A QUARTER WAVE DESIGN FOR CRAB CROSSING IN THE LHC *

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Abstract

The aperture constraints of the LHC interaction region and the alternating crossing schemes at two collision points calls for a superconducting (SC) deflecting cavity with very compact dimensions at low frequencies for the purpose of crab crossing. A new concept of using a superconducting quarter wave like design, ideally suited to address the LHC constraints at 400 MHz, is proposed. The optimized RF cavity design and associated advantages of using a quarter wave resonator are presented. Higher order modes and frequency tuning of the cavity are also presented.

INTRODUCTION

Crab crossing for the luminosity upgrade in the LHC requires transversely compact cavities at a frequency of 400 MHz [1]. Alternating crossing angles at the two high luminosity interaction regions (IRs) further require that the cavities are compact in both transverse planes to be compatible for both IRs. The beam pipes at the location of the crab cavities, immediately after the separation dipole (D_2) are only 194 mm apart. The large β-function at this location requires an aperture of approximately 84 mm. Given these boundary conditions, the maximum cavity envelope cannot be greater than 150 mm to be compatible with the LHC IR footprint.

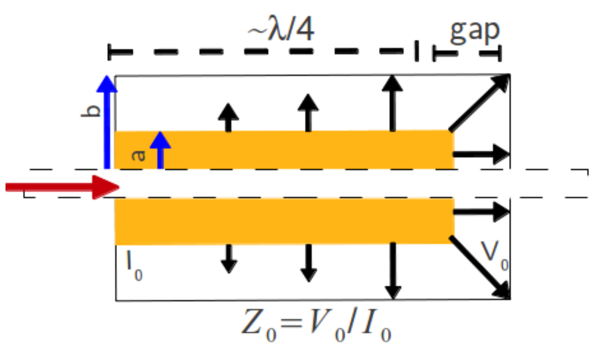

Figure 1: Schematic of a simple quarter wave resonator and representative electric field arrows in a longitudinal configuration.

The natural starting point is a basic coaxial quarter wave TEM resonator which is most compact in its class. As shown in Fig. 1 the quarter wave TEM line is electrically terminated at one end and open at the other at about a quarter wavelength of the fundamental mode frequency. At resonance, a high voltage is developed at the open end. The longitudinal configuration shown in Fig. 1 is typically used for acceleration of high-β particles and a vertical configuration for low-β applications. Due to it compactness and simple design over a large velocity range, it is widely used in low velocity ion acceleration where other cavities concepts are less efficient. A comprehensive review of superconducting quarter wave cavities, describing their advantages and applications can be found in Ref. [2, 3].

QUARTER WAVE FOR DEFLECTION

The high voltage across the gap with the appropriate orientation can also be used to impart a transverse deflection or crab the beam. Due to the asymmetry of the quarter wave, the distance between the beam center to the bottom base plate can be made as compact as required. However, a non-zero longitudinal voltage is inevitable with the same phase as the crabbing mode [2]. A pedestal on the base plate (see Fig. 2) at the open end along with shaping of the inner conductor can be used to suppress this longitudinal voltage. The presence of the pedestal in some cases also improves the deflection performance. Fig. 2 also shows the parametrization of the cavity for optimization studies.

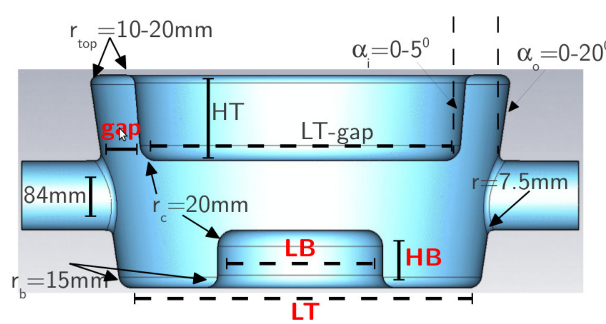

Figure 2: Cross section of the quarter wave with geometrical parametrization.

Cavity Optimization

For efficient deflection and reasonable surface fields, the cavity length *LT* should be close to $\beta\lambda/2$. During design optimization of the 400 MHz quarter wave cavity several topologies were studied of which three are shown in Fig. 3. The ellipticity in the transverse plane was adjusted to always fit within the 150 mm envelope and stay clear of the adjacent beam pipe for a vertical orientation to provide a vertical deflection. For the deflection in the horizontal plane, it is sufficient to keep the bottom pedestal small. 3D

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electromagnetic code CST-Microwave studio was used for optimization studies.

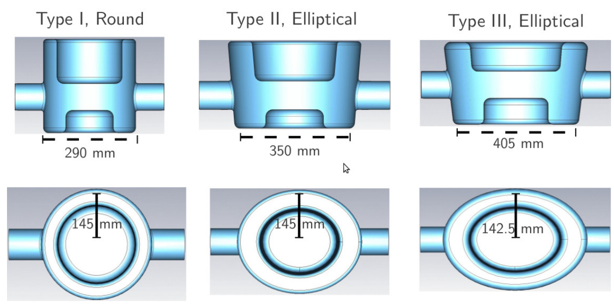

Figure 3: Longitudinal cross sections and top views of the quarter wave geometries.

