

BBA AND COUPLING CORRECTION AT CLIC RTML

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Abstract

The CLIC Ring To Main Linac (RTML) must transport the electron and the positron bunches through more than 20 km of beamlines with minimal emittance growth. The turnaround loops (TAL) are one of the most critical sections. In this paper a study of the Beam-Based Alignment (BBA) techniques in the Turnaround loop (TAL) of the CLIC RTML is presented. In order to reduce the emittance growth, the one-to-one(1:1) and dispersion-free steering (DFS) corrections have been tested. The results showed that the emittance growth budgets can be met both in the horizontal and vertical planes. The impact of coupling errors due to magnets roll on the emittance has also been studied and a coupling correction scheme has been designed. By inserting the correction scheme into the RTML dispersive region, the vertical emittance can be largely compressed. While this coupling correction result is very preliminary and more further studies are needed.

INTRODUCTION

CLIC is one of the future accelerators designed for the particle physics after LHC. The concept of two-beam acceleration can provide colliding beam energy up to 3 TeV [1]. The RTML section is the part of CLIC that connects the damping rings and the main linacs. The sketch of the RTML is shown in Fig. 1 [1]. The RTML sections for electrons and positrons are composed by the same subsystems (two bunch compressors, booster linac, central arc, vertical transfer, long transfer line, and turnaround loops), with the difference that there is no spin rotator in the positron line. In this paper we will focus on the electron RTML, and in particular the TAL. The TAL is a complex subsection featuring a lattice that must be achromatic, isochronous while minimizing ISR emittance growth.

In order to guarantee a luminosity of the order of $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, CLIC accepts a very strict emittance growth budget for the RTML. The normalized emittances are respectively 500 and 5 nm·rad for horizontal and vertical plane at the entrance of RTML, and they should be smaller than 600 and 10 nm·rad at its exit [1]. Pre-alignment of dipoles and quadrupoles has been considered to be of the order of 100 μm , assuming the BPM resolution of 1 μm [1]. These values are such that BBA must be used in order to preserve the small emittances to magnets errors.

It must also be noticed that, at the entrance of the RTML, the vertical emittance is only 1% of the horizontal emittance. This implies that even very small coupling between horizontal and vertical plane will introduce large emittance growth in the vertical plane. It is known that it is hard in technique to align the rotation errors less than 100 μrad . So, a coupling correction scheme must be envisaged.

In this paper, we will use the CLIC beam tracking software PLACET, which is intended to simulate the dynamics of a beam in the presence of wakefields [2] in order to assess the performance of BBA in the TAL, and the impact of coupling errors on the beam quality.

BBA IN THE TURNAROUND LOOPS

The turnaround loops feature the most complex lattice in RTML so it is also very difficult to do the BBA. The dipoles are selected as the correctors and one dipole is added after each quadrupole. We used a gaussian distribution to misalign the lattice, with σ_{pos} denoting the standard deviation. All the quadrupoles and Beam Position Monitor (BPM) are misaligned. BPM also has a resolution $\sigma_{\text{res}} = 1 \mu\text{m}$. One-to-one (1:1) and DFS are used to improve the orbit. The 1:1 is a simple and faster algorithm which is often used first to correct the misalignment errors. We use the Eq. 1 to get strength of the dipole correctors for the 1:1 correction.

$$\theta = \min \|\Delta \mathbf{u} - \mathbf{R}\theta\|_2^2 + \beta^2 \|\theta\|_2^2; \quad (1)$$

Here, θ is the strength of the dipole correctors. $\Delta \mathbf{u} = \mathbf{u} - \mathbf{u}_0$ represent the beam position difference recorded by BPMs between misalignment machine and perfect machine. \mathbf{R} is the response matrix between the dipole correctors and the BPMs. β is damping factor which is used to avoid the large fluctuation of corrector strength.

In the real world, BPMs always have non-zero resolution and alignment errors, we need DFS to correct this. The strength of correctors are got according to Eq. 2.

$$\theta = \min \|\Delta \mathbf{u} - \mathbf{R}_1 \theta\|_2^2 + \omega^2 \|\Delta \eta - \mathbf{D}\theta\|_2^2 + \beta^2 \|\theta\|_2^2 \quad (2)$$

Here, $\Delta \mathbf{u}$ has the same meaning as in Eq. 1 and \mathbf{R}_1 is same as \mathbf{R} . ω is weight factor. $\Delta \eta = \Delta \mathbf{u}_{\text{dis}} - \Delta \mathbf{u}$ represent the dispersion recorded by BPMs, here $\Delta \mathbf{u}_{\text{dis}}$ denote beam position difference between misalignment machine and perfect machine for the beam with energy $E_0(1 + \delta)$, E_0 is the nominal beam energy. In this study, we set the δ to be 0.5%. \mathbf{D} is the dispersion response matrix.

Simulation Setup

The effectiveness of One-to-one correction (1:1) and DFS depends on the response matrix. In order to compute numerically the response matrix \mathbf{R} and the dispersion response matrix \mathbf{D} , a bunch containing 100'000 particles was used. Such a large number of particles was chosen to average out the stochastic effects of the synchrotron radiation emission.

