DESIGN AND VERTICAL TEST OF DOUBLE QUARTER WAVE CRAB CAVITY FOR LHC LUMINOSITY UPGRADE *

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Abstract

A Proof-of-Principle (PoP) Double Quarter Wave Crab Cavity (DQWCC) was designed and fabricated for the Large Hadron Collider (LHC) luminosity upgrade. Vertical cryogenic test has been done in Brookhaven National Lab (BNL). We report the test results of this design.

INTRODUCTION

One of the luminosity upgrade options of LHC consists in the vertical and horizontal crabbing of the beams. To do this, a PoP superconducting RF DQWCC has been designed by BNL and CERN. The prototype was fabricated by Niowave, Inc. After the surface treatments at Niowave and BNL, this cavity was tested in the vertical cryogenic test facility at BNL. After the test, additional surface treatments have been done at Argonne National Lab (ANL) to reduce the residual surface resistance in preparation for a further cryogenic test at BNL.

CAVITY DESIGN AND FABRICATION

Figure 1 shows the geometry of the DQWCC, with its RF design introduced elsewhere [1]. The cavity looks like a section of a coaxial structure, with its center conductor cut and separated to form two capacitive plates, with a vertical electric field in between at the fundamental mode, and thus offers the crabbing voltage needed. In the fundamental mode electro-magnetic field distribution, the electric field is concentrated in the area between two capacitive plates and the magnetic field is concentrated in the coaxial area, also shown in Figure 1. The envelope of this cavity is optimized to fit the size limit of IP5 in LHC for both crabbing directions. Comparing to the former quarter wave versions [2, 3], the present one is optimized to cancel the on-axis accelerating (longitudinal) field and to reduce the overall nonlinearity of the deflecting voltage as a function of offset [1].

The finite element model software ANSYS was used to simulate the mechanical strength of this crab cavity. The results and the reinforcement design have been presented elsewhere [4] to meet the safety requirements at both BNL and CERN. The reinforcement components, as well as the cavity, were fabricated and assembled at Niowave [4].

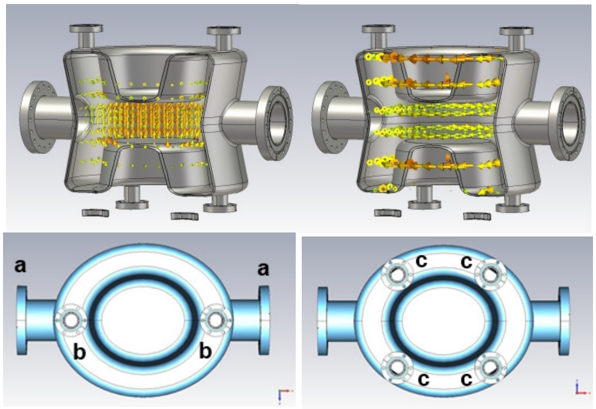

Figure 1: Geometry of the double quarter wave cavity, electric field (top left) and magnetic field (top right) of the fundamental mode. Ports are labelled as: a, beam pipe; b, FPC and pickup coupler; c, HOM.

TEST PREPARATION

Surface Treatment

The cavity was chemically treated using 1:1:2 Buffered Chemical Polish (BCP) solution of HF (49% wt), HNO_3 (69% wt), and H_3PO_4 (85% wt) to etch 150 μm Nb. Once at BNL the cavity was visually inspected, then leak checked, and finally baked for 10 hour at 600°C in a vacuum oven. After the baking the resonant frequency was measured to be 403.3117 MHz. The cavity quality factor at room temperature was 5,400, in agreement with simulation result for Nb's room temperature electric conductivity at 6.2×10^6 /(Ω·m). The cavity was then shipped back to Niowave for a light BCP (30 μm material removal) and High Pressure Rinse (HPR). After that it was shipped back to BNL for assembly and cryogenic test.

FPC and Pickup Coupler Setup

The FPC probe, with its configuration shown in the left of Figure 2:, is set to provide $1.8\text{x}10^8$ to $5.7\text{x}10^{10}$ Q_{ext} with 20 mm travelling length. The nominal position of FPC is set to be 8.7 mm away from the cavity inner surface, with Q_{ext} at $4.0\text{x}10^9$. The motion of the FPC is controlled by a stepper motor mounted on the dewar top-plate and connected to the FPC by means of a drive shaft and a gear box to transfer vertical motion to horizontal motion.

