



LARP PROTOTYPE RFD CAVITY PROCESSING, TESTING AND MEASUREMENTS (LARP/AUP)

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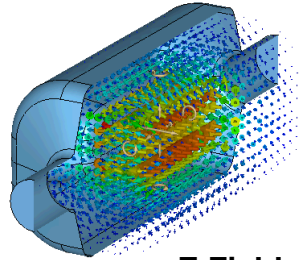
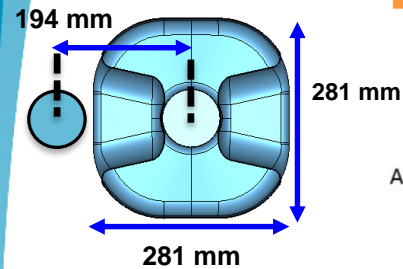
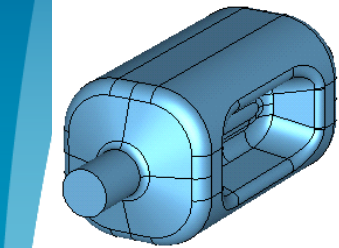
8th HL-LHC Collaboration Meeting – CERN – 15-18 October, 2018

Outline

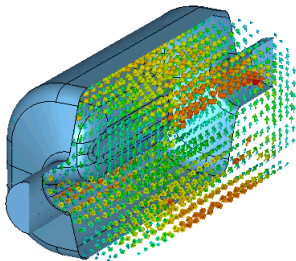
- LARP Prototype Cavity
- Cavity Fabrication, Processing and Testing at Jefferson Lab
 - Cavity processing
 - Cold rf tests without HOM couplers
 - Room temperature measurements with HOM couplers (RFD-CAV-002)
 - Cold rf tests with HOM couplers (RFD-CAV-002)
- Cavity Processing at ANL (RFD-CAV-001)
 - BCP on the Rotational Tool
 - High Pressure Rinsing
- Cavity Testing at Fermilab (RFD-CAV-001)
 - Cold validation rf test
 - Cold rf tests after processing at ANL
- Summary and Future Plans

LARP Prototype RFD Cavity Design

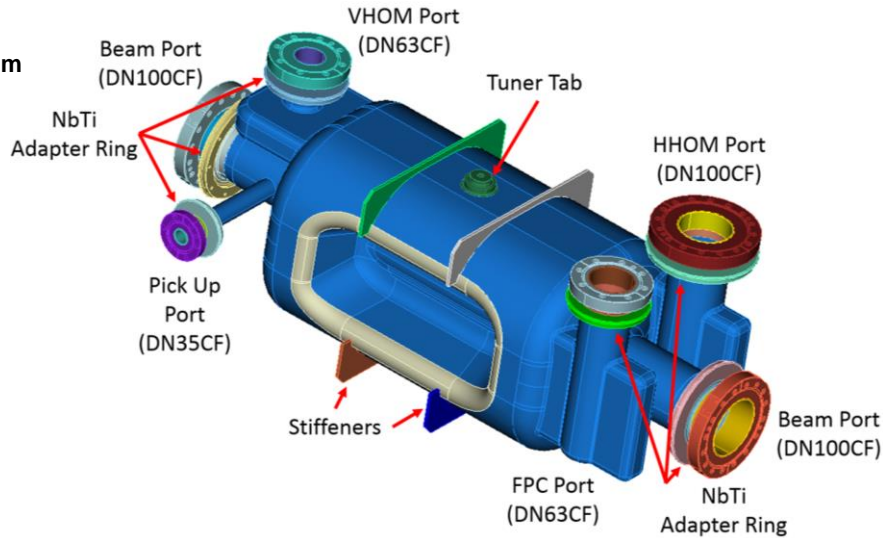
- LARP prototype design is a fully integrated design
- Operates in TE_{11} like mode
- Crabbing in horizontal plane
- Meet the compactness requirement for LHC



E Field



H Field



	SPS	
Frequency	400.79	MHz
Aperture	84	mm
Nearest HOM	633.5	MHz
E_p^*	3.6	MV/m
B_p^*	6.2	mT
$[R/Q]_t$	429.7	Ω
Geometrical Factor (G)	106.7	Ω
$R_t R_s$	4.6×10^4	Ω^2
At $E_t^* = 1.0$ MV/m		
V_t	3.4	MV
E_p	33	MV/m
B_p	56	mT

LARP Prototype Cavity Fabrication

(Sep 2014 – Jan 2017)

- Two prototype cavities were fabricated
- Sub-assemblies fabricated at Niowave Inc. and final welding completed at Jefferson Lab



Parts of HHOM,
FPC & VHOM
waveguide
stubs

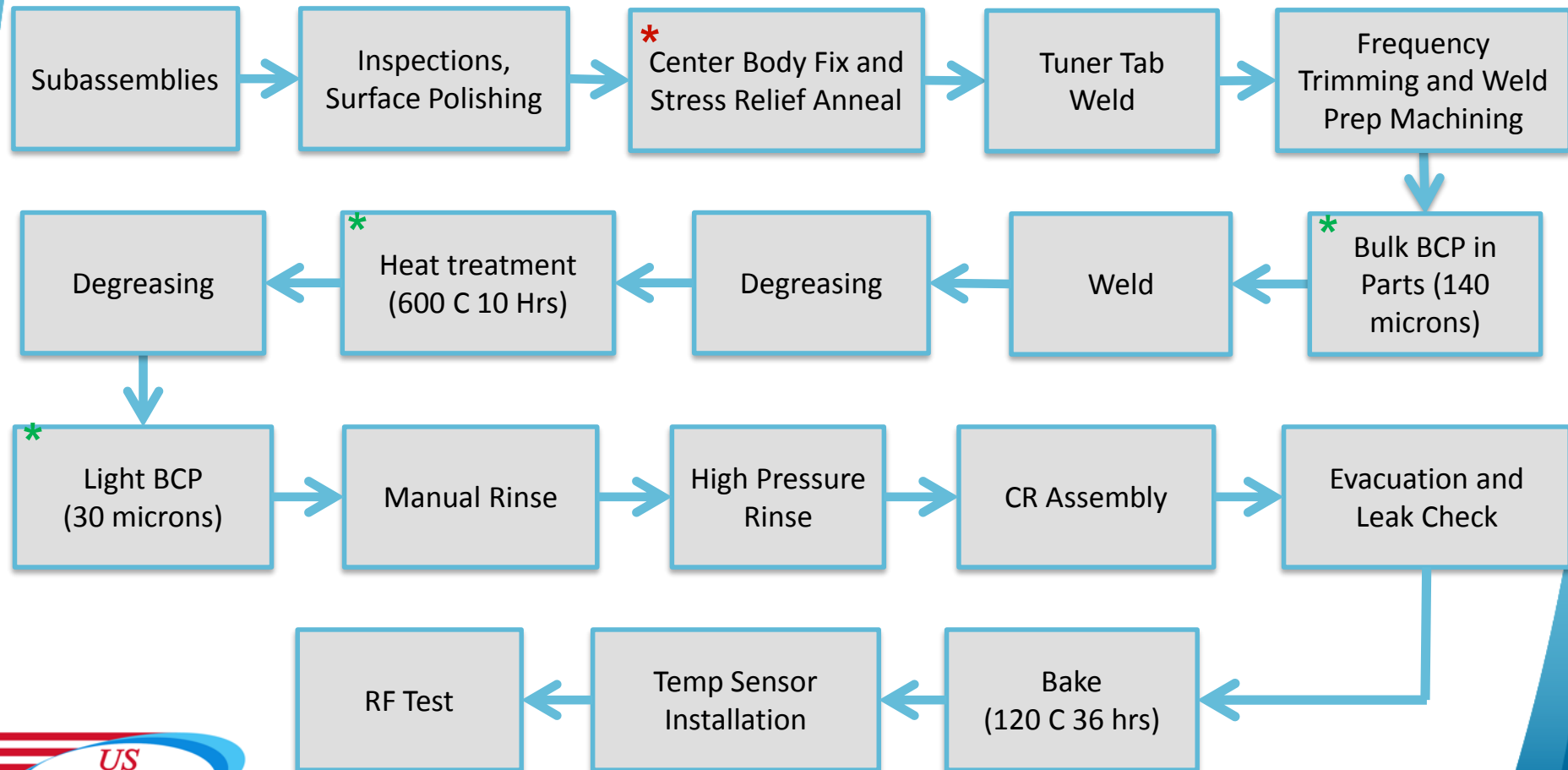


LARP Prototype Cavity Processing Flow

- Processing and rf testing completed at Jefferson Lab
- * Annealing performed only for CAV-001
- * Both cavities were reprocessed with bulk BCP, heat treatment and light BCP after initial welds

USLARP Crab Cavity Test Results –
HyeKyoung Park (JLab) – International
Review of the Crab Cavity Performance
for HiLumi (April, 2017 – CERN)

Inspection and frequency measurement between each step



RF Testing of Bare Cavities at Jefferson Lab

- RFD-CAV-001 → Two rf tests
 - Reprocessed and retested after first test to improve the performance due to poor welds
- RFD-CAV-002 → One rf test
 - Rewelded and reprocessed before the test to fix the incomplete welds
- FPC and Pick Up ports with Q_{ext} of
 - Input probe → $Q_{\text{ext}} \sim 5 \times 10^9$
 - Pick Up probe → $Q_{\text{ext}} \sim 2 \times 10^{11}$

Cavity mounted in the test stand at Jefferson Lab

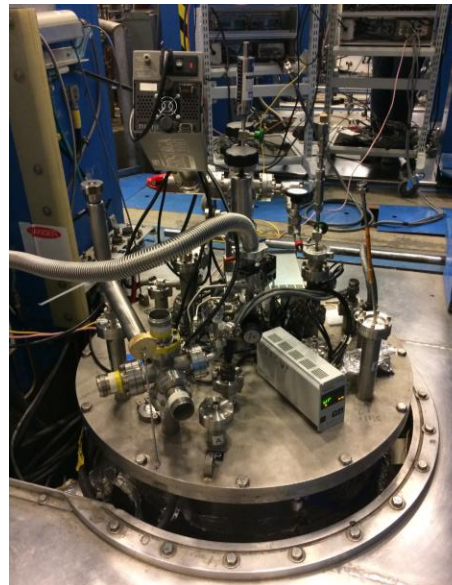


Safety valve

Pick Up Port
 $Q_{\text{ext}} \sim 2 \times 10^{11}$

FPC Port
 $Q_{\text{ext}} \sim 5 \times 10^9$

Test stand loaded in dewar

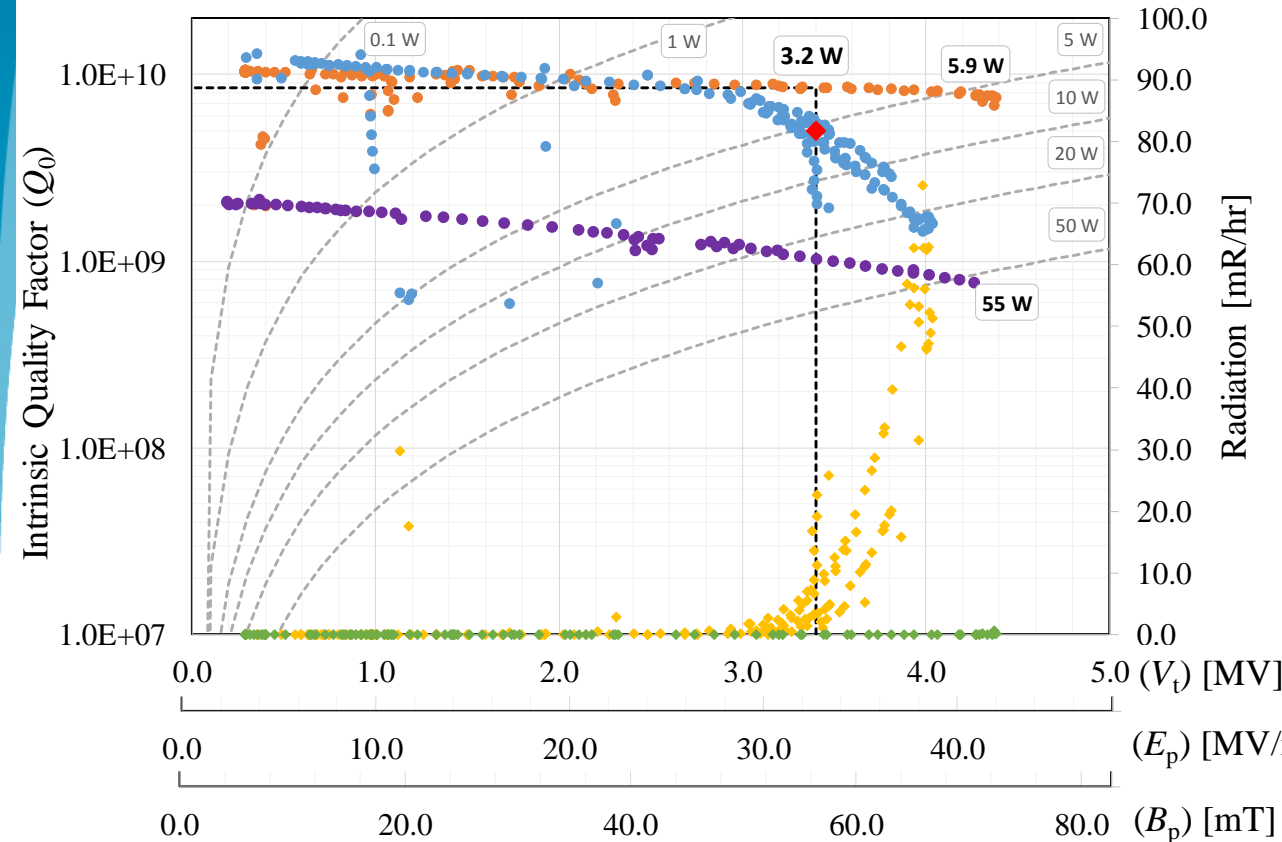


Cavity assembly



Cavity Performance – RFD-CAV-001 (At JLab)

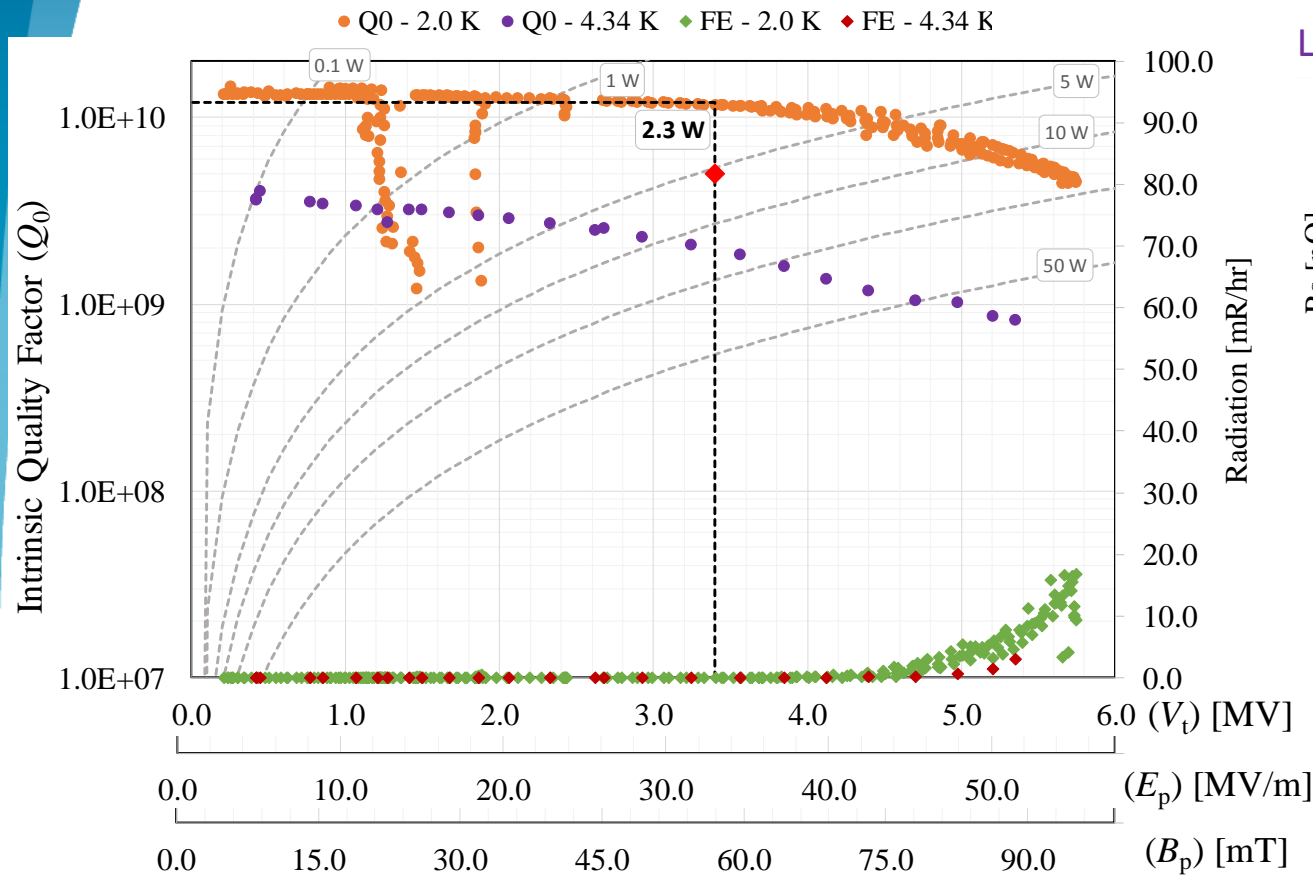
• Test 1 - 2.0 K • Test 2 - 2.0 K • Test 2 - 4.2 K • FE - Test 1 - 2.0 K • FE - Test 2 - 2.0 K



