Final-focus systems for multi-TeV linear colliders

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In *Phys. Rev. Lett.* 86, 3779 (2001), a compact final focus system (FFS) was presented. This scheme was compared to the nonlocal chromatic correction FFS concluding with the superiority of the local system. Nevertheless, the sensitivity of the system to errors and its mitigation was missing in the comparison. In this paper, an extended comparison of the Compact Linear Collider local FFS and an improved nonlocal FFS is presented at 3 TeV and 500 GeV. We demonstrate that, at high energies, luminosity delivered by the ideal machine is no longer the most important figure of merit but the recovered luminosity after tuning with imperfections, where the improved traditional scheme shows a better performance. This result might have an important relevance also for ILC at 1 TeV.

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I. INTRODUCTION

The next generation of multi-TeV linear colliders such as the Compact Linear Collider (CLIC) [1,2] needs to focalize the beam to very small sizes to achieve a luminosity of the order of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. This strong focalization is driven by the final doublet (FD) within the final focus system (FFS) that demagnifies the beam coming from the linac from hundreds of nanometers to just a few nanometers. Since the beam is not completely monochromatic, particles with different energies are focalized at different points. The FFS must compensate this effect by means of sextupoles and other higher order multipoles. When realistic imperfections are included such as element misalignment or field errors, the performance of the system is seriously affected. Therefore techniques to bring the system to its nominal performance must be designed and demonstrated with simulations. These techniques are usually referred to as tuning.

II. FINAL FOCUS SCHEMES

Historically there have been two main approaches to the FFS design. Some of the first designs with chromaticity correction consisted of a scheme with two dedicated sections for horizontal and vertical chromatic correction (CCX and CCY respectively). In this scheme the optics presents a high-dispersion function and high- β value where sextupoles are placed in pairs. The transformation matrix between sextupoles is $M = -\mathcal{I}$ in order to cancel the geometric aberrations introduced. Early designs of the CLIC FFS followed this

approach [3]. This design was experimentally validated in final focus test beam (FFTB) [4] reaching 70 nm vertical beam while the expected was 52 nm [5]. The difference was explained by a beam jitter of about 40 nm [6]. Two variations of this design consisted in adding more sextupoles [7] and following an odd-dispersion scheme [8].

An alternative scheme was proposed in [9] with the aim of reducing the total length of the system correcting the chromaticity locally, placing a pair of sextupoles interleaved with the FD. Upstream of the FD a bending section is needed to create the required dispersion at the sextupoles for the chromaticity compensation. A second order dispersion aberration produced by the sextupoles is canceled provided that half of the horizontal chromaticity arises from upstream of the FD. The geometric aberrations also introduced by the sextupoles are canceled adding two more sextupoles placed in opposite phase with them and also upstream of the bending section. One more sextupole is used to correct higher order aberrations. This scheme is more compact than the traditional scheme and the momentum bandwidth is larger due to the locality of the correction. This new scheme, used in the later designs of the Next Linear Collider, is currently considered for the ILC [10] and CLIC [1] FFS baseline designs and it is being tested at ATF2, where recently vertical spot sizes of about 44 nm have been reached while the design is 37 nm. The 7 nm discrepancy is under investigation.

The transfer map between two locations of a beam line is expressed in the form

$$z_f = \sum_{jklmn} X_{z,jklmn} x_0^j p_{x0}^k y_0^l p_{y0}^m \delta_0^n, \quad (1)$$

where z_f represents any final coordinate (x_f, p_{xf}, y_f, p_{yf}), the initial coordinates are represented with the zero

