MONOENERGETIC ELECTRON BEAMS WITH ULTRALOW NORMALIZED EMITTANCE GENERATED FROM LASER-GAS INTERACTION *

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Abstract

High quality electron bunches were generated by using 2 TW, 80 fs high contrast laser pulses interacting with helium gas targets. In optimized experimental condition, we got tens of MeV monoenergetic electron beams with small energy spread and the normalized emittance reaches 0.07π mm·mrad. Experimental and simulation results show that proper plasma densities make the injection more stable and the acceleration length much longer on the premise of self-modulation and self-trapping, which significantly reduce the beam size and the divergence angle. Due to their ultra small emittance and high initial energy, such bunches can be suitable electron sources for high current linear accelerators.

INTRODUCTION

One crucial requirement for realizing next-generation synchrotron light sources, colliders and linac-based free-electron lasers (FELs) is high brightness electron sources which possess extremely high peak current and small normalized emittance. This is a tremendous challenge to traditional electron guns due to their relatively low accelerating gradient and strong bunch self-field interaction. Plasmas can tolerate as high as 1 GV/cm electric fields which is at least 3 orders higher than radio-frequency cavities. Therefore plasma-based accelerators can effectively damp the space charge instabilities and produce much shorter and smaller electron bunches. It has been more than 30 years since Tajima and Dawson first proposed the laser wakefield accelerator (LWFA) [1]. In the last 10 years, especially after the generation of quasi-monoenergetic electron beams [2-4], LWFA has made big progress. GeV-level electron beams were reported by several teams [5-7]. One important mechanism responsible for generating monoenergetic electron beams is so-called bubble/blowout acceleration, which requires ultra-short ($c\tau\sim\lambda_P$) and ultra-intense ($I>10^{19}$ W/cm^2) laser pulses [8, 9]. In such case, almost all the trapped electrons are injected from nearly the same position on axis at the vertex of the bubble in "matched condition", making the injection and acceleration process very stable. It helps to form a compact, collimated and monoenergetic electron bunch. The beams' divergence angles can be as small as 1 mrad under this mechanism [10, 11]. However, relatively low plasma densities decreases the restoring forces and increase the bubble volume, while high laser power increases the initial transverse momentum of the trapped electrons, both of which affect the normalized emittance. In addition, matching is always difficult shot by shot for high power lasers.

On the contrary, self-modulated laser wakefield acceleration (SM-LWFA) works with longer laser pulses and higher plasma densities [12, 13]. It was originally proposed as an alternative method to LWFA before the availability of the sufficiently short and intense driving laser pulses [14-16]. Under this mechanism, drive lasers are tuned by plasma waves and break into one or several short pulses, making the laser intensity high enough to start self-injection. Although the electron energy is limited by short diphase length, some recent experiments have demonstrated the probabilities of generating tens to hundreds MeV monoenergetic electron beams by using several TW sub-hundred femtosecond laser pulses, which is high enough to avoid space charge effects [17-21]. Owing to higher plasma densities, SM-LWFA can produce a relatively small accelerating structure and provide larger focusing forces, making it possible to further diminish the bunch size and divergence angle. However, the plasma densities were typically 4×10^{19} to 5×10^{20} cm-3 in these experiments, resulting in too short plasma wavelength (1.5~5.3 μm) to match with the modulated pulse length as proposed in standard LWFA. Thus these interactions are unstable, resulting in the beam divergence up to tens mrad.

In this paper, we present the generation of well-collimated mono-energetic electron bunches from a 2 TW, 80 fs, high contrast laser pulse interacting with moderate density plasmas. Different from previous SM-LWFA experiments, we choose a lower density to increase injection stabilities and effective accelerating length. As a result, 23 MeV quasi-monoenergetic electron beam with an ultra-small emittance of 0.07π mm·mrad is produced, which is comparable to the most advanced photocathode rf guns. By taking Particle-In-Cell (PIC) simulations, we infer that the small normalized emittance ascribe to a combination of SM-LWFA and subsequent bubble-like acceleration.

EXPERIMENTS

Our experiments were carried out on the XL-II Ti: sapphire laser facility at the Institute of Physics, Chinese Academy of Sciences. The 800 nm p-polarized laser pulses are compressed to produce 80 fs, 160 mJ pulses on the target. The amplified spontaneous emission (ASE) contrast ratio was around 10^8 within the time scale of ten picoseconds. As showed in Fig. 1, the laser beam is focused by a gold-coated off-axis parabolic (OAP) mirror in an f/6 cone angle into an 8 μm diameter spot on a rectangular nozzle gas jet. Considering the energy concentration is about 35%, the vacuum-focused laser intensities should be 2.4×10^{18} W/cm^2, corresponding to the normalized vector potential a_0=1.1. The Rayleigh length Z_R is estimated to be 180 µm. The gas jet is generated by a pulsed slit-shaped (1.2 mm long and 10 mm wide) supersonic Laval nozzle.

