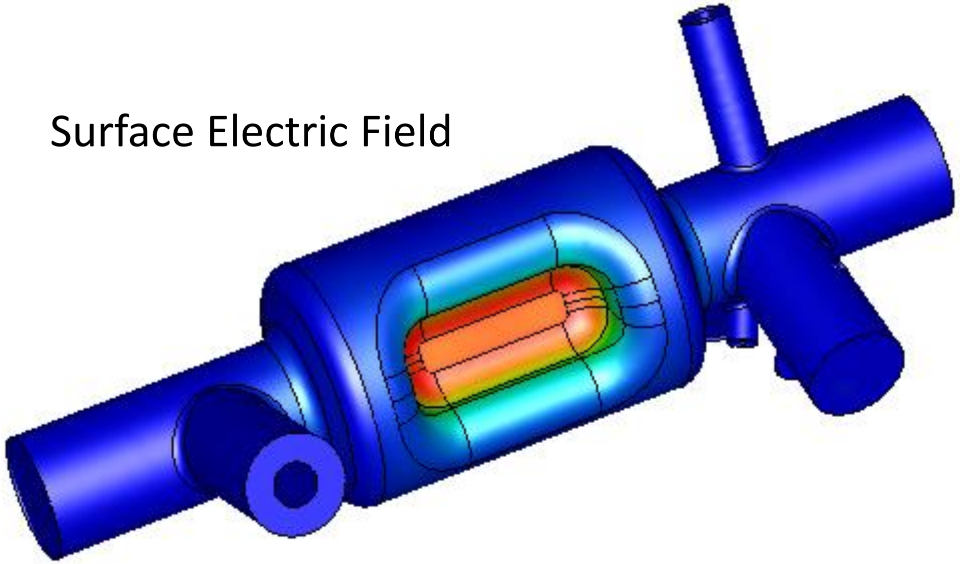
Property	Value
Operating frequency [GHz]	1.3
1st HOM [GHz]	2.089
E_p/E_t^*	3.81
B_p/E_t^* [mT/(MV/m)]	6.78
B_p/E_p [mT/(MV/m)]	1.78
G [Ω]	129.88
R/Q [Ω] (V^2/P)	439.51
R_tR_s [Ω^2] (V^2/P)	5.71×10^4
*Reference length $V/E_t = \lambda/2$ [mm]	115.3
V_t max per cavity [MV]	1.36
E_p [MV/m]	44.94
B_p [mT]	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

1.3 GHz RFD Cavity Fields

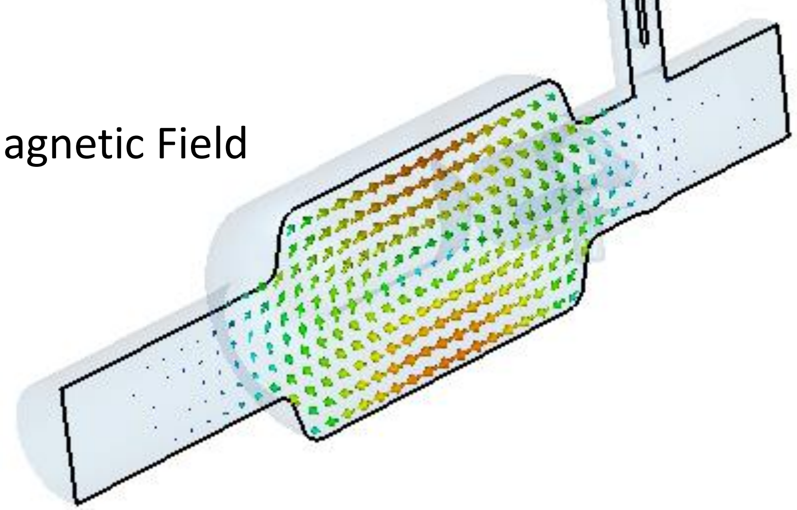
Electric Field



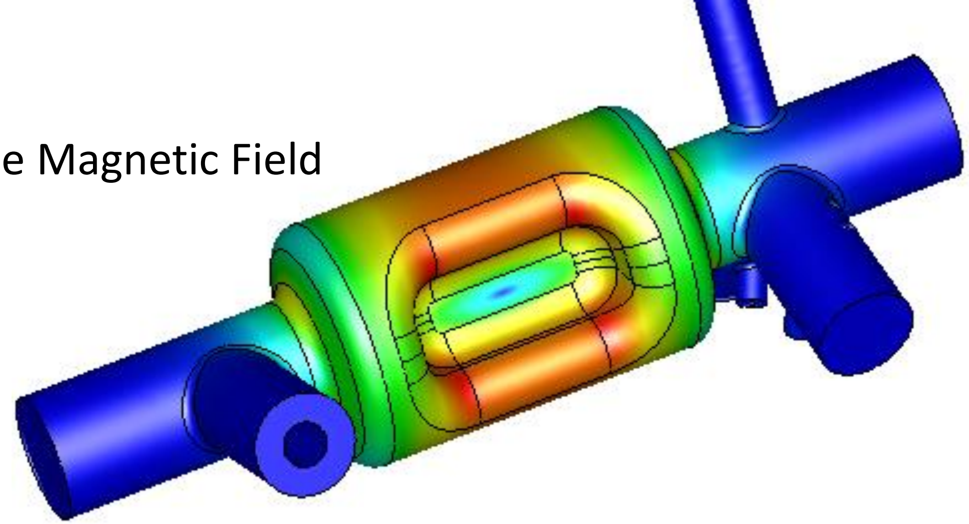
Surface Electric Field



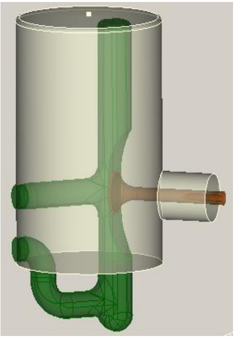
Magnetic Field



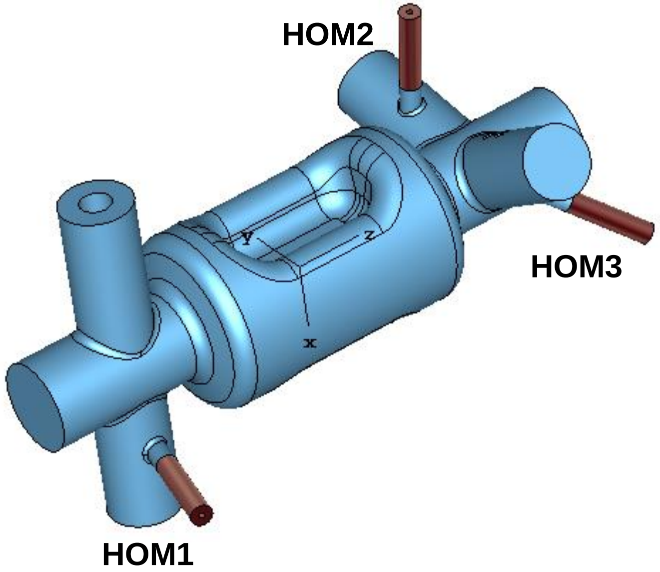
Surface Magnetic Field

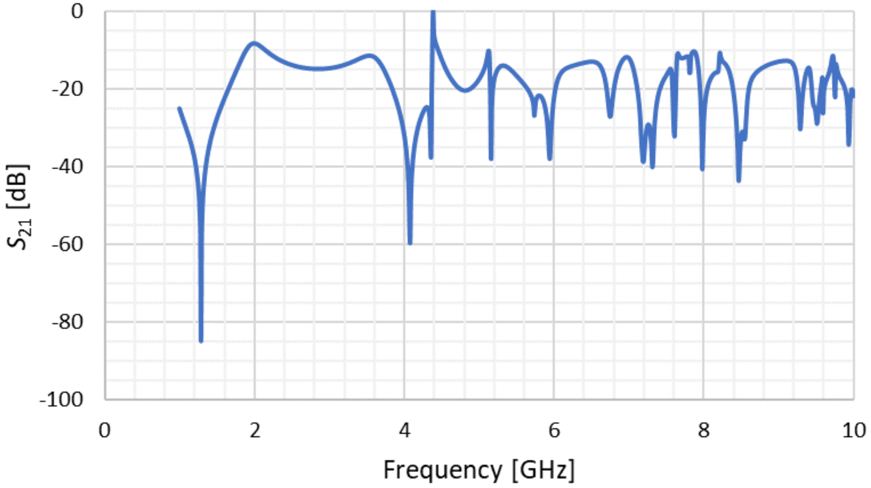


Higher Order Mode Damping



TESLA type HOM coupler

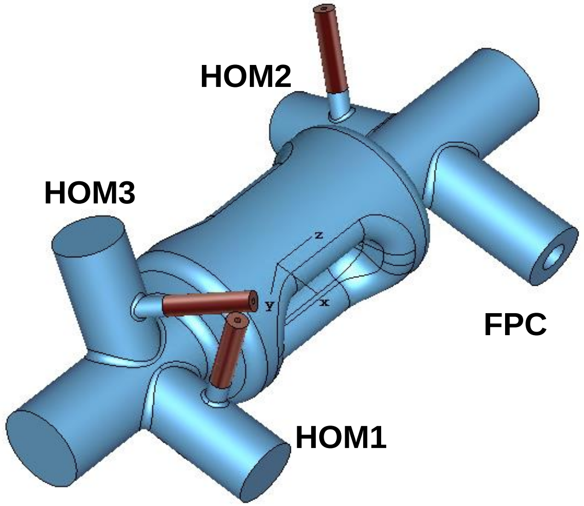




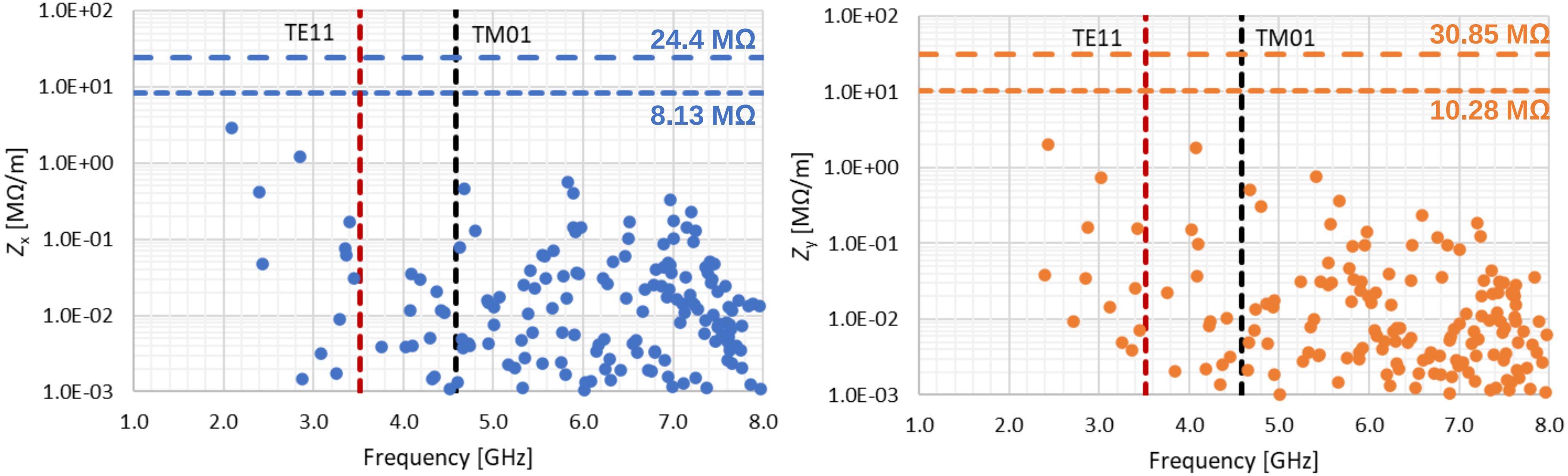
- TESLA HOM coupler with the notch at 1.3 GHz
  - A notch at 4.08 GHz
- Damping using 3 TESLA type HOM couplers
  - Damper design used in the LCLS II cavities
  - Compact damper design → Allows to place dampers on the beam pipes

Transverse HOM Impedances – 3 HOM Dampers

- 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 we explored damping with two HOM dampers



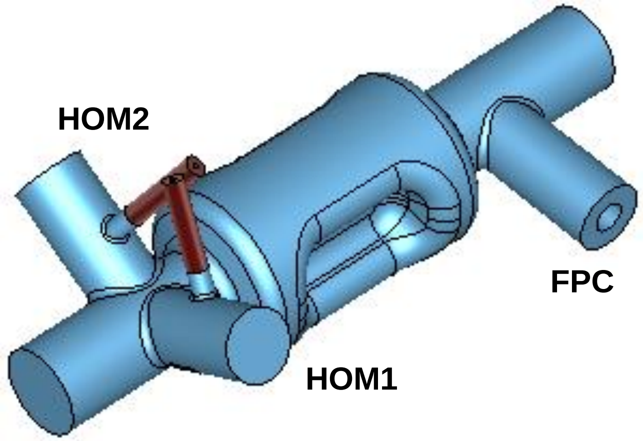
With large margin in impedance threshold, reduce number of dampers to 2