The first optimization step was performed for the type I round geometry with a maximum cavity envelope radius of 145 mm. The cavity wall angles α were set to zero with a gap length of 42.5mm. Fig. 4 show the magnetic field contours as a function of bottom pedestal length and height with frequency tuned to 400 MHz. Only 20% improvement is seen in the surface magnetic field and even smaller improvement in the electric field. A minimum accelerating voltage normalized to the deflecting voltage of 27% remains to be compensated.

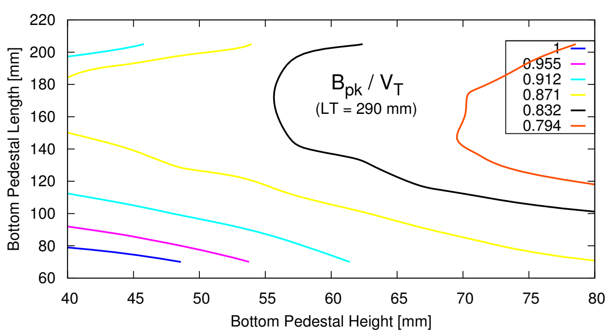

Figure 4: Magnetic field contours for varying pedestal height and length for the round cavity geometry with $LT = 290mm$.

As a next step, improvement of the both surface fields and accelerating field were accomplished by lengthening the structure, but with an elliptical profile. Ellipticities between 1.2 (type II like) to 1.5 (type III like) were used. With careful length tuning of *LT* and *LB* and a sufficient pedestal height (80mm), the acceleration can be completely suppressed as illustrated in Fig. 5. However, a smaller ellipticity (i.e. shorter structure) is preferred for better surface electric field performance.

A highly eccentric shape can add to manufacturing complexity and lead to loss of mechanical stability. A proportional reduction of the gap at a high magnetic field region for a fixed gap due to the ellipticity is inevitable. Therefore, a slightly shorter cavity than the zero suppression is chosen at the expense of a small residual accelerating voltage. Further improvement of the surface fields were accomplished by increasing the gap within the inner and outer conductors and appropriate smoothing of edges. A wall angle, α, is introduced on the inside and outside walls for the same purpose which may in addition help for multipacting suppression. Multipacting trajectories and their onset as a function of surface field for the three geometries are discussed in Ref. [4]. Table 1 shows a list of the geometrical parameters (see Fig. 2) for each of three geometries reaching fairly optimized values.

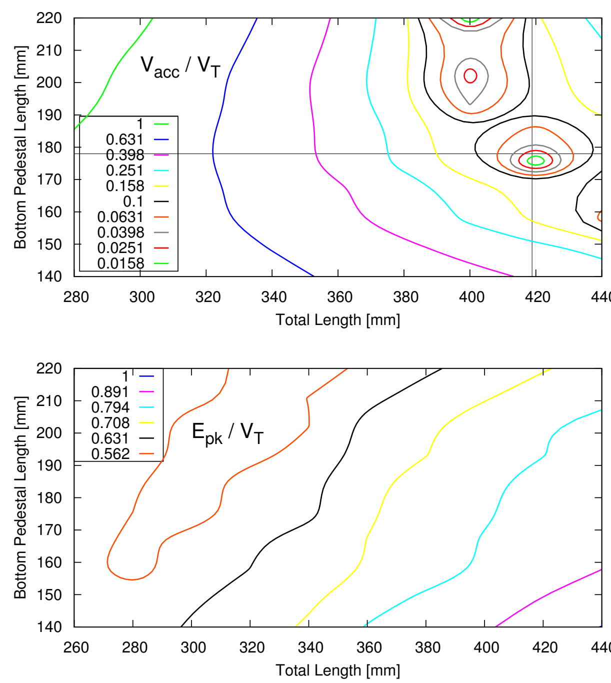

Figure 5: Contour plots of accelerating voltage and peak electric field normalized to deflecting voltage as a function of *LT* and *LB*

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Table 1: Geometrical parameters for the three geometries reaching fairly optimized RF performance. The beam pipe diameter of 84 mm was used

	unit	Type I	Type II	Type III
LT	[mm]	290	350	405
LB	[mm]	160	170	209
HB	[mm]	60	55	80
Gap	[mm]	42.5	60	60
$\alpha_{i,o}$	[deg]	0/0	5/10	4.7/20
HT	[mm]	139.5	117.2	90.2
r_{top}, r_b, r_c	[mm]	10,15,20	10,15,20	20,15,20
Ellipticity		1.0	1.21	1.42

The corresponding RF performance for the three geometries are listed in Table 2. This comparison table is representative of the evolution towards a type III like optimum geometry with good surface field to kick voltage ratio. The transverse and longitudinal fields along the beam axis are plotted in Fig. 6. It should be noted that a 5mm negative vertical offset is also sufficient to completely suppress the

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residual accelerating voltage which could serve as the reference axis. The type III topology should be compared to the KEKB conventional TM_{110} type cavity with 34 MV/m and 97 mT surface fields for a 3 MV transverse voltage, but at approximately 4 times the transverse size.

