US-AUP RFD Couplers for HL-LHC CC

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For the US-HL-LHC-AUP collaboration

International Review of the Crab Cavity for the HL-LHC – June 19th–21st 2019

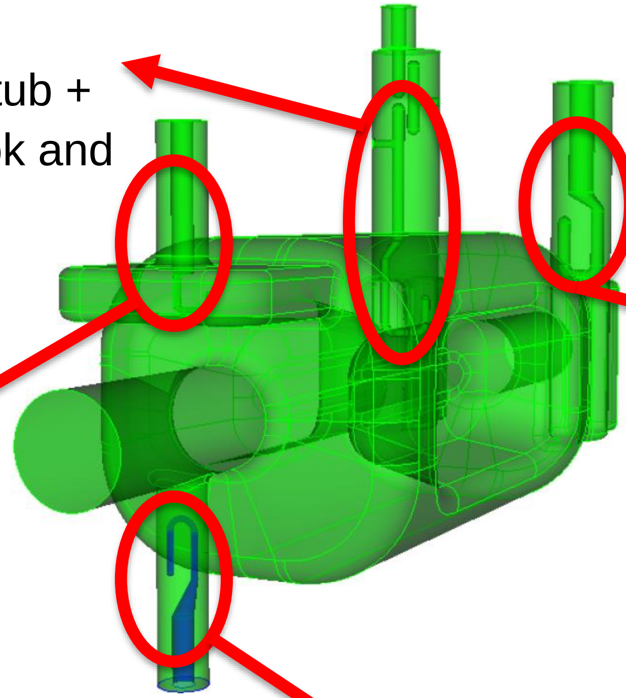
Outline

- **HOMs couplers and field probe design:**
  - Field probe design update after SPS DQW test
  - HHOM and VHOM design evolution (LARP→HL-LHC-AUP)
- **HOMs couplers fabrication and processing experience**
  - HHOM and VHOM fabrication for LARP RFD prototypes
  - HOMs couplers warm RF measurements
  - HHOM test box and coupler QC
  - RFD cavity+HOMs couplers cold measurements (VTA)
- **HOMs couplers summary of lessons learnt through LARP and AUP**

Couplers for RFD CC overview

HHOM:

- It couples to Horizontal polarization HOMs
- Cutoff waveguide stub + high-pass filter (hook and tee)



FPC:

- Waveguide stub + hook
- Qext: 5×10^5

VHOM:

- Waveguide stub selectively couples to accelerating HOMs and vertical dipole HOMs
- No filter needed

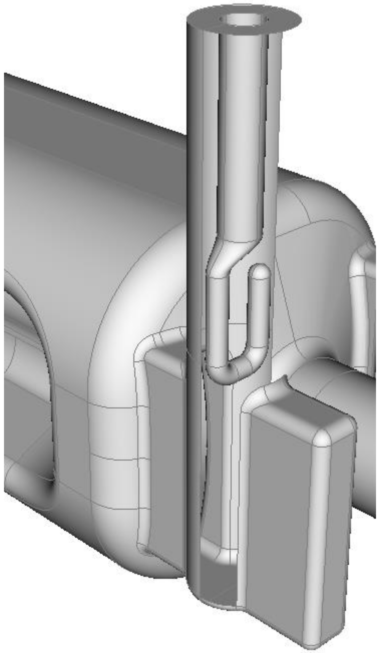
Pickup port:

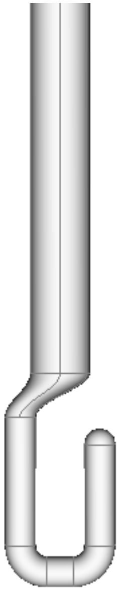
- On the V-HOM side of cavity
- Qext ~ 2×10^{10}

Fundamental Power Coupler

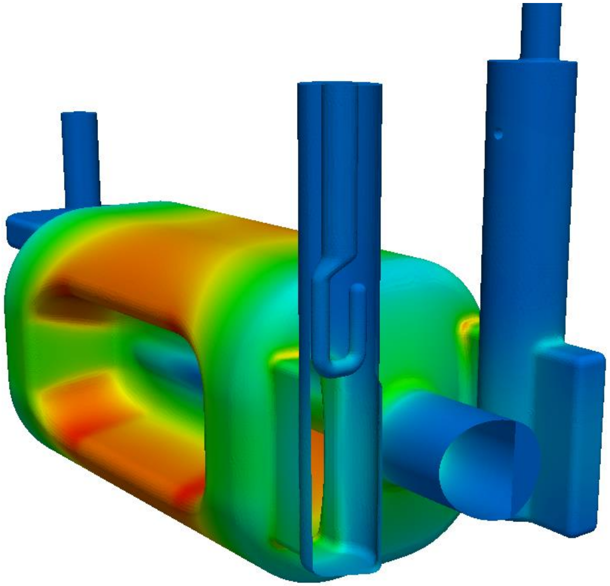
FPC:

- Qext: 5×10^5
- Outer diameter: 62 mm
- Inner diameter: 27 mm





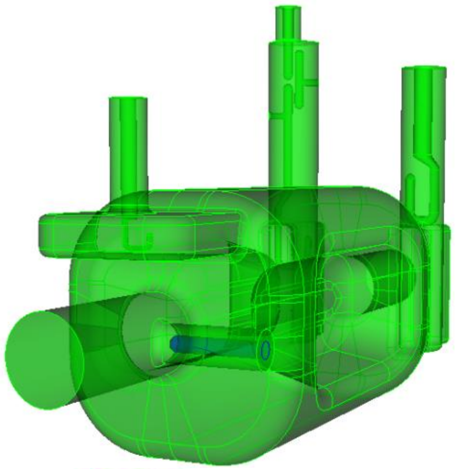
Coupling hook
(Cu with internal water cooling)

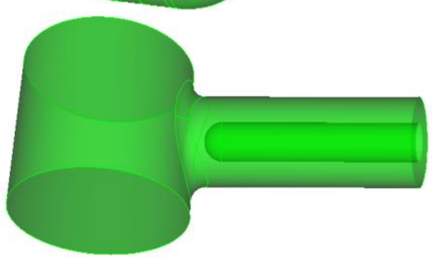


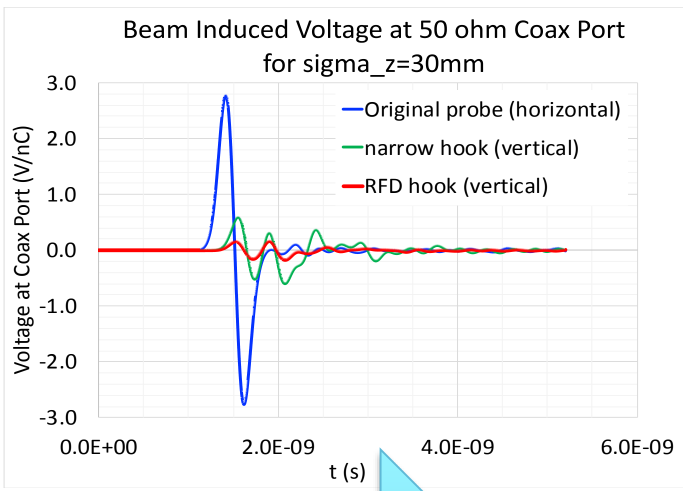
Hook shape antenna enhances coupling, thus minimizing RF heating on the FPC center conductor, no changes in the RF design going from LARP to AUP.

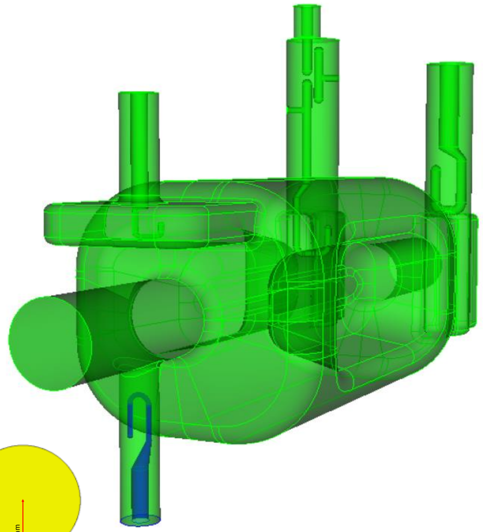
Field pick up evolution

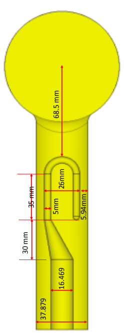
- DQW SPS test showed strong beam coupling on the field PU.
- Both DQW and RFD PU design have been changed to reduce the induced beam voltage <0.3V.
- RFD PU has been rotated by 90 degrees.
- It is now closer to the cavity body by 5.5 mm
- Hook design has been adopted to increase coupling to H field.





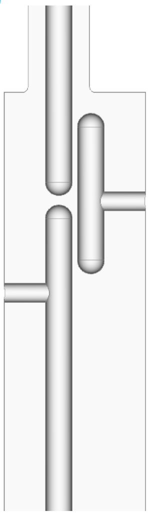


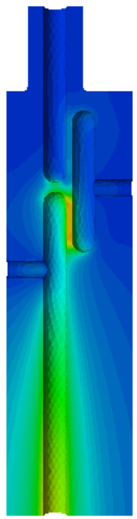


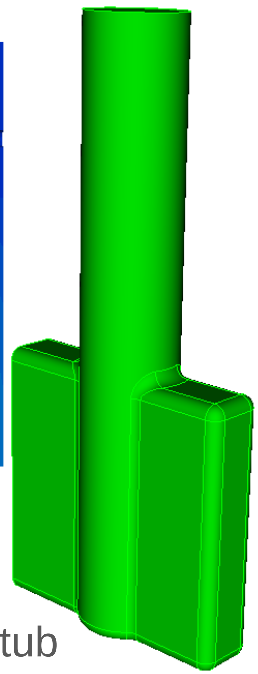


HHOM Re-optimized for HL-LHC-AUP

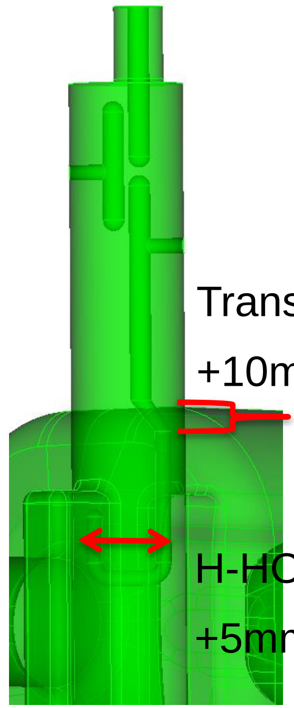
rejection of
operating mode





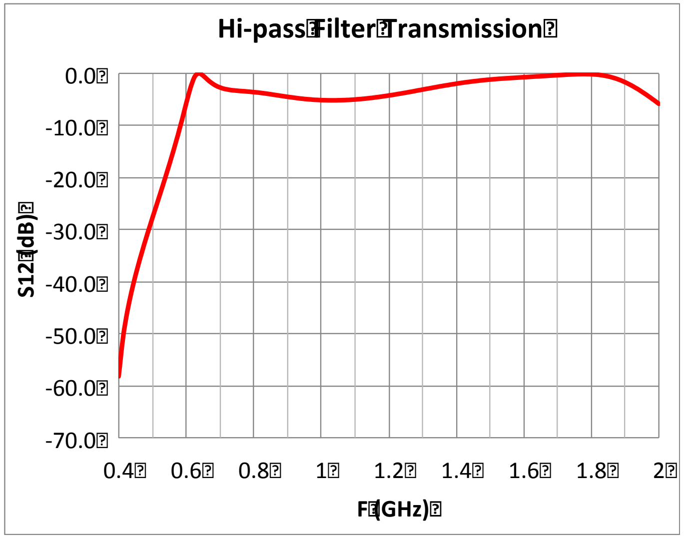


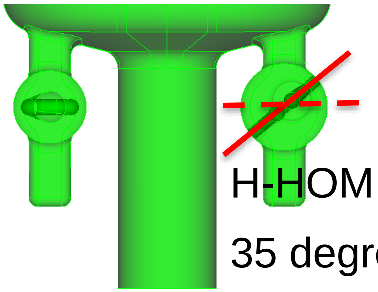
Larger
waveguide stub
size (170x40)



Transition
+10mm higher

H-HOM width
+5mm wider



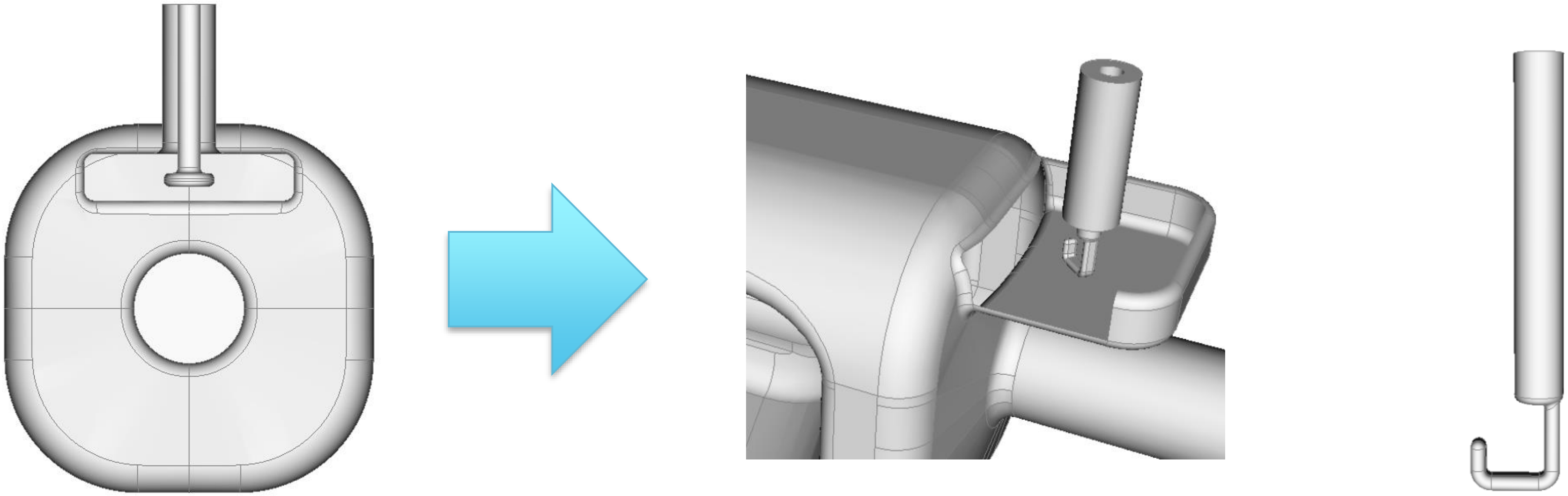


H-HOM hook
35 degree angle

Improved damping with minimal change to the LARP prototype HOM coupler design.

RF performance of LARP HOM couplers measurements still applicable to AUP design.

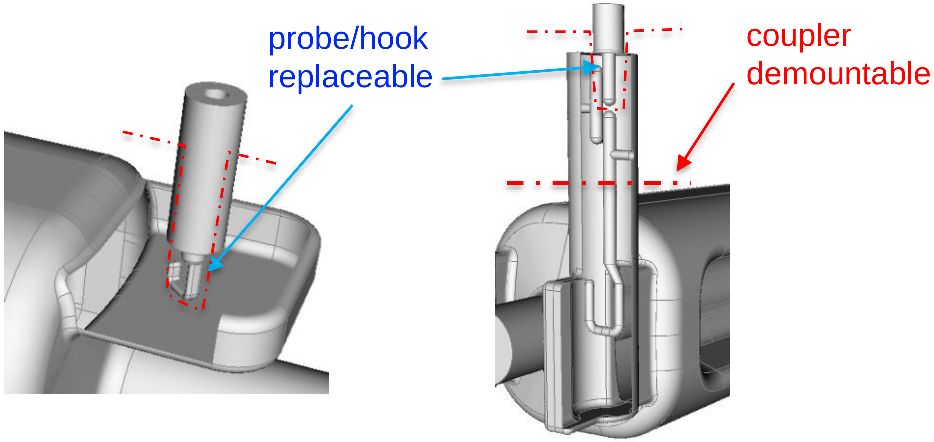
V-HOM Coupler changes for HL-LHC-AUP

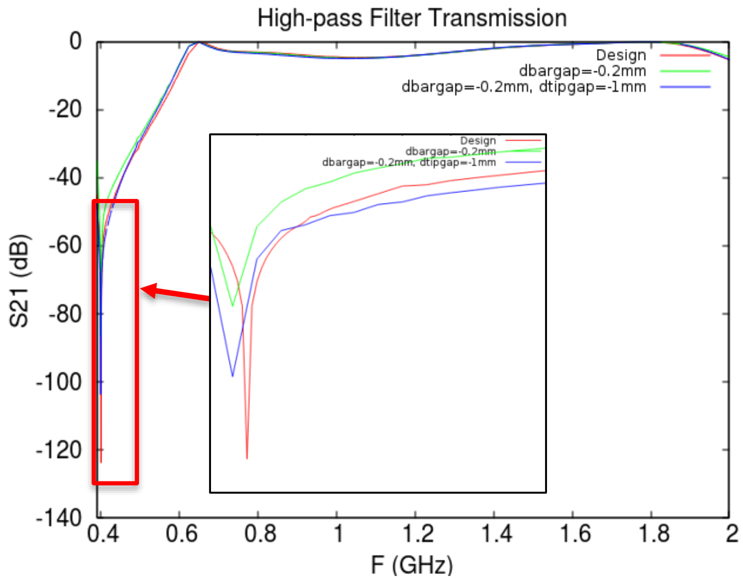


- Replaced the straight probe with a hook shaped probe
- Hook probe provides both electric and magnetic coupling, improving damping of HOMs at higher frequencies
- Waveguide stub dimension slightly larger than LARP prototype (same dimension as HHOM) to enhance coupling

HHOM and VHOM adjustments

- Both HOM couplers can be tuned to compensate for manufacturing errors
- There are available mitigation means which can be used to further minimize dimension errors effects





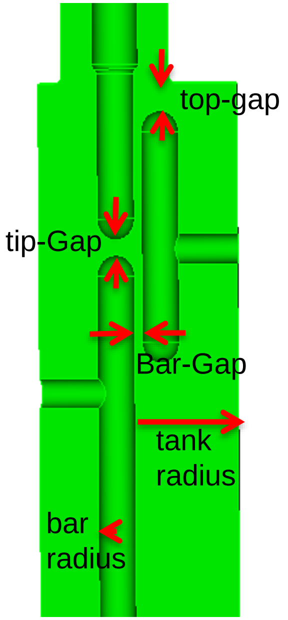
- Rotating, tweaking HOM coupling hook
- Effective to cavity dimension errors
- Adjusting HHOM pickup probe depth/dimension
- Effective to HOM coupler dimension errors