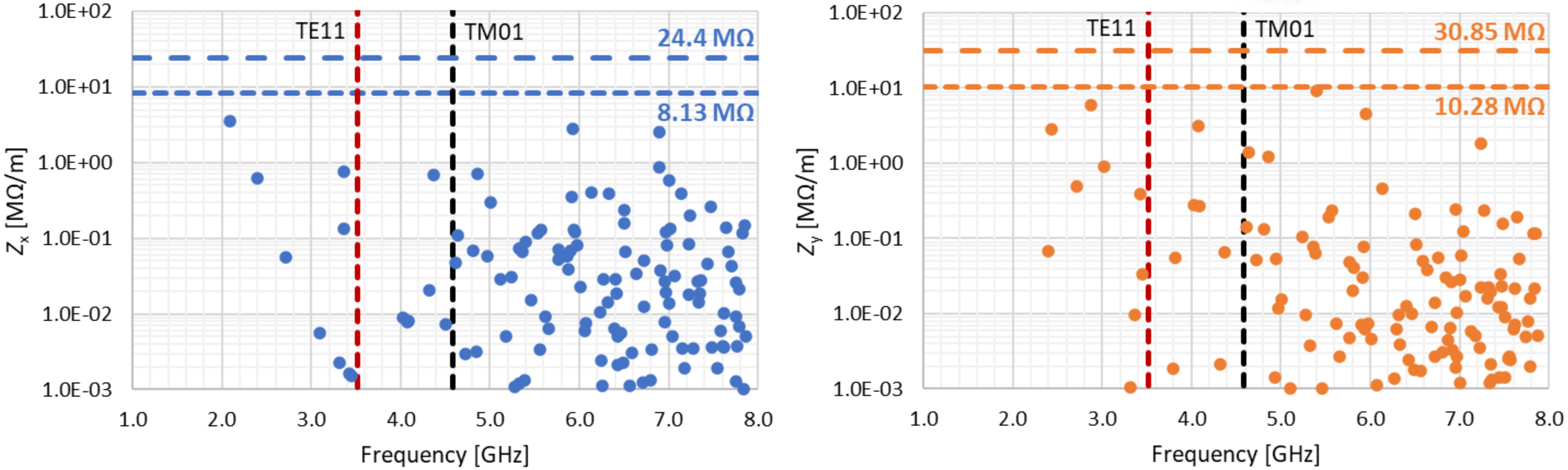


- Impedances calculated using circuit definition

Transverse HOM Impedances – 2 HOM Dampers

- 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)
- Damping with 2 HOM dampers
  - Placed on one end of the cavity with no interference with the FPC

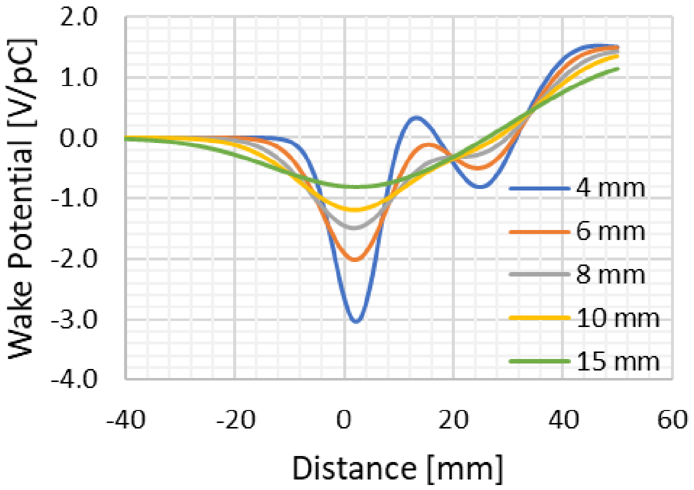


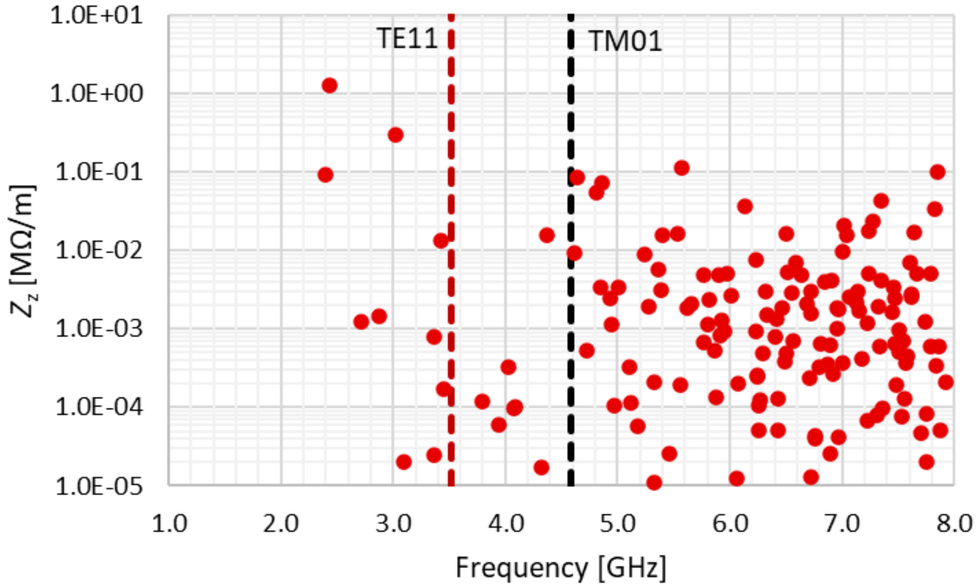


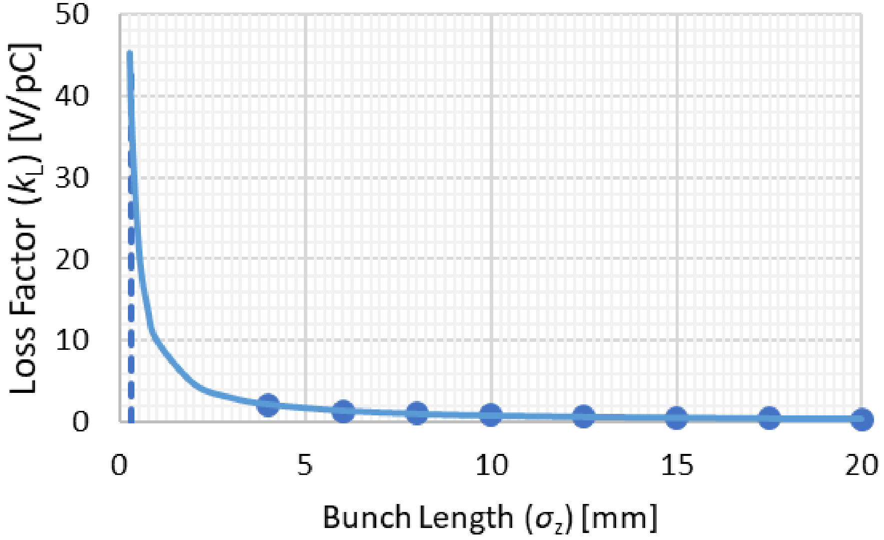
- Impedances calculated using circuit definition

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 → 37 V/pC
- Opportunity for collaboration



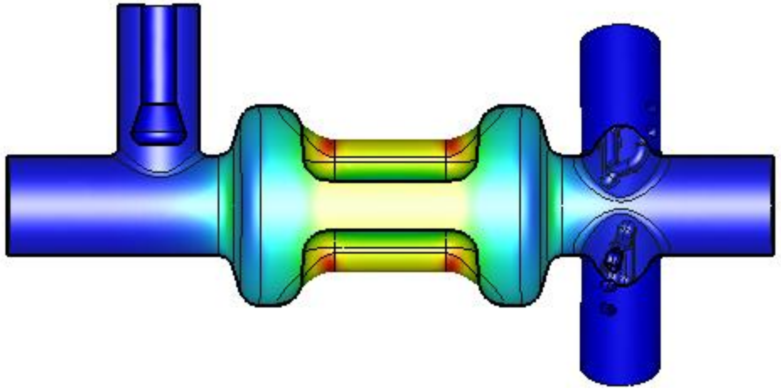


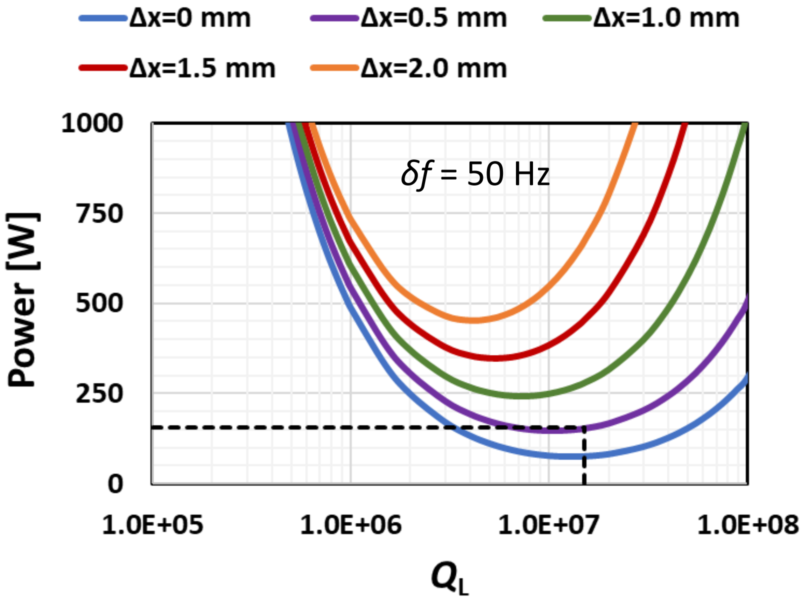


Fundamental Power Coupler

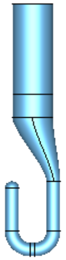
- Coupling using coaxial antenna
  - Similar to LCLS II power coupler
- Beam current: I_b = 8.75 mA
- Design parameters:
  - Beam offset: Δx = 0.5 mm
  - Microphonics: δf = 50 Hz
- Cavity parameters:
  - R/Q (V^2/P_{diss})= 444.8 [Ω]
  - Total V_t for 125 GeV = 1.845 [MV]
  - V_t per cavity = 0.9225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

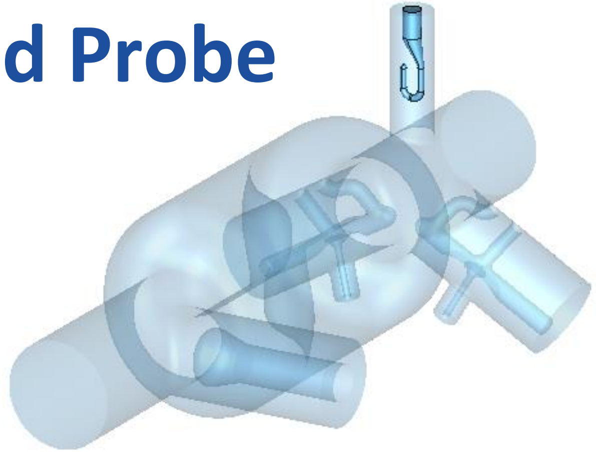
Parameter	Value
Q_{ext}	1.5×10^7
RF Power at the cavity [W]	154
RF heating at Cu probe [W]	0.65