BBA was tested for different σ_{pos} misalignment levels, simulating 100 different random machines. The final observables were the average emittance, and the 90% percentile of the distribution of 100 final emittances. BBA was

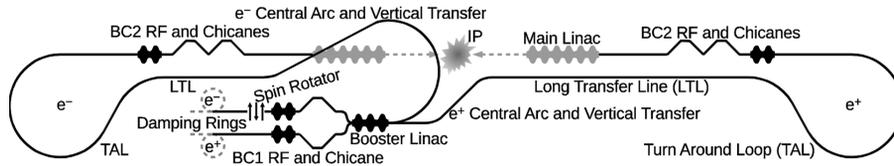


Figure 1: Sketch of the RTML.

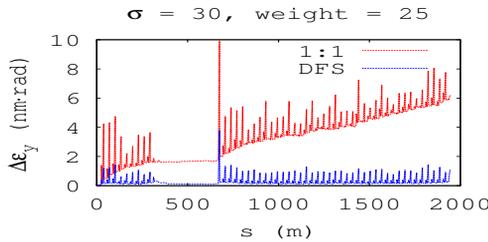


Figure 2: Emittance growth along the lattice.

performed tracking a bunch with 20,000 particles. When applying the correction, the TAL was split into three parts. The first and third parts were those composed of periodic cells, and were divided into small bins: each bin containing 8 cells with 4-cell overlapping between neighbor cells. The second part was treated as a single bin. This kind of split method was the same as the previous BBA study on CLIC RTML [3] and allows to correct TAL step by step.

The free parameter β was set to 5 for 1:1 correction and to 3 for the DFS correction. This limits the strength of the dipole correctors to avoid large values, while allowing convergence.

Scan of the Weight Factor

The theoretical optimum of the weight factor ω in DFS is

$$\omega^2 = \frac{\sigma_{\text{pos}}^2 + \sigma_{\text{res}}^2}{2\sigma_{\text{res}}^2}.$$

In reality, when one takes into account effects such as wakefields or radiation, the optimum might be located at a slightly different value. For this reason it is advisable to perform a scan of different values, around the theoretical optimum. We choose $\sigma_{\text{pos}} = 30 \mu\text{m}$ to scan the weight factor. The scan results show that the emittance growth does not change much for ω in the region $[2^4, 2^8]$. Finally $\omega = 25$ is chosen for our following DFS correction.

Result of the BBA

After applying the 1:1 and DFS for $\sigma_{\text{pos}} = 30 \mu\text{m}$, the vertical emittance growth is shown in Fig. 2. For an uncorrected TAL, the vertical emittance growth is too large and the beam is lost. One-to-one and DFS greatly improve the situation.

The residual emittance growth noticeable at the end of the turnaround loop will seemly be reduced when we will perform a correction including also the BPMs in the downstream sections, that is the bunch compressor BC2. Further-

more, given the fact that the emittance growth in the arcs is mainly due to dispersive effects, we consider as figure of merit for the final emittance the value at the last valley, where the dispersion is closed.

One-to-one and DFS have been tested against different misalignments σ_{pos} : 5, 10, 20, 30, 40 and 50 μm . The results are shown in Fig. 3, where each curve represents the average result of 100 machines. In the figure 90% means the 90% percentile. The black dashed line shows the emittance-growth budget. For the horizontal plane this is 100 nm · rad and for vertical plane it is 1 nm · rad. The top plot shows the horizontal emittance growth. 1:1 can increase the tolerance to about 10 μm for 90% percentile. After DFS, this tolerance can be larger than 50 μm . The bottom plot shows the vertical plane result. 1:1 can only correct the misalignment of σ_{pos} equals 5 μm for 90% percentile. After DFS, the tolerance can be increased to 40 μm .

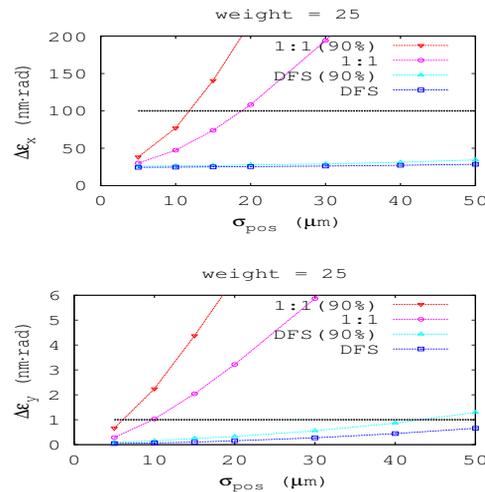


Figure 3: Emittance growth versus the σ_{pos} .

COUPLING CORRECTION IN THE RTML

In an ideal linear lattice, the transverse motion of particles can be treated separately in horizontal and vertical plane. In practice it is hard to completely remove the rotation error, and small angles persist after the pre-alignment phase. These element rotations introduce beam coupling between horizontal and vertical plane. As the horizontal emittance is 100 times larger than the vertical one, even very small rotations introduce large vertical emittance growth. For the same reason there should be no harm to the horizontal emittance coming from the vertical one.