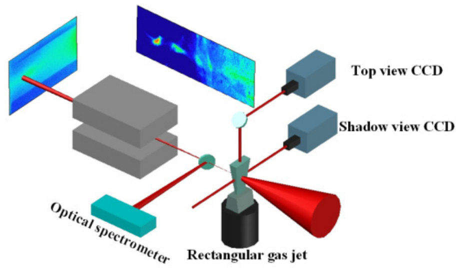

Figure 1: Schematic of experimental setup.

In order to detect the spatial profile and the energy distribution of the accelerated electron bunches, we used a spectrometer which is composed of a small but strong ($B_{max}\approx 0.9$ T) permanent magnet, phosphor plates with Al filters and CCD cameras. The magnet with the following dimensions: 60 mm long, 10 mm gap and 40 mm wide (with a 10 mm slit to increase energy resolution), was placed 150 mm downstream the interaction point. The strength of the stray field outside the magnet is smaller than 2 mT. 2 phosphor plates were pasted on the side and exit of the magnet, allowing simultaneous single-shot measurement of electrons from 3.5 MeV to 25 MeV (lateral) and 20 MeV to 50 MeV (forward). In addition, the magnet were fixed on a movable stage so that we could remove it and measured the beam divergence by a big phosphor screen mounted on the exit flange of the vacuum chamber easily. A charged coupled device (CCD) camera with narrow band interference filters at 800 nm was placed perpendicular to both laser propagation and polarization directions (topview) to observe the light emission from the focus point. It could also be used to measure the length and position of the plasma channel. In addition an 80 fs probe beam was employed to detect the shadowgraph. Transmitted lights were reflected by a pellicle beam splitter after the magnet with the 98% transmission at 800 nm and collected by a fiber optic spectrometer (HR 2000, Ocean Optics). The forward scattering spectrum and then the plasma density information could be obtained from the spectrometer.

RESULTS

The ASE contrast is one of the most important parameter for electron acceleration using laser pulse with only 2 TW power. No good electron bunches are observed if the contrast is lower than 10^6. On the other side, when the contrast is higher than 10^7, small monoenergetic electron bunches can be obtained after scanning the nozzle position and backpressure carefully. Obviously, high contrast can guarantee the laser interacting with plasmas in density which is not reduced by the laser pre-pulse. In the case of monoenergetic electrons generated, as shown in Figs. 2a and 2b, a long and narrow plasma channel is observed via topview and shadow view images. We know that the laser beam propagates near 1 mm (~ 5 Rayleigh lengths) in the plasma without obvious diffraction. It indicates that the laser is well self-guided in the experiment which is consistent with the theoretical estimation: $P > P_c \approx 16.2 \times (n_c/n_e)$ GW $\approx$ 1.6 TW, provided the plasma density is $0.01n_c$, where $n_c=m_e\omega^2/4\pi e^2$ is the critical density for propagation of the laser in the plasma.

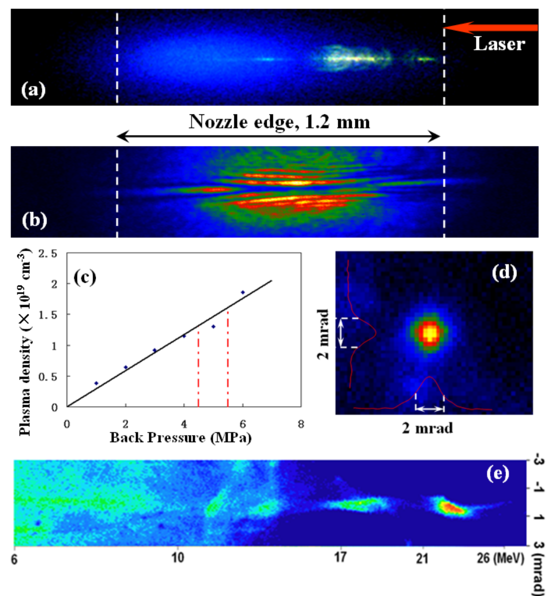

Figure 2: Experiment results: typical top-view and shadow-view images are showed in (a) and (b), respectively. Pressure dependent plasma density is calculated from transmitted light spectrum and presented in (c). Monoenergetic beams can only be generated in backing pressure between the red dashed lines. Electron beam profile obtained on an 18-µm-Al foil wrapped phosphor screen and spectra obtained after the dispersive magnet are shown in (d) and (e), respectively.

