Crab Cavity Design and Modeling

Zenghai Li

May 8, 2014

Acknowledgements

ODU/JLAB

Jean Delayen, Subashini De Silva, HyeKyoung Park, Rocio Olave

BNL

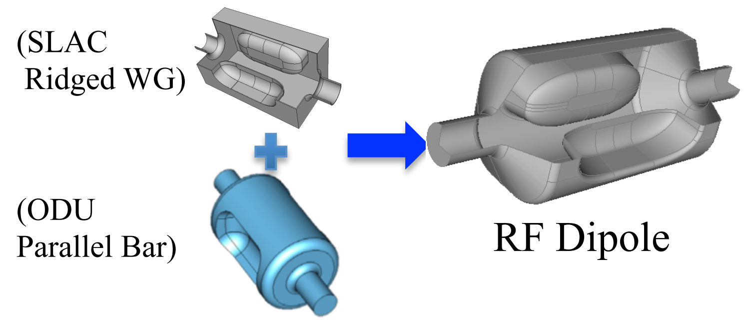
Qiong Wu, Binping Xiao, Silvia Verdú-Andrés

Tom Nicol (FNAL) and CERN team on integration details

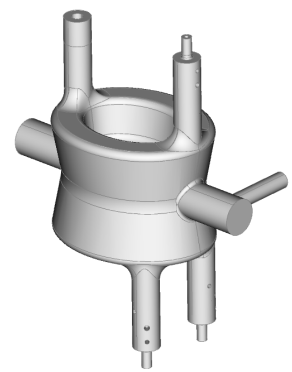
Simulations used *ACE3P* parallel finite element multi-physics codes developed under the support of DOE SciDAC program. Simulations were carried out on supercomputers at NERSC supported by DOE Contract No. DE-AC02- 05CH11231.

Cavity Design and Modeling

- RF Dipole (RFD) cavity Design
  - WG HOM coupler design improvement
  - Hi-pass filter HOM coupler design
  - Vertical and Horizontal crabbing coupler configurations
  - FPC coupler
  - Imperfection study
  - RFD Lorentz force detuning calculation



- Double Quarter Wave (DQW) cavity
  - FPC/HOM port
  - HOM coupler RF field evaluation
  - HOM coupler Multipacting analysis
  - HOM coupler damping evaluation
  - FPC coupler RF heating evaluation

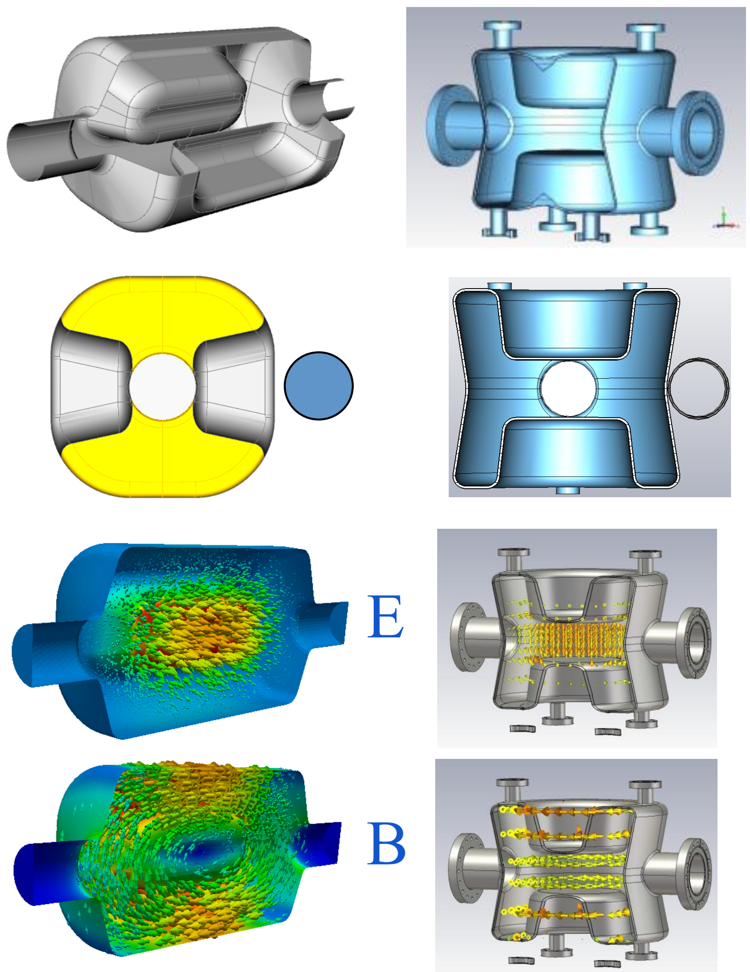


DQW (BNL)

- Summary and Plan

RFD, DQW Parameters

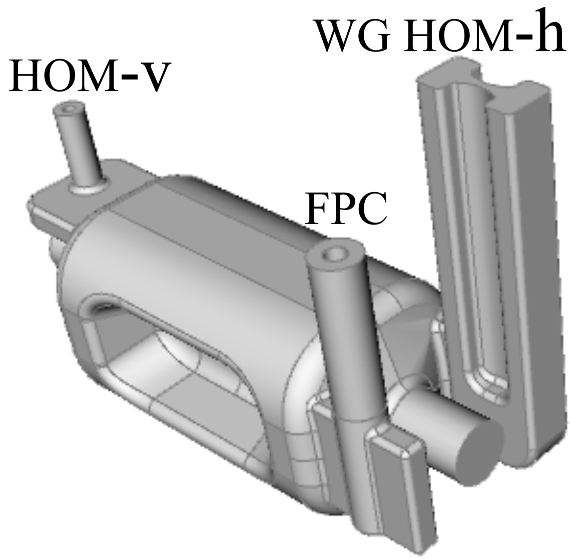
RFD DQW



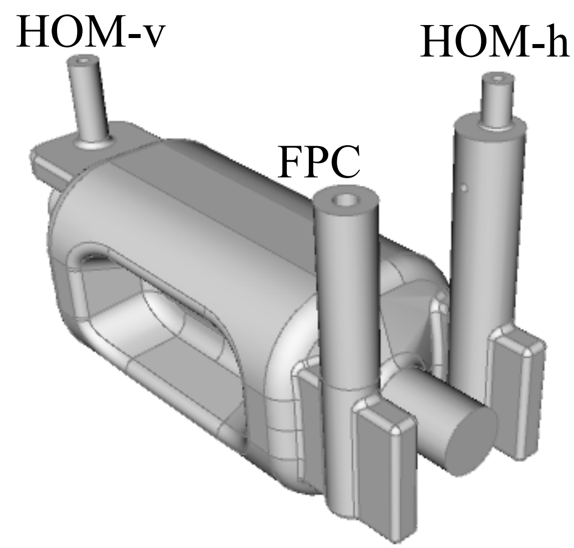
	RFD	DQW
Frequency (MHz)	400	400
Operating Mode	TE11	
Lowest dipole HOM (MHz)	633	683
Lowest acc HOM	715	579
Iris aperture (diameter) (mm)	84	84
Transverse dimension (mm)	281	278/332
Vertical dimension (mm)	281	278
Longitudinal dimension (w/o couplers) (mm)	556	390
R_T (ohm/cavity)	433	428
V_T (MV/cavity)	3.34	3.34
Bs (mT)	55.6	69.3
Es (MV/m)	33.4	39.6

- Deflect mostly by E field
- No lower order mode
- Compact

HOM Damping for RFD - Two Coupler Design Options



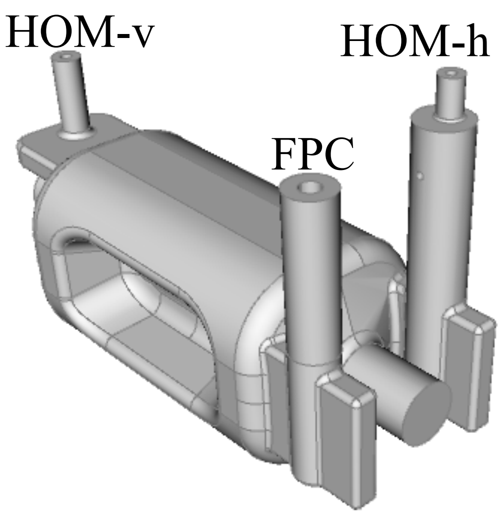
- Ridged waveguide H-HOM coupler
- No filter needed, need enough length to minimize power leakage
- High power handling option



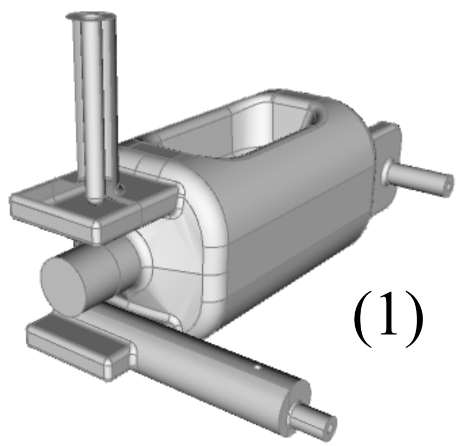
- Hi-pass filter H-HOM coupler
- Relatively compact
- Need to understand high power handling capability

Two designs have the same coupler-to-cavity interface

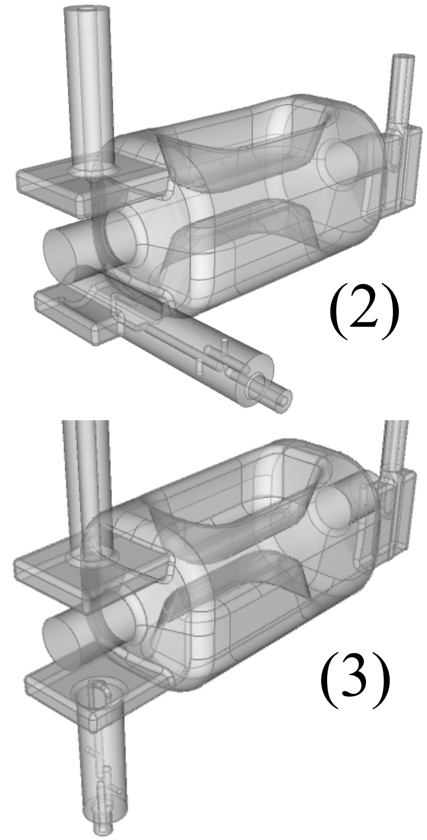
Horizontal and Vertical Crabbing - Coupler Configurations



