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CLIC – Note – 1012

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

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

Abstract

Long-term ground motion misaligns the elements of the main linac of CLIC over time. Especially the misaligned quadrupoles create dispersion and hence the beam quality is decreased gradually due to an effect called chromatic dilution. Over longer time periods, orbit feedback systems are not capable to fully recover the beam quality and have to be supplemented by dispersion correction algorithms. In this paper, such and dispersion correction algorithm is presented, which is an extended version of the well-known dispersion free steering algorithm. This extended algorithm can recover the beam quality over long time scaled without stopping the accelerator operation (on-line). Tolerances for different imperfections of the system have been identified and a strong sensitivity to the resolution of the wake field monitors of the main linac accelerating structures has been identified. This problem can be mitigated by using a local excitation scheme as will be shown in this work.

Presented at: 4th International Particle Accelerator Conference, Shanghai, China, 12 - 17 May 2013

Geneva, Switzerland
Date 12/05/2013

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN – ACCELERATORS AND TECHNOLOGY SECTOR

CERN-ACC-2013-0091

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INTRODUCTION

Ground motion effects are an important issue for the main linac of CLIC, but also for other accelerators. While orbit feedbacks are capable of preserving the beam quality over short time scales (some minutes), secondary effects deteriorate the beam emittance over longer periods, as can be seen in Fig. 1. Ground motion misaligns the beam position monitors (BPMs) with time, such that dispersion is build up in the new reference orbit. This dispersion in combination with the large energy spread of the beam leads to an emittance increase due to chromatic dilutions.

The well-known dispersion free steering algorithm (DFS) [2] is capable of mitigate this effect. However, for the application of DFS, large beam energy variations are introduced and the accelerator has to stop its usual operation. To avoid this accelerator down time, an on-line version of the basic DFS algorithm is presented in this work. It is capable of correcting dispersive orbits parasitically, without stopping the operation of the accelerator. While the concept of the on-line DFS algorithm has been already introduced earlier [3], in this paper the robustness of the algorithm with respect to different imperfections and excitation schemes is investigated.

CORRECTION ALGORITHM

Since the on-line DFS algorithm has already been introduced [3], it will only be rephrased here briefly.

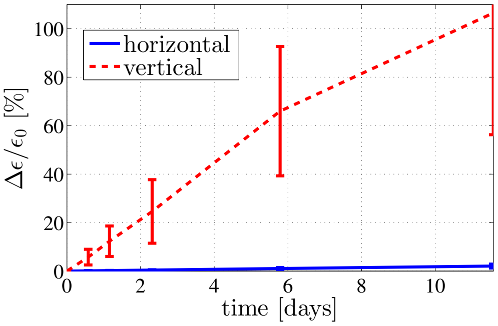

Figure 1: Simulations of the relative emittance growth over long time scales with orbit feedback in the main linac of CLIC. The used ground motion is generated according to the ATL law [1] with a constant A of 0.5×10^{-6} $\mu m^2/m/s$, which is the baseline for CLIC. The results have been averaged over 10 random samples of ground motion. For the initial normalised 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%.

The basic dispersion correction can be facilitated with the well-known Dispersion Free Steering algorithm (DFS), in which quadrupole position changes or corrector magnet actuations $\boldsymbol{\theta}$ are calculated by

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

where $\boldsymbol{b}$ and $\boldsymbol{\eta}$ are the measured orbit and dispersion. The variables $\boldsymbol{b}_0$ and $\boldsymbol{\eta}_0$ symbolise the reference beam orbit and the target dispersion. The matrices $\boldsymbol{R}$ and $\boldsymbol{D}$ are the orbit and dispersion response matrices, $\boldsymbol{I}$ is the unity matrix and ω and β are weights that are usually determined via simulations.

As an input for the calculation in Eq. (1), the dispersion $\boldsymbol{\eta}$ has to be measured. In contrast to the basic DFS algorithm, this measurement is performed for the on-line DFS algorithm parasitically during the accelerator operation. To accomplish this, small beam energy perturbations are introduced. Since the introduced dispersive beam offsets are small compared to the BPMs noise, many measurements have to be combined in a stochastic way via estimation algorithms. Here, the well-known least squares algorithm is used to estimate the dispersion. If the simple excitation of a constant energy variation ΔE with alternating sign is used,

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the full least squares estimation simplifies 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 the previous BPM measurements, N is the number of averaged measurements and $\boldsymbol{E}$ is the vector of induced energy variations.

