Lattice Scaling and Emittance Control in the CLIC Main Linac

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Abstract

For the main linac of the CERN linear collider (CLIC), emittance degradation due to wake fields and misalignments was previously investigated at unvarying injection energy and scaling of the betatron function. In particular, to keep a constant stability margin along the linac, the scaling retained was such that β^2/γ was constant. Recent developments suggest that the lattice scaling along the linac should be modulated differently in order to better balance the effects of the wake fields with respect to the chromatic dispersion. This may help to reduce the emittance dilution as would also a reasonable increase of the injection energy compatible with a bunch compressor. In the case of 250-GeV CLIC linacs, it was found that independent scaling of the cell length and focusing strength, and scaling laws different from the one mentioned above allow a better control of the growth of the small emittances foreseen, especially in the vertical plane. This approach, combined with a simultaneous adjustment of the injection energy and an improvement of the trajectory mastering, has made it possible to relax the alignment tolerances on the quadrupoles and the cavities while keeping the final emittances at their required level.

I. BETATRON SCALING WITH ENERGY

Scaling assumptions different from the one that keeps constant the stability margin [1] can be made when including, besides the wake fields, the emittance and trajectory chromaticity as another source of emittance dilution. One of those, which involves a variation of the phase advance per cell μ along the linac, can for instance be defined by [2]

$$\frac{1}{4f(s)}\left(\hat{\beta}(s)-\check{\beta}(s)\right)=\tan\frac{\mu}{2}=\left[\frac{\gamma_0}{\gamma(s)}\right]^{\alpha} \qquad (1)$$

where f is the focal distance of the quadrupoles, and $\check{\beta}$ and $\hat{\beta}$ the minimum and maximum of the β-functions. The basic relation between f, μ and the distance L_c separating two successive quadrupoles

$$\sin\frac{\mu}{2}=\frac{L_c}{2f} \qquad (2)$$

implies that a modulation of μ requires different scaling laws for f and L_c. Having found that constant focusing up to a given energy followed with a scaling according to (1) with $\alpha = 1$ gives no improvement in emittance control with respect to the $\sqrt{\gamma}$-law for β, we decided to try independent scalings of the cell length $2L_c$ and focal distance f [3]. Giving the preference to continuous and smooth variations of these quantities with s, they can be characterized by

$$\frac{L_c(s)}{L_{c0}}=\left(\frac{\gamma(s)}{\gamma_0}\right)^{\alpha_a} \qquad \frac{f(s)}{f_0}=\left(\frac{\gamma(s)}{\gamma_0}\right)^{1-\alpha_q} \qquad (3)$$

which mean that $\sin\mu/2$ varies with γ to power $\alpha_a + \alpha_q - 1$ by virtue of (2) and β-average with γ to power α_b, close to α_a since $\beta \sim L_c$. The hope was to be able to reduce μ with the distance along the linac and simultaneously limit the increase of the β-functions. This comes from the observation [2] that emittance dilution due to chromatic effects decreases when α increases from 0 to 1, while the blowup due to wake fields favours $\alpha = 0$. Since wake fields dominate in the first part of the linac and chromaticity rises with energy if the focusing is not relaxed, there must be an optimum balance between these two effects that depends on the choice of α_a and α_q for the linac considered. In CLIC (30 GHz, 80 MV/m), we found such a balance for $\alpha_a = 0.3$ and $\alpha_q = 0.6$. This means that μ decreases gently from the initial 95° with $\alpha \cong 0.2$ (Eq. (1)), while β-average rises with γ to power 0.4 about, instead of $\sqrt{\gamma}$ (Fig. 1).

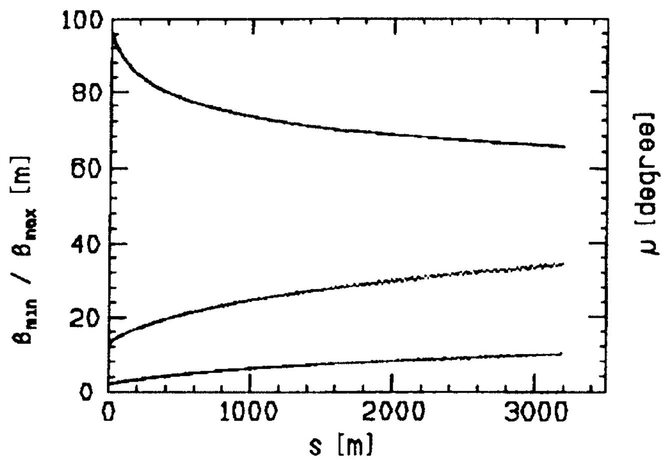

Fig. 1: CLIC Twiss functions with scaling of Eq. (3)

