AUP HL-LHC RFD Cavity RF Design

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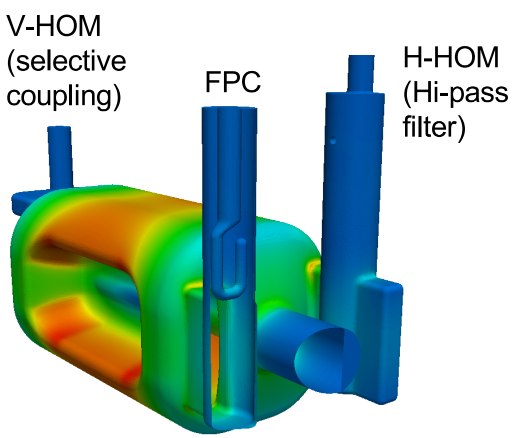
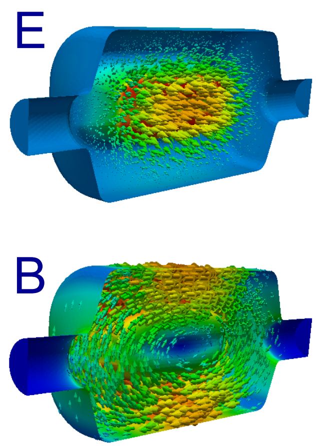
HL-LHC RFD Design Freeze Review – FNAL – March 15, 2018

Outline

- Issues to be addressed for the HL-LHC crab cavity to meet HiLumi operation requirements
  - High HOM beam power at 760 MHz mode
  - High octupole current for compensating HOM effects
- RFD design Improvements
  - Cavity shape - to minimize HOM beam power at 760MHz
  - HOM couplers - to minimize HOM impedance
- Dimension sensitivity analysis
- Summary

LARP Prototype RFD Crab Cavity

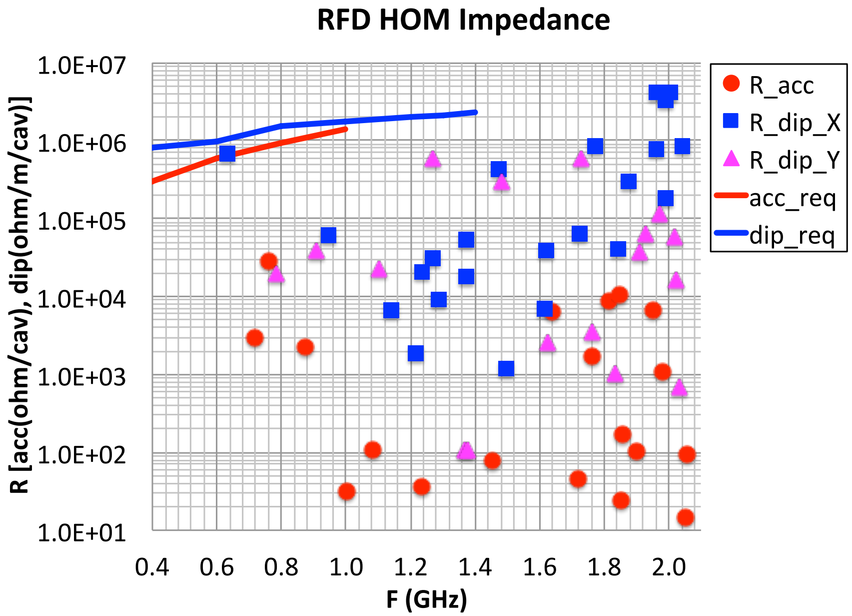


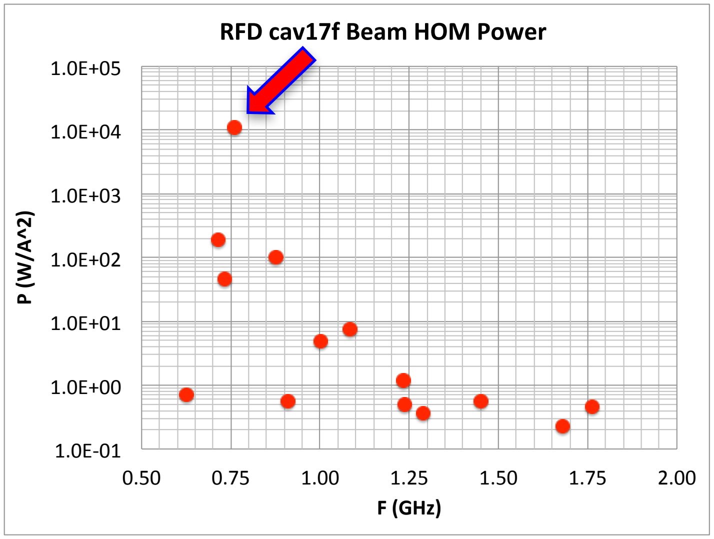


LARP Prototype RFD Crab Cavity	
Frequency (MHz)	400.79
Operating Mode	TE11
Lowest dipole HOM (MHz)	633
Lowest acc HOM	715
High R/Q acc HOM	760.9
Iris aperture (diameter) (mm)	84
Transverse dimension (mm)	281
Vertical dimension (mm)	281
Longitudinal dimension (w/o couplers) (mm)	556
R_T (ohm/cavity)	433
V_T (MV/cavity)	3.34
Bs (mT)	55.5
Es (MV/m)	32.6

- No lower order mode
- Compact, clears the second beam pipe
- Minimal multipole fields with shaped pole face

760 MHz Mode Issue of the LARP Prototype Cavity





International Review of the Crab Cavity Performance for HiLumi

April 3-5, 2017 CERN

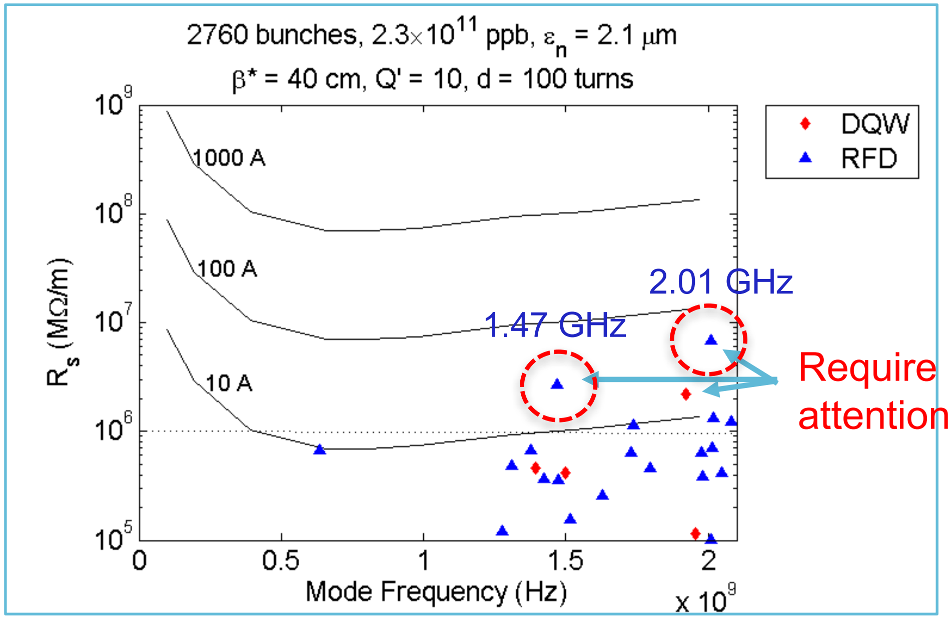
- Impedance meets beam dynamics requirements (2016)
- (Elias Métral, Joint LARP CM26/Hi-Lumi Meeting, SLAC, 19/05/2016)

- Acc. HOM mode at 760.94 MHz too close to beam resonance at 761.50 MHz
- Resulting in beam HOM power >10kW
- Design spec for beam power: < 1kW

Requirements from recent beam dynamics study

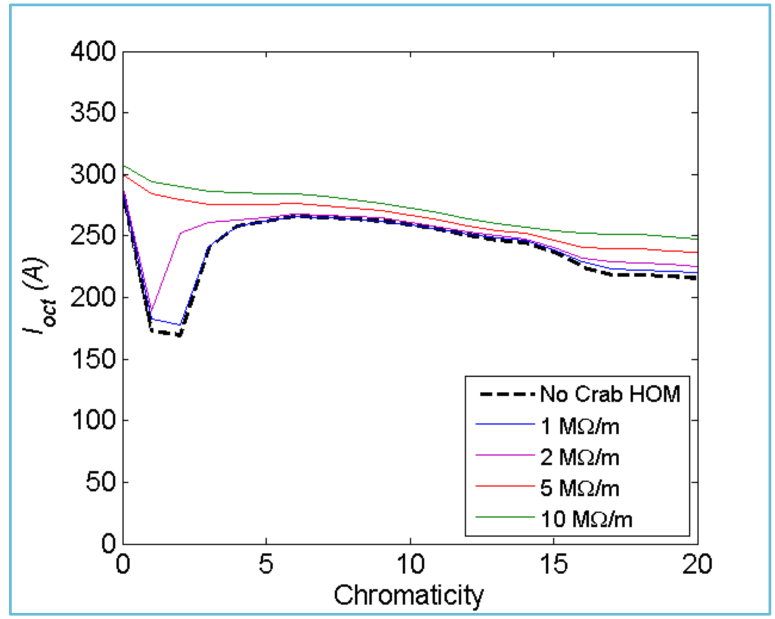
- Most HOMs require negligible octupole current, even if they fall on the couple-bunch line