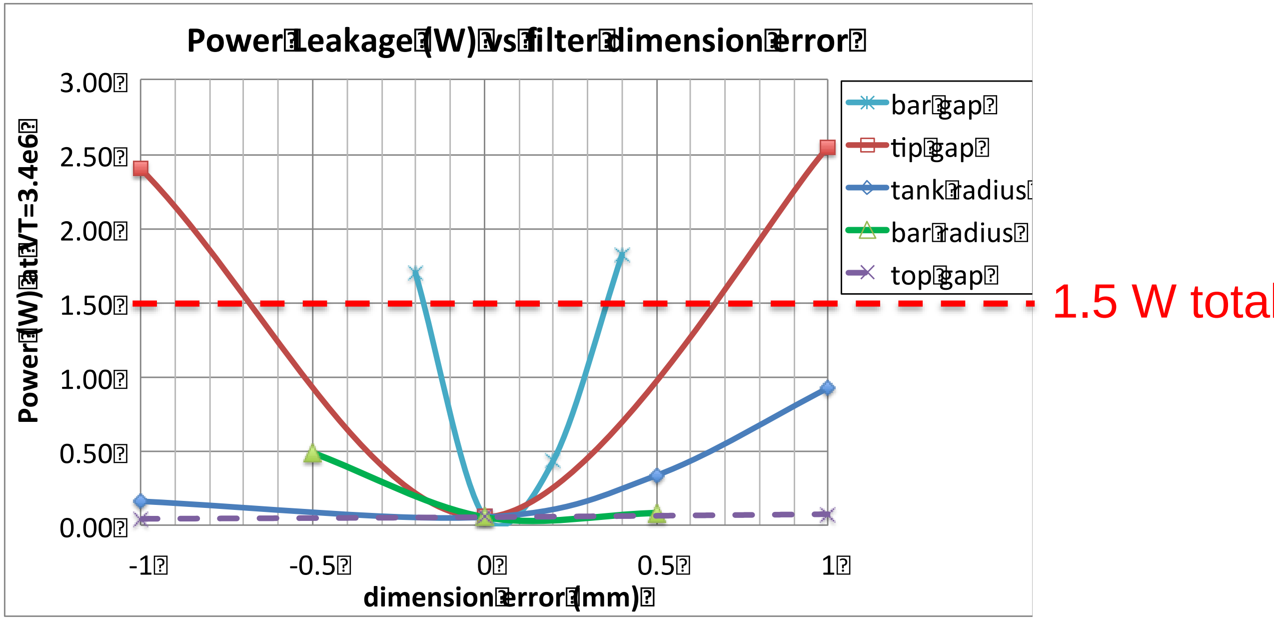
Example: adjusting HHOM tip-gap improves degraded rejection due to bar-gap error

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

Fundamental Power Leakage Due to HHOM Filter Dimension Errors

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

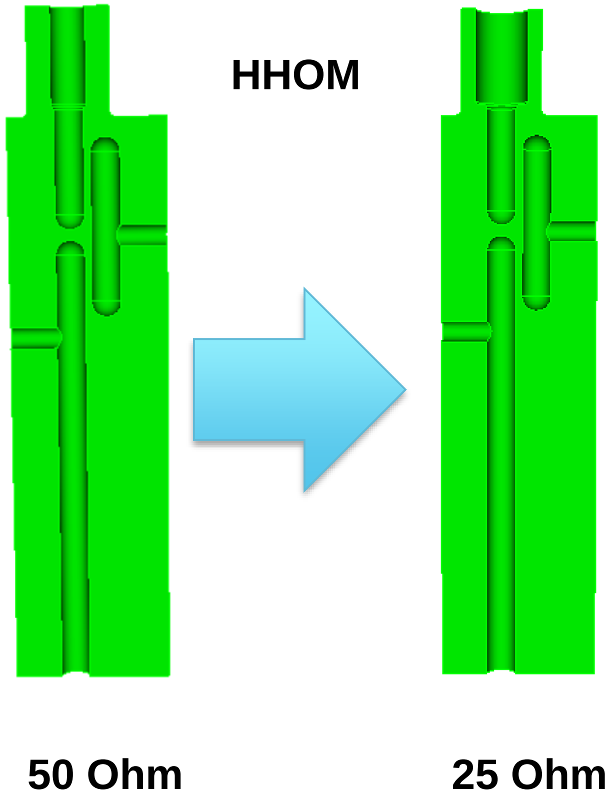


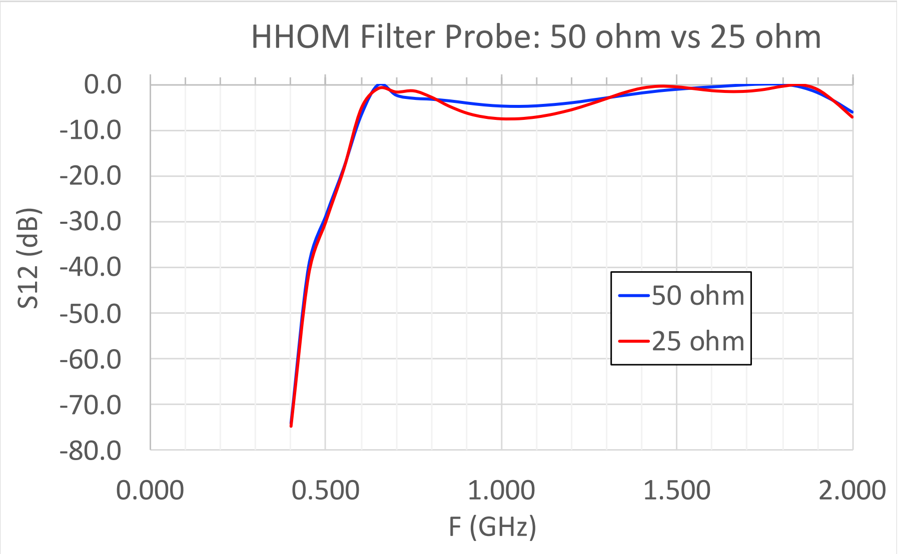


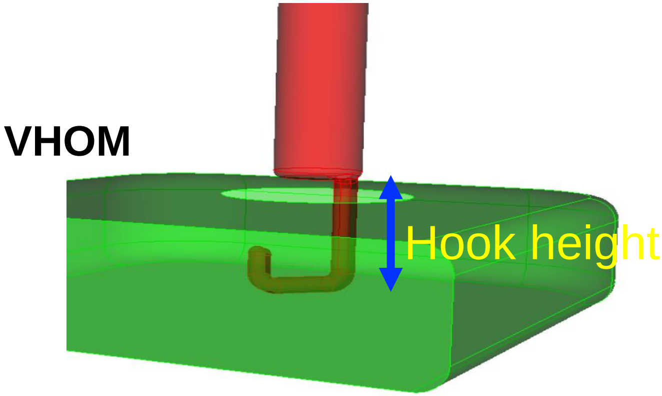
With achievable filter dimension tolerances, RF power leakage will be contained within 1.5 W

HOM Filter from 50 Ohm to 25 Ohm

- The inner conductors of both VHOM and HHOM feed-throughs have been changed to 25 Ohm, to increase their robustness.
- Only HOMs probes needed to be re-optimized for 25 Ohm lines.

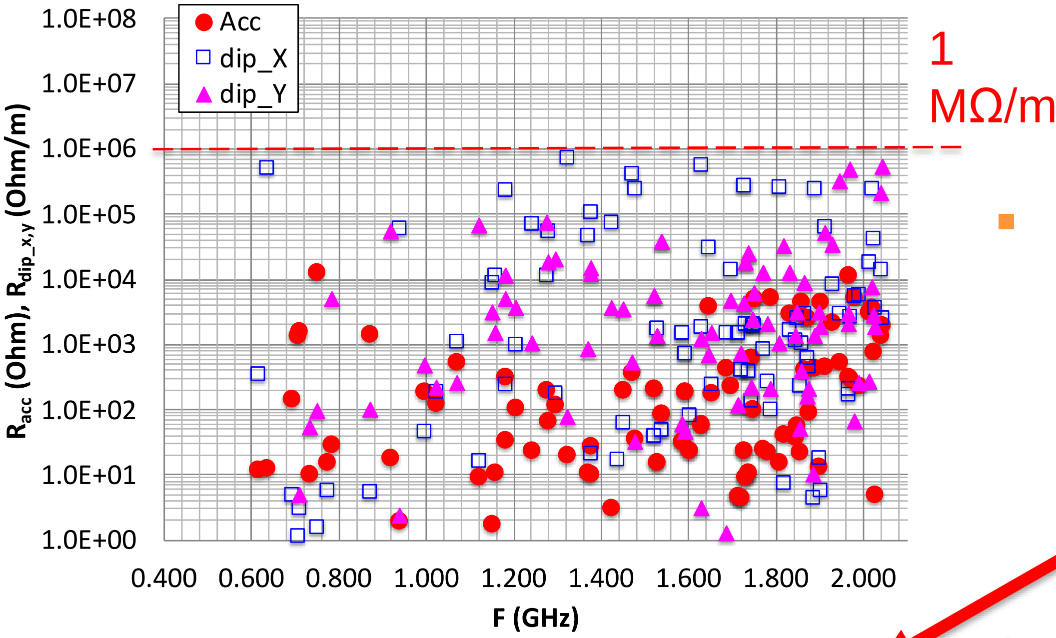




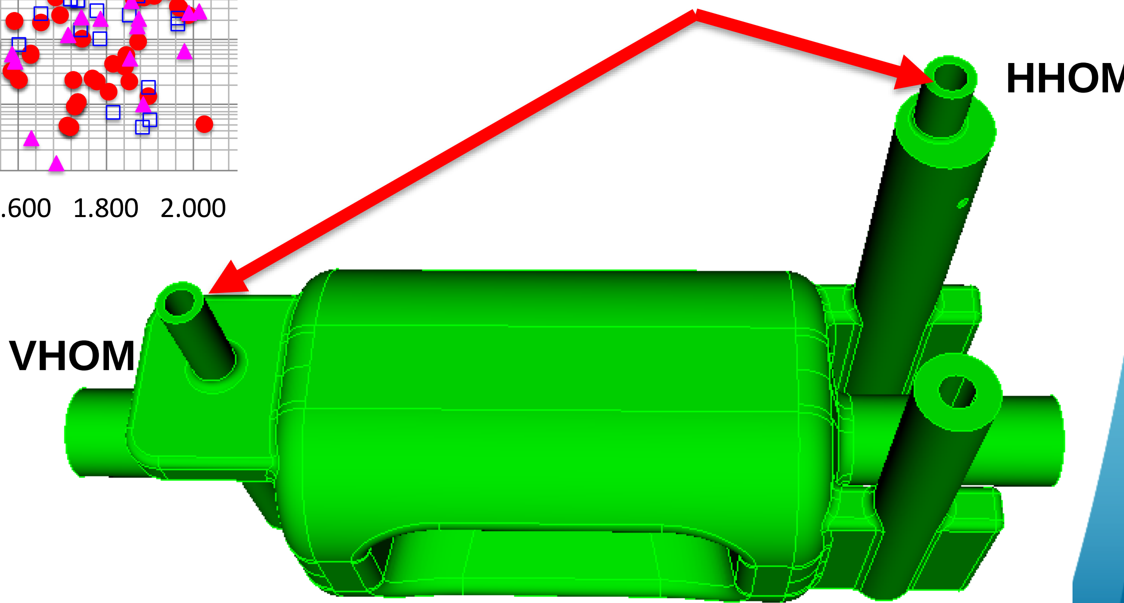


HOMs impedance for 25 Ohm lines

- Re-designed RF probes bring HOM impedance below 1 MΩ/m up to 2 GHz

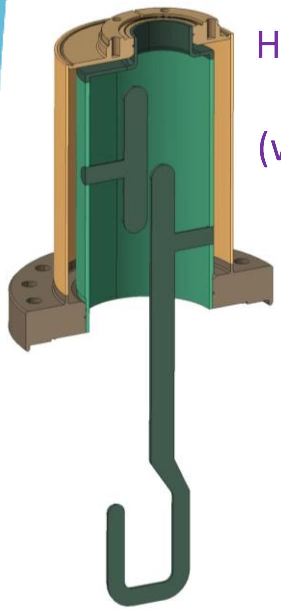


- Both HOMs dampers now have thicker inner conductor feed-thrus



Fabrication of LARP Prototype Cavity HOM Couplers

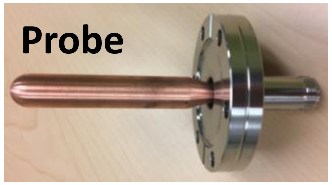
- Pre-prototype HHOM coupler was fabricated first to determine the fabrication process
- Two sets of HHOM and VHOM couplers are being fabricated at Jefferson Lab
- HHOM coupler without Helium jacket was used in cold tests at Jefferson Lab
- Second set of couplers are shipped to Fermilab for tests with RFD-CAV-001



HHOM coupler with He jacket (without the probe)

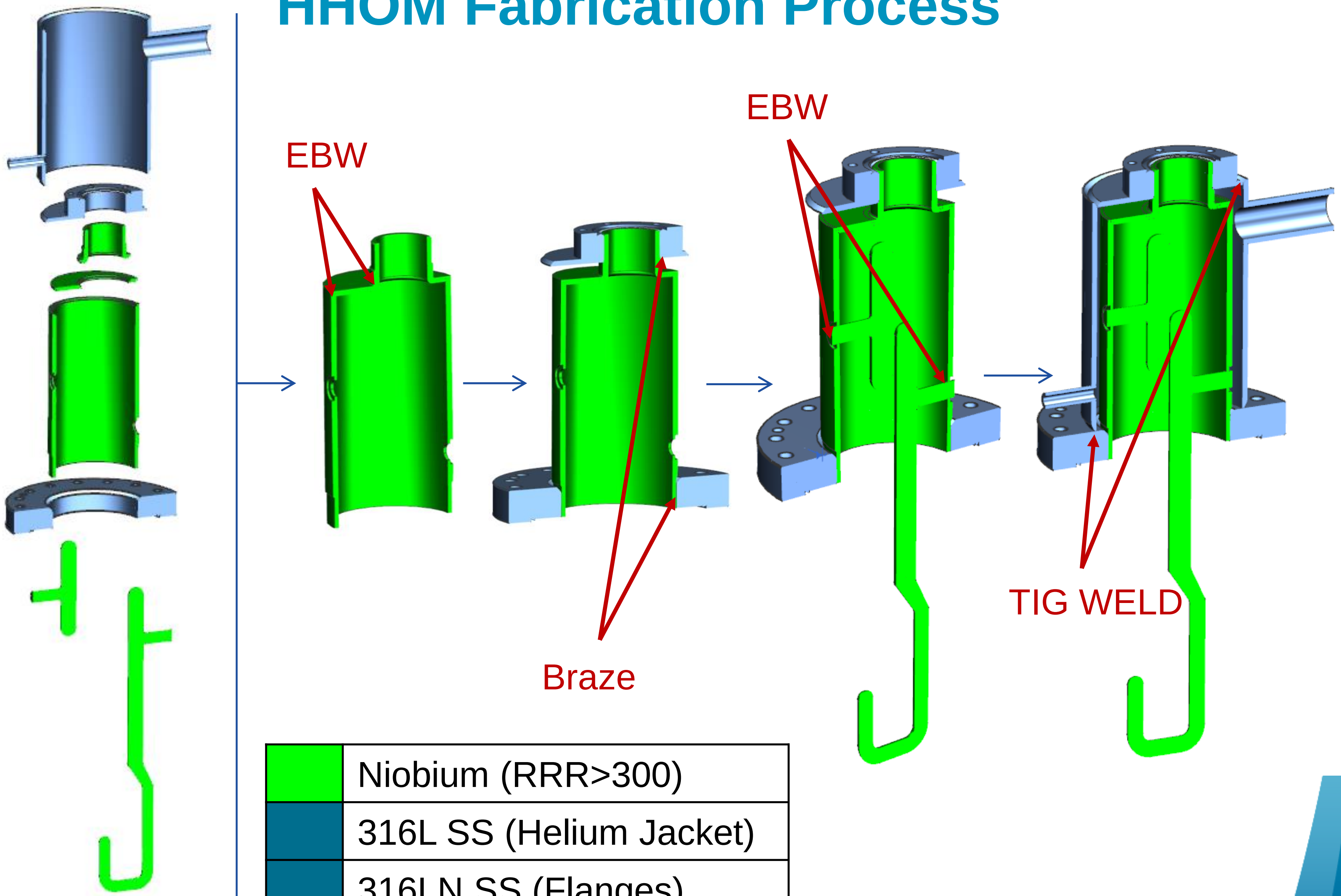
Parts of the HHOM prototype

Completed prototype HHOM coupler



Completed prototype VHOM coupler

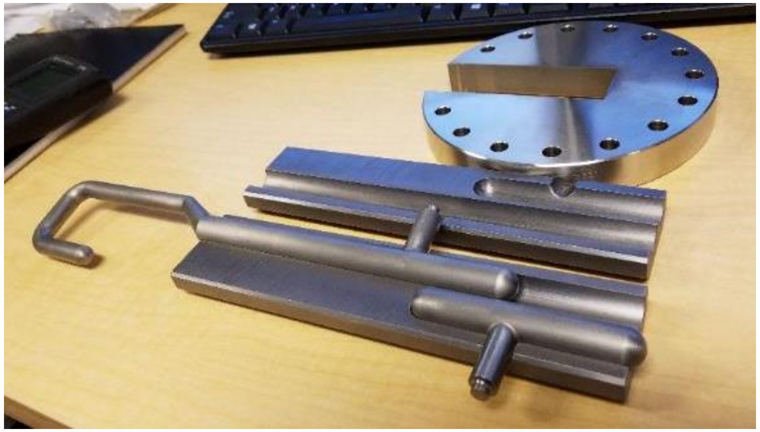
HHOM Fabrication Process

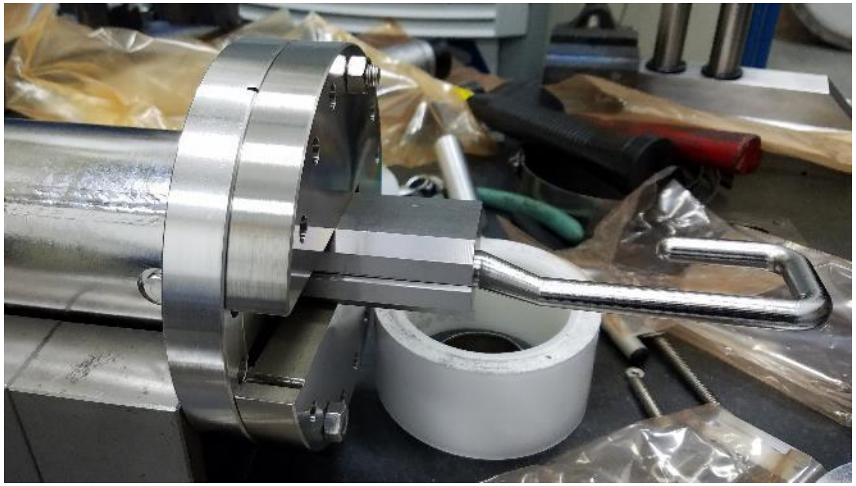


	Niobium (RRR>300)
	316L SS (Helium Jacket)
	316LN SS (Flanges)

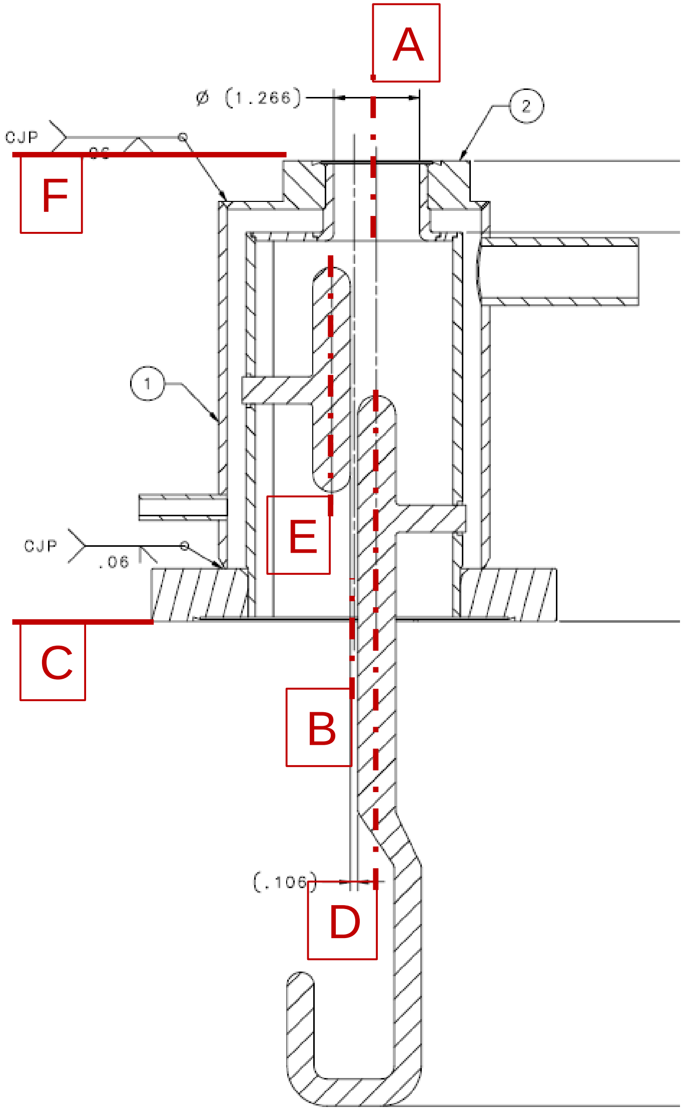
HHOM Fabrication – Hook/Tee EBW

- Clam-shell fixture used to fix the distance between Hook and Tee, and control their position within the inner can.