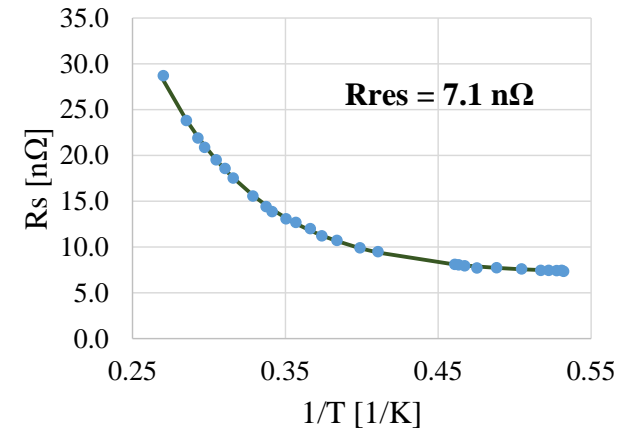
At 2.0 K	Test 1	Test 2
Max V_t [MV]	4.0 MV	4.4 MV
E_p [MV/m]	38	42
B_p [mT]	66	73
Q_0 at 3.4 MV	5.5×10^9	8.5×10^9
P_{diss} at 3.4 MV [W]	4.9	3.2

- Test 1: After final welding of the cavity
 - Surface inspection showed rough welds and weld splatter on cavity surface
- Another round of bulk BCP done before Test 2
- At low fields for both rf tests Q_0 is $> 1.0 \times 10^{10}$
- Multipacting was processed easily and didn't reoccur
- No field emission observed during Test 2

Cavity Performance – RFD-CAV-002 (At JLab)



Low temp bake at 120 C – 6 hours

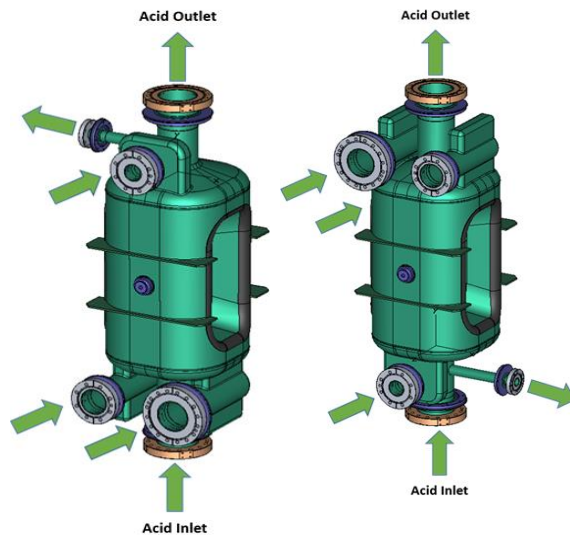


- Cavity rewelded due to incomplete welds and reprocessed with bulk BCP
- Cavity quenched at 5.8 MV with a Q_0 of 4.6×10^9 (17 W)
- No field emission up to 4.5 MV
- Multipacting was processed easily and didn't reoccur

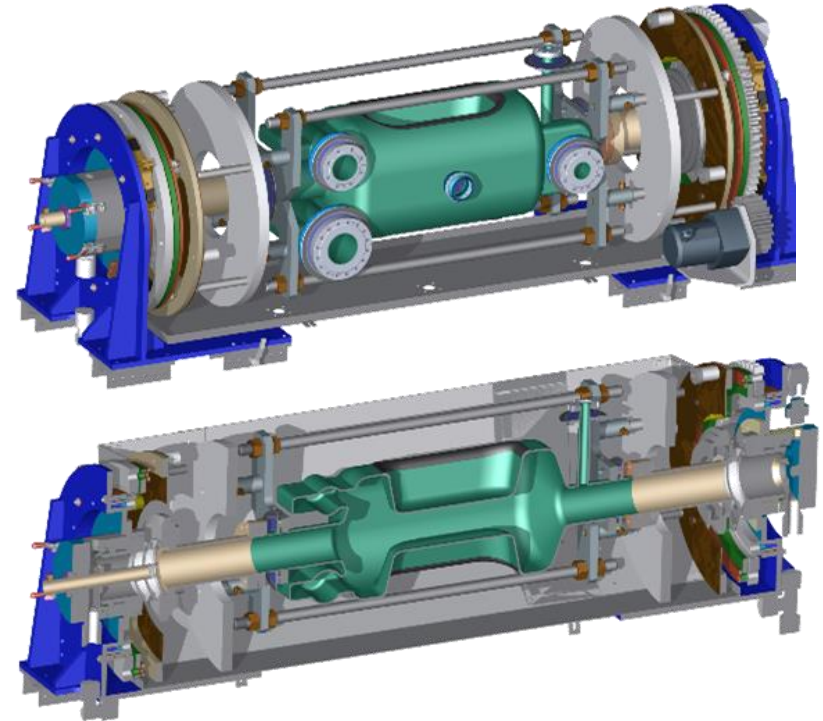
At 2.0 K	Test
Max V_t [MV]	5.8
E_p [MV/m]	56
B_p [mT]	96
Q_0 at 3.4 MV	1.2×10^{10}
P_{diss} at 3.4 MV [W]	2.3

Processing and of Bare Cavities (At ANL)

- RFD-CAV-001 sent to Fermilab
- RFD cavities BCP has been performed at JLab in a static set-up
- New rotational BCP tool has been developed at ANL
 - Allows more uniform removal
 - Better acid circulation and drainage



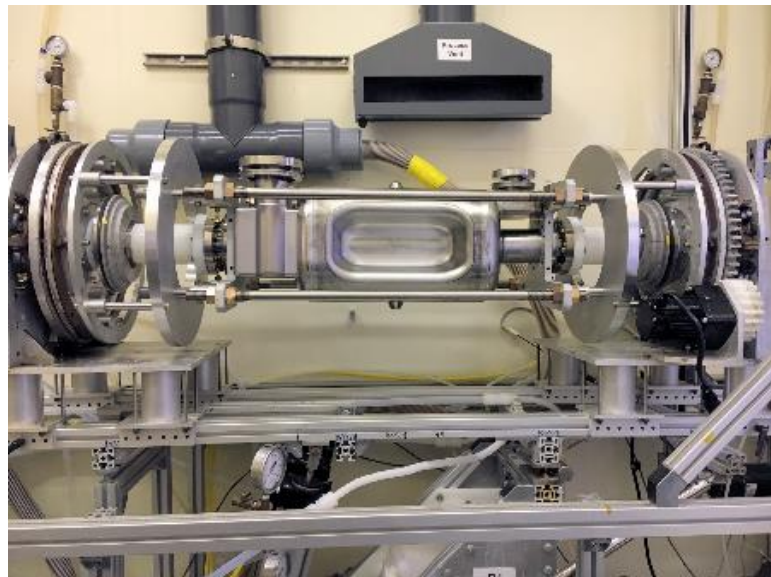
Static RFD cavity BCP scheme at JLab



Rotational BCP tool for RFD cavity at ANL

Upgraded BCP Tool (At ANL)

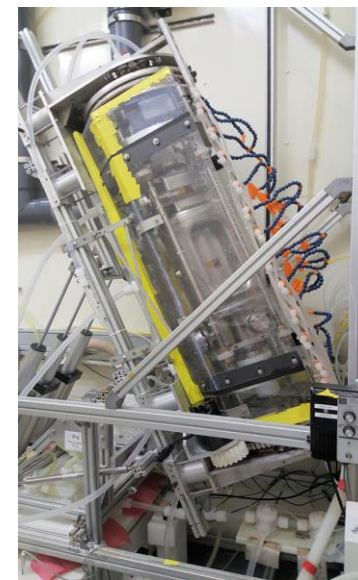
- In addition, the BCP tool can tilt the cavity for better acid evacuation or improved rinsing right after BCP procedure
- Cavity temperature is kept under control using chilling water on the outside of the cavity
- First rotational BCP performed in April 2018



Horizontal position of the BCP tool



Vertical position of the BCP tool

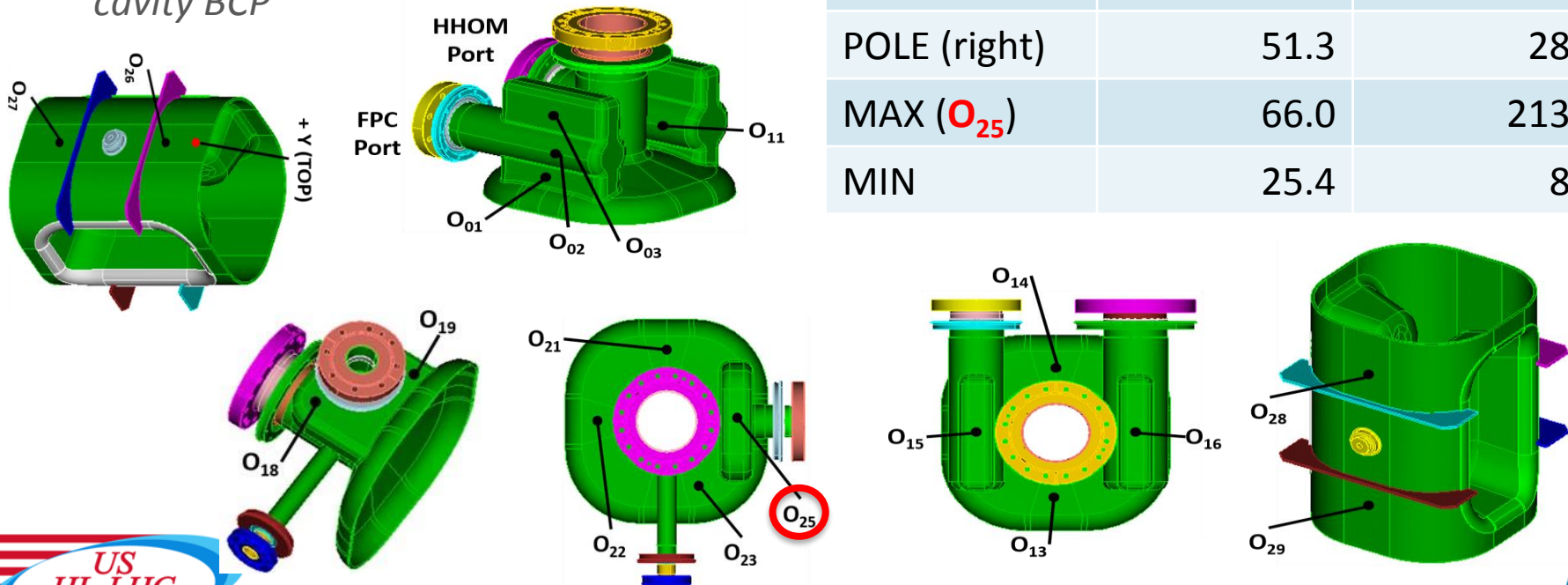


Rinsing position after BCP

Material Removal of the Cavity in the Rotational BCP Tool

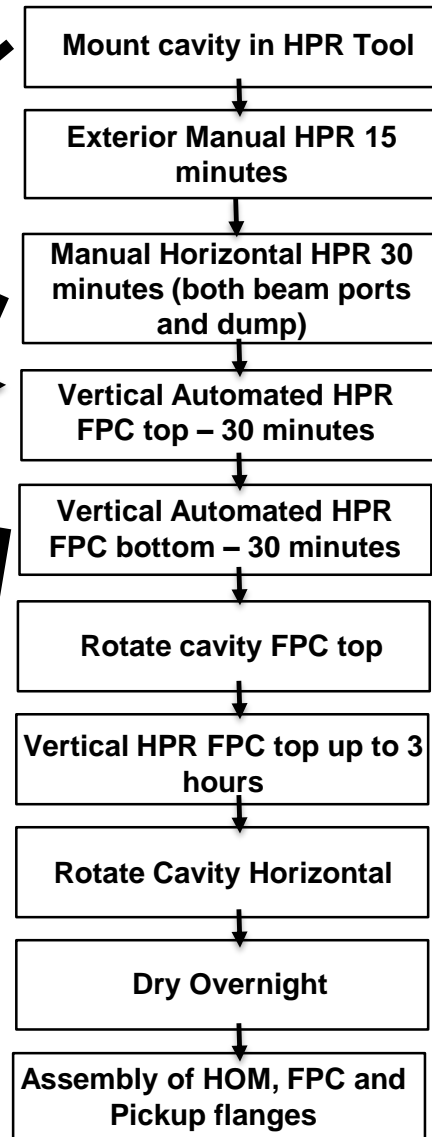
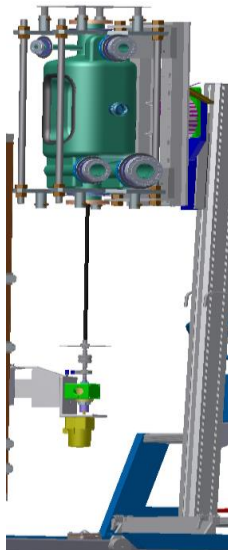
- Material removal has been compared between the two BCP procedure: AVG removal is 48 microns for ANL, 40 microns for JLab
- Uniform removal confirms better process compared to BCP performed on static RFD: Standard deviation in etch data drops to 1/3 going from static to rotating cavity BCP*

Location	ANL BCP 48 μm	JLAB BCP 40 μm
HHOM	46.1	22.5
VHOM	55.0	58.6
FPC	48.6	28.4
BODY	44.5	25.1
POLE (left)	51.8	26.2
POLE (right)	51.3	28.7
MAX (O ₂₅)	66.0	213.7
MIN	25.4	8.5



High Pressure Rinsing Tool (At ANL)

- Final procedure with feedback from JLab/ODU
- Use of a high pressure rinse set-up using multiple ports → combination of hand-HPR and automated procedure
 - ANL automatic tool has been upgraded to allow automated beam ports HPR
 - HHOM, VHOM FPC and PU ports are rinsed by hand



RF Testing of Bare Cavity at Fermilab

- Testing of RFD-CAV-001
- Test 1
 - Cavity shipped under vacuum to Fermilab and rf tested
- Test 2
 - RF test after light BCP
- Test 3
 - RF test after improved HPR to reduce field emission