(no other sources of impedance) (Nov. 2017)



- In order not to affect the operational scenarios we need to keep the CC HOMs below 1 MΩ/m

Ultimate scenario
2760 b, 2.3×10^{11} ppb, β^* = 40 cm, ε_n = 2.1 μm



S. Antipov, D. Amorim, N. Biancacci, X. Buffat, L. Carver, F. Giordano, G. Mazzacano, A. Mereghetti, E. Metral, S. Redaelli, B. Salvant, 7th HL-LHC Collaboration meeting, CIEMAT, Madrid – 15.11.17 (Nov. 2017)

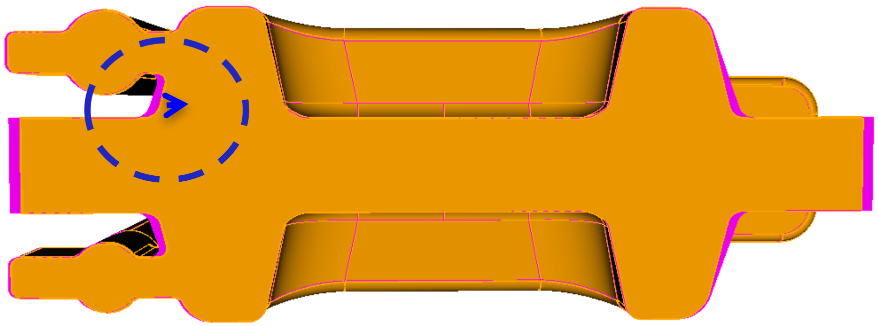
Requirement Summary

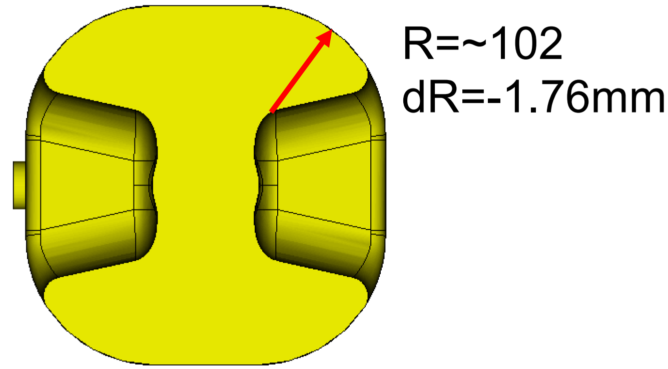
- 760 MHz beam HOM power <1kW
- Transverse impedance < 1MΩ /m
- HOM Filters Output Power $\leq 1.5\ W$ *at* $400.79\ MHz$
- Longitudinal HOM shunt impedance $R_{sh} < 200\ \mathrm{k\Omega}$
- Field multipole of operating mode

  Most important, sextupole $b_3 < 1000$ mT/m^2 at total 10MV deflection voltage

Minimizing 760 MHz Mode beam power, by detuning HOM frequency farther off beam resonance

Beam line spacing: 40.079 MHz, 19^{th} harmonic at 761.5 MHz





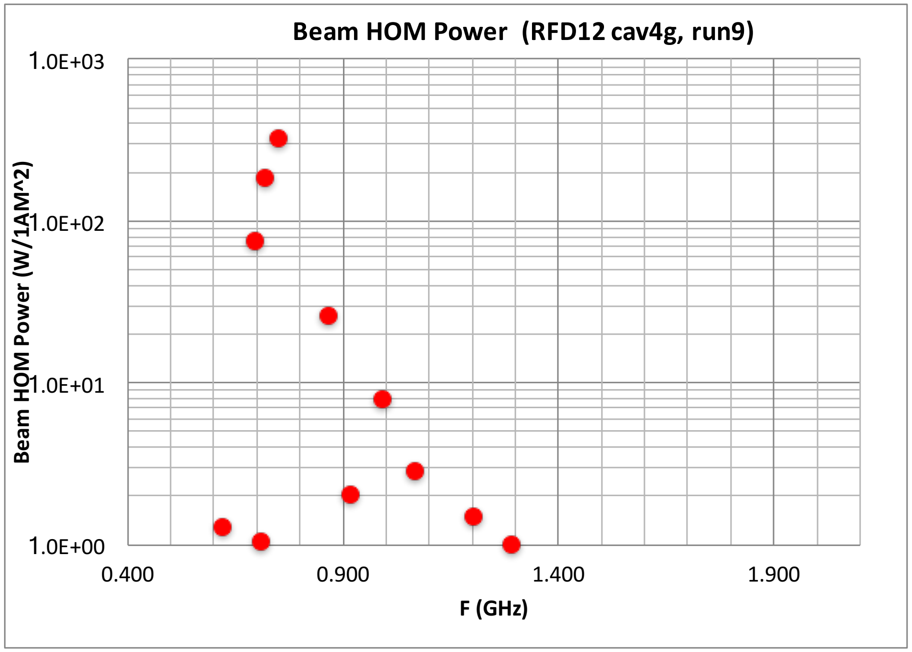
- Various options explored to detune the 760 mode
- Approach adopted: reducing gap volume around beam pipe region
  - 400 MHz dipole and 760 MHz monopole modes opposite in dF sensitivity
  - lowers frequency of 760 mode (target: |dF| > 6MHz)

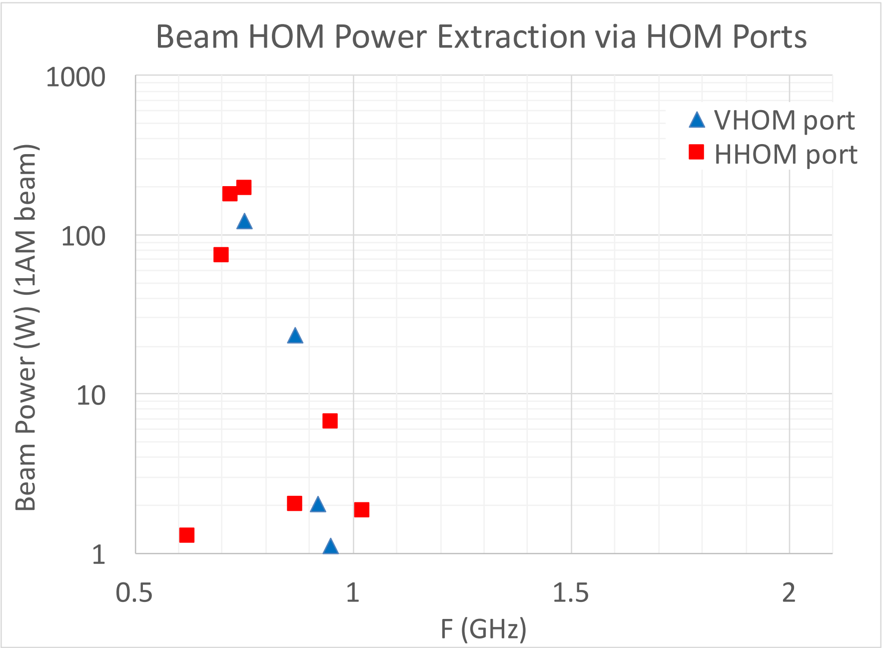
- Operating mode frequency
- tuned to 400.79 MHz by adjusting rounding "R" by -1.76mm

Achieved -9 MHz detuning of the 760 MHz mode from beam resonance of 761.5MHz

New frequency of this longitudinal HOM : 752.2 MHz

Beam HOM Power Reduced from ~10kW to ~ 500W





- HOM power calculated for 1-AM beam
- σ_z=76mm

Beam HOM power below 1 kW. Meet design requirement.

