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the Large Hadron Collider***

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COMPACT HIGHER ORDER MODE FILTER FOR CRAB CAVITIES IN THE LARGE HADRON COLLIDER*

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Abstract

A double quarter wave crab cavity was designed for the Large Hadron Collider (LHC) luminosity upgrade. Starting from the analytical calculation of simplified RLC circuit, a compact Higher Order Mode (HOM) filter is developed for this cavity. Finite element simulation results are presented. The design concept is generic and can easily be adapted to other cavities.

INTRODUCTION

The LHC at CERN is an energy frontier machine in high-energy particle physics. To maintain its scientific progress and exploit its full capability, a major upgrade called LHC luminosity upgrade will be needed. As a part of the luminosity upgrade, the use of crab cavities was proposed to correct the geometric effects of the wider crossing angles as a consequence of the reduced beam sizes with the IR upgrade [1, 2]. To fit the geometric limit of the LHC beam pipes, the conceptual Proof-of-Principle (PoP) design of three compact crab cavities were successfully performed, with all three prototype cavities fabricated and cryogenically tested.

To apply these designs to the SPS section of LHC, the PoP cavities need to be expanded with all their accessories, which include the HOM filter to reflect the deflecting mode, with a frequency to be tuned to 400.730 ~ 400.850 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 [2].

In the following paragraphs, the current design of all three cavities will be introduced, following with the analytical model and the 3D model of a compact HOM filter that can easily be adapted to other cavities, finally we estimate the power that this filter should deal with.

CRAB CAVITIES

The design of the crab cavity for LHC luminosity upgrade is essential, but challenging due to the geometric constrain in both SPS and IP5, and relatively low crabbing frequency at ~400 MHz.

The geometries of the current three designs: the

Double Quarter-Wave Crab Cavity (DQWCC) at BNL/CERN, the 4-rod crab cavity at Lancaster University and the RF dipole crab cavity at ODU/SLAC, are shown in Figure 1 [3-5], with the frequencies of lowest HOMs needs to be considered, f_{HOM1} , in these three cavities at 570 MHz, 600 MHz, 584 MHz, respectively [3, 5]. One should note that in the four-rod cavity, the first HOM at 437 MHz has a low impedance so it doesn't need any real damping. The first dangerous one (except for the LOM that will be dealt separately using a LOM filter) at about 600 MHz makes it easier to design the HOM filter [6].

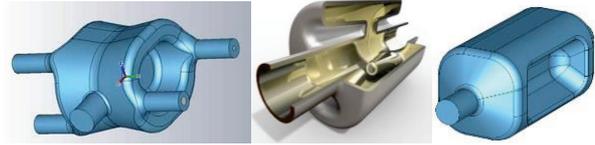


Figure 1: Geometries of the DQWCC, 4-rod cavity and RF dipole cavity (from left to right).

HOM FILTER

The design of the HOM filter requires a sufficient reflection at desired frequency f_0 for accelerating or deflecting mode, with a number at 400.730 ~ 400.850 MHz for deflecting mode in our case, and an efficient pass band starting from f_{HOM1} .

Chebyshev high pass filters with 2 or 3 stages are normally adopted for the HOM filters due to their sharp rising from f_0 to f_{HOM1} [7,8]. The HOM filter does not require a stop band from zero to a frequency between f_0 and f_{HOM1} . A stop notch at f_0 will make the HOM filter function properly.

Analytical Model

In our design, a modified Chebyshev high pass filter with only one stage is used to simplify the construction, cooling and tuning. The simplified LC filter circuit shown in Figure 2 contains a π structure, with the capacitor changed to a band stop cell by adding an inductor in parallel to the capacitor.

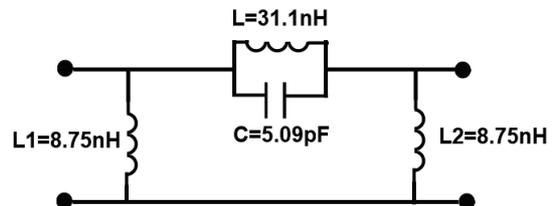


Figure 2: Simplified LC circuit of the HOM filter.

