400MHz Half-Wave Resonator Crab Cavity For LHC Upgrade

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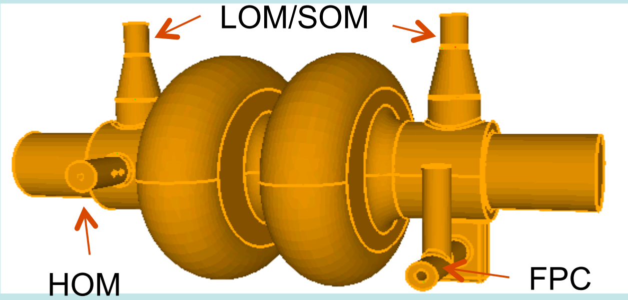
LARP

Outline

- SLAC Crab cavity studies prior to LHC-CC09
- New design considerations
- Compact half-wave spoke resonator (HWSR) crab cavity
  - Cavity RF parameters
  - LOM, HOM-v damping couplers
  - HOM-h damping coupler
  - FP coupler
  - Multipacting analysis
- Summary

SLAC Crab Cavity Studies Prior to LHC-CC09

800 MHz Elliptical

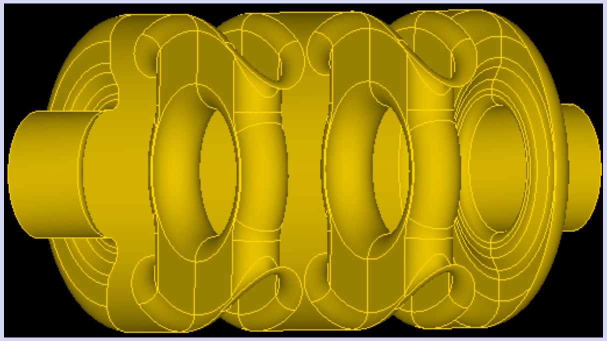


(LARP-CM11 baseline)

Design complete

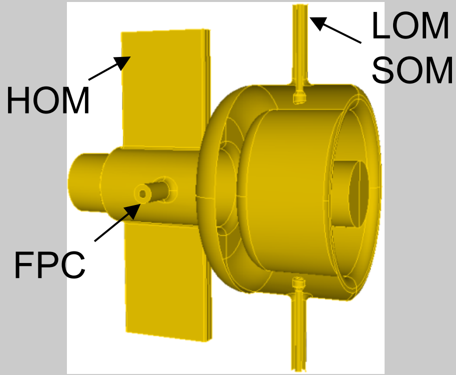
- Cavity shape optimized
- FP, LOM, SOM, HOM couplers designed
- Multipacting analyzed
- Sensitivity and tolerances studied
- Dimension fit global scheme

800 MHz Spoke



- Cavity shape preliminary study performed
- Cavity radius: ~150 mm
- Design could fit both global and local schemes

400MHz-Coaxial



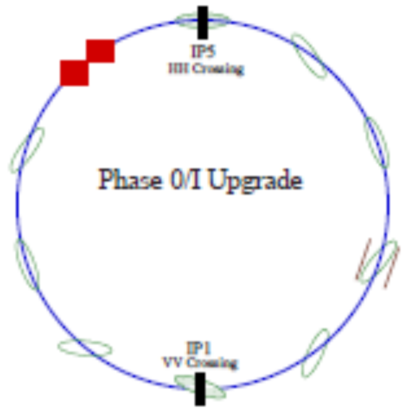
- Cavity shape optimized
- FP, LOM, SOM, HOM couplers designed
- Multipacting analyzed
- Design could fit the global scheme, not the local scheme

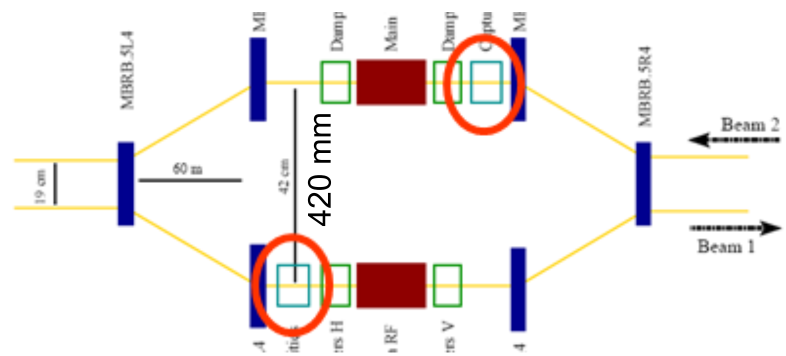
New Design Considerations

- Compact size to fit in tight beam line separation at the crab cavity location
- 400 MHz in frequency
- Effective damping of unwanted modes (LOM & HOMs)
- Minimize potential multipacting

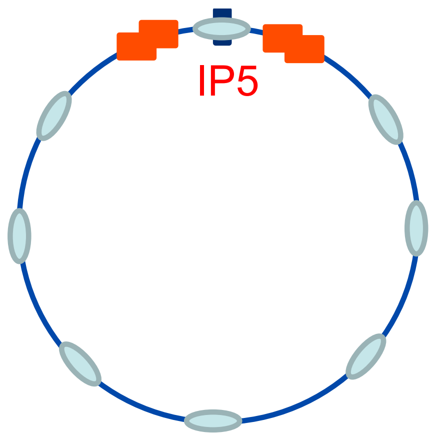
Cavity Size

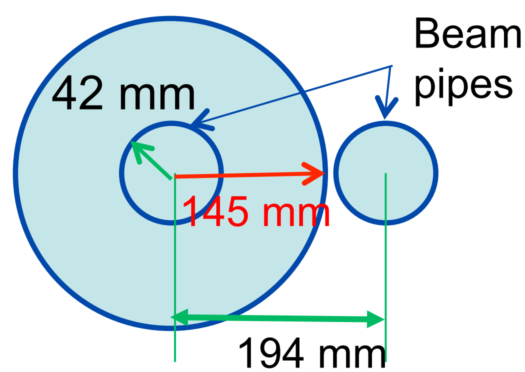
Global Scheme:
Beam-beam
separation: 420mm





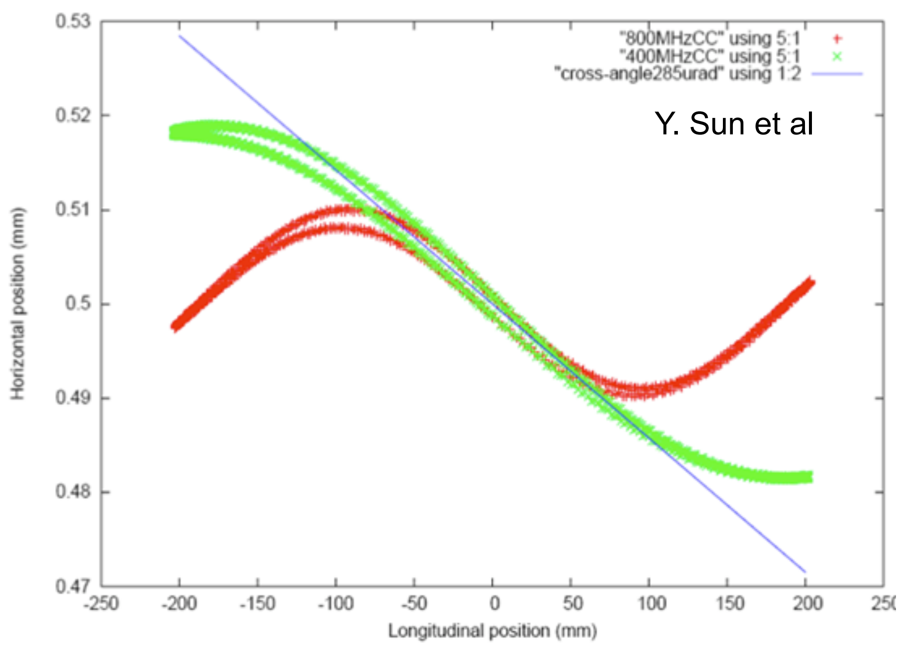
Local Scheme:
Beam-beam
separation: 194mm

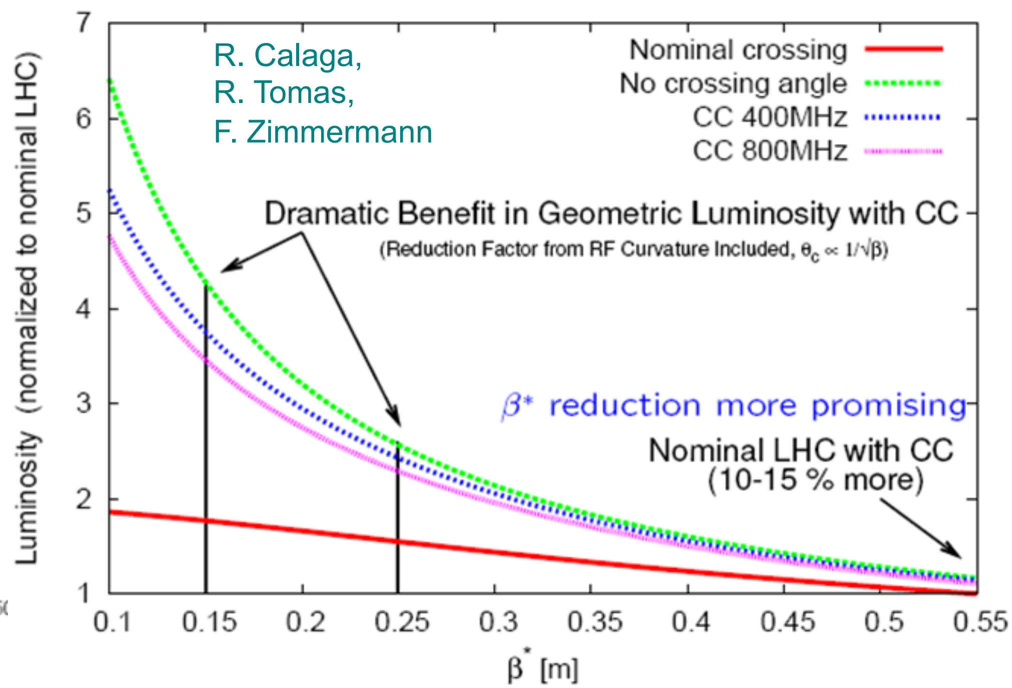




- A single design for both local and global schemes
- **Cavity dimension determined by local scheme (~145 mm)**

