BEAM-BASED ALIGNMENT OF CLIC ACCELERATING STRUCTURES UTILIZING THEIR OCTUPOLE COMPONENT

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Abstract

Alignment of the accelerating structures is essential for emittance preservation in long linear accelerators such as the Compact Linear Collider (CLIC). The prototype structures for CLIC have four radial waveguides connected to each cell for damping wakefields and this four-fold symmetry is responsible for an octupole component of the radio-frequency fields, phase-shifted 90 degrees with respect to the accelerating mode. The octupole field causes a nonlinear dependence of the transverse beam deflection with respect to the position within the accelerating structure. By transversely moving the beam with two upstream steering magnets, and observing the deflection with beam position monitors or screens, the electromagnetic center of the structure can be found. We discuss the applicability of this method for aligning the beam in the accelerating structures.

INTRODUCTION

The Compact Linear Collider (CLIC) is a proposed lepton collider for physics on the TeV scale [1]. To achieve reasonable compactness, CLIC uses high gradient, normal-conducting accelerating structures. Accelerating gradient of 100 MV/m has been demonstrated experimentally [2]. CLIC will operate with repetition rate of 100 Hz and short macroscopic pulses. Thus in order to achieve luminosity of 2×10^{34} cm^{-2}s^{-1}, the beam size at the interaction point must be in nano-meter size. This puts strong requirements on low emittance from the damping rings and emittance preservation. In order to avoid emittance growth in the main linac there are very low tolerances on misalignment of quadrupoles and acceleration structures since misalignments cause wakefields which deflect the beam and lead to increased emittance. The topic of alignment of accelerating structures has been extensively studied theoretically [3–5] and experimentally [6–8]. The intrinsic mechanical alignment [9] has also been adressed.

In this report we propose a method for aligning the CLIC accelerating structures utilizing an octupole mode of the rf fields that is co-propagating with the accelerating mode. This mode which is 90 degrees out of phase compared to the accelerating mode is known, both theoretically [10] and experimentally [11, 12]. In [12] we measured the strength of the octupolar field and compared to simulations. Since the octupole field is nonlinear, the transverse deflection of the beam is also nonlinear and can be used for finding the center of the structure [13].

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BEAM-BASED ALIGNMENT

The multipole expansion of a field can be written in complex form as

$$B_y + \mathrm{i}B_x = C_{n-1}\,(x + \mathrm{i}y)^{n-1} \tag{1}$$

and $n = 4$ yields the octupole field. The beam kick for an electron, traveling in positive z-direction can be calculated according to

$$\Delta x' - \mathrm{i}\Delta y' = \frac{C_3 l}{(B\rho)}\,(x + \mathrm{i}y)^3 \tag{2}$$

where we have assumed thin lens approximation, $C_3 l$ denotes the integrated octupole strength and $(B\rho)$ the beam rigidity. At a distance L downstream from the octupole field, the beam will have shifted horizontal position $\Delta\hat{x}$ according to

$$\Delta\hat{x} = L\Delta x' \tag{3}$$

and similarly for vertical position shift $\Delta\hat{y}$. In order to determine the position shifts of the beam centroid we average over the particle distribution. By combining (2) and (3) we get

$$\Delta\hat{X} - \mathrm{i}\Delta\hat{Y} = \frac{C_3 l}{(B\rho)} L \left\langle (x + \mathrm{i}y)^3 \right\rangle. \tag{4}$$

We can expand these terms involving x and y and for a Gaussian beam distribution we can easily evaluate the expectation values, e.g. by using the technique described in Appendix A in [12]. If we denote first moments as capital letters, i.e. $\Delta\hat{X} = \langle\Delta\hat{x}\rangle$ and $X = \langle x\rangle$ etc., we obtain

$$\begin{aligned}\Delta\hat{X} &- \mathrm{i}\Delta\hat{Y} \\ &= KL\left[(X + \mathrm{i}Y)^3 + 3\left(\sigma_x^2 - \sigma_y^2 + 2\mathrm{i}\sigma_{xy}\right)(X + \mathrm{i}Y)\right]\end{aligned} \tag{5}$$

where we have defined $K = \frac{C_3 l}{(B\rho)}$ to be the integrated octupole strength normalized to beam energy. Furthermore, (X, Y) denote the beam centroid position inside the octupole field. We note that the position shifts of the beam centroid at a distance L from the octupole field depends on beam centroid transverse position and beam size inside the octupole.

The beam deflection due to the octupole field depends on the transverse position inside the octupole field. We can determine the center of the accelerating structure by measuring the beam position shifts at different transverse positions. By moving the beam parallel to the beam axis using two steering magnets we can control the beam position inside the octupole (X, Y). If the acceleration structure is mounted on a girder we could also move the structure instead. Furthermore, we can measure the beam position shifts using a beam position monitor (BPM) downstream of the structure.