HHOM Final Inspection



A: Axis of probe port
B: Axis of damper can
C: Plane of large flange
D: Axis of hook
E: Axis of tee
F: Plane of small flange

GD&T	#1	#2	Unit
Perpendicularity D to C	89.56	90.25	Deg
Perpendicularity E to C	89.15	89.21	Deg
Perpendicularity A to C	91.02	90.33	Deg
Parallelism F to C	179.66	179.80	Deg
Concentricity A and D	2.29	2.69	mm

#1 Complete coupler, #2 He jacket weld not complete.

Processing of LARP Prototype Cavity HOM Couplers

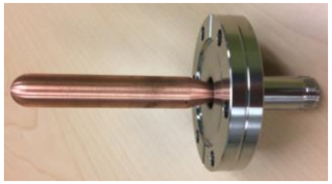
HHOM Coupler

- Bench BCP done on the prototype HHOM filter, fixture can be used in the BCP cabinet
- Total removal
  - 1st iteration: 25 micron of removal and 2nd iteration: 13 micron of removal
  - Total removal from 2 BCPs <40 microns
  - No heat treatment done
- HHOM filter is ultrasonic degreased and manual HPRed before assembly

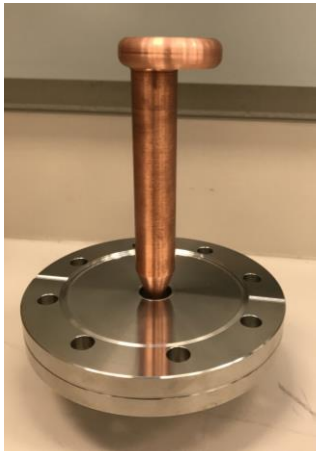
VHOM and HHOM Probes (Cu)

- Ultrasonic degrease

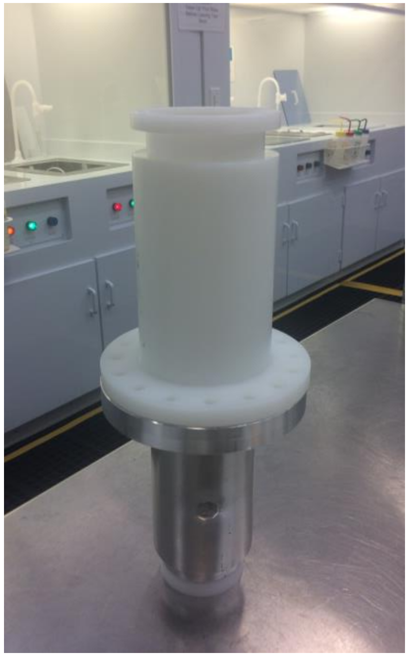
HHOM Probe



VHOM Probe

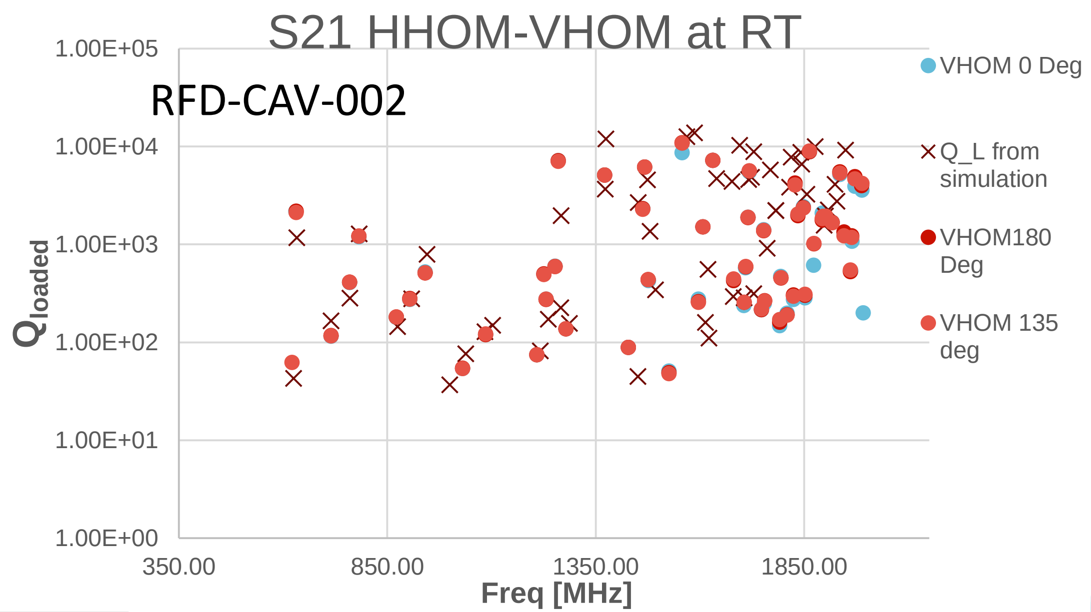


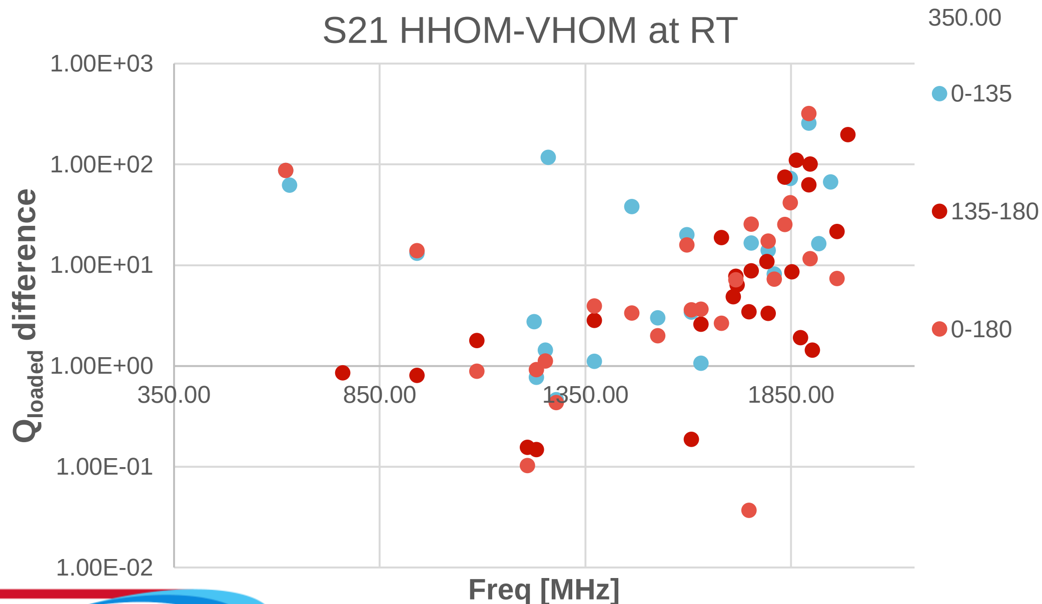
BCP fixture



Measurements of HOMs: Q_L at RT

- Measurements of Q_L are in good agreement with simulation up to ~1.65 GHz
- Q_{ext} of fundamental mode can be tuned rotating the HOMs Cu probes→ minor changes of loaded Q for HOMs

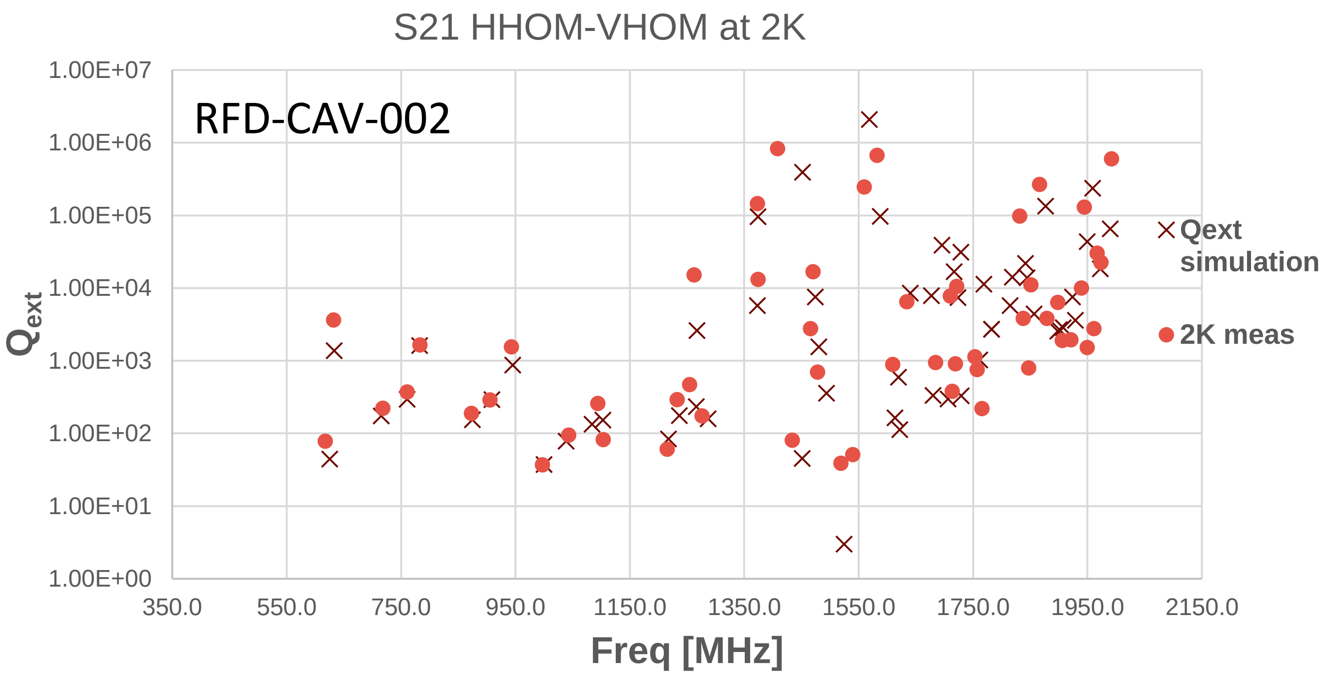




- Difference in loaded Q for all measurable HOMs at RT:
  - VHOM probe at 0, 135 and 180 degrees with respect to design position

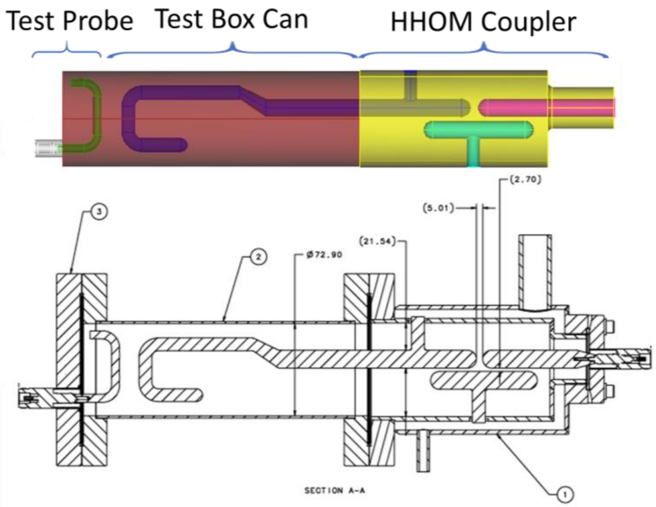
Measurements of HOMs: Q_{ext} at 2K

- Measurements of Q_{ext} are possible for most HOMs when the cavity is in helium bath at 2K.
- Good agreement with simulations despite manufacturing imperfections of cavity and HHOM coupler.

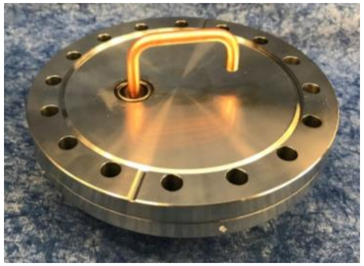


HHOM Test Box

- Fabricated at JLab with HL-LHC-AUP funding to ODU
- Test box can – SS can with 6" conflat flanges
- Test probe – Cu probe brazed on to coaxial feedthrough
- Test box can and test probe dimensions were measured using CMM to determine the offsets in fabrication

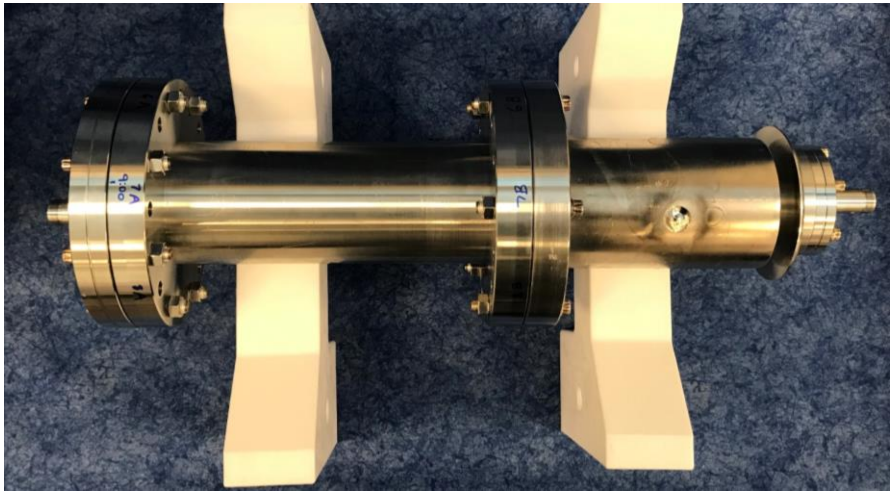


Test box can with HHOM coupler



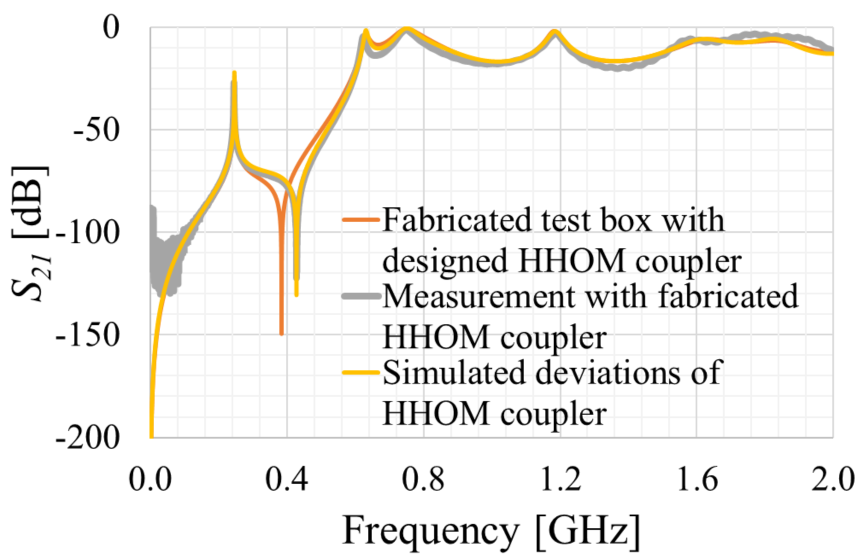
Test probe

Full test box assembly with HHOM coupler

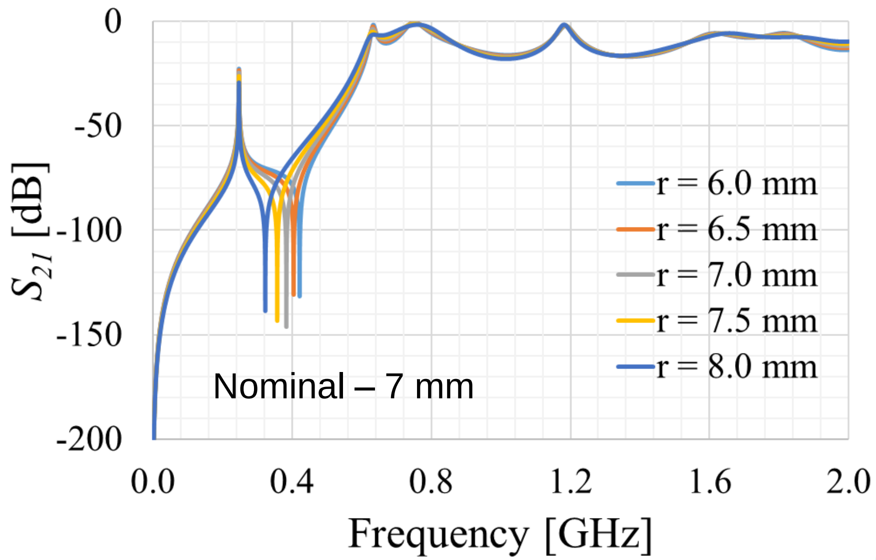


Measurements on RF Test Box

- Test box can and test probe dimensions were measured using CMM to determine the offsets in fabrication
- Comparison of S21 transmission between designed and fabricated rf test box (with designed HHOM coupler)
- Deviations < 0.5 dB in frequency range 620-2000 MHz
- Measured HHOM coupler shows a shift in the notch
- Shift corresponds to a shift of 0.6 mm in T and Hook with respect to Probe
- Rejection of fundamental mode can be tuned adjusting Cu probe (radius and/or length)

