RF Dipole Cavity Proof-of-Principle Design and Test Prototype Design

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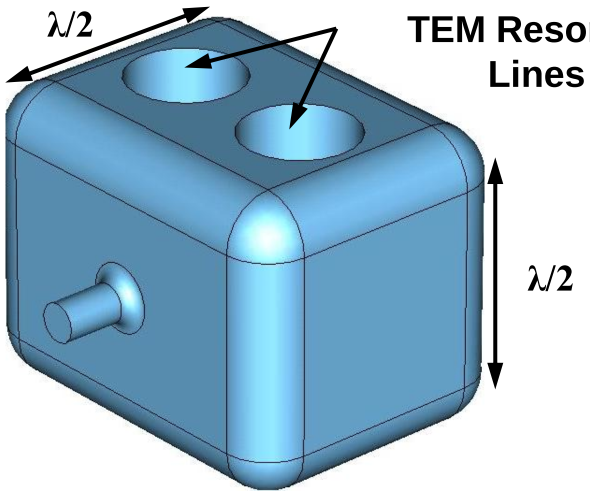
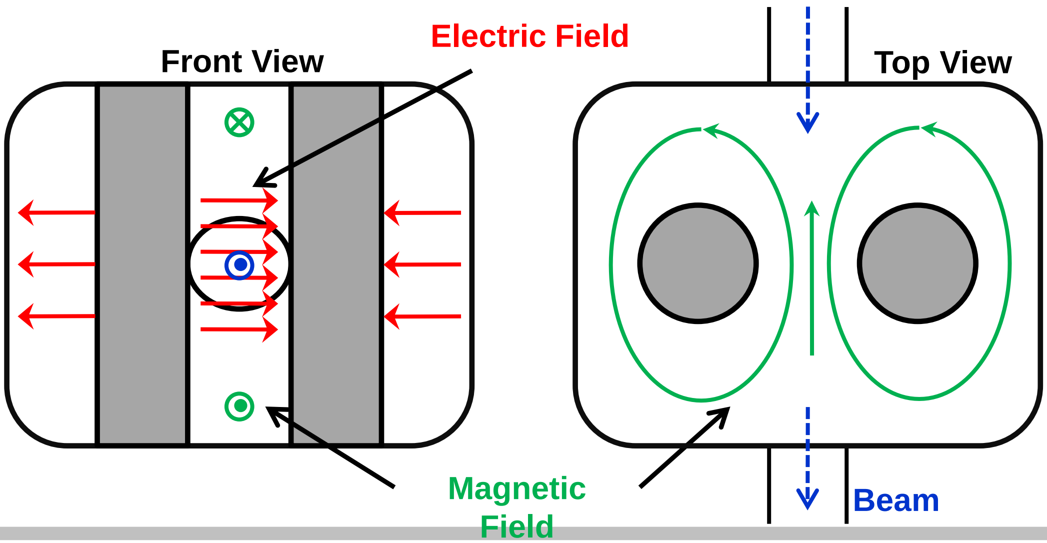
Main Cast of Characters

- Subashini De Silva (ODU)
- HyeKyoung Park (ODU)
- Rocio Olave (ODU)
- Zenghai Li (SLAC)
- With help from
  - Tom Nicol (FNAL)
  - JLab team
  - CERN team
  - Niowave team

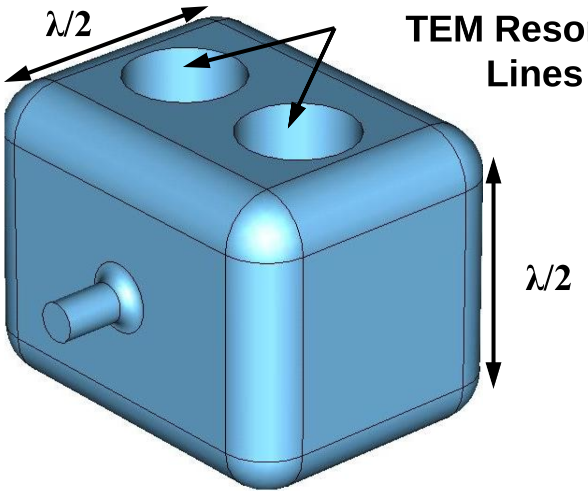
Parallel-bar Cavity Concept

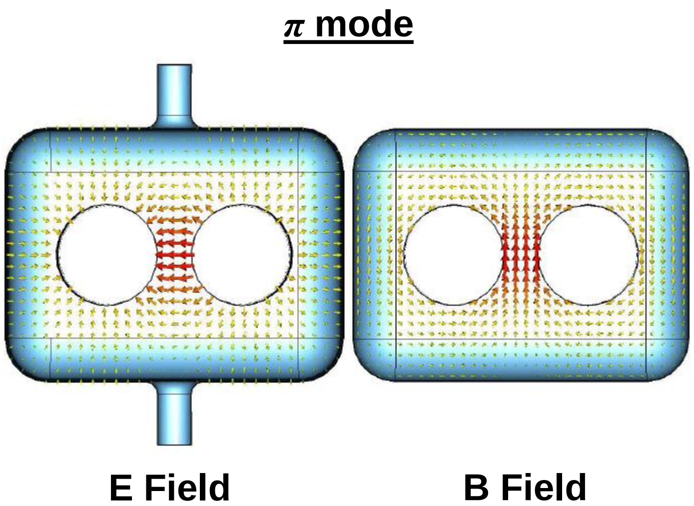
- 2 half-wavelength resonant lines operating in opposite phase



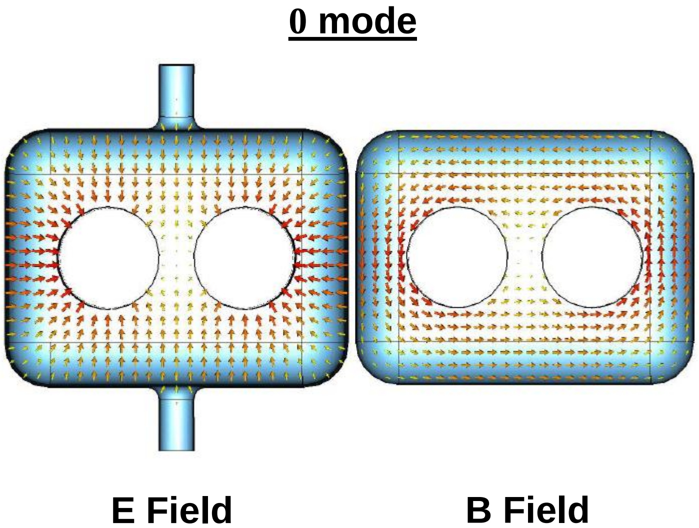


Parallel-bar Cavity Concept

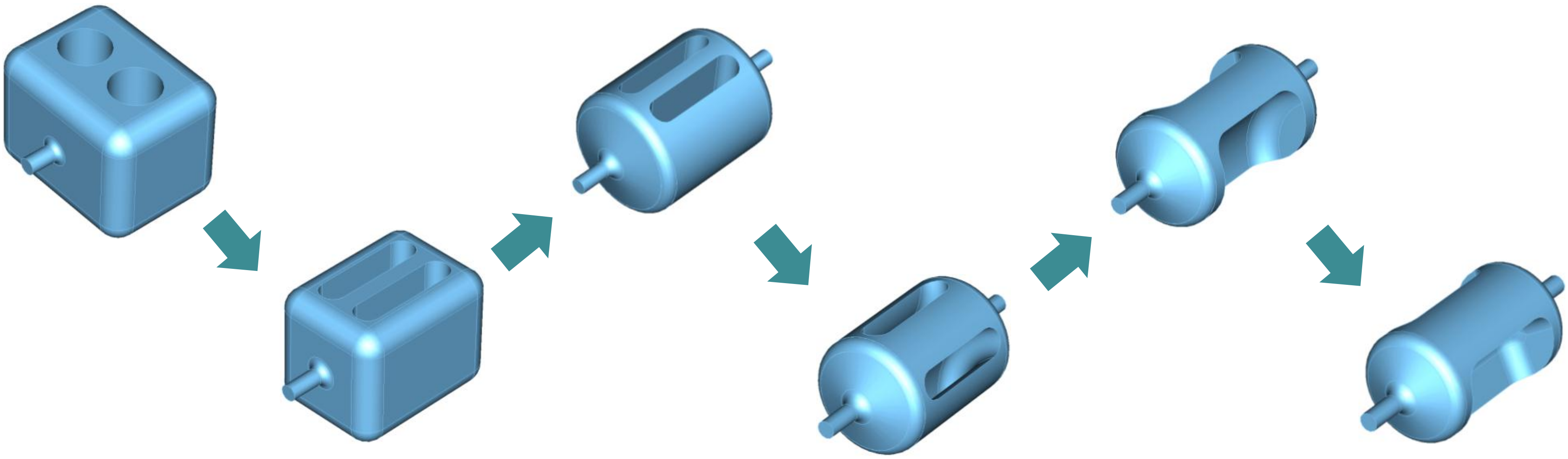




- Two degenerate fundamental TEM modes
  - π mode :- Deflecting or crabbing mode
  - 0 mode :- Accelerating mode
- Degeneracy is removed with the inclusion of beam pipe and rounding cavity edges

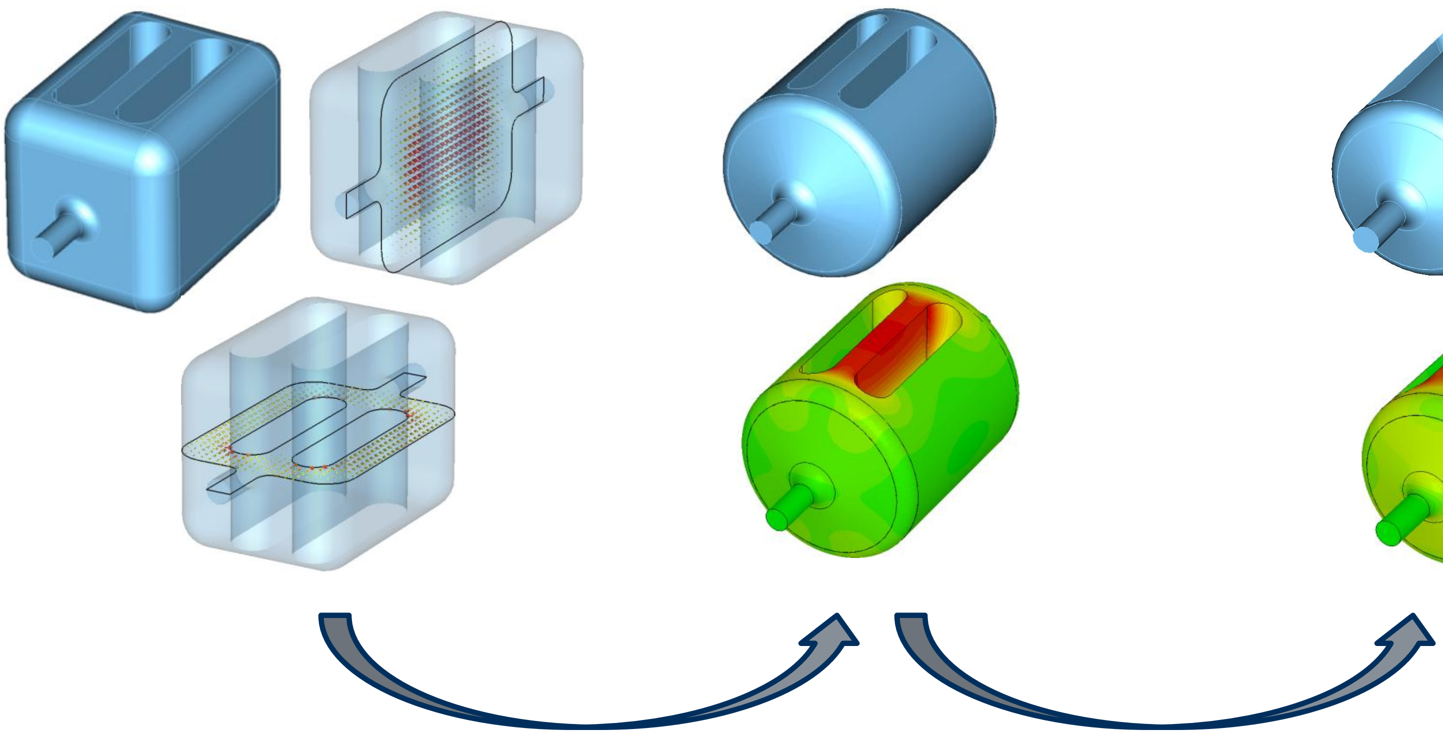


From Parallel-bar to RF Dipole Cavity



- Aspects of optimization
  - Lower and balanced peak surface fields
  - Stability of the design
    - Cylindrical shape is preferred to reduce flat surfaces
  - Cavity processing
    - Curved end plates for cleaning the cavity
  - Wider separation in Higher Order Mode (HOM) spectrum
  - Multipacting

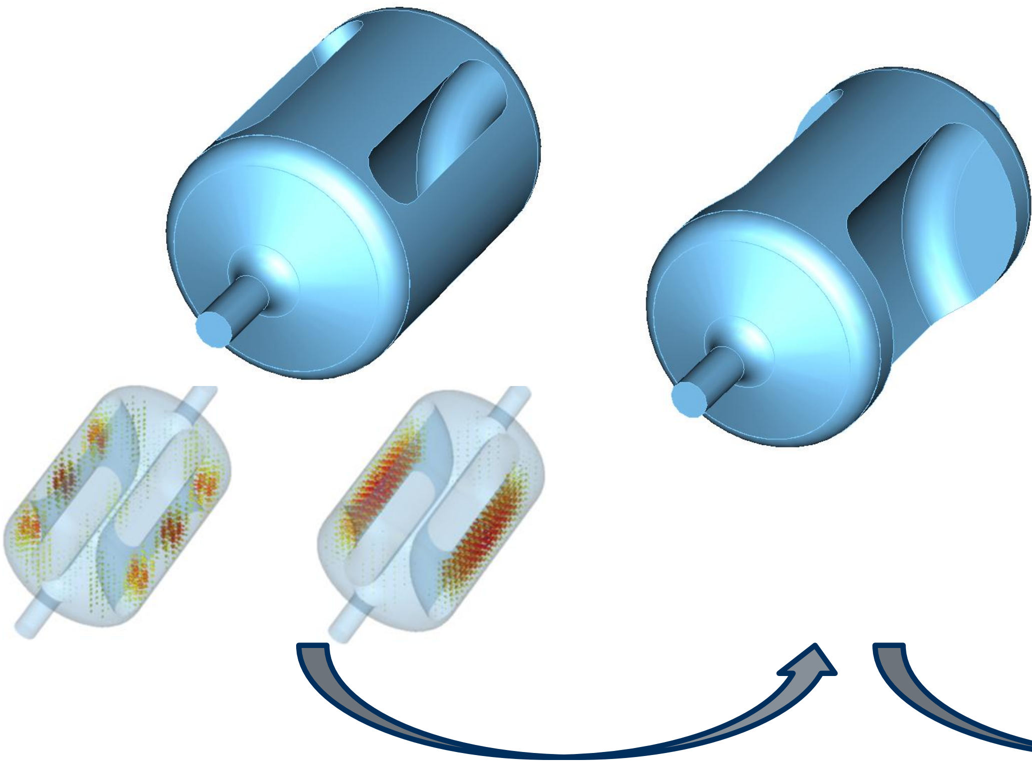
Design Evolution

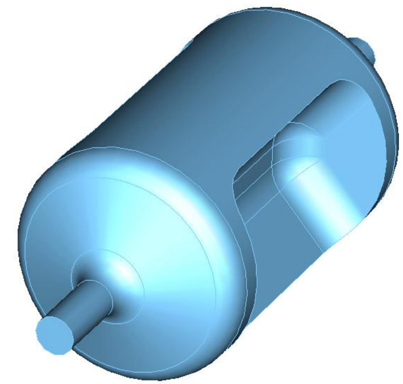


- To increase mode separation between fundamental modes
- ~18 MHz → ~ 130 MHz
- To improve design rigidity → Less susceptible to mechanical vibrations and deformations

- To lower peak magnetic field
- Reduced peak magnetic field by ~20%

Design Evolution





Balanced Peak Fields

$$\frac{B_P}{E_P} \approx 1.7 - 2.0 \text{ mT/(MV/m)}$$

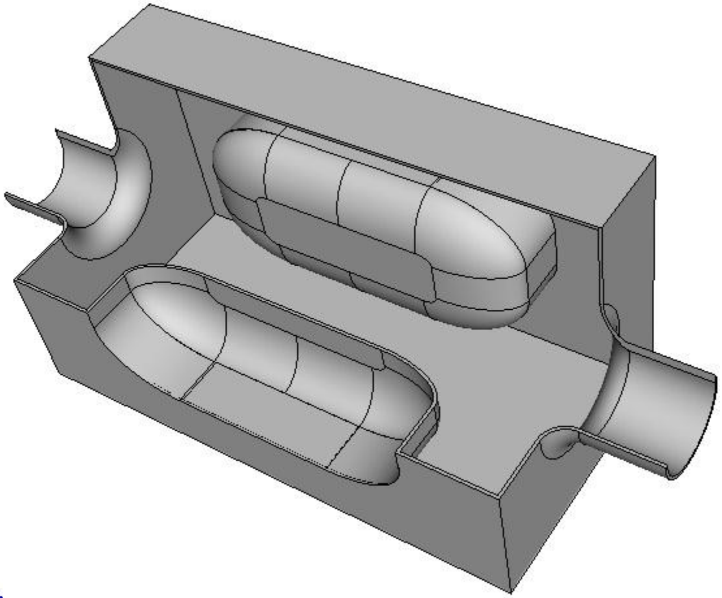
- Transition from TEM-type design to TE-like design
- To remove higher order modes with field distributions between the cavity outer surface and bar outer surface
- Eliminate multipacting conditions

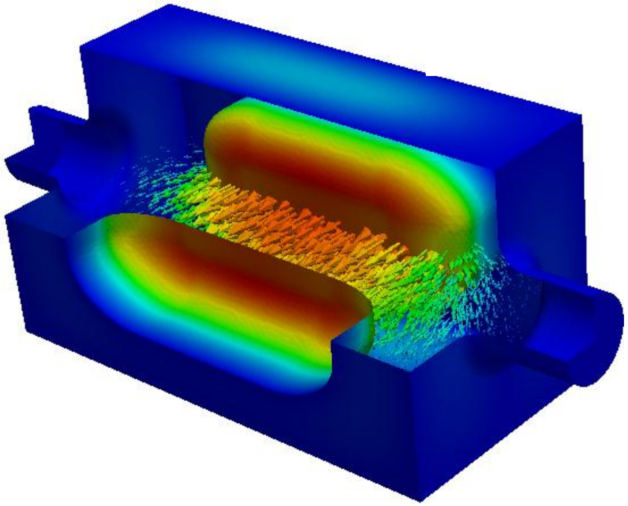
- To lower peak magnetic field
- Reduced peak magnetic field by ~25%
- To achieve balanced peak surface fields
- $B_P/E_P \approx 1.8$ mT/(MV/m)
- Reduced field non-uniformity

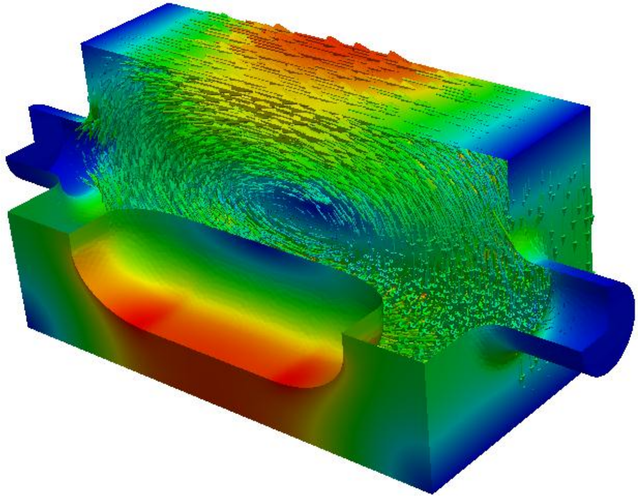
High Luminosity LHC LARP

Old Dominion University SLAC National Accelerator Laboratory

Ridged Waveguide Cavity (SLAC)

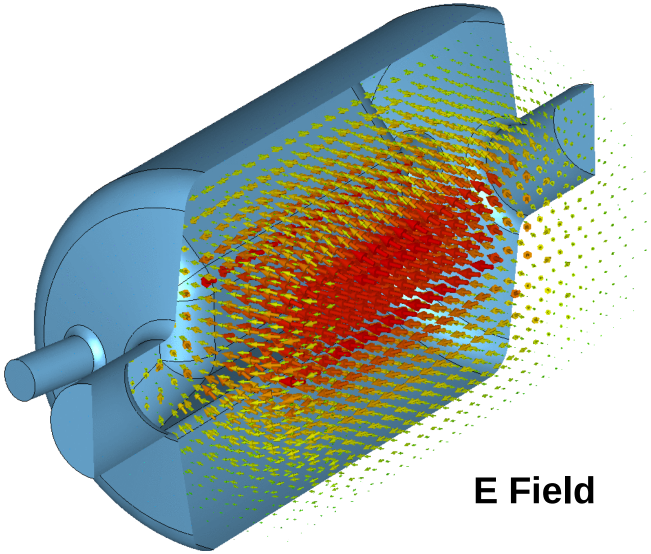


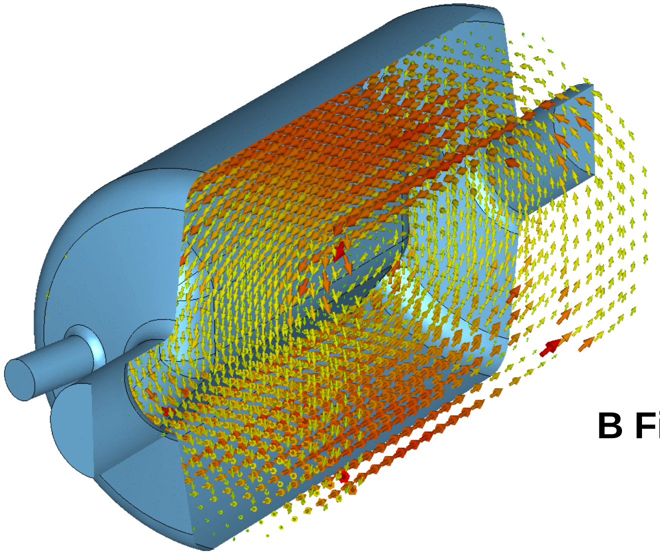


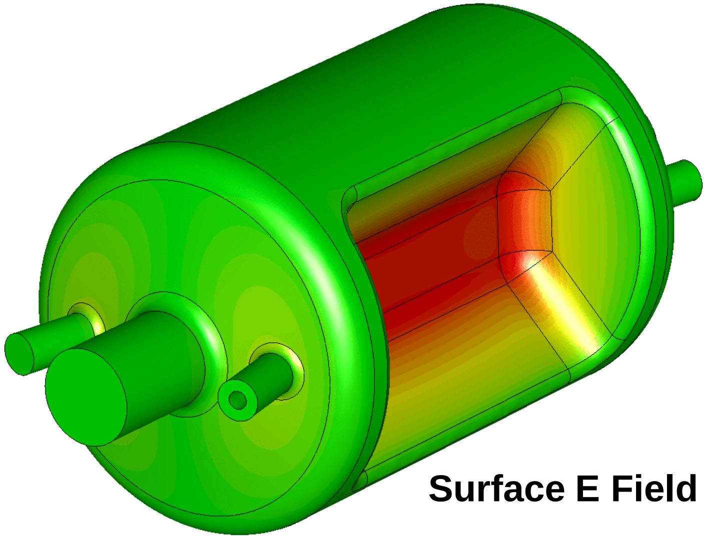


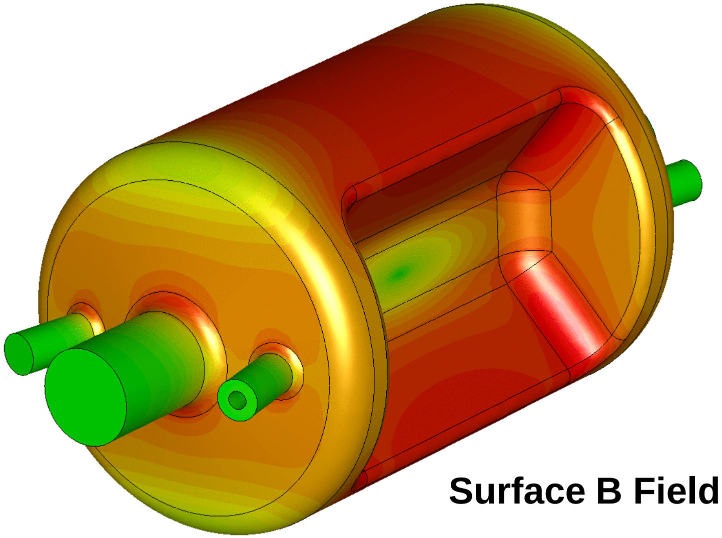
400 MHz LHC Crabbing System – Zenghai Li

