ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPRB098

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

S. Verdú-Andrés†, I. Ben-Zvi[1], 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. Burt[2], J. A. Mitchell, Lancaster University, UK
Z. Li, A. Ratti, SLAC, Menlo Park, CA 94025, USA
[1]also at Stony Brook University, NY 11794, Stony Brook, USA
[2]also 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 adequate fundamental power coupling and HOM damping during operation in LHC and to reduce heat load of its different components [5]. It includes 3 identical HOM filters to provide sufficient damping of the LHC beam induced HOM power [6]. The new cavity-port interface leads to a 11% lower maximum peak surface magnetic field, with the highest field located in the cavity body, not in the filter (see Fig. 1). This new cavity design, named SPS-series DQW, also satisfies the spatial constraints imposed by the second beam pipe of LHC to provide crabbing kick in both vertical and horizontal configurations. Table 1 lists the RF properties of the SPS-series DQW cavity.

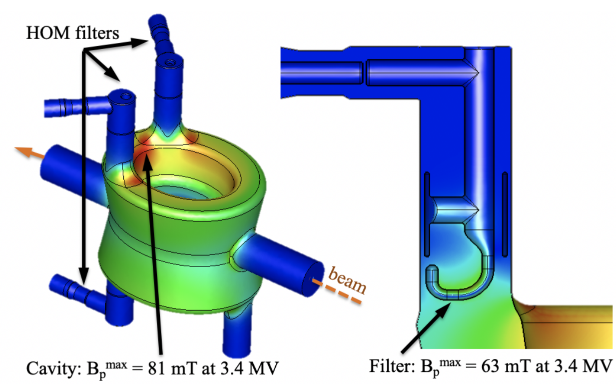

Figure 1: Magnetic field distribution of the fundamental mode using 5-color heatmap scale for: [left] cavity and [right] section view of HOM filter.

Table 1: RF Properties of SPS-Series DQW Cavity

Fundamental, crab mode frequency	400	MHz
First HOM frequency	570	MHz
Nominal deflecting voltage (V_t^{nom})	3.4	MV
Max. peak electric field at V_t^{nom}	37.7	MV/m
Max. peak magnetic field at V_t^{nom}	72.8	mT
Geometric shunt impedance (R_t/Q)	429	Ohm
Geometric factor (G)	87	Ohm

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-

* Work supported by the US DOE through the US LHC Accelerator Research Program (LARP) and through Brookhaven Science Associates LLC under contract No. DE-AC02-98CH10886 and contract No. DE-SC0012704. Also supported by the European Union HL-LHC Project.
† sverdu@bnl.gov

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPRB098

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 multipacting (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 cm^2, is sized to extract about 1 W heat maximum assuming that the heat flux in 2 K superfluid helium is 1 W/cm^2.

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.

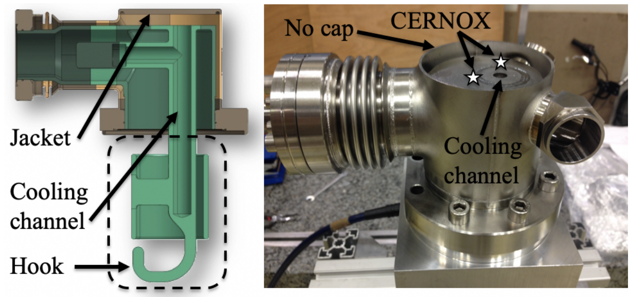

Figure 2: [Left] Section view of HOM filter; the region receiving BCP is framed. [Right] Detail of the jacketed HOM filter used for cold tests without the top cap.

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.

