800MHz Elliptical-shape Crab Cavity RF Design For LHC Upgrade

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LARP

Acknowledgements

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- Work used computing resources of NCCS/ORNL and NERSC/LBNL
- Work supported by US LARP program

Outline

- Design Considerations
- Shape and frequency considerations
- 800-MHz elliptical cell optimization
- LOM, SOM, HOM damping coupler design
- Input power coupler design
- Multipacting analysis
- Tolerance Studies
- Beamloading and power requirement
- Summary

Design Considerations

Goal is to achieve head-on collisions at the IP
Working crab cavity exists - KEK-B 509MHz crab cavity

Crab cavity
- **Should produce needed rotation to the beam**
  - Eliminate potential gradient limiting factors, such as multipacting, in the design
- **Have minimal side effects to the beam**
  - Effective LOM, SOM, HOM damping
- **Can fit into existing space on beamline**
  - Cryostat integration – RF, static heating and geometry constraints
- **Required development schedule should be compatible with upgrade timeline**

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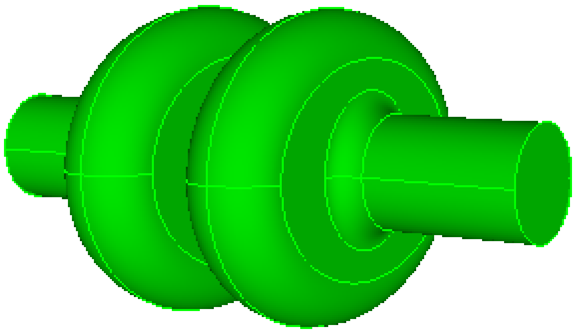
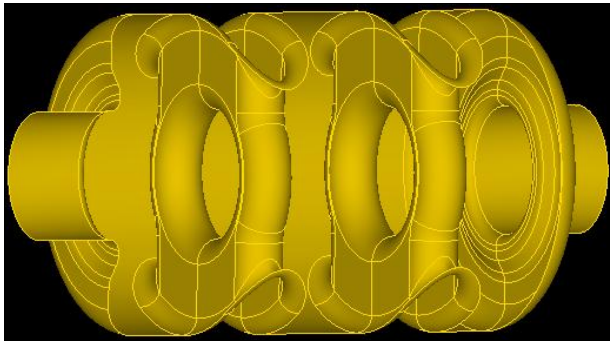
Shape and Frequency

- 800 MHz Elliptical



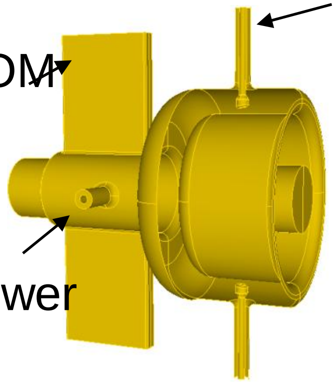
(LARP-CM11 baseline)

800 MHz Spoke



Cavity radius: 150 mm

400MHz-Coaxial



- Different designs being worked on in other labs

- **The 800-MHz, 2-cell elliptical shape, was chosen as baseline design at LARP-CM11**
  (choice of 2-cell was based on a scaled version from a 400-MHz design, Rama)

The Elliptical Shape

- Considered “simpler”
- More engineering experiences with elliptical shapes
- Working cavity with such a shape exist (KEKB)
- Coupler design also followed more conventional end-pipe coupling approach

- Likely lead to short development time

- R&D focus is to optimize the shape and couplers to develop a fully RF functional design, further optimize to realize a engineering design

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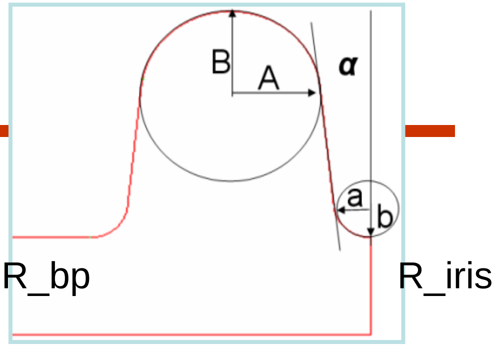
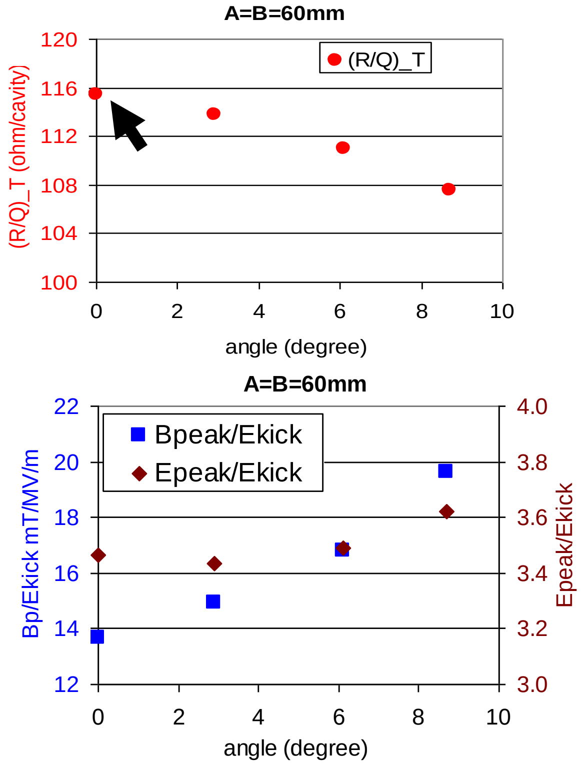
Cell Shape Optimization

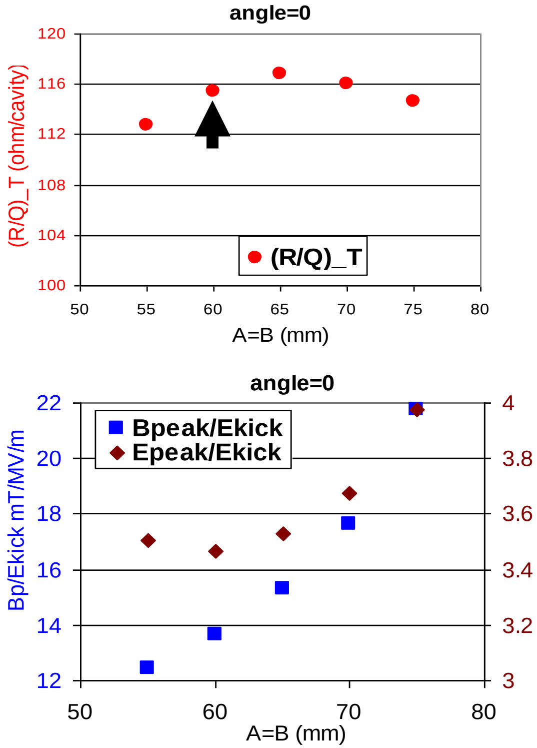


- $r_{bp}=r_{iris}$=70mm, cell length=187.5mm
- Optimize disk parameters for low E_{peak} and B_{peak}

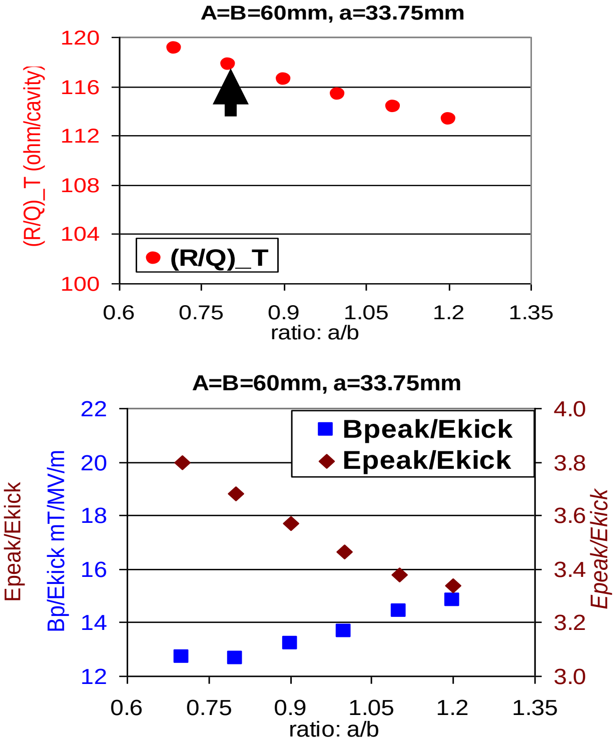
disk angle



disk thickness

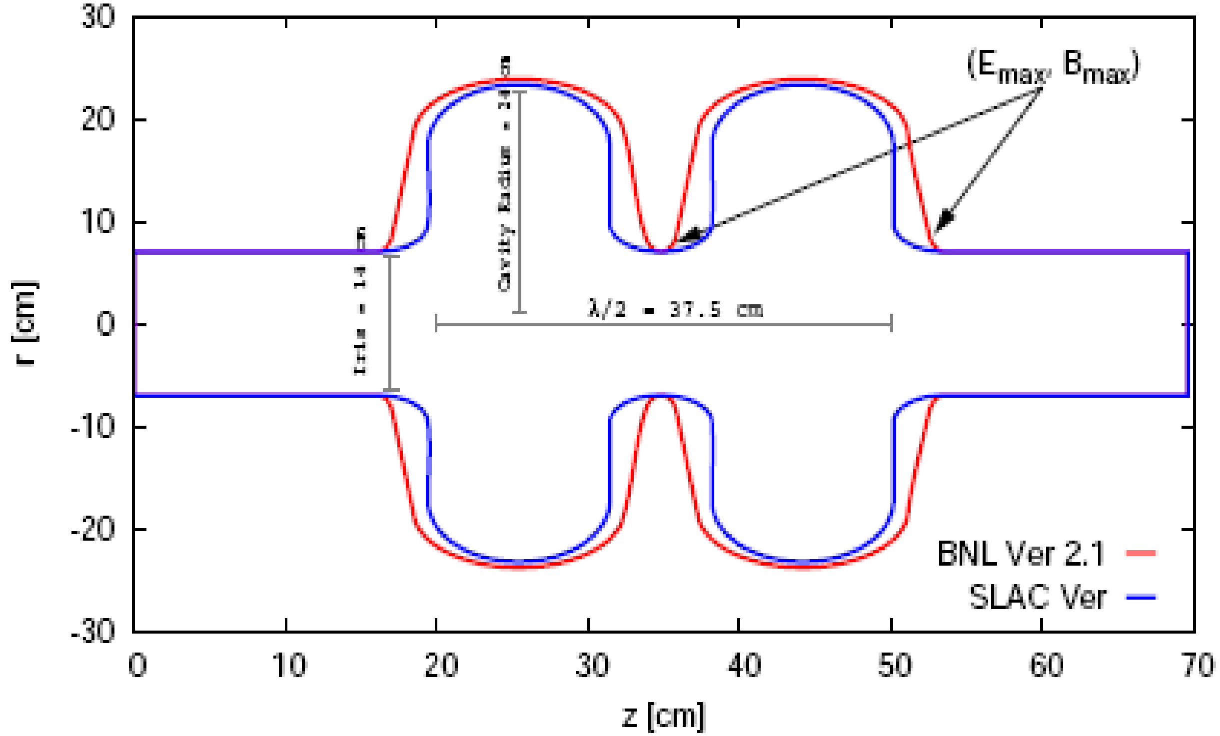


iris ellipticity



The Low Surface Field Shape - 2D

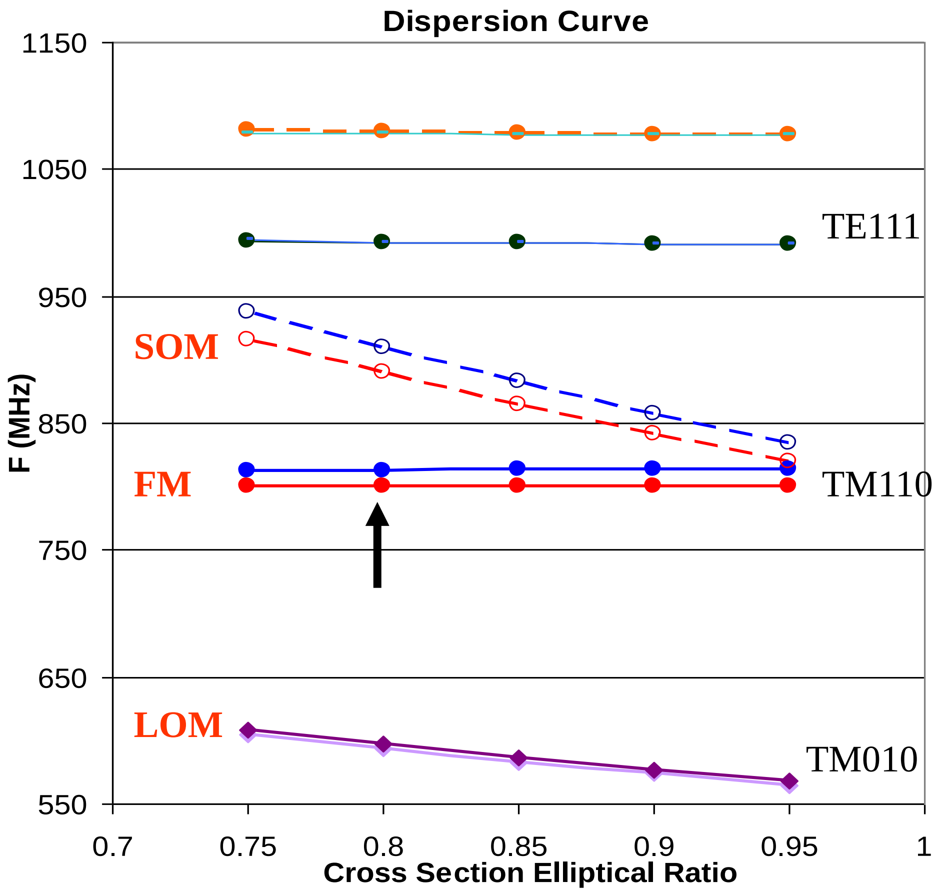
Optimized shape vs scaled version (from 400 MHz, Rama)