RF Field Profile of RF Dipole Cavity









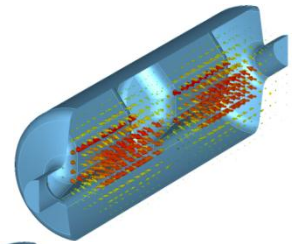
RF Dipole Cavity Properties

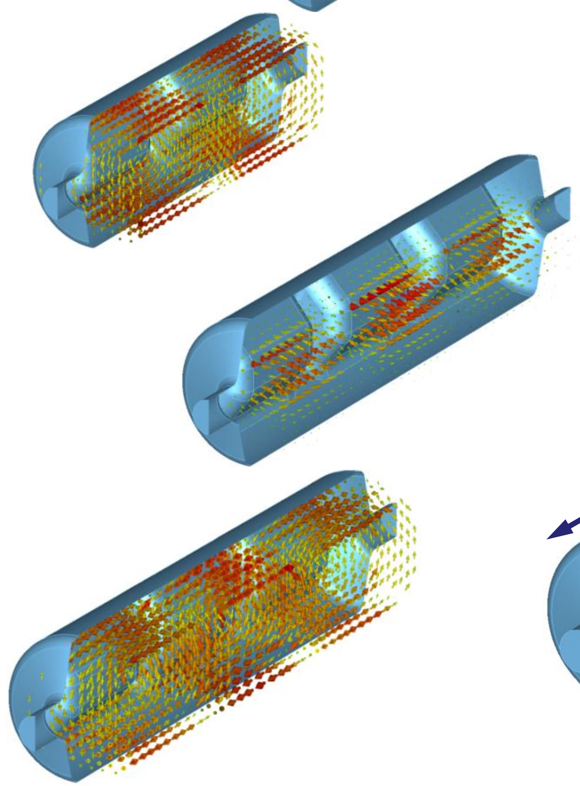
- Compact design
  - Supports low frequencies
- Fundamental deflecting/crabbing mode has the lowest frequency
  - No LOMs, no need for notch filter in HOM coupler
  - Nearest HOM widely separated (~ 1.5 fundamental)
- Low surface fields and high shunt impedance
- Good balance between peak surface electric and magnetic field
- Good uniformity of deflecting field due to high degree symmetry

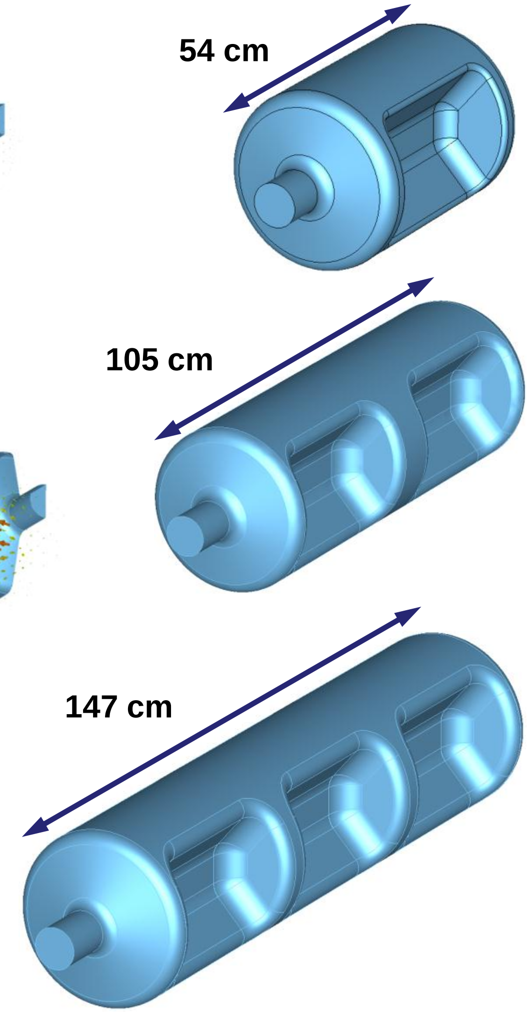
Multi-cell RF Dipole

- Reduced total cavity and cryomodule length
- Existence of same order modes (SOMs)
  - SOMs have lower frequency than fundamental
  - No. of SOMs = No. of cells

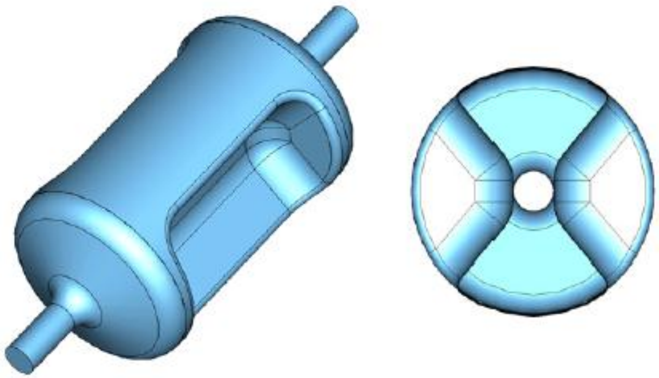
	2 cell	3 cell	
Frequency	400	400	MHz
SOMs	374.5	351.6 / 376.8	MHz
Aperture	84	84	mm
Cavity length	105	147	cm
Cavity diameter	34.5	35.4	cm
V_T^*	**0.375**	**0.375**	MV
E_p^*	**4.26**	**4.75**	MV/m
B_p^*	**7.4**	**7.77**	mT
$[R/Q]_T$	488.4	708.1	Ω
Geometrical Factor (G)	127.8	131.8	Ω
R_TR_S	**6.2×10^4**	**9.3×10^4**	Ω^2
At E_T^* = *1* MV/m			



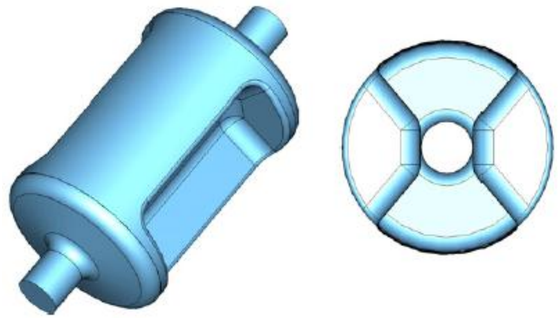




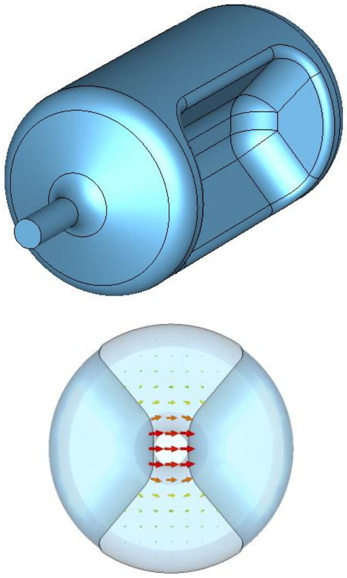
RF Dipole Development Activities at ODU



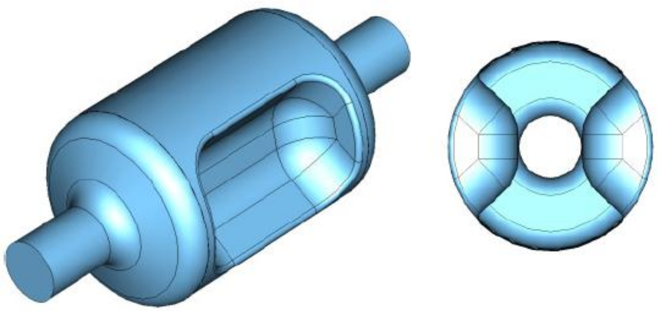
499 MHz JLab Upgrade Deflector
Built and Tested



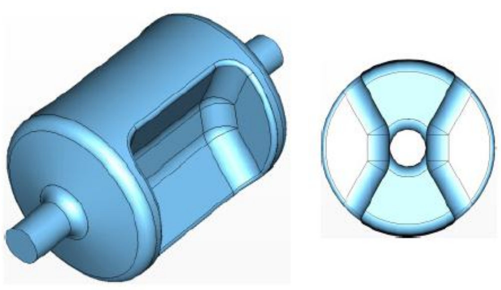
400 MHz LHC Crabbing System
Built and tested



325 MHz LCLS II Separator
Designed



750 MHz MEIC Crabbing System
Built and tested



365 MHz Project X Deflector
Designed

Design Specifications for 400 MHz P-o-P

- Basic Properties

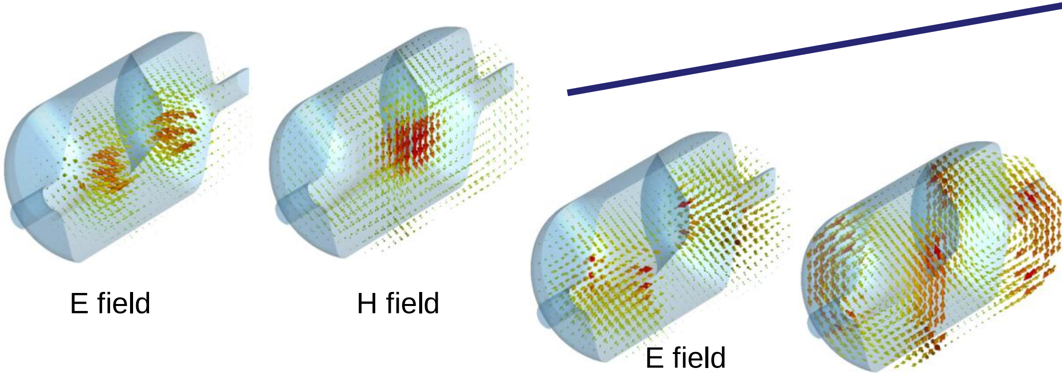
Property	Value	Unit
V_T^*	0.375	MV
E_p^*	4.02	MV/m
B_p^*	7.06	mT
B_p^*/E_p^*	1.76	mT/ (MV/m)
U^*	0.195	J
$[R/Q]_T$	286.95	Ω
Geometrical Factor (G)	140.86	Ω
R_TR_S	4.04×10^4	Ω^2
At $E_T^* = 1$ MV/m		

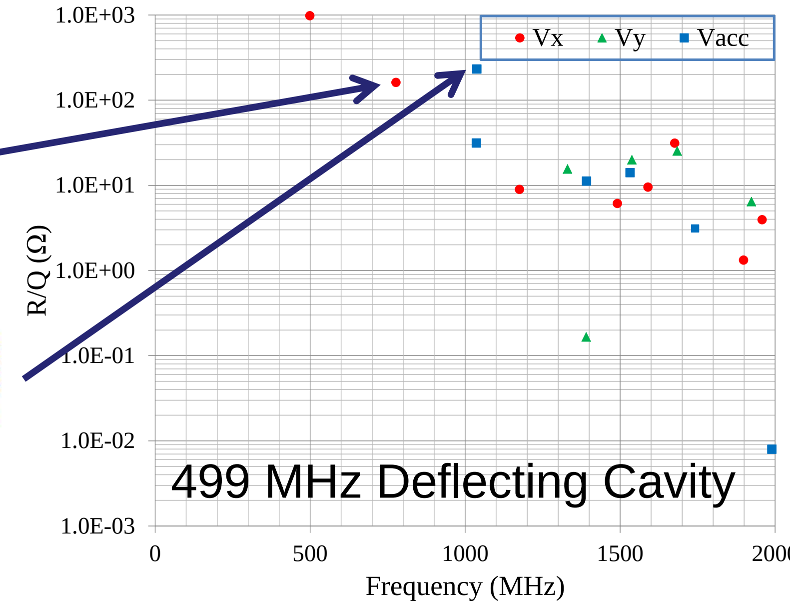
- Required fields

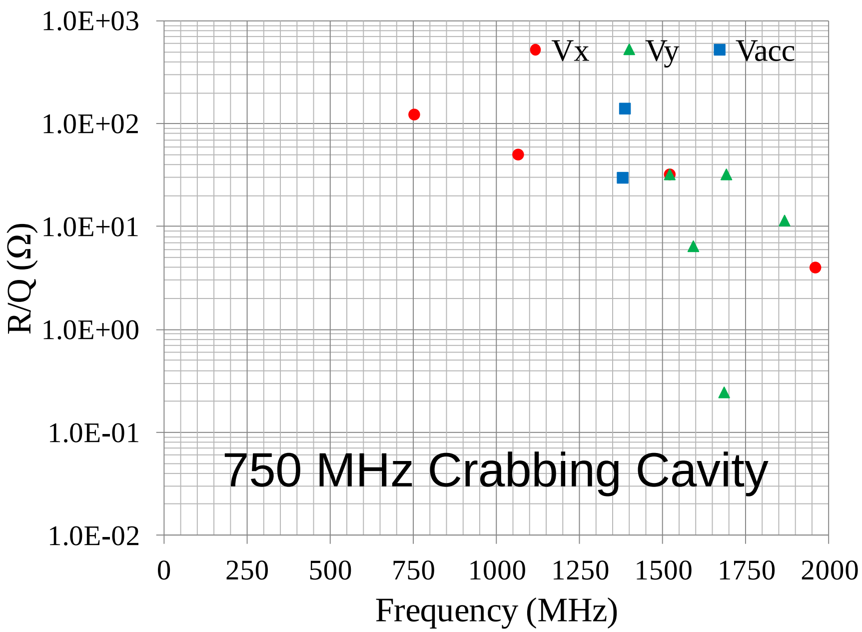
Property	Value		Unit
V_T	3.4	5.0	MV
E_p	36.5	53.6	MV/m
B_p	64.0	94.2	mT
T	2.0	4.2	K
R_{BCS}	1.3	70.0	nΩ
R_{res}	20.0		nΩ
R_s	21.3	90.0	nΩ
$P_{diss}(3.4\ MV)$	6.0	25.8	W
Q_0	6.7	1.6	$\times10^9$

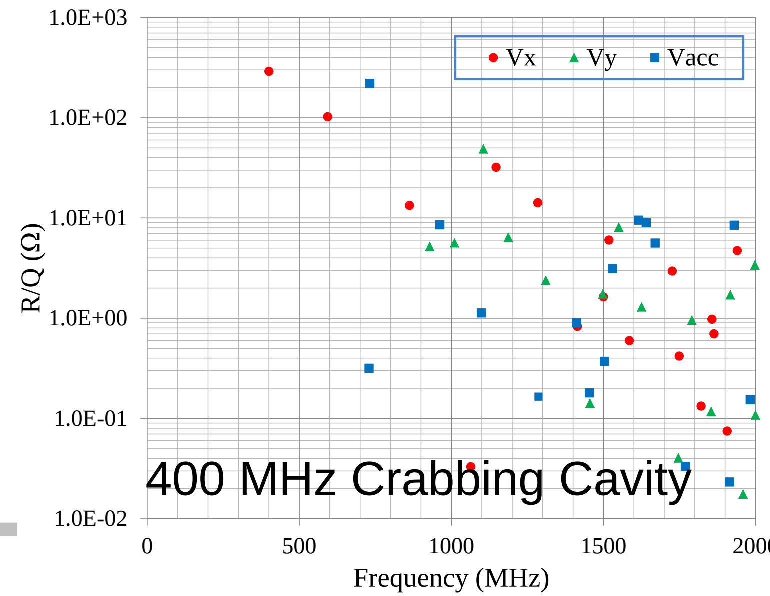
HOM Properties of the RF Dipole Cavity

- Widely separated Higher Order Modes
- No Lower Order Modes







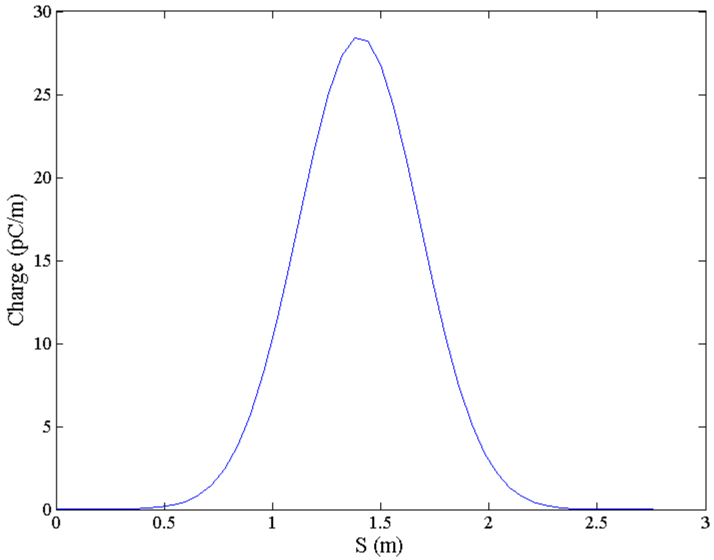


Wakefield and Impedance (400 MHz)

- T3P – EM Time Domain Solver in the SLAC ACE3P Suite

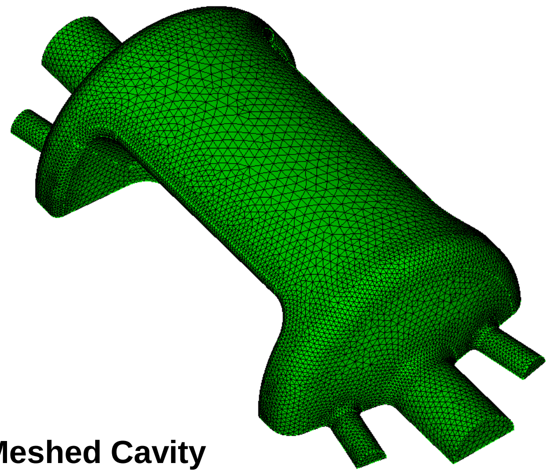
- Bunch Parameters
  - σ = 0.014 m
  - charge = 1 pC

$$\lambda(s) = \frac{1}{\sigma\sqrt{2\pi}} \exp[-\frac{(s-s_0)^2}{2\sigma^2}]$$



- Wakefield Parameters
  - # of points = 50,000
  - Time stamp (dt) = 0.2 ns
  - Maximum wakefield distance (S) = 3000 m
  - RMS frequency for a 1.4 cm bunch ≈ 2.5 GHz

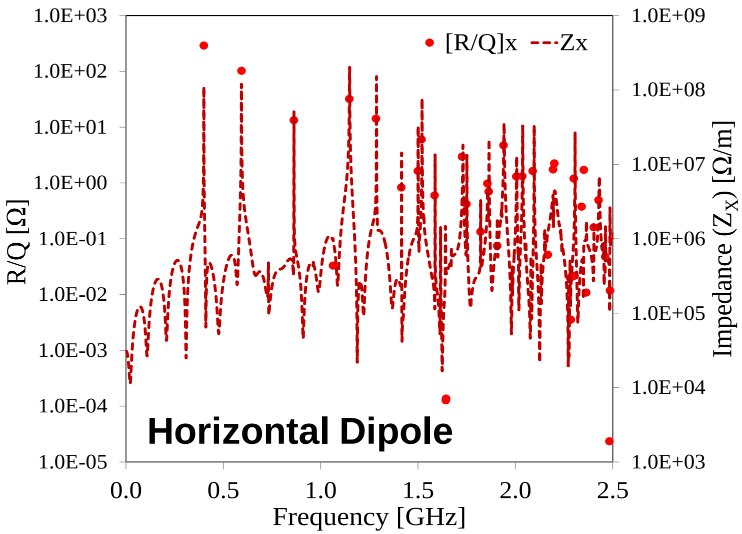
$$f_{RMS} = \frac{c}{\sqrt{2}\pi\sigma}$$



Meshed Cavity
No. of elements = 324560

Wakefield Analysis

T3P – Time domain wakefield and transient solver in the SLAC ACE3P suite

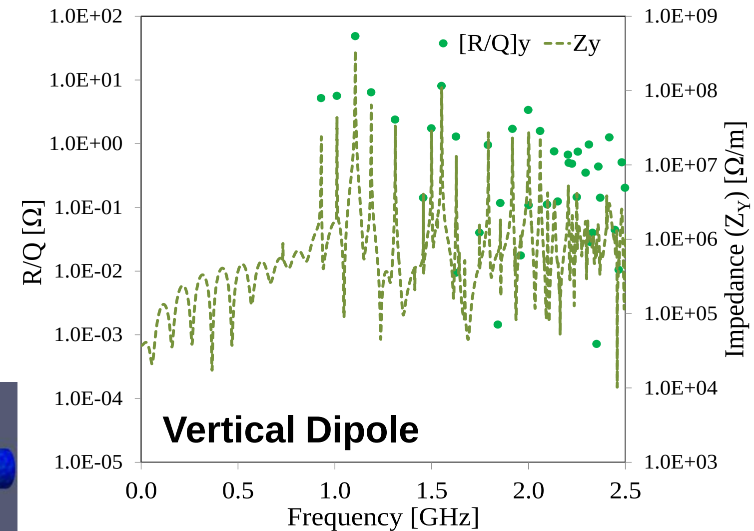


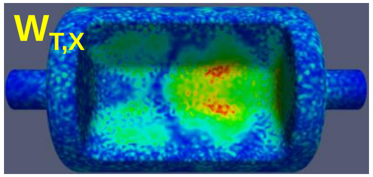
400 MHz

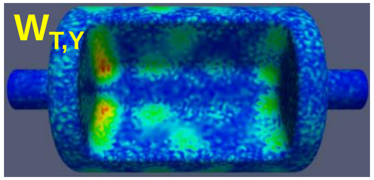
Crabbing Cavity

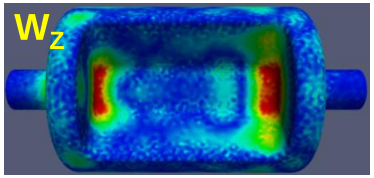
For a Gaussian bunch of

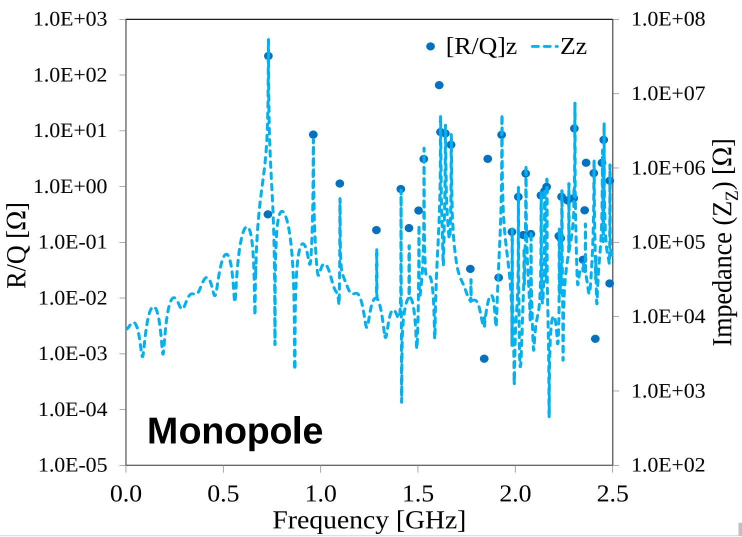
σ_{z_rms} = 0.5 cm

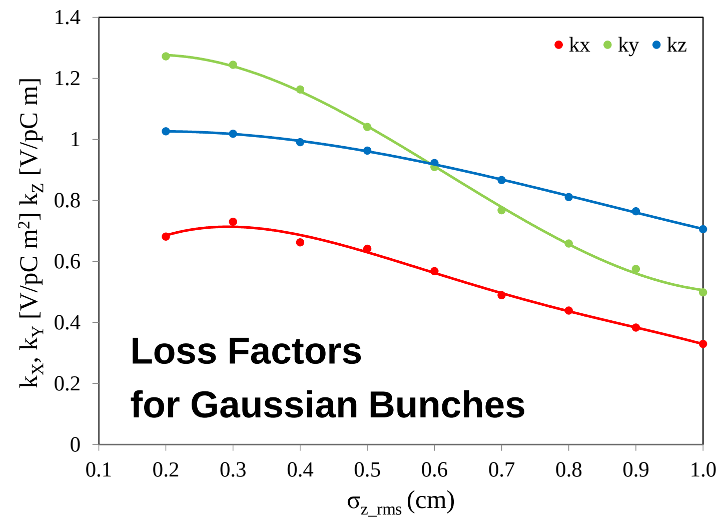






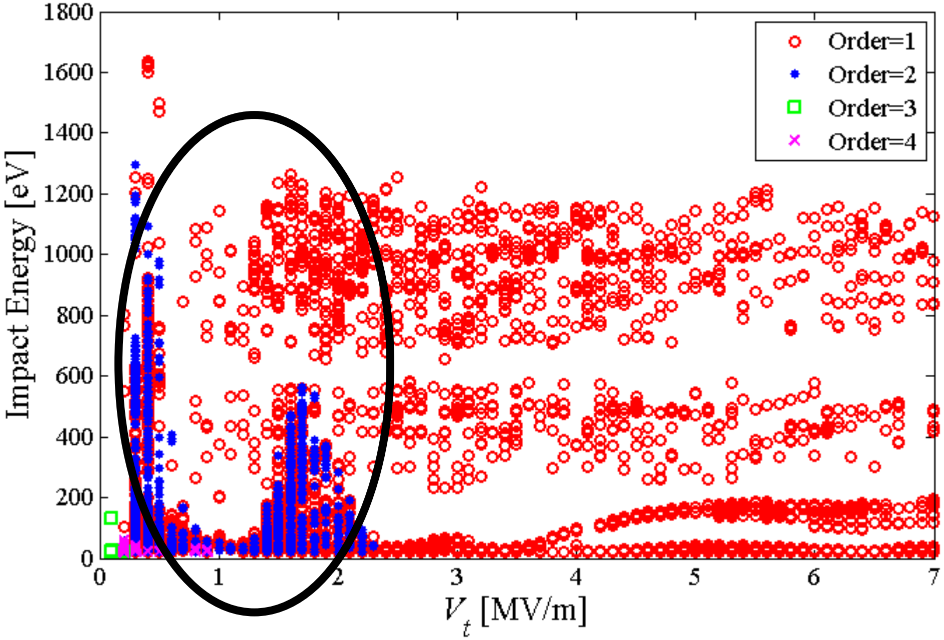




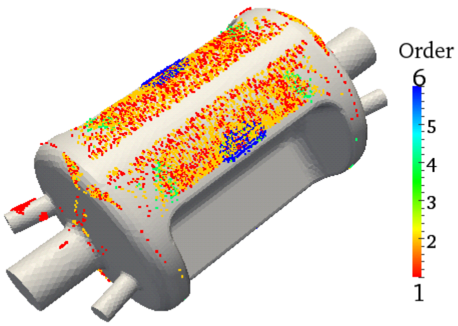


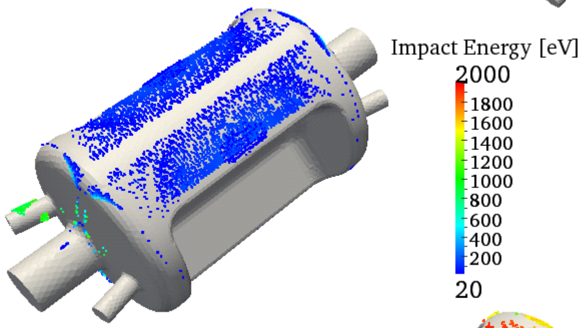
Multipacting in Proof–of–Principle Design

