INVESTIGATION OF A RIDGE-LOADED WAVEGUIDE STRUCTURE FOR CLIC X-BAND CRAB CAVITY

V.F. Khan, R. Calaga and A. Grudiev
CERN, Geneva, Switzerland

Abstract

In conventional crab cavities the TM_{11} mode is used to deflect the beam. It is necessary to damp all the other modes, namely the accelerating i.e. lower order mode (LOM), same order mode (SOM) and higher order modes (HOMs). In addition to this, as the TM_{11} mode is not the fundamental mode, it is generally not excited with the highest shunt impedance. This necessitates damping of the high shunt impedance modes to acceptable level. Here we report on the investigation of an alternative design of the X-band crab cavity for CLIC, based on ridge-loaded waveguide. In this type of cavity, the deflecting mode is the fundamental mode and has the maximum shunt impedance. However, the geometry of the cavity is chosen to optimise the ratio of group velocity to shunt impedance to minimise the effect of beam loading. The other modes are excited above the crabbing mode and are damped using wave-guides of appropriate cut-off frequency. Other advantages are: contribution of the higher order dipole modes is negligible and no SOM. However, the higher order monopole mode needs damping.

INTRODUCTION

In linear colliders such as CLIC, multi-bunch particle beams are designed to collide at a small crossing angle to avoid unwanted collisions. Deflecting or crab cavities are used to maximise the luminosity by tilting the bunches. In general, conventional disc loaded cavities are used to excite a dipole mode to deflect the beam. However, in such cavities other modes also exist that need to be damped. These modes are: the LOM that is excited below the operating dipole mode, this mode is the fundamental TM_{010} mode. The SOM which has the same frequency as the operating mode but has a different polarisation and the HOMs. The baseline design for CLIC crab cavity relies on this conventional method [1]. The LOM, SOM and HOMs are damped using waveguide damping method. However, due to the fact that the LOM is excited below the operating mode, waveguide cut-off method cannot be used for fundamental mode rejection from the damping waveguides. Instead, symmetry of the mode has to be used. This makes the geometry more sensitive from the fabrication tolerances point of view.

In this paper we discuss possibility of using a ridge loaded waveguide type structure to deflect the beam. The geometry of this structure is similar to that of a waveguide with periodic ridges from the top and bottom sides. The vertical gap between the two ridges forms an aperture for the beam propagation. Herein, the deflecting E-field is generated from ridge to ridge. In this case, the deflecting mode is the fundamental mode with the lowest frequency. There are no LOM and SOM excited; the HOMs excited in this case are damped using a cut-off waveguide damping method. The geometry of the ridge and the cavity shape are optimised for an acceptable beam loading at a realistic offset of the beam. The rf requirements of the CLIC crab cavity are discussed in the next section. A detailed optimisation procedure for the ridge loaded crab cavity and the damping scheme are elaborated in the following sections. The final section concludes our analysis of the alternative design.

CLIC CRAB CAVITY REQUIREMENTS

The nominal CLIC beams of 1.5 TeV, crossing at an angle of 20 mrad need a maximum of 2.55 MV of kick voltage [2]. At an operating frequency of 11.994 GHz and a standard phase advance (SPA) of $2\pi/3$, ~20 MV/m transverse gradient in a structure of 15 cells gives the necessary kick. Though crab cavities are designed for deflecting the beam, for realistic offsets there will be some acceleration of the beam and associated beam loading of the cavity. This causes change of the amplitude and corresponding phase error. An error in the rf amplitude leads to an error in the crossing angle and an error in the phase causes a transverse offset in the bunch centre at the IP [3]. These errors should therefore be minimized together with the beam loading effect hence a travelling wave (TW) structure is a natural choice [3]. The structure should be designed such that the beam loading power is much lower than the high input power required to maintain the deflecting fields. The acceptable limit of beam loading (amplitude error) in CLIC is 2% for a luminosity loss of 2% [2]. The geometric optimisation is entirely governed by the beam loading criterion. The alternative design of the waveguide ridge loaded crab cavity is described in the following section.

