

STUDY ON THE DESIGN OF THE X-BAND WAVEGUIDE-DAMPED STRUCTURE*

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Abstract

The design of waveguide-damped structure is optimized to reduce the magnitudes of surface electromagnetic fields and strongly suppress long-range transverse wakefields of the 380 GeV Compact Linear Collider facility currently under study. The optimization is mainly discussed with the elliptical shape of the iris, the wall shape of the damping waveguides, the position of the high-order-mode damping loads and the widths of the waveguide openings of the entire sequence of damping waveguides.

INTRODUCTION

The Compact Linear Collider (CLIC) facility is currently under study by the European Organization for Nuclear Research (CERN). It is envisioned as a three-stage accelerator that aims to achieve a 3 TeV center-of-mass collision energy in the final stage [1]. In particular, the first stage of the accelerator structure, denoted as the CLIC380, is envisioned to accelerate electron and positron beams up to a centre-of-mass collision energy of 380 GeV with an average acceleration gradient of 72 MV/m [2]. The CLIC380 is an X-band $2\pi/3$ mode structure and composed of damping waveguide cells that are each terminated by damping loads for absorbing high-order modes (HOMs). The CLIC380 functions in the multi-bunch operation mode and the wakefield effect is strong. Thus, the CLIC380 structure requires suppression of the magnitudes of both surface electromagnetic fields and long-range transverse wakefields.

To reduce the magnitudes of surface electromagnetic fields, we have optimized both the elliptical shape of the iris and the wall shape of the damping waveguides. Meanwhile, in order to strongly suppress long-range transverse wakefields and maintain the stability of the beam, we adopt linearly decreasing on the widths of the waveguide openings of the entire sequence of damping waveguides in the direction of beam propagation. We also studied on the position of the HOM damping loads in the waveguide structure to make the damping waveguide structure more compact while satisfying all design targets. For the CLIC380 structure, the transverse kick should be below 3.4 V/pC/m/mm at the distance between each two bunches. A new enhance factor is introduced to diagnose the multi-bunch enhancement on transverse wakefields, which is detail discussed at third section. Meanwhile the enhance factor is below 5 and the temperature rise is less than 40 K.

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GEOMETRY OF THE DAMPING WAVEGUIDE CELL

As illustrated in Fig. 1, the radius of the iris aperture a and the thickness of the iris d are crucial geometrical parameters that affect the group velocity, radio frequency (RF) efficiency and wakefield characteristics of the beam [3]. Nonetheless, the width of the waveguide opening iw and the waveguide width w are important free parameters that can be adjusted for optimizing the design of the damping waveguide cell. In addition, the shape factor e of the elliptical iris, which is illustrated in the longitudinal section of the iris in Fig. 1, is variable, and the radius of the cavity b is adjusted to meet the 11.994 GHz frequency requirement. All other parameters can be set as constant values in every cell.

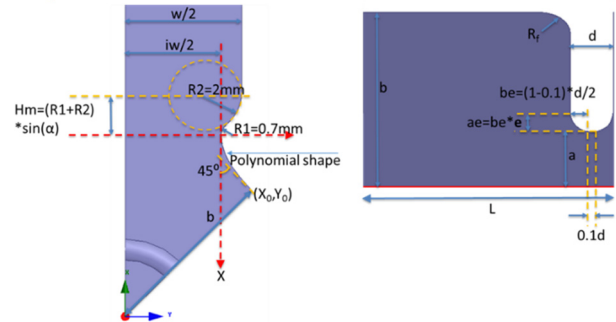


Figure 1: Geometry of the damping waveguide cell.

