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STATUS OF AN AUTOMATIC BEAM STEERING FOR THE CLIC TEST FACILITY 3

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Abstract

An automatic beam steering application for CTF 3 is being designed in order to automatize operation of the machine, as well as providing a test-bed for advanced steering algorithms for CLIC. Beam-based correction including dispersion free steering have been investigated. An approach based on a PLACET on-line model has been tested. This paper gives an overview of the current status and the achieved results of the CTF3 automatic steering.

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Abstract

An automatic beam steering application for CTF 3 is being designed in order to automatize operation of the machine, as well as providing a test-bed for advanced steering algorithms for CLIC. Beam-based correction including dispersion free steering have been investigated. An approach based on a PLACET on-line model has been tested. This paper gives an overview of the current status and the achieved results of the CTF3 automatic steering.

INTRODUCTION

The Compact LInear Collider (CLIC) study has shown that advanced beam-based correction will be needed to reach nominal performance of several parts of the collider [1], [2]. The CLIC Test Facility 3 (CTF3) has been constructed at CERN in order to demonstrate feasibility of several key concepts of CLIC [3]. New areas are added to CTF3 for each new phase, making operation more complicated, and it is therefore of significant interest to ease the operation of this machine. The purpose of the work described here is thus two-fold:

- test of correction algorithms devised for CLIC on a real machine
- aid operation of CTF3 by automating beam steering (currently performed by hand)

CORRECTION APPROACHES

The correction algorithms investigated here are ”all-to-all” (A2A) and dispersion-free steering (DFS) [4]. In this paper we use ”correction” and ”steering” interchangeably. Both algorithms can be implemented using response matrices. Their effect when applied to a defined lattice segment is ideally:

- A2A: steers the beam to get BPM zero-readings, by simply inverting the response matrix of the nominal machine optics
- DFS: minimizes the difference of dispersive trajectories, using responses corresponding to optics with different $\Delta p/p$; weighted against A2A

Matrix inversion for both candidates is performed in the Least-Squares sense, using SVD. Smoothing can be introduced by taking out corrector modes corresponding to small singular values, effectively smoothing out noise effects. Furthermore, defect BPMs and/or correctors can be taken easily into account by zeroing rows and/or columns of the response matrix. A2A and DFS then find the global solution within the defined lattice segment (this is why we say ”all-to-all” rather than ”1-to-1”).

For quick and effective correction computer model generated responses are needed. With model-based steering, one can perform all-to-all steering for a lattice segment in few tens of seconds. In comparison, to obtain machine responses in CTF3 takes from 1/4 h to 1/2 h per optics, per plane, totaling to hours if one wants to do dispersion-free steering. On the other hand, model-based steering require a good correspondence model/machine, and obtaining the needed model accuracy might be challenging.

TEST-CASE: THE CTF3 LINAC

The CTF3 linac, characterized by operation with full beam-loading [5], was chosen as ”test-lattice”, because of higher applicability wrt. [1], [2]. We apply correction on a straight part of the linac, with regular lattice structure consisting of 11 girders (”nr. 5” to ”nr. 15”), where each girder supports a quadrupole triplet, one corrector coil, and one BPM, as shown in Figure 1. For girders 5,6,7,11,12,13 and 15 there are in addition two accelerating structures, fed by one klystron, located between the corrector and the BPM.

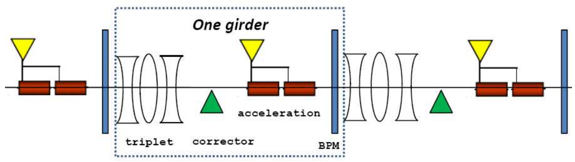

Figure 1: Structure of the CTF3 linac (not to scale)

Dispersion and emittance growth

Dispersion measurement and DFS were in this work performed by scaling magnet currents. We therefore consider only dispersion building up from the start of the test-lattice (we do not consider, and cannot mitigate, upstream dispersion). There are no powered dipoles in the test-lattice, so the dispersion comes mainly from parasitic dispersion due to quadrupole offsets (we also get a small contribution from the correctors, dispersion due to incoming beam offset/angle and due to transverse wakes). We note that our 11 cell lattice accomodates little more than a single betatron-oscillation, and we therefore expect dispersion to be small, even for the uncorrected case (no resonant build-up possible). The CTF3 component alignment tolerance is 100 μm

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rms. PLACET simulations estimate the resulting dispersion growth to 5 mm (rms of 100 seeds). By simulation we estimate emittance growth without correction, assuming a bunch-length of 1.6 mm and an initial normalized emittance of 100 μm, to be in the order of percent, and an ultimate test of DFS would be to compare emittance growth before and after correction.