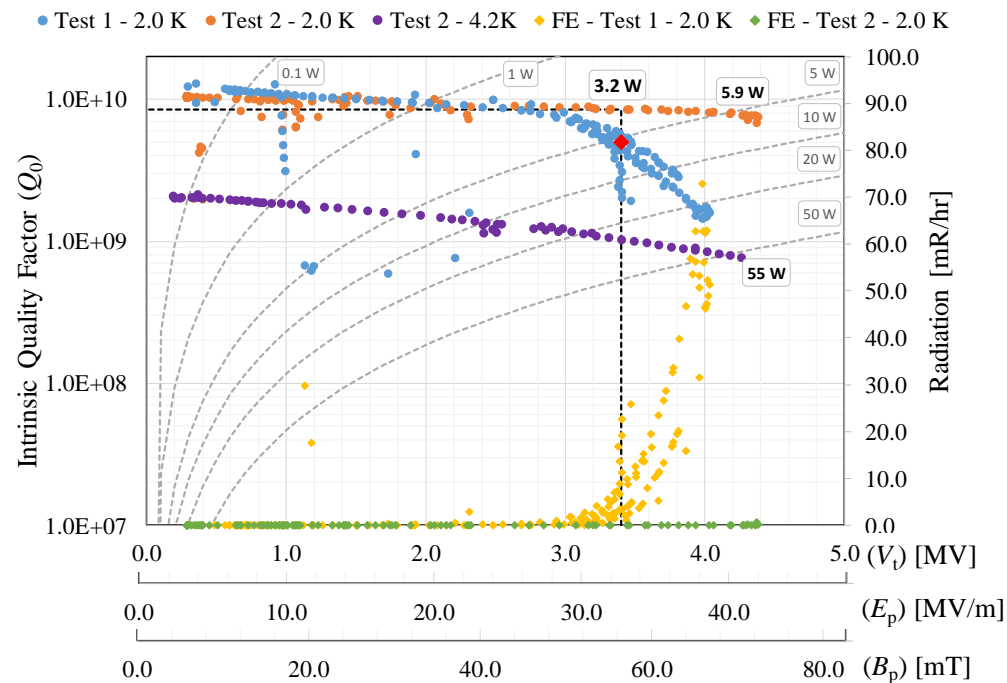
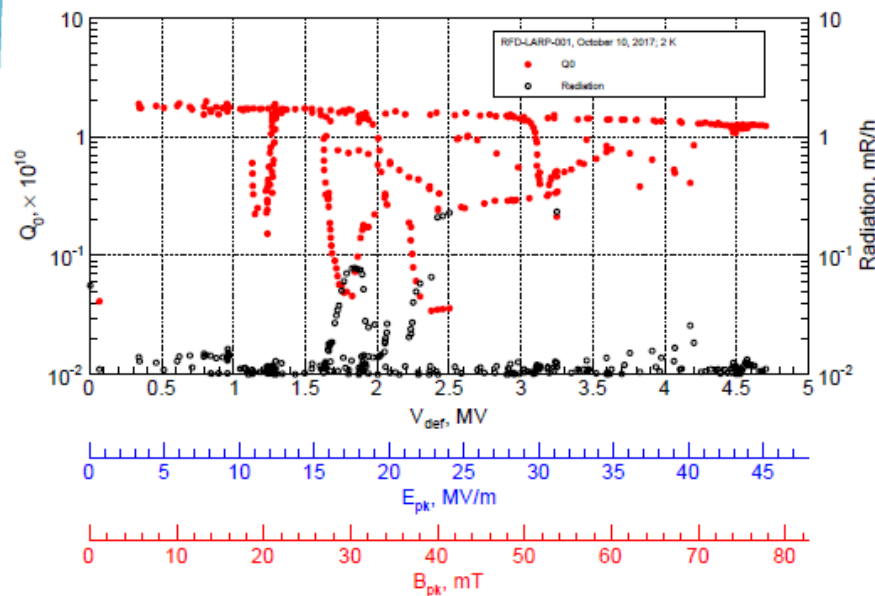
Cavity before
cleanroom
assembly at
Fermilab



Cavity
insertion in
VTS #3

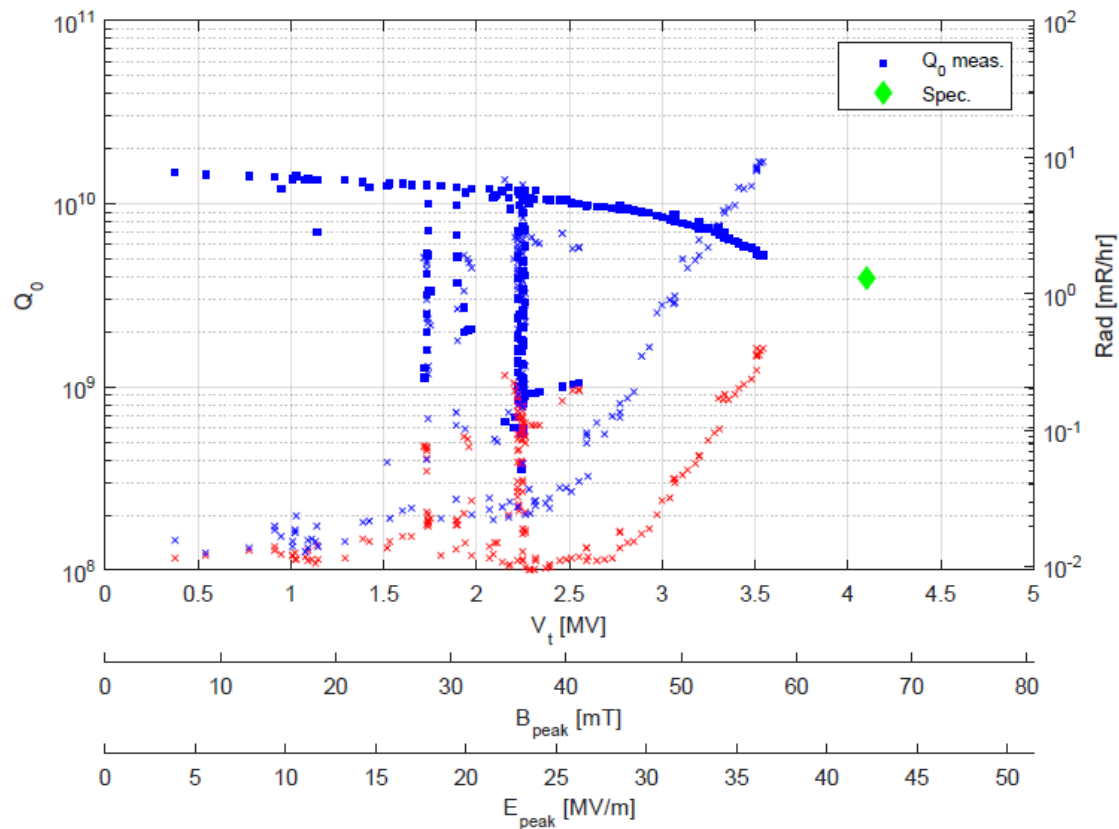
Test 1 (At Fermilab)

- Dedicated 500W Amplifier was installed and functioned flawlessly
- Cavity quenched at $V_t = 4.68$ MV
- Quality Factor $Q_0 > 1 \times 10^{10}$ up to quench field
- FNAL results are consistent with previous JLab-ODU test
- Low radiation, cavity is still clean, installation of additional hardware was successful
- **Successful test, confirms FNAL readiness to begin testing of RFD cavities for HL-LHC AUP**



Test 2 (At Fermilab)

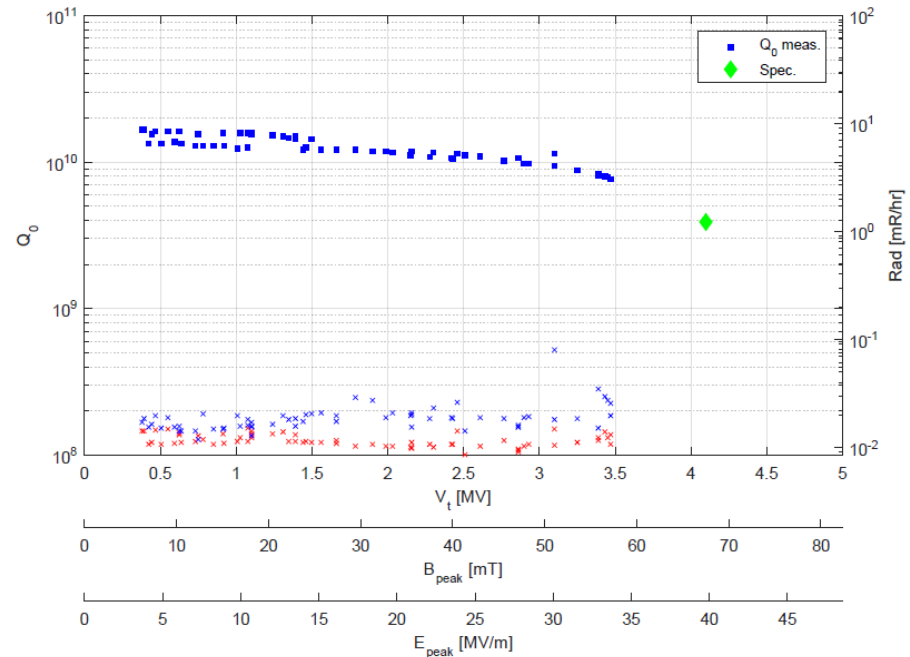
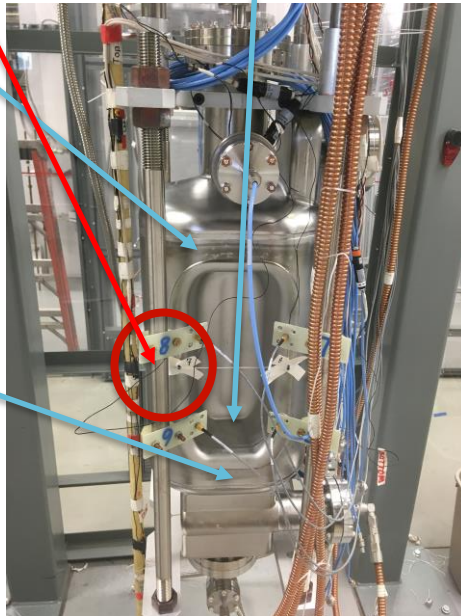
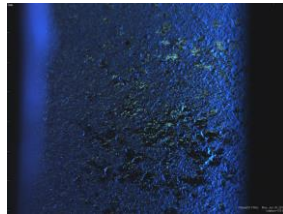
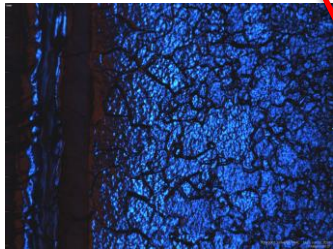
- Results of 2nd test at FNAL, after light BCP at ANL, were affected by field emission
- Q_0 at low field, up to 2 MV, above 1×10^{10} validates the BCP procedure at ANL
- Cavity quenched at 3.5 MV with consistent field emission, not meeting the required value of $Q_0 = 3.9 \times 10^9$ at $V_t = 4.1$ MV.
- HPR procedure has been modified to reduce FE



Test 3 (At Fermilab)

- HPR procedure has been modified to reduce FE: No radiation (Following updated procedure)
- 3rd test after HPR at ANL showed improved FE but still low V_t at quench, consistent with previous test
- Optical inspection shows overall good surface except for some unusual pitting in the electrode areas (not responsible for quench)
- Quench location (not accessible with camera) detected with 2nd sound and thermal sensors (possible local defect, investigation ongoing)

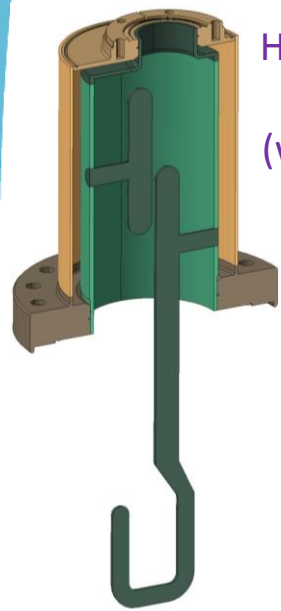
Quench spot
(At weld of pole to
center body)



Fabrication of LARP Prototype Cavity HOM Couplers

HOM Damper Fabrication – Naeem Huque (JLab)

- 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

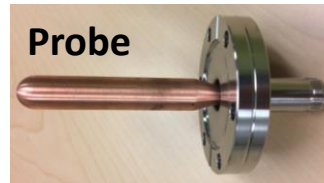


HHOM coupler with
He jacket
(without the probe)

Parts of the
HHOM prototype



Completed prototype HHOM coupler



Completed
prototype
VHOM coupler



Processing of LARP Prototype Cavity HOM Couplers

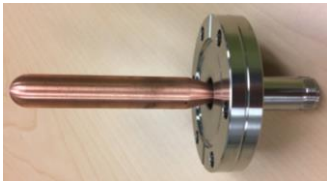
HHOM Coupler

- 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
 - No heat treatment done
- HHOM filter is ultrasonic degreased and manual HPR rinsed before assembly

VHOM Coupler and HHOM Probe

- Ultrasonic degreased

HHOM Probe



VHOM Probe



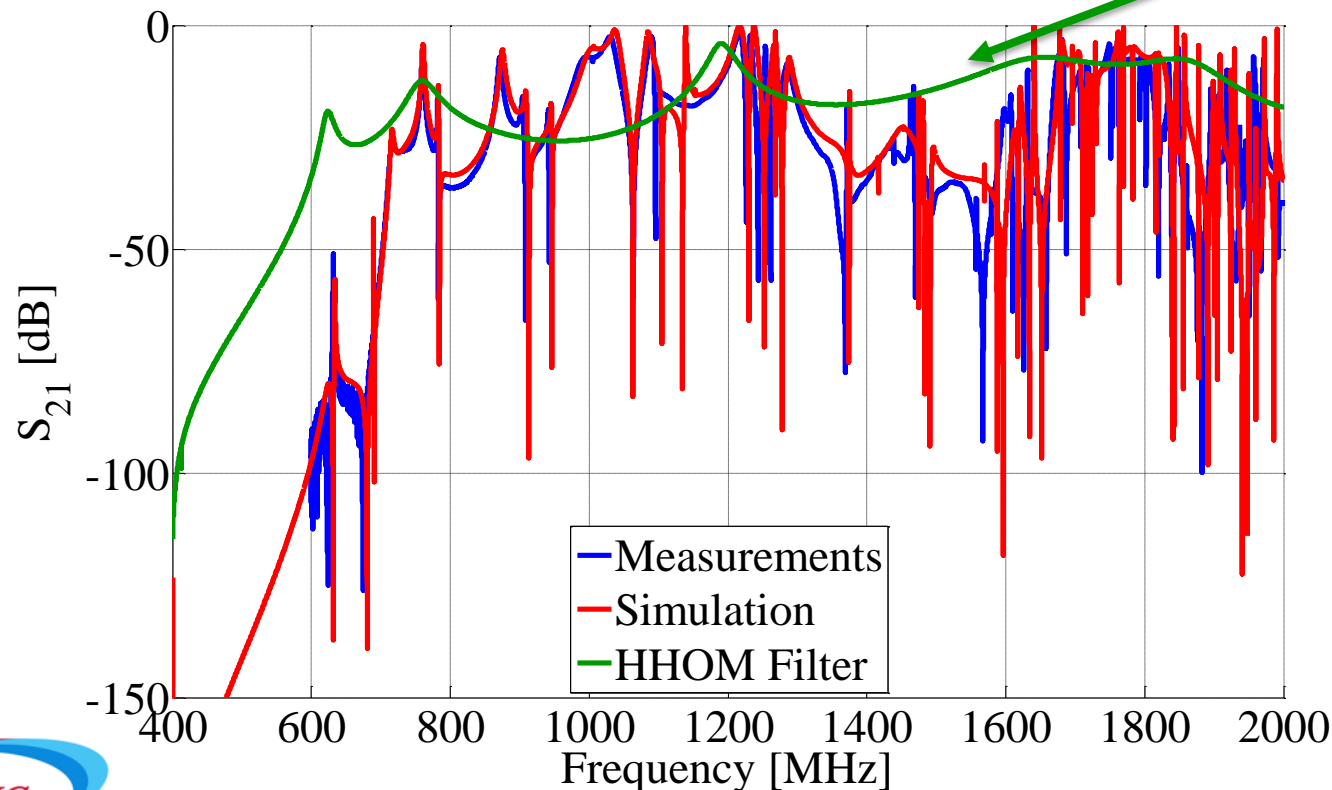
BCP fixture



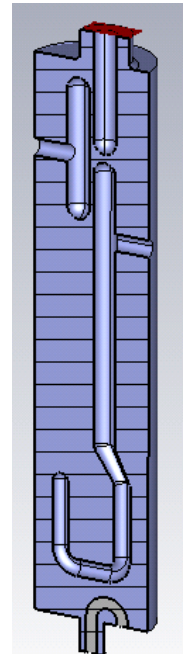
Comparison of Transmission between Simulation and Measurements

