RF MODELING USING PARALLEL CODES ACE3P FOR THE 400-MHz PARALLEL-BAR/RIDGED-WAVEGUIDE COMPACT CRAB CAVITY FOR THE LHC HILUMI UPGRADE*

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Abstract

Schemes utilizing crab cavities to achieve head-on beam-beam collisions were proposed for the LHC HiLumi upgrade. These crabbing schemes require that the crab cavities be compact in order to fit into the tight spacing available in the existing LHC beamlines at the location where the crab cavities will be installed. Under the support of US LARP program, Old Dominion University (ODU) and SLAC have joined efforts to develop a 400-MHz compact superconducting crab cavity to meet the HiLumi upgrade requirements. In this paper, we will present the RF modeling and analysis of a parallel-bar/ridged-waveguide shaped 400-MHz compact cavity design that can be used for both the horizontal and vertical crabbing schemes. We will also present schemes for HOM damping and multipacting analysis for such a design.

INTRODUCTION

A crabbing scheme [1] has been adopted as the baseline tool for the LHC HiLumi upgrade. The nominal scheme for the HL-LHC is the local crabbing with the 400 MHz superconducting deflecting cavities. The luminosity increase due to the implementation of crab cavities is expected to be up to 16% and 63% for nominal β* of 55cm and upgrade β* of 25cm respectively. In the local crabbing scheme, the available horizontal space for the crab cavity is limited to a 150-mm radius due to a small beam-to-beam separation. This limitation also applies to the vertical dimension as the cavity would also be installed at a different IR to perform vertical crabbing (rotate cavity by 90 degrees about beam axis). Because of this tight space limitation, a conventional elliptical design at 400-MHz would not fit. To meet such a design requirement, significant effort has been devoted in the RF design to develop a compact cavity at 400-MHz. Exotic cavity shapes have been explored among various design teams. With the support of the US LARP program, ODU and SLAC have joined efforts on a common compact design which was evolved from two different design concepts [2,3,4].

The cavity shape in consideration is shown in Figure 1. The deflection is on the plane of the double ridges. The operating mode is a TE11 like mode. The electric field is enhanced in the gap of the two ridges which contributes to most of the deflection. Table 1 presents the major geometry and RF parameters of two slightly different shapes. Three cavities will be needed per beam to produce up to 10-MV deflecting voltage. The peak surface electric and magnetic fields at the maximum deflecting voltage are 36-MV/m and 60-mT respectively, both are considered readily achievable.

HOM damping is essential to maintain beam stability. In the present design, there are no lower order modes (LOM) as compared to conventional designs, which is advantageous for the design of damping of unwanted modes. In this paper we present the RF modeling of the cavity using the parallel suite ACE3P, especially focusing on the two HOM damping schemes under consideration and the multipacting analysis of the cavity.

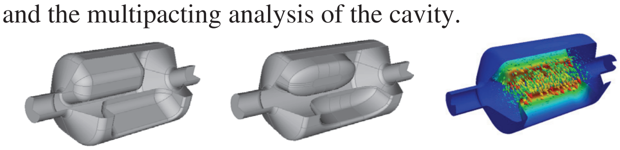

Figure 1: Double ridged crab cavity: Model-1, Model-2 and electric field between the two plates.

Table 1: Crab Cavity RF Parameters

Parameters	Model-1	Model-2
Operating mode Frequency	400 MHz	400 MHz
Operating Mode	TE11 like mode	TE11 like mode
Lowest accelerating mode Frequency	731 MHz	714 MHz
Lowest vertical HOM Frequency	784 MHz	757 MHz
Lowest horizontal HOM Frequency	594 MHz	612 MHz
Iris aperture (diameter)	84 mm	84 mm
Transverse dimension	295 mm	281 mm
Vertical dimension	295 mm	288 mm
Longitudinal dimension	620 mm	638
Transverse Shunt Impedance	323 ohm/cavity	339 ohm/cavity
Required deflecting voltage per cavity	3.3 MV	3.3 MV
Peak surface magnetic field	55 mT	59 mT
Peak surface electric field	36 MV/m	30 MV/m

* This work was supported by DOE Contract No. DE-AC02-76SF00515 and was partially supported by the DOE through the US LHC Accelerator Research Program (LARP). Computations used computer resources at NERSC, LBNL.
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ISBN 978-3-95450-115-1

FIELD UNIFORMITY

The deflecting field in the compact design has certain amount of non-uniformity in the beam region. Fig 2 shows the E and B field profiles at the center cross section of the cavity. A multipole analysis yielded a position dependence of the deflecting voltage to the second order (*x,y* in mm) as shown in Eq. 1. A second order vertical deflecting voltage also exists due to the field non-uniformity. These values are roughly 1% at a radius of 10-mm for the present design. The requirement on the field non-uniformity is yet to be analysed. The pole shape could be optimized should a more uniform field is required.

