A METHOD FOR DETERMINING THE ROLL ANGLE OF THE CLIC ACCELERATING STRUCTURES FROM THE BEAM SHAPE DOWNSTREAM OF THE STRUCTURE

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Abstract

The Compact Linear Collider (CLIC) accelerating structures have a four-fold symmetry from the radial waveguides for damping higher order modes. This symmetry allows for an octupole component of the rf fields to co-propagate with the main accelerating field. The effect of this octupole component has been observed at the CLIC test facility 3. In CLIC the accelerating structures are mounted together on a moveable girders. There are four vertical and four horizontal actuators on the girder, which allows for 5D control in a limited range and for instance we can roll the girder. By observing the beam shape perturbed by the octupole field on a screen downstream from the structure we can determine the roll angle and thus align the structure azimuthally. Here we discuss a possible method and show some results.

INTRODUCTION

The Compact Linear Collider (CLIC) [1] is a proposed linear electron-positron collider with possibility to go to the TeV energy scale. CLIC uses normal-conducting accelerating structures and in order to achieve the target luminosity a nano-meter beam size is required at the interaction point. The small beam size puts strong constrains on low emittance beam from the damping rings and on emittance preservation along the main linac. To avoid emittance growth the CLIC accelerating structures most be aligned with respect to the beam to a micro-meter precision. This is planned to be facilitated by wakefield monitors with a resolution of 3.5 µm connected to the accelerating structures [1].

The four-fold symmetry from the wakefield damping radial waveguides of the CLIC accelerating structure allows for an octupole component of the RF fields that has the same fundamental frequency but is shifted 90 degrees in phase. This octupole component has been known from simulations [2] and measured [3, 4] at the CLIC test facility (CTF3) at CERN. Furthermore, it has been proposed to utilize this octupole component for beam-based alignment of the accelerating structures [5,6], which also have been tested experimentally [7]. In this report we investigate possibility for azimuthal alignment of the structures by determining the roll angle of the beam perturbed by the octupole component of the RF fields. We show some results from simulations and results from an experiment at CTF3 where we used an artificially large beam in the transverse plane and observe the shape of the perturbed beam downstream of the CLIC accelerating structure.

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METHOD

A beam perturbed by an octupole field is subjected to non-linear kicks according to the Lorentz force and the magnetic field for a multipole is given by a multipole expansion which can be written in complex form. For an octupole field we have

$$B_y + \mathrm{i}B_x = C_3\,(x + \mathrm{i}y)^3\,. \tag{1}$$

In the thin lens approximation, the kick can be expressed as

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

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

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

and similarly for vertical position shift $\hat{y}$.

How do we determine the roll angle from a screen image of the perturbed beam? We calculate radial integrals of the beam image and plot the values as a function of azimuthal angle θ. If $f(x, y)$ describes the transverse beam distribution on the screen we can calculate the radial integral for a specific θ as

$$I(\theta) = \int_0^R f(r\cos\theta, r\sin\theta)dr. \tag{4}$$

Then we divide the plane into N azimuthal slices and we write $\theta = \frac{2\pi n}{N-1}$, where $n = 0 \ldots N-1$, and take the discrete Fourier transform (DFT) of this function

$$c_k = \frac{1}{N}\sum_{n=0}^{N-1} I(\theta(n))\mathrm{e}^{-2\pi \mathrm{i}kn/N}. \tag{5}$$

The complex coefficient c_k gives the amplitude and phase of the harmonic k. The amplitude is simply $|c_k| = \sqrt{\mathrm{Re}(c_k)^2 + \mathrm{Im}(c_k)^2}$ and the phase is given by

$$\mathrm{Arg}(c_k) = \tan^{-1}\left(\frac{\mathrm{Im}(c_k)}{\mathrm{Re}(c_k)}\right). \tag{6}$$

Due to the symmetry of the magnetic field we will get a symmetry in the perturbed beam distribution as well. As we shall see, for an octupole field, which has a four-fold symmetry, the fourth harmonic will be accentuated and from the change in phase angle of the fourth harmonic the roll angle can be determined.