Field Probe



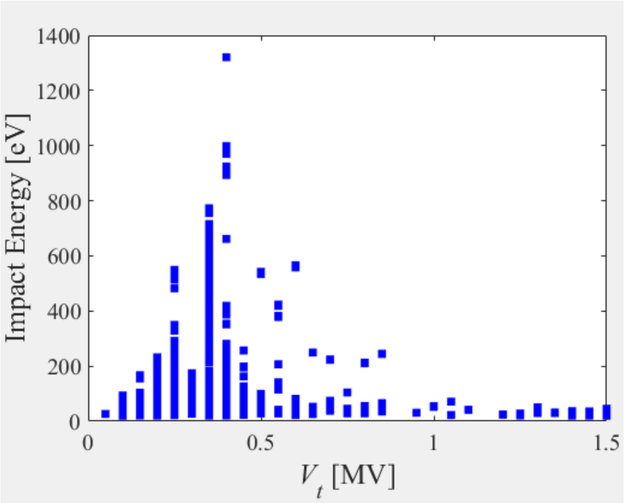


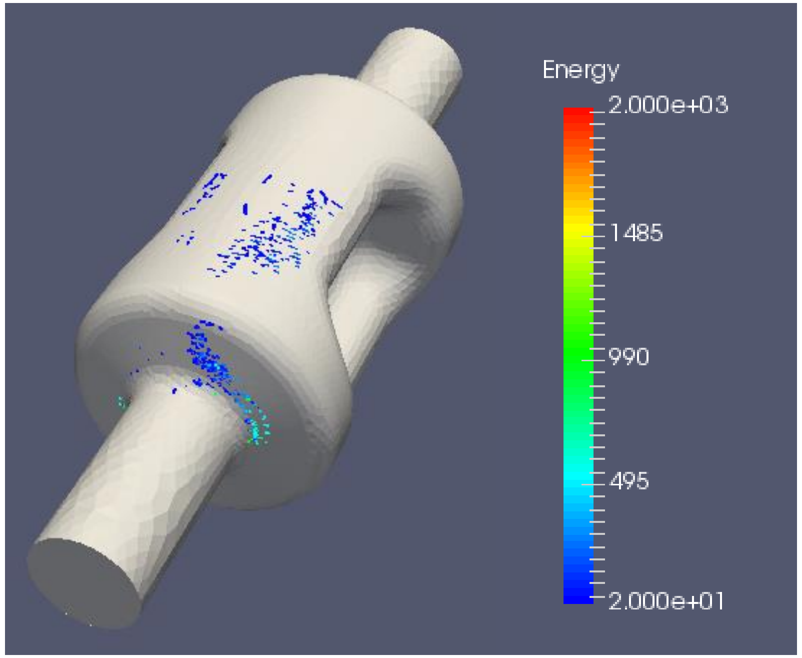
- Coupling using hook coupler
- Field probe:
  - $Q_{ext} < 1.0\times10^{10}$
  - Extract ~200 mW at 0.9225 MV

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
    - Opportunity for collaboration

Multipole Analysis

- Higher order multipole components for the time varying electromagnetic field

Proceedings of IPAC2012, New Orleans, Louisiana, USA TUPPR027

STUDY OF MULTIPOLAR RF KICKS FROM THE MAIN DEFLECTING MODE IN COMPACT CRAB CAVITIES FOR LHC*

J. Barranco García, R. Calaga, R. De Maria, M. Giovannozzi, A. Grudiev, R. Tomás
CERN, Geneva, Switzerland

$$E_{acc}(r,\phi,z,t) = E_z(r,\phi,z)e^{j\omega t} = \sum_{n=0}^{\infty} E_z^{(n)}(z)r^n e^{jn\phi}e^{j\omega t}$$

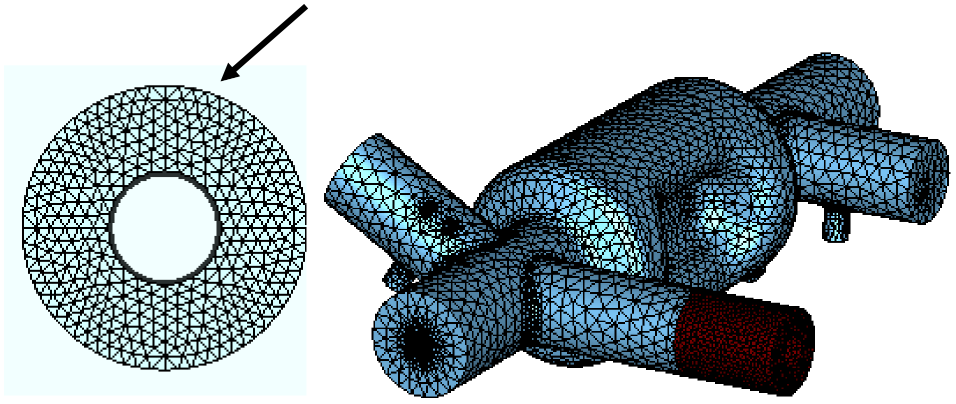
$$E_z^{(n)}(z) = \frac{1}{r^n}\int_0^{2\pi} E_z(r,\phi,z)e^{jn\phi}\mathrm{d}\phi$$

$$E_{acc}^{(n)}(z,t) = E_z^{(n)}(z)e^{j\omega t} = \frac{1}{r^n}\int_0^{2\pi} E_z(r,\phi,z)\left[\boxed{\cos(n\phi)} + \cancelto{0}{j\boxed{\sin(n\phi)}}\right]e^{j\omega t}\mathrm{d}\phi$$

Normal components

Skew components

- 64 mesh points on the 5 mm cylinder



2.4M mesh cells

Panofsky-Wenzel Theorem Method

$$\Delta p_t^{(n)}(z) = -j\frac{q}{\omega}\int_{-\infty}^{+\infty}\nabla_t E_z^{(n)}(z)e^{j\omega t}\mathrm{d}z$$

$$\Delta p_t^{(n)}(z) = -j\frac{q}{\omega}nr^{n-1}\int_{-\infty}^{+\infty}E_{acc}^{(n)}(z,t)\mathrm{d}z$$

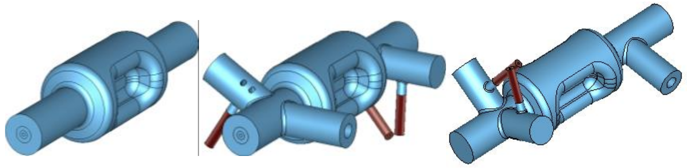
$$\Delta p_t^{(n)}(z) = \frac{1}{c}r^{n-1}\int_{-\infty}^{+\infty}F_t^{(n)}(z)\mathrm{d}z$$

$$A_z^{(n)} + jB_z^{(n)} = \frac{1}{qc}F_t^{(n)}(z) \quad [\mathrm{T/m^{n-1}}]$$

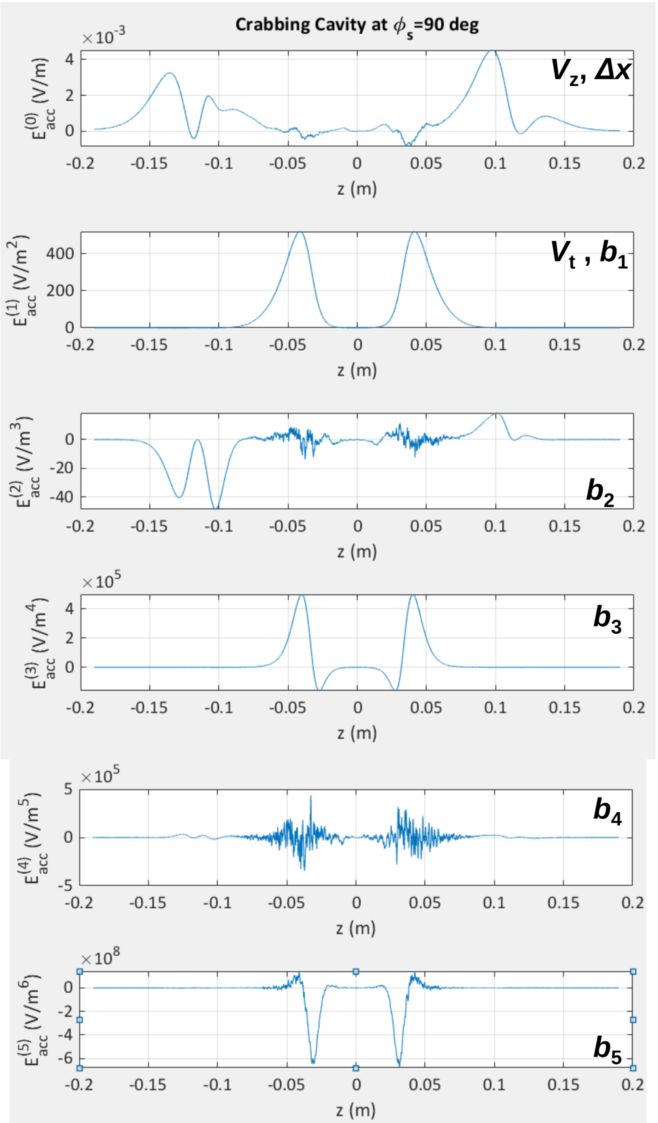
$$a_n + jb_n = \int_{-\infty}^{+\infty}\left[A_z^{(n)} + jB_z^{(n)}\right]\mathrm{d}z \quad [\mathrm{T/m^{n-2}}]$$

Multipole Components

- Higher order multipole components for
  - Bare cavity
  - Cavity with FPC and 3 HOMs
  - Cavity with FPC, 2 HOMs and FP
- Multipole components normalized to V_t = 1 MV
- Calculated at a beam offset of 5 mm
- No impact on b_3 and b_5 from FPC & HOM dampers on the beam pipe
- FPC & HOM dampers impact the shift in electrical center

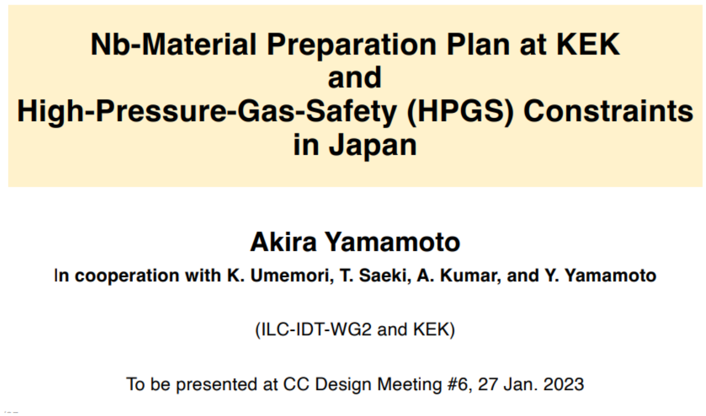


Component	No FPC &HOMs	With FPC & 3 HOMs	With FPC, 2 HOMs & FP
V_t [MV]	1.0		
b_0 [mT m^2]	0.0	0.0	0.0
b_1 [mT m]	3.34	3.34	3.34
b_2 [mT]	-1.0×10^{-3}	-0.24	0.12
b_3 [mT/m]	**4377.3**	**4384.5**	**4408.5**
b_4 [mT/m^2]	80.07	360.13	135.22
b_5 [mT/m^3]	**-5.39×10^6**	**-4.66×10^6**	**-4.63×10^6**
V_z [V]	-7.0×10^{-4}	-171.3	-330.6
Δx [µm]	-1.7×10^{-4}	-41.6	-80.2



Stress Analysis - Specification

- Analysis at 2.2 atm external pressure
- 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 – 3 mm
- Boundary conditions – Cavity constrained at beam pipes and FPC
- Allowable stress For Medium Grain (MG) < 39 MPa

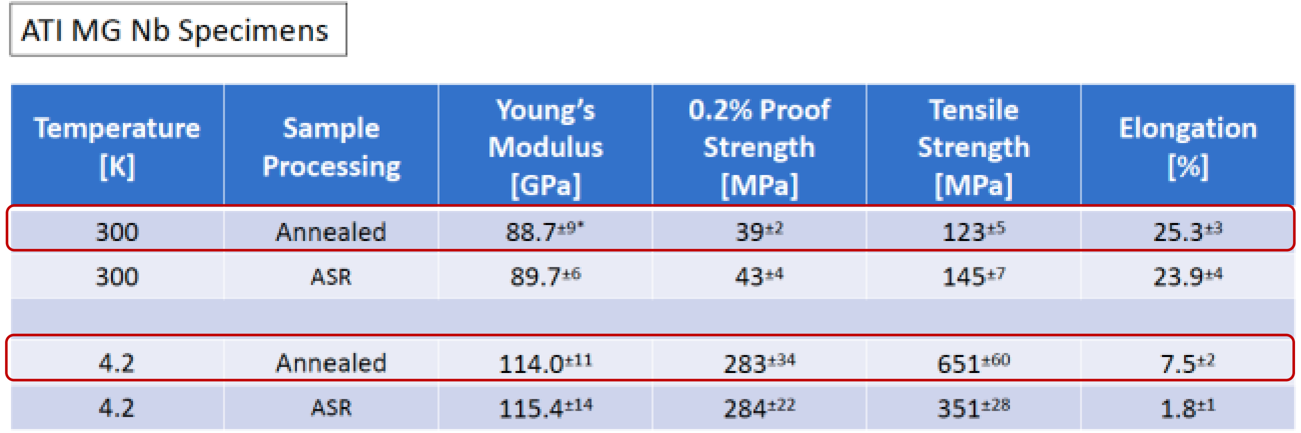


Nb-Material Preparation Plan at KEK
and
High-Pressure-Gas-Safety (HPGS) Constraints
in Japan

Akira Yamamoto
In cooperation with K. Umemori, T. Saeki, A. Kumar, and Y. Yamamoto

