HIGHER ORDER MODE FILTER DESIGN FOR DOUBLE QUARTER WAVE CRAB CAVITY FOR THE LHC HIGH LUMINOSITY UPGRADE*

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Abstract

A Double Quarter Wave Crab Cavity (DQWCC) was designed for the Large Hadron Collider (LHC) luminosity upgrade. A compact Higher Order Mode (HOM) filter with wide stop band at the deflecting mode is developed for this cavity. Multi-physics finite element simulation results are presented. The integration of this design to the cavity cryomodule is described.

INTRODUCTION

The LHC High Luminosity upgrade (HL-LHC) envisages the implementation of the crab-crossing technique [1-4] to correct the geometric effects of the wider crossing angles at which bunches collide, and hence maximize the LHC's luminosity. To fit the geometric limit of the LHC beam pipes, a compact HOM filter is designed for DQWCC to reflect the deflecting mode at 400 MHz back to the cavity, and to offer a pass band to the HOMs up to 2 GHz. Modes with frequencies above 2 GHz are expected to be Landau damped due to natural frequency spread, chromaticity, Landau octupoles and synchrotron oscillations [5].

CRAB CAVITY

The DQWCC, with its cross section shown in Fig. 1(a) [2, 6], can be considered as two quarter-wave resonators sharing a load capacitor, thus dubbed a double quarter wave cavity. For the 400 MHz fundamental mode, there is a transverse electric field between the two capacitive plates, offering the crabbing voltage when the beam passes at an appropriate phase. The frequency of the lowest HOM is 170 MHz higher than the fundamental mode frequency. Due to the installation of the thermal and magnetic shielding, shown in Fig. 1(c), the total height of the cavity plus HOM filter is confined within 350 mm from the beam axis.

* Work partly supported by US DOE through Brookhaven Science Associates LLC under contract No. DE-AC02-98CH10886 and by the US LHC Accelerator Research Program (LARP). This research used resources of the National Energy Research Scientific Computing Center, which is supported by US DOE under contract No. DE-AC02-05CH11231. Research supported by EU FP7 HiLumi LHC - Grant Agreement 284404.
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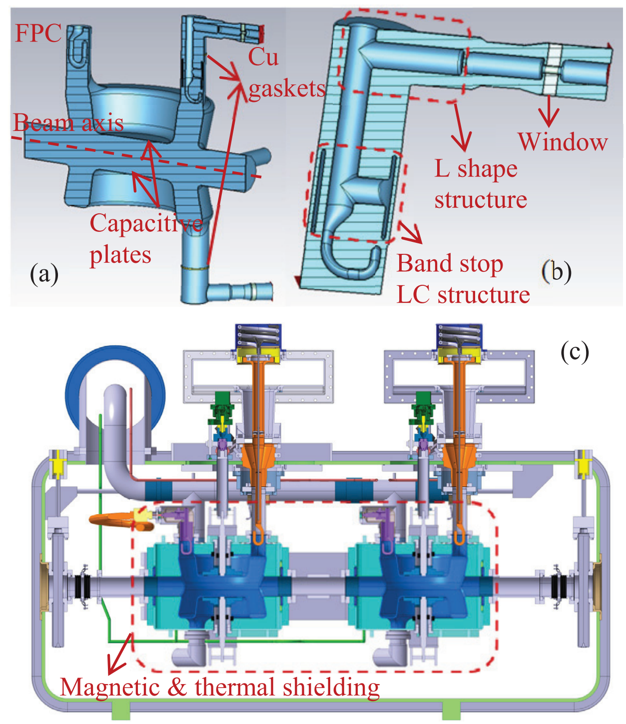

Figure 1: (a) DQWCC with 3 HOM filters, (b) HOM filter; (c) Cryomodule with two DQWCCs.

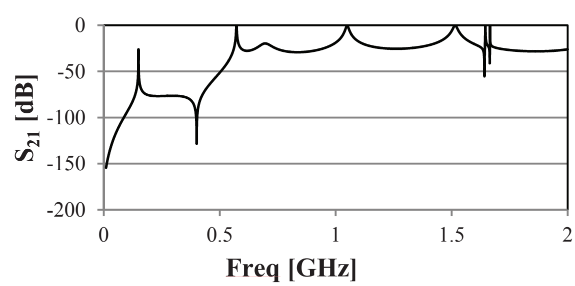

Figure 2: S_{21} of the HOM filter, with TE_{11} mode on the hook side and TEM mode on the port side.

