OPTIMIZATION ON RF PARAMETERS OF A CHOKE-MODE STRUCTURE FOR THE CLIC MAIN LINAC

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Abstract

A choke-mode damped structure for the main linac of a Compact Linear Collider (CLIC) was designed and named "CDS-C". The wakefield suppression of this structure fits the beam dynamics requirements and is verified by the GDFIDL simulations. Compared to the baseline design of the CLIC main linac, the CDS-C design has lower RF-to-beam efficiency and high surface electromagnetically field. Optimization using a genetic algorithm on the RF parameters of CLIC choke-mode structure is carried out. A new design of the tapered choke-mode structure is designed and increases the RF-to-beam efficiency and reduces maximum surface field.

INTRODUCTION

The choke-mode damped accelerating structure was proposed to damp higher-order modes (HOM) induced by beam. Compared to other damped structure such as waveguide damped structure, the choke-mode structure is easier to be manufactured and has lower pulse heating. Holding these potential advantages, the choke-mode structure is being studied as an alternative design for the main linac of the Compact Linear Collider (CLIC) [1].

A structure with 24 tapered choke-mode cells and two matching cells was designed and named "CDS-C" [1]. It operates at 11.994 GHz in the 2π/3 mode at an accelerating gradient of 100 MV/m. The iris radii of the first cell and the last cell are 3.15 mm and 2.35 mm, respectively. The population accelerated bunches are 3.72×10^9 and with 0.5ns separation (6 RF cycles). These parameters are same as the CLIC-G design, which is now the nominal design of the CLIC main linac with the waveguide-damped scheme. Shown in Fig 1, the geometry of a CDS-C cell had been optimized for the HOMs damping. Wakefield simulations on the CDS-C structure using GDFIDL code confirmed that it has sufficient suppression to the long-range transverse kick.

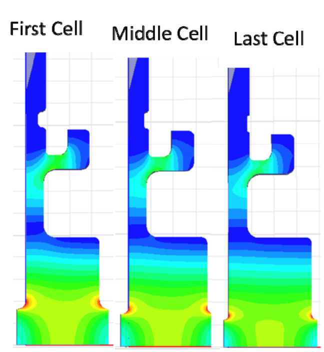

Figure 1: Choke-mode cells of CDS-C.

The radio frequency (RF) parameters of the CDS-C design are calculated by RF simulation. They are listed in Tab. 1 and are compared with the CLIC-G design. As indicated in Tab. 1, the choke-mode design significantly reduced the pulsed temperature raise, but it has a higher maximum surface electrical field and the power flow. The RF-to-beam efficiency of the CDS-C design is lower, which means that more input power is needed to achieve the same gradient. Since parameters like iris dimensions and bunch population of the CDS-C design are directly taken from the CLIC-G design, these parameters are optimized for the structure using waveguide damped scheme and maybe not optimal for the choke-mode structure. Therefore, another optimization on RF parameters of choke-mode structure should be carried out.

Table 1: RF parameters of CDS-C and CLIC-G [1, 2]

Parameters	CDS-C	CLIC-G
Peak input power (MW)	67.5	60.5
Filling time (ns)	72.4	64.8
RF-Beam efficiency (%)	24.2	27.5
Maximum surface E-field (MV/m)	246	235
Maximum Sc* (MW/mm^2)	5.72	5.39
Maximum pulsed temperature rise (K)	23.0	47.5

*Sc : modified poynting vector [3]

OPTIMIZATION ON TAPERED CHOKE-MODE STRUCTURE

As shown in Fig. 1, a choke-mode cell includes two parts: the main cavity and the choke. The main cavity is similar to the normal undamped accelerating structure. The choke reflects the accelerating mode, but unwanted higher-order modes can pass the choke to be damped in the load. The dimensions of the choke are fully optimized for the wakefield suppression in the CDS-C design. Therefore, the focus point of optimization on the choke-mode cell is the geometry of the main cavity; more specifically is the geometry of the iris.

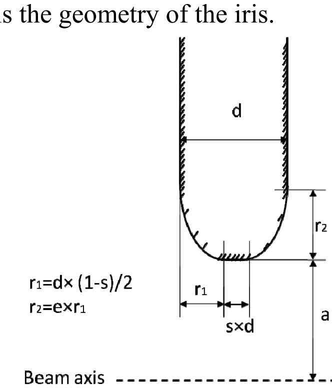

Figure 2: Geometry variables of iris.

An elliptical iris with a flat-top segment as shown in Fig. 2 is utilized. Four geometric variables are considered in this shape: *a* is the iris aperture, *d* is the iris thickness, *e* is the eccentricity of the ellipse, and *s* is the length of the flat-top segment divided by the iris thickness.

