Global Trajectory Correction Algorithms in CLIC and Main Linac Alignment Tolerances

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Abstract

Alignment tolerances in linear colliders are closely dependent on the expertise in beam trajectory handling, particularly in CLIC where wake fields dominate. Control of the on-momentum trajectory only can be considered as in a straightforward one-to-one scheme. However, more sophisticated processes can be contemplated, involving several correctors and beam position monitors. Moreover, it is possible to apply gradient variations from the nominal values in order to simulate and better compensate dynamical effects, as first suggested at SLAC. The present paper describes various methods applied with assumptions reflecting the most recent characteristics of the CLIC main linac and beam. Calculations for several sets of parameters are presented. Alignment requirements are alleviated and fall in the feasibility domain while maintaining the previously mentioned key parameters within specifications.

I. INTRODUCTION

Global trajectory correction algorithms were first successfully proposed at SLAC for the NLC [1], their advantage being to better cope with misalignments affecting magnets and accelerating structures of a linac than a straightforward one-to-one scheme. These global schemes aim at the minimization of an expression of the form:

$$\phi = \sum_j \frac{(xj + Xj)^2}{\sigma_\xi^2 + \sigma_b^2} + \frac{(\Delta xj + \Delta Xj)^2}{2\,\sigma_\xi^2} \qquad (1)$$

The first term is related to the nominal momentum trajectory and xj and Xj are the measured and calculated deflections at j, whereas the second one deals with off-momentum phenomena. In the case of the Dispersion-Free (D.F.) algorithm, Δxj and ΔXj are the measured and predicted trajectory differences between particles with energy excursion $\delta = \Delta p/p_0$ and particles at nominal momentum p_0. A customary weighting of both terms is applied considering σ_ξ the r.m.s. pick-up reading resolution and σ_b their r.m.s. alignment error which disappears in the second term where only trajectory differences are involved. Instead of a D.F. process, one can try to simulate and hence correct for the influence of wake fields experienced by particles having off-centred trajectories in the accelerating structures; these wake field kicks always have the same direction on a given side of the machine axis. A Wake-Free (W.F.) algorithm tries to mimic them by generating an anti-symmetrical gradient variation of the focusing and defocusing lattice quadrupoles; the induced trajectory differences are then minimized. Both the D.F. and W.F. methods require one to vary the strength of lattice quadrupoles, but in the former process the F and D chains are moved in synchronism, whereas in the latter case they are affected in opposite directions. Measuring the trajectory at each pick-up for nominal setting and every perturbed configuration provides the quantities xj and Δxj. The determination of Xj and ΔXj requires the knowledge of all transfer matrix coefficients R_{12} (i,j) from any kick i to a pick-up j > i, again at nominal setting and for every detuned situation. When these coefficients only reflect the basic machine FODO model, they exhibit non-linearities with energy deviation which can be treated [2]. However, in the case of CLIC, with wake fields at full strength, this description is not sufficient for good convergence, and they have to be determined by measurement in the presence of the wakes and of the beam-energy dispersion along the linac. Their behaviour is then much more linear. In practice a given kick is generated at i, looking at the response at the subsequent locations j. With the beam-energy dispersion, the effect of a kick is damped after some distance. Good accuracy requires therefore the regeneration of these kicks regularly along the linac [3].

II. APPLICATION TO THE CLIC MAIN LINAC

Both D.F. and W.F. algorithms have been tested in the case of the CLIC main linac. CLIC (stage 1) with final c.m. energy of 0.5 TeV is considered, which implies an accelerating structure length of 3200 m and 320 quadrupoles per linac. Beam parameters are described in [4]; an injection energy of 5 GeV is considered with a 90° phase advance FODO lattice; the usual $(E/E_0)^{1/2}$ scaling is applied for B.N.S. damping considerations; external focusing by means of RF quadrupoles located at each lattice quadrupole is used with a relative strength of a few per cent.