RF DESIGN OF THE FILTER

The HOM filter, shown in Fig. 1(b), consists of a band stop LC structure right above the hook to minimize the RF loss on the Cu gasket that will be used to connect the cavity and the filter, shown in Fig. 1(a), and an L shape structure on the top to form a pass band starting from 570 MHz, the frequency of the first HOM. There are three

ISBN 978-3-95450-168-7

HOM filters in each cavity, with one on the FPC side with the port along the beam pipe direction and the other two on the opposite side with the port 60 degrees away from the beam pipe port. This symmetric design is adopted to lower the multipolar components of the fundamental mode field. The S_{21} of this design, with TE_{11} mode on the hook side and TEM mode on the port side, is shown in Fig. 2. The rejection at 400 MHz shows a 34 MHz stop band with $S_{21} < -80$ dB, and the minimum at -128 dB. However, the rejection for the first HOM at 570 MHz is only -2 dB.

HOM SHUNT IMPEDANCE

The longitudinal *R/Q* is calculated using:

$$\left(\frac{R}{Q}\right) = \frac{|V_z|^2}{\omega U}$$

and the transverse $(R/Q)_T$ is calculated using:

$$\left(\frac{R}{Q}\right)_T = \frac{|V_z(r_0) - V_z(0)|^2}{\omega U \left(\frac{\omega}{c} r_0\right)^2}$$

for beam instability we use:

$$\frac{Z_T}{Q} = \frac{\omega}{c}\left(\frac{R}{Q}\right)_T$$

V_z is in complex format in the above formulas.

CST Microwave Studio® is used to calculate the longitudinal and transverse *R/Q*, as well as the Q_{ext} of each HOM.

The longitudinal impedance is shown in Fig. 3(a), and the transverse impedance is shown in Fig. 3(b), with the impedance in circuit definition. The highest impedance for a longitudinal mode appears at 959 MHz, with a value of 0.10 MΩ/cavity. Below 1.75 GHz, there are two modes with a transverse impedance above 1 MΩ/m/cavity. The frequencies of these two modes are 747 MHz and 927 MHz. The mode at 1.75 GHz shows a very high transverse impedance and requires further optimization. This high impedance is caused by the combination of the low coupling to this mode resulting from the HOM port aperture location, and the high S_{21} attenuation of the filter at this frequency. There are four more modes above 1.75 GHz with a transverse impedance higher than 1 MΩ/m/cavity.

POWER ESTIMATION

The external Q from the HOM filters is 7.9×10^9 at the fundamental mode; the stored energy is 10 Joule at the nominal transverse kick voltage of 3.34 kV. The fundamental power loss is estimated to be 1.1 W for each HOM port. The RF loss on each Cu gasket is estimated to be less than 10 mW.To estimate the HOM power, we use beam spectrum for a 25 ns bunch spacing in HL-LHC, and the shunt impedance and the external Q of each HOM as calculated in previous section. For all HOMs below 2.0 GHz, the total power extracted is 5.3 W per cavity. Together with the power from the fundamental mode, each HOM damper extracts no more than 2.9 Watt power.

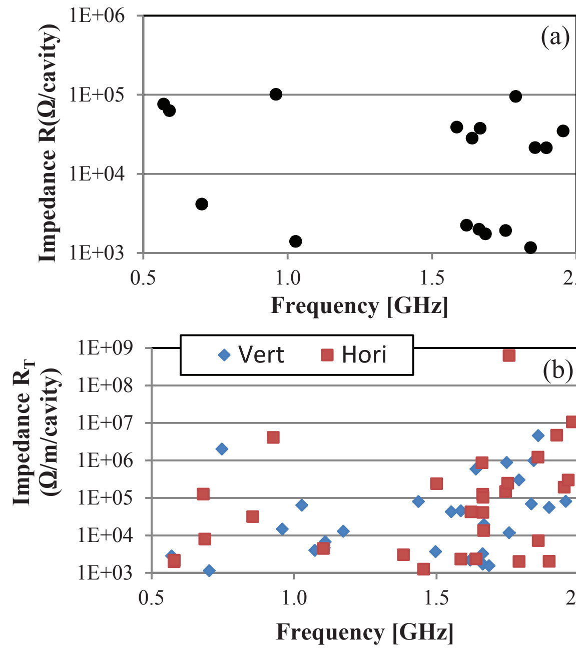

Figure 3: DQWCC shunt impedance (a) Longitudinal; (b) Transverse.

