CRYOGENIC RF PERFORMANCE OF DOUBLE-QUARTER WAVE CAVITIES EQUIPPED WITH HOM FILTERS

S. Verdú-Andrés†, I. Ben-Zvi1, Q. Wu, B. P. Xiao, BNL, NY 11973, Upton, USA
R. Calaga, O. Capatina, CERN, Geneva 23, CH 1211, Switzerland
N. Huque, A. McEwen, H. Park, T. Powers, JLAB, Newport News, VA 23606, USA
G. Burt2, J. A. Mitchell, Lancaster University, UK
Z. Li, A. Ratti, SLAC, Menlo Park, CA 94025, USA
1also at Stony Brook University, NY 11794, Stony Brook, USA
2also at STFC, Daresbury, UK

Abstract

Crab cavities are one of the several components included in the luminosity upgrade of the Large Hadron Collider (HL-LHC). The cavities have to provide a nominal deflecting kick of 3.4 MV per cavity while the cryogenic load per cavity stays below 5 W. Cryogenic RF tests confirmed the required performances in bare cavities, with several cavities exceeding the required voltage by more than 50%. However, the first tests of a Double-Quarter Wave (DQW) cavity with one out of three Higher-Order Mode (HOM) filters did not reach the required voltage. The present paper describes the studies and tests conducted to understand the limiting factor in the operation of a DQW cavity with HOM filters. The recipe to meet the performance specification and exceed the voltage requirement by more than 35% is discussed.

INTRODUCTION

Crab cavities are one of the several components included in the luminosity upgrade of the Large Hadron Collider (HL-LHC) [1]. The baseline HL-LHC program considers the installation of two different types of compact crab cavities, the Double-Quarter Wave (DQW) [2] and the Radio-Frequency Dipole (RFD) [3]. The DQW cavities will provide a vertical deflecting kick for crab crossing in the interaction region of ATLAS (with vertical crossing) and the RFD cavities will provide the horizontal deflecting kick for crabbing in the interaction region of CMS (with horizontal crossing) [1].

Early cryogenic RF tests of a Proof-of-Principle (PoP) DQW cavity demonstrated the possibility of operating the cavity beyond the nominal deflecting kick (3.4 MV), reaching 4.7 MV before quench. The PoP DQW cavity was equipped with small, 20 mm-diameter ports to facilitate the cleaning of the cavity’s interior and host the test probes [4], but these ports were too small to host the Fundamental Power Coupler (FPC) and the HOM filters required for operation with the LHC beam.

In the following years, the DQW cavity design was revisited to incorporate larger, 62 mm-diameter ports for ad-

Table 1: RF Properties of SPS-Series DQW Cavity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental, crab mode frequency</td>
<td>400 MHz</td>
</tr>
<tr>
<td>First HOM frequency</td>
<td>570 MHz</td>
</tr>
<tr>
<td>Nominal deflecting voltage ($V_{nom}$)</td>
<td>3.4 MV</td>
</tr>
<tr>
<td>Max. peak electric field at $V_{nom}$</td>
<td>37.7 MV/m</td>
</tr>
<tr>
<td>Max. peak magnetic field at $V_{nom}$</td>
<td>72.8 mT</td>
</tr>
<tr>
<td>Geometric shunt impedance ($R_g/Q$)</td>
<td>429 Ohm</td>
</tr>
<tr>
<td>Geometric factor ($G$)</td>
<td>87 Ohm</td>
</tr>
</tbody>
</table>

Four identical SPS-series DQW cavities were fabricated: two prototypes built under the umbrella of the US LHC Accelerator Research Program (LARP) by Niowave Inc. and JLab [5] and two other built and fully dressed into a cryomod-
ule by CERN for beam tests in the Super Proton Synchrotron (SPS) [7]. All the HOM filters were fabricated by CERN.

