THE BALLISTIC ALIGNMENT METHOD*

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Abstract

In order to preserve the very small beam emittance in the main linacs of future high-energy linear colliders a new alignment method, the so-called ballistic alignment method, has been developed. A description of the method is given and it is applied to the Compact Linear Collider (CLIC) [1]. In this scheme the quadrupoles are divided into bins which are corrected one after the other. In the first step, the quadrupoles in a bin are switched off to use a ballistic beam to align the beam position monitors (BPMs). Next, a simple one-to-one correction is used to align the quadrupoles. The dependence of the emittance growth on different error sources is investigated.

1 INTRODUCTION

In the main linac of CLIC, the beams are accelerated in $30\,\mathrm{GHz}$ structures. The high rf frequency allows for high acceleration gradients and therefore a high centre-of-mass energy, but also leads to strong transverse wakefield effects.

Descriptions of the CLIC main linac lattices are given in [2]. Here, the focus is on the machine with $E_{cm} = 1\,\mathrm{TeV}$, for which the lattice consists of 8 sectors of FODO cells of constant length and phase advance; the most important parameters are listed in Table 1. The ballistic alignment is followed by tuning the emittance with bumps to achieve an emittance growth of $\Delta\epsilon_y/\epsilon_{y,0} \leq 40\,\%$ however using the technique alone would not compromise the luminosity much, in contrast to the situation at higher energies.

In the CLIC lattice, a BPM is placed in front of each quadrupole; this is a significant difference to the NLC where the BPMs are positioned in the centres of the quadrupoles which allows very good relative alignment of the BPM and quadrupole using a shunt method [3]. On the other hand, placing the BPMs outside the magnets allows the CLIC design the use of very precise rf BPMs which have large outer diameters [4]. The alignment technique has been tailored to this difference; other possibilities are also being investigated [5].

2 DESCRIPTION OF THE METHOD

The linac is divided into bins which are corrected one after the other. Each bin starts with a quadrupole and ends with a BPM. The next bin starts with the quadrupole immediately following this BPM. The quadrupoles in the bin are switched off except for the first one. Its field strength is halved in order to minimise the beam size at the end of the bin. With correction coil of the first quadrupole, the beam is centred in the BPM at the end of the bin. Then, the positions of the other BPMs are redefined such that they are centred on the beam. This can be done either by moving them or by adding an offset to the measured position values. The quadrupoles are switched on again and their positions are adjusted so that again all BPMs show no offset.

In practice, the quadrupoles can not be switched off in a single step, since the beam can reach rather large offsets and might hit the beam pipe. By reducing the magnet strengths gradually and adjusting the correction coil in parallel this can be avoided. Furthermore, because the beam jitters transversely, it is not possible to steer it exactly to the centre of the last BPM. It is therefore necessary to use the position information once it is close to the centre and correct the measured values assuming a linear trajectory. The positions of the BPMs are moved using this corrected signal. When the quadrupoles are switched on again one has to use the same precautions as when switching them off.

Table 1: Parameters of the CLIC main linac and beam at $E_{cm} = 1\,\mathrm{TeV}$. The ϵ_x has not yet been fixed, its final value is taken overestimating the effects of coupling slightly.

Part. per bunch	N	$4 \cdot 10^9$
Initial horizontal emittance	ϵ_x	$1.48\,\mu\mathrm{m}$
Initial vertical emittance	ϵ_y	$0.05\,\mu\mathrm{m}$
Bunch length	σ_z	$50\,\mu\mathrm{m}$
Linac active length		$5500\,\mathrm{m}$
Fill factor		$74\,\%$
Gradient	G	$100\,\mathrm{MV/m}$

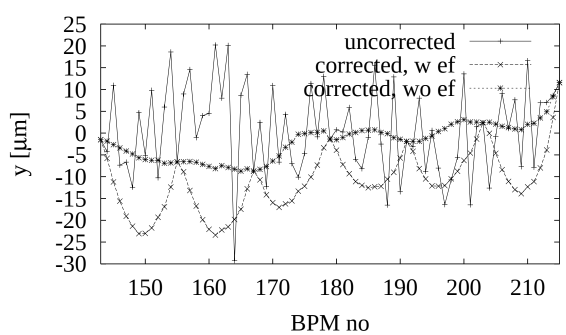

Figure 1: BPM positions before and after the ballistic correction step. The earth field was taken to be completely uncompensated (w ef) and fully compensated (wo ef).

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A simple one-to-one correction is performed correcting the quadrupoles to again centre the beam in all BPMs.