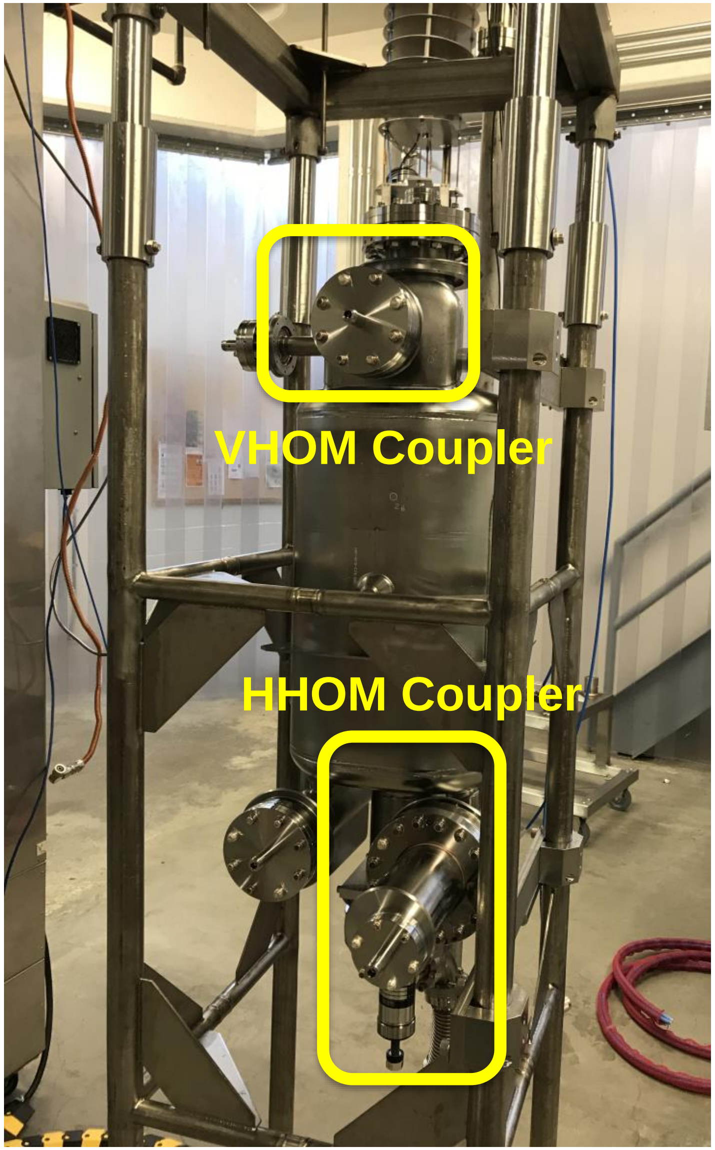


Deviation HHOM S21 measurement from simulation



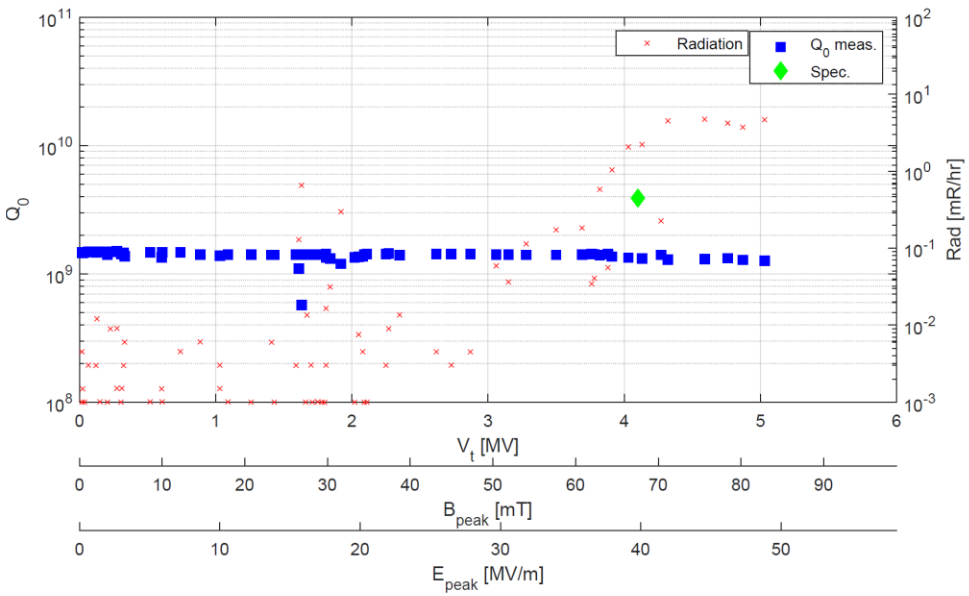
Notch tuning with radius of HHOM probe

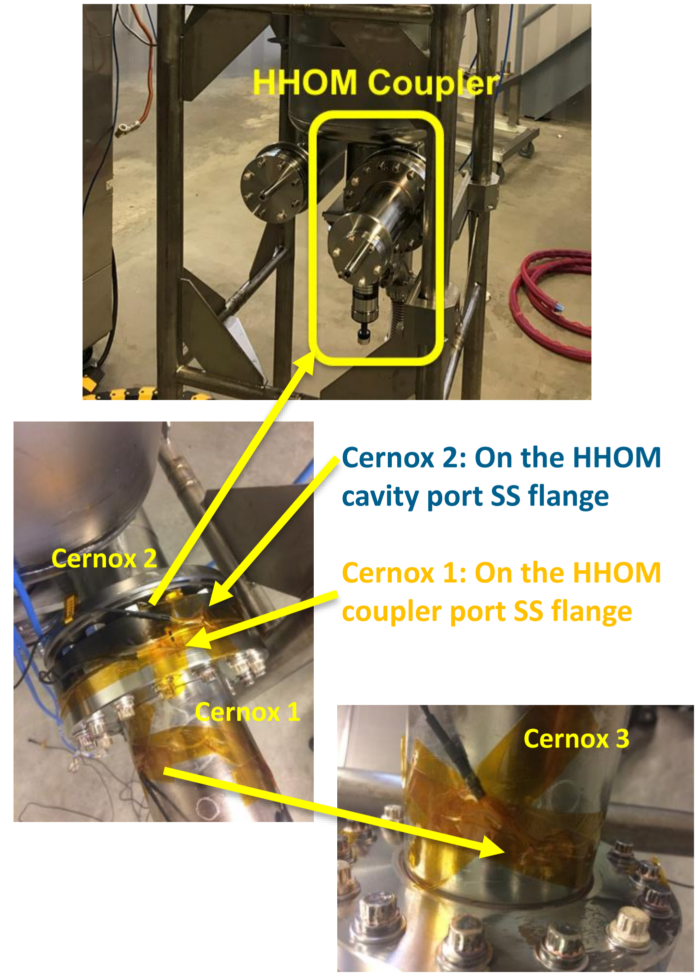
Cold test of RFD Cavity + HOM Couplers



- Cold test of RFD-CAV-002 with HOM couplers
- Measurements were carried out with HHOM and VHOM couplers fabricated at Jlab (HHOM2 and VHOM2)
- HHOM Coupler has no Helium jacket welded
- To maintain consistency – same input probe, pick up probe and similar assembly configuration was followed as for the bare cavity RF test

First Test with both HOM Couplers





1st Test HHOM&VHOM– Cavity with terminated HHOM and VHOM

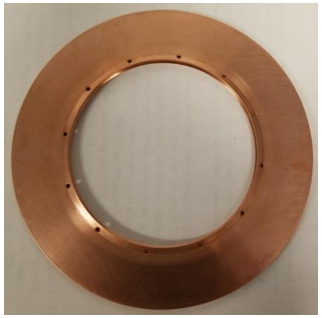
- Strong coupling of fundamental mode through VHOM coupler (Q_{ext} ~2×10^9)

<u>Findings:</u>

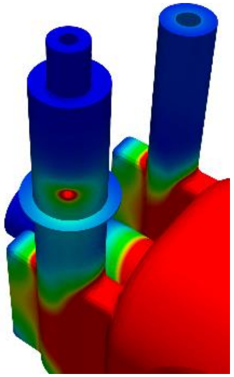
- Cavity didn't quench → RF power limited
- Reduced Q_0 compared to Q_0 of the bare cavity test Q_0 heating of the HHOM coupler
- No new multipacting levels and similar field emission as in the bare cavity test

RFD cavity + HHOM and VHOM validation

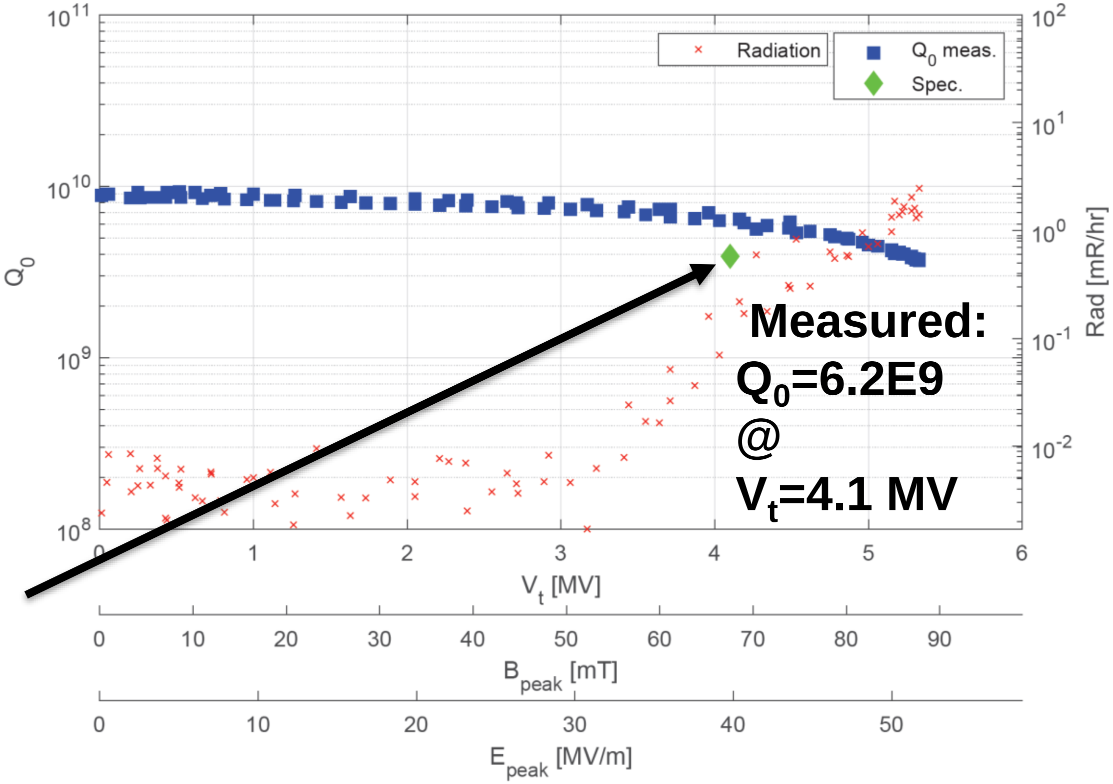
- RFD2 cavity has been successfully tested with all RF ancillaries.
- HHOM RF leakage has been resolved **Q_0 exceeds requirement, quench Vt is 5.5 MV>4.1 MV.**
- HHOM and VHOM dampers design has been successfully tested.
- Fundamental mode rejection has been tuned for both HHOM and VHOM.



Regular gasket on HHOM coupler (left) and RF gasket (right)



Requirement:
Q_0=3.9E9
V_t=4.1 MV



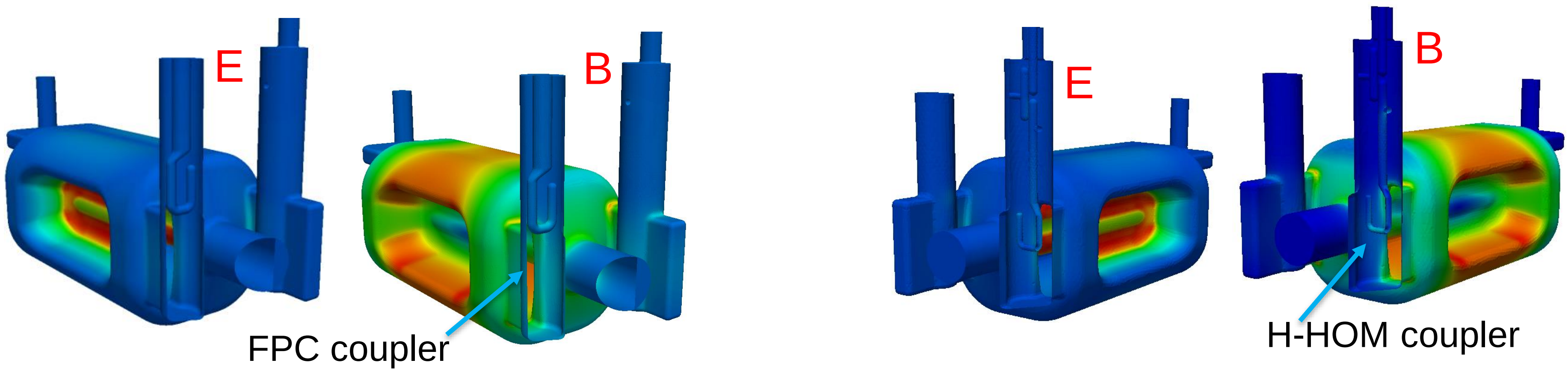
Summary and lessons learnt

- All couplers for RFD CC satisfy requirements for HL-LHC:
  - PU has been recently re-designed to limit the coupling with beam (SPS test lesson)
  - HHOM and VHOM design now satisfies requirements of mode damping for 25 Ohm lines
- Fabrication and processing (2 sets) of HOM dampers through LARP:
  - EBW of Hook and Tee is the most critical step in the process, refinement will be applied for HL-LHC couplers
  - Light BCP (<40 micron) for HHOM coupler lead to good VTA performance
  - RF measurements at RT, including HHOM test box, and at 2K show good agreement with simulations for all measurable modes
  - HHOM test box design is completed
  - Both HHOM and VHOM probes can be used to tune the damper, also for fundamental mode rejection
- Cavity + HOM dampers cold tests:
  - Initially low Q_0 has been measured, due to dissipation of magnetic field in the SS flange
  - Cavity and HOM couplers have been tested successfully with RF gasket that avoids heating and additional losses.

BACK-UP SLIDES

Low Surface Fields on Coupler Surfaces

Couples are placed at the low field regions, minimizes RF heating

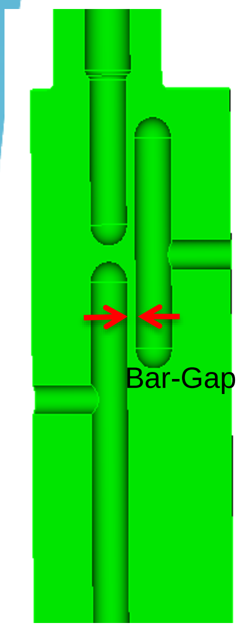


At VT = 3.4MV	E_S (MV/m)	B_S (mT)
H-HOM Hook	5.4	14
H-HOM T	2.4	1.3
H-HOM probe	0.6	0.4
FPC Hook	1.4	7.6

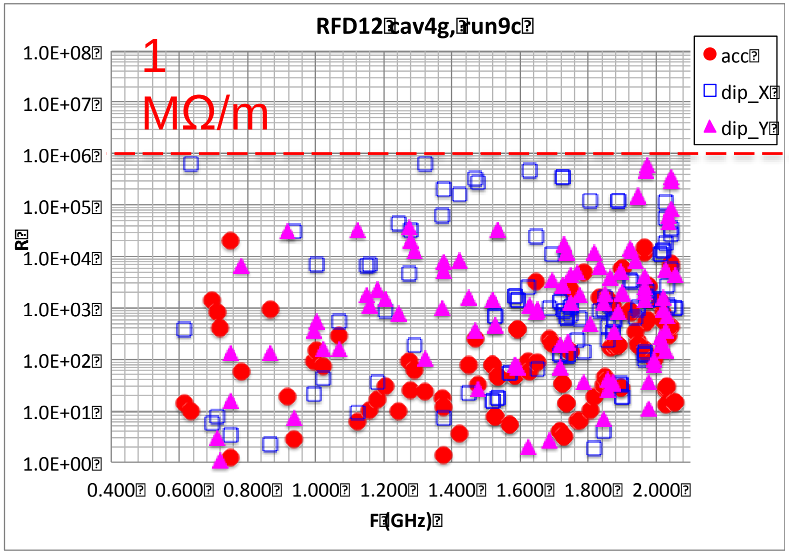
Coupler opening does not induce high surface field

HHOM coupler filter bar-gap

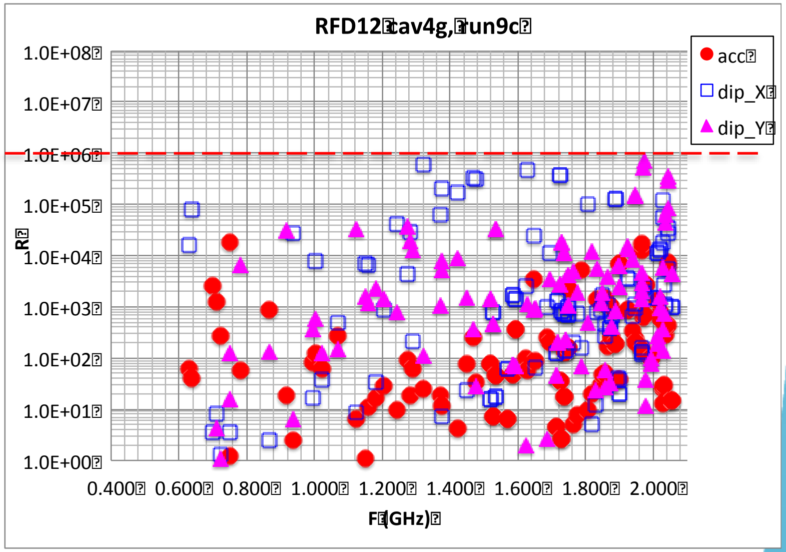
(design: bar_gap=2.8mm)



