Progress on the Final Focus System for CLIC

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Abstract The present status of the final focus system for CLIC is described. In order to minimize both geometric and chromatic aberrations, it consists of chromatic correction sections with pairs of sextupoles for each plane and dipoles to make the necessary dispersion. An optimized telescope compresses the beam to the desired spot size. Luminosity enhancement due to pinching has been studied using the particle distribution including synchrotron radiation in quadrupoles, assuming an equal bunch meeting head-on. Correction of orbits in the presence of position and excitation errors has been studied by computer simulation.

1 Introduction

The Final Focus System (FFS) of CLIC should achieve an RMS spot size of $60 \times 12\,nm^2$ [1]. For bunches of 5×10^9 particles pulsed at $1.69\,kHz$, this corresponds to a Gaussian luminosity $\mathcal{L}_G = 4.7 \times 10^{32}\,cm^{-2}s^{-1}$ or, taking into account the expected enhancement due to the pinch effect, to the design luminosity $\mathcal{L} = 1.1 \times 10^{33}\,cm^{-2}s^{-1}$. The transverse emittances and bunch length are given by the CLIC parameter list [1]

$$\begin{aligned} \epsilon_x &= 1.5 \times 10^{-12}\,m \\ \epsilon_y &= 0.5 \times 10^{-12}\,m \\ \sigma_z &= 200\,\mu m. \end{aligned} \tag{1}$$

We describe here the present status of the FFS by discussing successively the optics design, the effect of synchrotron radiation, the computation of luminosity enhancement, and finally the correction of misalignment errors. Detailed account of the first two items can be found in [2].

2 Optics Design

Compression of the transverse beam size is provided by a 4-lens telescope with horizontal×vertical demagnification of 25×75. The last two lenses are based on permanent magnet quadrupoles with $1\,mm$ diameter and $1.4\,T/mm$ pole-tip field [3]. The selected telescope optimizes the following figure of merit

$$F = \frac{1}{\sum_j l_j \times \sum_i \mid g_i \mid} \tag{2}$$

where l_i are the 5 drift lengths and g_j the 4 quadrupole strengths. Its total length is $L_{Tele} = 128.4\,m$. Its lattice layout and orbit β-functions are displayed [4] in Fig.1. With a typical energy spread $\delta = \frac{\Delta p}{p_0} = 2 \times 10^{-3}$, the chromatic aberrations, expressed by large second-order coefficients [5] $T_{126} = 370\,m$ and $T_{346} = 140\,m$ are responsible for a blow-up of the transverse sizes of a beam by a factor of over 12. As in the SLC[6], these aberrations are pre-compensated in a Chromatic Correction Section (CCS). Sextupoles are placed into a region where non-zero dispersion is created by bending magnets. These sextupoles in turn create second order aberrations. However, the purely geometric ones are cubic in the cosine and sine optics functions, evaluated at the location of the sextupoles. Therefore they cancel when using a pair of equal-strength sextupoles separated by a π-phase shift, over which the optics functions change sign [7]. On the other hand, the purely chromatic aberration, given by T_{166}, is zero if the dispersion is equal at the two sextupoles. Finally, the sextupole contribution to T_{116} and T_{336} is zero if they lie, in both planes, at a multiple of $\pi/2$ phase shift from the IP. Thus, the sextupoles do not produce any second order aberrations apart from the desired terms T_{126} and T_{346}. The corresponding contributions of the telescope can then be compensated by adjusting the strengths of the sextupoles.

All this is achieved by placing each sextupole pair into a 2π-phase shift regular FODO lattice with half quadrupoles at both ends and symmetric with respect to its center. Both half-cells are identical and also symmetric with respect to their center, where the phase shift is $\pi/2$ and the sextupoles are located. The dispersion created by two identical bending magnets is symmetric with respect to the center of the cell. This implies that it vanishes at both ends of the 2π-sections. In the vertically correcting section, the sextupoles are located at maximum β_y and hence couple mainly to the vertical aberration T_{346}. In the horizontally correcting one, the sextupoles sit at maximum β_x and couple mainly to the horizontal aberration T_{126}. This is done simply by reversing the sign of the cell quadrupoles from one section to the other.