Obvious blue shifts in transmitted light spectrum were observed in our experiments, which provided clear evidence for the occurring of the strong self-modulation [22]. It's due to the forward Raman instabilities. We calculate the real plasma density by taking: $\omega_p=\omega_0\pm\Delta\omega$ and $n_e=m_e\omega_p^2/4\pi e^2$. As shown in Fig. 2c, the plasma density varies from 3.8×10^{18} cm^{-3} to 2.2×10^{19} cm^{-3}, corresponding to the backpressure changing from 1 MPa to 6.5 MPa. No electron bunch appears when the pressure is lower than 4.5 MPa. On the other side, hot electrons with extremely large divergence angle are found when the pressure is higher than 5.5 MPa. We achieve high quality monoenergetic electron bunches only when the plasma density within 1.3 ~ 1.65×10^{19}cm^{-3}.

Typical electron beam profile and energy spectrum are presented in Figs. 2d and 2e. As shown in Fig. 2d, the beam is bright and well collimated. After calibration, we know the FWHM beam divergence $\theta \approx 2$ mrad. While

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from Fig. 2e, we know the electron bunch is monoenergetic with the peak more than 20 MeV, the energy spread less than 7% and the bunch charge about 6 pC. The vertical beam divergence is 2 mrad which well agrees with the beam profile measurement in Fig. 2d. Assuming the initial beam size $\sigma_{x,y}$ equals 1/8 of the laser focal spot size (1/e^2 radius) [10], we can estimate the normalized electron beam emittance $\varepsilon_n \approx \sigma_{x,y} \cdot \gamma \cdot \pi \cdot \theta = 0.07\pi$ mm·mrad, where $\gamma = 40$ is the electron Lorenz factor. This value is at least 4 times lower than previous Laser plasma experiments, reaching or even exceeding the most advanced electron guns' level in traditional accelerator domain [23].

DISCUSSION AND SIMULATION

For further understanding of our experiment results, we carry out numerical simulations by using 2-D PIC program OOPIC [24]. In our simulations, the simulation box is 100 μm in x-direction and 80 μm in y-direction and meshed into 2500× 400 cells. We fix the laser condition, scan the plasma density and compare simulation results to our experiment. Fig. 3 reveals the evolution of the laser pulse and the electron density.

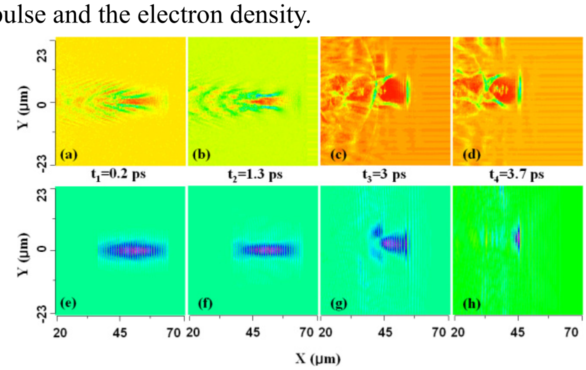

Figure 3: Simulation results: 2D snapshots of plasma density (a-d), and laser pulse evolution (e-h) at time t_1 = 0.06 mm/c (3a, 3e), t_2 = 0.4 mm/c (3b, 3f), t_3 = 0.9 mm/c (3c, 3g) and t_4 = 1.1 mm/c (3d, 3h).

At the beginning as presented in Figs. 3a, 3b, 3e and 3f, we see when a laser pulse propagates into plasmas, transverse ponderomotive forces push the near-axis electrons away and produce a high density electron sheath around and after the laser. At the same time, obvious self-focusing of the laser pulse occurs. As interaction continues, the pulse becomes narrower and larger due to strong modulations between the laser and plasma waves. When the modulated wakefield amplitude is beyond the threshold of the wavebreaking, self-injection occurs. Some background electrons are captured and accelerated by the longitudinal electric field. Because of the laser energy loss and the beam-loading effects, the injection will be shut down quickly. Then this group of electrons can be continuously accelerated for several hundreds of micrometers until dephasing occurs.

In our simulations, we found the beam quality was sensitive to the plasma density. If the density was lower than 1×10^{19} cm^{-3}, no self-injection happens. On the other side, if the plasma density was higher than 2.5×10^{19} cm^{-3}, some electrons can be injected but the beam qualities decrease rapidly due to the instabilities of the wakefields. Within this small density interval, monoenergetic bunches can be generated. For our best condition, we obtained a beam with the energy of about 25 MeV and the energy spread of 5%.

SUMMARY

We present our recent SM-LWFA experiment results in which we obtained 23 MeV monoenergetic electron beams with small energy spread (~7%). In this experiment, we use small laser pulse interacting with optimized plasma densities to balance the SM-LWFA and LWFA in an acceleration procedure. Strong focusing and stable accelerations make the beam small and tightly collimated with the normalized emittance merely 0.07π mm·mrad, which is the smallest one in laser-plasma acceleration regime so far as we know. By exploring this laser plasma parameter space, we develop a new way to generate ultra short and ultra small electron beams for future light sources and colliders.

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