

EFFECTS OF ACCELERATING STRUCTURES ON ON-LINE DFS IN THE MAIN LINAC OF CLIC

J. Pfingstner^{1,2,*}, E. Adli¹, D. Schulte²

¹University of Oslo, Oslo, Norway, ²CERN, Geneva, Switzerland

Abstract

Long-term ground motion will create significant dispersion in the time-scale of hours in the main linac of CLIC. To preserve the emittance to an acceptable level, a dispersion correction with on-line dispersion-free steering (DFS) is inevitable. For this on-line technique, the dispersion has to be measured using beam energy variations of only about one per mil in order to not disturb the operation of the accelerator. For such small energy variations, the interaction of the particle beam and the accelerating structures creates large enough additional signals components in the measured dispersion to cause the dispersion correction to not work properly anymore. In this paper, the additional signals are described and their effect on the DFS algorithm is analysed. Finally, methods for the mitigation of the deteriorating signal components are presented and studied via simulations.

INTRODUCTION TO ON-LINE DFS

Linear colliders are very sensitive to element misalignments, due to their ultra-small beam emittances. These misalignments are not only of static nature, but change over time as a result of the impact of ground motion. For time scales below a few minutes, the ground motion induced luminosity loss can be mitigated with orbit feedback systems and mechanical magnet stabilisation systems [1]. Over longer time periods, however, it is not sufficient to correct only the beam orbit. Also the steadily increasing dispersion has to be addressed. For the CLIC main linac, e.g., this dispersion causes an emittance growth in the more critical vertical direction of $\Delta\epsilon_y = 0.75$ nm per hour. This simple empirical law has been found via simulation studies. It assumes ground motion according to the ATL law [2] with a constant A of 10^{-5} $\mu\text{m/s/m}$.

To avoid this emittance growth, a scheme has been proposed in which the dispersion is corrected during the accelerator operation in a transparent way (similar to an orbit feedback). This scheme, named online dispersion free steering (DFS), is based on the well-known DFS algorithm [3]. The DFS algorithm consists of two steps. Firstly, the dispersion $\eta(s)$, where s is the longitudinal position in the beam line, is determined via the beam orbit change $\Delta x(s)$ of two measurements $x_{E_0}(s)$ and $x_{(1+\delta)E_0}(s)$ due to a change in beam energy of δE_0 , where E_0 is the nominal beam energy,

$$\eta(s) = \frac{\Delta x(s)}{\delta} = \frac{x_{(1+\delta)E_0}(s) - x_{E_0}(s)}{\delta}. \quad (1)$$

The dispersion $\eta(s)$ is then used to compute and apply quadrupole magnet misalignments $\theta(s)$ that cancel $\eta(s)$ in

* juergen.pfingstner@cern.ch

a least square sense. Additional constraints can be imposed in the computation of $\theta(s)$, to limit the amplitude of the correction and to not create too large beam orbit excursions [4]. In practice DFS is not applied in one step to the whole linac, but rather in a sequential fashion to overlapping subsection called bins (36 in the case of the CLIC main linac).

The basic form of DFS is intended to be used in the commissioning phase and during performance tuning campaigns. In these cases, large relative energy variations δ (5% to 10%) can be used, since the beams are not used for physics data taking. If DFS should be used on-line, however, only small δ in the order of 1 per mil are acceptable (energy acceptance of the beam delivery system). This results in small orbit variations $\Delta x(s)$, which reduces the measurement quality dramatically, due to the higher relative measurement noise of the beam position monitors (BPM). To recover the necessary measurement quality, an averaging method has been proposed and successfully tested in simulations [5].

Robustness studies have revealed, however, that the on-line DFS algorithm is sensitive to certain effects due to accelerating structures [6], namely wake fields and structure tilts. In this paper, the influence of these effects on the on-line DFS algorithm is analysed and modifications to the algorithm are proposed that recover the performance of the dispersion correction. These modifications are tested in simulations and the final emittance growths are reported.