II. CHOICE OF INJECTION ENERGY

Raising the injection energy would reduce the wake-field impacts while increasing the pre-acceleration cost. But acceleration is necessary between the damping ring and the linac owing to the need for bunch compression. Therefore, the injection energy will only be known after a detailed study of the bunch compressors, but a first guess may come from the simple arguments given below.

At the exit of the 3-GeV damping ring [4], the bunch length σ_z and energy spread σ_E are about 2.2 mm and 1.5‰, while at the entrance of the linac σ_z should be of the order of 0.17 mm and σ_E between 0.5 and 1%, say. The bunch must then be compressed by a factor ~ 13 and this would correspond to an energy spread close to 2% in a one-stage compressor. Accelerating the beam to 9 GeV would subsequently reduce σ_E by a factor 3, to about 0.65%, i.e. within the interval assumed to be tolerable. However, $\sigma_E = 2\%$ at the end of such a compressor would enhance chromatic effects and it might be better to have two compressors of a factor 3.6 with intermediate acceleration to 9 GeV. Thereby, σ_E would never exceed 0.65% in the compressors. More studies are required to define both the number of stages and the tolerable (in view of emittance preservation) energy spread at injection; however, it seems today that the injection energy should be about 9 GeV rather than 5 GeV, as previously selected.

III. MASTERING OF BEAM TRAJECTORY

Since the kicks on the trajectory are linear with the misalignment amplitudes and the correction is obtained by moving quadrupoles, a single one-to-one correction should converge to the same final trajectory independently of the initial size of the quadrupole displacements. Nevertheless, if the numerical model in the simulations is not perfect, and if real-life inaccuracies in the correction setting or quadrupole jitter are included, the quality of the correction depends weakly on this initial size. In order to remedy this dependence, the possibility to iterate the one-to-one correction as many times as required has been added in the main-linac tracking program [5]. This procedure tends to realign the quadrupoles with the beam, towards the linac ideal line.

Since the wake fields are strong in CLIC, it is important to have beam-position monitors associated with the cavities rather than with the quadrupoles. The present idea consists of installing these monitors at the beginning of each girder (about 1.3-m long) supporting four accelerating sections. The additional information acquired between quadrupoles can be exploited for the correction, while keeping the idea of local correction. It is only a matter of determining every correcting kick by minimizing all the trajectory deviations measured downstream but only as far as the next quadrupole, i.e. the function

$$\Phi = \sum_{j<i<j+1} \left(\langle x \rangle_i - \frac{b_i}{f_j} \mathrm{d}x_j \right)^2 , \qquad (4)$$

where j is the quadrupole index and i the monitor index. f_j and $\mathrm{d}x_j$ are the focal length and the quadrupole displacement that reduce the average bunch position $\langle x \rangle_i$ at all monitors between quadrupoles j and j+1. b_i is the transfer coefficient from quadrupole j to monitor i (separated by a distance ℓ_i and an energy difference $E_i - E_j$),

$$b_i = \ell_i \frac{E_j}{E_i - E_j} \log \frac{E_i}{E_j} \qquad (5)$$

generalized to include the wake fields [5]. The solution which annuls the derivatives of Φ with respect do $\mathrm{d}x_j$ and thereby minimizes Φ can be written as follows, once the errors on the monitor signals $\xi_{m,i}$ and on the quadrupole displacements $\xi_{d,j}$ are included

$$\mathrm{d}x_j = \frac{\sum_i \left(\langle x \rangle_i + \xi_{m,i} \right) \frac{b_i}{f_j}}{\sum_i \left(\frac{b_i}{f_j} \right)^2} + \xi_{d,j} . \qquad (6)$$

This algorithm aims at reducing the deviations in all the cavities rather than centring the beam in the next quadrupoles and relaxing the cavity tolerances at same performance.

