TUNING STUDIES OF THE CLIC 380 GEV FINAL-FOCUS SYSTEM

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Abstract
We present tuning studies of the Compact Linear Collider final-focus system under static imperfections including transverse misalignments, roll errors and magnetic strength errors. The tuning procedure consists of beam-based alignment for correcting the linear part of the system followed by sextupole pre-alignment and use of multipole tuning knobs. The sextupole pre-alignment is very robust and allows the tuning time to be greatly reduced.

INTRODUCTION
Future linear colliders typically have low repetition rates and rely on ultra-small beam sizes at the interaction point (IP) to achieve high luminosity. This requires small emittances and tight tolerances for emittance preservation in the main linacs. For the Compact Linear Collider (CLIC) [1,2] 380 GeV energy stage, the nominal luminosity of $1.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ is reached by focusing the beams to rms beam sizes of $\sigma_x / \sigma_y = 149 / 2.9$ nm at the interaction point. In Table 1, we summarize the target beam parameters. After the two main linacs the beams are collimated in the beam delivery system and transported to the final-focus system where the beams are demagnified before collision at the IP. The current baseline consists of a local chromaticity correction scheme [3] and an $L' = 6$ m, which allows the final-doublets to be mounted outside the detector volume [4,5]. Tuning of the final-focus system is particularly challenging due to the nonlinear optical elements and this is a topic that has been studied extensively for the CLIC 3 TeV machine with static imperfections [6–8] and also including dynamic imperfections [9]. In this report we consider single-beam tuning of the CLIC 380 GeV final-focus system under the effects of static imperfections, with the aim to improve on the tuning procedure and tuning time.

Multiparticle simulations, including synchrotron radiation, are done in PLACET [10] with $10^5$ macroparticles. The luminosity is evaluated using beam-beam simulations based on GUINEA-PIG [11]. In order to have a more realistic energy spread in the incoming beam we use a beam from an integrated simulation [12] where particles are tracked all the way from the exit of the damping ring to the end of the main linac. In this report, for simplicity, we only consider single-beam tuning which means that we only simulate a single beamline and mirror the beam distribution at the interaction point for the beam-beam simulation.

TUNING PROCEDURE
The tuning procedure aims to achieve nominal performance when the system has imperfections. Our procedure consists of the following steps:

1. Beam-based alignment (BBA) with all multipoles switched OFF
2. Pre-alignment of sextupoles by powering them one-by-one and monitoring luminosity
3. Sextupole linear knobs (transverse position)
4. Octupole linear knobs (transverse position)
5. Sextupole linear knobs (transverse position), second iteration.

In order to have a robust method different subsystems should, if possible, be corrected independently. The different steps are presented briefly below and more details can be found in [13].

Beam-Based Alignment
To have sufficient chromatic correction and not introducing additional imperfections it is important to have a well-corrected linear system. We perform all-to-all beam-based alignment where we move the quadrupoles to correct trajectory and dispersion. The linear system can be expressed [14] as

\[
\begin{bmatrix}
\frac{\tilde{y}_{\text{traj}}}{\tilde{\gamma}} \\
\frac{w_{\text{disp}}}{\tilde{\delta}}
\end{bmatrix} = \begin{bmatrix}
R_{\text{traj}} \\
R_{\text{disp}}
\end{bmatrix} \tilde{c}
\]

(1)

where trajectory and dispersion depends linearly on the corrector settings $\tilde{c}$, which in our case are the quadrupole transverse positions. The response matrices $R_{\text{traj}}$ and $R_{\text{disp}}$ are measured on the misaligned machine and we put a weight $w$ on the dispersion to have trajectory and dispersion treated equally. Finally, the last line in (1) is introduced for numerical stability during inversion and favors solution with small corrector magnitudes.

Table 1: CLIC 380 GeV Beam Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norm. emittance, linac end ($\sigma_x/\sigma_y$)</td>
<td>900 / 20 nm</td>
</tr>
<tr>
<td>Norm. emittance, IP ($\sigma_x/\sigma_y$)</td>
<td>950 / 30 nm</td>
</tr>
<tr>
<td>Beta function at IP ($\beta_x^<em>/\beta_y^</em>$)</td>
<td>8.2 / 0.1 mm</td>
</tr>
<tr>
<td>Target IP beam size ($\sigma_x/\sigma_y$)</td>
<td>149 / 2.9 nm</td>
</tr>
<tr>
<td>Bunch length</td>
<td>70 mm</td>
</tr>
<tr>
<td>rms energy spread</td>
<td>0.35 [%]</td>
</tr>
<tr>
<td>Bunch population</td>
<td>$10^9$</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>352</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>50 [Hz]</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$1.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Peak luminosity</td>
<td>$0.9 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
</tbody>
</table>

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**Sextupole Pre-Alignment**

Transverse misalignments of the sextupoles have great impact on the luminosity and a robust procedure is essential for successful tuning. We propose a pre-alignment method of the sextupoles before applying the sextupole linear knobs with the motivation that this method can bring the machine to a state where the knobs can be very effective with a lower risk of converging to a local maximum. The naming convention of the six sextupoles in the CLIC final-focus is SF6, SD5, SF5, SD4, SF1, SD0 where SD0 is closest to the IP. In order to check the sensitivity on luminosity we simulated a perfect system and introduced a single imperfection by offsetting only one sextupole at the time. The maximum luminosity occurs when the sextupoles are centered. However, when all sextupoles are misaligned the maximum luminosity for a single sextupole might not occur when it is centered since an offset compensates for the aberrations introduced by offsets of other sextupoles. To avoid this issue we pre-aligned the sextupoles and powered them one-by-one.