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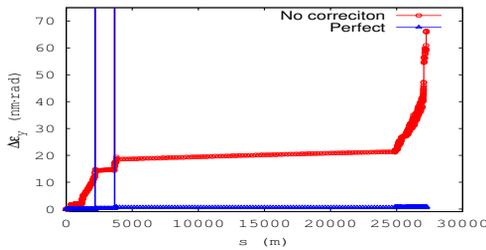


Figure 4: Emittance growth along the lattice.

Figure 4 shows the mean emittance growth of 100 machines along the RTML lattice with dipole and quadrupoles rotated $\sigma = 100 \mu\text{rad}$. As expected, the horizontal emittance doesn't grow much and stays below the budget, $600 \text{ nm} \cdot \text{rad}$. The largest values in the plot are due to the dispersion in the center arc and in the turn-around-loop. They decrease to normal values when the beam comes to a non-dispersive region. On vertical plane, the emittance grows rapidly: the final emittance is $71.3 \text{ nm} \cdot \text{rad}$, well beyond the budget of $10 \text{ nm} \cdot \text{rad}$.

In order to simplify our study, we first tried to rotate the beam in several locations of RTML in the transverse plane. This gave us a direct information on what are the most effective locations for a coupling correction section. In our simulation, the rotation angles θ were tested in a range $[-5, 5] \text{ mrad}$. Firstly, the beam is rotated at several non-dispersive regions of RTML: the end of SR, BC1, CA, TAL and BC2, start of CA, LTL and TAL. The results show that the vertical emittance can not be reduced significantly. On the other hand, locating the correction scheme in the dispersive cells of CA and TAL, the vertical emittance is largely reduced. This implies that most of the vertical emittance growth comes from vertical dispersion. Since residual dispersion can typically be removed by a global dispersion correction, we used the `PLACET` option "DispersionFreeEmittance", which removes the contribution of dispersion from the emittance allowing to isolate the contribution of coupling. We will use the option for the following study.

Skew Quadrupole Correction Scheme

In principle at least four skew quadrupoles are needed to perform a coupling correction. The phase advance between these skew quadrupoles are shown in Fig. 5.

At the end skew section, another phase advance $\Delta\phi_x = 0$, $\Delta\phi_y = \frac{\pi}{2}$ is added at the end of correction section, which

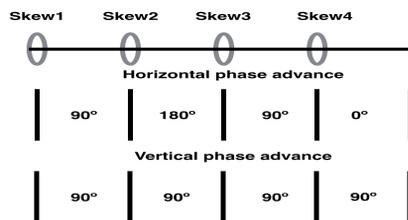


Figure 5: Skew quadrupoles correction layout.

will make the section transparent if the skew quadrupoles are off.

Thin lens approximation for skew quadrupoles are used to get the total transfer matrix. Then the function "fmins" in `OCTAVE` is used to minimize the four coupled beam items: $\langle xy \rangle$, $\langle x'y \rangle$, $\langle xy' \rangle$ and $\langle x'y' \rangle$. We also try to minimize horizontal and vertical emittances together.

First Results

The skew correction sections are at first put in all non-dispersion regions separately as before. Unfortunately there is still no big improvement observed. As previously described, we put the skew correction section in the middle of CA and TAL. This time the vertical emittance reduced efficiently. The results is shown in Fig. 6. The solid red line with circles shows the average emittance growth of uncorrected machines. The dashed pink line shows the preliminary corrected result with one skew correction section in the CA and one in the TAL. The emittance growth due to dispersion has been removed using the `PLACET` option. The solid blue line with triangles is the emittance growth for perfect a machine.

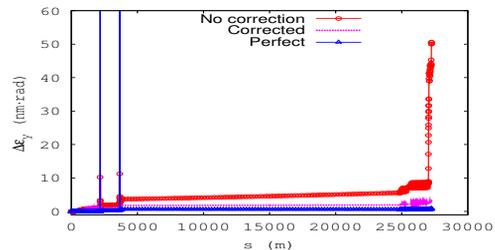


Figure 6: Preliminary result of coupling correction.

The vertical emittance has been strongly reduced, from $55.6 \text{ nm} \cdot \text{rad}$ to $8.3 \text{ nm} \cdot \text{rad}$. For the remaining emittance growth, one source is the misaligned BC1 which leads the emittance growth at boost linac. Another source is the BC2. When beams leaves the TAL, the beam property may become a little worse, giving emittance growth in BC2.

SUMMARY

Using beam-based alignment techniques, we succeed to increase the alignment tolerance of quadrupoles and BPMs to $40 \mu\text{m}$ in the most challenging subsection of the CLIC RTML: the Turnaround Loops. We have also assessed the performance of a coupling correction section using four skew quadrupoles. By putting this section to the dispersive region of RTML, the vertical emittance can be efficiently reduced. This is a preliminary result and more further detailed studies are needed.

REFERENCES

- [1] CLIC Conceptual Design Report, A Multi-TeV Linear Collider Based on CLIC technique, 2012
- [2] D. Schulte et al., The tracking Code `PLACET`
- [3] Thibaut Linear, Study of pre-alignment tolerances in the RTML, CLIC note 943.