DYNAMIC EFFECTS DURING BEAM-BASED ALIGNMENT*

D. Schulte, A. Latina, CERN, Geneva, Switzerland

P. Eliasson, University of Uppsala, Sweden

November 16, 2007

Abstract

Complex beam-based alignment procedures are needed in future linear colliders to reduce the negative effects of static imperfections in the main linac on the beam emittance. The efficiency of these procedures could be affected by dynamic imperfections during their application. In this paper we study the resulting emittance growth.

1   INTRODUCTION

In the following, we will evaluate the impact of dynamic imperfections on the beam-based alignment of the main linacs in CLIC and ILC. The presence of dynamic imperfections causes a loss of luminosity, which one tries to minimise using feedback. In order to achieve the luminosity goal, dynamic imperfections need to be limited. In addition to the direct luminosity loss, the imperfections also impact the measurements that are performed during the beam-based alignment. This will reduce the efficiency of these methods leading to a further luminosity loss. Obviously the impact on the static alignment can be considered acceptable, if the indirect luminosity loss remains below the direct one.

2   CLIC ALIGNMENT STRATEGY

In CLIC all accelerating structures are mounted on girders. The beginning of each girder is connected to the end of the upstream girder thus forming a long chain. The articulation points of this chain are equipped with movers. Each girder can support up to eight accelerating structures. The quadrupoles and beam position monitors (BPMs) are mounted on independent girders that can also be moved.

The initial static imperfection can be found in table 1. The quadrupole roll has been neglected in these simulations, since we are interested in the difference of the alignment with and without dynamic effects.

CLIC will be aligned in several stages. First, a simple one-to-one steering is performed in order to make the beam pass the main linac. This procedure is followed either by ballistic alignment or by dispersion free steering. Here, we will use dispersion free steering. The main linac is divided into bins each containing 36 quadrupoles with an overlap of 18 quadrupoles. These bins are aligned one after the other using the nominal beam and two test beams and minimising the function

$$\sum_{i=0}^{n}(y_{0,i})^2 + w_1 \sum_{i=0}^{n}(y_{1,i} - y_{0,i})^2 + w_2 \sum_{i=0}^{n}(y_{2,i} - y_{0,i})^2$$

Here, $y_{0,i}$ are the BPM readings for the nominal beam and $y_{1,i}$, $y_{2,i}$ are the BPM readings of the first and second test beam, respectively. The first test beam is accelerated with a

Table 1: Assumed initial static imperfections for CLIC.

Imperfection	with respect to	value
Structure offset	girder	$7\,\mu$m
Girder end point	cradle	$5\,\mu$m
cradle	survey line	$12\,\mu$m
BPM	survey line	$14\,\mu$m
Quadrupole	survey line	$17\,\mu$m
BPM in structure	real structure centre	$5\,\mu$m

lower gradient than the nominal one. The second test beam starts with a lower energy at the linac entrance but is accelerated with the same gradient as the nominal beam. Minimising the difference between the first test beam and the nominal one will thus minimise dispersive effects due to the phase extension of the bunches. The second test beam will minimise dispersive effects due to the incoming beam energy spread. The relative weights w_1, w_2 of the figure of merit needs to be optimised to achieve best performance.

The dispersion free steering is followed by an alignment of the RF structures. Each of the structures is equipped with an internal beam position monitor. Starting at the upstream end, the articulation points of the girders between two consecutive quadrupoles are moved in order to minimise the average offset of the beam in the structures. Once this is achieved, one moves to the girders between the next pair of quadrupoles. This is a relatively slow process. In this paper we do not include the dynamic effects during this alignment procedure. In order to simplify the simulations, the movement of the articulation points is modelled by moving each structure independently. Previous simulations that compared this simplified procedure to the full modelling found that the results are very close[2].

Finally, tuning knobs are used to further minimise the emittance. The knobs consist of a number of accelerating structures that are moved transversely in order to minimise the beam emittance at the end of the linac. In the simulations, the knobs are modelled in a simplified fashion, assuming perfect resolution for the emittance measurement. More detailed simulations have been performed previously [3].

3   SIMULATION PROCEDURE

All simulations have been performed using PLACET [1] for a set of 25 different machines. We expect the largest impact of the dynamic imperfections to arise during the dispersion free steering, since during this step differences of trajectories are used to optimise the machine. As a consequence the dispersion free steering was studied simulating each beam pulse in full detail. In contrast, the initial and final one-to-one steering as well as the RF alignment and the knob optimisation have been simulated assuming no dynamic imperfections. This implies that the direct impact of the dynamic imperfections on the beam emittance is not visible in the simulations. Further studies of the impact of dynamic imperfections on the other steps of the alignment procedure will need to be carried out.

