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Tuning of the Compact Linear Collider Beam Delivery System

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Abstract

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Abstract

Tuning the Compact Linear Collider (CLIC) Beam Delivery System (BDS), and in particular the Final Focus (FF), is a challenging task. In simulations without misalignments, the goal is to reach 120% of the nominal luminosity target, in order to allow for 10% loss due to static imperfections, and another 10% loss from dynamic imperfections. Various approaches have been considered to correct the magnet misalignments, including 1-1 correction, Dispersion Free Steering (DFS), and several minimization methods utilizing multipole movers. In this paper we report on the recent advancements towards a feasible tuning approach that reaches the required luminosity target.

INTRODUCTION

The CLIC is an international study for a potential future linear lepton collider, colliding positrons and electrons at up to 3 TeV centre of mass energy [1]. The design is based on normal conducting elements, making use of a novel two-beam acceleration scheme in order to have a reasonable power consumption.

In order to reach a satisfactory luminosity target, the CLIC design comprises a vertical beam size on the order of one nanometre. This is an unprecedented small beam size for linear colliders, which imposes strict alignment tolerances for the machine. The pre-alignment has a transversal misalignment tolerance of about 10 µm (also called static imperfections), while the dynamic imperfections can only be fractions of a nm for the most sensitive magnets.

The correction of the static imperfections is not straight forward. Not only are the target specifications challenging, but with the high energy, the synchrotron radiation effects makes the tuning response highly non-linear. Advanced simulations have been developed over several years in order to try to achieve the required tuning performance [2].

The baseline design allows for a 10% reduction of the luminosity due to static imperfections (compared to a theoretical perfectly aligned machine), and another 10% reduction from dynamic imperfections. Currently the best results are achieved using a combination of beam-based alignment techniques, a Simplex algorithm optimising the luminosity, and orthogonal multipole knobs.

BEAM-BASED ALIGNMENT TECHNIQUES

The typical set of observables for the CLIC BDS is either the BPM readings, and/or the luminosity signal once the lattice is tuned well enough that the beams are actually colliding. The correctors are typically modulating magnet strengths and/or transversal movements of magnets. In the following we will go through the currently implemented algorithms used to optimise the CLIC BDS. These were also described in [2, 3].

1-1 Correction

The 1-1 correction is the first algorithm used to correct the lattice. We have a set of BPM measurements $\mathbf{x}$, and a set of corrector values $\boldsymbol{\phi}$. Correctors in 1-1 correction are the quadrupole movers. If we assume n BPMs and m quadrupole movers, then we need the $n \times m$ response matrix R such that

$$\mathbf{x} + R\boldsymbol{\phi} = 0 \tag{1}$$

The corrector values are then found by matrix inversion.

The 1-1 algorithm does not need any luminosity signal to perform. It will be inherently limited by the BPM alignment tolerances (10 µm).

Dispersion Free Steering

A residual dispersion at the Interaction Point (IP) will increase the beam size. The Dispersion Free Steering has been successfully implemented in past lepton accelerators [4]. The algorithm tries to simultaneously minimise the orbit and the dispersion according to

$$\begin{pmatrix} \mathbf{x} \\ \boldsymbol{\eta} \\ 0 \end{pmatrix} + \begin{pmatrix} R \\ \omega D \\ \beta I \end{pmatrix} \boldsymbol{\phi} = 0. \tag{2}$$

Here, $\mathbf{x}$ are the orbit readings (vertical and/or horizontal), $\boldsymbol{\eta}$ is the dispersion at the same set of BPMs, R is the orbit response matrix, D is the dispersion response matrix, and I is the identity matrix. ω and β are weighting factors. The last line

$$0 + \beta I \boldsymbol{\phi} = 0 \tag{3}$$

is added to avoid too large corrector kicks to be applied from singularities during the Singular Value Decomposition (SVD). Because the DFS is using the difference between two dispersive orbits, it will not be limited by BPM alignments in the same way as the 1-1 correction. Rather, it will be limited by the BPM accuracy (10 nm).

Multipole Knobs

As described in [2], the five sextupoles in the CLIC BDS have been used to develop 10 independent multipole knobs, 5 vertical and 5 horizontal. Each knob will ideally correct only one parameter, for example horizontal dispersion. The algorithm is optimising the luminosity by a parabolic fit for each of these knobs separately.

