FPC AND HOM COUPLER TEST BOXES FOR HL-LHC CRAB CAVITIES

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Abstract

The LHC luminosity upgrade will involve the installation of thirty-two 400 MHz SRF crab cavities. The cavities have two variants known as the RF dipole [1] and double quarter-wave [2][3] crab cavities. Each cavity has a fundamental power coupler (FPC) at 400 MHz and two or three HOM couplers. Before integration onto the cavities it is necessary to condition the FPC, and to measure the transmission on the HOM couplers at low power to ensure they operate as designed, each requiring a special test box. The FPC test box should provide a high transmission between two couplers without creating high surface fields. The low power HOM test boxes should be terminated to a load such that the natural stop and pass-bands of the couplers are preserved allowing the reflection to be measured and compared to simulations. In addition, due to the possibility of high HOM power in the LHC crab cavities, the concept of creating a broadband high power HOM coupler test box in order to condition and test the couplers at high power has been investigated. The RF design of all test boxes is presented and discussed.

INTRODUCTION

Prior to installation on the LHC, the HL-LHC crab cavities are to be tested in CERN's cryogenic test facility SM18, and on the SPS (Super Proton Synchrotron) in 2017-2018. These tests will be used to verify both the double quarter wave (DQW) and the RF dipole (RFD) cavity (shown in Fig. 1) in operation on a beam, and as such require a fully assembled cryomodule. The manufacture of the cavities for these tests has begun and is expected to be completed in 2016.

Along with the cavities themselves, the fundamental power couplers (FPCs) and the higher order mode (HOM) couplers for the crab cavities are also required. The FPC has many components already procured and is expected to be assembled and conditioned using a test box in early 2016. The HOM coupler manufacture has recently started. Once complete the HOM couplers will require testing to ensure the couplers have the stop and pass-bands at the correct frequencies, prior to their use in the cavity tests. To test the FPC and HOM couplers, various test boxes will be required.

The main focus of this testing is to ensure the components have the correct frequency response, and to condition the interior surfaces prior to operation.

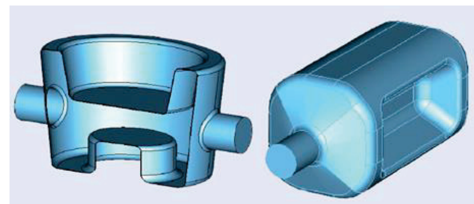

Figure 1: The DQW (left) and RF dipole (right) crab cavities for HL-LHC.

FPC TEST BOXES

For the FPCs, the primary concern is conditioning, as they need to support high power during operation. In order to condition the FPCs effectively a test box is required to ensure matching and the design frequency and which can support 0.5MW/m input power without exhibiting high peak fields.

Double Quarter Wave

The first test box to be investigated was the DQW FPC test box. The DQW FPC hook is shown in Fig. 2.

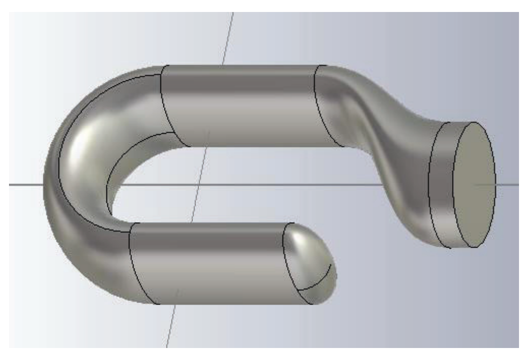

Figure 2: The DQW FPC hook.

Multiple designs were considered for the test box, with the final design being a quarter wave resonator, as shown in Fig. 3. In this design a standing wave is set up on the inner rod, with a magnetic field peak at the supported end, and an electric field peak at the open end. The hooks are positioned towards the end of the cavity as shown, this ensures that the hooks are primarily magnetically coupled.

The most important parameter in the quarter wave resonator are the length of the inner rod, which determines the resonant frequency; and the distance between the couplers and the inner rod, which determines the coupling of the hooks to the cavity, and in most cases determines the value of the peak fields in the cavity.