MODEL IDENTIFICATION

A linac model implemented in PLACET was to be used for the model-based correction. It was decided to verify and eventually improve the model before using it for steering. An attempt to use "LOCO-type" global identification [6] was initiated (not applied to the linac before), and a new identification code was written in Octave for this purpose. Improvement of the model with this method turned out to be difficult because of the triplet cells (see below) combined with imprecise response measurement (the same response point was found to vary up to 10% rms, due to beam jitter, different working points, hysteresis etc).

Triplet cells

The linac focusing is done with quadrupoles in triplets, powered 2+1 or 1+1+1, with a single BPM and corrector per triplet cell (see Figure 1). The similarity of difference orbit when changing either of the outer quadrupoles, as well as almost opposite orbit of the middle quad, leads to near degeneracies which becomes difficult to resolve with imprecise data. Quantitatively we see this by error propagation through the covariance matrix $(\frac{\partial E}{\partial K}^T \frac{\partial E}{\partial K})^{-1}$ [7]; inputting the imprecision of the response points, the standard uncertainty of the parameter estimates is for many of the quadrupoles of the same order as the parameter itself, even when disregarding the first few triplet cells (the least constrained ones). As comparison, with quadrupole currents frozen, the uncertainty of the corrector gains is $\sim 1\%$. The phase-difference between model and machine was shown to be reasonable small by direct SVD analysis, and it was therefore decided to go on with quadrupole parameters frozen. The trustworthiness of individual corrector gain identification with quadrupoles frozen is not clear, and therefore the only parameters fitted before correction was global scaling + the ratio of the calibration factor of the two different corrector types in the test-lattice.

Requirement for model-machine correspondence

After identification we still have a certain mismatch between model and machine. We want to estimate, by simulation, the error accepted on the model parameters while still achieving adequate correction. To study this, A2A was applied to a perturbed model using ideal model responses. Each quadrupole strength was randomly scaled by an rms value of $\sigma_{\Delta k}$ %. The maximum resulting BPM readings after 5 iterations of A2A, averaged over 100 machines, are shown in Table 1. For strength rms error of up to 12%, A2A still converges to BPM readings $< 100\mu$m (Perfect BPMs were assumed for these simulations).

Table 1: Correction convergence with model discrepancy

$\sigma_{\mathbf{\Delta k}}[\%]$	4	6	8	10	12	14	16	20
y [mm]	0	0	0.02	0.04	0.1	0.3	0.7	3.6

CORRECTION RESULTS

All-to-all

Using machine responses both planes were corrected to within 0.15 mm rms in two iterations (this illustrates some imprecision in the machine responses and/or machine jitter). Then, correction was performed using responses calculated from the PLACET model. The calculation of the responses takes less than 5 seconds. Both planes did converge, but needed up to to four iterations before reaching the convergence criterion, showing that the model of the linac is not perfect but good enough for steering. Each iteration takes from 10 to 20 seconds, depending on whether a corrector has to switch polarity or not.

Non-functioning correctors or BPMs can be taken into account by first identifying them (e.g manually or from machine responses). A device is disregarded by the algorithm by simply setting the corresponding row or column to zero. One corrector was very unreliable during this work (DVD1420), and was turned off and the corresponding column set to 0. The resulting system is under-actuated (10 correctors and 11 BPMs), and instead of trying to achieve zero BPM readings A2A finds the least-square solution. The result after model-based A2A correction, with one defect corrector in the vertical, is show in Figure 2. The oscillatory pattern in the vertical corresponds to the uncorrectable BPM mode, belonging to the zero singular value which is due to the defect corrector. Dispersion after A2A steering was measured to less than 5 mm (error margin of about 0.5 mm). This is comparable to dispersion measured after manual correction of the machine. We conclude that model-based all-to-all correction seems to work well, is reasonably fast, and robust wrt. corrector or BPM defects.

