SIMULATION AND MEASUREMENTS OF CRAB CAVITY HOMS AND HOM COUPLERS FOR HL-LHC*

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Abstract

Two Superconducting Radio-Frequency (SRF) crab cavities are foreseen for the High Luminosity LHC (HL-LHC) upgrade. Preliminary beam tests of the Double Quarter Wave (DQW) crab cavity will take place in the Super Proton Synchrotron (SPS) in 2018. For damping of the cavity's Higher Order Modes (HOMs) the DQW has three identical on-cell, superconducting HOM couplers. The couplers are actively cooled by liquid heluim. In this paper, electromagnetic simulations of the HOMs and HOM couplers are presented. A novel approach to pre-installation spectral analysis of the HOM couplers is then presented, detailing both simulated and measured data. Measurements of the cavity HOMs at warm and in Vertical Test Facilities (VTFs) at both JLAB and CERN are detailed, comparing the measured characteristics of each mode to that of the simulated data-sets. Finally, the measured cavity data is compared with the test box measurements to see by what extent any reduction in damping can be predicted.

INTRODUCTION

To damp the HOMs in the DQW crab cavity, the transmission response of the three identical HOM couplers was deigned to provide high transmission at the frequencies of high impedance modes, whilst rejecting the fundamental mode at ~ 400 MHz. The high transmission peaks are notated as the 'filter interaction regions' and the rejection of the fundamental mode is achieved with a band-stop response at this frequency.

with a band-stop response centred around this frequency. The HOM coupler designed for the SPS DQW crab cavity [1] is shown in Fig. 1 and it's S_{21} response is plotted in Fig. 2.

HOM COUPLER TEST BOXES

Complex HOM coupler geometries could result in a deviation from RF performance criteria due to inaccuracies in machining processes. From this, a motivation for test-stands capable of accurately defining the coupler's spectral response produced two 'test-boxes' [2]. The manufactured test-boxes can be seen in Fig. 3.

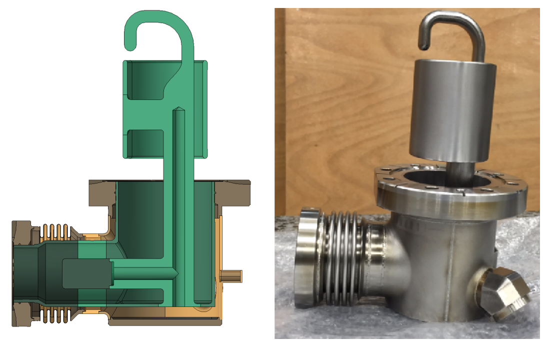

Figure 1: CAD model (left) and photograph (right) of the HOM coupler for the SPS DQW crab cavity.

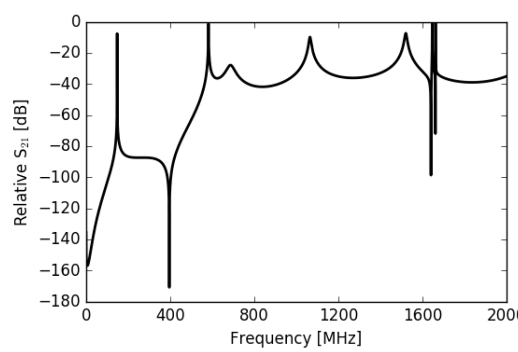

Figure 2: Transmission characteristics for the SPS HOM coupler. Relative amplitude is used as a waveguide port is located on open vacuum.

Although the test boxes were designed to give an accurate representation of the coupler's spectral response, minor differences between the test-box and coupler response were still present. This difference was optimised to best represent

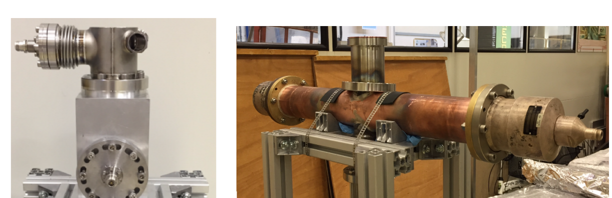

Figure 3: Test box designs for the DQW crab cavity HOM couplers. The designs are denoted the L-bend transmission (left) and coaxial chamber (right) test-boxes.