Table 2: Initial CLIC beam parameters used in the studies.

Parameter	symbol	unit	value
Bunch charge	n	particles	5.2×10^9
Bunch length	σ_z	μm	65
Vertical emittance	ϵ_y	nm	10
Horizontal emittance	ϵ_x	nm	660

The dispersion free alignment of each bin is performed with the following steps:

- Change gradient to first test beam and measure one pulse

- Change gradient to nominal and adjust bunch compressor for second test beam and measure one pulse

- Change to nominal and measure one pulse

- Perform calculations and apply correction to quadrupoles

- Modify target for BPMs to the expected new beam position

No feedback is used during the correction.

4 CLIC RESULTS

The CLIC simulations have been performed using a two-dimensional scan in w_1 and w_2. For the case with no dynamic effects, the smallest emittance growth is found for $w_1 = 10^4$ and $w_2 = 900$. This is the case directly after the dispersion free steering ($\Delta\epsilon_y \approx 90$ nm), after the RF alignment ($\Delta\epsilon_y \approx 1.1$ nm) and after the use of emittance tuning knobs ($\Delta\epsilon_y \approx 0.4$ nm, using three pairs of knobs). The RF alignment yields a very large improvement of the emittance. This is due to the fact that the initial offsets of the structures are highly correlated, which increases the impact of their wakefields. The offset of a girder with respect to the survey line leads to an offset of eight consecutive structures. The RF alignment reduces the effective offset of the structures by minimising the mean offset to the beam, which minimises the wakefield kick. One should note that it is not important whether the structure on the girder are scattered around the mean value, as the single bunch wakefield kicks will cancel [1]. The structure offsets are then completely determined by the error of the internal structure BPM, which is assumed to be 5 μm.

In CLIC, the short pulse duration does not allow one to use an intra-pulse feedback system, except at the interaction point. The relevant beam emittance is the multi-pulse emittance, the phase space taken by the beam during a sequence of pulses. Hence the beam orbit jitter is a part of this emittance and consequently it needs to be limited. Further studies have been performed assuming quadrupole jitter of 10 nm from pulse to pulse during the dispersion free steering. This would lead to an multi-pulse emittance growth of $\Delta\epsilon_y \approx 16$ nm, which is not acceptable. An acceptable quadrupole jitter level would be about 1 nm.

The optimum choice of weigths w_1 and w_2 has not been changed significantly compared to the static case. But the emittance growth increased noticeably; one finds $\Delta\epsilon_y \approx 16$ nm after dispersion free steering, $\Delta\epsilon_y \approx 1.6$ nm after RF alignment and $\Delta\epsilon_y \approx 0.7$ nm

---

[1]The scatter has an influence if the wakefields of the different structures are not identical; this needs to be considered for multi-bunch studies, where the differences can be larger than for the single bunch case.

after the use of tuning knobs. One can conclude that after RF alignment the indirect emittance growth contribution of the quadrupole jitter is significantly smaller than the direct one. In case of an acceptable quadrupole jitter of 1 nm, the additional emittance growth due to the dynamic imperfections there is limited to $\Delta\epsilon_y \approx 0.016$ nm after RF alignment before and to $\Delta\epsilon_y \approx 0.007$ nm after application of the knobs. This seems very acceptable and is well below the direct emittance growth.

Beam jitter at the linac entrance has been studied assuming an RMS amplitude of $2\,\mu$m, which leads to a direct multi-pulse emittance growth of 7.2 nm. The additional indirect emittance growth is 2.5 nm after DFS, hence smaller, and is further reduced by RF alignment and the tuning knobs.

5   SIMULATIONS FOR ILC

A very significant difference exists between ILC and CLIC regarding the beam jitter. In ILC the long pulse duration allows the use of intra-pulse orbit feedback. In principle, it is possible to correct beam jitter that is generated in or before the main linac when the beam enters the beam delivery system. Hence the beam jitter needs to remain limited in order to avoid emittance growth but the orbit motion as such does not cause a problem. For a quadrupole jitter of $\sigma_{jitter} = 500$ nm the emittance growth is $\delta\epsilon_y \approx 6$ nm.

