LARP – HiLumi Meeting

May 18-21, 2016

RF-Dipole Cavity
Frequency Analysis and Tuning Plans

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Old Dominion University

HiLumi HL-LHC PROJECT

CAVITY PROCESSING PLAN

Inspection	Process step	Description
Visual Inspection Radiography	**Surface Grinding**	Mechanical grinding un-even weld / surface pits
CMM	**Bulk BCP**	Total removal of 140 microns
• Thickness Measurement • Frequency Measurement for Trimming	**Trimming**	• Trimming of center body for frequency • 3 mm weld trimming
	Final Weld	Welding of end plates to center body
Optical Inspection	**Heat Treatment**	600 ^{o}C for 10 hours in furnace
	Light BCP	Total removal of 20 microns
Thickness Measurement	**High Pressure Rinse**	• Rinsing in 2 iterations • Proper rotation to drain cavity completely
	Assembly	Cavity assembly of cavity in clean room
	Low Temp Bake	120 ^{o}C bake for 24 hours
	RF Test	Test with and without HOM couplers • High power rf tests at 4.2 K and 2.0 K • Surface resistance measurements

*** Expected Frequency Shifts**

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BULK BCP OF SUB-ASSEMBLIES

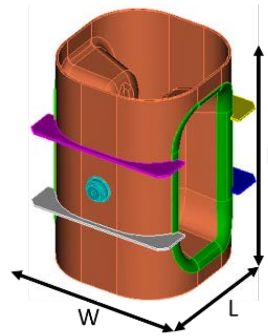
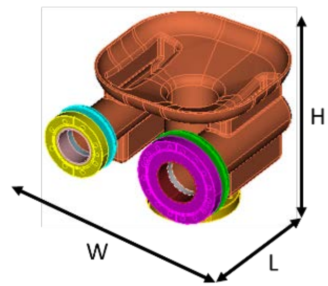
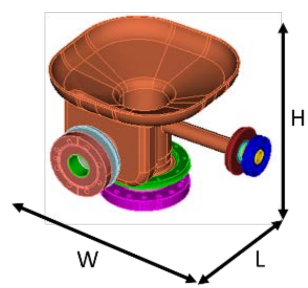
- **Dimensions**: Technical drawings from Niowave Inc.
- **Weights**: Courtesy – Carlo Zanoni, Raphael Leuxe - CERN

- BCP acid mixture:

HF (49 %) : HNO_3 (69.5 %) : H_3PO_4 (85 %)   1 : 1 : 2

- Acid density:
  - HF (49 %) – 1.30 g/ml
  - HNO_3 (69.5 %) – 1.42 g/ml
  - H_3PO_4 (85 %) – 1.685 g/ml
  - **BCP mixture (1:1:2) – 1.5225 g/ml → 12.7 lb/gal**

- Additional volume included since parts are longer than given in drawings

Sub-Assembly	Parameter	Value	Unit
	**SA-1 – Center Body**		
	Height (H)	16.6	in
	Length (L)	12.3	in
	Width (W)	11.9	in
	Volume	7.24 + 0.35	gallons
	Weight	43.3	lb
	Weight with acid	139.7	lb
	**SA-2 – End Plate with HHOM**		
	Height (H)	11.0	in
	Length (L)	13.5	in
	Width (W)	13.46	in
	Volume	1.73 + 0.17	gallons
	Weight	35.4	lb
	Weight with acid	59.6	lb
	**SA-3 – End Plate with VHOM**		
	Height (H)	8.5	in
	Length (L)	13.5	in
	Width (W)	18.077	in
	Volume	1.15 + 0.17	gallons
	Weight	24.0	lb
	Weight with acid	40.8	lb

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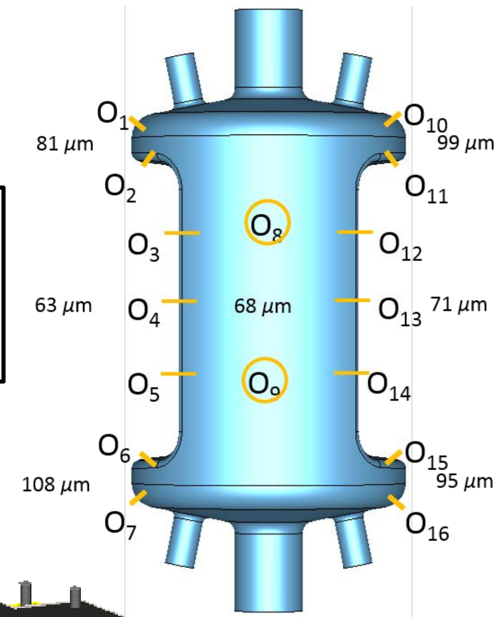
BULK BCP OF SUB-ASSEMBLIES

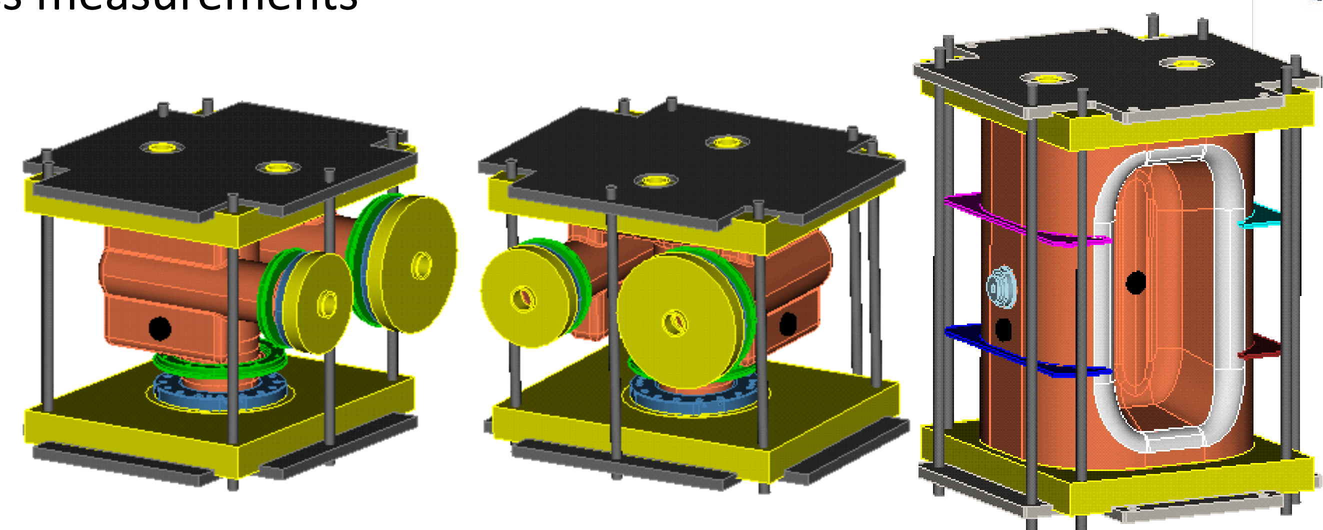
- Bulk BCP performed in sub-assemblies before trimming for target frequency
- Why: to eliminate frequency shift due to
  - Manufacturing and welding deviations
  - Non-uniform chemical etching
- Goals:
  - Total removal of 140 microns
  - Have uniform removal by flipping the sub-assemblies at each 35 microns
- Thickness measurements

Detailed procedure: Talk from A. McEwen (Jefferson Lab)

