DIFFERENT OPTIONS FOR DISPERSION FREE STEERING IN THE CLIC MAIN LINAC

D. Schulte, CERN, Switzerland

Abstract

Sophisticated beam-based alignment is essential in future linear colliders to preserve the beam emittance during the transport through the main linac. One such method is dispersion free steering. In this paper different options to implement this method are discussed, based on the use of different accelerating gradients, RF phases and bunch particle types during a beam pulse.

INTRODUCTION

The elements of the CLIC main linac can only be put in place with limited accuracy. Small misalignments of the quadrupoles and accelerating structures can lead to significant emittance growth when the beam is transported through the linac. The required limit for this growth is $\Delta\epsilon_y \leq 5\,\mathrm{nm}$, which cannot be reached with the precision of the initial survey. Beam based alignment is thus required. This is based on the priciple that if an imperfection affects the beam in a significant way, one can use the signal from this beam to correct the overall effect of this error.

In the case of CLIC, it is forseen to proceed in four stages. In the first, the beam is steered through the centres of all the beam line beam position monitors (BPMs) to make it pass the main linac. In the second stage, the quadrupoles are aligned, either using ballistic alignment [1] or as described here dispersion free steering [2]. In the third stage, the RF structures are aligned to the beam using the beam position monitor that is built into each of them. In the fourth stage, the emittance is further reduced by emittance tuning bumps. A description of the lattice can be found in reference [3].

DISPERSION FREE STEERING

Misalignments of the quadrupoles in the main linac introduce dispersion into the beam which in turn leads to a growth of the effective emittance. This effect can be suppressed by correcting the quadrupole positions using dispersion free steering. The main linac is split into groups of BPMs and correctors, called bins, that are corrected one after the other. In each bin the beam is not only steered into the centres of the BPMs but also the differences of the trajectories of beams at different energies are minimised. In a bin with n BPMs and using the nominal beam and m other beams with different energies the target function is

$$\chi^2 = \sum_{i=1}^{n} w_{0,i} y_{0,i}^2 + \sum_{j=1}^{m} \sum_{i=1}^{n} w_{j,i} (y_{j,i} - y_{0,i})^2 \quad (1)$$

Here, $y_{0,i}$ are the offsets of the nominal beam in the BPMs and $y_{j,i}$ are those of test beam number j. The weigths w depend on the precision and resolution of the BPMs σ_{BPM} and σ_{res}, respectively, but also on the leverage provided by the differences of the beams. Often $w_{0,i} = 1/\sigma_{BPM}^2$ and $w_{j,i} = 1/(2\sigma_{res}^2)$ are used. It should be noted that only ratios of the different weights are important; in the further discussion $w_{0,i} = 1$ and $w_{j,i} = w_1$ is used. It is also possible to add another term which limits the movement of the quadrupoles or the corrector strengths.

Different approaches exist to produce the beam trajectories at different energies. First, one can modify the quadrupole strengths from pulse to pulse to simulate a change of the beam energy. But in this case, small movements of the quadrupole centres resulting from the strength variation can lead to significant emittance growth. Second, one can switch structures on and off from pulse to pulse or modify the gradient. It seems advantageous to always use the same configuration for each test beam. In this case remanent dispersion left after the correction of one bin will be corrected in the next one. Third, one can attempt to modulate the bunch energy within one beam pulse. This can be done by varying the gradient or RF phase along the pulse. It seems possible to sample the beam position at least twice along the pulse, which allows the trajectory for the nominal beam and the difference to be determined for a test beam at the same time. In the new CLIC scheme, the beam before the linac consists of two half trains with bunches spaced at twice the spacing they will have in the linac. These trains are then merged. It seems therefore possible to arrange to have different bunch properties in these two half trains. This could even go as far as to combine electrons and positrons in a single pulse. With specialised BPMs one can then determine the mean and the difference trajectory of the half trains.

Using different energy bunches within the same beam

Table 1: Assumed alignment errors for the initial survey for the relevant components.

	Symbol	Value
BPM position error	σ_{BPM}	$10\,\mu$m
BPM resolution	σ_{res}	$0.1\,\mu$m
Cavity position error	σ_{cav}	$10\,\mu$m
Cavity angle error	$\sigma\prime_{cav}$	$10\,\mu$radian
Cavity re-alignment error	$\sigma_{realign}$	$10\,\mu$m

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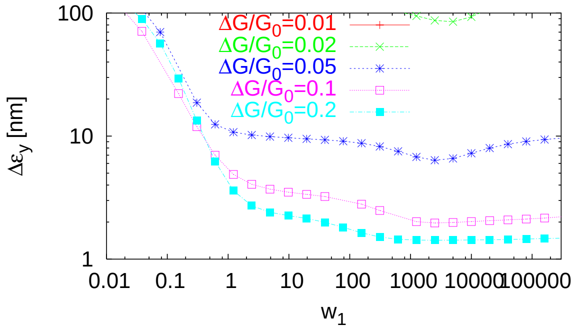

Figure 1: The final beam emittance as a function of the weight w_1 for the trajectory differences for different gradient variations.

