A NEWLY DESIGNED AND OPTIMIZED CLIC MAIN LINAC ACCELERATING STRUCTURE

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Abstract

A new CLIC main-linac accelerating-structure design, HDS (Hybrid Damped Structure), with improved high-gradient performance, efficiency and simplicity of fabrication is presented. The gains are achieved in part through a new cell design which includes fully-profiled rf surfaces optimized to minimize surface fields and hybrid damping using both iris slots and radial waveguides. The slotted irises allow a simple structure fabrication in quadrants with no rf currents across joints. Further gains are achieved through a new structure optimization procedure, which simultaneously balances surface fields, power flow, short and long-range transverse wakefields, rf-to-beam efficiency and the ratio of luminosity to input power. The optimization of a 30 GHz structure with a loaded accelerating gradient of 150 MV/m results in a bunch spacing of seven rf cycles and 32 % rf-to-beam efficiency.

INTRODUCTION

In order to reach the CLIC design luminosity and energy (~10^{35} $cm^{-2}sec^{-1}$ and 3 TeV, respectively) in power-efficient way, multiple-bunch trains of about 0.5 nC each are accelerated on each machine cycle with an average gradient of 150 MV/m [1]. The design of an accelerating structure capable of this is constrained by a number of very demanding beam dynamics requirements and rf effects: a short-range transverse wakefields limit, long-range transverse wakefield suppression, rf breakdown and rf pulsed surface heating.

As more experimental data about rf breakdown has become available and when these constraints have been considered simultaneously, it has become clear that the existing designs of the CLIC main linac accelerating structure, the TDS (Tapered Damped Structure) [2] and later the XDS (conveX Tapered Structure) [3], are not satisfactory. In this paper, a new geometry and design approach is described giving a structure which not only finally satisfies both beam dynamics and rf constraints (at least to our present level of knowledge of them) but also brings a distinct improvement in rf-to-beam efficiency of 32% and a novel assembly technique.

The first key improvement has been to increase higher order mode damping by combining iris slots and radial waveguides – hybrid damping and hence the name HDS (Hybrid Damped Structure) - allowing the bunch spacing to be reduced from 20 to 7 rf cycles. The second key improvement is a new optimization procedure which is based on the interpolation of the structure parameters and allows millions of structures to be analysed taking into account the full and extremely complex interplay between rf and beam dynamics parameters.

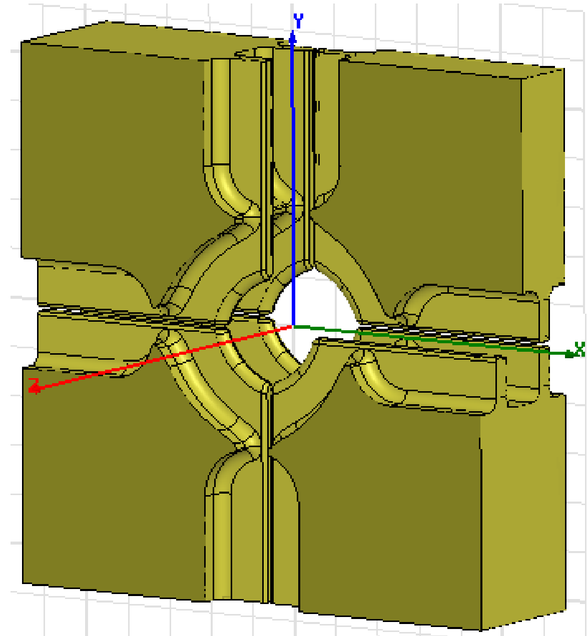

Figure 1: Geometry of the HDS cell. Two cells are shown to better demonstrate shape of the cell cavity, slotted iris and damping waveguides. For the same reason one quarter of one of the cells is removed from the picture.

HDS DESIGN

The HDS design was illuminated by the idea that iris slots could be introduced in addition to the damping waveguides in order to improve suppression of long-range transverse wakefields with little increase of the pulsed surface heating. The geometry of the HDS cell is shown in Fig. 1. In fact, the coupling in the HDS of the (dominant) lowest dipole mode to the slots becomes significantly stronger than the coupling to the damping waveguides. The waveguides are retained because there are higher-order transverse modes with the rf phase advance per cell close to 0 and longitudinal higher-order modes (TM_{0n}), which are weakly or not at all coupled to the slots. These modes are generally well damped by the waveguides.

Because the lowest dipole mode is coupled mainly to the slots rather than to the waveguides, and the weak dependence of this coupling on the damping waveguide aperture size, the surface of the cell outer wall can be increased compared to the XDS. This *reduces* pulsed surface heating, due to a lower current density, while simultaneously improving damping.

The slots however introduce a number of difficulties which have had to be addressed. One of them is that the surface electric field is enhanced in the area where the slots end in the center of the iris. This field enhancement is eliminated by composing the beam aperture out of four circular arcs which have a radius larger than the distance from the beam axis to the iris tip a, which can be observed in Fig. 1. Because the ends of the slots are further from the center of the cell than the middle of the iris arcs, they are exposed to lower surface electric field. Each cell consequently consists of four quadrants which have no contact because of the slots cut both the iris and the wall between damping waveguides of adjacent cells. A structure can thus be formed from four quadrants in which the cells, irises, slots, damping waveguides and other subsystems are milled into the outside each piece as is shown in Fig.2.

