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TEMPORAL CHARACTERIZATION OF ELECTRON BUNCHES FROM SELF-INJECTION AND IONIZATION INJECTION IN A LASER WAKEFIELD ACCELERATOR

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Abstract

Plasma based accelerators (PBAs) have a proven capability to generate high energy electron beams with ultrashort duration (~ 10 fs) and high peak current (~ 10 kA), which opens the opportunity for compact free electron lasers. To meet the requirements of such challenging applications, controllable injection is highly needed to produce high-quality and highly stable electron beams. As we know, the beam parameters, including the current profile, strongly depend on the injection process. To explore the underlying physics and optimize beam parameters in PBAs, a temporal characterization is highly required for different injection schemes. Based on coherent transition radiation(CTR) method, the preliminary experiment to measure beam temporal profiles from both self-injection and ionization injection schemes in a single-shot mode has been performed at Tsinghua University. And the simulations using the similar experimental parameters have been performed to interpret the different injection processes, which show some agreement with the experimental results, especially for the features of bunch durations.

INTRODUCTION

Plasma based accelerators have the potential to attain a large acceleration gradient on the order of 100 GeV/m, three orders of magnitude larger than that in conventional radio-frequency (RF) accelerators [1,2]. Recently, many experimental and theoretical studies have shown that PBAs can generate high-quality electron beams [3-5], which demonstrates the feasibility of PBAs for challenging applications of X-ray free electron lasers (X-FEL) and high energy colliders in a compact size [6, 7].

It is known that controllable injection is critically important for the generation of high quality stable electron beams in PBAs. Besides its high energy gain and special transverse beam characteristics, the temporal features (bunch duration and current profile) of electron beams are also crucial for the application of PBAs. To better understand the underlying mechanism of injection processes and to improve the performance for the application of LWFA, it's necessary to study the temporal characteristics of beam for different injection schemes.

The bunch length of beam generated from PBA is mostly dependent on the injection process, typically at the level of few femtoseconds [8,9], thus the measurement with sub-femtosecond resolution is needed. For the common used methods of current profile measurement in conventional accelerators, such as transverse-deflecting structures and electro-optic methods [10,11], this resolution is difficult to achieve. So the CTR spectrum based on frequency-domain method [8,12,13] are utilized to measure ultrashort electron beams generated from a laser wakefield accelerator in this paper.

THEORY

When the beam passes through a boundary of two media with different refractive index, transition radiation is emitted. The transition radiation energy distribution of beam having N_e electrons can be given as [14,15]:

$$\frac{d^2W}{d\omega d\Omega} = \langle\frac{d^2W_e}{d\omega d\Omega}\rangle[N_e + N_e^2|F(\omega,\theta)|] \tag{1}$$

where ω is the radiation frequency, Ω is solid angle at observation direction, which has an angle θ between beam direction. $\langle\frac{d^2W_e}{d\omega d\Omega}\rangle$ is the weighted average of transition radiation for single electron which is given as Ginzburg-Frank formula:

$$\frac{d^2W_e}{d\omega d\Omega} = \frac{r_e m_e c}{\pi^2}\frac{\beta^2\sin^2\theta}{1-\beta^2\cos^2\theta} \tag{2}$$

where r_e, m_e and c are the classical electron radius , electron mass and the speed of light respectively,and $\beta = v/c$ is the normalized velocity of electron. In the right-side of Eq. (1), the term including N_e^2 is the coherent transition radiation mainly for wavelength $\lambda \gg \sigma_z$ (beam length), which contains the information of beam shape, while the term including N_e is incoherent radiation mainly for $\lambda \ll \sigma_z$. Since the form factor $F(\omega,\theta)$ is Fourier transform of beam profile, we can reconstruct the beam current profile using the CTR spectrum. For the beam generated in a LWFA, typical beam length is about few femtoseconds to tens of femtoseconds, thereby causing CTR spectrum mainly located at infrared band.

BEAM CURRENT MEASUREMENT BASED ON CTR

The experimental setup is shown in Fig. 1. A 40-fs, 500-mJ drive laser is focused to a spot size of $w_0 = 10\ \mu$m by an off-axis parabola (OAP) of focal length $f = 480$ mm with 55% enclosed energy ratio. The plasma is created by laser ionization of helium gas or mixed gas in a 2 mm-diameter supersonic gas jet, and the density is measured to about 1-2×10^{19} cm^{-3} with a wave-front sensor. To

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generate the transition radiation and block the remanent drive laser, a 72 μm-thick aluminium tape with is placed 7 mm away behind the gas jet. The forward CTR is collected by OAP1 (f = 190 mm) after reflected by a gold-coated silicon wafer. Another two OAPs (OAP2 of f = 300 mm and OAP3 of f = 100 mm) are used to collimate the CTR into a homemade mid-infrared (MIR) spectrometer with a 2.5 mm-width CaF_2 prism.