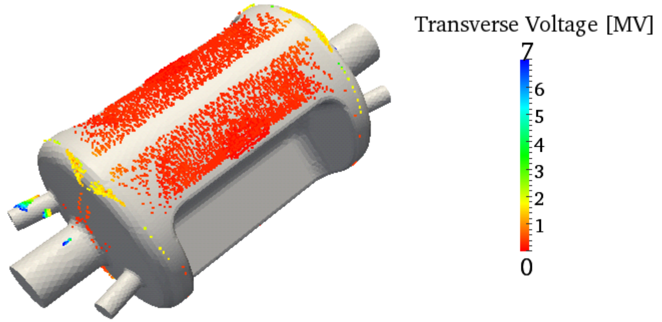
- Multipacting analysis using Tack3P in SLAC – ACE3P suite



Expected multipacting levels at very low V_T of low orders with low impact energies





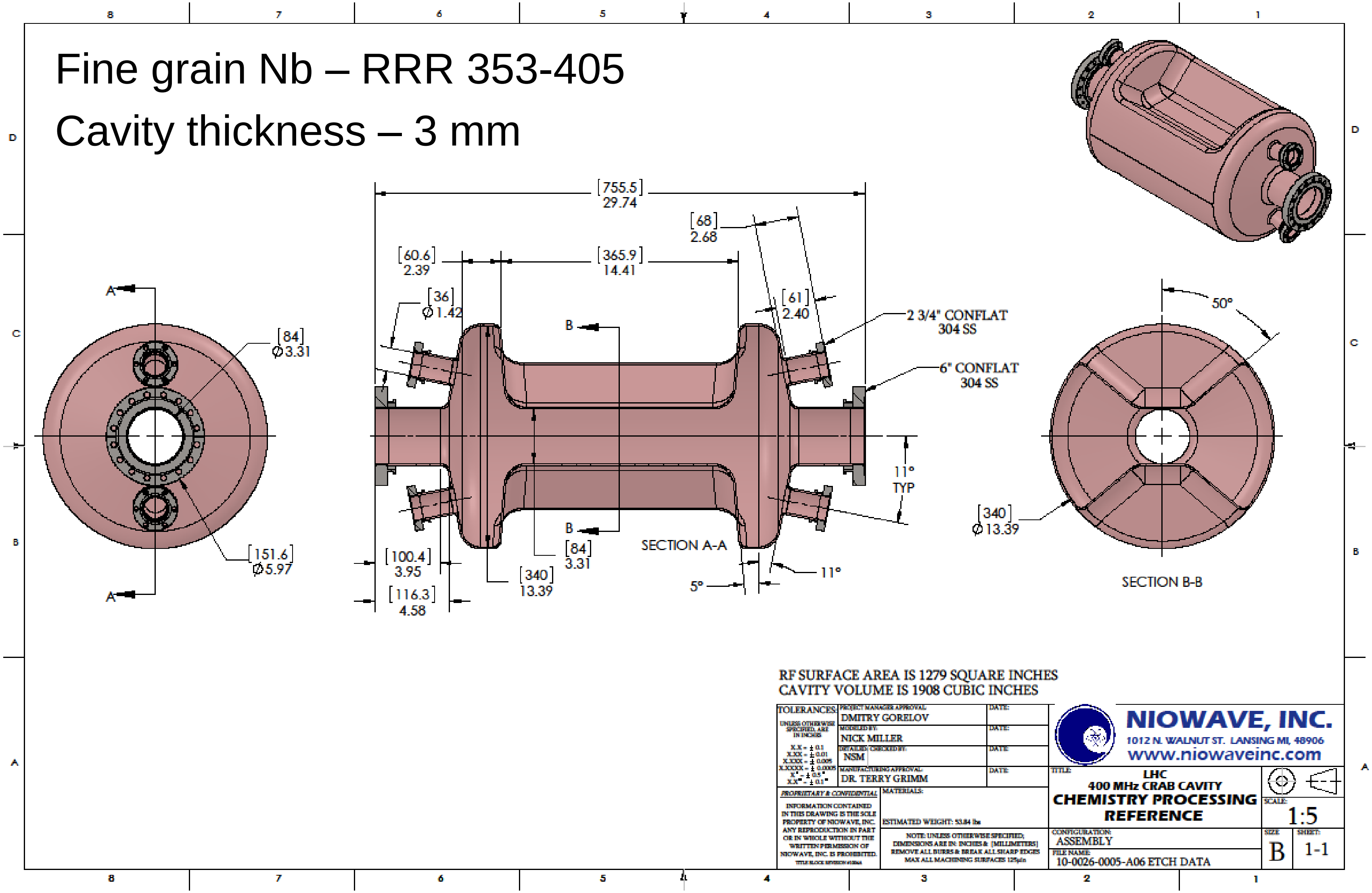


- A multipacting barrier was observed in the first 2 K test at very low fields
- Increasing the power processed the cavity and no multipacting was observed in the following 4.2 K and 2 K tests

Fabrication

Fine grain Nb – RRR 353-405

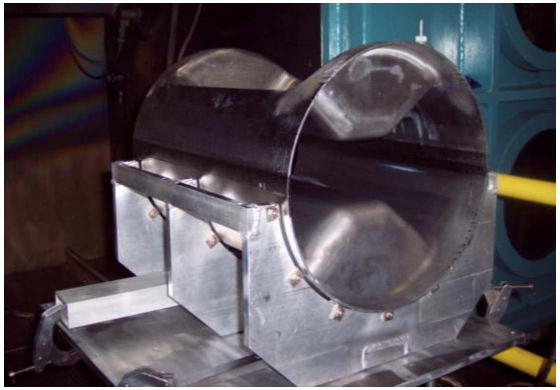
Cavity thickness – 3 mm



Fabrication

- End plates with brazed stainless steel flanges

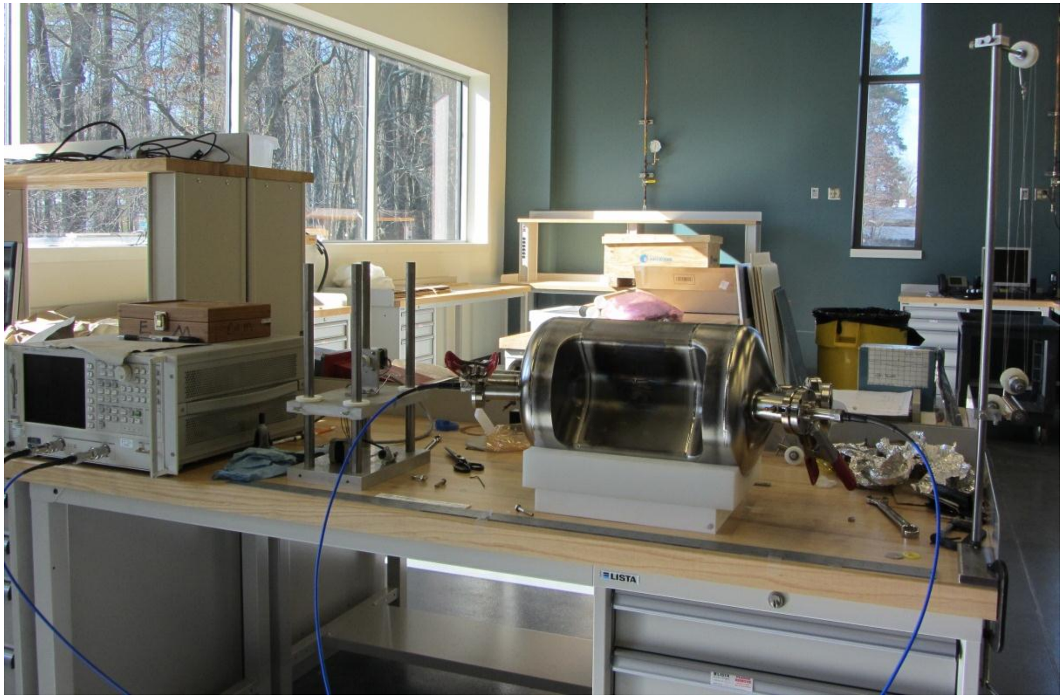
- Center shell formed in two halves

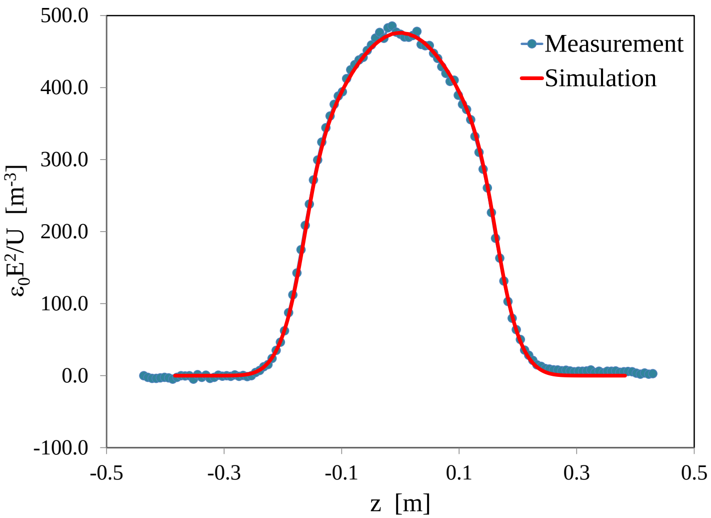


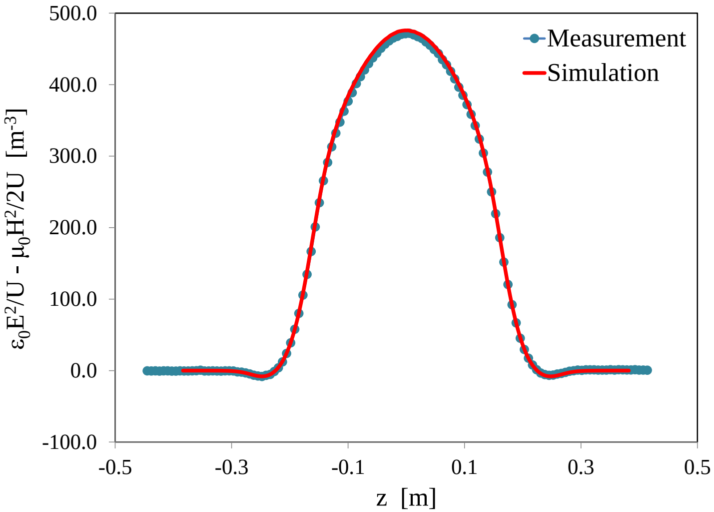
- Finished cavity shipped to ODU –March, 2012

Field Profile Measurement

- On-axis transverse electric field was measured using a Teflon bead
- Both on-axis transverse electric and magnetic fields were measured using an Al metallic bead





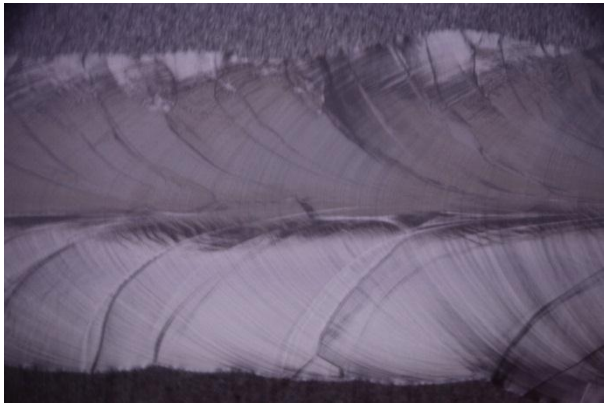


Optical Inspection

- All the welding seams were inspected ~ 180 images

- Grain boundaries

- Weld seam



Surface Treatment, Preparation, and Testing

- Bulk BCP – 85 μm
- Heat treatment – At 600^0 C for 10 hours
- Light BCP – ~10 μm
- High Pressure Rinse – 3 passes
- Assembly in the clean room

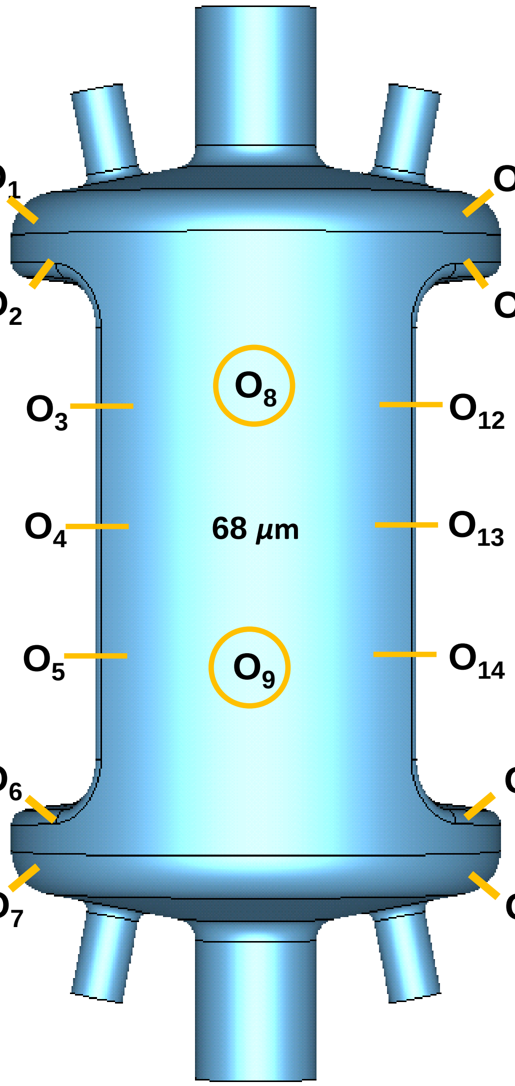
BCP Cabinet

HPR Cabinet

- RF Test Plan
  - High power tests at 2 K and 4 K
  - Rs vs. T
  - Pressure test
  - Lorentz detuning
  - No He processing was done

- RF Tests Performed
  - 2 K high power test
  - Cavity warmed up to 4 K
  - 4 K high power test
  - Cavity cooled down to 2 K
  - 2 K high power test

Chemical Processing



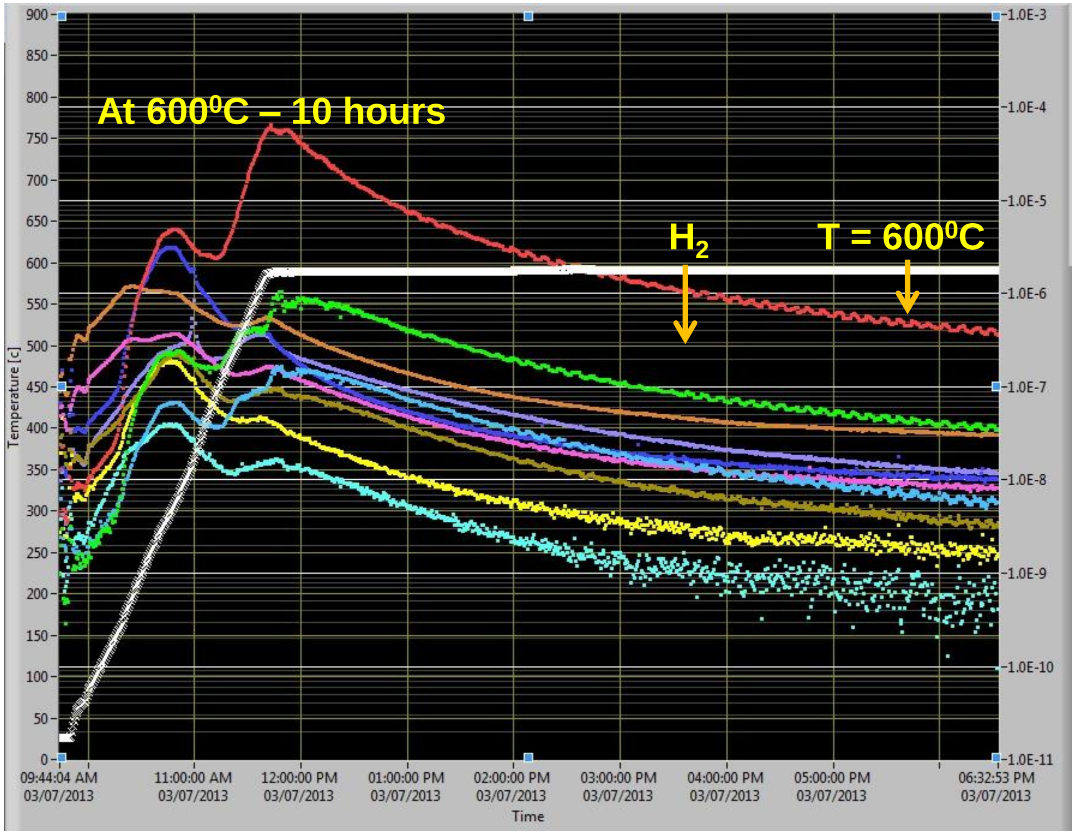
Bulk BCP

- Planned total removal – 120 μm
- Acid mixture was contaminated with glycol
  - Reduced etch rate from 2.7-2.8 μm /min to 1.8 μm/min
- Average removal 85 microns
  - Average removal in edges > 90 μm
  - Average removal on flat surfaces < 70 μm

Light BCP

- Removal of 10 μm after heat treatment

Heat Treatment

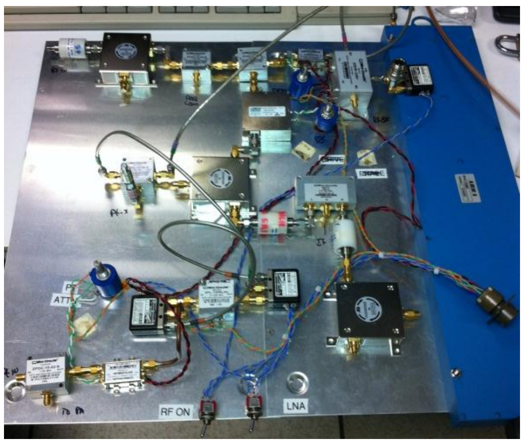


Assembly

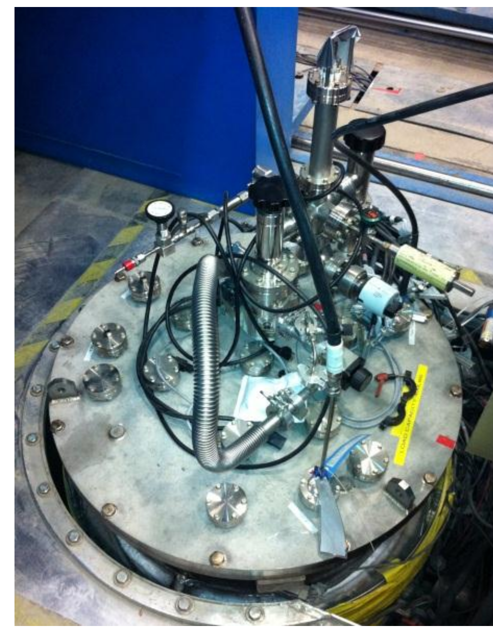
- Followed by a HPR of 3 passes
- Ultrasonic degreased hardware
- Leak tested
- Assembly in clean room

Preparation for Test

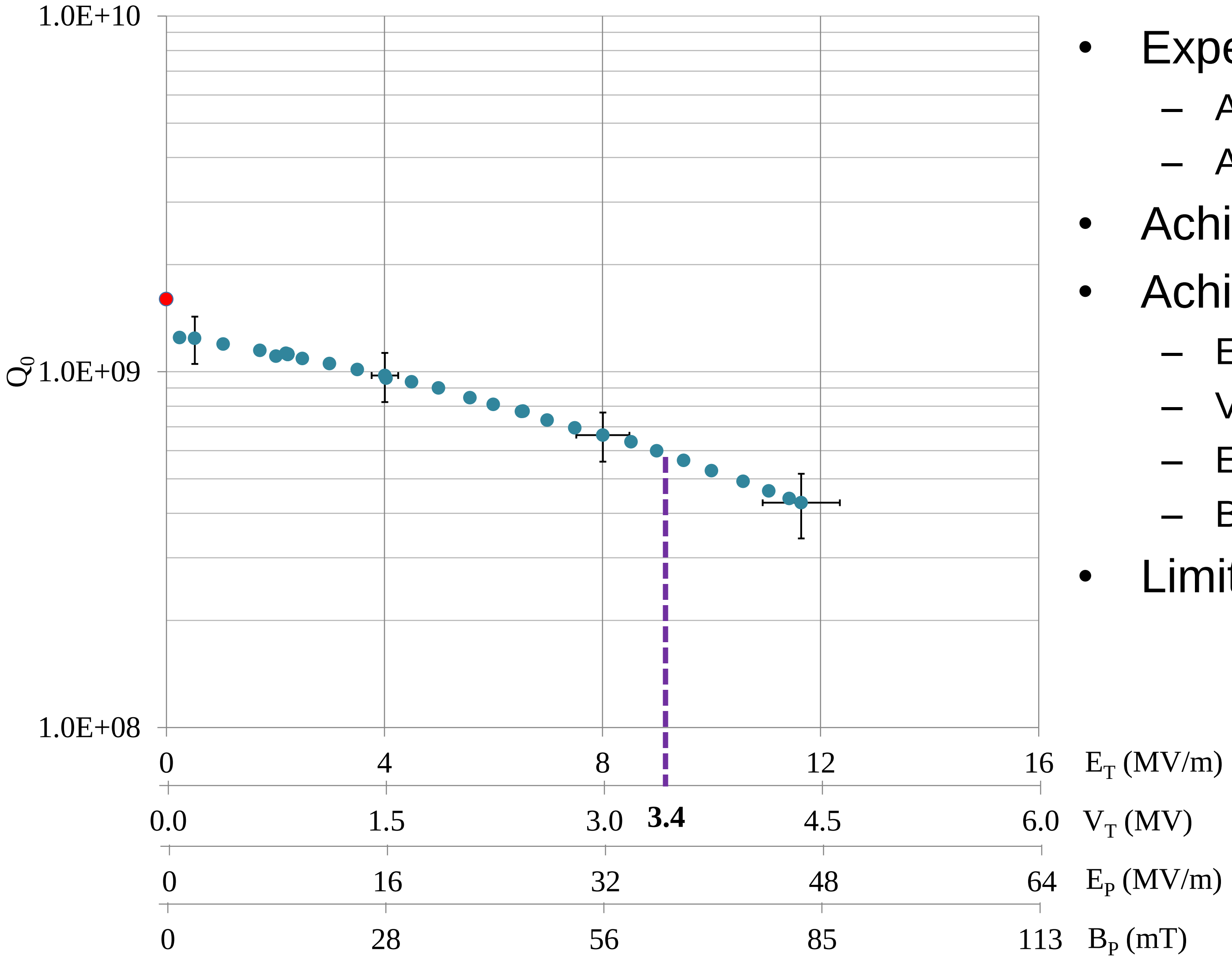
- Cable calibration
  - $Q_1 = 2.76\times10^9$
  - $Q_2 = 8.62\times10^{10}$
- LLRF control



