OPTIMUM FREQUENCY AND GRADIENT FOR THE CLIC MAIN LINAC*

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Abstract

A novel procedure for the optimization of CLIC main linac parameters including operating frequency and the accelerating gradient is presented. The optimization procedure takes into account both beam dynamics and high power rf constraints. Beam dynamics constraints are given by emittance growth due to short- and long-range transverse wakefields. RF constraints are given by rf breakdown and pulsed surface heating limitations of the accelerating structure. Interpolation of beam and structure parameters in a wide range allows hundreds of millions of accelerating structures to be analyzed to find the structure with the highest ratio of luminosity to main linac input power, which is used as the figure of merit. The frequency and gradient have been varied in the ranges 12-30 GHz and 90-150 MV/m respectively. It is shown that the optimum frequency lies in the range from 16 to 20 GHz depending on the accelerating gradient and that the optimum gradient is below 100 MV/m. Based on our current understanding of the constraints, changing the frequency and gradient from current values of 30 GHz and 150 MV/m to the optimum ones doubles the luminosity for the same main linac input power. Nevertheless, overall extension of the collider and investment cost considerations are not taken into account and impose gradient larger than 100 M/m to 120 MV/m.

INTRODUCTION

In order to reach the CLIC design luminosity and energy ($\sim 10^{35}$ cm^{-2}sec^{-1} and 3 TeV, respectively) in a power-efficient way, multiple-bunch trains of about 0.5 nC each bunch 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 wakefield limit, long-range transverse wakefield suppression, rf breakdown and rf pulsed surface heating.

The design performance of the CLIC main-linac accelerating structure has been significantly improved during the last few years. The first key improvement is a novel structure design based on the hybrid damping of the higher order modes, the Hybrid Damped Structure (HDS) [2]. The second key improvement is a new optimization procedure based on the interpolation of the structure parameters which allows millions of structures to be analyzed taking into account the full and extremely complex interplay between rf and beam dynamics parameters. A detailed description of these two key improvements can be found in [3].

In this paper, we present the extension of the optimization procedure described in [3] to include the frequency and average accelerating gradient (called gradient later on) in the CLIC main-linac. In the following two sections, the scaling of relevant beam dynamics and rf parameters is presented. Finally, the results of the CLIC main-linac accelerating structure optimization are presented.

BEAM DYNAMICS PARAMETERIZATION

For each case considered in the optimization, beam parameters have been adjusted to maintain the same transverse and longitudinal effects as in the current parameter set and from this the luminosity has been determined. A more detailed description of the logic of the parameter choice can be found in [4]. In general the bunch charge and length are determined by the main linac, the horizontal bunch size at collision by the damping ring and beam delivery system and the vertical bunch size by all the systems. The minimum distance between the bunches in a train is also determined by the main linac. We will first give an overview of the parameter scaling for a constant gradient; in the end we comment on the gradient dependence.

The bunch charge and length are dependent on the single bunch wakefields in the main linac which is calculated using parameterization derived in [5]. The relatively lower energy of the bunch tail compared to the bunch head is compensated by letting the bunch arrive slightly before the oscillating accelerating field reaches its maximum, thus increasing the acceleration of the bunch tail. The minimum bunch length for a given charge is then determined by the final rms energy spread which must be below 0.35% with a phase difference below 12 degrees. The linac lattice has been designed to minimise the emittance growth [6]. The bunch charge is chosen such that the wakefield kick at the tail of the bunch, $W_T(2\sigma_z)N$, is constant.

The minimum distance between bunches is determined by the long-range transverse wakefields. Due to the strong damping of the transverse RF modes, the kick from one bunch on the next dominates the wake. The additional emittance growth due to the long-range effect is small compared to the short-range effect for a kick of $|WNe|<6.4e-6$ VC. The bunch spacing is chosen to be the smallest which fulfils the kick limit and is typically in the range of 5-8 rf cycles.