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the stop-band frequency without perturbing the higher frequency sections to significantly. The simulated difference of the HOM coupler at 2 K and the response of the test box at 300 K was hence logged in the frequency domain. This was to allow post-measurement scaling to analyse where the position of the stop-band and interaction regions are located in operation.

Test Box Measurements

Inadequate flanges on the coaxial chamber meant it was not deemed as safe to use with the DQW HOM couplers. For measurements with the L-bend transmission test-box, both measurements of the full spectral response and of the stop-band were taken for each coupler. The couplers were each measured on side A and most checked on side B. The probes and port nomenclature are shown in the annotated vacuum model, Fig. 4. All transmission measurements taken were done so using the two identical ‘wall-connection’ pick-up probes (X and Y). For all measurements detailed in this paper, only one coupler was fixed onto the test-box and the other port blanked with a metallic plate.

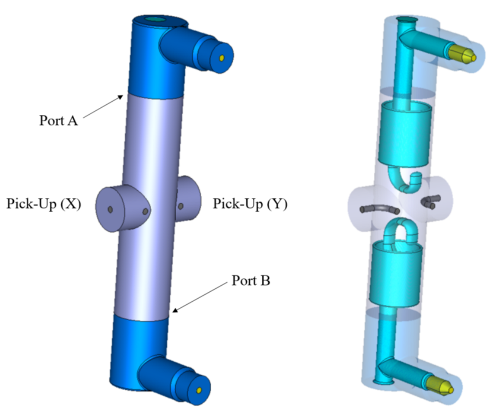

Figure 4: Vacuum model of the L-bend transmission test box with two couplers mounted.

Each of the broad-band spectral transmission measurements taken are plotted along side the simulated response [3] in Fig. 5. The transmission response around the frequency of the first DQW HOM and the stop-band filter sections are plotted Fig. 6 and Fig. 7 respectively. Note, the frequency domain measurement plots (Figs. 5, 6 and 7) represent a scenario where the coupler is measured on ‘Port A’ of the test box with pick-up ‘X’. Note, in this paper coupler numbers refer to the number engraved on the flange of the manufactured HOM coupler.

From the test box results, comparative broad-band analysis showed the response of ‘Coupler 4’ deviated from the simulated response much more than any of the other couplers. The spectral analysis for this coupler was compared with the results for each side of the test box and each pick-up probe to evaluate whether it was a faulty connection. In all instances, the broad-band spectral response deviated from the simulated in the same manner.

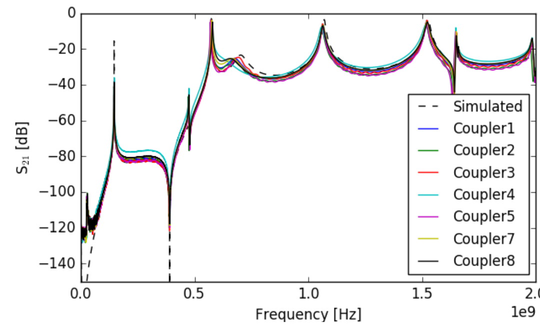

Figure 5: Full spectral measurements of the HOM couplers. Broadband calibration not applied for the first three couplers measured (Couplers 7, 8 and 2).

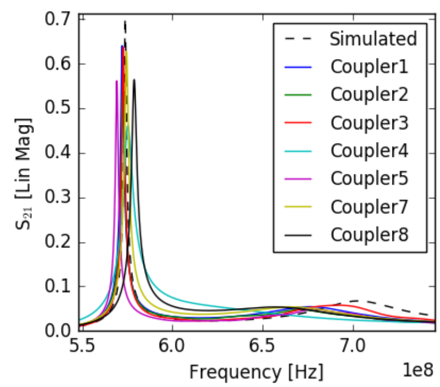

Figure 6: Test-box S_{21} for the frequency range around the first HOM.

Post measurement analysis of the spread of the stop-band frequency as well as the high transmission ‘interaction region’ peak frequencies was then compared for each coupler. The value of each stop-band frequency compared with the simulated test-box response for the ideal coupler is shown in Fig. 8. The error-bars represent the standard deviation between two identical pick-ups. The error is therefore due to a rotational or axial misalignment of the coupler, creating a capacitive mismatch between the two pick-ups.

