Static beam-based alignment for the Ring-To-Main-Linac of the Compact Linear Collider

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Abstract: The Compact Linear Collider (CLIC) is a future multi-TeV collider for the post-Large Hadron Collider era. It features high-gradient acceleration and ultra-low emittance to achieve its ambitious goals of high collision energy and peak luminosity. Beam-based alignment (BBA) techniques are mandatory for CLIC to preserve the ultra-low emittances from the damping rings to the interaction point. In this paper, a detailed study of BBA techniques has been carried out for the entire 27 km long “Ring-To-Main-Linac” (RTML) section of the CLIC, to correct realistic static errors such as element position offsets, angle, magnetic strength and dynamic magnetic centre shifts. The correction strategy is proved to be very effective and leads to a relaxation of the pre-alignment tolerances for the component installation in the tunnel. This is the first time such a large scale and complex lattice has been corrected to match the design budgets. The techniques proposed could be applied to similarly sized facilities, such as the International Linear Collider, where a similar RTML section is used, or free-electron lasers, which, being equipped with linacs and bunch compressors, present challenges similar to those of the CLIC RTML. Moreover, a new technique is investigated for the emittance tuning procedure: the direct measurement of the interactions between the beams and a set of a few consecutive laser wires. The speed of this technique can be faster comparing to the traditional techniques based on emittance reconstructed from beam size measurements at several positions.

Keywords: Accelerator Subsystems and Technologies; Accelerator modelling and simulations (multi-particle dynamics; single-particle dynamics); Beam dynamics

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1 Introduction

The Compact Linear Collider (CLIC), alongside the International Linear Collider (ILC), is one option for the next-generation electron-positron linear collider for the post-Large Hadron Collider era. The CLIC conceptual design report (CDR) was published in 2012 [1]. CLIC can reach a centre-of-mass energy of 3 TeV, which provides an opportunity to study the physics beyond the Standard Model. The highlight of the CLIC is the concept of two-beam acceleration, which can provide an acceleration gradient of 100 MV/m. The designed peak luminosity of the CLIC is $2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ [1], which requires very high beam quality.

The Ring-To-Main-Linac (RTML) is a 27 km long section of the CLIC which connects the damping ring and the main linac. It also matches the beam properties such as beam energy and bunch length. A sketch of the RTML is shown in figure 1. It is composed of eight subsystems [1]: the spin rotator (SR) providing the polarized electron beam, the booster linac (BL) increasing the beam energy from 2.86 to 9 GeV, the two bunch compressors (BC I and BC II) compressing the bunch length from 1800 to 44 µm, the other four subsystems mainly transporting the beam including the central arc (CA), the vertical transfer line (VTL), the long transfer line (LTL) and turnaround loop (TAL).

In order to reach the high peak luminosity, the emittances of the CLIC beam need to be extremely low. At the beginning of the RTML, the normalized emittances are 500 and 5 nm rad for...
the horizontal and vertical planes, respectively. At the end of the RTML, they should be smaller than 600 and 10 nm rad, respectively, including design emittance growth (i.e. due to synchrotron radiation), and static and dynamic effects.

In this study we focus on the correction of the static effects because the correction of the dynamic ones, which is normally based on substantially different tools (e.g. feedback or feed-forward loops), largely depends on the effectiveness of the underlying static correction. In such a case the emittance budgets are fixed to $\epsilon_x < 580$ nm rad and $\epsilon_y < 8$ nm rad [1]. Here, $\epsilon_x$ and $\epsilon_y$ denote the normalized horizontal and vertical emittances, respectively. The goal of static beam-based alignment (BBA) is that at least 90% of the randomly misaligned machines should have emittances smaller than the budgets.

The static alignment tolerances have already been studied for each subsystem of the CLIC RTML [2, 3]. However, it can be foreseen that performing the BBA for the entire RTML is much more difficult than for a individual section. Moreover, in the previous study only the position misalignments from the quadrupoles and beam position monitors are considered. For a realistic study, we must consider more alignment errors, such as rotation errors and magnet strength errors.