(ILC-IDT-WG2 and KEK)

To be presented at CC Design Meeting #6, 27 Jan. 2023



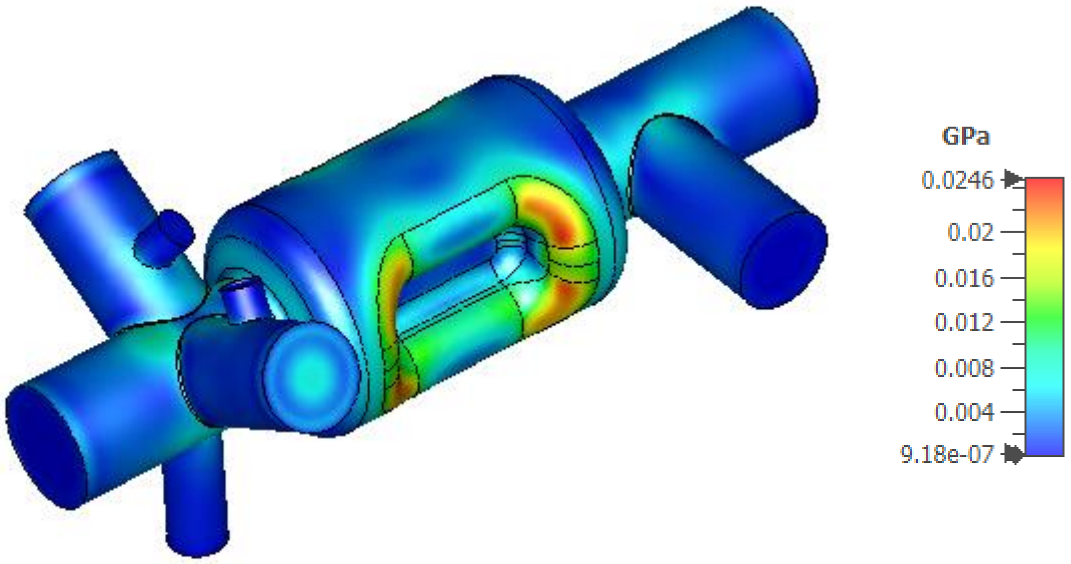
ATI MG Nb Specimens

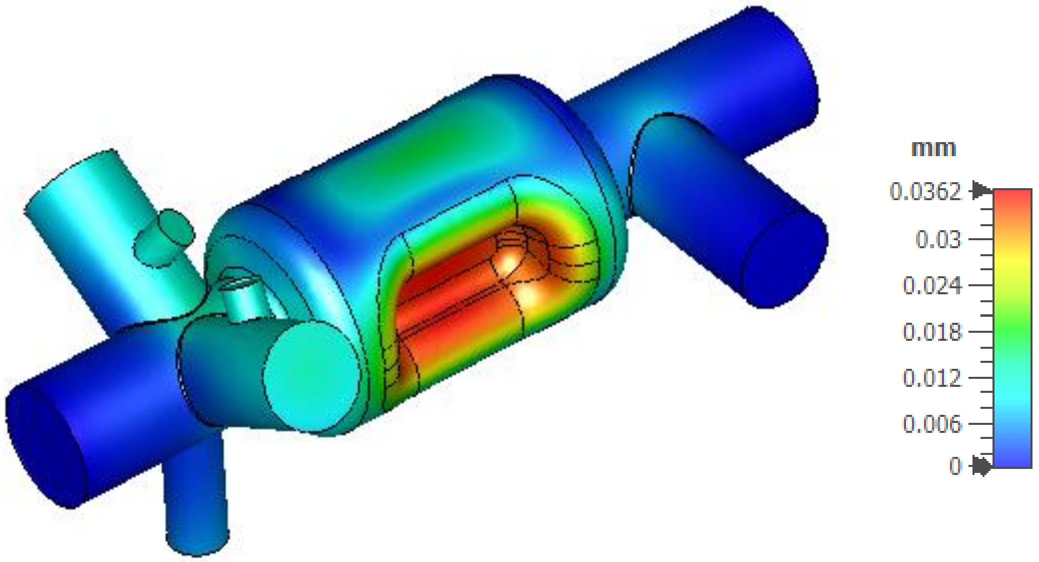
Temperature [K]	Sample Processing	Young's Modulus [GPa]	0.2% Proof Strength [MPa]	Tensile Strength [MPa]	Elongation [%]
300	Annealed	$88.7^{\pm9*}$	$39^{\pm2}$	$123^{\pm5}$	$25.3^{\pm3}$
300	ASR	$89.7^{\pm6}$	$43^{\pm4}$	$145^{\pm7}$	$23.9^{\pm4}$
4.2	Annealed	$114.0^{\pm11}$	$283^{\pm34}$	$651^{\pm60}$	$7.5^{\pm2}$
4.2	ASR	$115.4^{\pm14}$	$284^{\pm22}$	$351^{\pm28}$	$1.8^{\pm1}$

Stress Analysis

- Allowable stress < 39 MPa (For MG)
- Maximum stress is 24.6 MPa
- Initial analysis shows cavity doesn’t require stiffening
- Cavity can be machined with varying thickness

Case	Max. Stress [MPa]
Cavity with HOMs	24.6

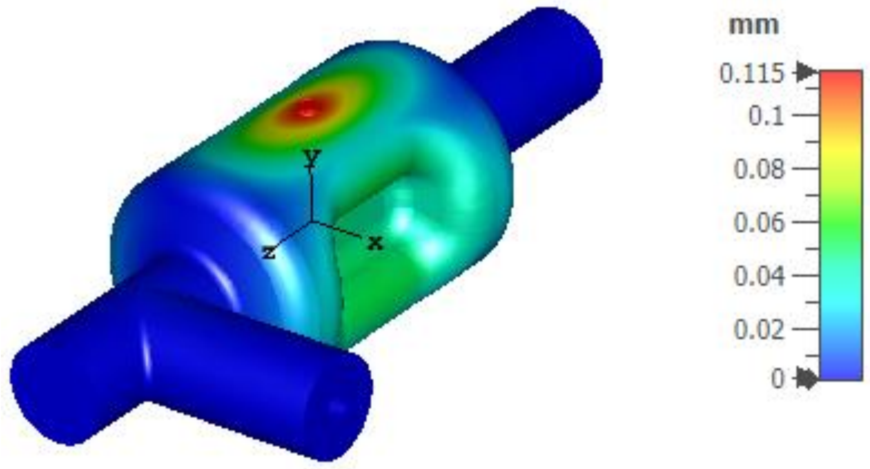


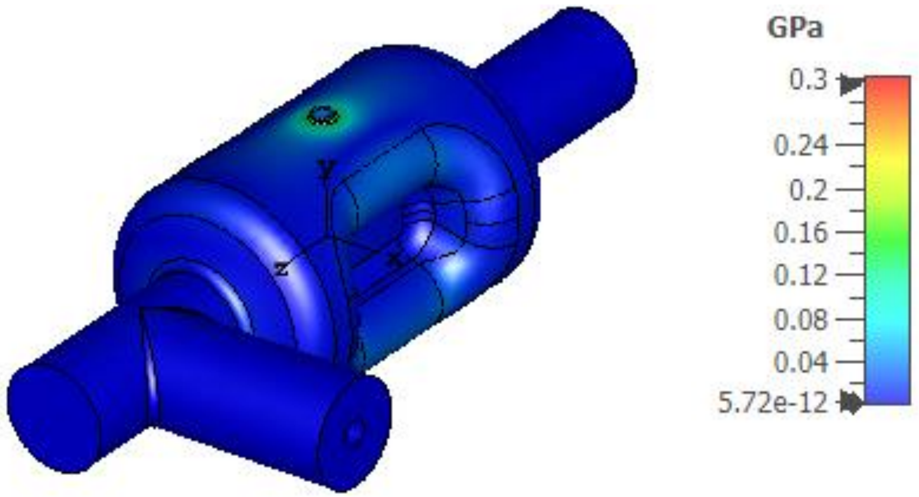


Tuning Sensitivity

- Nb material properties at cryo temperature for annealed MG
  - Young's modulus – 114 GPa (1.65×10^7 psi)
- Cavity thickness – 3 mm
- Cavity constrained at beam pipe ports and FPC

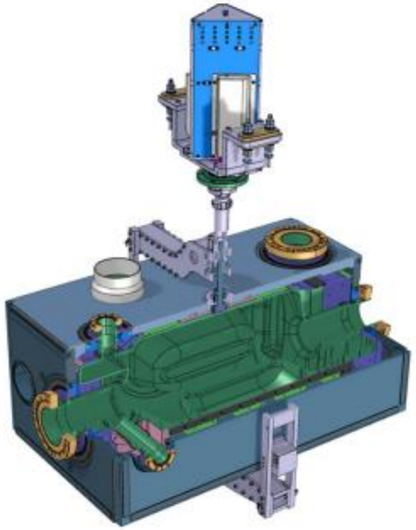
Total Displacement	Tuning Sensitivity	Tuning Range
0.23 mm	8.5 MHz/mm	1.96 MHz

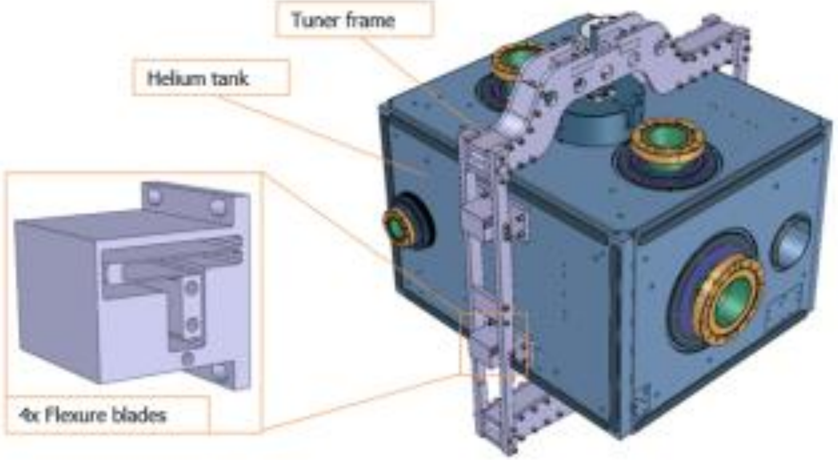


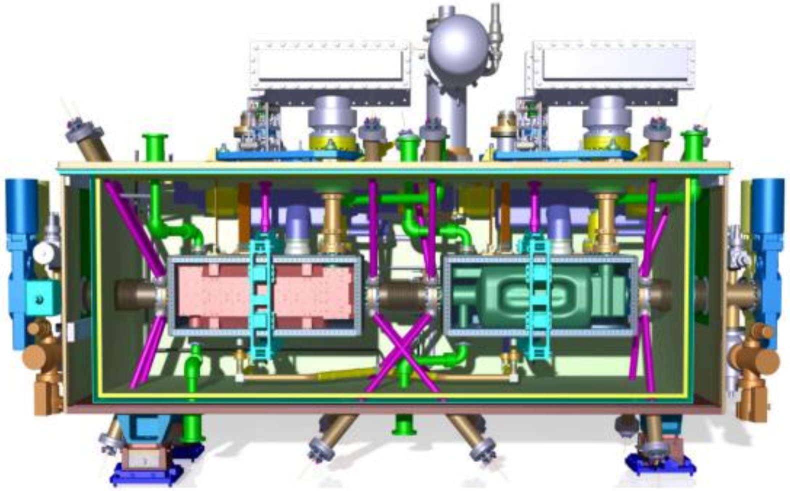


Tuning Concept

- Tuning requirement: 100-180 kHz
  - Requires 11 µm displacement each side
- Tuning concept similar to LHC RFD crab cavity for HiLumi upgrade
  - Symmetric deformation on top and bottom walls
- Using a piezo tuner is worth investigating due to small displacement
  - Opportunity for collaboration





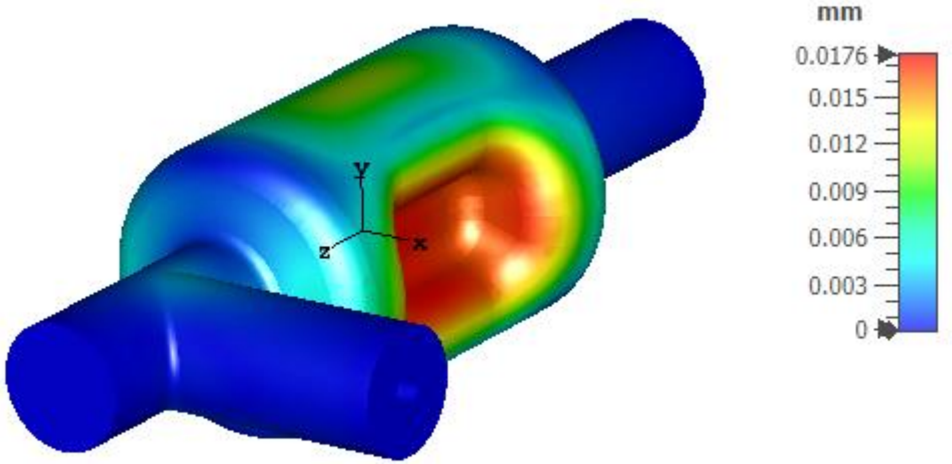


Status of the HL-LHC Crab Cavity Tuner – K. Artoos – SRF 2019
Development of a Novel Supporting System for High Luminosity LHC SRF Crab Cavities – T. Jones – SRF 2017