Analysis of the results clearly showed an offset with the test-box port used. This offset is seen to be in the same direction and of similar magnitude (3.43 MHz ± 0.89 MHz). Due to the consistency of the deviations, meteorology on the test box will be performed and an independent target frequency for each port can then be applied to the data-sets.

The change of the interaction region frequencies are shown in Figs. 9 and 10. The frequency deviation of interaction region 2 is shown in an additional plot due to the deviated frequency response being an order of magnitude greater than that of the other regions. For coupler 4 the IR2 peak is not apparent and hence the peak value is calculated at the minimum frequency over the range sampled. The plots show data from side ‘A’ using pick-up ‘X’. The value for the magnitude of the frequency difference seen between pick-ups is (0.31 MHz ± 0.41 MHz).

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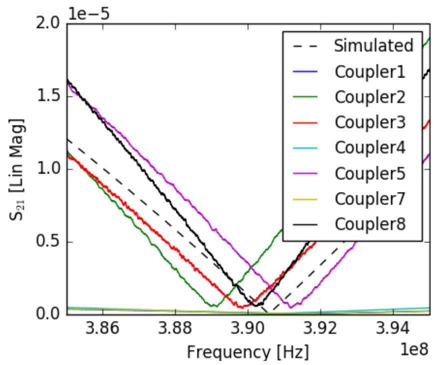

Figure 7: Test-box S_{21} for the stop-band filter section at the cavity's fundamental mode frequency. Calibration errors for couplers 1, 4 and 7 mean the amplitude is perturbed.

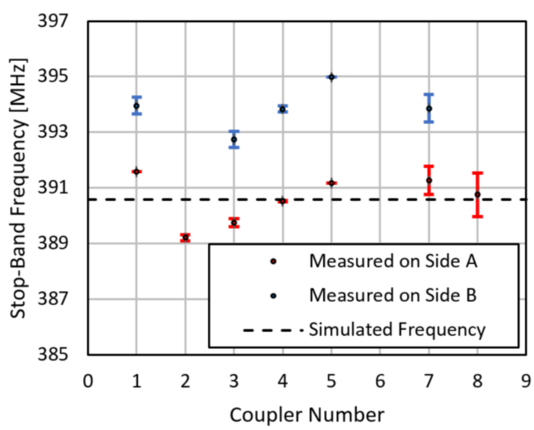

Figure 8: Measured stop-band frequency (at point of minimum transmission).

DRESSED CAVITY ANALYSIS

Thus far, two tests with HOM couplers on the cavity have taken place. The first was at JLAB where a single HOM coupler was tested on the first cavity built by Niowave [4], 'NWV-DQW-001'. Secondly, cold tests of the 'CERN-DQW-001' helium vessel assembly took place at CERN [5]. Measurements of the spectral responses for both tests are shown in Figs. 11 and 12. The spectral measurements were taken in segments of 500 and 300 MHz respectively for each test to increase the resolution of the traces.

Comparison with Simulation

For all of the visible modes, the differences in frequency and Q_{ext} between the simulated and measured datasets were quantified. The frequency deviations for both cavities are shown in Fig. 13 and measured and simulated Q_{ext} values for the CERN test are plotted in Fig. 14.

From the deviation of the frequency and Q_{ext} from the simulated values, two main conclusions were made. Firstly, the mode frequency deviation for the tested cavities is within ± 15 MHz. This value is slightly perturbed by the fact that some measured mode frequencies may have deviated from the simulated such that they are now closer to the frequency

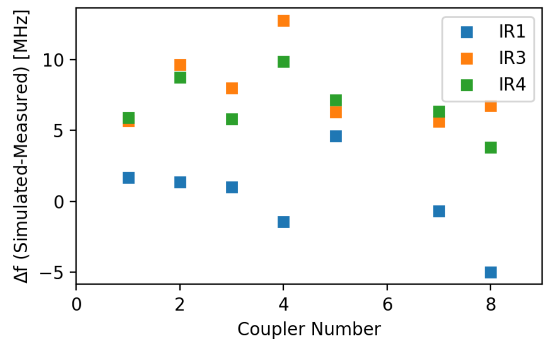

Figure 9: Deviation of the interaction region frequencies to those of the test-box simulations for interaction regions 1, 3 and 4.