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subindex and $X_{z,jklmn}$ are the map coefficients of the corresponding final coordinate. According to this formalism, chromaticity is given by [11]

$$\xi_y^2 = \frac{1}{\beta_y^*} \left(X_{y,00101}^2 \beta_{y0} + X_{y,00011}^2 \frac{1}{\beta_{y0}} \right), \quad (2)$$

where X_y are the coefficients of the transfer map defined by Eq. (1) between the beginning of the line and the IP, β_{y0} and β_y^* are the vertical β functions at the starting point and at the interaction point (IP) respectively. If chromaticity is not corrected the vertical spot size at the IP, σ_y^* , becomes

$$\sigma_y^* \approx \sigma_{y,0} \sqrt{1 + \xi_y^2 \sigma_\delta^2}, \quad (3)$$

where $\sigma_{y,0} = \sqrt{\epsilon_y \beta_y^*}$ is the linear vertical beam size and $\sigma_\delta = \Delta p/p$ is the rms energy spread. In Table II the chromaticity for both schemes at different energies is given using Eq. (2). Also in Table II the length of the FFS is shown. One can see that, in order to avoid strong synchrotron radiation effects, the length of the traditional FFS must be about 1 kilometer longer than the local scheme, but representing a factor 2 shorter than the initial designs [3] due to further optimization of the system. At low energies,

both systems have a similar length. The system design and optimization is carried out using advanced numerical techniques based on MADX [12] and MAPCLASS [13,14], a code for linear and nonlinear optimization of the beam size. The beam size is sequentially optimized order by order matching sextupole and higher order multipole magnet strengths until higher order contributions are negligible. One can see in Fig. 3 that beyond order 5, the beam size does not increase anymore as also obtained in [13] for the 3 TeV case. One can see that the compensation of aberrations is similarly performed in all the cases.

The lattice design of the local correction scheme, after several years of optimization [15–17], uses six sextupoles at 3 TeV [Fig. 1 (top)] and five at 500 GeV c.m. energy, two octupoles and one decapole [Fig. 2 (top)].

The traditional scheme [18,19] uses four pairs of main sextupoles (two pairs in CCX and two pairs in CCY) and two pairs of octupoles, two in the FD region and two more upstream of the FD, to correct geometric aberrations introduced by the sextupoles [Fig. 1 (bottom) for 3 TeV and Fig. 2 (bottom) for 500 GeV]. Some secondary sextupoles are added to the chromatic correction sections in order to better correct chromaticity and to increase the momentum bandwidth following the approach shown

FIG. 1. Optics of the CLIC 3 TeV local correction scheme (top) and dedicated correction scheme (bottom) final focus system showing the optical functions, where η is the dispersion function. Above the layout is shown where in blue are represented bending magnets, in red quadrupoles and in black sextupoles.

FIG. 2. Optics of the CLIC 500 GeV local correction scheme (top) and dedicated correction scheme (bottom) final focus system showing the optical functions. Above the layout is shown where in blue are represented bending magnets, in red quadrupoles and in black sextupoles.

FIG. 3. High order optimization using MAPCLASS for CLIC FFS at 3 TeV (top) and 500 GeV (bottom).

in [7]. The β functions at the sextupole locations and the sextupole length have been chosen after an iterative optimization process. High β functions keep sextupole strengths low and chromatic correction is better performed but the system is more sensitive to errors in those locations. Low β functions increase tolerances but also increase

FIG. 4. Beam at the entrance of the final doublet for the local and the traditional FFS for CLIC at 3 TeV c.m. energy. Particles of the incoming beam are placed on an ellipsoid of $15\sigma_x$ and $50\sigma_y$ and a flat energy distribution with 1.4% E_0 width.

sextupole strengths over the maximum allowed by technology. After several iterations, the final lattice consists of sextupoles of 70 cm with the apertures and fields presented in [20] and the β functions shown in Fig. 1.

A. Beam halo

Figure 4 shows the halo distribution for CLIC at 3 TeV at the entrance of the FD as expected from the collimation gaps. Unlike in [9] we observe that the optimized traditional chromatic correction scheme presents a more compact halo distribution in the vertical plane.