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

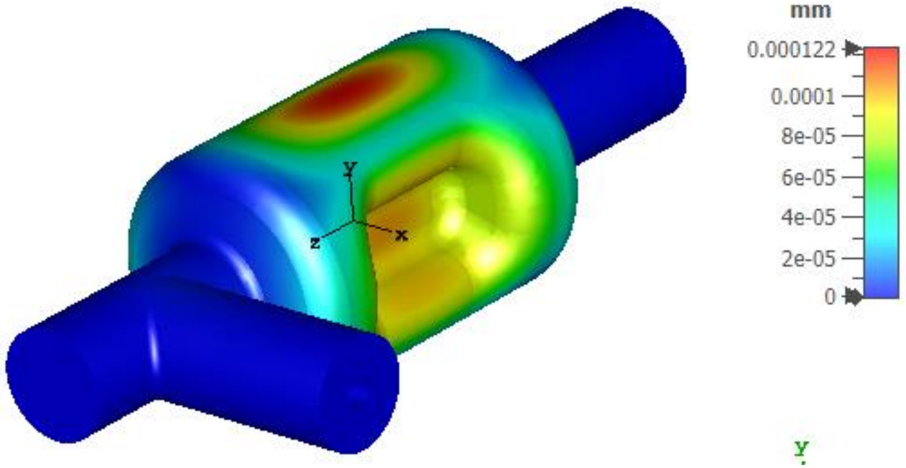
Cavity Type	**d*f*/d*P* [Hz/mbar]**
1-cell	– 561.3



Lorentz Detuning

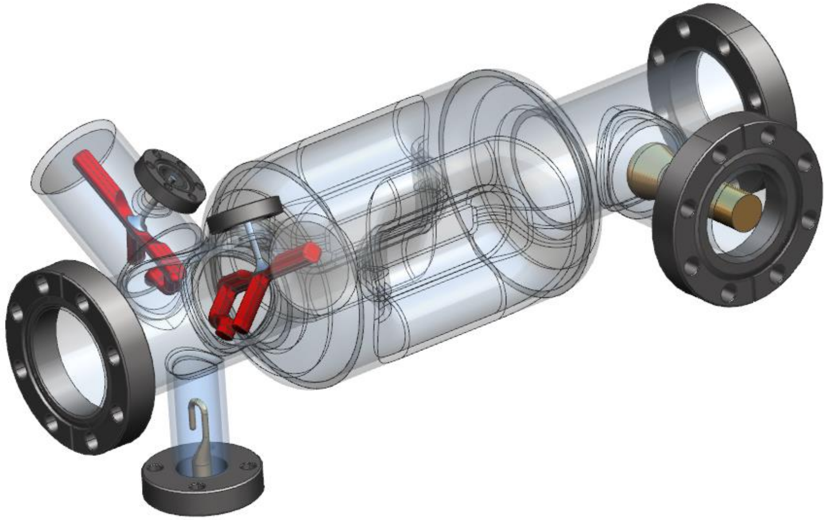
- Nb material properties at cryo temperature for annealed MG
  - Young's modulus – 114 GPa (1.65×10^7 psi)
  - Poisson's ratio – 0.38
- Cavity thickness – 3mm
- Cavity constrained at beam pipe ports and FPC
- Lorentz detuning can be reduced by tuner
  - Tuning by push/pull at top and bottom of the cavity

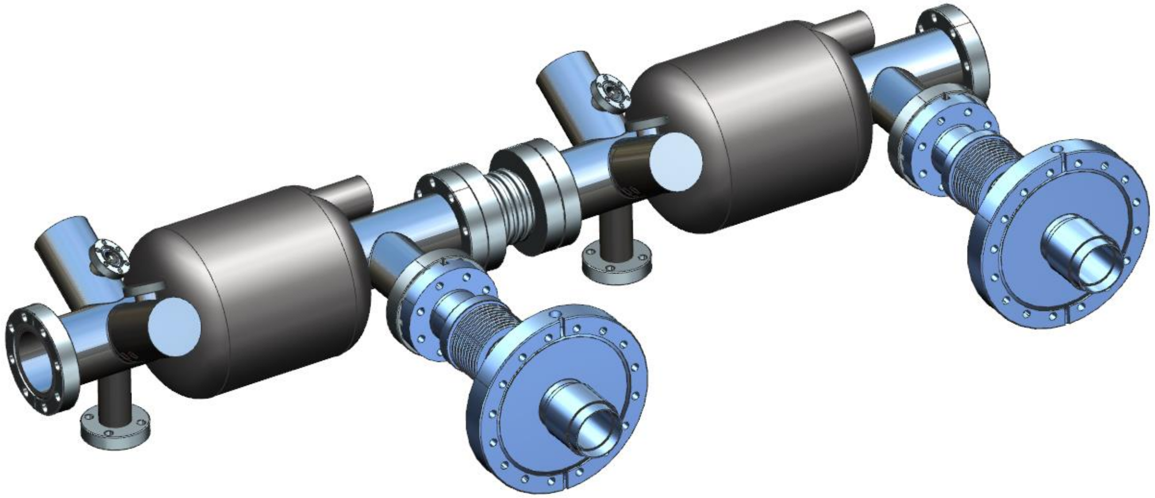
Cavity Type	k_L [kHz/(MV)^2]	V_t [MV]	Δf [kHz]
1-cell	-3.67	1.35	6.7

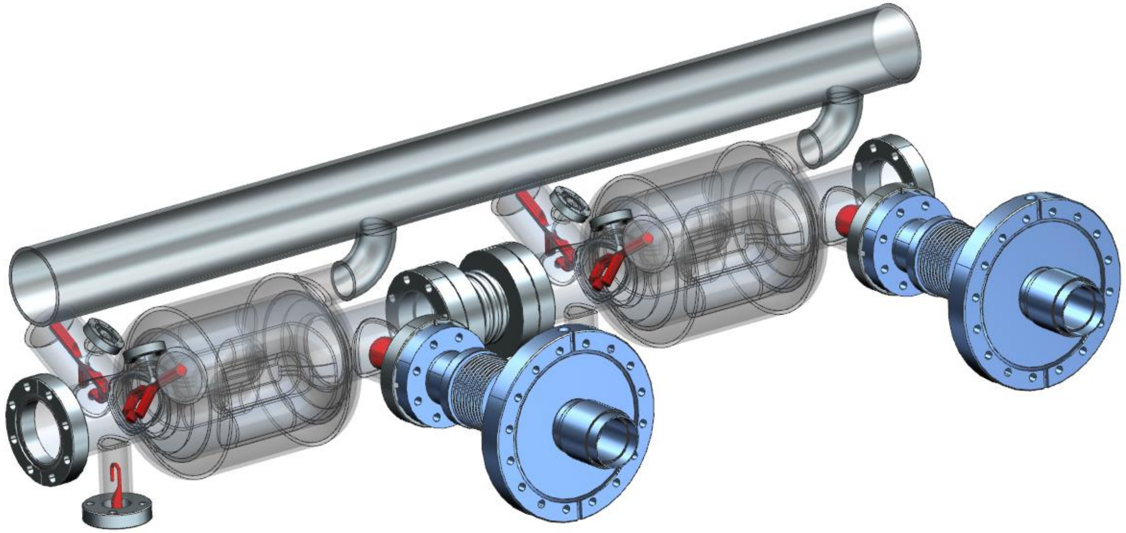


Conceptual He Vessel and Cryomodule Design – 125 GeV

- 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)
  - 47% extra margin
- 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

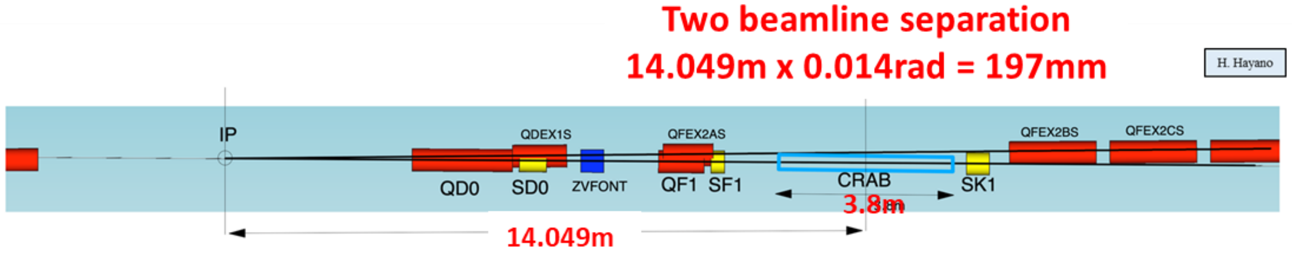




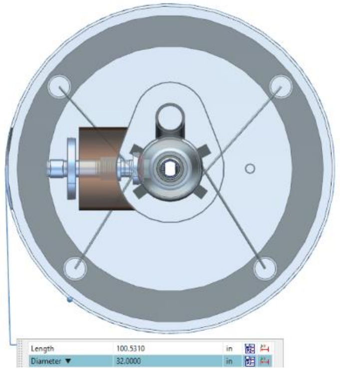


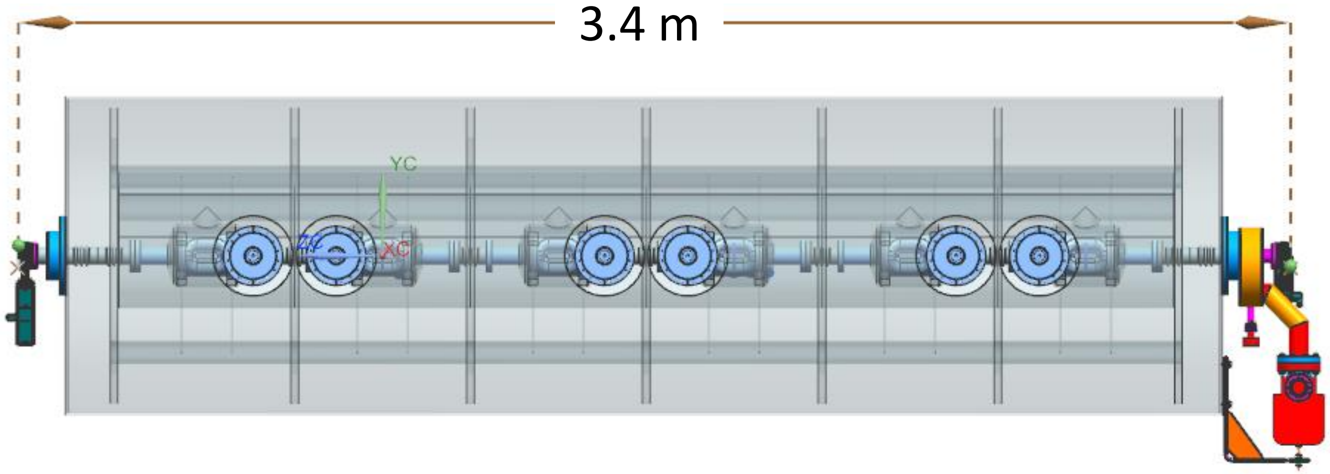
Conceptual He Vessel and Cryomodule Design – 500 GeV

- Cryomodule required to fit in within 3.8 m
- 6 cavities in a single cryomodule
  - Second beam pipe – 20 mm beam pipe
  - Total achievable – 8.16 MV (1.36 MV V_t per cavity)
  - ~10% extra margin
- Design concept follows JLab C100 cryomodule
- Cryomodule length = 3.4 m
- Cryomodule diameter = 0.82 m

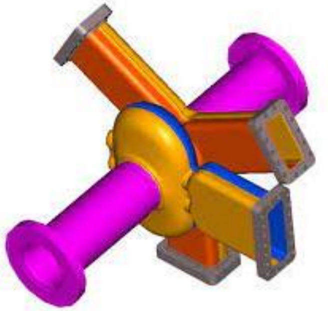

Two beamline separation

14.049m x 0.014rad = 197mm





Cavity Fabrication Processes



- General fabrication processes:
  1. Machining 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