The minimum transverse beam size depends mainly on the transverse emittances produced by the damping ring and on the beam delivery system. The vertical emittance will also grow in the main linac but the choice of scaling described before ensures that this growth is independent of the structure chosen. For simplicity the emittances are
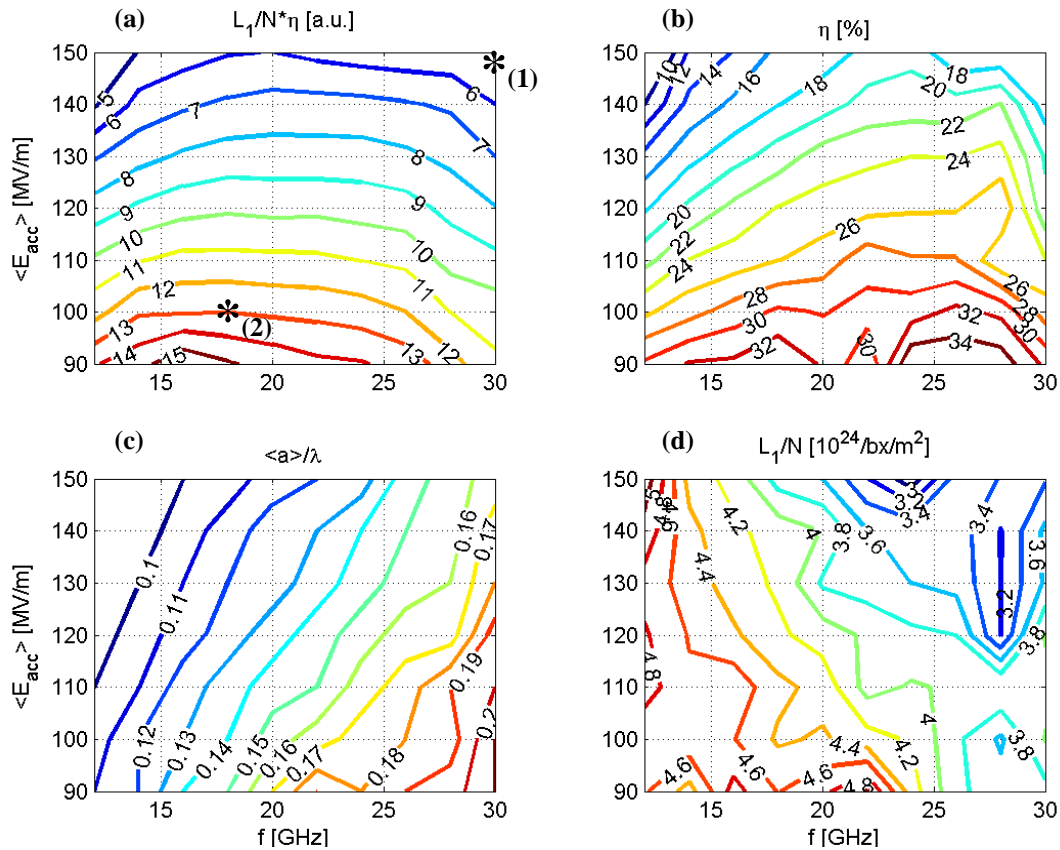
Figure 1: Results of the CLIC main-linac accelerating structure optimization. Lines of constant parameters: figure of merit (a), rf-to-beam efficiency (b), average iris radius to the wavelength ratio (c), and luminosity per bunch X-ing normalized to the bunch population (d) are plotted as function of average accelerating gradient and frequency.

assumed to be independent of the bunch charge, although a lower bunch charge would give a somewhat smaller emittance in the damping ring. The current damping ring and beam delivery system produces beam sizes that correspond to a Gaussian distribution with a width of 60nm in the horizontal and 0.7nm in the vertical plane but the distribution has significant tails. Highest luminosity is reached using these minimum beam sizes but the emission of beamstrahlung in the collision can dilute the luminosity spectrum. Therefore the contribution to be optimised is the luminosity within 1% of the nominal centre-of-mass energy. The horizontal beam size is increased if this increases this part of the luminosity. The simulations of the collision are performed with GUINEA-PIG [7].

When the accelerating gradient is changed, the same dependence on beam energy is used in the main linac for the magnet spacing and strength. Due to the increasing length and hence spacing between the emittance tuning sections, the bunch charge needs to be decreased almost linearly with the gradient and for simplicity linear scaling is assumed. In addition, the kick of each bunch on the next needs also to be reduced linearly with the gradient.

RF PARAMETERS AND CONSTRAINTS

Parameters of the accelerating structure are calculated at different frequencies and gradients based on the interpolation of the single cell parameters of the fundamental and the first dipole modes (the rf parameters) and the bunch charge and bunch spacing (the beam dynamics parameters). The single cell rf parameters are scaled using standard frequency scaling and are independent of the gradient. In contrast, the parameters of the structures are both frequency and gradient dependent due to the bunch charge frequency and gradient dependency. The structure parameters are calculated over the whole range of optimization which includes first and last cell iris radii and thicknesses, rf phase advance and, what is new, frequency and gradient. Results are stored to be used at the final step of optimization. During this step the rf constraints are applied to all structures and only those which satisfy these constraints are evaluated in terms of luminosity per main-linac input power which is the figure of merit for the best structure.

