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# DESIGN OF LHC CRAB CAVITIES BASED ON DQW CRYOMODULE TEST EXPERIENCE*

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*Abstract*

A cryomodule with two Double-Quarter Wave (DQW) cavities was designed, built and tested with the SPS beam in 2018. Each cavity was equipped with an RF pickup antenna to monitor field amplitude and phase. The pickup antenna also included a section expressly designed to couple and extract one of the Higher-Order Modes (HOM) at 1.754 GHz. The SPS beam tests evidenced direct coupling of the beam to this pickup antenna, in a similar way that a beam position monitor pickup couples to the passing beam. This undesired coupling had an impact on the RF feedback system responsible to regulate the cavity field and frequency. The present paper proposes a new DQW cavity design with improved antennae which provides adequate fundamental mode extraction while providing a reduction of both direct coupling to the beam and heat dissipation.

## INTRODUCTION

Crab crossing will help increase the luminosity in the High Luminosity Large Hadron Collider (HL-LHC). Crab crossing will be realized for the Interaction Points (IP) of ATLAS (IP 1) and CMS (IP 5) [1], which currently collide bunches in the vertical and horizontal planes, respectively. To implement the crab crossing, the head and tail of a colliding bunch must receive a transverse momentum kick of the same magnitude and opposite direction. The kick, typically in the order of several Mega-Volts (MV) [2], is provided by a type of transverse deflecting Radio-Frequency (RF) cavity called crab cavity. A transverse deflecting cavity delivers a sinusoidal time-varying transverse voltage kick; the crabbing is obtained when the cavity is operated such that the bunch centroid is at the cavity center when the phase is zero.

The HL-LHC crab cavities deliver a nominal deflecting kick of 3.4 MV per cavity at 400 MHz. The baseline HL-LHC crabbing system uses the Double-Quarter Wave (DQW) cavities for crab crossing in the vertical plane. The DQW cavities are compact, superconducting RF cavities which fundamental mode provides a transverse deflecting kick [3].

In LHC, the second beam pipe imposes a tight spacial constraint to the cavity's width. The DQW cavities have a "waist" to accommodate the second beam pipe and the cavity's height is chosen to meet the tight spacial constraint, so the cavities can be used for crab crossing in both the vertical and horizontal planes [4] as illustrated in Fig. 1.

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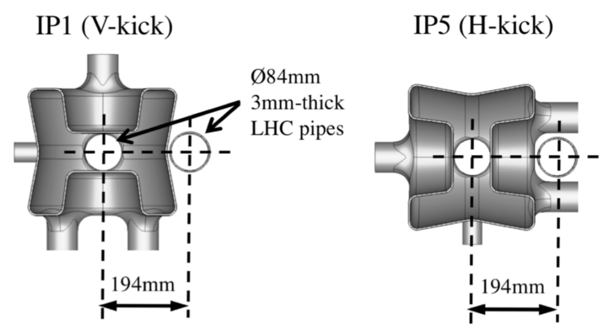


Figure 1: The DQW cavity satisfies the LHC geometric constraints imposed by the second beam pipe to provide a deflecting kick for both vertical and horizontal crossing planes.

All the HL-LHC DQW cavities present an elliptical cross section that enhances the figure of merit of maximum peak surface magnetic field over deflecting voltage ($B_p/V_t$). Below we discuss the design evolution of the different HL-LHC DQW cavity series. The design evolution of the Higher-Order Mode (HOM) filters is discussed elsewhere [5, 6].

## THE DQW PoP-SERIES

A first DQW cavity was designed and fabricated in 2012 to validate the DQW concept. The Proof-of-Principle (DQW PoP-series) cavity has 6 dummy ports. These dummy ports, with a diameter of only 20 mm, are not intended to handle the large power levels required for adequate fundamental power coupling and HOM power extraction during operation with beam, but to ensure cleaning of the high-magnetic field region. The largest peak magnetic field is found in the blending of the dummy ports ($B_p/V_t = 25.1$ mT/MV). The DQW PoP-series cavity is shown in Fig. 2.

The cryogenic RF tests of a DQW PoP-series prototype at BNL demonstrated reliable operation beyond the 3.4 MV required for HL-LHC, reaching 116 mT before quench at 4.6 MV [7].

