BEAM-BASED ALIGNMENT IN CTF3 TEST BEAM LINE

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Abstract

The CLIC linear collider is based on the two beams acceleration scheme. During acceleration of the colliding beams, the drive beam suffers a large build up on its energy spread. In order to efficiently transport such a beam, beam-based alignment techniques together with tight pre-alignment tolerances are crucial. To evaluate the performance of these steering algorithms, a beam-based steering campaign has been conducted at the Test Beam Line of the CLIC Test Facility. In the following we present and discuss the obtained results.

INTRODUCTION

The Compact Linear Collider, CLIC, [1][2] is based on the two beams acceleration scheme: the colliding beams will be accelerated by decelerating a high intensity, low energy drive beam, DB. During its deceleration, the DB will increase its energy spread up to 90%. In this condition the beam transport is very challenging: beam-based alignment techniques together with tight pre-alignment tolerances are crucial to obtain the nominal performance. To reach the required level of pulse to pulse DB current jitter ($< 7.5 \times 10^{-4}$ [2]) the quadrupoles magnetic centre has to be pre-aligned with a RMS offset of 20 μm with respect to the laser straight reference. A beam-based steering campaign has been conducted at the Test Beam Line (TBL, [3]) of the CLIC Test Facility (CTF3) to evaluate and check several algorithms.

The TBL line consists of 8 FODO cells typically running with $\mu_x = \mu_y = 90°$ phase advance per cell. Each of the 16 quadrupoles is mounted on horizontal and vertical movers to allow beam based alignment (BBA) and has a BPM close by. At the moment of our experiments only 4 out of 16 Power Extraction and Transfer Structure (PETS) were installed in TBL. Hence the total deceleration produced on the beam was only 15%, having, as we will discuss later, a direct impact of the algorithm choice. In this condition the TBL beam transmission was, within the BPMs accuracy, almost complete even before automatic BBA. Nevertheless as we showed in simulations using the PLACET code [4] (Fig. 1), increasing the number of PETS beyond 8 and with full recombination current ($I_B = 28$ A) it is likely to require BBA even for routine operation. So the goal of this work is two-fold:

- to demonstrate the effectiveness of the BBA algorithms that will be used in CLIC,
- to ease the future operation of TBL and CTF3 lines.

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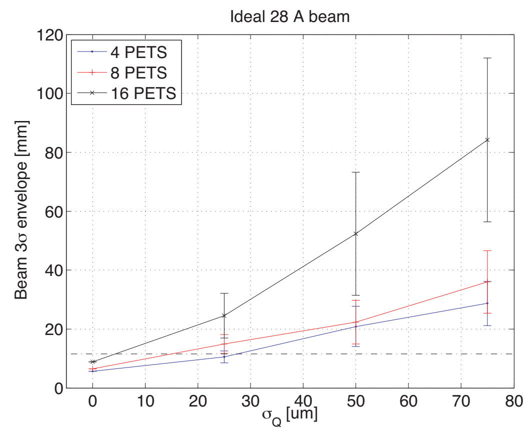

Figure 1: Effect of the quadrupoles misalignment on the TBL beam envelope at the end of the line. For comparison, the mechanical aperture of the PETS is $R = 11.5$ mm (dashed line). In the plot we show the results of a Montecarlo simulation: we vary the RMS misalignment of the quadrupole magnetic centre (σ_q) and we compute the 3σ envelope of the beam at the end of the line (99th percentile over 1000 seeds). We consider three different scenarios (4, 8 and 16 PETS in TBL) using the fully recombined beam ($I_B = 28$ A).

BEAM BASED ALIGNEMENT METHODS

In order to achieve the CLIC required DB efficiency and pulse-to-pulse reproducibility, the DB size has to be minimized along the decelerator. Neglecting the injections errors at the start of the decelerator, the DB envelope growth is dominated by the offset of the quadrupole magnetic centre with respect to the laser straight line. Since (1) the relation between quadrupole offset and envelope is non-linear, (2) the beam envelope is difficult to observe along the machine, instead of minimizing directly the envelope we can address the associate linear problem where we consider as observables to minimize (a) the horizontal and vertical betatron orbits and/or (b) the dispersive orbits at the BPMs all along the decelerator. These two different approaches are referred in the following as all-to-all and Dispersion Free Steering (DFS) correction [5]. The advantage of the DFS with respect to the all-to-all algorithm is its robustness against BPM accuracy being based on differential positions.

The response matrix, R, between observables and quadrupole positions is in general ill-conditioned: due to the finite BPM precision we cannot directly invert the problem but we can effectively correct the system using Singular Value (SV) filtering: we neglect in the correction all the quadrupole eigen-directions that are barely detectable by the BPMs (corresponding to the lower singular values of the R's SV Decomposition). An equivalent approach is to consider as additional observables the correction vector itself that is the required offset of the quadrupoles. In this condition the algorithm tries to minimize the correction with respect to the pre-aligned machine thus becoming stable without SV filtering.