Horizontal crabbing

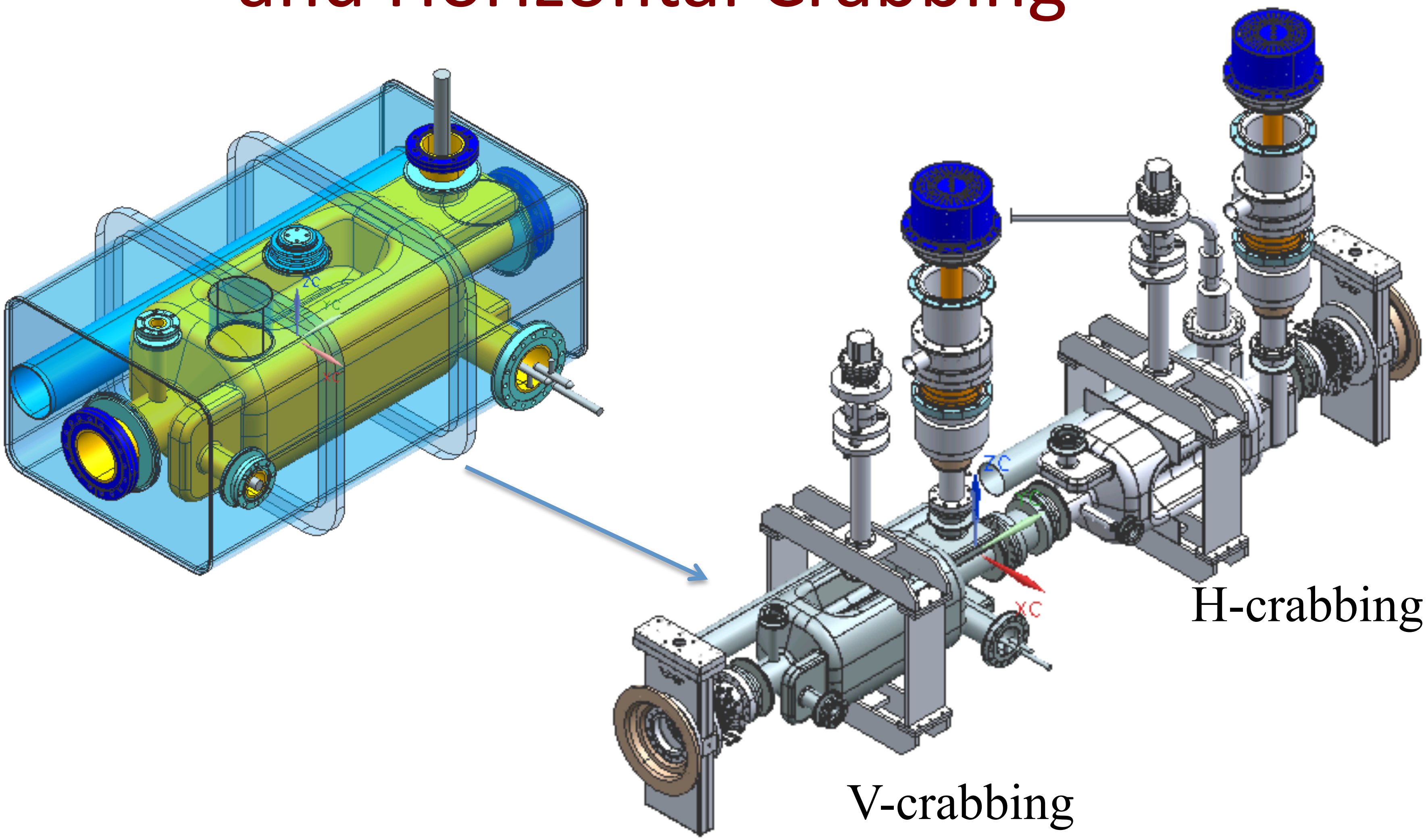


Vertical crabbing



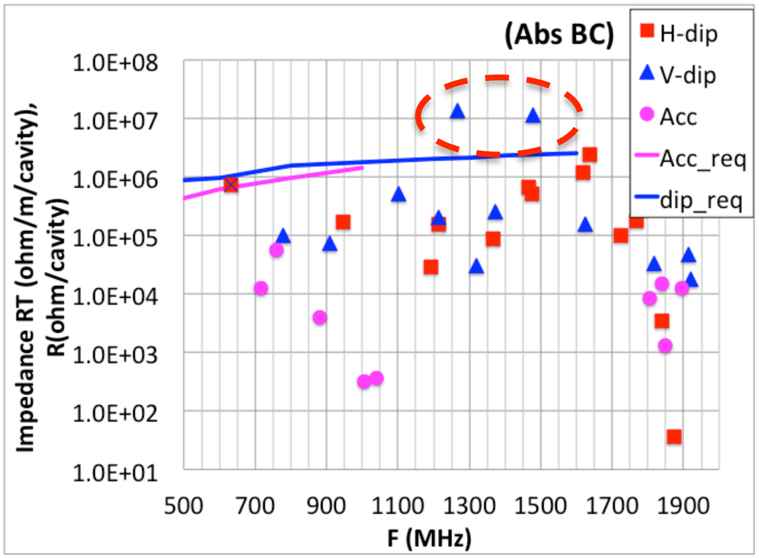
- Could realize H- and V-crabbing with "minimal" change in FPC Port
  - FPC using hook coupling for Horizontal and probe for Vertical
- Same HOM damping Qext for H- and V-crabbing (1, 2…)
- Horizontal and vertical designs share the same coupler-to-cavity interface

Coupler Layout for Vertical and Horizontal Crabbing

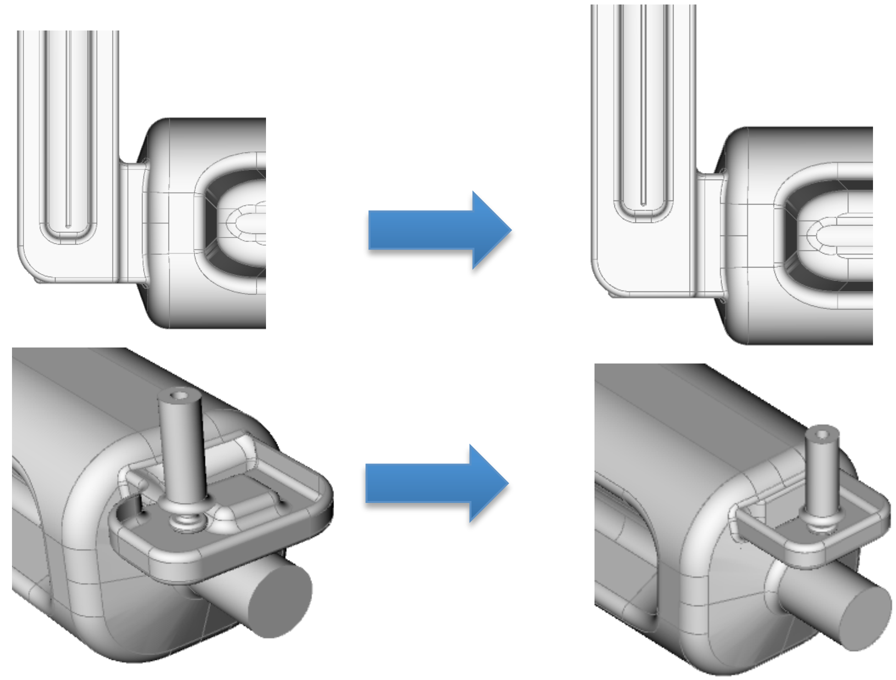


Improved WG HOM Couplers

To damp a few "problematic" Modes



(two modes have high impedance)



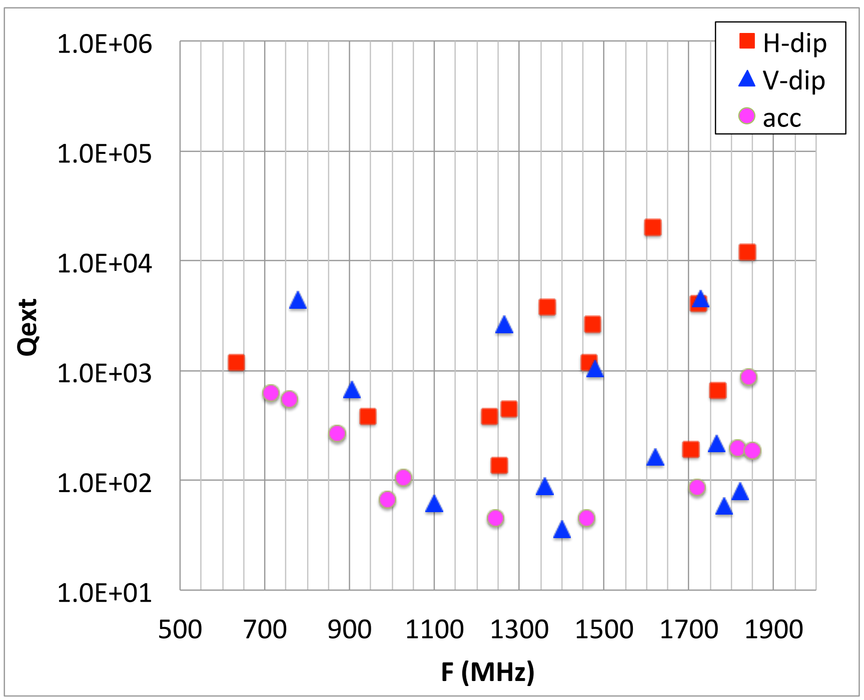
Older design

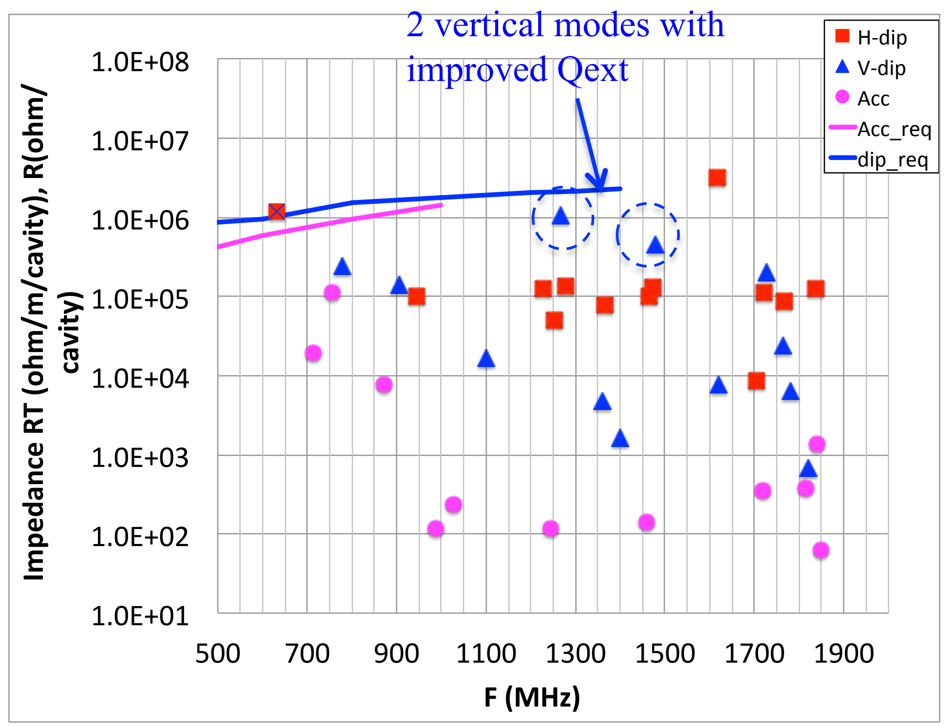
Improved design

- H-HOM coupler – moved up the starting position of the ridged gap
- V-HOM Coupler – simplified wg stub, coax pickup moved toward symmetry plane
- No field enhancement in couplers

Damping Results of New WG HOM Coupler

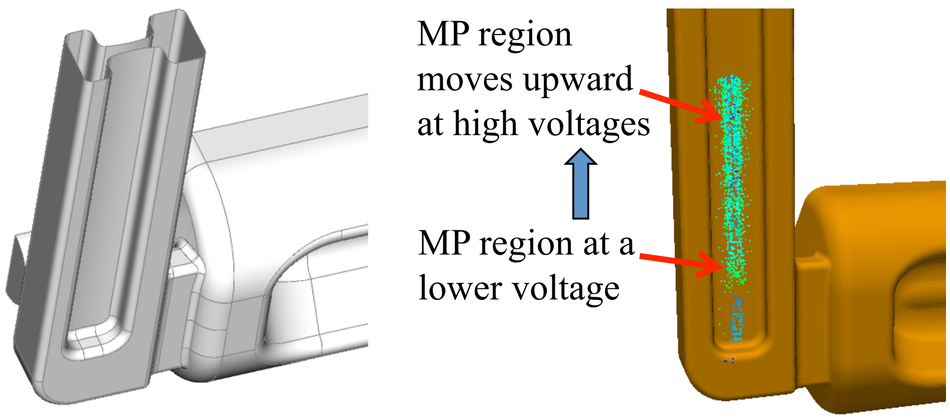
- Qext of modes at 1.265 and 1.479 GHz lowered by more than 10X
- Effective Damping Achieved for All HOMs up to 2 GHz
- Engineering design for the SPS test cavity

