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BEAM TILT CHARACTERIZATION USING PASSIVE STREAKING STRUCTURES

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Abstract

Passive wakefield devices such as corrugated structures have demonstrated great potential for longitudinal phase space control and diagnostics in FELs. In this paper, we will discuss the application of corrugated structures in beam tilt characterization. We show that a tilted beam experiences asymmetric kicks when passing through corrugated metal jaws and the asymmetry of streaked profiles is related to the degree of tilt. Practical implementation of beam tilt correction is discussed.

INTRODUCTION

Passive streaking devices, such as corrugated structures, have emerged as powerful tools for longitudinal beam diagnostics in free-electron lasers (FEL), enabling precise measurements of the temporal beam profile through time-dependent wakefield kicks [1–4]. These devices allow reconstruction of the electron bunch length and longitudinal phase space in FEL beamlines and are critical for optimizing FEL performance. Recent studies have further demonstrated their utility in tailoring longitudinal phase space via wakefield interaction [5–7], underscoring their versatility in beam manipulation and diagnostics. While longitudinal diagnostics are well-established, the characterization of spatiotemporal correlations, particularly beam tilt (X-Z correlation), remains a significant challenge. Such tilts arise in high-brightness beams due to transverse-longitudinal coupling from wakefield effects in accelerating structures or coherent synchrotron radiation (CSR)-induced energy spread during strong compression [8]. These correlations degrade beam quality, leading to suboptimal FEL gain, and are difficult to diagnose with conventional methods.

In this work, we propose a method to characterize beam tilt using corrugated structures. We show that when a tilted beam traverses different corrugated jaws, it experiences asymmetric transverse kicks, producing a corresponding asymmetry in the streaked image. By comparing the streaked profiles from opposing jaws, one can extract information about the tilt magnitude and direction. As a proof of concept, we simulate a tilt correction procedure based on minimizing this asymmetry and demonstrate effective reduction of the beam tilt through upstream optical tuning.

WAKEFIELD OF CORRUGATED STRUCTURES

As most beam tilt occurs in the X-Z plane, we will consider wakefields of a beam with X-Z tilt in a vertical dechirper

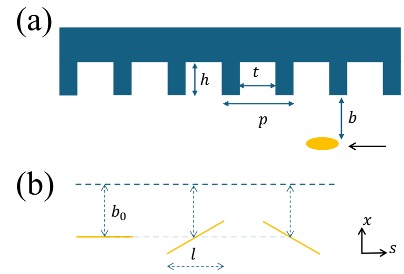

Figure 1: (a) Cartoon of an e-beam near a single plate corrugated structure. (b) Beams with different tilt orientation. $\mu = 0$ (left), $\mu > 0$ (middle), and $\mu < 0$ (right).

that streaks horizontally. The dipole and quadrupole wake functions near the single jaw of a vertical dechirper are given by [9]

$$w_{xd}(s) = \frac{2}{b^3} s_{0x} \left[1 - \left(1 + \sqrt{\frac{s}{s_{0x}}}\right) e^{-\sqrt{\frac{s}{s_{0x}}}}\right] \quad (1)$$

$$w_{xq}(s) = \frac{3}{b^4} s_{0x} \left[1 - \left(1 + \sqrt{\frac{s}{s_{0x}}}\right) e^{-\sqrt{\frac{s}{s_{0x}}}}\right] \quad (2)$$

where s is the bunch longitudinal coordinate with head at $s = 0$ m, b is the particle offset from dechirper plate, $s_{0x} = \frac{8b^2 t}{9\pi\alpha^2 p^2}$, p and t are the period and longitudinal gap of the structure (see Fig. 1), $\alpha = 1 - 0.465\sqrt{t/p} - 0.07(t/p)$.

