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OPTIMUM FREQUENCY AND GRADIENT FOR THE CLIC MAIN LINAC ACCELERATING STRUCTURE

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Abstract

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Recently the CLIC study has changed the operating frequency and accelerating gradient of the main linac from 30 GHz and 150 MV/m to 12 GHz and 100 MV/m, respectively. This major change of parameters has been driven by the results from a novel main linac optimization procedure. The procedure allows the simultaneous optimization of operating frequency, accelerating gradient, and many other parameters of CLIC main linac. It takes into account both beam dynamics (BD) and high power RF constraints. BD constraints are related to emittance growth due to short- and long-range transverse wakefields. RF constraints are related to RF breakdown and pulsed surface heating of the accelerating structure. The optimization figure of merit includes the power efficiency, measured as a ratio of luminosity to the input power, as well as a quantity proportional to total cost.

INTRODUCTION

From almost the very beginning of CLIC [1] the operating frequency of the main linac accelerating structure was 30 GHz which gave a compromise between the efficiency and peak power, and and machinability and wakefield considerations. The original gradient was 80 MV/m for a 2 TeV collision energy. Eventually it was increased to 150 MV/m [2] in order to reach the CLIC design luminosity and energy (~10^{35} $cm^{-2}sec^{-1}$ and 3 TeV, respectively) in a power-efficient way and with an affordable site length. Since then several attempts have been made to find a better choice of the frequency and gradient for CLIC [3, 4].

In [4], a new optimization procedure has been used which is based on the interpolation of the accelerating structure parameters allowing millions of structures to be analyzed. The demanding beam dynamics requirements, a short-range transverse wakefield limit and long-range transverse wakefield suppression, are taken into account as well as high-power rf effects such as, rf breakdown and rf pulsed surface heating. The results indicated that 18 GHz and 100 MV/m are a better choice for CLIC if the ratio luminosity to the input power is considered to be paramount. Two things limited the validity of the results: first was the absence of a cost analysis and second was the lack of high gradient experimental data at 30 GHz. The latter difficiency called into question the frequency scaling of the rf breakdown constraints used in the optimization.

In this report, the extension of the optimization procedure described in [4] to include both a parameterized cost model and updated rf constrains is presented. Finally, the results of the CLIC main-linac accelerating structure using the new optimization are presented and discussed.

PARAMETERIZED COST MODEL

In the new parameterized cost model , the total cost is given by the sum of the investment cost and the exploitation cost for 10 years. It is calculated as a function of several parameters of the linac: the repetition frequency f_{rep}, the RF pulse energy for the whole linac W, the accelerating gradient E_{acc}, the structure length L, the operating frequency f and the rf phase advance per cell $\Delta\varphi$.

The model uses as a reference point a cost estimate which was done for a 30 GHz, 150 MV/m machine as described in [5]. Cost are scaled with the assumption that the cost per meter of accelerating structure varies according to the function

$$C_{\mathrm{acc}} = C_{mat} \cdot (f\,/\,30\mathrm{GHz})^{-3/2} + C_{mach} \cdot (f\,/\,30\mathrm{GHz})^{3/2} \cdot (\Delta\varphi\,/60^0)^{-2/3}$$

C_{acc} is the cost per meter of accelerating structure, C_{mat} *is* the material cost per meter of accelerating structure of the reference and C_{mach} is the cost of structure machining and assembly of the reference. This rule is based on scaling the required machining time and material mass and was benchmarked with the procurement costs of prototype structures at 30 GHz and 11.4 GHz. The effect of structure length L was modeled assuming that costs per meter of accelerator scale in proportion to $L^{-2/3}$. For other quantities like tunnel, magnet and instrumentation costs a simple linear scaling with cost ~E_{acc}^{-1} is assumed. The main cost of the drive beam the is determined by the total RF energy per machine pulse, which directly affects the number of required klystrons and modulators. The average RF power affects the total required charging power supply capacity. Electricity costs are based on the integrated consumption over 10 years of operation with 200 days per year and 95% up-time. The same unit costs were used as in estimates for the ILC [6].

UPDATED RF CONSTRAINTS

The following three rf constraints have been 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: $P_{in}\,/C\cdot\tau_p^{1/3}\cdot f < 156$ MW/mm/ns$^{2/3}$

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}, τ_p and f denote input power, pulse length and frequency respectively. C is the circumference of the first regular iris. The value used for the power constraint (3) is different from the one used in the previous optimization [4].