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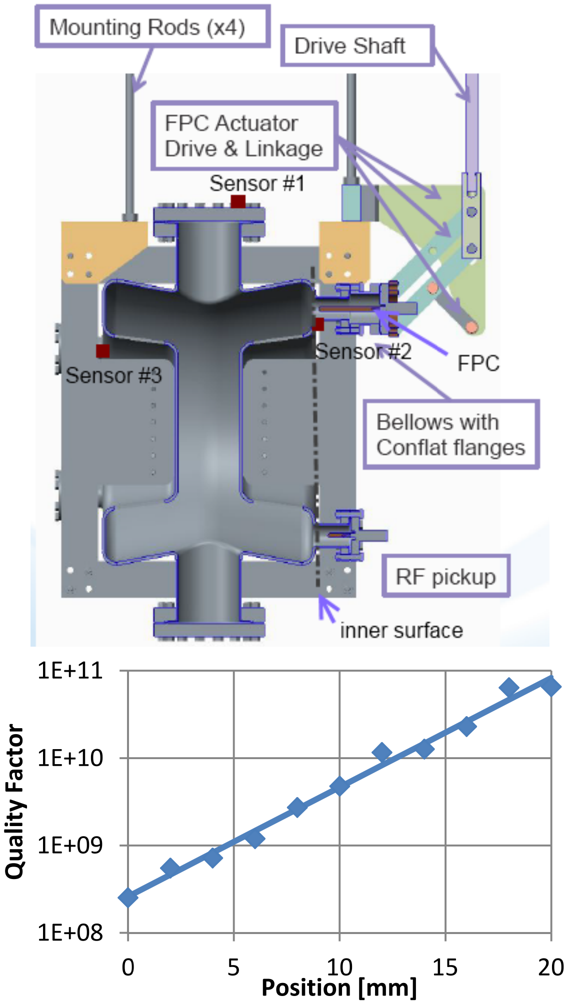

Figure 2: FPC configuration and its position vs Q_{ext}. The top figure also shows installation details. In the bottom plot, dots are from the simulation results, the solid line is the linear fitting for log(Q) vs position.

The pickup coupler position is set to be 20.7 mm away from the cavity inner surface, corresponding to 10^{11} Q_{ext}. The assembling error is controlled within 0.5 mm, corresponding to $8.77\text{x}10^{10}$~$1.17\text{x}10^{11}$ Q_{ext}.

Vertical Test Setup

A dewar with 28" in diameter that can be fitted into the small vertical test facility (SVTF) at BNL was used for the cryogenic test. An ion pump was installed on top of the Dewar top plate for active pumping during the tests. The motion of the stepper motor on the Dewar top-plate was limited by hard stops at the low torque end of the motor gear, along with electrical switch stops right outside the dewar.

Three Lakeshore Cernox^{TM} thermal sensors were mounted onto the cavity, with their positions show in Figure 2: sensor #1 on the top beam pipe flange (port a in Figure 1), #2 on the FPC port (port b in Figure 1) and #3 on the HOM port (port c in Figure 1) which is blanked-off during the tests. Sensor #1 also acts as an indication of liquid helium level, in addition to the liquid helium sensor.

In the design of the RF control system, an RF pin diode switch was used: in CW mode, it worked as an on-off switch for decay measurement; in pulsed mode, a function generator was attached to generate pulsed signal to the amplifier.

CRYOGENIC TESTS

The cavity was cooled down to 4.2 K with a cooling rate higher than 2.0 K/min between 150 K and 50 K to avoid Q-disease. After the first cold test, the cavity was further cooled to 2.0 K for the second cold test. To evaluate the Q-disease effect, it was then warmed up to room temperature, and slowly cooled down to 4.2 K, with a cooling rate lower than 0.5 K/min and let it remained in the region of Q-disease between 50 and 150 K for at least 5 hours. The third cold test was performed after that. The measured quality factor Q_0 for different deflecting voltage V_t levels for the cavity for these three tests are shown in Figure 3. For all three tests, data points were taken for both increasing and decreasing the field inside the cavity. The calibration of the RF cables/components was performed before and after the testing to assure the validity of the measurements. There was a 5% uncertainty in power readout from the RF power meters.

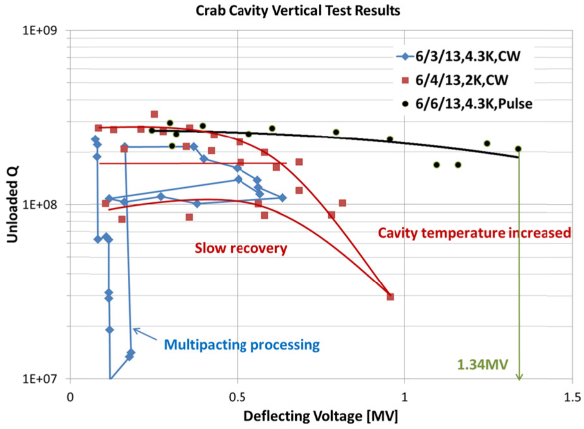

Figure 3: Cryogenic tests: 4.2 K CW test after fast cool-down, 2.0 K CW test after fast cool-down and 4.2 K pulsed after slow cool-down.

Measurements with CW mode were applied to the first two tests. During the first test, multipacting was found for the region of 0.07-0.16 MV, the multipacting region was overcome by increasing the power delivered into the cavity. After the field increased to 0.4 MV, sensor #1 showed a temperature higher than bath temperature at 4.2 K, and Q_0 started to decrease. The Q_0 was at around 10^8. In the second test at a lower bath temperature 2.0 K, no improvement on the Q_0 value was found. After the field increased to 0.6 MV, the reading from sensor #1, the one on the top beam pipe flange, started to increase, and Q_0 started to decrease. These two tests were both limited by the thermal effect, with a maximum RF power from the amplifier at around 100 Watt, with the coupling at ~0.53 for 4.2 K and at ~0.60 for 2.0 K, with FPC coupler adjusted to be all the way into the cavity. In the third test, pulsed mode was applied to reduce the thermal effect, with a maximum 200 Watt RF power applied to the cavity and coupling coefficient close to the value of the first test. Duty factor of the pulsed mode was tuned to ensure that the thermal sensor #1 readout to be stable at 4.2 K. The Q_0 vs V_t curve did not show any degradation until 1.4 MV, limited by the RF power amplifier.