EFFECTS DUE TO ACCELERATING CAVITIES

The sources of dispersion in a particle beam can be traced back to different types of dipole kicks. In linear accelerators without bending magnets, the main sources of dipole kicks are misaligned quadrupole magnets (feed-down effect). The purpose of the DFS algorithm is to cancel this dispersion, by adding new dispersion created by intentionally offsetting quadrupole magnets. However, there are also other sources of dipole kicks in linear accelerators that create dispersion. These dipole kicks originate from accelerating structures, either because of imperfect alignment, e.g. tilts, or due to transverse wake fields. In the following, it will be shown that the dispersion due to dipole kicks from accelerating structures create undesirable signals in the dispersion measurement Eq. (1) that deteriorate the performance of the on-line DFS correction. Also strategies to suppress these unwanted signals are presented.

Deteriorating effects of transverse wake fields: An offset of the beam in an acceleration cavity creates transverse wake fields. These transverse wake fields are zero

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2015). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

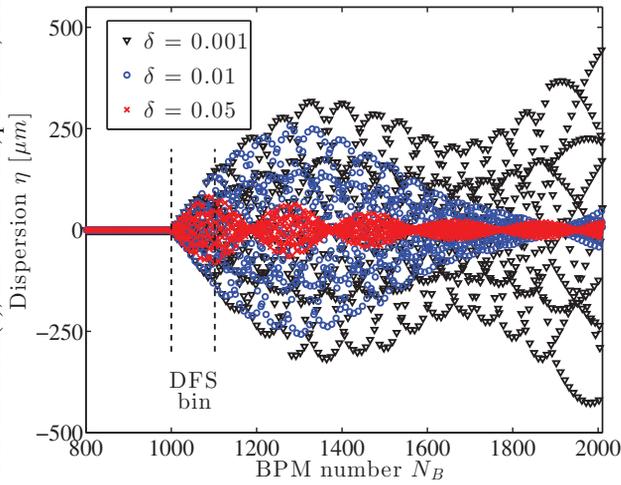


Figure 1: Simulated dispersion measurement due to a single dipole kick at the location of quadrupole number 1000 in the CLIC main linac. Different relative energy variations δ have been used, while no measurement noise has been included.

at the head of the beam, but grow towards the tail. Consequently, dispersion of different strength is created along the beam, rising from the head to the tail. This is fundamentally different to dipole kicks from quadrupole magnets, where the whole beam is exposed to the same dipole field. As a result, dispersion from transverse wake fields cannot be corrected by DFS, because it is based on quadrupole magnet corrections. The DFS correction will only add dispersion to the head and the tail so that the average dispersion along the beam is minimised. But there is still dispersion of different sign present in the head and tail and the overall emittance growth cannot be reduced. Also, this cancellation is only valid over the current correction bin, but does not stop the wake field dispersion to produce large, deteriorating signal artefacts in the dispersion measurement of the next bin. Moreover, the created cancellation is not robust and subsequent RF alignments (mechanical structures to the beam alignment) or ground motion will cause large $\Delta\epsilon_y$.

To understand why the wake field effects are worse for DFS applied with smaller energy variations δ (per mil level) than with larger δ (per cent level), the dispersion due to a simple dipole kick for different δ is plotted in Fig. 1. Within the DFS bin, the dispersion is in a linear regime and is only weakly dependent on δ . This is the case for the dispersion due to quadrupole magnet misalignments, since the upstream dispersion has been already corrected. However, wake fields from upstream of the current bin cannot be corrected and will create signals in the dispersion measurement. This wake field dispersion signal is much stronger for smaller δ , which causes the high wake field sensitivity of DFS for small δ .

Remedy for transverse wake field effects: Since the dispersion due to wake fields is created upstream of the DFS bin to be corrected, it is advantageous to introduce the relative beam energy variation δ for the dispersion measurement

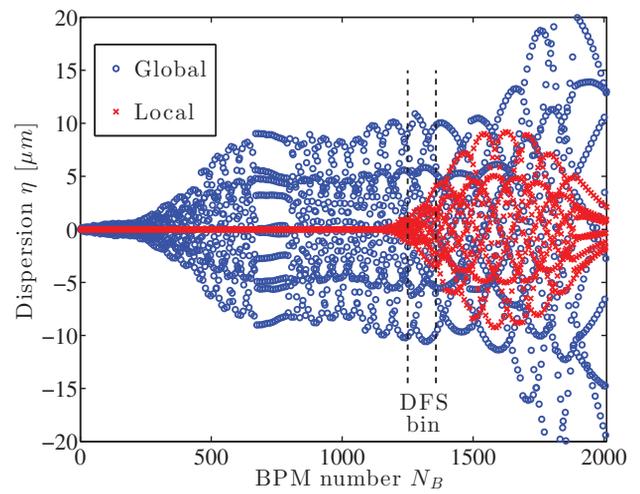


Figure 2: Simulated dispersion measurement with misaligned accelerating structures.

only shortly before the bin to be corrected. In this case, much fewer cavities are passed with different beam energies and therefore less dispersion is created. Additionally, the created wake field dispersion stays mainly in a linear regime and does not grow to large values.