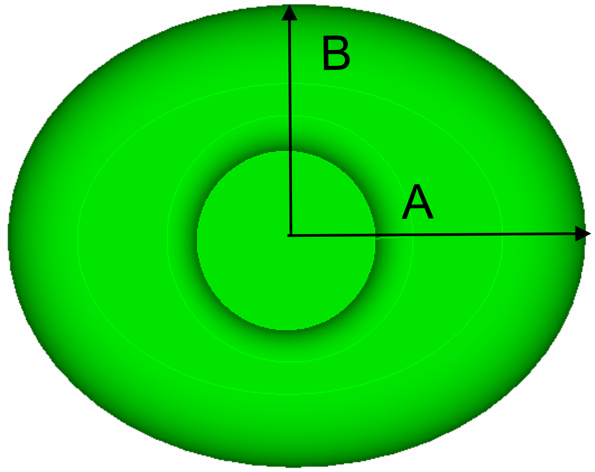
Side wall may need to include a small angle for engineering purpose

Mode Split: Cell Squash Ratio

- **Squash ratio is chosen to optimize mode separation.**
- **Max Dx is limited by available horizontal space**



Fc=1.2GHz@R_beampipe=70mm



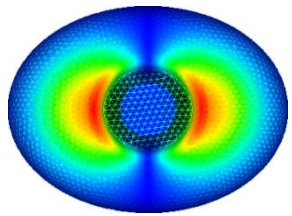
- Racetrack or Elliptical

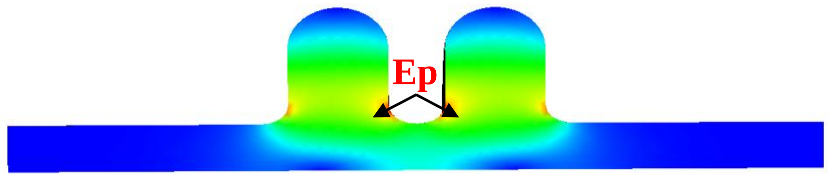
B/A	A	$(F_y\text{-}F_x)$ (MHz)
0.90	235.97	42
0.85	240.10	65
0.80	**244.92**	**89**

Cavity RF Parameters

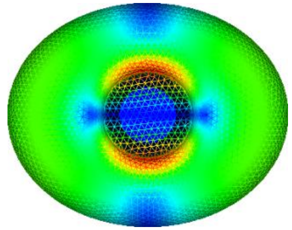
TM110-pi mode

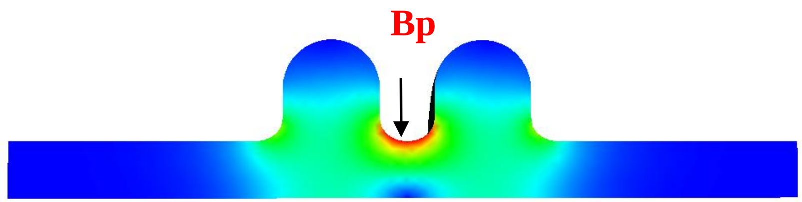
E-field





B-field





Frequency	800 Hz
$(R/Q)_T$	117 ohm/cavity
Deflecting Voltage V_T	2.5 MV
Deflecting Gradient E_{kick}	6.67 MV/m
E_{peak}	25 MV/m
B_{peak}	83 mT
Mode separation (Opt.-SOM)	89 MHz

For comparison:

TESLA TDR cavity peak fields

Eacc: 25-30MV/m,

Ep:50-60MV/m,

Bp=107-128mT

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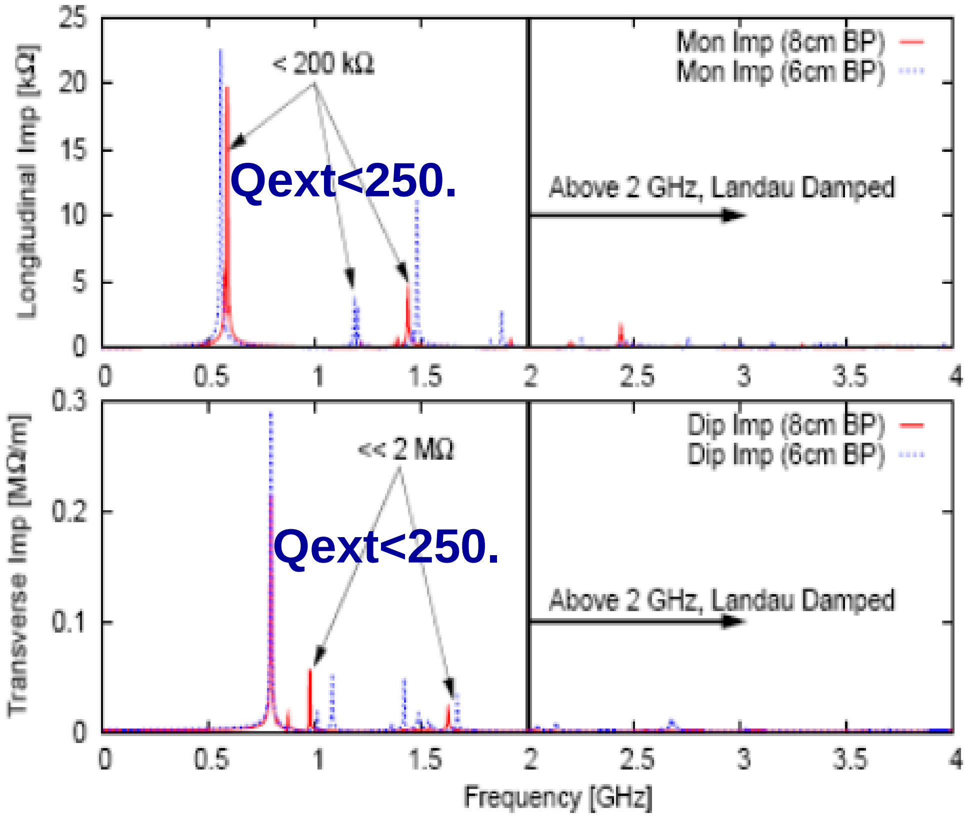
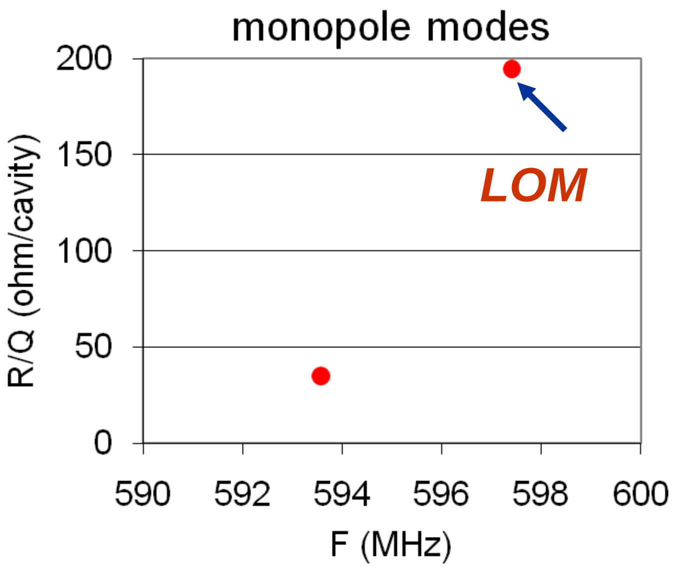
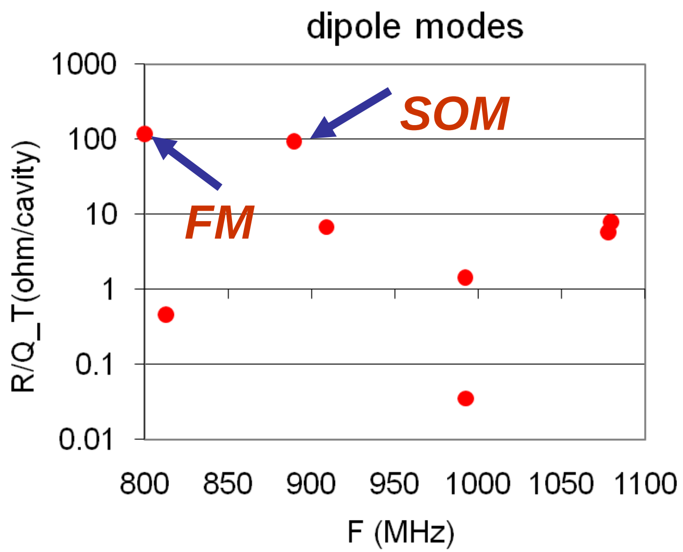
Damping Requirement