It is also possible to achieve a ballistic beam by moving the centres of the quadrupoles in the bin onto the beam trajectory. This can be achieved by slightly varying their strength and finding a position where they do not change the trajectory. This implementation also works in simulations giving very promising results. It will not be considered in the following, since an error analysis remains to be done.

3 ERROR SOURCES

Even if the quadrupoles are switched off, the beam does not follow a straight trajectory. The transverse wakefields of the structures deflect the beam. If the bin is relatively long this deviation can become large. In order to prevent this from leading to an instability in the correction scheme, one has to either calculate the trajectory including the effect of the structures or to iterate the ballistic step.

The magnetic field of the earth also bends the trajectory. This effect can be reduced by shielding the beam line or by adding small dipoles to compensate the measured earth field. Even if this is not done, it is possible to take the effect into account in the correction algorithm as long as the field is measured. Other field sources may exist, for example, the remanent field in the quadrupoles when they are switched off. They can disturb the trajectory if the quadrupole centres are far from the beam trajectory. The alignment procedure can be repeated to yield convergence. While, in the first step, the quadrupoles can have large offsets with respect to the beams, these will be reduced after the first iteration due to the "few-to-few" correction with the quadrupoles switched on. This reduces the effect of the remanent fields on the beam trajectory, resulting in a beam that is closer to being really ballistic. Finally, the magnetic centres of the quadrupoles may shift as the magnets are switched on or off. In this case, some residual effect can be found.

4 ASSUMED TOLERANCES

All elements are assumed to be initially scattered around a straight line that defines the ideal beam line. These position errors are assumed to follow a normal distribution with a sigma of $\sigma_{BPM} = \sigma_{struct} = 10\,\mu\mathrm{m}$ for the BPMs and structures and $\sigma_{quad} = 50\,\mu\mathrm{m}$ if not otherwise mentioned. The resolution of the BPMs is $\sigma_{res} = 0.1\,\mu\mathrm{m}$, the vertical and horizontal jitter of the beam at the linac entry are $\sigma_{jitt,y} = 0.1\sigma_y$ and $\sigma_{jitt,x} = 0.1\sigma_x$, respectively. The beam also has a constant offset of $\sigma_{off,x} = \sigma_{off,y} = 10\,\mu\mathrm{m}$ in the two planes. The remanent field of the quadrupoles is assumed to have a uniform distribution in the range $0 - 2\,\%$ of the full gradient. The centres are shifted between the two states by a Gaussian with $\sigma_{centre} = 10\,\mu\mathrm{m}$, these shifts are constant from one iteration to the next.

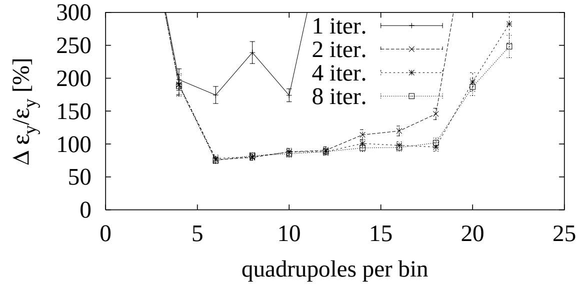

Figure 2: The normalised emittance growth for different number of quadrupoles per correction bin.

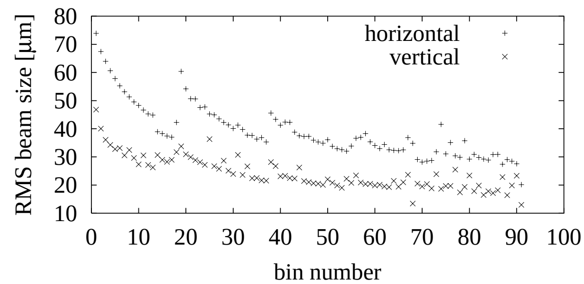

Figure 3: The maximum beam size along the linac during the ballistic correction step.

Only single bunch effects will be considered in the following. All simulations were performed using the code PLACET [6] for 100 different machines. The random number generator was set to the same initial state for each simulation.

5 CONVERGENCE

The length of the correction bin is important: if it is too short, the contribution from the kinks between bins becomes important; if it is too long, the transverse size of the ballistic beam becomes large and the beam starts to deviate significantly from a straight line due the different imperfections. In Fig. 2, the normalised emittance growth is shown for different numbers of quadrupoles per bin. The response coefficients are calculated without taking the wakefields into account. With a bin length of 6 quadrupoles, the method leads to good results, and, with two steps, the method converges. For long sectors, it starts to become bad again. This could be avoided by doing the ballistic step in several iterations with a small gain.

