ON-LINE DISPERSION FREE STEERING FOR THE MAIN LINAC OF CLIC

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Abstract

For future linear colliders as well as for light sources, ground motion effects are a severe problem for the accelerator performance. After a few minutes, orbit feedback systems are not sufficient to mitigate all ground motion effects and additional long term methods will have to be deployed. In this paper, the long term ground motion effects in the main linac of the Compact Linear Collider (CLIC) are analysed via simulation studies. The primary growth of the projected emittance is identified to originate from chromatic dilutions due to dispersive beam orbits. To counter this effect, an on-line identification algorithm is applied to measure the dispersion parasitically. This dispersion estimate is used to correct the beam orbit with an iterative dispersion free steering algorithm. The presented results are not only of interest for the CLIC project, but for all linacs in which the dispersive orbit has to be corrected over time.

INTRODUCTION

Linear colliders and light sources often require very small beam emittances and beam sizes to reach their goals. This fact makes these machines inherently sensitive to ground motion effects. For short time scales orbit feedbacks can be used to mitigate these effects by steering the beam with the help of beam positioning monitors (BPMs) (see [1] for the CLIC case). For longer time scales, this steering is not sufficient to preserve the beam quality as can be seen in Fig. 1. To be able to operate CLIC over longer time periods, it is essential to correct this remaining emittance growth. The development of such an algorithm is the topic of this paper.

The main reason for the remaining emittance growth is that the BPM positions itself will drift from their original position, which results in a dispersive beam orbit. The according chromatic dilutions decrease the beam quality over time. In the literature, a technique named dispersion free steering (DFS) can be found, which has been developed to correct similar chromatic dilutions (see [3] and [4]). In this paper we modify and extent this basic DFS method, such that it can be used to correct long term ground motion effects in an on-line mode. On-line means in this case that the DFS correction is applied during the normal accelerator operation in a parasitic way, without stopping the physics program. The methode will be explained an evaluated on the example of CLIC, but can be easily utilised for other accelerators.

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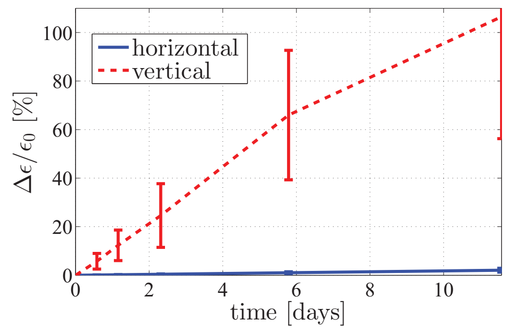

Figure 1: Simulations of the relative emittance growth over long time scales with orbit feedback in the main linac of CLIC. The used ground motion is generates according to the ATL law [2] with a constant A of $0.5\times10^{-6}\,\mu m^2/m/s$, which is the baseline for CLIC. The results have been averaged over 10 random samples of ground motion. For the initial horizontal and vertical emittance 600 nm and 10 nm have been used. The action of the orbit feedback was assumed to be perfect and therefore simulated by applying one-to-one steering without BPM noise, which is an optimistic approximation. It can be seen that already after 1 day the emittance has increased by about 10%.

ON-LINE DFS ALGORITHM

In this section, we will first introduce the basic DFS algorithm. After that the modifications necessary to apply this algorithm in an on-line mode will be discussed.

Basic DFS Algorithm

The DFS algorithm consists of two steps. In the first, the dispersion $\boldsymbol{\eta}$ at the BPMs is measured by varying the beam energy. This energy change can be created by changing the acceleration gradient, scaling the magnet strength and/or changing the initial beam energy. In the second step, corrector actuations $\boldsymbol{\theta}$ are calculated such that at the same time the measured dispersion $\boldsymbol{\eta}$ as well as the beam orbit $\boldsymbol{b}$ are corrected. Such actuations can be calculated by solving the following system of equations for $\boldsymbol{\theta}$ (see [5] for more details)

$$-\begin{bmatrix} \boldsymbol{b}-\boldsymbol{b}_0 \\ \omega(\boldsymbol{\eta}-\boldsymbol{\eta}_0) \\ \boldsymbol{0} \end{bmatrix} = \begin{bmatrix} \boldsymbol{R} \\ \omega\boldsymbol{D} \\ \beta\boldsymbol{I} \end{bmatrix}\boldsymbol{\theta}, \qquad (1)$$

where $\boldsymbol{b}_0$ and $\boldsymbol{\eta}_0$ are the reference beam orbit and target dispersion respectively. The third set of equations in Eq. (1) with the unity matrix $\boldsymbol{I}$ on the right side is used to damp too high corrector actuations. The weights ω and β can be

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chosen to minimise the emittance, which is easiest done in simulation via a parameter scan. The matrices $\boldsymbol{R}$ and $\boldsymbol{D}$ are the orbit and dispersion response matrix.