Courtesy F. Zimmermann, R. Calaga

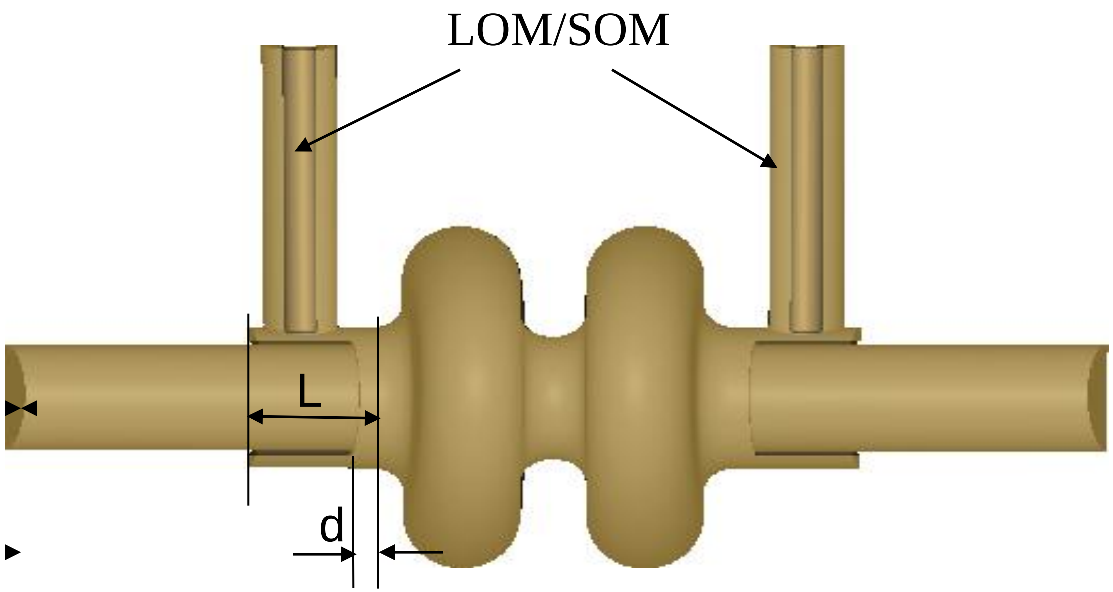


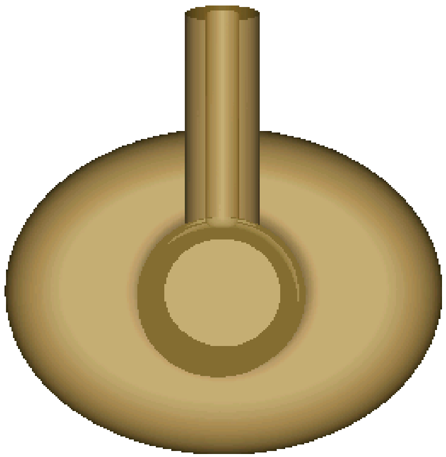




Strong damping needed for high R/Q LOM and SOM modes

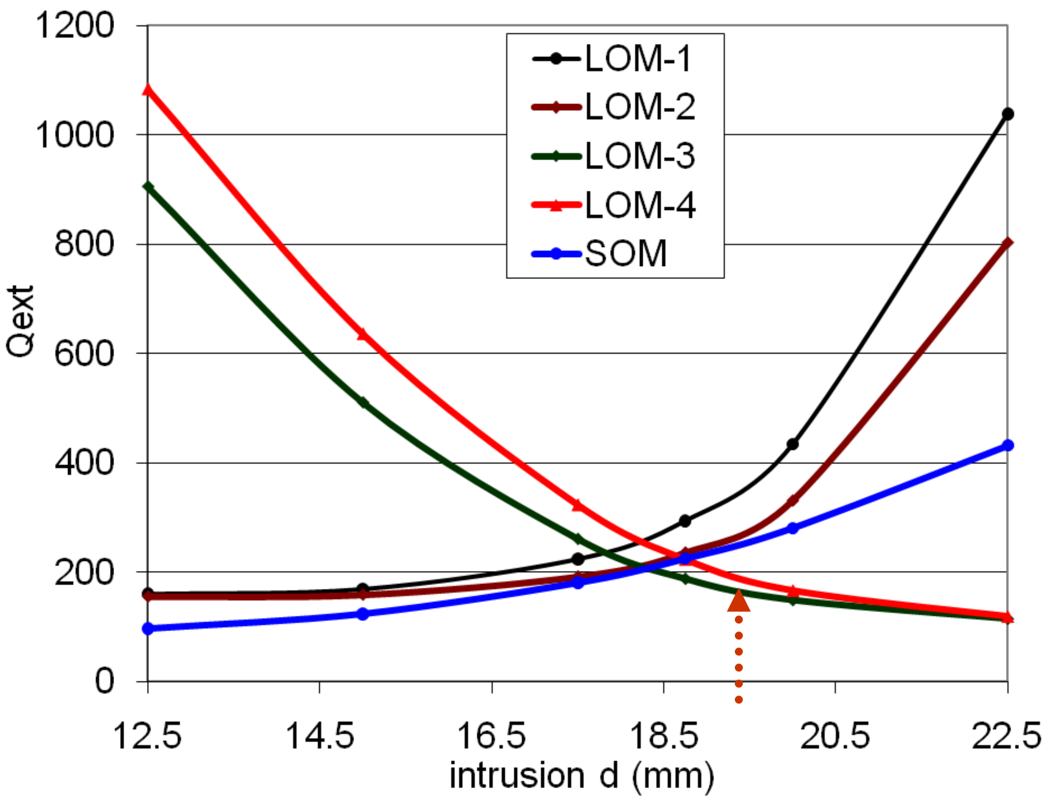
LOM/SOM Coax-to-Coax Coupler Design

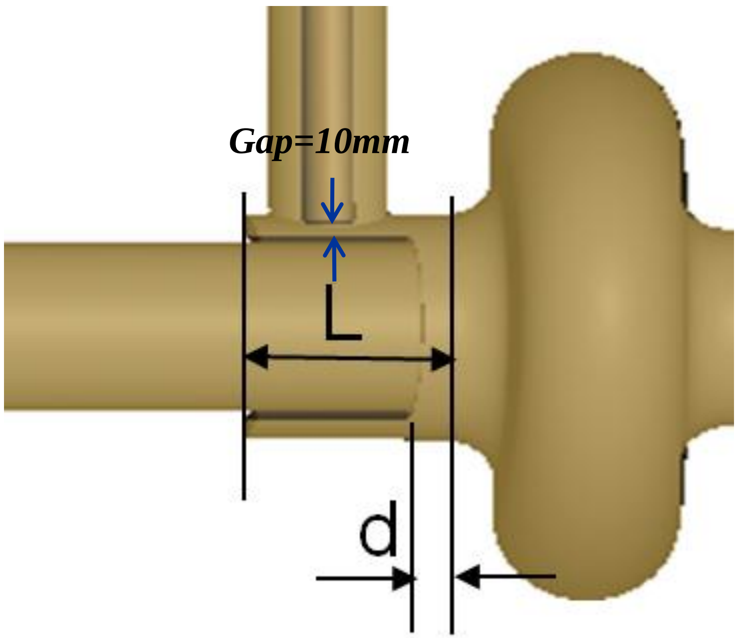




- Compact structure that can provide strong damping to unwanted modes
- Use the electric node in the vertical plane to reject operating mode. No filter needed. Can handle potential large beamloading power

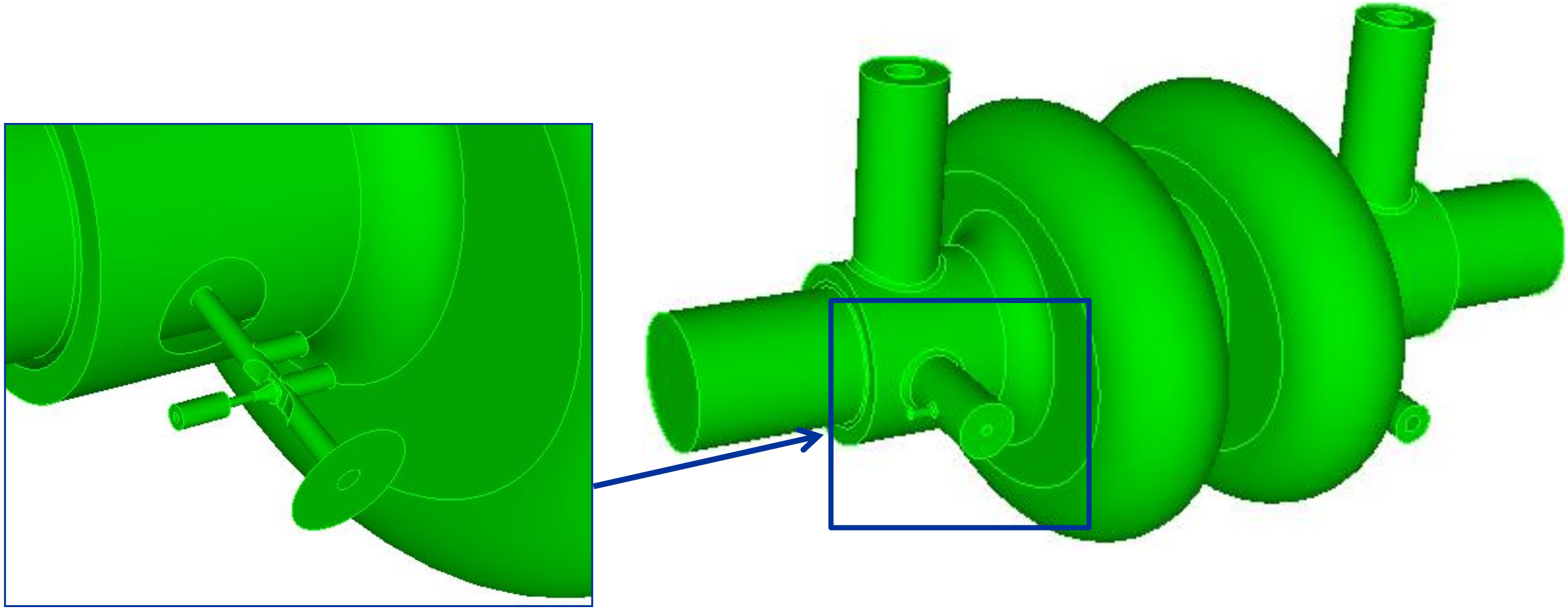
LOM/SOM Optimization





- There are two additional LOM modes due to the coupling of the cavity modes to the shorted coaxial beampipe TEM modes.
- Using a smaller gap can further improve the LOM an SOM damping.

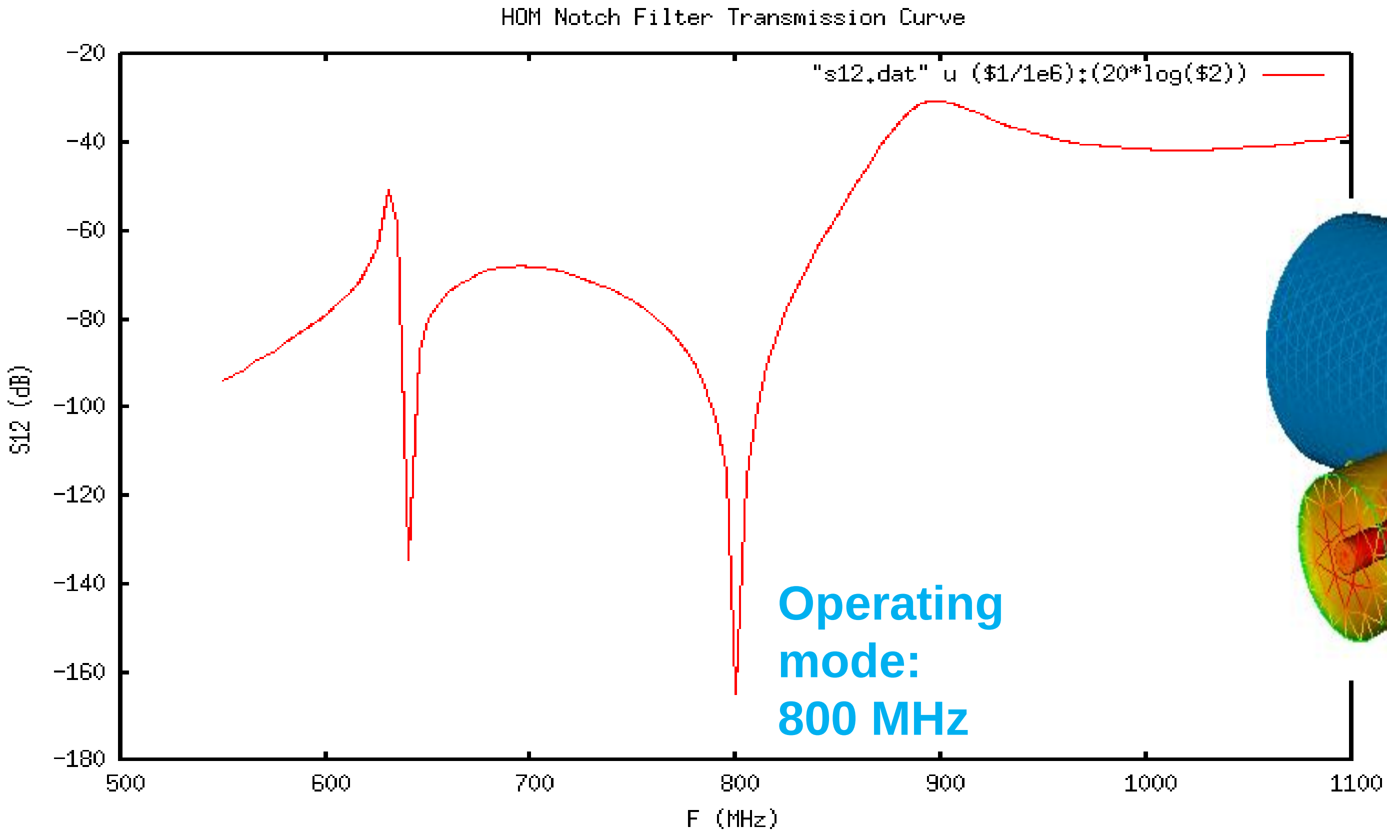
HOM Coupler Design

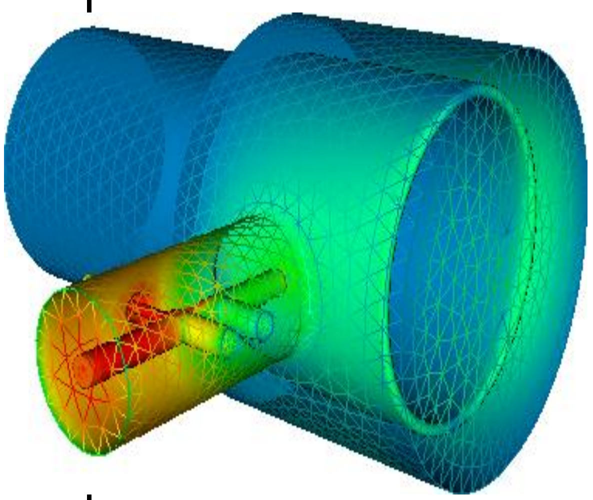


- Damp horizontal plane dipole modes
- Two-stub antenna geometry
- With notch filter to reject the operating TM110 mode at 800MHz.

