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RF PERFORMANCE RESULTS OF RF DOUBLE QUARTER WAVE RESONATORS FOR LHC HIGH LUMINOSITY PROJECT

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Abstract

The LHC High Luminosity (HL-LHC) project includes, among other key items, the installation of superconducting crab cavities in the LHC machine. The Double Quarter Wave (DQW) crab cavity will be utilised to compensate for the effects of the vertical crossing angle. Two bare DQW series cavities were manufactured in Germany by RI Research Instruments and validated successfully at CERN through a cold test at 2 K. Two DQW series cavities were produced in-house at CERN, integrated into a titanium helium tank, and equipped with RF ancillaries. This paper addresses the cavities preparation processes and summarizes the results of cryogenic tests of DQW cavities at CERN.

INTRODUCTION

The HL-LHC project aims to increase the design luminosity by 5-7 times compared to LHC nominal value [1]. This will be achieved in part by using two pairs of RF superconducting crab cavities, both up- and down-stream of the LHC Interaction Points (IPs): 1 (ATLAS) and 5 (CMS), to partially compensate for the geometric reduction in luminosity due to the beam crossing angle at the IPs. The beam crossing angle is necessary to separate bunches immediately before and after the collision point. This leads to a reduction in the geometric overlap of the colliding beams, thereby decreasing the instantaneous luminosity [2]. The crab cavities are designed to impart an appropriate transverse kick to the head and the tail of the bunches to restore the almost head-on collisions at the IP. Due to the difference in the crossing plane at the IPs, two distinct types of crab cavities are required: the Double-Quarter Wave resonator (DQW) at IP5 to provide compensation for the vertical crossing angle and the Radiofrequency Dipole (RFD) crab cavity at IP1 for the horizontal crossing angle. The machine constraints near the IPs limit the cavity transverse dimension therefore the HL-LHC crab cavities are characterized by an unconventional, compact, and complex design. Moreover, they require very precise control of the RF phase so that the rotation of the beam before the collision is precisely cancelled on the other side of the IPs. Each cavity operates at 2 K and is designed to provide a transverse kick voltage of 3.4 MV at 400.79 MHz. They will be assembled in cryomodules, each containing two identical cavities.

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DQW cavities (see Fig. 1) are subject to a complex manufacturing procedure [3], as a consequence of their design, requiring rigorous RF inspections to ensure that the cavities are in the appropriate frequency range at each stage of the production process. In addition, RF surface treatment, cold test preparation, and a contamination-free quality control system ensure that the cavities will meet both performance and frequency specifications when operating in the LHC machine. The production of the DQW cavities follows similar procedures as for the RFD cavities [4].

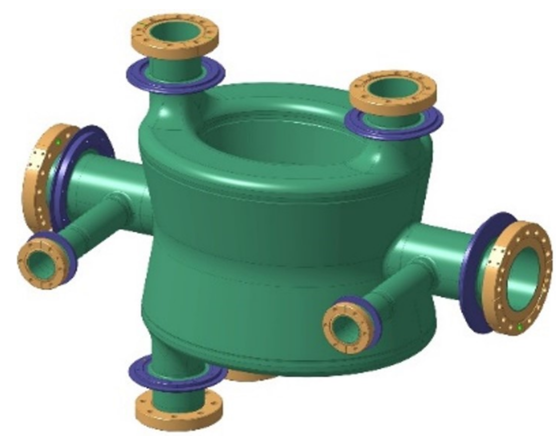

Figure 1: The DQW cavity geometry.

Two DQW series bare cavities were manufactured so far by Research Instruments GmbH (RI) in Germany and tested at 2 K at CERN. The cavities are currently at RI for helium tank assembly. The manufacturing of six additional DQW cavities is ongoing at RI and is expected to be completed by 2024. In addition, two series DQW cavities were produced in-house at CERN, integrated into a titanium helium tank and finally equipped with RF ancillaries. Bare, jacketed and dressed cavity configurations have been validated through cryogenic tests in a vertical cryostat at the CERN SM18 facility. To ensure full control of the process, and thus the comparability of cold test results, the cavities were subjected to the same preparation process. This paper addresses some of the major challenges in preparing, processing and testing the DQW cavities.