## THE DQW SPS-SERIES

A cryomodule with two DQW cavities was recently the world's first to crab proton bunches in the Super Proton Synchrotron (SPS) of CERN, an important milestone towards the final installation of crab cavities in the HL-LHC [8, 9]. The cavities utilized for crabbing the bunches of SPS are based on the DQW SPS-series design [4]. Two other cavities of the

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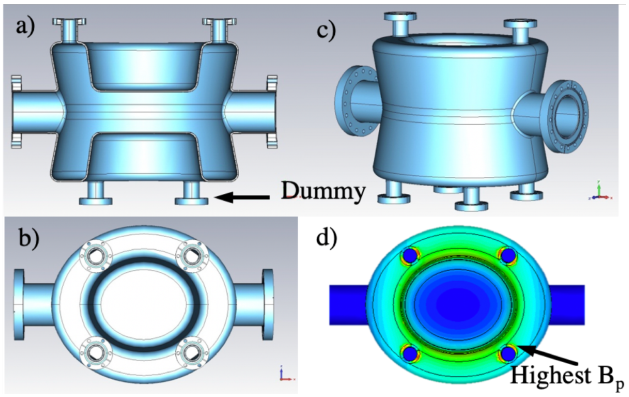


Figure 2: The DQW PoP-series cavity: a) cross-section side view; b) bottom; c) perspective view; d) magnetic field distribution using 5-color heatmap scale.

same design were fabricated in the US. The maximum deflecting voltage reached by the four DQW SPS-series prototypes was in the range of 4.7 – 5.9 MV [4, 10, 11], well above the 3.4 MV nominal deflecting voltage and reaching magnetic field values as high as 125 mT ($B_p/V_t = 21.2$ mT/MV).

A DQW SPS-series cavity has 4 large ports, one for the Fundamental Power Coupler (FPC) and three for the HOM dampers, as displayed in Fig. 3. The SPS-series has larger ports (62 mm-diameter) for adequate power handling. The port-cavity interface is optimized to reduce the $B_p/V_t$ with respect to the PoP-series. To enable a smooth interface, the elliptical racetrack of the PoP-series is modified for the SPS-series to have a constant width. The maximum peak surface fields in a DQW SPS-series cavity are located in between the two HOM ports, as shown in Fig. 3.

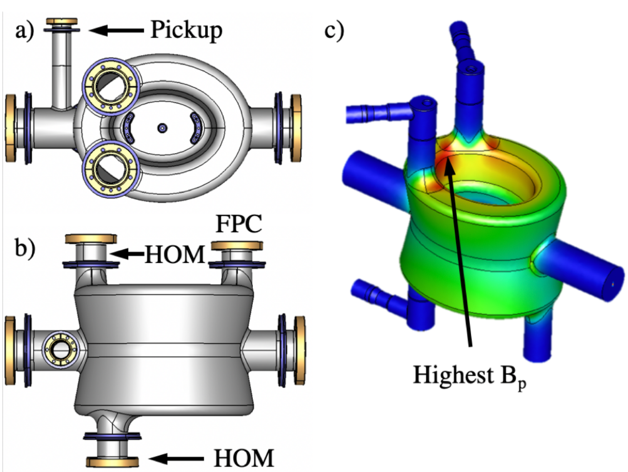


Figure 3: The DQW SPS-series cavity: a) bottom view; b) side view; c) magnetic field distribution in 5-color heatmap (shows cavity and HOM filters).

The cavity also has a small port opened in one of the beam pipes. This small port hosts a dual-function antenna, as shown in Fig. 4. The hook section couples to the fundamental mode to extract sufficient power for monitoring of the cavity's field and control purposes. The T-section couples electrically to the 1.754 GHz mode. Fig. 5 shows the electric field distribution around the pickup antenna for modes at 400 MHz and 1.754 GHz. The 1.754 GHz mode does not couple well to the HOM dampers located in the main cavity body, so the DQW SPS-series relies on its pickup antenna to extract most of the 1.745 GHz power [12].