HOM filter Transmission Curve

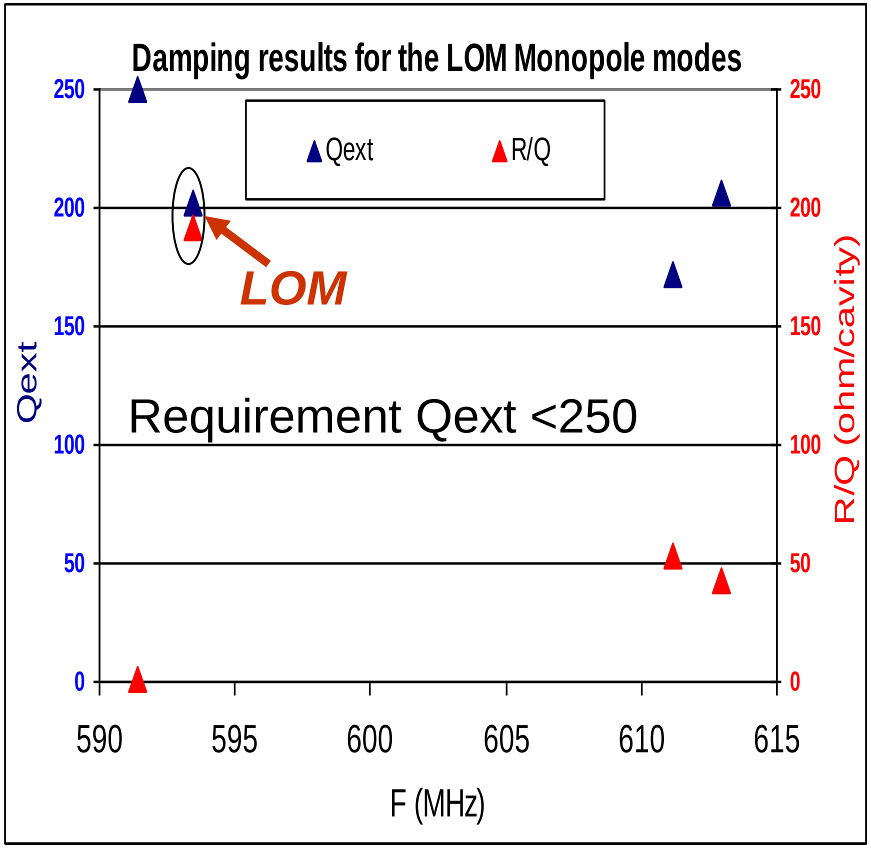
- **Notch filter sensitivity: 0.2MHz/micron**
- As a comparison: TESLA cavity HOM Filter @1.3GHz : 0.1MHz/micron



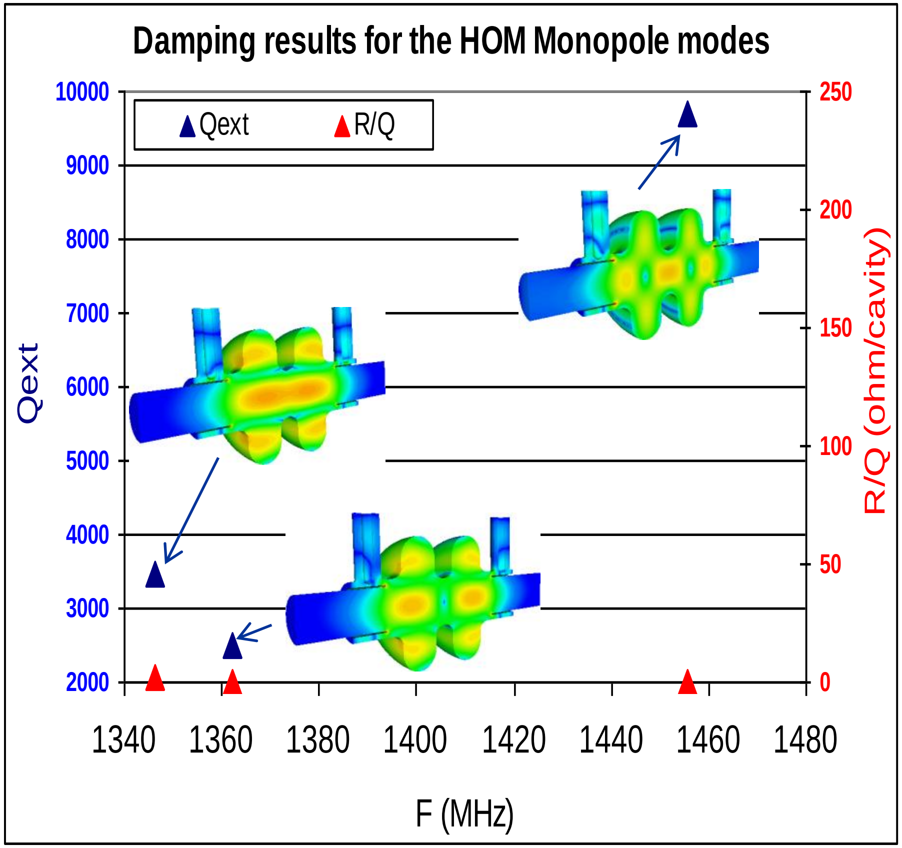


Damping Results: Monopole Mode

LOM Monopole Modes

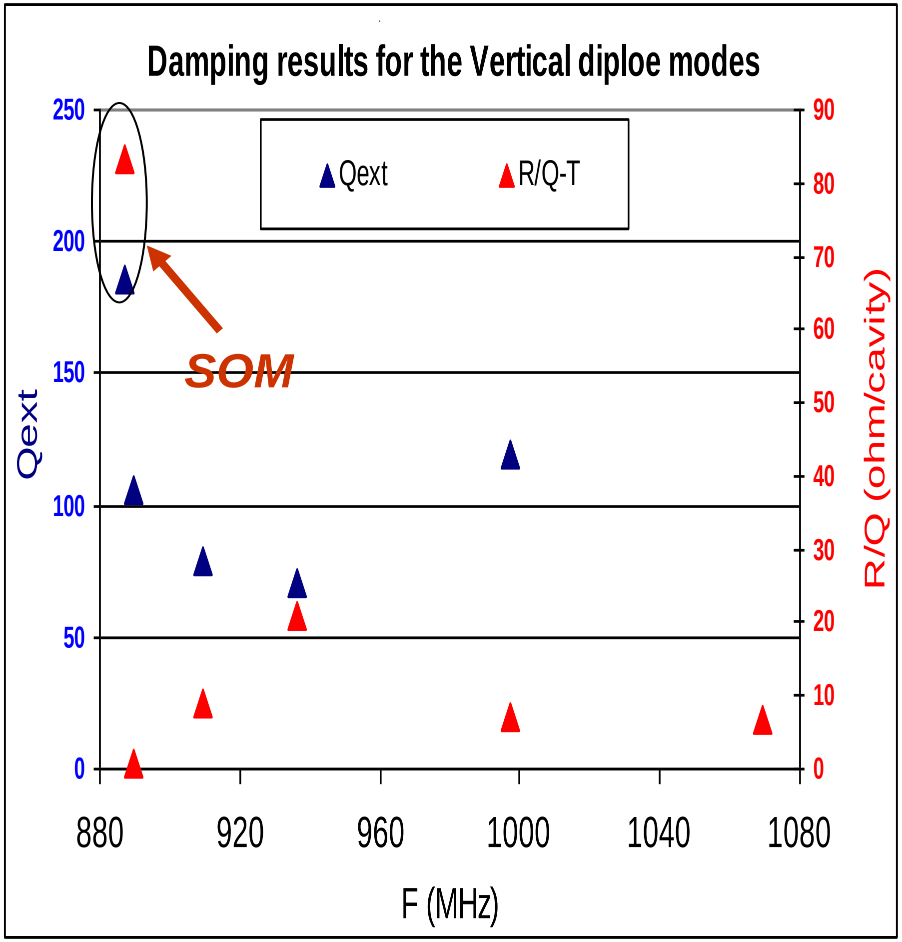


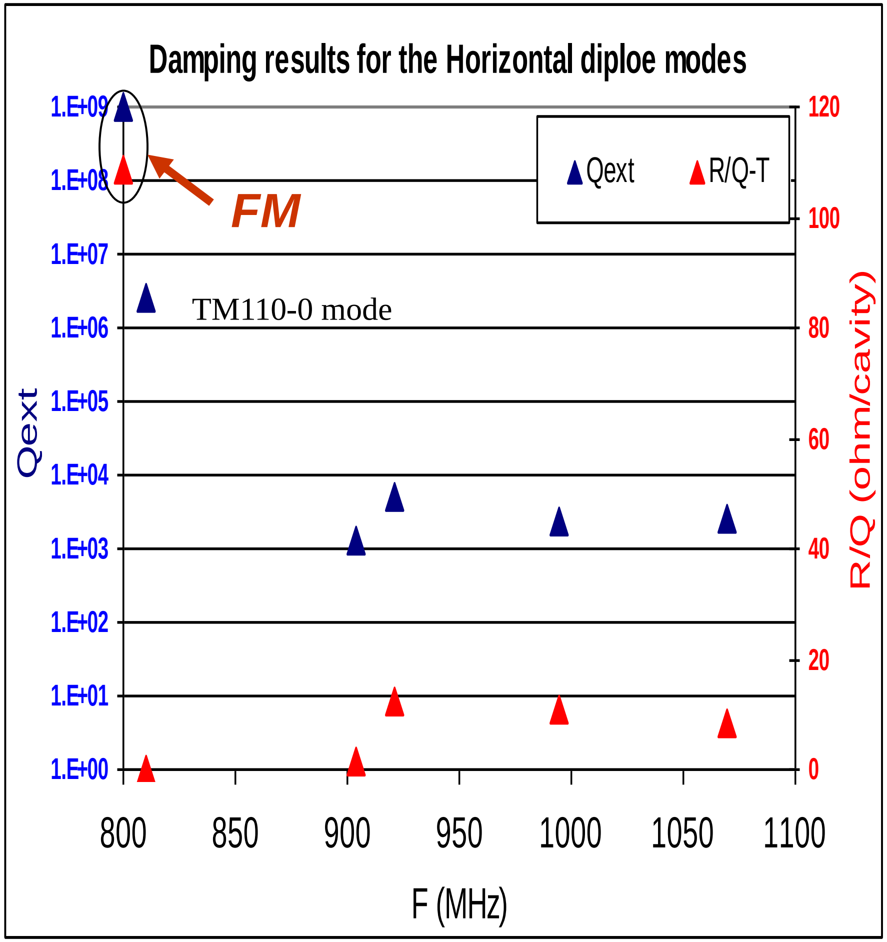
Higher-order Monopole Modes



(Fc=1.466GHz)

Damping Results: Dipole Mode





TM110-0mode damped by FPC

R/Q and Qext of HOM, LOM, SOM

Damping up to 1.5GHz

Monopole		
f	R/Q	Qext
5.91E+08	1.10	250
5.93E+08	191.20	202
6.11E+08	53.10	172
6.13E+08	42.40	206
1.35E+09	2.30	3464.16
1.36E+09	0.40	2491.76
1.46E+09	0.00	9705

Horizontal DIpole		
f	R/Q_T	Qext
8.00E+08	**117.00**	**1.00E+06**
8.10E+08	0.03	1.00E+06
9.04E+08	1.30	1332.8
9.21E+08	12.40	5181.53
9.95E+08	10.70	2431.54
1.07E+09	8.50	2555.57

Vertical Dipole (SOM)		
f	R/Q_T	Qext
8.87E+08	83.40	185
8.90E+08	0.64	106
9.09E+08	9.10	79
9.36E+08	20.99	71
9.97E+08	7.10	119
1.07E+09	6.90	322