- 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)

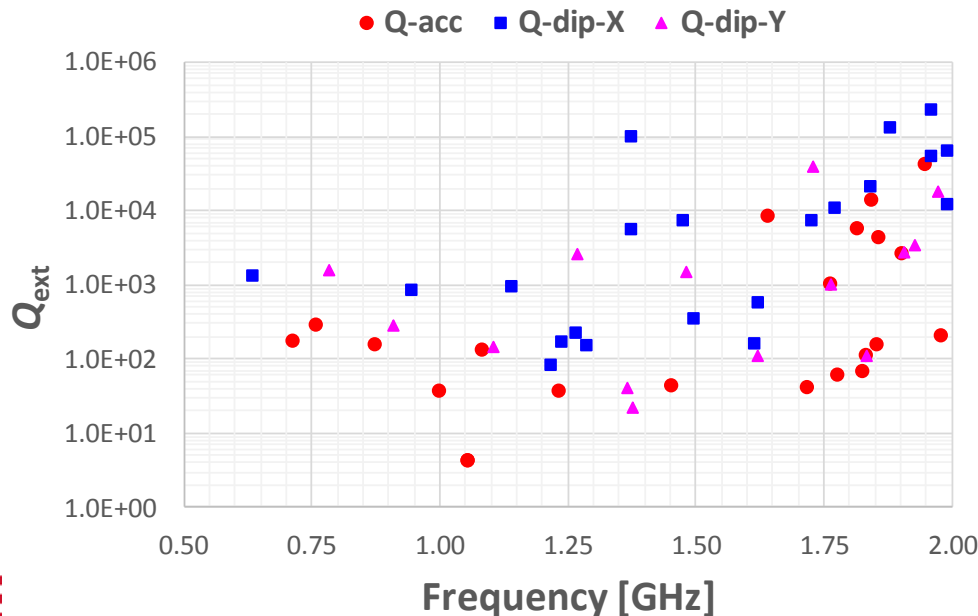
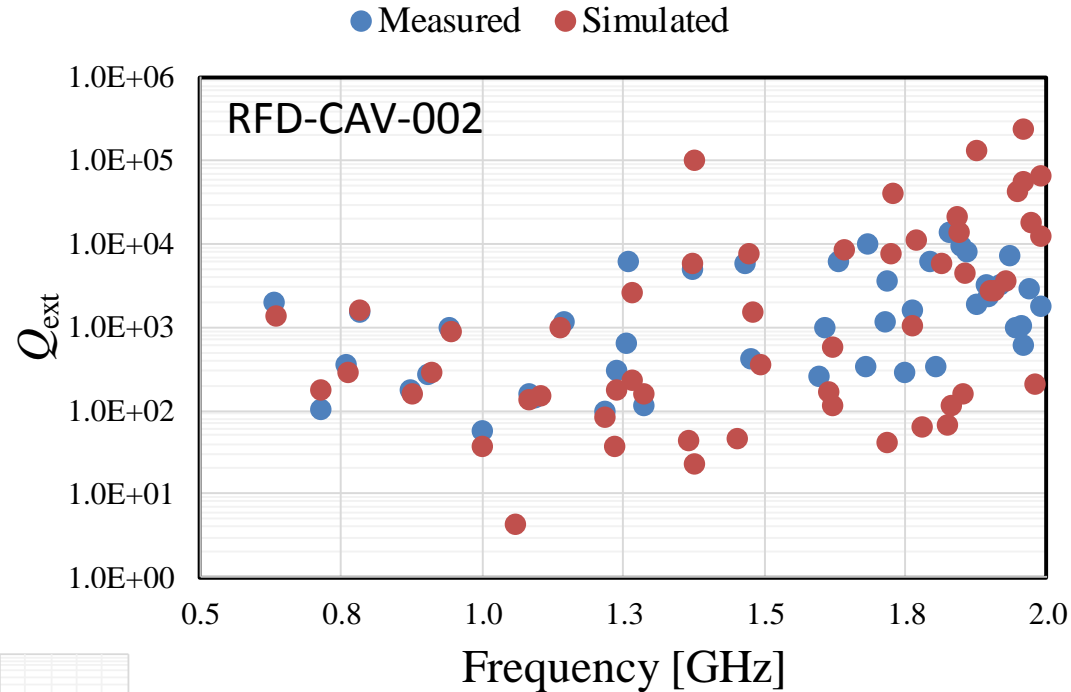


HHOM Filter in Test Box



Measurements of Q_{ext} at Room Temperature

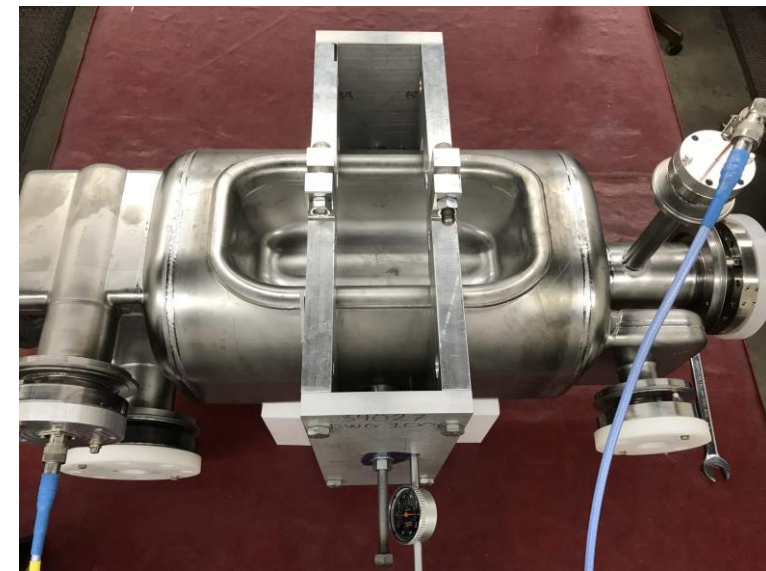
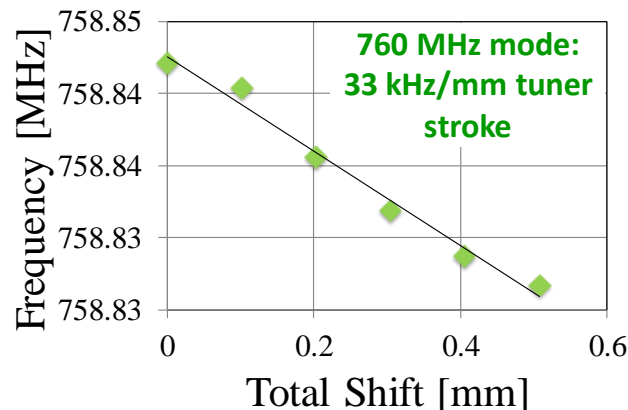
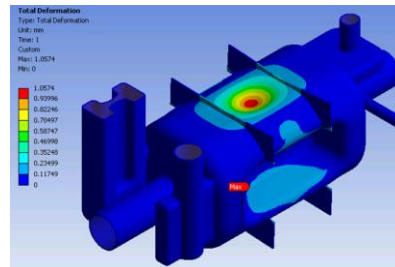
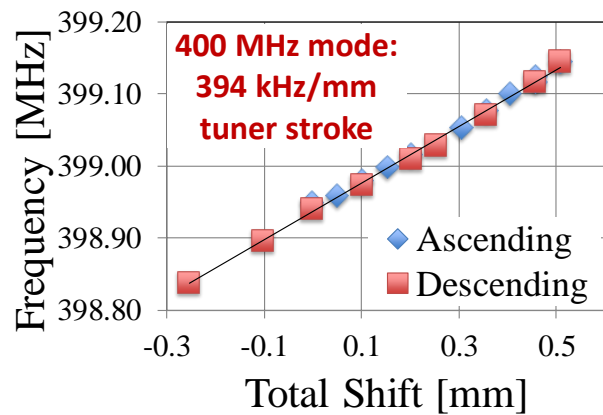
- Measurements of Q_{ext} are in good agreement with simulation up to ~ 1.65 GHz
- Q_{ext} of fundamental mode through:
 - HHOM: 4×10^{11}
 - VHOM: 3×10^9



- At higher frequencies, high Q_{ext} values cannot be accurately measured

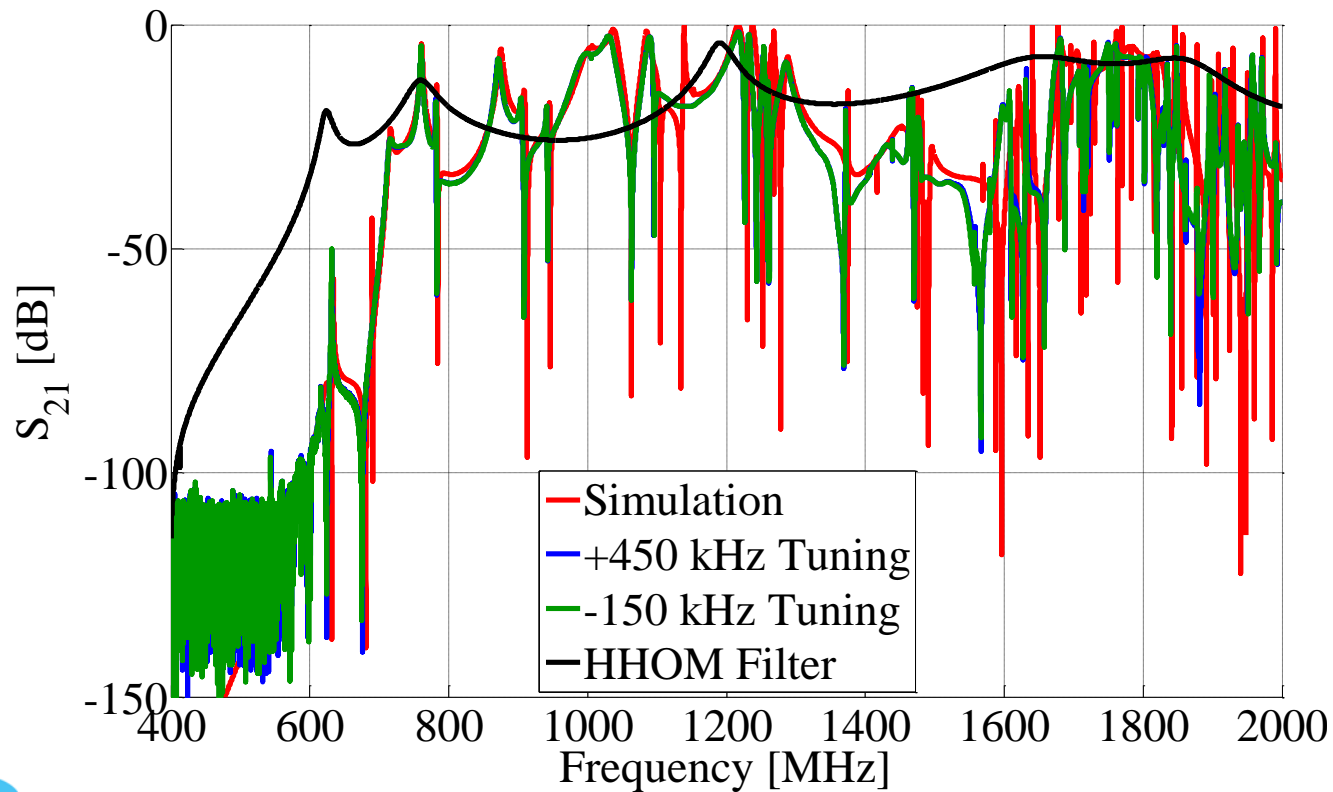
Tuning Sensitivity Measurements

- Cavity is pushed and pulled symmetrically at the top and bottom surface (In the high magnetic field region)
- At 400 MHz: Simulated sensitivity is 345 kHz/mm (HyeKyoung Park)
- **HOM of interest – 760 MHz mode**
 - 760 MHz mode is close to a beam resonance line

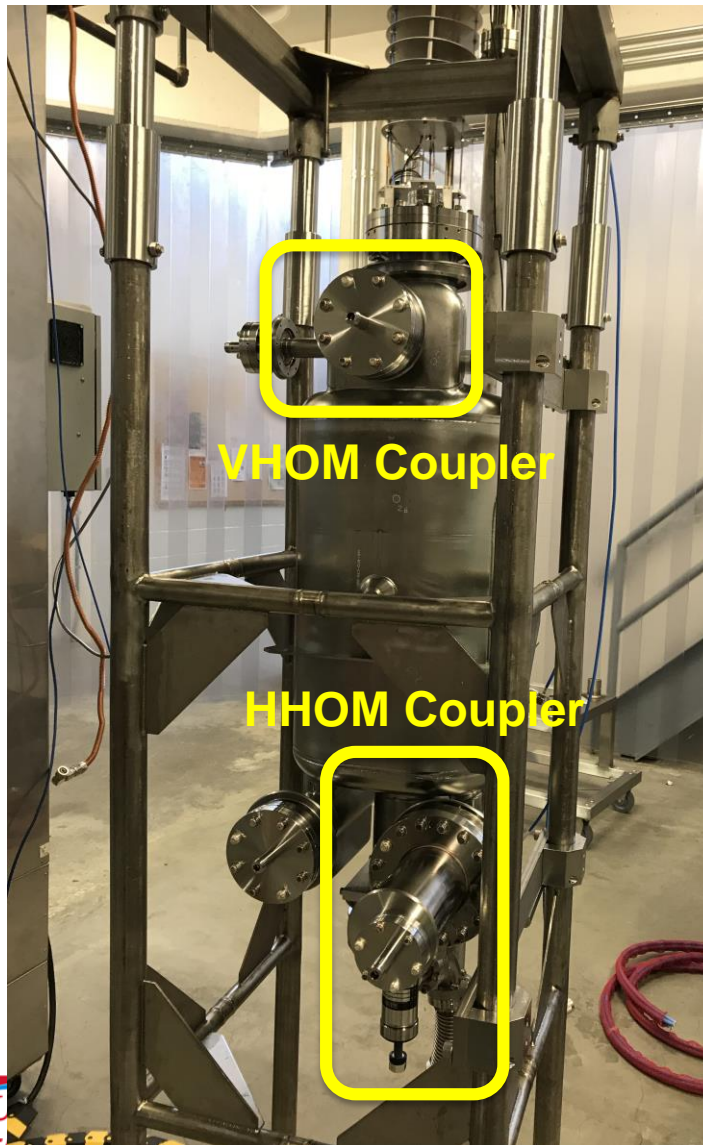


Tuning Sensitivity Measurements of HOMs

- 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**



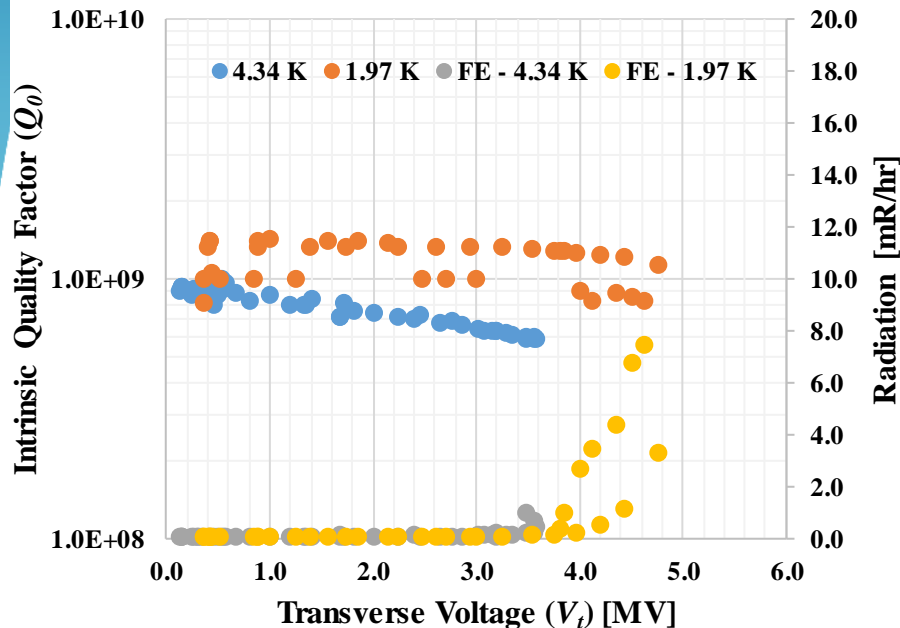
Set Up for Cryogenic Measurements of LARP Prototype Cavity with HOM Couplers