TEST RESULTS ANALYSIS

The Q_0 was limited to few 10^8 for all three tests even at field level lower than 0.1 MV, and it did not improve by cooling down from 4.2 to 2 K, which indicates that the residual resistance limits the cavity performance.

The residual losses from trapped DC magnetic field should not be an issue for this test, as the dewar used for this test is the same as the one for another superconducting cavity was tested, and a difference in performance for operation at 2 K and at 4.2 K could be measured for that cavity [5].

The high residual resistance might come from the oven where the cavity was baked out. Some impurities in the oven could have been transferred to the cavity. The BCP that was performed to the cavity afterwards, however, should have removed the impurities from the cavity surface. The low field emission during the test also did not show a strong support on this possibility.

Another possibility is that the cavity suffers from Q-disease. The third test after a slow cool-down was done in purpose to enhance the Q-disease to the cavity. The cavity performances were compared to the previous measurements, taken after fast cool down, with no significant difference between them.

The highest temperature on the cavity surface was reported by the thermal sensor #1 located on the beam pipe region. This is an indication of high losses in this region. However, dissipated heat in the FPC bellow and in the flanges of the beam pipe and the PU (all in stainless steel) is not enough to explain the low Q measurement. The next paragraph shows that the losses on all these stainless steel and copper components will limit the Q_0 to the 10^9 range, an order of magnitude higher than the currently achieved Q_0.

NEXT STEPS

The temperature reading on the blank-off flange of one of the beam ports increased as the RF power - in CW mode - was increased. CST Microwave Studio was used to evaluate the RF induced heat in the different cavity components during the cryogenic test at 2 K. The parameters used for the simulation are listed in Table 1. All simulations are normalized to 1 Joule stored energy.

The simulation results are shown in Table 2. From where we can see no change needs to be made for the pickup coupler. Nb plated stainless steel flanges provided by CERN will be used to replace the stainless steel flanges for the beam pipe ports, the four small HOM ports will wear Cu disk gaskets. The loss on the Cu probe is comparable to its external Q, being the probe on its nominal position. The loss is mainly on the tip and first 20 mm section of the probe. The reason for the high losses is that the probe is an electric probe being inserted on a high magnetic field region. The Cu probe will be Nb plated for the next test.

Table 1: Parameters for RF Induced Heat Simulation

Material	Conductivity [1/(Ω·m)]	Corresponding surface resistance R_s
Bulk Nb/Nb film	4.0e18	20 nΩ
Stainless steel	2.0e6	28 mΩ
Cu	2.5e9	0.8 mΩ

Table 2: Parameters for RF Induced Heat Simulation

Component		RF induced heat	Q
Nb cavity	20 nΩ R_s	0.576 W	4.34e9
	1 nΩ R_s	0.029 W	8.69e10
Beam pipe flanges (2 in total)	Stainless steel	1.16 W	2.15e9
	Nb-plated	0.83 μW	3.01e15
HOM port flanges (4 in total)	Stainless steel	29.3 mW	8.54e10
	Cu disk gasket	0.84 mW	3.00e12
FPC with stainless steel feedthrough[1]	Cu probe	2.84 W	8.78e8
	Nb-plated probe	10.0 mW	2.516e11
Cu pickup coupler with stainless steel feedthrough[2]		8.7 mW	2.87e11

[1] Probe 0.0 mm away from the cavity inner surface with 3.94e8 Q_{ext}

[2] Probe 20.7 mm away from the cavity inner surface with 1.00e11 Q_{ext}

In preparation for the future cold test, apart from Nb plating some cavity components, further surface treatment was performed at ANL. First, the cavity underwent an ultrasonic cleaning, which improved significantly the brightness of the cavity outer surface. Then the cavity was BCP etched 40 micrometers for 40 minutes with the temperature reading outside the cavity carefully controlled in 10~16°C range. The cavity was then rinsed with distilled water, and ultrasonically degreased with a 2% Liquinox solvent immersing the cavity, followed by another rinsing in a bath of water. Finally the cavity went through HPR with deionized water at a pressure of 1200 psi. The cavity was shipped back to BNL for cryogenic test after the surface treatment.

SUMMARY

A PoP DQWCC was designed and fabricated. After the surface treatment in Niowave and BNL, the cryogenic test was performed in the SVTF at BNL. Cu probe and the large stainless steel flanges will be Nb-plated, and the small stainless steel flanges will be covered by Cu disk gaskets. A second cycle of BCP and HPR were done at ANL. The cavity is ready for the second cryogenic test at BNL.

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