BEAM-BASED ALIGNMENT FOR THE CLIC DECELERATOR*

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Abstract

The CLIC Drive Beam decelerator requires the beam to be transported with very small losses. Beam-based alignment is necessary in order to achieve this, and various beam-based alignment schemes have been tested for the decelerator lattice. The decelerator beam has an energy spread of up to 90%, which impacts the performance of the alignment schemes. We have shown that Dispersion-Free-Steering works well for the decelerator lattice. However, because of the transverse focusing approach, modifications of the normal DFS schemes must be applied. Tune-up scenarios for the CLIC decelerator using beam-based alignment are also discussed.

INTRODUCTION

The purpose of the CLIC decelerator is to produce the correct RF power for the main beam, timely and uniformly along the decelerator, while achieving a high power extraction efficiency. Uniform power production implies that the electron drive beam must be transported to the end with very small losses. The transverse motion will be perturbed by quadrupole misalignment as well as wake field deflections.

RF-power is produced by Power Extraction and Transfer Structures (PETS) (more than 1300 for each decelerator sector). The PETS fundamental mode is tuned to the frequency of the bunch train (12.0 GHz), and the field builds up resonantly. This field drains out of PETS with a finite group velocity of β_g=0.46, implying steady-state deceleration after a transient of $\lceil(\frac{l_{PETS}}{z_{bb}})\frac{(1-\beta_g)}{\beta_g}\rceil$ = 11 bunches (z_{bb} is the bunch distance and l_{PETS} the PETS length). Each steady-state bunch will have a substantial energy spread, due to the finite bunch size. Figure 1 shows the energy profile at the end of the decelerator. This paper focuses on transverse beam dynamics. Some complementary topics, including detuning and longitudinal stability, have been discussed in [1].

We start by summarizing the alignment tolerances needed to mitigate the effect of transverse wakes and to provide a starting point for beam-based alignment. We then discuss beam envelope growth and alignment schemes to reduce it. We will see that the large energy spread provides a challenge, suggesting the need for advanced alignment schemes. Input parameters for this study are based on [2], slightly adapted in order to achieve a maximum energy spread at the end of the lattice of $S \equiv (E_0 - E_{min})/E_0 = 90\%$ (reference for the decelerator studies). Details about the parameters and the simulation method are presented in the accompanying paper [3].

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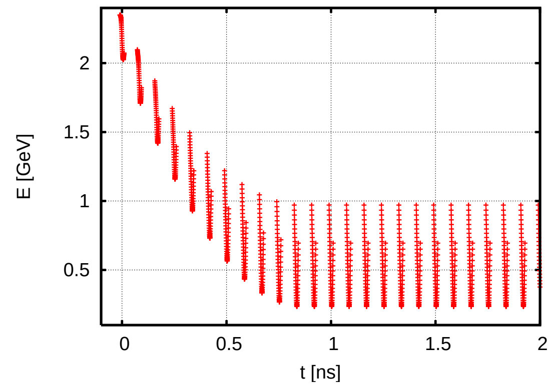

Figure 1: Energy profile after deceleration (start of pulse)

ALIGNMENT TOLERANCES

A study has been performed in order to find the alignment tolerances resulting from beam dynamics requirements [4]. It was required that a single type of misalignment should result in a maximum increase in the beam centroid envelope of 1 mm. For the quadrupoles the resulting misalignment tolerance is not feasible with planned static alignment, and the tolerances given below represents the expected residual error. The tolerances are shown in Table 1, and are used for the simulations in this paper. BPM resolution is further discussed below; initially a value of 2 μm is used.

Table 1: Alignment tolerances

Misalignment	Symbol	Value	Unit
PETS misalignment	σ_{PETS}	100	μm
Quadrupole misalignment	σ_{quad}	20	μm
BPM misalignment	σ_{BPM}	20	μm
BPM resolution	σ_{res}	2	μm
Pitch/roll misalignments	$\sigma_{\theta,\phi}$	1	mrad

BEAM ENVELOPE GROWTH

Simulation Criterion

As simulation criterion for minimum-loss transport we require the entire 3-sigma beam envelope, defined as $r \equiv \max \sqrt{(|x_i| + 3\sigma_{x,i})^2 + (|y_i| + 3\sigma_{y,i})^2}$, to be within half the available aperture, a_0, to have a margin for unmodelled effects of higher order wake fields. There will be $\sim$ 50 decelerator sectors, and we require 99% confidence that all sectors simultaneously adhere to this criterion. This implies that 99.98% of random instances of a single sector must fulfill $r < \frac{1}{2}a_0 = 5.75$mm. It is not feasable to simulate enough machines to do a direct verification of this. Instead, 500 machines are simulated and the tail of the resulting beam envelope distributions will be inspected.