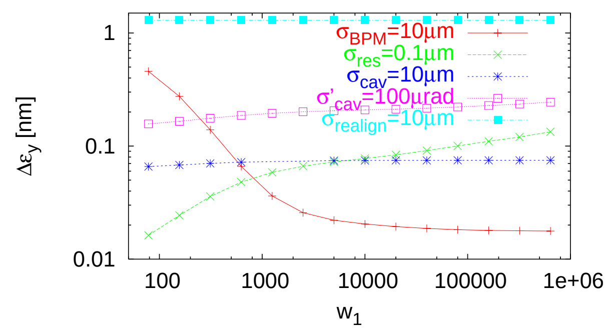

Figure 2: The final beam emittance growth as a function of the weight w_1 for the different error sources seperately.

pulse has the advantage of requiring less time for the correction. In addition the machine cannot move between the measurements, so the influence of dynamic imperfections is reduced.

An energy spread can be generated in the linac by accelerating different bunches either at different RF amplitudes or phases. The RF amplitude can be varied along the bunch train by modifying the input power of the structure. In CLIC, this can easiliy be achieved by manipulations of the drive beam using delayed switching [4]. In other linear colliders the klystron power can be modified during the pulse. The phase of the RF can be less easily varied along the train in CLIC, except if one at the same time also modifies the RF amplitude. However, the main beam bunches can easily be offset in the longitudinal plane with the help of the bunch compressor by introducing an energy deviation of some bunches before the compressor. The latter will transform this energy deviation into a longitudinal shift. This method also conveniently generates an incoming energy spread which helps to correct the dispersion in the beginning of the linac. If the energy spread exceeds the bandwidth of the bunch compressor or if a larger energy spread is required, one can even consider using two seperated bunch compressors one for each half-train. They would then be optimised to compress the bunches to the nominal length at the given, different input energies.

SIMULATION RESULTS

Different methods of dispersion free steering have been simulated using PLACET [6]. All the above mentioned correction steps have been simulated. In all cases the nominal and one additional beam are used for the correction.

Gradient Variation

Since the energy difference is generated during the passage through the main linac, the alignment of the first part needs to be treated seperately. Here, we will assume that the beams enter already with an energy difference that is equal to the gradient difference that they experience later.

The results of the simulations are shown in Fig. 1, for different gradient variations and the assumed misalignments of table 1. For small weights on the trajectory differences the results of the simple one-to-one steering are recovered. For larger weights the emittance growth depends on the gradient difference. If it is a percent, the emittance is actually increased by the minimisation of the trajectory differences. In the case of a gradient difference of 5% or above the emittance is reduced by increasing w_1 until the procedure finally becomes unstable for too large w_1.

In the following, the emittance growth for a gradient difference of 20% will be discussed. Figure 2 shows the dependence of the growth on the weight w_1 for different error sources. The effect of the initial misalignment of the structures is very small and does not depend strongly on the chosen weight. The effect of the re-alignment error of the structures dominates the overall emittance growth and is also almost independent of w_1. The contributions of the initial BPM misalignment are decreasing with w_1, the growth due to the BPM resolution is increasing with w_1. For a good compromise $w_1 = 10^4$ they both do not contribute significantly. It should be noted that all the emittance growths scale quadratically with the size of the initial errors.

The earth's magnetic field and stray fields from machine equipment can affect the correction performance. Simulations that include a homogeneous field of $1\,\mathrm{Gauss}$ (which is somewhat larger than the earth's field) show only a moderate emittance increase of $0.05\,\mathrm{nm}$. However, larger fields could become a problem.

Dispersion in the incoming beam may reduce the efficiency of dispersion free steering. The dispersion at the entrance of the linac can be measured with an accuracy of about $\sqrt{2}0.1\,\mu\mathrm{m}/0.2$. Simulations show that even a dispersion of $10\,\mu\mathrm{m}$ would be acceptable and lead to an emittance growth of about $0.02\,\mathrm{nm}$.