Combining the iteration procedure with the one-to-few algorithm described above allows a trajectory reduction by almost three orders of magnitude after two iterations (Fig. 2) and a realignment of the quadrupoles on the beam path within less than 5 μm r.m.s. (Fig. 3), starting from 50 μm.

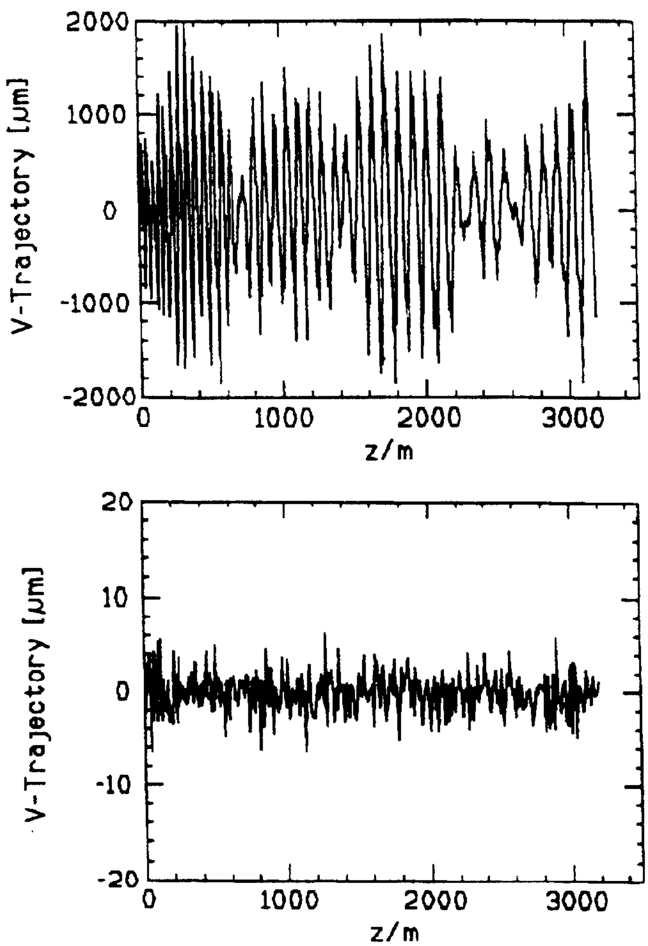

Fig. 2: Trajectory reduction after two iterations

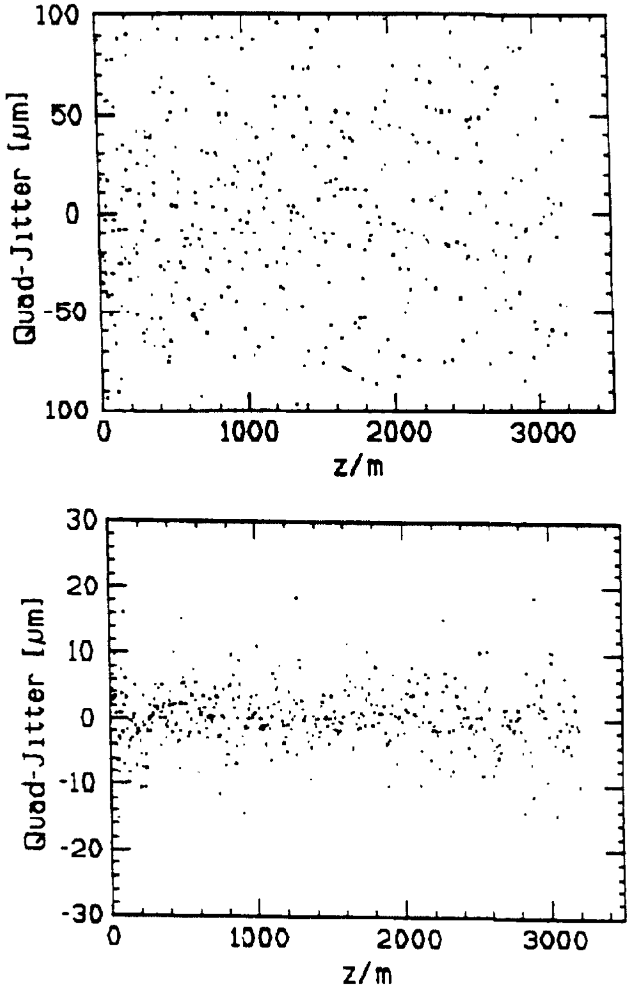

Fig. 3: Reduction of quadrupole scattering after two iterations of the correction