New Design Parameter Comparison

RFD Crab Cavity		
	LARP Prototype	New Design
Frequency (MHz)	400.79	400.79
Lowest dipole HOM (MHz)	633	636
Lowest acc HOM	715	699
High R/Q acc HOM	760.9	**752.2**
Transverse dimension (mm)	281	281
Vertical dimension (mm)	281	281
R_T (ohm/cavity)	427	431
V_T (MV/cavity)	3.34	3.34
Bs (mT)	55.5	55.1
Es (MV/m)	32.6	35.0

- Frequency of high beam power mode (760MHz) 9.3 MHz below beam resonance
- Good RF parameters maintained

US HL-LHC AUP

Multipole $B_{3,}$ $B_{5,}$ B_7

Assume Def mode symmetry (only cos term)

$$E_{acc}(r,\varphi) = \sum_n E_{acc}^n r^n \cos(n\varphi) \qquad (e^{j\omega z.c} \text{ included in } E_{acc}^n)$$

$$\Delta\vec{p}_{\perp}^{(n)}(r,\varphi) = \frac{1}{c}\int_0^L F_{\perp}\,dz = \frac{je}{\omega} n r^{n-1}\left(\hat{u}_r \cos(n\varphi) + \hat{u}_{\varphi}\sin(n\varphi)\right)\int_0^L E_{acc}^n(z)\,dz$$

$$b_n = \int_0^L B^{(n)}\,dz = \frac{1}{ec}\int_0^L F_{\perp}^{(n)}\,dz = \frac{nj}{\omega}\int_0^L E_{acc}^{(n)}\,dz$$

$$\Delta\vec{p}_{\perp}^{(n)}(r,\varphi) = e\vec{V}_T(r,\varphi) = e\sum_n b_n r^{n-1}\left(\hat{u}_r \cos(n\varphi) + \hat{u}_{\varphi}\sin(n\varphi)\right)$$

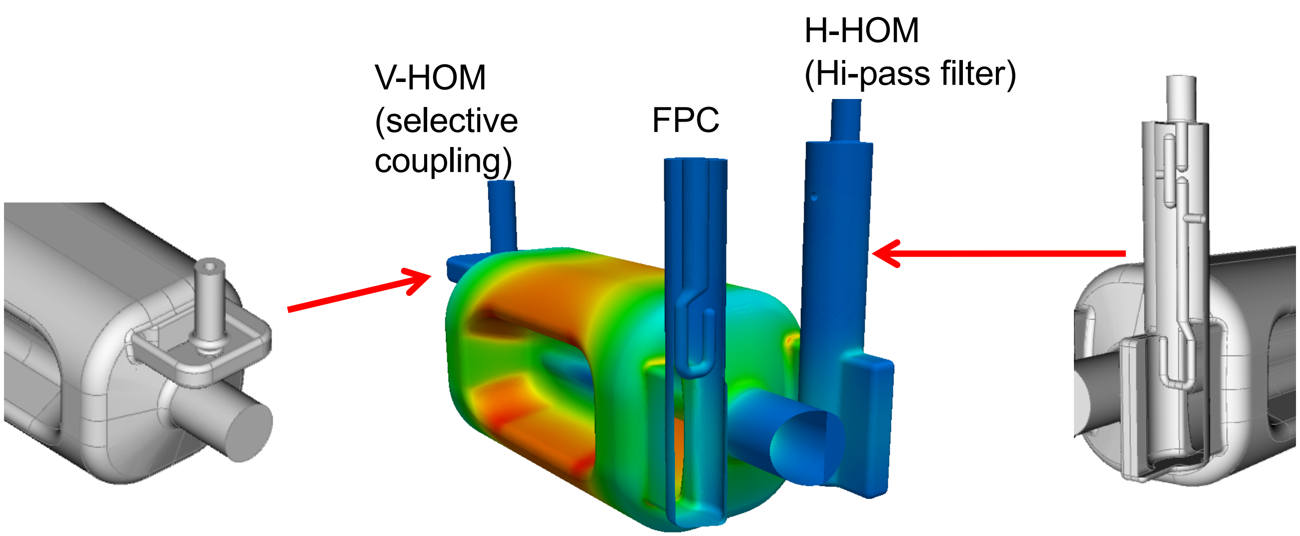
$$V_{def} = b_1$$

Component	Value (total VT=10 MV)
b3	429 mT/m^2
b5	-1.8e6 mT/m^4
b7	-4.9E+08 mT/m^6

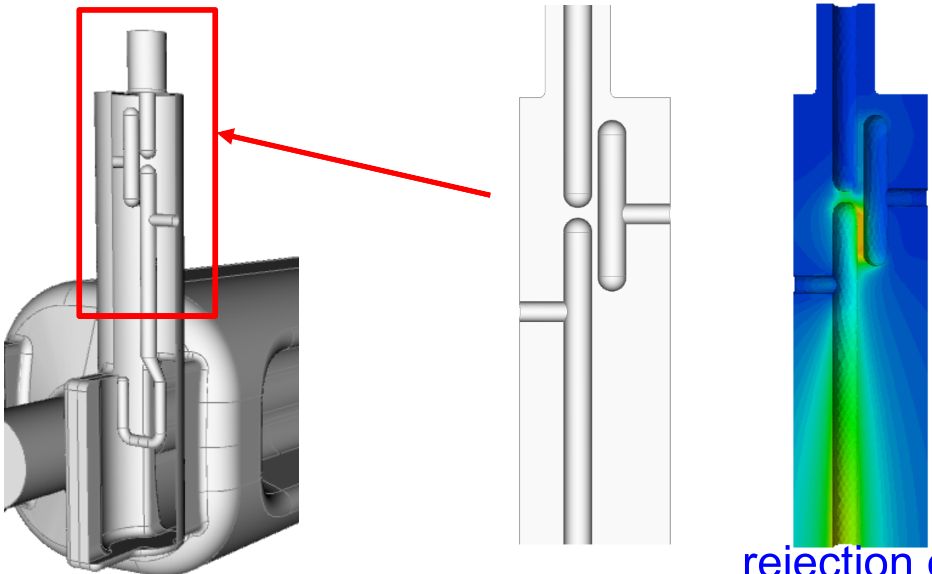
- Multipole components barely changed as compared with LARP prototype design
- b3 < 1000 mT/m^2, meet design requirement

HOM Impedance Improvements

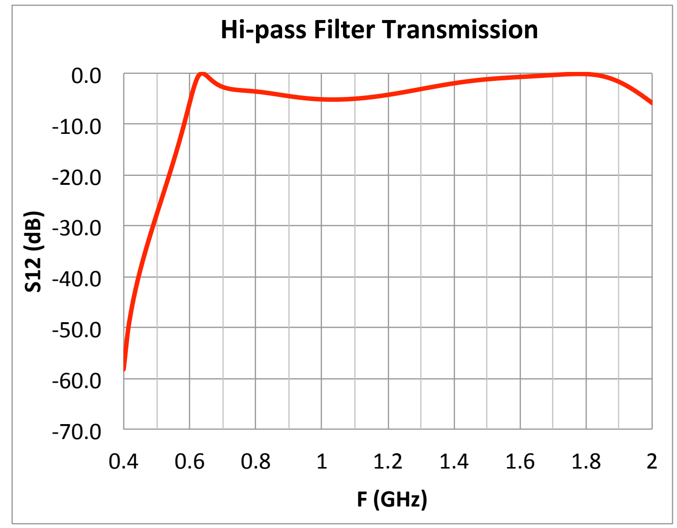
- Cavity shape modification altered the damping of HOM
- Re-optimized both H-HOM and V-HOM couplers
- Simplified port interface



H-HOM Coupler
Cutoff waveguide stub + high-pass filter



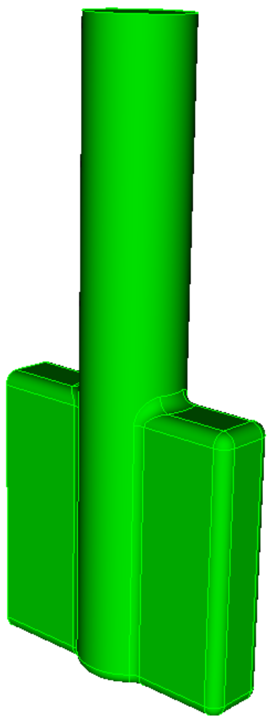
rejection of operating mode

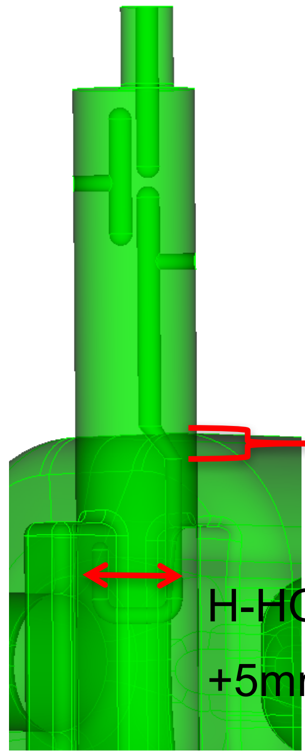


- HHOM coupler and filter in low field region – minimizes RF heating
- Waveguide stub add additional rejection of operating mode – loosening tolerance on filter dimensions

HHOM Coupler Modifications to Enhance Damping

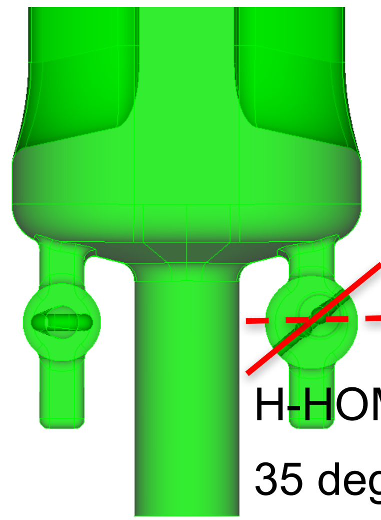
Larger waveguide stub size (170x40)