RF simulations on a single choke-mode cell with identical irises at both sides are carried out to study the dependence between RF parameters (as output) and geometric variables of iris (as input) [4]. Accelerating gradient of the cell is set to 100MV/m. The corresponding output RF parameters of this cell include *Q* is the quality factor, *R* is shunt impedance; *Vg* is group velocity; *Es* is the maximum surface electrical field, *Sc* is the maximum surface modified pointing vector; and *Hs* is the maximum surface magnetic field. Based on the simulation results of RF parameters, approximate functions of geometric variables are established using polynomial fitting. Instead of RF simulation, the output RF parameters could be calculated directly and quickly from given geometric variables using these approximate functions.

The RF parameters of a tapered structure could be calculated from each single cell. The amplitude of field in the n-th single cell could be calculated by the input power P_n from the preceding cell or the coupler. Then the accelerating gradient and maximum surface field could be determined by this field amplitude. After calculating the power loss at the wall and the beam loading, the power flowing to next cell P_{n+1} is then determined. Thus, the RF parameters of all the cells in the structure are successively calculated. To obtain an exact average gradient of 100 MV/m, the proper peak input power P_0 is determined using iterations. Given this peak input power, the RF parameter of the tapered structure is calculated.

$$G_n = \sqrt{\frac{R_n}{Q_n}\frac{\omega}{Lv_n}P_n} \qquad (1)$$

$$\Delta P_n = \frac{G_n^{\ 2}}{R_n} + I_b G_n L = P_n - P_{n+1}$$

Where G_n is the accelerating gradient of n-th cell, ω is the accelerating frequency, L is the cell length, I_b is the average current of the beam, v_n is the group velocity, Q_n is quality factor and R_n is shunt impedance. Using this method, the RF parameters of a given tapered structure could be quickly estimated. This will save lots of calculating time in the optimization. However, there are 25 irises (24 cells) in the tapered structure and each iris has four geometric variables. The large amount of independent variables will cost infinite enumerating time. Therefore, a search algorithm should be used in the optimization to improve the searching efficiency.

Genetic algorithms are search algorithms that mimic the natural evolution and will be used in the optimization of tapered choke-mode structures. Genetic algorithms regard all possible solutions as creatures. Independent geometric variables are genomes (or chromosomes) that represent all information of one solution. The resulting RF parameters represents the fitness of this solution. Better RF performance results in higher fitness. During the evolution, solutions with higher fitness survive and produce offspring (reproduction), whereas those with lower fitness are discarded. The survivals will create better solutions after generations of selection [5].

We implement a genetic algorithm to search the optimum solution for the tapered choke-mode structure. Since the number of geometric variables of all cells, in this algorithm only geometric variables of some independent irises in the structure are encoded into the chromosomes of a solution. For the other irises, geometric variables are calculated by the polynomial fitting. The reproduction is accomplished by making several copies of each solution with shifting some chromosomes' values (mutation). Then new generation of solutions (offspring) are created. A fitness function is used to evaluate the performance of all solutions and decide whether reserve or discard them. The fitness function is calculated by RF efficiency and maximum surface field:

$$F(I) = 2\times\eta(I)\frac{L_b(I)/N_b(I)}{10^{21}m^{-2}} - 2\times\frac{Es(I)}{MeV} \qquad (2)$$
$$-100\times\frac{Sc(I)}{MW/mm^2} - 3\times\frac{\Delta T(I)}{K} - 450$$

Where I is a candidate solution, η is RF-beam efficiency, L_b is the luminosity per bunch, N_b is the bunch population, *Es* is the maximum surface field, *Sc* is the maximum modified poynting vector, ΔT is the maximum surface field. In order to prevent the premature convergence and maintain the genetic diversity in the genetic algorithm [5], the fitness function considering competition is developed. The fitness value of one solution will decrease when there are other solutions with better fitness in its neighborhood genetic space.

In this genetic algorithm, we create 800 initial solutions randomly. Geometric variables of 5 irises (irises numbering: 1, 7, 13, 19 and 25) are encoding into the chromosomes. Each solution born 4 children, during the selection 800 solutions will be kept to the next iteration. Shown in Fig. 3, the maximum fitness value of all solutions is observed to nearly converge after 800 steps of iterations. Then the solution with this maximum fitness value could be seen as the optimal solution. If the time spend on calculating RF parameters of a tapered structure is regarded as 1, then the total searching time is about 2×10^6. The detail RF and wakefield results of the optimal solution will be presented in the next section.

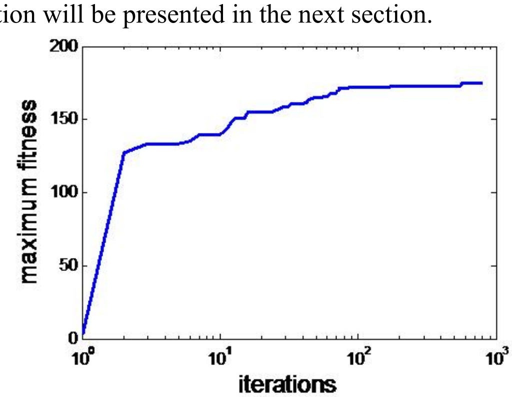

Figure 3: The evolution of maximum fitness value.

