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LESSONS LEARNED FROM RF-DIPOLE PROTOTYPE CAVITIES FOR LHC HIGH LUMINOSITY UPGRADE*

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Abstract

The rf-dipole cavity has successfully demonstrated the principles of using a compact cavity operating in TE_{11}-like mode in generating a transverse kick. Several proof-of-principle rf-dipole cavities have been fabricated and the rf tests have demonstrated high transverse gradients. The rf-dipole geometry has been adapted into a square-shaped geometry designed to meet the dimensional constraints for the LHC also maintaining crabbing in both horizontal and vertical planes. Recently, two prototype rf-dipole cavities intended for the test at SPS for have been completed that is designed to accommodate the FPC and HOM dampers. The performance during the rf tests have shown excellent results on achieving the design requirements of operation for the crab cavities for SPS. This paper presents the experiences and lessons learned during the cavity preparation and testing, including process validation, frequency tracking.

INTRODUCTION

A prototype rf-dipole cavity have been designed for the LHC High Luminosity Upgrade [1] to crab the proton beam in horizontal plane. Set of two crabbing cavities will be installed in a single cryomodule to be tested in SPS prior to installation in LHC. Two prototype cavities of SPS-style have been completed successfully with the performance of the bare cavity cryogenic tests exceeding design specifications [2]. The fully fabricated cavity is shown in Fig. 1. The rf tests of both the cavities have achieved transverse kicks of 4.4 MV and 5.8 MV well above the design requirement of 3.4 MV. The corresponding intrinsic quality factors at nominal voltage of 3.4 MV are 8.5×10^9 and 1.2×10^{10} that corresponds to power dissipations of 3.2 W and 2.3 W respectively.

Figure 1: 400 MHz prototype rf-dipole cavity.

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CAVITY FABRICATION

The two cavities were fabricated by Niowave Inc. under DOE SBIR/STTR program and completed at Jefferson Lab under US LARP. The cavity center body and end plates were formed with 4 mm high RRR Nb sheets. The FPC, HHOM, VHOM and beam pipes were formed with 3 mm Nb sheets. The stamped parts are shown in Fig. 2. The formed parts are welded in to 3 sub-assemblies consisting of center body, end group with FPC and HHOM couplers and end group with VHOM coupler and pick up port as shown in Fig. 3.

Figure 2: Formed parts of the two rf-dipole cavities.

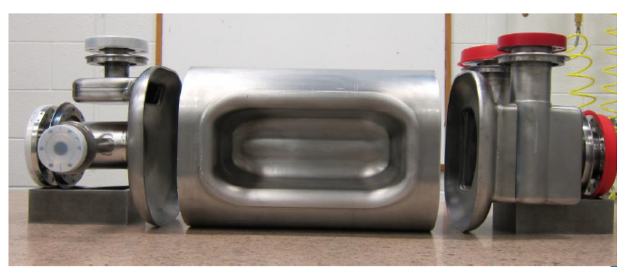

Figure 3: Sub-assemblies of the rf-dipole cavity.

The 3 sub-assemblies of both the cavities were thoroughly investigated for any pits or protrusions on the inner surface. All the uneven welds were grinded as shown in Fig. 4 especially near the poles where peak magnetic field is high.

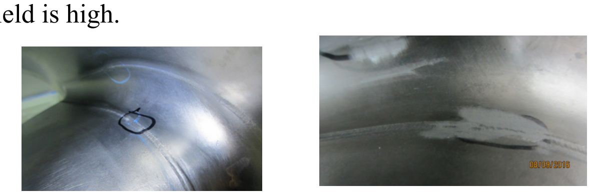

Figure 4: Surface polishing of the rf-dipole cavity.

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Cavity Welding

The final two welds of the rf-dipole cavities were completed at Jefferson Lab electron beam welding machine. The machine issues during the welding resulted with poor welds in both the cavities. The RFD-002 cavity had incomplete welds and was rewelded. Both cavities showed heavy under bead and weld splatter as shown in Fig. 5. Measures were taken to remove the weld splatter as best as possible. However, the process was challenging due to the limited access to the inner surface through the beam pipes.

