BEAM-BASED ALIGNMENT STUDIES AT CTF3 USING THE OCTUPOLE COMPONENT OF CLIC ACCELERATING STRUCTURES

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Abstract

The Compact Linear Collider (CLIC) uses normal-conducting accelerating structures that are sensitive to wakefield effects and therefore their alignment is extremely important. Due to the four-fold symmetry of the structures, they allow for an octupole component of the RF fields. By scanning the beam transversely we can determine the center of the structures from the shifts in beam position due to the kicks from the octupole field. We present some initial results from measurements at the CLIC test facility 3 at CERN.

INTRODUCTION

The Compact Linear Collider (CLIC) [1] is a proposed linear electron-positron collider on the TeV scale based on a normal-conducting technology. To achieve the luminosity of 2×10^{34} cm^{-2}s^{-1}, a nano-meter beam size at the interaction point is required. This puts challenging requirements on low beam emittance coming from the damping rings and emittance preservation in the main linac. The alignment tolerances for the tens of thousands of accelerating structures are very tight since misalignments cause wakefields and emittance growth during acceleration of the beam. Two accelerating structures are mounted together to form a super-structure and every super-structure will be equipped with wakefield monitors for aligning the beam. The wakefield monitors will have a required resolution of 3.5 µm [1], and there are prototypes being tested [2] at the two-beam test-stand at CLIC test facility 3 (CTF3) [3].

The CLIC accelerating structures have four radial waveguides connected to each cell with the purpose of damping wakefields. This four-fold symmetry allows for an octupole component of the RF fields that have the same fundamental frequency as the accelerating field but is phase-shifted 90°. The effect of this octupole component on the beam has been simulated [4] and measured [5, 6]. A beam-based method for aligning the CLIC accelerating structures utlizing this octupole component has previously been proposed [7,8] but not tested experimentally. In this report we present some results from measurements performed at CTF3.

METHOD

Here we present a summary of the method, for a more detailed derivation see Ref.s. [7, 8]. The beam position shifts due to an octupole field can be expressed in complex form as

$$\Delta\hat{X} - \mathrm{i}\Delta\hat{Y} = KL\left\langle\left[\left(x - \tilde{X}\right) + \mathrm{i}\left(y - \tilde{Y}\right)\right]^3\right\rangle \quad (1)$$

where $\Delta\tilde{X}$ and $\Delta\tilde{Y}$ denote the horizontal and vertical position shifts of the beam centroid, L is the distance downstream of the field and $K = \frac{C_3 l}{(B\rho)}$ is the integrated octupole strength normalized to beam energy. Angle brackets indicates averaging over all particles and $\tilde{X}$ and $\tilde{Y}$ denote the transverse offsets. After expanding the right hand side and calculating the expectation values, we get the position shifts as a function of beam centroid position inside the octupole field and the transverse offsets. In order to determine the offsets we scan over different transverse position of the beam centroid and measure the position shifts downstream. For a scan procedure of N steps we can express the fit problem as

$$\begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ \vdots \\ z_N \end{bmatrix} = \begin{bmatrix} 1 & (X_1 + \mathrm{i}Y_1) & (X_1 + \mathrm{i}Y_1)^2 \\ 1 & (X_2 + \mathrm{i}Y_2) & (X_2 + \mathrm{i}Y_2)^2 \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ 1 & (X_N + \mathrm{i}Y_N) & (X_N + \mathrm{i}Y_N)^2 \end{bmatrix} \begin{bmatrix} k_1 \\ k_2 \\ k_3 \end{bmatrix} \quad (2)$$

where (X_j, Y_j) denotes the beam centroid position inside the octupole field. The position inside the field can be varied by steering the beam with magnets or by moving the accelerating structure itself. The left hand side

$$z_j = \Delta\hat{X}_j - \mathrm{i}\Delta\hat{Y}_j - KL\left(X_j + \mathrm{i}Y_j\right)^3 \quad (3)$$

contains the measured beam position shifts $\Delta\tilde{X}$ and $\Delta\tilde{Y}$. The fit parameters k_i are

$$\begin{aligned} k_1 &= 3KL\left(\tilde{X} + \mathrm{i}\tilde{Y}\right)\left(\sigma_y^2 - \sigma_x^2 - 2\mathrm{i}\sigma_{xy}\right) - \left(\tilde{X} + \mathrm{i}\tilde{Y}\right)^3 \\ k_2 &= 3KL\left(\tilde{X} + \mathrm{i}\tilde{Y}\right)^2 - 3\left(\sigma_y^2 - \sigma_x^2 - 2\mathrm{i}\sigma_{xy}\right) \\ k_3 &= -3KL\left(\tilde{X} + \mathrm{i}\tilde{Y}\right) \end{aligned} \quad (4)$$

and from k_3 we get the offsets $\tilde{X}$, $\tilde{Y}$. Note that the fit parameters k_1 and k_2 also depend on the beam size which is not necessarily known. However, only k_3 is needed for determining the offsets.