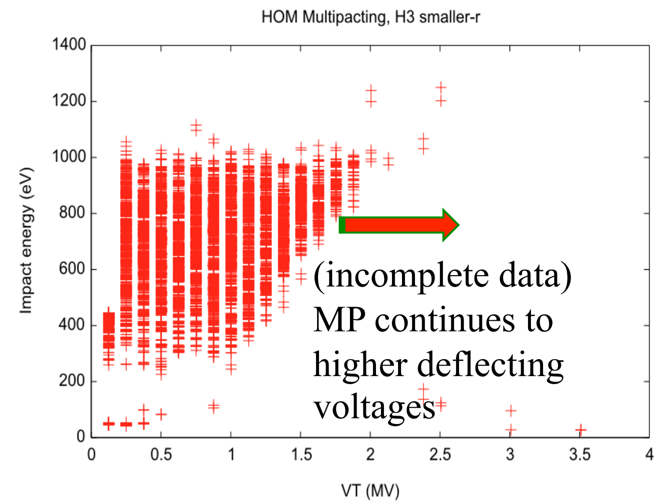




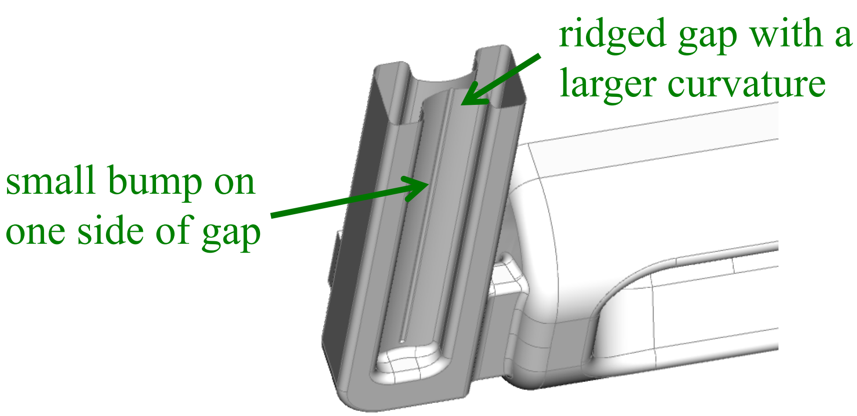
MP Suppression in WG HOM Coupler

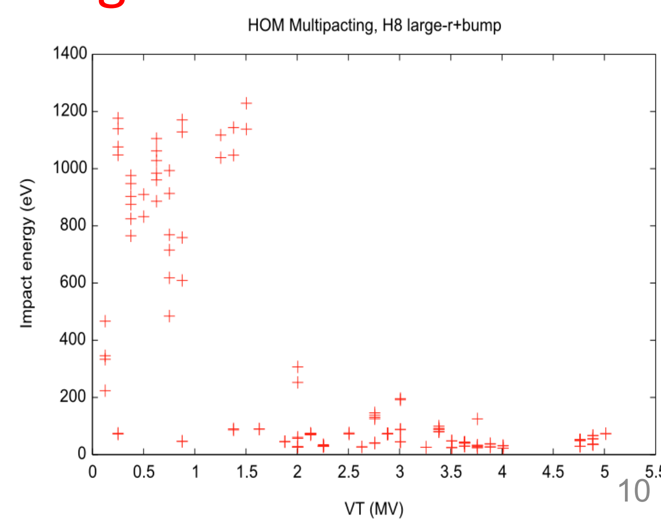
- Significant MP in the ridged gap region (flat, smooth surface)





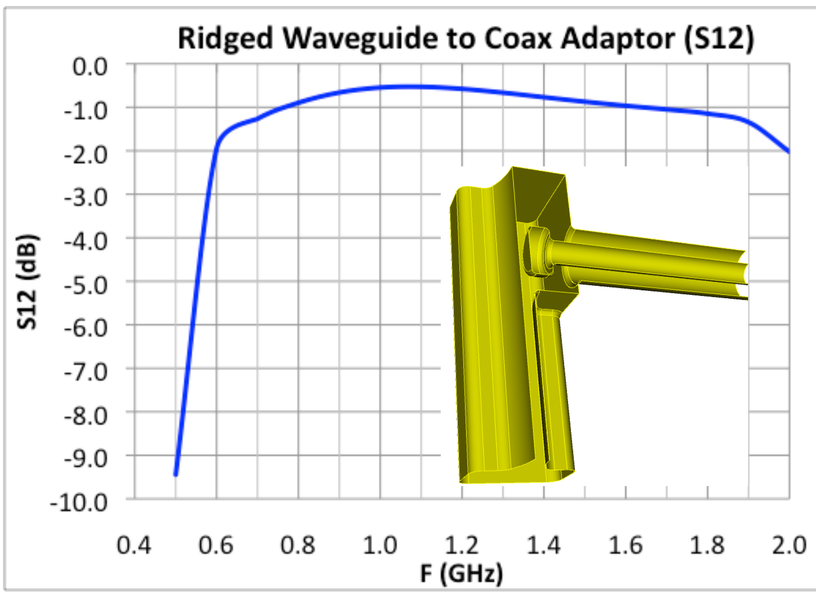
- MP suppressed for the prototype cavity design

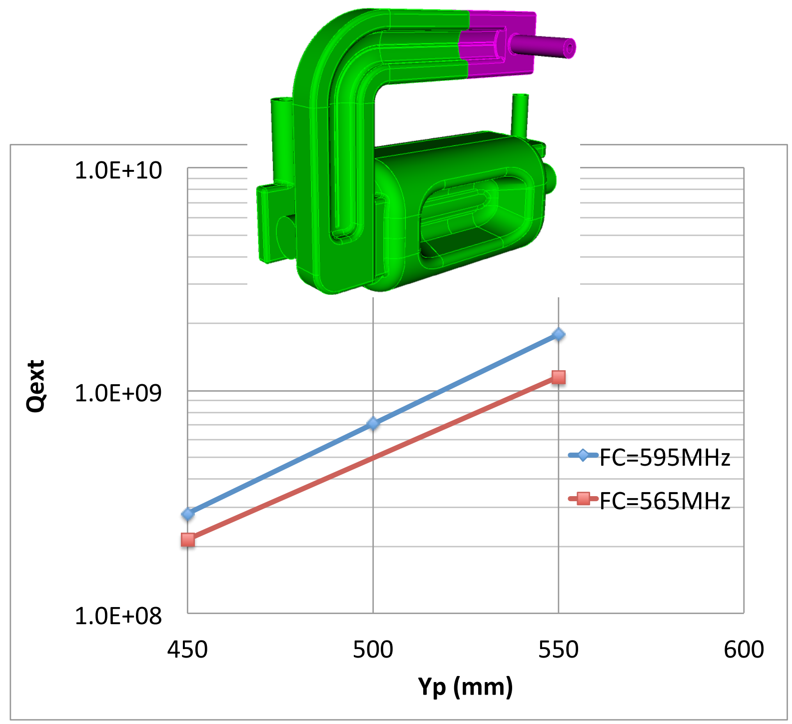




WG HOM Coupler to Load

- WG-coax adaptor then to load
- Or WG directly to load

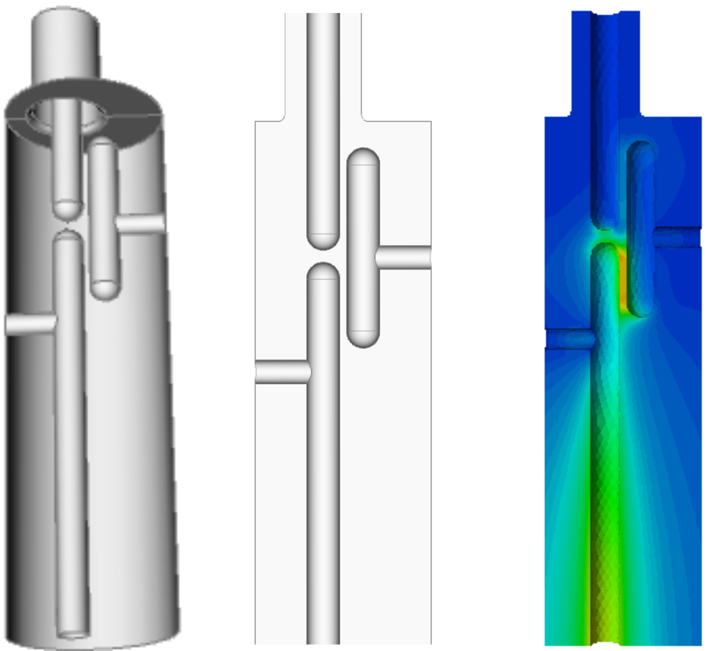




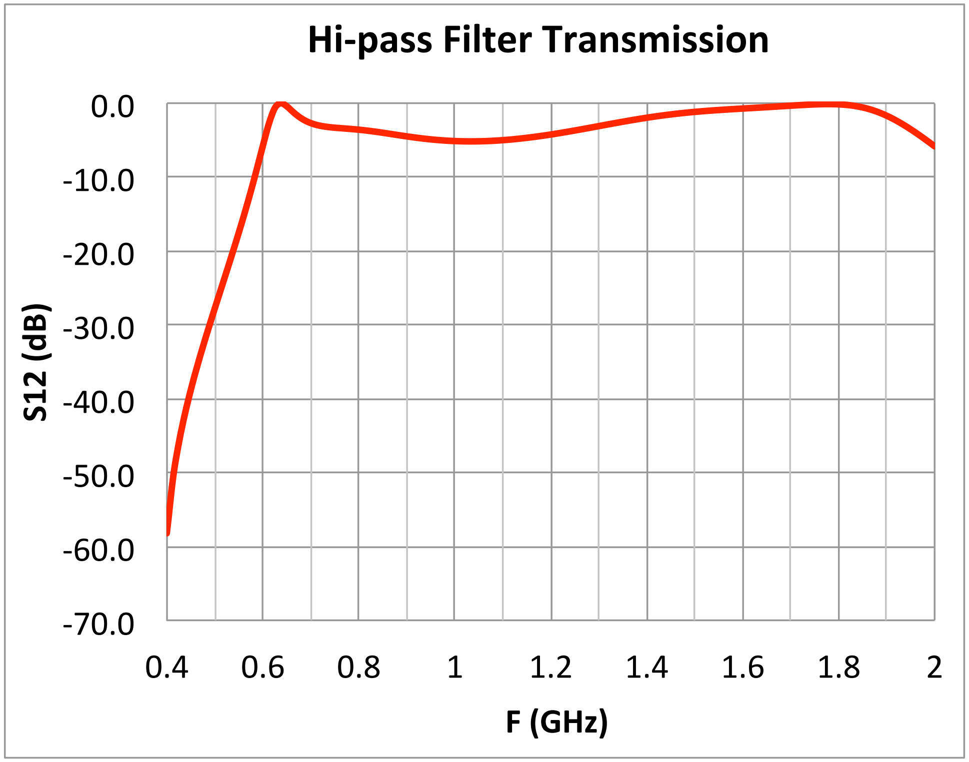
- Ridged waveguide needs to have enough length to reduce power leakage
- A section of WG needs to be SC to reduce wall heating due to evanescent field
- May consider bend WG horizontally to save vertical space

Hi-pass Filter H-HOM Coupler

A compact HOM coupler design option

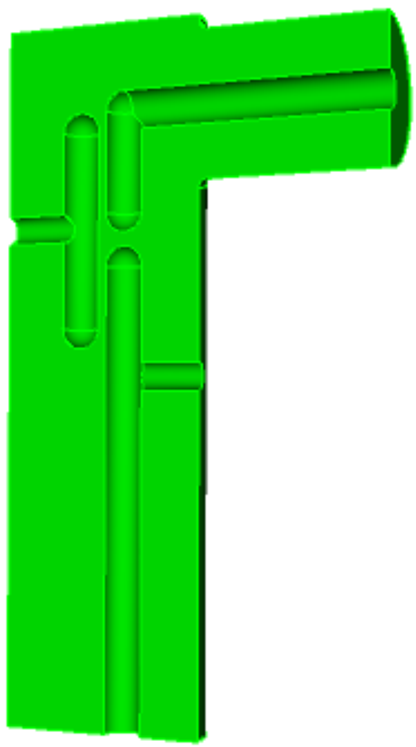


rejection of operating mode



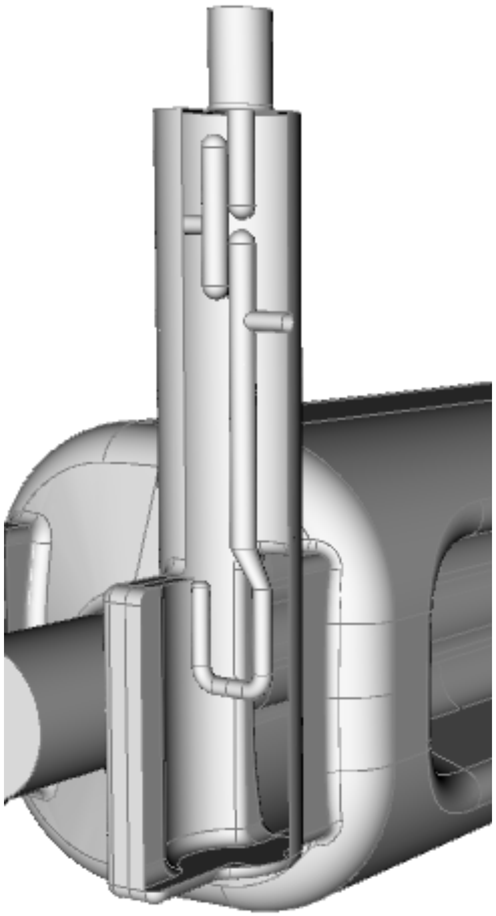
- Center rod diameter: 14 mm
- Larger cylinder diameter: 74 mm
- 50 ohm port: 14mm/32.2mm