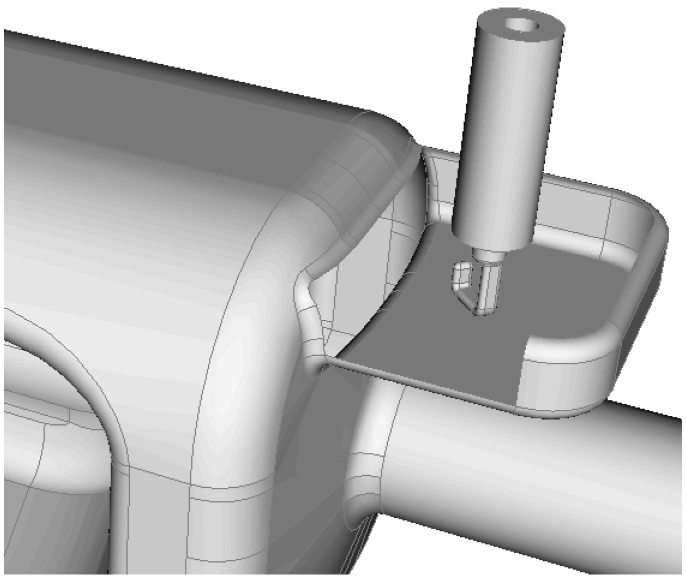
Transition
+10mm higher

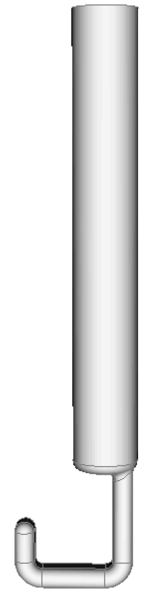
H-HOM width
+5mm wider



H-HOM hook
35 degree angle

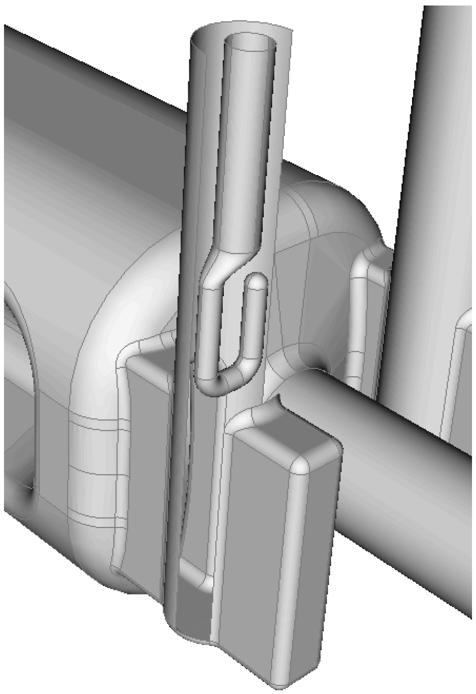
V-HOM Coupler
Cutoff waveguide stub + hook pickup

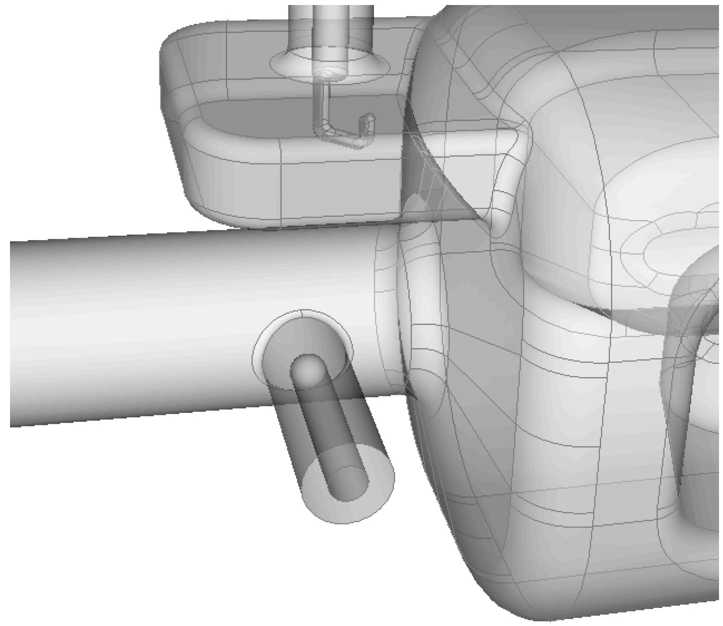




- Waveguide stub selectively couples to acc and vertical HOMs – no filter needed
- Hook provides both electric and magnetic coupling, improving damping of HOMs at higher frequencies
- Waveguide stub dimension slightly larger, (same as HHOM) , to enhance coupling

FPC and Field Pickup Port
(minor location adjustment from the LARP prototype)





FPC:

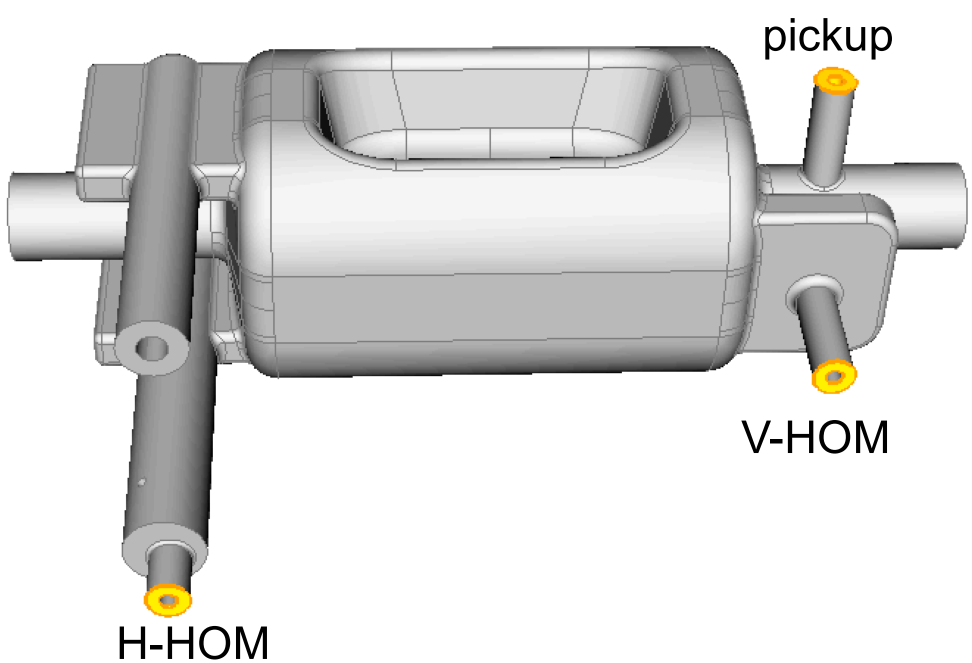
- Waveguide stub + hook
- Qext: $5x10^5$

Pickup port:

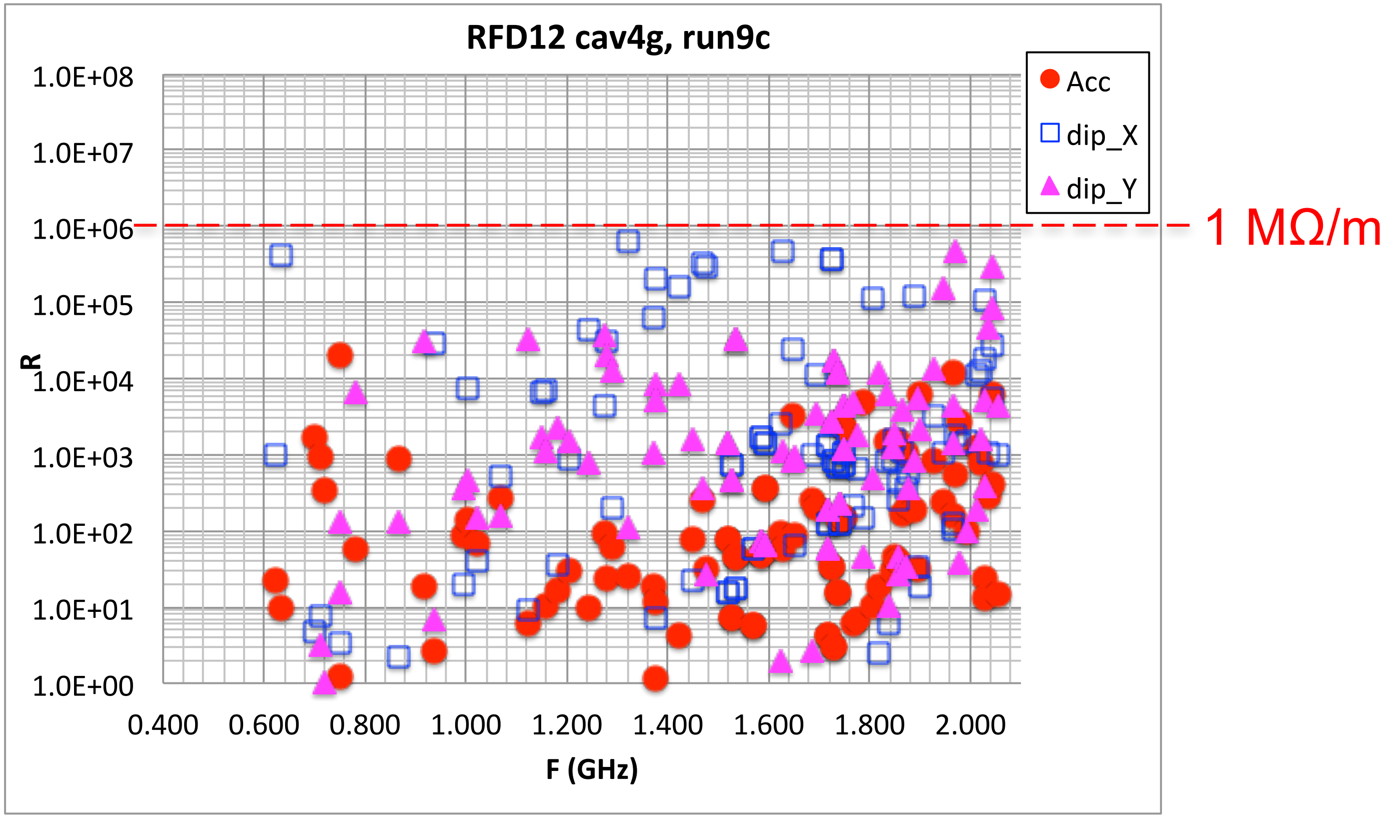
- On the V-HOM side of cavity
- Need to pickup ~ 1.5W. Qext ~ $2x10^{10}$

