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TUNING STUDIES OF THE CLIC 380 GeV FINAL-FOCUS SYSTEM

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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 $1.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ is reached by focusing the beams to rms beam sizes of $\sigma_x / \sigma_y = 149 / 2.9 \text{ nm}$ 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 $L^* = 6 \text{ m}$, 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.

Table 1: CLIC 380 GeV Beam Parameters

Norm. emittance, linac end ($\varepsilon_x/\varepsilon_y$)	[nm]	900 / 20
Norm. emittance, IP ($\varepsilon_x/\varepsilon_y$)	[nm]	950 / 30
Beta function at IP (β_x^*/β_y^*)	[mm]	8.2 / 0.1
Target IP beam size (σ_x/σ_y)	[nm]	149 / 2.9
Bunch length	[μm]	70
rms energy spread	[%]	0.35
Bunch population	[10^9]	5.2
Number of bunches		352
Repetition rate	[Hz]	50
Luminosity	[$\text{cm}^{-2} \text{ s}^{-1}$]	$1.5 \cdot 10^{34}$
Peak luminosity	[$\text{cm}^{-2} \text{ s}^{-1}$]	$0.9 \cdot 10^{34}$

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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

$$\begin{bmatrix} \vec{y}_{\text{traj}} \\ w \vec{y}_{\text{disp}} \\ \vec{0} \end{bmatrix} = \begin{bmatrix} R_{\text{traj}} \\ w R_{\text{disp}} \\ \beta \mathbf{I} \end{bmatrix} \vec{c} \quad (1)$$

where trajectory and dispersion depends linearly on the corrector settings \vec{c} , which in our case are the quadrupole transverse positions. The response matrices R_{traj} and R_{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.

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.

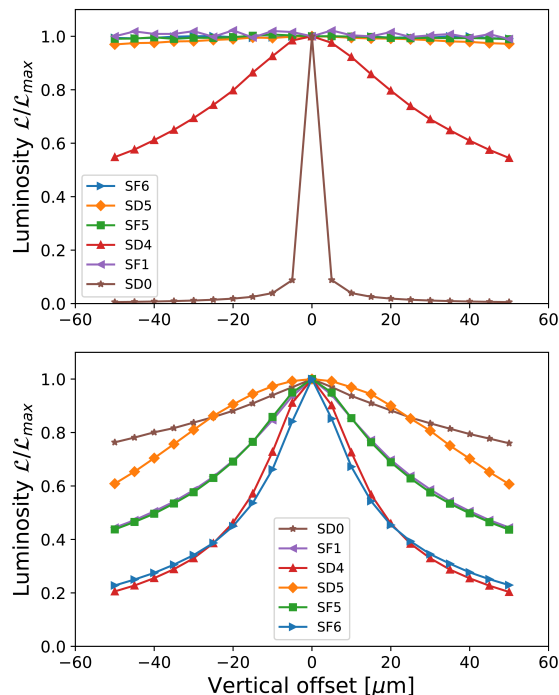


Figure 1: The sextupoles are powered and aligned in two different order. Upper: downstream order with only sensitivity for *SD4* and *SD0*. Lower: optimum order with sensitivity for all sextupoles.

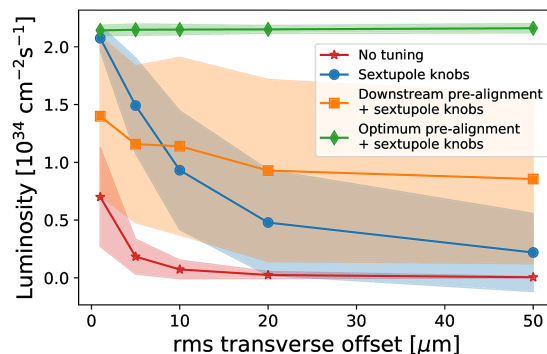


Figure 2: Mean values and 1 standard deviation (shaded areas) for 3 different tuning methods applied to 10 perfect machines with different rms transverse sextupole offsets as only imperfection. We show the results of the misaligned machines without tuning, tuning using the sextupole knobs and then pre-alignment using the downstream order and the upstream order followed by using the sextupole knobs.