In this paper, we first determine a reasonable misalignment scenario in section 2. Then the BBA correction methods and the response matrices which are used in the corrections are introduced in sections 3 and 4. The details of the simulation procedure and the correction results are presented in sections 5, 6 and 7. Finally, our conclusions are given in section 9.

All work in this paper is simulated using the beam tracking software placet [4]. This software is intended to simulate the dynamics of a beam in the presence of wakefields, synchrotron radiation and other effects.

## 2 Imperfections

Static imperfections after the pre-alignment include element position offsets and rotation errors, which induce orbit distortions, dispersion, wakefields and the beam coupling, which transfers emittance between the horizontal and vertical planes. Given that the initial horizontal emittance is 100 times larger than the vertical emittance, the coupling can be a fatal effect for the vertical emittance [5]. Besides, the magnets have unavoidable strength errors, causing the change to the beam orbit.

The simulation setup is as follows: all magnets in the RTML, including dipoles, quadrupoles and sextupoles, are misaligned. The horizontal and vertical positions are misaligned according to a gaussian distribution with standard deviation $\sigma_{\text{pos}} = 30 \, \mu m$. Traditional alignment techniques, through optical surveying, achieve 100 $\mu m$ root mean square (RMS) pre-alignment of the accelerator components. placet simulations showed that it is hard to fulfil the tight emittance budget with...
Table 1. The values of misalignment for different magnets.

|        | $\sigma_{\text{pos}}$ (µm) | $\sigma_{\text{roll}}$ (µrad) | $\sigma_{\text{res}}$ (µm) | Strength (%/perthousandzero) |
|--------|---------------------------|-------------------------------|---------------------------|-----------------------------|
| Dipole | 30                        | 100                           | —                         | 1                           |
| Quadrupole | 30                        | 100                           | —                         | CA and TAL: 0.1; Others: 1   |
| Sextupole | 30                        | 100                           | —                         | 1                           |
| BPM    | 30                        | 100                           | 1                         | —                           |

such a loose RMS pre-alignment. It has been demonstrated that pre-alignment errors of 10 µm RMS accuracy, which is necessary for the CLIC main linac components, can be achieved with sophisticated alignment techniques (see the PACMAN project [6]). Therefore $\sigma_{\text{pos}} = 30$ µm offset errors should be a reasonable value. For the magnets’ installation, magnet rotation errors are inevitable. These errors are set to have an RMS angle $\sigma_{\text{roll}} = 100$ µrad.

All beam position monitors (BPMs) are also misaligned with the same position and angle errors, $\sigma_{\text{pos}}$ and $\sigma_{\text{roll}}$ respectively, and feature a resolution of 1 µm. Since the current BPM technology has proved capable of giving BPM resolutions of the order of 20 nm, 1 µm BPM resolutions in CLIC RTML seem realistic, if not conservative.

Errors in the magnetic strength of the magnets have also been considered. Strength errors in magnets introduce dispersion, $\beta$-beating and beam coupling. For dipoles and sextupoles, standard errors of 0.1% RMS have been considered. Since the CA and TAL are the most complex sections of the RTML, featuring an achromatic and isochronous lattice, the strength errors for quadrupoles in these sections have been set to a tighter 0.01%. For the quadrupoles in other sections, 0.1% errors have been considered.

A summary of the misalignments and imperfections mentioned above is shown in table 1.

When applying dispersion-free steering (DFS) (see section 3.2), one needs to measure the residual dispersion in the lattice. This is normally done using a test beam running at a different beam energy than the nominal one. This is not possible at some locations in the RTML, such as the LTL and the following TAL, since a change of the beam energy would cause a change of the beam bending radius, provoking a geometric mismatch between beam and beam line. At these locations, we scale the magnets’ strength in order to measure the dispersion, while preserving the correct magnetic rigidity in the bending magnets to keep the beam on its nominal geometrical orbit. It has been observed experimentally that, when the magnets’ strength is scaled, the centre of quadrupoles and sextupoles are shifted [7, 8]. This affects and undermines the dispersion measurement, rendering the DFS algorithm significantly less effective. For this reason this effect has also been taken into account. In our study, the magnets’ strength is scaled by 5.0%. We assume that the magnet strength scaling will induce a magnet center shift of 0.35 µm [9].