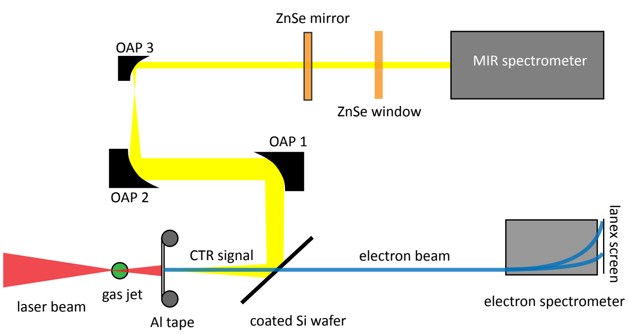

Figure 1: The experimental setup for bunch profile measurement based on CTR method.

The range of our MIR spectrometer is from 1 μm to 8 μm, limited by the trade-off among the transmission of CaF_2, the chip size and the pixel size of infrared camera (Pyrocam-III from Ophir Photonics). A ZnSe 0-degree mirror with high reflective broadband coating (700 nm-900 nm) is inserted to avoid the damage induced by the leaked 800 nm laser, and a ZnSe window is used to transfer CTR out of vacuum chamber. Considering ~ 30% total transmission efficiency and ~ 50% collection efficiency, only 10%-15% energy of CTR can be finally detected by MIR spectrometer

RESULT

The beam was self-injected when pure helium gas was used and the plasma density was measured to about 1.5×10^{19} cm^{-3} in this case. Ionization injection occured when a mixed gas of helium(99%) and nitrogen(1%) was used and the plasma density was about 1×10^{19}cm^{-3}.

The typical profiles and energy spectra of electron beams are shown in Fig. 2, with a broad energy spread and ~100 MeV maximum energy gain for both injections simulation results. However, there is a slight difference for the beam charges, ~ 70 pC for self-injection while ~ 46 pC for ionization injection.

Figure 3 show the CTR spectra, and the reconstructed the current profiles based on Kramers-Kronig(KK) [16] and Gaussian-fitting methods. To reliably retrieve the phase in KK method, the spectrum need to be fully known, thus the missing low frequencies are extrapolated using a Gaussian function(blue lines in Fig.3(a) and (b)). It is found that the triangular shape with different durations is obvious for these two current profiles generated by different injection schemes(seen in Fig. 3(c) and (d) respectively). To avoid the inaccuracy caused by minimal phase retrieve from KK

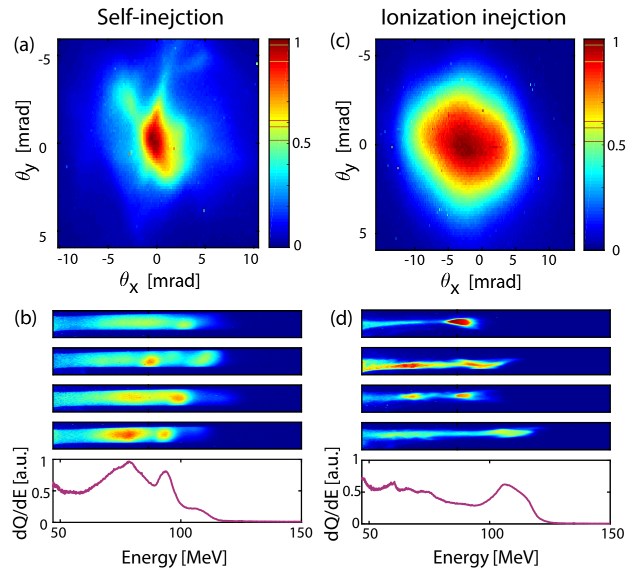

Figure 2: Typical electron beam profile(a)(c) and energy spectrum(b)(d) in different injection schemes.

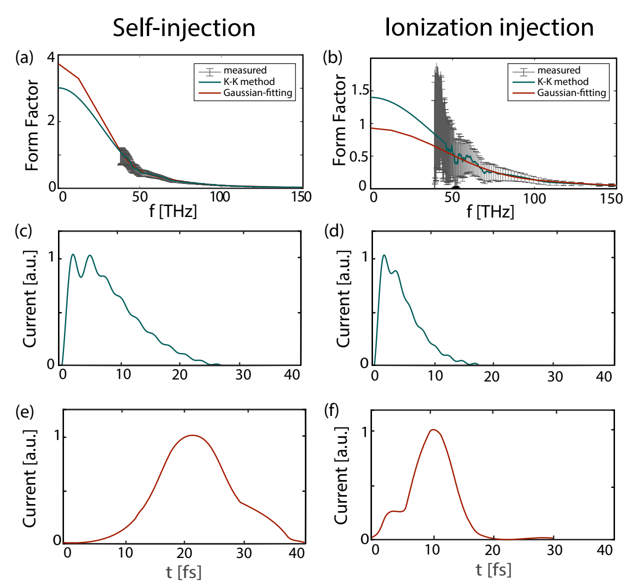

Figure 3: CTR spectra and reconstructed current profiles: The CTR spectrum (a)|(b), reconstructed current profile by KK method (c)|(d) and Gaussian fitting method (e)|(f) for self-injection|ionization injection.

