A COMPACT ALTERNATIVE CRAB CAVITY DESIGN AT 400-MHz FOR THE LHC UPGRADE *

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Abstract

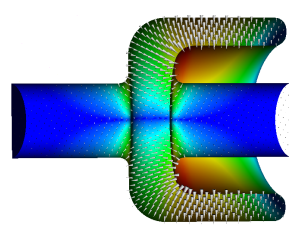
Crab cavities are proposed for the LHC upgrade to improve the luminosity. In the local crabbing scheme, the crab cavities are located close to the interaction region and the transverse separation between the two beam lines at the crab cavity location can only accommodate an 800-MHz cavity of the conventional elliptical shape. Thus the baseline crab cavity design for the LHC upgrade is focused on the 800-MHz elliptical cavity shape although a lower frequency cavity is preferable due to the long bunch length. In this paper, we present a compact 400-MHz design as an alternative to the 800-MHz baseline design. The compact design is of a half-wave resonator (HWR) shape that has a small transverse dimension and can fit into the available space in the local crabbing scheme. The optimization of the HWR cavity shape and the couplers for the HOM, LOM, and SOM damping will be presented.

INTRODUCTION

A small angle (0.3~0.5mrad) crab scheme has been proposed for the LHC to realize beam-beam head-on-collisions to increase the luminosity by a factor of 3-10 via an IR upgrade [1,2]. The available location on the LHC beamline where crab cavities could be installed has limited transverse space. In the local crabbing scheme in particular, the crab cavities are located close to the interaction region and the transverse separation between the two beam lines at the crab cavity location can only accommodate an 800-MHz cavity of the conventional elliptical shape. Thus the 800-MHz elliptical cavity shape[3] has been adopted as the baseline design for the LHC upgrade. The size of the 800-MHz cavity could fit into the tight space between the beam lines at the proposed crab cavity locations. Cavities with frequencies higher than 800-MHz will produce significant non-linearity in the crabbing kick along the bunch and cannot be considered. The luminosity increase due to the implementation of the 800-MHz crab cavity is expected to be 12% and 43% for nominal β^* of 55cm and upgrade β^* of 25cm respectively. However, lower frequency cavities are preferable since they will produce more linear transverse kick along the bunch. For example, with a 400-MHz cavity, the luminosity could be improved over the 800-MHz by about 6% and 20% for the nominal and upgrade β^*s respectively. The size of the 400-MHz of the conventional elliptical shape would be roughly twice as large as the 800-MHz cavity and cannot fit into the available space of the LHC beamlines. We have investigated a compact 400-MHz half-wave resonator (HWR) design as an alternative to the 800-MHz baseline design. This compact cavity is of a coaxial shape that has a small transverse dimension and can fit into the available space in the local crabbing scheme. In this paper, we present the optimization of the 400-MHz HWR cavity shape, the SOM, LOM, HOM damping couplers, and the analysis and mitigation of multipacting.

CELL PROFILE

Deflecting cavities typically operate with the TM110 dipole mode in the horizontal plane to provide transverse kick to the beam. In the case of crab cavity application, the beam is in phase quadrature with the RF so that there is no kick to the bunch center but the head and the tail of the bunch get kicks in the opposite directions. The bunch gets rotated around the bunch center, crabbed, as it travels down the beamline. The compact 400-MHz design in consideration is a half-wave resonator (HWR) coaxial shaped cavity. The operating mode is of the TM110 like. The length of the coaxial cavity is roughly half wavelength as shown in Figure 1. The cell profile is optimized to minimize the surface electric and magnetic fields. The dipole TM110 modes are degenerate in an azimuthally symmetric cavity. In order to reduce the mode coupling between the operating mode (horizontal) and the unwanted same order mode (SOM) (vertical), the cavity geometry is squashed to break the symmetry. The squash induces a mode separation of about 60-MHz between the operating mode and the SOM. The shorter axis of the squashed geometry is in the horizontal plane, the crabbing plane, to minimize the transverse dimension. The RF parameters of the HWR crab cavity are shown in Table 1.



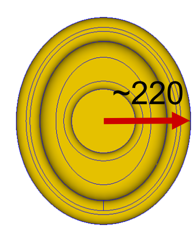


Figure 1: Cell profile of the half wave resonator 400MHz crab cavity. Left: cavity z-y cross section, the arrows show the mode pattern of the electric field; Right: cavity x-y cross section shown the squashed shape to split the degeneracy of the x and y polarized dipole modes.

