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CYOGENIC TEST OF DOUBLE QUARTER WAVE CRAB CAVITY FOR THE LHC HIGH 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. A vertical cryogenic test has been done at Brookhaven National Lab (BNL). The cavity achieved 4.5 MV deflecting voltage with a quality factor above 3×10^9. We report the test results of this design.

INTRODUCTION

The energy-frontier machine LHC at CERN is designed for high-energy particle physics, with energies up to 7 TeV per nucleon. Instead of upgrading the energies, the High Luminosity upgrade of the LHC (HL-LHC) will use the crab-crossing technique [1-4] to modify the angle at which bunches collide, and hence maximize the LHC's luminosity.

There are three phases for the LHC crab cavity project. The first one aims to validate the cryogenic performance of proof-of-principle (PoP) cavities. They must demonstrate a deflecting voltage of 3.34 MV per cavity. The second phase and the third phase will focus on fully dressed cavities in the Super Proton Synchrotron (SPS) and in the LHC. Eventually four cavities per beam will be needed at each side of the IP, i.e., 32 cavities in total plus spare ones.

The Quarter wave resonators (QWRs) first was proposed as a deflecting/crabbing cavity by Ben-Zvi [5, 6]. This design eventually evolved into a symmetric double quarter wave structure [1]. There is no lower order mode (LOM) or same order mode (SOM) exists in DQWCC, and its crabbing mode is the lowest resonant frequency, f_0. The first higher order mode (HOM) is well separated from the fundamental frequency f_0 by about $f_0/2$ due to the large capacitance. We describe the design, fabrication, and our results from testing the PoP DQWCC, built as part of the HL-LHC upgrade in this paper.

CAVITY DESIGN

The DQWCC shown in Fig. 1 can be considered as two quarter-wave resonators sharing a load capacitor. At the fundamental mode, there is a transverse electric field between capacitor's two plates, offering the crabbing voltage when the beam passes at an appropriate phase. Besides the two beam pipe ports, six extra ports are located on the top and bottom, with two on the top and four on the bottom, as shown in Fig. 1. These ports are designated for a fundamental power coupler (FPC), an RF pickup (PU) probe, and higher order mode couplers.

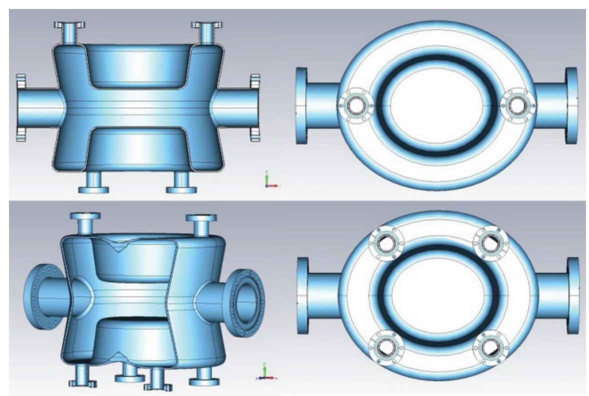

Figure 1: Geometry of the DQWCC. Top-left: Front sectional view; Top-right: Top view; Bottom-left: Front left sectional perspective view; Bottom-right: Bottom view.

Table 1 lists the key RF parameters of the DQWCC using CST Microwave Studio® with more than half a million tetrahedral meshes.

Table 1: Key RF Parameters of the Double Quarter Wave Crab Cavity

Fundamental mode frequency f_0 [MHz]	400
Nearest HOM frequency f_1 [MHz]	579
Deflection voltage V_t [MV]	3.34
R_t/Q (fundamental mode) [Ω]	406
Geometry factor [Ω]	85
Peak surface electric field E_{peak} [MV/m]	35.9
Peak surface magnetic field B_{peak} [mT]	83.9
Residual accelerating voltage V_{acc} [kV]	1.6
Stored energy [J]	10.9

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CAVITY FABRICATION AND MEASUREMENTS

Fabricating and Processing the Cavity

The cavity body was fabricated by Niowave, Inc., and was chemically treated with a 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 of the inner niobium's surface. The cavity was inspected, visually, then checked for leaks, and finally baked for 10 hours at 600°C in a vacuum oven at BNL and was then shipped back to Niowave for another light BCP (removing 30 µm material) and a high-pressure rinse (HPR) with de-ionized ultra-pure water. Then, it was shipped to BNL for assembly and cryogenic testing.