For CLIC, such a local energy change can be introduced by slightly changing the charge of the drive beam bunches that are sent to the decelerator before the DFS bin to be corrected. A global scheme, as initially envisioned, would change the beam charge of all drive beam bunch instead. The dispersion signals from wake fields without applying DFS correction for the global and the local scheme with δ of 0.001 are compared in Fig. 2. The wake fields have been created by applying RF alignment with a wake field monitor resolution of $3.5 \mu\text{m}$ (CLIC specification). The parasitic dispersion signal in the correction bin is strongly suppressed for the local scheme.

Deteriorating effects of structure tilts: In the case of tilted accelerating structures, not only longitudinal electric fields \vec{E}_{acc} , but also a transversal field \vec{E}_{kick} are applied to the beam. As illustrated in Fig. 3, the according transverse kick is

$$\Delta x'_{tilt} = \frac{eL_{cav}\vec{E}_{cav}\sin(\varphi)}{E_b} \approx \frac{eL_{cav}\vec{E}_{cav}}{E_p}\varphi, \quad (2)$$

where e is the electron charge, L_{cav} is the cavity length, E_p the particle energy, and the cavity tilt $\varphi \ll 1$. These tilt kicks $\Delta x'_{tilt}$ create a change of the beam trajectory, which can be very well corrected by a simple 1-to-1 steering. The dispersion created by the tilt kicks is small and can be neglected with respect to the corresponding emittance growth.

However, there is another effect that causes problems for the DFS algorithm. During the dispersion measurement, it is necessary to change the energy of the particle beam. This is achieved by changing the acceleration gradients \vec{E}_{cav} . Due

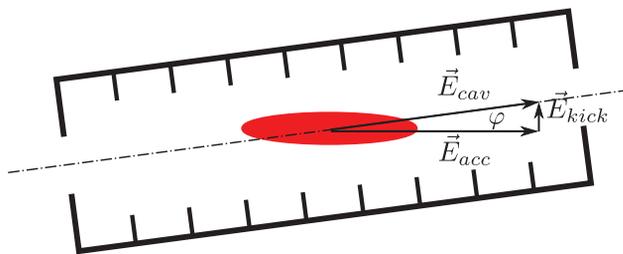


Figure 3: Coupling of the acceleration field \vec{E}_{cav} into the transversal direction in the case of a tilted accelerating cavity.

to structure tilts, this change of \vec{E}_{fav} also causes a change of the transverse kick of the cavity according to Eq. (2).

As a result, the dispersion measurement in Eq. (1) does not only contain the real dispersion, but also the orbit change due to the gradient changes in the tilted cavities. It can be shown that the influence of this orbit change is significantly stronger for the local energy change scheme compared to the global scheme. This is due the fact that in the local scheme the energy change has to be created in a relatively short part of the linac. Therefore, relative to δ stronger gradient changes are applied.

Remedy for structure tilt effects: As a countermeasure against the effect of structure tilts, the accelerating gradients are not changed in the corrected DFS bin anymore. However, in the area where the energy change is created, such a gradient change is unavoidable. The corresponding influence on the measured dispersion is visualised in Fig. 4. The energy change δ has been either created artificially in a step-like manner before the DFS bin (black triangle), or via the local scheme in the area labelled as *energy change* (blue circles). The step-like change delivers the real dispersion due to the cavity tilts that should be corrected. As can be observed, this dispersion is very small. The local scheme (realistic scenario), however, creates large signal artefacts in the dispersion measurement due to the orbit change. This orbit change is created in the area where δ is build up. Note that in this area, the dispersion has already been corrected, and the measured signal can therefore be only attributed to the orbit change. Hence, this part of the measurement can be used to prediction of the orbit change signal in the DFS bin. By subtracting the estimated signal from the measurement, the influence of the structure tilts can be efficiently removed in the corrected dispersion η_{corr} (red crosses).