<u>Bulk BCP removal of 400 MHz P-o-P RFD cavity</u>



<u>SA-2 & SA-3</u>
At wave guide stub



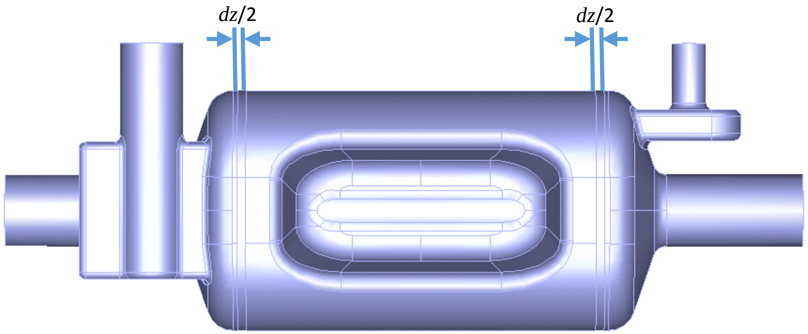
<u>SA-1</u>
At high electric field and flat magnetic field surface

Bulk BCP tooling assemblies – Schematic only

CAVITY TRIMMING AND WELD PLAN

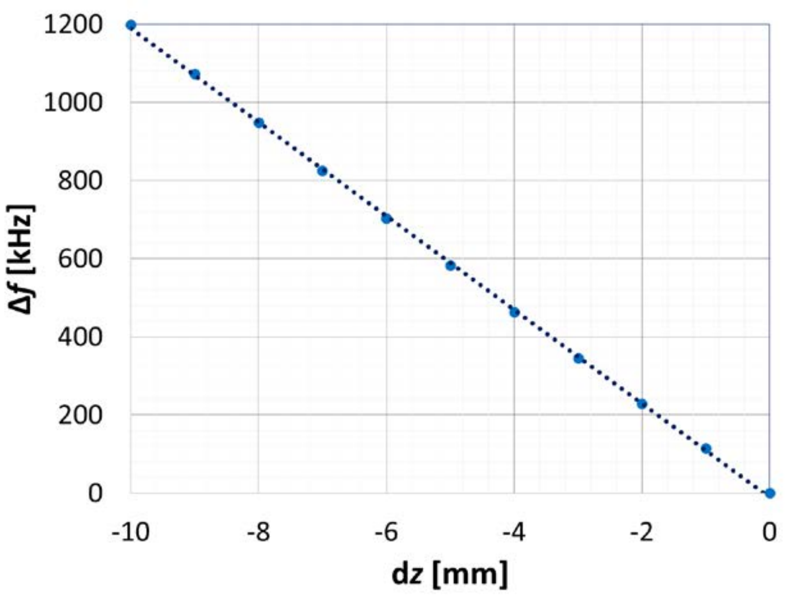
Bulk BCP → Trim to Target Frequency → Trim to 3mm for Final Welding → Weld Prep Chemistry → Final Welding

- Trim center body to achieve target frequency at pre welding



- **df/dz = -119.85 kHz/mm**
- 3 mm weld plan: to minimize the cavity deformation during welding

Trimming Curve



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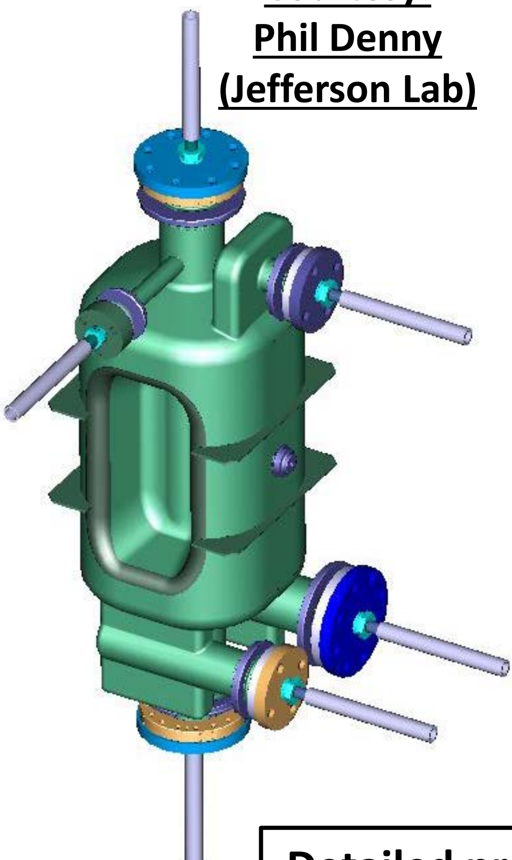
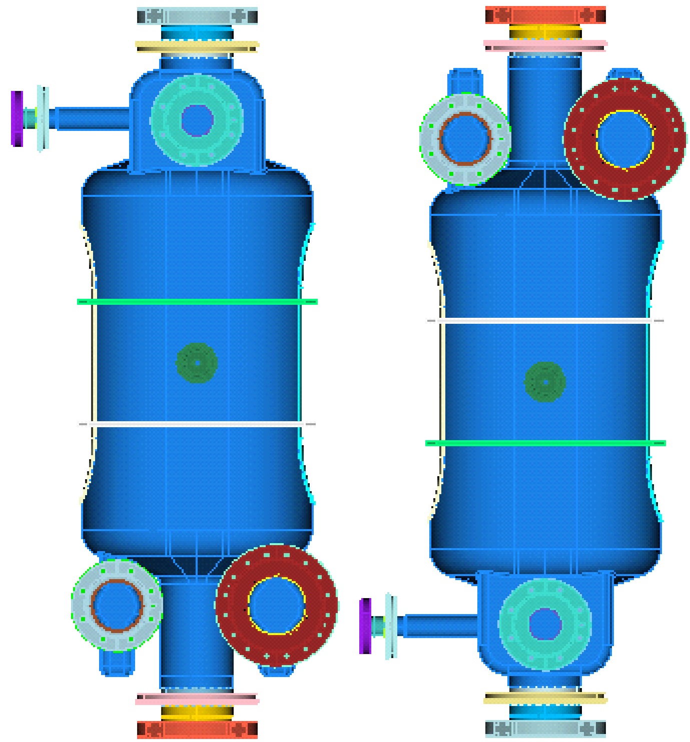
LIGHT BCP / HIGH PRESSURE RINSING

- Light BCP: Total removal of ~20 microns
- Minimum removal of 10 microns at each surface