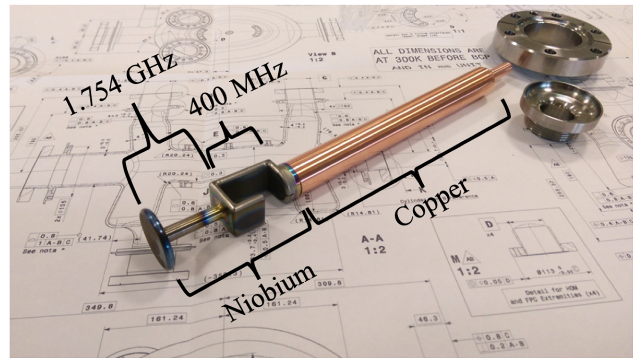


Figure 4: Parts of the DQW SPS-series pickup.

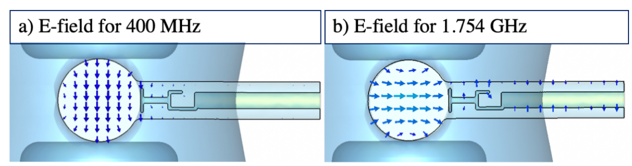


Figure 5: Electric field distribution around the DQW SPS-series pickup for modes at 400 MHz and 1.754 GHz.

## *Direct Coupling Between Beam and Pickup*

The signal extracted through the pickup port during the SPS beam tests showed a low frequency component comparable to the SPS revolution frequency of 43.45 kHz. This puts in evidence the direct coupling between beam and pickup. Fig. 6 displays the signal readout from the pickup port during operation with 4 batches of 36 bunches each. The beam signal adds up to the cavity signal used to monitor and control the cavity field. This is an undesired situation that may jeopardize the adequate control of the cavity.

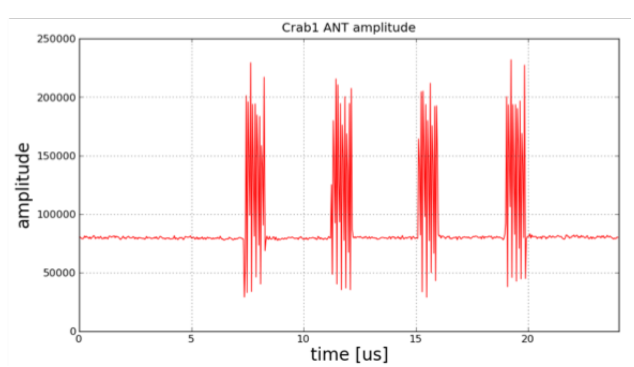


Figure 6: Signal at pickup port in a DQW SPS-series cavity during SPS operation with 4 batches of 36 bunches each.

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CST simulations [13] revealed the T-section to be responsible for direct coupling. Fig. 7 displays the calculated voltage signal at the pickup port output due to the passage of a single bunch ($\sigma_z$ = 30 mm, $Q_b$ = 1 nC) through the DQW cavity for the SPS-series pickup with and without the T-section. Removing the T-section reduces the direct coupling between pickup and beam by almost an order of magnitude; it also reduces the coupling to the fundamental mode.

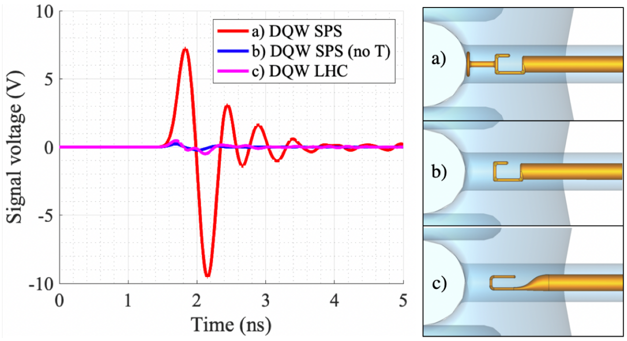


Figure 7: Calculated voltage signal at pickup port of DQW cavity due to the passage of a single bunch for three different pickup designs: a) SPS-series, b) SPS-series without T-section, and c) LHC-series.

The pickup design of the Radio-Frequency Dipole (RFD) cavity [14], to be used in the HL-LHC for crabbing in the horizontal crabbing plane, raised similar concerns [15]. The design of the RFD cavity has been modified consequently to reduce the direct beam coupling [16].