Hi-pass Filter With 90-deg Bend



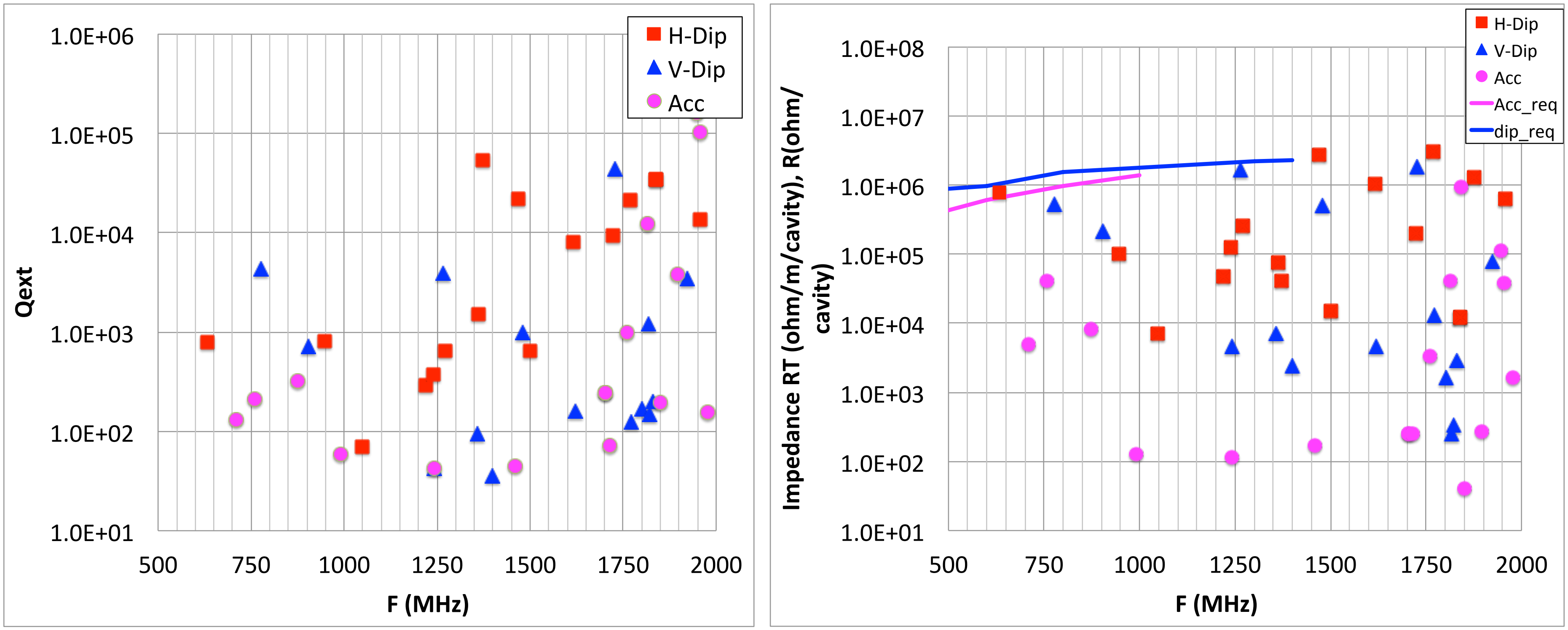
- Bend sideways to save vertical space
- Details being optimized

RFD With Hi-pass Filter H-HOM Coupler



- Coupler demountable from cavity
- 50 ohm pickup demountable from filter body
- Low fields in coupler
- Coupling hook and T need to be superconducting (minimize RF heating)

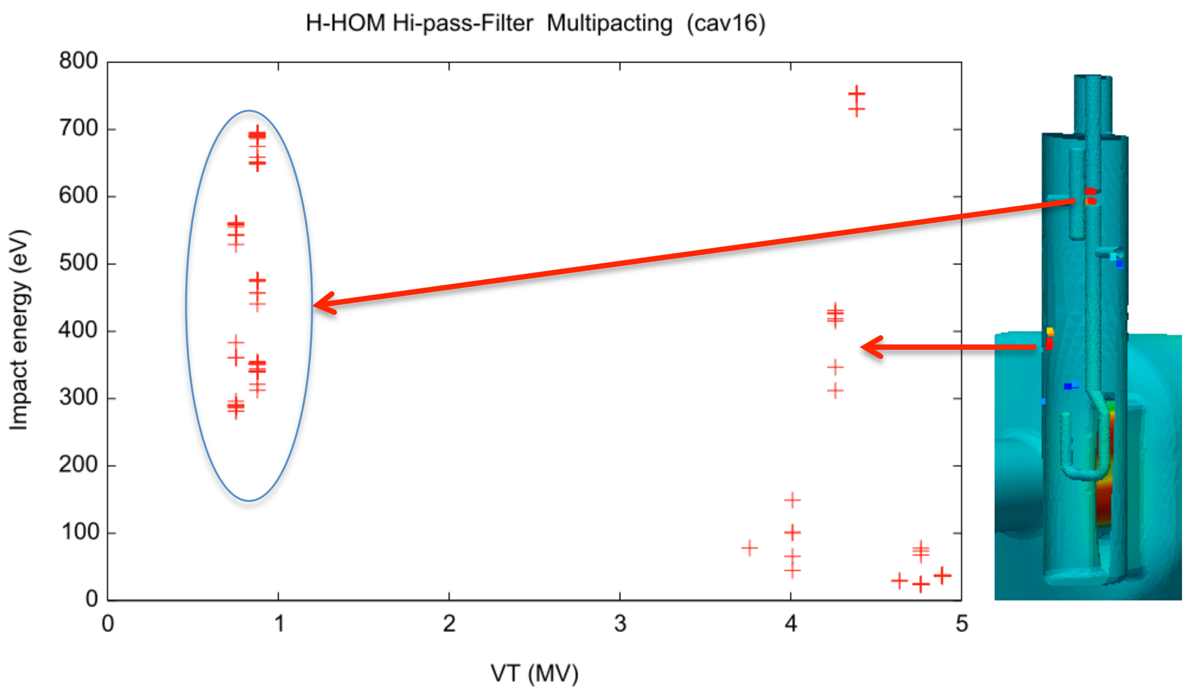
Damping Results of Hi-pass Filter HOM Coupler

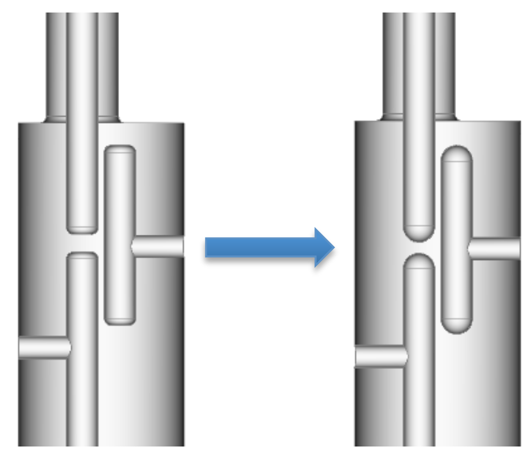


- All modes well damped, as good as WG coupler damping
- Solid lines are design requirement (LHC-CC10)

No Significant Multipacting in Hi-pass Filter 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



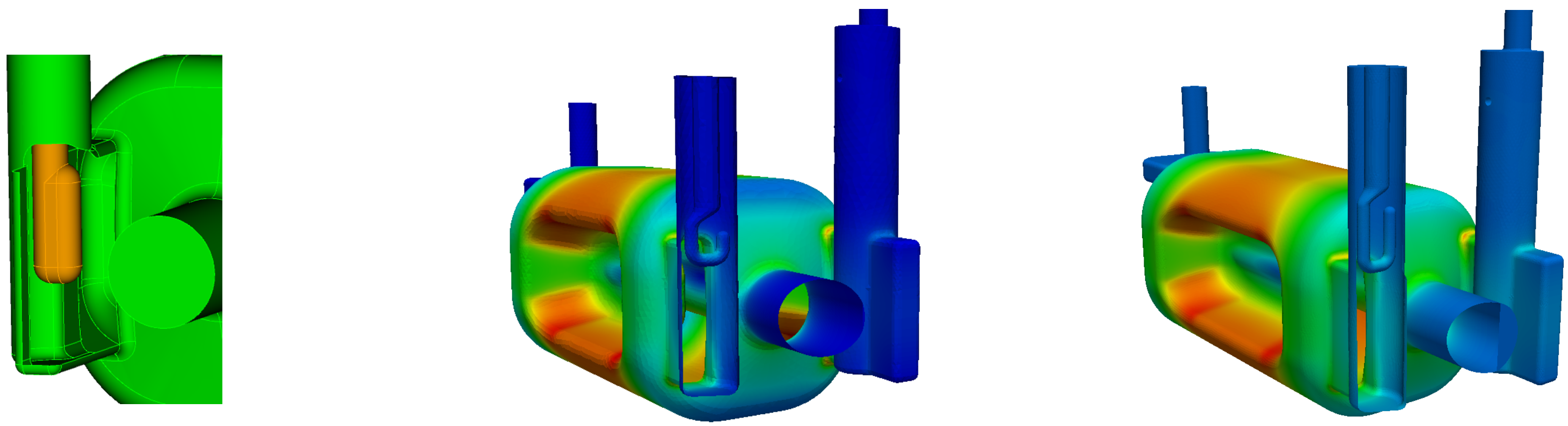


MP trajectories in the gap Removed

FPC Coupler

Using a hook coupling instead of a probe (Horizontal crabbing)

- High RF surface heating on the probe shape antenna
- Replaced with a hook coupling, optimized to reduce RF heating



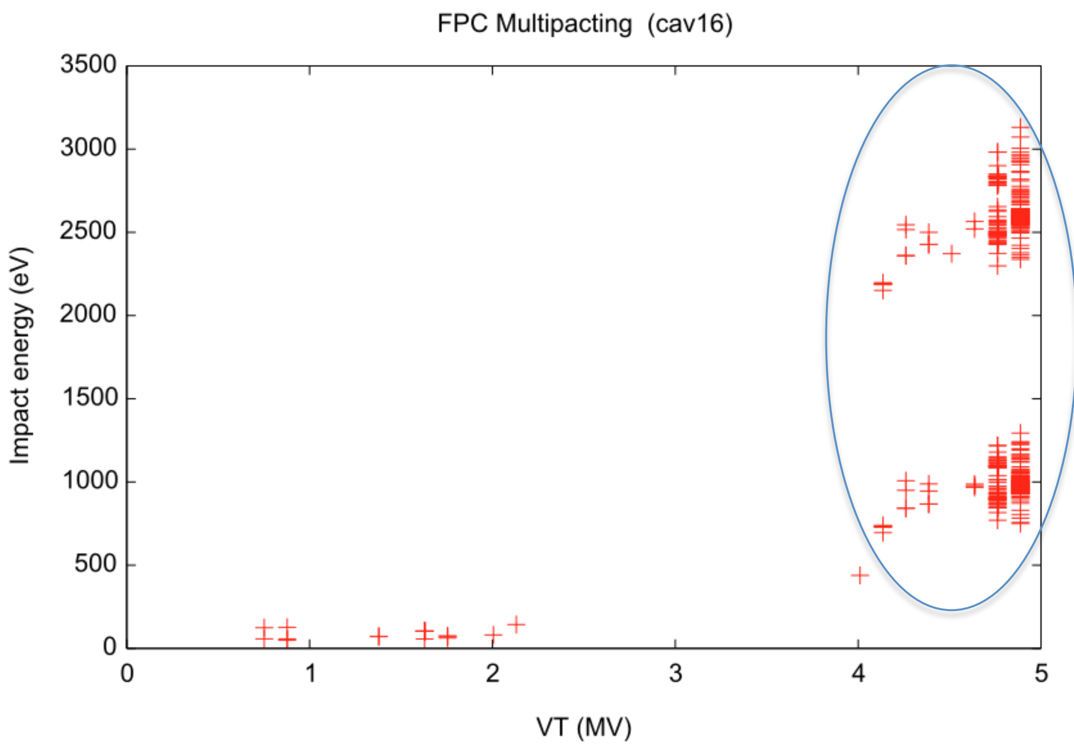
676 W 178 W 69 W

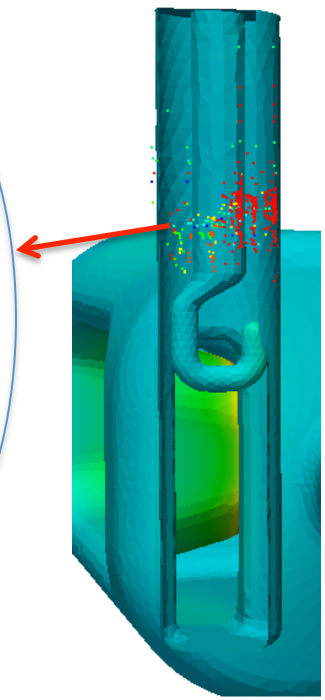
Hook heating at 3.4 MV deflecting voltage (Horizontal crabbing)