However, the pre-alignment in the optimum order showed excellent robustness with the resulting luminosity virtually independent on the starting sextupole offsets.

Linear Knobs

The linear multipole knobs consist of collective transverse movements of the magnets along directions that have

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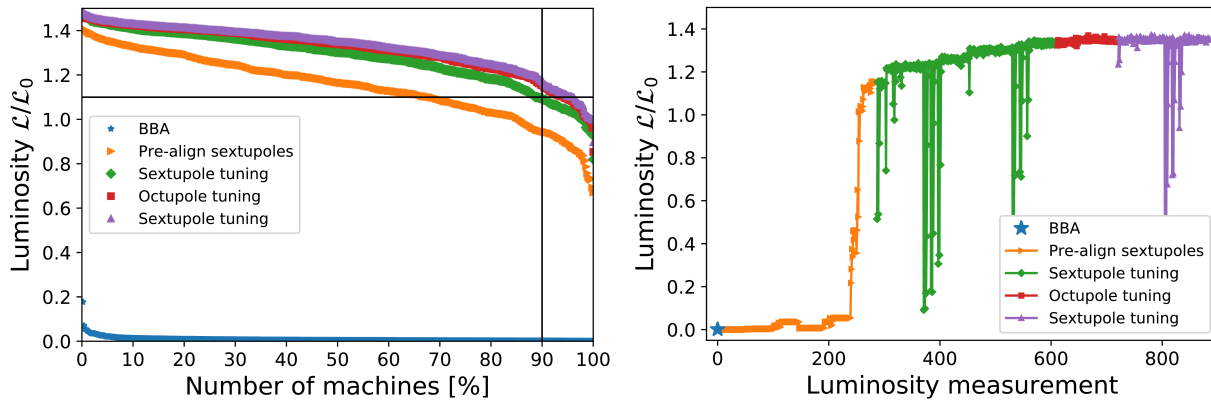


Figure 3: Left: The luminosity after the different tuning steps plotted against the number of machines that reach that level. At the end of the tuning a total of 95% reach the tuning goal of 110% of nominal luminosity L_0 . Right: Luminosity evolution of the median machine. A total of 900 luminosity measurements was required for the complete tuning procedure.

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 σ_{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

$$R = \begin{bmatrix} \frac{\partial \sigma_{xx}}{\partial X_1} & \dots & \frac{\partial \sigma_{xx}}{\partial X_6} & \frac{\partial \sigma_{xx}}{\partial Y_1} & \dots & \frac{\partial \sigma_{xx}}{\partial Y_6} \\ \frac{\partial \sigma_{xx'}}{\partial X_1} & \dots & \frac{\partial \sigma_{xx'}}{\partial X_6} & \frac{\partial \sigma_{xx'}}{\partial Y_1} & \dots & \frac{\partial \sigma_{xx'}}{\partial Y_6} \\ \vdots & \dots & \vdots & \vdots & \dots & \vdots \\ \frac{\partial \sigma_{zz}}{\partial X_1} & \dots & \frac{\partial \sigma_{zz}}{\partial X_6} & \frac{\partial \sigma_{zz}}{\partial Y_1} & \dots & \frac{\partial \sigma_{zz}}{\partial Y_6} \end{bmatrix}. \quad (2)$$

We compute a normalized response matrix \tilde{R} by multiplying the first row in (2) by $\frac{1}{\sigma_x^2}$, the second line by $\frac{1}{\sigma_x \sigma_{x'}}$ and so on. The orthogonal directions can be found by using singular value decomposition (SVD): $\tilde{R} = U\lambda V^T$ 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

Table 2: Static Imperfections Applied to quadrupoles, Multipoles and BPMs of the Final-Focus System

Transverse misalignment	10 μm rms
Roll error	100 μrad rms
Strength error	0.01 % rms
BPM resolution	20 nm

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.

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