The dipole and quadrupole wake potential are given by

$$W_d(s) = \int_{-\infty}^{s} \mathrm{d}s' \int_{-\infty}^{\infty} \mathrm{d}b'\; w_{xd}(s - s', b')\rho(s', b') \quad (3)$$

$$W_q(s) = \int_{-\infty}^{s} \mathrm{d}s' \int_{-\infty}^{\infty} \mathrm{d}b'\, \Delta b\; w_{xq}(s - s', b')\rho(s', b') \quad (4)$$

here s' and b' are the longitudinal coordinate and offset of the source particle, ρ is the spatiotemporal profile of the beam, Δb is the horizontal offset between source and probe particle and depends on the form of $\rho(s', b')$. Consider a pencil beam with bunch length l, where its horizontal coordinate x and longitudinal coordinate s are related by $x = \mu(s - l/2)$. Here μ denotes the tilt in the x-s space [8]. As illustrated in Fig. 1(b), the local offset b is then $b = -\mu(s - l/2) + b_0$, where b_0 is the nominal offset of beam centroid to jaw. To model the effect of beam tilt on wakefield kicks, we calculate the dipole and quadrupole wake voltage for a bunch with charge Q passing near a single vertical dechirper plate of length L using the following beam and structure parameters: $l = 60\,\mu$m, $Q = 250$ pC, $L = 2$ m, $p = 500\,\mu$m, $t = 250\,\mu$m, $b_0 = 500\,\mu$m. The results are shown in Fig. 2. For a fixed centroid offset b_0, beams with different tilt values experience different transverse kicks due to the variation in local offset along the bunch. This leads to an asymmetric wakefield

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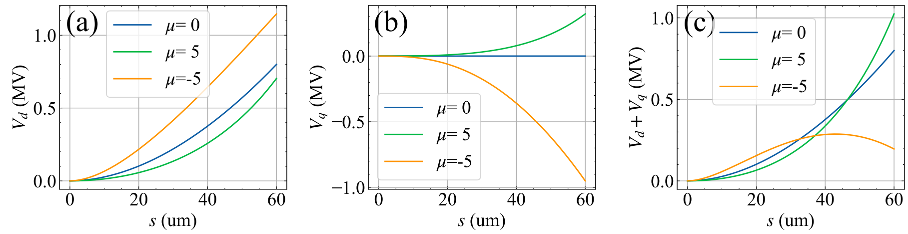

Figure 2: Dipole (a), quadrupole (b) and combined (c) wake voltage for a pencil beam with different tilts.

response which depends on the direction and magnitude of the tilt. A beam without tilt placed near either jaw at the same nominal offset will receive symmetric kicks, resulting in symmetric streaked profiles. In contrast, a tilted beam interacting with opposite jaws will experience distinct and asymmetric streaking effects. This asymmetry in the streaked image—arising from the asymmetric wakefield response near different jaws—can thus serve as a diagnostic signature of beam tilt.