ISBN 978-3-95450-178-6

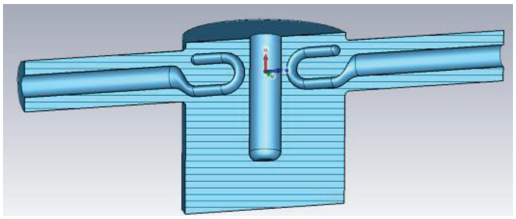

Figure 3: Final Design for the DQW FPC test box.

This design presents a match of $S_{11} \leq -30dB$ over a 4MHz bandwidth, with peak fields of 2.71MV/m at an input power of 0.5MW.

The field maps for this design are shown in Fig. 4 and Fig. 5, and $S_{11}$and S_{21} are shown in Fig. 6.

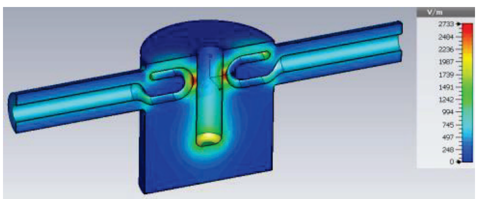

Figure 4: Electric field map at 400MHz for the DQW FPC test box. (Absolute magnitude, linear scale).

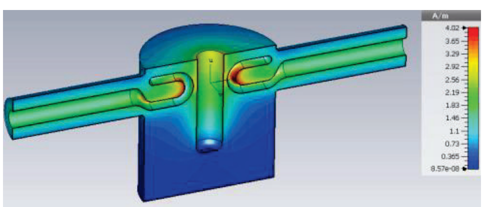

Figure 5: Magnetic field map at 400MHz for the DQW FPC test box. (Absolute magnitude, linear scale).

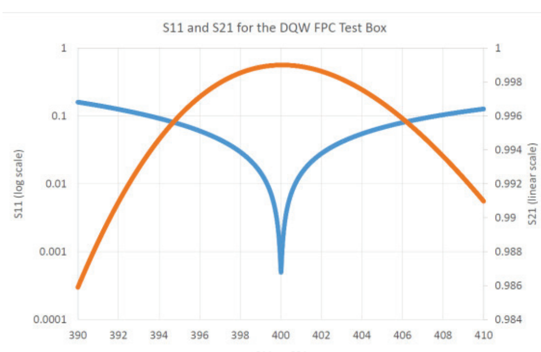

Figure 6: The reflection coefficient for the DQW FPC test box over a 20MHz span centered on the operating frequency.

RF Dipole

For the RFD FPC hooks, a QWR design was used again. The peak fields in this design are higher than in the DQW case, as a result it is necessary that the hooks be positioned further from the inner conductor to keep the peak fields low. This gives a lower coupling, and hence a narrower bandwidth. However, the test box is able to match the hooks within the initial parameters of 3MV/m peak fields at 0.5MW with a reflection coefficient below -30dB. The RF dipole FPC is shown in Fig. 7, and the full test box design is shown in Fig. 8.

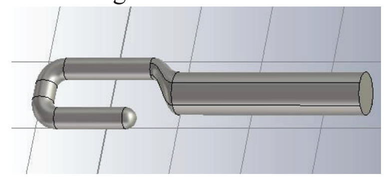

Figure 7: The RF dipole FPC hook.

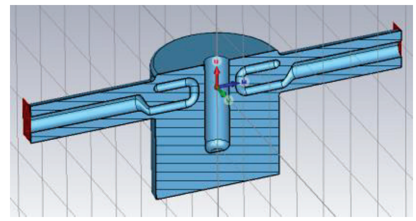

Figure 8: Final design for the RFD FPC test box.

With this design, a match of $S_{11} \leq -30dB$ over a 2MHz bandwidth was achieved, with peak fields of 2.86MV/m at an input power of 0.5MW. The field maps are shown in Fig. 9 and Fig. 10, and $S_{11}$and S_{21} are shown in Fig. 11.

