RF TESTS OF RF-DIPOLE PROTOTYPE CRABBING CAVITIES FOR LHC HIGH LUMINOSITY UPGRADE*

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Abstract

The superconducting rf-dipole crabbing cavity is one of the two crabbing cavity designs proposed for the LHC high luminosity upgrade. The proof-of-principle (P-o-P) rf-dipole cavity operating at 400 MHz has demonstrated performance exceeding the design specifications. The prototype cavity for SPS beam test has been designed to include the fundamental power coupler, HOM couplers, and all the ancillary components intended to meet the design requirements. The crab cavities will be installed in the SPS beam line prior to the installation in LHC; this will be the first crabbing cavity operation on a proton beam. The fabrication of two prototype rf-dipole cavities is currently being completed at Jefferson Lab. This paper presents the details on cavity processing and cryogenic test results of the rf-dipole cavities.

INTRODUCTION

The LHC High Luminosity Upgrade consists of an upgrade in the magnet system and installation of crabbing cavities in the LHC ring [1]. The crabbing cavities allow the head-on collision of bunches at the interaction point, hence increasing the luminosity up to 5×10^{34} cm^{-2}s^{-1} with an integrated luminosity of 250 fb^{-1} per year. Crabbing systems will be installed at both ATLAS and CMS interaction points. These crabbing cavities also reduce the pile up of colliding bunches at the interaction point. Each crabbing system includes eight crabbing cavities per interaction point and bunches are crabbed in vertical plane at ATLAS and in horizontal plane at CMS. The vertical crabbing of bunches will be carried out by the double quarter wave cavity and rf-dipole cavities will crab bunches in the horizontal plane.

Two prototype cavities of each type were fabricated by Niowave Inc. and completed at Jefferson Lab under US-LARP. The full prototype rf-dipole cavity design is shown in Fig. 1.

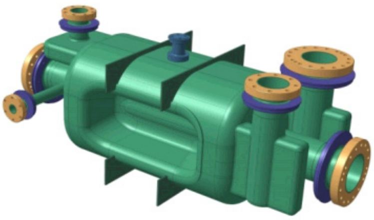

Figure 1: 400 MHz prototype rf-dipole cavity.

RF-DIPOLE DESIGN

The rf-dipole cavity has been designed to operate in a TE$_{11}$-like mode where the primary contribution to the kick is given by the transverse electric field [2]. A square shaped design in adapted in the prototype design to meet the dimensional constraints [3]. The rf properties of both P-o-P and prototype cavities are listed in Table 1.

Table 1: RF Properties of Cylindrical Shaped P-o-P and Square Shaped Prototype RF-dipole Cavities

Parameter	**P-o-P Cavity**	**Prototype Cavity**	**Units**
Nearest HOM	590	633.5	MHz
Peak electric field (E_p*)	4.02	3.6	MV/m
Peak magnetic field (B_p*)	7.06	6.2	mT
Geometrical factor	120	107	Ω
$[R/Q]_t$	287	430	Ω
$R_t R_s$	3.4×10^4	4.6×10^4	Ω^2
At E_t* = 1 MV/m			
V_t	3.4		MV
E_p	36.5	33	MV/m
B_p	64	56	mT

The prototype cavity will operate at peak fields of 33 MV/m and 56 mT at nominal operating voltage of 3.4 MV.

MULTIPACTING ANALYSIS

The multipacting analysis of the bare cavity was completed using the Track3P code from SLAC ACE3P suite [4]. The bare cavity doesn't include any FPC or HOM couplers.

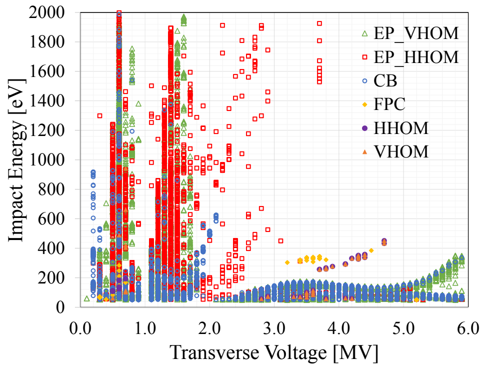

Figure 2: Impact energy of resonant particles as a function of transverse voltage.

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The simulation analyses the resonant trajectories for a period of 50 rf cycles within the range from 50 eV to 2000 eV of impact energy. As shown in Fig. 2 strong resonant particles are present at transverse voltages below 2.0 MV. There are no resonant particles present in the coupler ports in the bare cavity, and most of the particles are on the center body and end plates.

Figure 3 shows the location of the resonant particles on the cavity at the end of 50 rf cycles. The impact energies of the secondary particles generated at the end plates varies in the range that results in a secondary emission yield > 1. There are very few resonant particles at the center body near the poles with very low impact energies.

