

BEAM-BASED ALIGNMENT FOR THE REBASELINING OF CLIC RTML

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Abstract

The first stage of the CLIC is proposed to be at 380 GeV. So the Ring To Main Linac (RTML), which transport the beams from the damping ring to main linac with minimal emittance growth, should be restudied due to the new beam properties. In this paper the two bunch compressors in the RTML are redesigned. Then a complete study of the static beam-based alignment techniques along RTML is presented. The beam-based correction includes one-to-one and dispersion-free steering, then a global correction using tuning bumps is applied to reduce the final emittance and mitigate the effects of coupling. The results showed that the emittance growth budgets can be met both in the horizontal and vertical planes.

INTRODUCTION

CLIC is a future linear accelerator designed for the high-energy physics after the LHC. The concept of two-beam acceleration at the hearth of CLIC can provide collision energies of multi-TeV [1], which can open the possibility to study new physics beyond the Standard Model. For the first stage of operation, the centre-of mass of CLIC is 380 GeV, which allow high precise study of Higgs and top physics [2].

The Ring-to-Main-Linac (RTML) is one part of CLIC, which transports the beam from the damping ring to the main linac, with the critical task of preserving the nanometer-sized emittance from the damping rings. The beam bunches are also accelerated and longitudinally compressed during the transportation. The sketch of the RTML can be found in the CLIC CDR [1]. There are two RTML arms in CLIC: one for the electron beam, and another one for the positron beam. They are very similar and feature: two bunch compressors (BC1 and BC2) to compress the beam, a booster linac (BOO) for acceleration, a central arc (CA), a vertical transfer (VT), a long transfer line (LTL), and a turnaround loop (TAL) for the transportation. The electron RTML arm is equipped also with a spin rotator (SR).

The normalized emittances at the beginning of RTML are 700 and 5 nm · rad for the horizontal and the vertical planes, respectively. In order to guarantee the high luminosity of $0.9 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, a strict emittance-growth budget for the RTML has been established: at the end of RTML, the emittances must be smaller than 850 and 10 nm · rad [2]. This budget includes: the design emittance growth due to synchrotron radiation and wakefields, and the emittance growth due to static and dynamic effects. The horizontal and vertical budgets for the design emittance growth and for the static effects are 120 nm in the horizontal plane, and a 3 nm in the vertical plane respectively. Dynamic effects are not included in this paper, but they aren't deemed to be critical. The strict requirements on the beam transport impose

tight tolerances on the position and angle pre-alignments of magnets. The standard pre-alignment techniques leave residual errors at the level of 100 μm r.m.s. [3], which is much larger than the lattice tolerance. Static beam-based alignment (BBA) techniques must be used to increase the tolerance to misalignments.

The static BBA on RTML for the CLIC final stage (3 TeV) has been applied successfully [4]. This gives us a good start point for the BBA on the new 380 GeV stage. The main differences between the 380 GeV and final 3 TeV stage from a beam dynamics viewpoint are: the bunch charge is increased from 0.65 to 0.85 nC, and the bunch length is changed from 44 to 70 μm . The larger bunch charge makes the bunch more sensitive to coherent synchrotron radiations (CSR), which can induce a significant horizontal emittance growth. At the same time, the longer final bunch length helps decreasing the impact of CSR, implying less emittance growth.

In this paper, all results are simulated with the CLIC beam tracking code PLACET [5].

NEW BUNCH COMPRESSOR

In order to get the new 70 μm bunch length for the 380 GeV energy stage, the two bunch compressors are re-optimised. The requirements for the bunch compressors are:

- The final bunch length is 70 μm
- The beam is fully compressed at the end of RTML
- The final relative energy spread is less than 1.7%
- The emittance growth should be minimised.

The algorithm SIMPLEX is used to optimise the two bunch compressor designs while minimising the CSR-induced emittance growth. For this purpose, five free parameters can be tuned in the two bunch compressors: the RF voltages of BC1 and BC2; the chicane angle for BC1; and the angles of the two chicanes of BC2. The result of this optimisation are reported: $G_{BC1} = 15.90 \text{ MV/m}$, $G_{BC2} = 98.27 \text{ MV/m}$, $\theta_{BC1} = 4.42^\circ$, $\theta_{BC2,1} = 1.56^\circ$ and $\theta_{BC2,2} = 0.10^\circ$.