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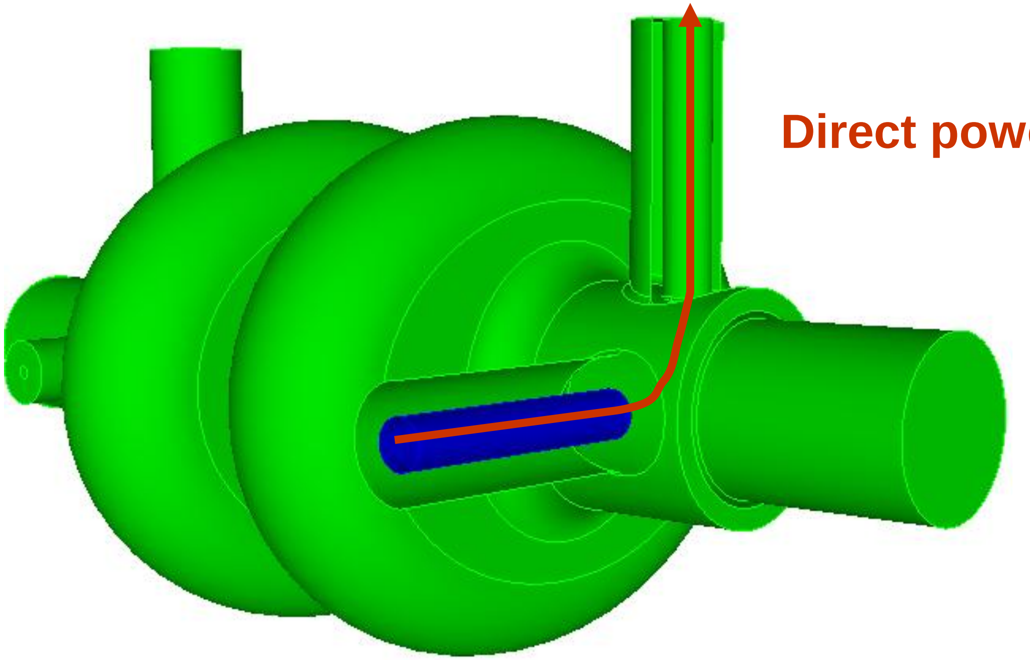
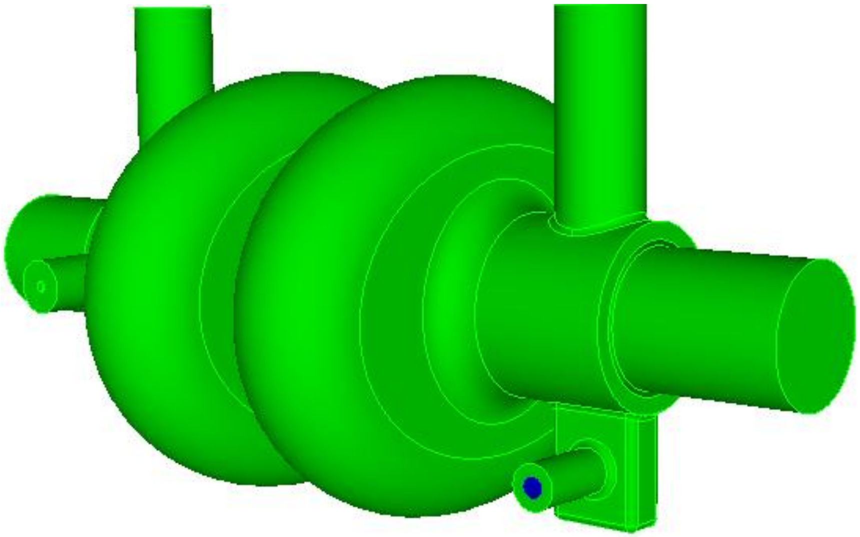
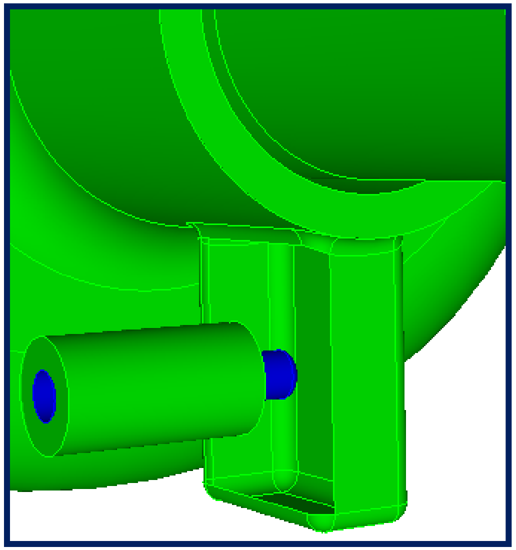
Original FPC With Electric Coupling



- FPC – coax coupler electrically couples to operating mode
- Found significant coupling to the LOM/SOM coupler – large power leakage
- Need a different design to eliminate coupling

Input Coupler With Magnetic coupling

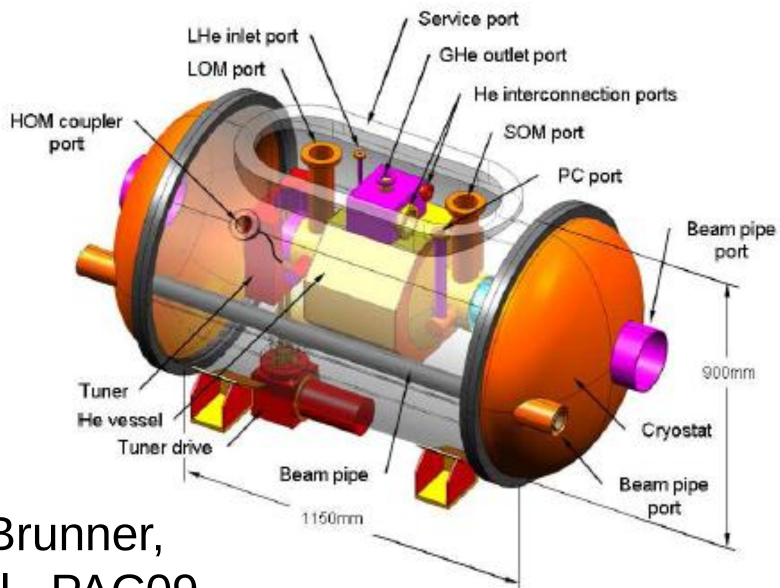




- Coax coupler with a waveguide stub in the vertical plane to establish magnetic coupling
  - Electric node at the LOM/SOM coupler preserved
  - Eliminates FPC to LOM/SOM coupling
- Coupling sensitive to position of coax tip (can achieve Qext as low as 10^4 if needed, e.g. in case of cavity is off)

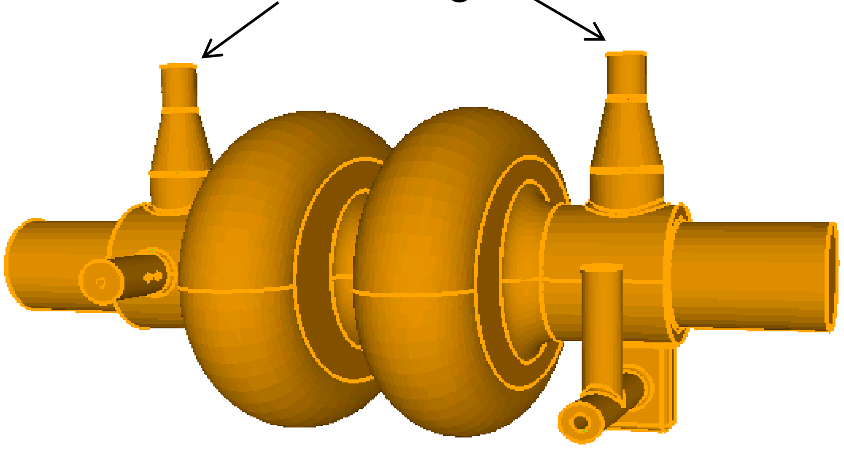
Integration Into Cryostat

- LOM/SOM coupler tapered to smaller radius to minimize static heating – (no effects on damping)
- Elbow to turn FPC to vertical direction, (cryostat can only have ports on top)