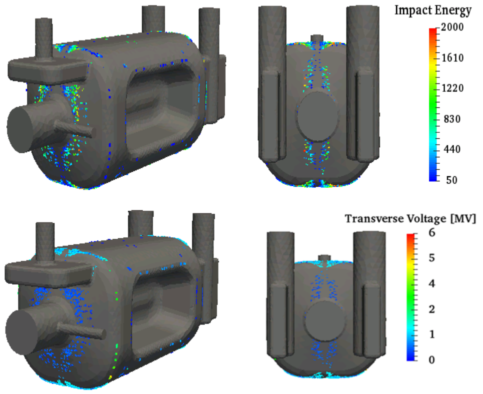

Figure 3: Impact energy (top) and the transverse voltage (bottom) of the resonant particles of the rf-dipole bare cavity.

CAVITY PROCESSING

The rf-dipole cavity was received at Jefferson Lab in 3 sub-assemblies consisting of two end groups and center body. The cavity was processed following bulk BCP of the sub-assemblies prior to the completion of the two final welds. The welded cavity was heat treated at 600 C for 10 hours and followed by light BCP. The cavity was high pressure rinsed and assembled for rf testing. The detailed procedure of rf-dipole cavity processing is given in Ref. [5]. Prior to rf test the cavity was baked at low temperature of 120 C.

RF TEST RESULTS

The two rf-dipole prototype cavities (RFD-001 and RFD-002) rf testing were carried out in the vertical test area at Jefferson Lab. The FPC and pick up ports of the cavity were used in coupling power with the input probe ($Q_{\mathrm{ext}}=5\times10^9$) and field probe ($Q_{\mathrm{ext}}=2\times10^{11}$).

High Power Test Results

The test results of RFD-001 are shown in Fig. 4. During Test I the cavity quenched at 4.0 MV, where the Q_0 degraded after 2.5 MV due to field emission. Higher levels of field emission were observed during the test. At nominal voltage of 3.4 MV the operating Q_0 is 5.5×10^9. At low fields the cavity Q_0 was greater than 10^{10} that corresponds to a surface resistance of 8.2 nΩ where the rf-dipole cavity geometric factor is 107 Ω.

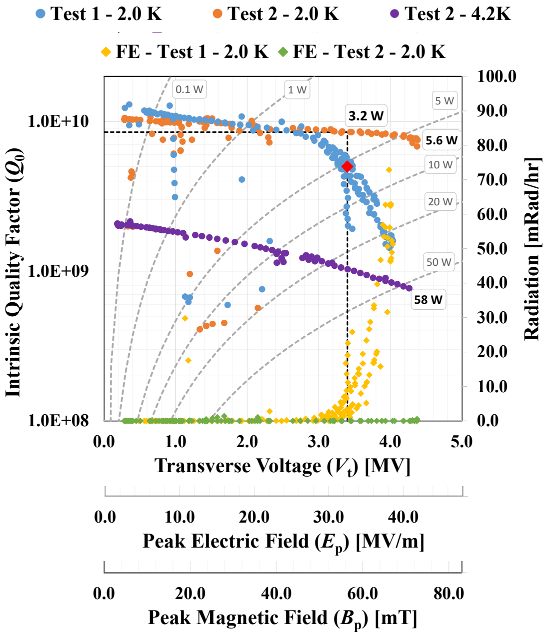

Figure 4: Q_0 at 4.2 K and 2.0 K of RFD-001.

The RFD-001 cavity was reprocessed after the weld inspection due to poor quality of the welds. The second test of the cavity showed improved results as shown in Fig. 4. The Q_0 of Test II at low fields was 1.04×10^{10} with a surface resistance of 10.3 nΩ. At operating voltage of 3.4 MV the cavity Q_0 was 8.5×10^9 with a corresponding surface resistance of 12.6 nΩ. The power dissipation at operating voltage is 3.2 W. The cavity achieved peak surface fields of 42 MV/m and 73 mT with a transverse voltage of 4.4 MV and a power dissipation of 5.6 W. No field emission was detected until the cavity quenched at 4.4 MV.

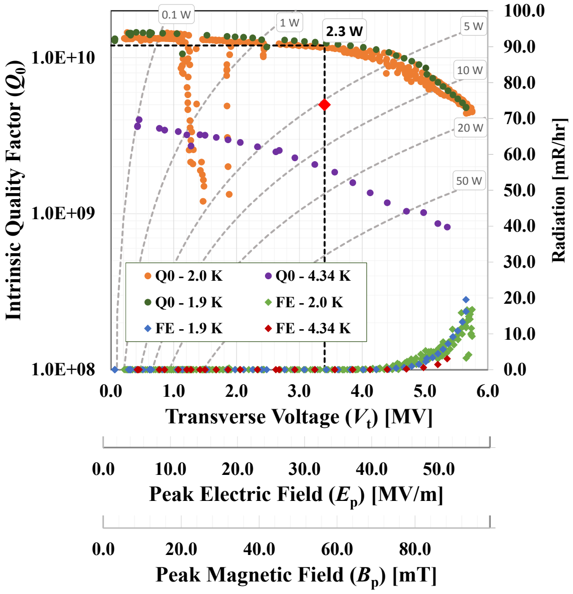

Figure 5: Q_0 at 4.2 K and 2.0 K of RFD-002.