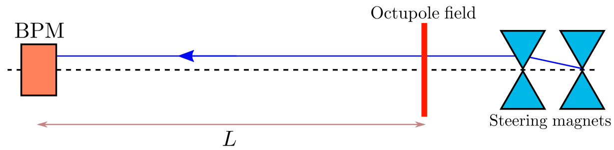

Figure 1: Setup with a single octupole field. The beam can be scanned transversely and parallel to the beam axis by using two upstream steering magnets. We measure the beam position shifts at a distance L downstream from the accelerating structure with the octupole field component.

We will assume that BPMs are used, but screens, wire scanners etc. could also be used. The position shift is given by the difference of beam position when there are rf fields and when there are no rf fields in the accelerating structure. A schematic of the setup is shown in Fig. 1.

We do not know the beam position inside the octupole. However, we can control the position and then we can arbitrarly define a coordinate system inside the octupole field. Then there will be a systematic offset between this coordinate system and the electromagnetic center of the structure. If we can determine this offset we know where the electromagnetic center-axis of the accelerating structure is and thus we can align the beam properly.

From now on we assume that the integrated octupole strength, beam energy, distance between accelerating structure and the BPM are known parameters. The transverse offset $(\tilde{X} + \mathrm{i}\tilde{Y})$ inside the structure is unknown. From (4) we get that

$$\Delta\hat{X} - \mathrm{i}\Delta\hat{Y} = KL\left\langle\left[\left(x-\tilde{X}\right)+\mathrm{i}\left(y-\tilde{Y}\right)\right]^3\right\rangle \tag{6}$$

and we have again used $K = \frac{C_3 l}{(B\rho)}$. The right hand side of (6) contains five unknown variables: the horizontal and vertical position offsets $(\tilde{X}, \tilde{Y})$, beam size σ_x^2, σ_y^2 and correlation σ_{xy}. We collect variables that are known or measurable on the left hand side and rewrite in the following form

$$z = k_1 + k_2\,(X + \mathrm{i}Y) + k_3\,(X+\mathrm{i}Y)^2 \tag{7}$$

where

$$z = \frac{\Delta\hat{X}}{KL} - \mathrm{i}\frac{\Delta\hat{Y}}{KL} - (X+\mathrm{i}Y)^3 \tag{8}$$

and

$$\begin{aligned} k_1 &= 3\left(\tilde{X}+\mathrm{i}\tilde{Y}\right)\left(\sigma_y^2 - \sigma_x^2 - 2\mathrm{i}\sigma_{xy}\right) - \left(\tilde{X}+\mathrm{i}\tilde{Y}\right)^3 \\ k_2 &= 3\left(\tilde{X}+\mathrm{i}\tilde{Y}\right)^2 - 3\left(\sigma_y^2 - \sigma_x^2 - 2\mathrm{i}\sigma_{xy}\right) \\ k_3 &= -3\left(\tilde{X}+\mathrm{i}\tilde{Y}\right). \end{aligned} \tag{9}$$

In order to determine $\vec{k} = (k_1, k_2, k_3)$ we perform a series of measurements with different transverse positions (X_j, Y_j). The fit can be expressed as $\vec{z} = A\vec{k}$ where $\vec{z}$ is a column vector containing the measured position shifts, i.e. $z_j = \frac{\Delta\hat{X}_j}{KL} - \mathrm{i}\frac{\Delta\hat{Y}_j}{KL} - \left(X_j + \mathrm{i}Y_j\right)^3$. The matrix A contains the complex monomials evaluated at each scan step, i.e. horizontal and vertical beam position inside the octupole field. For a scan of N measurements we get

$$\begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ \vdots \\ z_N \end{bmatrix} = \begin{bmatrix} 1 & (X_1+\mathrm{i}Y_1) & (X_1+\mathrm{i}Y_1)^2 \\ 1 & (X_2+\mathrm{i}Y_2) & (X_2+\mathrm{i}Y_2)^2 \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ 1 & (X_N+\mathrm{i}Y_N) & (X_N+\mathrm{i}Y_N)^2 \end{bmatrix} \begin{bmatrix} k_1 \\ k_2 \\ k_3 \end{bmatrix}. \tag{10}$$

We can find the fit parameters k_i of the least squares solution using the pseudo inverse and write the solution as $\vec{k} = \left(A^\dagger A\right)^{-1} A^\dagger \vec{z}$, where † denotes the Hermitian transpose. From the real and imaginary parts of k_3 we retrieve the offsets $\tilde{X}$ and $\tilde{Y}$.

Table 1: CLIC Beam Parameters at the Beginning of the Main Linac [1].

