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HL-LHC CRAB CAVITY HOM COUPLERS: CHALLENGES AND RESULTS*

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Abstract

To compensate for the detrimental effect of the crossing angle on luminosity production in the High Luminosity Large Hadron Collider's (HL-LHC) interaction regions, superconducting crab cavities (vertical and horizontal) will be installed at the two interaction regions of the ATLAS and CMS experiments. Both cavity designs use multiple Higher Order Mode (HOM) couplers to reduce beam instabilities and heat loads caused by the very high proton current in the HL-LHC. The conceptual RF designs of the HOM couplers are firstly presented, evaluating HOM damping requirements, fundamental mode rejection and dynamic heat load constraints. A special focus is given to the coupler's characteristic impedance (Z_0), to improve the robustness during transport and operation. Following this, RF measurements of the HOM couplers before installation and when installed on the superconducting cavities are detailed, analysing deviations from the simulated case.

INTRODUCTION

The 'dressed' Double Quarter Wave (DQW) [1,2] and Radio Frequency Dipole (RFD) [3,4] crab cavities are shown in Fig. 1, highlighting the Higher Order Mode (HOM) couplers used in each case.

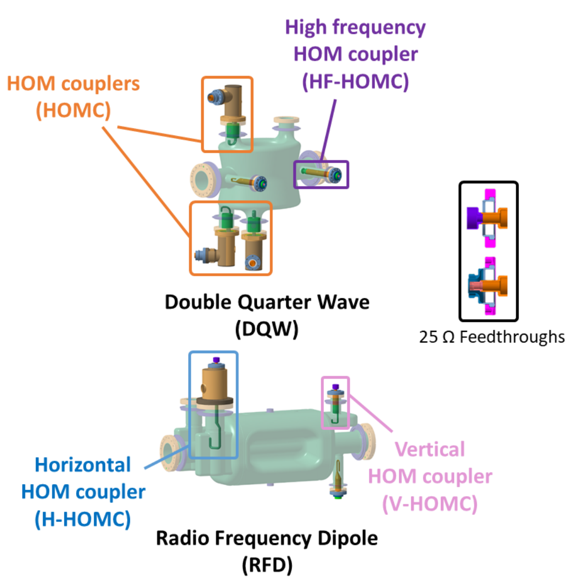

Figure 1: Double Quarter Wave (DQW) and Radio Frequency Dipole (RFD) 'dressed' crab cavities, highlighting the HOM couplers and feedthroughs.

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The DQW cavity uses three on-cell, coaxial, superconducting HOM couplers [2] to damp the HOMs, whist providing a stop-band at the cavity's fundamental mode frequency of 400 MHz. In addition to the three on-cell couplers, a beampipe coupler is used to damp two horizontally polarised transverse modes, for which there is a field node at the position of the three other HOM couplers.

The RFD crab cavity uses a Vertical and Horizontal HOM Coupler (V-HOMC and H-HOMC) [5] to damp high impedance transverse HOMs in the respective planes. The H-HOMC is also used to damp modes with a large longitudinal impedance. In order to minimise fundamental mode leakage, the two couplers are mounted on waveguide 'stubs' with cut-off frequencies above 400 MHz. An additional band-stop ladder filter is incorporated into the H-HOMC's geometry to provide further rejection.

TRANSPORT CONSIDERATIONS AND CHANGING Z_0 FROM 50 TO 25 Ω

Both cavity designs, ancillaries and RF feedthroughs will be manufactured and assembled in several locations across Europe, the United States and Canada. During the prototyping phase, the RF feedthroughs (Fig. 1) were identified as a potential risk in the final cryomodule transport to CERN. With a characteristic impedance of 50 Ω, the inner conductor at the Alumina (Al_2O_3) [6] window has a diameter of only 3 mm. The forces associated with air, sea and road transport [7] impose stresses which put the feedthroughs at risk of deformation and fracture - resulting in an unusable cryomodule.

To improve the robustness of the feedthroughs, the characteristic impedance of the HOM couplers was changed from 50 to 25 Ω, in order to increase the inner conductor diameter at the window to 14 mm (when optimised for the full bandwidth). Simulations showed that changing the CERN feedthrough design to the new characteristic impedance increased the ultimate tensile stress by a factor of 4. To test the hypothosis, feedthroughs with inner diameters of 6 and 14 mm were manufactured (3 mm, i.e. 50 ohms, was simply too small to manufacture). Physical drop tests of HOM coupler assemblies showed that the feedthroughs with the larger diameter could sustain a drop of at least 2 times that of the 6 mm versions [8], validating the principle.

SIMULATIONS

The simulated impedance spectra for the two cavities, with HOM couplers adapted and tuned for the new characteristic impedance, are shown in Fig. 2. The imposed limits were 200 kΩ and 1 MΩ/m for the longitudinal and transverse modes respectively. In addition to the improved struc-

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tural rigidity of the feedthroughs, both cavity impedance spectra are within the design specifications and, in the case of the DQW, slightly improved with respect to several low frequency HOMs of concern (primarily the 580 MHz mode) [2].