-0.2mm

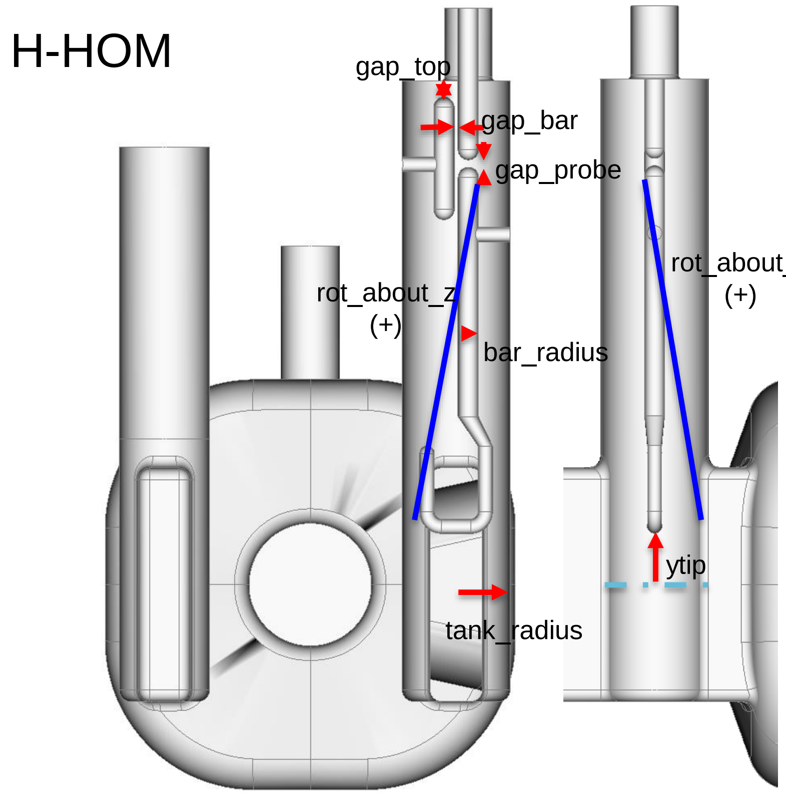


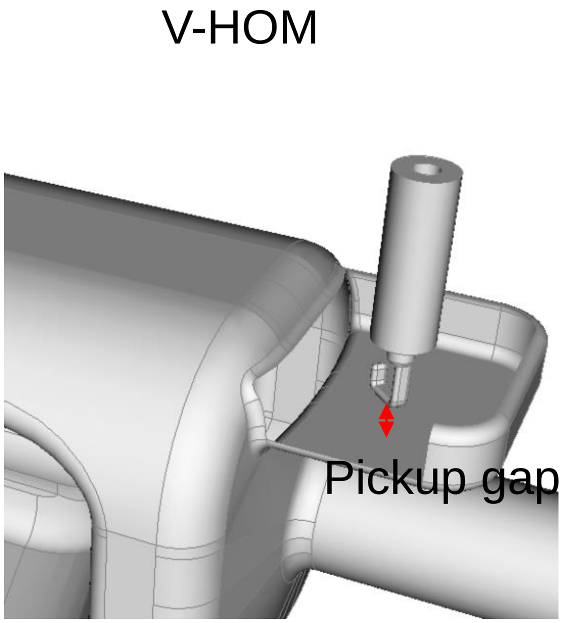
+0.4mm



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

HOM Coupler Dimension Sensitivity to HOM Impedances and Operating Mode Rejection

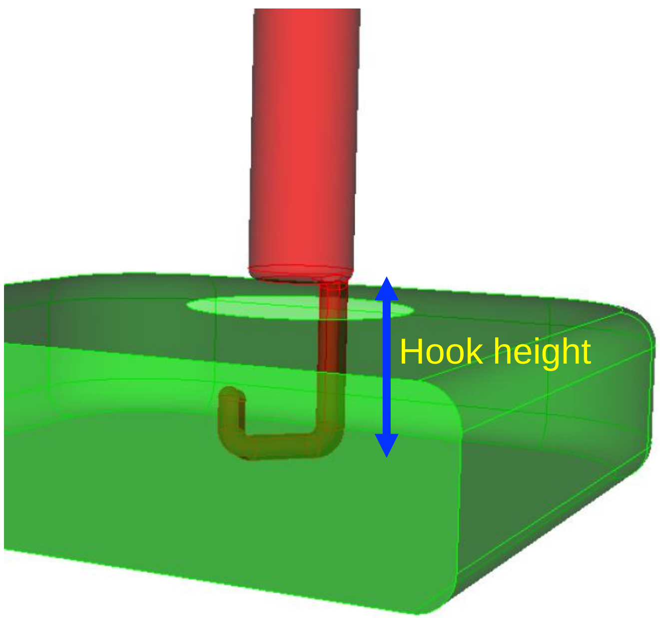


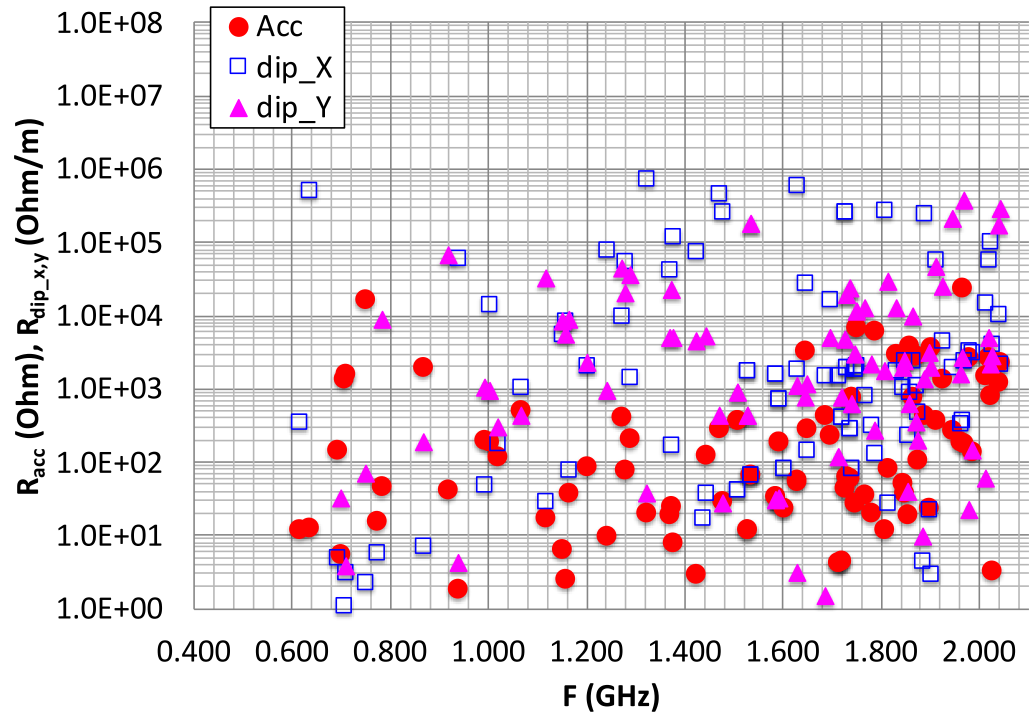


- HOM damping
- Filter performance - rejection of 400.79 MHz operating mode

Cavity With 25 ohm HOM ports

25ohm HOM port
VHOM Hook height: 45mm
VHOM hook angle: 45 deg

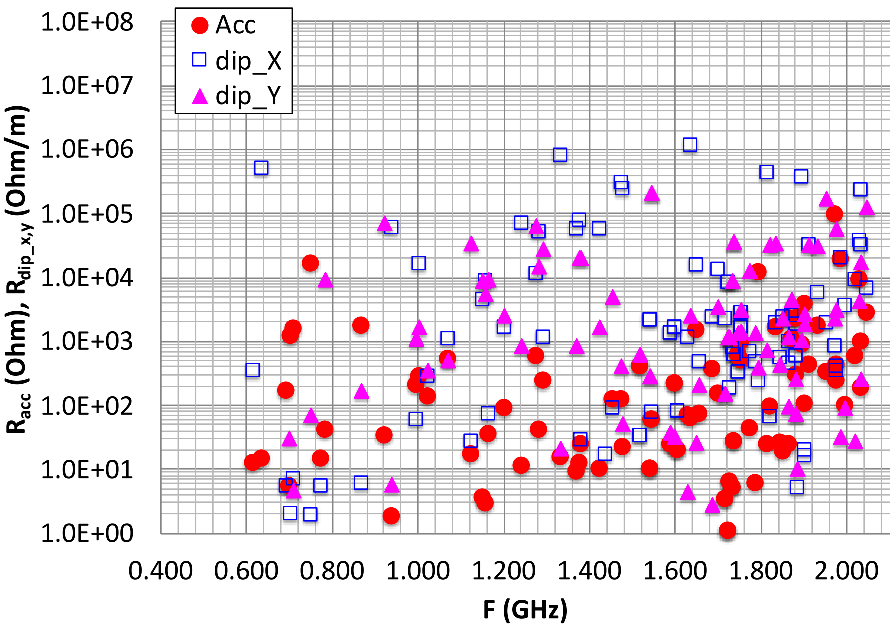




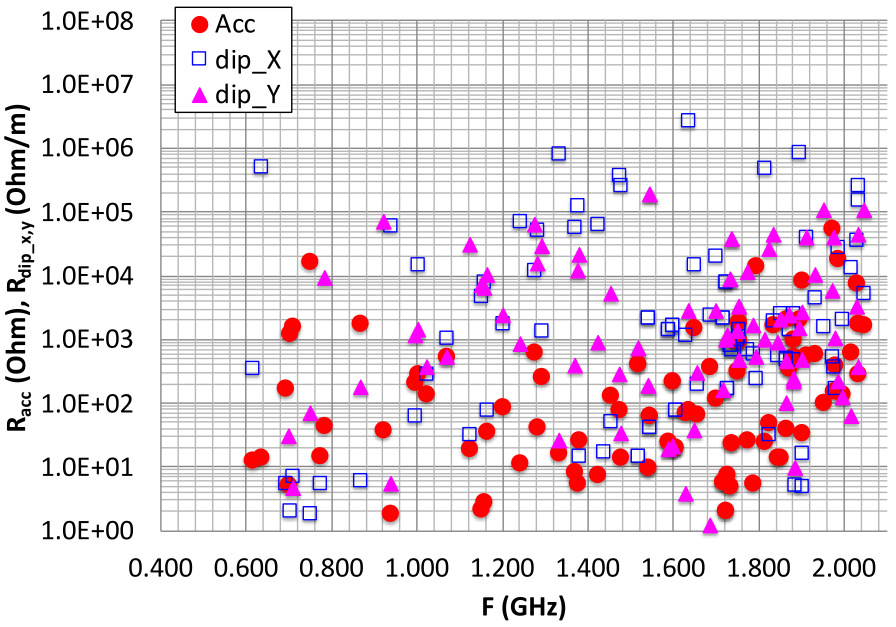
Cavity 5mm shorter

25ohm HOM port
cavity length 5mm shorter
VHOM Hook height: 45mm

VHOM hook angle: 45 deg



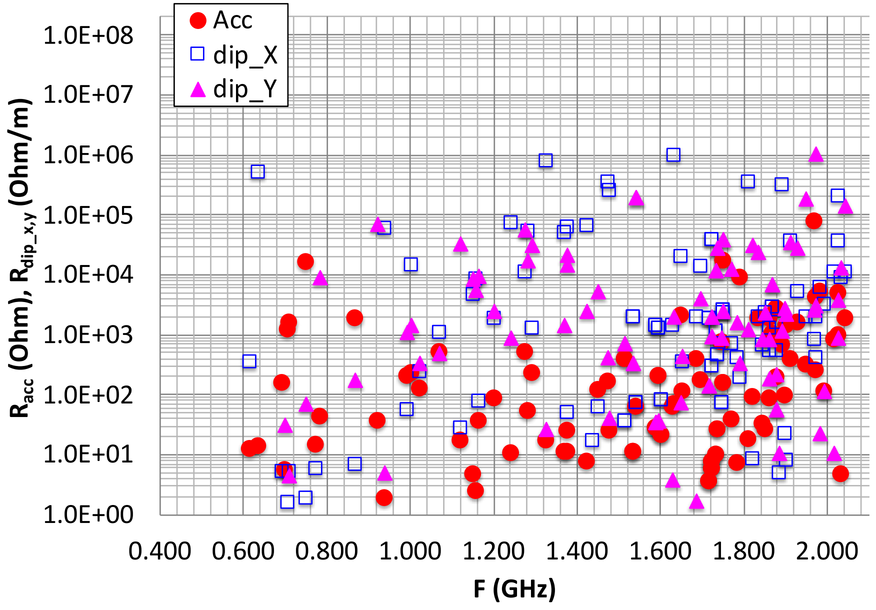
VHOM hook angle: 70 deg



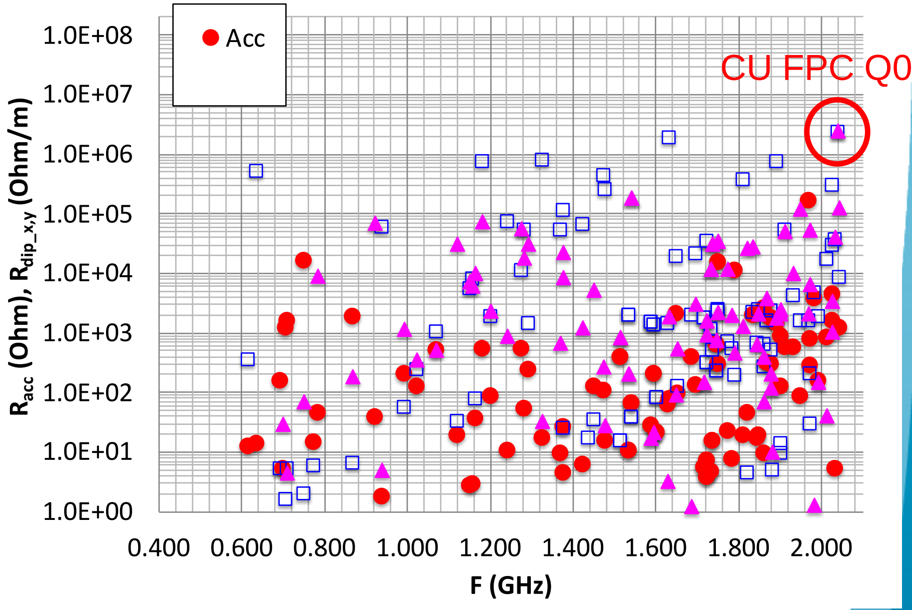
Cavity 3mm shorter

25ohm HOM port
cavity length 3mm shorter
VHOM Hook height: 45mm

VHOM hook angle: 45 deg

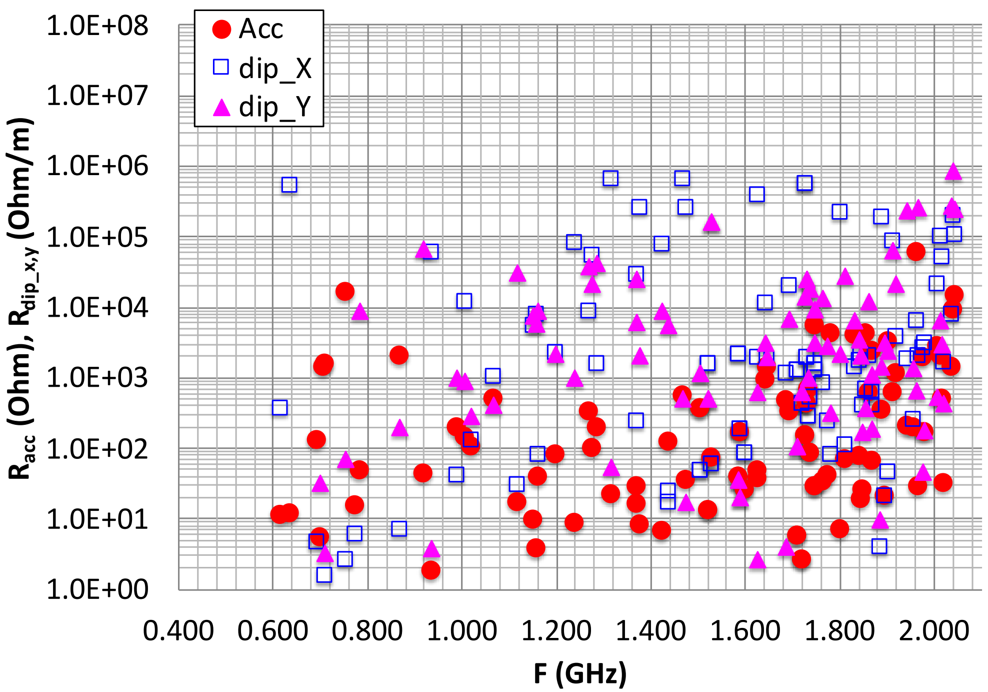


VHOM hook angle: 70 deg



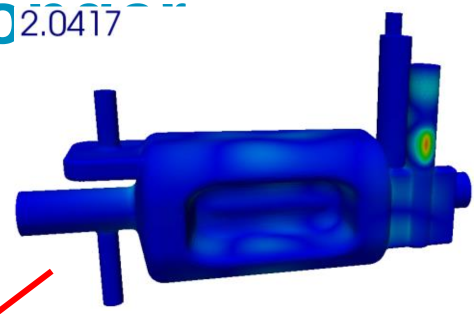
Cavity 3mm longer

25ohm HOM port
cavity length 3mm longer
VHOM Hook height: 45mm
VHOM hook angle: 45 deg