<u>Courtesy:</u>
<u>Phil Denny</u>
<u>(Jefferson Lab)</u>

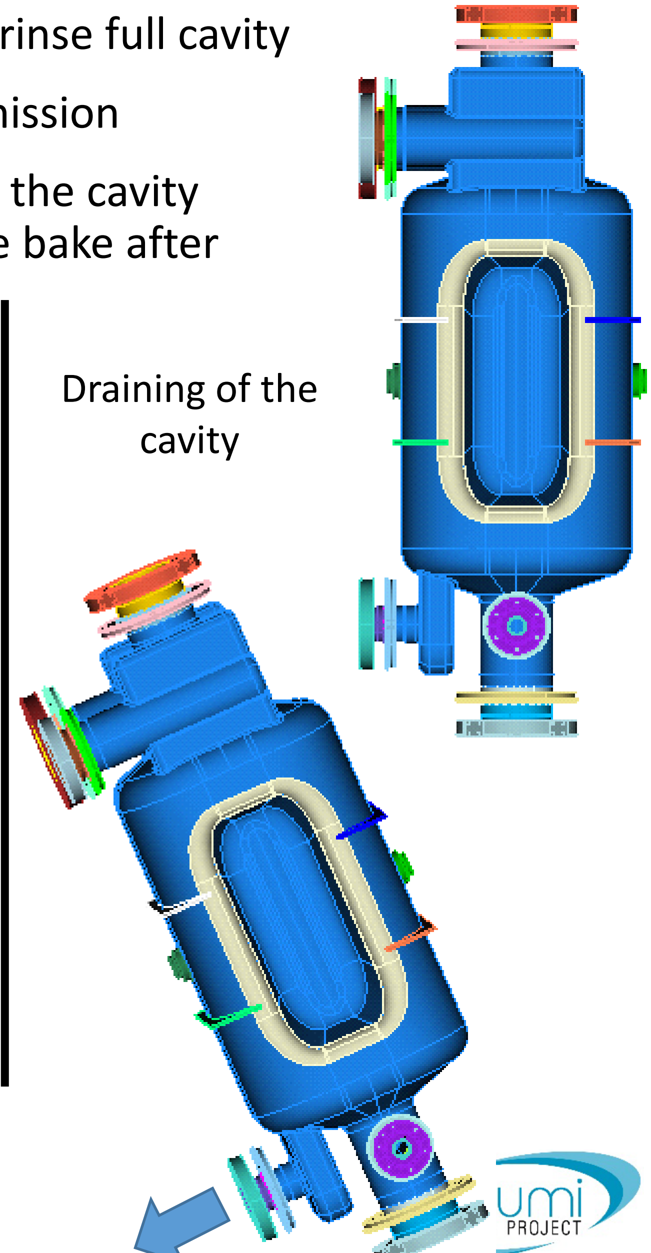


- HPR: 2 iterations in order to rinse full cavity
- Important to reduce field emission
- Drain completely by rotating the cavity followed by low temperature bake after



1st iteration   2nd iteration

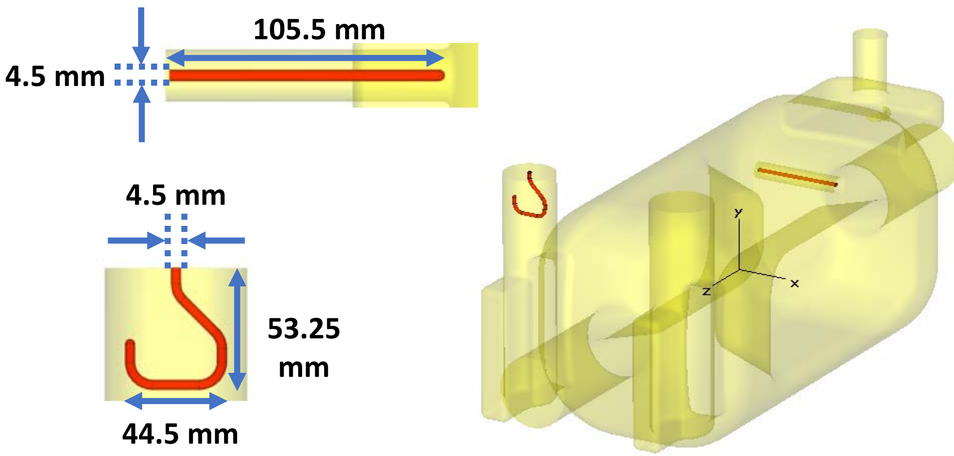
Draining of the cavity



Detailed procedure and tooling: Talk from A. McEwen (Jefferson Lab)

ASSEMBLY: COUPLING – RF TEST PROBES

- FPC and Pick Up ports are used for VTA rf test



Coupling Factors for VTA Test

Parameter	Value
Geometrical Factor (*G*)	107 Ω
Residual Resistance (R_{res})	10 nΩ
R_s at 2.0 K	11.3 nΩ
Q_0 at 2.0 K	**9.5×10^9**
R_s at 4.2 K	81.3 nΩ
Q_0 at 4.2 K	**1.32×10^9**

- Probe calibration:
  - Q_{ext} (FPC): ~6.0×10^9
  - Q_{ext} (Pick Up): ~5.0×10^{10}

- Use same probe for all the VTA tests
  - Bare cavity test
  - Bare cavity test with HOM couplers
  - Cavity with He-vessel test

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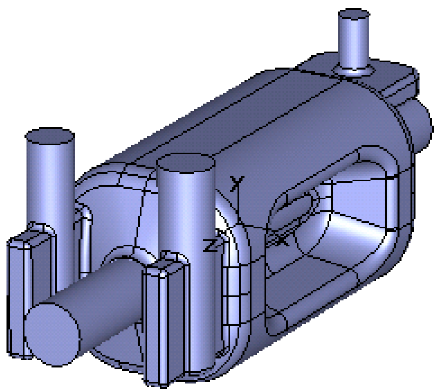
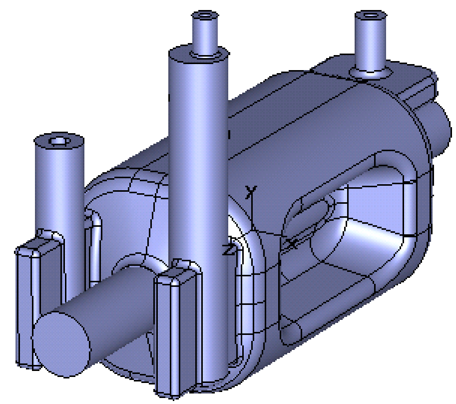
FREQUENCY TUNING PLAN – ASSEMBLY & TESTING

Welded Bare Cavity (f_0) → (1) → **Fully Assembled Cavity with HOM Couplers (f_1)** → (2) → **Evacuated Cavity (f_2)** → (3) → **Cooled Down Cavity (f_3)** → (4) → **Cavity with Tuner Activated (f_4)** → (5) → **Operational Cavity with RF On (f_5)**

- **Step (1)**: Mounting couplers – FPC probe, demountable HHOM coupler and VHOM probe

Bare Cavity





Fully Assembled Cavity

- **Frequency shift due to mounted couplers δf = 4.906 kHz**
- Mounting of couplers increases the cavity frequency
- Measured at room temperature (20 °C) in air

FREQUENCY TUNING PLAN – ASSEMBLY & TESTING

Welded Bare Cavity (f_0) → (1) → **Fully Assembled Cavity with HOM Couplers (f_1)** → (2) → **Evacuated Cavity (f_2)** → (3) → **Cooled Down Cavity (f_3)** → (4) → **Cavity with Tuner Activated (f_4)** → (5) → **Operational Cavity with RF On (f_5)**

- **Step (2)**: Evacuated cavity has two effects
  - Pressure effect
  - Dielectric effect

- Pressure effect:
  - df/ dp = -80 Hz/torr [Ref. H. Park]
  - At 1 atm (760 torr)

$$\delta f = \frac{df}{dp}\delta p = -80 \times 760 = -60.8 \text{ kHz}$$

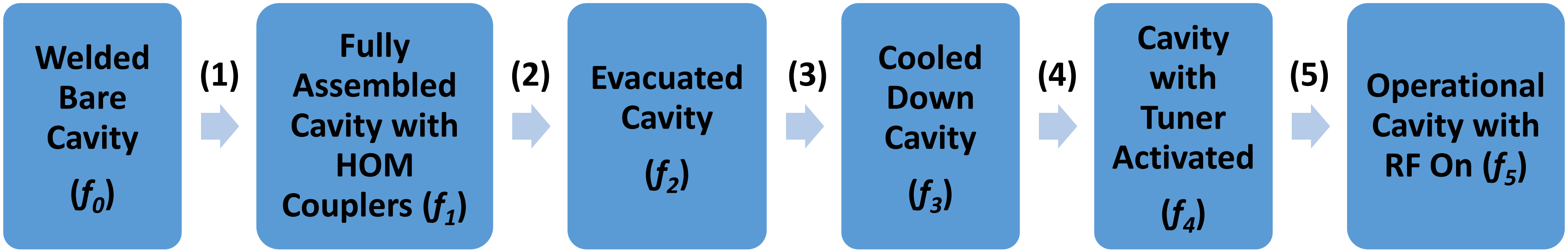
- Dielectric effect:

$$f_{Air} = \frac{1}{\sqrt{1.00059}} f_{Vacuum}$$

  - Evacuated cavity increases the cavity frequency

- Evacuated cavity measurements are done at room temperature (20 ^{o}C)