Parameter [unit]	value
Beam energy [GeV]	9
Beta function [m]	10
Normalized emittance, horizontal [nm]	600
Normalized emittance, vertical [nm]	10

NUMERICAL ANALYSIS

In order to estimate the errors in determining the offsets with this method we perform a numerical analysis. We use parameters for the beginning of the CLIC main linac [1], summarized in Table 1. The integrated octupole component at nominal rf power are given from simulations to be 73.5 kTm/m^3 [10]. We assume the distance between the accelerating structure and BPM L to be 3 m. From the emittances and beta functions we can calculate the beam sizes. We assume there is no correlation, i.e. $\sigma_{xy} = 0$. The iris of the CLIC accelerating structure is about 4 mm and we assume that we can move the beam ±1 mm transversely inside the accelerating structure. We scan in a cross, i.e. first scan horizontally and then scan vertically with a total of $N = 40$ points. For this analysis we assume that the offsets are 10 times the rms beam sizes, i.e. $\tilde{X} = 10\sigma_x$ and $\tilde{Y} = 10\sigma_y$. The resulting position shifts for the vertical part of the scan are plotted in Fig. 2. We note that the resulting position shifts are rather small, a few micrometers. By increasing the distance between the accelerating structure and BPM we would increase the resulting position shift.

In order to estimate the errors in the offsets determined from the fits we we add Gaussian random noise to the measured position shifts and then solve (10). The BPM resolution is according to CLIC specifications 50 nm [1]. We assume the error in measured position shift to be $\sqrt{2}\sigma_{\mathrm{BPM}}$ where σ_{BPM} is given by the BPM resolution. The combined parameter KL consists of integrated octupole strength, which in turn depends on rf power delivered from the drive beam. In CLIC the tolerance of rf jitter is such that the resulting gradient should vary no more than 3.6×10^{-4}. We assume that the jitter in KL is no more than 0.1%. The

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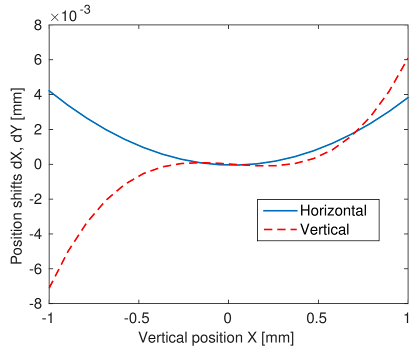

Figure 2: The resulting position shifts at the BPM at different vertical positions inside the octupole field.

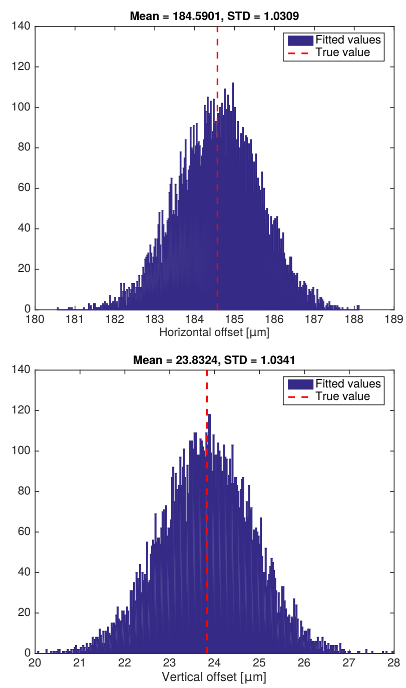

Figure 3: Histograms of the fitted offsets.

assumed parameters are summarized in Table 2. We repeat the whole procedure 10^4 times and plot the histograms of the fitted offsets $\tilde{X}$ and $\tilde{Y}$, see Fig. 3. The resulting errors in the fitted offset are $\sigma_{\tilde{X}} \approx \sigma_{\tilde{Y}} \approx 1\,\mu$m.

Table 2: Assumed Parameters and Errors

Parameter [unit]	value
BPM resolution [nm]	50
Integrated octupole strength [kTm/m^3]	73.5
Distance to BPM, L [m]	3
Error in position shift, $\sigma_{\Delta\hat{X}}$,$\sigma_{\Delta\hat{Y}}$ [nm]	71
Error in KL, σ_{KL} [rel.]	0.1%

Up till this point we have only considered random errors. Now we will consider what happens if we do not know the KL parameter properly. Figure 4 shows a relative systematic error in KL and the resulting relative error in fitted offsets. There is almost a linear relation.

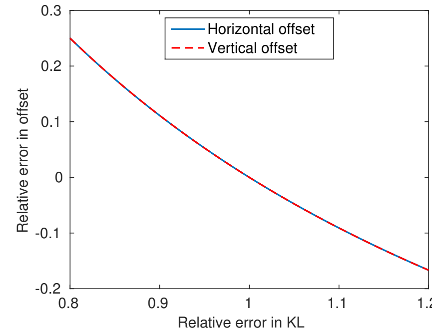

Figure 4: The resulting relative error in fitted offset for given systematic relative error in KL.

CONCLUSION

We demonstrated a method of aligning the beam using an octupole component in CLIC accelerating structures. Assuming CLIC tolerance and no systematic errors and resulted in an error in the offsets of 1 μm. What remains to be done is a full analytical error analysis. In CLIC several accelerating structures will be installed together in a module. This means that it will probably not be possible to power a single structure.

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