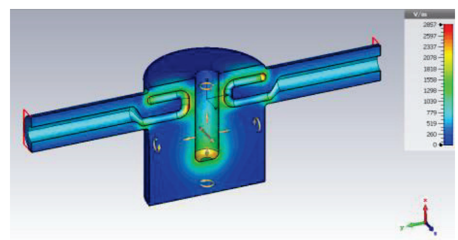

Figure 9: Electric field map at 400MHz for the RFD FPC test box. (Absolute magnitude, linear scale).

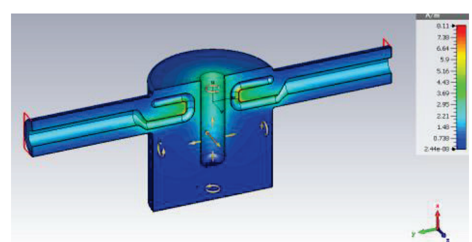

Figure 10: Magnetic field map at 400MHz for the RFD FPC test box. (Absolute magnitude, linear scale).

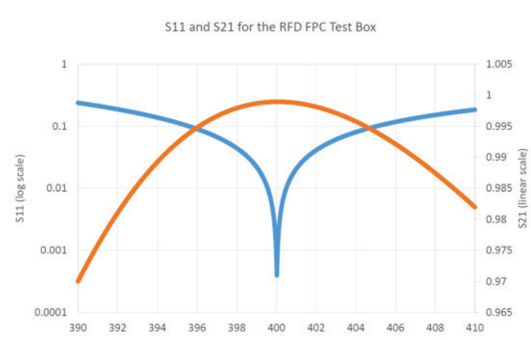

Figure 11: $S_{11}$and S_{21} for the RFD FPC test box over a 20MHz span centered on the operating frequency.

LOW POWER HOM TEST BOXES

Once the HOM coupler has been manufactured it is necessary to terminate the coupler to a matched load to measure its frequency response. The correct frequency response of the HOM couplers is crucial so as to reject the operating frequency at 400 MHz, whilst allowing high transmission at the frequency of high impedance HOMs. The capacitive and inductive elements in the designs are quite sensitive to tolerances, and it is necessary to test the couplers and tune them to the required behavior.

Normally a HOM coupler is tested by attaching to a beampipe section loaded with a lossy dielectric, however the HOM couplers for LHC are connected directly to the cavity itself hence this method would not be appropriate. It is hence necessary to design a matched load which doesn't alter the frequencies of the couplers natural frequency response without having significant reflections

There are two HOM coupler designs to be investigated, the DQW HOM coupler and the horizontal HOM coupler from the RFD. The first considered was the DQW HOM coupler.

Double Quarter Wave

The first low power test box investigated was that for the DQW HOM couplers, shown in Fig. 12. The coupler has a parallel LC circuit to filter the cavity 400 MHz signal, a series LC circuit for the hook to couple to the cavity fields and an LC high pass filter at the bend to further reduce the 400 MHz signal in a manner less sensitive to mechanical tolerances.

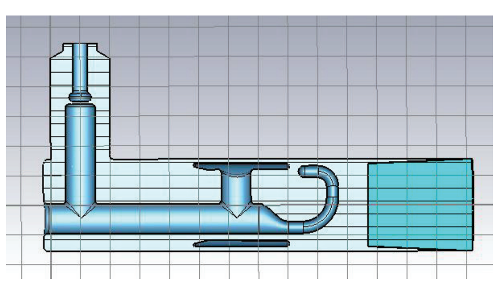

Figure 12: The DQW HOM coupler terminated into a 70 mm long conical SiC absorber with radii 31mm and 28 mm.

The termination for this coupler should be matched above cut-off while attenuating strongly below cut-off. If the 400 MHz filter response is to be observed strong coupling to the absorber is required. The diameter of the outer conductor is 62 mm hence has a cut-off frequency of 2.8 GHz, which is well above the frequency excited by the LHC beam hence the operation below cut-off is the most critical. Below cut-off there is no wave but an exponential decay of the field. Above cut-off most RF absorbers involve a slow taper of the impedance to avoid reflections, however below cut-off this is less important. The fields will however be perturbed by the absorber and the end plate to which the absorber is mounted. A SiC absorbing material is chosen as a standard RF absorbing material used in high power, vacuum environments.