FREQUENCY TUNING PLAN – ASSEMBLY & TESTING



- **Step (3)**: Cooled down cavity has two effects
  - Pressure effect
  - Thermal shrink
- Pressure effect:
  - d*f*/ d*p* = -80 Hz/torr [Ref. H. Park]
  - Δ*p* [4.2 K] = 1 atm (760 torr) → Δ*p* [4.2 K] = -60.8 kHz
  - Δ*p* [2.0 K] = 23 torr → Δ*p* [2.0 K] = -1.84 kHz
- Thermal shrink from 20 °C to 4.2 K/2.0 K:

$$f_{Cryo\ Temp} = \frac{1}{(1-0.00143)} f_{Room\ Temp}$$

  - Similar frequency shift at both 4.2 K and 2.0 K

<u>Thermal expansion of niobium</u>

(BNL Cryogenic Data Notebook)

THERMAL EXPANSION OF NIOBIUM

Sources of Data: Erfling 1942.

Other References: Hidnert and Krider 1933.

Discussion: Also termed columbium.

Table of Selected Values

Temp. °K	$\frac{L_{293} - L_T}{L_{293}}$	$\frac{1}{L}\frac{dL}{dT}$ per °K	Temp. °K	$\frac{L_{293} - L_T}{L_{293}}$	$\frac{1}{L}\frac{dL}{dT}$ per °K
0	143 x 10^{-5}	0.	140	99.4 x 10^{-5}	.56 x 10^{-5}
10			160	87.7 "	.59 "
20	143 "	.03 x 10^{-5}	180	75.5 "	.62 "
30	143 "	.09 "	200	63.0 "	.64
40	141 "	.17 "	220	50.0 "	.66
50	139 "	.24 "		"	
60	137 "	.31 "	240	36.7 "	.67 "
70	133 "	.36 "	260	23.1 "	.68 "
80	129 "	.40 "	273	14.1 "	.69 "
90	125 "	.44 "	280	9.2 "	.69 "
100	121 "	.47 "	293	0.0	.70 "
120	111 "	.52	300	-5.0	.70 "

Taken from NBS 29

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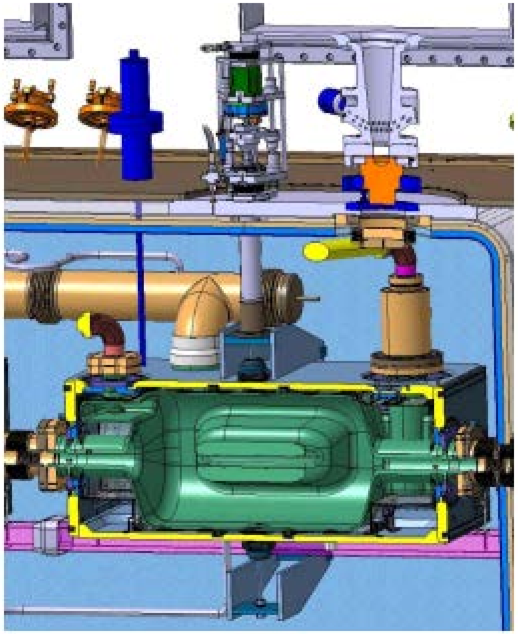
FREQUENCY TUNING PLAN – ASSEMBLY & TESTING

Welded Bare Cavity (f_0) → (1) → **Fully Assembled Cavity with HOM Couplers (f_1)** → (2) → **Evacuated Cavity (f_2)** → (3) → **Cooled Down Cavity (f_3)** → (4) → **Cavity with Tuner Activated (f_4)** → (5) → **Operational Cavity with RF On (f_5)**

- **Step (4)**: Tuner activation
- Full tuner range 200 kHz
- During operation top and bottom cavity surfaces are only pushed and pushed equally
- RFD cavity tuner effect:
  - Pushed tuner → Increases frequency
  - Pulled tuner → Reduces frequency
- Tuner in activation: Pushed at a half-way position which is the neutral position
  - Cavity is always under compression
  - Frequency range [-100, +100] shifted to [0, 200] kHz
  - **δf = 100 kHz**



RFD cavity with tuner – K. Artoos (SRF 2015)

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- **Step (5)**: Lorentz detuning
- Lorentz coefficient for RFD cavity: is $k_L = -51.1\ \mathrm{Hz/(MV/m)^2}$ [Ref. H. Park]

$$\delta f = k_L E_T^2 = -121.92 \times \left(\frac{3.4}{0.375} \right)^2$$

- When RF is on and cavity operating at 3.4 MV frequency shift due to Lorentz detuning: **δ*f* = - 10.022 kHz**
- Lorentz detuning reduces the cavity frequency
- **Final target frequency of fully assembled cavity for SPS/LHC (f_5) = 400.79 MHz**

FREQUENCY TUNING RECIPE

Bare Welded Cavity

400.000,475 MHz

↓ Mount couplers: + 4.906 kHz

Assembled Cavity

400.005,381MHz

↓ Pump on cavity : 760 torr differential (– 60.8 kHz) and dielectric effect (+ 117.672 kHz)

Evacuated Cavity

400.062,253 MHz

↓ Cool down to 2.0 K : thermal shrinkage (+ 572.993 kHz) and lower pressure to 23 torr (+ 58.96 kHz)

Cooled Down Cavity to 2.0 K

400.694,206 MHz

↓ Tuner activation to bring it to mid range: + 100.0 kHz

Tuner Activated Cavity

400.794,206 MHz

↓ Lorentz detuning: – 4.2 kHz

Operational Cavity with RF On at V_t=3.4 MV

400.790,000 MHz

FREQUENCY TUNING SEQUENCE FOR ASSEMBLY

Frequency Tracking in Real Time	Frequency Shift [kHz]	Frequency [MHz]
Welded Bare Cavity (f_0)		**400.006,071**
Shift due to mounted couplers	**+ 4.906**	
Fully Assembled Cavity with HOM Couplers (f_1)		**400.010,977**
Pressure effect (760 Torr differential)	**– 60.800**	
Dielectric effect air to vacuum	**+ 117.968**	
Evacuated Cavity (f_2)		**400.068,145**
Thermal shrinkage	**+ 572.917**	
Cooled Down Cavity at 4.2 K ($f_{3,\,4.2\,K}$)		**400.641,062**
Pressure from 760 Torr to 23 Torr in He tank	**+ 58.96**	
Cooled Down Cavity at 2.0 K ($f_{3,\,2.0\,K}$)		**400.700,022**
Shift due to tuner activation to its mid range	**+ 100.000**	
Cavity with Tuner Activated (f_4)		**400.800,022**
Lorentz Detuning	**– 10.022**	
Operational Cavity with RF On (f_5)		**400.790,000**