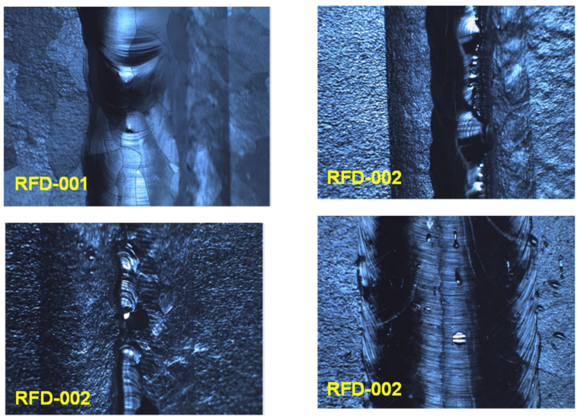

Figure 5: Weld under bead (top), incomplete welds (bottom left), and weld splatter (bottom right) of the final welds in the rf-dipole cavities.

CAVITY PROCESSING

The rf-dipole prototype cavity processing sequence is shown in Fig. 6 [3].

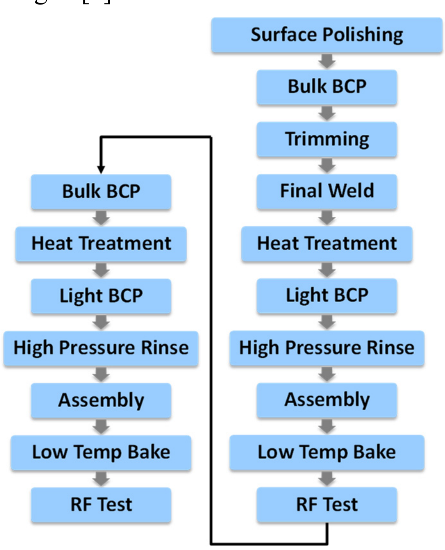

Figure 6: Cavity processing sequence followed for both rf-dipole cavities.

The sub-assemblies of the rf-dipole prototype cavities were bulk BCPed prior to the final welding in order to control the frequency shifts in achieving the target frequency (Fig. 7). A set of snorkels was used to direct the acid in to the waveguide stubs in the end groups and to displace hydrogen generated during processing. The target removal during the bulk BCP is 140 μm. The center body was flipped after 70 μm removal to achieve a uniform removal. However, the end groups were not flipped due to orientation.

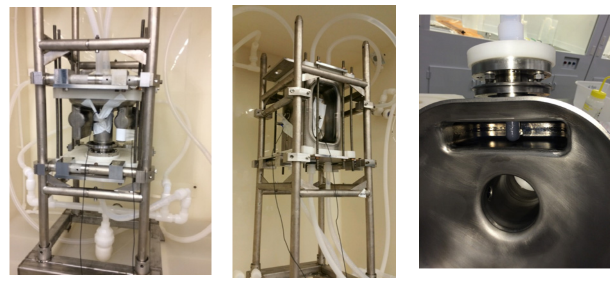

Figure 7: Bulk BCP of sub-assemblies: end group with FPC and HHOM couplers (left), center body (middle), and snorkel attached to the end group with VHOM coupler (right).

In RFD-001 cavity a light BCP of 30 μm was done after the cavity welding and heat treatment was completed. Additional reprocessing was performed as shown in Fig. 6, due to poor welds including an 80 μm bulk BCP and 20 μm light BCP. Similarly, the RFD-002 was reprocessed with a 100 μm bulk BCP and 20 μm light BCP after the final welding. The cavities was flipped at the half point of removal during the bulk BCP of the fully welded cavity. The cavities was oriented with VHOM coupler at the bottom in order to minimize the collection of rinsing water and easy drainage.

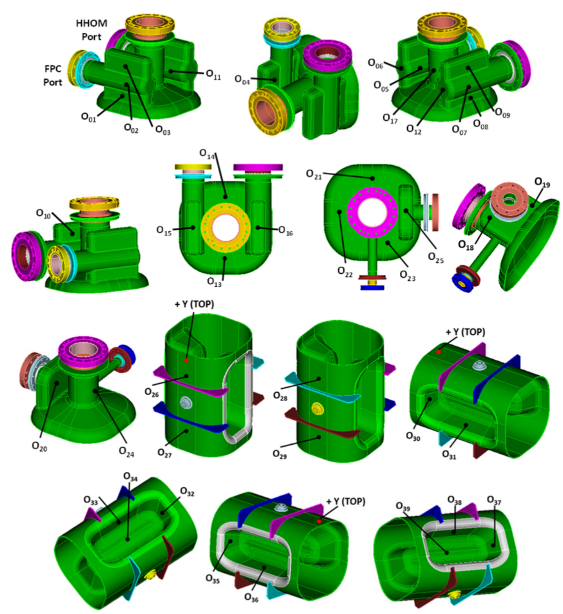

Figure 8: Locations of thickness measurements.