Vertical Tests (VT) of bare LARP prototypes at 2 K showed excellent performance, exceeding the nominal deflecting voltage (3.4 MV) with a 40% margin (up to 5.9 MV). Large peak fields were reached, equivalent to about 30 MV/m in a TESLA-type cavity. The Field-Emission (FE) onset appeared at 4.1 MV, above the nominal deflecting voltage. Heat load was lower than 5 W at 3.4 MV, as required, with a surface resistance of about 9 nΩ at 2 K [5].

**COLD TESTS OF CAVITY AND FILTER**

First tests of several DQW cavities with one or more HOM filters could not go beyond 3.3 MV [8, 9], significantly lower than for bare cavity tests. There was no sign of significant radiation or multipactoring (closest band was at 2-3 MV).

A performance improvement campaign was initiated in 2017 with the scope of understanding the performance limitations of the DQW cavity and filter assembly and eventually push the operation beyond the 3.4 MV nominal deflecting voltage by a comfortable margin of at least 20% (4.1 MV). The tests were performed in the SRF facility of JLab using the LARP prototypes and one of the CERN HOM filters.

**Effect of Surface Treatment**

All the HOM filters tested up to date had received a minimal surface treatment consisting of flash (20 µm) Buffered-Chemical Polishing (BCP) exclusively in the hook section and manual pressure rinsing. The insufficient surface treatment followed by the HOM filters was the main cause of the early quench, as shown by the higher voltages achieved by subsequent improvement of the filter RF surface between Oct’17 and May’18 (see Table 1). With a complete surface treatment including bulk BCP (only on hook section), high-temperature (600°C) degassing and low-temperature (120°C) baking, the cavity plus filter assembly could reach 4.7 MV with no evidence of High-Field Q-Slope (HFQS).

**Thermal Studies and Quench Location**

The section of the HOM filter emerging out of the DQW cavity is equipped with its own helium jacket and a cooling channel is opened in the main filter body for passive cooling of the hottest region, at the hook [10]. The cooling channel of the HOM filter, with a section of 1 cm², is sized to extract about 1 W heat maximum assuming that the heat flux in 2 K superfluid helium is 1 W/cm².

For nominal operation, cavity and filter will be surrounded by a limited helium given by the enclosed volume between the helium jacket and the niobium. However, for these studies the cavity was without its helium jacket and the top cap of the filter’s helium jacket was not assembled to allow the installation of a couple of CERNOX thermosensors by the cooling channel aperture (see Fig. 2). The thermosensors registered a temperature increase on this location for several tests (May’17, Oct’17, Sep’18), which suggested a thermal runaway initiating in some part of the main filter body.

The thermal behaviour of the HOM filter was studied for different voltage levels with CST [11]. The study assumes the temperature-dependent thermal conductivity and BCS surface resistance for niobium [12], with a residual surface resistance of 5 nΩ. For deflecting voltages above 4.5 MV, the power dissipated in the hook is larger than 1 W (Fig. 3) and the filter becomes thermally unstable, what probably causes the quench at 4.7 MV observed in the May’18 test.

**Retraction of HOM Filter**

To discriminate if the quench was coming from the cavity or the filter, a 20 mm-thick NbTi spacer was inserted between the HOM filter and its cavity port. Retracting the HOM filter by 20 mm reduced the fields in the filter by a factor 2 – being the field in the cavity the limiting factor – and the dissipated heat in the hook by a factor 4. Higher voltages were reached with this configuration – 5.1 MV, as demonstrated in the Sep’17 test – close to the values obtained in the bare test of the DQW2 cavity – 5.3 MV in Sep’17. The Q-switch of 1.7×10¹⁰ appearing in the Sept’18 test at 1.6 MV (see Fig. 4) is attributed to the NbTi spacer becoming normal conductor.