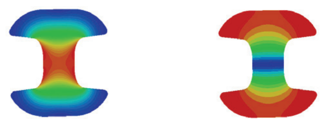


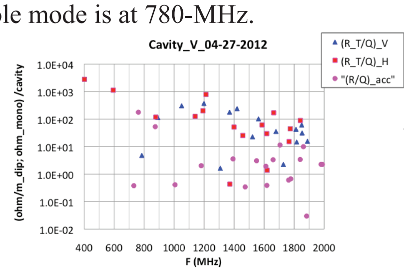
Figure 2: E and B field profile at center cross section.

$$V_X(x,y) = 1.0 + 0.953\times10^{-4}(x^2 - y^2) \quad (1)$$
$$V_Y(x,y) = -1.905\times10^{-4}xy$$

HOM DAMPING

Mode Spectrum

The mode spectrum was calculated using Omega3P. The impedance spectrum up to 2-GHz frequency is shown in Fig 3. All the HOM frequencies are well above that of the operating dipole mode. The first HOM is a horizontal dipole mode which is at around 600-MHz. The first accelerating mode is at 760-MHz and the first vertical dipole mode is at 780-MHz.



$$\frac{R_{shunt}}{Q} = \frac{|V_z|^2}{\omega U}$$
$$\frac{R_T}{Q} = \frac{\omega}{c}\left(\frac{|V_z(r_0)|^2}{\omega U (r_0\omega/c)^2}\right)$$

Figure 3: Mode spectrum.

Damping Schemes

Effective damping is required to preserve beam quality and stability. The large separation of HOMs from the operating mode allows more options in the design of damping schemes. We have explored two damping designs as shown below – the waveguide coupler and the high-pass filter coaxial coupler.

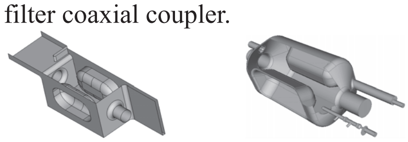


Figure 4: Waveguide and coaxial damping schemes.

Waveguide damper. The waveguide damping scheme utilizes a narrow rectangular waveguide that couples to the cavity at the end plate. The cutoff of the waveguide is around 550-MHz so that the operating mode will not propagate while all the HOMs can be damped. One damping waveguide would be sufficient to provide the damping needed for each of the *x* and *y* planes. However, one may want to add a symmetrising stub to maintain field symmetry. Figure 5 shows the coupling of the coupler to the lowest HOM accelerating mode and horizontal dipole mode. The Qext of the HOMs is shown in Figure 7. A strong damping was achieved using waveguide couplers.

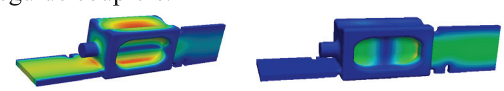


Figure 5: Damping of HOMs via waveguide couplers.

Coaxial coupler. A pair of high-pass coaxial couplers is required on the deflecting plane to reject the operating mode. The damper on the other plane will utilize a pair of regular coaxial couplers as they do not couple to the operating mode. A preliminary two-stage high-pass filter coax coupler is shown in Fig 6. The RF transmission has a stop band at the operating frequency and has a good broadband transmission above the first HOM frequency. The Qext of HOMs with the coaxial couplers is summarized in Fig. 7, which has a higher Qext in general as compared with the waveguide couplers.

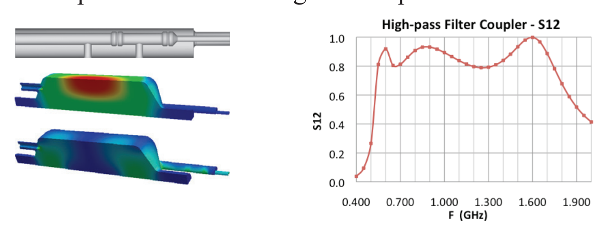


Figure 6: Two stage high-pass coaxial coupler for HOM damping.

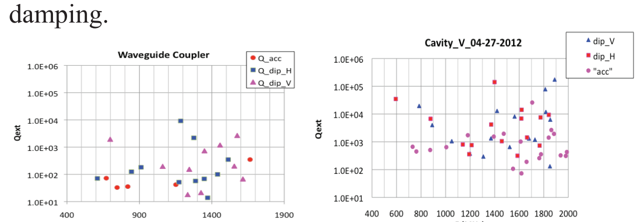


Figure 7: Damping Qext. Left) waveguide coupler; Right) coaxial coupler.

Impedance

The impedances of the HOMs ((R/Q)*Qext) are summarized in Fig. 8 (slightly different cavities between the two plots). The solid lines are the impedance budget for dipole HOMs (blue) and accelerating HOMs (purple) respectively. All the modes are well damped with the waveguide couplers. The impedances of a few modes in the coaxial damping scheme are higher than the design requirement due to higher Qext. Further optimization is needed in the high-pass filter design to bring the high Qext modes down to an acceptable level.