2.8 GHz SPX Cavity Fabrication at JLAB

Cut fixture plate

machined fixture base

RRR>250 large grain Nb ingot

EDM wire cut Nb template

Machine outside surface

Machine inside surface with 30um unfinished

Milling tool head for last inner finish

Machine inner surface on the base

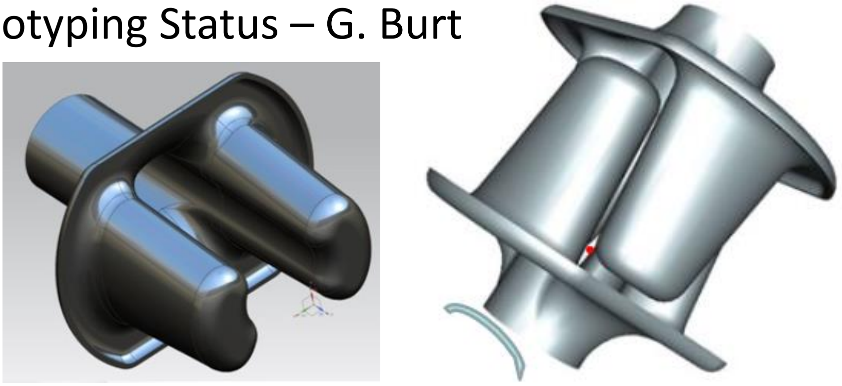
Finished first half with 4mm wall thickness

Match to other Al model half

Outside finish of first half

EDM wire cut Nb template for Y WG

400 MHz 4-Rod Crab Cavity Prototyping Status – G. Burt



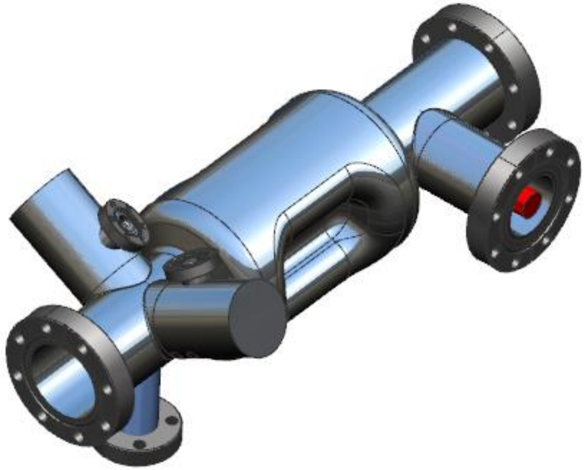
Cavity Fabrication Processes

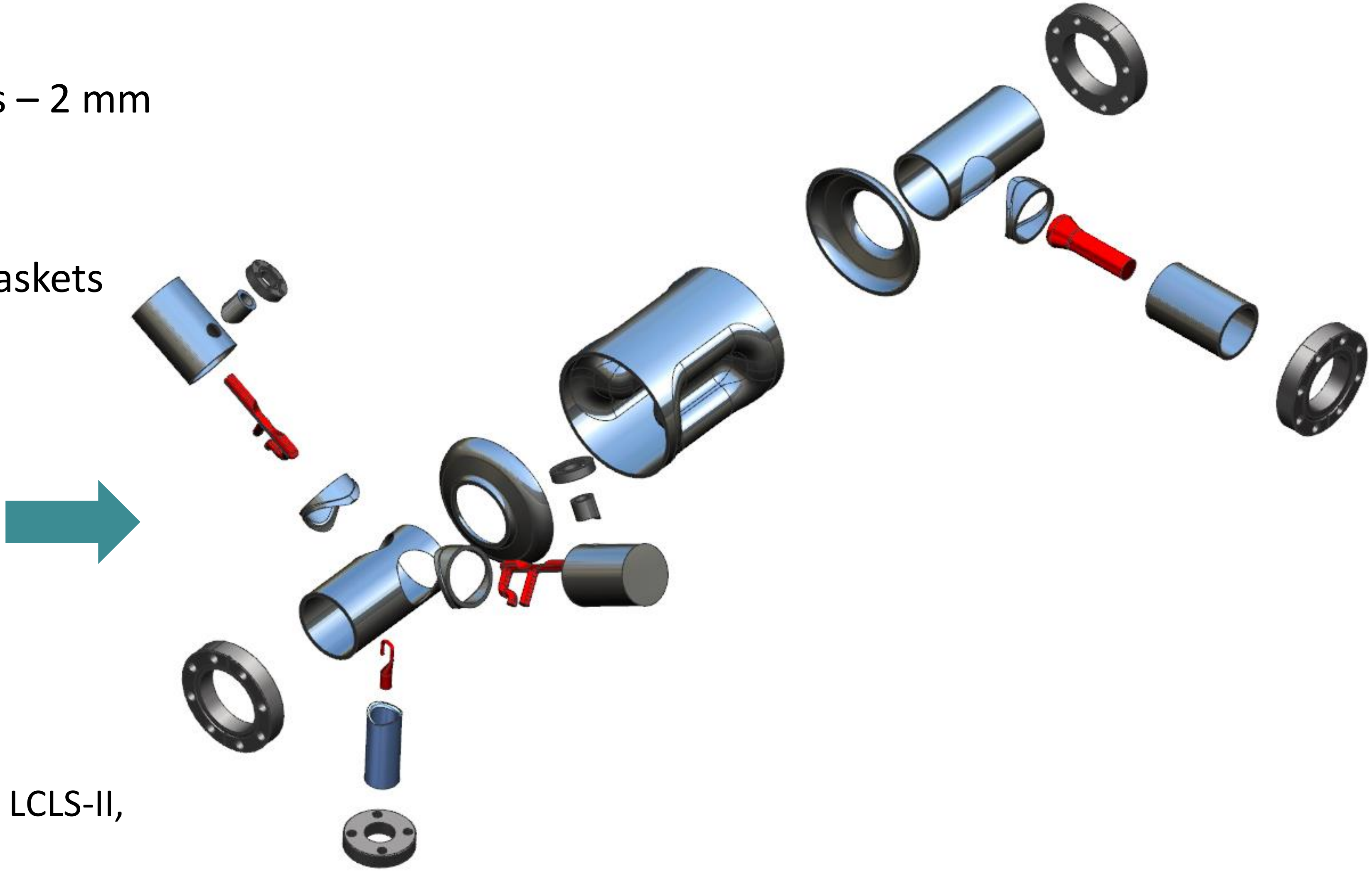
- General fabrication processes:
  2. Stamping and forming using Nb sheets
     - Well understood technology
     - Requires forming and machining dies
     - Also requires more fixturing to achieve tolerances

960 MHz 2-cell RFD Cavity Fabrication at JLAB

Cavity Components of 1.3 GHz RFD Cavity

- 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

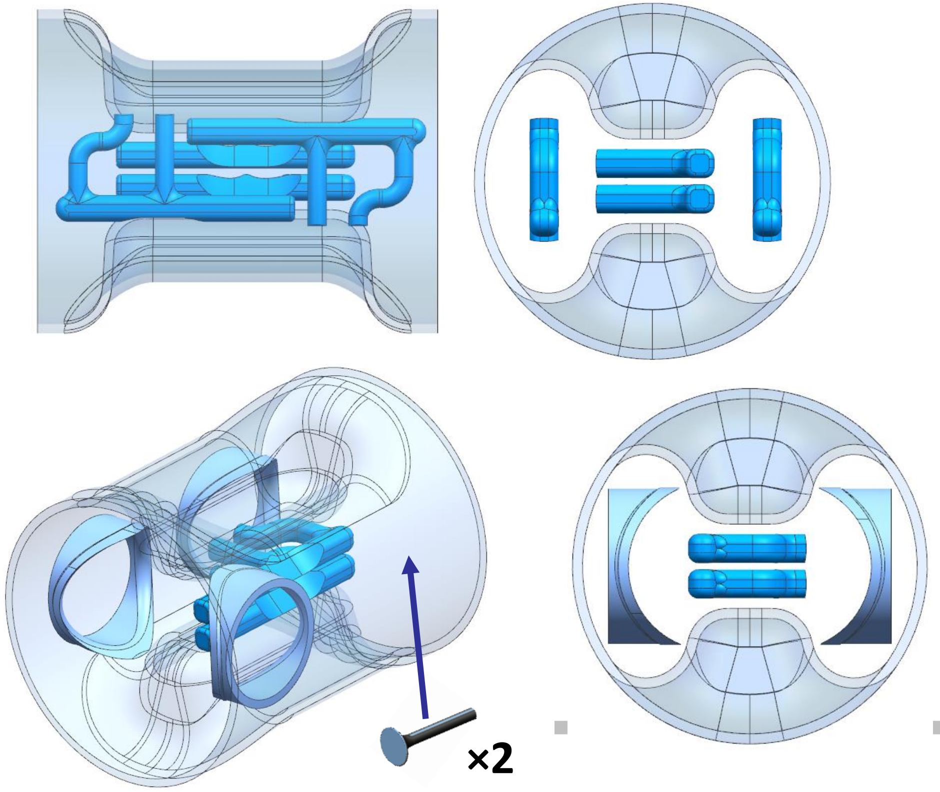




- HOM coupler fabrication
  - TESLA HOM couplers used in XFEL, LCLS-II, CEBAF-C100, and ILC
  - Well understood fabrication process

Fabrication Options for 1.3 GHz RFD Cavity – Option 1

1. Hybrid – Machining and stamping → Preferred Method
    - Machining for body out of MG forged ingot
    - Stamping for the ends
    - Combines the best of both processes
    - All HOM hooks can be machined out of material removed from the body

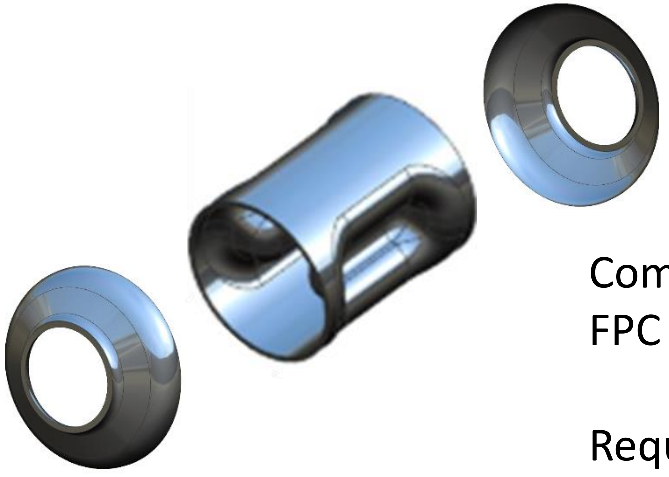


1. Stamp end cap (×2)

Requires set of forming dies and machining dies

2. Wire EDM center body

3. Weld end caps to center body



Complete end groups with FPC and HOM ports

Requires welding fixtures

Fabrication Options for 1.3 GHz RFD Cavity – Option 1

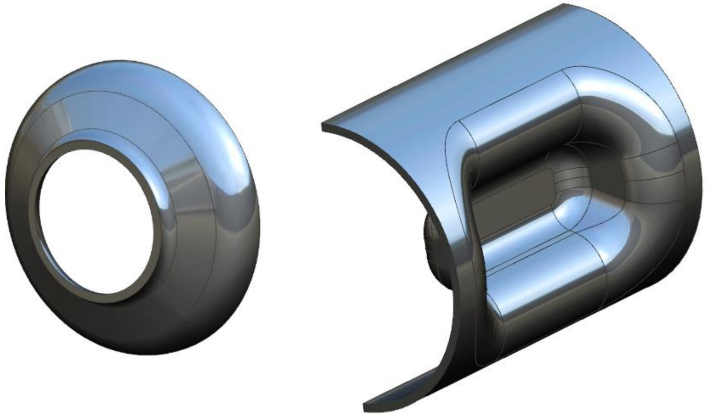
Cavity Parts (Nb)	Material Type	Dimensions [mm]	Qty	Weight [kg]
Center body	MG forged ingot	Ø 110 mm × 140 mm	1	11.4
End caps	Disc	Ø 130 mm × 3 mm	2	0.7
Beam tubes	Sheets	115 mm × 180 mm × 2 mm	2	0.8
HOM cans	Sheets	65 mm × 148 mm × 2 mm Ø 45 mm × 2 mm	2	0.4
FPC tube	Sheets	84 mm × 148 mm × 2 mm	1	0.3
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**