While the retraction of the filter allows reaching higher voltages, it is not considered as a solution because it reduces the coupling to some modes and consequently the damping. The pursue of even higher voltages, if needed, will require a revision of the HOM filter thermal properties.
Table 2: Summary of LARP SPS-Series DQW Prototype Cold Tests

<table>
<thead>
<tr>
<th>Test</th>
<th>VT assembly</th>
<th>Surface preparation Cavity</th>
<th>Surface preparation Filter</th>
<th>(V_{\text{max}}) (MV)</th>
<th>(V_{\text{FE}}) (MV)</th>
<th>(Q^{\text{low}}) (\times 10^{10})</th>
<th>(Q^{\text{nom}}) (\times 10^{10})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb’17</td>
<td>DQW1</td>
<td>Bulk BCP, 600°C, light BCP, HPR, 120°C</td>
<td>N/A</td>
<td>5.9</td>
<td>4.1</td>
<td>1</td>
<td>0.6</td>
</tr>
<tr>
<td>May’17</td>
<td>DQW1, HOM1</td>
<td>None</td>
<td>Flash BCP, rinse</td>
<td>2.8</td>
<td>N/A</td>
<td>1</td>
<td>N/A</td>
</tr>
<tr>
<td>Jun’17</td>
<td>DQW2</td>
<td>Bulk BCP, 600°C, light BCP, HPR, 120°C</td>
<td>N/A</td>
<td>5.3</td>
<td>3.3</td>
<td>0.9</td>
<td>0.5</td>
</tr>
<tr>
<td>Sep’17</td>
<td>DQW2</td>
<td>Light BCP, HPR</td>
<td>N/A</td>
<td>5.3</td>
<td>4.1</td>
<td>1</td>
<td>0.6</td>
</tr>
<tr>
<td>Oct’17</td>
<td>DQW2, HOM1</td>
<td>Light BCP, HPR</td>
<td>Flash BCP, rinse</td>
<td>3.6</td>
<td>N/A</td>
<td>1</td>
<td>0.6</td>
</tr>
<tr>
<td>Jan’18</td>
<td>DOW2, HOM1</td>
<td>None</td>
<td>Bulk BCP, 600°C, light BCP, rinse</td>
<td>3.1</td>
<td>2.6</td>
<td>1</td>
<td>N/A</td>
</tr>
<tr>
<td>May’18</td>
<td>DQW2, HOM1</td>
<td>HPR, 120°C</td>
<td>120°C, rinse</td>
<td>4.7</td>
<td>3.2</td>
<td>1</td>
<td>0.7</td>
</tr>
<tr>
<td>Sep’18</td>
<td>DQW2, HOM1, spacer</td>
<td>HPR, 120°C</td>
<td>None</td>
<td>5.1</td>
<td>2.7</td>
<td>0.9</td>
<td>0.5</td>
</tr>
</tbody>
</table>

CONCLUSIONS AND OVERVIEW

The availability of prototypes proved useful to investigate performance limitations and essay improvements for the LHC DQW cavities. The studies conducted during this campaign found that the HOM filters should receive the same surface treatment as any other SRF cavity and proved the sufficiency of the standard SRF surface treatment (bulk BCP, high-temperature degassing, light BCP, low-temperature bake) for cavity and filter to exceed the required deflecting voltage (4.7 MV before quench) with a comfortable margin (38%). The cryogenic load is lower than 5 W at 3.4 MV with pretty low surface resistance of 10 nΩ at low fields. Large peak fields are reached – 106 mT in cavity at quench field of 4.7 MV – but still not as high as for other BCPed Nb cavities. A quench in the HOM filter, likely of thermal nature, limits Continuous-Wave (CW) operation.

To test the reproducibility of the results here discussed, the performance improvement campaign will continue in 2019 with the test of a different HOM filter prototype of the same design on one of the LARP cavities used in this study. Later, a cavity equipped with more than one HOM filter will be tested to validate operation in a closer configuration to the LHC DQW cavity setup with 3 HOM filters.

ACKNOWLEDGEMENTS

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REFERENCES