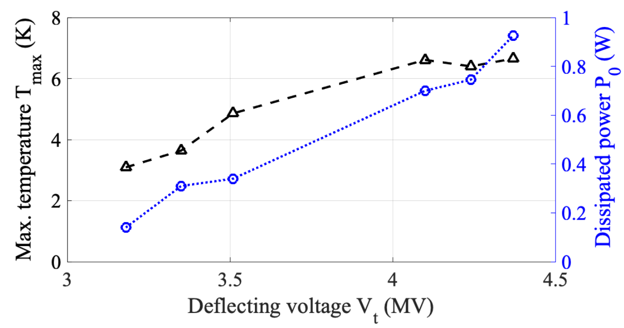

Figure 3: Maximum temperature and power dissipated in HOM filter in function of the deflecting voltage.

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'18 test – close to the values obtained in the bare test of the DQW2 cavity – 5.3 MV in Sep'17. The Q-switch of $1.7{\times}10^{10}$ 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.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPRB098

Table 2: Summary of LARP SPS-Series DQW Prototype Cold Tests

Test	VT assembly	Surface preparation Cavity	Surface preparation Filter	V_t^{max} (MV)	V_t^{FE} (MV)	Q_0^{low} ($\times 10^{10}$)	Q_0^{nom} ($\times 10^{10}$)
Feb'17	DQW1	Bulk BCP, 600°C, light BCP, HPR, 120°C	N/A	5.9	4.1	1	0.6
May'17	DQW1, HOM1	None	Flash BCP, rinse	2.8	N/A	1	N/A
Jun'17	DQW2	Bulk BCP, 600°C, light BCP, HPR, 120°C	N/A	5.3	3.3	0.9	0.5
Sep'17	DQW2	Light BCP, HPR	N/A	5.3	4.1	1	0.6
Oct'17	DQW2, HOM1	Light BCP, HPR	Flash BCP, rinse	3.6	N/A	1	0.6
Jan'18	DOW2, HOM1	None	Bulk BCP, 600°C, light BCP, rinse	3.1	2.6	1	N/A
May'18	DQW2, HOM1	HPR, 120°C	120°C, rinse	4.7	3.2	1	0.7
Sep'18	DQW2, HOM1, spacer	HPR, 120°C	None	5.1	2.7	0.9	0.5

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.

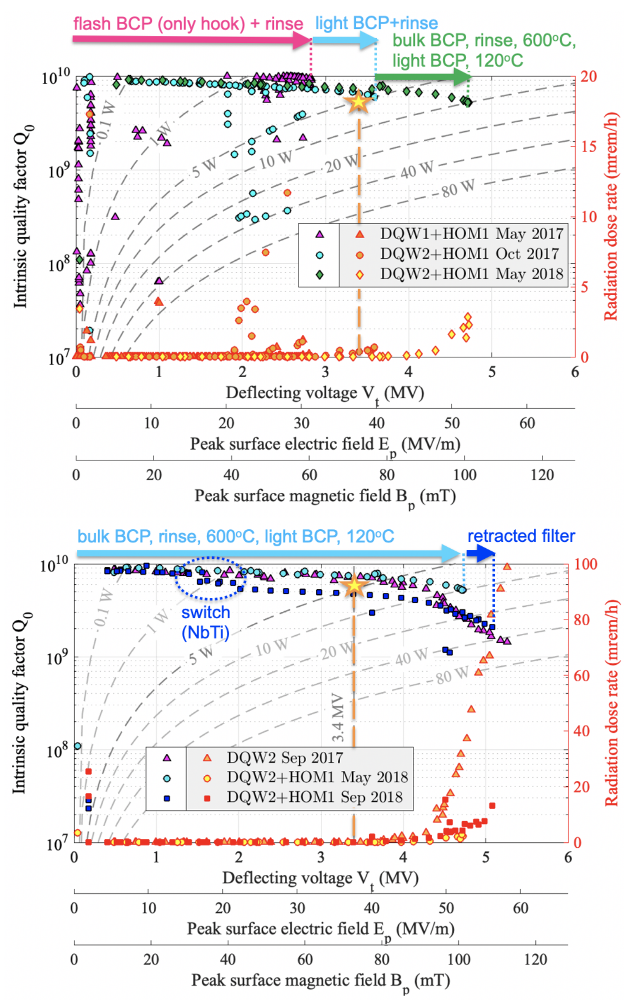

Figure 4: Q_0 vs V_t curves for selected tests. The yellow star marks the target of 5 W heat load maximum at 3.4 MV.