ERROR ANALYSIS

In this section we calculate the effect of fabrication errors, including the cavity fabrication errors and HOM filter fabrication errors, on the performance of the HOM filter. For example, the impedance, the Qext of the fundamental mode, the peak electric field and magnetic field on the cavity and on the HOM filters.

We evaluate the effect of the cavity fabrication errors associating with the parameters shown in Fig. 4(a), including half of the cavity height HT, half of the cavity length L1, half of the cavity waist Rmi, and diameter of the beam pipe aperture APER, as well as the effect of the HOM filter fabrication errors associated with the parameters shown in Fig. 4(b). The value of each error is shown in Table 1. The port of the HOM filter on the FPC side should be aligned along the beam pipe direction and the other two on the opposite side should be 60° away from the beam pipe port, the fabrication errors of these angles are evaluated to be away from their designed position by ±1°.

With the above fabrication errors, there is no significant (more than 50%) increase of the impedance value comparing with the design, except the first HOM at 570 MHz, which shows a maximum change from

0.17 MΩ to 0.47 MΩ when the position of the vertical rod Rod1P shifts left 0.5 mm, still within a reasonable range.

For the 400 MHz fundamental mode with 3.34 MV kick, with the above fabrication errors, the minimum coupling from three HOM ports is 6.3×10^9, corresponding to 1.4 W power at each HOM port to the load outside the cryomodule. The peak electric field on the hooks ranges from 19.4 to 29.7 MV/m, while on the cavity ranges from 37.0 to 38.8 MV/m. The peak magnetic field on the hook ranges from 46.2 to 58.7 mT, while on the cavity ranges from 70.4 to 71.6 mT. The peak fields on the hooks are reasonably lower than those on the cavity.

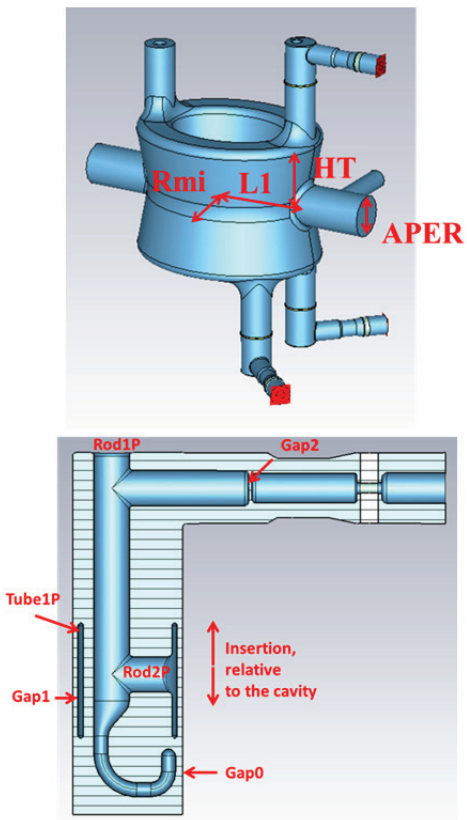

Figure 4: Illustration of the parameters for fabrication error evaluation of the (a) cavity; (b) HOM filter.

Table 1: Fabrication Errors

Parameter	Error [mm]	
APER	-0.2	+0.4
HT	-0.4	+0.4
L1	-0.8	+0.8
Gap0	-0.4	+0.5
Gap1	-0.4	+0.5
Gap2	-0.5	+0.5
Rod1P	-0.5	+0.5
Rod2P	-0.5	+0.5
Tube1P	-0.5	+0.5
Insertion	-0.5	+0.5

SUMMARY

A compact HOM filter is developed for DQWCC for LHC luminosity upgrade. The simulation shows a 128 dB attenuation notch at ~400 MHz, with a 34 MHz stop band with more than 80 dB attenuation. Power estimation showed a 2.9 W power extraction from each HOM port using the 25 nS HL-LHC beam spectrum. The impedances of all longitudinal modes are no more than 0.10 MΩ/cavity, and one mode at 1.75 GHz appears to have high transverse impedance. Extensive error analysis shows a significant impact on the impedance at 570 MHz, which is still within a reasonable range. With the fabrication errors, the coupling from the HOM ports to the fundamental mode is higher than 6.3×10^9, with the peak electric field on the cavity 7.3 MV/m higher than that on the filters, and the peak magnetic field on the cavity 11.9 mT higher than that on the filters.

ACKNOWLEDGEMENTS

The authors would like to thank Zenghai Li at SLAC, Frank Marhauser and Haipeng Wang at JLab, for their help on the filter design and analysis.

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ISBN 978-3-95450-168-7