RIDGE LOADED CRAB CAVITY

The ridge loaded waveguide cavities have been proposed for crabbing applications in the past and are described in detail in [4-5]. For crabbing applications they are attractive due to their compactness. In order to compare this design with the baseline design we chose the same operating frequency of 11.994 GHz and a 10 mm gap between the ridges (aperture radius a = 5 mm). In a conventional disc loaded cavity, the rf energy flow (group velocity, v_g) is restricted by introducing the irises. In the baseline design v_g/c ~3.0% for a = 5.0 mm; whereas in the ridge loaded cavity, the rf energy flows without much restriction from the ridges. The lack of irises, for the same aperture gap increases the group velocity hence the input

ISBN 978-3-95450-122-9

power requirement by an order of magnitude compared to the baseline design. In order to control the group velocity we explore the high phase advance (HPA) of $5\pi/6$ per cell. The HPA operation reduces the group velocity to some extent but not close enough to the practical limits. For the SPA structure, even if the gap between the ridges is reduced down to a = 3.0 mm, the shunt impedance ($(R/Q)_T$) improves however, without much change in the group velocity. Reducing a below this value will increase the short range wakefields and will not be acceptable from the beam dynamics point of view [6].

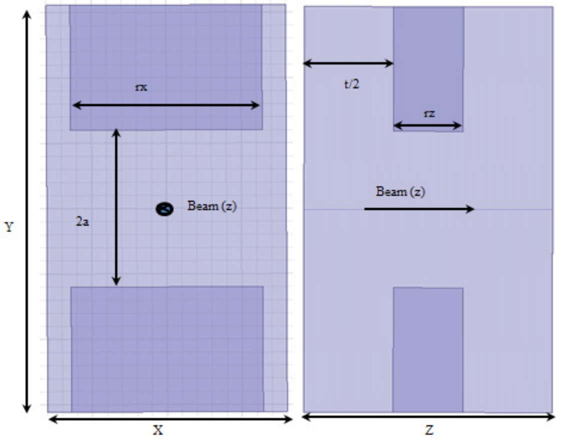

Figure 1: Rectangular ridge loaded cavity.

Modification in the ridge dimensions does not make much difference in the v_g because mainly the power flow is between the ridges. Adopting a rectangular outer shape of the cavity gives an extra handle to manipulate the v_g. In this case the vertical dimension is used to tune the cell to the operating frequency and the horizontal dimension is used to tune the v_g to a desired value. Detailed profile of a rectangular ridge loaded cavity is shown in Fig. 1.

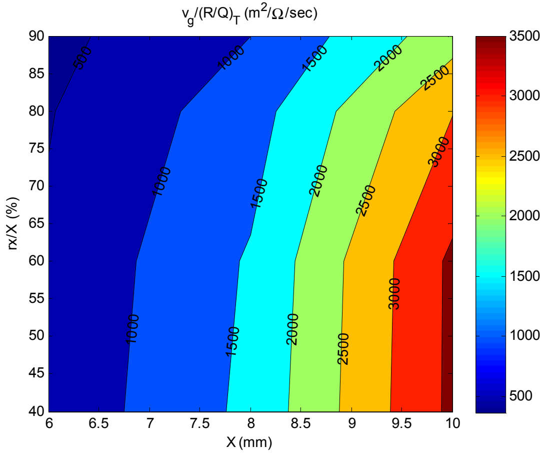

Figure 2: Geometric dependence of $\chi = v_g/(R/Q)_T$ for an HPA structure at a beam offset of 0.4 mm.

Considering the minimum acceptable aperture of a = 3.0 mm we studied a detailed scan of various geometrical parameters. We observe that the group velocity strongly depends on the width of the cavity (X) and width of the ridge (rx). The input power required for the desired kick voltage is proportional to the ratio of group velocity to shunt impedance, χ ($m^2/\Omega/sec$). However, minimising the input power will naturally require higher shunt impedance which will cause a significant beam loading. For a beam offset of 0.4 mm, we conservatively took a beam loading of 0.5% to optimise the design. Fig. 2 illustrates scan of χ with geometric changes, various contours represent various beam loadings. The exact value of χ =2770 ($m^2/\Omega/sec$) for a beam loading of 0.5%. This implements X ~9.4 mm. A wider ridge will imply geometric wakes from the side walls and a smaller ridge may not exhibit a uniform dipole field. This reconciles to an rx/X =40%. The HOM wakefield damping in this structure is discussed in the following section.