In the coupling correction, the beam performance is tuned using signals generated by the beam laser interaction (see section 3.3). The signal errors are considered to be 1%.
3 Correction method

All correction algorithms presented in this paper use dipole kickers located downstream of each quadrupole magnet as correctors, and use BPMs located upstream of the magnet as pickups.

3.1 One-To-One

One-To-One (OTO) is a simple algorithm and is applied first. Each corrector is used to steer the beam through the centre of the downstream BPM. The strength of the dipole corrector can be written as

$$\theta = \min\{||\Delta u - R\theta||^2 + \beta_0^2||\theta||^2\}.$$  \hspace{1cm} (3.1)

Here $\Delta u = u - u_0$. $u$ and $u_0$ are the BPMs’ readings for the real and ideal machines, respectively. $R$ is the response matrix between correctors and readings of BPMs which will be mentioned later. $\beta_0$ is a free parameter that limits the strength of the dipole correctors to avoid large values, while allowing convergence.

3.2 Dispersion-free steering

In real machines, the BPMs’ positions are also misaligned. This will induce an additional dispersion, which can be removed by using DFS \cite{10,11}. The strength of correctors for DFS can be written as

$$\theta = \min\{||\Delta u - R\theta||^2 + \omega^2||\eta - D\theta||^2 + \beta_1^2||\theta||^2\}.$$  \hspace{1cm} (3.2)

Here, $\Delta u$ and $R$ have the same meaning as in eq. (3.1). $\eta$ is the additional dispersion and is expressed as $\eta = u_s - u_{s0} - \Delta u$, where $u_s$ and $u_{s0}$ represent the readings of BPMs of test beams for real and ideal lattices. The test beams are often got by reducing the nominal beam energy. $D$ is the dispersion response matrix and equals to $R_s - R$, with $R_s$ as the response matrix for the test beam. $\beta_1$ is a free parameter similar to $\beta_0$ in eq. (3.1). $\omega$ is a weight factor for the dispersion item. Theoretically, $\omega$ can be expressed as

$$\omega^2 = \frac{\sigma_{\text{pos}}^2 + \sigma_{\text{res}}^2}{2\sigma_{\text{res}}^2}.$$  \hspace{1cm} (3.3)

In reality, when one takes into account effects such as wakefields or radiation, the optimum of $\omega$ might be located at a slightly different value. For this reason it is necessary to perform a scan of different values around the theoretical optimum.

3.3 Emittance tuning bumps

After OTO and DFS corrections, the coupling effect and the orbit $\beta$-beating should also be corrected. It is known that the horizontal and vertical displacements of sextupole induce quadrupole and skew quadrupole effects, respectively. So the sextupoles in the CA and TAL can be used to correct the coupling effect introduced by the quadrupole rotation errors and the sextupole offsets. The orbit $\beta$ function errors can also be corrected at the same time using this method. We have assumed that these sextupoles can only be moved with a step size of 1 $\mu$m. This step size can be achieved using a stepping motor \cite{1}.
Table 2. Ideal beam sizes for the emittance tuning bumps.

| Number | At the end of LTL | At the end of RTML |
|--------|------------------|-------------------|
|        | Horizontal (µm)  | Vertical (µm)     | Horizontal (µm) | Vertical (µm) |
| 1      | 37.6             | 3.87              | 34.7            | 3.91          |
| 2      | 34.5             | 3.67              | 34.3            | 3.51          |
| 3      | 37.5             | 5.71              | 36.0            | 3.28          |
| 4      | 46.7             | 1.35              | 36.4            | 3.68          |

In this study, the first five sextupoles in the CA are used to tune the beam performance at the end of the LTL, and the first five sextupoles in the TAL are used to optimize the beam at the end of the RTML. Therefore, two measurement sections are set up in order to give tuning signals. One section is at the end of the LTL and the other is at the end of the RTML.