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RF PARAMETERS AND WAKEFIELD SUPPRESSION OF NEW DESIGN

Tab. 2 shows the RF parameters of the selected optimum solution and compares them with those of the original CDS-C design and the CLIC-G design. The RF simulation on this solution was conducted to verify the parameters. Fig. 4 shows the RF parameters distribution on each iris. The data show this solution has higher RF-beam efficiency and lower surface field compared with the CDS-C design. We named this optimum solution "CDS-D". It is the new design of CLIC choke-mode structure with 24 cells and a 100 MV/m working gradient. The iris radii of the first cell and the last cell in the new design are 3.49 mm and 2.50 mm, respectively. Compared with the CLIC-G, the maximum surface field and the pulsed temperature rise of CDS-D are lower, which is expected to restore some of its lower efficiency.

Table 2: RF parameters of CDS-D, CDS-C and CLIC-G

Parameters	CDS-D	CDS-C	CLIC-G
Bunch population (10^9)	4.50	3.72	3.72
Bunch luminosity ($10^{34}m^{-2}$)	1.43	1.22	1.22
Peak input power (MW)	79.3	67.5	60.5
Filling time (ns)	60.8	72.4	64.8
RF-Beam efficiency (%)	26.0	24.2	27.5
Maximum surface field (MV/m)	223	246	235
Maximum Sc (MW/mm^2)	5.17	5.72	5.39
Maximum pulsed temperature rise (K)	22.0	23.0	47.5

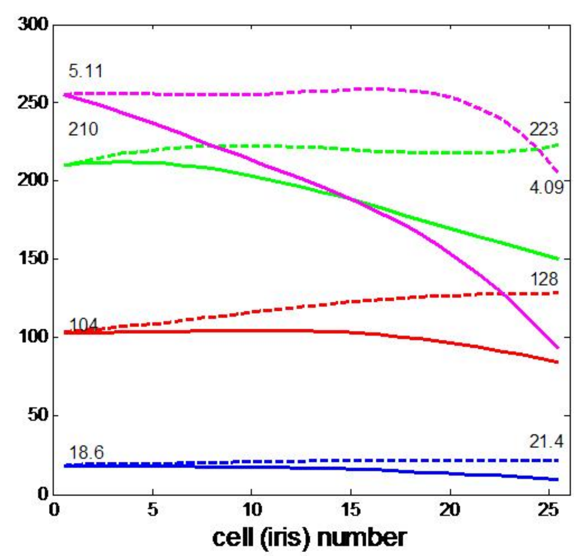

Figure 4: Field distribution on irises of CDS-D; red: accelerating gradient(MV/m); green: maximum surface electrical field(MV/m); blue: pulsed temperature rise (K); magenta: maximum modified Poynting vector (×50, MW/mm2)

According to beam dynamic studies to the CLIC main linac, the long-range transverse kick applied to the next following bunch should be less than 3.93×10^{-9} V/(pC m mm)/Q_b, where Q_b is the single bunch charge. For the case of the CDS-D design, this limited wakefield potential will be 5.46V/(pC m mm). Wakefield simulation using the GDFIDL code on the CDS-D design is done [6]. Shown in Fig. 5, the resulting transverse wakefield potential at the position of the second bunch is about 3.5 V/(pC m mm) and meets the beam dynamics requirements .

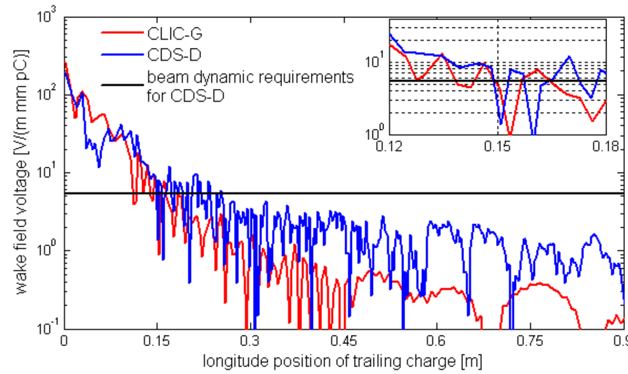

Figure 5: Transverse wakefield potential of the CDS-D.

CONCLUSION

The optimization on RF parameters of tapered choke-mode structure is carried out to increase the RF-to-beam efficiency and reduce the maximum surface field. Geometric variables of each iris in the structure are the focus input parameters in this optimization. A method is developed to quickly calculate output RF parameters of the tapered structure from given geometric variables without RF simulation. Based on this method, a genetic algorithm for tapered structure was utilized to search an optimum solution, which resulted in CDS-D.

The RF parameters of CDS-D show improved RF-beam efficiency and maximum surface field compared with the original CDS-C design. RF and wakefield simulations were performed to test the validity of the CDS-D design. However, further experiments on wakefield measurements and more high-powered tests are needed to verify the proposed structure..

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