WAKEFIELD DAMPING

All the HOMs above the operating mode need to be strongly damped, hence the cut-off waveguide damping scheme is more suitable in this case. Detailed investigation of the field configuration reveals that incorporating damping waveguides in the vertical plane of the cavity (i.e. Y dimension, Fig. 1) is the best choice available. As there is no significant HOM field in the horizontal plane, two waveguides per cell are adequate for HOM damping. A detailed profile of a waveguide damped ridge loaded cell with the E-fields of the deflecting and accelerating (first HOM) modes is presented in Fig. 3. The first HOM is excited just above the cut-off frequency at 12.9 GHz. Though this is a hybrid mode, has a dominating accelerating E-field configuration; this mode is strongly damped with a Q ~30.

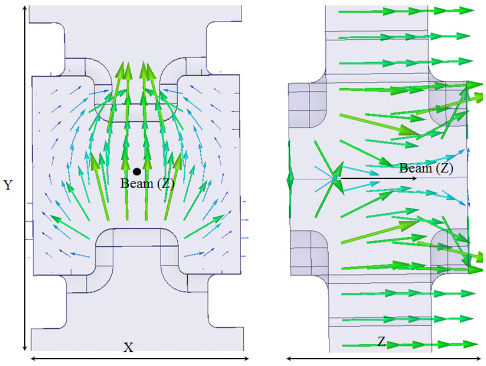

Figure 3: Deflecting and accelerating E-fields at 12 GHz (left) and 12.9 GHz (right) respectively in a waveguide damped cell.

The symmetry of the geometry has been used to reduce the computational time and study the wakefields excited in the structure due to the HOMs. Another advantage of using such symmetry planes is that individual contribution of the modes is clearly visible in the overall wakefield. The impedances and wakefields with all possible combinations of symmetry planes are illustrated in Fig. 4. It is clearly visible that only two modes have a significant effect on the beam, namely the operating dipole mode and the parasitic accelerating mode at 12.9 GHz. There are no significant higher order dipole modes in this structure. In order to check the adequacy of the damping method we employ the beam dynamics criterion [7] to ensure whether the beam emittance is acceptable in case of a coherent (F_c), rms (F_{rms}) and worst (F_w) case jitter. The amplification factors in this case: F_c =1.0006, F_{rms} =1.058 and F_w=1.73 are within the acceptable limits.

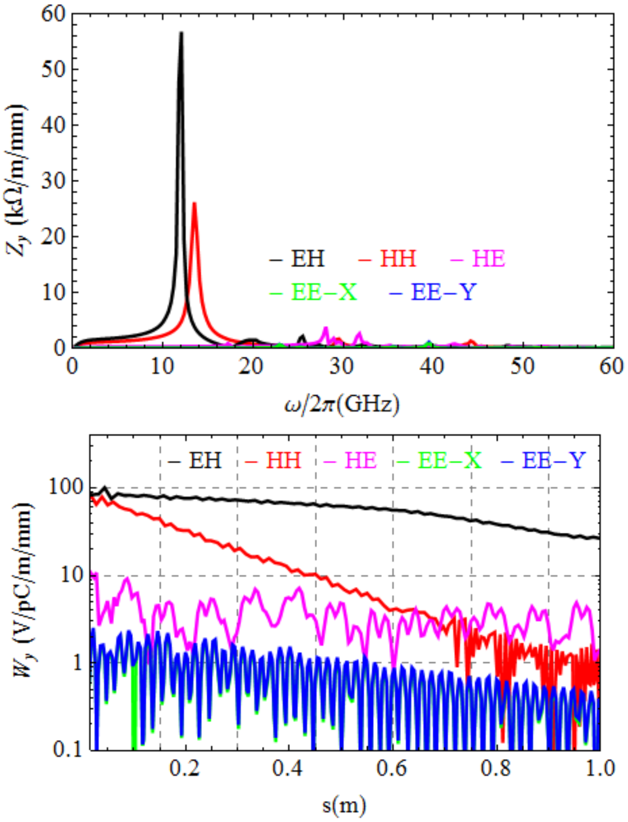

Figure 4: Impedances (top) and wakefields (bottom) of a quarter symmetry HPA ridge loaded structure.

