A FINAL FOCUS DESIGN FOR THE CERN LINEAR COLLIDER CLIC

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Abstract The present status of the final focus system for CLIC is described. It comprises a 25 x 75 de-magnifying telescope preceded by a chromatic correction section with two non-interleaved sextupole pairs in a dispersive region. The effect of synchrotron radiation in the dipoles and the last quadrupole is discussed.

INTRODUCTION

The parameter list for the 2 x 1 TeV electron-positron linear collider CLIC assumes presently a spot size of 60 x 12 nm² in order to achieve a luminosity of 10^{33} cm^{-2} s^{-1} with 5 x 10^9 particles per bunch at a repetition rate of 1.69 kHz. Such a small spot size with the design emittances ε_y = 0.5 x 10^{-12} m and ε_x = 3ε_y requires careful correction of the chromatic aberrations of the telescope even if the energy spread in the beam can be reduced to δ ≈ ±0.2%. This has been achieved with sextupoles in separate correction cells for the horizontal and vertical planes. Dispersion in these cells is created by weak bending magnets which produce only small emittance growth by synchrotron radiation while keeping the geometric aberrations acceptable. Synchrotron radiation in the last focusing quadrupoles, the so-called Oide effect, limits the performance of the final focus system to a spot size of 113 x 17 nm². Reducing both emittances by a factor 2 would be sufficient to achieve the design luminosity. For the telescope, permanent magnet quadrupoles with an aperture of 1 mm have been designed and model work has been initiated.

THE TELESCOPE

The basic module of the final focus system is a telescope which compresses the beam both horizontally and vertically. The transfer matrix of a telescope is diagonal

\[ R_{x,y} = \begin{pmatrix} -1/M_{x,y} & 0 \\ 0 & -M_{x,y} \end{pmatrix} \]

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Table 1: Parameters of the 25 x 75 telescope

<table>
<thead>
<tr>
<th>Drifts</th>
<th>L (m)</th>
<th>Quadrupoles</th>
<th>L (m)</th>
<th>g (m⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>4.53</td>
<td>Q1</td>
<td>0.5</td>
<td>0.023</td>
</tr>
<tr>
<td>L2</td>
<td>15.99</td>
<td>Q2</td>
<td>0.5</td>
<td>-0.027</td>
</tr>
<tr>
<td>L3</td>
<td>103.02</td>
<td>Q3</td>
<td>1.25</td>
<td>0.544</td>
</tr>
<tr>
<td>L4</td>
<td>0.35</td>
<td>Q4</td>
<td>1.25</td>
<td>-1.045</td>
</tr>
<tr>
<td>L5</td>
<td>1.25</td>
<td>Total length</td>
<td></td>
<td>~130 m</td>
</tr>
</tbody>
</table>

where $M_x$ and $M_y$ are the horizontal and vertical de-magnification factors. In the short lens approximation, the general problem of telescopes with up to 5 quadrupole lenses could be reduced to a quadratic equation. For reasonable choices of the 4 free parameters only one solution of this equation is physical, while the other one yields negative drift lengths. By looking for the maximum of the figure of merit $F$:

$$F = \frac{1}{\sum_i L_i \times \sum_j |g_j|}$$

where $L_i$ are the drift lengths and $g_j$ are the lens strengths, a single telescope is selected out of the 4-parameter family of solutions, which is always a 4-lens telescope. This optimization procedure also points towards a telescope with small vertical chromaticity. Finally, a thick lens telescope can be formed from the selected short lens solution with the matching routines of MAD or TRANSPORT.

For a maximum quadrupole gradient of 2.8 $T/mm$ (see below), the best results have been obtained for a telescope with de-magnifications $M_x = 25$ and $M_y = 75$. Its parameters are listed in Table 1.

**THE CHROMATIC CORRECTION SECTION**

Non-linear chromatic aberrations are well known to occur in the final lenses of a telescope and to spoil the image of the beam. Using TRANSPORT notation, the main problems stem from the second order chromatic matrix elements $T_{126}$ for horizontal aberrations, and $T_{346}$ for vertical ones, while the elements $T_{116}$ and $T_{336}$, as well as geometric second order aberrations, are either zero or very small. As in the SLC design, these aberrations are compensated in a chromatic correction section (CCS) by placing sextupoles into a region where non-zero dispersion is created by bending magnets. The sextupoles come in two pairs, one for each transverse dimension, and are separated by $\pi$ phase shift in order not to generate themselves second order geometric aberrations. Interlacing the two pairs allows a reduction of the number of dipole magnets and/or the total length, but creates third order aberrations which reduce the energy acceptance (bandwidth). A scheme where the sextupole pairs are not interlaced is therefore preferred.
Each cell contains dipole magnets to make local dispersion (cf. Fig. 1). In order to keep the elements $T_{116}$ and $T_{336}$ small, the sextupoles are located at $\pi/2$ phase shift. This can be achieved with symmetric $\pi$ transformers, with an odd number of quadrupoles placed symmetrically with respect to the central one. The minimum number of quadrupoles for such a symmetric transformer is five. The elements $T_{126}$ and $T_{346}$ are cancelled by adjusting the sextupole strengths. These are inversely proportional to the dispersion and hence to the field in the dipole magnets, which should be kept small to reduce emittance growth caused by synchrotron radiation.