FREQUENCY EVOLUTION AND TUNING

During the production of the DQW crab cavities, the fundamental frequency is regularly measured. Furthermore, several tuning stages are integrated into the manufacturing process to ensure precise control of the crabbing frequency with respect to the pre-defined targets.

Table 1 lists the target frequencies for the fundamental mode at various stages. For each step: buffered chemical polishing (BCP), heat treatment (HT), and vertical cold tests (VCT) for bare (BC), jacketed (JC), and dressed cavities (DC), a specific value of the target frequency is given. All values in Table 1 are expected to be met by measurements within a ±0.1 MHz tolerance.

Table 1: Frequency Recipe for the DQW Crabbing Mode

Step	Target (MHz)
Trimming (pre-welding)	401.71
Welding & Alt tuning	400.33
BCP & HT	400.53
BC at VCT (vacuum, 2 K)	401.06
Jacketing (in air, 300 K)	400.08
JC at VCT (vacuum, 2 K)	400.75
After dressing (vac., 300 K)	400.04
DC at VCT (vacuum, 2 K)	400.75
At operation (vac., 2 K)	400.79

Figure 2 shows the measured frequencies at some of the steps following the frequency tuning campaign for the fundamental mode. A DQW-C2-JC cavity during helium tank assembly is presented in Fig. 3.

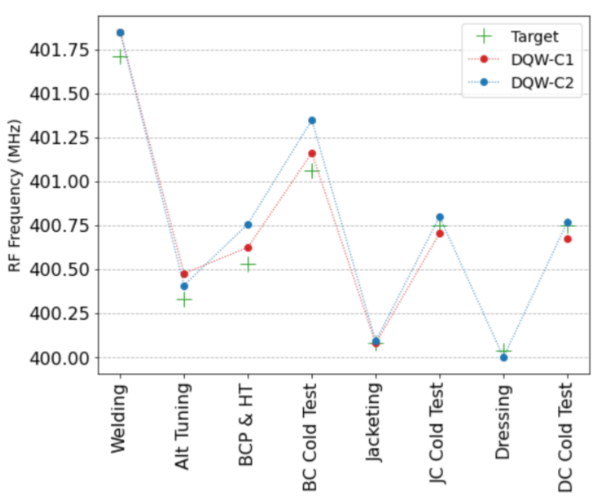

Figure 2: Frequency evolution of DQW cavities produced by CERN for the fundamental mode.

SURFACE PREPARATION AND CLEAN ROOM ASSEMBLY

The surface preparation procedure involves etching the inner RF surface by approximately 200 µm to remove the damaged niobium layer created during the manufacturing process. The cavities are subjected to few cycles of BCP to ensure uniform material removal throughout the complex

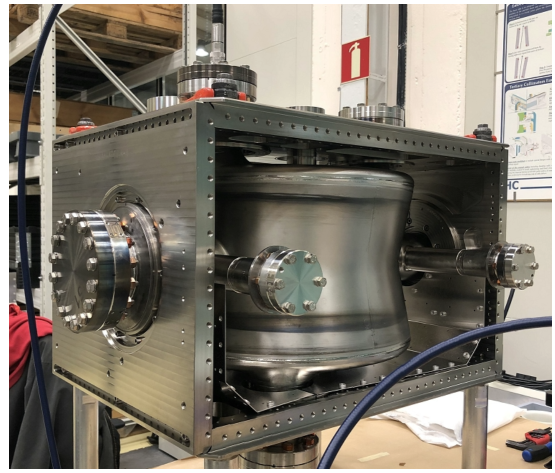

Figure 3: DQW cavity helium tank assembly.