MP SIMULATION USING TRACK3P

Multipacting (MP) is an issue of concern for superconducting resonators that may cause prolonged processing time or limit the achievable design gradient.

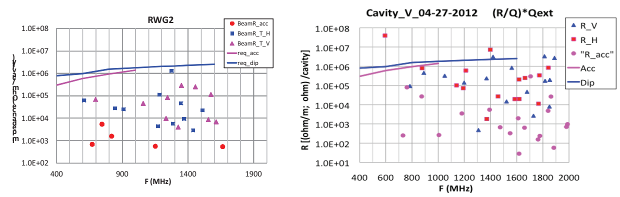


Figure 8: Impedance of the HOMs. Left) waveguide coupler damping; Right) coaxial coupler damping.

While most of the MP bands may be conditioned with RF, hard MP barriers may prevent the resonators from reaching the design voltage. Elimination of potential MP conditions in the cavity design could significantly reduce time and cost of conditioning and commissioning.

Multipacting analysis for the compact cavity with the coaxial damping couplers were carried out using Track3P. Track3P is a 3D particle tracking code in an unstructured finite-element mesh [5,6,7]. In a typical MP simulation, electrons are launched from specific surfaces at different phases over a full RF period. The initial launched electrons follow the electromagnetic fields in the structure and eventually hit the boundary, where secondary electrons are emitted. The tracing of electrons will continue for a specified number of RF cycles, after which MP trajectories are analyzed and the MP type (order: # of RF cycles to return to original site; point: # of sites per MP cycle) identified. MP involves particles with trajectories resonating with the RF. These particles will impact the surface at the same locations with constant energy. Those trajectories with impact energies within the range of secondary emission yield (SEY) larger than unity will be considered MP events. One can use the SEY curve (Fig 9) to estimate the MP strength.

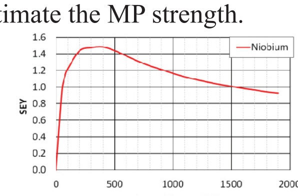


Figure 9: SEY dependence on impact energy for Niobium.

MP SIMULATION RESULTS

The field level was scanned up to 6-MV of deflecting voltage with a 0.15-MV interval. At each field level, 50 RF cycles were simulated for obtaining the parameters of the resonant trajectories. There are three major MP bands identified in the cavity. No significant MP condition was found in the coupler region.

MP Band from 0.5MV to 2.6 MV Deflecting Voltage

The resonant particles of this MP band are on the end plate as indicated by the purple circle in Fig 10. The trajectories are of one-point and of various MP orders. The impact energies of this MP band are around the peak SEY for Niobium. It could be a noticeable MP band in RF processing. We plan to modify the shape of the end plate to minimize these resonant conditions.

MP Band from 1.8-2.8MV Deflecting Voltage

The resonant particles of this MP band are mostly in the rounding corners of the cavity side (red circle region). These are first order and second order MPs with impact energies on the lower side of the SEY curve. It could yield a significant SEY, but is relatively softer than the previous one.

MP Band from 3-6MV Deflecting Voltage

The resonant particles of this MP band are in the end-plate rounding corners (cyan region). The MP is of the first order with low impact energies. It is not expected to be a strong barrier. The nominal operating voltage is 3.3-MV, which is in this MP band.

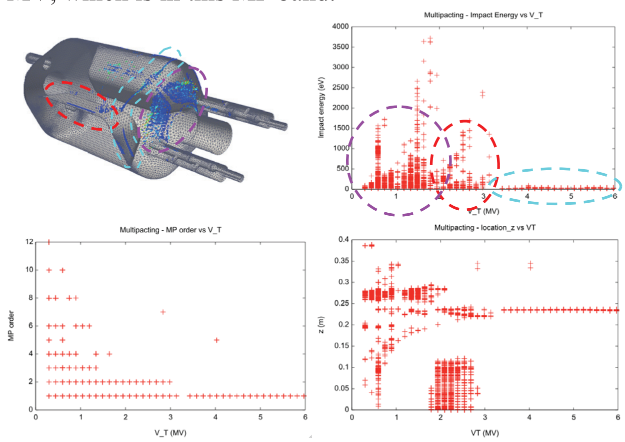


Figure 10: Multipacting conditions at different deflecting voltages.

SUMMARY

A compact crab cavity has been developed with a joint effort between ODU and SLAC. Preliminary damping schemes with waveguide and coaxial couplers are being developed. Effective damping is shown achievable with both damping schemes. Multipacting analyses were carried out and three MP bands were identified. There is no significant MP at the operating voltage. Further design optimizations on HOM damping and suppressing multipacting are underway.

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ISBN 978-3-95450-115-1