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 2π/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. As shown in Fig. 2, 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 AT 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 AT, occurs at the cell wall. Here, the distribution of Sc along the iris edge is largely dependent on the value of w. The optimal geometrical shape of the cell wall can be determined by adopting the following fourth order polynomial function [5]:

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

Where \( Y_0 = \frac{b}{\sqrt{2}} \left( \frac{-iw}{2} \right), \ x = A_0 + Y_0 \) and \( A_1 = A_0 - Y_0 \)

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 w 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 $\Delta T$ 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 $WT$ at two points along the beam direction $s$ are of particular importance. The first $WT$ 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 $WT$ 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 $WT$ 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](image-url)

Figure 4: Magnitude of transverse wakefields $WT$ for different waveguide opening widths $iw$ and waveguide widths $w$, where $s$ is the distance between two adjacent bunches and the $WT$ values of green lines are $\pm 3.4$ 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 $Nb$ is 352, and the number of electrons per bunch $Ne$ is $5.2 \times 10^9$. 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 $A_{kj}$. The values of $a_{jk}$ and the matrix $A$ composed of the elements $A_{jk}$ are defined as follows:

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

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

Here, $C$ is a constant coefficient, $WT$ 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 $WT$ calculated using GdfidL. The points of intersection are corresponding to $WT(z_{j-k})$ for $F_{rms}$ calculation. In this design, $C = 190$ m$^2$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.

$$F_{rms} = \frac{1}{Nb} \sum_{j=1}^{Nb} \sum_{k=1}^{j} \left| A_{jk} \right|^2$$

**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-
required 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 $\Delta T$. This is particularly problematic because the value of $\Delta T$ 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 $\Delta T$ from 39 K to 50 K.

Therefore, to obtain maximum transverse wakefield suppression while maintaining a sufficiently low $\Delta T$, 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 $\Delta T$ to less than 40 K.

Though simulation and analysis, the smaller $iw$ is in last cell, the smaller $\Delta T$, $W_T$ and $F_{rms}$ are in tapered structure when the average $iw$ is the same. The maximum $\Delta T$ 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 decreasing 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.

**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 $\Delta T$ in the last cell to $<40$ K. Meanwhile, the eccentricity of the iris and the wall profiles were optimized to further minimize $\Delta T$ 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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**REFERENCES**