cavity shape. After each iteration, an ultrasound measurement is performed to measure the cavity-wall thickness in several locations around the cavity body. The cavities produced at CERN were treated at CERN's rotational (BCP) facility [5] while the BCP for the RI produced cavities were done at the RI premises on a conventional stand. Following the BCP, the cavities underwent a high-temperature treatment at 650 °C for 24 h in an ultra-high vacuum furnace at RI, for post-purification in order to remove the hydrogen, and then etched again by 30 µm. Subsequently, the crab cavities were rinsed with ultra-pure water at high pressure (40 bar) (HPR) for several hours. The length of the process is determined empirically based on the quality of the outlet water. After the HPR, the cavity dries under the laminar flow in the ISO 2 clean room for at least 24 h. The cavity is assembled with its RF ancillaries and closed with Nb-coated stainless steel (316LN) flanges and OFE RF copper gaskets in the ISO 4 clean room environment to preserve the RF surface cleanliness. Specialized tools and procedures were developed to minimize the risk of deformation caused by the handling of the cavity, and to provide tailored measures to ensure the maximum possible cleanliness when assembling parts in the cavity.

RF TEST PREPARATION

The RF tests of DQW cavities are carried out in vertical orientation at 2 K in one of the cryostats available at the CERN SM18 test facility. The bare cavities are installed into a titanium stiffening frame to constrain the capacitive plates (similar to Helium tank) and prevent plastic deformation during cooling. The cavity is connected to the cryostat pumping line and is actively pumped until 130 K), the vacuum level is continuously monitored. Prior to the RF test, bare and jacketed cavities are baked at low temperature of 120 °C for 48 h.

Cold Test Set Up and Cool Down

The outer surface of the cavity is equipped with contact CERNOX® temperature sensors and three single-axis mag-

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netic flux probes. The cryostats are also equipped with radiation monitors for X-ray measurements and magnetic compensation coils to keep the ambient field around 0.5 µT during the cold test of bare crab cavities. From 300 K to 130 K, the cavity is cooled by means of the thermal shields of the cryostat, this takes ≈ 36 h. The maximum gradient between the hottest and coldest locations across the cavity is ≈10 K. The dewar is then filled with liquid helium and after about 3 h the cavity reaches a temperature of 4.5 K, then the cryostat is pumped to 2 K.

RF TEST RESULTS

A minimum of three RF tests at 2 K were carried out on each cavity to validate their performance at different stages. For the bare cavity configuration, the cavity is equipped with only the pickup and input probes. The jacketed cavity test consists of a bare cavity with a cold magnetic shield and a helium vessel. Finally, the dressed cavity test consists of a jacketed cavity with the final configuration of higher order mode (HOM) dampers and a field antenna.

At each RF cold test, the cavities systematically presented multipacting at low transverse voltages; below 0.5 MV, around 1.9 MV and below 3 MV. These barriers required some RF processing, using pulse and amplitude modulation to ensure stable RF measurement conditions. The multipacting band below 0.5 MV needed longer RF conditioning than the other bands. Furthermore, it was noted that this band could reappear during the same test, which was not observed for other bands. The input probe is inserted into the beam port on the FPC side and provides an external coupling Q_{ext} ≈ $1{\times}10^9$. The pickup probe is installed into the field antenna port for an external coupling Q_{ext} ≈ $1{\times}10^{12}$. For the dressed cavity test, the input probe described above is also used and the field antenna is used as the pickup (Q_{ext} ≈ $2{\times}10^{10}$). The different radiation values measured during the various tests cannot be interpreted comparatively. The tests were carried out in cryostats of differing depths, and thus there is variation in the location of the radiation sensors. Therefore, the radiation value should not be analyzed quantitatively but only qualitatively.

RI Cavities

Two DQW bare cavities manufactured by RI were delivered ready for RF cold test.