EXPERIMENTAL SETUP

During 2016 a prototype CLIC module was installed and operational at CTF3. This CLIC module has 4 accelerating structures mounted on a girder controlled by 6 stepper-motors that a allows for 5D (all rotations and x-y translation

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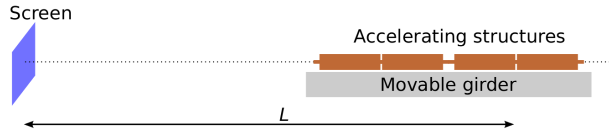

Figure 1: A schematic of the setup. Four accelerating structures are mounted on the movable girder but only the first two (the two on the right) are used. At a distance L downstream of the structure the beam position shifts can be measured with a screen.

Table 1: Experimental Parameters

Parameter [unit]	value
Distance L [mm]	5106
Beam energy [MeV]	194
Integrated octupole strength $C_3 l$ [kT/m^2]	73
Average RF power P_{ave} [MW]	18.6
Uncertainty RF power [MW]	1.8
Girder position interval [μm]	$\pm$1000

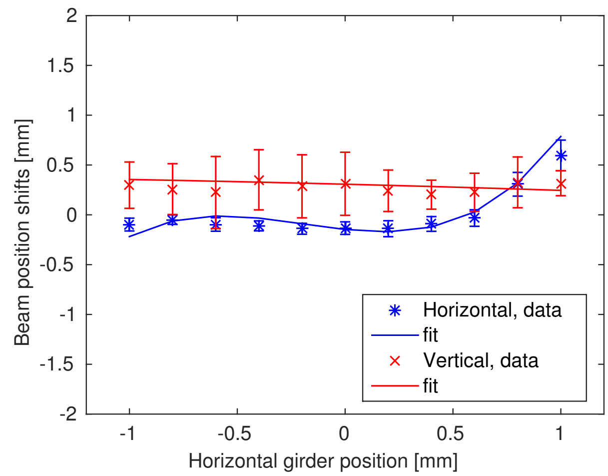

Figure 2: The measured beam position shifts for different horizontal girder positions. A third order behavior in horizontal position shifts is seen as expected.

but not longitudinal translation) position control in a limited range. At the time of this experiment only the first two upstream accelerating structures were significantly powered. A schematic of the experimental setup is shown in Fig. 1. At the two-beam test-stand RF power is delivered by deceleration of a drive beam operating at 0.8 Hz. The probe beam, which mimics the CLIC drive beam, can be operated at twice this frequency. This is very convenient since data from pulses both with and without RF power can be acquired quickly. At a distance L downstream a screen is mounted which makes acquisition of beam images possible. We set up a straight beam using as few magnets for steering and focusing as possible in order to suppress dispersive effects.

Table 1 lists the experimental parameters. The incoming RF power was measured for each pulse and then we calculated the average RF power for the whole scan. The uncertainty in RF power is given by the standard deviation of the measured RF power. The listed integrated octupole strength is valid for CLIC nominal RF power of $P_{nom} = 46$ MW and we have to rescale $C_3 l$ with $\sqrt{P_{ave}/P_{nom}}$ to get the expected integrated strength. In principle, the total uncertainty in KL depends also on uncertainties in L, beam energy and RF phase but in this case these are all negligible due to the large uncertainty in incoming RF power.

RESULTS

We performed a scan using a total of 21 scan steps, i.e. 21 different girder positions. The girder was always moved parallel to the beam. At each scan step, data from a total of 40 pulses where collected where 20 pulses where with RF power and 20 pulses without RF power. From Gaussian fits of the screen images we calculate the average beam position with and without RF power for each scan step. We use the standard deviation of the resulting positions as a measure of the uncertainty. From the beam positions we calculated the beam position shifts and their uncertainties. Then we made a fit according to Eqs. (2)-(3) weighted by the uncertainties. In principle we also have uncertainty in the girder position but this is negligible compared to the uncertainty in the measured beam position shifts and the uncertainty in RF power. Please note that Eq.s (2)-(3) are valid for a single octupole field but in our case we have two consecutive octupole fields. However, since the distance between the two accelerating structures is so small (about 25 cm center-to-center) compared to the distance to the screen, we can treat these as a single kick applied in the middle of the two structures. Furthermore, then we have to use twice the octupole strength and the resulting offsets will be the sum of the offsets of the two structures [8].