Simplex

The Nelder-Mead (Simplex) method [5] is an unconstrained nonlinear minimisation technique for multidimensional problems. The method uses a "Simplex", which essentially is an N-dimensional triangle with N+1 points. The target function is evaluated in each point of the Simplex. The worst point is “mirrored” through the centroid of the remaining points for a new point. If this new point is better the algorithm moves the Simplex in this direction, otherwise the Simplex shrinks towards the centroid. The method converges towards a local optimum.

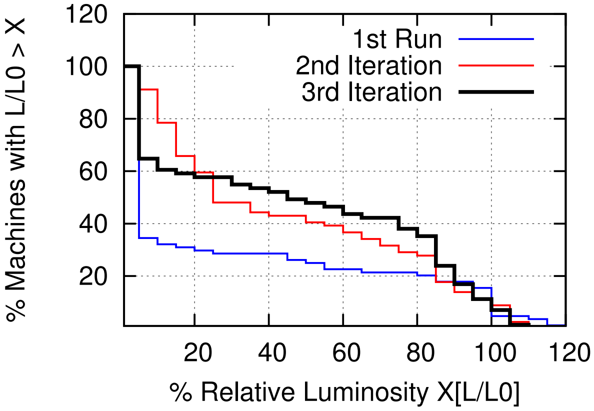

Figure 1: The result of tuning the nominal 3 TeV lattice after the first three iterations of BBA+Knobs. The vertical axis show the cumulative percentage of machines reaching a given luminosity.

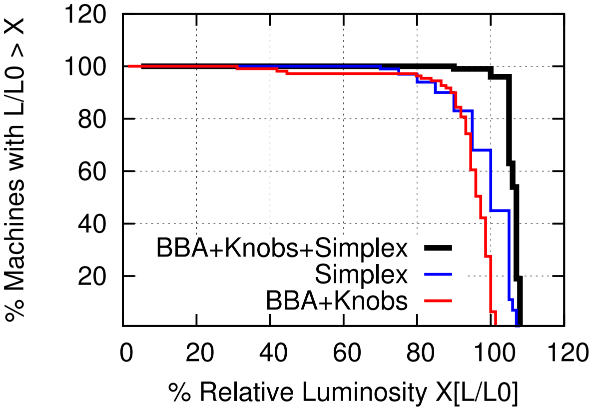

Figure 2: The results of tuning the 500 GeV lattice using local chromaticity correction. With the BBA+Knobs+Simplex the goal is not reached but it is very close. At least 80% of the machines are above the 100% threshold.

The Simplex method is used in the CLIC BDS tuning simulations as a final optimisation after the other algorithms (denoted BBA+Knobs) have been iterated numerous times. This combination has given the best results obtained so far for optimising the baseline 3 TeV design [2].

TUNING OF BASELINE DESIGN

The baseline optics design of the CLIC FF is based on the local chromaticity correction scheme [6]. We assume random misalignments of the elements to follow a Gaussian distribution with σ =10 µm. Past simulations [2] have shown that at high charge and after 5 iterations of the BBA+Knobs algorithm and Simplex, the goal of 90% of the seeds reaching 110% of the nominal luminosity was close to be reached. Tuning simulations at nominal charge are shown in Fig. 1. The cumulative number of machines are plotted as a function of the luminosity the machines reach at the end of the tuning simulation. After 3 iterations of the BBA+Knobs algorithm we see that the average luminosity of the machines is increasing after each iteration. About 40% of the machines have reached 80% of the nominal luminosity after three iterations.

The tuning of the 3 TeV lattice is still in progress and at least two more iterations with the BBA+Knobs will be performed. After that, the Simplex algorithm will be applied in order to optimise the luminosity at the IP further.

Recent studies [7] that consider an optimised FF design based on the traditional scheme reveal that using this approach, the tuning performance turns out to be much better, increasing the tuning speed by more than a factor 5 compared to the local scheme. This represents a longer time for physics due to the robustness of the system.

TUNING OF 500 GEV LATTICE

The lattice considered for the tuning at 500 GeV is the local chromatic correction of the FF system. The tuning required two algorithms: Beam-Based Alignment (BBA) with multipole knobs (BBA+Knobs), and Simplex. As for the 3 TeV machine, we assume random misalignments of the elements to follow a Gaussian distribution with $\sigma = 10$ µm. The first two tuning simulations have been done with BBA+Knobs and Simplex separately. During the third tuning, the solution obtained with the BBA+Knobs tuning have been used as initial conditions for the Simplex algorithm. Fig. 2 shows the results from the three tuning methods. There is a significant improvement of the luminosity when combining BBA, multipole knobs and Simplex. The results achieved are good and another iteration of BBA+Knobs+Simplex could improve the luminosity further.

