START-TO-END TRACKING SIMULATIONS OF THE COMPACT LINEAR COLLIDER

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Abstract

We present the current status of the beam tracking simulations of the Compact Linear Collider (CLIC) from the exit of the damping ring to the interaction point, including the ring to main linac (RTML) section, main linac, beam delivery system (BDS) and beam-beam interactions. This model introduces realistic alignment survey errors, dynamic imperfections and also the possibility to study collective effects in the main linac and the BDS. Special emphasis is put on low emittance transport and beam stabilisation studies, applying beam based alignment methods and feedback systems. The aim is to perform realistic integrated simulations to obtain reliable luminosity predictions.

INTRODUCTION

In order to achieve the design luminosity of the future linear colliders, preservation of an ultra low vertical emittance from the damping ring to the interaction point (IP) as well as sub-nanometre level beam stabilisation at the IP will be required. It is well known that different static and dynamic machine imperfections can lead to significant luminosity loss. To combat this luminosity degradation different alignment, feedback (FB) and tuning techniques are foreseen. In this context detailed integrated simulations, covering different subsystems and time-scales of the collider, are vital for assessing the reliability of the design luminosity.

In this paper we report on the progress towards fully integrated beam dynamics simulations of the Compact Linear Collider (CLIC) [1] from the exit of the damping ring to the IP. These simulations are based on the tracking code PLACET [2], which allows the simulation of the different linear collider subsystems in a modular fashion. In the interaction point the luminosity is calculated using the code GUINEA-PIG [3], which performs realistic simulations of the beam-beam interactions.

LOW EMITTANCE TRANSPORT

RTML

The ring to main linac transport (RTML) connects the damping rings with the main linac. It consists of a variety of beam lines, each serving a distinct function. Most notable beam lines are the two bunch compressors, the booster linac and the spin rotator because they actively change beam properties. Others are required to properly transport and characterise the particle distributions prior to their acceleration to collision energy. Electron and positron beams share the booster linac, all other beam lines are separated. Tight tolerances are imposed on the performance of the RTML, particularly on the emittance growth. The main contribution to emittance growth is due to incoherent synchrotron radiation in the arcs and loops. Simulations of the RTML showed that its performance is well within specifications [4].

Main Linac

Important progress has been made to simulate the beam-based alignment (BBA) process of the main linac of linear colliders starting from realistic survey alignment errors. The survey alignment process has recently been simulated for the ILC main linac by the LiCAS group [5], and in a similar way it can be applied to CLIC. This software simulates the reference alignment networks measured with conventional as well as novel techniques based on primary marker measurements, by using GPS measurements and laser tracker measurements. In principle, this software package could be incorporated to the PLACET code.

The required tolerances needed to keep a tolerable level of emittance growth in the main linac are not attainable with current state-of-the art mechanical alignment and survey techniques, and then further BBA and tuning procedures are required. For the CLIC main linac the following BBA strategy is foreseen: first, a simple one-to-one correction is applied to steer the beam to the centre of the BPMs; second, dispersion free steering (DFS) is used to adjust the beam trajectory to minimise the dispersion; then, the RF accelerating structures are aligned to the beam.

Table 1: Static Misalignment Errors in the CLIC Main Linac

Imperfection	Respect to	Value
BPM offset	Survey line	14 μm
BPM resolution		0.1 μm
RF cavity offset	Girder axis	10 μm
RF cavity tilt	Girder axis	200 μrad
Quadrupole offset	Survey line	17 μm
Quadrupole roll	Longitudinal axis	100 μrad
Girder intersection offset	Survey line	12 μm
Girder intersection mismatch	Articulation point	5 μm

Assuming realistic survey alignment errors (Table 1) and 10 nm initial vertical normalised emittance (injection from the RTML), Fig. 1 shows the average emittance dilution along the CLIC main linac after applying different BBA methods for 100 simulated machines. The corresponding emittance distribution at the end of the linac, after 1-to-1 + DFS + RF alignment, is shown in Fig. 2. An emittance mean value of 12.5 nm·rad has been obtained, with 90% of the events below the emittance growth budget $\Delta(\gamma\epsilon_y) \lesssim$ 5 nm for static imperfections.

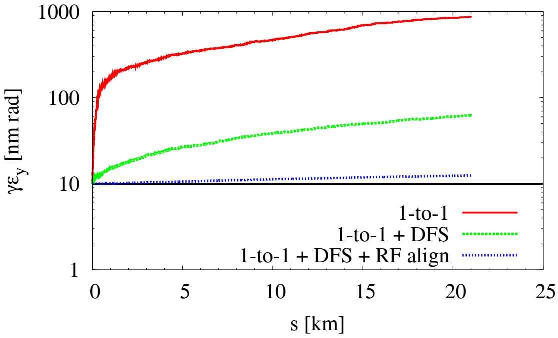

Figure 1: Emittance dilution in the CLIC main linac after applying different BBA methods.