method as far as possible, another reconstruction algorithm is used for a benchmark. By analysing the beam profiles and energy spectra in Fig. 2, one can see that the spectra usually have two peaks, which suggest that two beamlets exist for the beam current profiles. Therefore, a Gaussian fitting method are used to assume the current profile formed by of two Gaussian beamlets with a fixed time delay, and the results are showed in Fig. 3(e) and (f).

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DISCUSSION

According to the measured results, the bunch duration of ionization injection is shorter than that of self-injection based on these two above reconstruction methods. It is also found that the current shapes for injection schemes are similar when using the same reconstruction method, which means that the reconstructed results largely depend on the initial assumptions, and the direction of profile can't be distinguished due to the lost phase information

To verify the correctness of the measurement and reconstruction, three-dimensional particle in cell OSIRIS [17] simulations have been carried out using the similar experimental parameters. The simulation window has a dimension of 40.6μm×38.1μm×38.1μm with 1280×450×450 cells in the x, y and z directions, respectively.

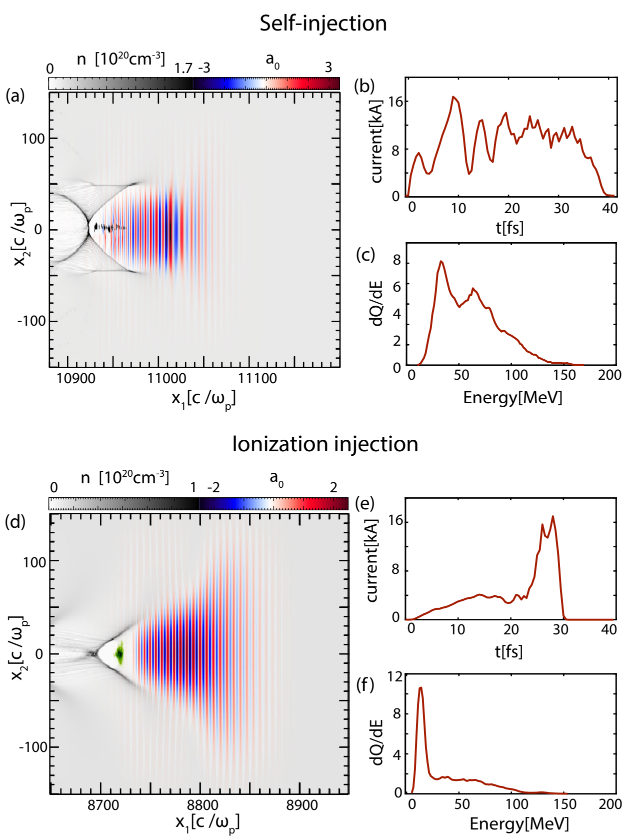

Figure 4: Simulation results of self-injection(a-c) and ionization injection mechanisms(d-f) in LWFA: snapshots (a)(d), current profiles (b)(e) and energy sprectra (c)(f).The plasma, laser field, and trapped ionized electrons are showed in colors of gray, blue-red, and green, respectively.

Figure 4 show the beam current profiles in these two cases are different: the current profile of self-injection is flat and that of ionization injection is composed of a short peak and a long tail. The tail in ionization injection has a low energy gain and low charge, including its relevant spectrum mainly located in low frequencies range, which inevitable leads to the only record of high peak section of current profiles caused by the missing low frequency and large signal-to-noise ratio for CTR spectra. The finial result obtained from experimental data is agreed with simulation in some aspects: the bunch length is 30-40 fs for self- injection, and that of the peak current of ionization injection is ∼ 10 fs long.

SUMMARY

The current profiles of electron beams generated from self-injection and ionization injection in a LWFA have been measured and reconstructed from CTR spectra. The beam duration of high current peak generated in ionization injection is shorter than that in self-injection. The diverse temporal features of electron beam generated in a laser wakefield accelerator are usually caused by the different injection processes. Since the beam current reconstruction rely on the phase retrieve and the measured spectrum (signal-to-noise ratio and spectrum range), the electron charge should been optimized and the CTR spectrometer should cover the full involved spectrum to further achieve reliable results.

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