Bare Cavity Results During the first cold test of DQW-R1-BC, the onset of the exponential rise of field emission at a voltage below 2 MV (Q_0 = $1{\times}10^9$) was the limiting factor for the maximum field reach. The cavity was then subjected to a second HPR, carried out at CERN, and re-tested. During the subsequent test, the maximum voltage achieved was 2.64 MV. Despite a shift of the radiation onset towards a higher transverse voltage and an increase of Q_0 value at low voltage, there was still a pronounced degradation of Q_0. Therefore, the cavity underwent a second light BCP of 30 µm and HPR. DQW-R1-BC performance was confirmed to be 5.77 MV and Q_0 $=1.6{\times}10^9$ through the third cold test, well beyond the recommended performance specification for bare cavities (>5 MV and P_{diss}≤10 W). The corresponding maximum peak electric and magnetic surface fields were E_{peak} = 64.6 MV/m and B_{peak} = 122.3 mT. The field emission onset was observed above 4 MV. At low fields, the cavity's Q_0 was $9{\times}10^9$ and the estimated residual surface resistance was 10 nΩ. The Lorentz force detuning coefficient (LFD) and pressure sensitivity were measured at −365 Hz/MV^2 (see Fig. 4) and −435.6 Hz/mbar (see Fig. 5), respectively.

During the first test, the DQW-R2-BC cavity reached the maximum transverse voltage equal to 5.1 MV (Q_0 = $4.5{\times}10^9$) and peak fields of E_{peak} = 57 MV/m and B_{peak} = 108.6 mT. From the calculated geometry factor and the measured intrinsic Q_0 which is dependent on temperature for a given low field value, the residual surface resistance was estimated to be 8 nΩ. The LFD coefficient was calculated to be −408.4 Hz/MV^2 (see Fig. 4), and the pressure sensitivity −483.9 Hz/mbar (see Fig. 5), calculated using the measurements of the fundamental frequency during the warm-up. The RF performance test results for DQW-R1-BC and DQW-R2-BC are shown in Fig. 6.

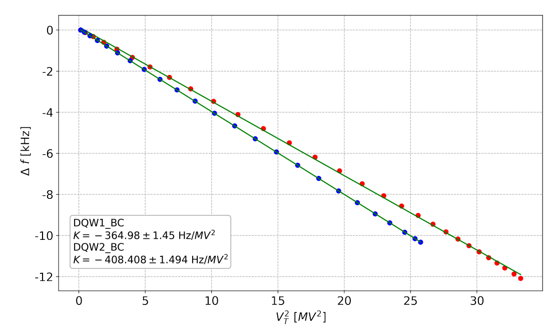

Figure 4: Measured Lorentz Force coefficients for DQW-R1-BC (in red) and DQW-R2-BC (in blue).

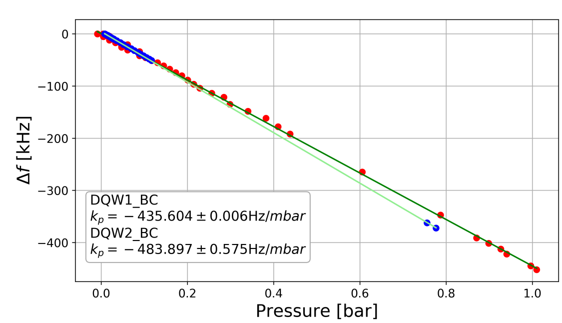

Figure 5: Pressure sensitivity for both bare DQW RI cavities (in red-DQW1 and in blue-DQW2).

DQW-R1-BC and DQW-R2-BC cavities are currently in the process of helium tank assembly at RI which will be

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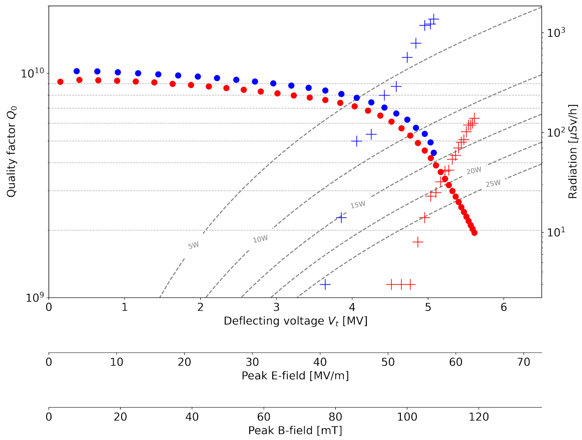

Figure 6: Performance results of DQW-R1-BC (in red) and DQW-R2-BC (in blue).

followed by the RF test at CERN at a nominal temperature of 2 K.