Only the vertical plane is considered. With a nominal aspect ratio of 29 [4], emittance preservation is much more critical in this plane, the aim being to maintain the emittance blow-up below a factor of four at the linac end, starting with a normalized emittance of $5 \cdot 10^{-8}$ nm at injection. Relative gradient variations δ of 3.5% in amplitude are used. These perturbations induce trajectory differences of several hundred microns, Figure 1, larger by two orders of magnitude than the expected alignment errors, and are also above the beam-energy dispersion one wants to cope with. Pick-ups and kicks are localized at every F and D quadrupole. Tests revealed that the correction processes are more efficient when pick-ups are distributed along the beam axis rather than attached to their adjacent quadrupole [2]; the number of pick-ups and correctors to be considered in a single application of the algorithm is of the order of 10 for the best efficiency.

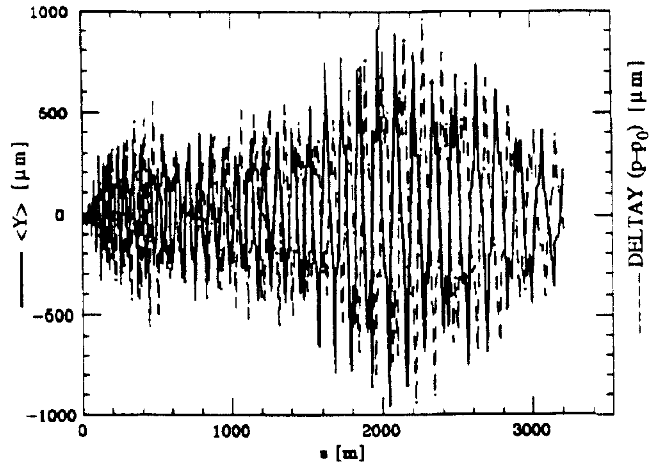

Figure 1. Vertical beam trajectory (solid line) and vertical dispersion for $\delta = +3.5\%$ (dashed curve) of the non-corrected CLIC linac in the 5-2-2 case.

Results are presented for r.m.s alignment errors of 5-2-2 μm and 5-5-5 μm respectively on quadrupoles, pick-ups, and accelerating cavities. The first set is so far considered realistic in CLIC alignment studies [5]. Pick-up resolution errors are expected to fall in the sub-micron range [6].

III. DISPERSION-FREE ALGORITHM RESULTS

In the 5-2-2 case the beam follows the vertical trajectory represented in Figure 1 (solid line). Dispersion effects for an energy excursion $\delta = +3.5\%$ from the nominal momentum are also shown (dashed curve).

Without correction the initial normalized emittance of $5 \cdot 10^{-8}$ nm blows up by three orders of magnitude.

The same data are given in Figure 2 after application of the D.F. process. A reduction of the trajectory peak-to-peak amplitude by two orders of magnitude is obtained, whereas the dispersive term is damped by about a factor 30. Figure 3 shows the normalized emittance evolution along the corrected linac reaching a value of $17 \cdot 10^{-8}$ nm at the exit.

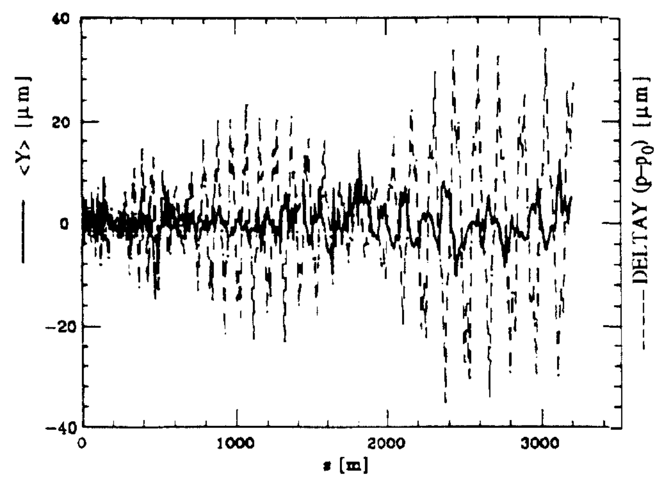

Figure 2. Vertical beam trajectory (solid line) and vertical dispersion for $\delta = +3.5\%$ (dashed curve) after D.F. correction in the 5-2-2 case.