During this tuning process, the tuning signals are normally the emittances measured using laser wire scanning [12]. However, this kind of emittance measurement is time-consuming work. In order to speed up the tuning, a new kind of signal is developed. This new signal is formed by the interactions between the beams and the eight lasers [13] — we call this beam-laser luminosity. The idea for doing this is by using the luminosity measurement for a collision between the beam and the laser with the luminosity as a function of the beam’s size, so that the number of scattered photons is related to the beam size. When the beam sizes for the misaligned machines are almost the same as the sizes for the perfect lattice at several different positions, these malfunctioning machines are well corrected.

At the end of the LTL, there is a section which matches the beam between the LTL and the TAL. In this matching section, eight consecutive quadrupoles are selected: the four horizontal focusing quadrupoles are used for the horizontal beam sizes (the β functions reach the maximal values at these places) and the other four vertical focusing quadrupoles are used for vertical beam sizes. The ideal beam sizes after the corresponding quadrupoles are listed in table 2. These values are found by the simulation by tracking the beam through the perfect lattice. We put a laser after each quadrupole with the laser spot sizes the same as the ideal beam size.

At the end of the RTML there is a section with four FODO cells to diagnose the beam size. Similarly to what is done for the first correction section, the horizontal focusing quadrupoles are used for the horizontal beam sizes and the vertical focusing quadrupoles are used for the vertical beam sizes. The nominal beam sizes at each of the eight quadrupoles, which are used as targets for the tuning bump, are listed in table 2. Lasers are put after each quadrupole with the laser spot sizes the same as the ideal beam size.

From one beam emittance measurement study at ILC [12], we know that for a beam with size \( \sigma_x = 10 \, \mu m \) and \( \sigma_y = 1 \, \mu m \), the laser wires used to scan the beam have spot size errors of 0.01% for the horizontal plane and 1.1% for the vertical plane. The beam size for our study is larger than the beam size in ILC’s measurements. Therefore, it is safe to consider the errors from the laser spot sizes as 0.01% for the horizontal plane and 1.0% for the vertical plane.

For each beam-laser collision, the scattered photons are collected to form a signal. In the simulation, these horizontal and vertical signals are found through the formulae \( s_x = \sum_i G(x_i, \mu_x, \sigma_{l,x}) \)
and \( s_y = \sum_i G(y_i, \mu_y, \sigma_{l,y}) \). Here, \( G \) denotes a gaussian distribution, \( x_i \) and \( y_i \) are the horizontal and vertical positions for the \( i \)th particle, \( \mu_x \) and \( \mu_y \) are the average horizontal and vertical positions, and \( \sigma_{l,x} \) and \( \sigma_{l,y} \) are the laser spot sizes, respectively. The summations run over all the particles. We consider a 1\% photon detection error for this kind of signal. In order to get the 1\% signal error, the peak power of the laser wire should be about 80 and 10 MW for the horizontal and vertical planes, respectively. During the tuning, we first move the laser position in order to find the maximal signal. In principle, the maximal signal can be found when the centres of the laser and the beam coincide. Then the four signals from the four horizontal collisions are added together to form the final horizontal signal \( S_x \). The four signals from the four vertical collisions are also added together to form the final vertical signal \( S_y \). The summation of the horizontal and vertical signals with proper weight forms our final tuning signal.

The Nelder-Mead simplex minimization algorithm is chosen to perform the optimization [14].

4 Response matrix

The response matrices for the OTO and DFS represent the linear approximation of the BPMs to each dipole corrector. Good system knowledge is essential for the operation of modern accelerator facilities [15]. The entire response matrix is formed with columns. Each column of the response matrix is obtained by setting a unit kick to the corresponding corrector, and recording the response of the all the downstream BPMs with respect to the initial orbit.

The dispersion matrix \( D \) can be obtained in a similar way using the test beam instead of the nominal beam. In the SR, LTL and TAL, the test beams are found by scaling the magnets’ strength by 5.0\%. In bunch compressor I and II, the RF phases are changed in order to obtain a test beam with 5.0\% lower energy. In the BL, CA and VTL, the RF gradient in the BL are decreased by 5.0\% to find the test beams.