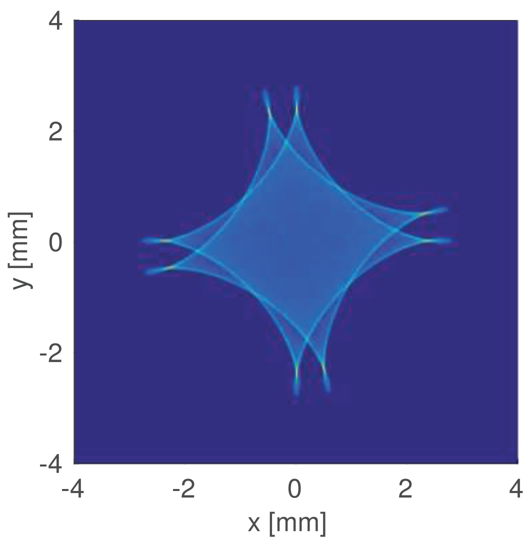

Figure 1: The resulting beam shape for a circular uniform beam perturbed by an upright octupole field and the same beam perturbed by the octupole field rolled 12° counter-clockwise. The four-fold symmetry is clearly visible.

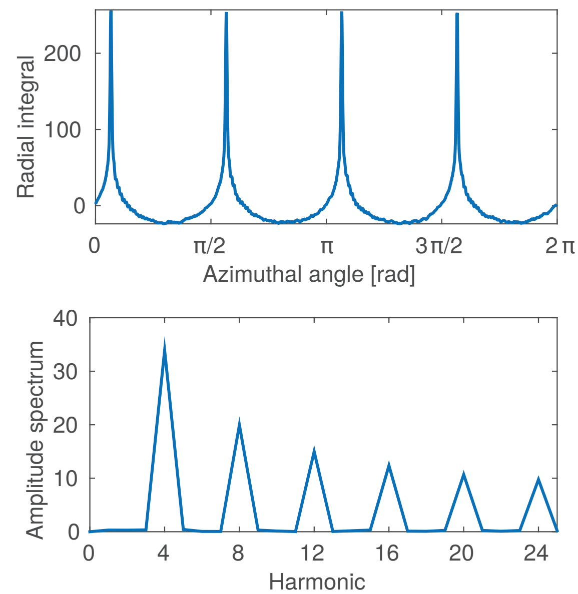

Figure 2: Upper: Radial integrals for 1000 azimuthal slices. The mean value has been subtracted to surpress DC part of the amplitude spectrum. Lower: The first 25 harmonics of the DFT of the radial integral. The DC part i suppressed and we see only the fourth harmonic and its multiples.

SIMULATION

We set up a simple simulation model in MATLAB with incoming beam of 10^6 particles from a uniform circular distribution and no divergence. We track the particle through an octupole field followed by a drift. Then we extrapolate the particles onto a 300×300 pixel grid, which resembles the number of pixels available from the images we used in the experiment in the following section. Figure 1 shows the resulting diamond beam shape from an upright octupole field and an octupole field with a counter-clockwise 12° roll angle.

We calculate the radial integrals according to (4) for 2000 azimuthal slices and for each slice we integrate from the origin to $R = 3.5$ mm. In order to suppress the DC part of the frequency spectrum we subtract the mean value from $I(\theta)$, and then we calculate the DFT according to (5). Figure 2 shows the radial integrals $I(\theta)$ and the amplitude spectrum for the first 25 harmonics for the 12° rolled case. We can clearly see that the fourth harmonic and its multiples, i.e. peaks at 4, 8, 12 etc., dominate the amplitude spectrum. From the fourth harmonic we calculate the phase angle according to (6). We do the same for the upright case and from the difference in phase angles of the fourth harmonics we get 4 times the roll angle, the factor 4 can be understood from the four-fold symmetry of the beam shape. We retrieved the 12° roll within 1 mrad.

EXPERIMENT

This method was tested in the CLIC test facility 3 where a prototype CLIC module with four accelerating structure was installed. However, at the time only two of the accelerating structures where powered. In the CLIC modules, the accelerating structures are mounted on movable girders enabling 5D, precise control of the girder. In addition to transverse movement, this also allows the girder to be rolled ±3 mrad.

We set up a large, straight beam from the CALIFES photo-injector. The small aperture of 4 mm of the CLIC accelerating structure collimates the beam and effectively result in a circular beam. We adjust the RF phase to achieve maximum octupole strength and 5 m downstream from the accelerating structures we observe the beam on a screen. Between the accelerating structures and the screen we had a pure drift since no magnetic elements were active. A sample image of the perturbed beam is shown in Fig. 3 and the radial integral and amplitude spectrum is shown in Fig. 4.