Initially a conical absorber was investigated with the tip placed 20 mm from the end of the coupler. A 100 mm long absorber was simulated. The narrow radius at the top of the cone was varied to observe the variation in the reflections, shown in Fig. 13. It can be seen that the frequencies vary very little as the radius is changed but the reflections change significantly. Most frequencies show less reflection when the absorber is close to cylindrical, and less when strongly conical, with the exception of the narrow resonance at 1.66 GHz.

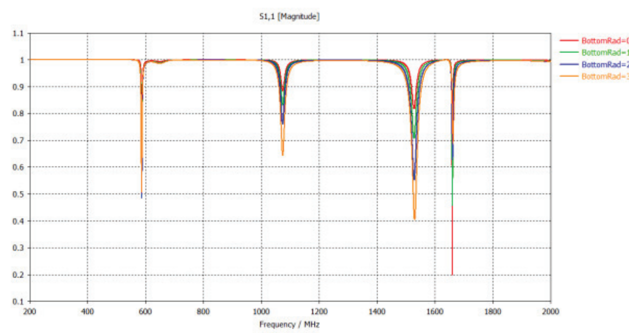

Figure 13: Variation in the narrow radius of the conical absorber.

As a comparison the reflection when the cavity is terminated in an open boundary condition 20 mm from the end of the coupler is shown in Fig. 14. As can be seen the reflections are significantly lower with the open boundary. The frequency shift and S11 minima for the cylindrical 100 mm absorber and open boundary, both 20 mm away are shown in Table 1. As can be seen the frequencies agree to within 6 MHz, more than adequate for tuning a coupler.

It is important that the absorber doesn't alter the frequency response of the coupler hence the frequency of the 2nd reflection minima, at 1.07 GHz was observed as a function of absorber position, shown in Fig 15, for a 100 mm long cylindrical absorber. The frequency shifts by 1.4 MHz between 2mm away and 32 mm away, which is well within requirements. At 2 mm away the reflection drops to 0.24. As the coupler is superconducting cleanliness is critical hence 2mm is likely to small a gap to ensure there is no possibility of touching, hence a 10 mm separation is chosen.

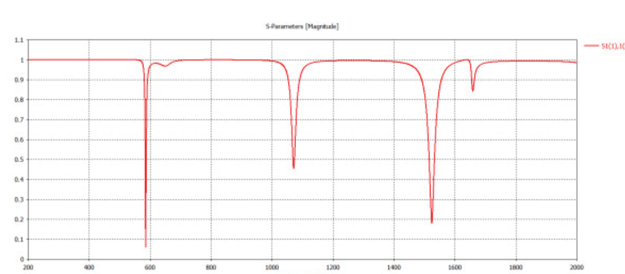

Figure 14: Reflections when the coupler is terminated in an open boundary.

ISBN 978-3-95450-178-6

Table 1: Frequency Shift of Reflection Minima with a Conical Absorber

Absorber		Open		
f / MHz	s11 min	f / MHz	s11 min	Δf / MHz
585.0	0.505	585.7	0.06	-0.7
1074.4	0.644	1071.4	0.455	3.0
1530.2	0.404	1524.5	0.18	5.7
1662.7	0.688	1658.9	0.842	3.8

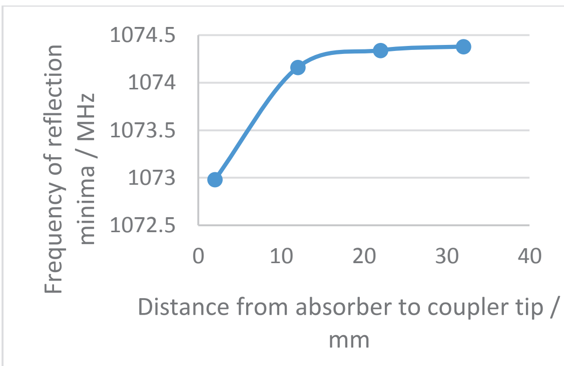

Figure 15: Frequency of the 2nd reflection minima as a function of absorber position.