- Test with 500 W rf amplifier

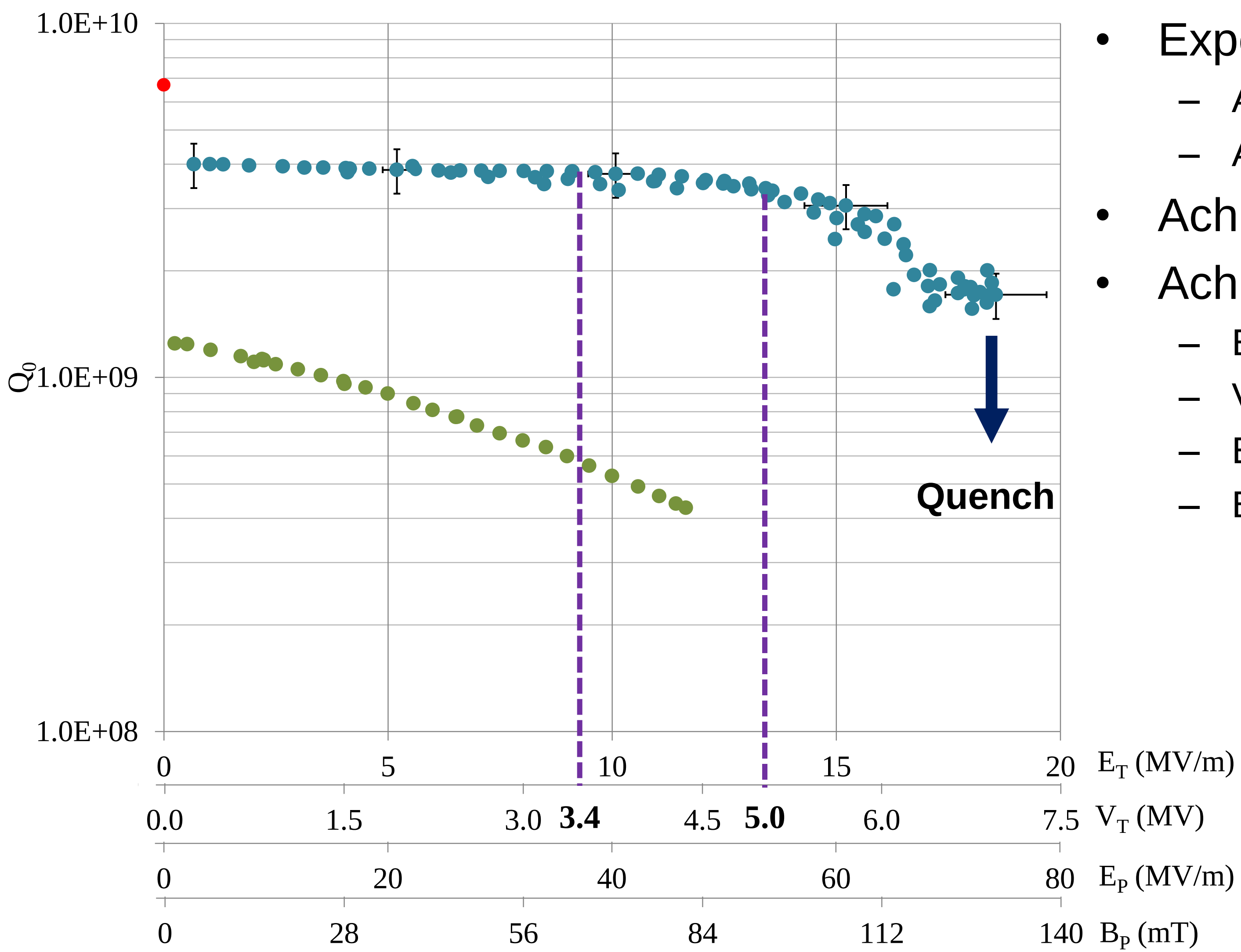


4.2 K Test Results



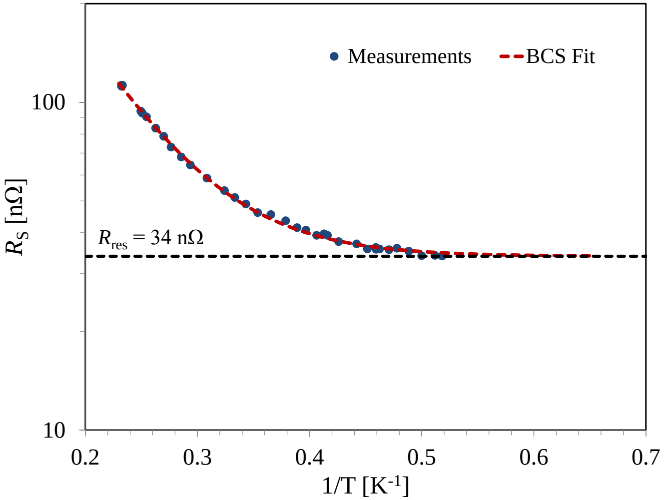
- Expected $Q_0 = 1.6\times10^9$
  - At R_S = 90 nΩ
  - And R_{res} = 20 nΩ
- Achieved $Q_0 = 1.25\times10^9$
- Achieved fields
  - E_T = 11.6 MV/m
  - V_T = 4.35 MV
  - E_P = 47 MV/m
  - B_P = 82 mT
- Limited by rf power

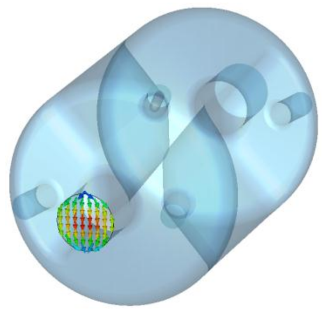
2 K Test Results

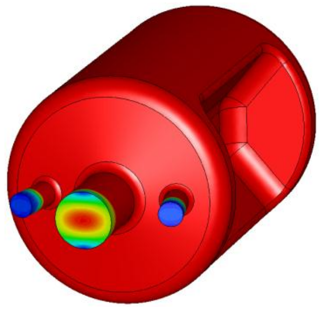


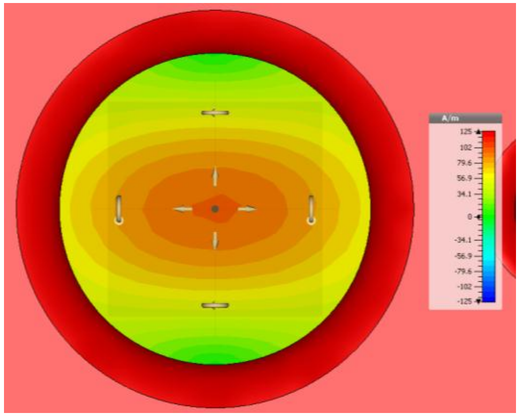
- Expected $Q_0 = 6.7\times10^9$
  - At R_S = 22 nΩ
  - And R_{res} = 20 nΩ
- Achieved $Q_0 = 4.0\times10^9$
- Achieved fields
  - E_T = 18.6 MV/m
  - V_T = 7.0 MV
  - E_P = 75 MV/m
  - B_P = 131 mT

Residual Surface Resistance - Low Field Q

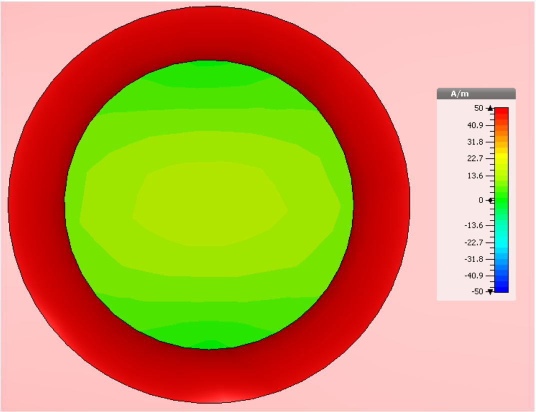








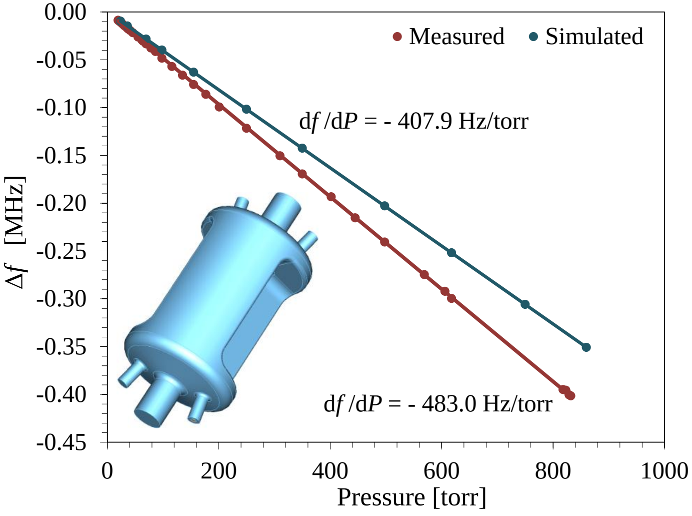
Beam line port

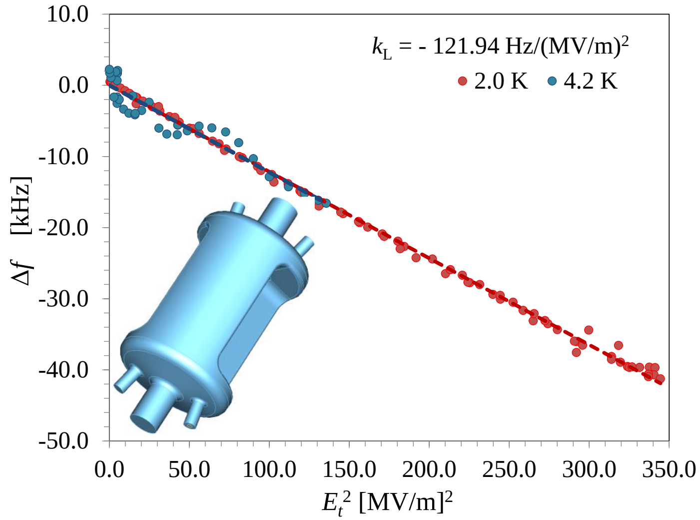


Coupler port

- Calculated Q due to stainless steel flanges : 3.7 10^9
- Measured Q : 4.0 10^9

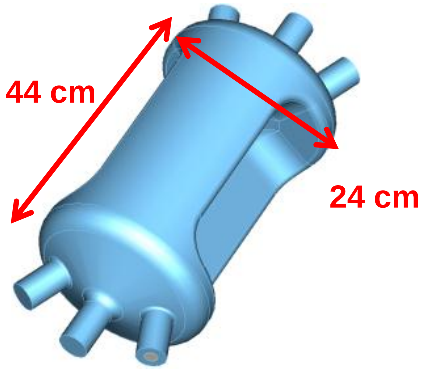
Pressure Sensitivity and Lorentz Detuning





- Simulated Lorentz coefficient (k_L)
  - 400 MHz → -117.3 Hz/(MV/m)^2

499 MHz RF-Dipole Cavity

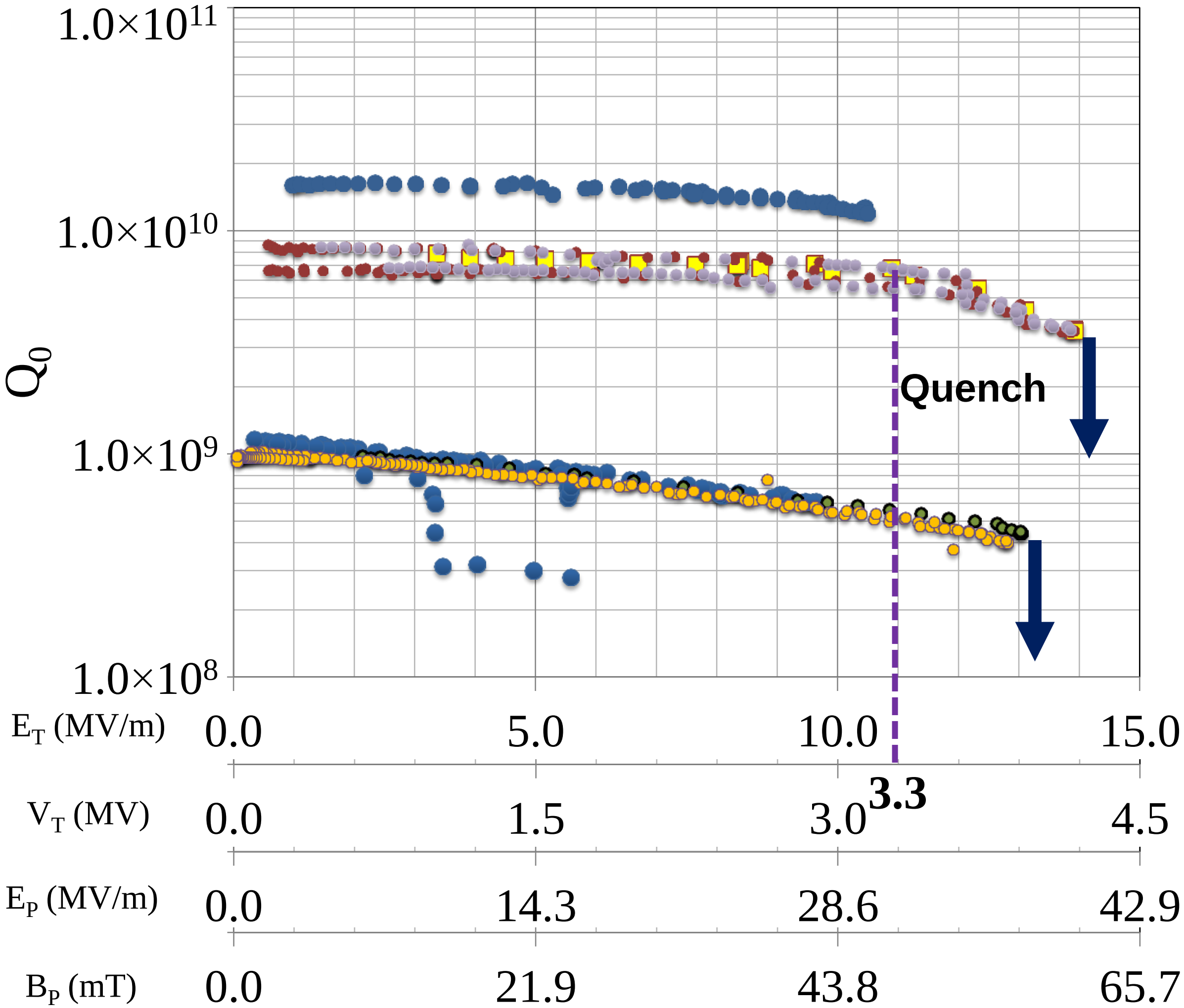


RF Properties – 499 MHz Cavity		
Aperture Diameter (d)	40.0	mm
Nearest HOM	777.0	MHz
E_p^*	2.86	MV/m
B_p^*	4.38	mT
$[R/Q]_T$	982.5	Ω
Geometrical Factor (G)	105.9	Ω
$R_T R_S$	1.0×10^5	Ω^2
At $E_T^* = 1$ MV/m		

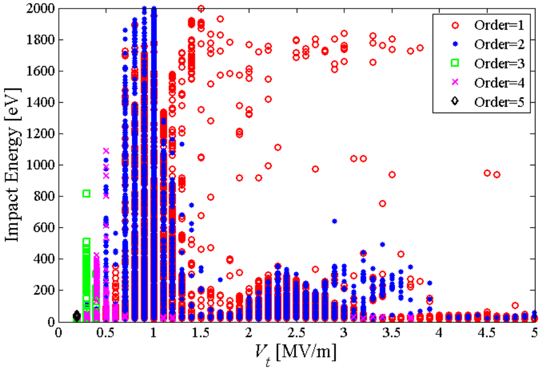
Surface Processing Procedure

- Bulk BCP of ~150 μm
- Average removal
  - 1st treatment: 108 μm
  - 2nd treatment: 200 μm
- Heat Treatment → H_2 degassing at 600^0C – 10 hours
- Light BCP – Removal of 10 μm (2nd time: 20 μm) after heat treatment
- High pressure rinsing in 2 passes
- Cavity Assembly – with fixed coupling

499 MHz RF-Dipole Cavity

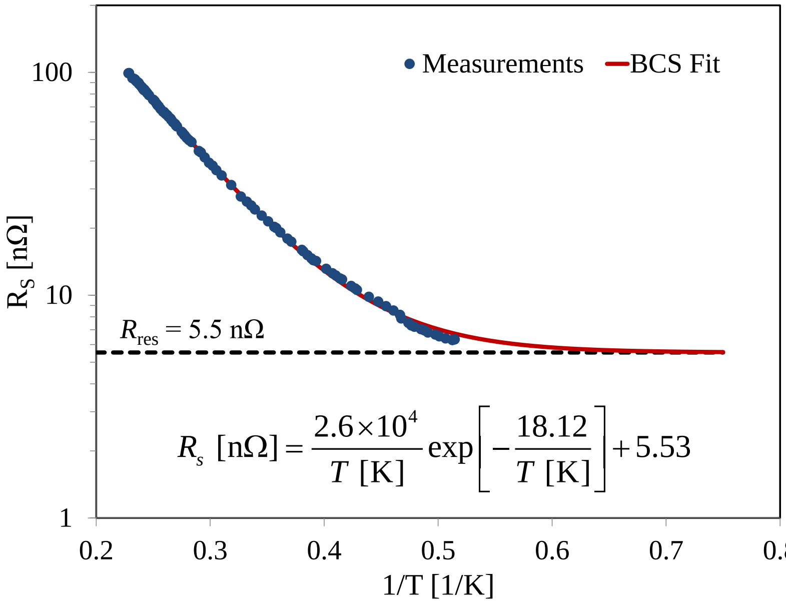


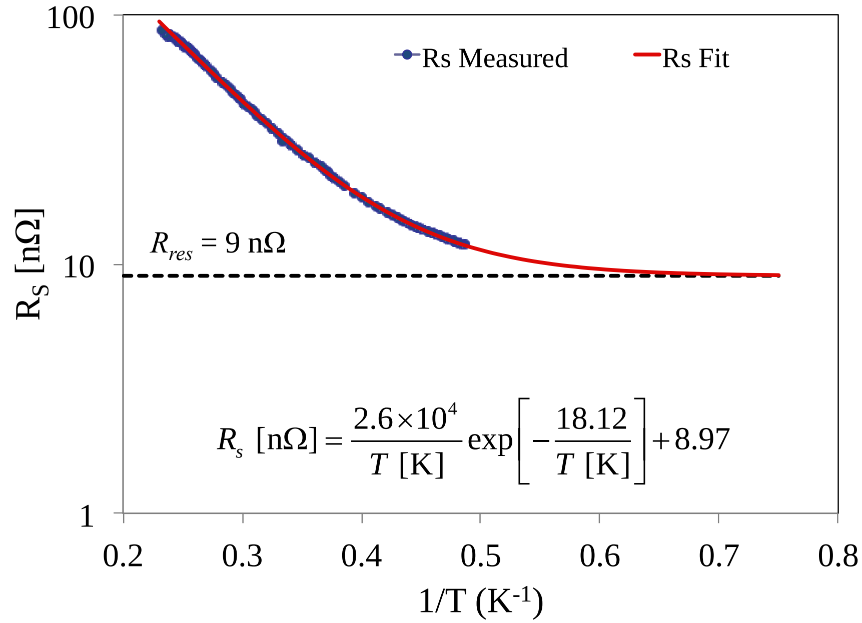
- Multipacting was easily processed during the 4.2 K rf test



- No multipacting levels were observed in the reprocessed cavity
- Design requirement of 3.3 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

499 MHz – Surface Resistance



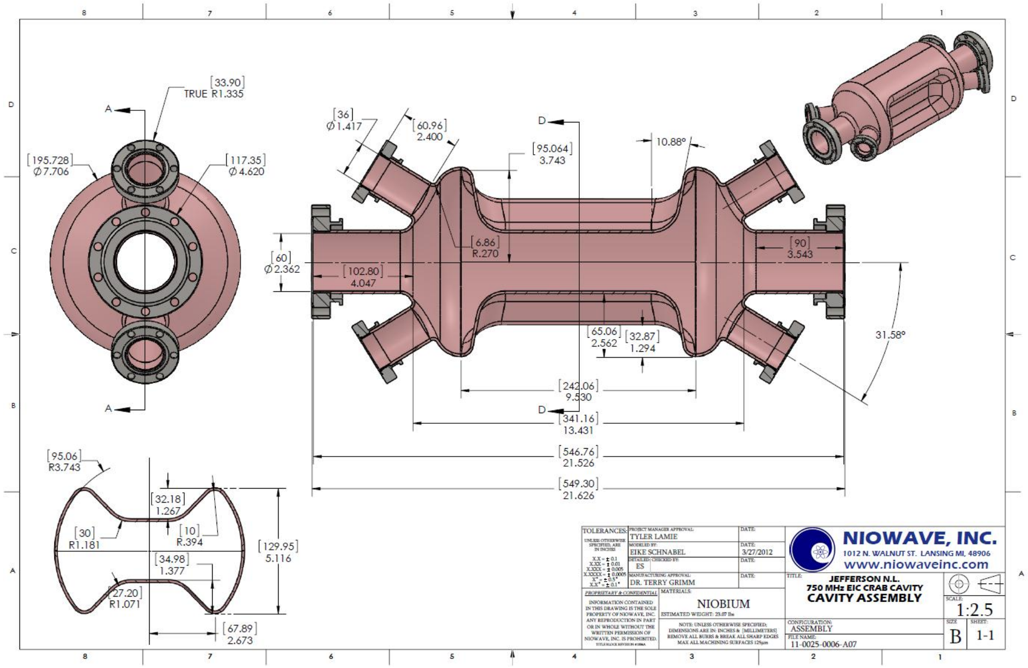


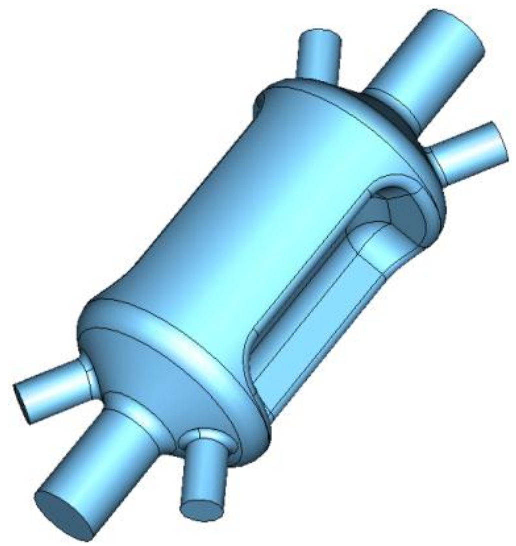
- Measured Q_0
  - 1st Test: 1.6×10^{10}
  - 2nd Test: 8.1×10^{9}
- Reduced Q_0 at 2.0 K with surface reprocessing
  - 1st bulk BCP removal: 108 μm
  - 2nd bulk BCP removal: 200 μm
- Q_0 dropped with the increase in residual surface resistance
- Residual resistance
  - 1st Test: 5.5 nΩ
  - 2nd Test: 9.0 nΩ