We collected data for a total of 70 pulses: 10 pulses at the original position and 30 pulses with the girder rolled 2.5 mrad counter-clockwise and 30 pulses with the girder rolled 3.5 mrad clockwise. The asymmetric interval was due to starting position of 0.5 mrad roll from the center position. For each pulse we determine the roll angle by calculating and analyzing the radial integral $I(\theta)$ from 2000 azimuthal slices. The uncertainty we find by calculating the mean and rms over the pulses for the three different positions. The results are summarized in Table 1. It is clear from the results that we have measured roll angles in the correct order of magnitude but for all three cases the relative uncertainties exceed 100%. The large relative uncertainties in the measured roll angles are due to the relative large spread in resulting phase angles of the fourth harmonic. We thus conclude that with these experimental conditions we did not

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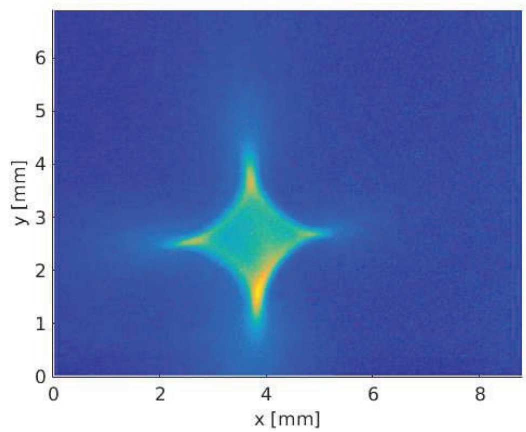

Figure 3: Screen image from measurement at the CLIC test facility of the beam perturbed by the octupole field.

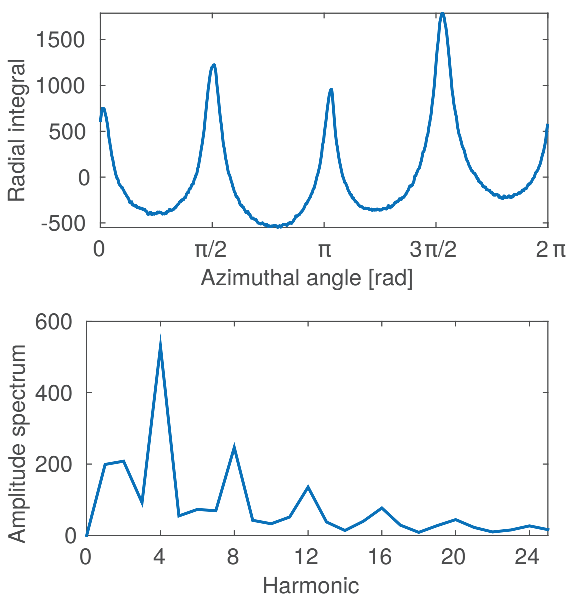

Figure 4: Upper: Radial integrals for 2000 azimuthal slices of the measured beam. Lower: The first 25 harmonics of the DFT of the radial integral. Now we also see first, second and third harmonics in addition to the accentuated fourth harmonic.

achieve sufficient resolution to detect these small girder rolls.

The limited resolution comes from the spread in phase angle of the fourth harmonic for the different pulses. As we have seen in simulations, asymmetry in the incoming beam distribution limits the accuracy in the phase angle of the fourth harmonic. It is evident from Fig. 3 that we do have more particles in the up-down peaks than in the left-right peaks and this is also visible in the amplitude spectrum in Fig. 4. There are several possible sources for this: non-uniform incoming particle distribution or an additional quadrupole component of the RF fields. Also, since we have a pure 5 m drift between accelerating structures and screen, a difference in divergence of the two planes might also result in non-uniform distribution on the screen. Another possible source of spread comes from the rather large fluctuation in delivered RF power from the deceleration of the drive beam. At the time of the experiment we had an average RF power of 22.9 MW with 1.1 MW rms fluctuation.

Table 1: Results: The Measured Roll Angles and Uncertainties for the Three Different Girder Positions

Girder roll angle (mrad)	Measurement (mrad)	Uncertainty (mrad)
2.5	4.5	6.5
3.5	1.7	6.5
6	6.2	7.8

CONCLUSION

We investigated a method for determining the roll angle of a CLIC accelerating structure by observing the beam shape on a screen downstream of the structure. The method is based on calculating radial integrals of the resulting diamond beam and from the Fourier transform we get the phases for the different harmonics and from the fourth harmonic we can determine the roll angle. The method works well on simulated data and was also tested on experimental data from CTF3. However, due to a combination of insufficient range of the roll of the girder in the CLIC module together with jitter of the incoming beam and RF power fluctuations, the resolution was not sufficient to measure the roll angle experimentally.

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