Port Interface Simplified to Same Dimension

- Diameter for all ports, HHOM, VHOM, field pickup: 37.879 mm
- One feed through design for all ports



HOM Impedance of the New Design



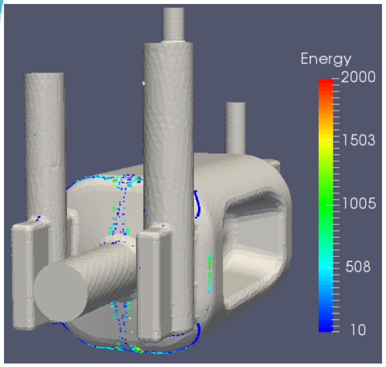
HOM impedance below 1 MΩ/m up to 2 GHz
Longitudinal shunt impedance < 200 k Ω
Meet requirement

RF Heating of Coupler Elements

Power [W/(3.4MV/cavity]	LARP Prototype	AUP HL-LHC New Design	
FPC hook	69	73	Copper NC
H-HOM hook	0.0007	0.0014	Nb SC
V-HOM (probe) HOOK	0.47	0.51	Copper NC
Field pickup probe		0.09	Copper NC

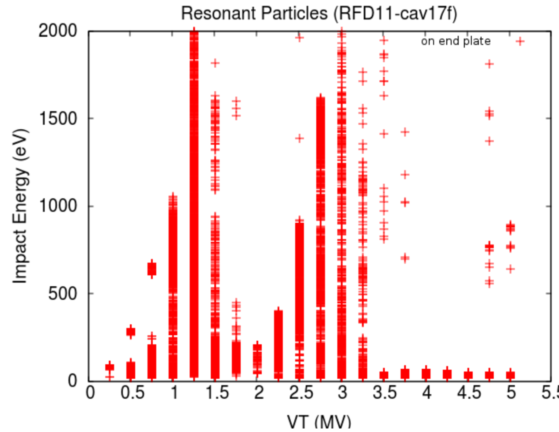
Low RF heating on coupler elements
No thermal issue

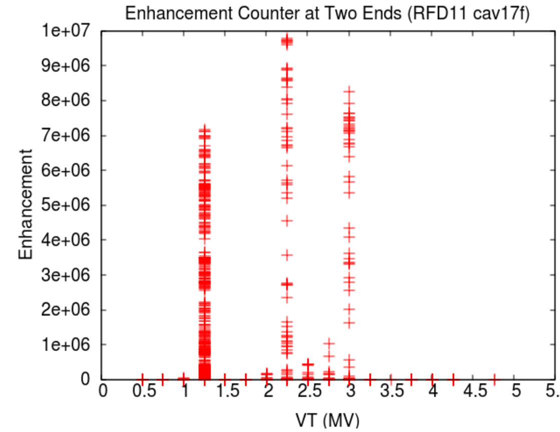
Multipacting



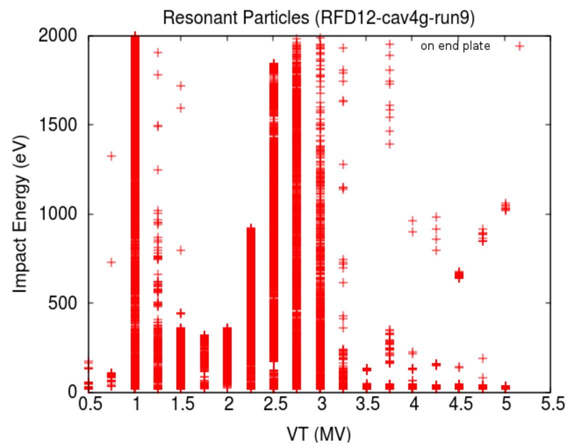
Multipacting mostly on end-plate

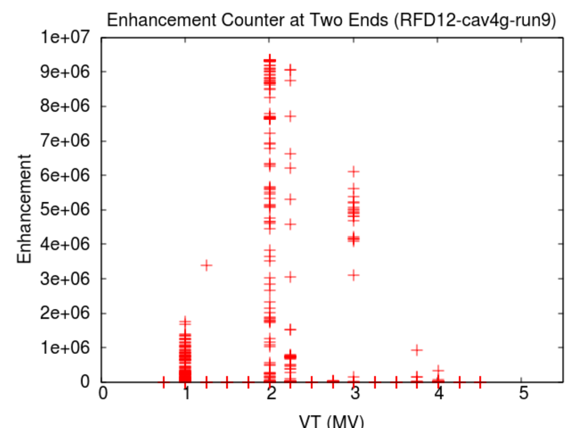
LARP prototype (RFD11-cav17f)





New design (RFD12-cav4g)





Impact Energy

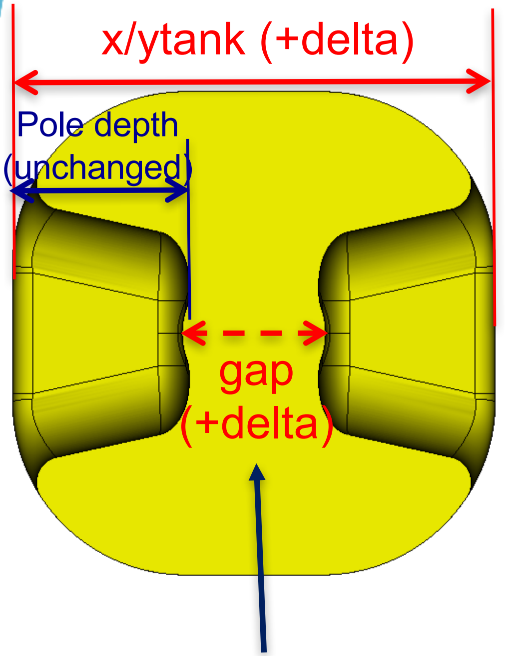
Enhancement Counter

Similar to LARP prototype cavity.