Dispersion free steering

Since A2A correction gives a very small residual dispersion (showing reasonably small misalignments), we do not expect to improve this result, given the beam jitter and limited BPM resolution of 10 μm. As test-case we instead *simulate* misalignment of 3-6 mm for a few BPMs. A2A will now steer the beam into the simulated centre, creating a position bump in the real trajectory. The red line of Figure 3 shows the position bump (the plot shows *real* BPM readings, as opposed to the readings with *simulated* misalignments that the correction algorithm sees). This bump increases the local dispersion by a factor 3, up to 15 mm, as shown in red in Figure 4.

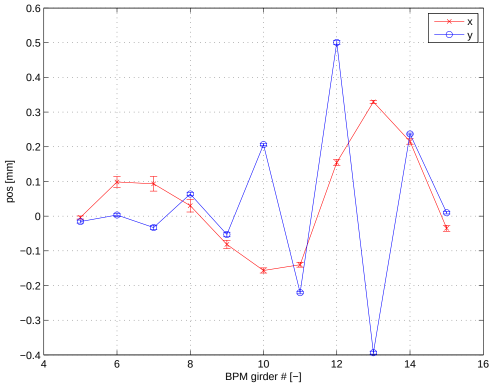

Figure 2: Model-based A2A (BPM readings for both planes)

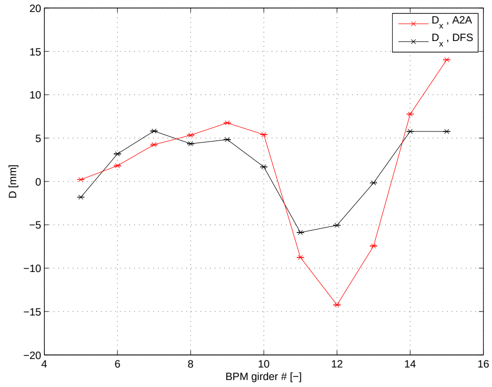

Figure 4: DFS versus A2A (dispersion after correction)

One of the salient features of dispersion-free steering is that absolute BPM position readings are mostly disregarded, and instead difference readings are used to minimize the difference of dispersive trajectories. We therefore expect a successful DFS to find an orbit with smaller dispersion than A2A, while being mostly oblivious to the simulated BPM misalignment. However, the performance of the DFS depends on the precision with which the difference orbit can be obtained. We had dispersion of ~ 10 mm and a dispersion measurement precision of ~ 0.5 mm for $\Delta p/p = 10\%$, with present machine conditions. It was therefore not straightforward to find a good solution for DFS, but after substantial trials with different weighting wrt. the zero-reading (w_1/w_0=10 used), different SVD-cuts (70% used) and different $\Delta p/p$ (0.2 used), solutions were found that clearly indicates how the dispersion and position bump is reduced, shown in blue in Figure 3 and 4. The BPM readings including the simulated misalignments (seen by our correction algorithms) would show a large bump after the DFS, giving operators indications of large BPM misalignment. Finally, we note that applying DFS without simulated BPM misalignment gave similar performance as with these misalignments.

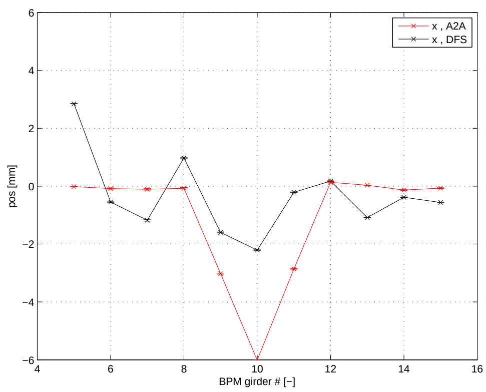

Figure 3: DFS versus A2A (*real* BPM readings after correction)

The initial large offset after DFS is due to incoming beam offset/angle (reproduceable in simulations). Machine-based responses were used for the dispersion-free steering. The results show that when dispersion is significant after A2A correction, for instance due to large BPM misalignment, DFS can provide a solution with lower dispersion and at the same time indicating the source of the problem. However, as correction algorithm for CTF3, DFS does not give a clear advantage over A2A.

CONCLUSIONS

The triplet structure impeded further model improvement. Model-based A2A has been applied successfully in a robust way to the CTF3 linac. DFS performance was superior to A2A in a test-case with artificially large BPM misalignment. However, for nominal linac operation we recommend A2A because of its faster execution.

ACKNOWLEDGEMENTS

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