The main linac of ILC differs from the one of CLIC in two significant points. First, it is not laser straight but follows an equipotential of gravity. Hence one does not minimise the dispersion along the linac but rather aims to achieve a target value that corresponds to the matched case. This leads to a modified version of the dispersion free steering, called dispersion steering in the following. Second, the accelerating structures of ILC (conventionally named cavities) cannot be moved. Hence, no RF alignment is possible. For these studies, we use the same simplified version of the main linac lattice as for the RDR studies in 2006.

Two further differences exist in the simulations. For ILC we used only a single test beam and assumed that the first three FODO cells of the linac were already aligned. For this test beam, the gradient in the cavities has been reduced to 90%, except for the first 40 cavities that have been set to zero acceleration. A more advanced scheme would be to use the bunch compressor to generate a different energy beam as described above for CLIC. The results yielded by this method are documented in [4]. The number of quadrupoles per correction bin has been set to 40 with an overlap of 20. In addition, we did not use emittance tuning knobs after dispersion free steering. As in the above simulations, the dispersion steering has been followed by one-to-one steering, assuming no dynamic imperfections during the process. The initial static imperfections are listed in table 3.

For ILC the alignment simulations have been performed for a perfectly stable machine and one with a very large quadrupole jitter of 500 nm. The results can be seen in Fig. 1. For the stable machine a very large contribution arises from the quadrupole roll; the optimum weight yields $\Delta\epsilon_y \approx 3$ nm. The coupling can easily be corrected after the main linac. The dynamic effects increase the final emittance by about $\Delta\epsilon_y \approx 2$ nm.

Table 3: Assumed initial static imperfections for ILC.

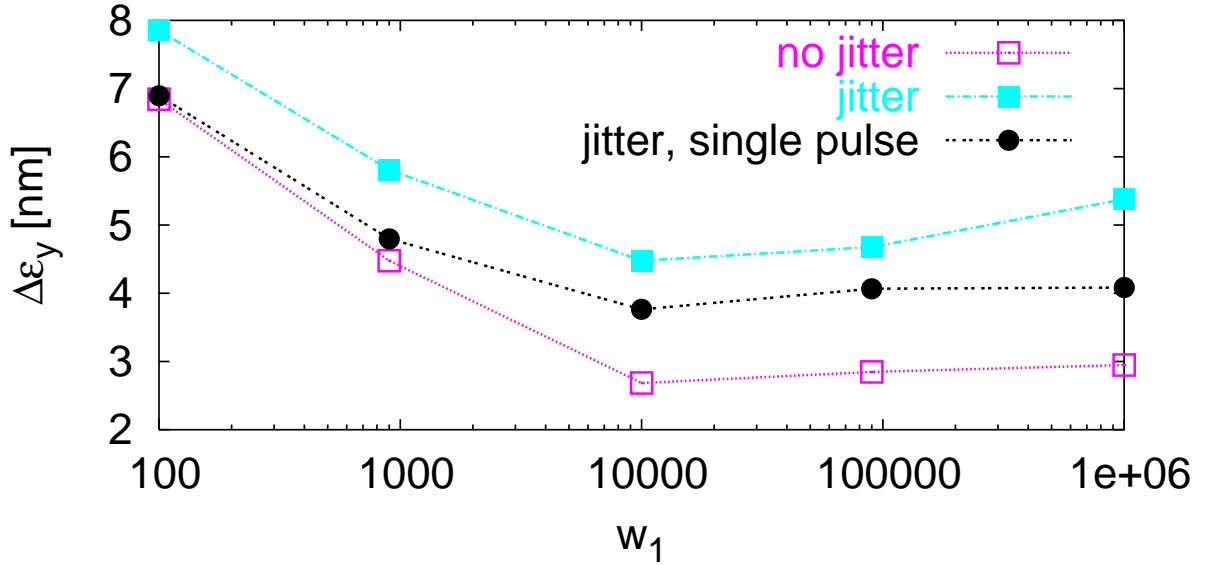| Imperfection	with respect to	size
Cavity offset	module axis	$300\,\mu$m
Cavity tilt	module axis	$300\,\mu$radian
Quadrupole offsets	module axis	$300\,\mu$m
Quadrupole roll	module axis	$300\,\mu$radian
BPM offsets	module axis	$300\,\mu$m
module offsets	survey line	$200\,\mu$m
module tilts	survey line	$20\,\mu$radian

Figure 1: Emittance growth in ILC after use of dispersion steering in presence of quadrupole jitter.

For a quadrupole jitter of $100\,$nm, the effect would be only $\Delta\epsilon_y \approx 0.1\,$nm, which seems perfectly acceptable.