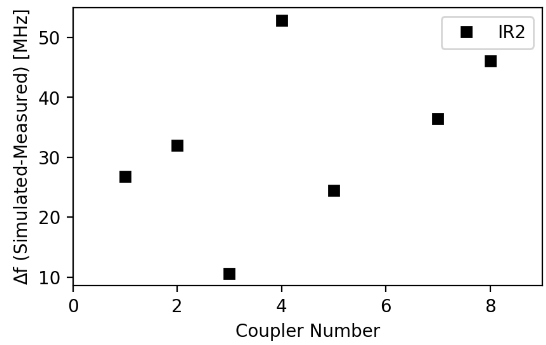

Figure 10: Deviation of the frequency of interaction region 2 to that of the test-box simulation.

of a different simulated mode. This means that the post processing script would compare the measured mode to a different simulated mode. This error scales with frequency as both the mode population and geometric sensitivity increase. However, for future considerations of the HOM power due to excitation via the beam spectrum, the data-sets provide a tolerance for calculations.

Secondly, a small number of the measured Q_{ext} values differed from the simulated by many orders of magnitude. In addition to deviations in HOM damping, this could be due to either simulation errors or, again, an incorrect mode comparison due to frequency shifts greater than half of the frequency domain mode spacing. The ratio of the simulated to measured Q_{ext} was hence plotted for analysis and can be seen in Fig. 15 for both tests. Benchmarking in other electromagnetic simulation codes should be carried out to ensure the simulated external Q-factors are reliable.

Finally, it should be noted that in transmission measurements between the two HOM couplers on the underside of the cavity, an additional transmission peak at 574 MHz is observed. This has been logged but is compared with the 571 MHz mode from simulations.

Analysis

Referring to the ratio of the simulated to measured Q_{ext}, a value less than 1 indicates that the damping is worse than the design value. For the CERN-DQW-001 data, if the upper

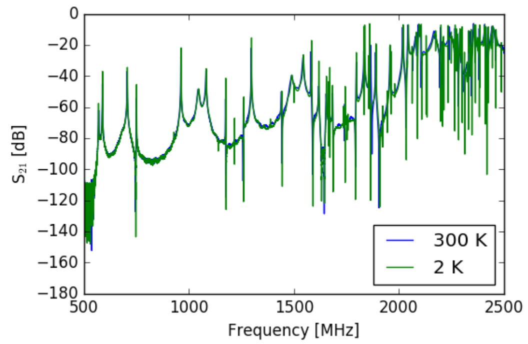

Figure 11: S_{21} between the only mounted HOM coupler (DQW FPC side) and the cold-test power coupler.

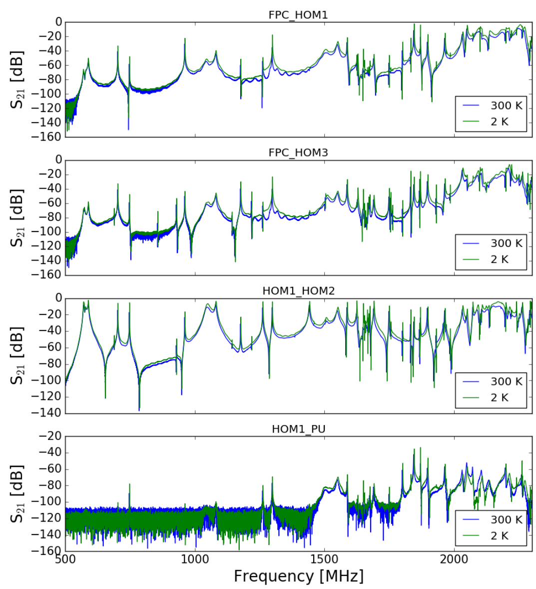

Figure 12: Example of four of the transmission measurements taken on the partially dressed 'CERN-DQW-001' cavity in the vertical test facility.

y-range is set to 0.01, two modes are seen. The measured frequencies of these modes are 748.56 MHz and 1.76 GHz. The modes at these frequencies are known to be of high impedance [6]. For the higher frequency mode, this mode is not damped by the HOM couplers but by the pick-up probe as it is difficult to achieve coupling with this mode from the HOM coupler locations. For the tests of the CERN-DQW-001 in the vertical test facility, the pick-up for SPS was not used. The low ratio of the simulated to measured Q_{ext} is hence predicted and validates the need to couple to this mode with a coupler additional to the HOM couplers in their current positions.