Sources of Envelope Growth

The beam envelope will grow due to the following effects :

- spurious dispersion induced by quadrupole offsets
- adiabatic undamping due to deceleration by the PETS
- transverse kicks due to the PETS dipole wake and RF

The beam is modelled as bunches consisting of slices in z with variable energy and with second order moments to represent the transverse particle distribution of each slice. We first note that since we are interested in the envelope, and not the emittance, the relative orientation of the distribution phase-advances (decided by the lattice chromaticity) is irrelevant for our study. The beam envelope will be determined by the motion of the slice centroids, plus the adiabatic undamping of the distributions. The latter will grow by a factor $\sqrt{\gamma_i/\gamma_f}$, leading to a maximum envelope for a perfect beam going through a perfect machine of $r_{ad} = \sqrt{3^2\sigma_x^2 + 3^2\sigma_y^2} \approx 3\sqrt{2L_{cell}\varepsilon_N/\gamma_f} = 3.3$ mm ($\mu_{cell} \approx 90^o$ assumed).

In order to discuss other contributions to the envelope growth and the choices of steering algorithms, we imagine a ”pencil beam” consisting of centroids only. We denote the maximum centroid offset as r_c. Typical residual misalignments of quadrupole and BPMs will be of the order 20 μm rms. For a regular FODO lattice without deceleration we estimate the final rms centroid offset, due to sporious dispersion, by doing an ensemble average over the sum of quadrupole kicks yielding $r_{c,rms} \approx \frac{\sigma_{quad}}{\cos(\mu_{cell}/2)} 2\sqrt{2N_{cell}}$ =1.8 mm. The PETS will induce additional growth due to adiabatic undamping, RF-kicks and transverse wakes. Including all effects in the simulations we find $r_{c,rms} = 11$mm, where the dipole wake causes an amplification of approximately 20% (PETS design / misalignment tolerances are such that the effect of dipole wakes shall not be dominant [4]). Figure 2 shows the uncorrected total envelope (NC), maximum of 500 machines. We note that it largely exceeds our criterion, implying a need for steering.

STEERING

1-to-1 Correction (SC)

We consider first a simple 1-to-1 correction scheme, where the total beam centroid is steered into the centre of each BPM. Quadrupole movers are assumed as correctors in this study. In Figure 2 we observe the resulting envelope. We see that although the envelope is now much smaller, we still have a significant residual envelope. A particular problem is that the 1-to-1 correction steers the steady-state part of the beam, while the particles constituting the transient high-energy head will move on highly dispersive trajectories, and might drive the envelope. Closer inspection reveals that it is indeed the transient part that drives the envelope. After 1-to-1 correction the beam envelope is slightly larger than our criterion (even for a limited number of machines). This leads us to the study of Dispersion-Free steering, in order to reduce the dispersive error.

Dispersive-free Steering (DFS)

The idea of Dispersion-free steering is to reduce the energy dependence of the centroid trajectories [6]. BPM reading i is related to a corrector kick j via the response matrix element, $b_i = R_{ij}(p)c_j$. For the decelerator, $R_{ij}(p)$ and therefore also b_i, are highly non-linear in the momentun p. However, we assume linear optics, so b_i is linear in c_j. With perfect knowledge of our system, and perfect measurement, we could in principle use correctors to zero the difference between two arbitrary energy centroid trajectories, $y_0(s), y_1(s)$. For several reasons this solution is not attainable in practice; our models are not perfect and the precision of our BPMs is finite, leading to an unstable solution. The difference orbit is therefore weighted against the central orbit, resulting in the following metric to be minimized: $\chi^2 = w_0\Sigma y_{0,i}^2 + w_1\Sigma(y_{1,i} - y_{0,i})^2$ where the relative weighting should be in the order $w_1/w_0 = \sigma_{BPM}^2/\sigma_{res}^2$. Optimal weighting wrt. to r was found by simulation.

We must also ensure that ineffective corrector modes are not applied, because this would lead to large corrector offsets. By doing an SVD-analysis of the resulting matrix, we find indeed that $\sigma_{max}/\sigma_{min} \sim 10^7$. In this study we only include corrector modes with $\sigma_{max}/\sigma \sim 10^3$ or higher, yielding $\sigma_{quad,corrected} < 2\sigma_{quad}$.

Decelerator Challenges: Test-beam

One particular challenge for the decelerator is to find a suitable test-beam for difference-trajectory minimization; a higher energy beam will not be available, a lower energy beam will not be stable with the nominal optics [4]. We solve this by taking advantage of the PETS: since $\Delta E_{PETS} \propto I$, a test-beam with an energy difference increasing linearly wrt. to the nominal beam can be produced by reducing the current. The energy spread of the nominal beam increases linearly as well, therefore we do not get large dispersive errors at the start of the lattice. A practical manner to reduce the current is to use the combiner rings or delayed switching [5] to generate a bunch train with empty buckets. For these simulations we use a test-beam where every 3^{rd} bucket is missing. The net result has been shown to be similar to simply reducing the bunch charge (less practical in the real machine).

