FIRST START-TO-END BBA RESULTS IN THE CLIC RTML

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Abstract

CLIC is a design study for a 3 TeV linear collider designed for the high-energy frontier in the post-LHC era. The Ring To Main Linac (RTML) part of CLIC is a long section that must transport the electron and the positron bunches through more than 20 km of beamlines, with minimal emittance growth. A sequence of three beam-based alignment (BBA) techniques must be used to transport the beam: one-to-one correction (OTO), dispersion-free steering (DFS), and sextupole correction (SCS). The performance of the whole correction procedure is tested under several realistic imperfections: magnets position offsets, magnets rotation errors, magnets strength errors and emittance measurement errors. The results show that the emittance growth budgets can be met both in the horizontal and vertical planes.

INTRODUCTION

CLIC is a future accelerator designed for the high energy physics after LHC. The concept of two-beam acceleration can provide collision energies up to 3 TeV [1], which will open the possibility to study new physics beyond the Standard Model. The CLIC RTML must transport the beam from the damping ring to the main linac, while accelerating and longitudinally compressing the bunches. A sketch of the RTML can be found in the CLIC CDR [1]. There are two RTML sections in CLIC: one for the electron beam, and 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 transport. The electron RTML is equipped also with a spin rotator (SR).

The normalized emittances at damping ring extraction are 500 and 5 nm · rad for the horizontal and the vertical planes, respectively. In order to guarantee the high luminosity of 2×10^{34} cm^{-2}s^{-1} very strict emittance-growth budget for the RTML has been established: at the RTML end, before the injection into the main linac, the emittances must be smaller than 600 and 10 nm · rad [1]. These numbers must include: design emittance growth due to syncrhotron radiation, and emittance growth due to static and dynamic effects. The horizontal and vertical budgets for the design growth and for the static effects are: 80 nm in the horizontal plane, and a 3 nm in the vertical plane. Dynamic effects are not included in this paper. These 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. [2], which is larger than the lattice tolerance. The RTML will require better pre-alignment.

The CA and TAL are the critical subsystems that most contribute to the emittance growth. They feature a similarly complex lattice, to provide achromatic and isochronous transport while minimizing the emittance growth induced by incoherent synchrotron radiation (ISR). The study for TAL shows that the tolerance for quadrupoles and BPMs offset can be 40 μm [3] r.m.s.; this allows to transport the beam and to successfully perform BBA in the whole RTML.

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

LATTICE MISALIGNMENT

To assess the BBA performance, the RTML elements are misaligned in a realistic way, and instrumental errors are considered. The results shown are the average of several 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 $\sigma_{\text{pos}} = 30\ \mu$m. From alignment studies dictated by the tight requirements of the CLIC main linacs, we know that pre-alignment accuracy within 10 μm r.m.s. can be achieved [1]. So 30 μm r.m.s. offset error should also be a reasonable assumption.

When installing the magnets, the rotation errors will also be inevitable. This kind of errors are set to $\sigma_{\text{roll}} = 100\ \mu$rad.

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

Magnet strength errors are also present, introducing residual dispersion, $\beta-$beating and beam coupling. For dipoles and sextupoles, 0.1% r.m.s. strength errors are considered. Since the CA and TAL are the most complex lattice in the RTML, the strength error for quadrupoles in CA and TAL are set to be 0.01%. For all the other quadrupoles, 0.1% errors are set. Field qualities of this level have been proved, e.g., in permanent magnets [4].

CORRECTION METHODS

One-to-one correction (OTO) is a simple algorithm used to correct the initial orbit errors and to let a beam go through a beamline. The effect of OTO depends on the performance of the BPMs: perfectly aligned and precise BPMs would give a perfect correction. However, this is unrealistic and misaligned BPMs induce emittance growth. A BBA technique such as Dispersion-free-steering (DFS) is designed to cope with BPM errors, and is performed following OTO. The equations of OTO and DFS can be found in [3]. It is

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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. Given that the horizontal emittance is roughly 100 times the vertical one, coupling effects can seriously spoil the vertical emittance. 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

Given the considerable length of the RTML, about 27 km, it is considered unrealistic to perform OTO and DFS over the whole line at once. The RTML is therefore divided into several parts, corresponding to each subsystems. Some overlaps are foreseen between nearby parts to smooth the solution of BBA in the connections. Some sections are still too long even after this division (e.g., CA and TAL) and they are split into bins during correction.

The effectiveness of OTO and DFS depends on the response matrix, a matrix relating the response of each BPMs to each correctors. A bunch containing 100'000 particles was used to average out the stochastic effects due to synchrotron radiation (quantum excitation). In our study, two test beams are used in order to get the dispersion response matrix **D**. In BOO, we can change the RF cavity gradient to get a beam with different energy. So a test beam with $\delta = 5\%$ energy difference is used to get the **D**. In other parts of the RTML, however, the beam energy can not be changed directly. In these regions the magnet strengths are scaled instead, with $\delta = 5\%$; this is equivalent to changing beam energy ($\delta = 10\%$ for BC2).

In our study, the results are the average 100 different random machines. Each machine contains one bunch with 10,000 particles. The final observables are the average emittance, and the 90% percentile of the distribution of 100 final emittances.

OTO AND DFS RESULTS

Firstly, OTO and DFS corrections are applied. Three free parameters allow to control these methods: β_0 and β_1 to reduce correctors fluctuations in OTO and in DFS, respectively; and ω to weight the dispersion term in DFS. In each section β_0 and β_1 were 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

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

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 it was 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 horizontal plane, the bottom one 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 the whole RTML and DFS can be used. But the emittances are still very large. Only less than 10% machines transport emittances within the budget both in horizontal and vertical planes. DFS improves this result considerably: in the horizontal plane, 99% of the machines meet the budget; on the other hand in the vertical plane, although the number of machine is increased from 6% to 27%, the result is still far from the goal of 90% of the machines within the budgets. Coupling correction is needed.