The removal was measured after each step on 39 locations on the cavity body using an ultrasonic thickens gauge as shown in Fig. 8. The measured removal for RFD-001 and RFD-002 are shown in Fig. 9. The average removal of RFD-001 cavity after the first bulk and light BCP is 145 μm. and the finale average removal is 225 μm.

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Table 1: Simulated and Measured Frequencies of RFD-001 Cavity

Step (Recipe for 20 C, 50 % and 1013.25 mbar)	**Simulated**			**Measured**	
		Δ*f* [kHz]	***f*n [MHz]**	**Δ*f* [kHz]**	***f*n [MHz]**
Cavity after trimming and thinning			399.840296		399.846841
Shift due to bulk BCP		-39.441		-21.924	
Cavity after bulk BCP			399.800855		399.824917
Shift due to frame				-765.648	
Cavity after removing fixture			399.800855		399.059269
Weld shrinkage and weld bead		120.645		114.686	
Cavity after final weld			399.921500		399.173955
Shift due to heat treatment				-10.743	
Cavity after heat treatment					399.163212
Shift due to light BCP		-5.762		-16.473	
Cavity after light BCP			399.915738		399.146739
Pressure effect (23 torr)	-1.84				
Dielectric effect air to vacuum	130.341				
Thermal shrinkage	572.877				
Shift due to change in skin depth	28.000				
		729.378		755.615	
Cooled down cavity at 2.0 K			400.645116		399.902354

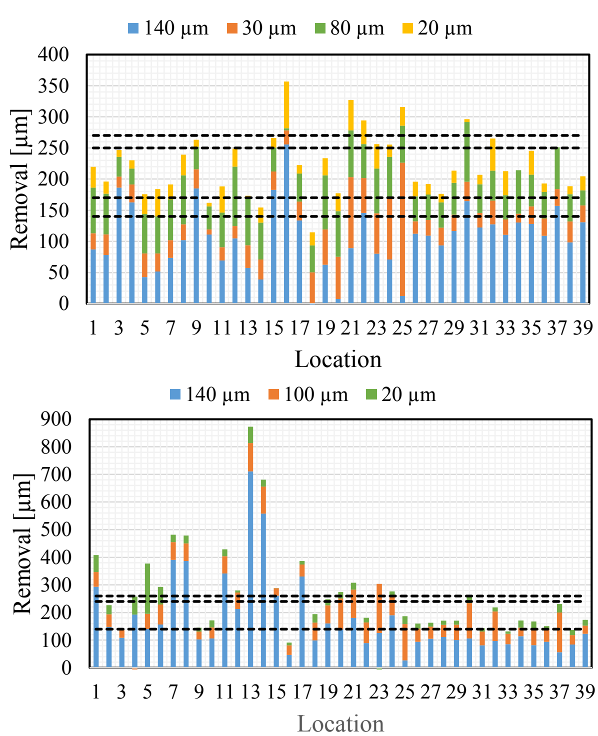

Figure 9: Measured removal after bulk and light BCP of RFD-001 (top) and RFD-002 (bottom).

The bulk BCP of end group with FPC and HHOM couplers of RFD-002 showed excessive removal at two locations possibly due to acid flow. The average removal after bulk BCP of the sub-assemblies of RFD-002 is 150 µm with a final average removal of 243 µm. Both cavities achieved similar average removal. However, the coupler ports showed stains after BCP processing that were removed with HF acid. The stains could be eliminated by using a rotating tool for BCP processing.

FREQUENCY TRACKING

The comparison of the simulated frequency recipe with the measurements are shown in Table 1 for the RFD-001 cavity. The frequencies are normalized to 20 C and 1 atm at 50% humidity. The frequency shifts during the cavity processing are in agreement with the simulation within ± 30 kHz. A frame was used during cavity trimming and weld thinning process to match the profiles of the end groups to the center body. The measured final frequency shift of 743 kHz at 2.0 K is due to the use of the frame that was unaccounted during the fabrication process.

CONCLUSION

The rf-dipole cavity fabrication and processing procedure is well understood in achieving the design specifications including rf performance of bare cavities and target cavity frequency after trimming. The followed process demonstrates the processing of complex rf-dipole prototype cavities. Further processing is planned in using a rotating tool (at ANL) to BCP the cavities. Following the completion of bare cavity test, next the cavities will be tested with HOM couplers.

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