Referring to the mode at 748.56 MHz, no such reduction in damping was forseen. Analysis of the test-box data was thus performed to see whether the damping reduction could

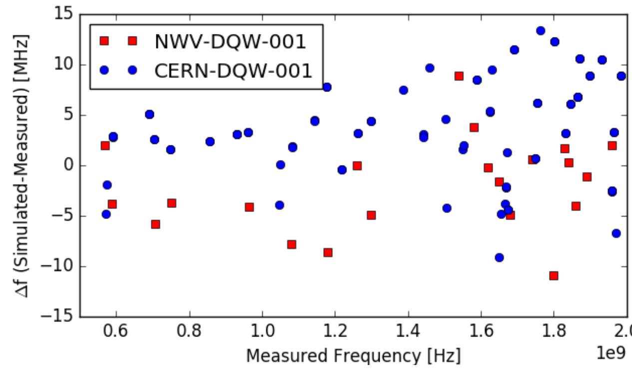

Figure 13: Measured mode frequency deviations from simulations for both tests at JLAB and CERN.

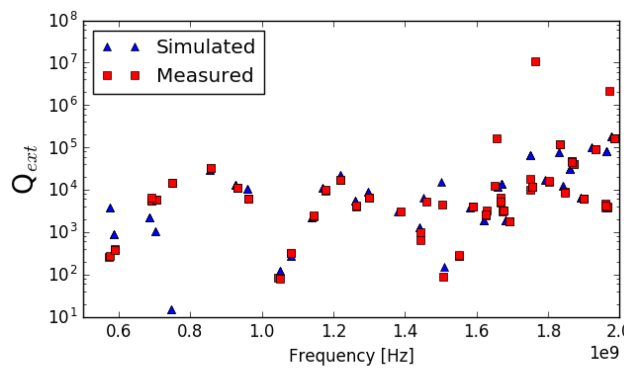

Figure 14: Measured mode frequencies and external Q-factors for the CERN test compared with the simulated values.

be predicted from the spectral response measurements. The shifts of the interaction region frequencies, Fig. 9 and Fig. 10, clearly show that the magnitude of the shift for the second interaction region (the peak seen at 687 MHz in the HOM couplers transmission response) is consistently lower in frequency. For the three HOM couplers used on the first cavity (2, 3 and 8) the measured shift was ~ -30 MHz. The average of the spectral response measurements for the three couplers used on the cavity was calculated and subtracted from the response of the simulated test-box. The frequency scaling necessary to revert the response back to that of the HOM coupler at 2 K was then applied. The difference in amplitude could then be evaluated. The ratio of the simulated to measured amplitude was 1.6 at this frequency, compared with the average change ratio of 1.08.

In addition to deviation at 748.56 MHz, another frequency area of interest was that of the first HOMs. From Fig. 15 it is clear that the damping of the first two higher order modes (at simulated frequency values of ~ 576 and 587 MHz) is better than that simulated. If the frequency deviation measured is applied to the simulated HOM coupler transmission response and the change in transmission is evaluated, the expected damping reduces. This is because the first mode reduces in frequency and the second increases and the modes are either side of a sharp transmission peak. This is shown visually in Fig 16.

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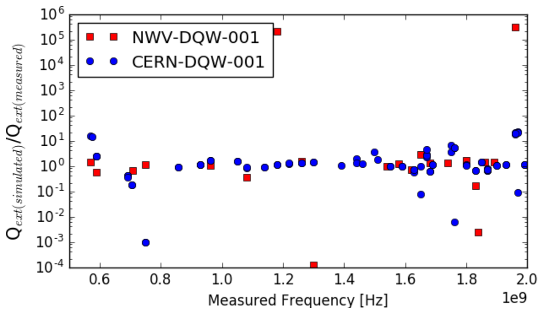

Figure 15: Ratio of the simulated to measured external Q-factors for both tests at JLAB and CERN.