## THE DQW LHC-SERIES

The cavity body remains the same as for the DQW SPS-series. Modifications exclusively affect some cavity ports and antennae.

### *Revisited Pickup Antenna*

With the scope of reducing the direct coupling to the beam, the dual-function pickup antenna of the DQW SPS-series is discontinued. Instead, the DQW LHC-series now features two small ports, one opened on each beam pipe. One of the small ports is equipped with a hook antenna to couple and extract sufficient fundamental mode power ($Q_e = 2.8 \times 10^{10}$; $P_e$ = 1.2 W at 3.4 MV) for monitoring and control purposes. The new antenna shows reduced direct coupling to the beam, as shown in Fig. 7.c. First RF-thermal studies of the new antenna find a maximum temperature increase of 0.12 K for an antenna made of copper ($Q_0 = 1.3 \times 10^{12}$; $P_0$ = 0.021 W at 3.4 MV). The calculations assume conservative material properties: an RF surface resistance of 1 mΩ – given by the anomalous skin effect plus 30% extra to account for surface roughness – for copper exposed to 400 MHz electromagnetic fields and thermal conductivity $K$ of 296 W/K/m. The other small port will host an antenna to couple and damp the 1.754 GHz. The realization of this design finds no issues from the integration point of view, as can be seen in Fig. 8. The dual-function pickup antenna involved a complicated manipulation of the extracted signal, to decouple the 400 MHz signal (to be used by LLRF for control purposes) from the 1.754 GHz (to be damped in a load). Having now both functions separated simplifies the signal processing.

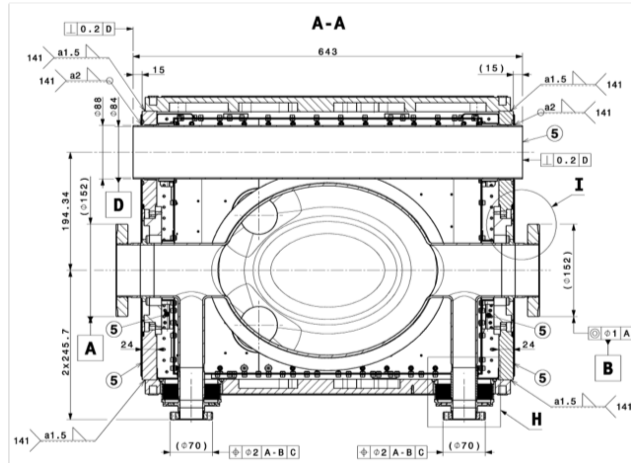


Figure 8: Top view cross-section of DQW LHC-series cavity equipped with two horizontal tubes into its helium vessel.

### *Port Length*

For validation RF tests of bare and dressed crab cavities at cryogenic temperatures, the DQW cavity ports use RF-seal copper gaskets and Nb-coated stainless-steel flanges. In this manner, the heat load contributed by the port joints is less than 1% of the total assembly loss.

One of the beam ports of the DQW SPS-series is shorter by 40 mm with respect to the other. For the DQW LHC-series, the short beam port will made as long as the other beam port (see Fig. 8). The losses in the port will drop by two orders of magnitude, making it possible to use a non-coated stainless-steel flange for that port as losses will be less than 1 mW at 3.4 MV deflecting voltage.

## CONCLUSIONS

The DQW LHC-series design incorporates minor changes with respect to the DQW SPS-series cavities tested with beam in SPS. The changes do not involve a modification of the main cavity body, where the maximum peak surface fields are located; the changes affect the cavity's ports and antennae. No integration issues are found that prevent the changes from being implemented. The two beam pipes of the DQW LHC-series have the same length. This choice allows reducing the heat load in the port that was elongated.

The DQW LHC-series incorporates two small ports, each opened on one of the beam pipes. The first small port hosts a pickup antenna designed to extract 1 W of fundamental mode for monitoring and control purposes. A first design of the new pickup antenna provided adequate external Q while presenting a reduced beam direct coupling and a reduced heat dissipation that allows making it out of copper. The

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second port is equipped with an antenna meant to couple to and extract the 1.754 GHz mode, which eventually can be used as a backup pickup. Further work on the pickup antenna will study thermal properties and transportation, which requires considering the RF feedthrough design [11, 17] and temperature-dependent material properties [18].

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