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The S_{11} and S_{21} of the above network are calculated using the formulas in Table 4.1 and Table 4.2 in [9]. One should note here since the LC structure is symmetric, either port can be used as the input port. Using software Mathematica™, S_{11} and S_{21} are calculated as a function of frequency from 0 to 3 GHz with the parameters shown in Figure 2. The calculation results are shown in Figure 3. In this design, the parameters of the original π structure determine the pass band, starting from ~ 600 MHz, and covers up to 3 GHz, the upper limit of our calculation. While the parameters of the band stop cell define the notch position, at ~ 400 MHz in this case.

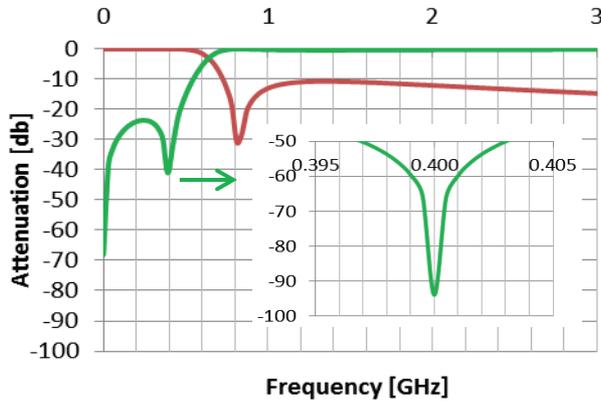


Figure 3: S_{11} (red curve) and S_{21} (green curve) of the above network.

3D Model

A coaxial structure has been chosen to simplify the assembling to the crab cavities. In the CST Microwave Studio®, A ring type capacitor is designed, together with three inductors connected into an “H” shape, as shown in Figure 4. The detailed parameters of these LC components are listed in Table 1. The input port, shown as red on the left side of Figure 4, will be connected to the HOM hook coupler. The detailed design of the HOM coupler will be introduced in the next paragraph using DQWCC as an example. The inner diameter (ID) of the input port is set to be 27 mm, and its outer diameter (OD) is set to be 62 mm, the same as the port for the FPC coupler. The output port, shown as red on the right side of Figure 4, will be connected to an HOM damper outside the cryomodule via a coaxial cable, using a type-N or 7-16 feed-through to isolate the vacuum inside the filter from the outside. The geometry of the output port can be easily reconfigured to adapt the feed-through without changing the RF response of the filter. The size of this filter is 120 mm in length, and a maximum 83 mm in diameter, with 3 mm Nb used to form the filter wall.

The through response S_{21} of this model is calculated using CST Microwave Studio®, the result is shown in Figure 5. As we expected, a notch with -96.2 dB in depth appears at ~ 400 MHz, with a 30 dB width at 0.62 MHz. The model has a high pass S_{21} (between -10 dB and 0 dB) at frequency range between

0.46 GHz and 2.40 GHz, covers the pass band requirements of all three crab cavity designs. The notches that appear at frequencies higher than 2.40 GHz, are produced by the complexity of the configuration, i. e. unwanted capacitance in the gap between capacitor and inductor, between inductor and inductor and between inductor and wall. They are not going to affect the filter performance since modes with frequencies above 2 GHz are expected to be Landau damped.

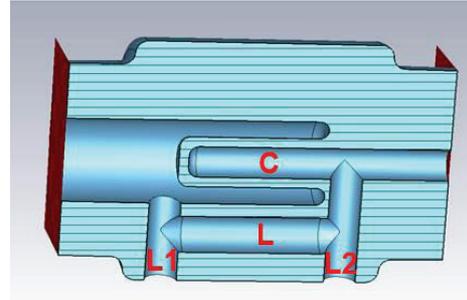


Figure 4: 3D model of the HOM filter.

Table 1: Parameters for the LC components in the 3D model.

	Inductance [nH]	Length [mm]	Diameter [mm]	
L1	8.71	25	10	
L2	13.33	33.5	10	
L	19.38	46	12	
	Capacitance [pF]	Length [mm]	OD [mm]	ID [mm]
C	5.09	43	16	10

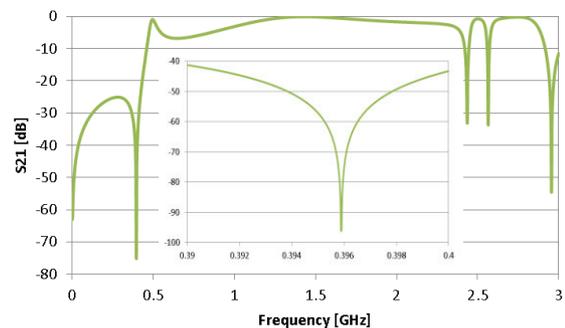


Figure 5: Through response of the 3D model.