To increase the robustness, this DFS algorithm is usually applied sequentially to overlapping sections of the accelerator. In the case of CLIC, the main linac is partitioned into 36 fully overlapping sections each consiting of about 28 FODO cells. Note that after the correction of one section, the dispersion of the sections downstream has changed as well. It is therefore necessary to re-measure the dispersion after each DFS correction of one section.

Problem of Low Energy Variations

The primary difference between the basic and the on-line DFS algorithm is that the dispersion cannot be measured straight forward. In the basic method, a large energy deviation will be used to create large dispersive offsets in the BPMs to increase the measurement accuracy. This is however not possible for an on-line algorithm, since only tiny energy variations can be tolerated due to the energy acceptance of the final focus system of CLIC. For the simulations in this paper an energy variation of only 0.5 per mill is used.

Two main problems arise from these small induced energy variations. First of all, the induced orbit variations will be small and the necessary accuracy of the dispersion measurement has to be recovered by combining many measured orbit samples in a stochastic way to filter the noise. This dispersion estimation will be discussed in the next section. The second problem due to the small energy variations comes from the fact that the used energy deviations are so small that they are in the order of the beam energy spread, which is strongly influenced by wakefields. Therefore, changes of wakefields due to the change of beam orbits or cavity positions start to influence the dispersion measurement. This problem can be resolved by an initial cavity alignment (see [6]) before the on-line DFS, which reduces the wakefield effects for the current beam orbit. It is also beneficial to perform a cavity alignment after each full DFS correction of the linac.

Dispersion Estimation

The dispersion is measured in this paper by changing the acceleration gradient, which can be accomplished for the main linac of CLIC by a modulation of the beam intensity of the drive beam. Additionally, the initial beam energy is varied with the help of a bunch compressor. Since the induced energy variations have to be small, the individual dispersion measurements will be disturbed strongly by the influence of BPM noise and the usual jitter of the initial beam energy and the accelerating gradients. Therefore, the dispersion is determined by using many measurements and combining them to a least squares (LS) estimate to ensure the necessary accuracy. Instead of determining the LS estimate via the usual calculation of the pseudo-inverse, a very efficient recursive version of the algorithm can be derived, if the induced energy variations are chosen to be the sequence $\{-\Delta E, +\Delta E, -\Delta E, +\Delta E, \dots\}$. In this case the LS estimate of the dispersion η_N at a BPM at time step $N \in 2\mathbb{N}$ can be written as

$$\eta_N = \left(\boldsymbol{E}^T\boldsymbol{E}\right)^{-1}\boldsymbol{E}^T\boldsymbol{b} = \frac{T_N}{N\Delta E} \quad \text{with} \tag{2}$$

$$\boldsymbol{E} = \begin{bmatrix} -\Delta E \\ +\Delta E \\ \vdots \\ -\Delta E \\ +\Delta E \end{bmatrix} \quad \text{and} \quad T_N = \sum_{i=1}^{N}(-1)^i b_i,$$

where $\boldsymbol{b} \in \mathbb{R}^N$ is the vector of previous BPM measurements. The so obtained estimate η_N can subsequently be used to calculate corrections θ for the next accelerator section according to Eq. (1). The question how many samples N have to be used to create an accurate enough estimate will be answered in the results section of this paper.

Integration of On-Line DFS and Orbit Feedback

When using the on-line DFS algorithm in combination with the orbit feedback, the interaction of the two subsystems has to be considered. At the dispersion estimation the beam energy changes induced by the on-line DFS will create orbit offsets that will couple to the action of the orbit feedback. By choosing the excitation to be a constant value with alternating signs, the induced disturbances are of the highest resolvable frequency of the orbit controller. Due to its design, the orbit controller frequency response demagnifies this frequency component strongly and the orbit feedback will couple only very weakly to the induced orbit offsets.

Another modification to the basic DFS algorithm is necessary, since the orbit controller will react on the changed beam orbits due to the on-line DFS corrections. The orbit feedback would aim to steer the beam back on its previous orbit. Therefore, the BPM centres of the corrected section have to be shifted electronically to the new reference orbit after the DFS correction.

If a section would be DFS corrected without considering the beam orbit in the rest of the downstream linac, the beam would be steered far from its reference orbit. This would lead to an unacceptable emittance growth. Also the orbit feedback would react strongly on the large offsets, which would also decrease the accuracy of the next dispersion estimate. Therefore, the expected beam orbit change $\hat{\boldsymbol{b}}$ in the BPMs after the current section has to be corrected with the correctors after the current section. Simulation showed that it is sufficient to use only the correctors of the next section, which reduced the necessary calculation time of the performed all-to-all steering. The according corrector actuations $\hat{\theta}$ can be calculated by solving

$$-\begin{bmatrix} \hat{\boldsymbol{b}} \\ \boldsymbol{0} \end{bmatrix} = \begin{bmatrix} \hat{\boldsymbol{R}} \\ \beta_0 \boldsymbol{I} \end{bmatrix}\hat{\theta}, \tag{3}$$

where β_0 is a damping factor for the corrector actuations.