5 Simulation procedure

BBA cannot be applied on the whole RTML at one step, otherwise the beam may blow up in the misalignment lattice. The RTML is split into eight regions: SR, BC I, BL, CA and VTL, LTL, TAL1, TAL2 (TAL is too complex so it is divided to two parts) and BC II. There are overlaps between adjacent parts in order to make good junctions for the BBA. After that, the ideal machine with a beam bunch containing \( 10^5 \) particles is used to get the response matrices for all parts of RTML.

The lattice is then misaligned. Each simulation is a Monte Carlo simulation with 100 different random configurations, which are called machines. In each machine, the beam bunch contains \( 10^4 \) electron particles to average out the stochastic effects due to the quantum photon emissions of synchrotron radiation.

In order to correct the static errors, OTO is applied first. After this correction, the beam normally goes back to the centre of the BPMs. Considering the BPM offsets and the resolution effect, DFS is then used to correct the dispersion. The BBA parameters \( \beta_0 \) and \( \beta_1 \) are scanned in the two-dimensional space \([1 : 7] \times [1 : 7]\). The dispersion weight parameter \( \omega \) is also scanned and set to be 30.
| section     | $N_{\text{quad}}$ | Overlap (%) |
|-------------|-------------------|-------------|
| SR          | 40                | 50          |
| BC1         | 100               | 50          |
| BL          | 100               | 50          |
| CA and VTL  | 40                | 50          |
| LTL         | 50                | 50          |
| TAL1        | 40                | 50          |
| TAL2        | 40                | 50          |
| BC2         | 30                | 50          |

Table 3. Parameters about the bin splitting.

| section     | $\beta_0$ | $\beta_1$ |
|-------------|-----------|-----------|
| SR          | 5         | 3         |
| BC1         | 4         | 5         |
| BL          | 5         | 2         |
| CA and VTL  | 4         | 3         |
| LTL         | 5         | 3         |
| TAL1        | 5         | 3         |
| TAL2        | 4         | 3         |
| BC2         | 1         | 1         |

Table 4. Best parameters for OTO and DFS.

After OTO and DFS, the horizontal emittance can be well corrected, but the vertical emittance is too large due to the coupling effect. The $\beta$-beating also induces emittance growth. The emittance tuning bump is then applied to correct these effects.

6 OTO and DFS correction

Although we have split the RTML into eight parts, each part is still too long to perform the OTO and DFS. Therefore, each part is then split into smaller bins to perform the corrections. The number of quadrupoles in each bin and the overlap level for every subsection are listed in table 3.

The free parameters $\beta_0$ and $\beta_1$ for OTO and DFS are then scanned in the two-dimensional space $[1 : 7] \times [1 : 7]$. The final parameters are listed in table 4.

The results at the end of the RTML after OTO and DFS are shown in figure 2. It is clear that the beam has been safely transported from the beginning of the RTML to the end, although the emittance is larger than the budget. In the horizontal plane, OTO has corrected 61% of machines, and after DFS there are 88% machines well corrected. However, in the vertical plane, there are only
4% of machines that stay within budget after OTO. DFS can largely improve this to 18%, but it still cannot meet the 90% percentile. We need the sextupole correction sections to improve this.

7 Emittance tuning correction

After the OTO and DFS corrections, the emittance tuning bump correction is applied further. This correction includes two sextupole correction sections. The first one uses the sextupoles in the CA to optimize the beam at the end of the LTL. The merit function used for this optimization is 

\[ f = 15 \times S_x + S_y \]

Here, \( S_x \) and \( S_y \) are the signals from the beam laser interactions described previously. The weight factor here is set to be 15, because the signal in the vertical plane is about 15 times larger than the signal in the horizontal plane.

The ten initial displacements of the five sextupoles in the CA for the \texttt{simplex} algorithm are all set to 0, and a step size of 1 \( \mu m \) is taken into account. The value of the assumed step size, 1 \( \mu m \), is probably pessimistic, as manufacturers of piezoelectric motors claim the ability to make very fine steps, in the nanometer scale.