CERN Cavities

Two series DQW cavities manufactured at CERN were tested at 2 K in three configurations as previously mentioned.

Bare Cavity Results DQW-C1-BC cavity did not meet the recommended performance specification as a bare cavity during the first test. The maximum transverse voltage measured was 2 MV and the test was stopped due to the exponential rise of field emissions leading to a degradation of Q_0 and the cavity field. The cavity was then subjected to an additional light BCP of 30 µm, HPR, and re-tested. However, only a marginal improvement in the cavity performance was observed during the subsequent test, the maximum voltage achieved was 2.64 MV. An attempt was made to improve the results using a helium processing technique but was unsuccessful. Hence, an additional light BCP of 30 µm and HPR were carried out for this cavity. Finally, DQW-C1-BC exceeded recommended performance during the third cold test, reaching 5.62 MV (Q_0 = 2×10^9) and peak fields of E_{peak} = 62.8 MV/m and B_{peak} = 119 mT. The field emission onset was observed well above 4 MV. The residual surface resistance of the cavity was estimated to be 8.1 nΩ, the measured LFD coefficient -366.8 Hz/MV^2 (see Fig. 7), and the pressure sensitivity -428.2 Hz/mbar (see Fig. 8). DQW-C2-BC exhibited excellent performance already during the first test, the maximum measured deflecting voltage was 6.17 MV (Q_0 1.6×10^9) and peak fields of E_{peak} = 69 MV/m and B_{peak} = 130.6 mT. No radiation was detected until the high field region (5.9 MV) and remained at a low level, less than 6 µSv/h. The measured mechanical properties of the cavity, the LFD coefficient and the pressure sensitivity were −357.6 Hz/MV^2 (see Fig. 7), −422 Hz/mbar (see Fig. 8), respectively. The residual surface resistance was estimated to be 7.25 nΩ, as shown in Fig. 9.

Performance results of CERN DQW bare cavities manufactured are shown in Fig. 10.

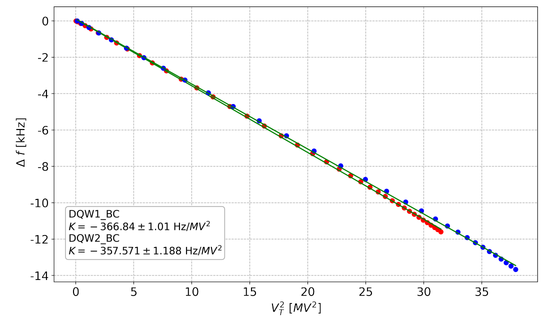

Figure 7: Measured Lorentz Force coefficients for DQW-C1-BC (in red) and DQW-C2-BC (in blue).

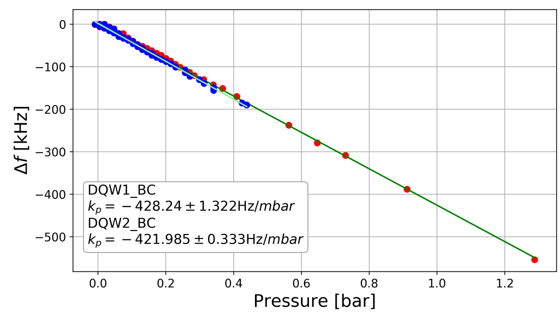

Figure 8: Pressure sensitivity for DQW-C1-BC (in red) and DQW-C2-BC (in blue).