750 MHz Crabbing Cavity for MEIC

- 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		

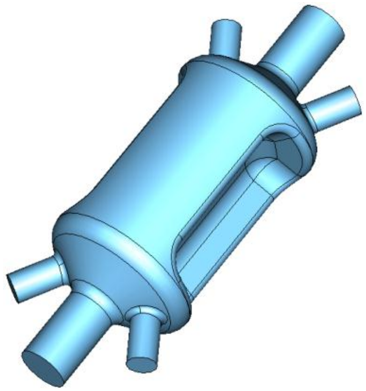


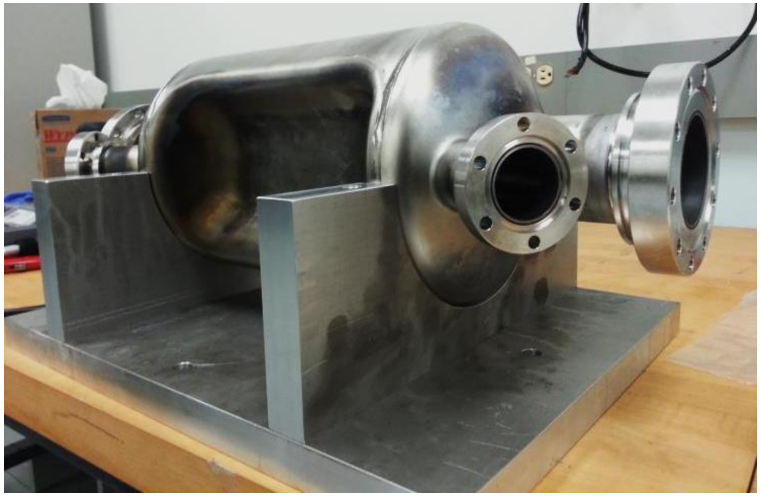


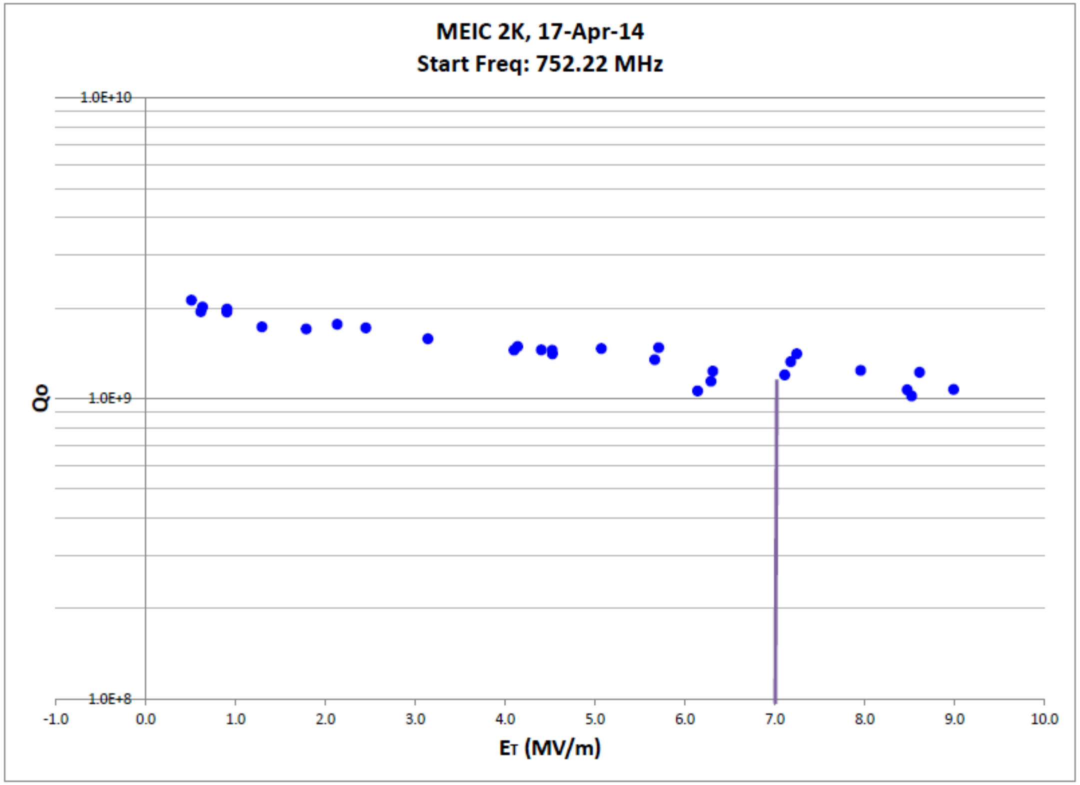
*** PhD project Alejandro Castilla**

750 MHz Crabbing Cavity for MEIC

- Substantial improvement after electro-polishing
- Multipacting easily processed and did not reoccur



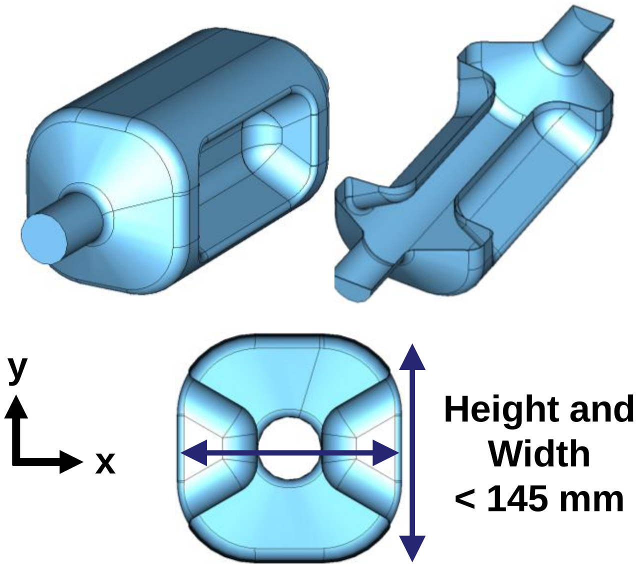


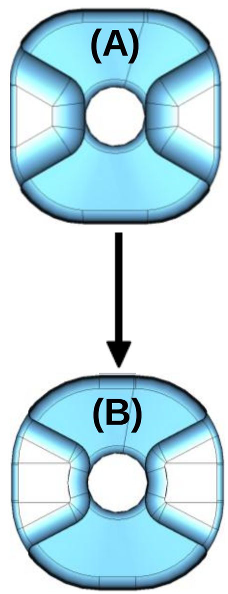


RF-Dipole Square Cavity Options

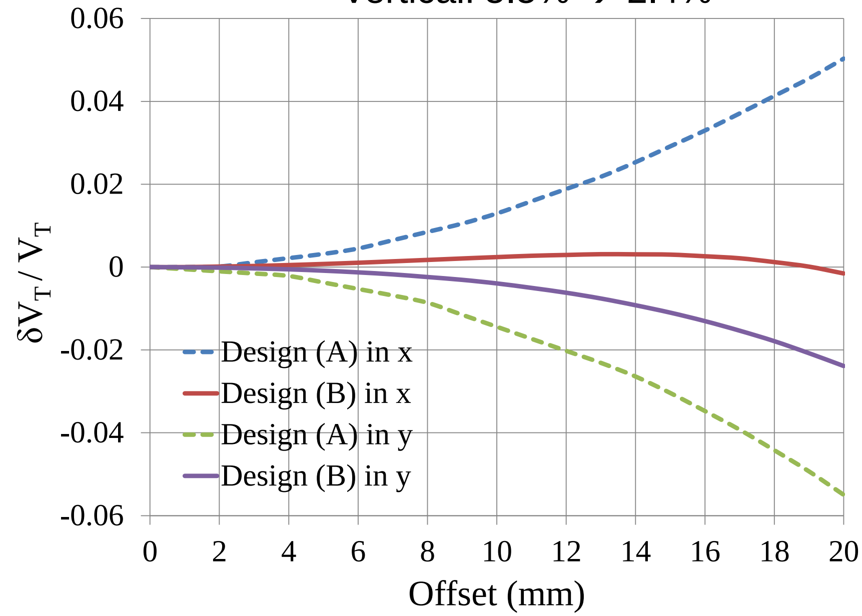
- Square-type rf-dipole cavity to further reduce the transverse dimensions
- Frequency is adjusted by curving radius of the edges
- RF-dipole cavity with modified curved loading elements across the beam aperture to reduce field non-uniformity

400 MHz Crabbing Cavity

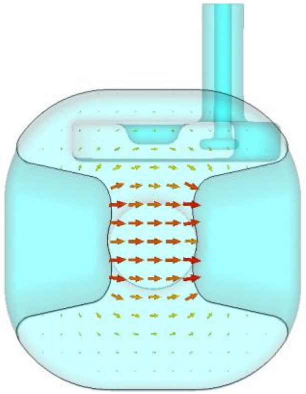


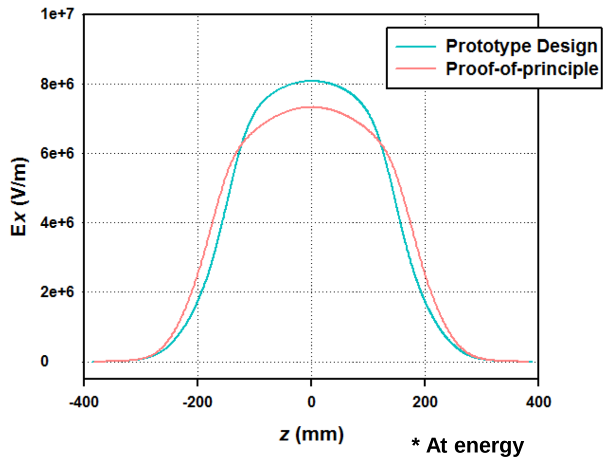


- Voltage deviation at 20 mm
  - Horizontal: 5.0% → 0.2%
  - Vertical: 5.5% → 2.4%



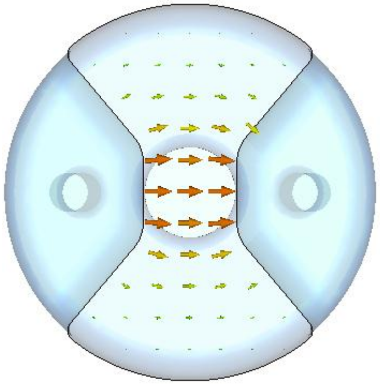
Prototype Design vs. Proof-of-Principle

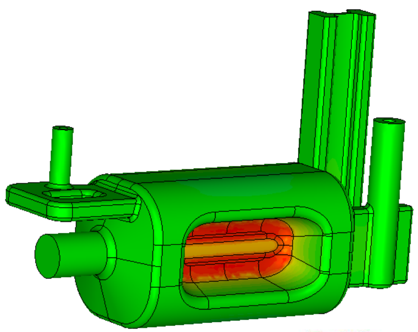




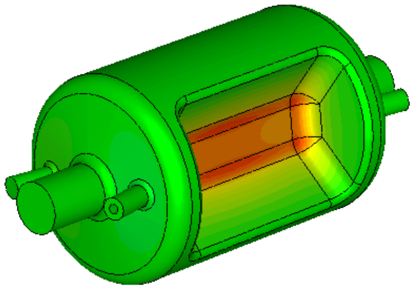
* At energy content of 1 J

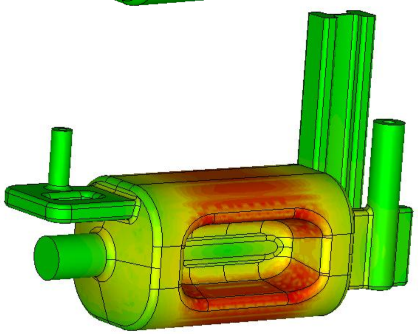
Transverse Electric Field



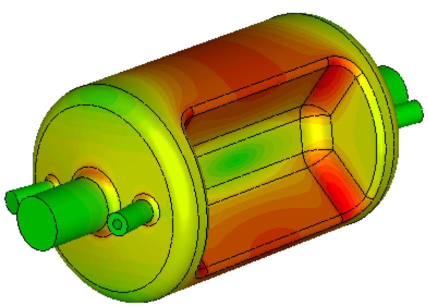


Surface Electric Field



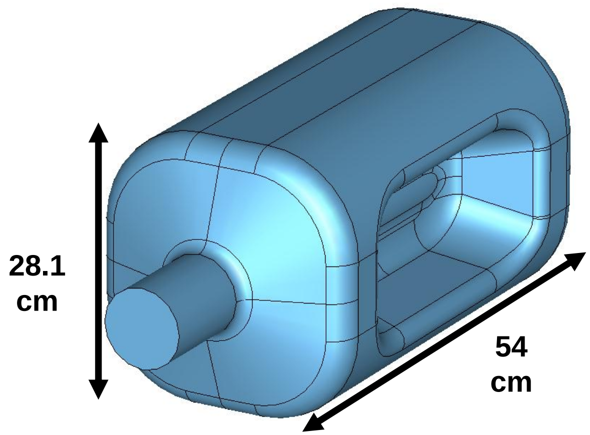


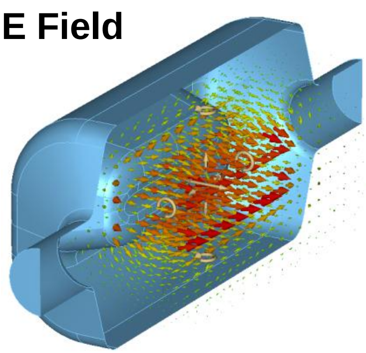
Surface Magnetic Field

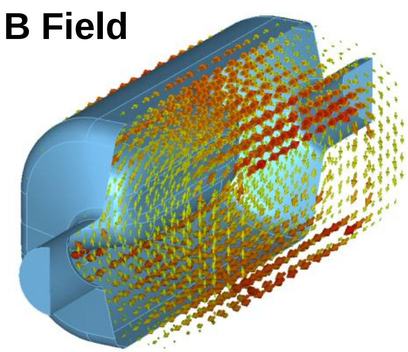


Prototype RF Dipole Design

Prototype design has improved rf-properties

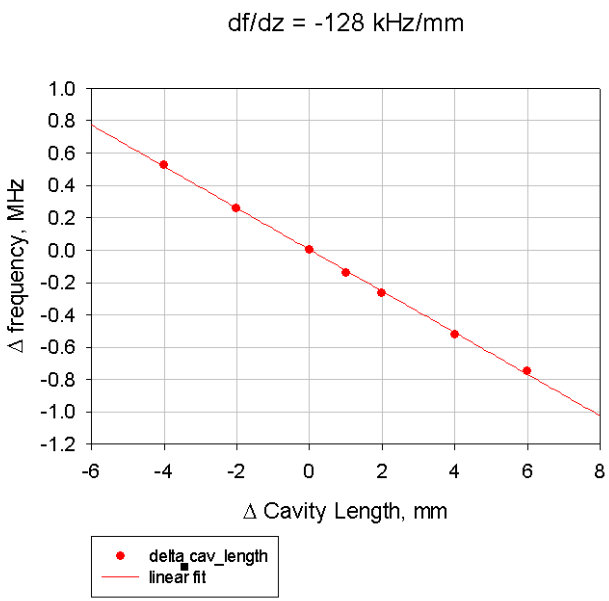


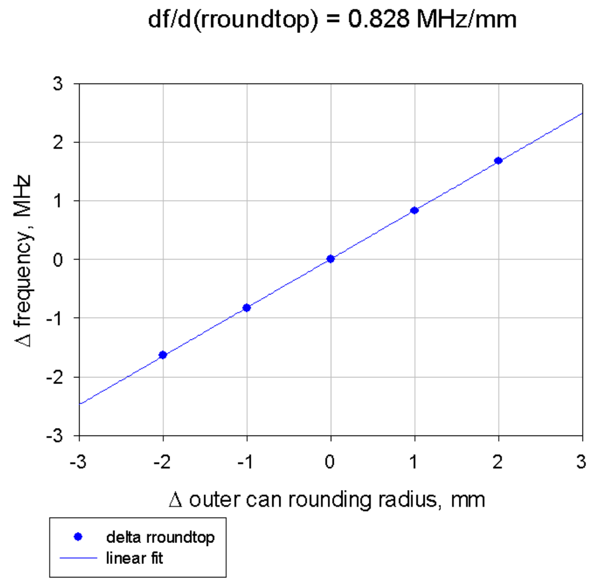


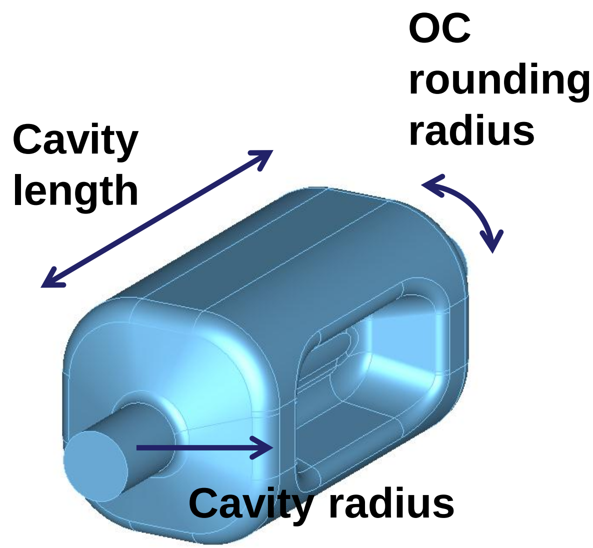


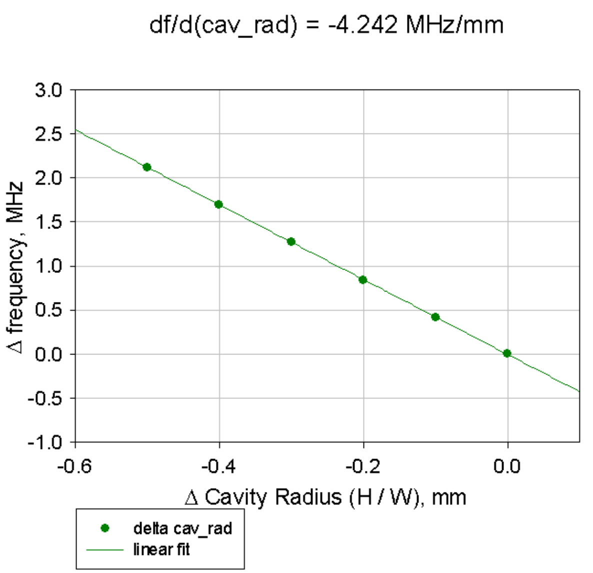
Parameters	Prototype	P-o-P	Units
Frequency of fundamental	400	400	MHz
Frequency of 1st HOM	632	590	MHz
Deflecting Voltage (V_T^*)	0.375	0.375	MV
Peak Electric Field (E_p^*)	3.65	4.02	MV/m
Peak Magnetic Field (B_p^*)	6.22	7.06	mT
Peak Electric Field (E_p^{**})	32.6	35.9	MV/m
Peak Magnetic Field (B_p^{**})	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			

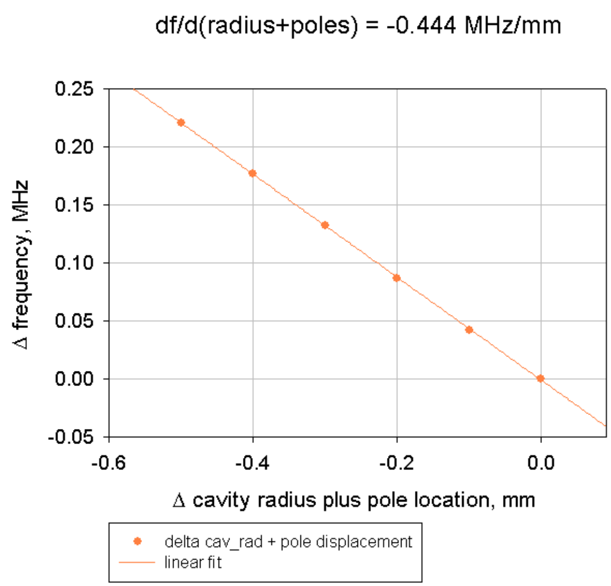
Frequency Sensitivity to Dimensions

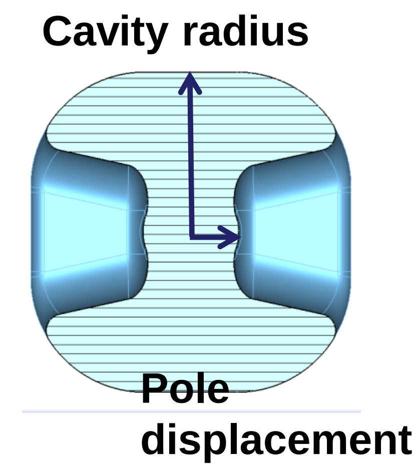








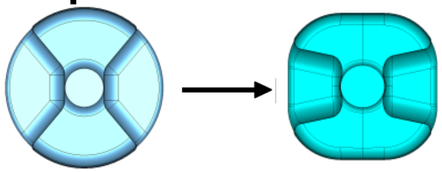


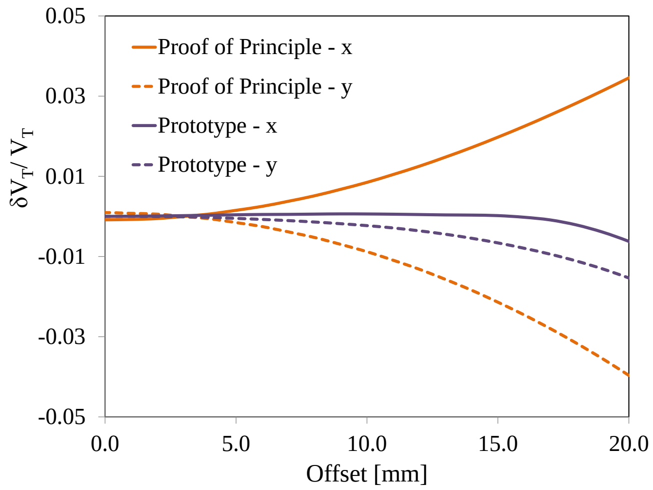


Prototype RF Dipole Design

Multipole analysis

- **Curvature around beam aperture to**
  - **Reduce field non-uniformity**
  - **Suppress higher order multipole components**





Voltage deviation at 20 mm ~ 1%

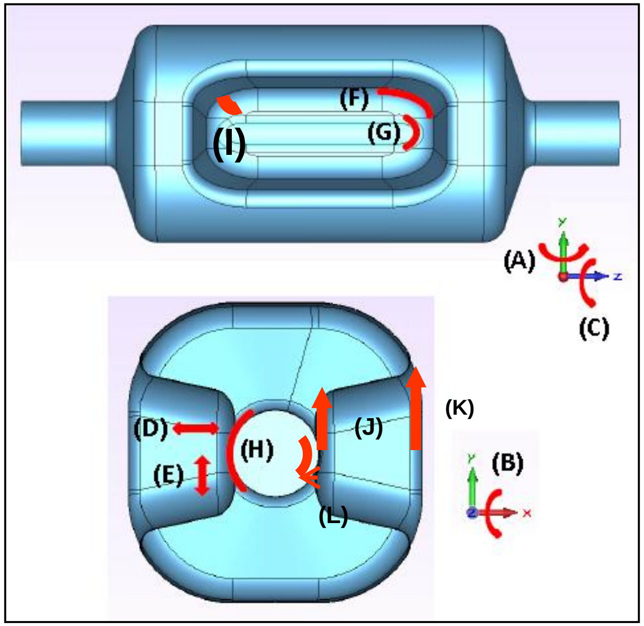
Higher Order Multipole Components

Multipole component		Units
V_T	10	MV
b_1	33	mT m
b_2	-0.004	mT
b_3	369	mT/m
b_4	18	mT/m^2
b_5	-1.9×10^6	mT/m^3

- Multipole component b_3 is reduced below requirements
- **No current specifications for other higher order multipole components**
- Shift in electrical center due to asymmetry of couplers

Prototype RF Dipole Design

Effect on multipole components of imperfections due to fabrication errors



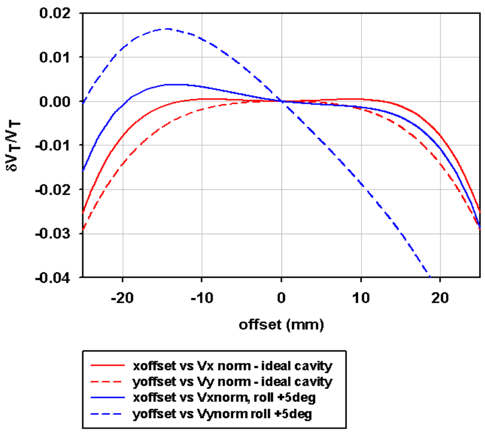
- (A) Yaw (rotation about y-axis) of one pole.
- (B) Pitch (rotation about x-axis) of one pole.
- (C) Roll (rotation about z-axis) of one pole.
- (D) Horizontal displacement of one pole.
- (E) Vertical displacement of one pole.
- (F) Blending radius along depth of one pole.
- (G) Blending radius of the feather-like structure near the beam line of one pole.
- (H) Aperture radius in one pole.
- (I) Blending radius at the outer corner of one pole
- (J) Width of pole (uneven) at beamline
- (K) Width of pole (uneven) at outer conductor
- (L) Aperture displacement at beamline

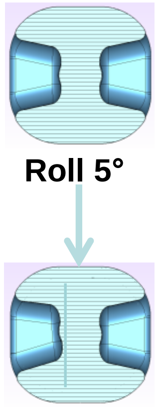
- Strength of the multipole components is mainly determined by the aperture region of the poles near the beamline.
- Analysis focused on individual imperfections of the ideal cavity poles due to fabrication or welding errors (no deformations due to tuning processes considered).