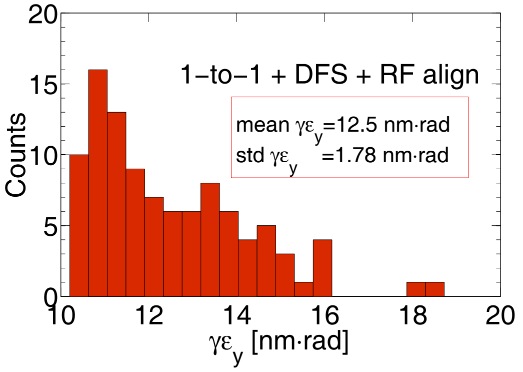

Figure 2: Emittance distribution (100 simulated machines) at the end of the CLIC main linac after 1-to-1, DFS and RF alignment correction.

Further improvement might be obtained by means of techniques such as applying dispersion-generating beam bumps to correct the remaining chromatic aberrations, and wakefield bumps [6].

Beam Delivery System

The alignment of the CLIC BDS has been addressed in [7]. There are two major challenges: the tight tolerances for the emittance preservation and its strong non-linear beam dynamics. For these reasons conventional beam-based alignment techniques, like DFS, are only partially successful and need to be followed by optimisation algorithms based on other observables, like beam sizes. It has been proved via realistic simulations that DFS can be used to align the CLIC collimation section with an emittance growth below 5%. However these pure alignment techniques fail in the final focus system.

More complex algorithms have been developed for BDS BBA. For example, a combination of kick minimisation [8] and x–y coupled 1-to-1 correction, taking thus into account the couplings when the sextupoles are turned on. This alignment routine proceeds in two phases: first, with the sextupoles off, then with the sextupoles on. Preliminary results are shown in Fig. 3 for the correction of 10 μm element misalignment in both axes along the CLIC BDS, average of 40 machines. The final emittance is corrected by approximately six orders of magnitude. Further tuning is necessary to achieve the emittance target.

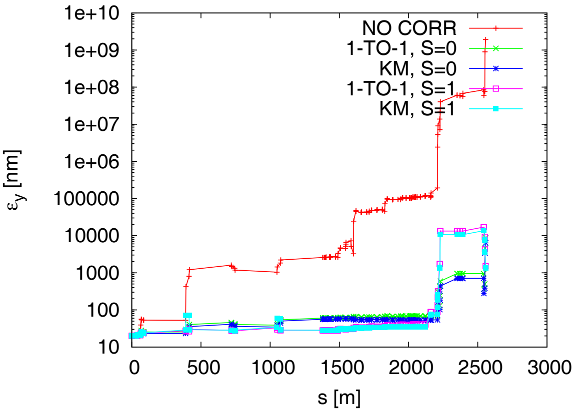

Figure 3: Emittance dilution due to 10 μm element misalignment along the CLIC BDS. Results after applying kick minimisation (KM) and x–y coupled 1-to-1 correction with sextupoles off (S=0) and on (S=1) are compared.

LUMINOSITY STABILITY

Unfortunately, the static imperfections are not the only issue of concern. Dynamic imperfections can also generate beam jitter and/or emittance dilution, which can dramatically degrade the luminosity. Alignment drifts over time due to ground motion (GM) and other vibration sources (for example, quadrupole vibrations and jitter in the gradients of the accelerating cavities) may occur.

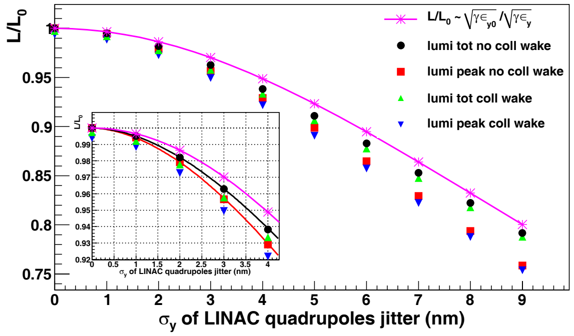

Figure 4: Total and Peak Luminosity loss according to RMS jitter of the main linac quadrupoles. The cases of a perfectly aligned BDS and a perfectly aligned BDS with collimator wakefields are shown. The relative emittance computed from the envelope of 100 machines is also shown.