ACKOWLEDGEMENTS

We are grateful to Niowave Inc. for lending us the cavities used for these tests and to the JLab SRF facility team for their support during the tests of the cavities. We also like to thank Haipeng Wang (JLab) for useful discussions.

REFERENCES

[1] R. Calaga, E. Jensen, G. Burt, and A. Ratti, "Crab cavity development", in The high luminosity large hadron collider, O. Brüning and L. Rossi, Ed. Geneva,Switzerland: World Scientific, 2015, vol. 22, pp. 137 – 156. doi:10.1142/9581

[2] R. Calaga, S. Belomestnykh, I. Ben-Zvi, J. Skaritka, Q. Wu, and B. P. Xiao,"A double quarter wave deflecting cavity for the LHC", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper WEPWO047, pp. 2408 – 2410.

[3] S. U. DeSilva and J. R. Delayen, "Cryogenic test of a proof-of-principle superconducting parallel-bar RF-dipole deflecting and crabbing cavity", *Phys. Rev. ST Accel. Beams*, vol. 16, p. 082001, 2013. doi:10.1103/PhysRevSTAB.16.082001

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPRB098

[4] B. P. Xiao *et al.*, "Design, prototyping and testing of a compact superconducting double quarter wave cavity", *Phys. Rev. ST Accel. Beams*, vol. 18, p. 041004, 2015. doi:10.1103/PhysRevSTAB.18.041004

[5] S. Verdú-Andrés *et al.*, "Design and vertical tests of double-quarter wave cavity prototypes for the high luminosity LHC crab cavity system", *Phys. Rev. ST Acc. Beams*, vol. 21, p. 082002, 2018. doi:10.1103/PhysRevAccelBeams.21.082002

[6] B. P. Xiao *et al.*, "Higher order mode filter design for double quarter wave crab cavity for the LHC high luminosity upgrade", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 3627–3629. doi:10.18429/JACoW-IPAC2015-WEPWI059

[7] R. Calaga, O. Capatina, and G. Vandoni, "The SPS tests of the HL-LHC crab cavities", in *Proc. IPAC'18*, Vancouver, BC, Canada, Apr.-May 2018, pp. 846 – 849. doi:10.18429/JACoW-IPAC2018-TUPAF057

[8] S. Verdú-Andrés, "DQW bare + HOM cavity tests & future plans (including cavity/HOM/PU update)", presented at HiLumi'17, Ciemat, Madrid, Spain, Oct. 2017, unpublished. https://indico.cern.ch/event/647714/contributions/2651550/attachments/1557663/2451694/VerduAndres_TestsAndFuturePlans_HiLumiCiemat_14Nov2017_v1.pdf

[9] A. Castilla, "CERN DQW tests summary", presented at HiLumi'17, Ciemat, Madrid, Spain, Oct. 2017, unpublished. https://indico.cern.ch/event/647714/contributions/2651553/attachments/1557480/2496073/cern_dqw_sum_v10.pdf

[10] F. Carra *et al.*, "Assessment of thermal loads in the CERN SPS crab cavities cryomodule", *J. Phys.: Conf. Ser.*, vol. 874, p. 012005, 2018. doi:10.1088/1742-6596/874/1/012005

[11] CST Studio Suite, version 2018, Computer Simulation Technology Program, CST AG, Darmstadt, Germany.

[12] P. Dhakal *et al.*, "Superconducting DC and RF properties of ingot niobium", in *Proc. SRF'11*, Chicago, IL, USA, Jul. 2011, paper THPO057, pp. 856 – 861.