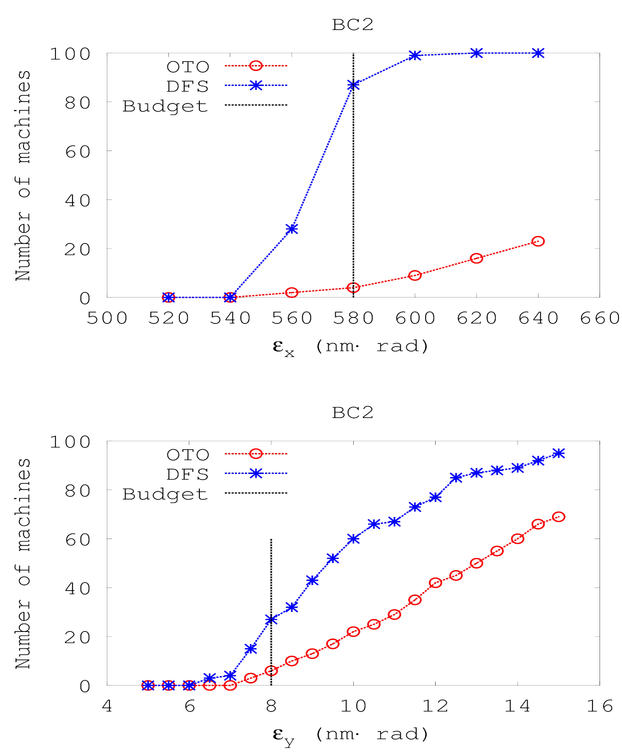

Figure 1: Emittance distribution after OTO and DFS at the end of RTML. The top plot is for horizontal plane and the bottom plot is for vertical plane.

COUPLING CORRECTION RESULTS

Two sextupole correction sections (SCS) are used to counteract beam x-y coupling. 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 correction aims at minimizing the beam transverse emittances as measured at the end of the LTL section, using the SIMPLEX algorithm. The merit function is chosen to be $f = \epsilon_x/500 + \sum_{i=\mathrm{end}-10}^{\mathrm{end}-5} \epsilon_{y,i}/5$, where "end" indicates the emittance measurement at the last BPMs. 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. Tab. 1 shows the effect of the emittance measurement error. Here the magnet strength errors are not included. It is interesting to notice that the horizontal emittance always stays within the budget, whereas the vertical emittance proves to be very sensitive the measurement errors: 2.0% errors make the coupling correction significantly less effective. Considering that appropriate filters could be envisaged to reduce the measurement noise, we considered 1% emittance measurement errors.

Table 1: The Effect of Emittance Measurement Error

Error (%)	$N_{\epsilon_x>600}$	$N_{\epsilon_y>8}$
0.1	0	0
0.3	0	1
0.5	0	5
1.0	0	8
2.0	0	15

The final emittance distributions after the coupling 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 line the budget stated in the CLIC CDR. The horizontal plane shows that nearly all machines stay in the budget. In the vertical plane, 91% machines have emittance smaller than 8 nm · rad. This means that the budgets are met in both planes.

DISCUSSION

The beam quality is very sensitive to the quadrupole magnets strength error. Our simulations show that preserving the beam emittances with 0.1% strength error is nearly impossible: 0.01% must be used. Such level of accuracy has been achieved in permanent magnets [4], an option that is being considered for the RTML quadrupoles. In our DFS procedure, the magnets' strength must be scaled in order to form a test beam. Experimental tests of DFS have shown that during the scaling, the magnets centre might be subjected to shifts, rendering the correction significantly less effective.

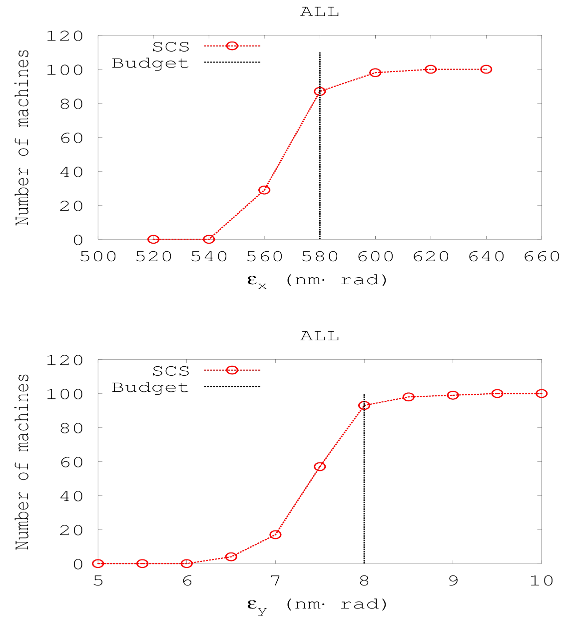

Figure 2: Emittance distribution after coupling corrections at the end of RTML. The top plot is for the horizontal plane, the bottom plot is for the vertical plane.

This effect is being studied and solutions will be presented in future publications.

SUMMARY

For the first time beam-based alignment techniques are applied to the whole CLIC RTML. The results show that in presence of reasonable errors like: magnets and BPMs alignment errors $\sigma_{\mathrm{pos}} = 30$ μm, $\sigma_{\mathrm{roll}} = 100$ μrad r.m.s.; BPMs resolution $\sigma_{\mathrm{res}} = 1$ μm; magnet strength error $\approx$ 0.01% r.ms.; sextupole movers step size of ≈ 1 μm , and 1% resolution from the emittance measurement stations, we are able to correct the whole RTML lattice and meet the CLIC CDR budgets.

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