Frequency: 800-MHz vs 400-MHz

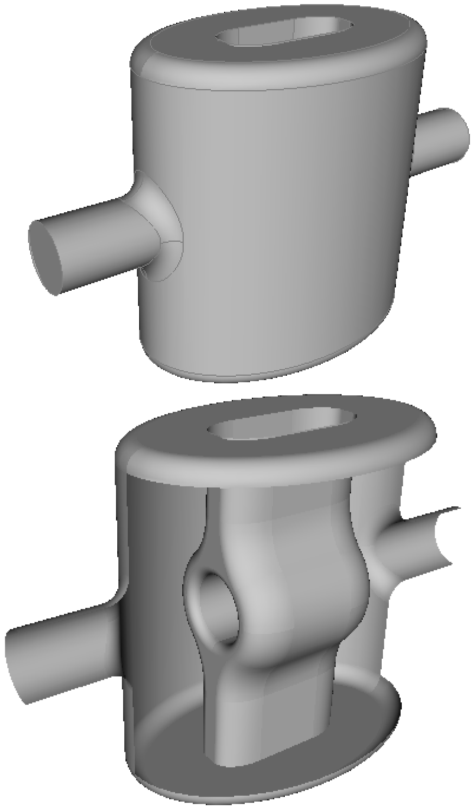


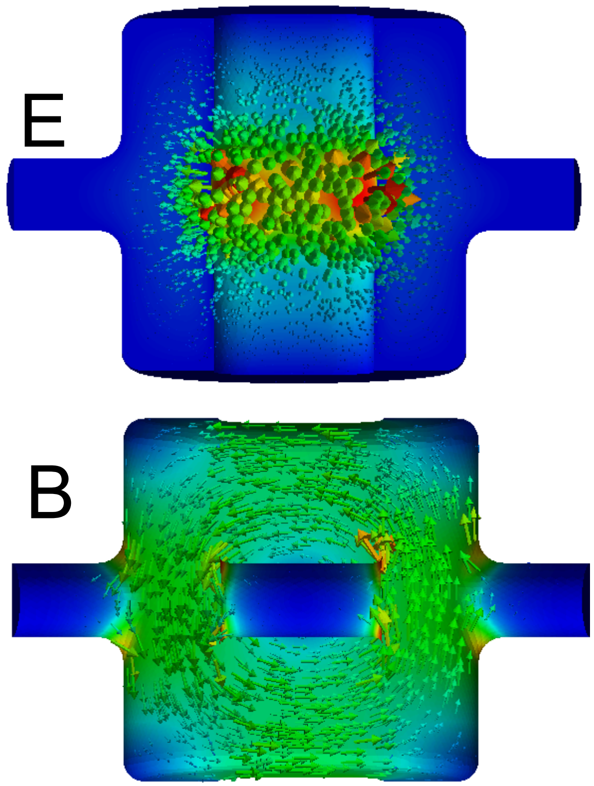


400 MHz is chosen for the present design

Compact 400-MHz HWSR Crab Cavity

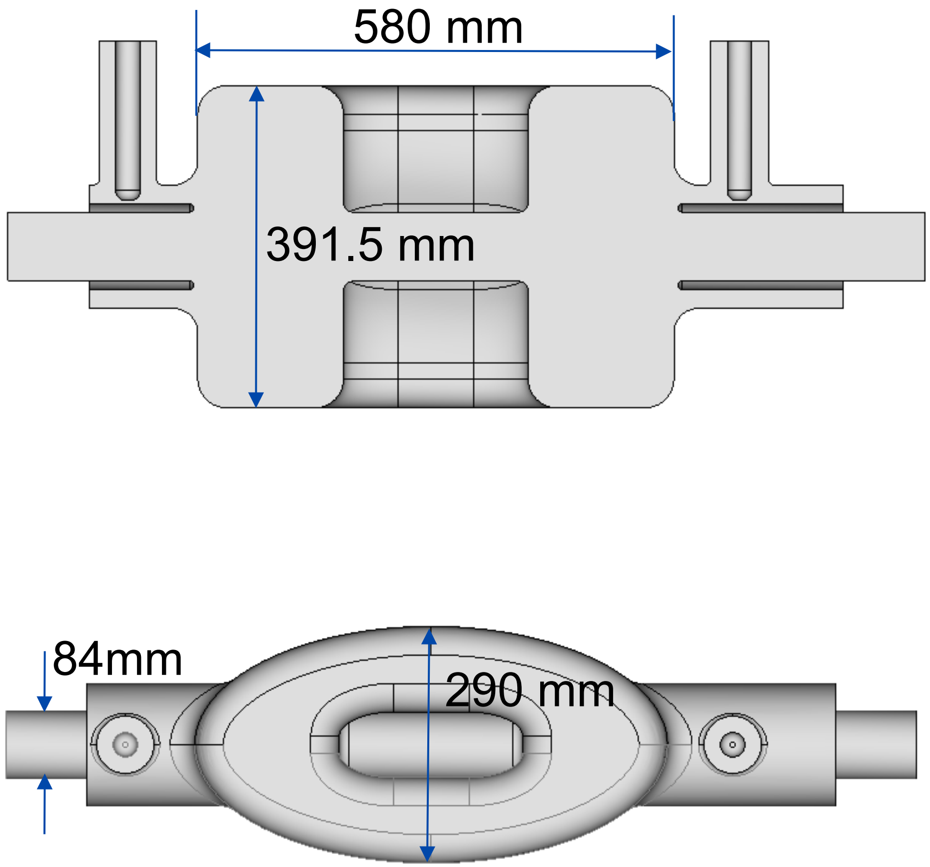
Half-Wave Spoke Resonator (HWSR)





TE11-like mode - Frequency determined by longitudinal and vertical dimensions

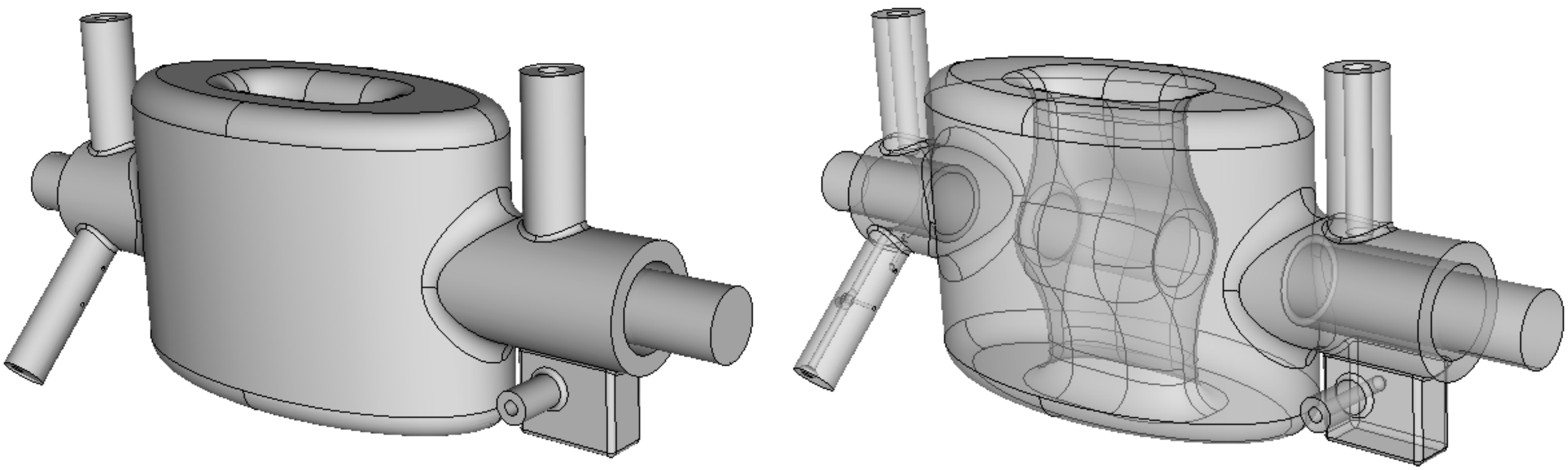
400 MHz HWSR Cavity Parameters



Parameters	
Cavity Width (mm)	**290**
Cavity Height (mm)	391.5
Cavity Length (mm)	580
Beam pipe radius (mm)	**42**
$(R/Q)_T$ (ohm/cavity)	215
E_S/V_T ((MV/m)/MV)	10.4
B_S/V_T (mT/MV)	19.5

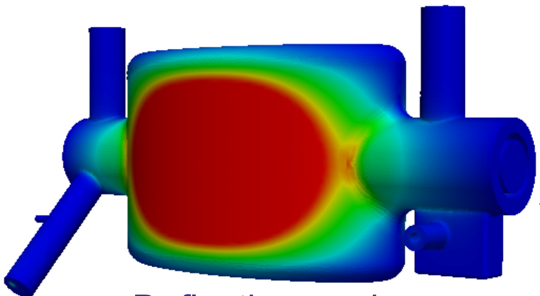
- 8 MV deflecting voltage required
- 2 cavities/beam, 4 MV each

400-MHz HWSR Crab Cavity with Couplers



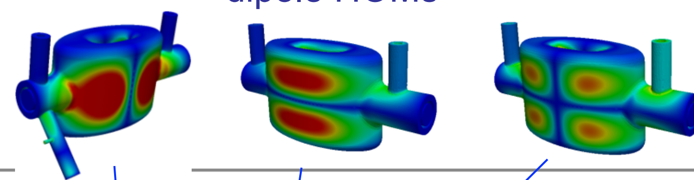
HWSR design fits in both global and local schemes