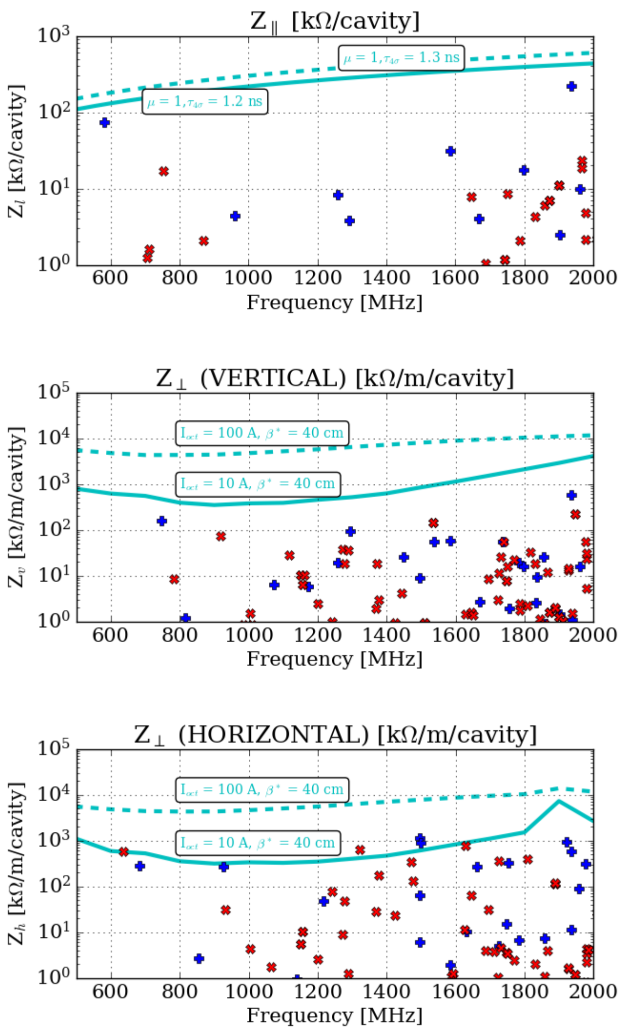

Figure 2: HOM impedances for the DQW (blue '+') and RFD (red 'x') crab cavities dressed with 25 Ω ancillaries.

Notably, each cavity has a 'high power' mode due to its longitudinal impedance and close proximity to a bunch spacing harmonic of an HL-LHC type beam (t_{bb} = 25 ns) [2]. The damping of these modes is sufficient to ensure a maximum forseen HOM power < 1 kW. Furthermore, the power handling of a 25 Ω coaxial line is empirically > 10 % larger than that of a 50 Ω coaxial line [9].

MEASUREMENTS AND QUALIFICATIONS

Thus far in the project, one test DQW cryomodule has been completed and was successfully tested with beam in 2018 [10] in the SPS. The ancillaries for this prototype used a characteristic impedance of 50 Ω. Currently, the collaboration is working towards an RFD cryomodule, where the two cavities will be dressed with 25 Ω ancillaries. The proceeding results will detail the measurements and qualifications for this system, presenting the first validations with the new characteristic impedance.

For qualification measurements, the 25 Ω characteristic impedance had to be transformed to that of standard RF measurement equipment (i.e. Z_0 = 50 or 75 Ω). To achieve the transformation, broadband impedance transformers were designed for the two HOM couplers.

The transformers are shown in Fig. 3 and were qualified by measuring two connected 'back-to-back', ensuring that the transmission was within the simulated design. The simulations of the broadband transformer qualifications predicted S_{21} > -0.5 dB over the entire frequency range. The measurements deviated from this prediction by 0.25 dB at two high frequencies (1.6 and 1.8 GHz). However, since the minimum S_{21} was -0.75 dB, the single adapters were qualified as having S_{21} < -0.5 dB over the entire range.

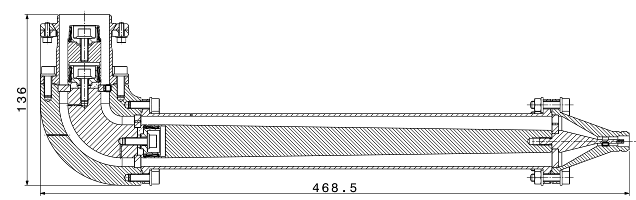

Figure 3: Broadband impedance transformer (Z_0 = 25 to Z_0 = 50).

Pre-installation Test-box Measurements

HOM coupler qualifications on a test-box allow prediction of the damping before cavity installation and the ability to strategically assign the most appropriate coupler to a given cavity [2]. For the H-HOMC, a test box was developed with the US-AUP collaboration to characterise the transmission response. A 'mask' was developed to qualify the couplers, ensuring they would provide sufficient rejection of the fundamental mode and a large enough transmission at the HOM frequencies, allowing the cavity HOMs to be damped sufficiently. The test box layout and measurement results of the first 3 H-HOMCs manufactured at CERN are shown in Fig. 4.