Small individual imperfections (~1 mm) have negligible effects on the multipole components, but may shift the electrical center and operating frequency.

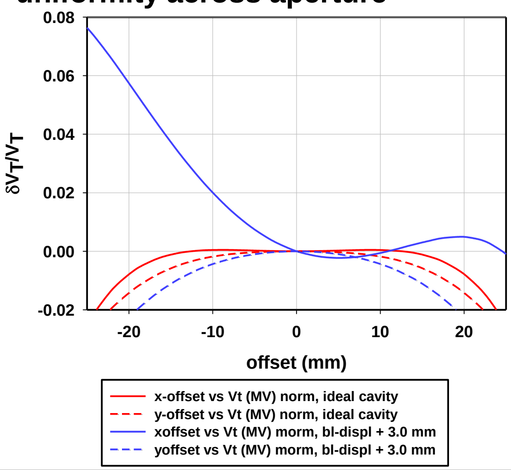
Prototype RF Dipole Design

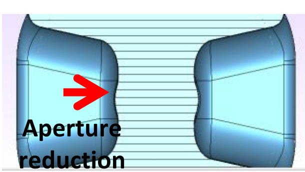
The largest effect on the multipole components observed is produced by the roll of a pole





The largest frequency shift observed is produced by the horizontal displacement) of a pole → loss of field uniformity across aperture



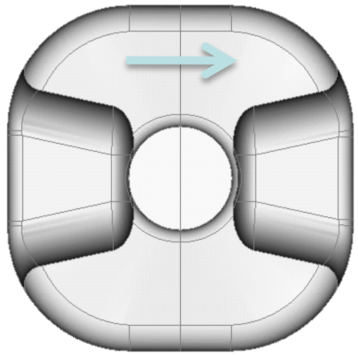


Imperfection	E center (mm)	b_1 (mT m)	b_2 (mT m/m)	b_3 (mT m/m²)	b_4 (mT m/m³)
None	0.00	33	-0.004	369	**18**
Yaw 1°	0.03	33	-0.031	361	411
Yaw 2°	0.12	33	-0.003	333	1581
Yaw 5°	0.75	33	-0.228	138	9835
Pitch 1°	0.00	33	-0.109	382	-181
Pitch 2°	-0.02	33	-0.504	404	-861
Pitch 5°	-0.09	33	-3.550	551	-5614
Roll 1°	0.01	33	-2.018	441	-1710
Roll 2°	0.02	33	-4.801	519	-3746
Roll 5°	0.14	33	-16.144	852	-11158
pole x-offset 1 mm	0.28	33	-9.52	655	-6021
pole x-offset 2 mm	0.52	33	-19.0	959	-13406
pole x-offset 3 mm	0.71	33	-27.6	1258	-21727
Note: Normalized to V_T = 10 MV					

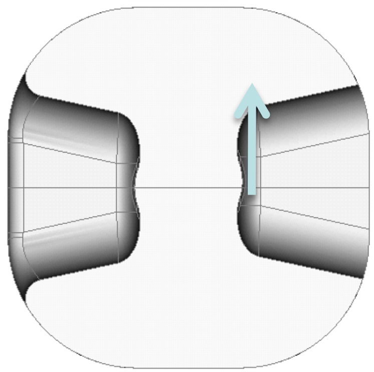
Prototype RF Dipole Design

Imperfection models studied

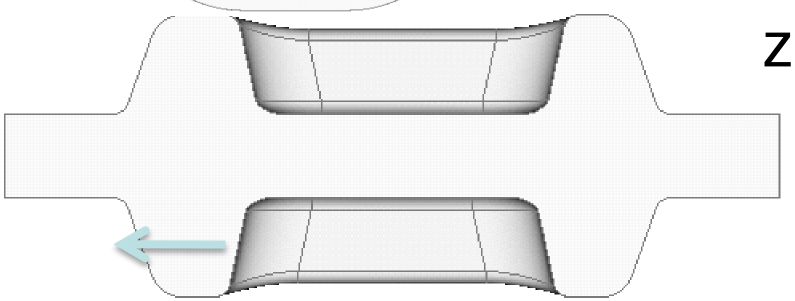
- xoffset



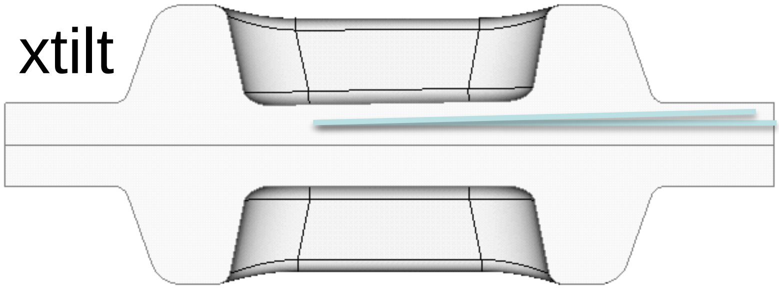
- yoffset



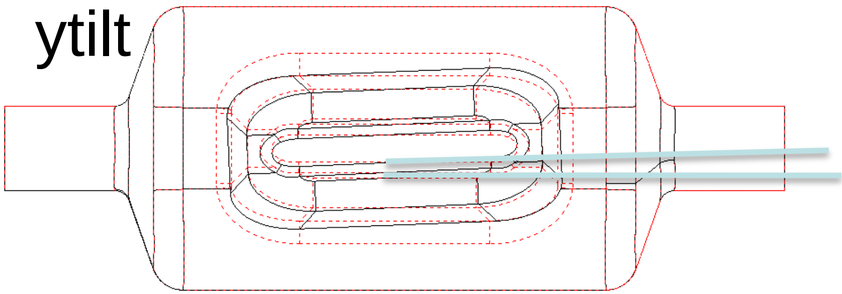
- zoffset



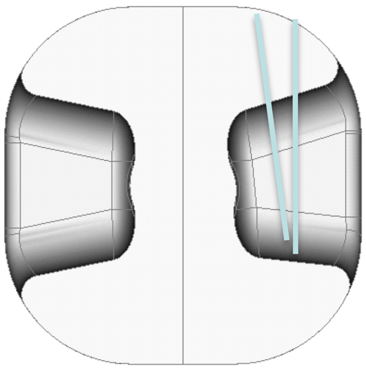
xtilt



ytilt



zrotate



Multipole Field with a Tilted/Offset Pole

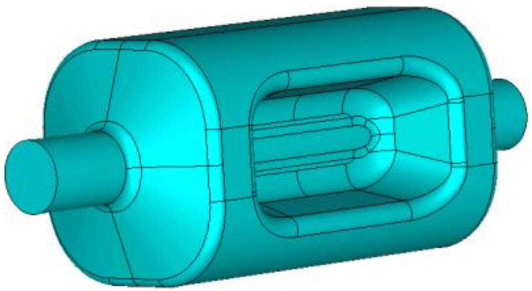
	xcenter off (mm)	Vy/Vx	B3 (mT*m)/m^2	B5 (mT*m)/m^4	B7 (mT*m)/m^6	B3 Skew	B5 Skew
xtilt 0.5 deg	0.73		492	2.2E+06	7.8E+08		5.4E+03
ytilt 0.5 deg	0.10	2.2E-03	489	2.3E+06	7.5E+08	49	5.5E+04
zrot 1 deg	0.10	7.9E-03	494	2.2E+06	7.0E+08	136	5.7E+03
xoff 2mm	1.55		677	2.1E+06	7.3E+08		1.6E+04
yoff 2mm	0.09	2.2E-03	536	2.2E+06	6.9E+08	311	2.1E+05
zoff 2mm	0.44		509	2.3E+06	7.2E+08	13	3.8E+04

Note: Normalized to V_T = 10 MV

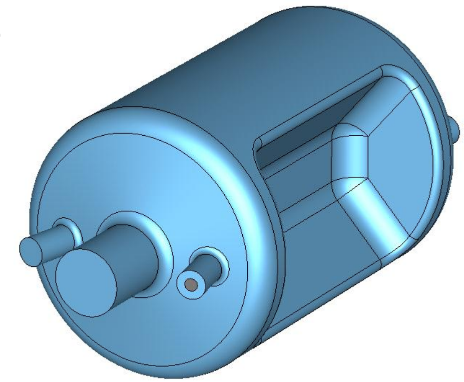
- Small effects on multipole fields
- Induce skew sextupole and deflection in other plane
- Cause shift in electric center
- In general, tolerance manageable

Prototype Design vs. Proof-of-Principle

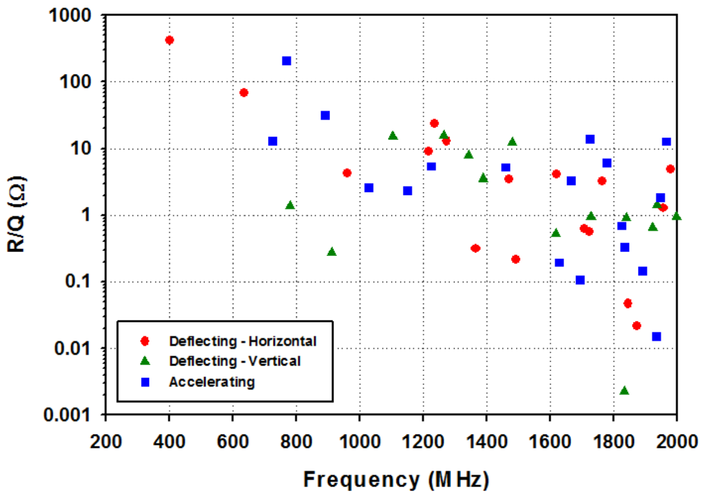
Higher order mode analysis



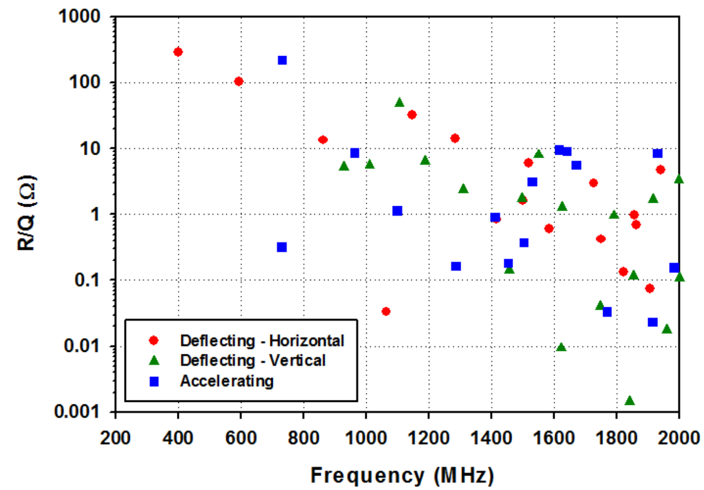
Wide frequency separation between modes



Nearest cavity mode ~230 MHz away



Nearest cavity mode ~190 MHz away

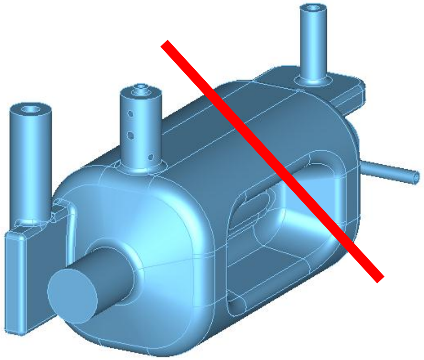


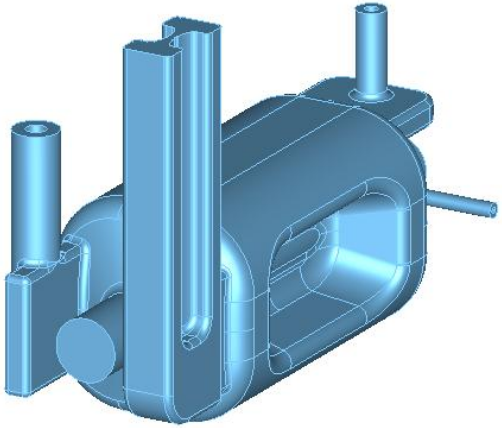
HOM Damping Considerations

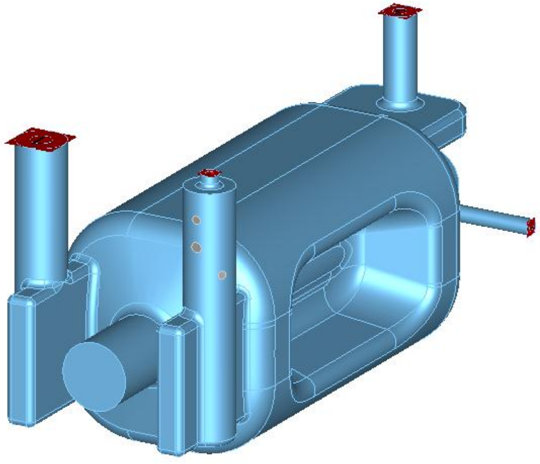
- Provide adequate coupling to HOMs
- Preserve the symmetry of the fundamental mode
- Minimize the number of HOM ports
- Locate HOM ports in low-field locations
- Minimize the number of filters for fundamental mode

HOM Damping

- 2 HOM ports
  - 1 port does not couple to the fundamental mode
    - Does not perturb the symmetry
    - No need for filtering the fundamental mode
  - 1 port couples to the fundamental mode
    - Aperture symmetrical to aperture for fundamental power coupler
    - 2 options for filter
      - Waveguide with cut-off frequency between fundamental and HOM
        - » High power handling
      - Lumped element
        - » Demountable

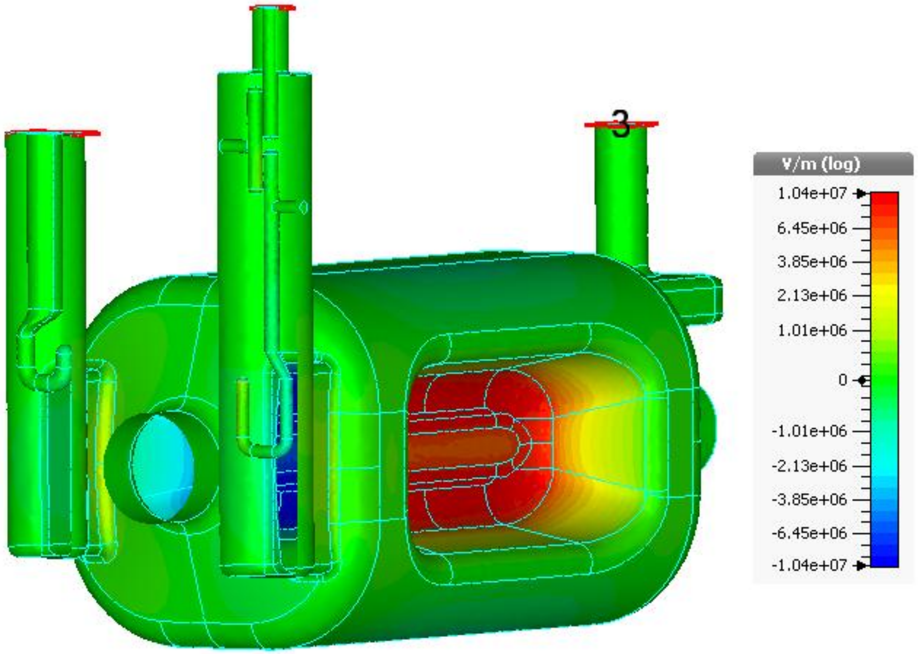


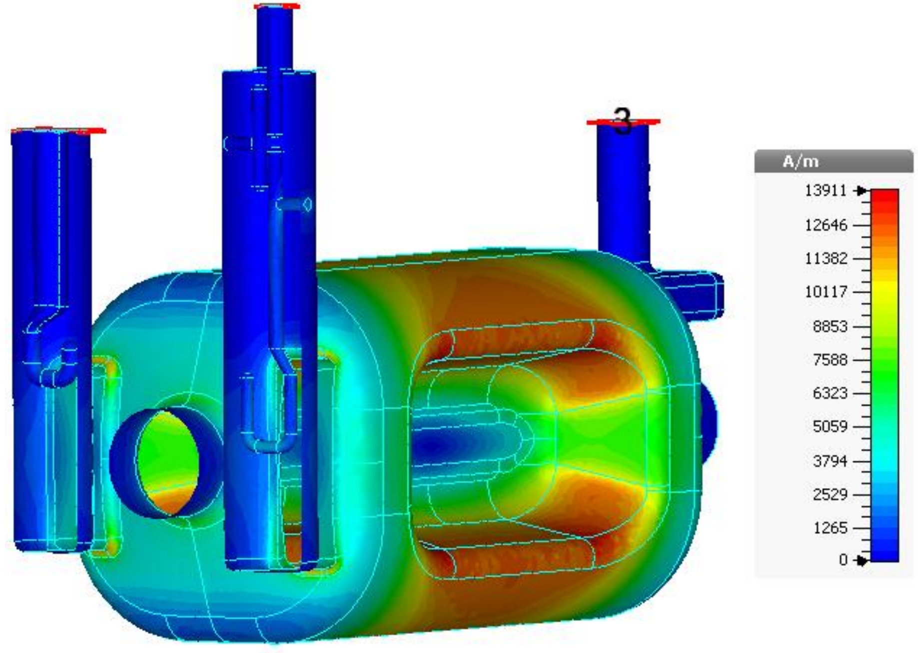




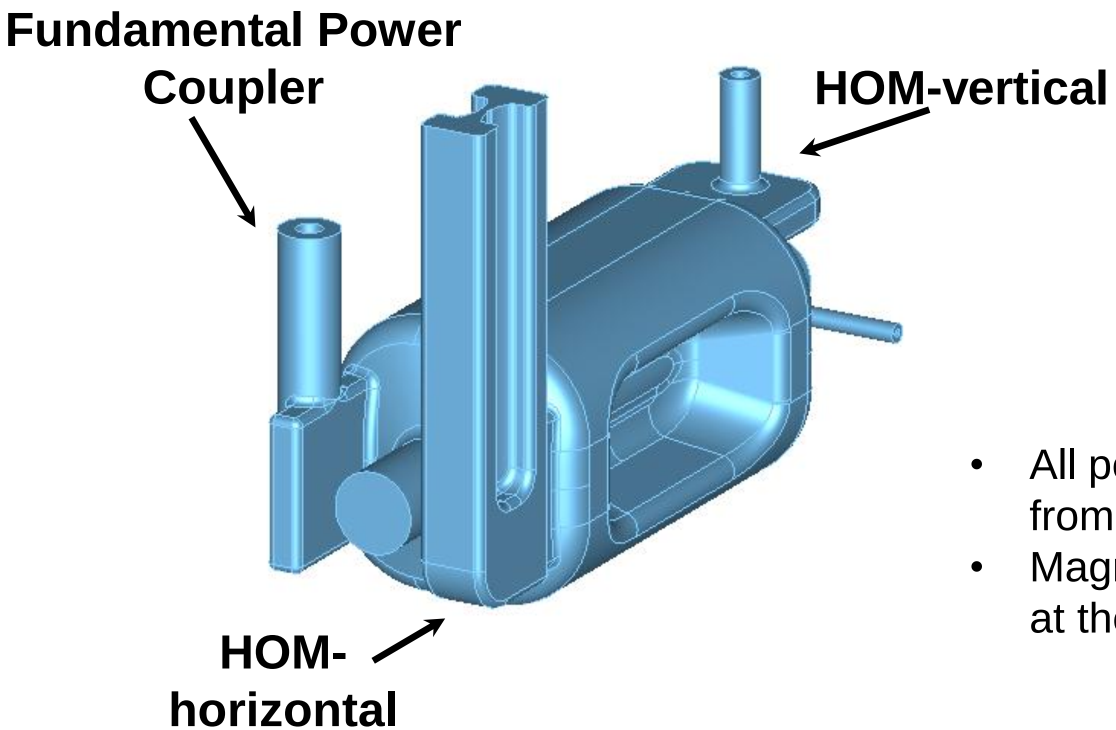
Surface Fields

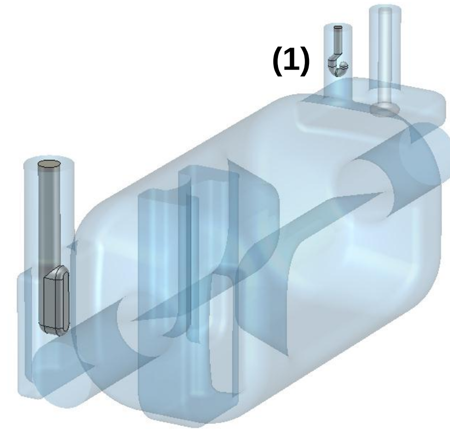
- Low surface field at coupler location: no enhancement
- Low surface field in coupler



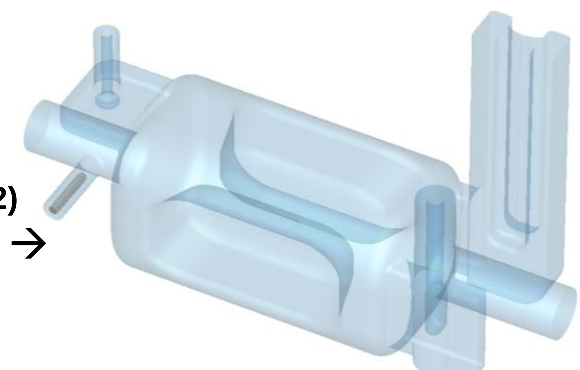


Prototype RF Dipole Coupler Ports Locations





- All penetrations to the He tank will be from top
- Magnetic coupling → Field enhancement at the port (still below B_{peak})

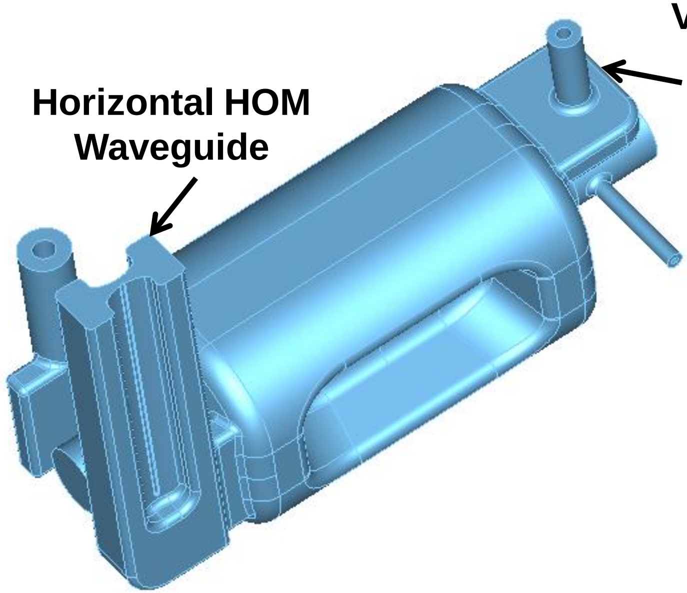


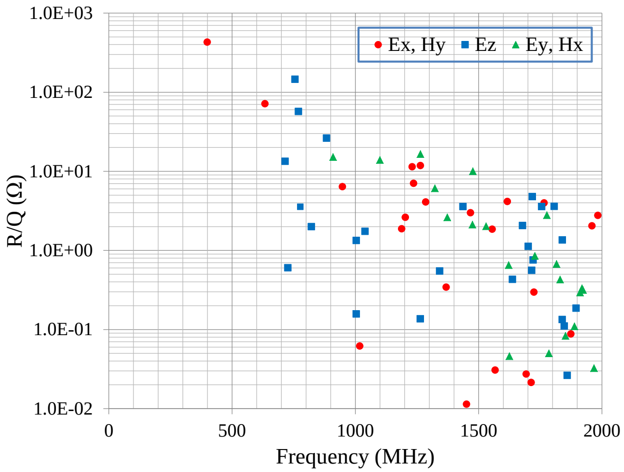
Electric coupling → No field enhancement