B. Synchrotron radiation

Synchrotron radiation in the bending sections and in the quadrupoles [21] is also a source of beam size dilution at the IP at high energies. At low energies the contribution is lower than that of the nonlinearities. Radiation in bending magnets mainly dilutes the horizontal beam size while radiation in quadrupoles affects mainly the vertical beam size. Since the FD is the same for both schemes at high energies the effect of radiation in quadrupoles is comparable. At low energies the FD is shorter for the traditional scheme and therefore radiation effects are more notable, without having a big impact on luminosity. In Table II the effects of synchrotron radiation in the transverse beam sizes are summarized after optimization. At high energies the horizontal beam size is affected by radiation in bending magnets by about 9%–15% beam size increase. The vertical beam size is strongly affected by the radiation in the last quadrupoles but this effect is not fully reflected in luminosity since the impact is mostly present in the tails of the beam (i.e., increasing the rms beam size) but the core of the beam remains practically the same.

III. LUMINOSITY

Simulations of beam collisions and luminosity computation are performed with GUINEAPIG [22] after tracking the beams through the FFS with PLACET [23]. The electron and the positron lines are considered to be

TABLE I. CLIC Design parameters at two different stages, 500 GeV and 3 TeV center of mass energy [1].

Parameter [units]	3 TeV	500 GeV
Center of mass energy $E_{c.m.}$ [GeV]	3000	500
Repetition rate f_{rep} [Hz]	50	50
Bunch population N_e [10^9]	3.72	6.8
Number of bunches n_b	312	354
Bunch length σ_z [μm]	44	72
IP beam size σ_x^*/σ_y^* [nm]	40/1	200/2.26
Beta function (IP) β_x^*/β_y^* [mm]	7/0.068	8/0.1
Norm. emittance (IP) ϵ_x/ϵ_y [nm]	660/20	2400/25
rms energy spread σ_δ [%]	0.3	0.3
Luminosity $\mathcal{L}_T$ [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	5.9	2.3
Peak luminosity $\mathcal{L}_{1\%}$ [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	2.3	1.4

TABLE II. Simulation results for the two FFS at two different energies. Total length of the FFS, last drift, chromaticity, synchrotron radiation effects on the transverse beam size and total and peak luminosity. The last column shows the ratio of the peak luminosity with and without including synchrotron radiation effects.

Scheme	Energy [GeV]	L_{FFS} [m]	L^* [m]	ξ_y	$\Delta\sigma_x/\sigma_{x0}$ (Bend) [%]	$\Delta\sigma_y/\sigma_{y0}$ (Quads) [%]	$\mathcal{L}_T$ [10^{34} cm $^{-2}$ s $^{-1}$]	$\mathcal{L}_{1\%}$ [10^{34} cm $^{-2}$ s $^{-1}$]	$\mathcal{L}_{1\%}/\mathcal{L}_{1\%}^{(w/o\text{SR})}$
Local	3000	447	3.5	82397	15	110	7.8	2.4	0.79
Traditional	3000	1503	3.5	91228	8.8	80	7.4	2.4	0.77
Local	500	553	4.3	66618	0.2	1.6	2.3	1.4	0.99
Traditional	500	660	4.3	76854	0.1	47.7	2.2	1.3	0.94

symmetrical and the offset at the IP is automatically corrected. The values of luminosity are summarized in Table II. At 3 TeV, the optimization of both schemes gives a luminosity above the value given in Table I. This margin is needed for imperfections. One can see that both systems present the same value of peak luminosity i.e., luminosity delivered by those particles with energy above the 99% of the nominal energy. At 500 GeV, the luminosity given by simulations of the local scheme is exactly the same value shown in Table I and there is no margin for imperfections. In that case, the traditional scheme presents a 7% less total luminosity than the local scheme. At low energies, both schemes present similar performance keeping their lengths within a reasonable value.

