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2D OPTICAL STREAKING FOR ULTRA-SHORT ELECTRON BEAM DIAGNOSTICS*

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Abstract

We propose a novel approach to measure short electron bunch profiles at micrometer level. Low energy electrons generated during beam-gas ionization are simultaneously modulated by the transverse electric field of a circularly-polarized laser, and then they are collected at a down-stream screen where the angular modulation is converted to a circular shape. The longitudinal bunch profile is simply represented by the angular distribution of the electrons on the screen. We only need to know the laser wavelength for calibration and there is no phase synchronization problem. Meanwhile the required laser power is also relatively low in this setup. Some simulations examples and experimental consideration of this method are discussed.

INTRODUCTION

At Linac Coherent Light Source (LCLS), an S-band RF transverse deflector (TCAV) is used to measure the bunch length with a resolution 10 femtosecond (fs) rms [1]. An X-band deflector (wavelength 2.6cm) is proposed recently to improve the resolution [2]. However, at the low charge operation mode (20pC), the pulse length can be as short as *fs*. It is very challenging to measure femtosecond and sub-femtosecond level bunch length. One of the methods is switching from RF to μm level wavelength laser to deflect the bunch. A powerful laser (~10s GW) is required to deflect such a high energy beam (GeV) in a wiggler. Synchronization is another difficulty: the jitter between the bunch and the laser can be larger than the laser wavelength, which makes single-shot measurement impossible.

To reduce the laser power, we propose to use ionized electrons from high energy electron beam and gas interaction for high energy electron bunch diagnostics. Similarly, the femtosecond X-ray streak camera uses X-ray ionization electrons to measure the X-ray pulse [3]. The electrons generated by beam-gas ionization have low energy (eVs). Therefore, a lower laser power is possible to deflect such low energy electrons. Note that there is no field ionization in our case. To avoid field ionization, which occurs in plasma case, gases species with high field ionization threshold should be considered.

For a linear polarized laser, the kick to the ionized electrons depends on the phase of the laser when the electrons are born and the unknown timing jitter between the electron beam and laser beam makes the data analysis very difficult. Here we propose to use a circular polarized laser to do a 2-dimensional (2D) streaking (both x and y) and measure the bunch length from the angular distribution on the screen, where the phase jitter causes only a rotation of the image on the screen without changing of the relative angular distribution. Also we only need to know the laser wavelength for calibration. A similar circular RF deflecting mode was used to measure long bunches [4]. We developed a numerical particle-in-Cell (PIC) code to study the dynamics of ionization electrons with the high energy beam and the laser beam.

PRINCIPLE

The electric field of an elliptical laser is

$$E_L(t) = \frac{E_0(t)}{\sqrt{1+\varepsilon^2}}\left\{\cos(\omega_L t+\varphi)\mathbf{e_x} + \varepsilon\sin(\omega_L t+\varphi)\mathbf{e}_y\right\} \quad (1)$$

Where E_0 is the amplitude of the laser field and ω_L is the angular frequency of the laser beam. Here ε=0 is a linear polarized laser and ε=1 is circular polarized one. The ionization electron has low energy and the effect of magnetic field on it can be neglected. The ionized electrons born at time t_0 receive momentum kicks during the passage of the laser pulse:

$$\Delta\mathbf{P}(t_0) = e\int_{t_0}^{\infty}\mathbf{E}_L(t)dt\,. \quad (2)$$

For a linear polarized laser, it becomes

$$\Delta P_x(t_0) \approx \frac{eE_{0x}(t_0)}{\omega_L}\sin(\phi_i)\,. \quad (3)$$

Where $E_{0x}(t_0)$ and ϕ_i are the laser field strength and phase when the ionization electron is born. The high energy beam (GeVs) and laser propagate in the same direction. It is a good assumption that they travel with the same speed c and the phase shift between them during the short ionization box length can be neglected. Therefore the laser phase seen by ionization electrons born at different beam longitudinal position z (in high energy beam frame) is given by $\phi_i(z) = \omega_L z/c + \phi_0$. Note that there is a similar dependence on the phase in the TCAV case.

For a circular polarized laser, the momentum kick on the ionized electrons due to the laser field is

$$\Delta\mathbf{P}_\perp(t_0) \approx \frac{eE_0(t_0)}{\sqrt{2}\omega_L}e^{i\phi_i}\,. \quad (4)$$

Both the kick strength and kick angle depend on the position of electrons where they were born along the high energy beam in z. If $E_0(t_0)$ is constant during the short period of bunch pulse (for instance, the length of laser pulse is much larger than the electron bunch length and electron bunch meets the laser during the laser peak field region), then all electrons receive the same amount of transverse kicker with the angle linearly dependent of