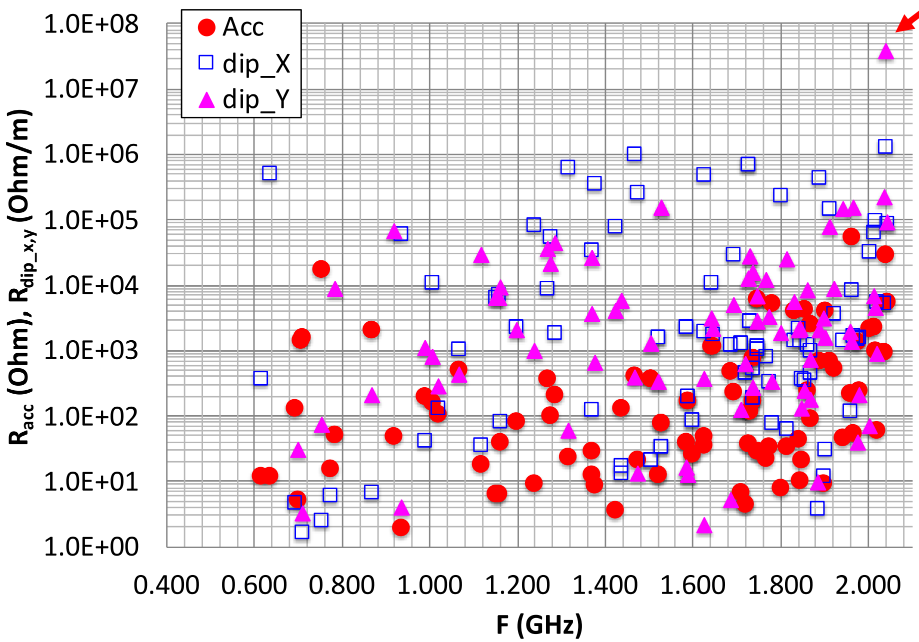


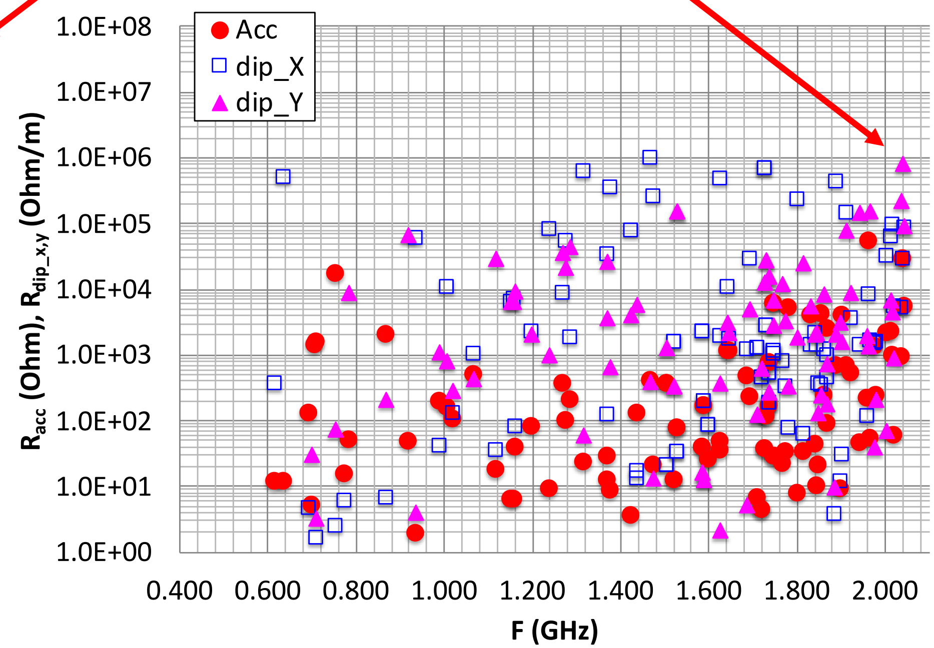
Cavity 3mm lo

25ohm HOM port
cavity length 3mm longer
VHOM Hook height: 45mm
VHOM hook angle: 70 deg



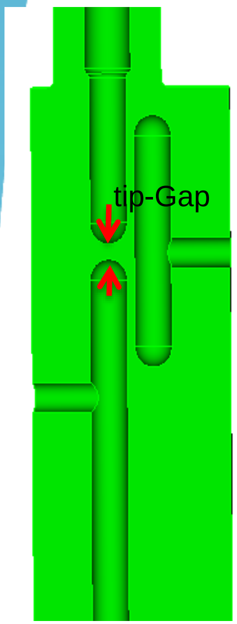
With Q of Cu FPC hook



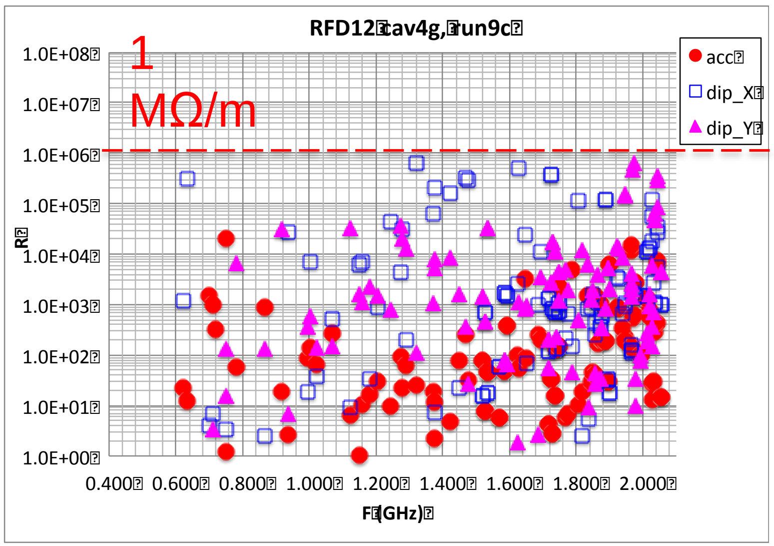


HHOM coupler example of error studies

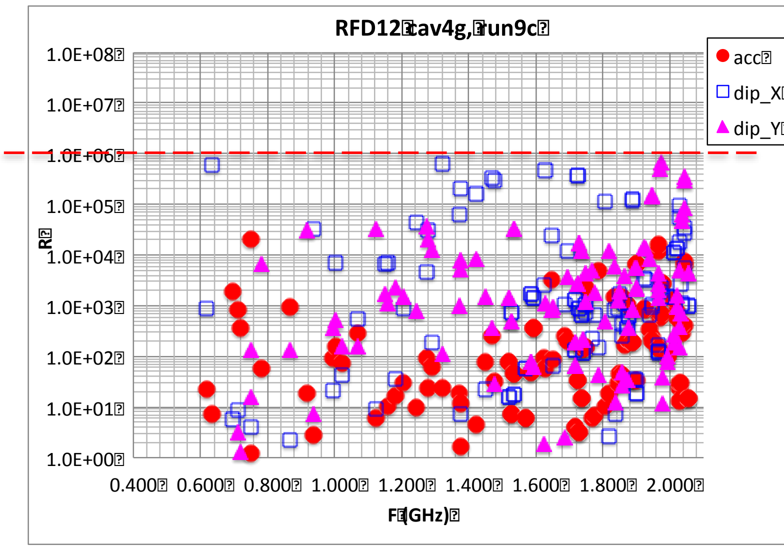
(design: tip_gap=5mm)



delta_gap = +1mm

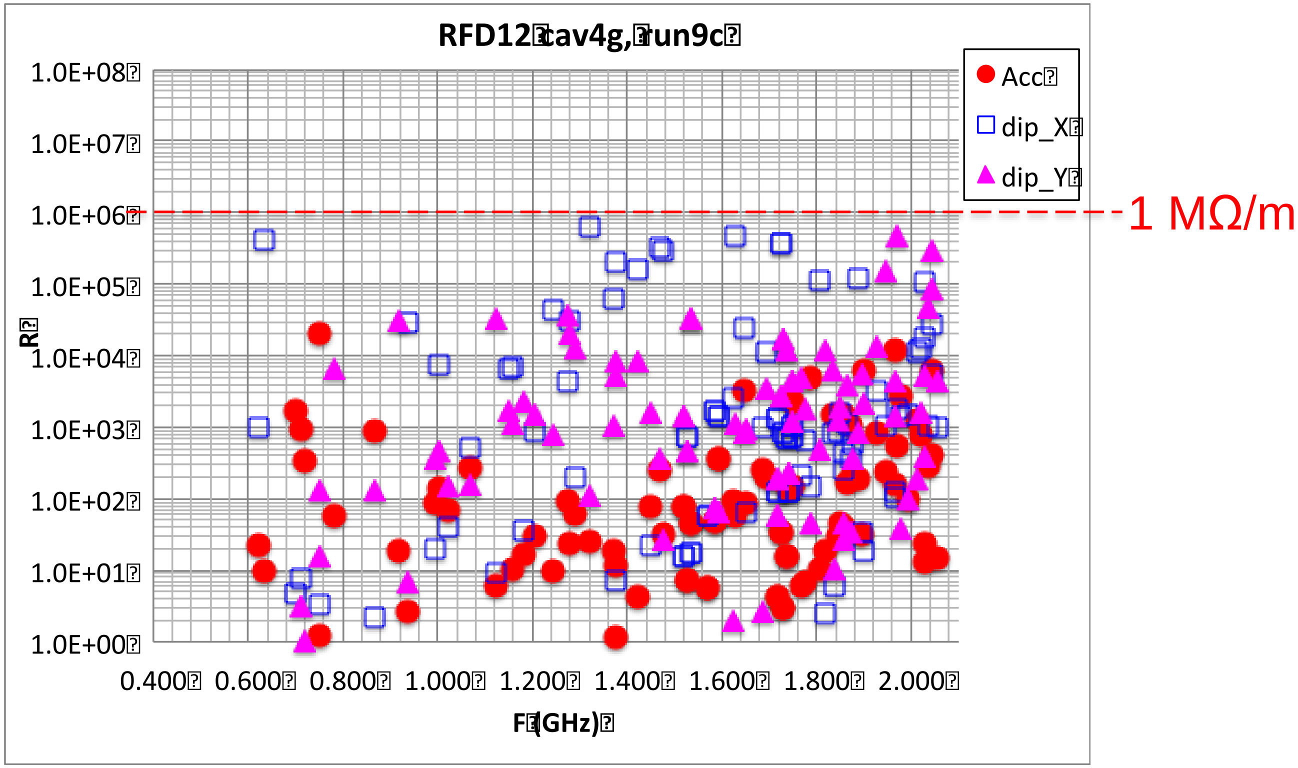


delta_gap = -1mm



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

HOM Impedance of the AUP couplers



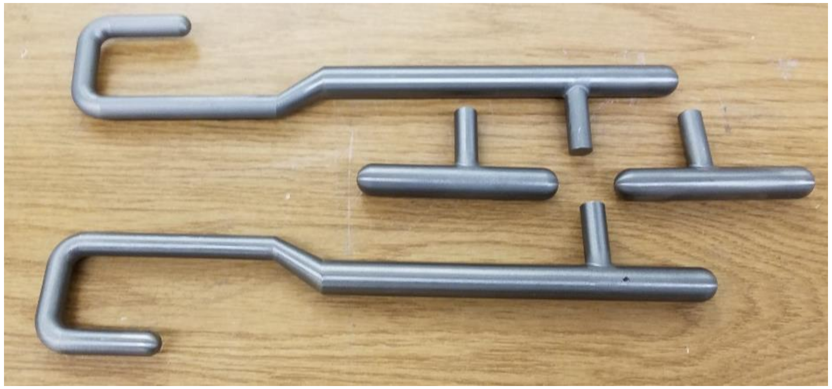
HOM impedance below 1 MΩ/m up to 2 GHz
Longitudinal shunt impedance < 200 k Ω
Meet requirement

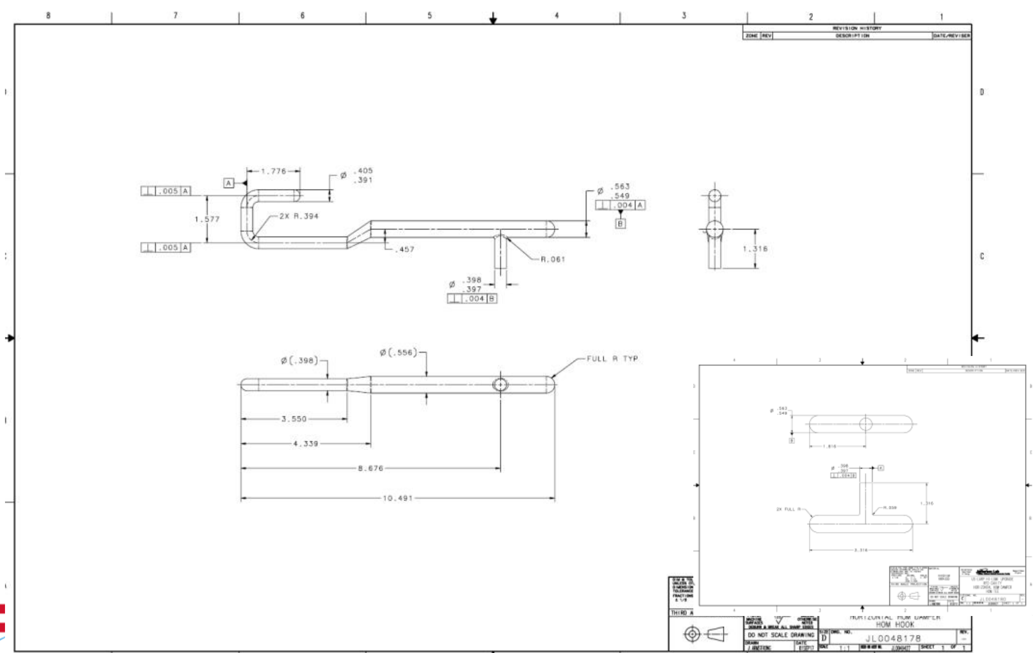
Fabrication – Hook and Tee

- The hook and tee were machined using the 5-axis CNC machine at the JLab machine shop.
- Blanks were first cut from the Nb plate using wire-EDM (photo top)
- Final machining was done on the CNC
- A test version was fabricated out of aluminum to test the CNC program (photo bottom)

HHOM Fabrication - Machining

- Machined parts are well within tolerance.





Jefferson Lab — PART NAME : HOM Damper/Hook JL0048178 — September 20, 2017 22:50 — REV NUMBER : — SER NUMBER : — STATS COUNT : 1

Feature	AX	NOMINAL	+TOL	-TOL	MEAS	DEV	OUTTOL
Perpendicularity Short U Member to Datum A — ⊥ IN PERP1 - LIN3 TO LIN5	M	0.000	0.005	0.000	0.000	0.000	0.000
Diameter Short U Member .391-.405 — ⌖ IN LOC1 - CIR11	D	0.391	0.014	0.000	0.399	0.008	0.000
Perpendicularity Long U Member to Datum A — ⊥ IN PERP2 - LIN3 TO LIN6	M	0.000	0.005	0.000	0.001	0.001	0.000
Perpendicularity .549-.563 Diameter to Datum A — ⊥ IN PERP3 - LIN3 TO LIN4	M	0.000	0.005	0.000	0.001	0.001	0.000
Diameter .549-.563 — ⌖ IN LOC2 - CIR9	D	0.549	0.014	0.000	0.555	0.006	0.000
Perpendicularity Short section (.391-.405 dia.) to Datum B — ⊥ IN PERP4 - LIN7 TO LIN4	M	0.000	0.005	0.000	0.000	0.000	0.000
Diameter short section (.391-.405 dia.) — ⌖ IN LOC3 - CIR10	D	0.391	0.014	0.000	0.400	0.009	0.000
Distance 1.577+/-.005 — ↔ IN DIST1 - LIN5 TO LIN6 (ZAXIS)	M	1.577	0.005	0.005	1.577	0.000	0.000

Jefferson Lab — PART NAME : HOM DAMPER HOM TEE JL0048180 — September 21, 2017 19:05 — REV NUMBER : — SER NUMBER : — STATS COUNT : 1

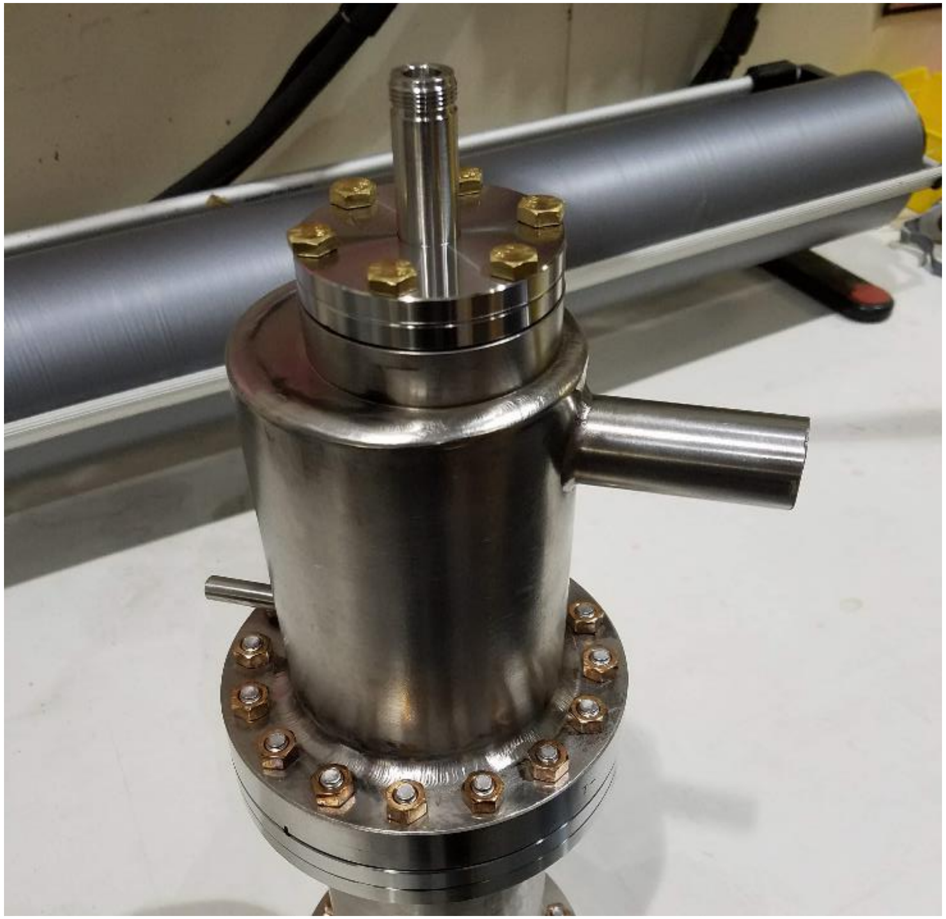
Feature	AX	NOMINAL	+TOL	-TOL	MEAS	DEV	OUTTOL
Perpendicularity Diameter .391-.405 to Datum B. — ⊥ IN PERP1 - LIN3 TO LIN4	M	0.000	0.005	0.000	0.000	0.000	0.000
Diameter .391-.405 — ⌖ IN LOC1 - CIR7	D	0.391	0.014	0.000	0.401	0.010	0.000
Diameter .549 -.563 @ one end . — ⌖ IN LOC2 - CIR9	D	0.549	0.014	0.000	0.557	0.008	0.000
Diameter .549 -.563 @ opposite end. — ⌖ IN LOC3 - CIR10	D	0.549	0.014	0.000	0.557	0.008	0.000

Fabrication – Hook/Tee EBW

- Further weld study needed to achieve uniform weldbead.
- Assembly was leak checked and pressure tested (37.7 psig=2.6 bar) as per ASME B31.3.