Shunt Impedance

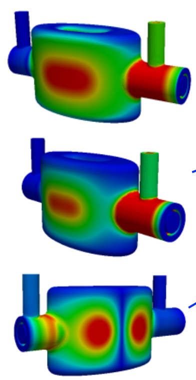


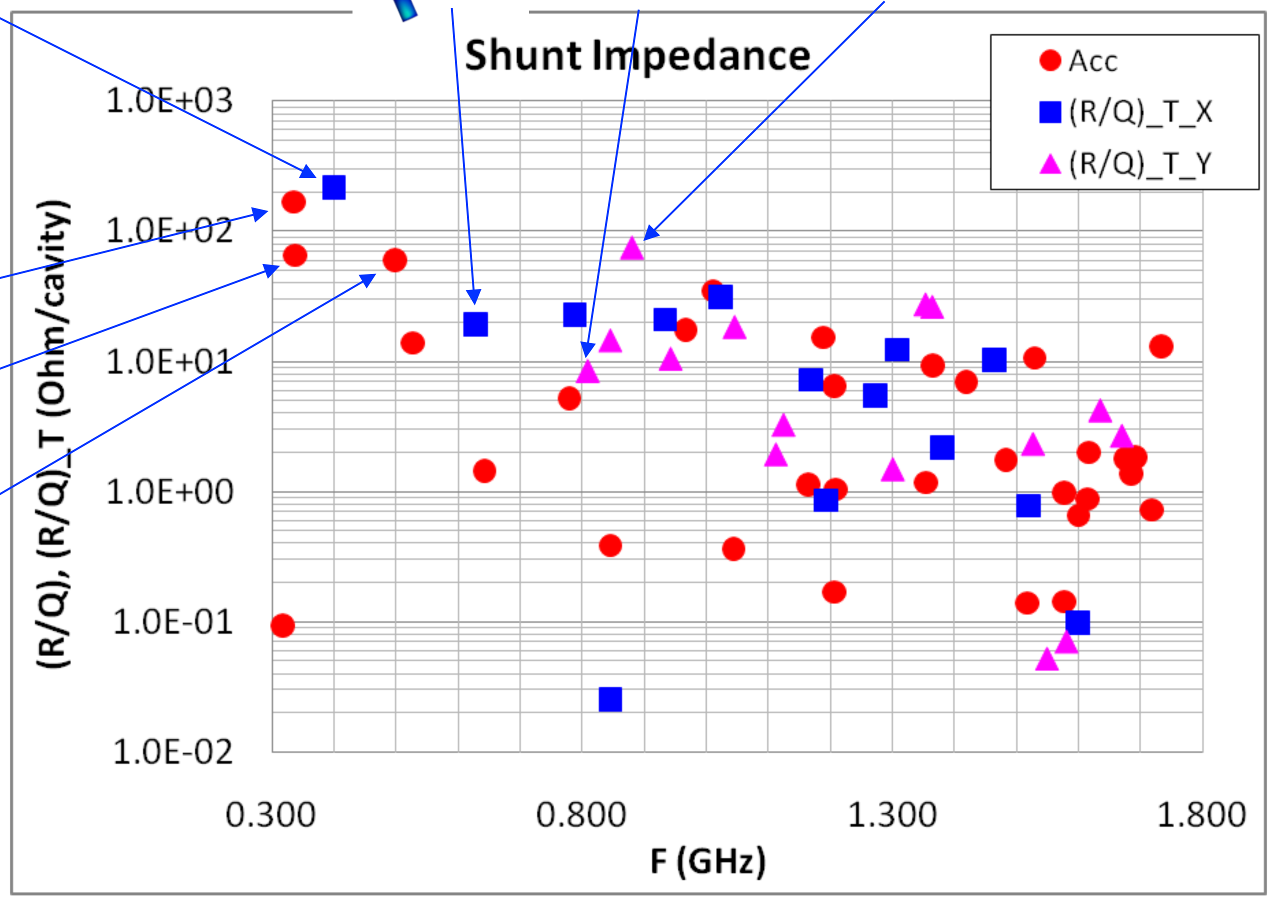
Deflecting mode

dipole HOMs



Acc modes





- No SOM !
- LOM 65 MHz below deflecting mode

Impedance Budget (LHC-CC09)

- Impedance requirement
  - Longitudinal (R): 80 kohm
  - Transverse (Z_T): 2.5 Mohm/m

Longitudinal shunt impedance

$$R_L = \left(\frac{R}{Q}\right) \bullet Q_{ext} = \frac{|V_z|^2}{\omega U} \bullet Q_{ext}$$

Transverse shunt impedance

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

Impedance for beam instability

$$Z_T = \left(\frac{Z_T}{Q}\right) \bullet Q_{ext} = \frac{\omega}{c} R_T$$

E. Shaposhnikova
LHC-CC09

Summary: longitudinal impedance budget

- Requirement for HOM damping in LHC given so far is 60 kOhm (defined by 200 MHz RF at 450 GeV)
- For nominal intensity
  - in 400 MHz RF system we have 80 kOhm for small emittance beam (1 eVs) at 7 TeV, 300 kOhm for 2.5 eVs
  - in 200 MHz RF system it is 70 kOhm , but the 400 MHz RF system can be used as Landau system
- Assumption: no loss of Landau damping due to broad-band impedance (ImZ/n > 0.1 Ohm, budget estimation in LHC DR - 0.07 Ohm), possible for small emittances (<0.7 eVs) at injection into 200 MHz RF system or at 7 TeV in the 400 MHz RF system (< 1 eVs)

➢ 10 kOhm for upgrade intensity and two identical cavities

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E. Shaposhnikova
LHC-CC09

Summary: transverse impedance budget

- Threshold for the nominal intensity and one cavity at 450 GeV determined by the damping time of 60 ms is 2.5 MOhm/m
- With margin for particle distribution:
  - 0.6/(1-f_r) MOhm/m f_r [GHz] < 0.8
  - 1.2(1+2f_r) MOhm/m f_r [GHz] > 0.8
  - 3 MOhm/m at 800 MHz → 0.4 MOhm/m for upgrade intensity and 2 cavities
- Additional factor proportional to local beta-function $\beta/\langle\beta\rangle$

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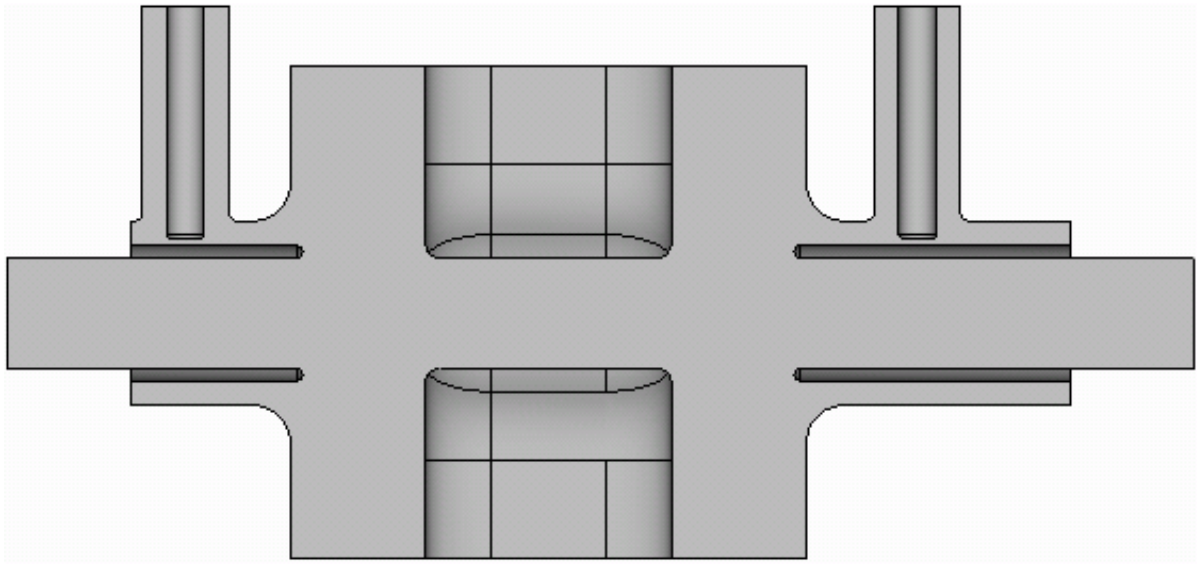
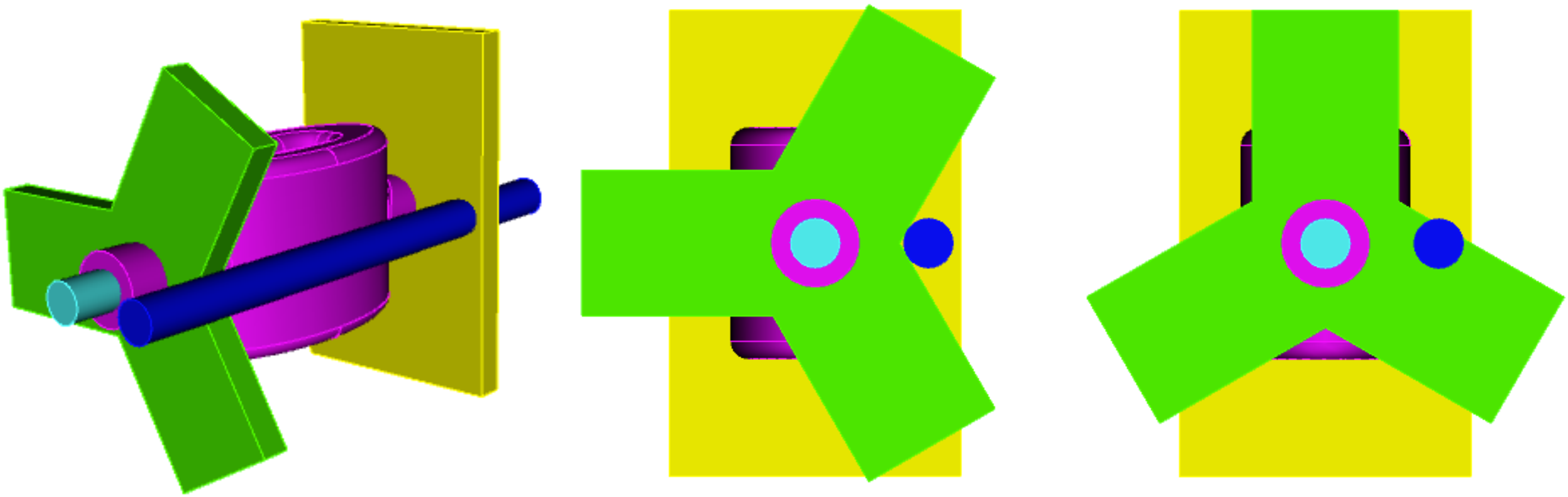
LARP