The complete CCS is obtained by concatenating the horizontal and vertical sections. Its total length is $L_{CCS} = 320\,m$. Its lattice layout and optics functions are shown in Fig.2.

3 Synchrotron Radiation Effects

In this design the sextupole pairs are not interlaced, thereby avoiding a major source of third order aberrations [7]. Former designs with interlaced sextupole pairs allowed a reduction of the number of dipole magnets and of the total length of the FFS, but were abandoned because of their too small energy acceptance.

However, even in our design the sextupoles should not be too strong because of higher order aberrations. Sextupole strengths are inversely proportional to dispersion and hence to the field in the dipole magnets. These fields too must be kept small in order to keep the emittance growth due to synchrotron radiation in the dipoles at an acceptable level. Beam tracking analysis leads to $245\,Gauss$ as the optimum value for the $19\,m$ long dipoles, corresponding to the moderate sextupole strengths of $90\,m^{-2}$ and $290\,m^{-2}$. The energy acceptance of the resulting FFS has been estimated with MAD [4] by calculating the dependence of β^* on the energy offset. The results are shown in Fig.3. The bandwidths, defined as doubling of the beta functions, are $\pm 0.41 \times 10^{-2}$ horizontally and $\pm 0.65 \times 10^{-2}$ vertically.

Tracking through the FFS is done with DIMAD [5]. The main results are as follows:

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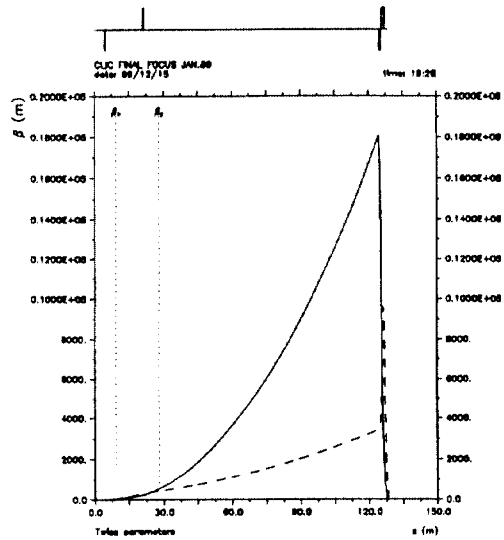

Figure 1: Lattice and orbit functions of the final telescope

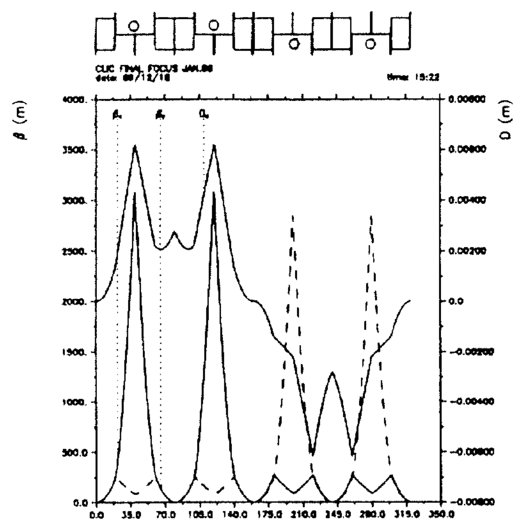

Figure 2: Lattice and orbit functions of the CCS

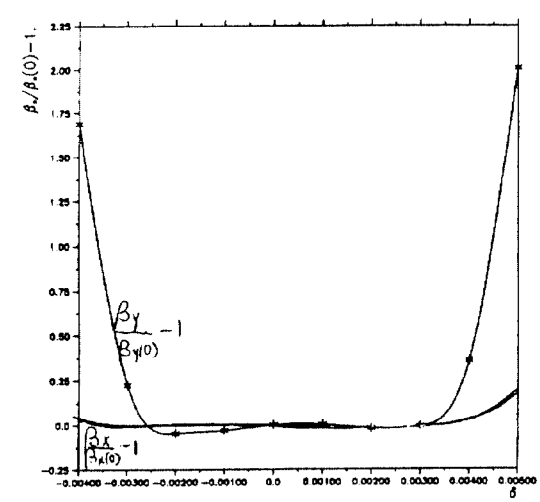

Figure 3: Horizontal and vertical energy acceptance of the FFS ($\beta_x^{(0)} = 4.17\,m, \beta_y^{(0)} = 1.62\,m$)