Fabrication – TIG Weld

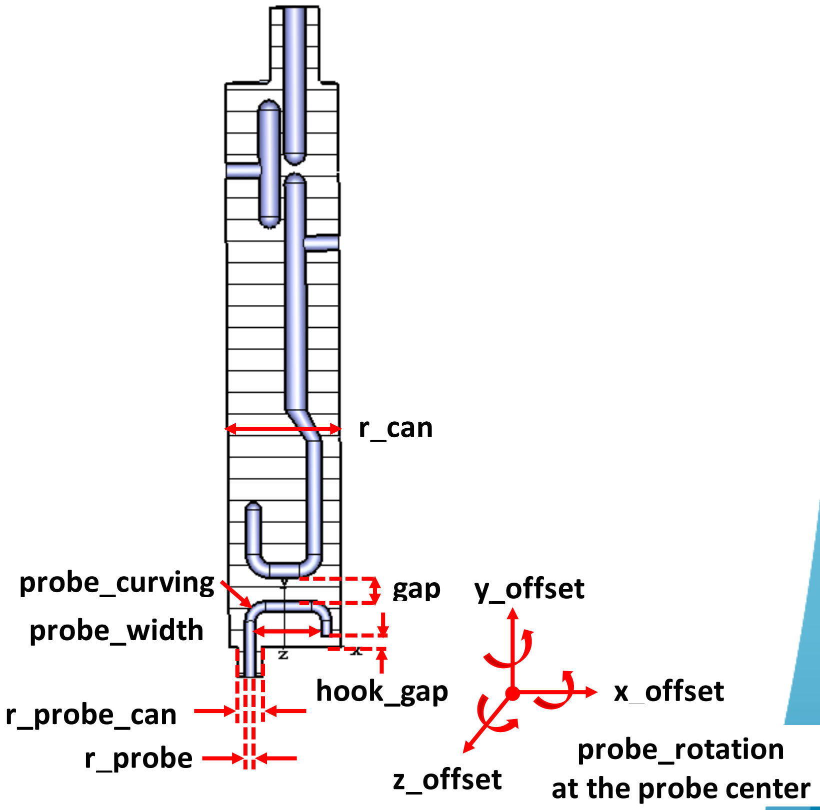
- Helium jacket is TIG welded to the stainless steel flanges
- Assembly was leak checked after the weld
- TIG weld conducted by a qualified welder as per Section IX of the ASME Code.



Error Analysis on RF Test Box

- Full set of errors were analyzed on both test box can and test probe

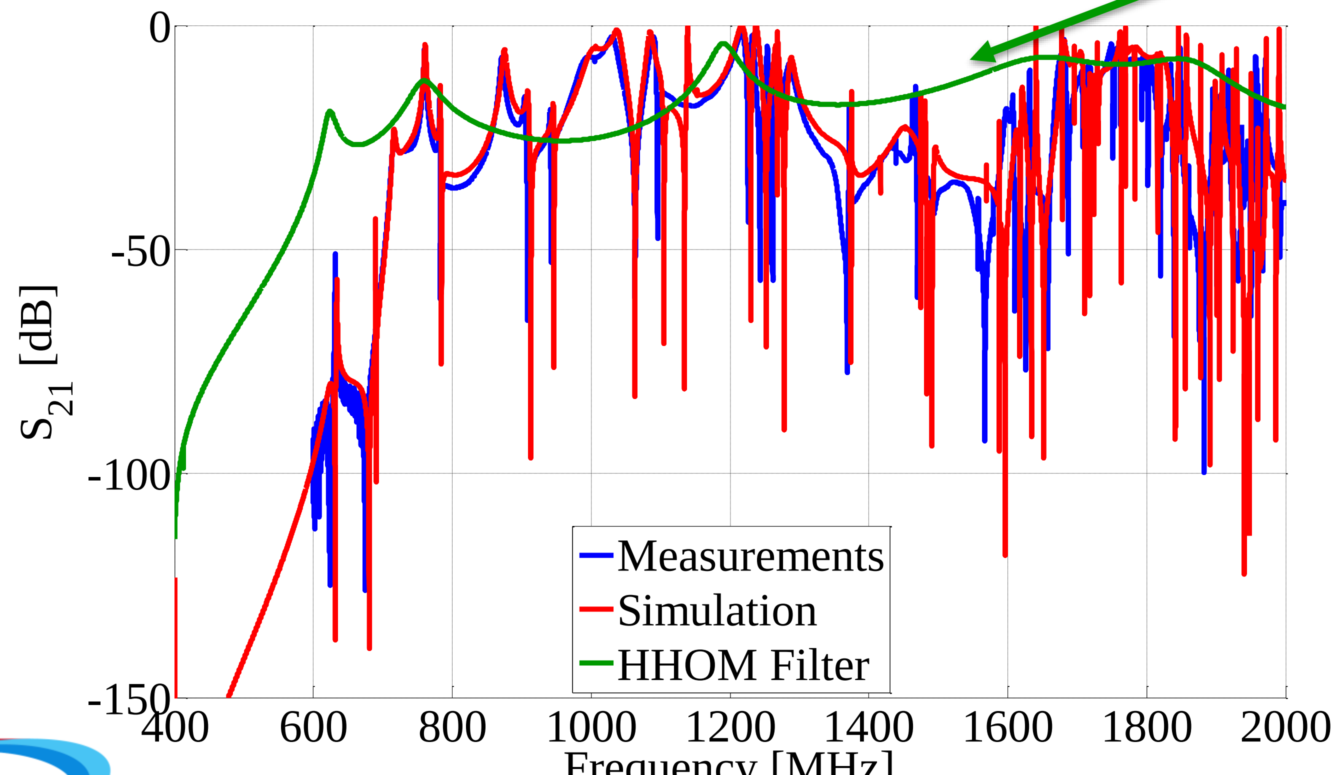
Parameter	Tolerance Value	Change in S_{21} [dB]
r_can	± 0.01"	0.15
can_height	± 0.005"	0.06
r_probe_can	± 0.01"	0.18
r_probe	± 0.005"	0.23
probe_concentricity	± 0.01"	0.12
probe_height	± 0.005"	0.07
probe_width	± 0.01"	0.15
probe_curving	± 0.01"	0.07
hook_gap	± 0.01"	0.17
probe_rotation (With respect to center of probe)		
x axis	± 1 deg	0.15
y axis	± 1 deg	0.02
z axis	± 1 deg	0.35



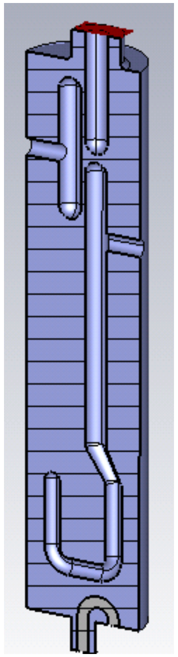
Comparison of Transmission between Simulation and Measurements

- S_{21} measurement from HHOM through VHOM on RFD-CAV-002
- Measurement and simulation match simulation for up to 2 GHz
  - Verifies the HHOM and VHOM couplers
  - Next Step: Measurements of HHOM filter with the test box
  - Working on the HOM test box design (Zenghai Li)

Jamie Mitchell (UK)

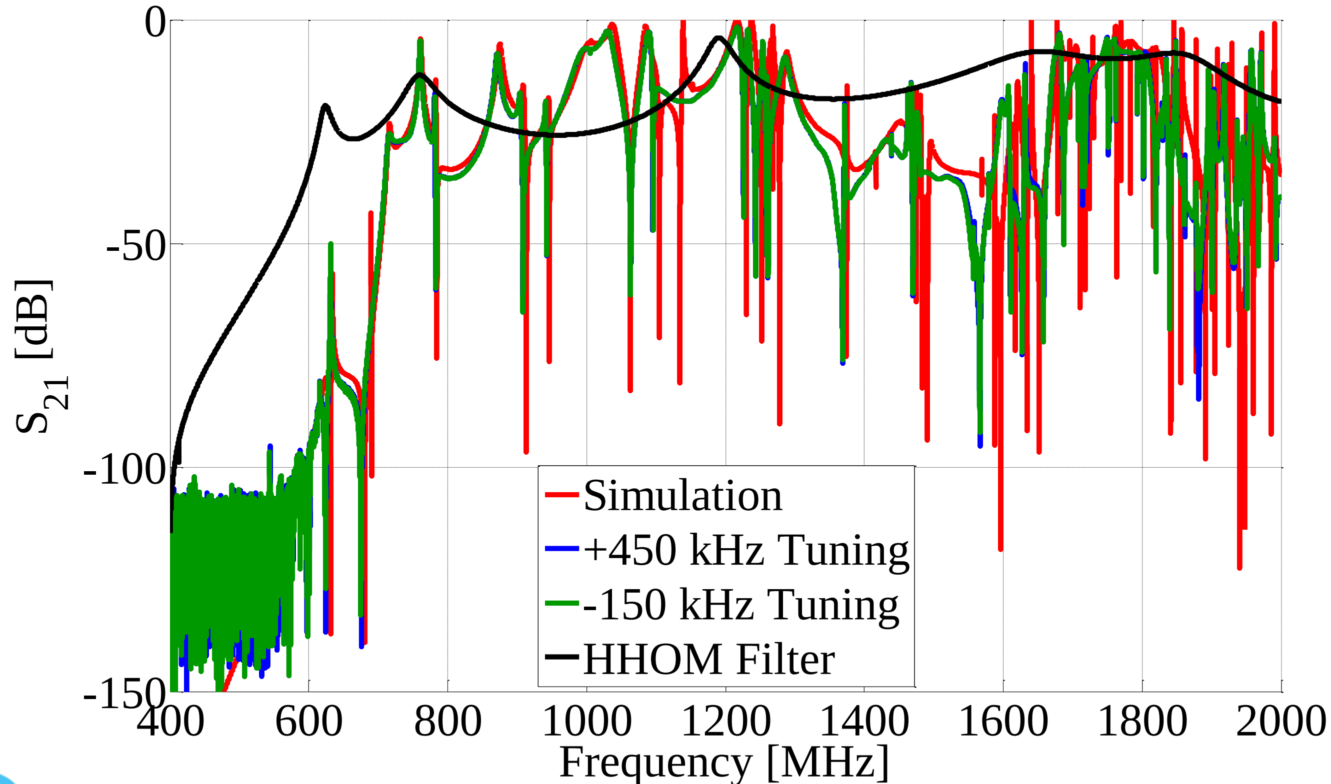


HHOM Filter in Test Box



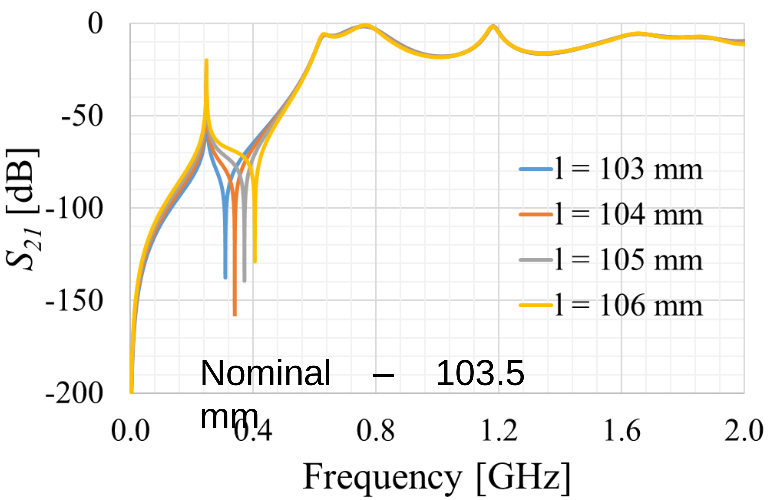
Tuning Sensitivity Measurements of HOMs

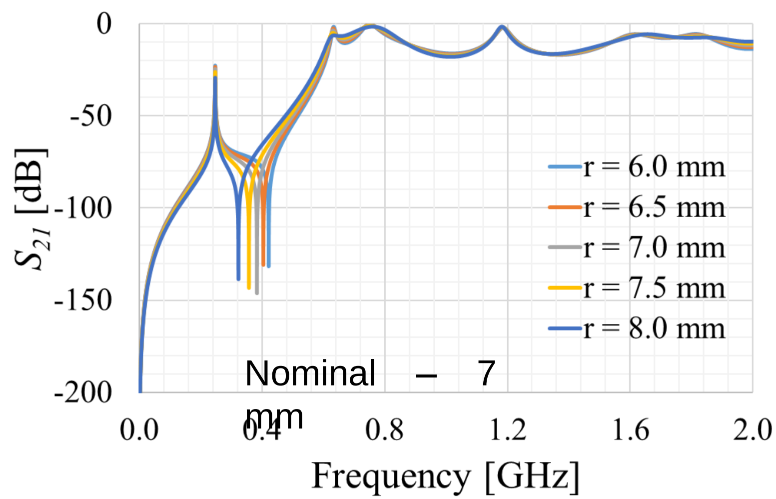
- Cavity pushed and pulled on a single side with a fundamental mode frequency shift of:
  - +450 kHz in compression
  - -150 kHz in tension
- **HOMs do not show frequency shift due to tuner motion**



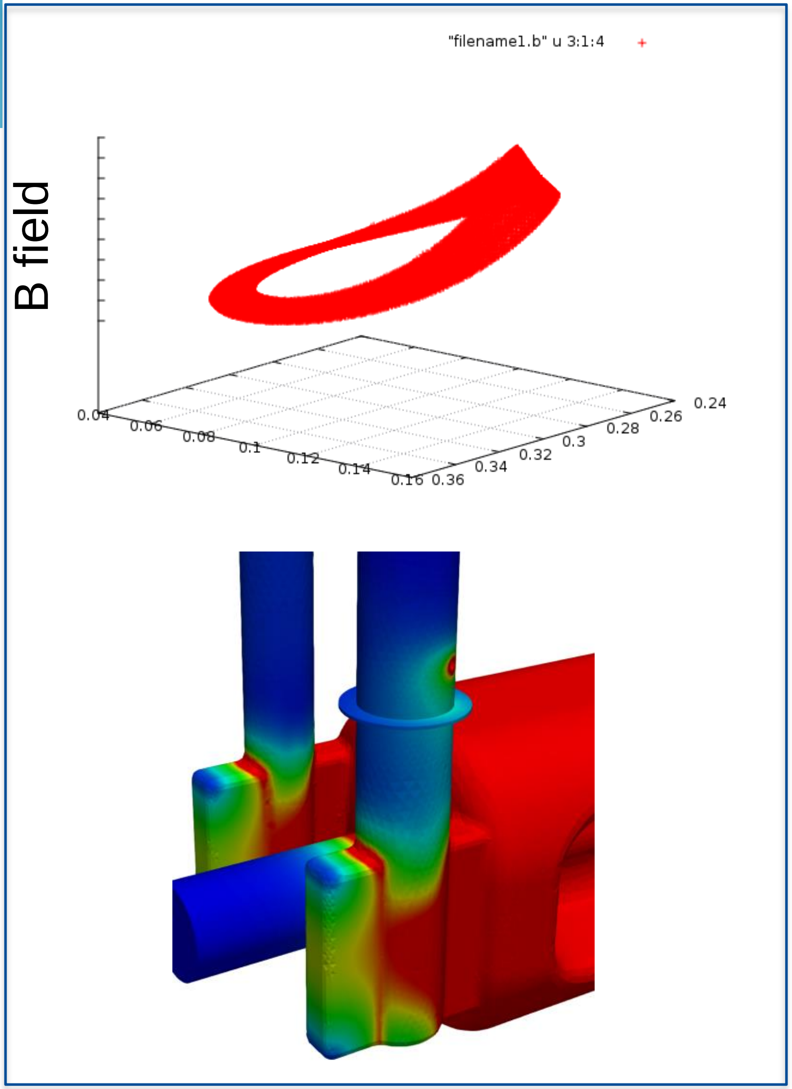
Tuning of HHOM Coupler

- Shift in notch in the HHOM coupler can be tuned by adjusting the Probe length and diameter
- Adjustments doesn't effect transmission at higher frequencies in HOMs
- Sensitivity of notch shift
  - Probe length – 32 MHz/mm
  - Probe diameter – 41 MHz/mm
- Requires better specification on minimum attenuation at the fundamental



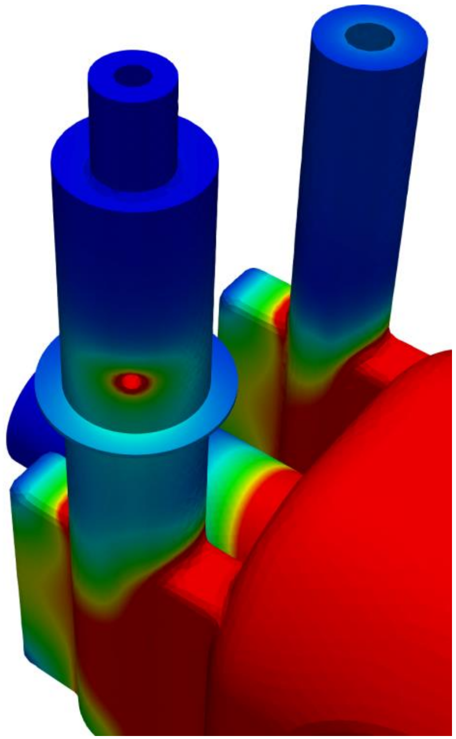


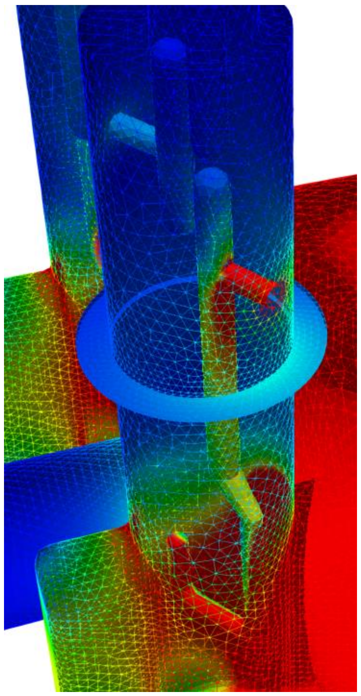
HHOM Cu Gasket: needs to short Nb "perfectly" at HHOM can ID



LARP RFD test:

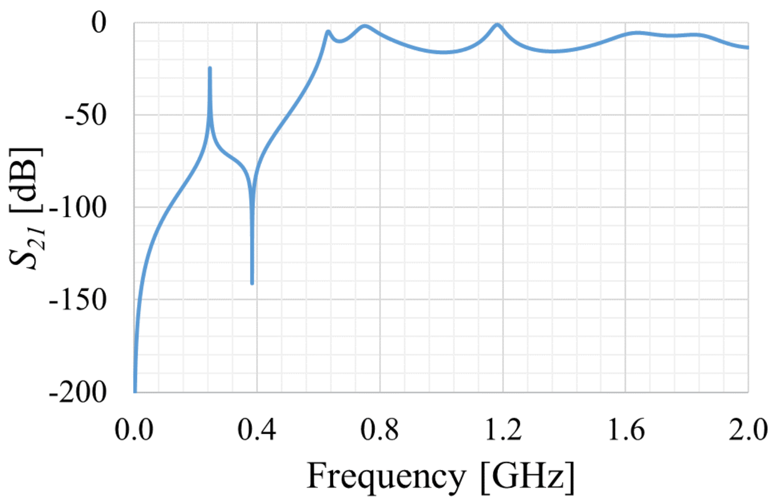
- Q0 with SS Flange: 6.5e8
- Likely cause is loss on SST flange at gasket gap