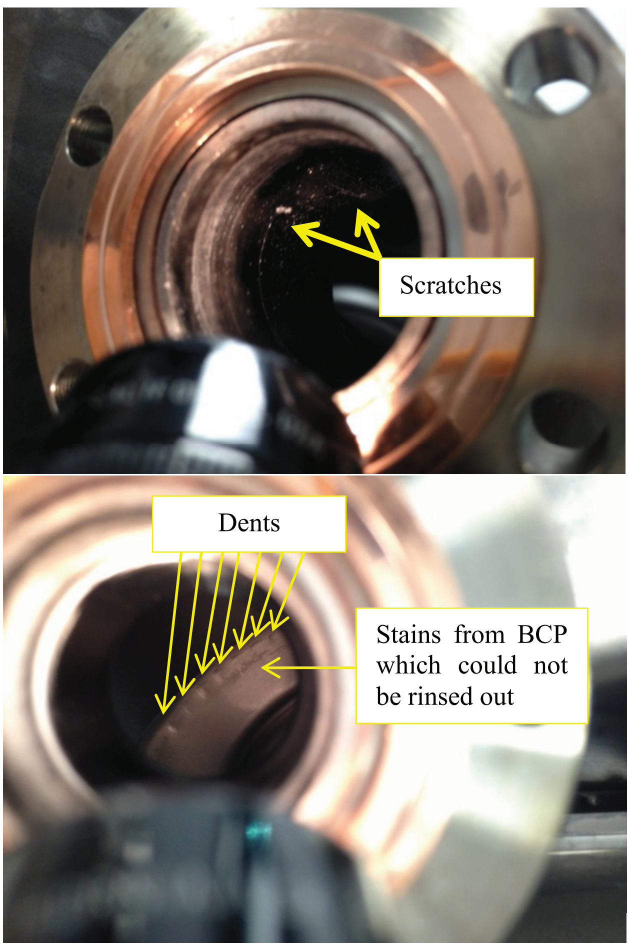

Figure 2: (a) Scratches at the entrance of a beam pipe port; (b) Stains and dents on the cavity interior surface.

After the first cold test, cavity was opened for surface and geometric inspection. Dents, scratches, and stains were found inside the cavity, shown in Fig. 2. We measured the cavity's thickness using an ultrasonic thickness detector; it was 140 µm thicker than expected, indicating that insufficient material was removed during chemical etching. Using a laser tracker to measure the cavity's profile revealed that the top and bottom caps, and two capacitive plates are tilted in the same direction with respect to the center beamline. After that, ANL undertook further surface treatment. First, the cavity underwent an ultrasonic cleaning, and was then etched with BCP to remove a further 40 µm layer, shown in Fig. 3(a). After that, the cavity was rinsed with distilled water, and ultrasonically degreased with a 2% Liquinox solvent; another rinsing in a bath of water followed this. Finally, the cavity went through another HPR with deionized water at a pressure of 1200 psi, shown in Fig. 3(b)&(c). The cavity then was shipped back to BNL for a second cryogenic test after baking for an additional 24 hours at 120°C with the cavity under vacuum.

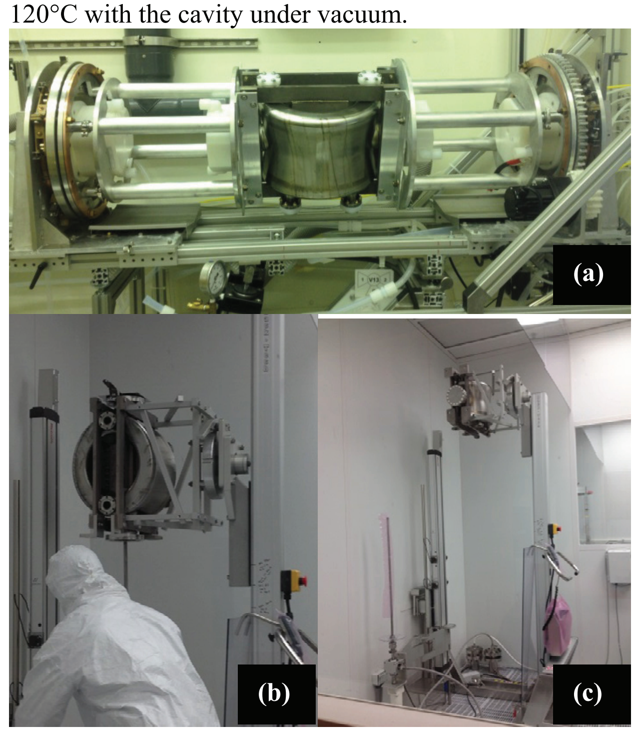

Figure 3: (a) DQWCC on the BCP equipment at ANL; (b) Setup the HPR at ANL; (c) DQWCC after HPR.

Cryogenic Testing and Analysis

The first cryogenic test was carried out in June, 2013. Q_0 was limited to below 3×10^8, even at the low field level, and did not improve after cooling from 4.3 K to 1.9 K. Heating was observed on the beam pipe's flanges in correlation with the decrease in Q_0, which indicated the poor quality of the niobium coating. The cavity reached a maximum deflecting voltage of only 1.34 MV, limited by the RF's power amplifier. No radiation was observed at this field level.

The second cryogenic test was performed in November 2013 after the cavity was treated additionally at ANL as described above. With a 1.9 K bath temperature, as the RF power was increased, the Q_0 started to degrade at 2.0 MV, associated with high radiation due to field emission, reaching its peak of 864 mR/h at 3.0 MV, as shown in Fig. 4. The Q_0 recovered after about 30 minutes of RF conditioning. The radiation level fell below 15 mR/h. The highest voltage reached during the test was 4.6 MV in the CW mode, limited by quench, also is shown in Fig. 4.

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Temperature rise was observed on the flanges of both beam pipes and the pickup port blending area during the test.