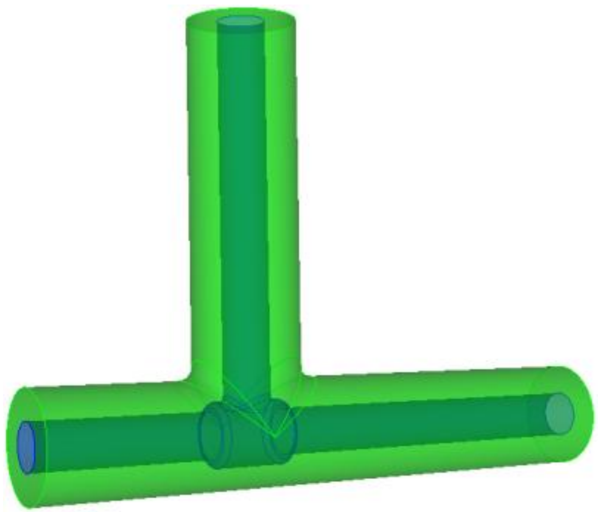


O. Brunner, et al., PAC09

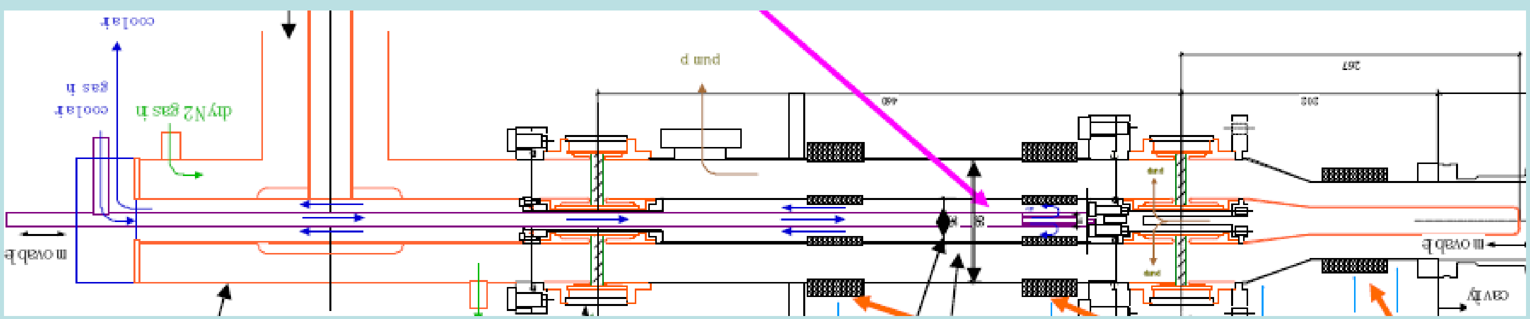
Smaller size to minimize static heating



The FPC Elbow



- To turn FPC to upright orientation
- Tristan Used similar design



Tristan Coupler

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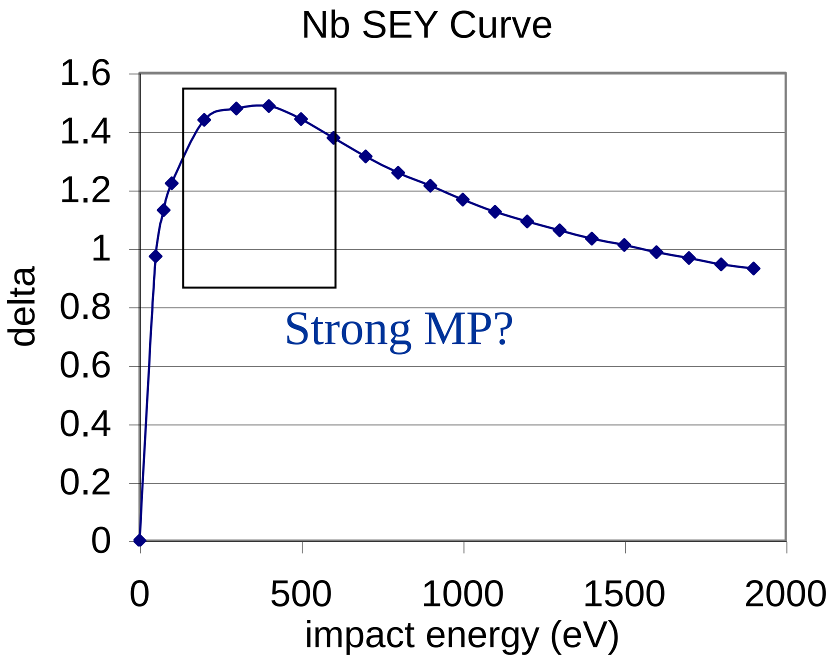
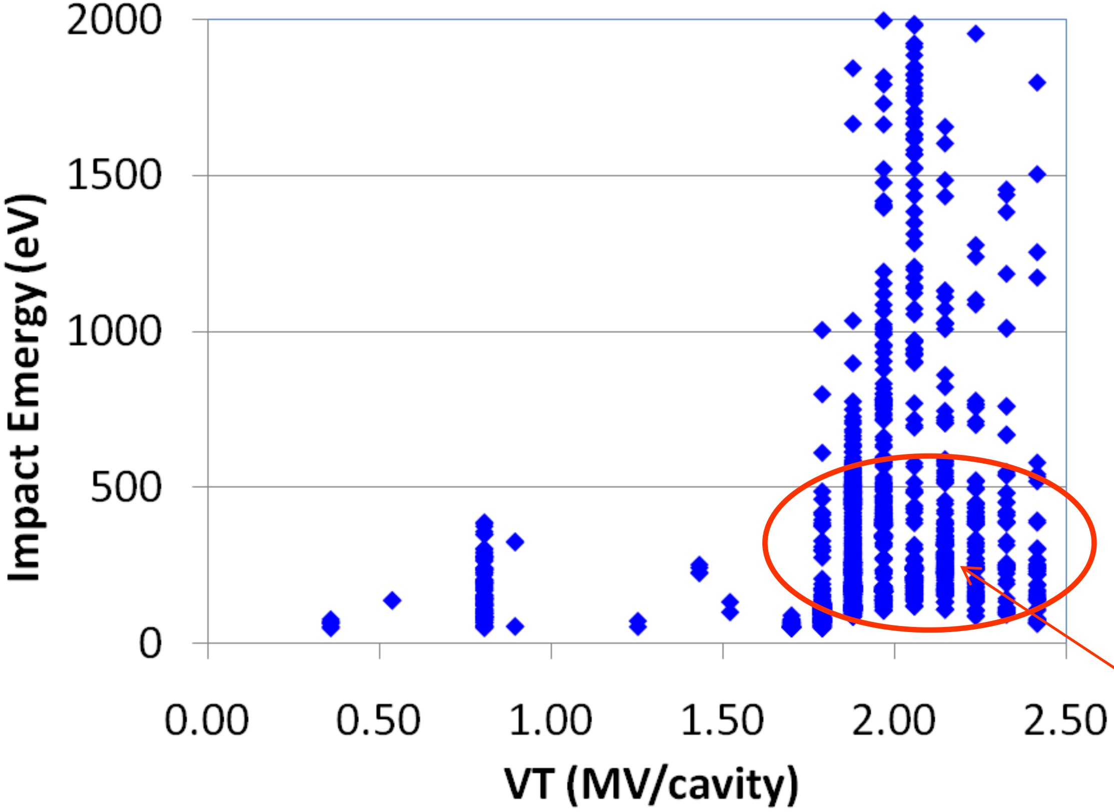
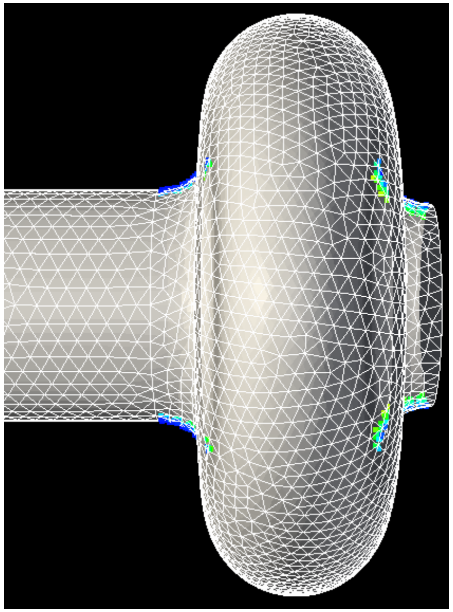
Multipacting

- Scan surface and field level
- Search for resonant trajectories
- Impact energy indicates MP strength (by SEY)
  - Remove potential hard MP barriers



Multipacting Around Disk Iris

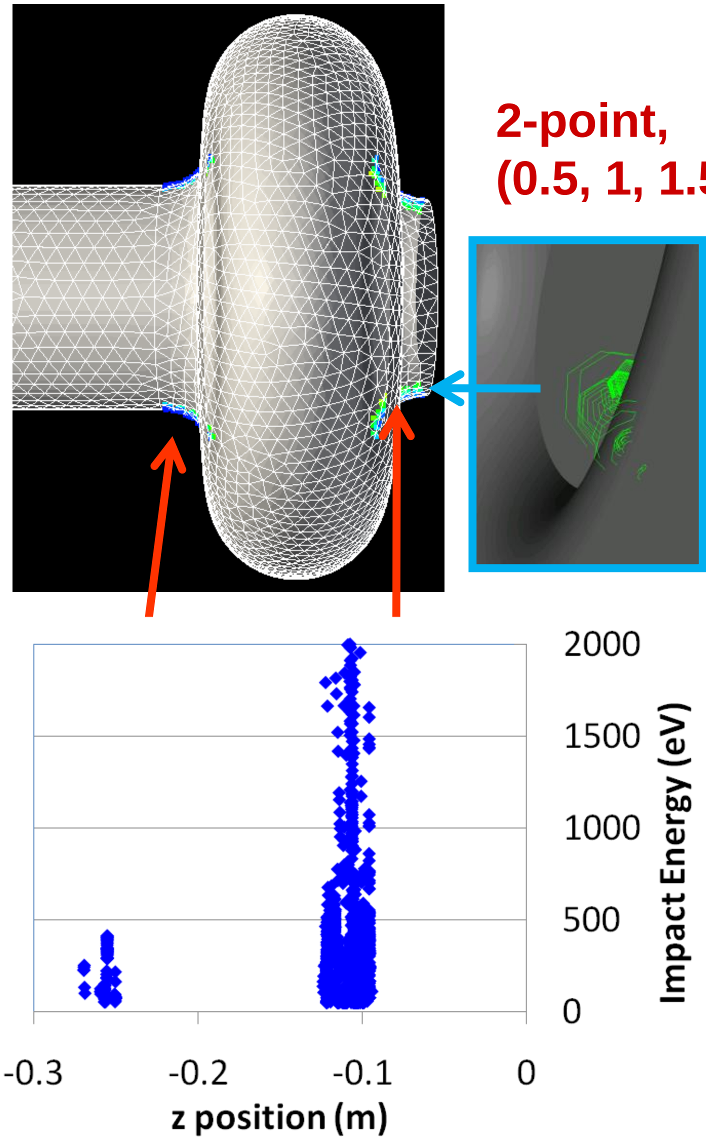


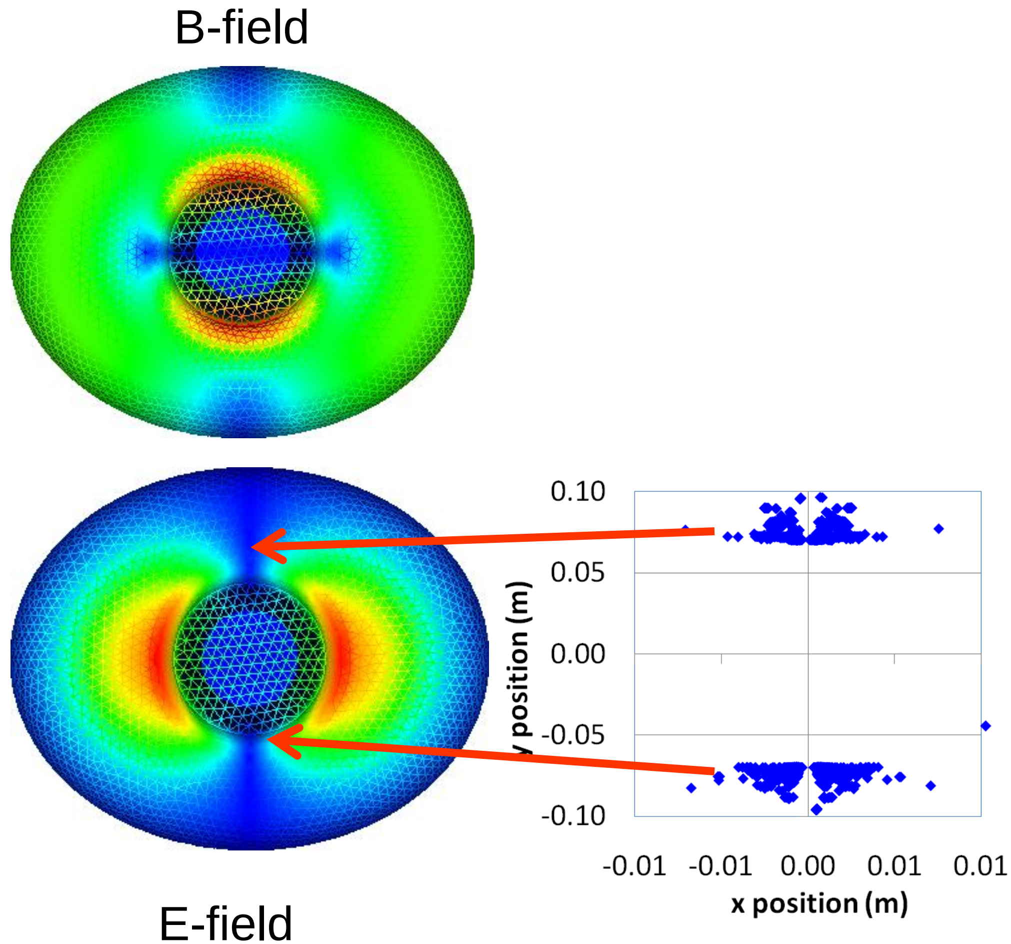


MP band around operating voltage

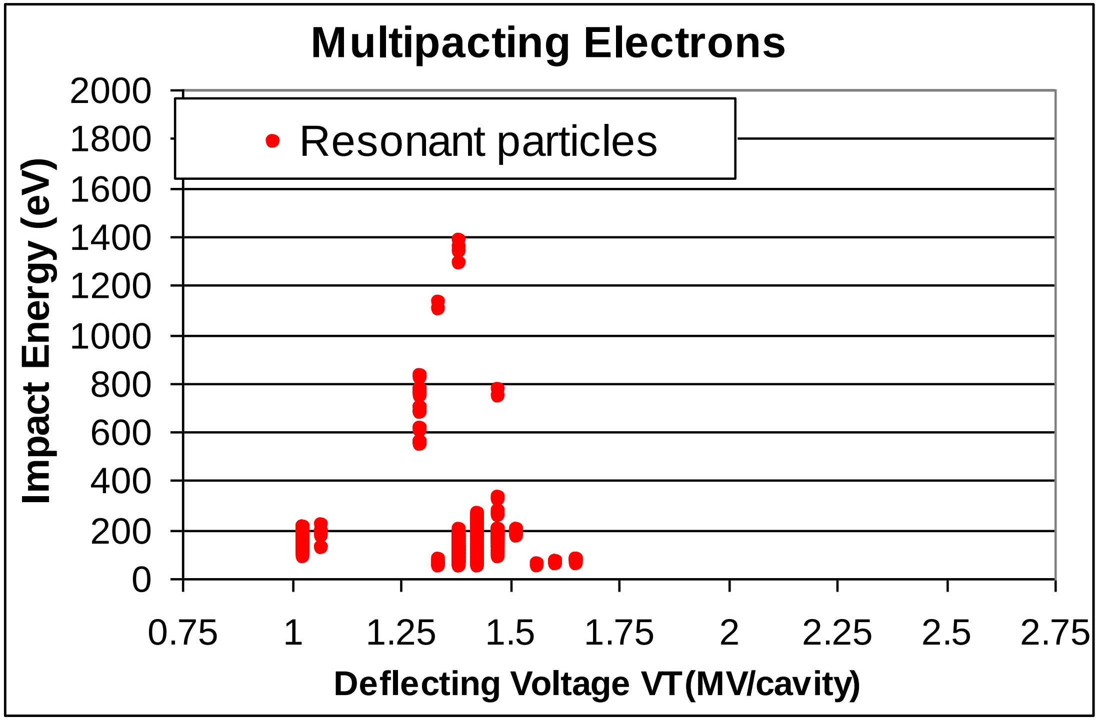
MP at the similar location found in KEKB 509MHz crab cavity, it was processed through.