LOM/HOM-v Couplers

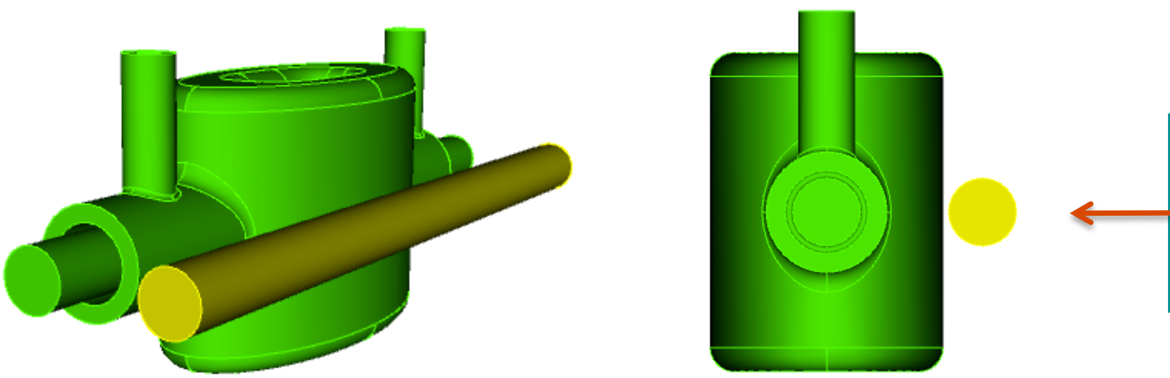


- On beam pipe coax-coax LOM/HOM-v damping couplers
- To damp accelerating modes and vertical HOMs

WG Coupler vs Coaxial Coupler

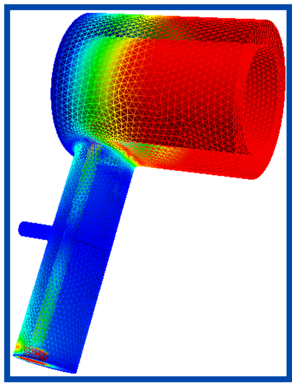


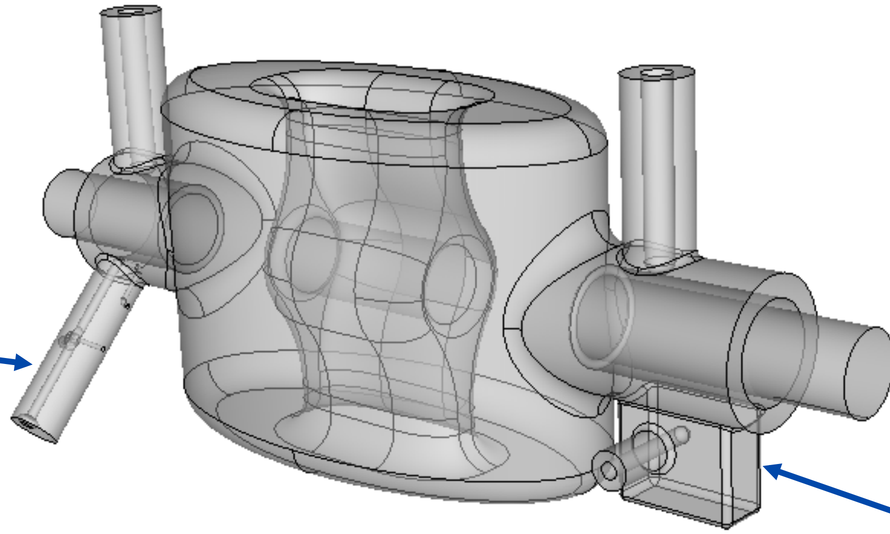
Waveguide couplers become large at low frequencies

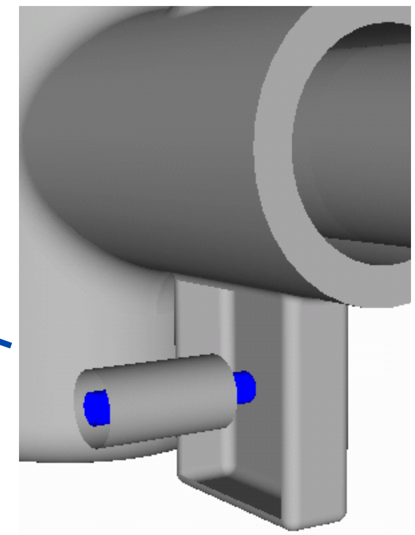


present design
coaxial couplers
compact in size

HOM and FPC Couplers



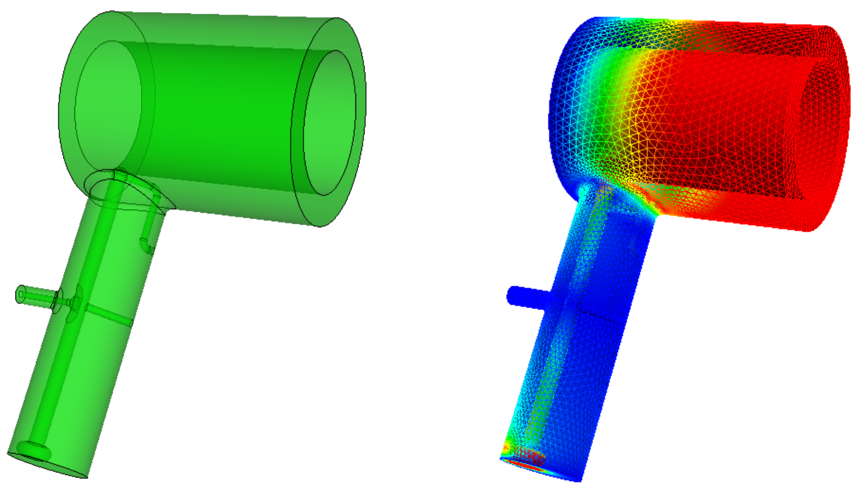


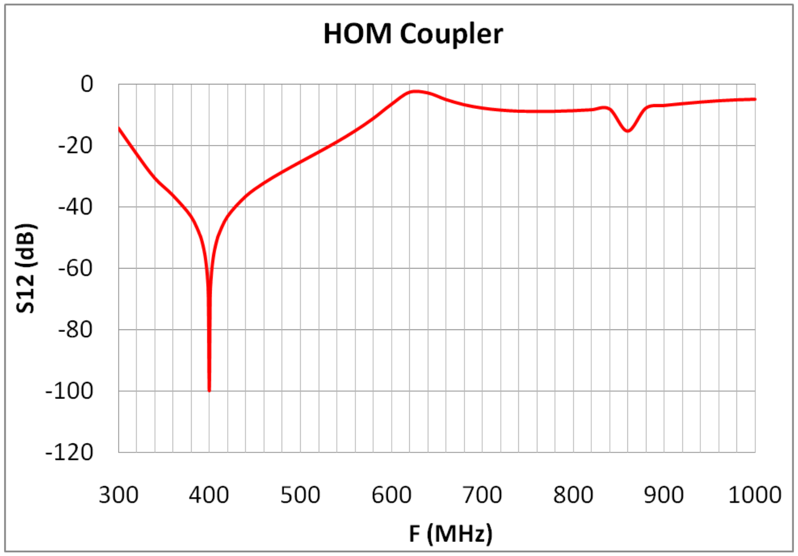


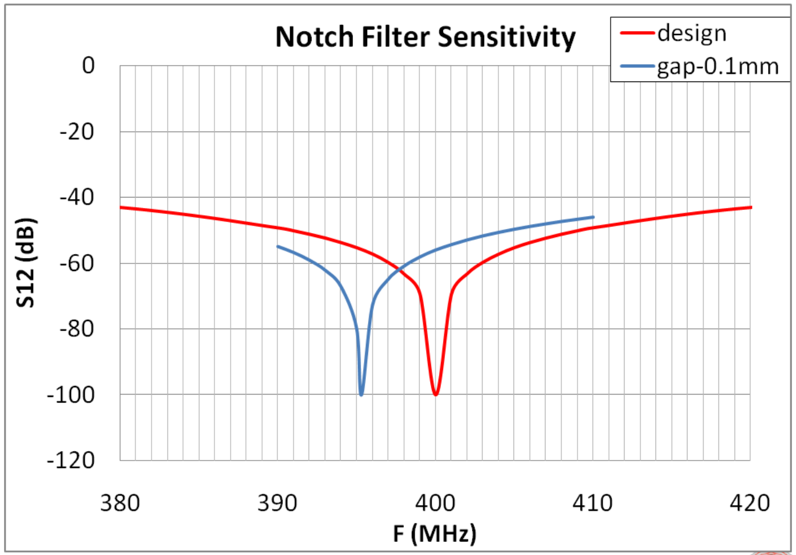
- HOM-h coupler similar to the 800-MHz design
- Notch filter to reject deflecting mode

- Input coupler with magnetic coupling
- Eliminates direct coupling from FPC to LOM/HOM-v

HOM Coupler Notch Filter







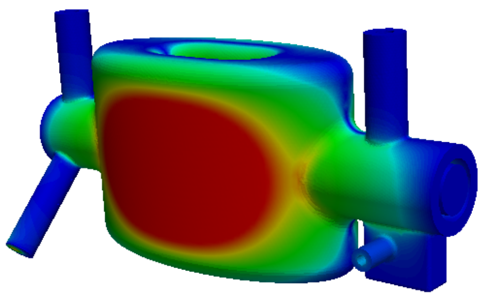
- Notch filter at 400 MHz
- Enhanced damping of the 1st horizontal HOM mode at ~600 MHz
- Filter sensitivity: 1-MHz/20-micron