IMPERFECTION TOLERANCES FOR DIFFERENT EXCITATION SCHEMES

The correction algorithm, introduced in the last section, was initially used in combination with a global excitation scheme [3]. This means that the necessary beam energy change was created all along the main linac in a coherent fashion. Therefore, the acceleration gradients of all acceleration structures were scaled by the necessary factor. Also the initial beam energy was changed which can be accomplished by a scheme introduce in [4]. However, imperfection studies with the tracking code PLACET [5] have revealed a high sensitivity of this correction scheme to the resolution of the wake field monitors of the acceleration structures, as can be seen in Fig. 2.

The observed high sensitivity is due to the following reason. Energy dependent effects upstream of the section to be corrected cause the beam to have an energy dependent trajectory offset when the dispersion of this sector is measured. Such energy dependent effects are especially wake field kicks, but also residual uncorrected dispersion. The mentioned trajectory offsets will be interpreted as local dispersion, even though the effect is created further upstream in the linac. Therefore, the local DFS correction will be performed with an incorrect dispersion and the correction is insufficient. There are two ways to omit this problem. Firstly, if the induced beam energy change becomes significantly larger then the beam energy spread, the local dispersion effect will become dominant compared to the effect that originate from upstream. Secondly, the energy dependent effects upstream will be smaller, if the beam moves along the linac only for a short distance with a different energy.

Since it is not possible to induce large energy variations for the on-line estimation, it seems to be beneficial to use an excitation scheme in which the necessary energy difference is build up over a short distance before the sector that has to be corrected. Such a scheme was designed and implemented in simulations. Always the decelerator before the sector to be corrected is used to build up the energy difference. This scheme has the additional advantage that the induced energy difference can be removed from the beam in the decelerator after the section to be corrected (apart from

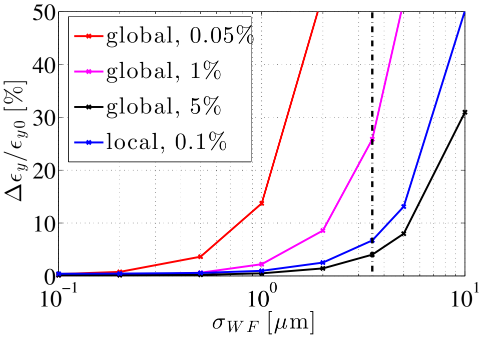

Figure 2: Decrease of the correction performance of the on-line DFS algorithm due to limited resolution of the wake field monitors of the accelerating structures of CLIC. The remaining relative emittance increase $\Delta\epsilon_y/\epsilon_{y0}$ is evaluated via simulations (averaged over 10 seeds) and is plotted for the global excitation scheme with an excitation of 0.5 per mill (red line), 1% (magenta line) and 5% (black line) and the local excitation scheme with 1 per mill excitation (blue line). The black vertical line indicated the current specification for the wake field monitors of CLIC. The local scheme with an excitation of 1 per mil delivers a sufficient correction and is approximately as robust as the global excitation scheme with an excitation of 5%. The latter one excitation would of course be infeasible for a parasitic correction.

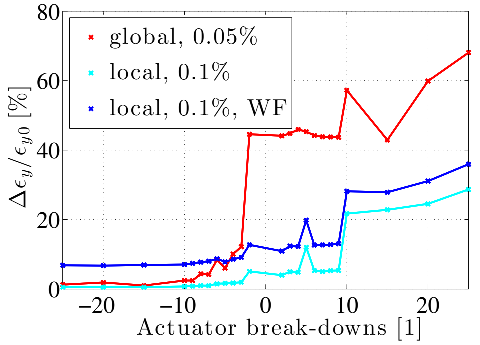

Figure 3: Decrease of the correction performance of the on-line DFS algorithm due to breakdowns of the alignment actuators of certain quadruples. In other words, only a subset of all quadrupoles can be moved by the on-line DFS algorithm to mitigate the emittance increase $\Delta\epsilon_y/\epsilon_{y0}$ in vertical direction. Positive numbers on the horizontal axis mean that only each nth quadrupole is used for the correction. Negative numbers indicate that each $-n$th quadrupole is not used for the correction. The plotted data corresponds to simulation results averaged over 10 seeds for the global (red) and the local excitation scheme with (blue) and without (cyan) wake field effects (3.5 μm wake field monitor resolution). The local excitation scheme proves to be much more robust than the local excitation scheme to alignment actuator breakdowns.