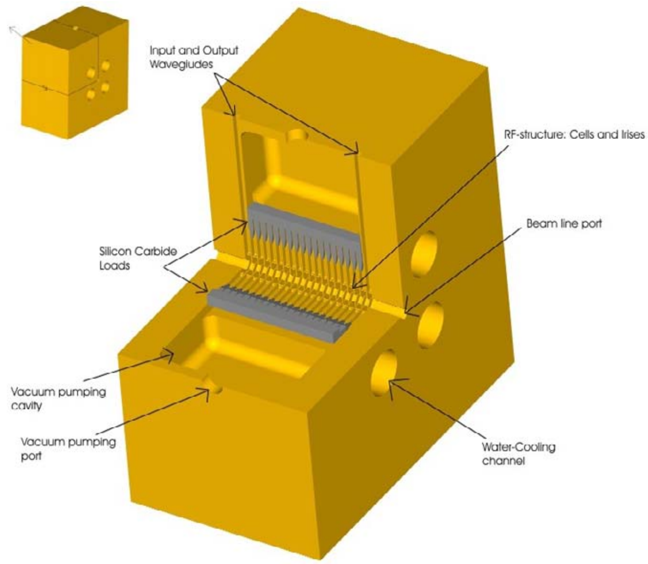

Figure 2: The HDS layout. Taking one of the quadrants out shows the inside of the structure: the chain of cells of accelerating structure, the damping waveguides, terminating loads, the vacuum pumping ports, the input and output waveguides, as well as four water-cooling channels.

This novel accelerating structure design and assembly gives a number of advantages compared to traditional structures in which individual cells are brazed together including,

- Reduction of the number of pieces per structure to four and a significantly decrease in surface area to be machined.
- Free choice of joining because of there are no rf currents between quadrants
- No water/vacuum joints nor brazed-on cooling channels.
- Excellent vacuum pumping.
- Slots can be as narrow as needed an profiled – an important feature for 30 GHz.

THE OPTIMIZATION PROCEDURE

The search for a new structure optimization procedure was motivated by the need to simultaneously vary iris diameter range, iris thickness range and phase advance while considering the effect on short-range transverse wakefield amplitude, long-range transverse wakefield suppression, rf-to-beam efficiency, surface fields and power flow. The simple approach of varying a single parameter at time was clearly impractical.

For a fixed rf phase advance, the entire procedure is repeated for different phase advances, the optimization procedure consists of three parts. In the first part, a set of nine individually optimised cell geometries are calculated for fundamental mode and lowest dipole mode characteristics of over an range of a, and iris thickness, d. This gives a two-dimensional parameter space for interpolation.

In the second part, parameters for $4 \cdot n_{d1} \cdot n_{d2} \cdot (n_{d1}-1) \cdot (n_{d2}-1)/2$ structures are calculated. Here $n_{d1}, n_{d2}, n_{d1}, n_{d2}$ mean number of variation in a_1, d_1, a_2, d_2, respectively, which are a and d in the first and last cells of a structure. For each structure the bunch charge N is determined from the results of beam dynamic simulations which take into account the effect of short-range wakefields on emittance growth [4]. The long-range wakefields of the lowest dipole mode is calculated based on interpolated parameters and uncoupled model. The value of the transverse wake envelope at the position of the second bunch $\|W_t\|_2$ is limited by the following condition [4]:

$$N \times \|W_t\|_2 < 4 \cdot 10^9 \times 20 \text{ V/pC/mm/m}.$$

Satisfying this condition gives the bunch separation in the number of rf cycles N_s.

In the third part of the optimization, structures are selected which satisfy the following rf constraints which are based on a structure made from CuZr alloy and Mo iris tips:

1. Surface electric field [5]: $E_{surf}^{\max} < 380$ MV/m.
2. Pulsed surface heating [6]: $\Delta T^{\max} < 56$ K.
3. Power [7]: $P_{in}\, \tau_p^{1/2} < 1225$ MW·ns$^{1/2}$.

Here $E_{surf}^{\max}$ and $\Delta T^{\max}$ refer to maximum surface electric field and maximum pulsed surface heating temperature rise in the structure, respectively. P_{in} and τ_p denote input power and pulse length. Since both $\Delta T^{\max} \sim \tau_p^{1/2}$ and $P_{in}\, \tau_p^{1/2}$ depend on pulse length conditions, 2 and 3 can always be satisfied by reducing the number of bunches in the train N_b. This reduction is however limited because the shorter the pulse the lower the rf-to-beam efficiency due to the fill time of the structure. Hence, N_b is chosen to make pulse as long as possible under pulsed surface heating and power constraints. Then, if the structure satisfies condition 1, rf-to-beam efficiency and other pulse length dependent parameters of the structure are scaled for this value of N_b.