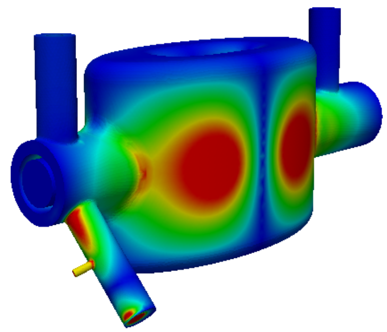
Damping of Dipole Modes

400MHz operating mode

628MHz

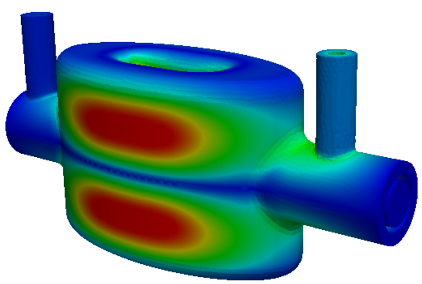
X-Dipole

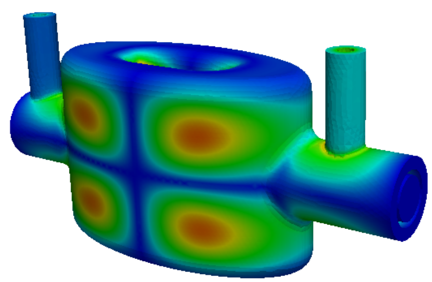




HOM coupler damps X-dipole modes

Y-Dipole





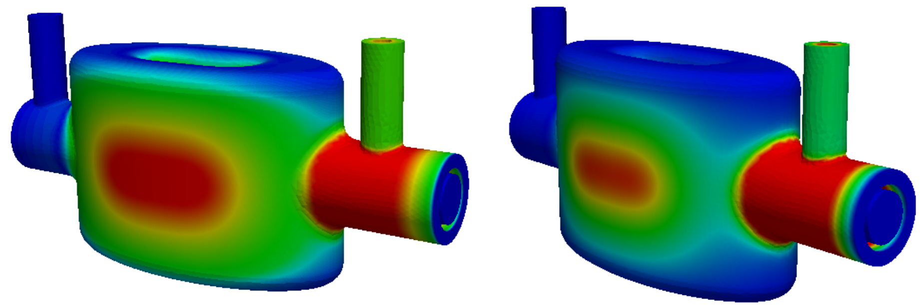
LOM/v-HOM couplers damp Y-dipole modes

810MHz

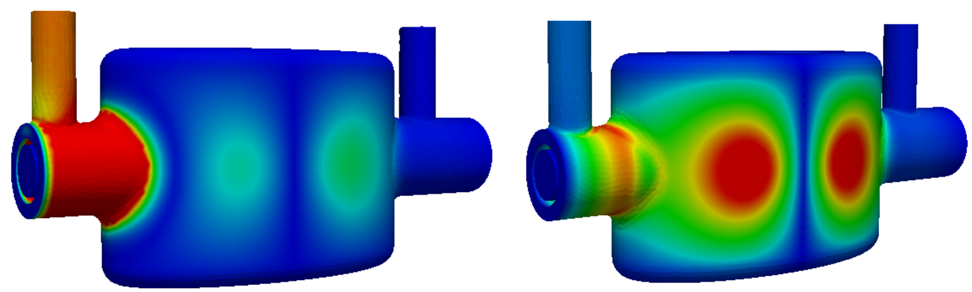
881MHz

Damping of Accelerating

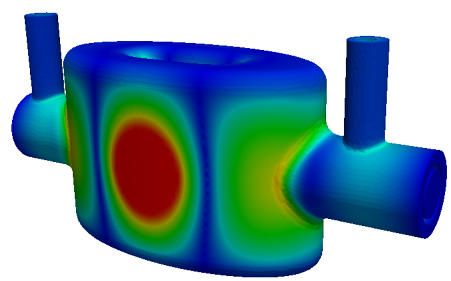
335 MHz, 337 MHz
damp by down stream coupler