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Table 1: RF parameters of the 400-MHz HWR crab cavity

Operating mode Frequency	400 MHz
Operating Mode	TM11
Same-Order Mode Frequency	342 MHz
Iris aperture (diameter)	160 mm
Transverse Shunt Impedance	47 ohm/cavity
Deflecting voltage per cavity	1.5 MV
Peak surface magnetic field	89 mT
Peak surface electric field	42 MV/m

MULTIPACTING SIMULATION USING TRACK3P

Multipacting is an important issue in superconducting cavities that could cause difficulties in high power process and/or even limit the achievable gradient. The multipacting of the crab cavity is analyzed using the Track3P code [4,5]. Track3P is a parallel 3D particle tracking code on the finite element mesh. The mesh with curved elements fitted to the curvature of the boundary allows high-fidelity modeling of the geometry which is important for particle emission and accurate surface field calculation. The RF fields for the particle tracking are imported from SLAC's finite element field solvers [5,6], Omega3P for resonant mode, S3P for traveling wave, and T3P for transient RF excitation as these codes share the same data structure. The Track3P simulation analyzes resonant conditions of particle trajectories, and calculates multipacting maps using impact energy and SEY data of the surface material. In a typical multipacting simulation, electrons are launched from specific surfaces at different RF phases over a full RF period. The initially launched electrons travel in the electromagnetic fields and some eventually hit the boundary, where secondary electrons are emitted based on the secondary emission yield (SEY, see Figure 3 for Niobium) of the surface material. The tracing of electrons will continue for a specified number of RF cycles, after which resonant trajectories are identified. Not all of these resonant trajectories contribute to multipacting. Only those with successive impact energies within the range of secondary emission yield larger than unity will be considered as multipacting events.

MULTIPACTING IN ELIPTICAL COAXIAL CELL DESIGN

Multipacting simulations were performed on the elliptical cell profile shown in Figure 1. The electrons were seeded on the whole structure surface and tracked up to 20 cycles to search for resonant trajectories. The deflecting voltage was scanned up to 2.0 MV per cavity. Most of the resonant trajectories were found on the outer cavity wall around the electric symmetry plane (vertical plane where E=0) as shown in Figure 2. There are also resonant trajectories in the two sections of the beam pipe close to the cavity, also on the electric symmetry plane. Figure 3 shows the distribution of impact energies of the resonant trajectories as a function of the deflecting voltage. The cavity geometry supports resonant impacts at a broad range of deflecting voltages. The impact energies of these trajectories cover the range of 200 to 400 eV where the secondary yield is maximum for Niobium as shown in Figure 3. These results indicate that there are potentially strong multipacting barriers at these voltage levels, which may cause the structure prolonged processing time or quench.

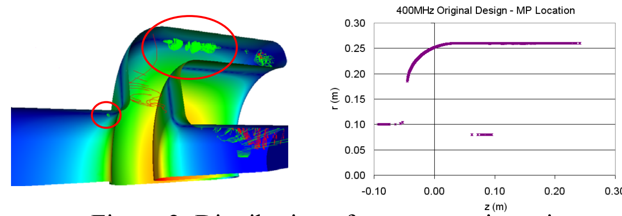

Figure 2: Distribution of resonant trajectories.

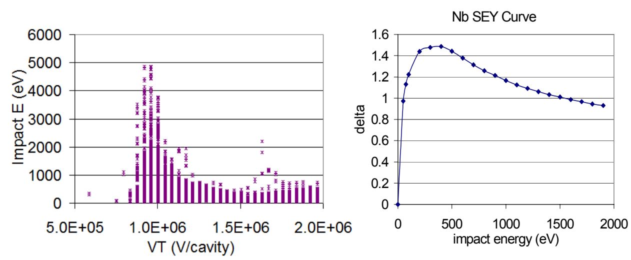

Figure 3: Left: impact energies of resonant trajectories versus deflecting voltage; Right: typical SEY distribution for Niobium. The SEY peaks at around 200-400 eV.

GEOMETRY OPTIMIZATION TO ELIMINATE MP

Certain conditions need to be met for multipacting to exist: 1) to have resonant trajectories; and 2) the impact energies of these trajectories are in the range of high secondary yield (larger than one). Thus the multipacting issue could be mitigated through careful design of the geometry to eliminate the resonant trajectory conditions or to shift the impact energy of the electrons to a lower secondary yield region. The challenge however is that the optimized cavity shape need to suppress multipacting in all the gradient levels up to (higher than) the operating gradient, no hard mutipacting barriers should exist in this gradient range.

The resonant trajectory conditions depend on the local field distributions as well as the E and B ratio. For the 400 MHz HWR cavity design, the resonant trajectories on the outer cavity wall were effectively eliminated by reducing the curvature of the outer wall and by reducing the spacing between the inner and outer walls as shown in Figure 4. The outer wall in the modified design is of a racetrack shape while the inner wall still of elliptical. The resonant trajectories on the beampipe were effectively removed by adding a groove in the multipacting region. The groove on one side of the beam pipe is replaced by the HOM coupler waveguide. The width of the groove and HOM coupler is chosen as 40 mm. The rounding around the groove/HOM opening is chosen such that there is no flat region between the cavity and the groove/HOM. The multipacting simulation results of the modified geometry are shown in Figure 4. Notice that there are only a sparse distribution of resonant trajectories and the impact energies are mostly below 100-eV, which is a significant improvement over the original elliptical cell profile. No multipacting found in the HOM and LOM/SOM couplers.