For CLIC it has been proposed to use the different gradients during a single pulse [5]. This can yield a further improvement; the emittance growth due to the dynamic effects is approximately halved,see Fig. 1. Once can conclude that the indirect luminosity loss is expected to be smaller than the direct one.

We also investigated the impact of gradient jitter during the acceleration. We used a very large value of 5% RMS gradient jitter for each set of 24 cavities that are powered by the same klystron. The gradient error is applied for each beam independently. The results are shown in Fig 2. The additional emittance growth is about $\Delta\epsilon_y \approx 3\,$nm. For a realistic jitter amplitude of 1.5% [6], one finds about $\Delta\epsilon_y \approx 0.2\,$nm, which is acceptable but still a noticeable correction to the overall emittance growth.
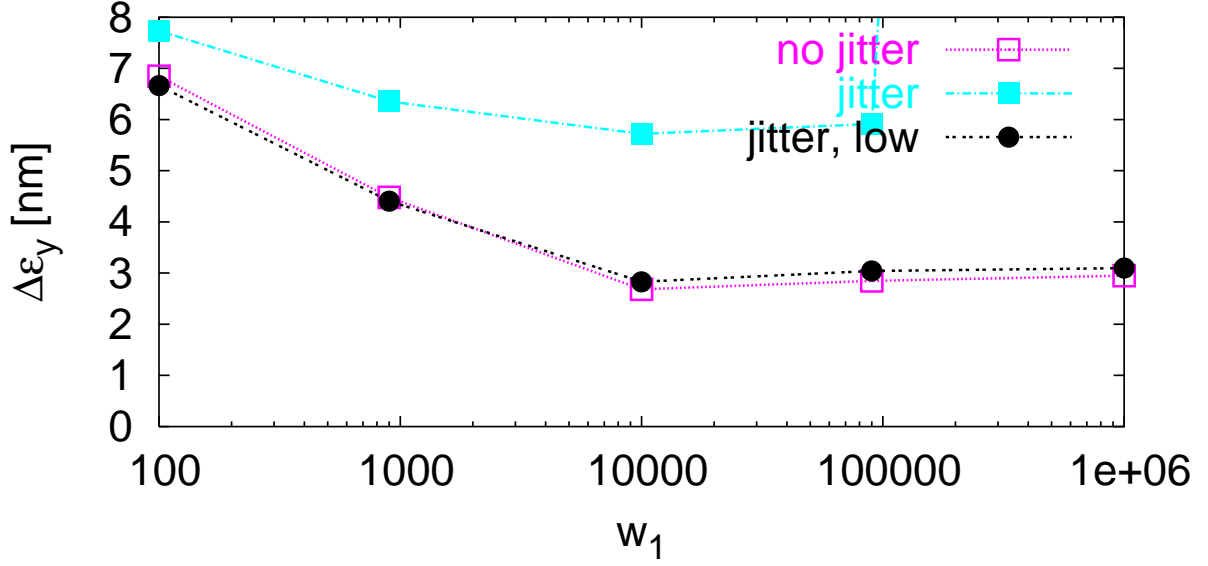
Figure 2: Emittance growth in ILC in presence of 5% RMS gradient jitter (1.5% for the "low" case), after use dispersion steering and subsequent one-to-one steering.

6 CONCLUSION

We have simulated the impact of dynamic errors during dispersion free steering. For CLIC the impact of quadrupole jitter and beam jitter at the entrance of the linac have been investigated. In both cases it has been found that the direct emittance growth due to the effects are larger than the secondary growth due to imperfect correction.

Also in ILC, quadrupole jitter does not seem to produce a very large additional emittance growth. The impact of pulse to pulse gradient jitter is not negligible but still acceptable at the predicted level.

For CLIC it has been suggested to use the different accelerating gradients during the same pulse [5]. In this paper we demonstrated the impact of such an approach for the example of ILC. The additional emittance growth due to the dynamic effects have indeed been halved.

The sensitivity to the dynamic imperfections will depend on the precise alignment scheme used. We expect it to become more severe when the energy difference between the beams is reduced during the dispersion free steering. Further study is required on this topic.

References

[1] https://savannah.cern.ch/projects/placet

[2] N. Leros and D. Schulte. CERN-CLIC-NOTE-525 and EPAC 2002.

[3] P. Eliasson and D. Schulte. CERN-CLIC-NOTE-629 and PAC 2005.

[4] A. Latina, D. Schulte. This conference.

[5] D. Schulte. CLIC-Note-545 (2003).

[6] N. Walker. Private communication.