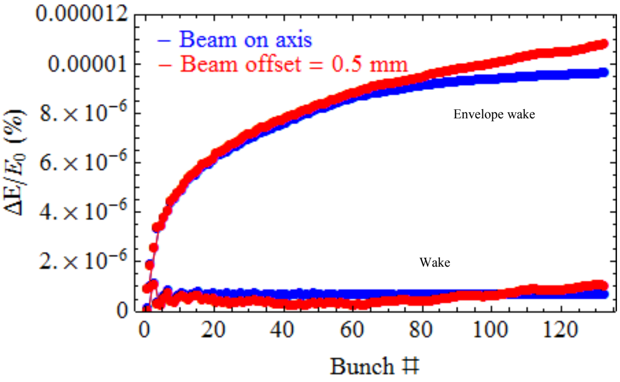

Figure 5: Energy spread in HPA structure.

The accelerating mode causes energy spread and it is illustrated in Fig. 5. A beam offset of 0.5 mm causes an energy spread of ~10^{-6}% which is just within the acceptable limits [8]. Detailed rf properties of an HPA waveguide damped ridge loaded cavity are illustrated in Fig. 6. An SPA cavity with similar damping has also been investigated; however, there is no obvious difference between the HPA and SPA cavities from the rf and wakefield damping points of view. A comparison of the rf parameters between the SPA, HPA and baseline design is presented in Table 1.

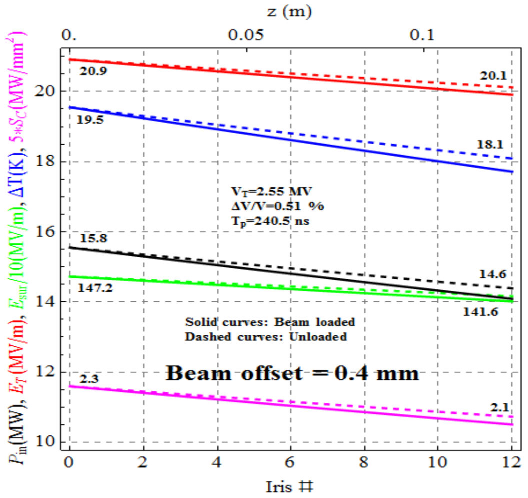

Figure 6: RF properties of an HPA ridge loaded cavity.

Table 1: RF Parameters of the Baseline and the New Alternative Designs

Cavity type	Baseline	Ridge loaded	
Φ (Deg.)	120	120	150
a (mm)	5.0	3.0	3.0
$(R/Q)_T$ (Ω/cell)	~50	87.85	108.5
v_g/c (%)	2.96	9.56	9.45
χ (m^2/Ω/sec)	1458	2718	2719
No of cells	12	15	12
P (MW)	13.4	15.85	15.8
ΔV/V (%)	~0.61	0.51	0.51
Es (MV/m)	86	165.6	147.2
ΔT (K)	20.4	22.2	19.5
Sc (MW/m^2)	~3.3	2.87	2.3

FINAL REMARKS

Though the surface E-field is on higher side, the ridge loaded cavity has similar rf properties compared to the baseline design. The damping is based on the cut-off waveguide method and not the symmetry of the modes, hence it is less sensitive to fabrication errors.

ACKNOWLEDGEMENTS

The authors would like to thank W. Wuensch, D. Schulte, A. Latina, P. K. Ambattu and G. Burt for their valuable suggestions and encouragement for this work.

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