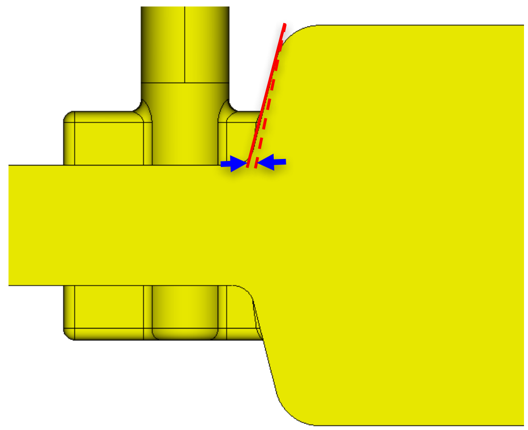
Will not be a problem

Cavity Dimension Sensitivity to HOM Impedances

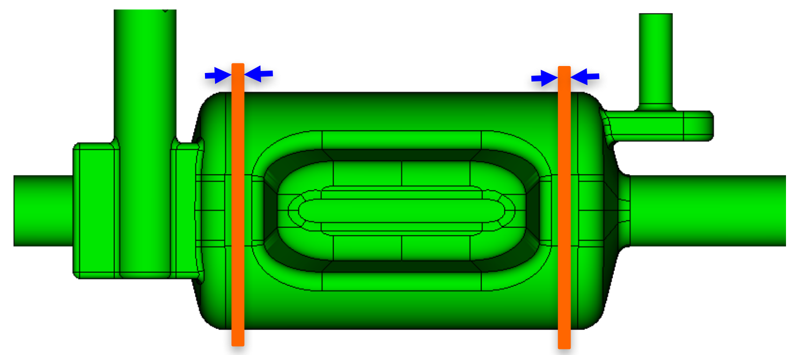
Transverse dimension



End plate tilt

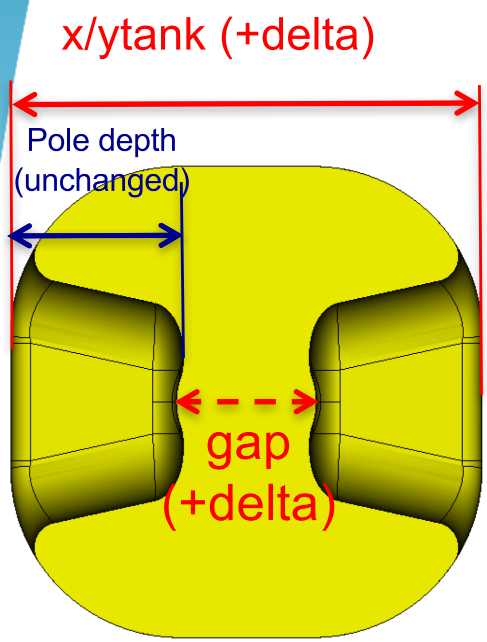


Trim

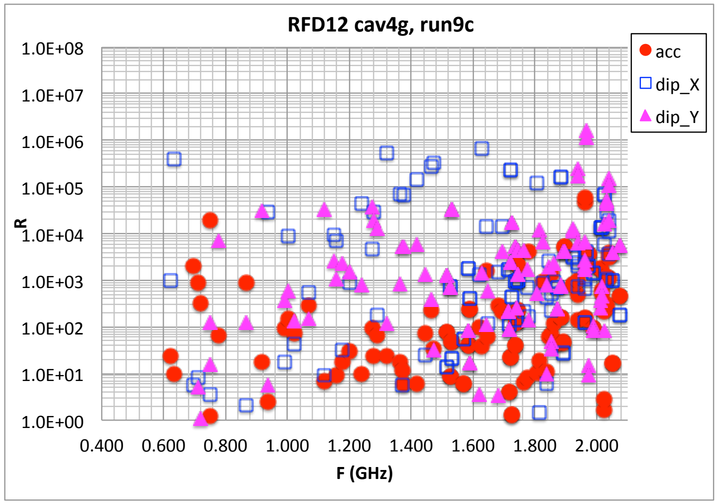


- Assume depth of the pole kept unchanged
  - Pole gap change same amount as cavity transverse dimension
  - Resulted in very small frequency deviation

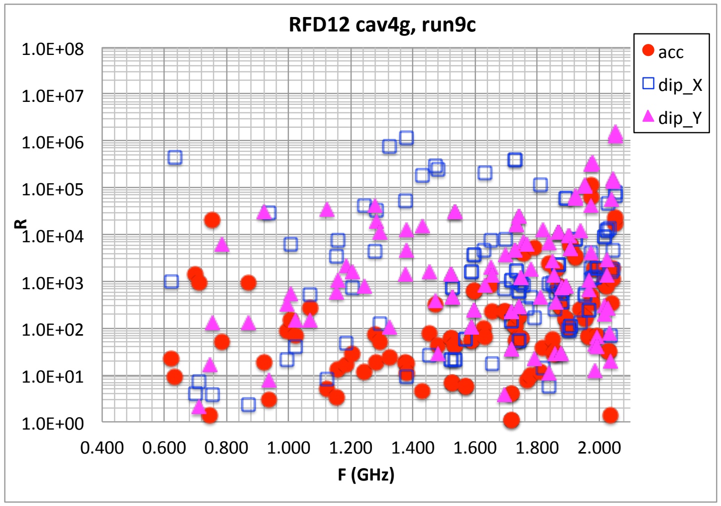
Cavity Transverse Size Error



- +0.75mm



- -0.75mm

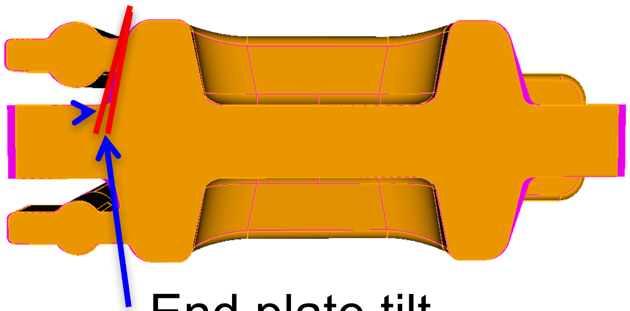


- Frequency offset within tuner range
- HOM Impedance maintained with a simple mitigation by rotating VHOM hook angle

(VHOM coupler hook orientation rotated for a mode at above 2 GHz (2.05) for better damping)

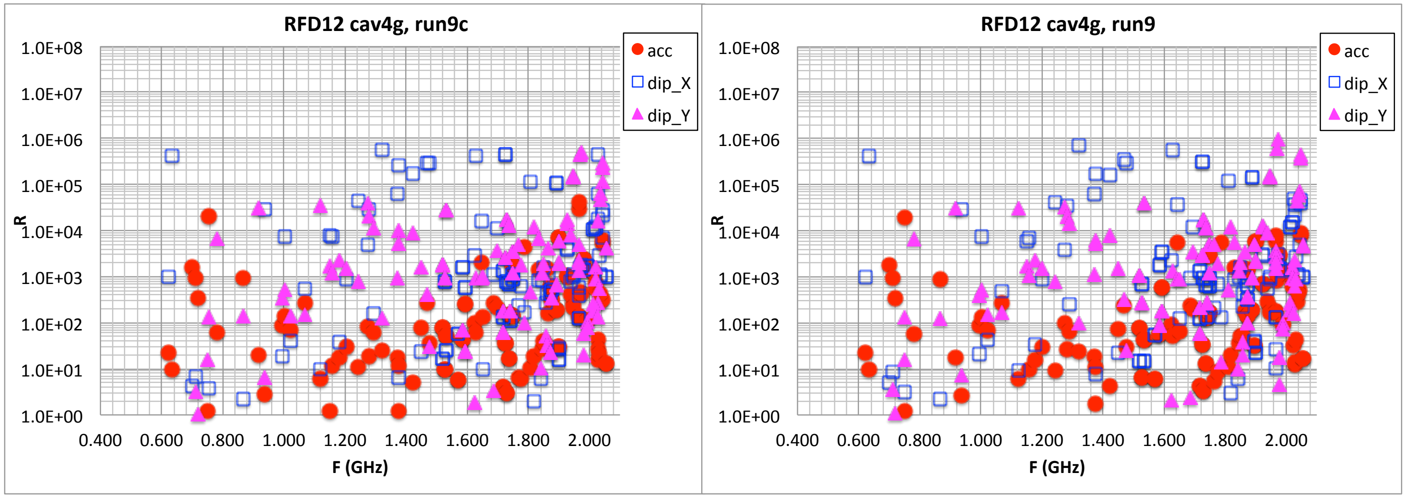
HOM impedance maintained in 1MΩ/m level with realistic cavity dimension error