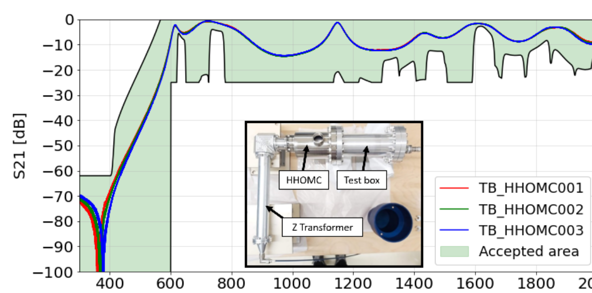

Figure 4: H-HOMC testbox and qualification measurements.

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Each H-HOMC measurement fit within the mask, qualifying the couplers and showing that the tolerances applied from the simulation studies were sufficient. The spread of the measured stop-band frequencies was 20 MHz. Notably, the deviation of the high frequency response between the three couplers was so low that it was not possible to strategically assign a given coupler to a specific cavity for HOM damping; the small 'spread' gives a strong indication that the manufacturing processes used are reproducible.

RFD Vertical Tests

Following the test box qualifications, the ancillaries and impedance transformers were installed and tested on the cavity at the operational temperature of 2 K. Using S_{21} measurements between the ancillaries, the frequency and quality factor of each mode was measured and compared to the simulated value. The measurements are shown in Fig. 5.

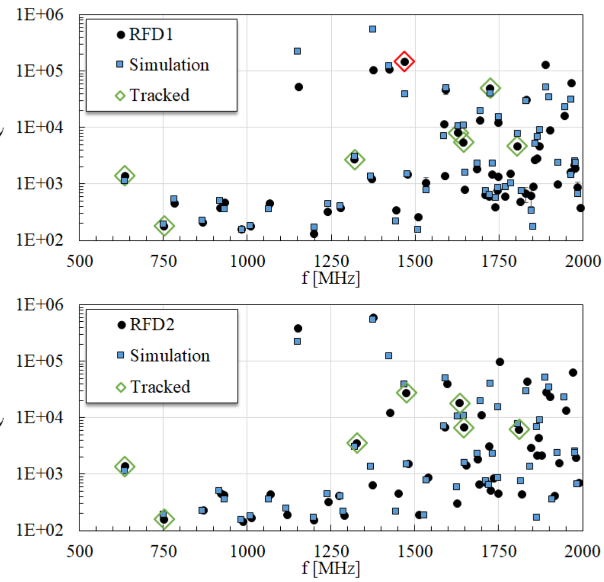

Figure 5: Measured and simulated HOM frequencies and quality factors for the two prototype dressed RFD crab cavities.

'Detrimental modes', i.e. HOMs with high impedance or high power, are highlighted in the plot. Generally, the simulated characteristics align well with the measurements for both cavities. For RFD1, there is one detrimental mode at 1470 MHz that is measured with a quality factor 3.8 times larger than the simulated value. This mode will be studied in the cryomodule tests and during tests with SPS beam. The deviation of frequency and quality factor of each mode was calculated and is detailed in Table 1, alongside the values for the DQW crab cavity [2].

These values quantify HOM deviation from the simulated case for the HL-LHC crab cavities, allowing a stochastic analysis of potential beam-cavity interactions. As the crab cavities are not manufactured using the same methods as those for typical accelerating cavities, the analysis provides an insight into the HOM characteristic deviation for similar 'axially asymmetric' cavities planned for future machines.

Table 1: Percentage Deviation of the Measured HOM Characteristcis from the Simulated Case

Cavity	Δf	ΔQ_e
SPS DQW 1	-0.29 ± 0.14 %	3.2 ± 57.0 %
SPS DQW 2	-0.44 ± 0.23 %	18.8 ± 51.1 %
SPS RFD 1	-0.12 ± 0.12 %	17.4 ± 34.4 %
SPS RFD 2	-0.03 ± 0.07 %	18.9 ± 49.8 %

In addition to the HOM characteristic measurements, operational thresholds were imposed on the fundamental mode leakage and characteristics of the RFD's 750 MHz HOM. The acceptance criteria and results for the two cavities are detailed in Table 2. Both cavity/ancillary systems met the acceptance criteria and were validated for 'cryostating' in the UK.

Table 2: RFD HOM Coupler Acceptance Tests

Acceptance Criteria	RFD1	RFD2
Fundamental mode		
$Q_{e(f_0)} > 3.0{\times}10^9$	$5.0{\times}10^{10}$	$> 9{\times}10^9$
750 MHz HOM		
728 < f [MHz] < 754	752.40	752.34
150 < Q_e < 500	181	158

CONCLUSION

For improved robustness, the characteristic impedance of the crab cavity HOM couplers was changed from 50 to 25 Ω.

Using impedance transformers, the H-HOMC couplers for the RFD were qualified on a 'test-box'. The two RFD ancillary sets were then installed onto the cavities and tested at 2 K. Their performance was assessed by comparing HOM parameters with simulations, evaluating them against several acceptance criteria and measuring the fundamental mode leakage. The HOM parameter measurements provided a first look into the deviation of manufactured crab cavity systems from that of simulations.

The qualified dressed cavities confirm the feasibility of using the 25 Ω couplers.

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