STATIC IMPERFECTION

To study effects of the static imperfections, the RTML elements are misaligned in a realistic way, and instrumental errors are considered. The results shown are the average of 100 random seeds.

All magnets in RTML, including dipoles, quadrupoles and sextupoles, are misaligned. The horizontal and vertical positions are randomly scattered from the nominal axis using gaussian distributions with standard deviations

$\sigma_{\text{pos}} = 30 \mu\text{m}$. From alignment studies dictated by the tight requirements of the CLIC main linacs, we know that pre-alignment accuracy within $10 \mu\text{m}$ r.m.s. can be achieved [1]. So the $30 \mu\text{m}$ r.m.s. offset error is a reasonable assumption. During the magnets installation we know that rotation errors are inevitable. This kind of errors are set to $\sigma_{\text{roll}} = 100 \mu\text{rad}$.

All Beam Position Monitors (BPMs) are misaligned with σ_{pos} and σ_{roll} , and are assumed to provide a resolution of $1 \mu\text{m}$. The current BPMs technology in CLIC main linacs can give BPM resolution of 20 nm . So $1 \mu\text{m}$ BPM resolution in CLIC RTML seems realistic.

Magnet strength errors are also presented, which can introduce dispersion, β -beating and beam coupling. For dipoles and sextupoles, 0.1% r.m.s. strength errors are considered. Since the CA and TAL feature the most complex lattice designs in the RTML, the strength error for quadrupoles in CA and TAL are set to 0.01% . For all the other quadrupoles, 0.1% error is used. Field qualities of this level have been proved, e.g., in permanent magnets [6].

In the algorithm Dispersion-Free-Steering (DFS), we need a test beam to measure the dispersion. The test beam is normally obtained by changing the beam energy. In some parts of the RTML, like the turnaround loop, this is obviously impossible. At these locations, we opted to scale the magnet strength in order to achieve the same effect. When the magnets strength are scaled, it was found experimentally that the centre of the magnets get shifted. In this paper, the magnets strength are scaled by 5.0% . We assume that this will induce a magnets centre shift of $0.35 \mu\text{m}$ [7].

CORRECTION METHODS

One-to-one correction (OTO) is a simple algorithm used to correct the initial orbit errors. The effect of OTO depends on the performance of the BPMs: perfectly aligned and precise BPMs can give a perfect correction. However, this is unrealistic and misaligned BPMs can induce emittance growth. The algorithm DFS is designed to cope with BPM errors, and is performed after OTO. The equations of OTO and DFS can be found in [8]. It is assumed that each quadrupole in the RTML is equipped with a transverse corrector kicker and a BPM.

Rotation errors of quadrupole magnets introduce coupling effects. The position errors of the sextupoles can also induce coupling effects. Given that the horizontal emittance is 140 times larger than the vertical one, coupling effects can seriously increase the vertical emittance and induce luminosity losses. Therefore, coupling correction is mandatory. It is known that transverse sextupole offsets introduce additional normal or skew quadrupole effects. These induced skew quadrupoles can be utilized to correct the coupling. Similarly, the induced normal quadrupoles can be utilized to compensate the β -beating from the magnet strength errors. In this study, two sextupole correction sections are used, exploiting some of the existing sextupoles in the lattice. The first five sextupoles in the CA are used to optimise the beam at the end of LTL, and the first five sextupoles in TAL are

used to optimise the beam at the end of RTML. The two correction sections refer to emittance measurement stations to qualify the beam.

SIMULATION SETUP

Considering the large scale of the RTML, it is unrealistic to perform OTO and DFS over the whole line at once. So the RTML is divided into sections, corresponding to each sub-systems. There are some overlaps between nearby sections to smooth the solution of BBA in the connections. After the division, some sections are still too long (e.g., CA and TAL) and they are split into bins during correction.

The effectiveness of OTO and DFS largely depends on the response matrix — a matrix relating the response of each BPMs to each correctors. A bunch containing $100'000$ particles is used to get the orbit and the dispersion response matrices, \mathbf{R} and \mathbf{D} respectively, following a method that reproduces the measurements used in real accelerators. The stochastic effects due to synchrotron radiation (quantum excitation) can be averaged out using this kind of bunch. In our study, two kinds of test beams are used in order to get the dispersion response matrix \mathbf{D} . In BC1 and BC2, the phase of the RF cavities are changed to decrease the beam energy. In BOO, CA and VT, the RF cavities gradient in BOO is decreased by 5% to get the test beam. In SR, LTL and TAL, the magnets strength are scaled by 5% .