The maximum gradient is limited by the surface electromagnetic field, and can be modified by adjusting the Poynting vector Sc [4] and the temperature increase ΔT at the cell wall due to pulse surface heating. As shown in Fig. 2, the maximum value of Sc is at the iris tip, and the maximum value of the magnetic field Hs , which is used to calculate ΔT , occurs at the cell wall. Here, the distribution of Sc along the iris edge is largely dependent on the value of e . The optimal geometrical shape of the cell wall can be determined by adopting the following fourth order polynomial function [5]:

$$Y = Y_0 + (X - X_0) + \left(\frac{X}{X_0} - 1\right)^2 \left(A_0 + A_1 \frac{X}{X_0} + A_2 \frac{X^2}{X_0^2}\right) \quad (1)$$

$$\text{Where } Y_0 = \frac{b}{\sqrt{2}} - \frac{iw}{2}, \quad X_0 = A_0 + Y_0 \quad \text{and} \quad A_1 = A_0 - Y_0$$

Here, an optimal selection of A_0 , A_2 , b and iw can remove irregularities in the distribution of Hs , and thereby control the pulse surface heating. This discussion is illustrated by plots of the Sc obtained along the iris edge with different values of e shown in Fig. 3(a), and plots of the Hs obtained

along the cell wall with different values of A_0 and A_2 shown in Fig. 3(b) using ANSYS HFSS software [6]. The results demonstrate that the maximum values of Sc and Hs are reduced by 2.3% and 2.7%, respectively, when employing optimal parameters. The reduction in Hs represents a decrease in ΔT of 1.4 K.

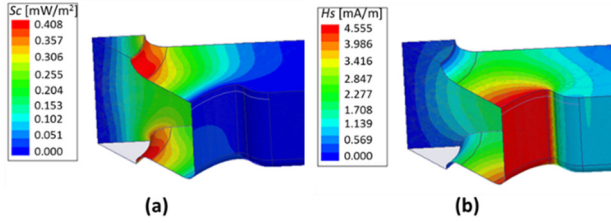


Figure 2: Electromagnetic field distribution on the surface of the CLIC380 when average gradient is 1 V/m: (a) Poynting vector Sc ; (b) magnetic field Hs .

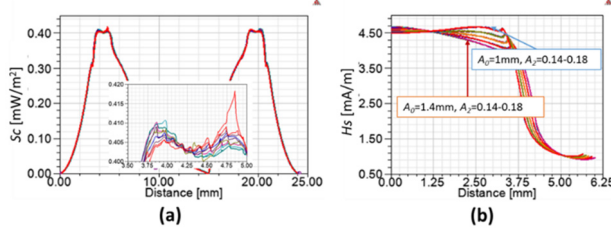


Figure 3: Simulated electromagnetic field distributions when average gradient is 1 V/m: (a) Sc along the iris edge with different values of e ranging from 1.46 to 1.54 in steps of 0.01; (b) Hs along the cell wall with different values of A_0 ranging from 1 mm to 1.4 mm in steps of 0.1 mm and A_2 ranging from 0.14 to 0.18 in steps of 0.01.

TRANSVERSE WAKEFIELD POTENTIALS

Long-range transverse wakefields can be calculated using the commercial wakefield simulation software GdfidL [7]. The accuracy of this software has been verified by comparing calculated results with experimental measurements [8]. The transverse wakefield suppression in the damping waveguide structure of the CLIC380 is influenced by iw and w simultaneously. In the analysis of transverse wakefields, the transverse wakefield potentials W_T at two points along the beam direction s are of particular importance. The first W_T value of interest is the transverse wakefield potential at the distance $s = 0.15$ m, which is the distance associated with the standard bunch separation of 6 RF cycles at $f = 11.994$ GHz (i.e., 0.5 ns). The second W_T value of interest is the bigger one of absolute envelope value of the transverse wakefield potential peaks nearest to $s = 0.15$ m. The requirement is that these two transverse wakefield potential W_T values of interest are less than 3.4 V/pC/m/mm. In terms of the optimization of transverse wakefield suppression based on iw and w , Fig. 4(a) shows that, if the value of w is fixed at 10.7 mm, the extent of wakefield suppression increases at $s = 0.15$ m with increasing iw . In contrast, Fig. 4(b) shows that, if the value of iw is fixed at 8.6 mm, an optimal value of w obtains a minimum peak transverse wakefield magnitude nearby $s = 0.15$ m.