Fabrication Options for 1.3 GHz RFD Cavity – Option 2

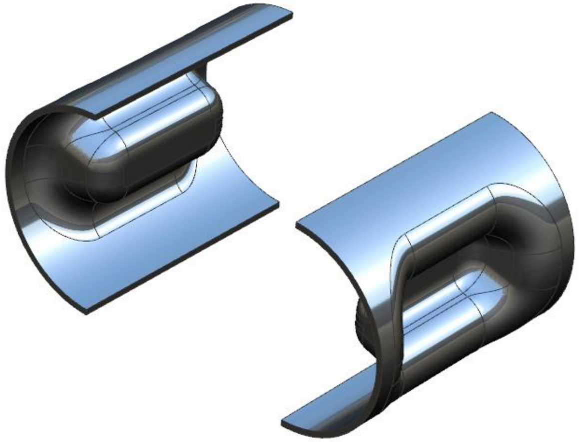
2. Stamping and forming using Nb sheets
   - Well understood technology
   - Requires forming and machining dies
   - Also requires more fixturing to achieve tolerances
   - Forming and machining dies fabricated with Al 7075

1. Stamp end cap and center body (×2)

Requires set of forming dies and machining dies



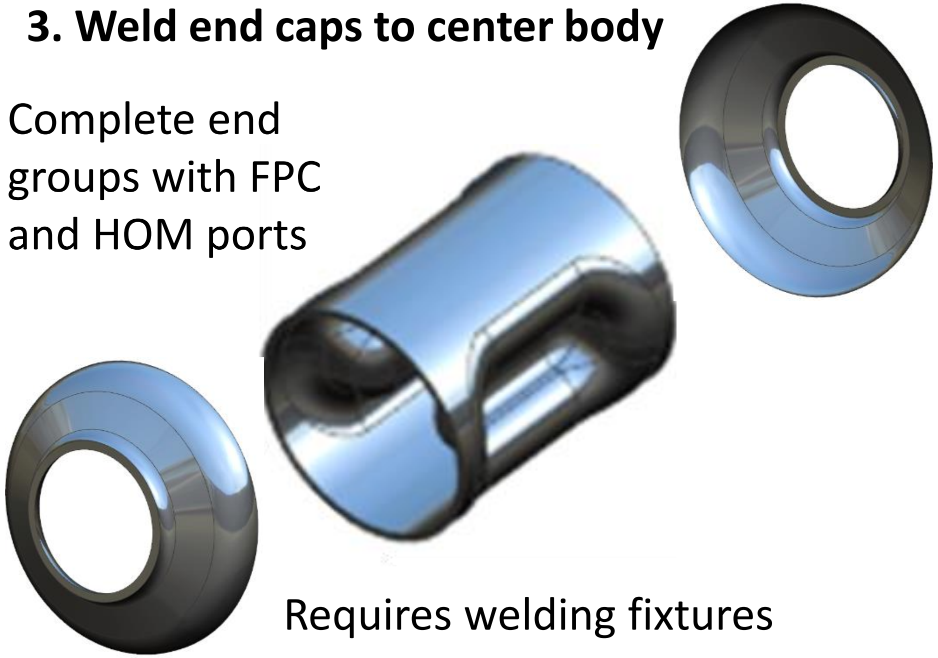
2. Weld center body



Requires welding and trimming fixtures

3. Weld end caps to center body

Complete end groups with FPC and HOM ports



Requires welding fixtures

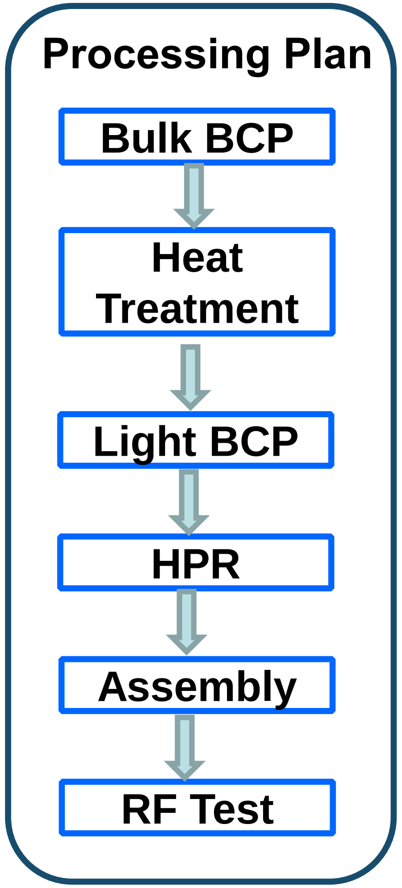
- Weld at the tuning location
- Can add a strip to off set the weld on the tuner location → Increase number of welds and distortions (Eg. JLEIC RFD cavity)

Fabrication Options for 1.3 GHz RFD Cavity – Option 2

Cavity Parts (Nb)	Material Type	Dimensions [mm]	Qty	Weight [kg]
Center body	Sheet	192 mm × 185 mm × 3 mm	2	1.9
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	Rod	Ø 50 mm × 25 mm	3	1.1
HOM hooks	Plate	88 mm × 45 mm × 10 mm	2	0.7
HOM probes	Rod	Ø 30 mm × 40 mm	2	0.5
Total				**6.7**

Processing and Testing Plan

- Chemistry – Bulk (120 µm) and light BCP (30 µm)
  - Optional light EP after BCP
- Heat treatment – 600 ^{O}C for 10 hours
- RF Test Plan
  - Test at 4 K and 2 K
- Test sequence
  - Bare cavity test
  - Cavity test with HOM couplers
- Qualify cavity with HOM couplers and demonstrate a V_t of 1.5 MV



Processing Plan

Bulk BCP → Heat Treatment → Light BCP → HPR → Assembly → RF Test

BCP Cabinet

HPR Cabinet

Summary

- 1-cell cavity meets current specifications in:
  - Dimensions, surface fields, mechanical stresses

- HOM damping:
  - Meets transverse impedance thresholds with wide margin
  - Further calculations on loss factor and transverse kick factors pending

- Cavity rf design is complete with FPC and HOM damping scheme
  - Multipacting analysis on the full cavity, inclusion of couplers is underway

- Concepts for
  - Cavity fabrication
  - Integration with tuners and He tank
  - Cryomodule

Summary

- Next steps for cavity prototyping
  - Full engineering analysis and design
    - Opportunity for collaboration
  - Detailed manufacturing plan

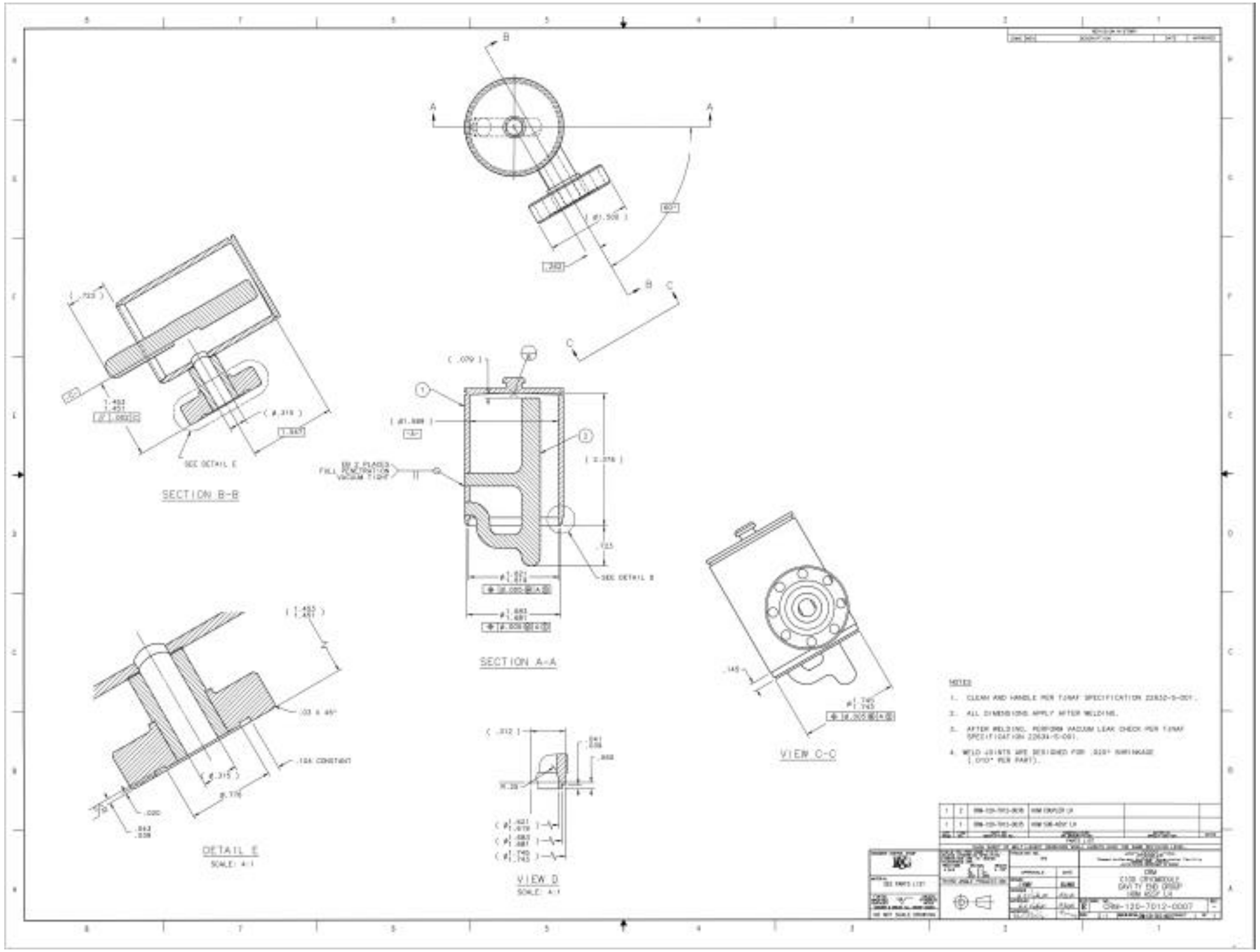
- All activities so far have been unfunded and “off the books”

- We (ODU/JLab) would like to proceed with prototyping
  - Will require real funding

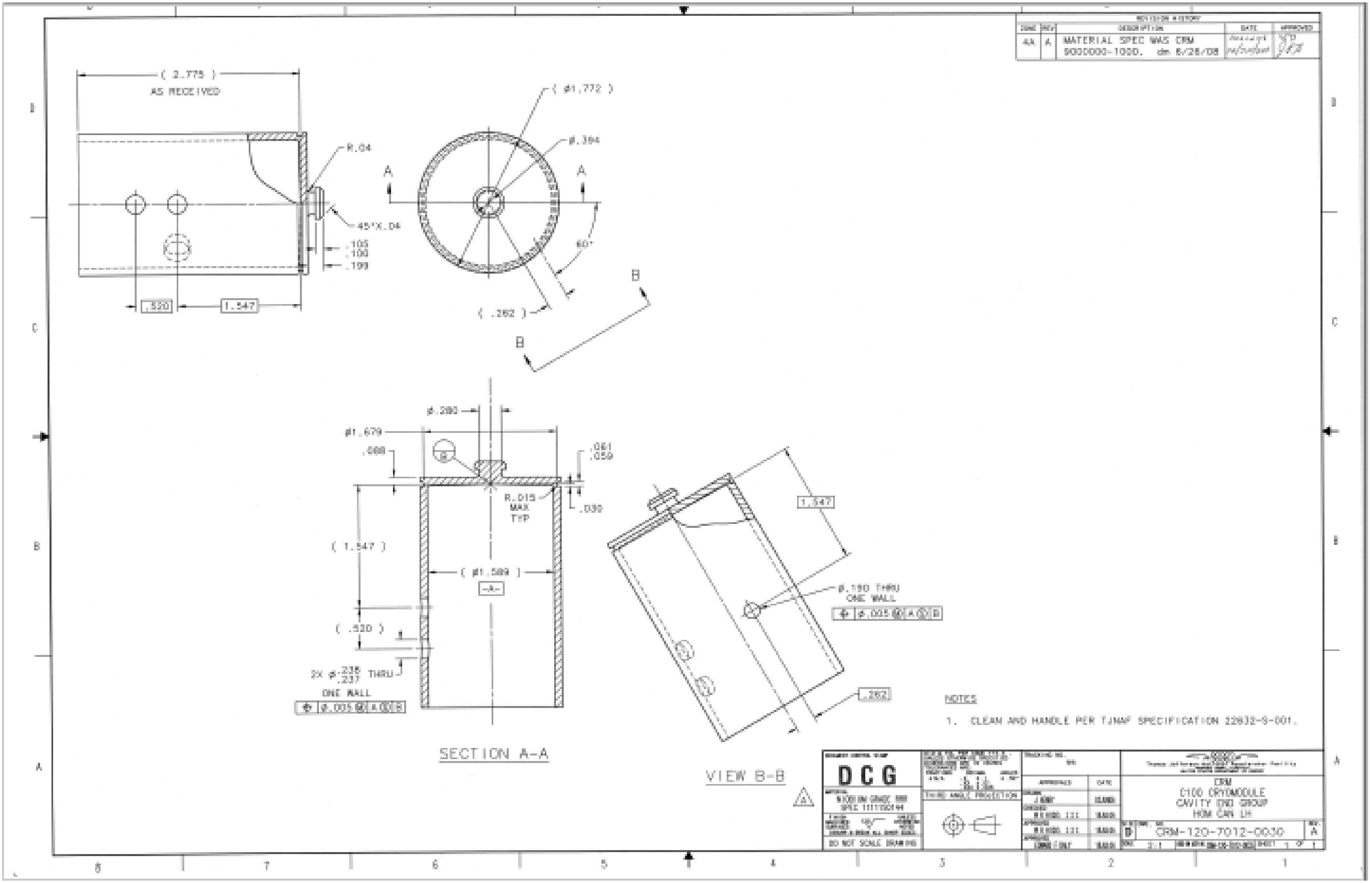
Back Up Slides

HOM Damper Fabrication

- Similar experience C100 HOM dampers



HOM Damper Fabrication



960 MHz 2-Cell RFD Cavity Fabrication

- Stamping of center body pole and end cap

Answers to Committee's Questions

- Assuming that you are awarded the project for the prototyping phase what are your next steps and who (which institutes) is on your team?