End Plate Tilt Error



+2mm

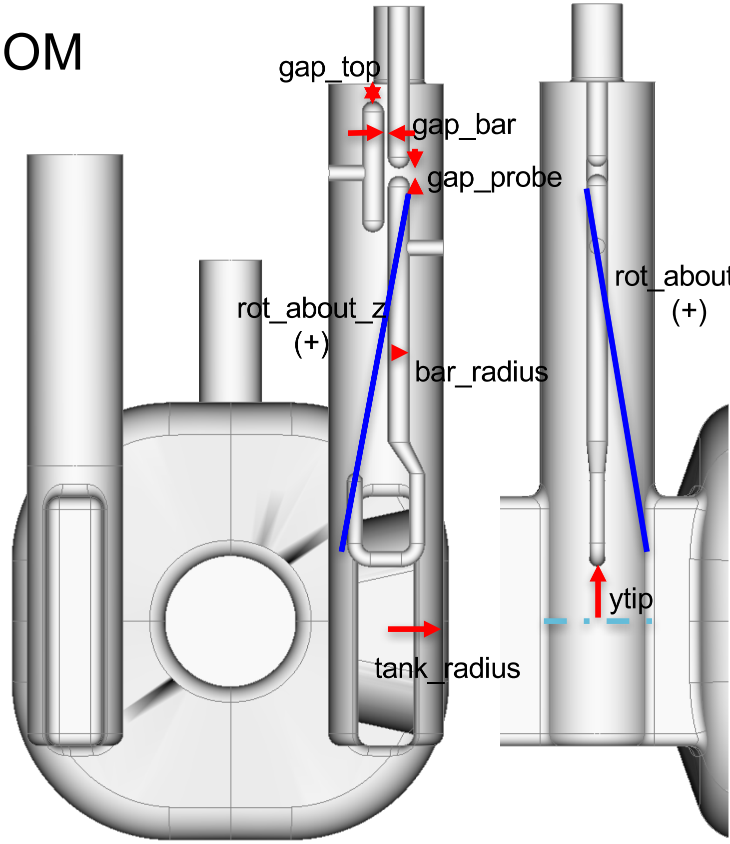
-2mm



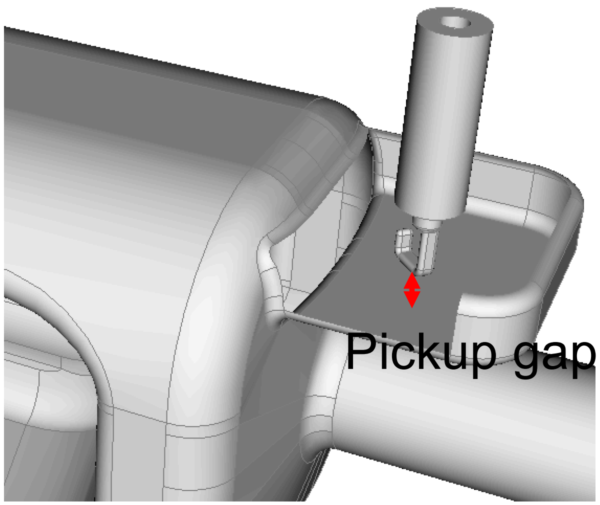
HOM impedance maintained in 1 MΩ/m level with realistic cavity dimension error

HOM Coupler Dimension Sensitivity to HOM Impedances and Operating Mode Rejection

H-HOM



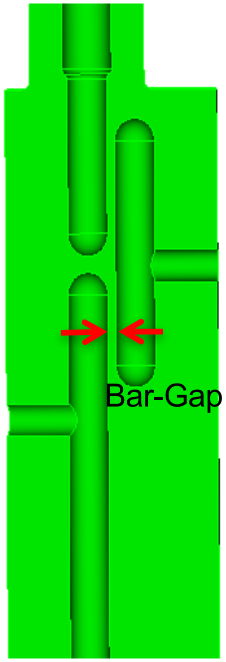
V-HOM



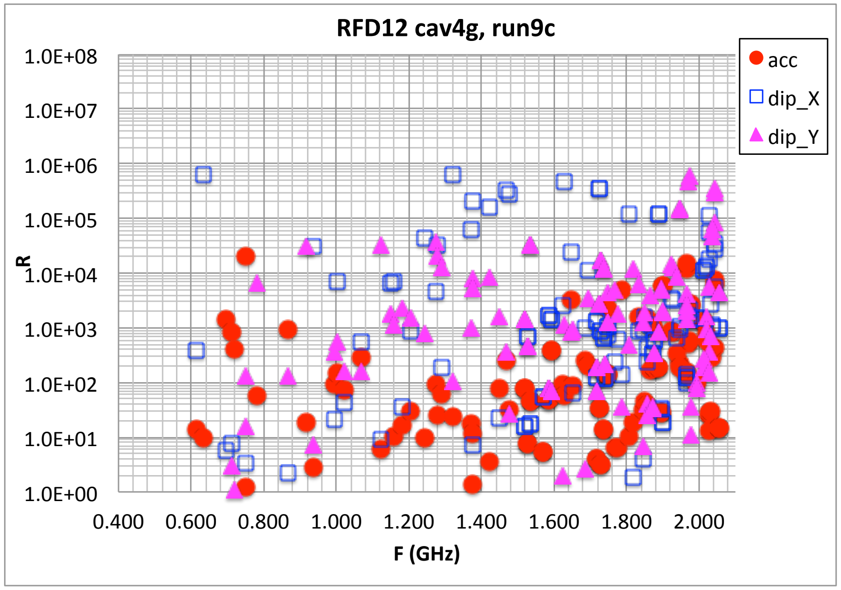
- HOM damping
- Filter performance - rejection of 400.79 MHz operating mode

HHOM coupler filter bar-gap

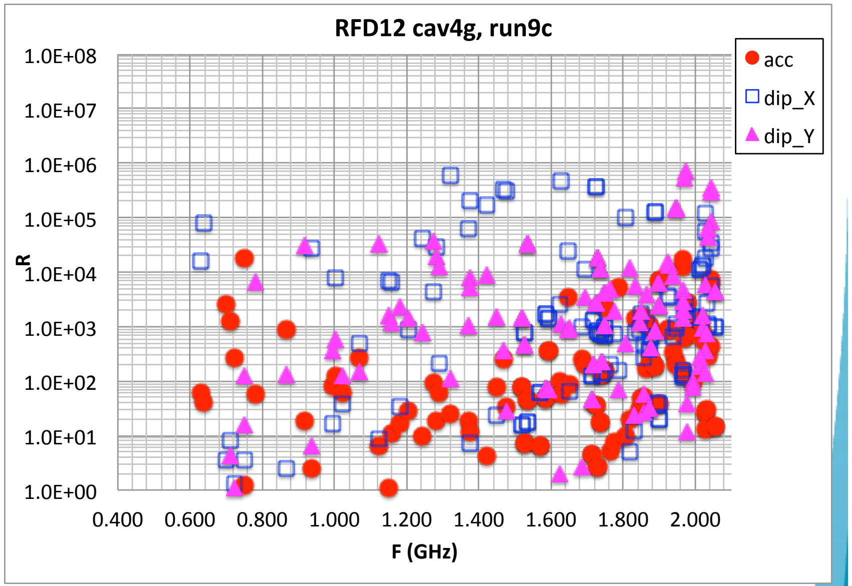
(design: bar_gap=2.8mm)



-0.2mm



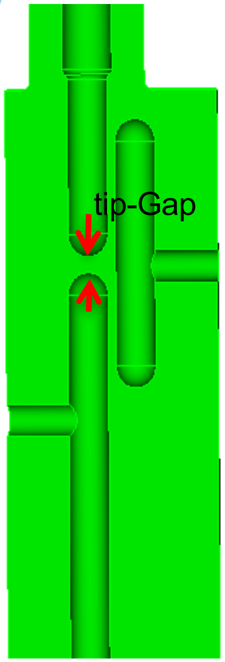
+0.4mm



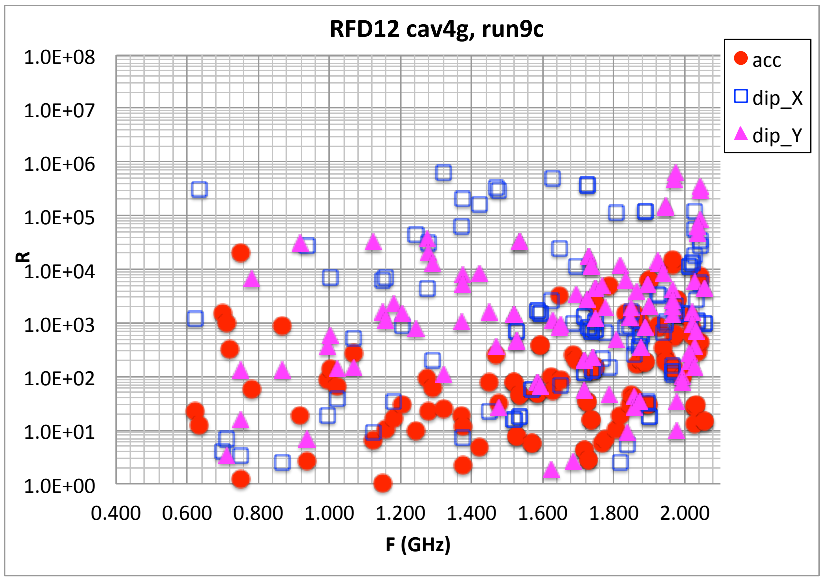
Impedance insensitive to bar gap error
Filter bar-gap dimension error barely affect impedance