Several other designs have been identified to possibly increase absorption. So far, five designs have been investigated for the DQW low power HOM test box. These designs are: a SiC cone situated in a section of cylindrical waveguide (the same diameter as the HOM coupler); an inverted cone situated in the same waveguide; a straight block of SiC situated in the same waveguide; a SiC cone situated in a length of coaxial waveguide; and a SiC cone situated in a waveguide with a cutoff frequency below 200MHz, after a taper connecting this waveguide to the HOM coupler. These designs are shown in Fig. 16. Improvements over a 30 mm cylinder are marginal and perturb the frequency more. Studies are currently ongoing.

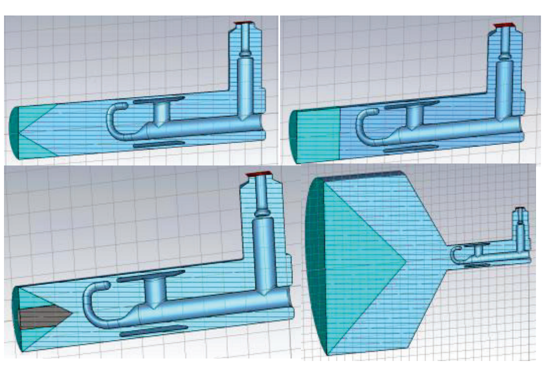

Figure 16: The four rejected designs for the DQW low power HOM test box. Inverted SiC cone (top left) straight block of SiC (top right), SiC cone in coaxial waveguide (bottom left), and tapered waveguide with SiC cone (bottom right).

Even with the open boundary we cannot see the notch at 400 MHz so we cannot tune that with this test set-up. In order to measure this the best solution is to utilise a 400 MHz cavity with a variable frequency, such as the FPC test box. Here we can sweep the frequency by varying the capacitive end plate and measure Qe vs frequency in order to find the notch frequency.

A possible alternative is to construct a copper DQW cavity and test the coupler directly on the cavity. While this doesn't allow direct measurement of the couplers natural frequency response it does allow you to measure the external Q of each mode. This method is however more time consuming and is also dependent on the cavity tolerances.

RF Dipole

The RF dipole cavity has two different HOM couplers per cavity, however, the vertical HOM coupler does not have any stopband so tuning is not required hence a test box is only required for the horizontal HOM coupler, shown in Fig 17. This coupler is connected to the cavity via a low height rectangular waveguide. The cut-off frequency of this section is 0.95 GHz, hence the design of this coupler is slightly more complex to avoid reflections. Work has begun on the design of the absorber, but further work is required at present.

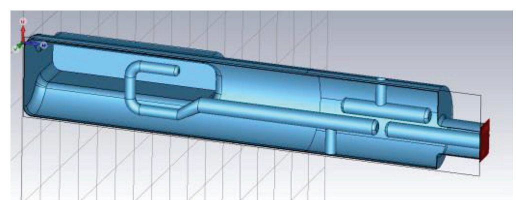

Figure 17: The horizontal HOM coupler for the RFD crab cavity.

High Power HOM Test Box

Due to the high HOM impedance of the cavities and large stored current in the LHC a significant power may flow through the HOM couplers of up to 1 kW. It was suggested that a possible high power test box could allow testing of the couplers at high power and potential conditioning at the frequency of the high impedance HOMs. It is not clear at present if such a technique is required. A high power HOM test box has been investigated for the DQW HOM couplers to see how such a device might work and to assess if such a test box is useful. This test box is required to produce a broadband match for the couplers, from 0.4-2GHz to allow a 1 kW transmission without requiring an excessive input power. A number of possible designs have been considered for this. Initially it was assumed that it may be possible to connect two coupler back to back may allow a broadband match but this only works at certain frequencies and is not tunable. In order to increase the tenability of this design a single stub and a trombone section, or a multi-stub tuner were envisioned. While both these design was fairly successful in simulations the complexity, high peak fields, and difficulty of mechanical supports makes the designs less practical. At present a variable pillbox cavity is being investigated. The cavity is shown in Fig. 18, and an example of mode tuning is shown in Fig. 19.