Different optimization criteria are possible. In the case of CLIC, the main goal is to reach design luminosity and energy in the most efficient way. Hence the optimum structure must provide the highest ratio of luminosity to main linac input power. In terms of the structure parameters this corresponds to maximum of figure of merit: $L_{b\times}\eta/N$, where $L_{b\times}$ denotes luminosity per bunch crossing in 1% of energy which is obtained in the beam dynamics simulations of CLIC main linac and beam delivery system [4]. Thus, the optimum structure is that which gives maximum of figure of merit among all structures satisfying conditions 1 through 3.

OPTIMIZATION OF THE CLIC MAIN LINAC ACCELERATING STRUCTURE

The optimization procedure section was been performed for a range of rf phase advances $\Delta\varphi$ of 50^o to 130^o. The iris radius a was varied from 1 to 2.5 mm, thickness d was varied from 0.3 to 0.75 mm for $\Delta\varphi < 90^o$ and from 0.5 to 1 mm for $\Delta\varphi \geq 90^o$. Both a and d step variation is 0.05 mm resulting in 217800 analyzed structures for each value of $\Delta\varphi$. The results show maximum figure of merit: $L_{b\times}\eta/N = 14.0$ at $\Delta\varphi = 70^o$. The optimisation was then performed once more at the optimum $\Delta\varphi = 70^o$ with smaller step (0.02 mm) of a and d variation, which results in larger number of analyzed structures: 7605000 and, consequently, in a better structure with figure of merit: $L_{b\times}\eta/N = 14.4$.

Table 1: Parameters of the best structure calculated without interpolation

Cell length: l_c [mm]	1.944
First and last iris radius: a_1, a_2 [mm]	2.14, 1.52
First and last iris thickness: d_1, d_2 [mm]	0.59, 0.37
Averaged a to wavelength ratio: $<a>/\lambda$	0.183
Number of particles in the bunch: N	2.8×10^9
Luminosity per bunch crossing: $L_{b\times}$ [m^{-2}]	1.22×10^{34}
Structure length: l [mm]	218
Bunch separation: N_s [rf cycles]	7
Number of bunches in the train: N_b	212
Pulse length: τ_p [ns]	58.2
Input power: P_{in} [MW]	160
Rf-to-beam efficiency: η, η_{Mo} [%]	33, 32.2

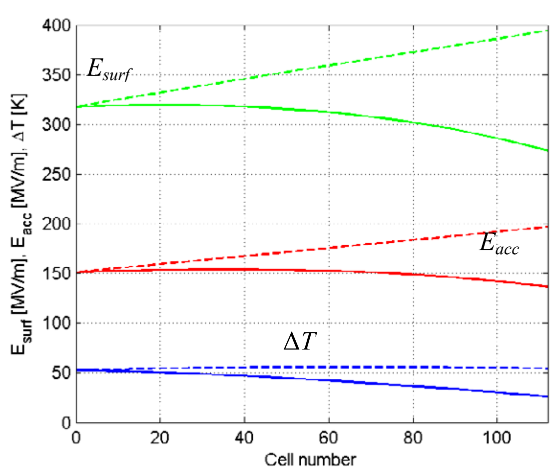

Figure 3: Pulsed surface heating temperature rise (blue), accelerating gradient (red), and maximum surface electric field (green) along the optimum structure with (solid) and without (dashed) beam loading.

A list of the optimized structure parameters, which are finally calculated without interpolation, is presented in Table 1. η_{Mo} refers to the rf-to-beam efficiency taking into account lower electrical conductivity of the Mo tips. Fundamental mode parameters as a function of cell number are shown in Fig. 3 and the transverse wake is shown in Fig. 4.

The theme obscurely stated in the parameter tables is that the overall performance of CLIC in terms of the luminosity to power ratio has been improved while simultaneously satisfying for the first time all of the beam dynamics and rf constraints described previously. Bringing the TDS or XDS designs into consistency would result in serious reductions of many previously published parameters. The main feature giving the improvement is the reduction in the bunch spacing from 20 to 7 fundamental rf cycles. This has a profound effect on the structure rf-to-beam efficiency which is increased despite the reduction of the pulse length by a factor of two and reduction in bunch charge by 30%.

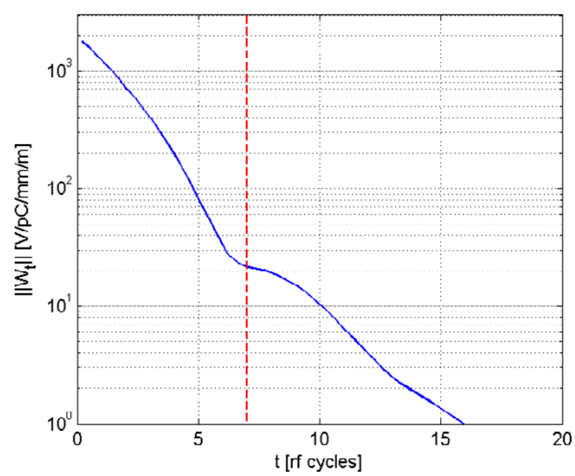

Figure 4: Envelope of the wake of the lowest dipole mode in the optimum structure.

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