Figures 2 and 3 show the resulting position shifts, plotted together with the results from the fit, for horizontal and vertical girder positions. From the real and imaginary parts of fit parameter k_3 we get the resulting offsets $\tilde{X}$ and $\tilde{Y}$:

$$\tilde{X}_{meas} = 392 \pm 53 \mu\text{m}$$
$$\tilde{Y}_{meas} = 6 \pm 92 \mu\text{m}$$

where we note that we had a much larger offset horizontally which we expected due to the quadratic dependence on horizontal position shift when the girder was moved vertically. If the beam was aligned perfectly horizontally we would see no position shifts in horizontal when the girder move vertically. This is what we observe vertically, i.e. when the girder was moved horizontally the vertical beam position shifts are essentially a straight line indicating a small offset vertically. The uncertainty in the vertical offset is larger than the horizontal due to the larger uncertainty in vertical position and vertical position shifts. This was due to vertical beam jitter induced by the laser of the photo injector.

The resulting resolution in this experiment is not sufficient for alignment with tolerance of 3.5 µm as required for

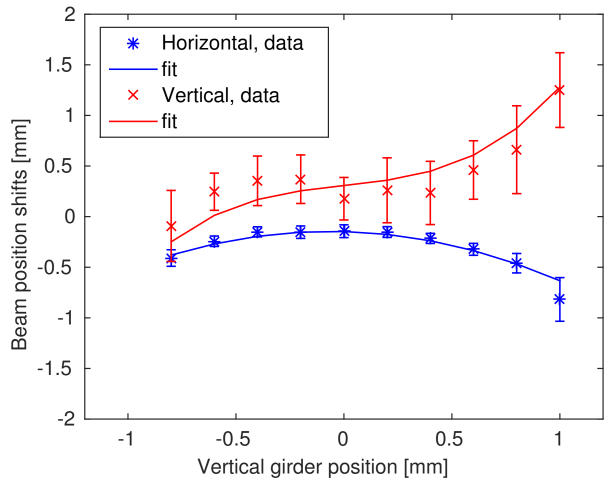

Figure 3: The measured beam position shifts for different vertical girder positions. Now we observe a third order dependence in vertical position shifts as expected. We also observe a quadratic dependence of horizontal position shifts which implies a horizontal offset.

CLIC. But the experiment can be improved in several regards in order to improve the resolution. For instance, we can increase the number of scan steps with the girder. However, at the time the control interface of the girder was completely isolated from the rest of the control system which made automation impossible and thus the scan procedure quite time consuming. In fact, we did another scan with a larger number of scan points but during that scan the RF power was severely reduced which gave poor results. If RF power is too low it means we need a wider scan range in order to get measurable position shifts from the weak octupole field. This in turn increase sensitivity to wakefields and other effects. Thus in order reduce these effects, ideally the maximum RF power should be used with small transverse movements of the girder. We note that in our experiment we had less than half of the CLIC nominal RF power of 46 MW.

Other sources for the large uncertainties in the determined offsets are the incoming beam jitter and fluctuations in RF power. For CLIC the required tolerances for beam jitter of the main beam and also the stability of the RF power delivered by the drive beam are very tight in order to ensure high luminosity. Thus for the CLIC parameters sufficient resolution can be achieved with this method at least for the low energy end of the main linac [7, 8].

Another limitation in achieved resolution comes from the resolution of CCD camera monitoring the screen. However, for this experiment the uncertainty is more likely dominated by fluctuations in RF power and beam jitter rather than the resolution of the CCD camera. Nonetheless, it is worth noting that for CLIC a screen would not be used but instead cavity beam position monitors with resolution of 50 nm. At the time of our experiment CLIC prototype cavity beam position monitors were installed in the beam line but we could unfortunately not use these due to issues with calibration.

CONCLUSION

We measured the transverse misalignments of CLIC accelerating structures at the CLIC test facility CTF3 by utilizing the octupole component of the RF fields. The center of the field can be inferred from the shifts in beam centroid position downstream of the field. The accelerating structures are mounted on movable girders and the beam position was measured on a screen. The resulting transverse offset was measured to 392 ± 53µm horizontally and 6 ± 92µm vertically. The larger uncertainty in vertical direction was due to a larger vertical beam jitter. The achieved resolution overall was limited by the experimental conditions at the time.

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