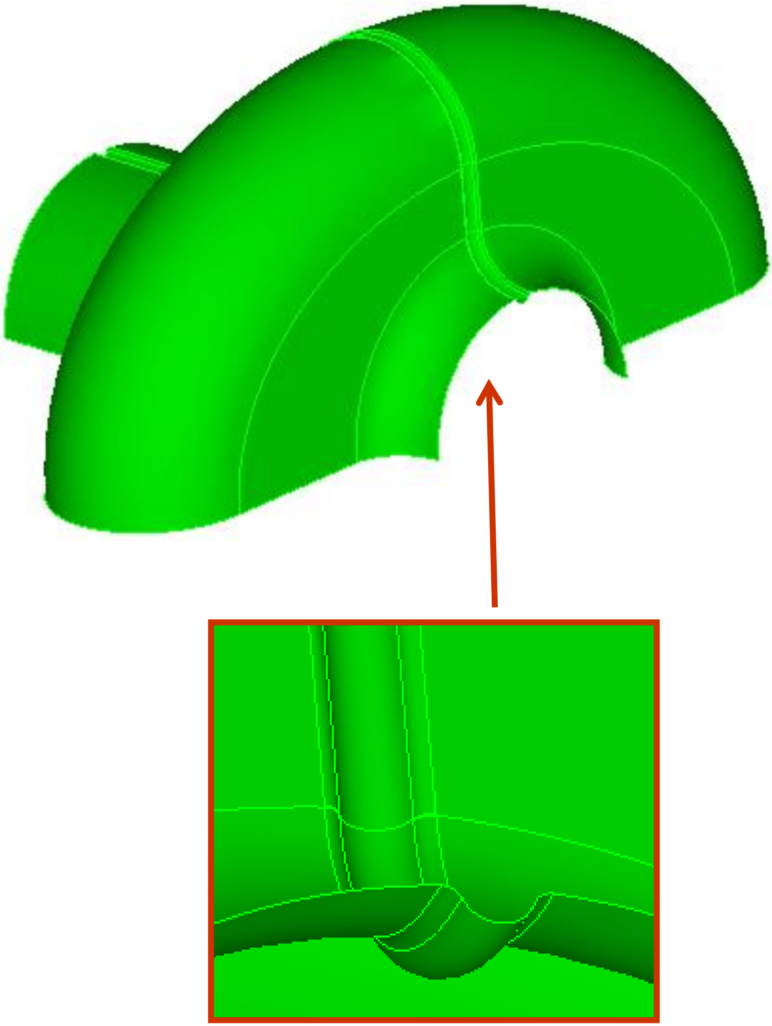
MP location and impact energy





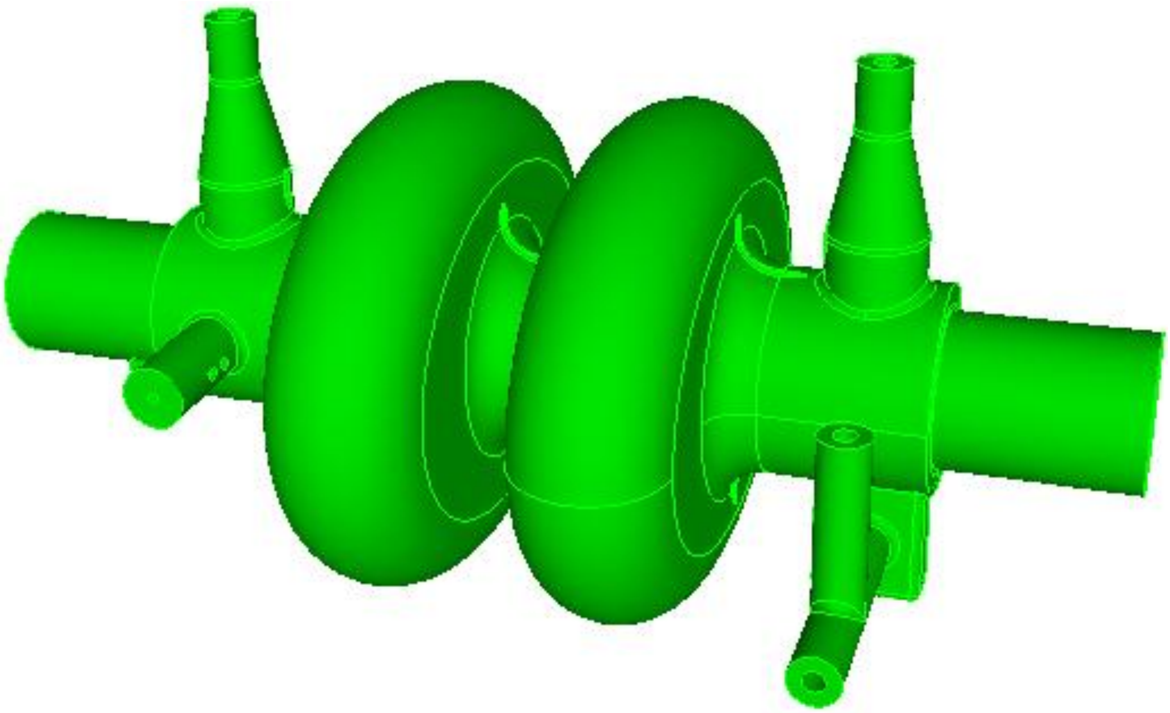
Groove On Disk To Suppress MP

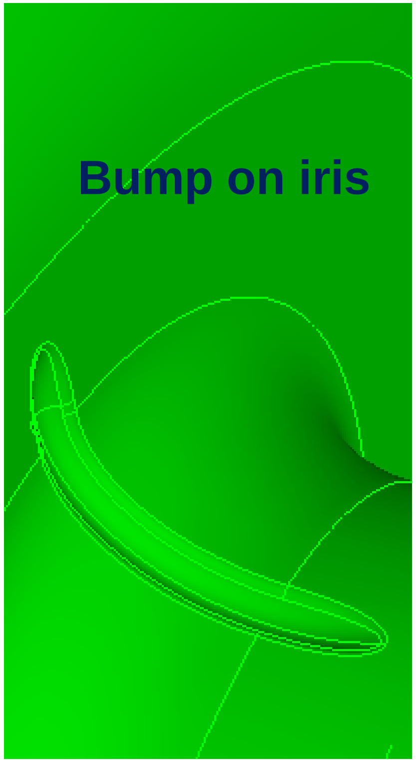




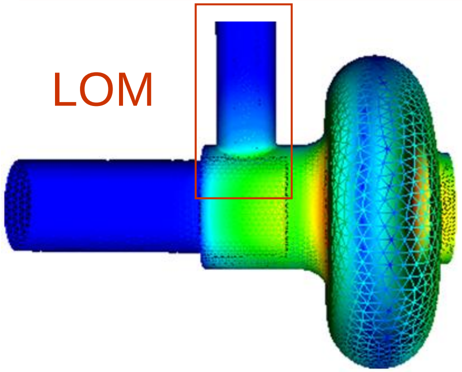
Adding groove along the vertical symmetry plane can suppress MP , with little effects on operating mode RF parameters.

- MP bump only around the disk iris, if more practical in engineering

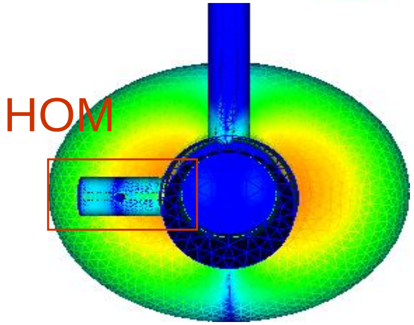




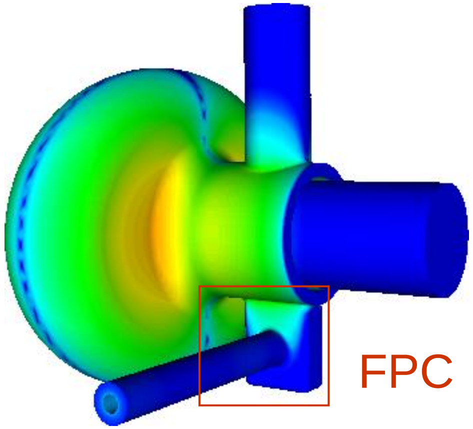
MP in the LOM/HOM/FPC Coupler



With fully rounded tip of LOM center conductor, No MP found



Found MP in HOM notch filter gap within Vt=1.5MV ~2MV., which can be suppressed by modifying the tip of probe



Found resonant trajectories with low Impact Energy (<130 eV.)
Not likely a big problem

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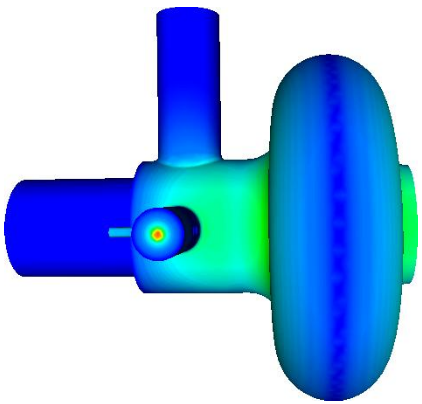
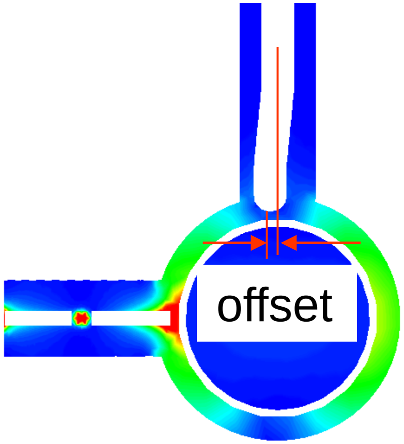
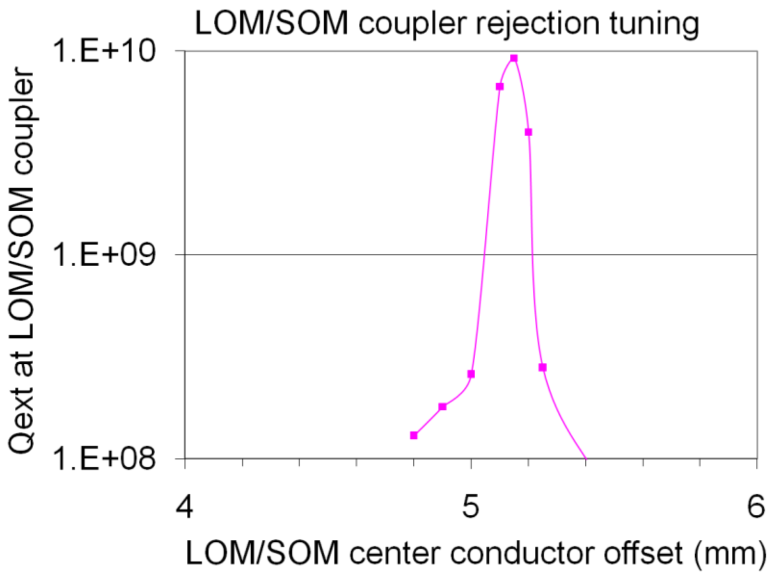
FM Rejection Of LOM/SOM Coupler

- **HOM coupler cause slight shift of electric node off the vertical plane**
- **The center conductor LOM/SOM coupler need to be slightly off the symmetry plane in order to preserve rejection to the operating mode**
  - **attached a adjustable tip (bent)**