The luminosity loss due to an uncorrected quadrupole misalignment (or quadrupole jitter) is shown in Fig. 4. Different RMS quadrupole jitters have been considered for the main linac while the beam is tracked through a perfectly aligned BDS. The collimator wakefields add a static luminosity loss of 0.6 %, while the tolerance for 1% dynamic luminosity loss is 1.3 nm. Finally, Fig. 4 also shows that the multi-pulse emittance is a good measure of the luminosity loss due to dynamic imperfections.

In order to compensate the beam orbit jitter due to component vibration, the following general approach can be adopted: selection of a site with sufficiently small ground motion; pulse-to-pulse FB systems for orbit correction in the linac and the BDS; active stabilisation of the FD quadrupoles and stabilisation of the detector surrounding the interaction region; well-engineered detector environment for low vibration; and a very fast intra-train FB system to keep the beams in collision. A more complete concept of mitigation of GM induced beam orbit jitter is described in Ref. [7].

Feedback Systems

In order to achieve the required beam stability goals, beam-based FB systems, operating at different time-scales, are foreseen to be distributed in the linac and in the BDS. In this paper we will focus on luminosity performance simulations using a pulse-to-pulse FB system in the BDS in combination with an intra-train FB at the IP, in terms of correcting beam jitter due to GM. FB systems for the CLIC main linac are described elsewhere [9].

In our simulations we have applied the so-called A. Seryi's GM models [10], which are well implemented in the code PLACET. These models are based on measurements at different sites. The time interval used to sample the GM is 0.02 s, corresponding to the repetition frequency at which CLIC trains are delivered (50 Hz). Table 2 shows the RMS vertical beam-beam displacement at the IP for each model of GM.

Table 2: RMS Vertical Beam-beam Offset at the CLIC IP due to 0.02 s of GM for 100 Random Seeds. With units of the nominal vertical beam size at the IP in brackets.

GM model	RMS Δy^* [nm]
A (CERN)	0.035 (0.04 σ_y^*)
B (SLAC and FNAL)	0.47 (0.52 σ_y^*)
C (DESY)	8.9 (9.9 σ_y^*)
K (KEK)	6.4 (7.1 σ_y^*)

A CLIC IP intra-train FB system has conceptually been designed and simulated [11]. This system is thought as an additional line of defence to cure the relative beam-beam offset at the IP. The IP fast FB system may also help to relax the stability tolerance of the final quadrupole doublet.

On the other hand, the design of a BDS pulse-to-pulse FB system is under development. Here we apply a few-to-few orbit correction based on the Singular Value Decomposition algorithm (SVD), using 59 BPMs and 58 controllers (dipole correctors) available in the CLIC BDS. We have assumed a BPM resolution of 10 nm.

Performance luminosity results are shown in Fig. 5 for different scenarios of GM, and for different operation cases with and without FB correction. These values correspond to the average over the luminosity results for 100 different random seeds of GM. Here no FD quadrupole stabilisation has been assumed. Even for the noisiest GM cases (models C and K), a combination of SVD inter-train orbit correction along the BDS and IP intra-train FB system might allow to reach about 80% of the design luminosity.

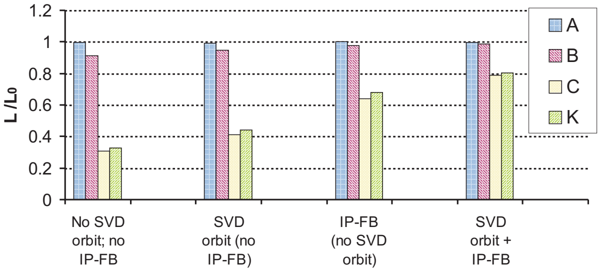

Figure 5: Relative luminosity with different models of GM (A, B, C and K) for the following cases: without any feedback, applying only orbit correction (SVD algorithm), applying only IP-FB, and applying SVD orbit correction + IP-FB. Here we have considered 10 nm BPM resolution for the SVD orbit correction.

SUMMARY AND OUTLOOK

In the context of low emittance transport and luminosity stability studies, the development of a start-to-end simulation model of CLIC is in progress. It is based on the tracking code PLACET, and allows the addition of accelerator subsystems in a modular way, from the exit of the damping ring to the IP. This model allows to study the influence of static and dynamic imperfections on the emittance/luminosity. In order to combat those imperfection effects, BBA, feedback systems (covering different time-scales) and tuning methods have been implemented. The first steps towards a fully integrated start-to-end simulation of CLIC have been made.

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