- From a practical angle, one of the first steps would be to try to secure funding

- We believe the rf design is sound and final but…..
  - Full multipacting analysis with all the couplers still need to be done
  - The rf design should be checked and validated by somebody else
  - Same with stress analysis, Lorentz detuning, pressure sensitivity, etc

- Proceed with next level conceptual engineering design
  - Variable thickness
  - Integration of HOM couplers
  - Integration with tuning system
  - Integration with He tank
  - Integration with cryostat

Answers to Committee’s Questions

- So far the team has been only ODU and JLab
  - On other projects we have productive collaborations with BNL, SLAC, FNAL, TRIUMF, CERN ……
- We would welcome collaboration with interested parties especially on items mentioned in previous slide
  - Would not want to mention names without checking with them first
- There are probably some parts of the project (e.g. cavity fabrication and testing) that we would like to keep
  - The ODU/JLab team has prototyped and large number of similar “exotic” cavities.
  - JLab fabrication, processing and testing facilities are familiar with fabrication and prototyping such cavities.
- We are well aware that we cannot do everything in the required time scale and welcome constructive collaborations

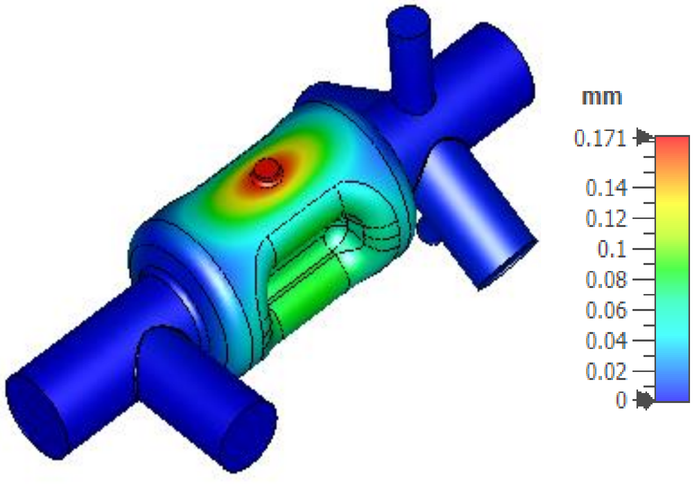
Answers to Committee’s Questions

- Past collaborations
  - SLAC : Optimization of RFD for LHC-HiLumi, multipacting
  - FNAL : Mechanical analysis, cavity fabrication and testing of LHC cavities
  - BNL : Design and development of EIC cavities
  - ANL : Cavity processing
  - CERN/Lancaster/TRIUMF : CERN HiLumi crab cavities and cryomodules

Answers to Committee’s Questions

- Present a slide or two on the considerations for the tuner design

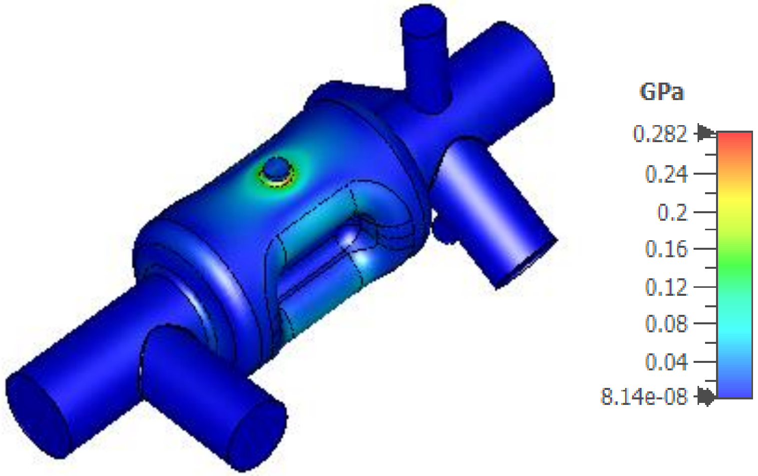
Total Displacement	Tuning Sensitivity	Max Tuning Range
0.23 mm	8.5 MHz/mm	±1.96 MHz



- Sensitivity: 8.5 Hz/nm
- Tuning range of 200 kHz corresponds to a total displacement of 24 µm
- Loaded bandwidth of 87 Hz ($Q_L = 1.5\times10^7$) corresponds to total displacement of 10 nm
- Tuning force (for 200 kHz) per side – 164 N

- Probably not achievable by a purely mechanical system

- Investigate piezo or magnetostrictive tuning system
  - Would also be able to control dynamic frequency variations (microphonics)



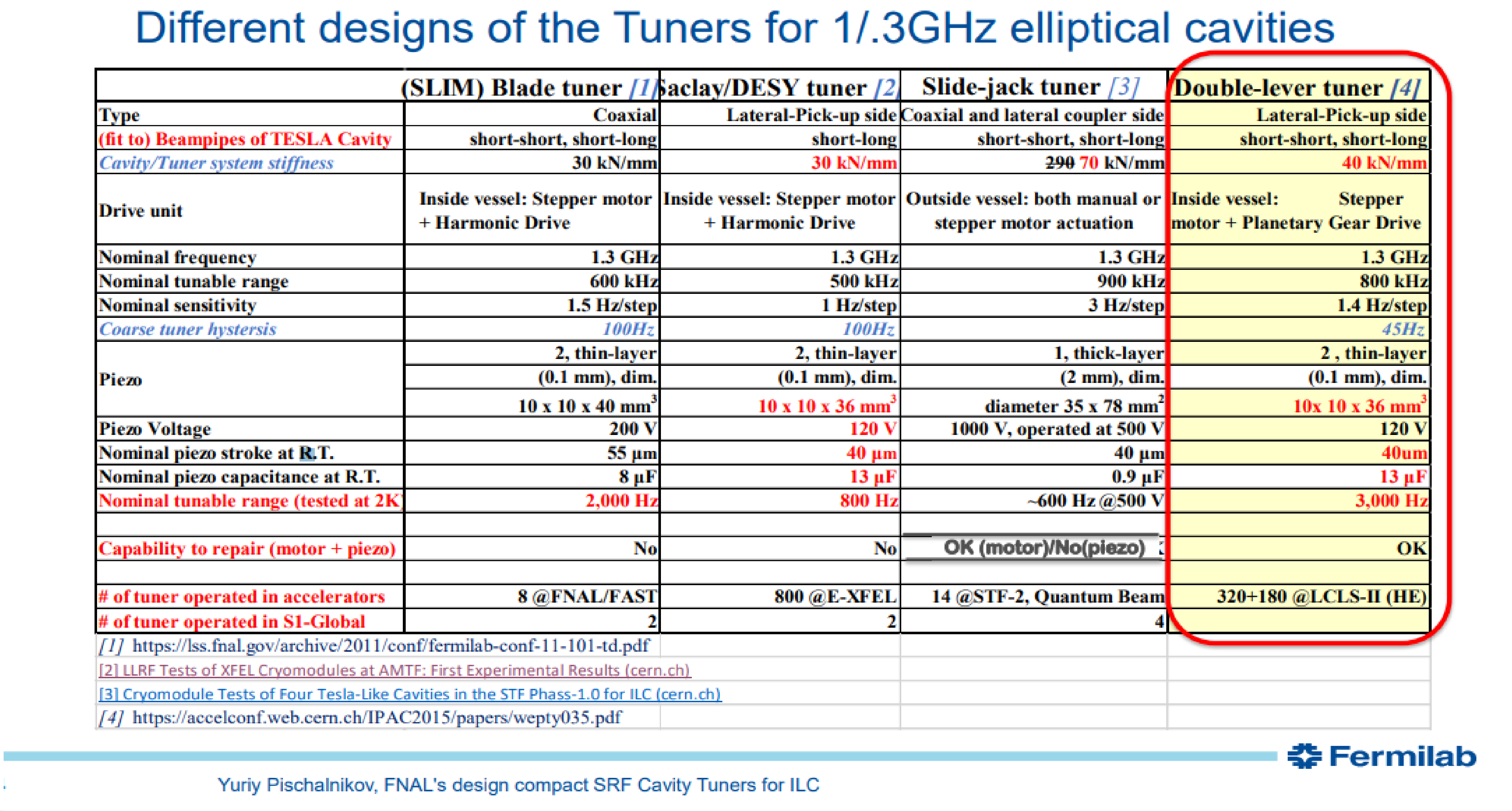
Answers to Committee’s Questions

- Tuner concept:
  - Coarse tuning by a mechanical tuner, Check if needed.
  - Fine tuning by a piezo or magnetostrictive tuner. Possibly sufficient.
  - One piezo on one side may be enough but put one on both sides for redundancy.

- Tuner operation: Use one side of the tuning range to either push or pull
  - To avoid dead band
  - To reduce pressure sensitivity and Lorentz detuning

- Tuner examples:
  - LCLS-II tuner

Answers to Committee’s Questions



Different designs of the Tuners for 1/.3GHz elliptical cavities

	(SLIM) Blade tuner *[1*	Saclay/DESY tuner *[2*	Slide-jack tuner *[3]*	Double-lever tuner *[4]*
Type	Coaxial	Lateral-Pick-up side	Coaxial and lateral coupler side	Lateral-Pick-up side
(fit to) Beampipes of TESLA Cavity	short-short, short-long	short-long	short-short, short-long	short-short, short-long
Cavity/Tuner system stiffness	30 kN/mm	30 kN/mm	~~290~~ 70 kN/mm	40 kN/mm
Drive unit	Inside vessel: Stepper motor + Harmonic Drive	Inside vessel: Stepper motor + Harmonic Drive	Outside vessel: both manual or stepper motor actuation	Inside vessel: Stepper motor + Planetary Gear Drive
Nominal frequency	1.3 GHz	1.3 GHz	1.3 GHz	1.3 GHz
Nominal tunable range	600 kHz	500 kHz	900 kHz	800 kHz
Nominal sensitivity	1.5 Hz/step	1 Hz/step	3 Hz/step	1.4 Hz/step
Coarse tuner hystersis	*100Hz*	*100Hz*		*45Hz*
Piezo	2, thin-layer	2, thin-layer	1, thick-layer	2 , thin-layer
	(0.1 mm), dim.	(0.1 mm), dim.	(2 mm), dim.	(0.1 mm), dim.
	10 x 10 x 40 mm^3	10 x 10 x 36 mm^3	diameter 35 x 78 mm^2	10x 10 x 36 mm^3
Piezo Voltage	200 V	120 V	1000 V, operated at 500 V	120 V
Nominal piezo stroke at R.T.	55 µm	40 µm	40 µm	40um
Nominal piezo capacitance at R.T.	8 µF	13 µF	0.9 µF	13 µF
Nominal tunable range (tested at 2K	2,000 Hz	800 Hz	~600 Hz @500 V	3,000 Hz
Capability to repair (motor + piezo)	No	No	OK (motor)/No(piezo)	OK
# of tuner operated in accelerators	8 @FNAL/FAST	800 @E-XFEL	14 @STF-2, Quantum Beam	320+180 @LCLS-II (HE)
# of tuner operated in S1-Global	2	2	4	

[1] https://lss.fnal.gov/archive/2011/conf/fermilab-conf-11-101-td.pdf

[2] LLRF Tests of XFEL Cryomodules at AMTF: First Experimental Results (cern.ch)

[3] Cryomodule Tests of Four Tesla-Like Cavities in the STF Phass-1.0 for ILC (cern.ch)

[4] https://accelconf.web.cern.ch/IPAC2015/papers/wepty035.pdf

Fermilab

Yuriy Pischalnikov, FNAL's design compact SRF Cavity Tuners for ILC