(Less heating and better cooling for Vertical with a probe)

Multipacting Analysis of FPC Coupler

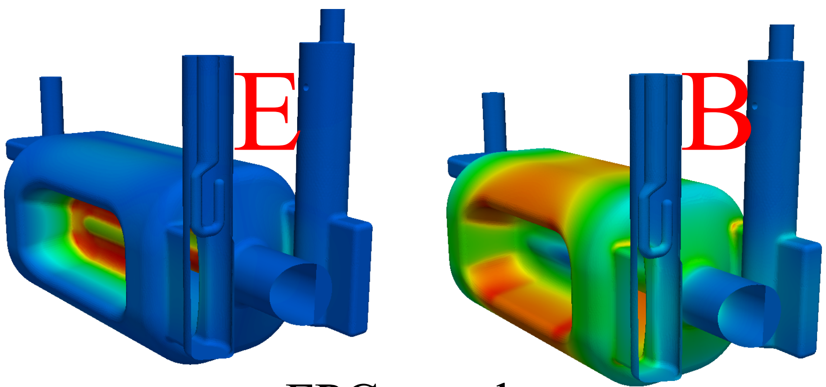
- No multipacting in the hook region
- Have resonant trajectories in the coaxial region at higher deflecting voltages – (typical in coax)
- No multipacting in coaxial region at nominal deflecting voltage of VT = 3.4 MV



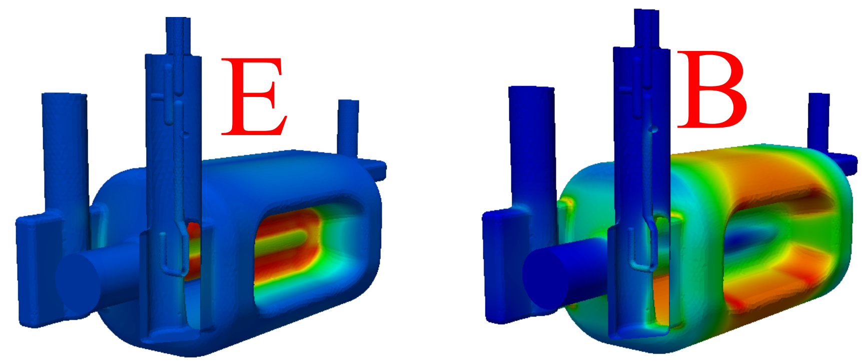


Typical MP in coaxial region at high VT

RFD: Surface Fields on Coupler Surfaces



FPC coupler



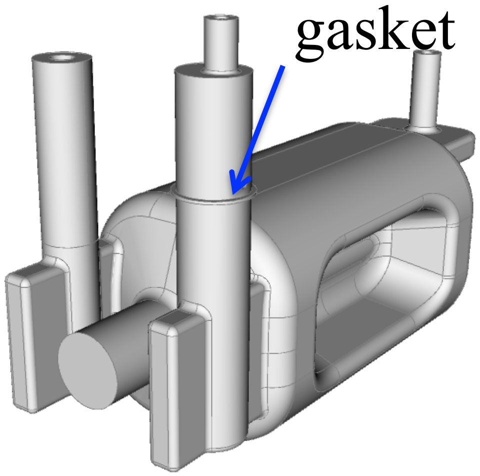
H-HOM coupler

At VT = 3.4MV	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

Low surface fields in both FPC and HOM couplers

RFD: Power Loss On Coupler Surfaces

VT = 3.4 MV	Material	Power Dissipation (W)
H-HOM Hook+T	Nb (Rs=10nΩ)	0.00089
H-HOM Probe	Cu (sigma=5.8e7, Rs=5mΩ)	0.084
V-HOM probe	Cu (sigma=5.8e7, Rs=5mΩ)	0.077
FPC Hook (Qext=5e5)	Cu (sigma=5.8e7, Rs=5mΩ)	69
FPC gasket*	Cu (at 2K, Rs=1mΩ)	0.018
H-HOM gasket*	Cu (at 2K, Rs=1mΩ)	0.226

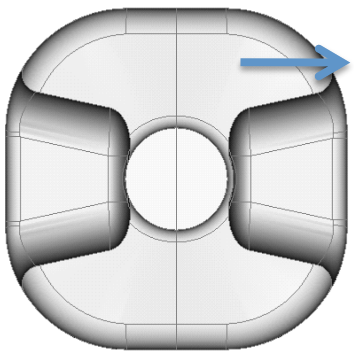


- Detailed gasket geometry needed for accurate calculation
- Thermal analysis needed to determine temperature profile

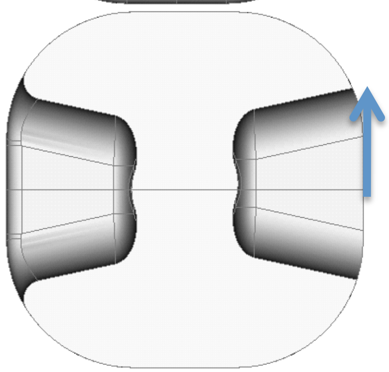
Effect of Dipole Pole Tilt and Offset

Imperfection models studied

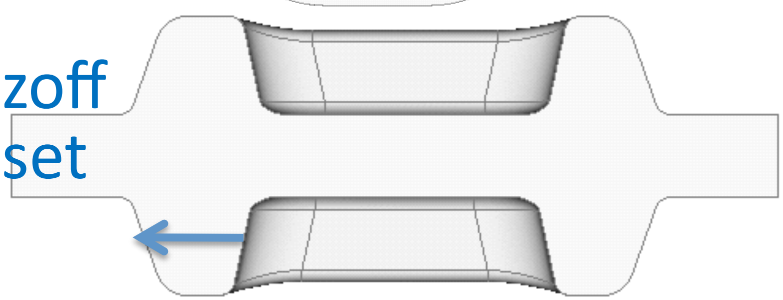
- xoff set



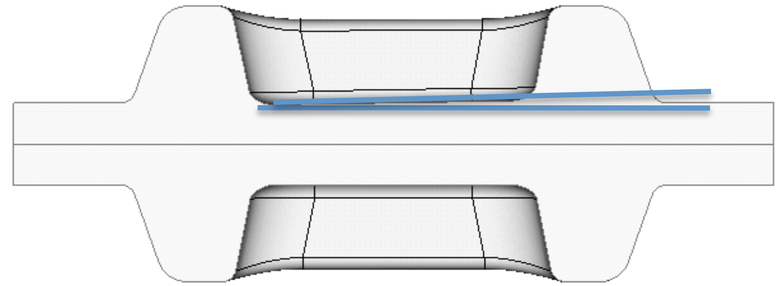
- yoff set



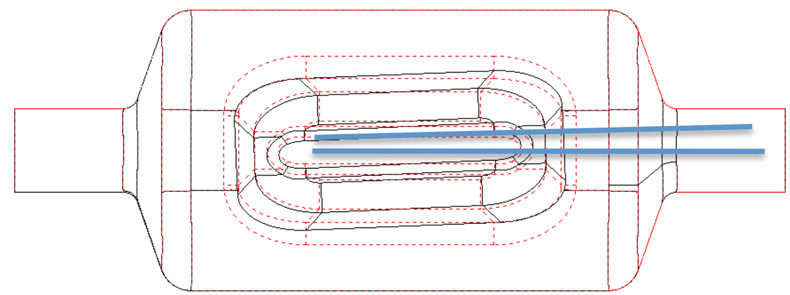
- zoff set



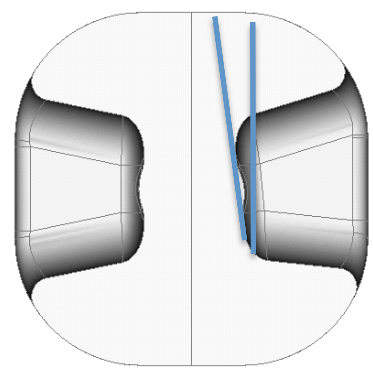
Xtilt



ytilt



zrotate



Multipole Field with a Tilted/ Offset Pole

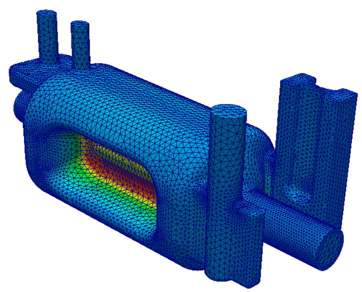
	xcenter off (mm)	Vy/Vx	B3 (mT*m)/m^2	B5 (mT*m)/m^4	B7 (mT*m)/m^6	B3 Skew	B5 Skew
xtilt 0.5 deg	0.73		492	2.2E+06	7.8E+08		5.4E+03
ytilt 0.5 deg	0.10	2.2E-03	489	2.3E+06	7.5E+08	49	5.5E+04
zrot 1 deg	0.10	7.9E-03	494	2.2E+06	7.0E+08	136	5.7E+03
xoff 2mm	1.55		677	2.1E+06	7.3E+08		1.6E+04
yoff 2mm	0.09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

- Small effects on multipole fields
- Induce skew sextupole and deflection in other plane
- Cause shift in electric center
- Seems good geometry tolerance

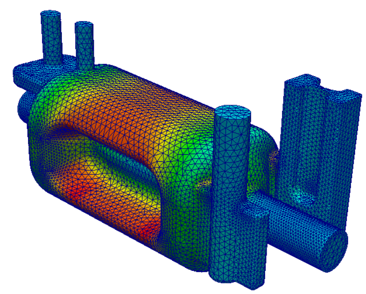
Lorentz Force Detuning

- Frequency shift due to shape deformation by RF field pressure
- Calculated using ACE3P multi-physics solver

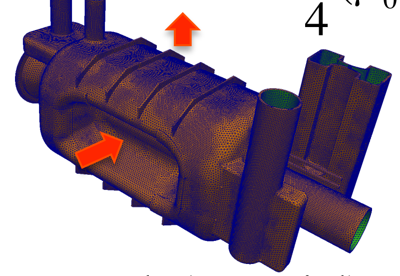
$$P = \frac{1}{4}(\mu_0 H^2 - \varepsilon_0 E^2)$$



E Field

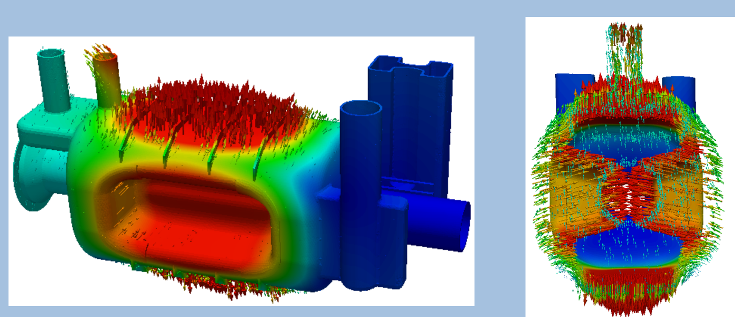


B Field

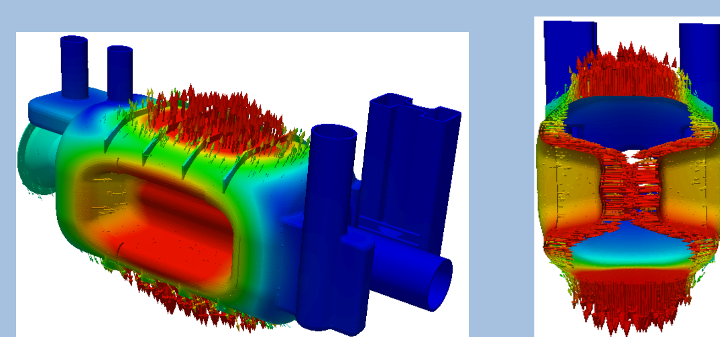


Mesh (material)