POWER ESTIMATION

In this section, we use the DQWCC as an example to show the estimation of the power that needs to be damped through the HOM filters to room temperature dampers. The estimation below is normalized to each cavity with a 3.3 MV kick.

The detailed geometry of the HOM couplers is needed for this estimation. The HOM couplers, with their configurations and positions showed in Figure 6, provide the coupling to the HOM modes. Since the

beam is well aligned in the center of cavity beam pipe, the monopole modes in longitudinal direction should be considered to generate most of the HOM power. The Q_{ext} , as well as the R/Q values of the related modes, are listed in Table 2.

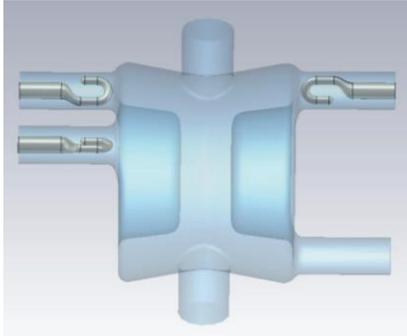


Figure 6: Configuration of HOM couplers.

Table 2: Q_{ext} and R/Q of monopole (longitudinal) HOM modes.

HOM frequency [GHz]	R/Q [Ω]	Q_{ext}
0.570	74.2	1788
0.965	90.4	1535
1.746	5.18	1678

Formula (2) in [7] is used to estimate the fundamental power loss from the HOM filter. For the setup with three HOM couplers, the loaded Q is 11,200; the stored energy is 10 Joule. Using the notch value calculated before at ~ 400 MHz, the fundamental power loss, with resonance frequency at the notch, is 0.54 mW for all three HOM ports; while the resonance frequency of the fundamental mode deviate from the notch frequency, the maximum fundamental power loss is estimated to be 0.54 Watt for all three HOM ports in the 30 dB 0.62 MHz mismatch range.

Code developed by Q. Wu et al. [7] is used to estimate the HOM power loss, with the high luminosity LHC beam parameters used in this calculation listed in Table 3 [10]. For all HOMs below 2.0 GHz, the total power extracted is 983.68 Watt, which is about 327.89 Watt per HOM damper. Most of the HOM power is contributed by the first longitudinal HOM, with a value of 915.40 Watt.

Together with the power from the fundamental mode, each HOM damper extracts no more than 328.07 Watt power. Such a high power, even most of which will be damped outside the cryomodule, will cause power dissipation on the filter. The filter will be made of 4 mm Nb sheet and bulk Nb to get a low surface resistance after careful surface treatment to minimize the power dissipation. The LC components inside the cylinder will be actively cooled with cooling path drilled inside the ‘‘H’’ shape structure formed by three

inductors. The design of the active cooling is underway. One should note this analytical calculation is based on the simplified model. For completeness, a 3D simulation using CST Particle Studio® will follow.

Table 3: High Luminosity LHC Beam Parameter.

Charge per bunch	35.2 nC
Revolution period	89.0 μ S
rms bunch length	0.25 nS
Number of bunches	3362
Number of RF buckets ¹	3362
Energy	7.00 TeV
Beam current	1.11 A

¹Based on a simplified model without bunch to bunch variation.

SUMMARY

A compact HOM filter is developed for crab cavities for LHC luminosity upgrade by extending the simplified analysis on LC circuit to the 3D microwave model. The simulation shows a -96.2 dB notch at ~ 400 MHz, with a 30 dB width at 0.62 MHz. The simulation also shows a high pass band between 0.46 GHz and 2.40 GHz, which will work for all three crab cavity designs. The power that the filter will deal with is estimated to be ~ 440 Watt. Such a high power will be damped outside the cryomodule. The design of the active cooling will follow.

ACKNOWLEDGEMENTS

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