FREQUENCY TUNING PLAN – FABRICATION

Cavity Sub-Assemblies (f_0) → (1) → **Bulk BCPed Sub-Assemblies (f_1)** → (2) → **Welded Cavity (f_2)** → (3) → **Light BCPed Bare Cavity (f_3)**

- **Step (1)**: Bulk BCP → Uniform removal of 140 microns

- Cavity trimming after bulk BCP: Will account for any frequency deviations due to weld beads, forming and machining errors

- **Step (2)**: Weld shrinking
  - Shrinkage of 0.008” per side
  - Total weld shrinkage = 4×0.008” = 0.8128 mm
  - Any non-uniformity in weld shrinkage may increase/decrease gradient
  - Does not effect the mechanical center of the cavity

- **Step (3)**: Light BCP → Uniform removal of 20 microns

FREQUENCY TUNING SEQUENCE FOR FABRICATION

Frequency Tracking in Real Time	Frequency Shift [kHz]	Frequency [MHz]
Welded Bare Cavity (f_0)		**400.006,071**
***Shift due to light BCP* (*20 microns*)**	**+ 5.762**	
Bare Cavity before Light BCP		**400.011,833**
Weld shrinkage	**– 92.528**	
Bare Cavity before Final Weld (Trimmed Cavity)		**399.919,675**
Shift due to bulk BCP	**+ 39.441**	
Bare Cavity before Bulk BCP (Formed Sub-Assemblies)		**399.959,116**

- The target frequency after bulk BCP and trimming of sub-assemblies: f_{target} = 399.919,675 MHz
- Since df/dz = – 120 kHz/mm, the frequency of sub-assemblies before trimming needs to be lower than f_{target}

CURRENT STATUS OF RFD CAVITIES

- Cavity parts for two RFD cavities parts received from Niowave Inc.
- Frequency of stacked cavities:
  - Cavity 1 – 400. 928008 MHz
  - Cavity 2 – 398.925087 MHz
- Target frequency should be lower than 400 MHz
- Status:
  - ***Cavity 1***
    - Center body is longer (room for trimming) and matches the end plates
    - However has a higher frequency than the target frequency
    - Current plan: to push poles inward (~0.5 mm per side)
    - Full plan under development for additional tuning
  - ***Cavity 2***
    - Frequency is lower than target frequency
    - Proceed with rf processing and welding
    - More details – Talk from A. McEwen

Stacked RFD Cavity

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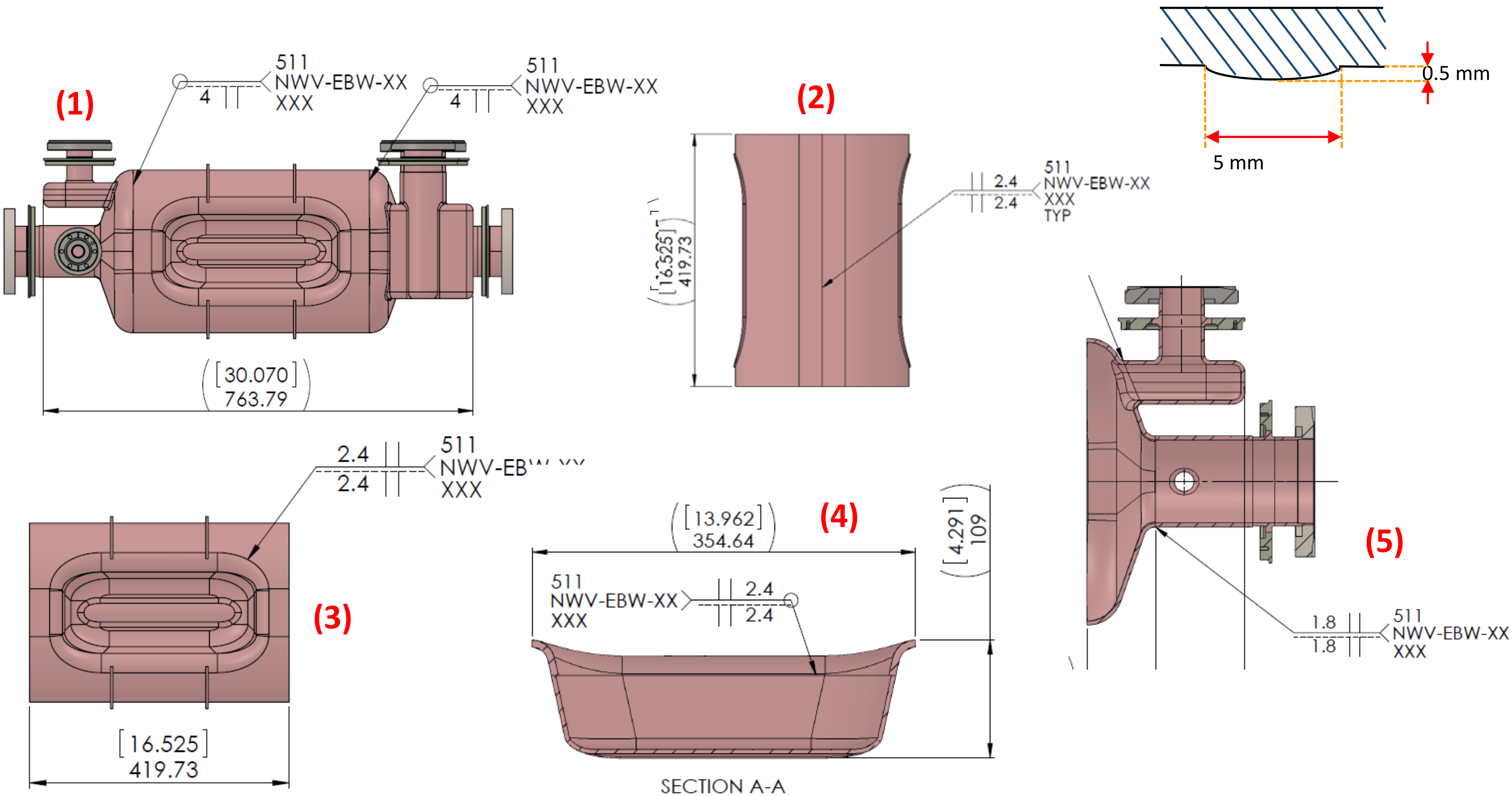
FREQUENCY ANALYSIS OF WELD IMPERFECTIONS

- Major welds analyzed with a weld bead of 0.5 mm depth and 5 mm thickness



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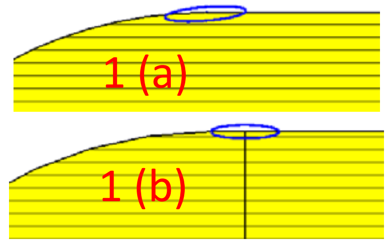
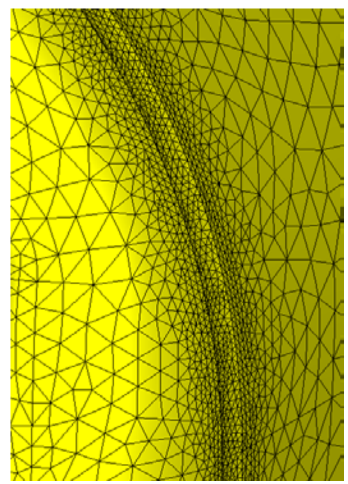
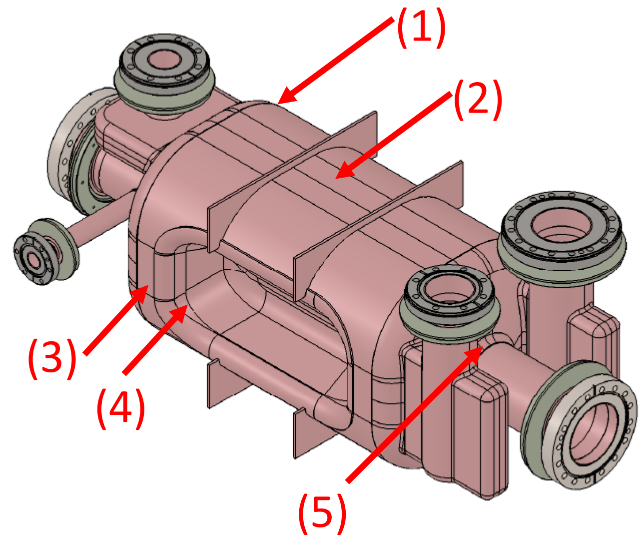
FREQUENCY ANALYSIS OF WELD IMPERFECTIONS