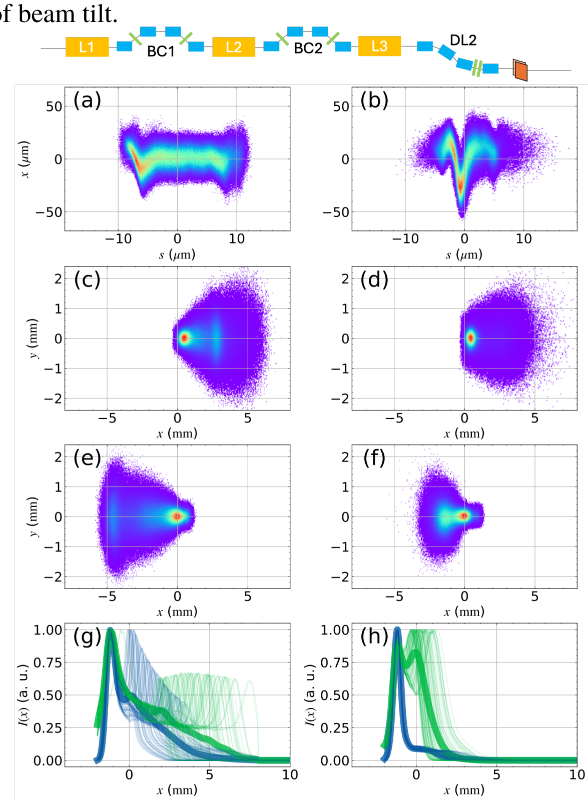

Figure 3: Top diagram: Layout of the LCLS beamline section between the injector and the undulator. (a–b): (s, x) phase space of simulated beam distributions at the dechirper entrance for the nominal (a) and overcompressed (b) beams (head to the right). (c–d): Streaked beam profiles at 100 m downstream with the right jaw inserted, for the nominal (c) and overcompressed (d) cases. (e–f): Same as (c–d), but with the left jaw inserted. (g–h): Horizontal projections of the streaked profiles under beam position jitter, for nominal (g) and overcompressed (h) beams. Thin lines show individual shots; thick lines show the averaged profiles. Profiles from one jaw are mirrored for comparison.

We examine the asymmetric streaking effect of tilted beams using realistic beam distributions in the LCLS beamline. Two electron bunch distributions—representing nominal and overcompressed conditions—were generated in ELEGANT simulation for a beam with charge $Q = 250$ pC and central energy $E_0 = 13.5$ GeV. The spatiotemporal profiles of the two cases at the entrance of the dechirper are shown in Figs. 3(a) and (b). As seen in Fig. 3(b), the overcompressed beam exhibits an obvious tilt in its core region.

We modeled the streaking effect of both beam distributions using a single-plate vertical dechirper, setting the central beam-to-plate offset to $b_0 = 250\,\mu$m. Simulations were performed with OCELOT [10], and the transverse beam profiles were compared after propagation to a screen located 100 meters downstream, with the left and right jaws inserted separately. The resulting profiles are shown in Fig. 3(c-f). For the nominal beam, the streaked profiles appear almost mirror-symmetric for both jaw configurations. In contrast, the overcompressed beam produces markedly different streaked profiles when interacting with opposing jaws—highlighting the sensitivity of the method to beam tilt.

Direct measurement of beam tilt in the X-Z plane typically requires a vertical deflecting cavity, which may not always be available in the beamline due to cost or complexity. As a more cost-effective alternative, comparing the streaked profiles obtained from left and right jaw insertions offers an indirect method of diagnosing tilt. By adjusting upstream optics to minimize the asymmetry between the two streaked images, one can effectively correct for the beam tilt.

A practical limitation of dechirper-based diagnostic method arises from beam centroid jitter and alignment errors. Since the transverse wakefields are highly sensitive to the beam's transverse offset relative to the dechirper plate, shot-to-shot fluctuations in beam position can introduce significant variation in the streaked profiles, complicating tilt diagnosis. To quantify this effect, we added a random horizontal offset of $\pm 50\,\mu$m to the initial beam distributions and propagated them through the dechirper at a fixed nominal offset of $b_0 = 250\,\mu$m. Figures 3(g) and (h) shows the resulting horizontal projections on a downstream screen. Despite the shot-to-shot variations introduced by position jitter, the overall trend remains consistent: beams with tilt produce noticeably asymmetric streaked profiles between left and right jaw configurations. This persistent asymmetry, observable in the averaged projection over many shots, demonstrates the viability of the method as a diagnostic tool for beam tilt, even in the presence of realistic jitter.

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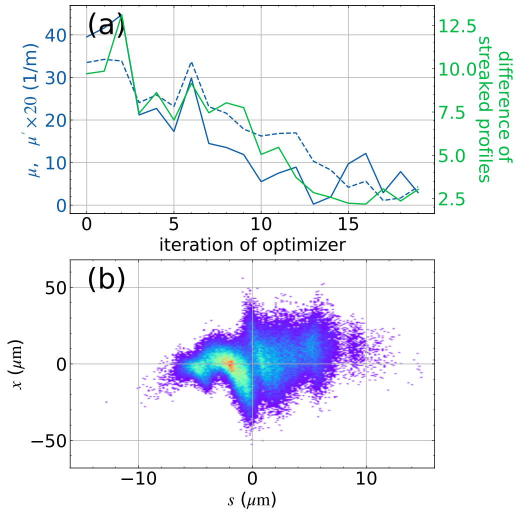

Figure 4: Measured streaking profiles for nominal (top row) and overcompressed beams (bottom row) when vertical dechirper is inserted from opposite sides.