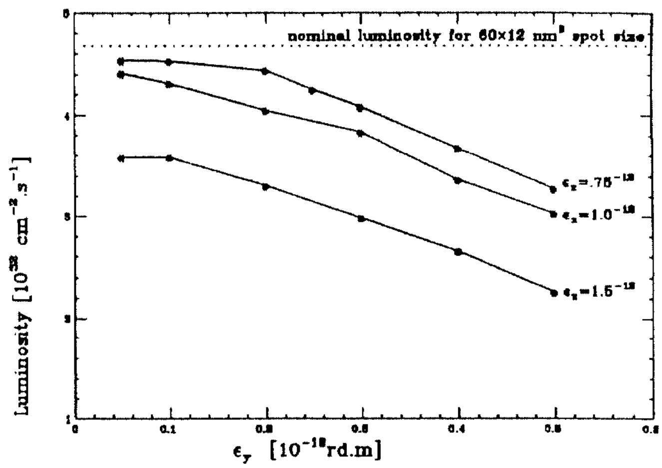

Figure 4: Luminosity dependence on horizontal and vertical emittances for a perfectly monochromatic beam

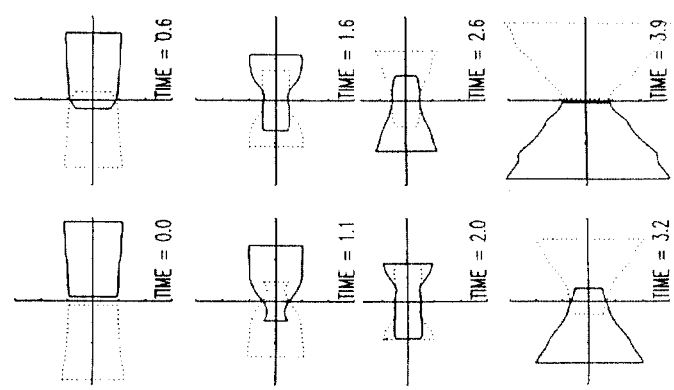

Figure 5: Beam-Beam effect for head-on collision of two bunches at the IP of CLIC

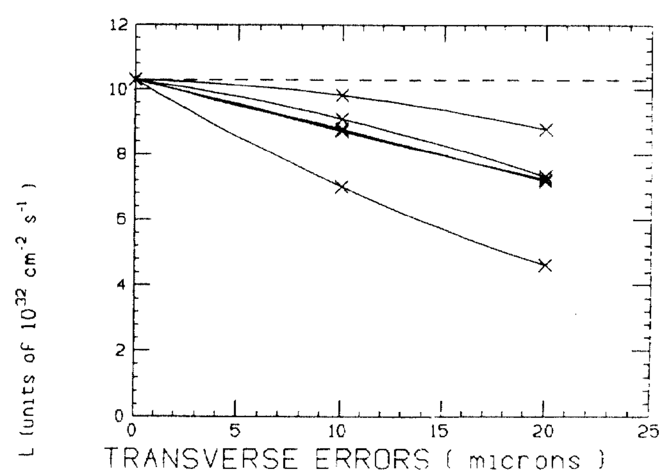

Figure 6: Reduction of luminosity with RMS misalignment error of magnetic elements and pick-ups in the CLIC FFS

Table 1: Operating the FFS at different energies

Energy (TeV)	1	0.75	0.5
$\sigma_x^* \, (nm)$	113.8	123.7	190.2
$\sigma_y^* \, (nm)$	28.8	29.9	37.8
$\mathcal{L} \, (10^{32} cm^{-2} s^{-1})$	1.71	1.71	1.38

1) Synchrotron radiation in the last quadrupoles.