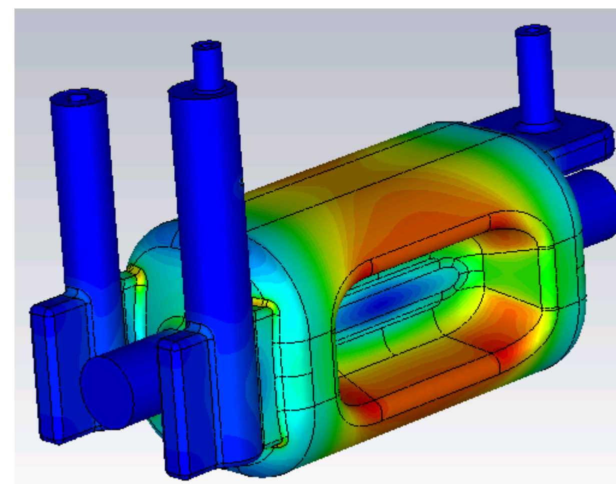
Weld	Frequency [MHz]	Δf [kHz]	B_p^* [mT]
Ideal Cavity	400.664013	-	56.37
Weld 1 (a)	**400.673775**	**9.8**	**55.55**
Weld 1 (b)	**400.666337**	**7.4**	**55.55**
Weld 2	400.680087	16.1	55.55
Weld 3	*400.726685*	*62.7*	*55.59*
Weld 4	400.702314	38.3	56.49
Weld 5	400.665127	1.2	56.33

* At 3.4 MV









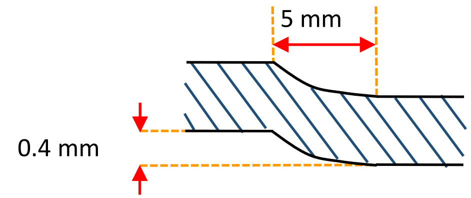
Surface Magnetic Field

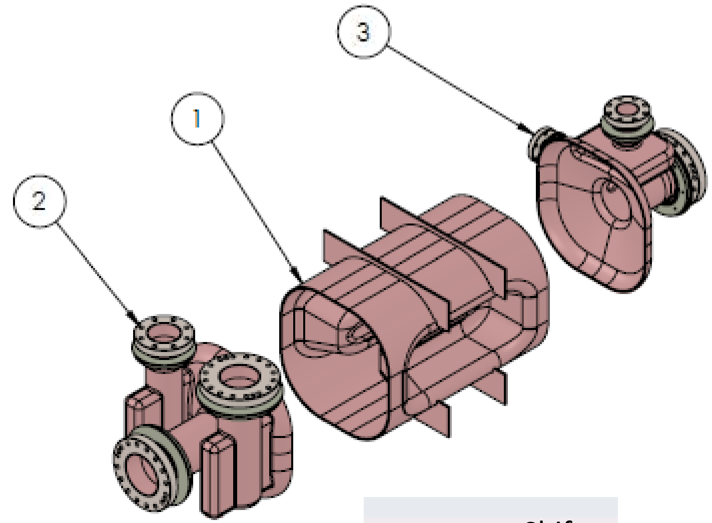
- Study does not include thermal shrinkage or BCP removal
- Frequency and field enhancement comparison with SLAC – ACE3P suite is on going

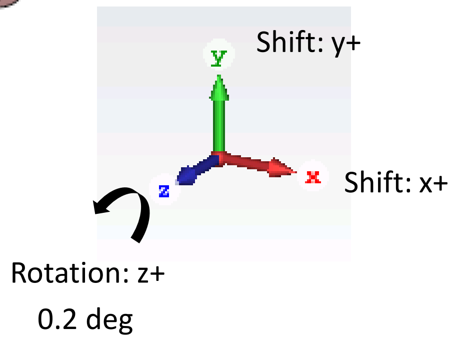
FREQUENCY ANALYSIS: WELD MISALIGNMENTS

- Misalignment in final subassembly weld

Weld	Frequency [MHz]	Δf [kHz]
Ideal Cavity	400.664013	-
Shift 2:x+ 3:x+	400.665363	1.35
Shift 2:x+ 3:x–	400.663756	-0.26
Shift 2:y+ 3:y–	400.663053	-0.96
Rotation: 2:z+ 3:z+	400.663740	-0.27
Rotation: 2:z– 3:z–	400.665136	1.12
Rotation: 2:z+ 3:z–	400.663707	-0.31



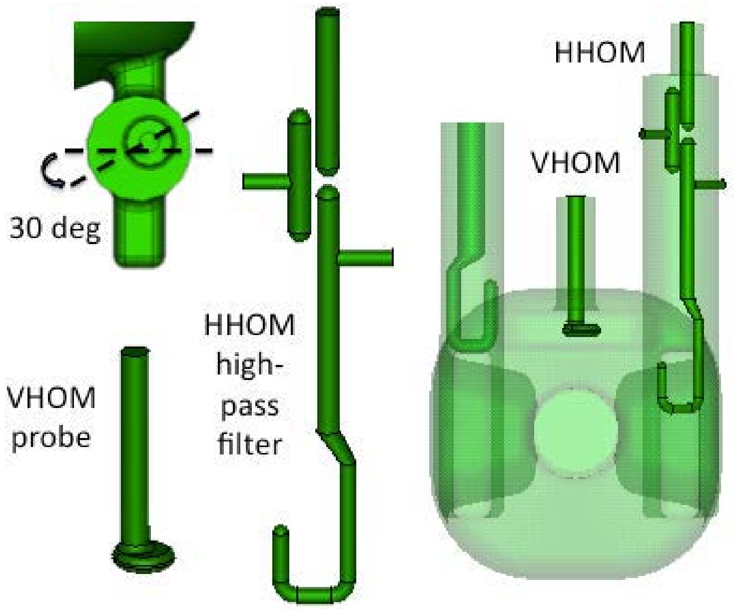




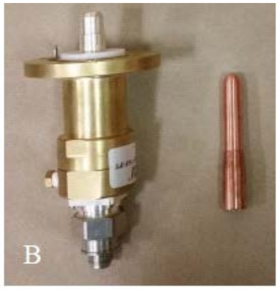
- No field enhancement
- Frequency shift is negligible

HOM COUPLER FABRICATION

- **Courtesy: Adam Rogacki – Niowave Inc.**
- Niowave Inc. - Development of HOM Couplers for the LHC Superconducting Crab Cavities
- Fabricated Cu prototypes of
  - Demountable HHOM coupler
  - VHOM coupler probes