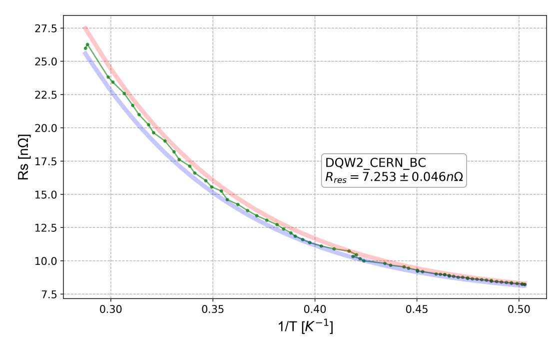

Figure 9: Measured surface resistance of DQW-C2-BC, as a function of temperature.

Jacketed Cavity Results The titanium grade 2 helium vessel is first bolted, and then welded around the bare cavity to form the jacketed cavity. A cold magnetic shield is installed between the cavity and the helium vessel to ensure efficient shielding of the ambient magnetic field. The jacketed cavities underwent a similar preparation procedure as for the bare cavities: HPR, cleanroom assembly of antennas and Nb-coated flanges, followed by a low-temperature bake-out. The input and pickup probes used for the cold tests were the same as for the bare cavities. Due to a passive magnetic shield inside the helium vessel, no active magnetic field compensation was used during the cold test. The cav-

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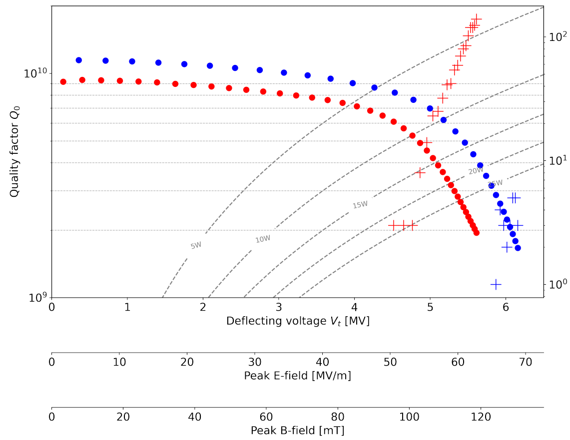

Figure 10: Performance results of DQW-C1-BC (in red) and DQW-C2-BC (in blue) both having been manufactured at CERN.

ities were tested fully submerged in a liquid helium bath. Therefore, all inlets and outlets of the helium vessel were left open to allow sufficient cooling of the cavity body. In order to be conservative, the measurement for jacketed and dressed cavities is purposely discontinued above ≈5 MV.

The results obtained for DQW-C1-JC are in good agreement with the bare cavity results. This cavity reached 5.1 MV , $Q_0 = 5{\times}10^9$, and peak fields of E_{peak} = 57.2 MV/m and B_{peak} = 108.2 mT. The field emission onset was observed above 3.4 MV (see Fig. 11). The residual surface resistance of the cavity was estimated to be 8.2 nΩ. The measured pressure sensitivity was −221.5 Hz/mbar (see Fig. 12). The maximum deflecting voltage reached for DQW-C2-JC was equal to 5 MV($Q_0 = 3.4{\times}10^9$) and peak fields of E_{peak} = 56 MV/m and B_{peak} = 105.8 mT. No field emission was observed until 4 MV as shown in Fig. 11. At low fields, the cavity's Q_0 was $1.2{\times}10^{10}$. The residual surface resistance of DQW2 cavity was estimated to be 7.3 nΩ, see Fig. 13 and pressure sensitivity was −243.7 Hz/MV^2 (see Fig. 12).

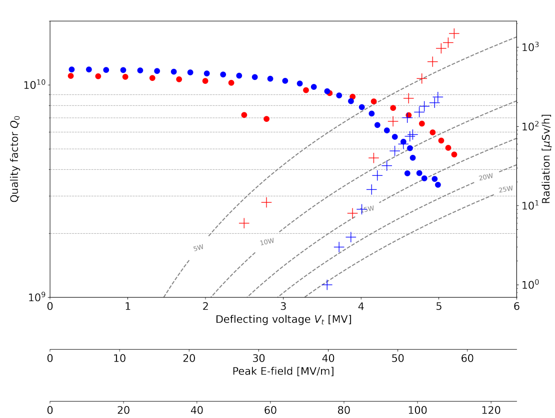

Figure 11: Performance results of the jacketed DQW cavities manufactured at CERN (in red- DQW-C1-JC and in blue- DQW-C2-JC).