In the following, a bin length of 12 quadrupoles is taken. For this case, the horizontal and vertical beam sizes during the ballistic correction step are shown in Fig. 3.

The effect of the earth's magnetic field on the correction is displayed in Fig. 4. It is significant but not enormous for the assumed values of $40\,\mu\mathrm{T}$ vertically and $20\,\mu\mathrm{T}$ horizontally. The latter value certainly depends on the direction of the linac. Already a small suppression of the field almost completely eliminates the effect. In the following, the

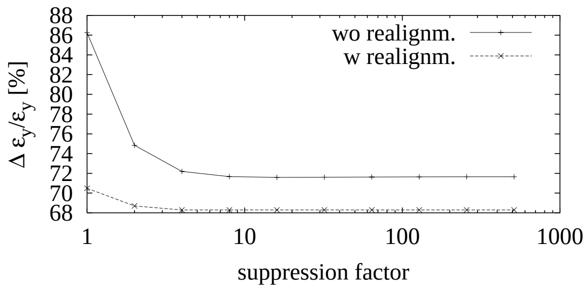

Figure 4: The dependence of the vertical emittance growth on the suppression of the magnetic field of the earth.

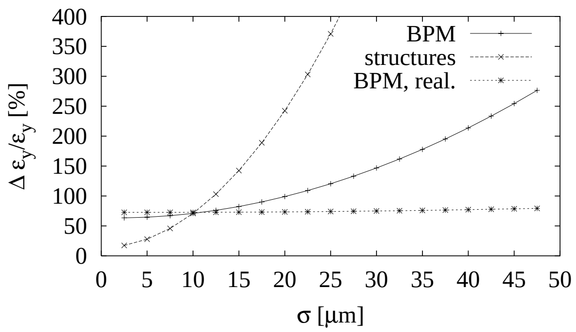

Figure 5: The dependence of the emittance growth on the size of σ_{struct} and σ_{BPM}.

earth's magnetic field will be disregarded.

6 INITIAL MISALIGNMENT

As can be seen in Fig. 5, the emittance growth depends strongly on the misalignment of the structures. The contribution from the initial misalignment of the BPMs is significantly smaller. It is possible to align the acceleration structures with respect to the beam after the ballistic correction using either the dipole signal from the structures or BPMs on the structure girders. Here, it is assumed that each structure can be aligned separately with a precision of $\sigma_{struct} = 10\,\mu\mathrm{m}$ which corresponds to the initial misalignment. The resulting emittance growth for different BPM offsets can also be found in Fig. 5. The emittance does not increase significantly with the initial BPM misalignments. Aligning the structures with the beam thus significantly relaxes the initial alignment tolerances not only for the structures themselves but also for the BPMs. Also, the effect of the earth's magnetic field is reduced, see Fig 4.

The emittance increase does not depend very much on the vertical beam jitter during correction. A jitter of $\Delta_y = 0.5\sigma_y$ leads to an additional emittance increase of only $2\,\%$. But a beam with large jitter requires a significantly larger aperture to avoid losses and not to be sensitive to quadrupolar wakefields. This is more likely to limit the allowed jitter, especially since the resolution can in principle be refined by averaging over many pulses.

The resolution assumed for the BPMs is very good. It

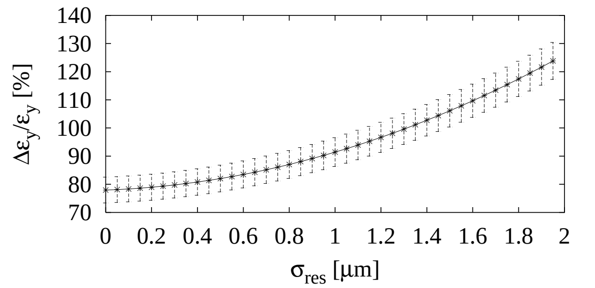

Figure 6: The emittance growth in the main linac versus the resolution of the BPMs.

affects the precision of their alignement to the beam in the first step of the correction and the precision of the one-to-one correction performed in the second step. It is assumed that the signal used to align the BPMs and that used later to align the beam have the same error size. Figure 6 shows the dependence of emittance growth on the resolution.

7 CONCLUSION

In this paper, the properties of the ballistic alignment method have been presented in some detail. This simple method is able to achieve a small emittance growth in a linac where the BPMs are not inside the quadrupoles. The effect of earth's magnetic field, remanent fields in the quadrupoles, and beam jitter can be kept under control. It has been shown that aligning the structures with the help of the beam can significantly relax the alignment tolerances on all elements.

8 REFERENCES

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