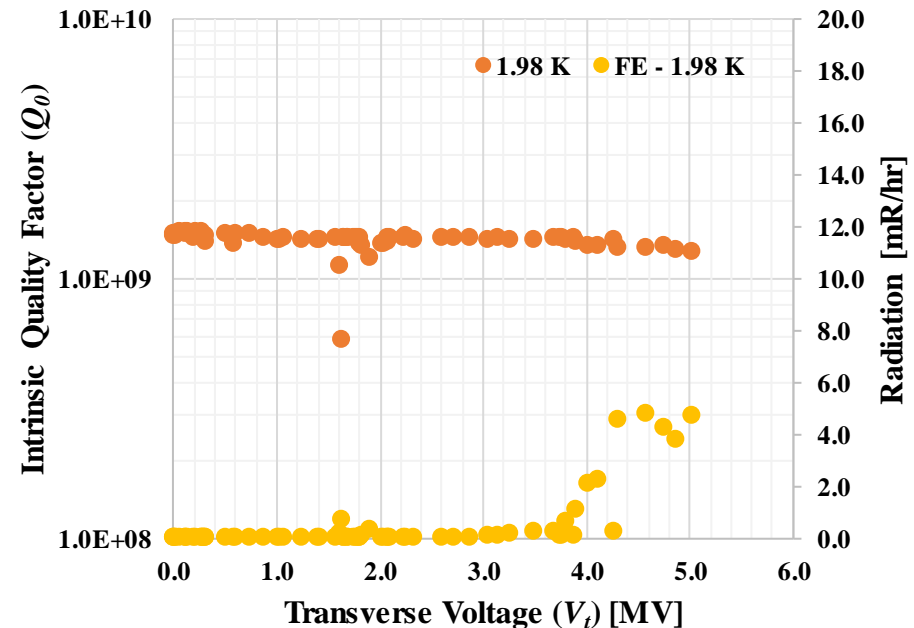
- Cold test of RFD-CAV-002 with HOM couplers
- Measurements were carried out with HHOM and VHOM couplers fabricated at JLab (HHOM2 and VHOM2)
- HHOM Coupler has no Helium jacket welded
- To maintain consistency – same input probe, pick up probe and similar assembly configuration was followed as in the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

Tests with both HOM Couplers

Test 1 – May 8, 2018



Test 2 – May 31, 2018



Test 1 – Test with HHOM and VHOM unterminated

- Burnt input power cable connector limited rf power to the cavity

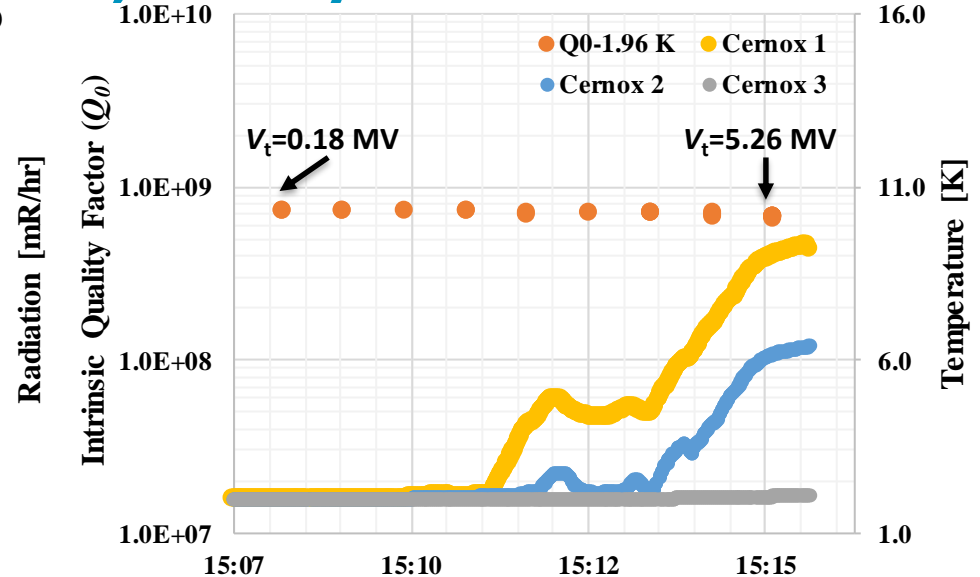
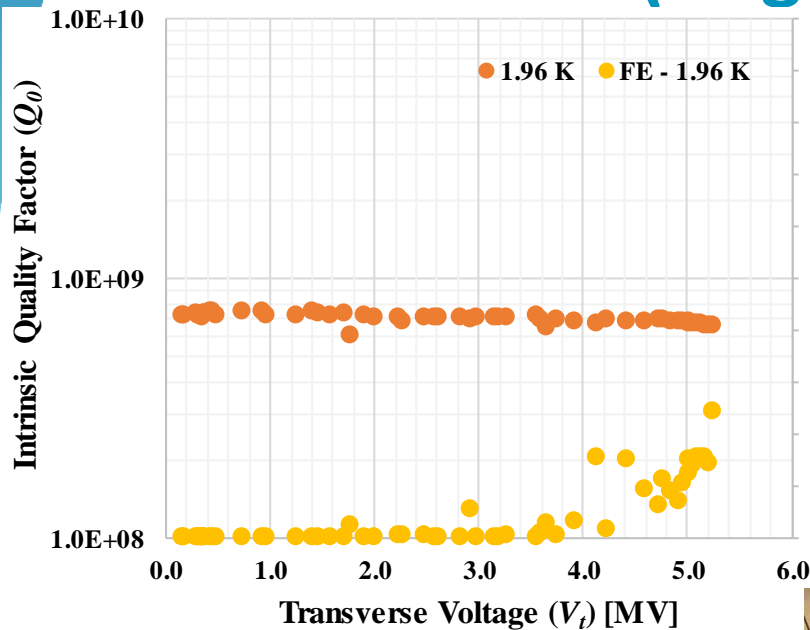
Test 2 – Cavity kept under vacuum from Test 1 and retested with terminated HHOM and VHOM

- Strong coupling of fundamental mode through VHOM coupler ($Q_{\text{ext}} \sim 2 \times 10^9$)

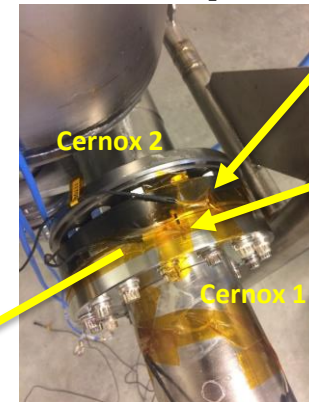
Findings:

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

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

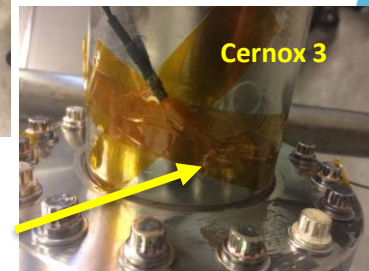


- Additional light BCP of 13 microns
- Cavity didn't quench \rightarrow RF power limited
- Reduced Q_0 (7.2×10^8) due to incorrectly sized Cu gasket which exposed stainless steel to rf fields
- Next step – Retest with an rf gasket
- Cernox sensors showed rf heating primarily on the SS flanges at the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



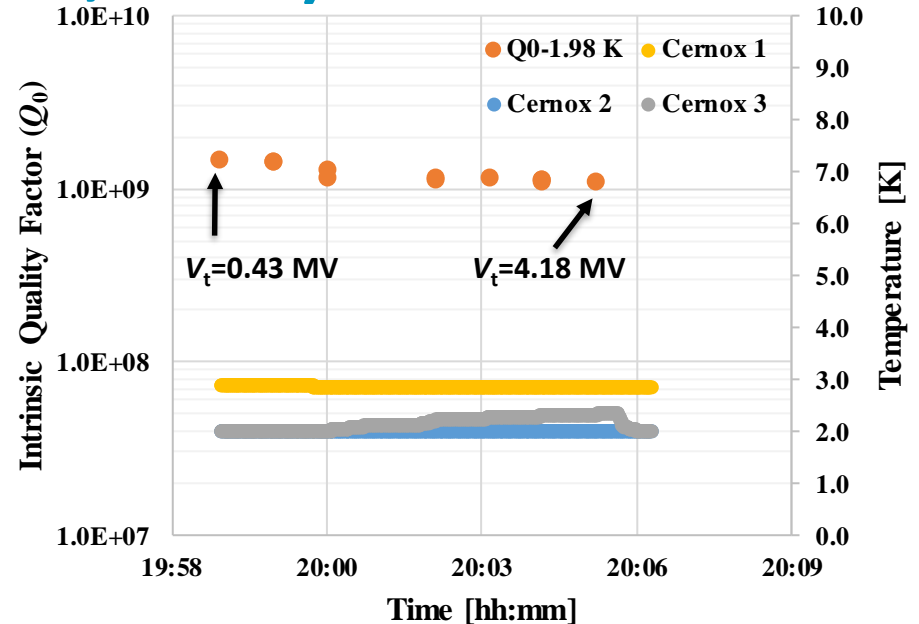
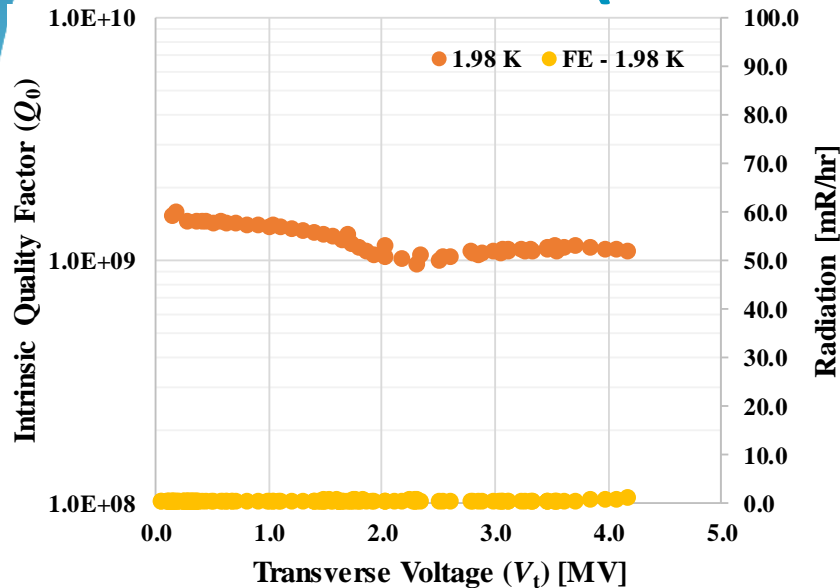
Cernox 2: On the HHOM cavity port SS flange

Cernox 1: On the HHOM coupler port SS flange



Cernox 3: Near the hook weld joint

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



- Measurements 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 ($Q_{\text{ext}} = 5.8 \times 10^9$)
 - Possibly due to the deviations between the probe, T and hook

Cernox 1: On the HHOM coupler port SS flange
Cernox 2: On the HHOM cavity port SS flange
Cernox 3: 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

Summary

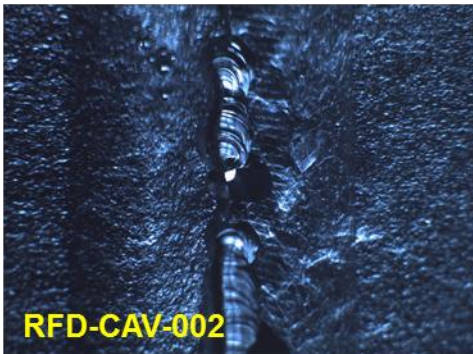
- Two LARP-RFD cavities have been fabricated and processed
- Performance levels of the bare cavities exceed the requirements in Q_0 , V_t and dynamic heat load above requirements for HL-LHC
 - Multipacting was processed completely and didn't reappear
 - RFD-CAV-001: Maximum $V_t=4.6$ MV, Q_0 of 1.2×10^{10} (2.3 W) at operating V_t
 - RFD-CAV-002: Maximum $V_t=5.8$ MV, Q_0 of 1.2×10^{10} (2.3 W) at operating V_t
- Rotational BCP and HPR systems at ANL have been developed to support RFD cavities
 - Despite early quench of the cavity processed, optical, visual inspection and thickness measurements validate the rotational BCP procedure
- Q_{ext} of simulation and measurements have been verified during warm measurements with HOM couplers
- Cold tests with HOM couplers showed no new multipacting levels or quenching of cavity with negligible field emission levels
 - Currently we are investigating low Q_0 and extra losses from the couplers

Back Up Slides

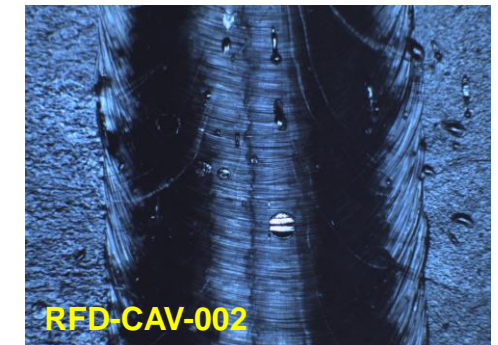
Fully Welded LARP Prototype Cavities

- Cavity 1 (RFD-CAV-001) –
 - After final welding cavity was rf tested → Q dropped due to field emission
 - Optical inspection showed rough under-beads and weld splatter
 - Cavity was reprocessed and retested after the optical inspection
- Cavity 2 (RFD-CAV-002)
 - Incomplete welds found at the optical inspection done after final welding
 - Cavity was rewelded and showed rough under-bead and weld splatter
 - Cavity was reprocessed before the test
- Poor quality of welds on both cavities due unexpected behavior of the welding machine

After initial
welds



After
rewelding



Frequency Measurements

- Frequency tracked during fabrication, processing, and rf testing (Shown for RFD-CAV-001)
- Frequency shifts are in agreement between simulation and measurements