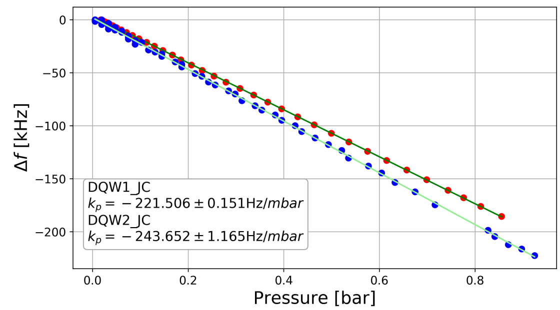

Figure 12: Pressure sensitivity for both jacketed DQW CERN cavities (in red- DQW-C1-JC and in blue- DQW-C2-JC).

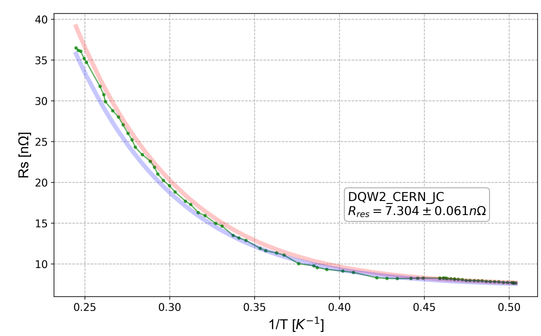

Figure 13: Measured surface resistance of the DQW-C2-JC, as a function of temperature.

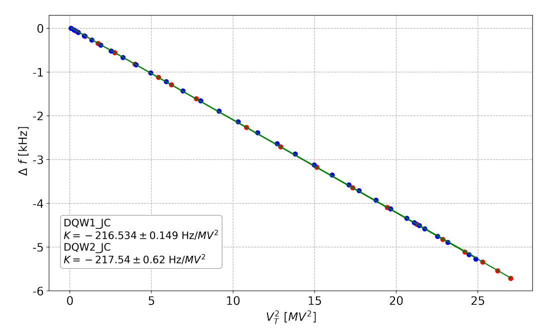

Figure 14: Measured Lorentz Force coefficients for both jacketed DQW cavities (in red- DQW-C1-JC and in blue- DQW-C2-JC).

The measured LFD coefficient for DQW-C1-JC was −216.5 Hz/MV^2 and −217.5 Hz/MV^2 for DQW-C2-JC, as can be seen in Fig. 14.

Dressed Cavity Results In the dressed cavity configuration, the jacketed cavity is equipped with three identical niobium HOM couplers, a High Frequency (HF) HOM coupler, a field antenna [6] and the same input probe as for the

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Table 2: Summary of Cavity Test Performance

Parameters	Spec	DQW1 BC*	DQW2 BC*	DQW1 BC	DQW2 BC	DQW1 JC	DQW2 JC	DQW2 DC
Resonant freq. [MHz]	400.79±0.15	401.22	401.17	401.16	401.35	400.70	400.8	400.78
Max V_t [MV]	≥4.1	5.77	5.1	5.62	6.16	5.1	5	4.05
Q_0 at 4.1 MV	$\geq 3.9\times10^9$	4.7×10^9	7.7×10^9	7×10^9	8.8×10^9	8.4×10^9	7.4×10^9	3×10^9
|LFD coeff.| [Hz/MV^2]	<400	365	408	367	358	217	218	220
|dF/dp| [Hz/mbar]	≤300	436	484	428	422	221	244	238
P_{diss} at 4.1 MV [W]	≤10	8	5	5.5	4.5	4.8	5.4	12.8

*Manufactured by RI.

bare and jacketed cavity tests. The fundamental power coupler (FPC) port is closed with a Nb-coated flange. Prior to the cold test, the cavity is treated with HPR, but the low-temperature bake-out of 120 °C is omitted so as not to stress the RF feedthroughs and coupler components. The dressed cavities are tested fully immersed in liquid helium, as is done for the jacketed cavities.