HHOM coupler filter tip-gap

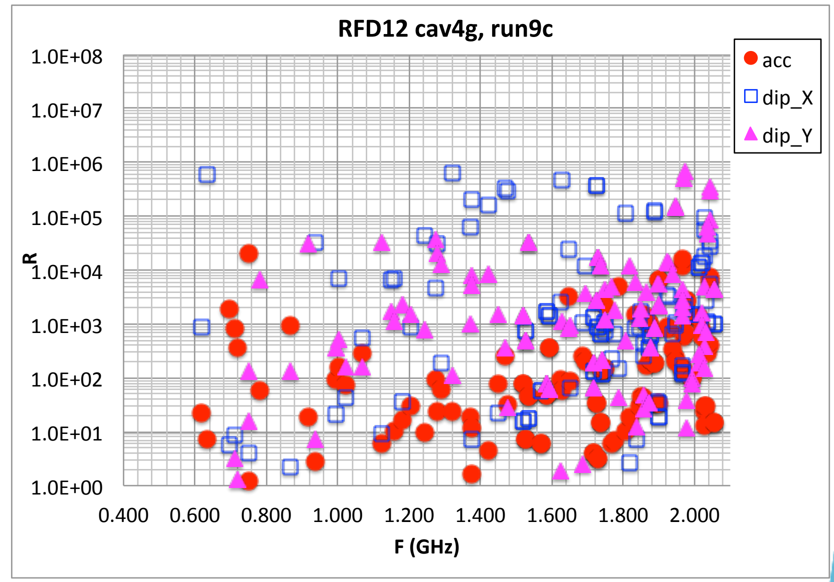
(design: tip_gap=5mm)



delta_gap = +1mm



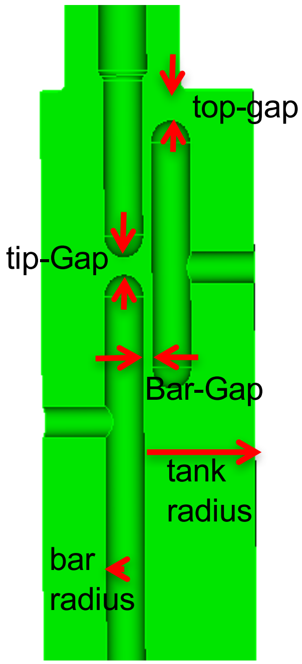
delta_gap = -1mm

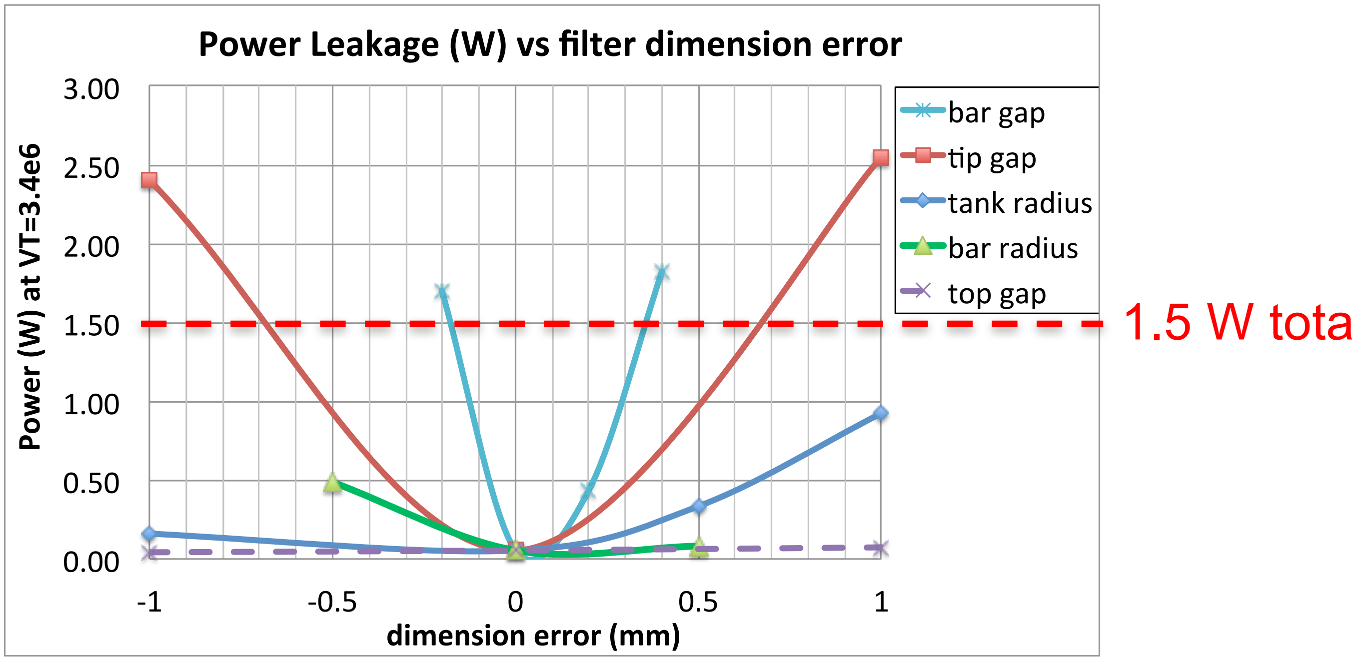


Impedance insensitive to tip gap error
Filter tip-gap dimension error barely affect impedance
(Similarly with other filter dimension errors)

Power Leakage Due to HHOM Filter Dimension Errors

- Filter dimension errors may weaken rejection of operating mode, lead to RF power leakage

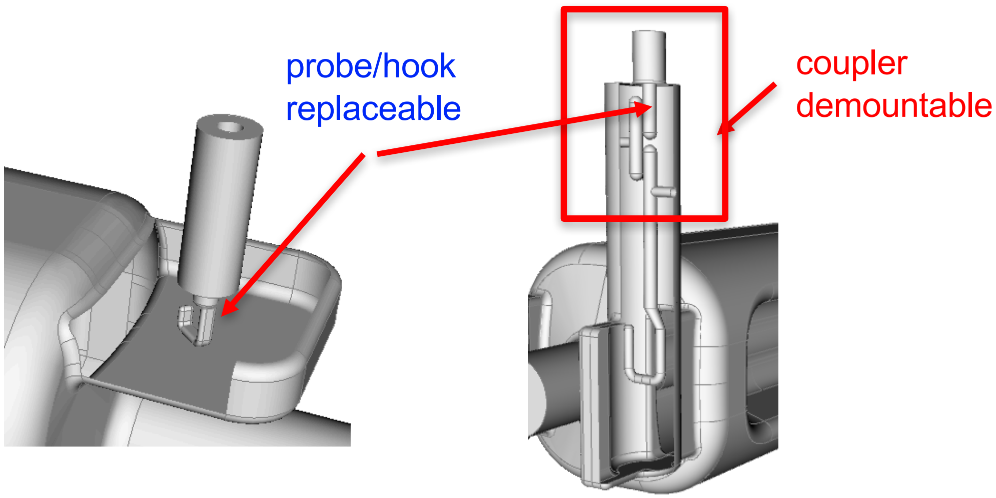


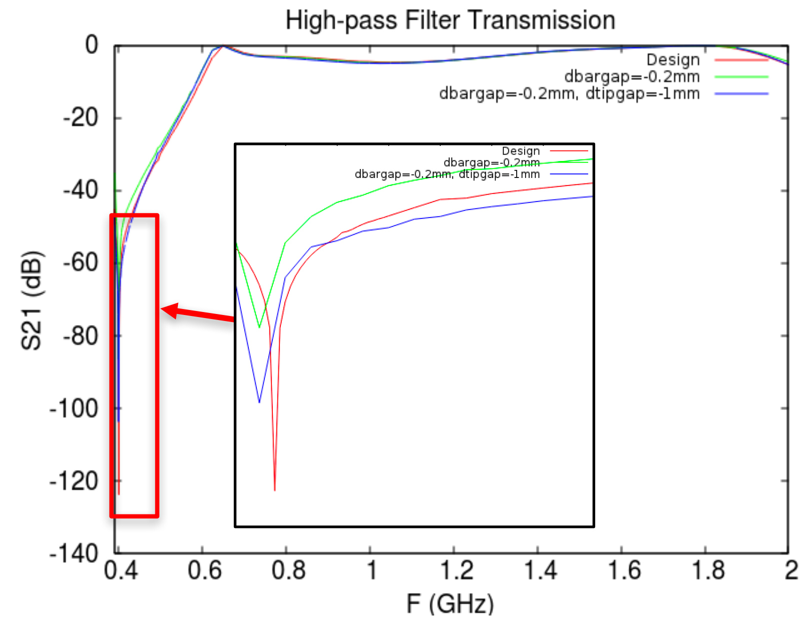


With achievable filter dimension tolerances, RF power leakage will be contained within 1.5 W

Dimension Error Mitigation

- Dimension tolerance shown to be achievable
- There are readily available mitigation means could be utilized to further minimize dimension errors effects





- Rotating, tweaking HOM coupling hook
  - Effective to cavity dimension errors
- Adjusting HHOM pickup probe depth/dimension
  - Effective to HOM coupler dimension errors

Example: adjusting HHOM tip-gap improves degraded rejection due to bar-gap error

Effect of dimension errors can be mitigated via re-tuning of demountable HOM couplers

Summary

- RFD cavity was re-optimized to resolve two important design issues
  1) Reduced beam HOM power of the "760MHz" mode
     meet 1 kW requirement
  2) Improved HOM damping
     meet 1 MΩ/m requirement
- New design meet all requirements
  - Accelerating mode shunt impedance: < 200 k Ω
  - Field multipole: b3 < 1000 mT/m^2
  - HOM filter power leakage : can be controlled within 1.5 W limit
- Sensitivity of HOM impedance on cavity and HOM coupler dimensions analyzed
  - Tolerance on dimension errors achievable
  - Sensitivity table generated for developing engineering tolerance specifications