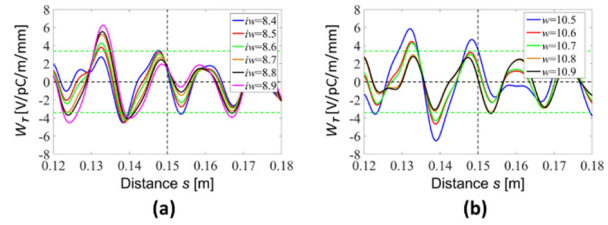


Figure 4: Magnitude of transverse wakefields W_T for different waveguide opening widths iw and waveguide widths w , where s is the distance between two adjacent bunches and the W_T values of green lines are ± 3.4 V/pC/m/mm: (a) as a function of iw with w fixed at 10.7 mm, (b) as a function of w with iw fixed at 8.6 mm.

However, long-range wakefields exert an effect not only between adjacent bunches but also over multiple bunches. For the CLIC380, the number of bunches N_b is 352, and the number of electrons per bunch N_e is 5.2×10^9 . Assuming that any bunch has an effect on subsequent bunches, we define the effect of bunch k on a subsequent bunch j as a_{jk} . However, we must also consider the multi-bunch regime, where bunches prior to bunch k generate a chain reaction of effects. Accordingly, we define the final effect of bunch k on bunch j as A_{jk} . The values of a_{jk} and the matrix A composed of the elements A_{jk} are defined as follows:

$$a_{jk} = \begin{cases} C \cdot W_T(z_{j-k}) \cdot N_e q_e^2, & j > k \\ 0, & j \leq k \end{cases} \quad (2)$$

$$A = e^a = \sum_{m=0}^{N_b} \frac{(i \cdot a)^m}{m!}$$

Here, C is a constant coefficient, W_T is the transverse wakefield potential, z_{j-k} is the position along the beam axis between bunches k and j , q_e is the electron charge and i is imaginary number. To ensure beam stability, a parameter F_{rms} as formula (3) is introduced to characterize the transverse wakefield enhancement caused by beam jitter [9]. For F_{rms} , we note that this is calculated using the maximum of the absolute values of the two transverse wakefield potential values of interest defined previously. The values of W_T calculated using GdfidL. The points of intersection are corresponding to $W_T(z_{j-k})$ for F_{rms} calculation. In this design, $C = 190 \text{ m}^2\text{GeV}^{-1}$ according to the linac layout, energy and acceleration gradient. In addition, F_{rms} is required to be less than 5 to keep the main CLIC380 linac stable in the ensuing discussion.

$$F_{rms} = \frac{1}{N_b} \sum_{j=1}^{N_b} \sum_{k=1}^j |A_{jk}|^2 \quad (3)$$

TAPERED CLIC380 STRUCTURE

The simulation model for the CLIC380 structure is shown in Fig. 5. The structure includes 31 regular damping cells and two matched coupling cells with an equivalent design as that of the damping cells. The values of the parameters a , d , and iw decrease linearly along the direction of beam propagation. The relatively large value of iw re-

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quired to ensure that the value of F_{rms} is less than the criterion value, but results in higher Sc and Hs , and correspondingly higher values of ΔT . This is particularly problematic because the value of ΔT increases from the first cell to the last cell in the CLIC380 structure. For example, the simulation model given in Fig. 5 with $w = 10.7$ mm and constant iw of each cell increased from 8.2 mm to 8.9 mm increases the maximum value of ΔT from 39 K to 50 K.

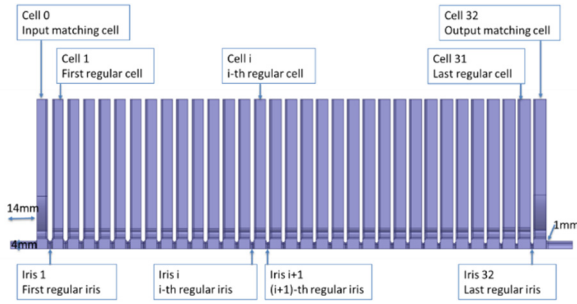


Figure 5: The simulation model of tapered structure.