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their position in z. The probability of ionization process is proportional to the number of high energy electrons. Therefore the ionization electrons have the same z distribution as the bunch profile. As a result, the angular distribution of electrons on the screen gives the bunch longitudinal profile

$$\rho(\phi_i) = \rho(\omega_L z / c + \phi_0) = \rho(2\pi z / \lambda_L + \phi_0). \quad (5)$$

If an electron bunch has bunch length Δz, the ionization electrons on the screen will form an arc of a circumference with angular width $\Delta\phi$, one can simply determine Δz as

$$\Delta z = \lambda_L \Delta\phi / 2\pi. \quad (6)$$

Therefore, the wavelength of the laser should be larger than the full bunch length, otherwise, the image on the screen will be longer than one circle and one can't distinguish the real bunch length. On the other hand, the wavelength of the laser should be the same order as the bunch length for an accurate measurement.

SET UP OF THE EXPERIMENT

Fig. 1 shows a sketch of the experimental set-up. The laser beam and electron bunch overlaps at the gas box (a nozzle is shown in Fig. 1) and ionization electrons are generated there. They are transversely deflected by the laser field and are longitudinally accelerated by a DC field to the screen located at downstream and form a circular image on the screen.

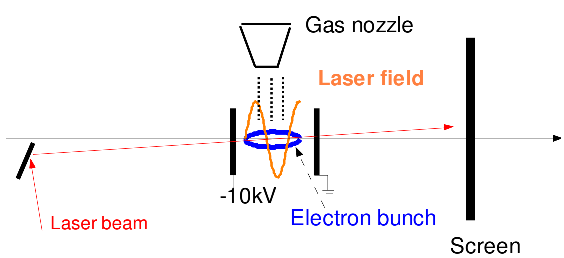

Figure 1: Schematic illustration of the experiment set-up.

SIMULATIONS

A PIC code has been developed to study the interaction of the charged particle with the laser beam and other types of fields. Some of the subroutines are adapted from 3D PIC code CLOUDLAND [5]. Table 1 shows the main parameters used in the simulations. Helium is chosen to avoid field ionization due to its high threshold of field ionization. The self-field of ionized particles is not included in the present study, which can be done when there is a realistic design of the experiment.

Fig. 2 shows a simulation with only the laser field. The image on the screen is perfectly a part of circle and the angular distribution reproduces the beam profile with a Gaussian distribution. The radius of the circle is proportional to the distance from the ionization box to the screen and the square root of the laser power.

Table 1: Main simulation parameters

Description	Value
Bunch charge	20pC
rms bunch length	1μm
rms transverse beam size	5μm
Gas species	Helium
Vacuum pressure	1.0×10^{-5}Torr
Ionization length	10mm
Distance from gas box to the screen	200mm
Laser FWHM	500fs
Laser wavelength	10μm
Laser peak power	1~5GW
DC voltage	10kV

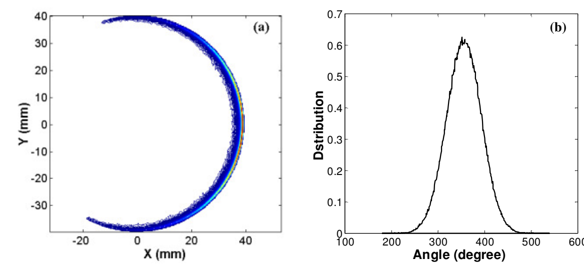

Figure 2: Image on the screen and its angular distribution, with laser field only.

Effect of timing jitter

The timing jitter between the electron bunch and laser converts to an angular jitter on the screen (Eq.4). Fig.3 shows the electron distributions on the screen with different phases 0^o, 90^o and 180^o. The phase simply rotates the image but without change of the distribution. We are interested in the relative angular distribution only. Hence this angle shift doesn't cause any problem on the data analysis. The circular polarized laser overcomes the timing issue and makes the measurement much easier. The small dot shape in the images is a marker of the tail of the bunch, so that we can clearly identify the rotation of the image.

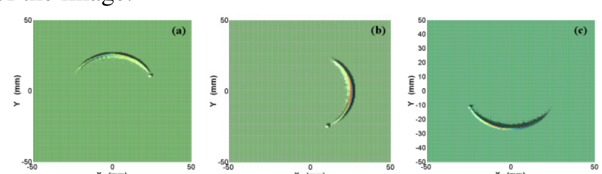

Figure 3: Dependence of screen image on the phase between the laser and electron bunch: 0^o(left),90^o(middle) and 180^o (right).

Effect of the field of high energy beam

The low energy electrons also see the field of high energy beam besides the laser field. For instance, the electric field of round Gaussian beam is

$$E_r = \frac{r_e m_e c^2}{e} \lambda_e \frac{2}{r}\left[1 - \exp\left(-\frac{r^2}{2\sigma_r^2}\right)\right] \quad (7)$$

The peak electric field near r=1.58σ_r with the parameters shown in Table 1 is about 13.0 *GV/m*. The beam field could spoil the image on the screen. Fig. 4. shows the results with both laser and beam fields. The beam field spreads out the particles distribution on the screen. The particles generated by the tail of the bunch are less spoiled because of the less effect of the beam's field. However, the angular distribution doesn't change much as shown in the figure. Therefore, we still can get accurate longitudinal beam profile even with the strong beam field, provided that the laser power is larger enough as discussed in the following.