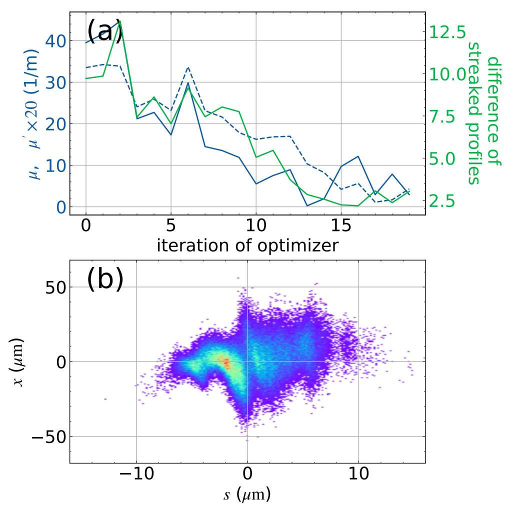

Figure 5: Simulated tilt correction. (a) Evolution of beam tilt μ (blue, solid) and scaled μ' (blue, dashed) as well as the difference of streaked profiles (green, solid). (b) (s, x) phase space of optimized beam distribution after tilt correction.

We verify the asymmetric streaking effect experimentally at LCLS beamline using a vertical dechirper for both nominal and overcompressed beams. The beam was first aligned with respect to both jaws using downstream beam position monitors (BPMs) while both jaws were inserted, ensuring equal centroid offsets. The jaws were then retracted one at a time to isolate the streaking effect from either side. Figure 4 shows representative streaked profiles after filtering based on upstream BPM readings and charge. As predicted by simulation, the overcompressed beam exhibits a more pronounced asymmetry between the left and right streaked profiles compared to the nominal beam.

SIMULATED TILT CORRECTION

Beam tilt can be corrected in dispersive sections of the beamline using multipole magnets [8]. To further evaluate the feasibility of the proposed diagnostic method, we perform a simulated tilt correction by adjusting quadrupoles located in the chicanes and doglegs—highlighted in green in Fig. 3. Starting from the tilted beam distribution shown in Fig. 3(b), we use the difference between streaked profiles from opposing jaws as the figure of merit for optimization.

In this optimization, we tune six quadrupoles in ELEGANT simulation to minimize the asymmetry between the left- and right-jaw streaked images. The resulting beam distribution at the entrance of the dechirper is then used in OCELOT to simulate the streaking effect from a single dechirper plate, The evolution of the profile difference in optimization is shown in Fig. 5(a). As the difference between the streaked profiles decreases, both the beam tilt μ and angular tilt μ' (the correlation between x' and s) are simultaneously reduced, demonstrating the effectiveness of the correction procedure. In practice, achieving this requires careful tuning to alternately minimize μ and angular tilt μ', as they are corrected at different phase advances. By varying the upstream optics to shift the phase advance between the dechirper entrance and the correction quadrupoles, one can effectively target each component in turn.

Figure 5(b) shows the spatiotemporal beam profile at the dechirper entrance after optimization. Compared to the initial distribution, the beam tilt is significantly reduced. These results confirm that asymmetric streaking can be used not only to diagnose but also to guide the correction of beam tilt in practice.

CONCLUSIONS

We have proposed a novel method for characterizing and correcting beam tilt in the X-Z plane using passive streaking with corrugated structures. By analyzing the asymmetry in streaked beam profiles obtained from opposite dechirper jaws, the magnitude of beam tilt can be diagnosed and then minimized via upstream optics tuning. Our simulations confirm the sensitivity and robustness of this method even in the presence of realistic beam position jitter.

However, practical challenges remain for robust implementation of this technique. Mechanical misalignments or jaw tilts could introduce additional asymmetries, potentially limiting measurement accuracy. Future work involves quantifying these effects, improving alignment tolerances, and validating the approach under realistic operational conditions. Overall, the continued improvement and integration of passive wakefield-based diagnostics promise enhanced capabilities for spatiotemporal beam control in high-brightness FELs.

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