The method starts with all sextupoles switched OFF. Then a single sextupole is powered and aligned by maximizing luminosity. Then a second sextupole is powered and aligned similarly while the first sextupole remains powered and since the first sextupole is already aligned the maximum luminosity occurs when the second sextupole is centered. Then a third sextupole is powered while the two previous remain powered and so on. The order in which the sextupoles are powered and aligned proved to matter, and interestingly enough the order has an important impact on the robustness of the method. We tried all (6! = 720) orders and looked for an optimum order where one has the maximum sensitivity in as many of the sextupoles as possible. Figure 1 shows the luminosity normalized to maximum luminosity for different vertical positions. In the top part the sextupoles are powered and aligned in the downstream order (SF6, SD5, SF5, SD4, SF1, SD0) and it is clear that for four out of the six sextupoles there is no sensitivity. The lower part of the figure shows the optimum order (SD0, SF1, SD4, SD5, SF5, SF6) and now there is sensitivity for all sextupoles on luminosity.

To test the impact of the sextupole pre-alignment we carried out a simplified study of 10 machines with transverse misalignments of the sextupoles as the only imperfection. We tested for different rms values of the offsets and performed tuning with three different methods: 1) directly applying the sextupole knobs, 2) pre-aligning the sextupoles in the downstream order and then applying the sextupole knobs and 3) pre-aligning the sextupoles in the optimum order and then applying the sextupole knobs. Figure 2 shows the mean values and standard deviation for the different methods. We also plot the misaligned machines and note that already at 1 μm rms of the sextupole offsets there was a dramatic impact on luminosity. Directly applying the sextupole knobs was sufficient for small offsets but for worse starting conditions the method was less successful. The pre-alignment in the downstream order was, as expected, not robust at all.

**Linear Knobs**

The linear multipole knobs consist of collective transverse movements of the magnets along directions that have
orthogonal effects on the beam. We design these knobs using multiparticle tracking simulations of the perfect machine and constructing a response matrix where each column is the change of the beam distribution parameters at the IP due to the transverse movement of a single magnet. We use second order moments $\sigma_{ij}$ with $i, j \in \{x, x', y, y', \delta, z\}$ for characterizing the beam distribution at the IP. We denote the position of sextupole $j$ as $X_j, Y_j$ and we get

$$R = \begin{pmatrix}
\frac{\partial \sigma_{xX}}{\partial X_1} & \cdots & \frac{\partial \sigma_{xX}}{\partial X_5} & \cdots & \frac{\partial \sigma_{xX}}{\partial X_n} \\
\frac{\partial \sigma_{x'X}}{\partial X_1} & \cdots & \frac{\partial \sigma_{x'X}}{\partial X_5} & \cdots & \frac{\partial \sigma_{x'X}}{\partial X_n} \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
\frac{\partial \sigma_{YX}}{\partial X_1} & \cdots & \frac{\partial \sigma_{YX}}{\partial X_5} & \cdots & \frac{\partial \sigma_{YX}}{\partial X_n} \\
\frac{\partial \sigma_{\delta X}}{\partial X_1} & \cdots & \frac{\partial \sigma_{\delta X}}{\partial X_5} & \cdots & \frac{\partial \sigma_{\delta X}}{\partial X_n} \\
\frac{\partial \sigma_{zX}}{\partial X_1} & \cdots & \frac{\partial \sigma_{zX}}{\partial X_5} & \cdots & \frac{\partial \sigma_{zX}}{\partial X_n}
\end{pmatrix}.$$  \tag{2}

We compute a normalized response matrix $\tilde{R}$ by multiplying the first row in (2) by $\frac{1}{\sigma_{xX}^2}$, the second line by $\frac{1}{\sigma_{x'X}^2}$, and so on.

The orthogonal directions can be found by using singular value decomposition (SVD): $\tilde{R} = UAV^T$ where the columns of $U$ and $V$ are orthonormal by construction. Each column of $V$ defines a knob and we scan across this direction and use a parabolic maximizer to find the knob setting that maximizes the luminosity. The octupole linear knobs are constructed in the same way.

### SIMULATION STUDY

To test the tuning procedure, we performed simulations on a large set of machines with randomly distributed static imperfections. Table 2 specifies the tolerances for the different components and we used these as rms values for our random imperfections. The tuning goal is that at least 90% of the machines should reach 110% of nominal luminosity. The additional 10% is to serve as a budget for dynamic imperfections. Figure 3 shows the result of a tuning study with 500 machines where the effectiveness of the sextupole pre-alignment is very clear. After the second iteration of tuning with sextupole linear knobs 90% of the machines reached 117% or more of nominal luminosity. The goal of 110% of nominal luminosity was reached by 95% of the machines. The plot on the right-hand side shows the luminosity evolution of the median machine. A total of about 900 luminosity measurements were required which is a substantial improvement compared to previous studies which required about 6300 luminosity measurements [8].

### CONCLUSIONS

In this paper we have investigated single-beam tuning of the CLIC 380 GeV final-focus system with static imperfections. Our tuning procedure consists of first correcting the linear part of the system using beam-based alignment followed by pre-alignment of the sextupoles by powering them one-by-one in an optimal order and lastly tuning with sextupole and octupole linear knobs. 95% of the machines in a simulation study of 500 machines with randomly distributed static imperfections reached the target luminosity of 110% of nominal luminosity, exceeding the goal of 90% of machines reaching 110%. The tuning procedure only required 900 luminosity measurements which is a substantial improvement compared to previous studies. The next step is to consider more realistic tuning scenarios with double-beam tuning, this is an ongoing effort.

### REFERENCES