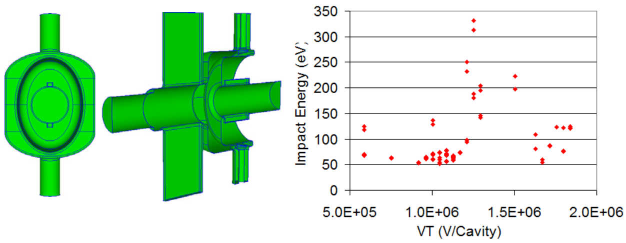

Figure 4: Left: optimized cavity shape that eliminates the multipacting trajectories; Right: impact energy of resonant trajectories as a function of deflecting voltage.

HOM, LOM, AND SOM DAMPING

To achieve a clean crabbing to the bunches, effective wakefield damping is crucial. In addition to the higher order modes (HOM), the lower order TM010 mode (LOM) and the same order mode (SOM) also need to be damped. Preliminary beam dynamics studies suggested that the damping Qext for the high R/Q LOM, SOM and HOM modes need to be below 250 [1,2].

The damping of the LOM and SOM modes are realized using a combined coax-probe coupler placed at the electric node of the operating mode on the outer wall. Both the LOM and SOM modes couple to the TEM mode of the coupler while the TM110 operating mode couples to the TE11 mode of the coax which is cutoff at 400-MHz. So the coupler naturally rejects the operating mode and no filter is needed, which is advantageous in higher power handling capability as the LOM modes may result in significant beam loading. The HOM coupler is a waveguide coupler placed on the beam pipe in the vertical plane along the beamline axis. With this orientation, the coupler can effectively couple to the horizontal dipole mode. The cutoff of the HOM coupler is above 400 MHz so that the operating mode will not be damped by this coupler. The beampipe in the HOM coupler region is enlarged to enhance HOM damping. The cavity with the proposed damping scheme is dispatched in Figure 4. (The input coupler is a coaxial type coupler on the end beam pipe which is not shown in Figure 4). The mode spectrum and damping results up to the beam pipe cutoff frequency (1.1-GHz) are shown in Figure 5. Figure 6 shows the field patterns of the high R/Q LOM, SOM and HOM modes and the damping of these modes via respective couplers.

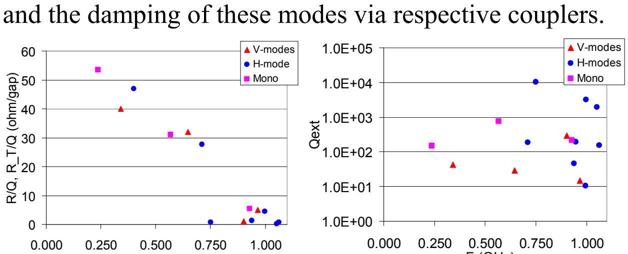

Figure 5: The shunt impedance R/Q and damping results for the LOM, SOM, and HOM modes.

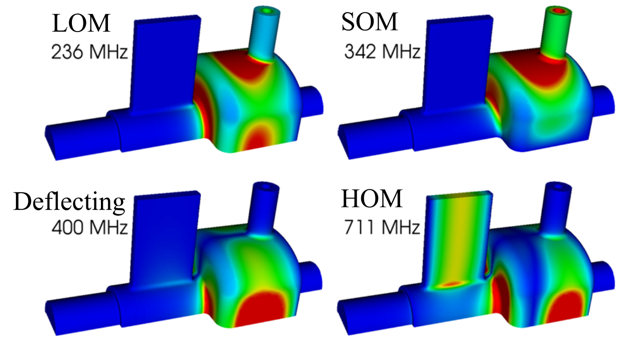

Figure 6: The LOM and SOM are damped by the combined coaxial coupler; the HOM is damped by the waveguide coupler; and the operating mode is not affected by these couplers.

SUMMARY

A compact 400-MHz design was presented as an alternative to the 800-MHz baseline design. The compact design is of a half-wave resonator shape that has a small transverse dimension and can fit into the available space in the local crabbing scheme. The HOM and LOM/SOM couplers were optimized to effectively damp the unwanted modes. The HWR cavity shape was optimized to eliminate the potential multipacting barriers.

ACKNOWLEDGMENTS

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REFERENCES

[1] LHC web and LHC/crab Wiki
[2] R. Calaga, et al, "Status of LHC Crab Cavity simulations and beam studies", this proceedings.
[3] L. Xiao, et al, "800MHz Crab Cavity Conceptual Design for the LHC Upgrade", this proceedings.
[4] C.-K. Ng, et al, "Simulating Dark Current in NLC Structures", Nucl. Instru. Meth. A558, 192 (2006).
[5] L. Ge, et al, "Multipacting simulations of TTF-III Power Coupler Components," Proc. of PAC07, Albuquerque, New Mexico, 2007.
[6] K. Ko et al, SciDAC and the International Linear Collider: Petascale Computing for Terascale Acelerator, Proc. SciDAC 2006 Conference, Denver, Colorado, June 25-29, 2006.
[7] L.-Q. Lee, et al, "Enabling Technologies for Petascale Electromagnetic Simulations", Proc. of SciDAC 2007, Boston, Massachusetts.
[8] http://www.scidac.gov.
[9] http://nccs.gov.
[10] http://www.nersc.gov.