DQW-C2-DC was tested twice. The first test was unsuccessful as the maximum deflecting voltage was limited to 2.8 MV. The HOM couplers (HOM1, HOM2 and HOM3) were treated with an additional light BCP of 30 µm followed by HPR before the subsequent cold test. During the second cold test, a vacuum leak occurred with the cavity immersed in superfluid helium. Therefore, it was decided to start active vacuum pumping and continue the test after thermal cycling to 20 K. Following this, the cavity achieved 4.07 MV ($Q_0 = 3\times10^9$) with a low field $Q_0 = 1.45\times10^{10}$ and the residual surface resistance was estimated to be 6.5 nΩ. The LFD coefficient was −267 Hz/MV^2 and the pressure sensitivity, measured during the warm-up at a fixed low field, was −229.8 Hz/mbar, in agreement with previous results from the same cavity. The cavity performance was limited by thermal quench, this was ascertained based on the behaviour of the transmitted power signal. To further improve the results during the third test, the RF ancillaries were subjected to another light BCP of 30 µm for HF HOM and 70 µm for the other three HOM couplers. DQW-C2-DC is undergoing preparations for a third cold test.

Prior to the first cold test of the DQW-C1-DC, the HOM couplers were treated with a BCP to ensure uniform treatment of all crab cavity components. An average thickness removal of 30 µm for HF HOM and 100 µm for the other three HOM couplers. The cavity is being prepared for the cold RF test.

Table 2 presents a performance summary for the different VCTs performed to date, including the specification parameters for comparison.

CHALLENGES AND DISCUSSION

The complex geometry of DQW crab cavities combined with strict project requirements call for a high level of quality control and continuous process adjustment throughout the entire cavity production span. Despite these challenges, the knowledge transfer from CERN to industry to facilitate the fabrication of the series HL-LHC crab cavities is progressing well, based on the first results achieved.

Several important lessons were learned during the assembly, preparation, and testing of the DQW cavities. The high field Q-slope and the maximum field reached are almost always dominated by the presence of field emission in the cavities tested at CERN. The recovery of poor RF performance is not always possible by applying an additional HPR alone, as observed with CERN-RFD cavities [4], and requires the use of additional BCP treatment in most cases. During the testing, it was established that a thermal cycle, up to ≈20 K, consistently improved the Q_0 of both the jacketed and dressed cavities by ≈400%, see Fig. 15.

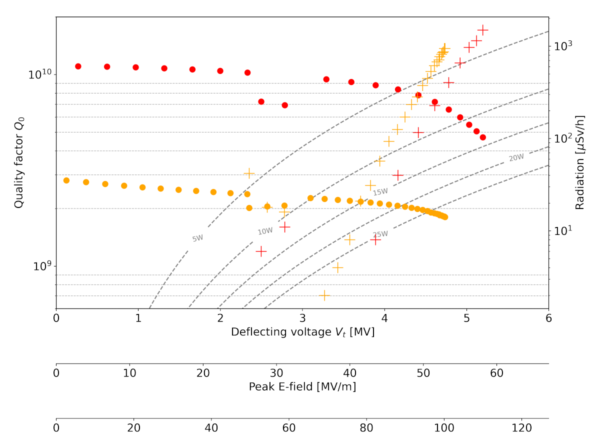

Figure 15: Performance results of DQW-C2-JC cavity before (orange) and after (red) the thermal cycle.

As the complexity of the cavity configuration increases through the stages of the VCTs, we observe a reduction in the maximum field achieved by the cavity. This is particularly pronounced for DQW crab cavities where the HOM couplers are located very close to the high field region of the cavity. Based on the current results there is sufficient margin to reach 3.4 MV after assembling these cavities into the cryomodule. The construction of the first LHC DQW cryomodule, which will house two cavities, is in preparation and should be completed by 2024.

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