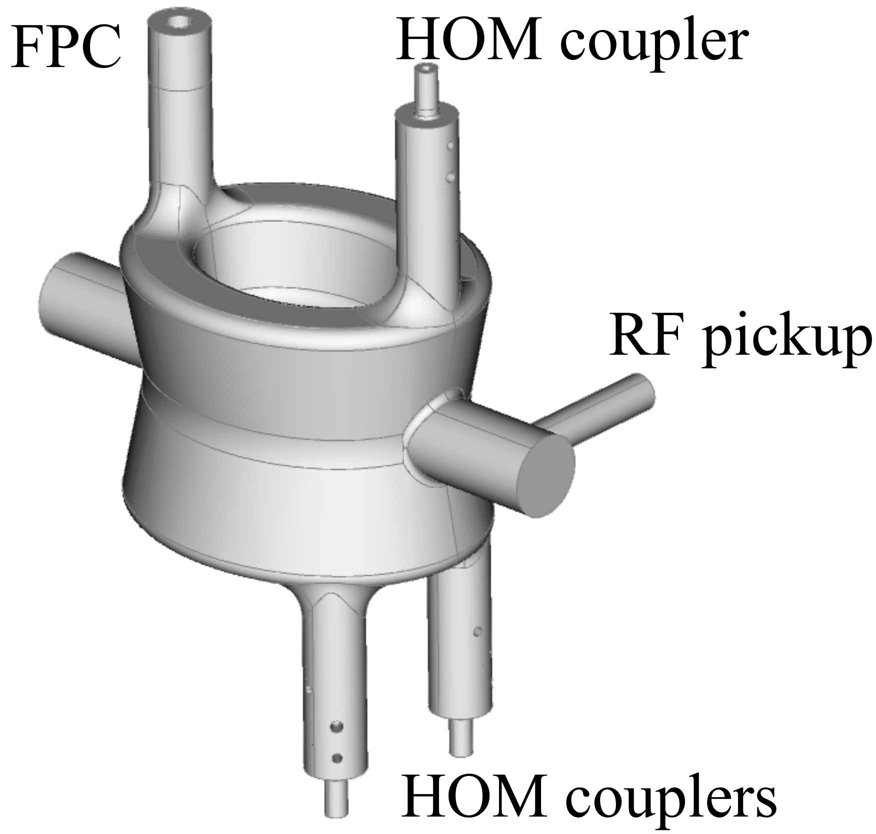
Ports free: dF = -3286 Hz/3.5MV



Ports fixed: dF = -3190 Hz/3.5MV



DQW Cavity with Couplers



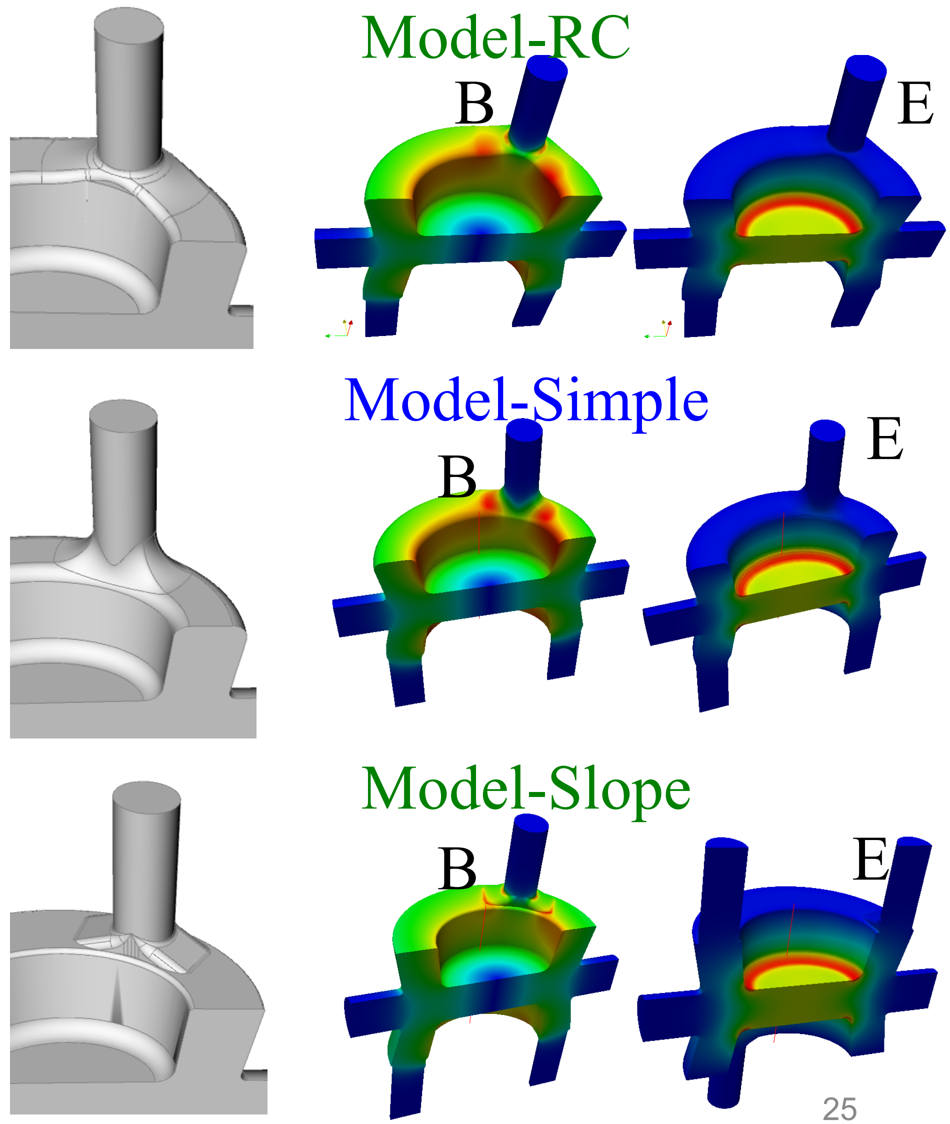
- Three HOM couplers in total
- High-pass filter to reject operating mode

DQW: Port Design Comparison/Selection

- Three port designs with different rounding profiles at the cavity-coupler interface analyzed
- Compared RF and surfaces fields of three designs for the final choice for DQW cavity

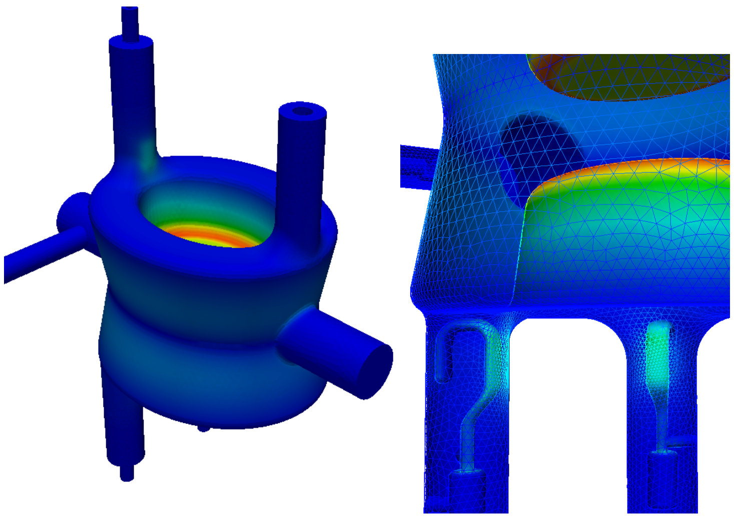
V_def/cavity: 3.34 MV			
	RC	Simple	Slope
R/Q (ohm)	426	428	428
Es (MV/m)	38.8	39.6	38.1
Bs (mT)	69.8	69.3	89.7
dCenter (mm)	0.62	0.51	0.53

design choice

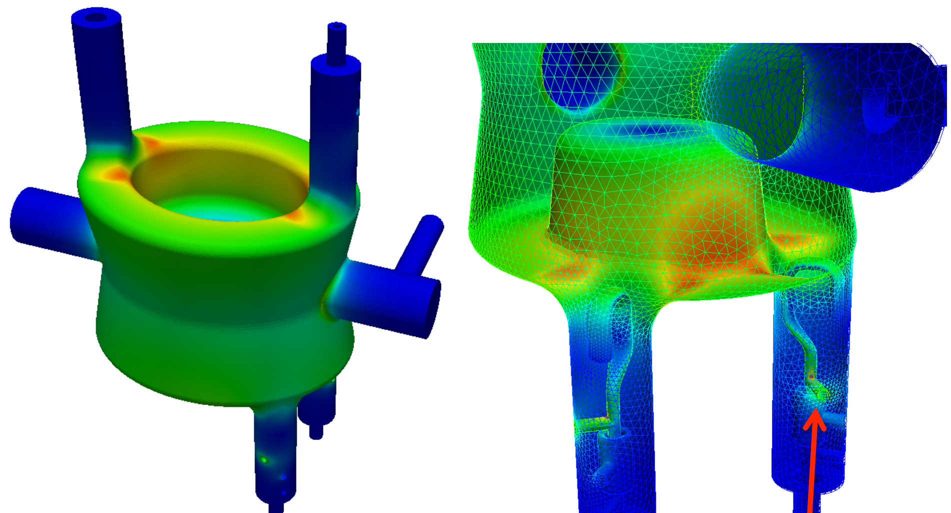


Surface Fields in HOM Couplers

- Non-negligible fields on the coupler hook antenna surface
- Highest B fields on the filter inner conductor surface, modification underway to reduce field enhancement



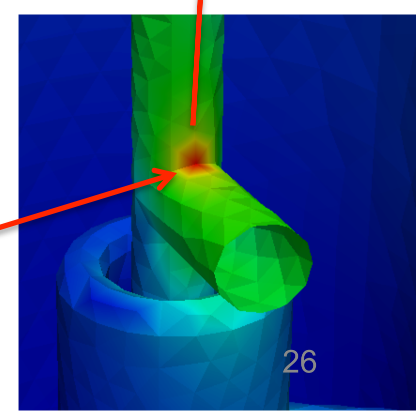
E surface field



B surface field

(2014-01-14 design)

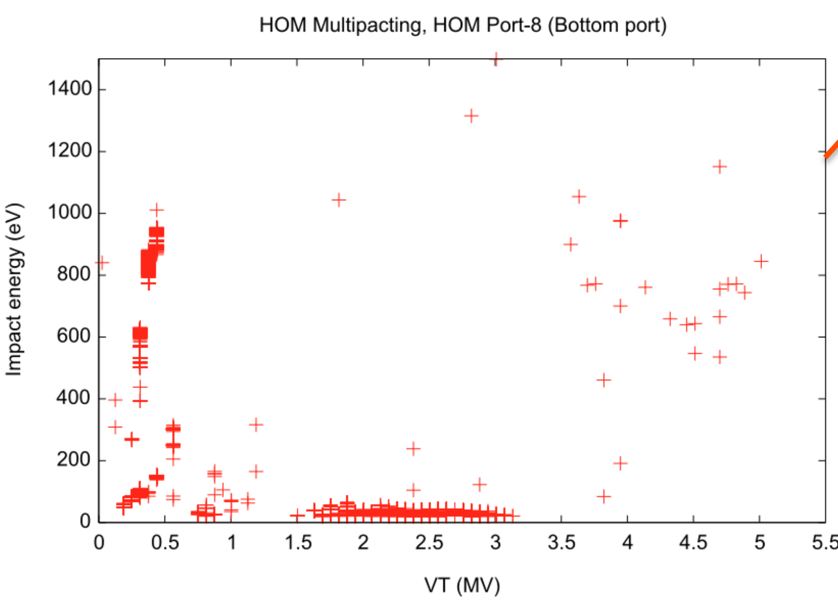
81mT/
3.4MV

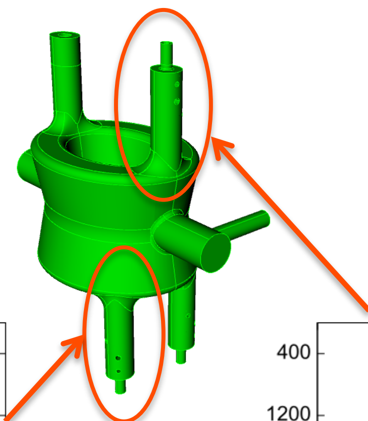


MP Map in HOM Couplers

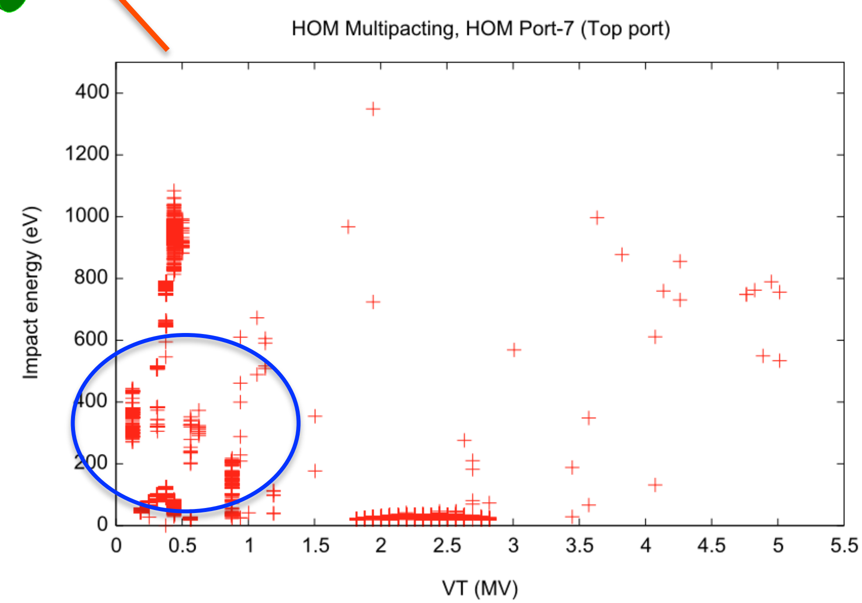
- Simulated using ACE3P Track3P multipacting analysis tool
- MP trajectories at the port opening and the filter capacitor regions
- Impact energies of MP bands at low V_T in range of significant SEY