Phase Shift

Before the main linac the CLIC beam is longitudinally compressed by a bunch compressor, which for convenience is modelled by the simple linear expression $R_{56} = \pm 1\,\mathrm{cm}$.

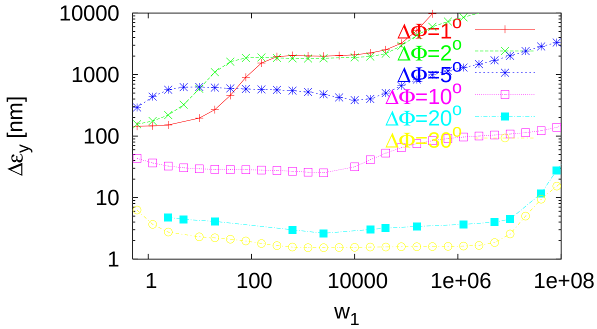

Figure 3: The emittance growth for different phase shifts.

The sign of R_{56} depends on the energy correlation in the incoming beam. In order to achieve a phase shift of 1° at $30\,\mathrm{GHz}$, an energy difference of 0.278% is needed.

The simulations show that good correction performance is only reached for a phase difference of at least 30°. The required energy difference in the bunch compressor of about 8.3% may exceed the range over which the compressor is linear (the RMS beam energy spread is about 2%).

Using Electrons and Positrons

The largest energy spread can be achieved by using electrons and positrons in the same linac. It is again possible to switch the particle type between different pulses or even to use electron and positron bunches within the same beam pulse. The main linac lattice is a simple FODO system and transports both charge types if the initial beta-functions are correctly matched.

Different modes of correction are possible. In the simplest, one would use some positron pulses in the electron linac simply for the alignment purpose. In this case only the electrons would be used for luminosity operation. In a more ambitious scheme, one would interleave the electron and positron bunches. The different types of bunches can be merged using a simple dipole before the linac and be split again with another dipole at the end. In a machine with two interaction points both could then run in parallel, one using electrons from the first linac and positrons from the second, the other using positrons from the first linac and electrons from the second.

In this scheme, the number of particles per bunch would remain unchanged compared to the cases with electrons in one linac only and positrons in the other. Also the distance between the bunches in a beam pulse will not be modified, except for a shift of half an RF wavelength for the bunches of opposite sign of charge. Hence the beam current (i.e. number of particles per second) remains unchanged. The theoretical integrated luminosity is the same in this scheme as in the one using only electrons in one linac and positrons in the other. However, the background per unit time (and per event) will be reduced by a factor two in the detectors. One may also gain from the fact that both beam delivery systems can be tuned in parallel. Additional advantages are the suppression of the fast beam-ion instability. While an electron beam can trap positively charged ions (e.g. those produced by ionisation) the mixed beam would be electrically neutral strongly reducing the ion density build-up close to the beam.

If the beam with the other particle type is only used for alignment purposes but the emittance tuning bumps are optimised for the nominal beam only, the final emittance growth is about $1\,\mathrm{nm}$ for the misalignments from table 1.

The main drawback of the mixed operation is that the optimisation of the emittance tuning bumps can become difficult. The simple correction of one bump after the other did not work sufficiently well for this configuration. A full optimisation of all the 20 degrees of freedom of the ten bumps allowed the emittance growth in both beams to be minimised to about $2\,\mathrm{nm}$. Further study is needed to provide a simple bump optimisation method.

CONCLUSION

Ballistic alignment is the reference correction method in the main linac of CLIC to align quadrupoles and BPMs. This method requires that quadrupoles are switched on and off and that the beam is transported over some distance without focusing. In principle, dispersion free steering is expected to give a similar performance. Three different implementations of such a method have been investigated. They yield results comparable to the ballistic alignment. The drawback of the variation of the gradient or RF phase is that the pulsed used to correct the machine can not be used for luminosity production. Using electrons and positrons in the same linac provides the largest lever arm for the correction technique. In principle, it can also allow the nominal pulse to be used for luminosity production and correction. This would certainly simplify the machine operation. It remains to be investigated if an efficient procedure can be found to optimise the emittance tuning bumps for both beams simultaneously.

ACKNOWLEDGMENT

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REFERENCES

[1] T. Raubenheimer and D. Schulte, PAC99 (1999)

[2] T. Raubenheimer and R. Ruth, NIM **A302**:191 (1991)

[3] D. Schulte, EPAC98 (1998)

[4] D. Schulte, CLIC-Note 434 (2000)

[5] D. Schulte, CLIC-Note 545 (2002)

[6] D. Schulte, CERN/PS 2000-028 (AE) (2000)