The shape of image on the screen varies with beam and laser due to the dynamic effects. Fig. 5 shows the electron distribution on the screen for the case of a larger beam rms size 10 μm and 15 μm. For a larger *rms* beam size, the beam's field becomes weaker; therefore, a lower laser field is required. However the required laser power actually increases becomes the power is proportional to square of the area. As a result, a small beam size at the ionization box position is desired to reduce the required laser power.

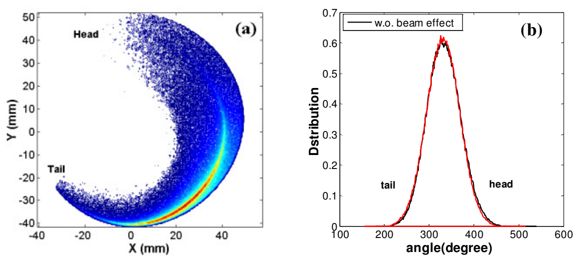

Figure 4: Image on the screen and its angular distribution with both beam field and laser field. The laser power is 1.2*GW* with a waist of 30*mm*.

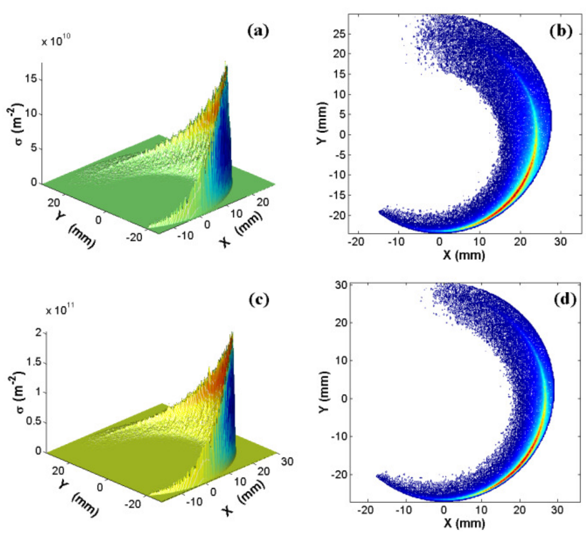

Figure 5: Particle area density (left) and image (right) on the screen with different beam size and laser power. (Top) the *rms* beam size is 10μm and the laser power is 1.8*GW*; (Bottom) The *rms* beam size is 15μm and the laser power is 5.0*GW*.

Effect of laser power

The required power of the laser mainly depends on the beam. First, the radius of the image varies with the laser field; Secondly, the laser field has to be strong enough comparing with the beam's field so that the beam's field doesn't spoil the angular distribution. Fig.6 shows the effect of laser power. With a weak laser power 0.45*GW*, the distortion of the profile is clearly shown. When the power is larger than 0.9*GW*, the profile agrees well with the expected Gaussian distribution and it doesn't change with laser power. Roughly speaking, the required laser field should be stronger than the peak filed of the bunch beam. Another important parameter is the laser waist. The waist should be larger enough than the beam's *rms* size so that the laser field seen by the electrons doesn't vary significantly.

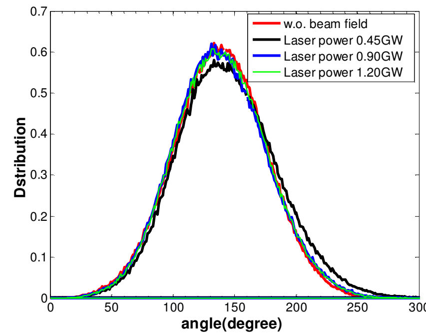

Figure 6: Effect of laser power on the angular distribution of the particles on the screen.

DISCUSSION AND SUMMARY

A PIC code has been developed to simulate the 2D optical streaking for ultra-short (~<μm) electron beam diagnostics using circular polarized laser and ionization electrons. The required laser power is at the order of 1GW for LCLS beam. The synchronization is not an issue and the bunch length can be easily calibrated. The strong beam's field spoils the distribution of the image, which can be mitigated by applying a strong laser field. Helium gas is chosen to avoid field ionization. One drawback of this method is the bunch length should be shorter than the wavelength of the laser. Therefore, this method only works for short bunch length measurement. It is possible to combine RF and optical deflector for long bunch measurement [6]. The similar approach may be used for the measurement linear polarized X-ray. However, the energetic ionization electrons with certain angular distribution may complicate the measurement.

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