The RFD-002 cavity was reprocessed due to the quality of welds prior to performing any rf tests. The multipacting levels were observed below 2.5 MV as shown in Fig. 5, similar to that seen in the simulation shown in Fig. 2.

The Q_0 at low fields was 1.33×10^{10} at 2.0 K and 1.44×10^{10} at 1.9 K. At operating voltage of 3.4 MV at cavity Q_0 was 1.2×10^{10} with a power dissipation of 2.3 W. The cavity quenched at 5.8 MV where the corresponding peak electric and magnetic surface fields are 56 MV/m and 96 mT. No field emission was observed up to 4.5 MV, where the radiation levels were low at high fields. The residual surface resistance of RFD-002 is about 7.1 nΩ as shown is Fig. 6.

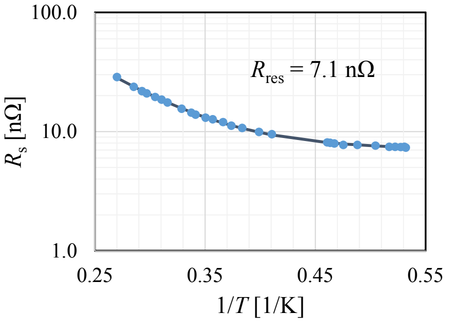

Figure 6: Surface resistance of RF-002.

Measurements of Mechanical Properties

The measured Lorentz coefficients (k_L) of RFD-001 and RFD-002 are shown in Fig. 7. The k_L for RFD-001 is -851 Hz/(MV)^2 and for RFD-002 is -702 Hz/(MV)^2. The simulated k_L for the RFD cavity without tuner acting on the cavity is -898 Hz/(MV)^2 [6]. At operating voltage of 3.4 MV the corresponding frequency shifts of the two cavities are 9.8 kHz and 8.1 kHz. The actual k_L with tuner acting on the cavity is -595 Hz/(MV)^2 that corresponds to a shift of 6.9 kHz at 3.4 MV.

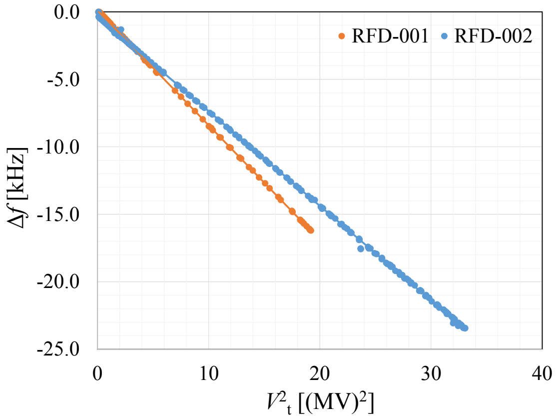

Figure 7: Measured Lorentz coefficients of both RFD-001 and RFD-002.

The measured pressure sensitivity of RFD-002 is shown in Fig. 8. In comparison to the simulated pressure sensitivity of -80 Hz/torr in the RFD cavity where the measured sensitivity is -79 Hz/torr.

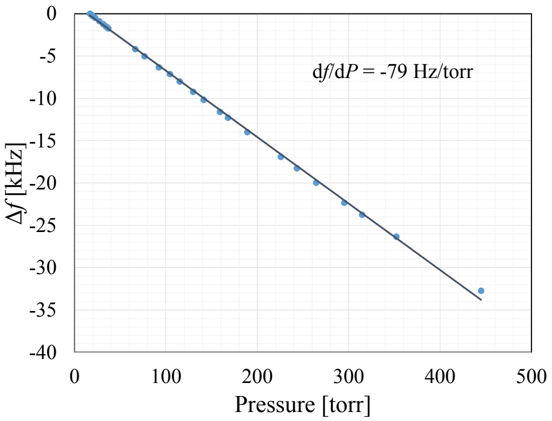

Figure 8: Pressure sensitivity of RFD-002.

CONCLUSIONS

The production and rf testing of the prototype type rf-dipole cavities are completed with performance exceeding the design requirements. The fabrication and cavity processing of the first two prototype type cavities has been explored in understanding the challenges of rf-dipole cavity production.

The RFD-001 and RFD-002 cavities achieved a transverse voltage of 4.4 MV and 5.8 MV with corresponding power dissipation of 3.2 W and 2.3 W. The Q_0 of 8.5×10^9 and 1.2×10^{10} exceeds the requirement of 5×10^9. No field emission levels were observed below 4.5 MV. The measurements of mechanical properties match the simulation results.

The rf-dipole cavities can achieve higher peak surface fields. The quench of RFD-001 at 4.4 MV was possibly due to a defect or weld splatter from the final welding. Therefore, the RFD-001 cavity is expected to be reprocessed at the rotating BCP/EP tool at Argonne National Lab and to be retested at Fermilab.

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