498 MHz, 526 MHz
Damp by upstream coupler



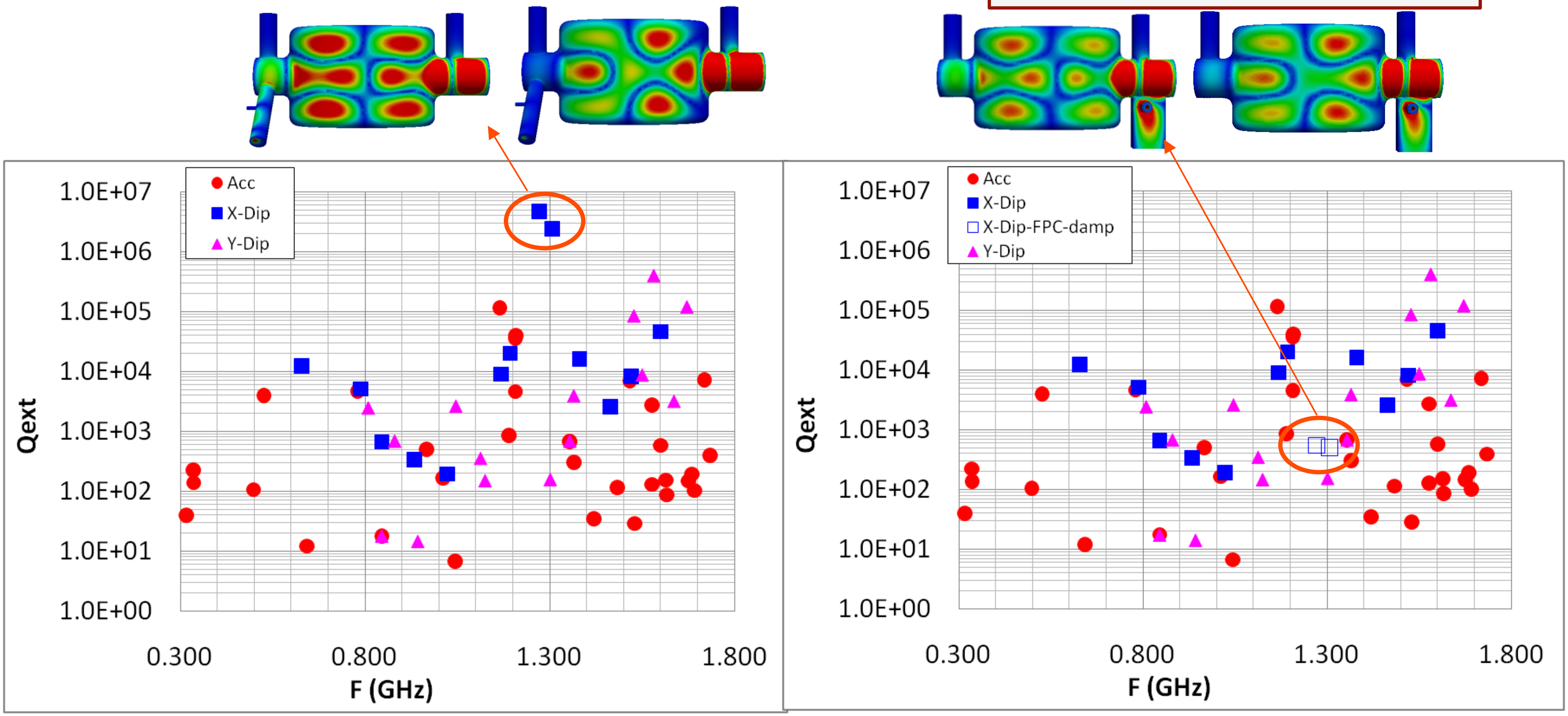
780 MHz



LOM/v-HOM couplers damp accelerating and vertical HOM modes

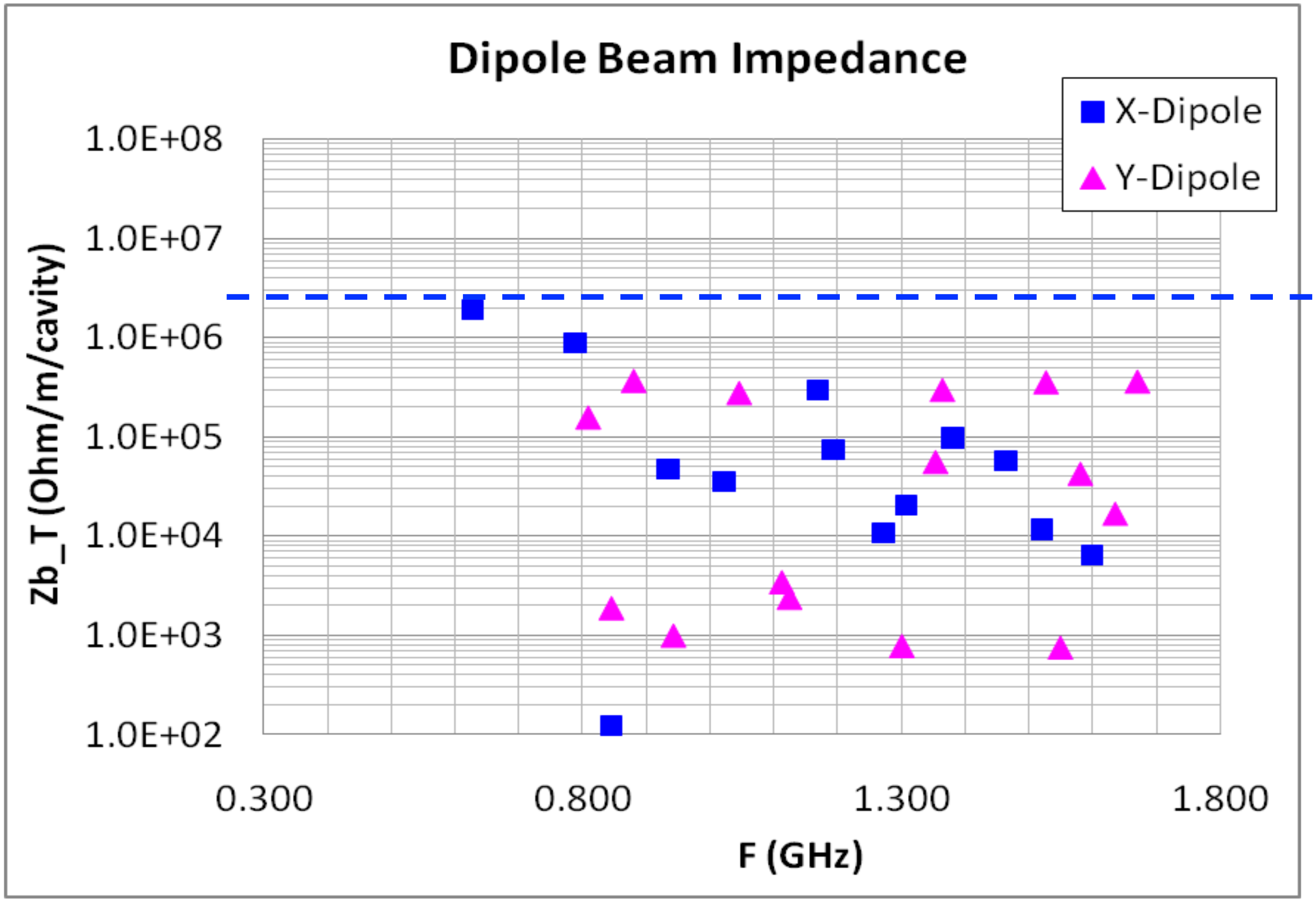
Damping Qext

2 high-Q modes damped through FPC waveguide stub



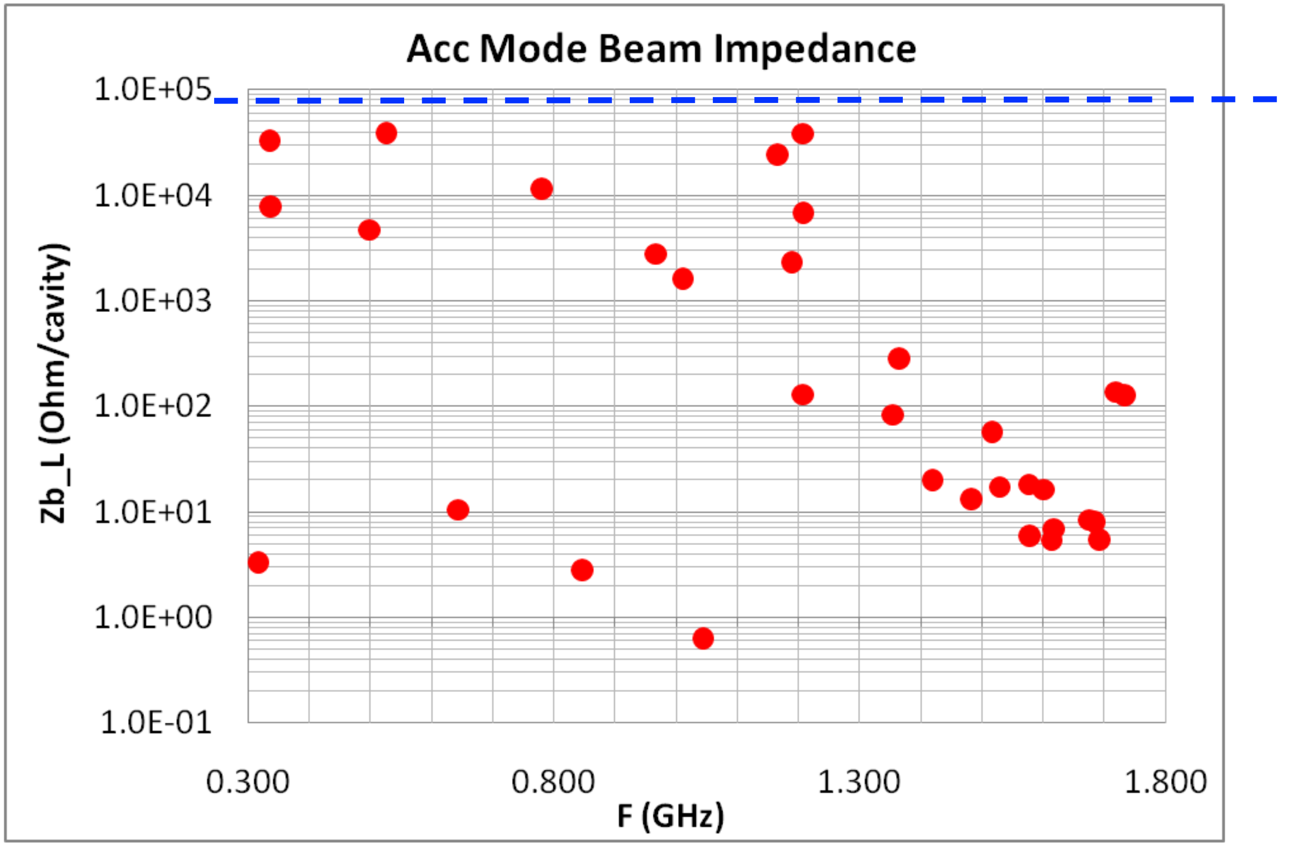
Effective damping demonstrated with these coupling schemes

Dipole Mode Beam Impedance



- Dashed line is the beam instability requirement for dipole modes

Acc. Mode Beam Impedance

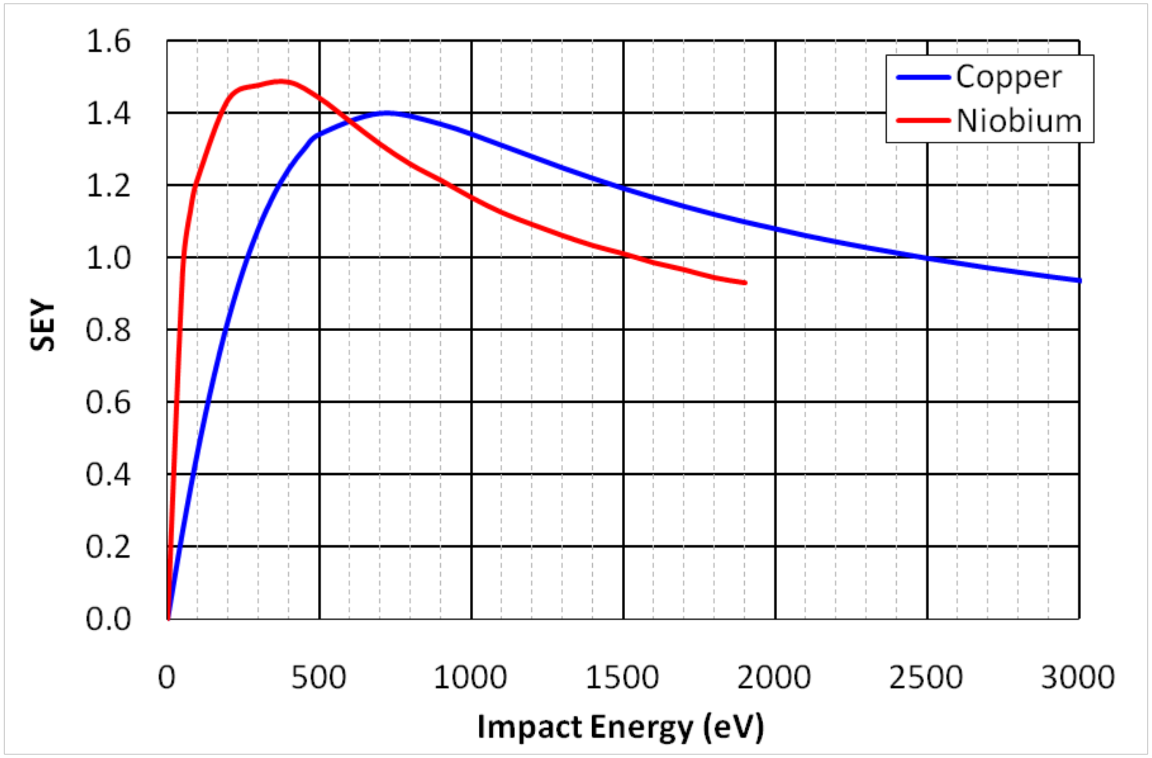


- Dashed line is the beam instability requirement for accelerating modes

Multipacting Analysis

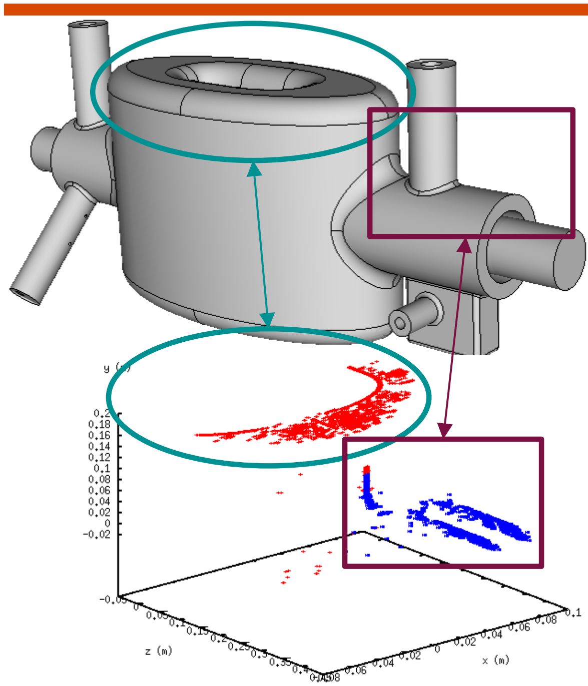
- MP simulation performed for both operating mode and the LOM mode
  - Operating mode: deflecting voltage scanned up to 5MV
  - LOM: beam loss power scanned up to 10kW (on resonance, max)
- Regions scanned for MP
  - Cavity
  - LOM/HOM-v couplers
  - FPC coupler
  - HOM-h coupler