In our study, 100 different random machines were simulated. The final observables are the final emittances distributions of 100 machines.

OTO AND DFS RESULTS

Firstly, the algorithm OTO and DFS corrections are applied. There are three free parameters to tune the performance of these methods: β_0 and β_1 to reduce correctors fluctuations in OTO and in DFS, respectively; and ω to tune the weight of the dispersion term in DFS. In each section β_0 and β_1 are scanned in a 2-D space $[1 : 7] \times [1 : 7]$ to find their optimum. The parameter ω depends on the BPMs parameters, and can be estimated theoretically as

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

When one takes into account effects such as wakefields or synchrotron radiation, the optimum might be located at a slightly different value. For this reason the ω is also scanned, in the region $[10:100]$ with the step size 10. The optimum was found for $\omega = 30$.

After applying the OTO and DFS, the emittance distributions at the end of RTML are shown in Fig. 1. The top plot shows the emittance for the horizontal plane and the bottom one shows the emittance for the vertical plane. In these plots the red-circled lines indicate the results after OTO and the blue-star lines show the DFS result.

For an uncorrected RTML, the beam would certainly be lost in such misaligned lattices. OTO greatly improves the

beam quality, so that the beam can travel through the RTML. But the emittances are still very large. In the horizontal plane 64% of the machines are well corrected. But in the vertical plane only 2% of the machines can be corrected. DFS improves this result considerably. In the horizontal plane, 82% of the machines meet the budget. But in the vertical plane, although the number of machine is increased from 2% to 16%, the result is still far from the goal of 90% of the machines within the budgets. Coupling correction is needed.

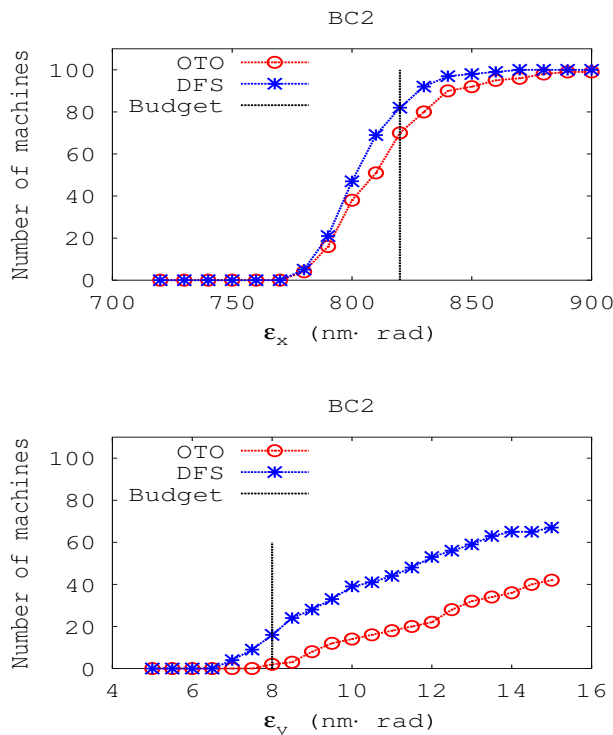


Figure 1: Emittance distribution after OTO and DFS at the end of RTML. The top plot is for horizontal plane and the bottom plot is for vertical plane. The emittances budgets are shown with vertical black lines.

SEXTUPOLE CORRECTION RESULTS

Two sextupole correction sections (SCS) are used to correct the transverse plane coupling and the β -beating effects. The first section use the sextupoles in CA to optimize the beam after LTL. The first five sextupoles in CA are moved both in the horizontal and the vertical planes to provide correcting normal and skew quadrupole effects. These account for 10 degrees of freedom to be optimized. The optimisation is done with the algorithm SIMPLEX. The merit function is chosen to be $f = \epsilon_x/700 + \epsilon_y/5$. The second SCS, utilizing the first sextupoles of the turnaround loop, works in the same way to optimise the final emittance at the end of the RTML. In both sections each sextupole is moved with a step size of 1 μm .