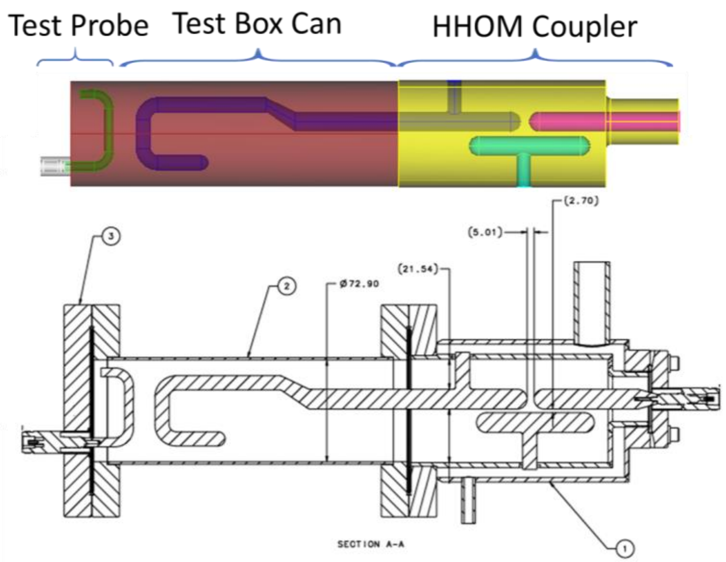




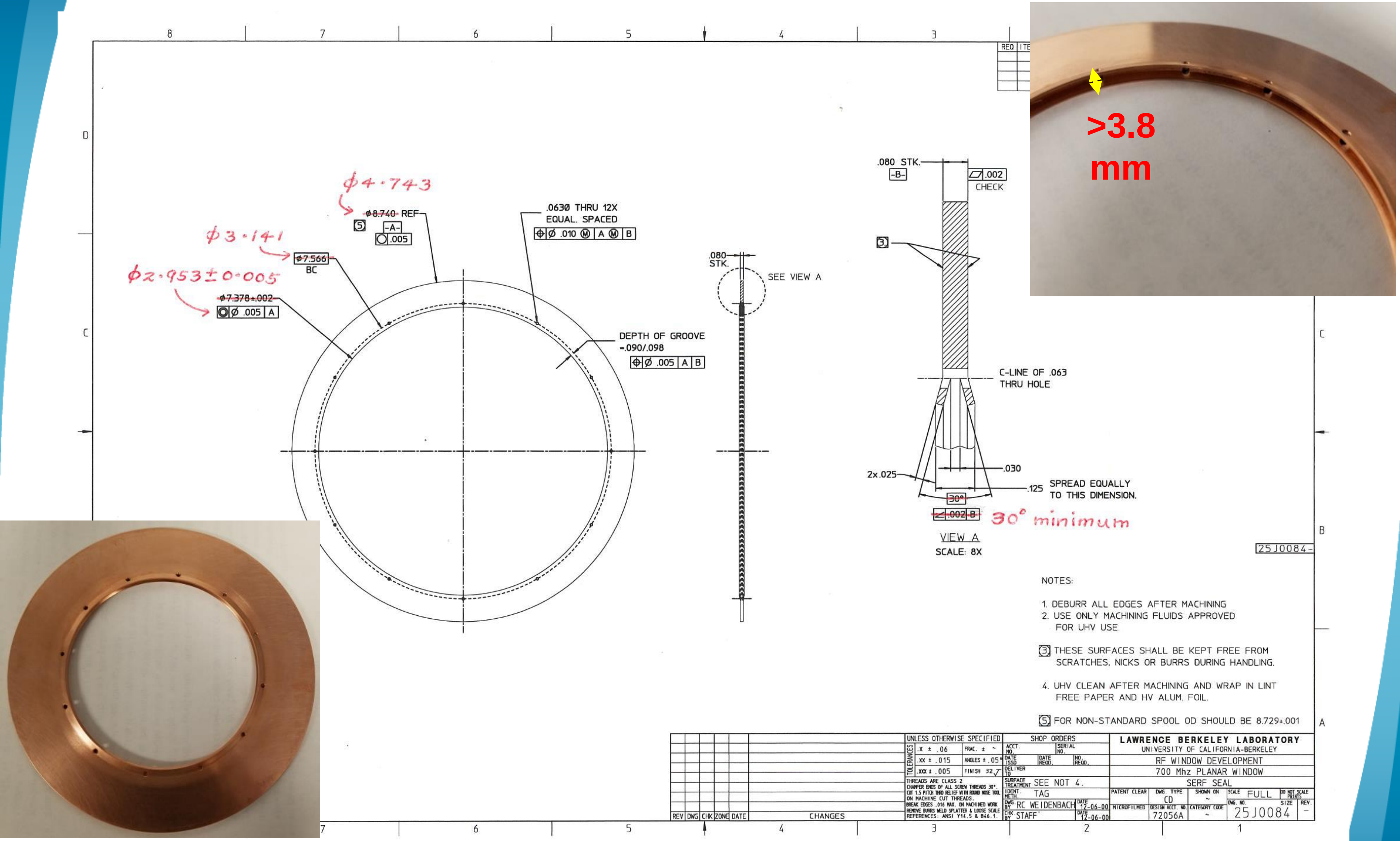
RF Test Box for RFD HHOM Coupler

- RF test box designed to characterize RFD HHOM coupler
- Design with a hook-shaped test probe
  - A notch at operating frequency of 400 MHz
  - Maximum transmission above 600 MHz up to 2 GHz

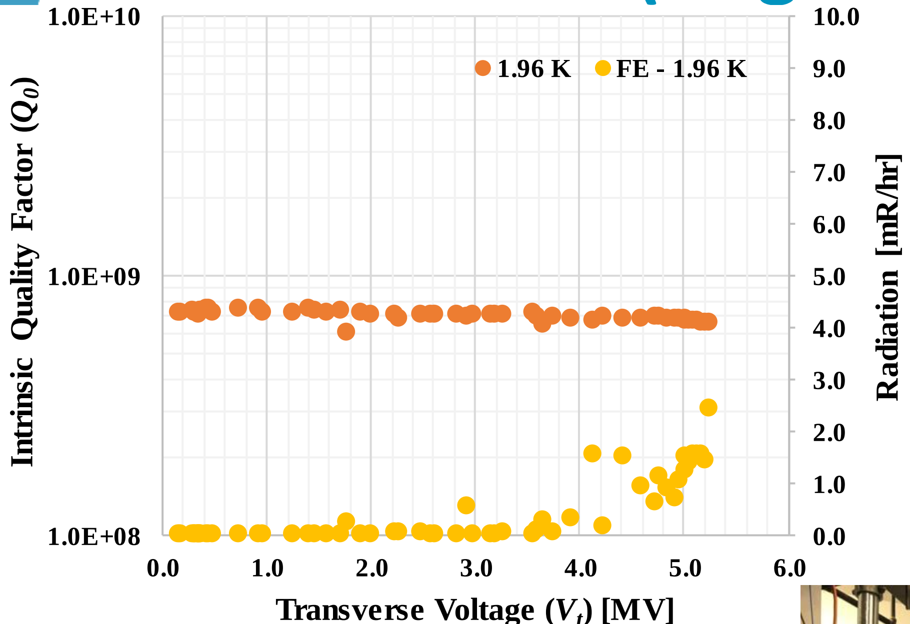


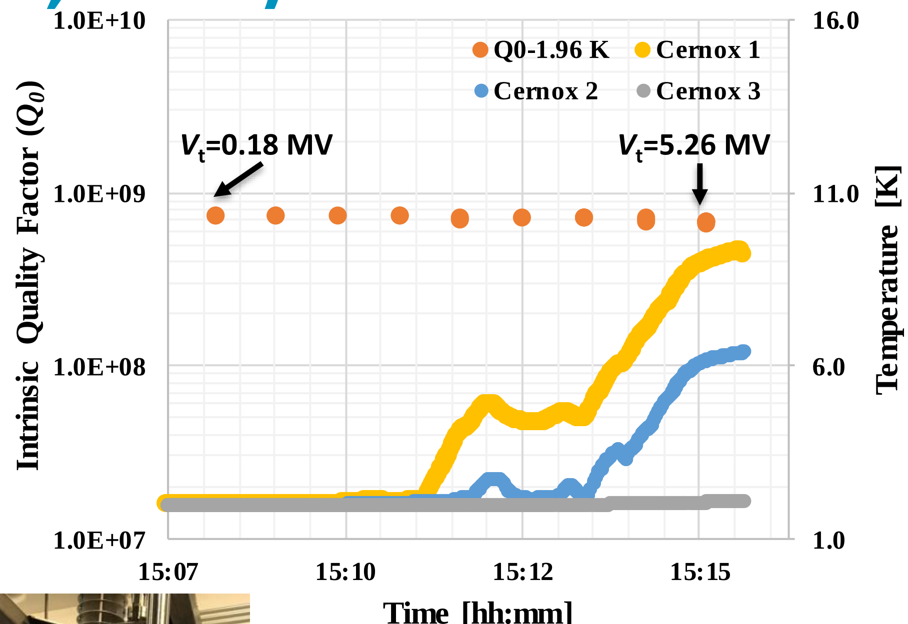


Proposed RF Gasket for HHOM

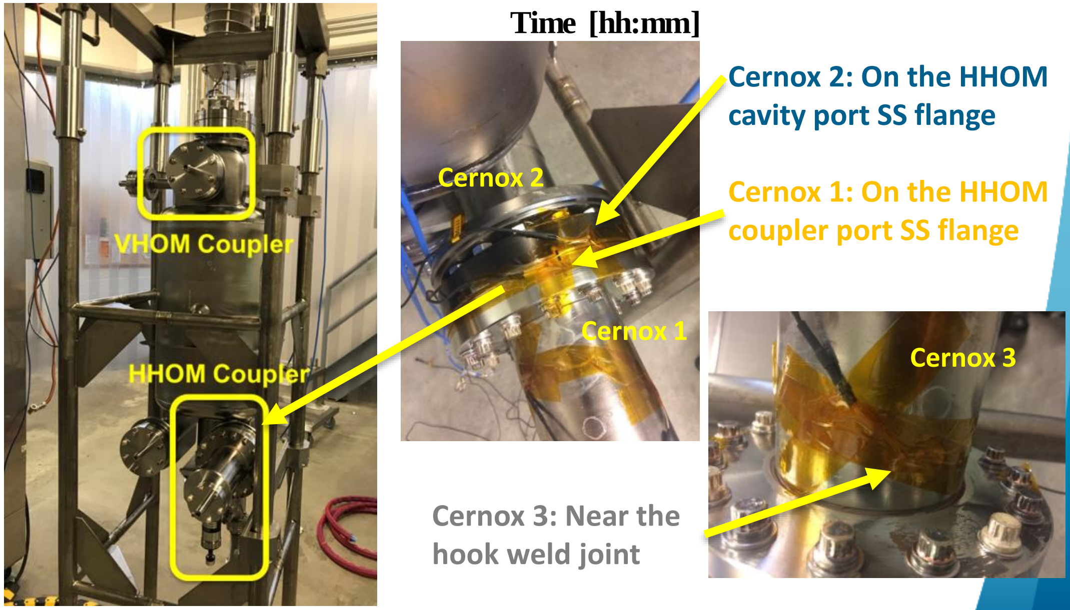


Test 3 with only HHOM Coupler (August 3, 2018)

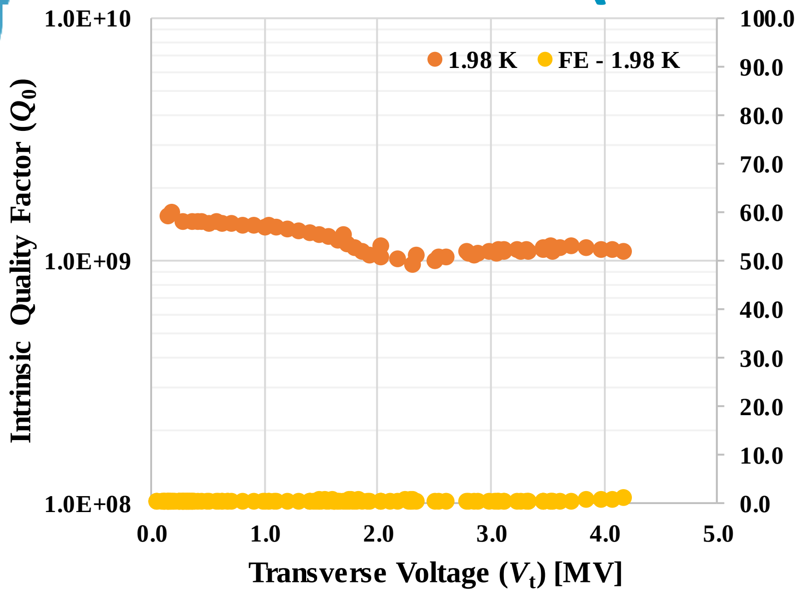


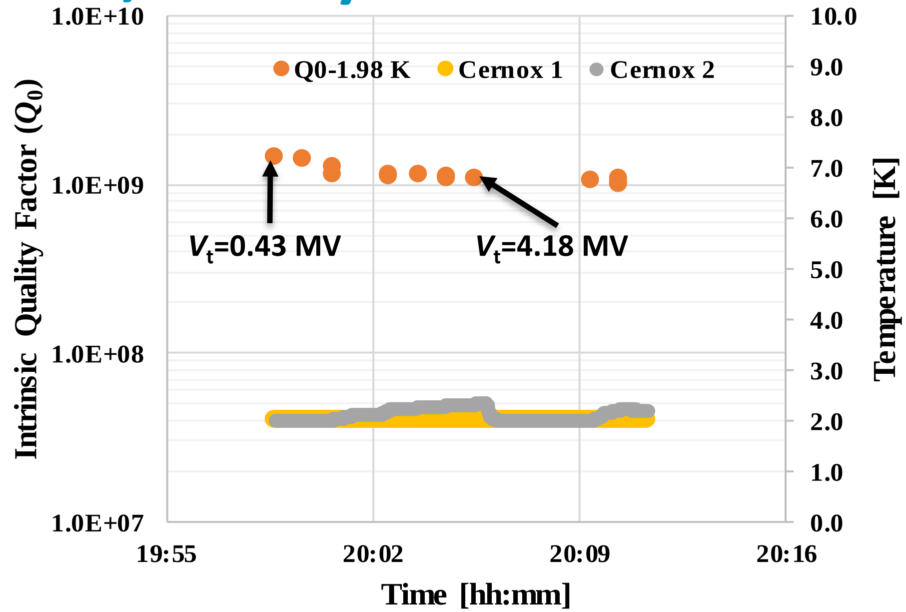


- Additional light BCP of 13 microns
- Reduced Q_0 (7.2×10^8) due to incorrectly sized Cu gasket which exposed stainless steel to rf fields
- Cavity didn't quench → RF power limited
- Next step – Retest with an rf gasket
- Cernox sensors showed rf heating primarily on the SS flanges at the HHOM coupler port and cavity port



Test 4 with only HHOM Coupler (October 9, 2018)





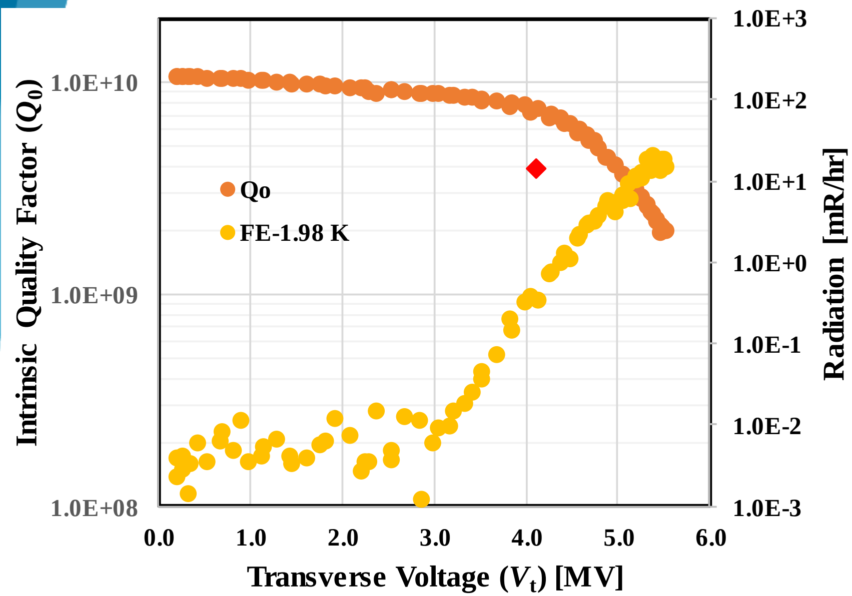
- Measurement with rf gasket at HHOM
- Q_0 improved to 1.4×10^9
- Q drop around 2.5 MV was due to multipacting
- HHOM coupler showed strong coupling of ($Q_{ext} = 5.8\times10^9$)
  - Possibly due to the deviations between the probe, T and hook

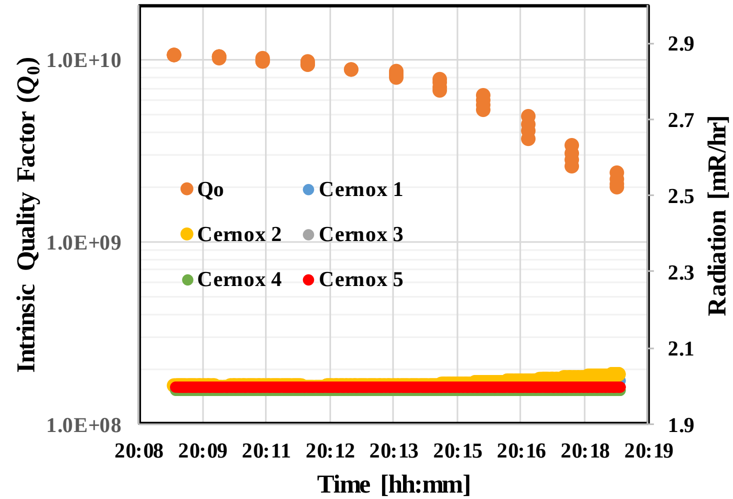
Cernox 1: On the HHOM cavity port SS flange

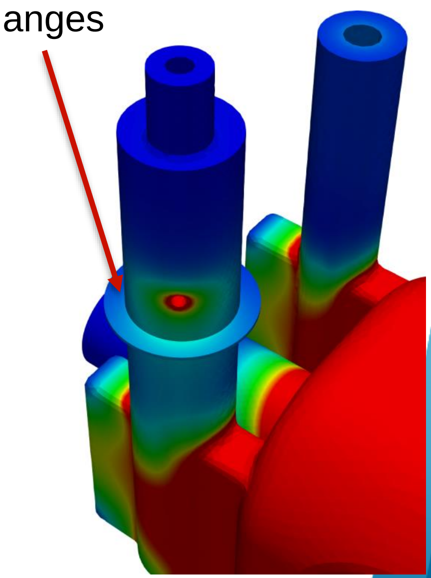
Cernox 2: Near the hook weld joint

- Cavity didn't quench → Performance was limited due to limitation on rf power on the cable (10 W) at the HHOM coupler
- Field emission was negligible

RFD2 Test 2 with both HOM Couplers (11/28/2018)







- RF gasket wasn't closing the gap between the two SS surfaces of the installed HHOM coupler → Fully covered rf gasket with Cu foil to increase the thickness
- Q_0 improved to 1.0×10^{10} at low fields → similar to Q_0 of cavity with no HOM couplers
- Reached V_t~5.5 MV before quench
- Field emission observed at V_t >3 MV
  - VHOM and HHOM was assembled without an HPR after slow cavity bleed from previous test