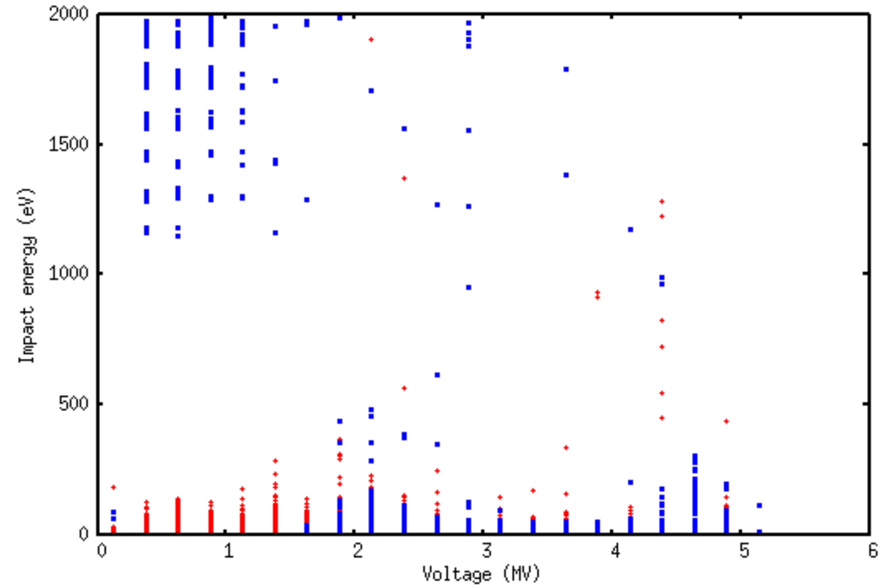
SEY for Niobium and Copper

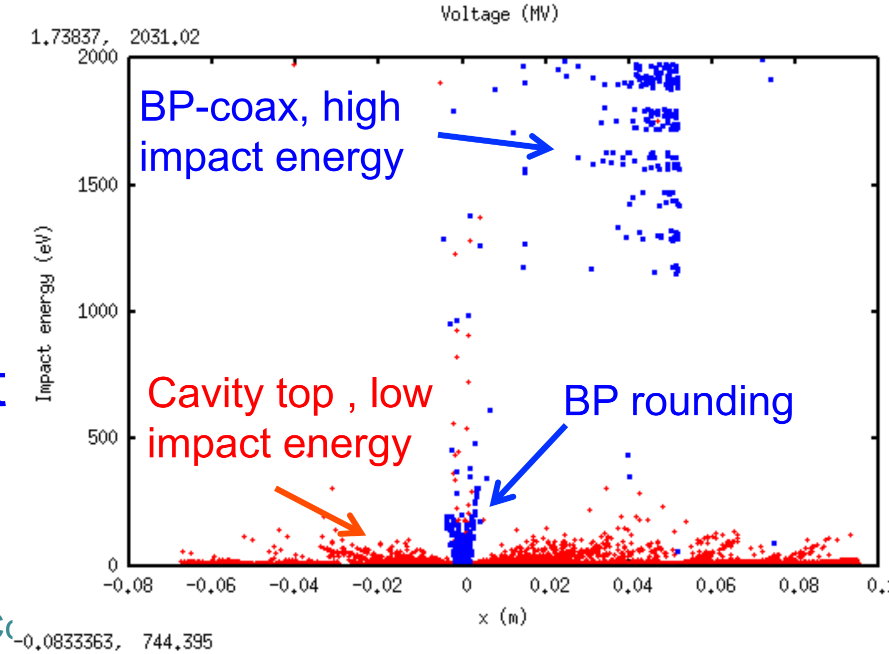


Niobium: cavity body, HOM coupler loop
Copper: Inner conductor of FPC and LOM/VHOM couplers

MP Of Operating Mode (1)

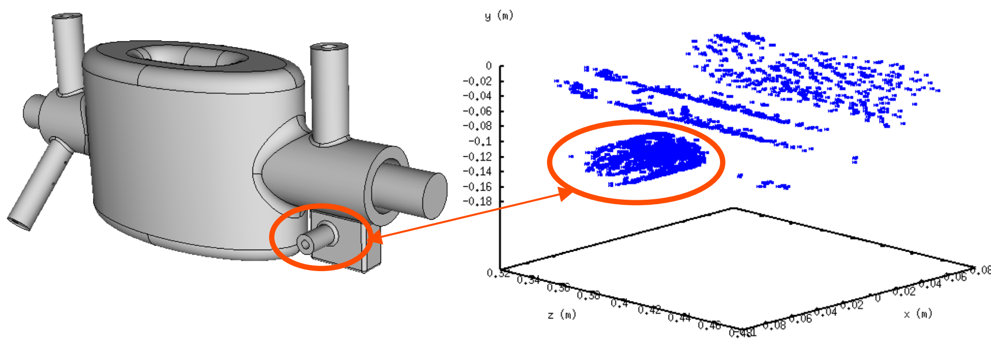


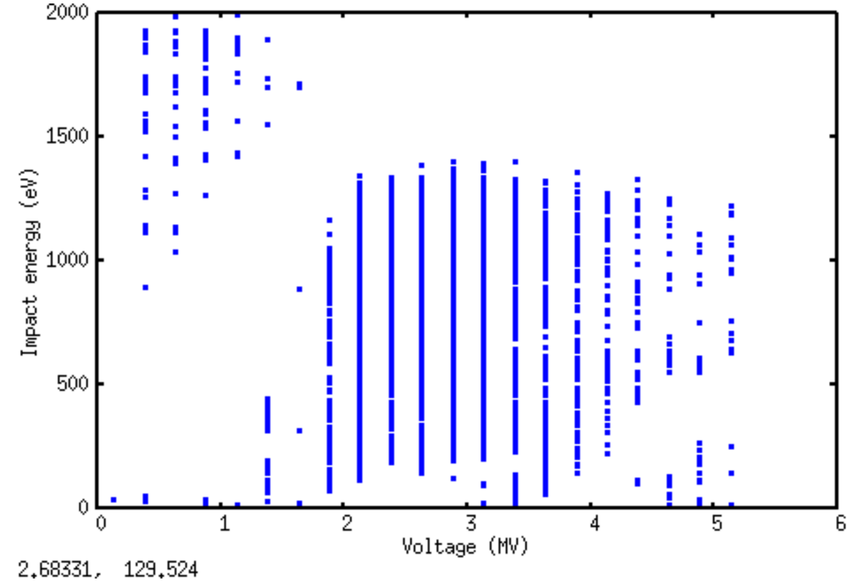




- Impact energy of most resonant trajectories not at the SEY peak
- Only low impact energy resonant trajectories at operating voltage

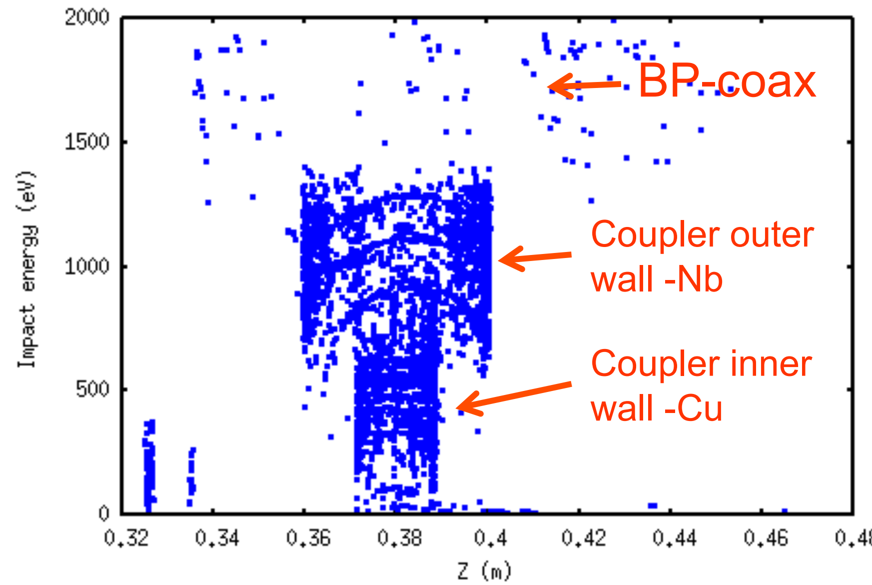
MP of Operating Mode (2) - FPC Coupler



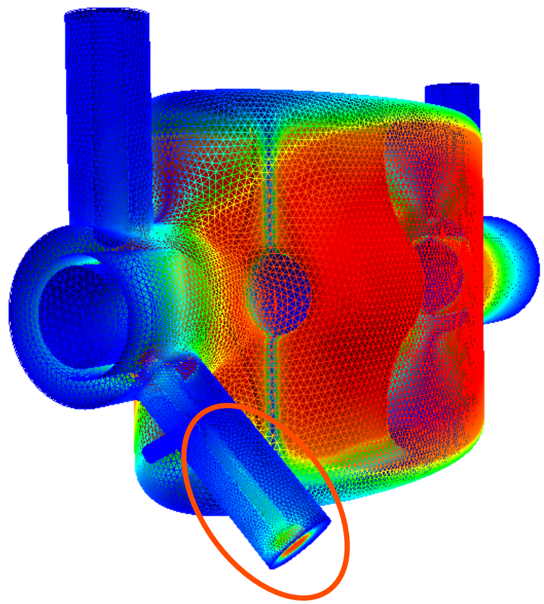


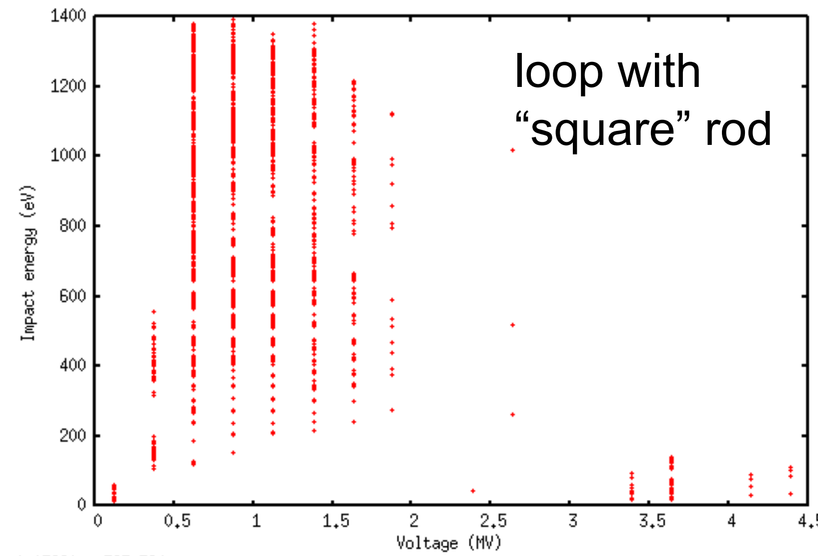
Resonant trajectories in the coax coupler region