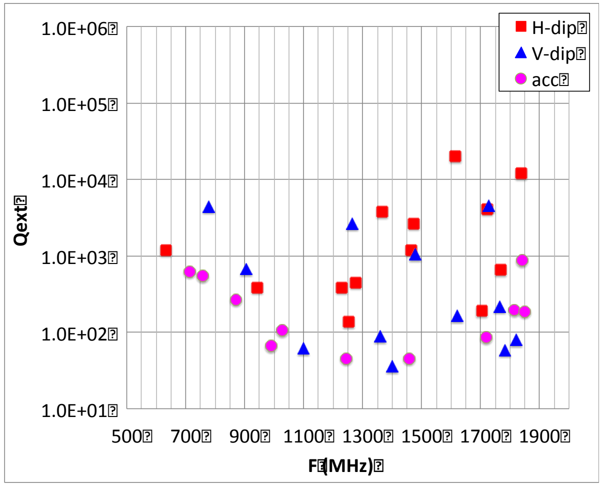
Pick Up Port Options

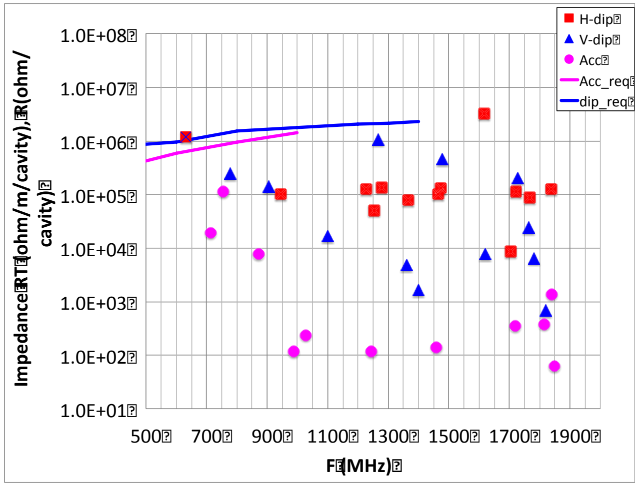
To achieve 1.0 W at 3.4 MV → Q_{ext} = ~3.0×10^{10}

Prototype RF Dipole Design



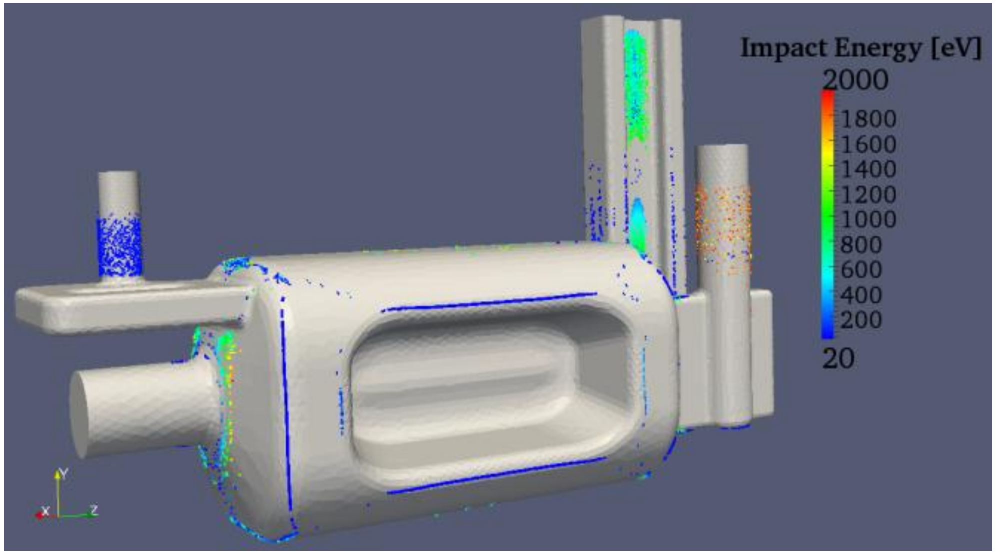


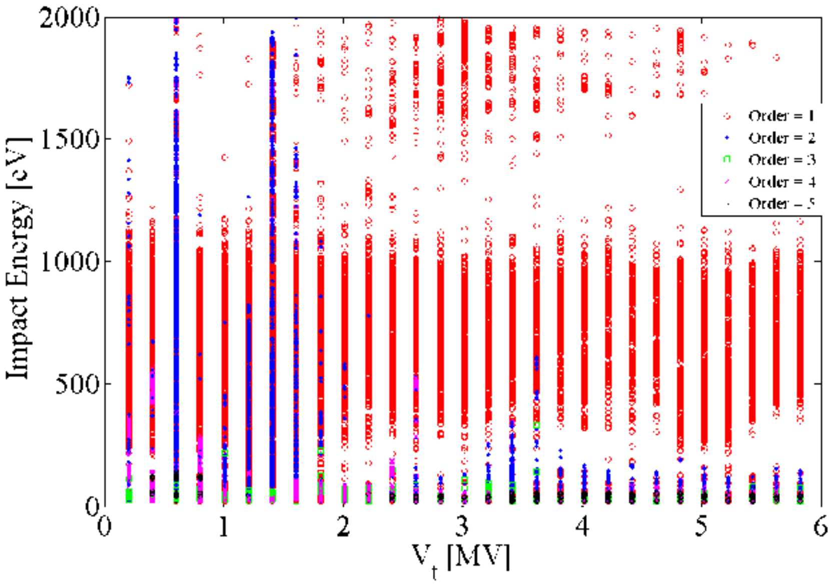




Vertical and horizontal HOM couplers optimized to damp high Q modes at 1.265 and 1.479 GHz

Prototype RF Dipole Design - Multipacting

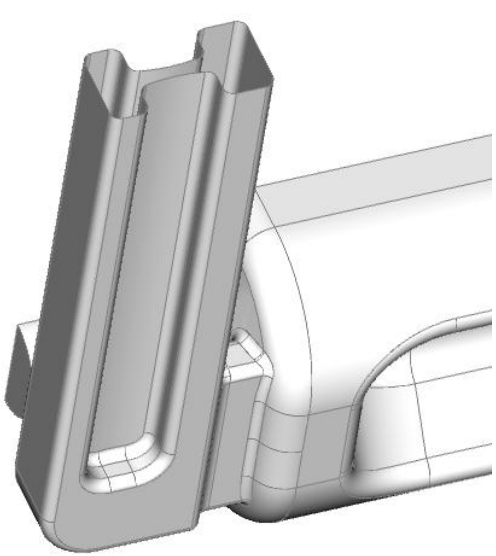


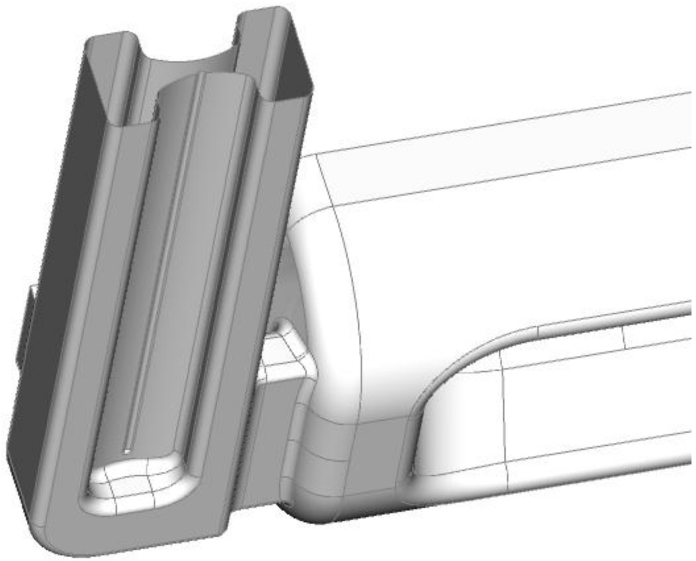


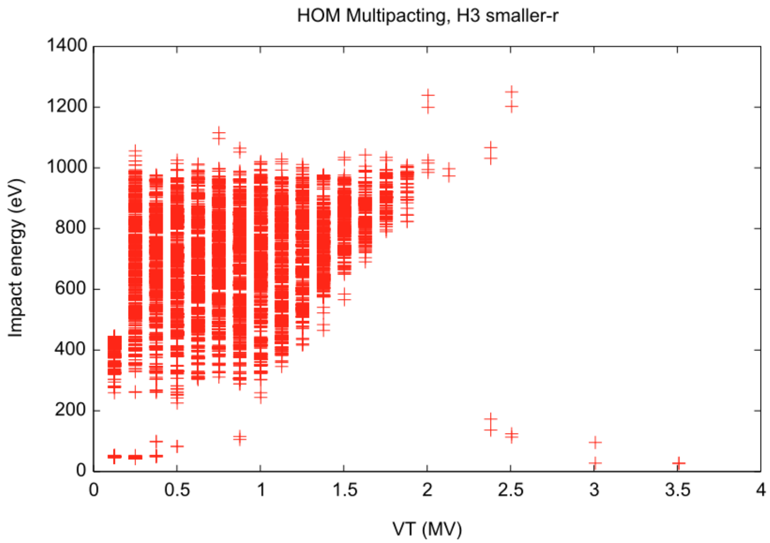
Using Track3P from the ACE3P Code Suite developed at SLAC

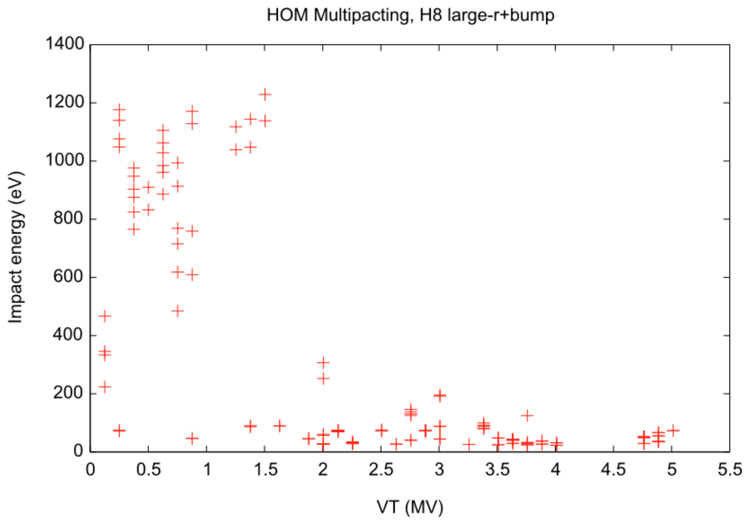
Experience from PoP cavity → multipacting in the cavity not a concern

Prototype RF Dipole Design - Multipacting



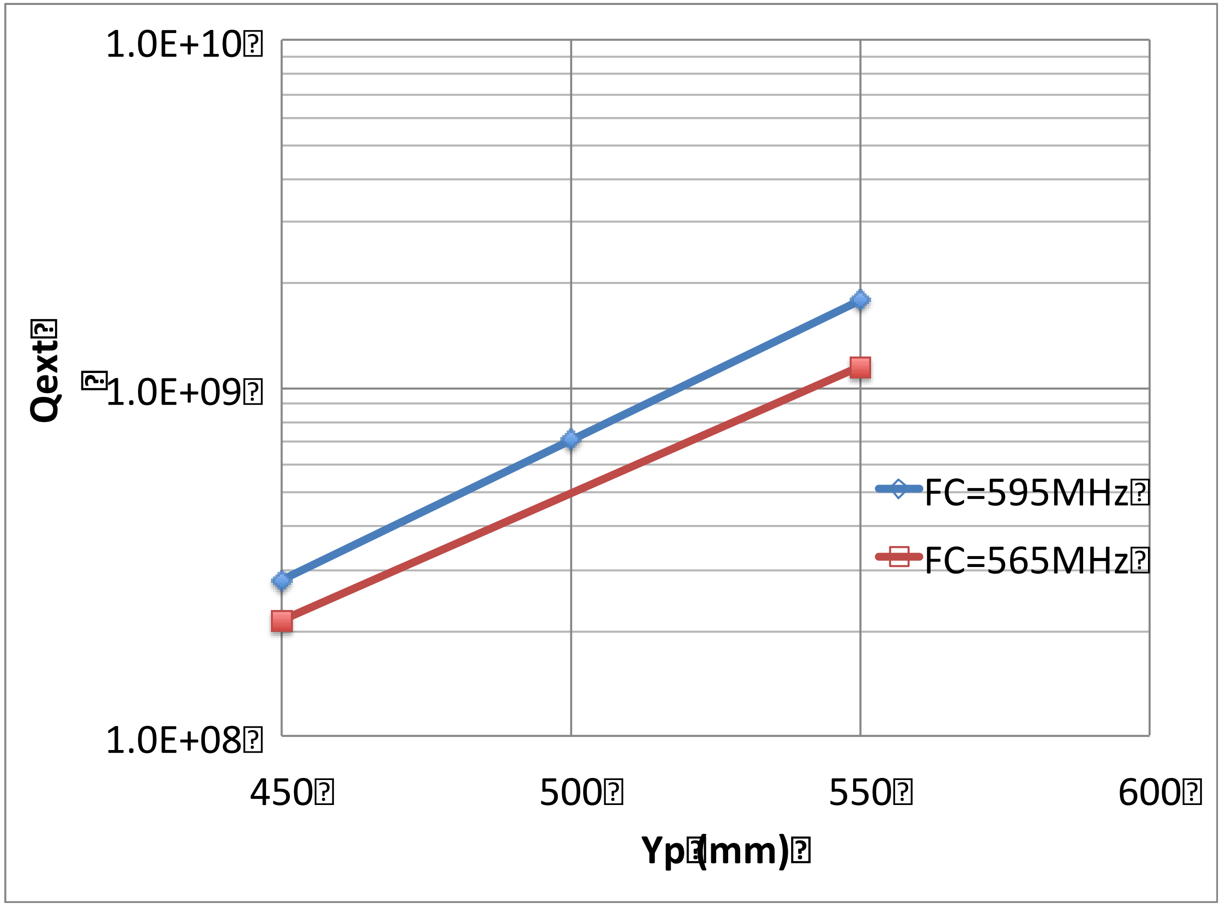




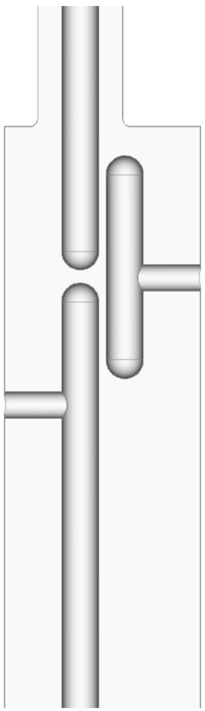


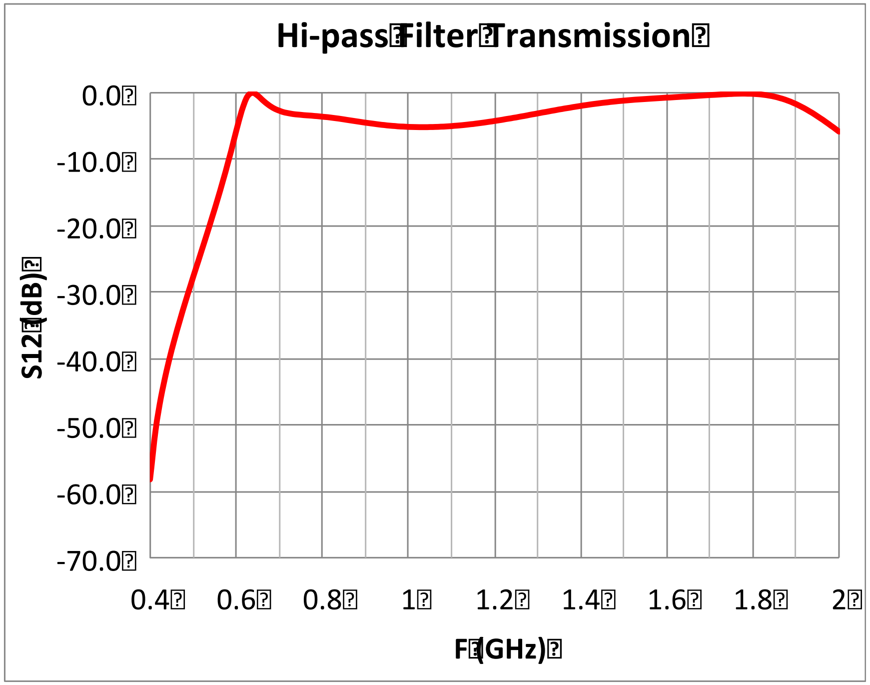
Waveguide Length

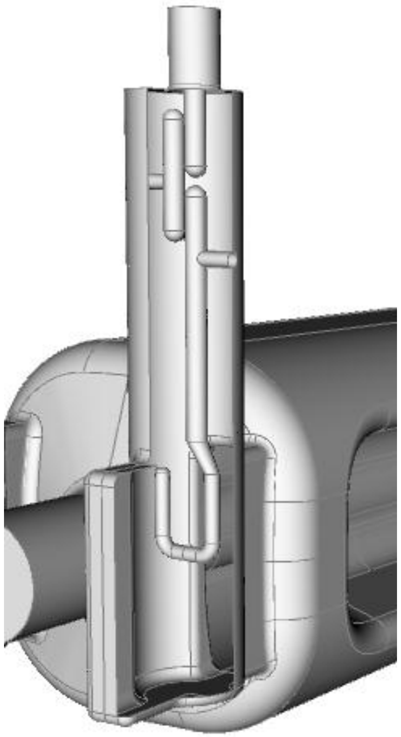
- Length of HOM waveguide to achieve $Q_{ext} > 10^9$ for fundamental mode



Hi-pass Filter H-HOM Coupler



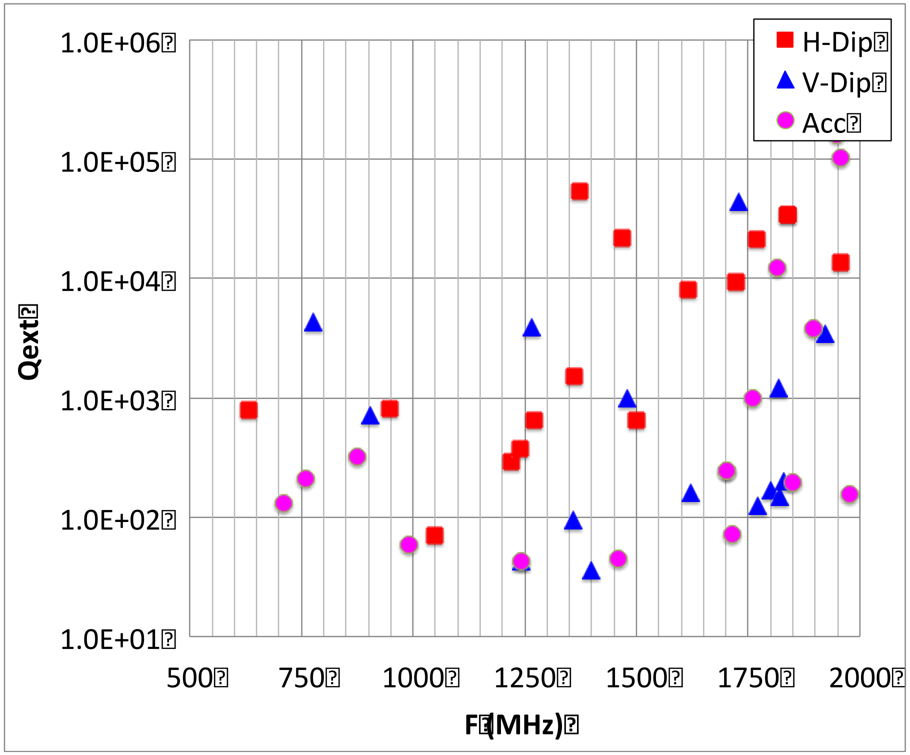


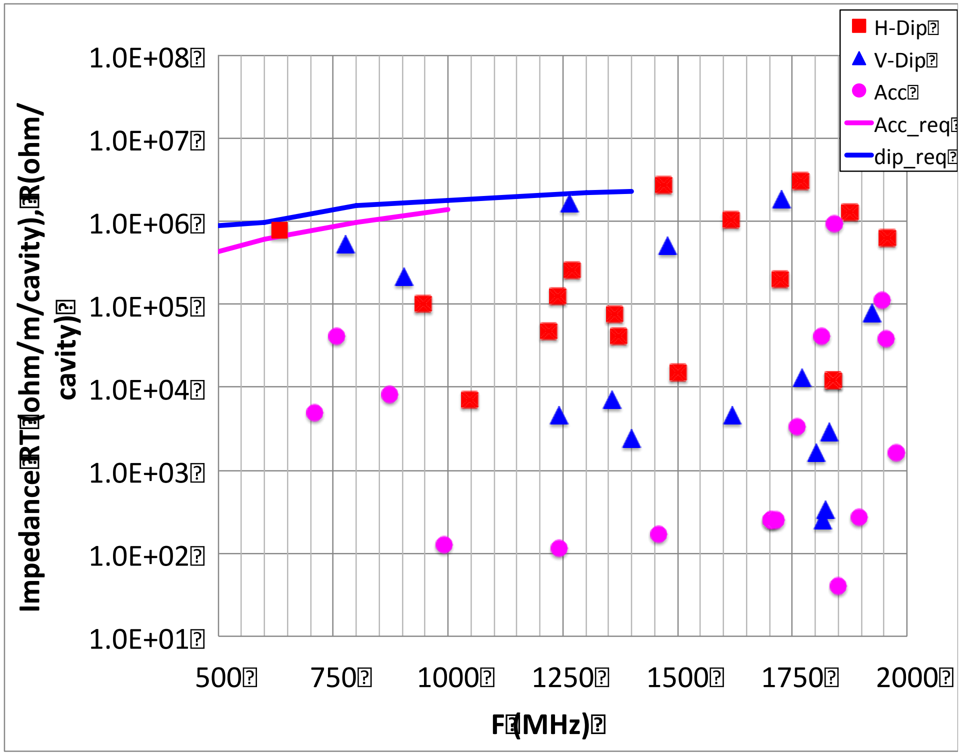


- Hi-pass filter
  - Center rod diameter: 14 mm
  - Larger cylinder diameter: 74 mm
  - 50 ohm port: 14mm/32.2mm

- H-HOM coupler with hi-pass filter and coupling hook

RFD: HOM Damping

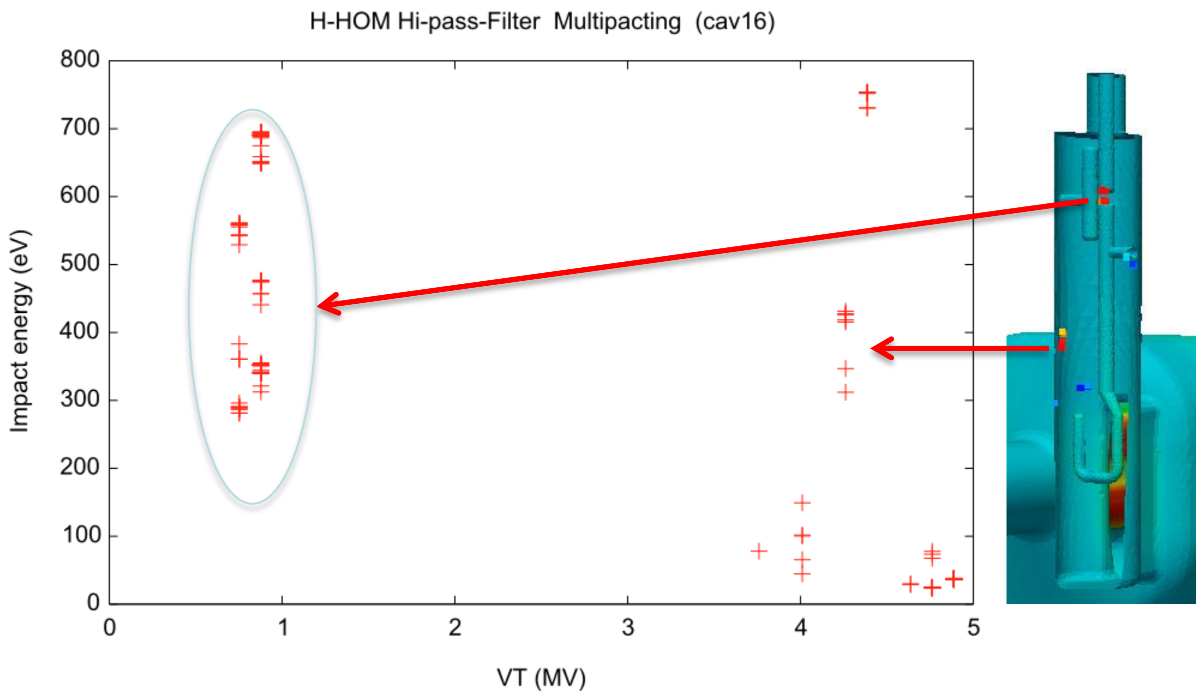


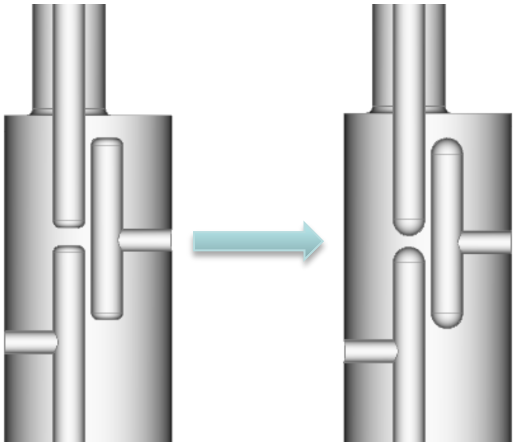


- All modes well damped.
- Solid lines are design requirement (LHC-CC10)