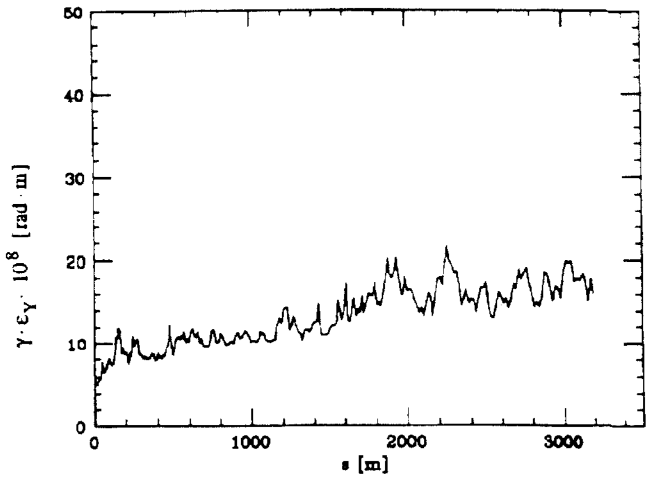

Figure 3. Normalized vertical emittance evolution after D.F. correction in the 5-2-2 case.

The application of the process is, however, not completely straightforward. Using 6 to 10 pick-up and corrector bins several iterations are required on the same region and a total number of more than 200 iterations is reached along the 3.2 km. Another striking feature is the weighting strategy to apply. Considering expression (1) and in agreement with the working hypothesis ($\sigma_b = 2$ μm and $\sigma_\xi \cong 0.5$ μm [6]) one ought to weight the dispersive term 10 times more than the trajectory. If such a strategy is applied the process efficiency is much reduced as far as the transverse emittance is concerned; on the contrary, good results are consistently obtained by stressing first the basic trajectory contribution by a factor of 10 or more. When acceptable results are thus obtained, they can be further improved by a factor 2 to 5 by resuming the iterative process with the two terms equally weighted. Any attempt to stress the dispersive term with respect to the trajectory leads quite systematically to bad results.

Requirements on the nominal vertical emittance are met, but a one-to-one scheme gives similar results [7] for this misalignment configuration.

IV. WAKE-FREE ALGORITHM RESULTS

This next section presents the results achieved when applying a W.F. algorithm with alignment tolerances relaxed to an r.m.s value of 5 μm for the three types of components (5-5-5 case). The trajectory and 'wake-free' term are represented in Figure 4 after this application, and the evolution of the vertical emittance along the corrected linac is given in Figure 5.

A total number of roughly 200 iterations were also necessary in that case; again, instead of stressing the 'wake-free' term in expression (1) 50 times more than would have been suggested by pick-up misalignment errors, a first pass was performed with equal weighting of the two terms, and then reinforcing again the basic trajectory contribution with respect to the other one: stressing this second term 10 times more was, however, found useful to better preserve the emittance during the first half-kilometre of the linac, i.e. at low energy when the disturbing wake-field forces are the most harmful. This is reflected on Figure 4: trajectory distortion amplitudes are kept within ± 10 μm, in agreement with expectations made on misalignment errors and are worsened at the beginning by the emphasis put on the wake-free term; this latter is, on the contrary, well controlled in the first part of the linac and then deteriorates progressively.

A normalized vertical emittance value of $16{\cdot}10^{-8}$ nm is obtained—Figure 5. Considering the longitudinal bunch distribution between $+3\sigma_z$ and $-2\sigma_z$ brings the final emittance value down to $14{\cdot}10^{-8}$ nm (dots).

With respect to a one-to-one scheme, a factor of more than three is now gained on the final emittance value [7].