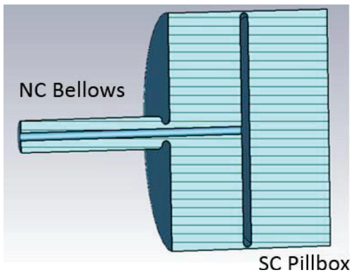

Figure 18: A basic model of a variable pillbox cavity. The section on the left contains the normal-conducting bellows, and no field. The section to the right is the superconducting region of high field where the couplers will be positioned.

This design consists of a moveable plate inside the cavity, which can be inserted/retracted through the use of bellows. It is possible that the box could also operate in a superconducting regime by using Nb sputtering, hence we seek to avoid fields on the bellows. The cavity operates in higher order TE and TM modes that do not couple to the TEM mode of the plate supports in the narrow region, allowing the bellows to be cut off to the field in the narrow region.

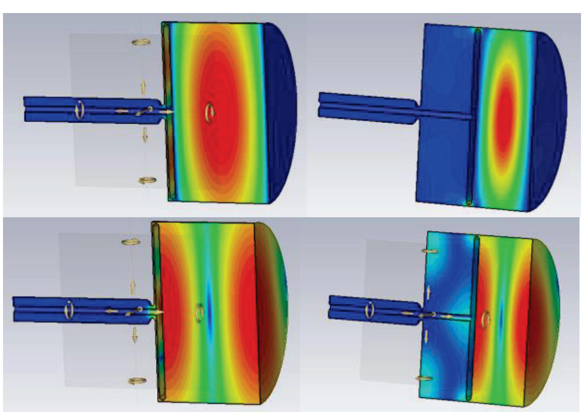

Figure 19: Manipulation of the TE_{111} mode from 500MHz (left) to 812MHz (right) through use of the variable plate (Electric field top, magnetic field bottom).

As the plate is moved, the frequency of the modes changes. Unfortunately as the plate is inserted more the supports inside the cavity allow a TE mode to resonate on the support rod reducing the frequency range the cavity can be tuned to for each mode. However using a number of modes, the entire frequency range can be covered. An example of the mode coverage is shown in Fig. 20, although only a few modes will be required. Work is ongoing to assess which modes will be utilized and the coupling to those modes.

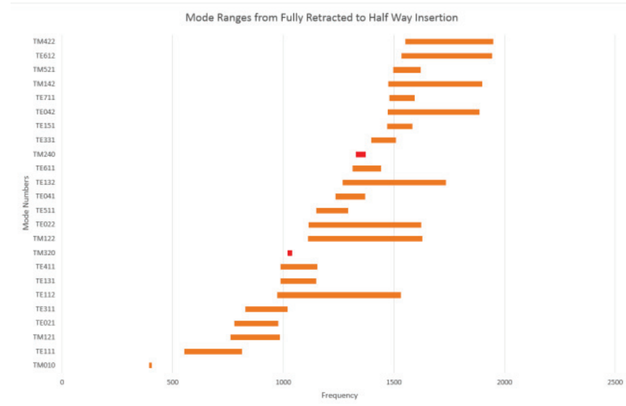

Figure 20: Plot of mode labels against frequency range in the variable pillbox cavity, from maximum length to half length.

SUMMARY AND FUTURE PLANS

A final design has been shown for the DQW and RFD crab cavity FPCs, each capable of matching the hooks to $S_{11} = -30$dB with peak fields below 3MV/m.

The final design is also presented for the DQW HOM low power test box, for tuning of the couplers. The frequencies found from coupling to a SiC absorber is found to be similar to simulations with an open boundary. However, further work is required on the low power RFD test box.

A high power test box for the DQW HOM couplers has also been considered, to produce a broadband match for the HOM couplers, allowing for high power conditioning. Work on this design is still ongoing.

The three completed designs will be manufactured towards the end of 2015, in preparation for the FPC and HOM coupler tests which will begin in Q1 of 2016. Following completion of the low RFD HOM test box, this will also be manufactured for these tests.

ACKNOWLEDGMENT

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404. This work was also supported by STFC through the Cockcroft Institute Grant.

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ISBN 978-3-95450-178-6