The emittance measurement error will also play an important role in this kind of correction. In this study, this kind of error is considered to be 1%.

It is found that after the sextupole correction, some machines still can not meet the horizontal emittance budget. We need to tune the horizontal emittance and then do the second sextupole correction again. But a larger weight will be given to the horizontal emittance in the merit function: $f = 5 \times \epsilon_x/700 + \epsilon_y/5$.

The final emittance distributions after the sextupoles corrections are shown in Fig. 2. The top and the bottom plots show the horizontal and the vertical planes respectively. The red-circled lines are the results, and the black lines are the emittances budgets. The horizontal plane shows that 94% of the machines stay within the budget. In the vertical plane, all machines have emittance smaller than 8 nm·rad.

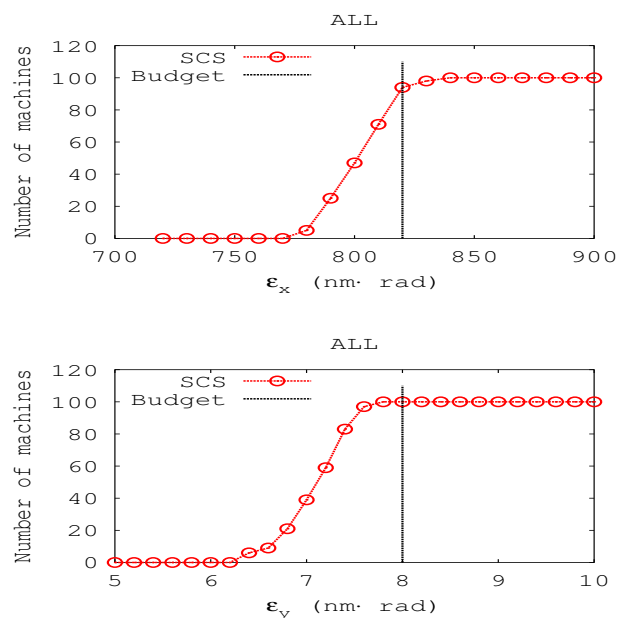


Figure 2: Emittance distribution after coupling corrections at the end of RTML. The top plot is for the horizontal plane, the bottom plot is for the vertical plane. The emittances budgets are shown with vertical black lines.

SUMMARY

In this paper, the two bunch compressors in the RTML are re-optimised in order match the new 70 μm bunch length for the CLIC 380 GeV stage. Static imperfections effects in the RTML were studied, showing that the beam-based alignment techniques are very effective to counteract the effect of realistic imperfections. A correction procedure including dispersion-free steering and emittance tuning knobs has been outlined and described. After such a correction procedure, the target emittance budget is achieved for more than 90 random seeds out of 100.

REFERENCES

- [1] M. Aicheler et al., “A Multi-TeV linear collider based on CLIC technology: CLIC Conceptual Design Report”, CERN-2012-007, Geneva, Switzerland, 2012.
- [2] P.N. Burrows et al., “Updated baseline for a staged Compact Linear Collider”, CERN-2016-004, CERN, Geneva, Switzerland, 2016, <http://dx.doi.org/10.5170/CERN-2016-004>.
- [3] M.G. Minty and F. Zimmermann, “Measurement and control of charged particle beams”, Springer, Berlin, 2003.
- [4] Y.L. Han et al., “First start-to-end BBA results in the CLIC RTML”, THPOR029, IPAC 2016 proceedings, Busan, Korea, May 8-13, 2016.
- [5] D. Schulte et al., “PLACET: a program to simulate the drive beams”, CERN-PS-2000-028-AE, CLIC-Note-437, CERN, Geneva, Switzerland, 2000.
- [6] J. Clarke et al., “The application of variable strength permanent magnet dipoles and quadrupoles”, CLIC Workshop 2016, CERN, Geneva, Switzerland, 2016, <https://indico.cern.ch/event/449801/contributions/1945293/>.
- [7] *Private communications with J. Clarke*, Science and Technology Facilities Council, UK.
- [8] Y.L. Han et al., “BBA and coupling correction at CLIC RTML”, MOPJE060, IPAC 2015 proceedings, Richmond, Virginia, USA, May 3-8, 2015.