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RESULTS

To test the on-line DFS algorithm proposed, it was integrated in the simulation framework described in [1], which include the beam tracking in the main linac of CLIC, ground motion generation and the action of the orbit controller. The algorithm was tested on a beamline that was misaligned with about 11 days of ATL ground motion, followed by a one-to-one steering.

To determine how many samples are needed to estimate the dispersion sufficiently well, a simplified procedure was used. Instead of using full-scale simulations, the real dispersion was determined in simulations and corrupted with artificial BPM noise. The influence of the BPM resolution on the on-line DFS correction result is shown in Fig. 2. The effective BPM resolution in the estimate has to be about 5 nm to not worsen the average on-line DFS correction by more than 2%. Assuming a BPM resolution of 100 nm, the noise has to be reduced by a factor of 20. Since the averaging reduces the remaining noise by the factor $1/\sqrt{N}$, where N is the number of used samples, N has to be 400, which corresponds to 8 s of CLIC operation. Considering further that this procedure is repeated for 36 linac sections over two iterations, the full correction time needed is about 10 minutes not including the time needed for the cavity alignment. Additionally to the influence of noise, also the DFS algorithm itself cannot correct the chromatic dilutions fully. With perfectly known dispersion, the initial vertical emittance growth of 107.6% was reduced to 2.5% on average.

The long time periods necessary for the averaging cannot be simulated directly in reasonable time. We therefore only performed full-scale simulations with an N of 100, which corresponds to a real-time operation of about 2 minutes. Different imperfections were applied and on average the emittance growth could be reduced after two iterations to 2.8% with no imperfections, 3.7% with orbit feedback turned on and 10.4% with realistic BPM resolution.

The results for one particular ground motion sample are shown in Fig. 3. It can be observed that at the corrections of the final sections the emittance grows for a short time period. We believe that this behaviour is due to a worse steering and an improvement is subject to future work. Simulations were also performed including short-term ground motion (model B [1]) in combination with the orbit feedback for the dispersion estimation. The observed effect due to the ground motion was seen to be negligible. Another tested imperfection is the jitter of the acceleration gradients. Also here no significant degradation was observed for the maximal specification of 0.5%.

CONCLUSIONS

In this paper an on-line DFS algorithm was presented. Simulation results show that it is capable of correcting dispersive beam orbits due to long term ground motion misalignments efficiently. Two iterations of the algorithm have found to be enough to reduce the according beam emittance growth very efficiently, which takes for CLIC about 10 min. Since the time constant of the correction is much smaller than the emittance growth, there is no need to run the algorithm continuously. The mutual interaction of the algorithm with the orbit feedback was found to be small. Also the influence of ground motion and decelerator gradient jitter can be neglected. The presented algorithm is therefore an essential contribution for the successful operation of CLIC over longer time periods.

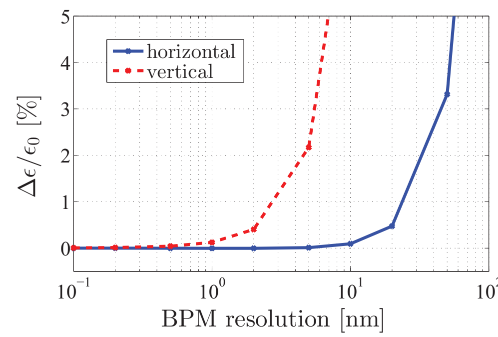

Figure 2: Relative emittance growth due to BPM resolution when using on-line DFS averaged over 20 random samples.

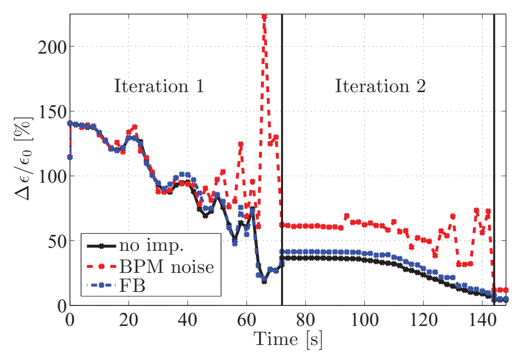

Figure 3: Relative vertical emittance during two iterations of the on-line DFS correction for one particular sample of ground motion. No imperfections are applied for the black curve (4% emittance growth). For the blue curve, the orbit feedback is turned on during the dispersion estimation. The mutual influence of the two subsystems is seen to be small (5% emittance growth). For the red curve a BPM resolution of 100 nm is used (12% emittance growth).

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