The following three rf constraints are used in the optimization:

1. Surface electric field: $E_{surf}^{max} < 380$ MV/m.
2. Pulsed surface heating: $\Delta T^{max} < 56$ K.
3. Power: $P_{in} \tau_p^{1/2}/C < 24$ MW·ns$^{1/2}$/mm.

Here E_{surf}^{max} and ΔT^{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. C is the iris circumference. The power constraint differs from the one

used in the previous optimization at fixed frequency and gradient [3] because of recent progress in understanding of the rf breakdown limits [8]. Currently, the limiting value is based on the experimental data obtained for Cu-structures at X-band [9] and for Mo-structure at 30 GHz [10]. The constraint will be modified as more experimental results become available and the constraints are better understood.

OPTIMIZATION RESULTS

The CLIC main linac accelerating structure optimization has been performed for a range of rf phase advances $\Delta\varphi$ of 50° to 130°, frequencies f of 12 to 30 GHz and average accelerating gradient $<E_{acc}>$ of 90 to 150 MV/m. The normalized iris radius a/λ was varied from 0.09 to 0.21, normalized thickness d/λ was varied from 0.025 to 0.075 for $\Delta\varphi < 90^{\circ}$ and from 0.05 to 0.1 for $\Delta\varphi \geq 90^{\circ}$. The total number of analyzed structures is 221,356,800.

The results of the optimization are presented in Fig. 1 by means of lines of constant value in the gradient (vertical axis) versus frequency (horizontal axis). The figure of merit $\eta L_{b\times}/N$ which is proportional to time-averaged luminosity in 1% energy spectrum divided by average input power for the main linac is shown in Fig. 1(a). It depends on the gradient but has a rather flat optimum in the region of 15-20 GHz. It also shows that the lower the gradient the higher the figure of merit. For example, changing the operating frequency and gradient from the present design values of 150 MV/m at 30 GHz to the optimum frequency of 18 GHz at 100 MV/m will reduce the average linac input power by factor 2.5. This implies a significant reduction in the running cost of CLIC as well as the part of the installation cost which is proportional to the average power such as cooling. It should be pointed out that the present figure of merit only relates to beam performances and wall plug power. A figure of merit including a simplified investment cost model is envisaged for further optimization in the future which will certainly drive to higher gradient with possibly slightly different RF frequency.

In order to get more insight into the mechanisms driving the optimum, the rf-to-beam efficiency, average structure aperture radius to the wavelength ratio and luminosity per bunch crossing normalized to the bunch population are plotted in Fig. 1(b-d), respectively. The efficiency shows a maximum at a frequency of about 25 GHz which is related to the change of the bunch spacing from 6 to 5 rf cycles and then it goes down at lower frequencies. On the other hand, the normalized luminosity increases at lower frequency because of the bigger aperture and because lower short-range wakefields allow a bigger bunch charge to be accelerated. This maximizes the product of these two quantities, which is the figure of merit, at around 18 GHz.

The detailed parameters of two structures which emerge from the optimization are presented in Table 1.

The structure positions on the gradient versus frequency plane are shown in Fig. 1(a) by the symbol *. The first structure is the best structure at the current design gradient and frequency. The second one is the best structure at 100 MV/m.

Table 1: Parameters of the structures

Structure number	1	2
Accelerating gradient: $<E_{acc}>$ [MV/m]	150	100
Frequency: f [GHz]	30	18
RF phase advance per cell: $\Delta\varphi$ [$^{\circ}$]	50	50
First, last iris radius: a_1, a_2 [mm]	2.1, 1.2	3.0, 1.6
First, last iris thickness: d_1, d_2 [mm]	.25, .45	0.4, 0.4
Averaged a to wavelength ratio: $<a>/\lambda$	0.165	0.14
Structure length: l [mm]	96	167
Bunch separation: N_s [rf cycles]	6	5
Number of bunches in the train: N_b	42	102
Pulse length: τ_p [ns]	14.7	43.6
Input power: P_{in} [MW]	85	70
Rf-to-beam efficiency: η [%]	16.1	30.4
Luminosity per bunch Xing: $L_{b\times}$ [m^{-2}]	$.7\times10^{34}$	1.3×10^{34}
Bunch population: N	2.0×10^9	3.1×10^9
Figure of merit: $\eta L_{b\times}/N$ [a.u.]	5.2	13.0

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