The resulting lattice, including the telescope, is shown in Fig. 1 together with the beta functions and the horizontal dispersion. The CCS is 320 m long, including eight 19 m-long bending magnets of 245 Gauss, so the total length of the system is 450 m. The largest bandwidths (cf. Fig. 2) are obtained with the horizontal correction cell in front of the vertical one, and with the vertically correcting sextupoles placed on either side of the central $\pi/2$ quadrupoles, while the horizontally correcting ones are split and located on both sides of the corresponding quadrupoles. The bandwidths (defined as doubling of the beta functions) can be seen in Fig. 2 to be $\pm 0.41\%$ horizontally and $\pm 0.65\%$ vertically.

**TRACKING RESULTS AND OIDE EFFECT**

Particle tracking through the above described Final Focus System has been done with DIMAD which provides an option for Synchrotron Radiation (SR) in the bending magnets. Another option has also been developed for use with DIMAD, and the results are in very good agreement. Simulation of SR in the quadrupoles is also possible with DIMAD, although the corresponding options are not described in the manual. In these simulations the beam is assumed to be Gaussian in all six dimensions. The initial beam size is optimized, and has to be adjusted in the linac or a matching section.

Without the effect of SR, the horizontal beam size is found to have a lower bound at $\sigma_y^* = 110\ nm$, which is obtained for $\beta_{0,x} = 4.17\ m$. At smaller beta values, third or higher order aberrations increase $\sigma_y^*$. The lower bound in the vertical plane is only $\sigma_y^* = 13\ nm$ for $\beta_{0,y} = 1.62\ m$, which shows that the bending magnets in the CCS are sufficiently weak.

It is expected that the vertical spot size will increase considerably due to emittance growth arising from SR in the last quadrupole. However, taking into account the non-Gaussian character of the beam after radiation, shows that the actual luminosity is given by a smaller "effective" vertical size $(\sigma_y^*)_{\text{eff}}$, defined such that

$$L^{-1} \propto (\sigma_y^*)_{\text{RMS}} \times (\sigma_y^*)_{\text{eff}}.$$  

For the CLIC emittances and the final quadrupole described below, these bounds are
18 nm in $(\sigma_y^*)_{RMS}$ (curve a of Fig.3) and 12 nm in $(\sigma_y^*)_{eff}$ (curve b of Fig.3). Using a simple program to compute the luminosity $\mathcal{L}$ from the transverse beam distribution obtained from tracking confirms this one-dimensional analysis. Fig.3 also shows these results for $(\sigma_y^*)_{RMS}$ (c) and $(\sigma_y^*)_{eff}$ (d) as function of the final vertical beta value $\beta^*_y$. Each point corresponds to 10,000 particles tracked. The effective spot height has a minimum at 17 nm, corresponding to a maximum luminosity of $1.7 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$, which is about a third of the design luminosity without enhancement by "disruption". Reducing $\beta_{0,x}$ to 1.5 m yields a 10% gain in luminosity, although $(\sigma_x^*)_{RMS}$ increases from 113 nm to 143 nm. This shows that the RMS spot size is affected by non-linearities more than is luminosity.

The minimum beam size is very sensitive to the vertical emittance $^1$:

$$(\sigma_y^*)_{eff} \propto \epsilon_y^{5/7}$$

Indeed, when both emittances are halved, the Oide effect is negligible and the design luminosity is reached with $\beta_{0,x} = 1.5 \text{ m}$ and $\beta_{0,y} = 1.62 \text{ m}$, again well within the non-linear regime of the Final Focus System since the RMS-spot size is $85 \times 18 \text{ nm}^2$.

**THE MAGNETS**

By far the most critical focusing element is the last quadrupole before the interaction point: for a gradient of some $3 \text{T/mm}$, its axis must be aligned with a precision of some tens of nanometers, and it should have a channel through which the spent beam can pass. In order to minimize its interference with the experimental apparatus around the interaction point, it should have small transverse dimensions. This
Figure 2: Horizontal and Vertical Bandwidths

Figure 3: Oide effect. The dotted line is the nominal $\sigma_y^*$

Figure 1: Schematic cross-section of the quadrupole
constraint, together with the fact that the quadrupoles will probably be immersed in the field of a spectrometer magnet, would favor the choice of pure permanent magnets, and this line of approach is indeed being followed up\(^9\). We believe, however, that it may be easier to keep the tolerances on the magnetic axis, and to provide passage for the spent beam, using a "hybrid" approach\(^{10}\). As shown schematically in Fig.4, rectangular blocks of permanent magnets\(^1\) deliver the magneto-motive force to poles made from soft magnetic material of simple geometry\(^2\). The upper and lower halves of the quadrupole are positioned with respect to each other by means of non-magnetic spacers\(^3\) providing a passage\(^4\) for the spent beam. Magnetic shunts\(^5\) give the possibility of adjusting the field in each half magnet. The poles themselves have only flat surfaces, the ideal hyperbola being approximated by simple 45° planes.

Thanks to the fourfold symmetry, this seemingly crude approximation yields a fairly clean quadrupolar field, depending mainly on the saturation characteristics of the material chosen for the poles\(^{10}\). For a ratio of gap to bore radius of 0.42 the gradient quality is within 0.1% (1%) out to 0.5 (0.9) times the bore radius. Assuming low-carbon steel for the poles, it is found that the maximum gradient corresponds to a poletip field of about 1.4 T. This can be varied over a range of 100% by suitable choice of thickness and position of the magnetic shunts.

It is envisaged to assemble the complete magnet from 20 to 100 mm long modules. The lateral spacers will be part of a rigid girder structure, fine adjustment of the axis being achieved by piezo-electric jacks.

For the magnetic measurement of the device, we envisage integration of the voltage induced in a wire displaced across the field. Forced vibration of the magnet table and/or natural vibration of the wire is also being investigated. Model work is underway both for the hybrid magnet design and for that based on pure permanent magnet elements.

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