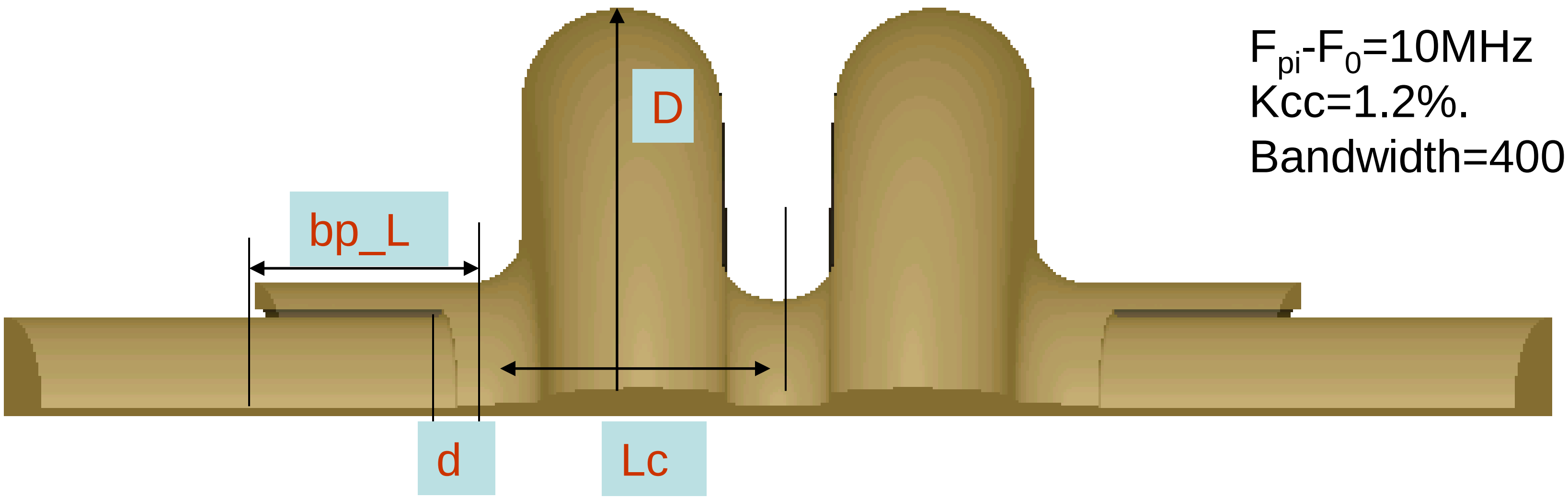






Curve width also indicates coupling sensitivity to position

Cavity Dimension Tolerance

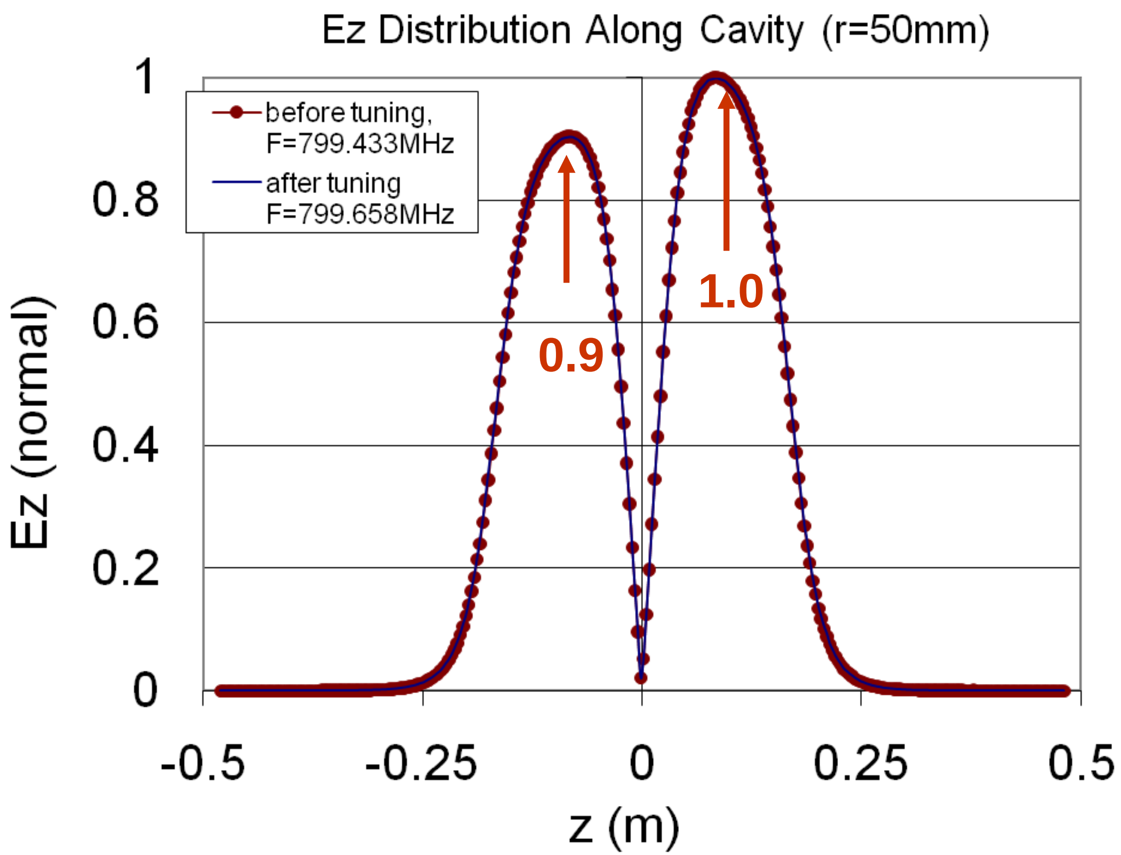


F_{pi}-F_0=10MHz
Kcc=1.2%.
Bandwidth=400Hz

parameters	Equator Radius D	Cell Length Lc	Coax tube Length bp_L	Coax tube Intrusion d
Df/d_size/cell	***3.2MHz/mm***	***452KHz/mm***	56KHz/mm	30KHz/mm

Modes damping have reasonable sensitive to these parameters
(see LOM/SOM optimization page)

Field Flatness due to Imperfections



F_{pi}-F_0=10MHz
Kcc=1.2%.
Bandwidth=400Hz

- **1 MHz cell frequency difference can cause about 10%field imbalance.**
- **Cavity impedance changes are negligible due to this imperfection.**
- **This field imbalance does not cause significant change in damping**

- Design Considerations
- Shape and frequency considerations
- 800-MHz elliptical cell optimization
- LOM, SOM, HOM damping coupler design
- Input power coupler design
- Multipacting analysis
- Tolerance Studies
- Beamloading and power requirement
- Summary

Beam Power Due to Unwanted Modes

- Assuming beam on resonance of all modes
- I_0=0.582 A
- σ_z=0.0755 m

$$P_{beam,mono,n} = I_0^2 e^{-\frac{\omega_n^2 \sigma_z^2}{c^2}} \left(\frac{R}{Q}\right)_{L,n} Q_{Loaded,n}$$

$$P_{beam,dip,n}(r_b) = I_0^2 e^{-\frac{\omega_n^2 \sigma_z^2}{c^2}} \left(\frac{R}{Q}\right)_{T,n} Q_{Loaded,n} \left(\frac{\omega}{c} r_b\right)^2$$

Beam Power (on resonance)

I=0.582A sigmaz=0.0755

MONO	f	Qext	R/Q	R	R*I*I(w)*G*G
	5.91E+08	250	1.10	2.75E+02	3.89E+01
	5.93E+08	202	191.20	3.86E+04	5.43E+03
	6.11E+08	172	53.10	9.13E+03	1.22E+03
	6.13E+08	206	42.40	8.73E+03	1.16E+03
	1.35E+09	3464.16	2.30	7.97E+03	2.92E+01
	1.36E+09	2491.76	0.40	9.96E+02	3.26E+00
	1.46E+09	9705	0.00	1.90E+01	3.22E-02
Total Mono Power (W)					7.87E+03

vertical dip	f	Qext	R/Q_T	R at 0.001m	
	8.871E+08	185	83.40	5.334	2.53E-01
	8.896E+08	106	0.64	0.024	1.10E-03
	9.092E+08	79	9.10	0.260	1.12E-02
	9.362E+08	71	20.99	0.571	2.16E-02
	9.971E+08	119	7.10	0.369	1.04E-02
	1.070E+09	322	6.90	1.115	2.16E-02
Total V-dip Power (w) at 1mm					3.19E-01

horizontal dip	f	Qext	R/Q_T	R at 0.001m	
	8.00E+08	**1.00E+06**	**117.00**	**3.28E+04**	**2.15E+03**
	8.10E+08	1.00E+06	0.03	8.63E+00	5.66E-01
	9.04E+08	1332.8	1.30	6.20E-01	2.72E-02
	9.21E+08	5181.53	12.40	2.39E+01	9.70E-01
	9.95E+08	2431.54	10.70	1.13E+01	3.22E-01
	1.07E+09	2555.57	8.50	1.09E+01	2.11E-01
Total H-HOM power (w) at 1mm					2.10E+00

Dipole Mode Beamloading

- Dipole mode beamloading $V_{T,b}$

$$\left(\frac{R}{Q}\right)_T = \frac{\left|V_z(r_0)\right|^2}{\omega U\left(\frac{\omega}{c}r_0\right)^2}$$

$$V_{L,b}(r) = I(\omega)\left(\frac{R}{Q}\right)_T Q_L\left(\frac{\omega}{c}r_b\right)^2$$

$$V_{T,b} = I(\omega)\left(\frac{R}{Q}\right)_T Q_L\left(\frac{\omega}{c}r_b\right)$$

f	Qext	R/Q_T	Vt_b (1mm) (V)
8.00E+08	1.0E+06	117.00	5.02E+05

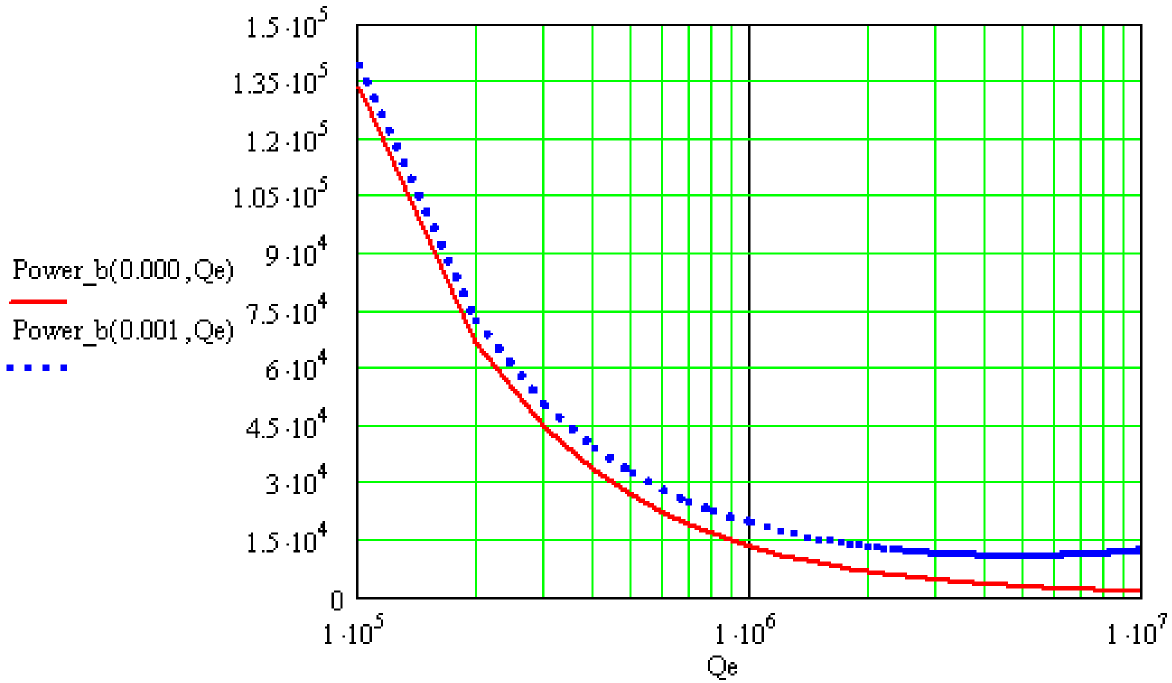
Input Power Requirement

$$V_T = 2\left(P_{in}\left(\frac{R_T}{Q}\right)\frac{\beta}{1+\beta}Q_L\right)^{1/2}$$

$$V_{T,b} = I(\omega)\left(\frac{R}{Q}\right)_T Q_L\left(\frac{\omega}{c}r_b\right) \qquad \text{(beam)}$$

$$P_{in,MAX} = \frac{\left(V_T + V_{T,b}\right)^2}{4\left(\frac{R_T}{Q}\right)\frac{\beta}{1+\beta}Q_L}$$

- V_T=2.5 MV/cavity
- (R_T/Q)=117 Ω/cavity
- QL ≅ Qext = 10^6
- P_{in} (r=0) = 13.4 kW/cavity



Summary

- 800-MHz, 2-cell elliptical shape was chosen as baseline design at LARP-CM11
- Detailed cavity design and optimization performed, progresses are being made to integrate into the cryostat design
  - Optimized shape to minimized the surface E and B fields
  - Optimized LOM/SOM, HOM and FM couplers to meet damping and power requirements
  - Performed MP analyses
    Identified potential hard MP barriers
    Geometry fixed to removed such barriers
  - Studied cavity dimension sensitivity and tolerances
  - Progress being made (with FNAL) towards a engineering design) – the cryostat integration (FNAL)