MP map on
bottom HOM coupler

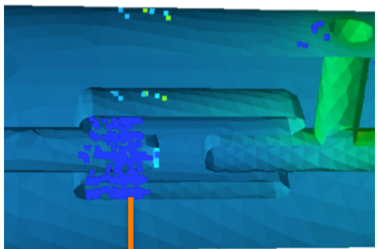




MP map on
top HOM coupler

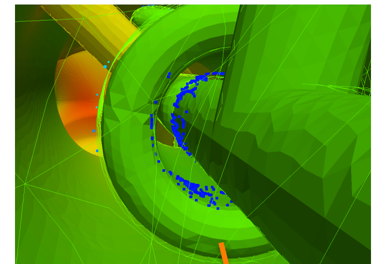


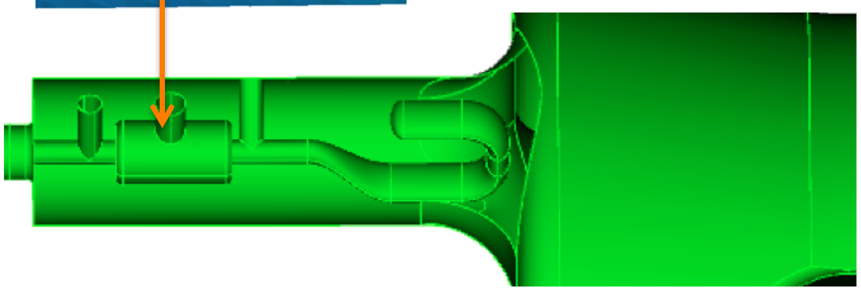
MP Location in HOM Couplers

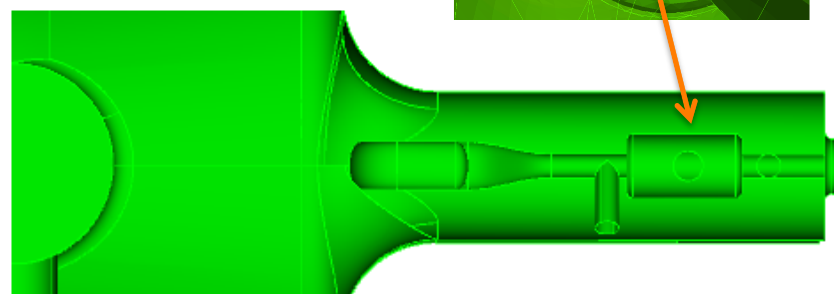


bottom HOM

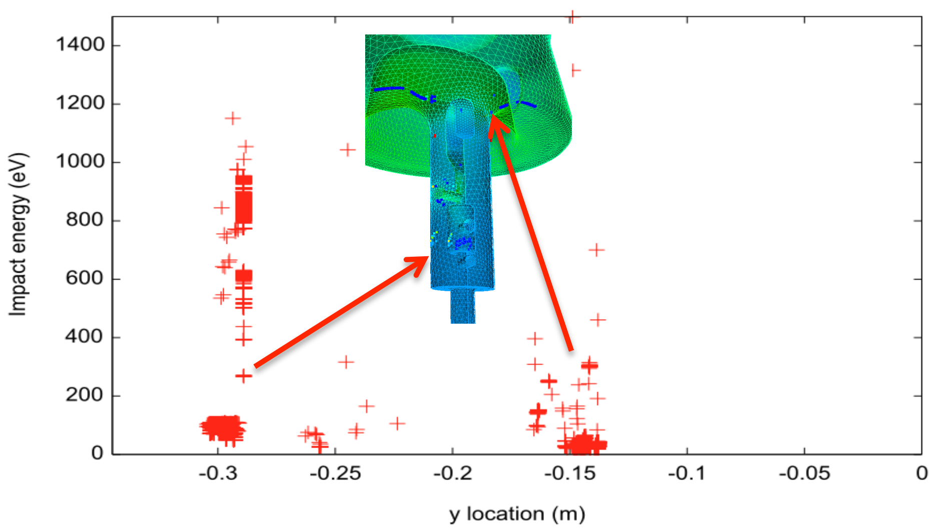
top HOM



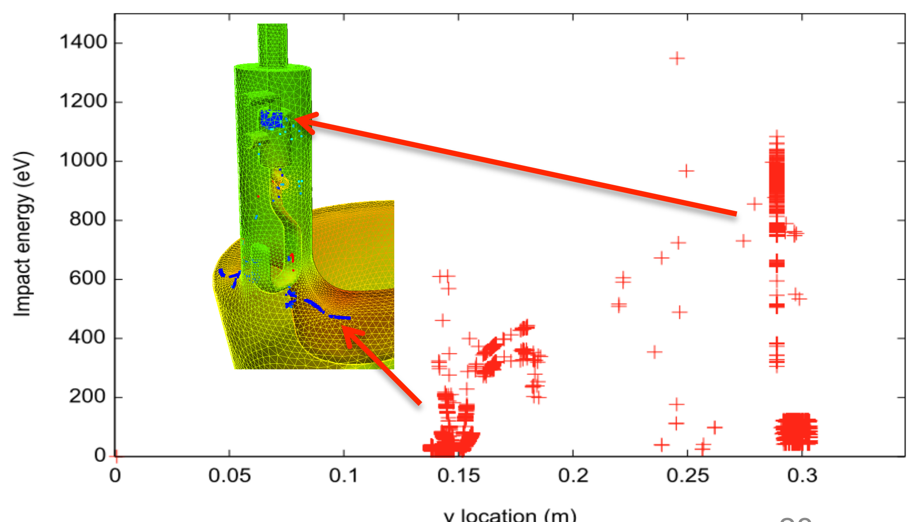




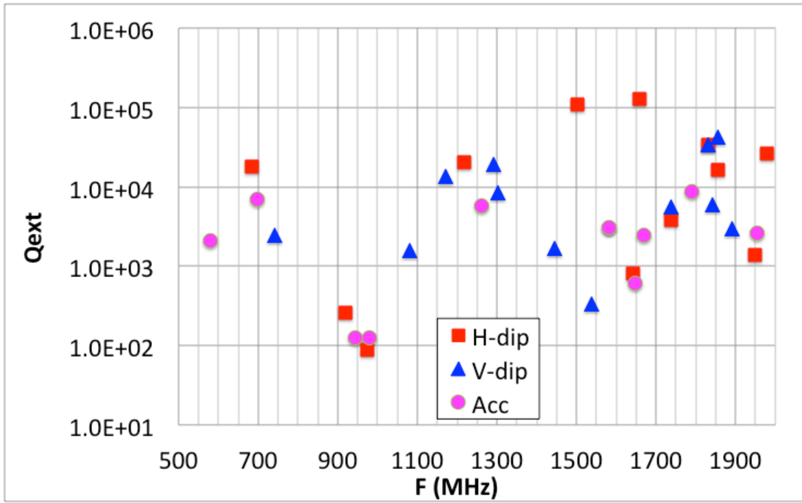
HOM Multipacting, HOM Port-8 (Bottom port)

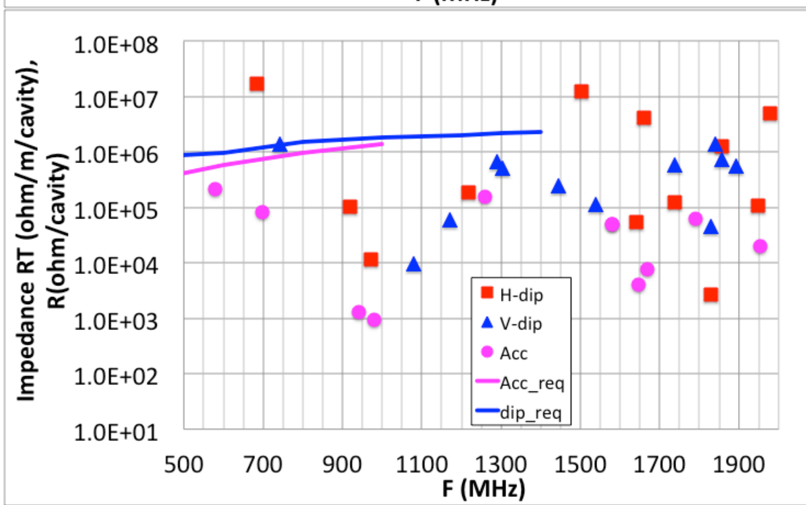


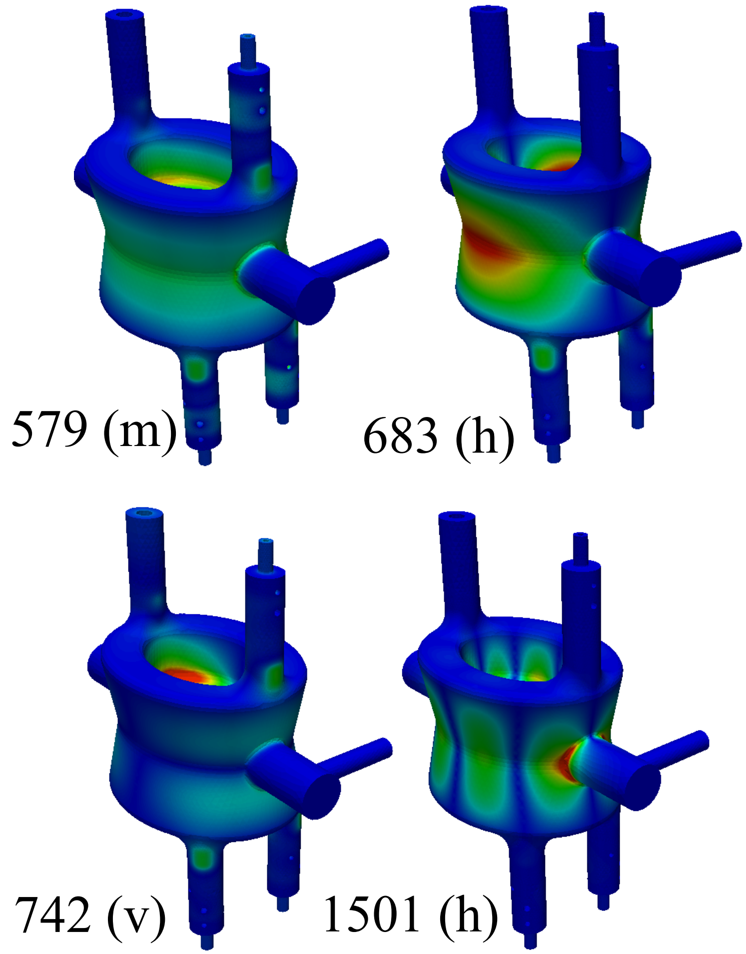
HOM Multipacting, HOM Port-7 (Top port)