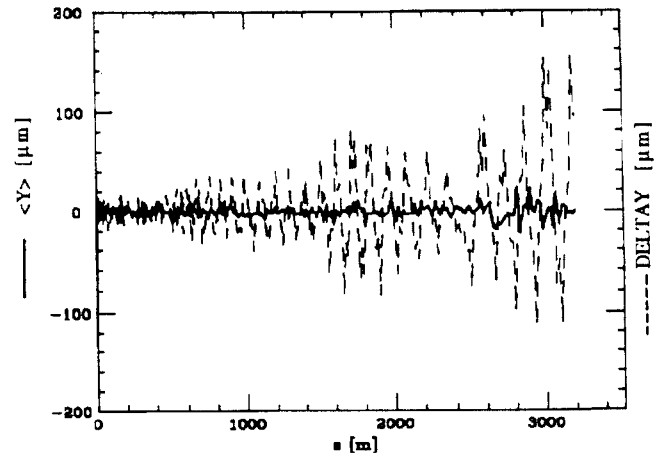

Figure 4. Vertical trajectory (solid line) and 'wake-free' term for a relative strength modulation of +/– 3.5% applied respectively on the QD and QF chains (dashed curve) after W.F. correction in the 5-5-5 case.

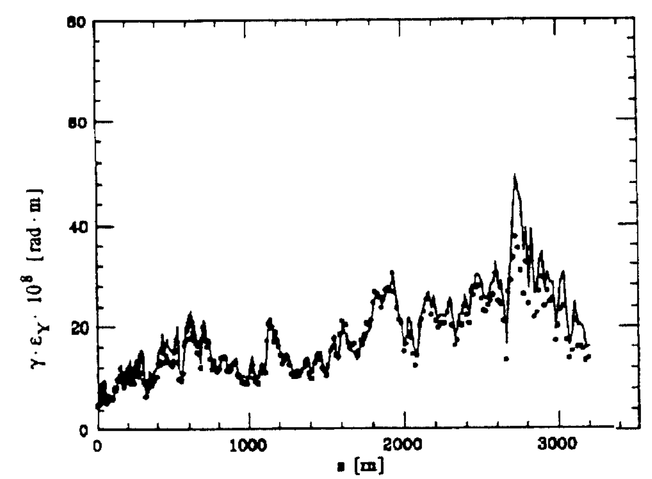

Figure 5. Normalized vertical emittance evolution after W.F. correction in the 5-5-5 case.

V. DISCUSSION

It is shown that, for CLIC, a global correction method can be contemplated as soon as alignment tolerances of pick-ups have to be relaxed beyond an r.m.s. value of 2 μm; below this value, a one-to-one scheme is as good at finding a solution. A W.F. algorithm looks more efficient than a D.F. one. This is not surprising when considering the huge wake fields of CLIC, and corroborates the conclusions of [1]. The application of such processes is not straightforward: in some cases the strategy to apply relies on the observation of the emittance behaviour as well as on the minimization of quantities provided by the signal of pick-ups located at lattice quadrupoles only. This can probably be attenuated by adding more pick-ups in the accelerating sections in order to better centre the trajectory in the R.F. cavities where wake fields are generated.

The contribution of the nominal trajectory term had to be made predominant most of the time for the best process efficiency; therefore a 'natural' weighting strategy relying only on pick-up misalignment errors and resolution was not adequate. The strategy to follow might depend on the machine which is considered and on the application of the method. Indeed, the relative importance of both terms in expression (1) varies with wake-field levels as well as with the energy or gradient excursions applied to evaluate quantities coming into the second term. In the case of CLIC, with a modulation amplitude of 3.5%, the importance of the two terms was roughly balanced, as can be observed in Figure 1.

VI. CONCLUSION

For CLIC, by virtue of a global algorithm, alignment contingencies can be alleviated by more than a factor of two, whilst the nominal value of the normalized vertical emittance is preserved; misalignment r.m.s. errors of 5 μm can be tolerated on pick-ups. This figure can probably approach 10 μm when applying these global correction methods to a machine with higher injection energy and new scaling laws [8]. Work is continuing in this direction.

VII. ACKNOWLEDGEMENTS

I had many helpful discussions with G. Guignard in the course of this study.

VIII. REFERENCES

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