The original concept of power over circumference (P/C) as a limit for travelling wave rf breakdowns [7] which was used in [4] has been improved in several respects. First, the limiting value has been reduced in order to correspond to the CLIC nominal breakdown rate (BDR) of ~10^{-7} per pulse. The value is based on the available data for X-band Cu-structures and typical scaling of breakdown rate versus gradient [8]. Second, new experimental data obtained at 30 GHz [9, 10] have shown that P/C measured at (or scaled using typical scaling laws to) the same pulse length and BDR is inversely proportional to the frequency. This is directly related to an experimental observation that scaled X-band and 30 GHz structures reach approximately the same gradient at the same pulse length and BDR [11].

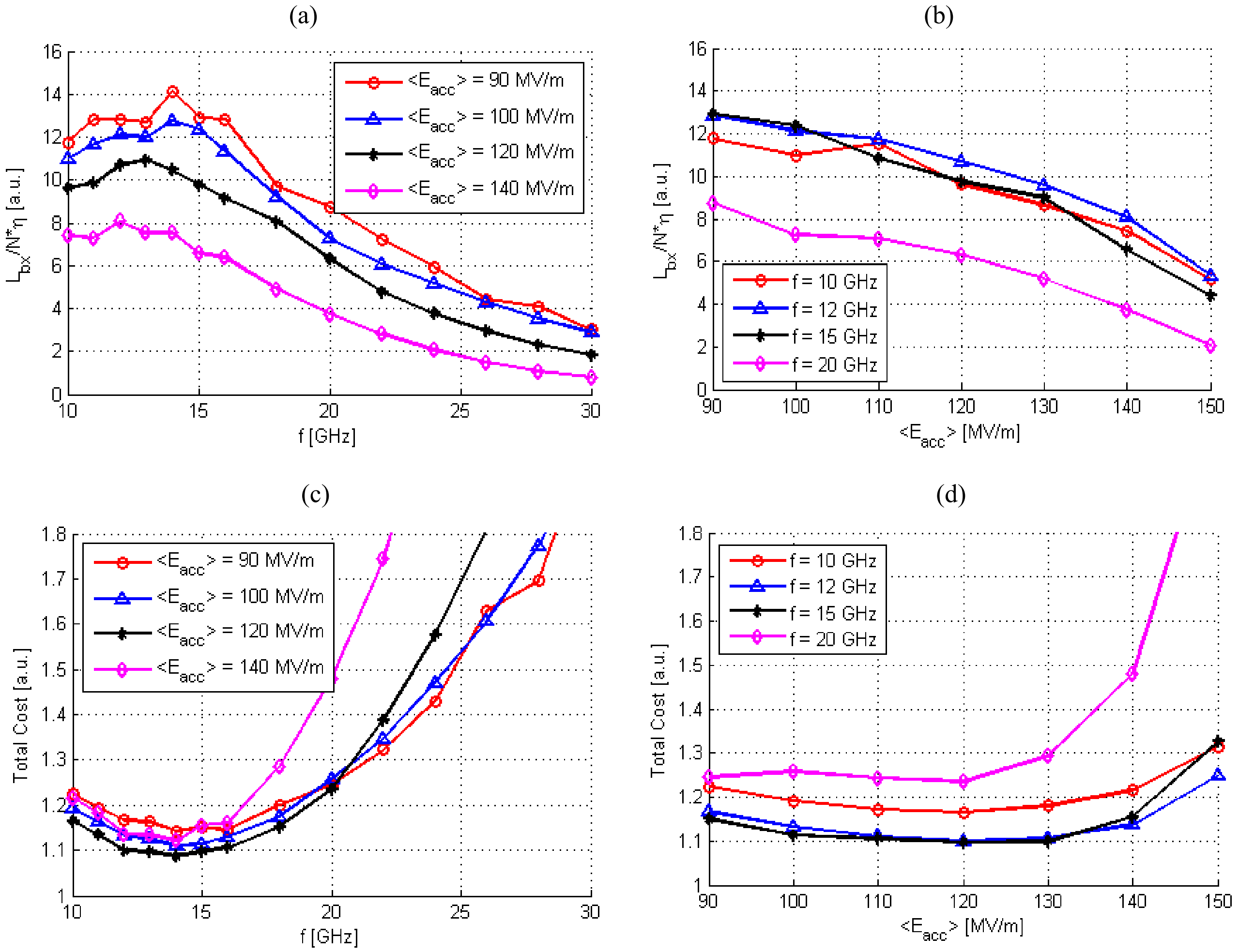

Figure 1: The results of optimization are presented both FoM on the top and for the total cost at the bottom.