Therefore, to obtain maximum transverse wakefield suppression while maintaining a sufficiently low ΔT , the values of the parameters iw decrease linearly along the direction of beam propagation, and the same w is used, shown in Fig. 6. In particular, we note that adjusting the value of iw in the last cell reduces the maximum value of ΔT to less than 40 K.

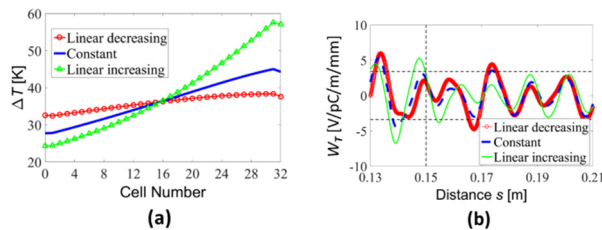


Figure 6: Temperature increase ΔT in each cell due to pulse surface heating and W_T obtained with the simulation model given in Fig. 7 for three different distributions of iw : (a) ΔT and (b) W_T .

Though simulation and analysis, the smaller iw is in last cell, the smaller ΔT , W_T and F_{rms} are in tapered structure when the average iw is the same. The maximum ΔT is mainly determined by the iw value of the last cell. Meanwhile, reducing the value of iw downstream corresponds to increasing the value of iw upstream, which achieves an overall stronger wakefield suppression effect. Accordingly, $iw = 8.2$ mm in the last cell and $iw = 9.2$ mm in the first cell are applied to the design.

HOM DAMPING LOADS

The entire CLIC380 structure, including the couplers, requires high-performance HOM damping loads to absorb HOMs shown in Fig. 7. To increase the absorption of HOMs, the tip should be relatively small to reduce reflection, and the tapered box should be relatively long. The HOM damping structure is composed of SiC, owing to its advantageous complex permittivity [10]. A larger value of Hd is beneficial for maintaining a stable Q-factor by de-

creasing the power dissipation at the fundamental frequency, while a smaller value of Sc is desirable for ensuring a compact cell structure. The optimum Hd results in Fig. 7(b) pertain to a value of Hd when the change in the Q-factor owing to the HOM damping structure is 1/10000, which provides a power dissipation of -40 dB at the fundamental frequency.

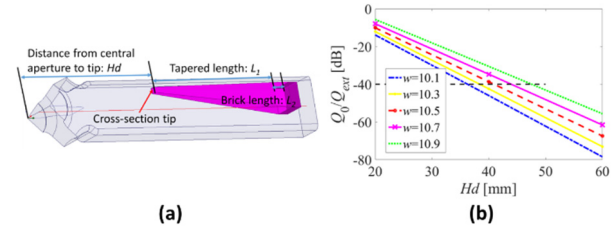


Figure 7: (a) Geometry of a single HOM damping load in a waveguide of a quarter damping waveguide cell. (b) Power dissipation of the HOM damping load at the fundamental frequency versus the distance Hd from the central aperture of the damping cell to the load tip.

CONCLUSION

This work presented an optimized design for the 380 GeV high-gradient RF acceleration structure stage of the CLIC to ensure a high RF-to-beam efficiency. The parameters iw and w of the damping waveguide cells were optimized to reduce long-range transverse wakefield potentials below the beam stability requirement of 3.4 V/pC/mm at the bunch separation distance. In addition, linearly decreasing values of iw were applied to the sequence of damping waveguide cells with respect to the direction of beam propagation to reduce the maximum value of ΔT in the last cell to <40 K. Meanwhile, the eccentricity of the iris and the wall profiles were optimized to further minimize ΔT and the magnitude of Sc . With all the above geometrical improvements, the transverse wakefield enhancement factor F_{rms} remains less than 1.2. The effect of reducing the value of Hd was also studied to make the damping waveguide structure more compact.

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