Parts



VHOM

HHOM

Completed HOM Couplers

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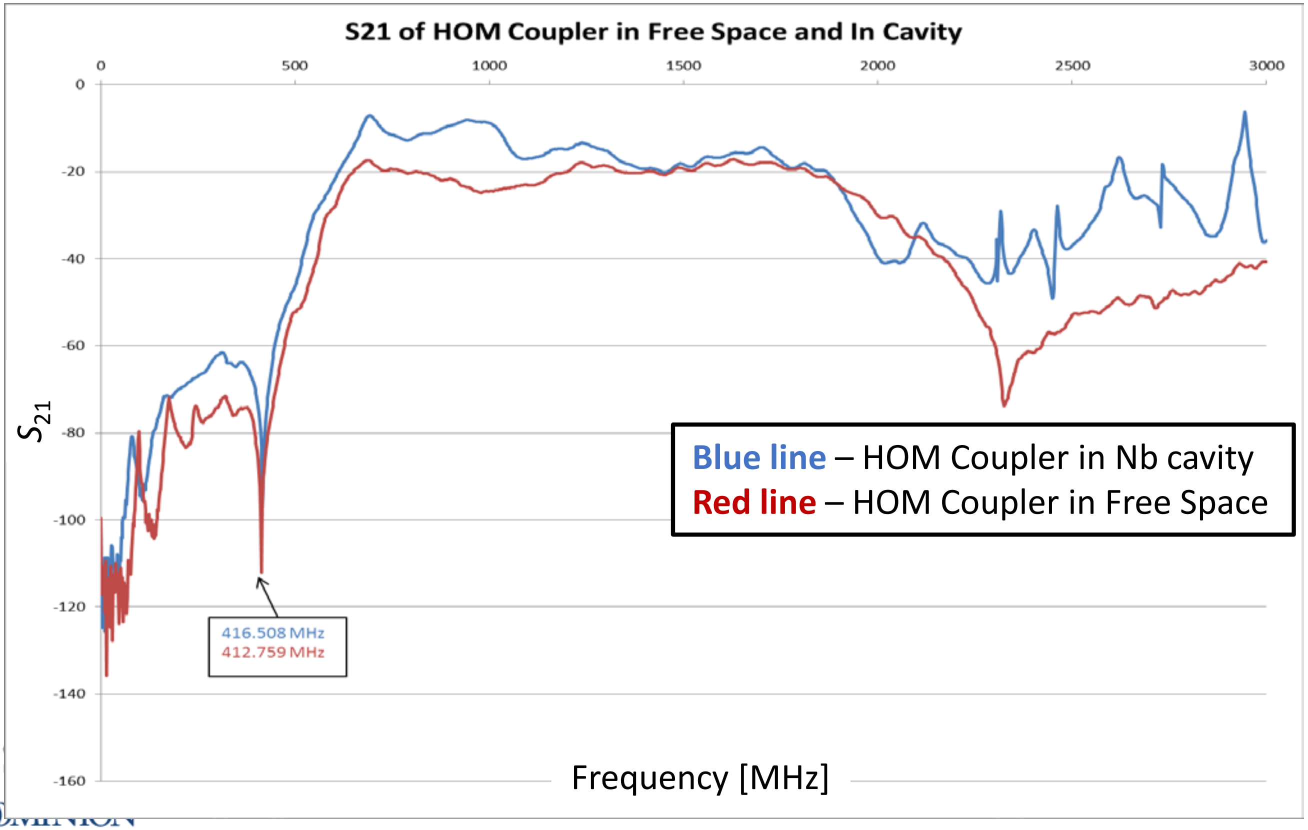
MEASUREMENTS WITH HOM COUPLER

- Measurement of S_{21} of bare HOM coupler and with stacked cavity
- Complete rejection of fundamental mode

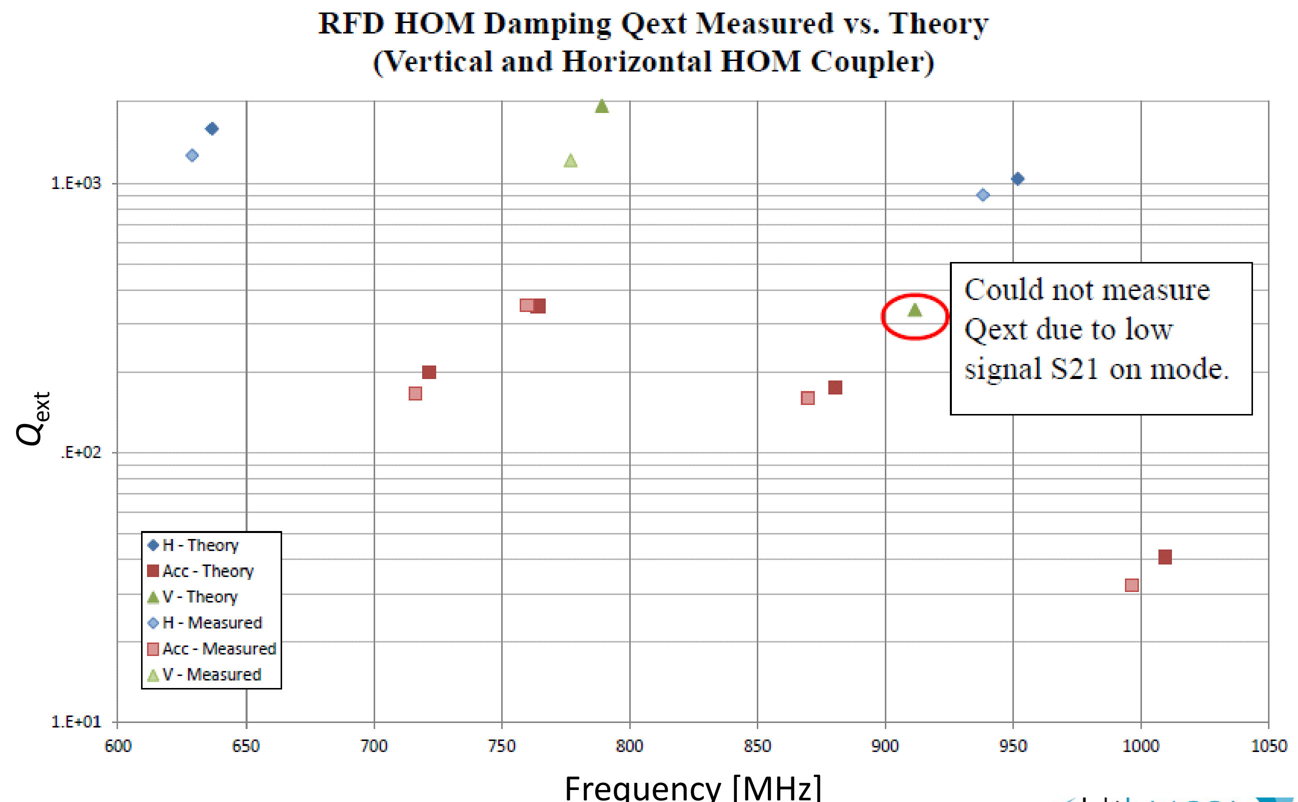
S21 Measurements of Soldered Assembly in Free Space



Courtesy: Adam Rogacki Niowave Inc.