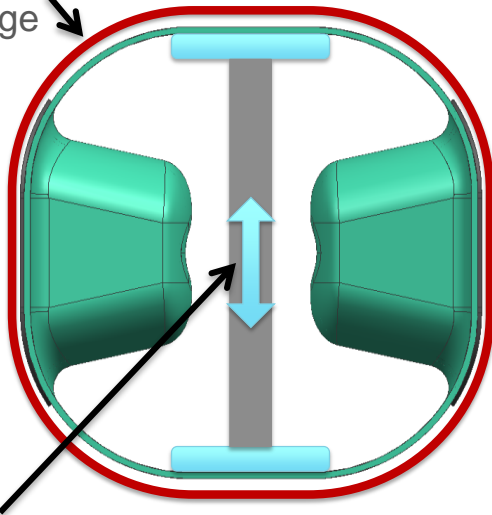
<u>Step (Recipe for 20 C, 50 % and 1013.25 mbar)</u>	<u>Simulated</u>		<u>Measured</u>	
	Δf [kHz]	f_n [MHz]	Δf [kHz]	f_n [MHz]
Cavity after trimming and thinning		399.840,296		399.846,841
Shift due to bulk BCP	-39.441		-21.924	
Cavity after bulk BCP				399.824,917
Shift due to frame			-765.648	
Cavity after removing fixture		399.800,855		399.059,269
Weld shrinkage and weld bead	120.645		114.686	
Cavity after final weld		399.921,500		399.173,955
Shift due to heat treatment			-10.743	
Cavity after heat treatment				399.163,212
Shift due to light BCP	-5.762		-16.473	
Cavity after light BCP		399.915,738		399.146,739
Pressure effect (23 torr)	-1.84			
Dielectric effect air to vacuum	130.341			
Thermal shrinkage	572.877			
Shift due to change in skin depth	28.171			
		729.378	755.615	
Cooled down cavity at 2.0 K		400.645,116		399.902,354

- The unaccounted frequency shift was due to the use of the frame during some of measurements
[400.645 – 399.902 = 743 kHz]

Arrival of Sub-Assemblies

- Incoming frequencies
 - RFD-1: 400.93 MHz (too high, center body warm-tuned later)
 - RFD-2: 398.93 MHz
- Fixing the center body of RFD-CAV-001
 - Use of fixtures during trim tuning of sub assemblies

Profile held at the edge



Jack mechanism

Frequency shift after fixing center body = 1.84 MHz



Fixture on center body to match end profiles for trimming

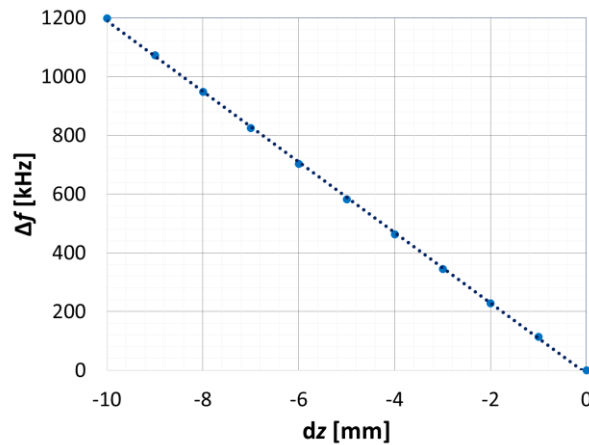
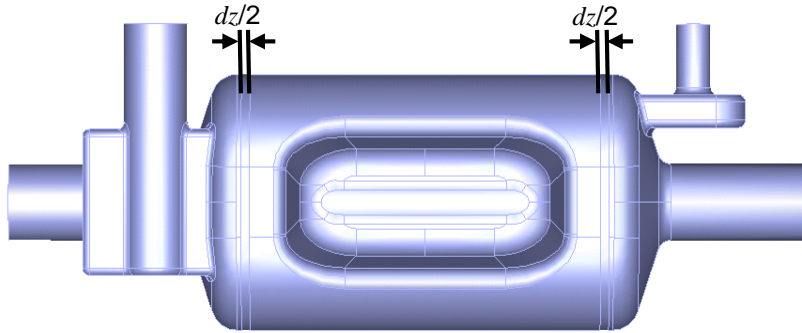


Frequency shift with and without fixture = -0.77 MHz

Measurements of Trimming Sensitivity

- Trimming sensitivity for RFD cavities

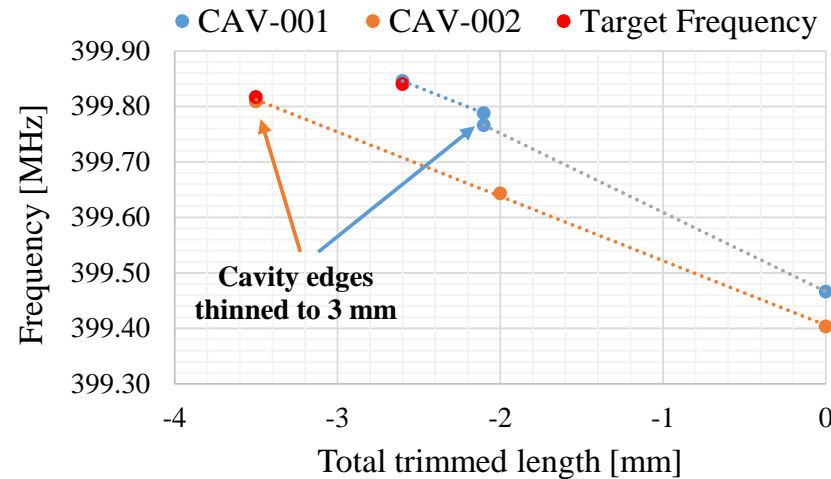
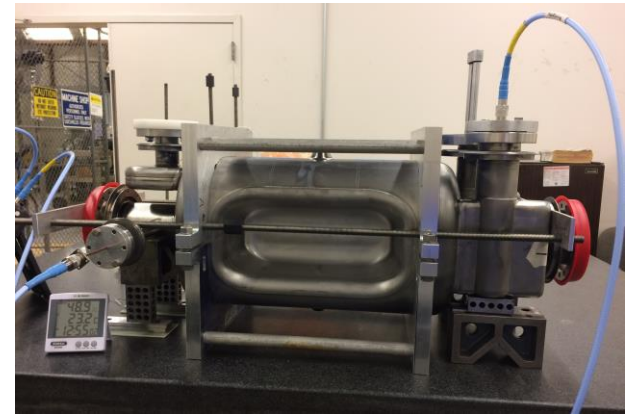
$$df/dz = -120 \text{ kHz/mm}$$



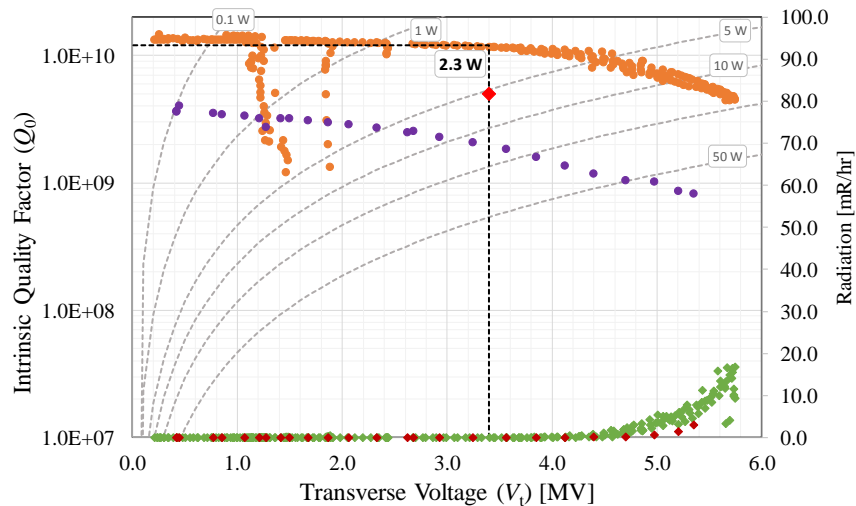
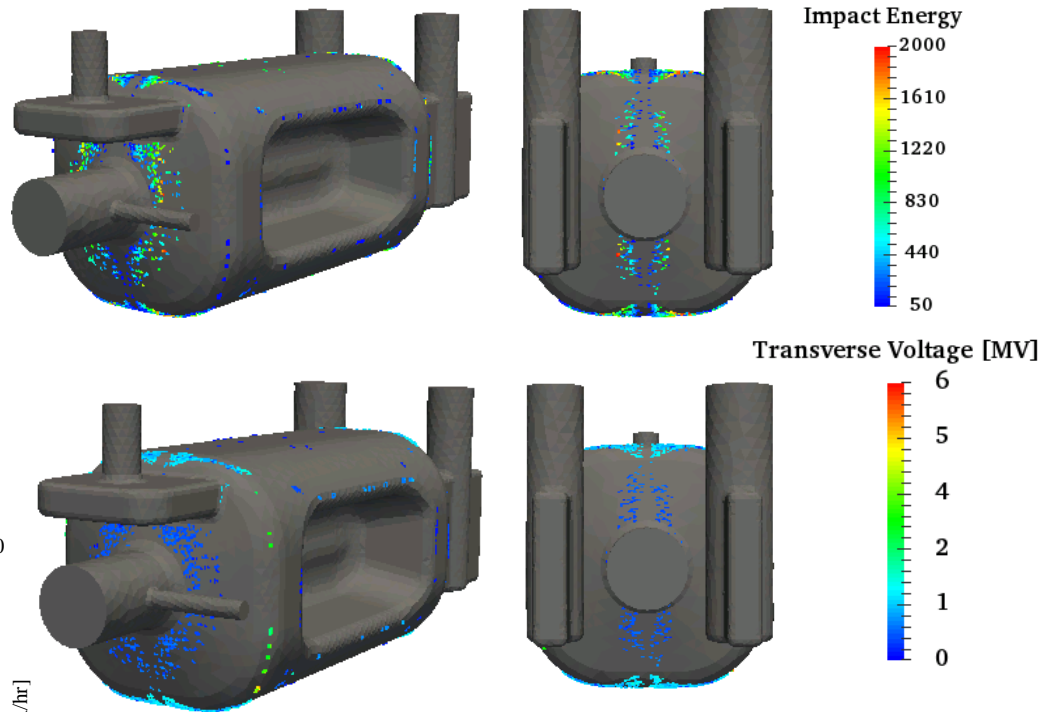
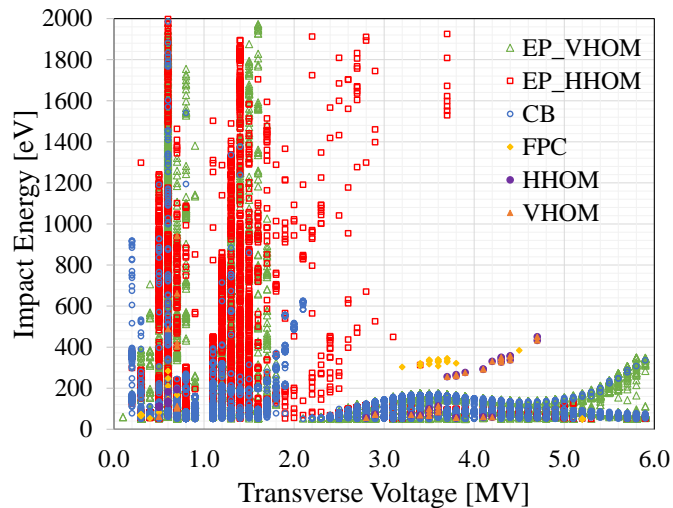
- Trimming sensitivity for LHC-RFD design is -115 kHz/mm

- Measured sensitivity:

- CAV001: -129.3 kHz/mm
- CAV002: -116.1 kHz/mm



Processing of Multipacting Resonances of LARP Prototype Cavity

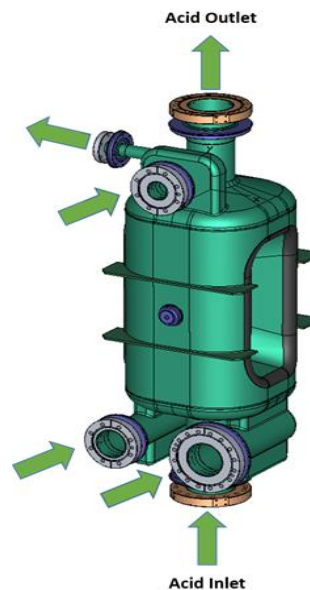


- Multipacting analysis done using Track3P code of SLAC ACE3P suite
- No resonances at high transverse voltage
- Simulation and measurements show similar multipacting barriers

Processing of Bare Cavities at Jefferson Lab

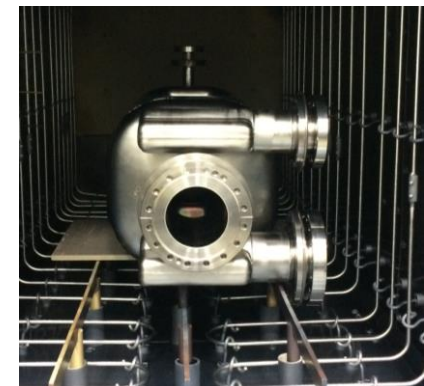
- Bulk BCP of sub assemblies with removal monitored by in-situ gauges
- Heat treatment at 600 C for 10 hours at fully welded cavities
- Light BCP of 30 microns
- HPR
 - Manual rinse outside clean room before HPR
 - 2 passes of HPR in the clean room

Bulk BCP & Light BCP



		Actual removal (microns)
RFD-1	HHOM end	113
	VHOM end	67
	Center body	122
RFD-2	HHOM end	264
	VHOM end	126
	Center body	95

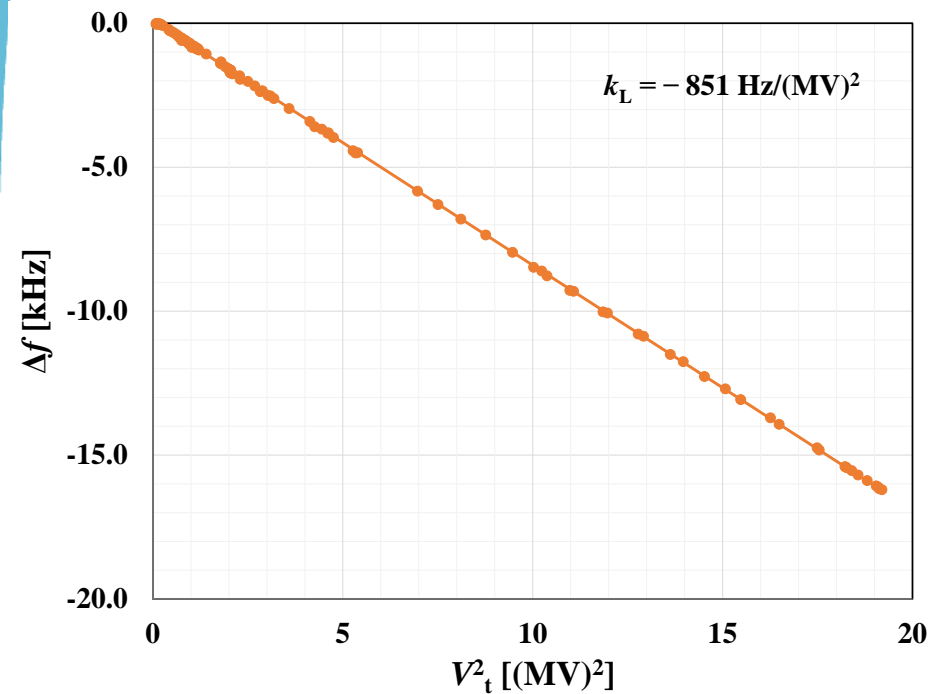
Heat Treatment



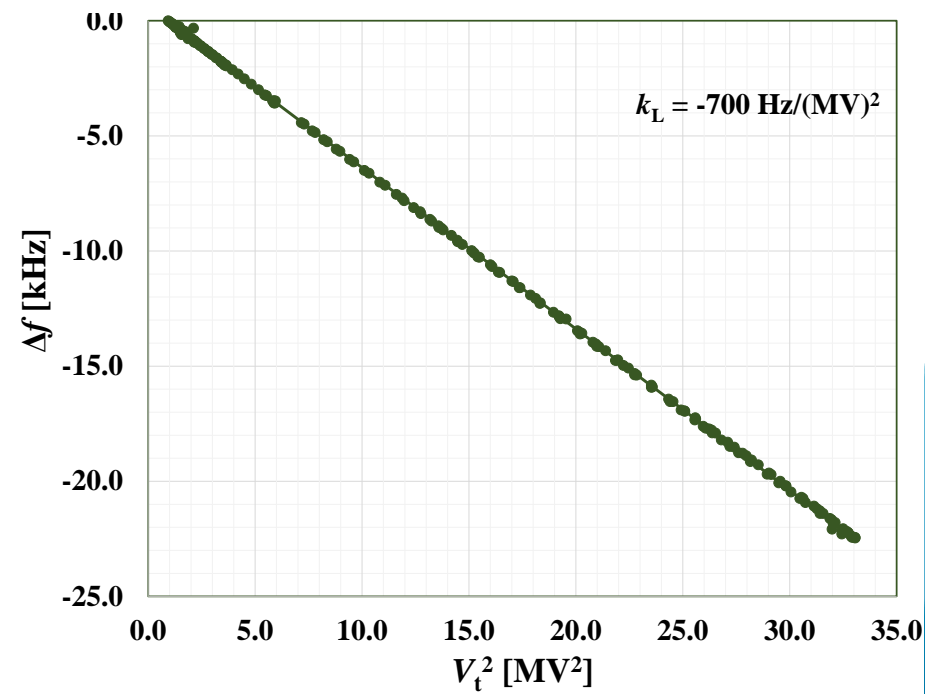
Measurements of Lorentz Force Detuning

- Lorentz force detuning coefficient measured at 2.0 K
- Simulated: - 900 Hz/(MV)² bare
- RFD-CAV-001: $k_L = - 850 \text{ Hz}/(\text{MV})^2$
- RFD-CAV-002: $k_L = - 700 \text{ Hz}/(\text{MV})^2$
- **FRS → Total frequency shift at 3.4 MV < 10 kHz**