As already mentioned, at the moment of the tests only 4 PETS were installed in TBL producing a modest deceleration. It was difficult to measure the differential orbit induced by the quadrupole misalignment between decelerated and unperturbed beam. This difficulty was further increased by a dispersive wave propagating to TBL from the CTF3 ring. This led us to implement a BBA algorithm based only on the minimization of the orbit. In this framework we could operate even with a less intense beam (typically no recombination or factor 4 recombination, instead of factor 8 recombination more suitable for the DFS).

As an alternative and complementary method, the quadrupole shunting technique (QST) has been investigated too. This technique tries to directly center the magnetic centre of a single quadrupole. It consists in moving the magnet to three different positions (-Δu, 0, +Δu), where u stands for x and y, by means of a mover on which the quadrupole is mounted. At each position the current of the quadrupole is initially shunted by $\pm\Delta I$. From the orbit difference recorded by the downstream BPMs the magnetic centre (x_0, y_0) is inferred (position were the orbit difference is null). The values of Δu and ΔI are adjusted at each iteration in order to reduce beam losses during the measurement. The process is iterated until the obtained BBA resolution does not improve further. This method is very powerful since uses differential BPM reading (robust against BPM accuracy) and it can predict the exact zeros of the quadrupole without using response matrix of the system. Nevertheless the main assumption is based on is that during the shunting the magnetic centre motion is negligible. In reality, as we will discuss, this assumption cannot always be applied. Moreover this technique is expected to require much more commissioning time for the CLIC decelerator than the all-to-all and DFS algorithms and cannot fit the powering constraint of the DB quadrupoles (series connection, limited ΔI).

EXPERIMENTAL RESULTS

The experiment of BBA in TBL line has been approached in three different ways: (1) a non-iterative correction using SVD filtering and high gain (G=1), (2) an iterative correction using low gain (G=0.1), (3) and using quadrupole shunting technique.

High gain correction

In this condition, we observe the beam orbit averaging it in sets of 10-50 consecutive pulses. This is needed to increase the algorithm robustness mainly with respect to injection error in TBL and energy jitter in the CTF3 linac [6]. Once the error orbit is observed we compute the required offset of the quadrupole movers. Typically the pseudo-inverse of the response matrix is computed using only the first 9 SVs out of the 16 in total: with these parameters the RMS value of the corrected orbit is significantly reduced and, in the meantime, the correction strength lies within the acceptable range of the hardware (maximum mover offset). Typical values of the orbit before and after the correction are reported in Table 1 for the vertical and horizontal orbit: the RMS horizontal orbit was reduced from 1.65 to 0.31 mm and the vertical one from 1.30 to 0.61 mm. Typical trajectories before and after BBA are reported in Fig. 2.

Table 1: Comparison of the orbit before and after BBA.

	Before BBA	After BBA
Mean H, V orbit [mm]	-0.90, -0.69	0.22, -0.07
RMS H, V orbit [mm]	1.65, 1.30	0.31, 0.61

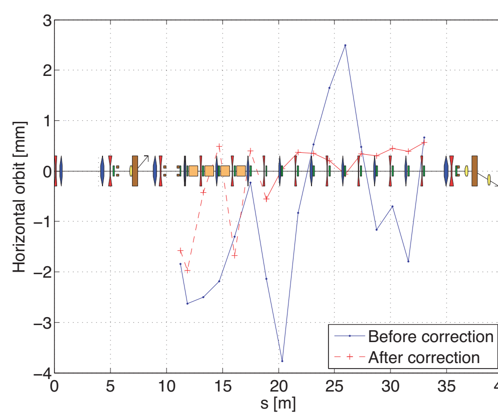

Figure 2: An example of the orbit correction performance in the horizontal plane before and after BBA.

The first part of the corrected trajectory (dashed line in Fig. 2) behaves like a damped oscillator. This is an expected behavior due to the error at the TBL injection and to the reduced SVs pseudo-inverse. In fact the algorithm will only partially use the quadrupole movers to correct the orbit error at the entrance of the line and it will take about one betatron oscillation to damp the oscillation. After this transient the corrected orbit reaches its steady state RMS. This approach has an important limit: due to the needed statistics on several beam pulses and to the CTF3 energy and orbit drift, when the corrections takes place the orbit used for correction is in general different from the actual orbit: this will originate a residual orbit even after correction. To avoid it, the use of a slow feedback correction is justified.