COMPENSATION OF EXPERIMENTAL SOLENOID

With the small and very flat beams, the experimental solenoid causes both optical distortions and emittance growth due to synchrotron radiation. Without any compensation of the solenoid field, about 99% of the luminosity is lost. As presented in more details in [8], the incoherent synchrotron radiation seems to cause a luminosity reduction in the 4-5% range, and the multipole knobs together with quadrupole movers seems to be sufficient to correct the optical distortions more or less perfectly.

POSSIBLE REFINEMENTS

The current set of algorithms show through detailed simulations that we are close to the goal of achieving 110% luminosity with a 90% certainty (leaving another 10% luminosity reduction for dynamic imperfections). However, some refinements are still needed to reach the target for a sufficient amount of machines. Improvements that could potentially give a higher luminosity includes e.g. the use of magnet tilts, and the development of higher order knobs for corrections. Furthermore, there are some remaining challenges that are not considered in the current tuning simulations.

2-Beam Tuning

In the beam tuning studies discussed so far, beam tuning has been performed with a single beamline. For the luminosity determination the beam is collided with its mirror image. This is done to reduce the simulation time. However, in future linear colliders, due to fast detuning of the final focus optics both beamlines will need to be tuned simultaneously.

As self-collision is often optimal, the luminosity at the start of the tuning will be lower when simulating two beamlines. And since the luminosity measurement is typically less precise for lower luminosity, tuning with both beamlines might take considerably longer time than for each beamline individually as finding the optimum for each multipole knob will be more difficult. Thus additional luminosity loss might be expected simulating both beamlines.

In [9] a first two-beam tuning study for the CLIC BDS is presented applying the beam-based alignment techniques with multipoles knobs.

Genetic Algorithm

A potential limitation of the current algorithms is that they all converge towards a local optimum. One algorithm which can be able to circumvent local optima is a genetic algorithm.

The genetic algorithm has been considered in the past for BBA [10] and for optics design [11]. The basic idea of the algorithm is to mimic the natural selection, and is part of a bigger family of algorithms known as "evolutionary algorithms".

A set of solutions (corrector strengths) are first randomly selected (the population). At each step of the process (generation), each solution (gene) in the population can mutate (randomly replace one or several of the corrector strengths) and/or crossover with another gene. At the end of each generation, there is a tournament to see which of the genes survive to the next generation.

This means that there are a multitude of parameters to optimise. First there is the size of the population and the number of generations, which will be limited by the simulation capacity available (or beam time in the real world). The range of the strengths are also important. Then one should select the probabilities for mutation and crossover. Finally the rules for the tournament can significantly change the convergence of the algorithm. This means that compared to e.g. the Simplex algorithm, significant effort is required to optimise the simulation parameters.

Genetic algorithm for tuning the lattice has been implemented in our tracking code PLACET through the Python interface, using DEAP [12]. The simulation will use an arbitrary list of parameters as correctors, and will optimise based on BPM readings and/or luminosity evaluation.

In Fig. 3 an example is shown where a population size of 40 is used to correct a lattice with random misalignments of 0.1 μm. This example simulation was excluding synchrotron radiation, which is known to significantly simplify the tuning complexity. After a total of 400 iterations, the algorithm has increased luminosity from 35% to almost 80%.

The genetic algorithms could potentially be a good complementary tool to the other algorithms already implemented.

SUMMARY

The tuning of the CLIC BDS is a complicated task. The present status of the simulations for tuning of the static imperfections look promising. Further refinements are needed to reach the challenging target of having a 90% chance to get to 110% of nominal luminosity.

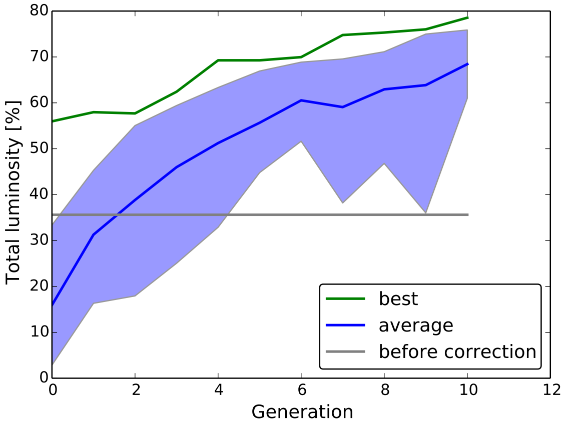

Figure 3: The total luminosity during a genetic algorithm optimisation using all quadrupoles to optimise luminosity.

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