OPTIMIZATION RESULTS

The CLIC main linac accelerating structure optimization has been performed in a range of f from 10 to 30 GHz and $<E_{acc}>$ from 90 to 150 MV/m for two different quantities. The first, the figure of merit (FoM) $\eta L_{b\times}/N$ has been maximized as in [4], where η is rf-to-beam efficiency, $L_{b\times}$ is luminosity per bunch crossing within 1 % of the energy spectrum and N denotes the bunch population. Then the total cost, calculated using the parameterized cost model described above, has been minimized. The results are presented in Fig. 1. The figure clearly shows that 150 MV/m and 30 GHz are not optimum parameters for CLIC. In Fig. 1 (a) and (c), the FoM and the total cost are shown as a function of frequency for different gradients. Both point to the same optimum frequency range of 12 to 15 GHz for all gradients considered. Finally, based on other considerations, mainly the availability of a frequency with extensively developed hardware, 12 GHz is chosen from the range as the best choice for CLIC.

The optimum gradient is not so obvious from the results of the optimization. In Fig. 1 (b), the FoM is shown as a function of gradient for different frequencies. Again as in [4], it indicates that for the whole frequency range considered, the lowest gradient gives the highest performance of the collider. However the gain becomes smaller at lower gradients, and is marginal at gradients below 110 MV/m. The dependence of total cost on gradient, which is shown in Fig. 1 (d), for different frequencies has different behavior. This has a minimum around 120 MV/m though it is rather flat, so the cost does not increase significantly even below 100 MV/m. Taking both the performance and the total cost considerations into account, a gradient of 100 MV/m is considered to be the best choice for CLIC. The lower gradient would increase the cost considerably, while the higher one would reduce the performance.

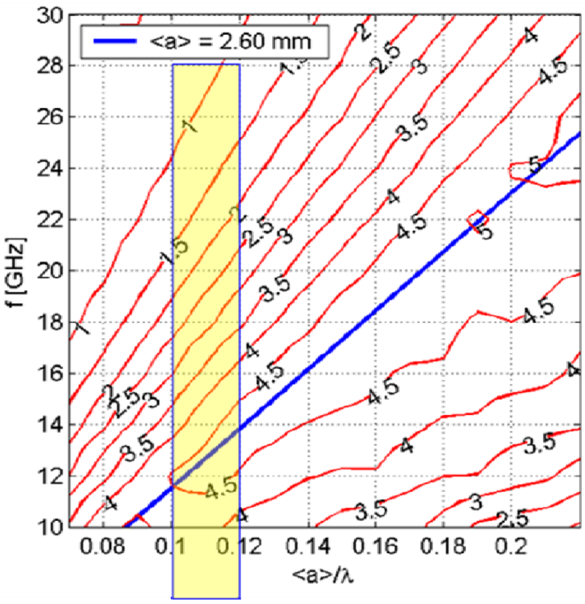

Figure 2: Lines of constant luminosity per bunch crossing normalized to the bunch population are plotted versus frequency and average ratio of aperture to the wavelength.

A closer look at the luminosity in 1 % of energy spectrum per bunch crossing normalized to the bunch population $L_{b\times}/N$ is useful to get more of an insight into the mechanisms driving the optimum. This very important parameter represents the beam dynamics requirements in the FoM. It is plotted in Fig. 2 as function of f and the average ratio of structure aperture to rf wavelength $\langle a\rangle/\lambda$. The lines of constant values of $L_{b\times}/N$ are shown in red. Higher values are better for beam dynamics. At each frequency, there is a maximum of $L_{b\times}/N$ which gives the optimum aperture at the frequency. In fact, this optimum aperture coincides very well with the straight blue line which shows the value of $\langle a\rangle/\lambda$ versus frequency for a structure with $\langle a\rangle$ = 2.6 mm. In other words, an accelerating structure with average aperture radius of 2.6 mm is the best from the beam dynamics point of view *independent of frequency*. The high gradient limitations have a different type of optimum. According to the presently available experimental data [11], scaled accelerating structures with the same $\langle a\rangle/\lambda$ show roughly the same gradient. This is shown in Fig. 2 by the yellow band covering range of $\langle a\rangle/\lambda$ from 0.1 to 0.12 and representing the area where a gradient of 100 MV/m can be achieved. The intersection of the blue line and the yellow band gives a range of frequencies where an accelerating structure with the optimum aperture providing gradient of 100 MV/m can be realised. Going lower in frequency reduces both the $L_{b\times}/N$ and the rf-to-beam efficiency of the structure.

CONCLUSIONS

The CLIC main linac accelerating structure optimization procedure taking into account complex interplay between beam dynamics and rf performance has been developed over the past few years. Recently new experimental data both at 30 GHz and at X-band have been obtained as well as a parameterized cost model of CLIC.Taking into account these last two ingredients, an optimization of CLIC frequency and gradient has been done which, together with some other considerations, resulted in major change of CLIC parameters from 150MV/m at 30GHz to 100MV/m at 12GHz. Following this change a new CLIC parameter set is under preparation [12]. The details of a new CLIC X-band accelerating structure design are presented in [13].

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