In order to isolate this effect from the one of chromatic aberrations we have considered a monochromatic beam, i.e. with a very small relative energy spread $\delta \ll 10^{-3}$. We found that for the design emittances the Oide effect [8,9] is quite sizeable and blows the beam spot size up by a factor 2. As shown in Fig.4, this effect is critically dependent on the emittances. With both the design emittances halved, it nearly vanishes. On the other hand, we checked that for fixed quadrupole strengths, it is independent of the energy of the beam from $1\,TeV$ down to $250\,TeV$.

2) For a beam with a Gaussian energy spread of 2×10^{-3}, third and higher order aberrations add up to the former effect. The optimum luminosity obtained is $\mathcal{L}_G = 1.71 \times 10^{32}\, cm^{-2}s^{-1}$ corresponding to about $114 \times 17\, nm^2$ spot size. When the pinch effect is included [10], one finds $\mathcal{L} = 3.02 \times 10^{32}\, cm^{-2}s^{-1}$, a luminosity enhancement factor of 1.77 is found. We are still a factor 3.6 below the design luminosity.However, halving both the horizontal and vertical design emittances would be enough to reach the desired luminosity.

3) Intermediate energies.

Table 1 gives the luminosity achieved at various energies if one operates the FFS as optimized for $1\,TeV$. It sets a lower bound on the result which can be obtained by increasing the field of the dipole magnets in the CCS taking advantage of the weakening of synchrotron radiation. The sextupole strengths are reduced accordingly and hence third order aberrations get smaller. Moreover, at fixed pole-tip field, one could increase the strength of the final quadrupoles and thus re-optimize the telescope.

4 Beam-beam Interaction

The interaction of particles in one bunch with those of the opposing bunch leads to a constriction of the orbits which is usually called "pinch effect". In Linear Collider jargon, it is also called "disruption" because the outgoing beam will be scattered or "disrupted". This effect enhances the luminosity, but may also increase the background if the outgoing beam hits a solid object such as the face of the next quadrupole.

Because of the large importance of this effect, a new computer program has recently been developed at CERN [10] which simulates the penetration of two bunches, using variable y mesh size for the geometry. This feature makes it both more accurate and faster, and thus has permitted variation of a large number of parameters. In particular, the program can be used to process the non-Gaussian distribution obtained by tracking particles through the final focus system including non-linear aberrations and synchrotron radiation. The result has been expressed in terms of an "equivalent" RMS beam height of two Gaussian beams which would collide with the same luminosity. The penetration of two equal bunches with disruption parameter D = 10 is shown in Fig.5.

5 Correction of Errors

Inclusion of the unavoidable errors in positioning and/or excitation of magnetic elements, as well as errors in the pick-ups used for measuring the beam position, leads to a very rapid degradation of the luminosity. Because of the small beam dimensions, extremely low tolerances would be required without correction, which cannot be met in practice.

Choosing the placement of the pick-ups and correctors judiciously such that their influence on each other is minimal ("orthogonal buttons"), it is possible to compute the required corrector strengths with the program MURTLE [12] to optimize orbits for random error distributions. For errors with a standard deviation of up to 20 microns, the reduction of luminosity after correction is found to be a tolerable 20 % on average (see Fig.6). Even larger errors may be permitted in the less sensitive elements.

6 Conclusions

We have described the current status of the study of the Final Focus System for CLIC. Relying essentially on numerical tracking simulation results, we have shown that, for the design emittances, the Oide effect strongly limits the luminosity which can be achieved at the interaction point. For our optimized FFS, the luminosity is too low by a factor 3.6, corresponding to a $17 \times 114\, nm^2$ effective spot size.

The only way to avoid the Oide effect is to reduce one or both (normalized) design emittances. This has the additional advantage of reducing higher order aberrations as well. Reduction of the design emittances by a factor two would be almost sufficient to reach the design luminosity. Such a reduction appears possible with present damping rings, but the emittance blow-up in the main linac has to be kept under control[11].

7 Acknowledgements

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