MEASUREMENTS WITH HOM COUPLER

- **Courtesy: Adam Rogacki – Niowave Inc.**
- HOM measurements obtained up to 1 GHz from the stacked RFD cavity
- Both frequency and Q_{ext} were lower
  - Measurements obtained without 30 deg rotation of HHOM coupler
  - Offsets possibly due to longer center body

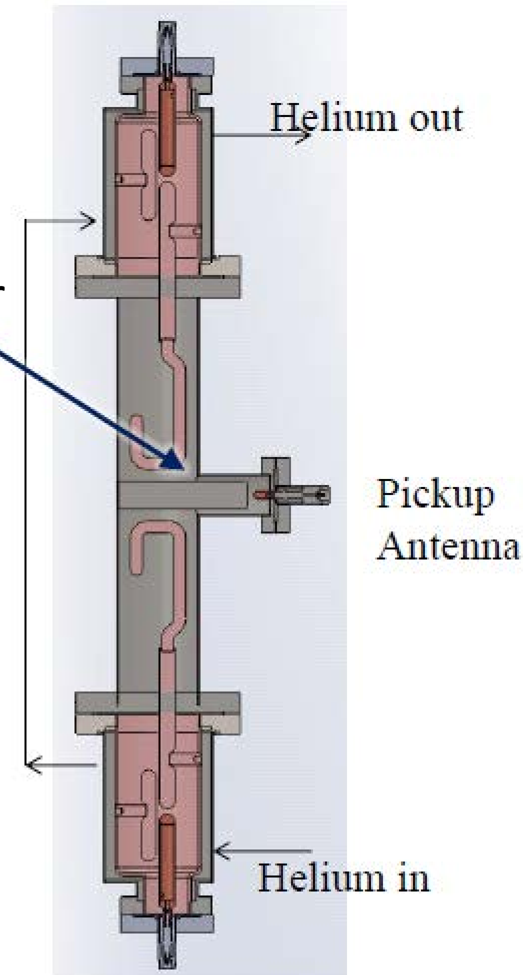


HOM COUPLER FABRICATION PLAN

- Fabrication of two Nb HHOM Couplers

Courtesy: Adam Rogacki
Niowave Inc.

<u>Schematic of the conceptual HOM test box</u>



- HOM test box design on going
- Measurements with HOM couplers
  - Test with Nb cavity at room temp and cryo temp
  - Test box test for measurements at room temp and cryo temp
- Possible measurements of HOM couplers at room temp using a Cu cavity

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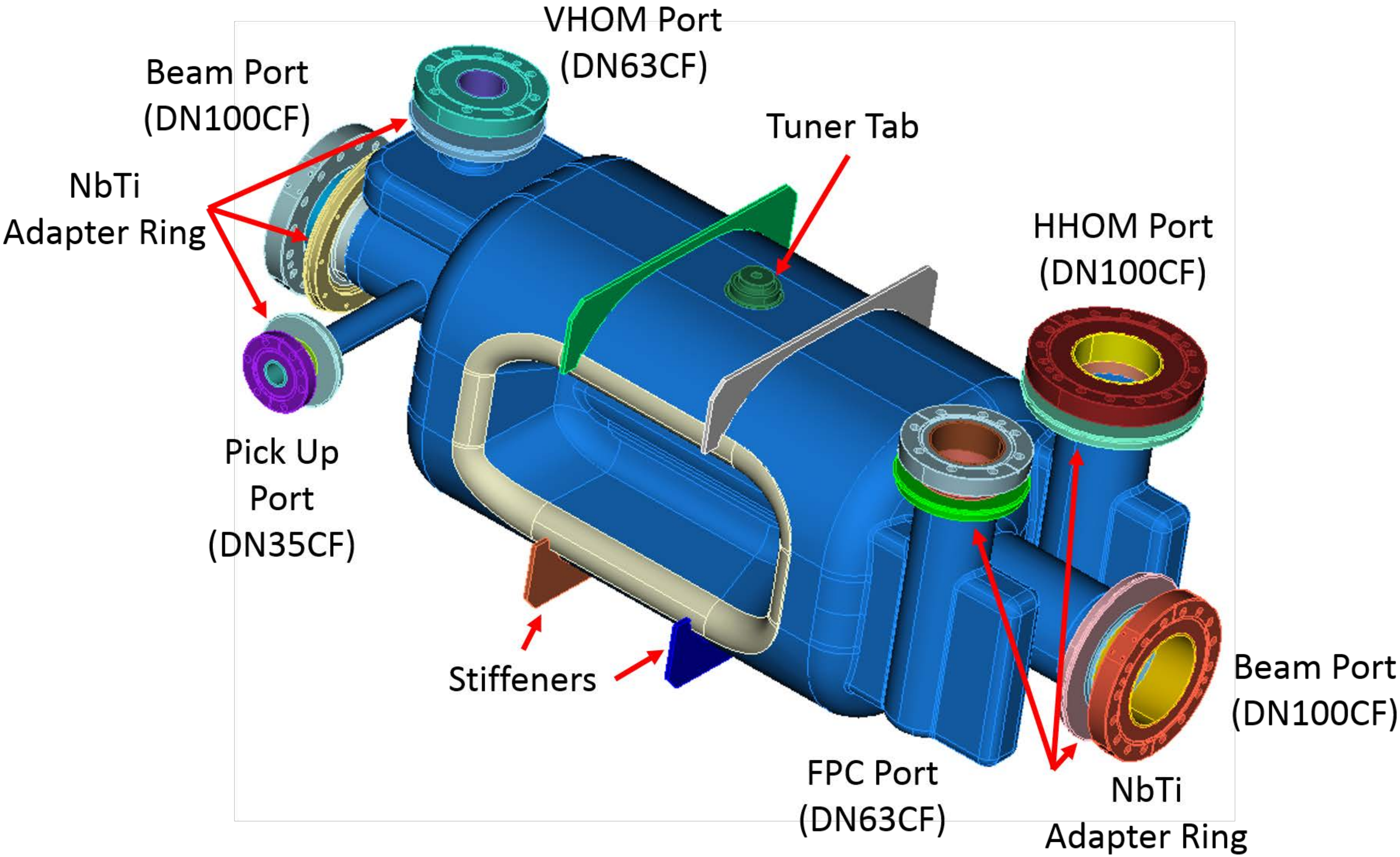
SUMMARY

- Parts of the two RFD cavities are received at Jefferson Lab from Niowave Inc. – April 28th, 2016
- One cavity (Cavity 002) has already initiated the process: Proceed to finish
  - Welding of the bare cavity
  - Cavity processing
  - RF testing
- Second cavity (Cavity 001): In discussion with Niowave Inc. to recover the target frequency
  - Current plan: Pushing poles inward (~0.5 mm per side) to reduce to target frequency
- Working with Niowave in the development of prototype HOM couplers
  - Room temp and cryo temp of measurements with HOM couplers
  - Measurements with Nb cavities and using a HOM test box
- Proof-of-Principle cavity testing at SM18, CERN to review (Alick Macpherson, Alex Castilla):
  - Surface preparation protocols
  - Handling and tooling
  - LLRF systems in SM18_V4*

THANK YOU


VHOM Port
(DN63CF)
Beam Port
(DN100CF)
Tuner Tab
NbTi
Adapter Ring
HHOM Port
(DN100CF)
Pick Up
Port
(DN35CF)
Stiffeners
Beam Port
(DN100CF)
FPC Port
(DN63CF)
NbTi
Adapter Ring

RFD Full Cavity Features

Parameter	Value	Unit
Cavity weight	102.52	lb
	46.5	kg
Cavity volume	32,612	cm^3
	8.62	gallons
Cavity surface area	0.9796	m^2
Dimensions		
Cavity length	36.2	in
	918.7	mm
Cavity width	16.2	in
	409.5	mm
Cavity height	14.2	in
	358.96	mm

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