The results at the end of the LTL are shown in figure 3. In the horizontal plane, the sextupole correction makes slightly worsen the emittance, making it 5 nm rad larger. However, this does not affect greatly the final results because the horizontal emittances of all machines are still far away from the budget. In the vertical plane, the emittances are much improved. More than 90% of machines have emittances less than 6.5 nm rad.

The second sextupole correction section uses the sextupoles in the TAL to optimize the beam at the end of the RTML. The merit function is the same as the first correction section. The 10 initial displacements for the algorithm \texttt{simplex} are also set to 0. The results after the correction are shown in figure 4. In the horizontal plane, 12% of machines not corrected well, but in the vertical plane, only 2% of machines exceed the budget. However, we still cannot meet the budget and further optimization in the horizontal plane is needed.

Figure 2. Emittance distributions at the end the RTML after OTO and DFS corrections. The left-hand plot shows the horizontal emittance and the right-hand plot shows the vertical emittance. The green longer dashed lines are the results after OTO correction and the blue shorter dashed lines are the results after DFS correction. The budgets are shown by the black vertical lines.
Figure 3. Emittance distribution results at the end the LTL. The left-hand plot shows the horizontal emittance and the right-hand plot shows the vertical emittance. The blue dashed lines are the results after DFS correction and the red solid lines are the results after emittance tuning bumps. The budgets are shown with the black vertical lines.

Figure 4. Emittance distribution results after emittance tuning bumps at the end of the RTML. The left-hand plot shows the horizontal emittance and the right-hand plot shows the vertical emittance. The budgets are shown with the black vertical lines.

8 Optimization of the horizontal emittance

In the previous emittance tuning process, the merit function in the SIMPLEX is

\[ f = 15 \times S_x + S_y. \]  

(8.1)

This function gives equal weight to the horizontal and vertical planes. We can try to give a larger weight to the horizontal plane. For example,

\[ f = 50 \times S_x + S_y. \]  

(8.2)

We expect that this will make the vertical emittance worse, but the new factors should give some improvement to the horizontal emittance.

The second sextupole correction has corrected 86% of all machines. This will give us a good starting point for further optimization. We apply the second sextupole correction again with a
Figure 5. Final emittance distribution results after the emittance tuning bumps at the end of RTML. The left-hand plot shows the horizontal emittance and the right-hand plot shows the vertical emittance. The budgets are shown with the black vertical lines.

larger weight factor of 50. The initial values for the simplex algorithm are taken from the previous optimization.

The final results can be seen in figure 5. In the horizontal plane, there are five machines exceeding the budget. In the vertical plane, there are also four machines exceeding the budget. By checking the indices of these malfunctioning machines, we know that there are in total nine machines that cannot be corrected well.

9 Conclusion

We apply sophisticated BBA techniques to the whole CLIC RTML through a realistic simulation including effects such as misalignments, wakefields, magnetic roll errors, incoherent synchrotron radiation and magnetic shift errors during correction. The tolerance for the magnet position offset has been improved to a value of $30 \mu m$, from initial estimates of $10 \mu m$ as in the CLIC Main Linac. The tolerance for the element rotation errors has been increased to the CLIC CDR design goal, i.e. $100 \mu rad$. The magnet strength error and the magnet center shift effect are also considered. In the emittance optimization procedure, the tuning signals are found by a new fast technique — from interactions between the beam and eight lasers. This work shows that low emittance transport in the RTML is possible, well below the tight emittance growth budgets needed to preserve the CLIC peak luminosity.

This is the first time that a 27 km long lattice of the RTML, which includes bunch compressors, booster linacs and arcs, can be well corrected to accept the realistic alignment errors. The BBA technique described in this paper for the CLIC RTML can also provide insights and useful directions for other projects, such as the ILC, where the RTML tuning is also challenging [16]. Moreover, these techniques can also be used with other large-scale facilities such as free electron lasers, whose lattices are similar to that of the RTML and share similar difficulties.
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