Table 2: RF parameters for the three geometries reaching fairly optimized RF performance

	unit	Type I	Type II	Type III
Frequency	[MHz]		400	
Next Mode	[MHz]	646	665	657
V_T	[MV]		3.0	
R/Q	[Ω]	259	319	345
E_{pk}	[MV/m]	50	42	43
B_{pk}	[mT]	120	81	61
V_a $(z = 0)$	[MV]	0.74	0.67	0.12

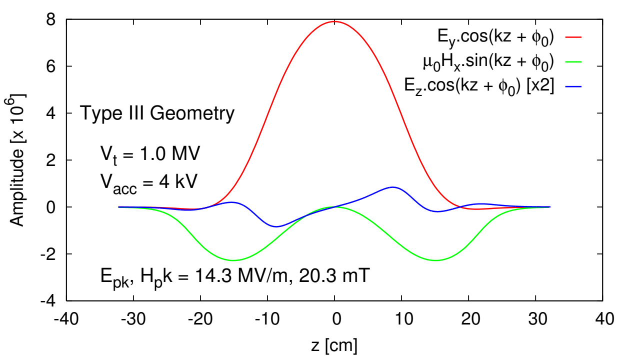

Figure 6: Transverse and longitudinal fields along the beam axis for type III cavity.

Higher Order Modes

The distinct advantage of the quarter wave is the large separation of the fundamental mode from the higher order modes (HOMs). This immediately allows for a simpler damping scheme and permits the use of a more robust high pass filter [4]. Unlike series LC resonant circuit (notch filter), a multi-stage filter does not rely on precise tuning of a narrow resonance and thus is less sensitive to manufacturing imperfections. All three topologies have the first HOM spaced at least 240 MHz away from the operating mode (see Table 2). Due to the asymmetry and the presence of the beam pipes, the modes are a hybrid mix of longitudinal and transverse components with one being dominant. Some purely longitudinal or transverse modes also exist. The cavities have a vertical symmetry plane perpendicular to the beam axis, but it is less useful to classify modes along this azimuth. Figure 7 shows the longitudinal and transverse R/Q for HOMs up to to 2 GHz. The empty circles correspond to the hybrid component of the non-dominant component which is usually negligible.

Using the impedance criteria in Ref [1], a Q_{ext} of 500-1000 for both longitudinal and transverse modes should be sufficient to stay well within the impedance budget. Damping simulations with two to four HOM couplers are underway [4].

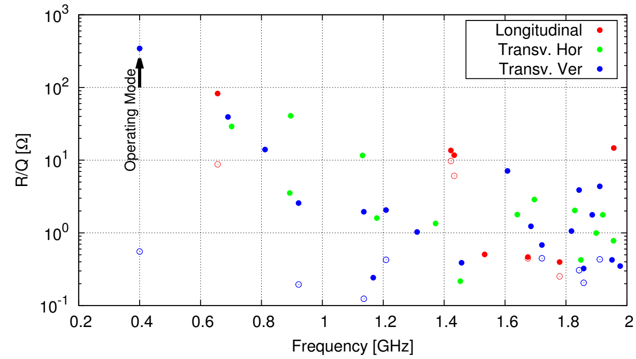

Figure 7: $R/Q_{||/\perp}$ usually the standard definition of $V^2_{||/\perp}/(\omega U)$ for HOMs up to 2 GHz.The empty circles correspond to the non-dominant component of a hybrid mode.

Cavity Tuning

The cavity compactness requirements also extends to the tuning system which has to fit within the IR region constraints. The azimuthal symmetry around the vertical axis naturally leads to push-pull mechanism on the inner resonators. A change of the semi-major axis by 1mm or a movement of 1mm in vertical direction of the top plate results in a frequency shift of approximately 1.5-2 MHz. Therefore, a stable tuning system along with mechanical stiffeners on the flat part of the inner conductors will be needed to minimize frequency perturbations from external vibrations. For fine tuning, only a small section of the top plate can be moved selectively. For example, a 40 mm section results in a change of approximately 50 kHz/mm.

CONCLUSION

A compact SC deflecting quarter wave resonator ideally suited for crab crossing in the LHC is designed. An optimization study leading to the type III geometry with low surface fields and minimum longitudinal voltage is proposed for a Niobium prototype. The HOMs frequencies and their R/Q values up to 2GHz were identified. The large frequency separation of 240 MHz or more between the operating mode and the HOMs allow for robust damping scheme using high pass filters. Frequency tuning concepts for both vertical and horizontal perturbations to the cavity geometry are under investigation.

REFERENCES

[1] R. Calaga, LHC-PW Workshop, Chamonix, 2012.
[2] I. Ben-Zvi, in the proceedings of SRF2011, Chicago, 2011;
[3] I. Ben-Zvi et al., presented at LHC-CC10, CERN, Geneva, 2010.
[4] Q. Wu et al., these proceedings.