Multipacting in Hi-pass Filter H-HOM Coupler

- MP resonances found in the gap if there are flat surfaces
- Eliminated MP with a full rounding
- Nominal deflecting voltage VT = 3.4MV

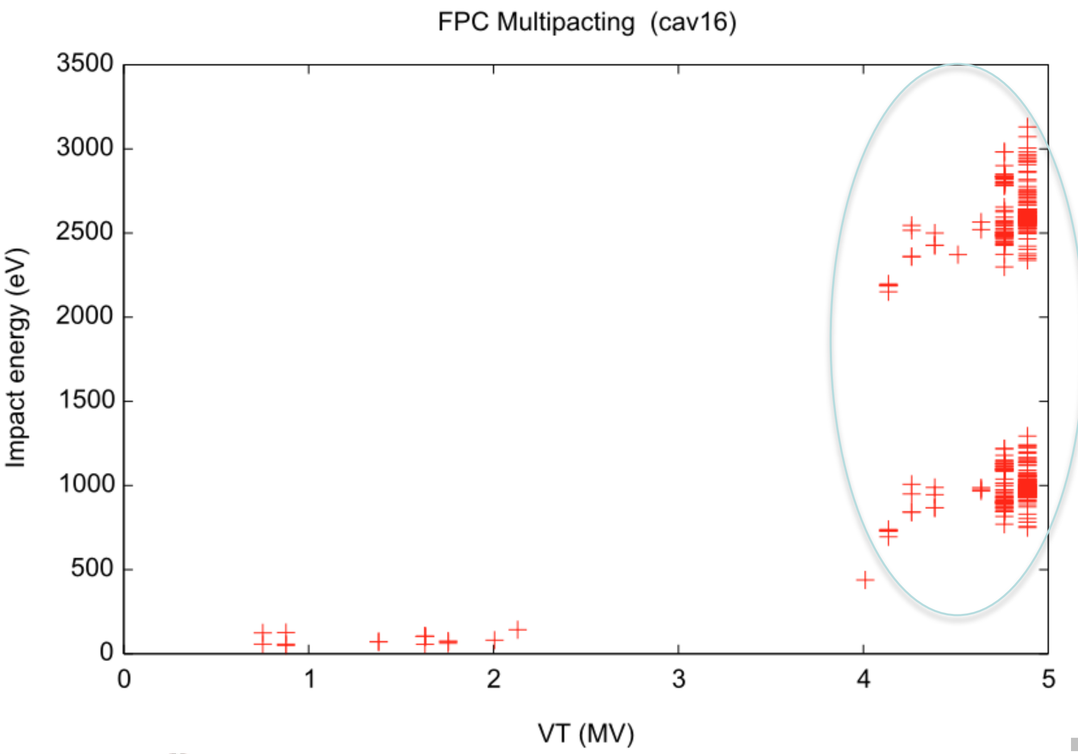




MP trajectories in the gap Removed

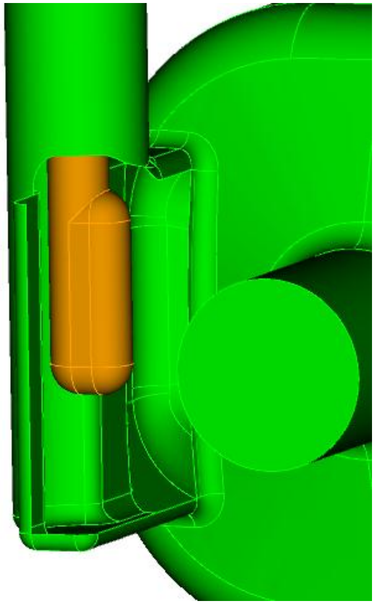
Multipacting in FPC Coupler

- No multipacting in the hook region
- Has resonant trajectories in the coaxial region at higher deflecting voltages
- Nominal deflecting voltage VT = 3.4 MV

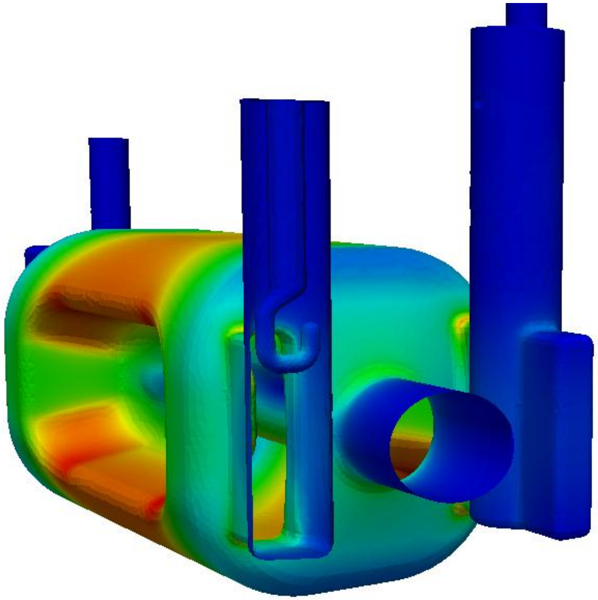


MP regular coaxial region at high VT

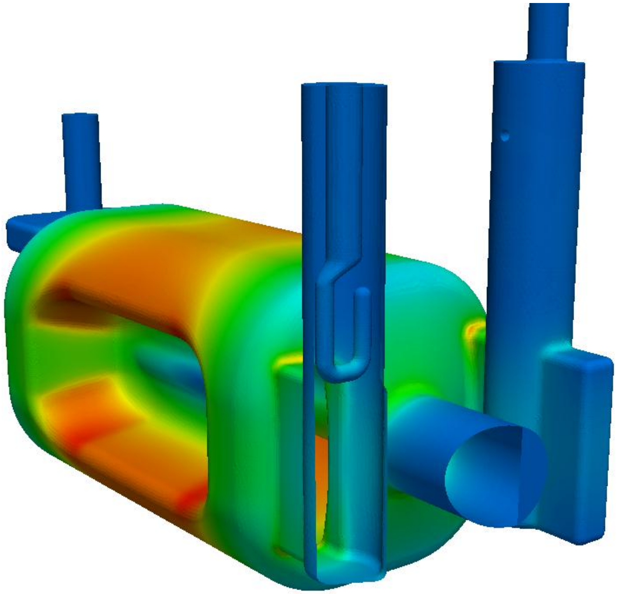
Power Dissipation on FPC Coupling Hook Antenna



676 W

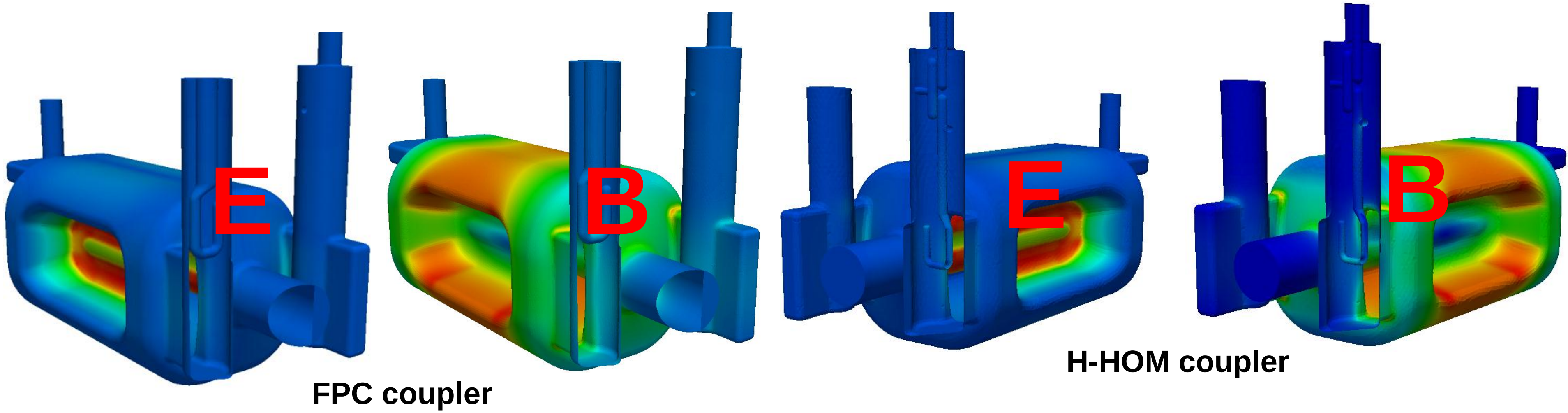


178 W



69 W

Surface Fields on FPC and HOM couplers

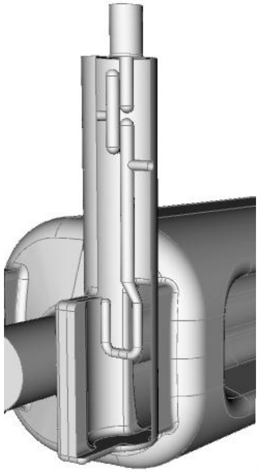


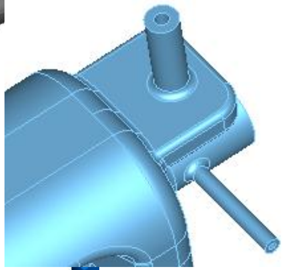
At 3.4MV deflecting voltage	E_S (MV/m)	B_S (mT)
H-HOM Hook	5.4	14
H-HOM T	2.4	1.3
H-HOM probe	0.6	0.4
FPC Hook	1.4	7.6

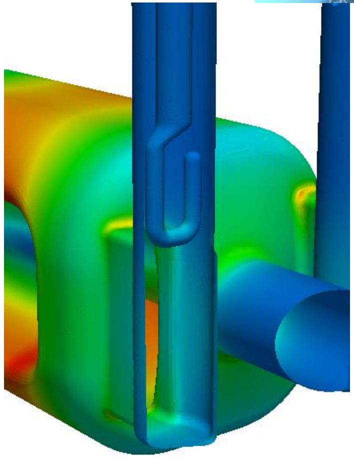
RFD: Power Loss On Coupler Surfaces

- At 3.4MV deflecting voltage

	Material	Power Dissipation (W)
H-HOM Hook+T	Nb (Rs=10nΩ)	0.00089
H-HOM Probe	Cu (Rs=5.2mΩ)	0.084
V-HOM probe	Cu (Rs=5.2mΩ)	0.077
FPC Hook (Qext=5e5) (shorter hook)	Cu (Rs=5.2mΩ)	178
FPC Hook (Qext=5e5) (New hook)	Cu (Rs=5.2mΩ)	69

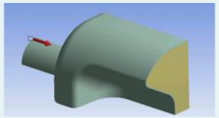
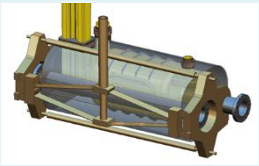
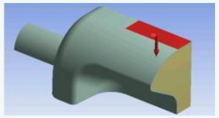
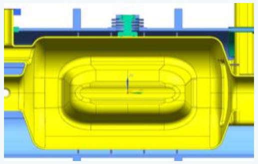
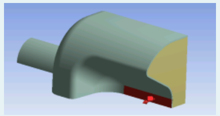


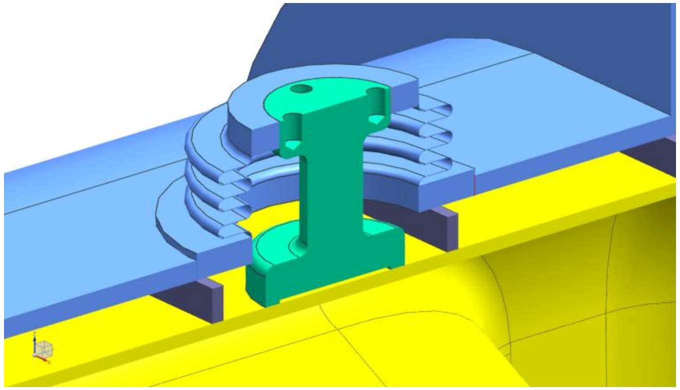


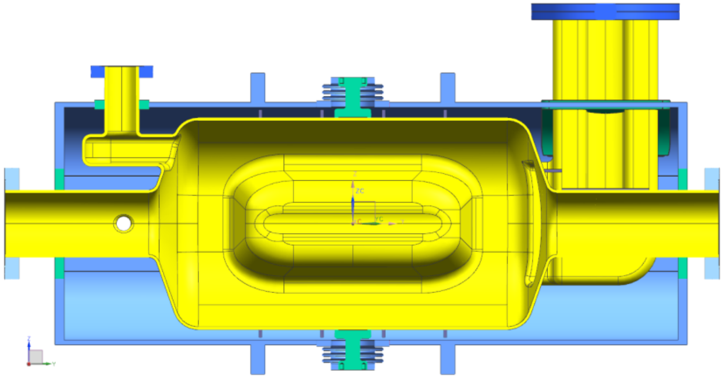


Prototype RF Dipole Design – Tuner Concept

Maintain symmetry to prevent shift of electrical center line

Tuning option	Hz/N	kHz/ mm	Note	
	-5	-90	Requires too large force	
	74	450	Force vs. frequency change in the practical range	
	71	930	Twice sensitive than above option at sensitivity vs cavity deformation	Same as above



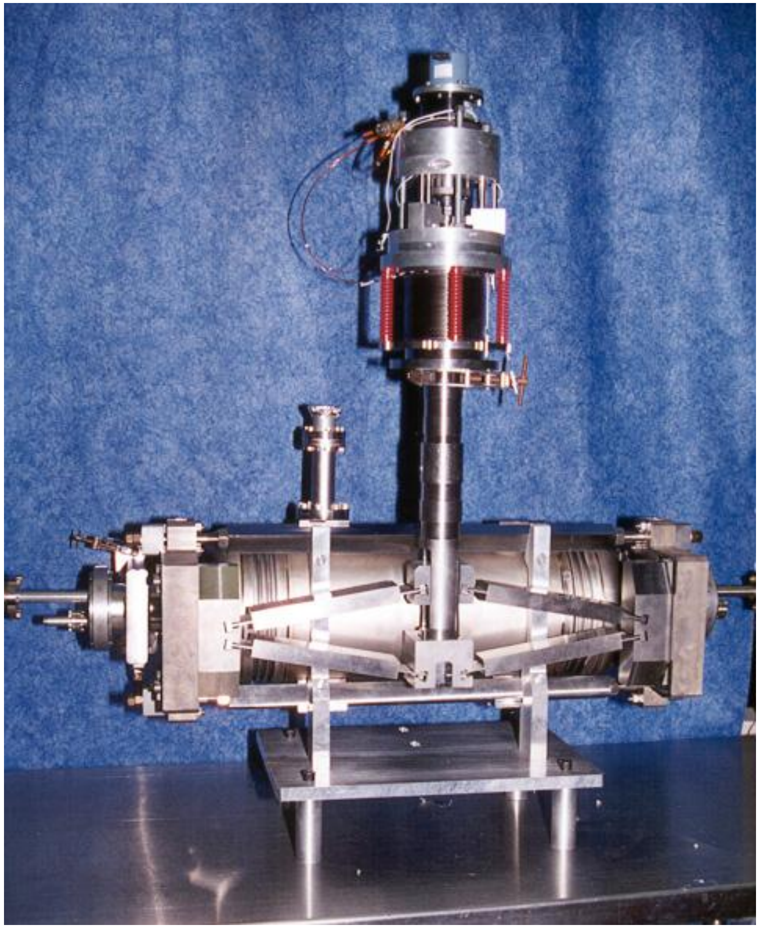


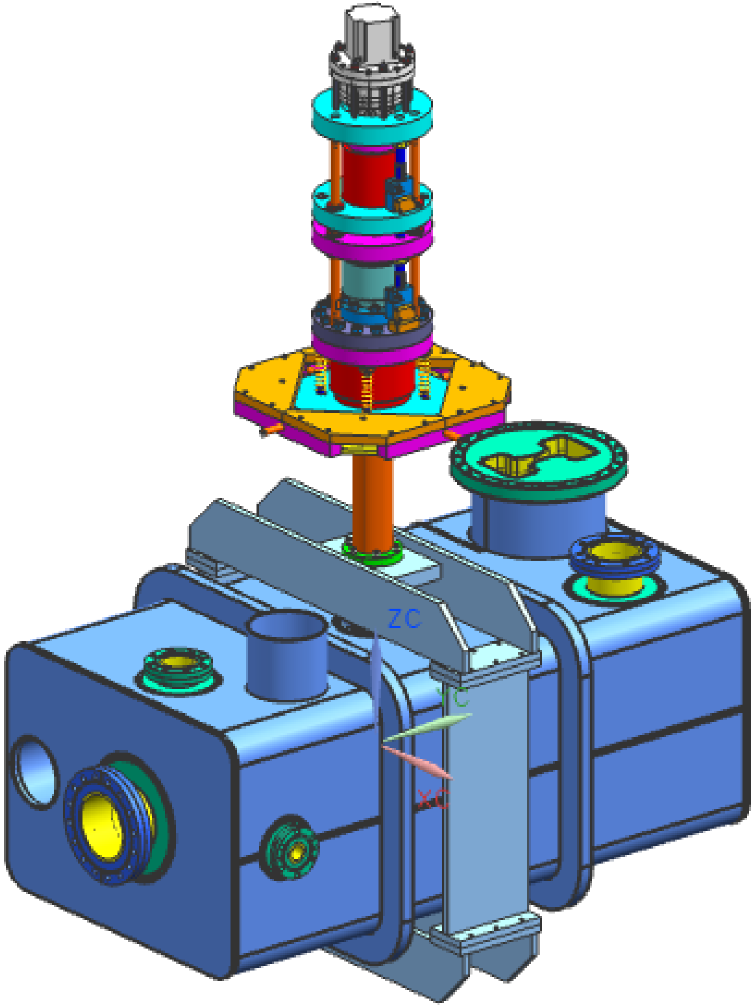
Simulations done with cavity with stiffeners **and** 2K material properties

- **Tuning from the top and/or bottom of the cavity**
- **Use as many common components as possible from other cavity designs.**
- **Thermal study needs to be done.**

Tom Nicol/Fermilab

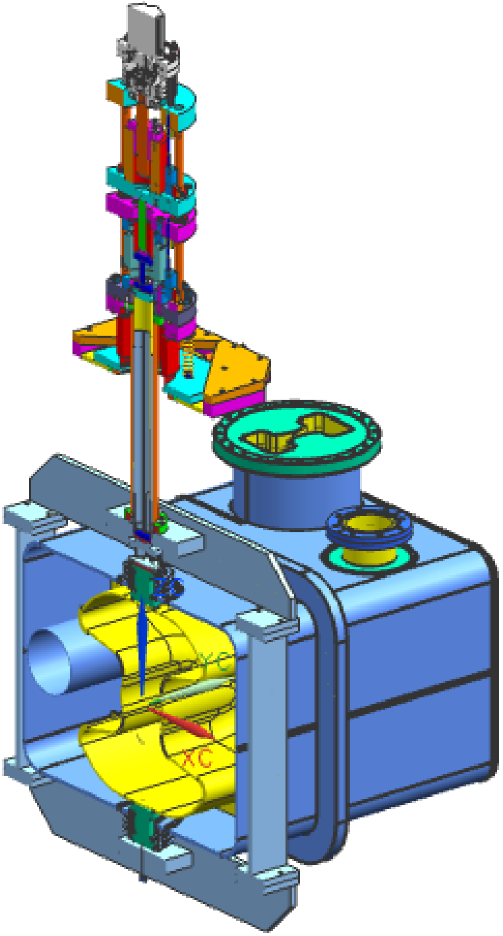
Prototype RF Dipole Design – Tuner Concept



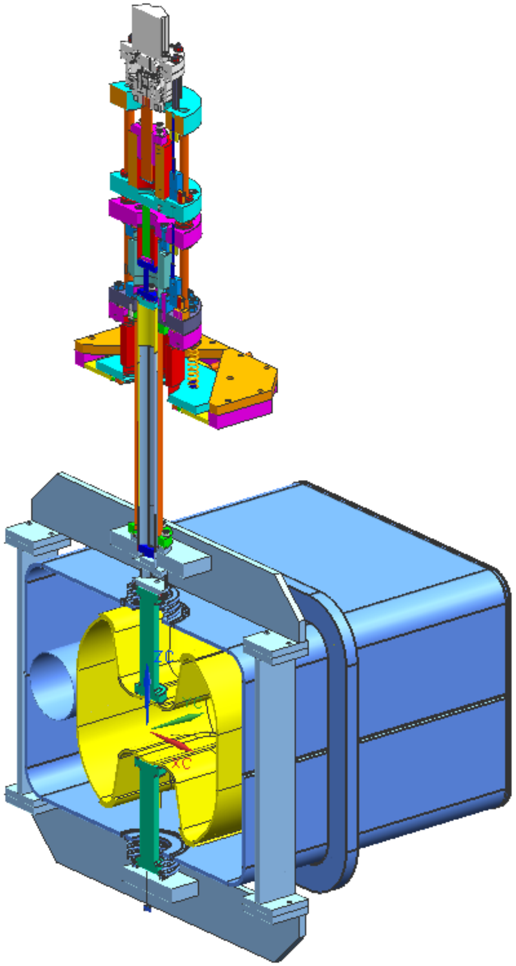


Based on the Jlab 12 GeV Upgrade Cryomodule Tuner

Prototype RF Dipole Design – Tuner Concept



Horizontal crabbing



Vertical crabbing

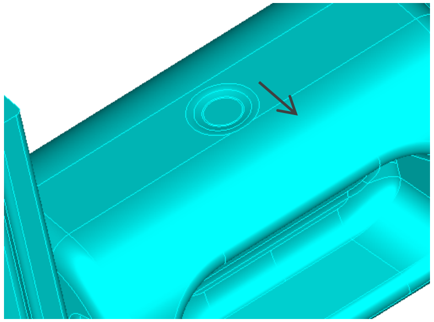
Tuner Effect at OC on Multipole Components

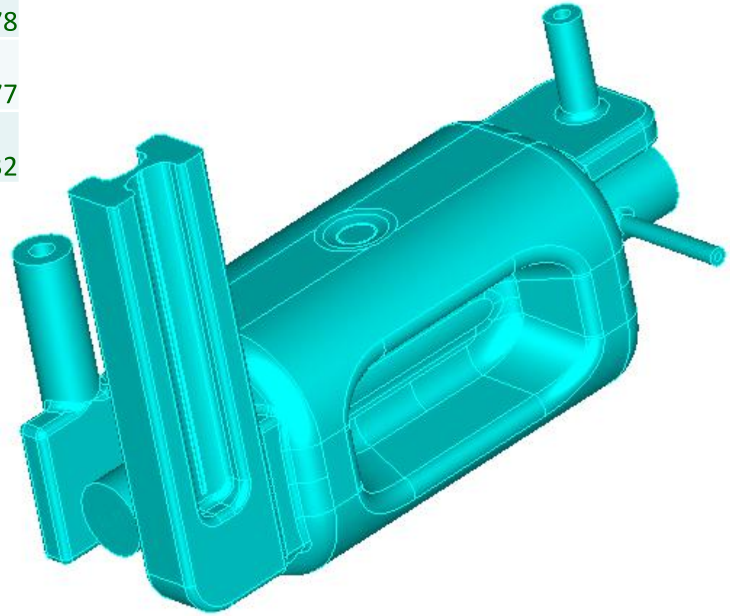
Deformation depth	b0 (kV)	b1	b2	b3	b4	b5
none	-1.03	33.10	0.40	454.66	-471.86	-1885114.32
3 mm	-1.07	33.08	0.40	451.77	-381.65	-1886364.78
5 mm	-1.08	33.09	0.41	453.52	-326.56	-1885200.90

deformation 3mm deep	b0 (kV)	b1	b2	b3	b4	b5
on x-axis	-1.07	33.08	0.40	451.77	-381.65	-1886364.78
3 mm x-axis offset	-1.09	33.08	0.43	452.71	-315.11	-18885977
5 mm x-axis offset	-1.06	33.08	0.39	451.16	-409.55	-1886432

Note: Normalized to V_T = 10 MV

No noticeable effect on higher order multipole components or shift on electrical center when tuner is applied centered or off-axis on the cavity





Summary

- 3 Proof-of-principle RF-Dipole cavities have been built and tested: 400 MHz, 499 MHz, 750 MHz
  - All have exceeded design requirements (400 MHz by a factor of 2)
  - Multipacting virtually non-existent
- Prototype RFD has improved properties over PoP
  - Lower surface fields and higher shunt impedance
  - Lower multipole components
- HOM damping with 2 couplers in low-surface field locations
  - One does not couple to fundamental mode
  - 2 options for 2nd one
- Fundamental and HOM coupler designs have low losses
- Tuner design is based on proven concept