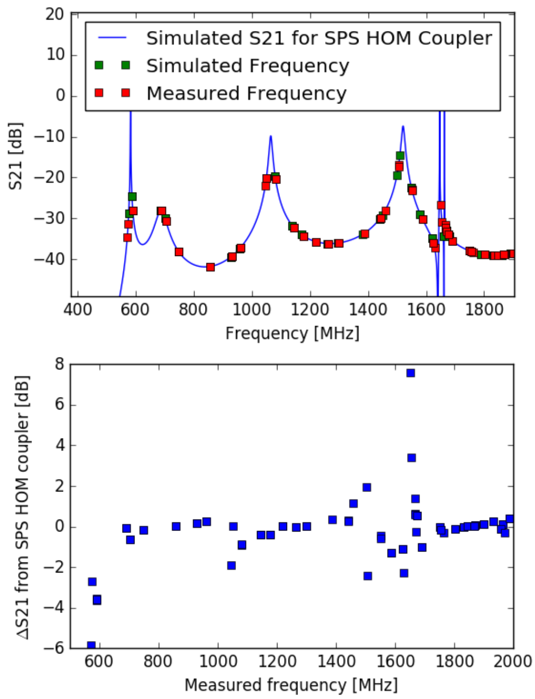

Figure 16: The relative change in the simulated HOM coupler S_{21} value with the shift in frequency measured for each mode on the CERN-DQW-001 cavity.

However, if the averaged three coupler accumulated response from the test box is again analysed and the frequency scaling applied, due to the shift in the interaction region frequency between the three couplers, the frequency range over which the HOM coupler has good transmission is broadened, but the peak value is reduced.

Compared to the simulated test box response, the damping was higher for both of these modes at their measured frequencies. For the first mode, the damping was still not as large as predicted from the simulated frequency, but for the second the damping predicted by the test box was higher by ~7 dB, agreeing with the cavity measurements. To show that the damping is indeed higher for the first mode, frequency dependant coupling factors must be applied to the HOM couplers to take into account that the coupling distribution varies between modes. This presents a further study see if pre-installation spectral analysis can be used to create the best damping for the specific cavity spectrum.

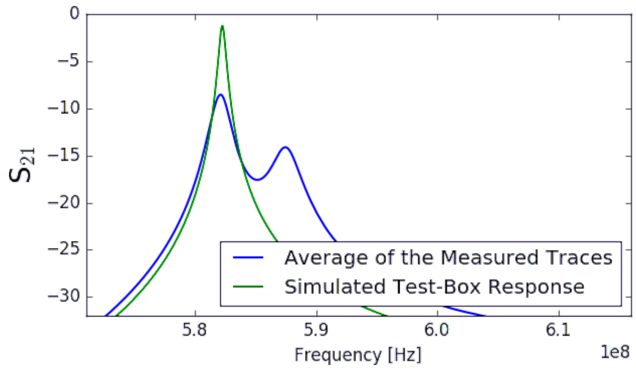

Figure 17: Simulated ideal and average measured (of 3 couplers used on CERN-DQW-001) HOM coupler transmission response on the L-bend test-box scaled to operation at 2 K.

CONCLUSION

Two devices were designed and built to provide broadband analysis of the transmission characteristics of the SPS DQW HOM couplers. Each of the SPS DQW crab cavity HOM couplers were measured on the L-bend transmission test box. Spectral measurements of the first cavities produced by Niowave and CERN were then taken and the frequency and Q_{ext} for each HOM was measured. The difference between the measured and simulated mode parameters were then compared. Measurements taken on the test-box were then compared with the cavity data-sets. Finally, explanations for the increase in damping of the first modes and decrease for the high-impedance mode at 749 MHz were provided by the test-box data-sets and a further study was proposed to take into account the frequency dependant field coupling distributions for the couplers.

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