RFD-CAV-001



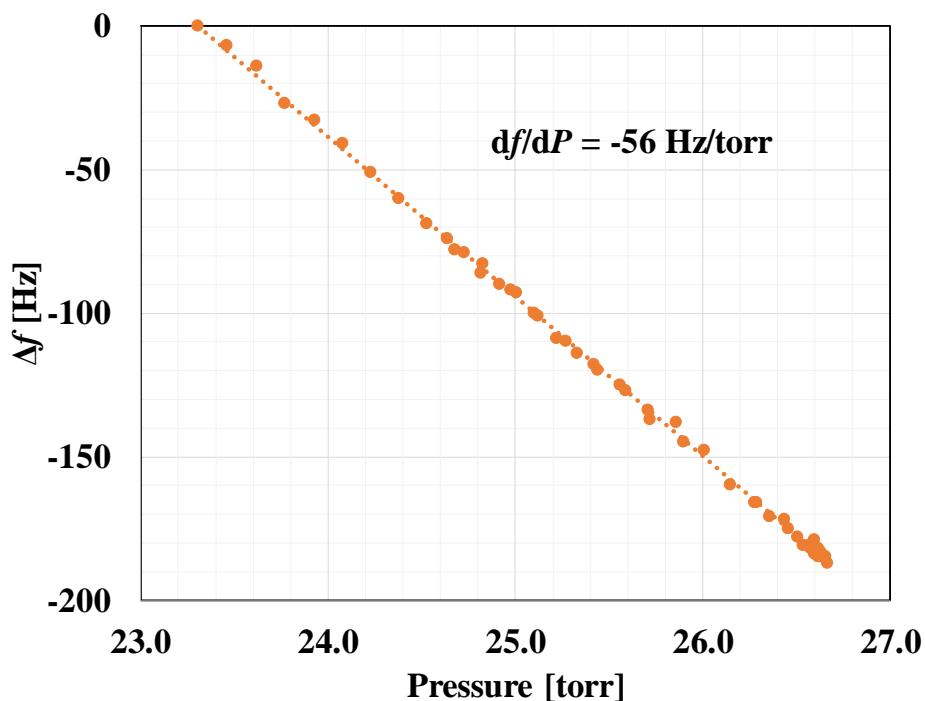
RFD-CAV-002



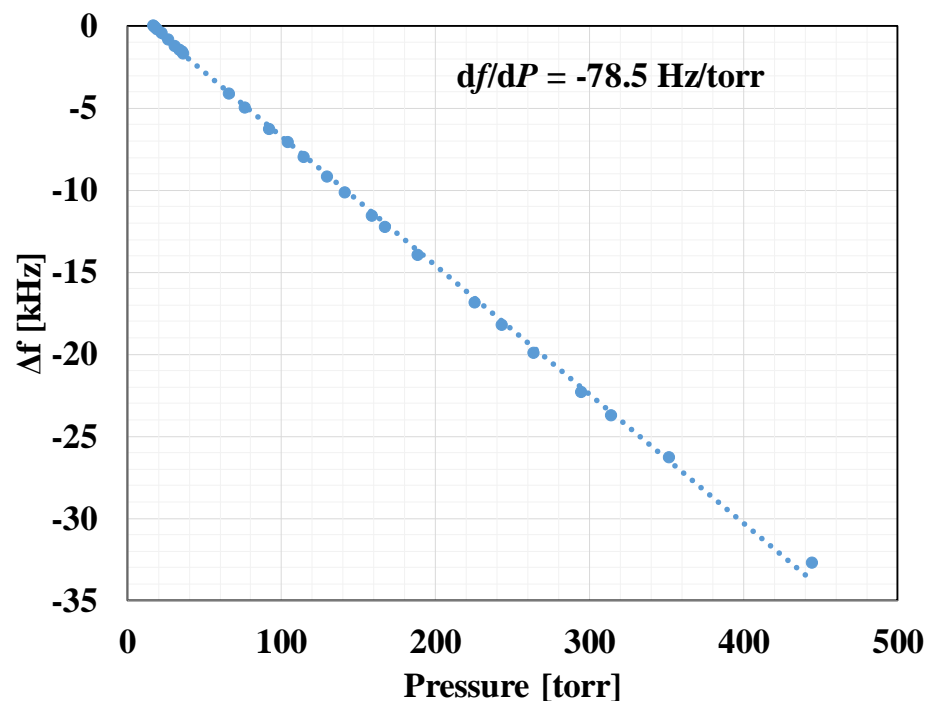
Measurements of Pressure Sensitivity

- Pressure sensitivity as simulated: $df/dP = -80 \text{ Hz/torr}$ of bare cavity
- RFD-CAV-001: $df/dP = -56 \text{ Hz/torr}$
- RFD-CAV-002: $df/dP = -79 \text{ Hz/torr}$
- **FRS → Pressure sensitivity < 200 Hz/torr (< 150 Hz/mbar)**

RFD-CAV-001



RFD-CAV-002

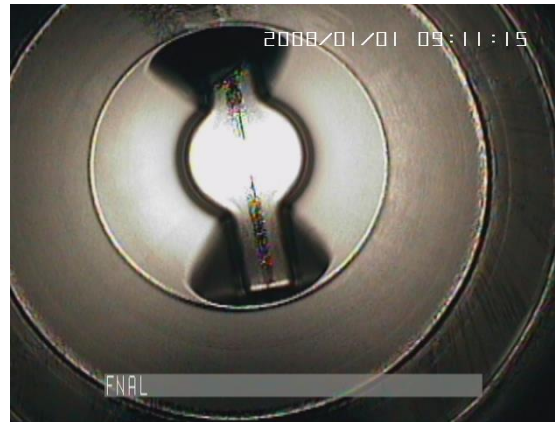


Visual Inspection of the Cavity

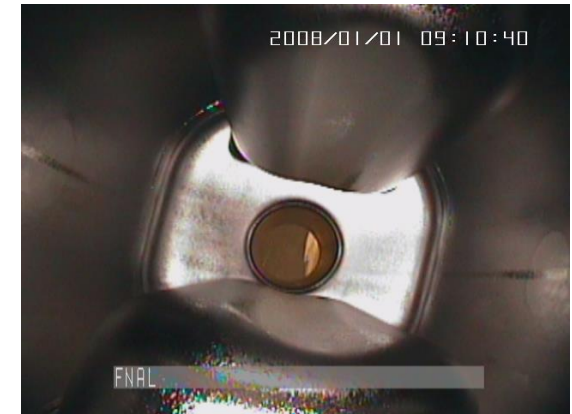
- Visual inspection after light rotational BCP showed the inner surface has a uniform matte looking.
- No signs of long and big bubble traces: slow rotation is preventing big bubbles formation in the acid mixture!
- No signs of chemistry residue: successful evacuation and rinsing



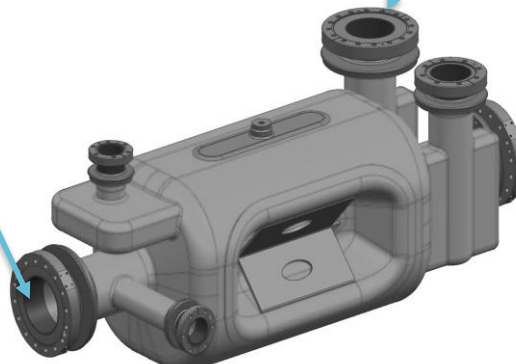
Beamtube1
view



HHOM
view

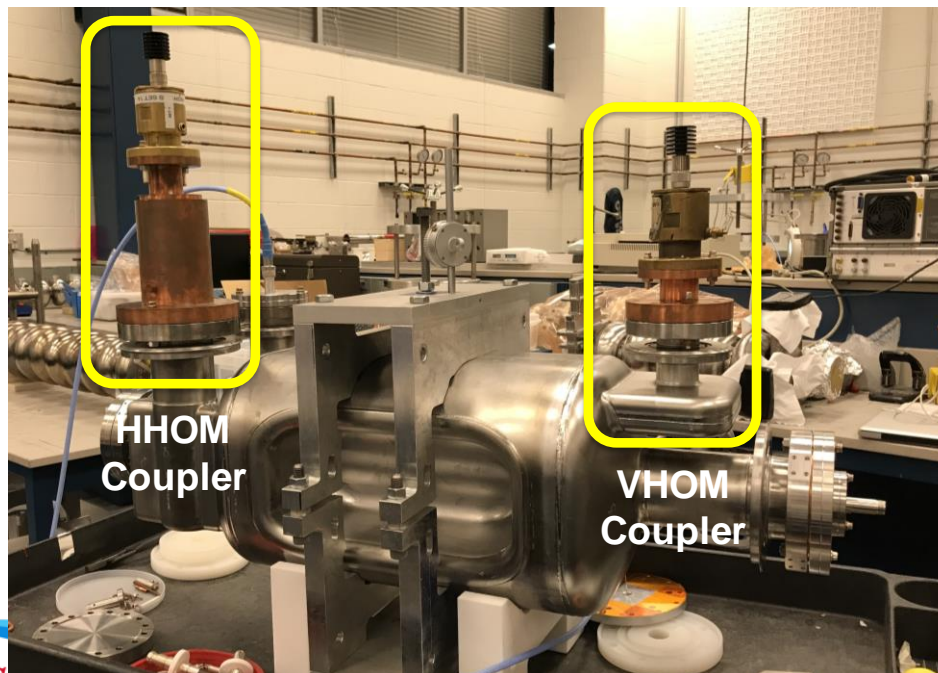


Beamtube2
view



Set Up for Room Temperature HOM Measurements

- Room temperature measurements were carried out with
 - Cu HOM couplers provided by Niowave
 - Nb HOM couplers fabricated at JLab
- Measurements were taken up to 2 GHz for the HHOM and VHOM couplers separately:
 - S_{11} : from HHOM/VHOM with FPC open
 - S_{21} : FPC to HHOM/VHOM with VHOM/HHOM open
 - S_{21} : HHOM to VHOM with FPC/Pick Up open



Test Input Probe



$$Q_{\text{ext}} = 1.7 \times 10^7$$

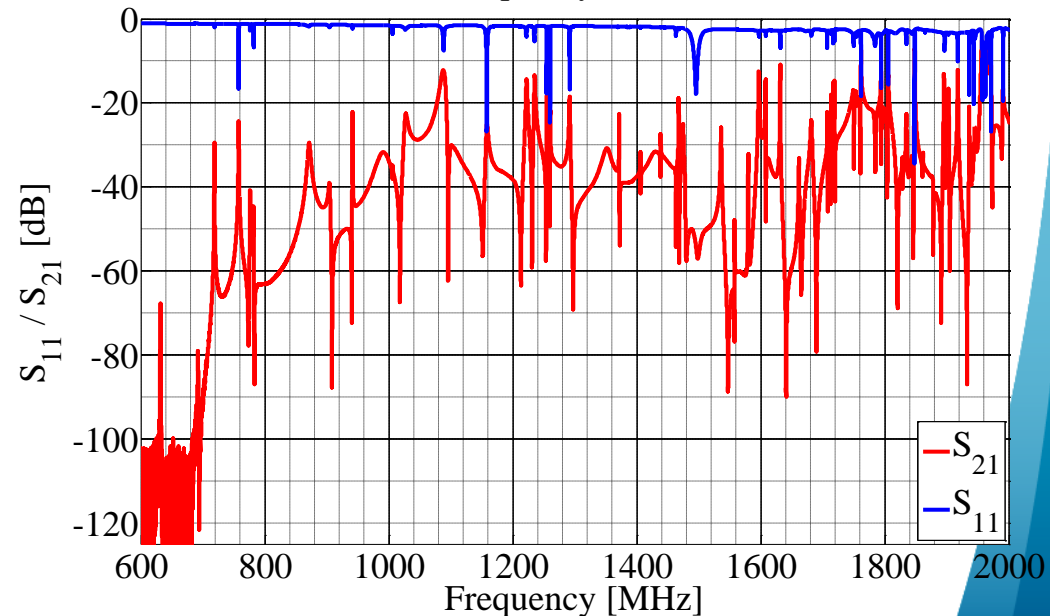
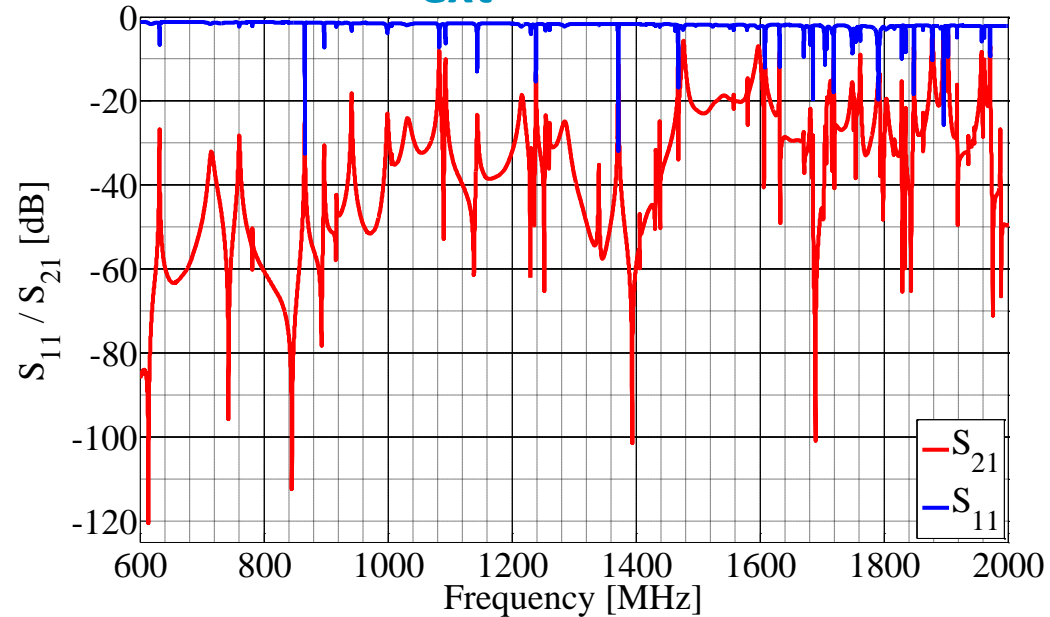
Measurements of Q_{ext}

Measurements:

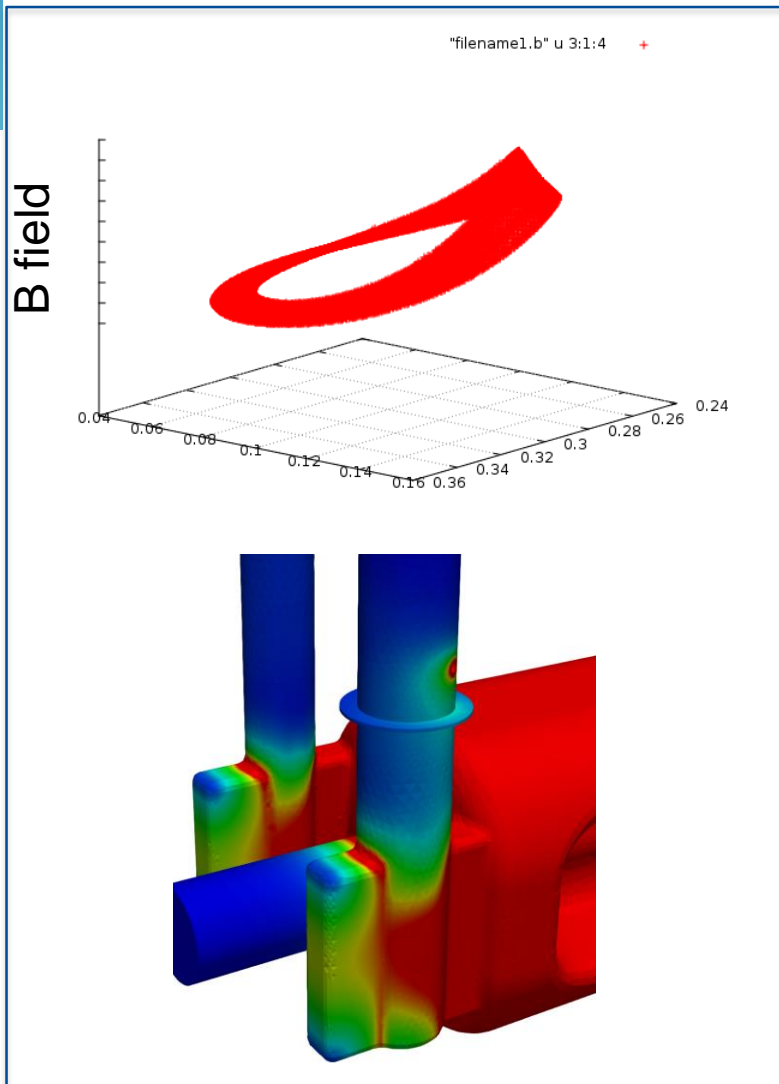
- $Q_{\text{ext,HHOM}} \rightarrow$
 - S_{11}/S_{21} from FPC through HHOM with VHOM open
- $Q_{\text{ext,VHOM}} \rightarrow$
 - S_{11}/S_{21} from FPC through VHOM with HHOM open

Combined Q_{ext}

$$\frac{1}{Q_{\text{ext}}} = \frac{1}{Q_{\text{ext,HHOM}}} + \frac{1}{Q_{\text{ext,VHOM}}}$$

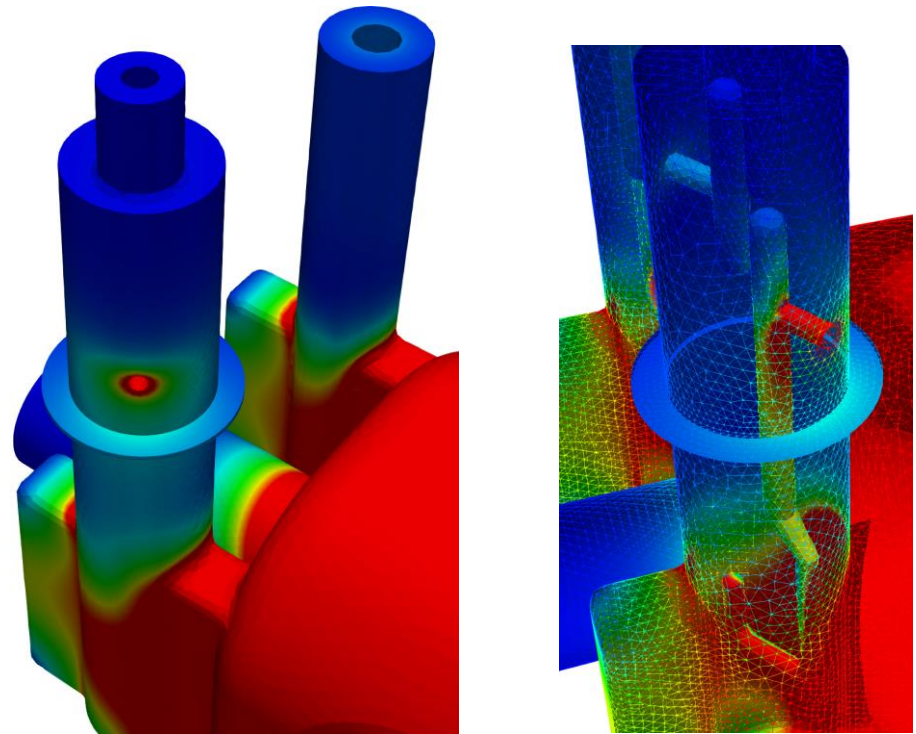


HHOM SS Gasket Heating



Simulated rf heating due to conflate Cu gasket at the HHOM coupler

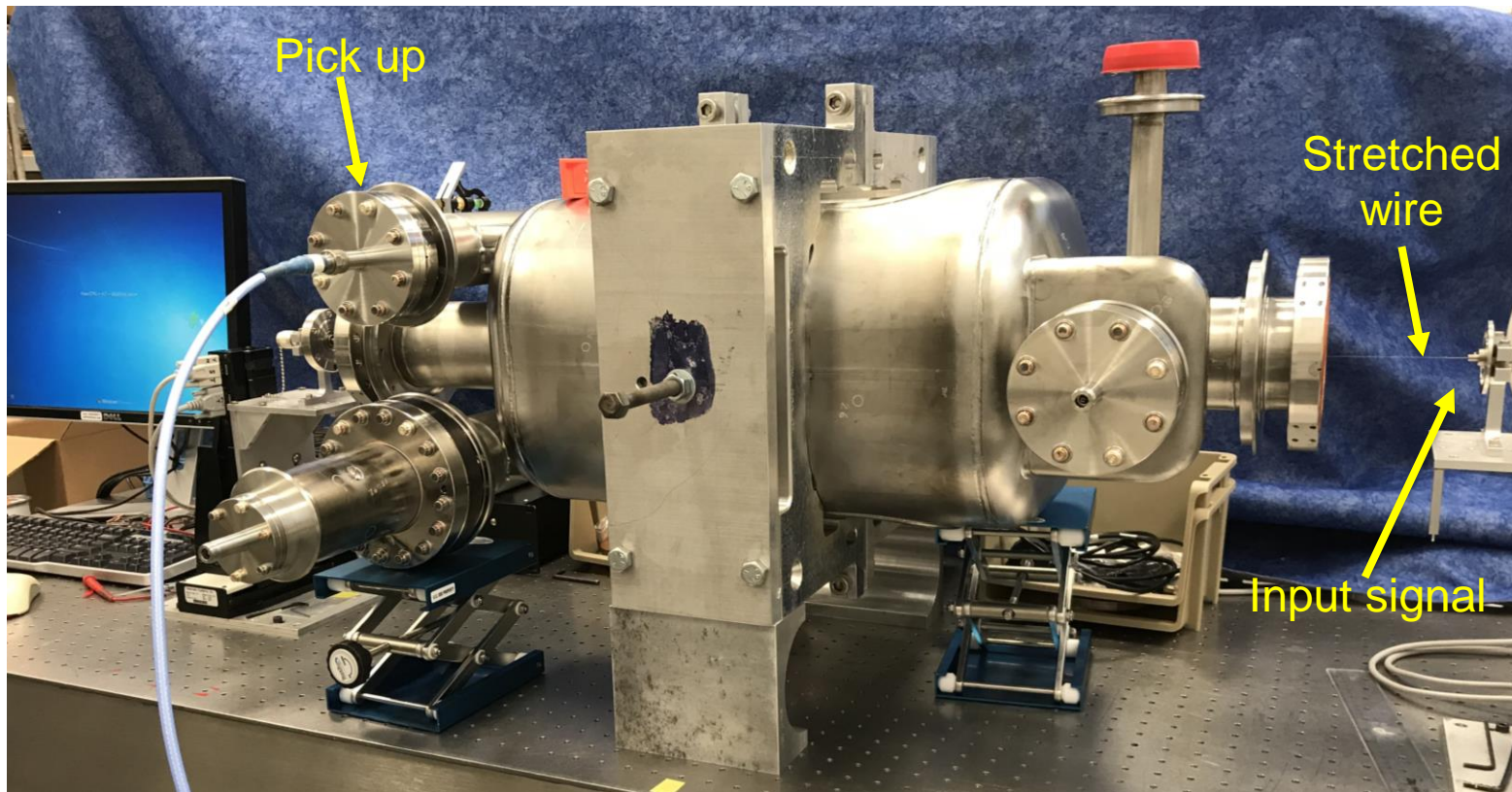
by Zenghai Li



Q_0 with SS Flange: 6.5×10^8

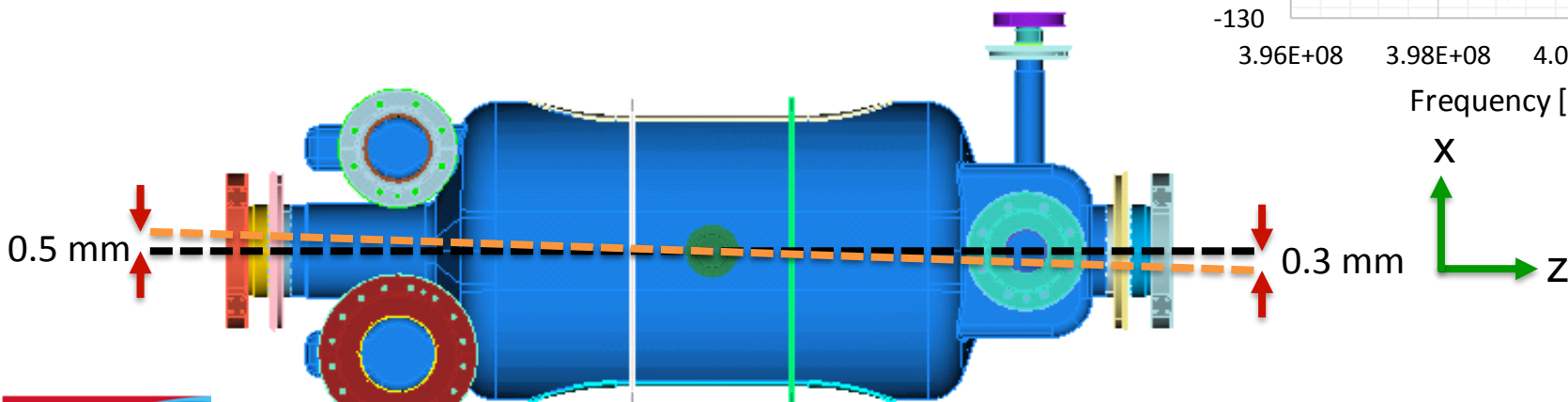
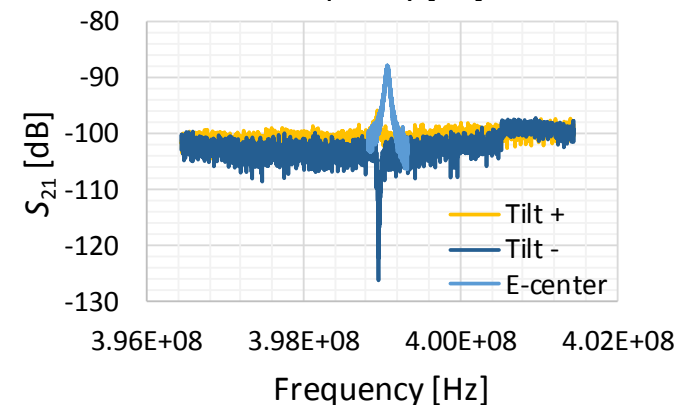
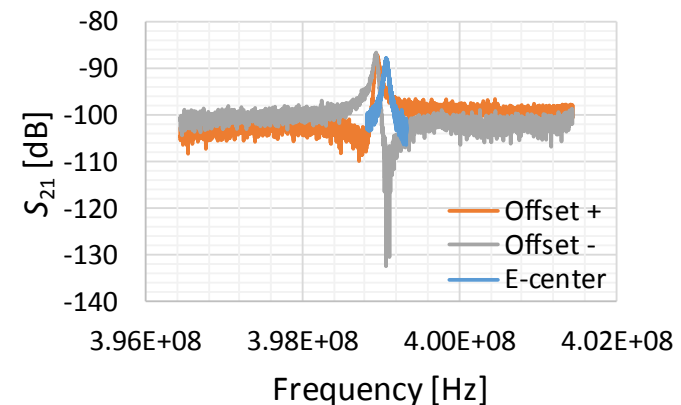
Set Up for Stretched Wire Measurements

- Stretched wire measurements were done to determine the electrical center of the RFD-CAV-002
- Set of initial measurements were done on the set up at Jefferson Lab
- Measurements were carried out with HOM couplers (with and without 50 Ω termination)



Preliminary Measurements of Electrical Center in LARP Prototype Cavity

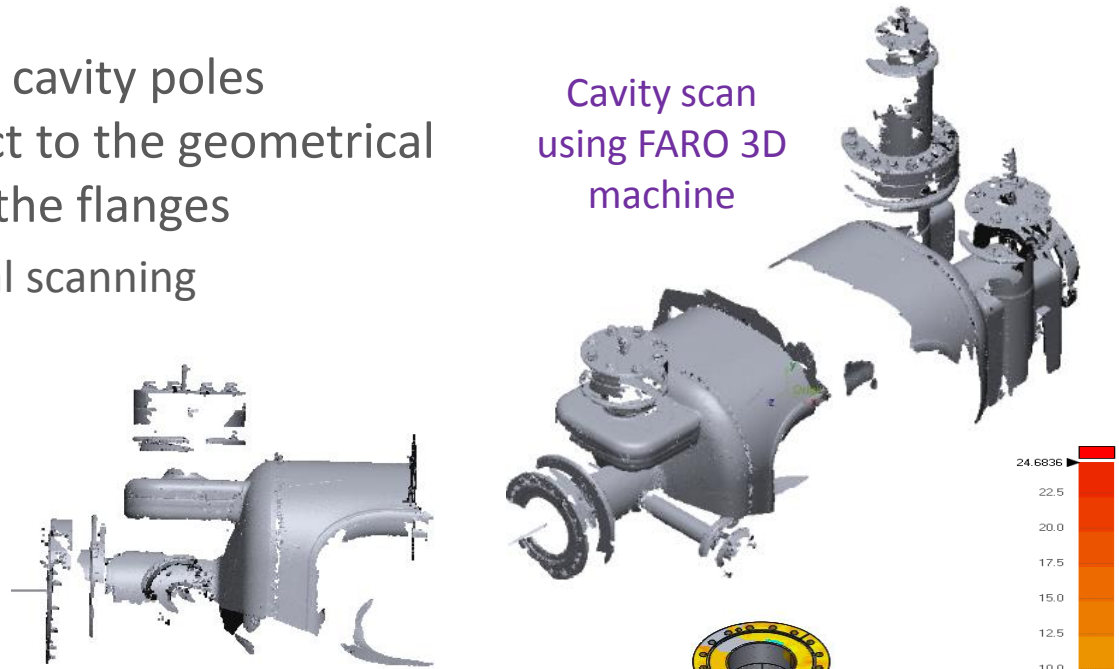
- Stretched wire measurements were done to determine the electrical center of the RFD-CAV-002
- Measurement of S_{21} transmission will be symmetric and lowest in magnitude along the electrical center
- Preliminary measurements show a 1 mm tilt in the electrical center relative to the geometrical reference line as defined by the flanges in the crabbing plane (in x direction)
- No change in electrical center
 - In vertical plane (in y direction)
 - With and without 50 Ω termination on HOM couplers



Next Steps for Electrical Center Measurements

- Measurements to define the cavity poles position location with respect to the geometrical reference line as defined by the flanges
 - Using either CMM or optical scanning

Cavity scan
using FARO 3D
machine



- Next measurements of electrical center
 - Measure with and without HOM couplers
 - Measure with the cavity in compression and in tension