Luminosity decreases rapidly when the beam has a difference in energy with respect to the nominal value. The beam energy jitter coming from the linac is expected to be up to 0.1% of the nominal energy [24]. Due to the fact that sextupoles are placed close to the FD, the local

correction scheme presents a wider energy bandwidth than the traditional scheme as it is observed in Fig. 5, where peak luminosity is taken as the important observable to characterize the impact of energy deviations. For such small incoming energy jitter, the luminosity loss for the traditional scheme is relatively low. In case an increased bandwidth is needed, it is possible to improve it by placing a sextupole in the betatron waist position upstream of the FD and move last dipoles in order to let some dispersion at the sextupole location following the idea exposed in [25].

IV. TUNING

Both schemes present a similar performance but, when we consider realistic imperfections, luminosity drops dramatically. The tuning is the procedure which brings the system to its design performance. Since the initial errors are unknown, the tuning simulation requires a statistical study. Usually more than 100 different machines with randomly distributed errors are considered in computer simulations. The simulated tuning reproduces a realistic tuning procedure in a real machine. The tuning techniques used in this simulation are widely described in [26–28], they use beam based alignment techniques and sextupole knobs. The knob generation procedure followed for this study and the detailed algorithm is explained in [28]. Figure 6 shows the results of the tuning simulations after one iteration of the algorithm. In the vertical axis is the number of machines that reach at least the luminosity shown in the horizontal axis, which is normalized to the nominal value of the luminosity given in Table I. We notice that the tunability of the local scheme is very challenging. Almost 70% of the machines do not reach 10% of the nominal luminosity. However, the traditional scheme presents a much better tunability, showing that 90% of the machines reach at least 80% of the nominal luminosity.

The number of luminosity measurements per iteration of the algorithm is about 300; that corresponds to a time span of about 5 minutes if a fast luminosity measurement takes 1 second [28]. Since the tunability of the local scheme is not satisfactory more iterations of the algorithm and a SIMPLEX optimization are required. This additional tuning step increases the number of luminosity measurements by an order of magnitude [28], and therefore more time is devoted

FIG. 5. Peak luminosity bandwidth for different schemes of CLIC FFS at 3 TeV (top) and 500 GeV (bottom).

FIG. 6. Luminosity distribution of 100 machines after BBA and MULTIKNOB algorithm procedure for an initial prealignment of $10\ \mu\text{m}$ for CLIC 3 TeV (top) and 500 GeV (bottom). Luminosity is normalized to the value given in Table I.

to tuning not usable for physics. In [28] the full tuning simulation of the local scheme was done using a higher bunch charge, 4.0×10^9 particles per bunch instead of the nominal charge of 3.72×10^9 [29], where 90% of the machines reach at least 90% of the nominal luminosity. At the nominal charge, this performance might not be reachable even with further tuning. Due to dynamic imperfections luminosity drops by 10% after 30 minutes [30] and then a new tuning is required to recover the full luminosity. Therefore, a tuning time much shorter than the time at which the dynamic effects become important is crucial to ensure the optimal tuning performance and more time devoted to physics.

V. CONCLUSIONS

In summary, we have compared the performance and tuning simulation of two different FFS schemes for CLIC at 3 TeV and 500 GeV center of mass energy. The study concludes that the traditional system is 1 kilometer longer than the local system but only at high energies. At low energies both systems require a similar length. The compensation of nonlinearities by both systems yields a comparable luminosity. Also the difference in the energy bandwidth is relatively small in the range of interest. The main difference comes from the tuning simulation, where we have demonstrated that the traditional FFS is much easier to tune at high energies, just one iteration of the proposed algorithm is needed to achieve the goal of 90% of the machines above 90% of the nominal luminosity while the local scheme would require more iterations and,

in consequence a tuning time that exceeds rapidly one hour without guaranteeing that 90% of the machines are above 90% of the nominal luminosity. A faster tunability translates into a larger integrated luminosity. Therefore, at high energies, the optimized traditional FFS features a higher performance and robustness than the local scheme that must be weighted against the cost of a longer tunnel.

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