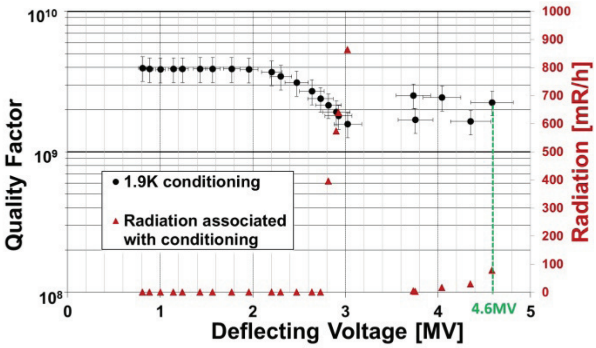

Figure 4: Conditioning of the DQWCC at the helium bath's temperature of 1.9 K. The black dots represent the quality factor and red triangles correspond to the associated radiation level.

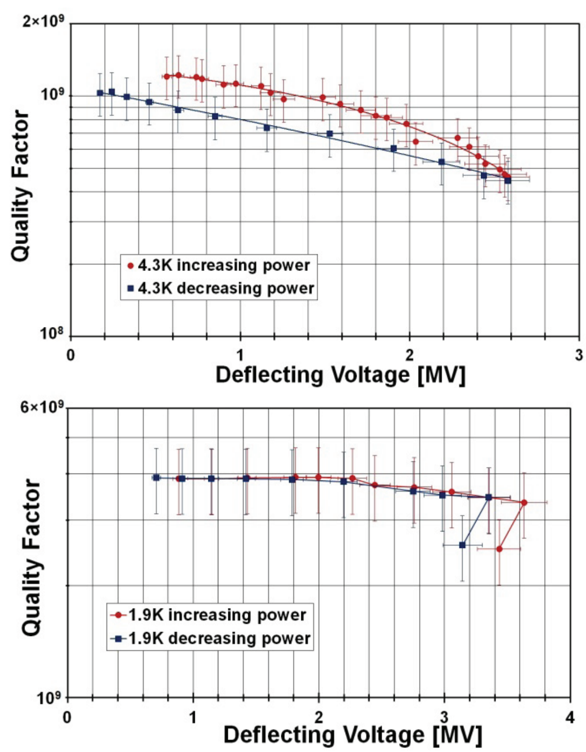

Figure 5: Cavity quality factor at 4.3 K (top), and 1.9 K (bottom) bath temperatures in the CW mode. The red curves were taken with RF power ramping up, and the black curves were taken with its ramping down.

Figure 5 shows the results from measuring the quality factor measurement after conditioning. At a liquid-helium bath temperature of 4.3 K, the measured Q_0 fell from 1.2×10^9 to 4.4×10^8 with the deflecting voltage increasing from 0.1 MV to 2.6 MV. The curve of the measurement of declining power, however, did not follow the measured curve of increasing power due to the residual stored heat from the high power. The measured Q_0 at 1.9 K ranged from 3.0×10^9 to 4.0×10^9. In the CW mode, the temperature of the beam pipe's flanges raised, causing the degradation of Q_0 starting at around 3.3 MV. The plots in Fig. 5 illustrate thermal hysteresis due to the heating of the beam pipe's flanges. The temperature increase also was observed at the pickup port's blending area.

The cavity was further tested in a pulsed mode to reduce the heating on these flanges. The highest voltage reached was 4.5 MV, limited by quench, consistent with the test results in the CW mode at 4.6 MV. The cavity quenches at a peak magnetic field of about 129.3 mT, and a peak electric field of about 49.4 MV/m.

After the cryogenic test, the cavity was opened for higher order modes room temperature measurements at BNL, and sent to ANL for surface treatments. The cavity was then shipped to CERN for further cryogenic tests, preliminary result was presented at [7].

CONCLUSIONS

We proposed using a double quarter wave resonator as a compact crab cavity for the LHC luminosity upgrade. We designed and fabricated a proof-of-principle cavity to validate that a cavity of such a complicated shape can deliver a deflecting voltage over the required 3.34 MV. During BNL's cryogenic tests, the cavity achieved a deflecting voltage of 4.6 MV, with a quality factor higher than 3.0×10^9. Possible reasons for the relatively low quality factor are associated with i) insufficient BCP etching, and ii) the poor quality of the niobium coating on the stainless steel flanges of the beam pipes. The cavity was further treated and was sent to CERN for cryogenic tests.

With the proof-of-principle DQWCC exceeding the design voltage by a satisfactory margin, we are proceeding with designing and fabricating two fully dressed prototype cavities. After verifying the cavities' performance in vertical tests, they will be installed in SPS for testing with the beam as the next step toward implementing the crab-cavity scheme in the HL-LHC.

The DQW design can be applied to other particle accelerators requiring deflecting or crab cavities, in particular to BNL's future electro-hadron collider, eRHIC [8]. In eRHIC, the 5- to 8-cm long ion bunches will collide with electrons at a crossing angle of 4 mrad. This would require a low crabbing frequency f_0 that currently is set at 225 MHz. The DQWCC is well suited for such low frequency application with its reasonable geometrical size [6, 9].

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