SIMULATION RESULTS

While the efficiency of the ground motion correction and the influence of several other imperfections have been already addressed in earlier publications [5, 6], only the effects of wake fields and structure tilts are numerically studied in this paper. For each of the following results 30 random seeds have been averaged and an energy variation δ of 0.001 has been used. For the first simulation, only wake field imperfections are created in accordance to the CLIC specification of

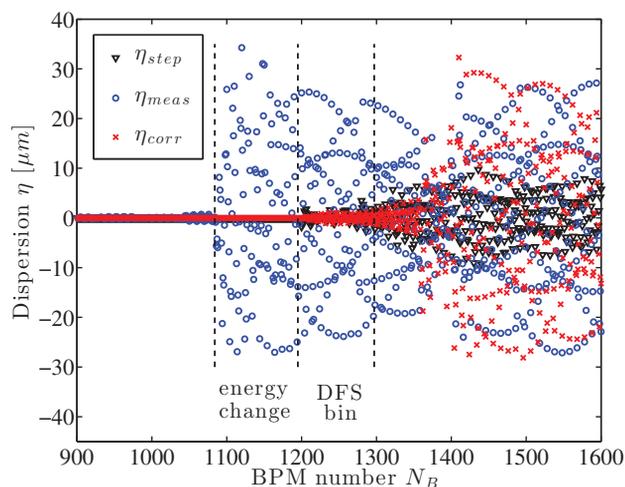


Figure 4: Simulated dispersion measurement with local energy change δ of 0.001 and random structure tilts of $140 \mu\text{m}$.

a random cavity to beam offset of $3.5 \mu\text{m}$ (due to RF alignment). With the global energy change scheme, the emittance growth after on-line DFS is 24% and therefore unacceptable. If instead the local scheme is applied, the emittance grows is 8% after on-line DFS and 9% if additionally the tilt orbit correction is used. This is very close to the unavoidable effect due to wake fields of 5%. For the second simulation, random structure tilts are applied with a standard deviation of $140 \mu\text{m}$. For this case, the application of on-line DFS with the local scheme results in an emittance growth of 121%. After applying also the tilt orbit correction, the emittance growth is reduced to 2%, where the emittance growth after 1-to-1 steering is 3%.

CONCLUSIONS

The on-line DFS algorithm is an essential tool for the operation of CLIC over longer time scales. Imperfections studies have shown, however, a high sensitivity to the resolution of the wake field monitors and to the tilts of the acceleration structures. In this paper, the problems these two imperfections cause for the DFS algorithm are analysed in detail with the help of simulation studies. This analysis is not only improving the understanding of the DFS algorithm in general, but it has also led to the development of effective counter-measures. In the case of the wake field monitor resolution, the sensitivity could be drastically reduced by adopting a scheme where the beam energy difference for the dispersion measurement is build up shortly before the correction bin. In the case of structure tilts, a parasitic orbit change in the dispersion measurement can be corrected by predicting the orbit changes in the correction bin with the help of orbit changes occurring further upstream. When applying these improvements, the emittance growth in the main linac of CLIC after on-line DFS correction is 9% and 2% for wake fields and structure tilts, respectively.

REFERENCES

- [1] J. Pfingstner, J. Snuverink and D. Schulte, *Ground-motion optimised orbit feedback design for the future linear collider*, Nucl. Instrum. Meth. A 703, 163-170 (2013).
- [2] V. Shiltsev. *Observations of random walk of the ground in space and time*, Phys. Rev. Lett. 104, 238501 (2010).
- [3] T. O. Raubenheimer and R. D. Ruth. *A dispersion-free trajectory correction technique for linear colliders*, Nucl. Instrum. Meth. A 302,191-208 (1991).
- [4] A. Latina and P. Raimondi, *A novel alignment procedure for the final focus of future linear colliders*, In Proc. of the 25th Linear Accel. Conf. (LINAC10), MOP026 (2010).
- [5] J. Pfingstner and D. Schulte, *On-line dispersion free steering for the main linac of CLIC*, In Proc. of the 26th Linear Accel. Conf. (LINAC12), MOPB042 (2012).
- [6] J. Pfingstner and A. Latina, D. Schulte. *Imperfection tolerances for on-line dispersion free steering in the main linac of CLIC*, In Proc. of the 4th Int. Part. Accel. Conf. (IPAC13), TUPME048 (2013).

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2015). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.