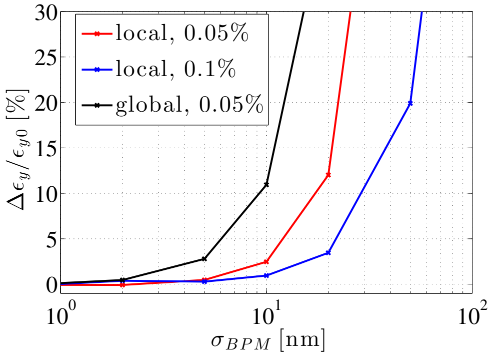

Figure 4: Decrease of the correction performance of the on-line DFS algorithm due to BPM noise. The emittance increase $\Delta\epsilon_y/\epsilon_{y0}$ in vertical direction after the correction is evaluated via simulations (averaged over 10 seeds). The results for the local excitation scheme for an excitation with 0.5 per mill (red curve) and 1 per mill (blue curve) and the global scheme with 0.5 per mill (black curve) are shown. Since the local scheme can allow for a large induced excitation the tolerances for the remaining BPM noise in the dispersion measurement is relaxed and therefore the dispersion estimation time can be reduced.

the sections contained in the last decelerator). Due to this reason, a larger energy change (in this case 1 per mil) can be induced compared to the global scheme (0.5 per mil). As a result, the estimation time can be reduced and at the same time the robustness of the scheme is improved.

As can be seen in Fig. 4, a remaining BPM noise in the dispersion estimation of about 10 nm hardly worsens the correction performance of the on-line DFS algorithm. Since the BPM resolution in the main linac is assumed to be 100 nm the noise level only has to be reduced by a factor of 10, which corresponds to an averaging time of 10^2 pulses. This corresponds to a reduction of the estimation time of a factor 4 compared to the global scheme. It has also been observed that no iterative correction is necessary, which shortens the estimation time by another factor 3 compared to the global scheme where 3 iterations had to be applied. These changes lead to a real-time correction time of 72 seconds for the local scheme (not including the necessary initial and final RF alignment [6]), compared to about 10 minutes for the global scheme. Additional to the reduction of the estimation time, the local excitation scheme is much more robust to wake fields (see Fig. 2). Also a higher robustness with respect to the breakdown of quadrupole movers can be observed in Fig. 3. And also the tolerances to acceleration gradient jitter (including wake field effects), which are depicted in Fig. 5, are well within the CLIC specifications.

CONCLUSIONS

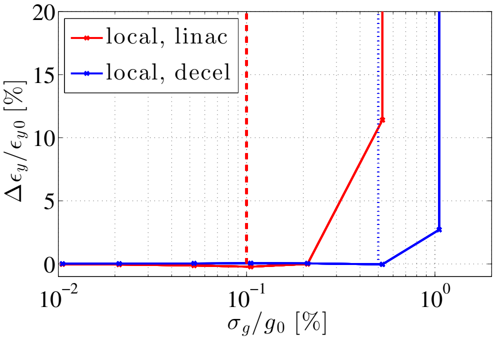

Figure 5: Decrease of the correction performance of the on-line DFS algorithm due to jitter in the acceleration gradients in the CLIC cavities, which corresponds effectively to beam energy errors. The emittance increase $\Delta\epsilon_y/\epsilon_{y0}$ in vertical direction after the correction is evaluated via simulations (averaged over 10 seeds). The emittance increase is shown for the local excitation scheme for jitter in the acceleration gradients coherent within one decelerator (blue curve) and coherent along the whole linac (red curve). An RF alignment with the nominal CLIC resolution of 3.5 μm has been included in the simulations, but the resulting emittance increase of about 6% has been removed in the plot. The dashed red and dotted blue vertical lines correspond to the CLIC tolerances of the gradient jitter per decelerator and the whole linac, respectively. As can be seen, both tolerances do not pose a problem for the operation of the local on-line DFS algorithm.

A correction algorithm, named on-line DFS, for the mitigation of long-term ground motion effects in the main linac of CLIC has been presented. While the principle possibility of the use of this algorithm has been already shown earlier [3], in this paper the robustness of the correction scheme is investigated. These studies have revealed, that the initially foreseen global excitation scheme has a too high sensitivity to the resolution of the wake field monitors of the acceleration structures. To resolve this problem a local excitation scheme has been introduce, which makes the on-line DFS also more robust to BPM noise and breakdowns of quadrupole positioning equipment. With these improvements the presented algorithm can be used not only in CLIC, but also for other accelerators to efficiently correct dispersive orbits in a parasitically manner.

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