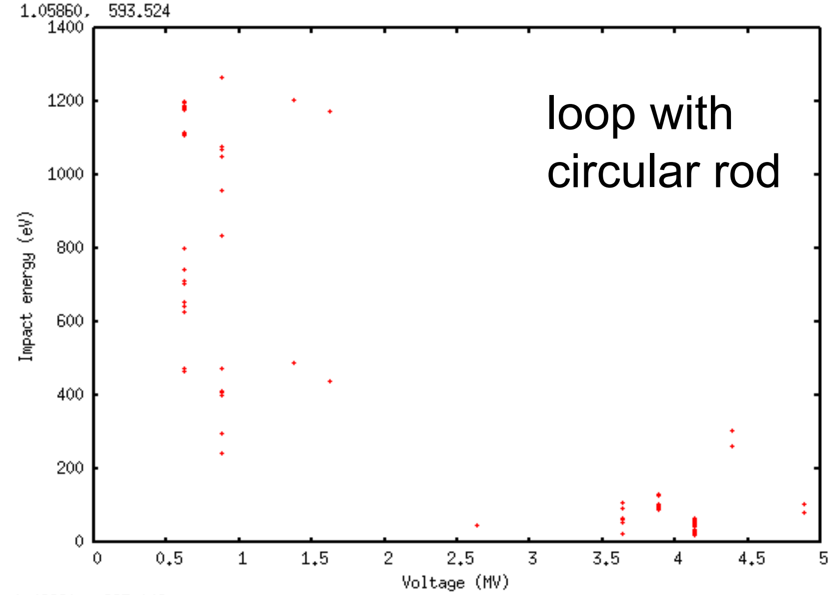
- Impact energy higher on outer surface (Nb) , lower on inner wall (Cu)
- Use coax of different impedance may help to mitigate the problem



MP of Operating mode (3) - HOM Coupler

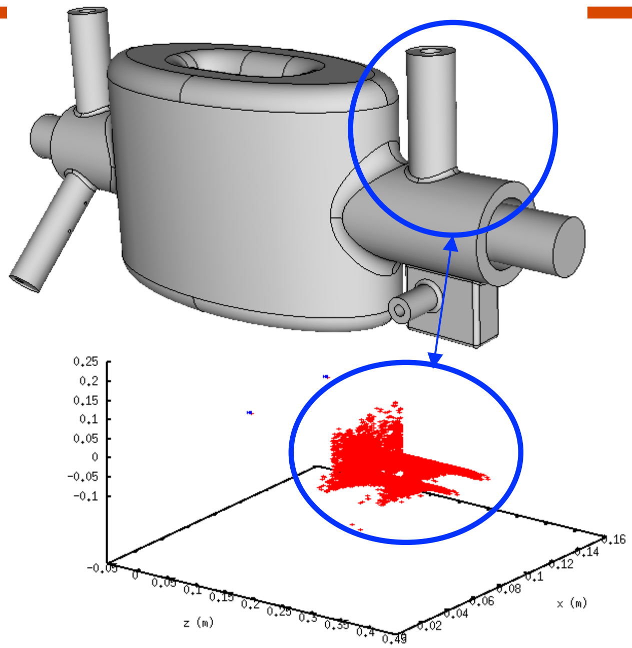


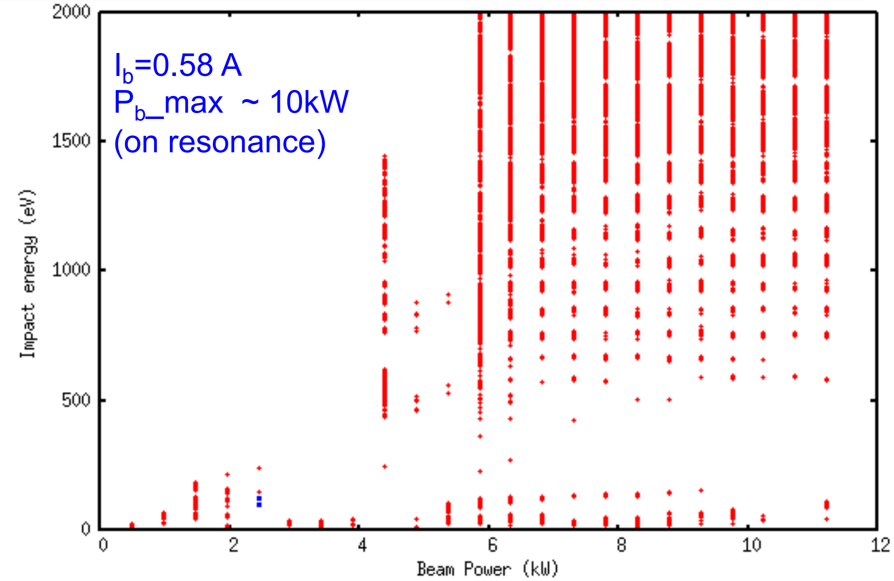


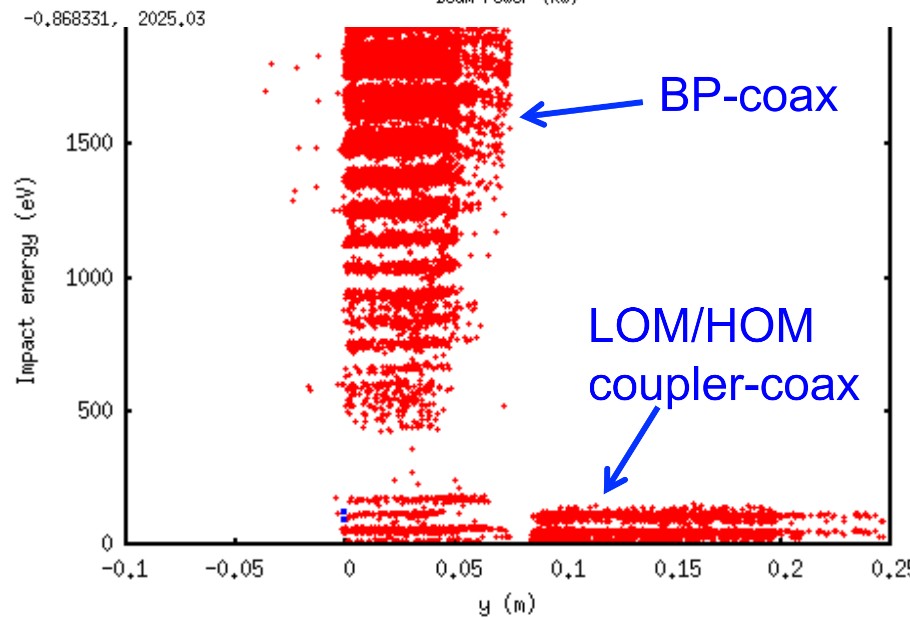


- **“square” rod**
  - 2-point MP between straight section of the loop and outer cylinder wall
- **Circular rod**
  - MP significantly suppressed

MP of LOM Accelerating Mode







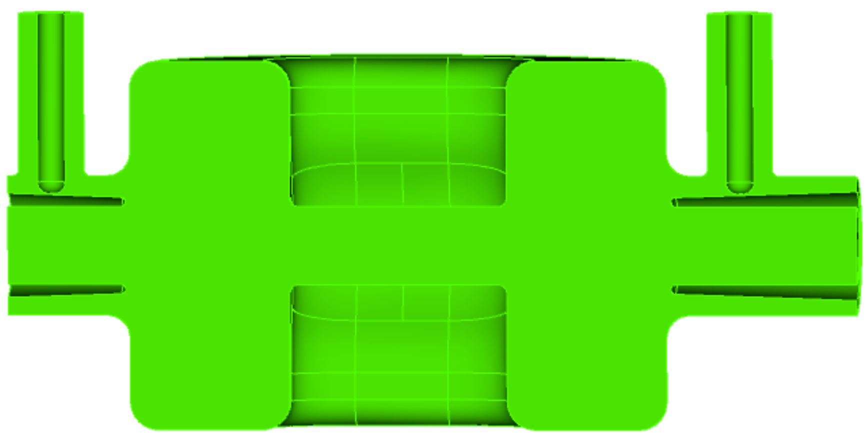
- Max beam power ~10 kW
- Resonant trajectories in BP coax above 4 kW beam power, with mostly high impact energy
- Resonant trajectories in coupler coax, with mostly low impact energy

Possible MP Improvements …

- Coupler coax: coax of different impedance may minimize resonant conditions

  (there are existing coaxial coupler operate at various power levels)

- Beam-pipe coax region: using tapered coaxial geometry or grooves
- …



Summary

- 400-MHz HWSR cavity fits both local and global schemes
- Cavity shape optimized to lower surface fields
- LOM/HOM-v/HOM-v couplers being optimized
  - Effective in damping
  - Current design meets beam instability requirements
- MP analyses performed
  - MP characteristics being analyzed – no big surprises
  - Possible MP improvements being explored

- All necessary components for HWSR cavity optimized, design would meet requirements. Further optimization continues.
- Cavity and coupler model ready for preliminary engineering studies