IV. RESULTS AND CONCLUSIONS

Emittance dilution calculations have been carried out for the CLIC main linac with 500-GeV centre of mass [6]. Adopting the independent scaling of Section I (with $\alpha_a = 0.3$, $\alpha_q = 0.6$) instead of the $\sqrt{\gamma}$-law gave a vertical blowup reduction of 33%, all other parameters being constant. Another gain of 25% came from raising injection energy from 5 to 9 GeV (Section II). The correction of the trajectory used iterations when needed and the one-to-few method described in Section III. All these improvements have been made with a view to relaxing the alignment tolerances, while aiming at normalized emittances of 1.8 μrad m horizontally and 0.2 μrad m vertically as required by the performance [6]. The r.m.s. quadrupole misalignments are limited to 50 μm, not by the correction efficiency, but by the trajectory excursion (Fig. 2 top) in cavity irises with 4-mm diameter. An r.m.s. spread of 10 μm in cavity positions is tolerable with position monitors in front of every girder. By contrast, these monitors which define the beam path have to be aligned within 2 μm r.m.s. Starting from emittances of 1.5 μrad m and 0.05 μrad m at linac injection, dilution reaches on average (statistics over eight machines) 20% horizontally and a factor four vertically (Fig. 4), giving emittances at the linac exit in agreement with the target values. It was checked also that tolerances of the order of 0.5 μm for the resolution and jitter of quadrupole displacements do not increase the emittance dilution by more than ~ 10%. These results show that we progressively succeeded in relaxing tolerances while keeping constant the emittance target values.

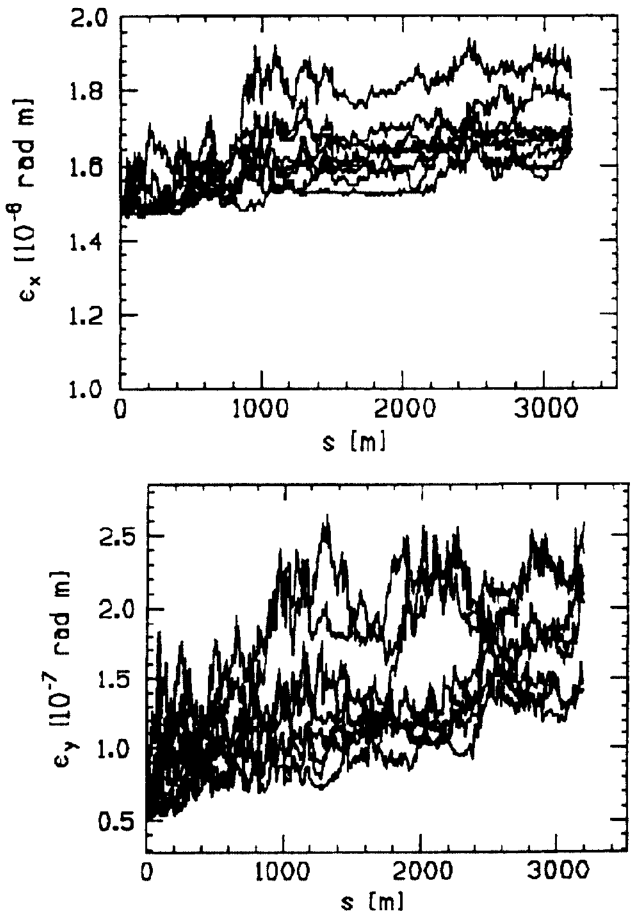

Fig. 4: Horizontal and vertical emittance dilution with new independent scalings

V. REFERENCES

[1] H. Henke and W. Schnell, CERN LEP-RF/86-18, 1986.

[2] V. Tsakanov, *ICFA Workshop on Linear Colliders*, Garmisch-Partenkirchen, 1992.

[3] G. Guignard, CERN-SL/93-12 (AP), 1993.

[4] J.P. Delahaye, J.P. Potier, CERN-PS/91-10 (LP), 1991.

[5] G. Guignard, CERN-SL/91-19 (AP), 1991.

[6] G. Guignard, "Beam stability simulations in CLIC linacs," *XVth Int. Conf. on H. E. Acc.*, Hamburg, 1992.