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Slow feedback correction

In this approach we correct after each single beam pulse (no average for a long observation period) applying only partially the correction (typically G=0.1). In doing so we are much more robust against errors in the synchronization of the BPM reading, BPM precision, limited precision of the response matrix of the system[1] and machine drifts.In Fig. 3 the measurements of the vertical and the horizontal positions of the first two BPMs of TBL is shown during the feedback loop. As expected the damping of the orbit is an exponential with the time constant of 1/G=10 pulses. After 50 pulses the only components still visible are the pulse-to-pulse uncorrelated jitter that cannot be compensated by our feedback. A complete test of the slow feedback loop on the TBL full length has still to be done but the result obtained on the first part of the line are very encouraging.

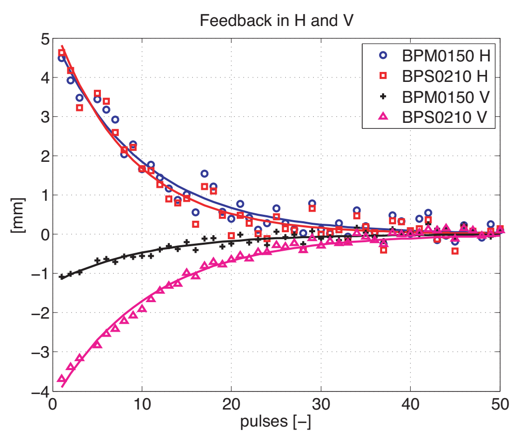

Figure 3: Measurement during orbit correction feedback.

Quadrupole shunting technique

An example of QST is shown in Fig. 4: we plot the orbit difference at 7 different BPMs when the ΔI is -20% and +20% of nominal current (I=2.56 A) for the three vertical positions of the quadrupole. The lines cross at the position 475 ± 25 μm indicating the magnetic centre of the quadrupole. We measured 9 quadrupoles out of 16 using QST: the obtained average error bar has been 200, 100 μm in the horizontal and vertical plane respectively. The limited precision of the measurements is probably due to the combination of the beam orbit jitter during the data acquisition, the precision of the BPMs if beam losses occur due to the induced beam perturbation, and the motion of the quadrupole magnetic centre due to the shunting. The latter contribution has been verified via direct magnetic measurements of a TBL quadrupole of similar characteristics [7]: in the range of our shunting current the measured motion of the magnetic centre is ≈ 7 μm. This effect even if not relevant at this stage in TBL, has to be taken into account in the design and the pre-aligment phase of the DB quadrupoles.

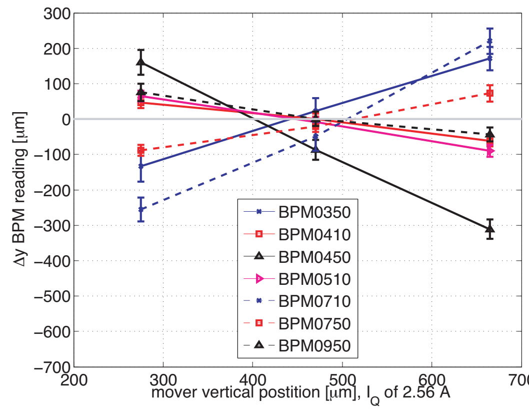

Figure 4: Example of quadrupole alignment using the QST.

CONCLUSIONS

In this work we reported the results of the beam based alignment in the Test Beam Line of CTF3.

The performance of the high gain correction algorithm appears to be limited by the beam orbit and energy drifts and not by the BPMs or movers resolution. To solve this problem a pulse-to-pulse orbit feedback has been set up and tested on the first BPMs of the line: it allowed to follow the CTF3 drifts and the results are in line with the expectation. In fact the residual orbit after correction is dominated by the uncorrelated pulse-to-pulse orbit jitter. After the test of the quadrupole shunting technique and the magnetic test of the TBL quadrupole, we pointed out a potential limit in the pre-alignment methods of the CLIC decelerator quadrupoles if its magnetic centre varies with the gradient: possible solutions are presently under investigation.

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[1] We know the linear response of the system, $\mathbf{R}$, within finite precision: the response matrix used for correction is $\overline{\mathbf{R}} = \mathbf{R} + \mathbf{\Delta R}$ that yields $\mathbf{X_n} = (\mathbf{I} - \overline{\mathbf{R}}^{+}\mathbf{R})^{\mathbf{n}} \times \mathbf{X_0}$, where X_n represents the residual orbit after n iteration. If $\overline{\mathbf{R}}$ is diagonalizable, we can still converge to $\lim_n \mathbf{X_n} = \mathbf{0}$ and only if the eigenvalues of $\mathbf{I} - \overline{\mathbf{R}}^{+}\mathbf{R}$ have module smaller than 1.