Our suggestion for dispersion-free steering has the advantages that the quadrupole strength is kept constant (avoids potential problems with change of quadrupole center with strength), and that the main beam and the test-beam could be combined in one pulse (avoids potential problem with relative offsets of the two beams).

RESULTS

Figure 2 shows the 3-sigma envelope for the cases of no correction (NC), simple 1-to-1 correction (SC) and dispersion-free steering (DFS) with BPM resolution of 2μm. Recalling the minimum achievable performance of $r_{ad} = 3.3$ mm, we conclude that the dispersion-free steering has very effectively suppressed the dispersive errors.

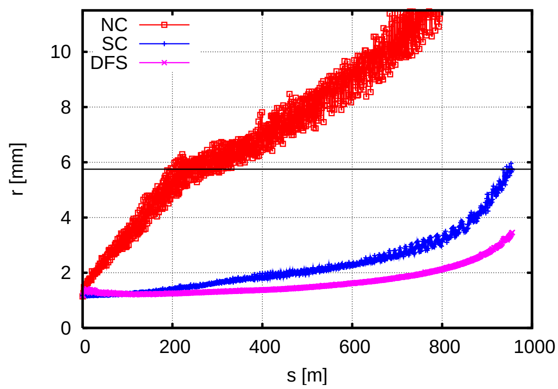

Figure 2: Beam envelope with no correction, simple correction and dispersion-free steering (maximum of 500 machines)

Dependence on BPM Resolution for DFS

For the dispersive -free steering, the maximum envelope depends linearly with σ_{res} when this error contribution becomes dominant ($> 6\mu$m in our case) . Table 2 shows the envelope versus resolution (maximum of all machines).

Table 2: Dependence on BPM resolution.

$\sigma_{\mathbf{res}}[\mu\mathbf{m}]$	1.0	2.0	4.0	6.0	8.0	10.0
r [mm]	3.4	3.5	3.6	3.7	3.9	4.2

Tail distributions versus CLIC target

Figure 3 shows the accumulated distribution of the envelopes for all machines, for the SC case, as well as DFS cases with BPM resolutions ranging from 1μm to 10μm. For a BPM resolution of 1 μm or 2 μm the tails have sharp fall off, while for higher resolutions tail sizes start to increase. Although the data available do not give a precise limit for the BPM resolution required, we do suggest a resolution of $\sigma_{res} = 2.0\mu$m. Requiring more precise BPMs will not improve the performance noticeably, and this choice also indicated good confidence wrt. to our simulation criterion for the entire CLIC.

OPERATIONAL ASPECTS AND TUNE-UP

Transport through an uncorrected machine will lead to losses, on average found to be in the order of several %. For initial alignment we propose to reduce the envelope

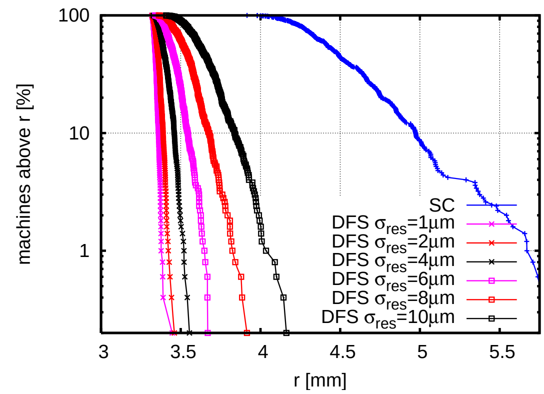

Figure 3: Histogram over all simulated machines

by inserting empty buckets between bunches (yielding less average current, adiabatic undamping and dipole wakes). With a few empty buckets between bunches, simulations show very small average losses. 1-to-1 steering, then DFS can then be performed, and the number of empty buckets can be gradually reduced until nominal beam is reached. This method would require BPMs to be sensitive down to a fraction of the nominal current. Finally, we note that to be robust against current/energy differences between response and real machine, corrections should be performed in bins.

CONCLUSIONS

We have shown that the CLIC decelerator needs beam based alignment in order to achieve small losses during operation, and that dispersion-free steering is an excellent candiate. An appropriate test-beam with empty buckets can be generated using combiner rings or delayed switching. For initial alignment one can use reduced current test-beams, and then increase the current to nominal. We estimate a BPM resolution of $\sigma_{res} = 2.0$ μm to be adequate.

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