HOM Damping



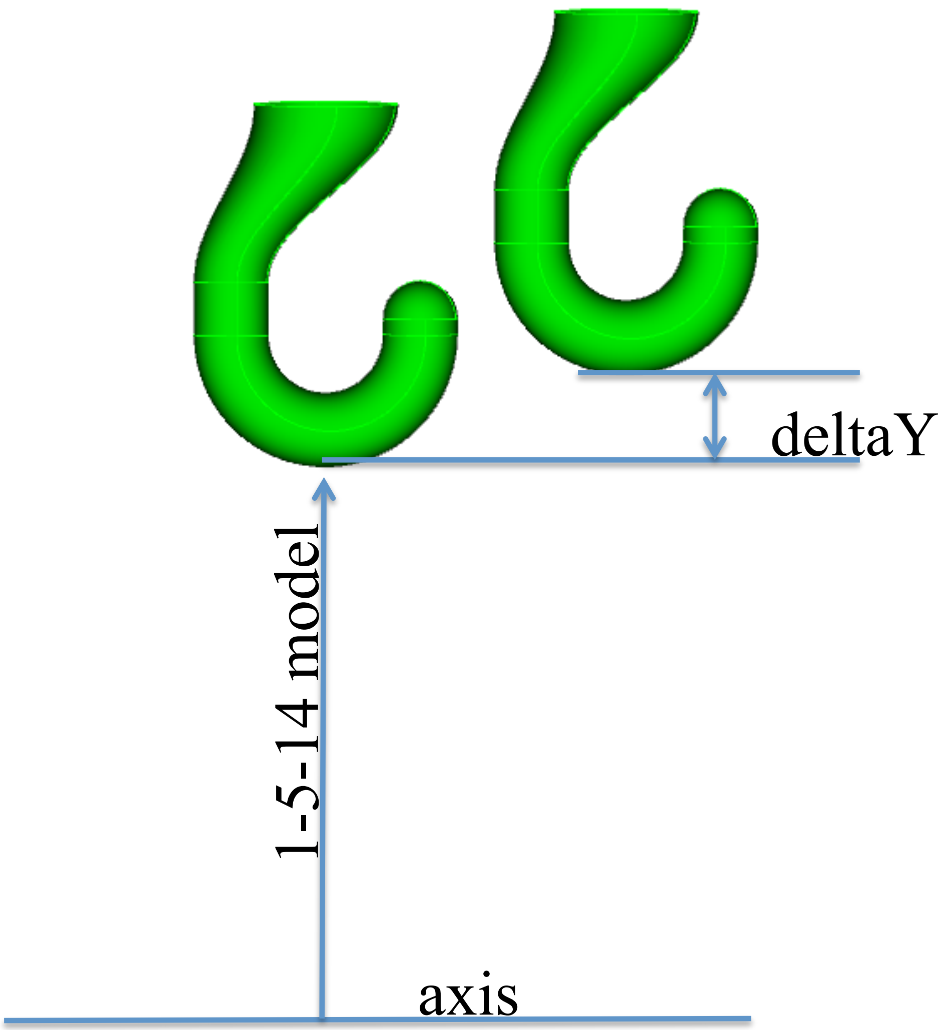


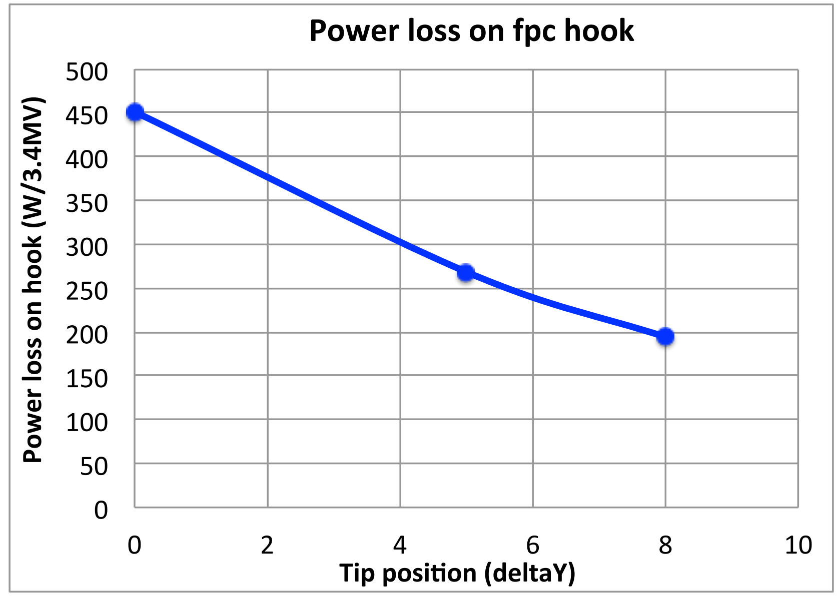


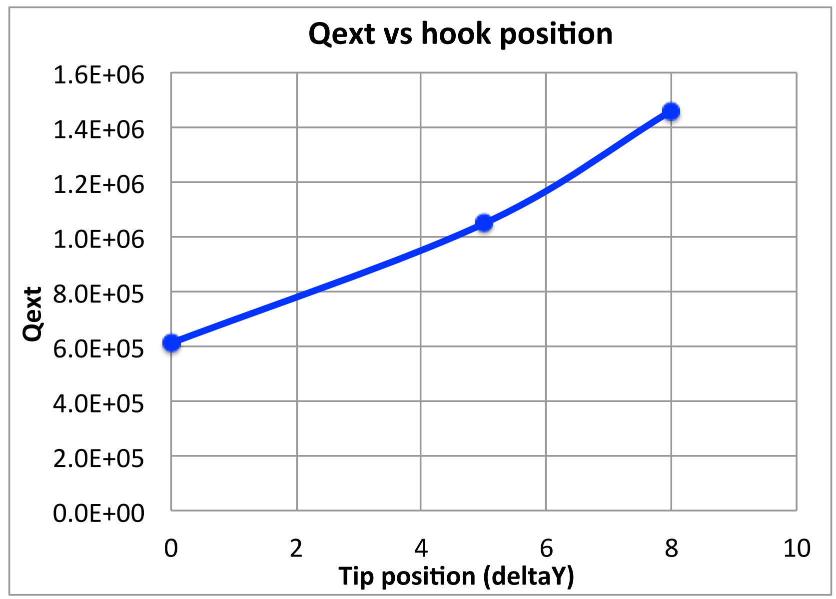
- Most of the HOMs are well damped, except a few modes may need improved damping
- Qext of deflecting mode (through HOM coupler): 9.4e9

DQW – FPC Coupler Heating

- VT=3.4MV

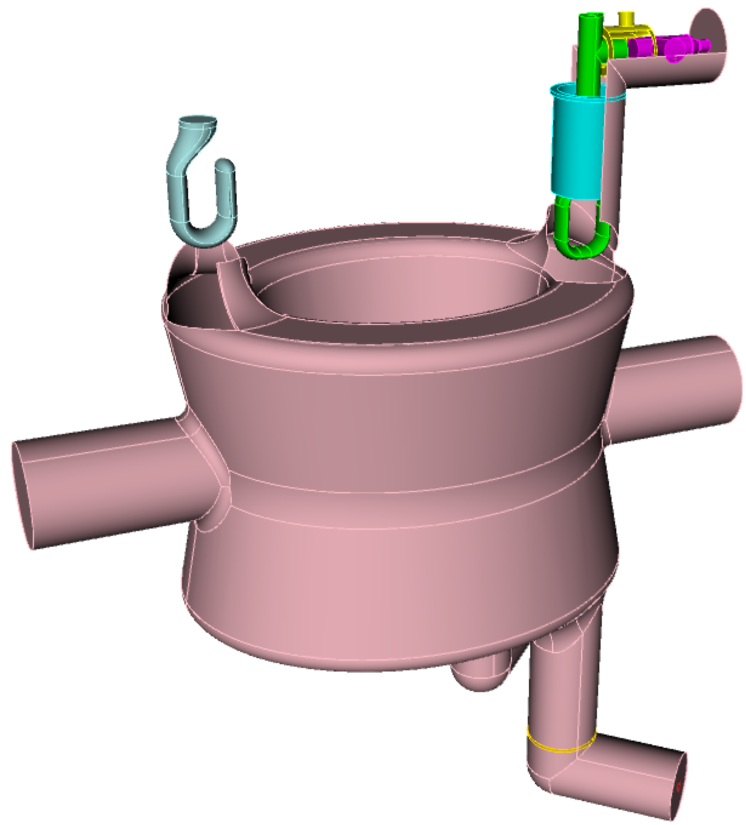






DQW With Improved Couplers

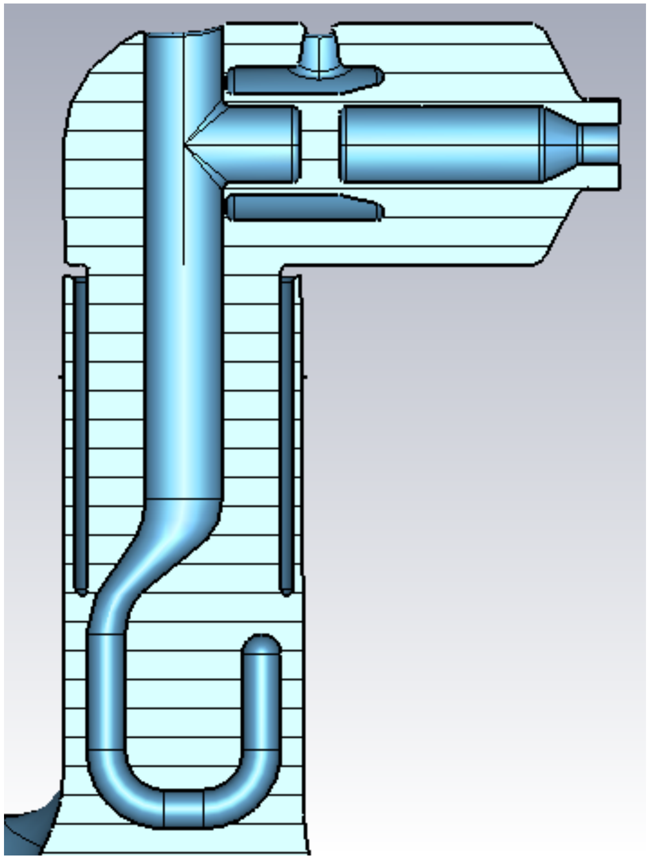
- 4/30/14 mode (Silvia)
  - New FPC coupler hook
  - New HOM hi-pass filter
- RF and multipacting analysis in progress

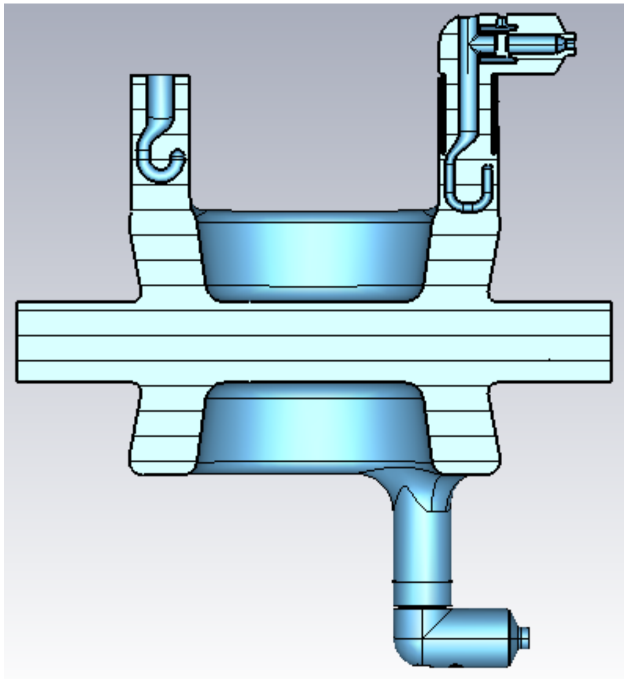


HOM filter

HOM coupler details (Binping) for ACE3P model

Based on model HOM-20mmrods_L_4D_best.cst
and model SPS-EDQWCC_HOM-20mmrods_L_4D_longer_triaxial_5mmCloser.cst





Parameter List

Name	Value
Cc1L	19
Cc2L	11.5
CcD	LD
L1D	LD
L1P	1
L2D	LD
L2P	1
LD	19.8
LcD	12.7
alpha	-10
alpha2	82.4

Length unit: mm

Summary

RFD

- HOM and FPC Couplers developed for both Vertical and Horizontal crabbing
- Two damping options, WG HOM coupler and Hi-pass filter HOM coupler fully developed
  - Both satisfy damping requirement and no significant multipacting
  - Both are applicable to Vertical and Horizontal crabbing
- Coupler-cavity interfaces are the same for both crabbing designs – same cavity body, "same" HOM couplers
- FPC coupler optimized to minimize RF heating (hook pickup for H-crabbing, E-probe for V-crabbing)

DQW

- Surface field and FPC coupler heating analyzed
- Multiphysics analysis and RF simulation of hi-pass filter HOM coupler helped to identify weak points in the original design
- Areas identified have been addressed in the new coupler design, detailed RF and multipacting analysis for the new design is in progress

Plan

- Evaluate impact of integration details on RF (modifications, etc)
- Multi-physics analysis of prototype – thermal, mechanical, Lorentz Force detuning, etc
- Cavity test setup and benchmark – Frequencies and RF measurement quantities at different testing stages
- Field emission and related issues

- Design and optimization toward the LHC implementation.