CONTROL AND PULSEWIDTH-MEASUREMENT OF LASER ACCELERATED ELECTRON BEAMS *

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Abstract

Laser acceleration has the possibility to generate a low emittance electron beam with an ultra-short duration over short acceleration lengths. In applications of these laser accelerated electron beams, stable and controllable electron beams are necessary. A stable monoenergetic electron beam is generated in the self-injection scheme by using a Nitrogen gas-jet target. The electron beam direction is controlled by the gas-jet position. We found the profile of the electron beam was manipulated by rotating the laser polarization. The electron beam is in the first bucket of the wake wave. In energy space, electron oscillations are observed.

INTRODUCTION

Laser wakefield acceleration (LWFA) [1], based on the effect of plasma wave excitation in the wake of an intense laser pulse, is now regarded as a basis for the next-generation of charged particle accelerators, competing with conventional accelerators in the energy gain per unit length. Recently electron bunches have been accelerated up to 1 GeV by LWFA [2]. In experiments, it has been demonstrated that LWFA is capable of generating electron bunches with high quality [3, 4]: quasi-monoenergetic, low in emittance, and a very short duration of the order of ten femto-seconds. Such femtosecond bunches can be used to measure ultrafast phenomena.

In order to generate a bunch with high quality, required for applications, the electrons should be duly injected into the wakefield and this injection should be controllable. The injection can happen spontaneously, due to a longitudinal or transverse break of the wake wave, caused by its strong nonlinearity [5] and with cluster-gas targets [6]. This regime leads to the acceleration of particles, although in an uncontrolled way. Several other schemes of electron injection were proposed in order to provide more controllable regimes including tailored plasma density profiles [7] and optical injection [8]. Recently we generated a stable electron beam by using an Argon gas target in the self-injection scheme [4]. When we use a Nitrogen gas target, we can also generate a stable electron beam. The electron beam can be manipulated by controlling the laser pulse and the target.

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In this paper we present the results of the electron beam control in the self-injection scheme. In order to control the electron beam position, we control the direction of the electron beam by the target position. We manipulate the electron beam profile by controlling the laser polarization. The electron beam is in the laser field and is oscillated by the field. From the oscillation, we estimate the electron pulse width.

EXPERIMENTAL SETUP AND CONDITION

The experiments have been performed with a Ti:sapphire laser system at the Japan Atomic Energy Agency (JAEA) named JLITE-X [9]. The laser pulse, which is linearly polarized, with 160 mJ energy is focused onto a 3-mm-diameter Nitrogen gas-jet by an off-axis parabolic mirror (OAP) with the focal length of 646 mm (f/22). The $1/e^2$ diameter of the focal spot is 32 μm. The energy concentration within this region is 60%. The pulse width of the laser pulse, τ, is 40 fs. The estimated peak irradiance from the measurement data, I_0, is 9.0×10^{17} W/cm^2 in vacuum corresponding to a dimensionless amplitude of the driver laser field $a_0 = 8.5 \times 10^{-10} \lambda_0[\mu\mathrm{m}]\sqrt{I_0[\mathrm{W/cm}^2]} = 0.65$, where λ_0 is the laser light wavelength of 800 nm. The laser polarization is controlled by a half wave plate. The thickness of the plate is less than 50 μm. The profile of the electron beam is measured with a scintillating screen (Kyokko, DRZ-High), and a charge-coupled device (CCD) camera. The electron energy is measured with a magnetic spectrometer composed of a dipole magnet, a scintillating screen, and a CCD camera. The CCD camera records the scintillation pattern. The charge of the electron beam is calculated from the scintillation signal. The signal was calibrated by using a conventional electron accelerator.

RESULTS AND DISCUSSION OF THE ELECTRON BEAM CONTROL

A 20 MeV quasi-monoenergetic electron beam is generated in the self-injection scheme by using a Nitrogen gas target at the plasma density, n_e, of 2.0×10^{19} cm^{-3} assuming 5 ionizations of N_2. The quality of the electron beam is stable, because the laser pulse is guided a long distance in a channel produced by cascade ionization due to the low ionization threshold [4]. We control the stable electron beam by the control of the laser pulse and the target.

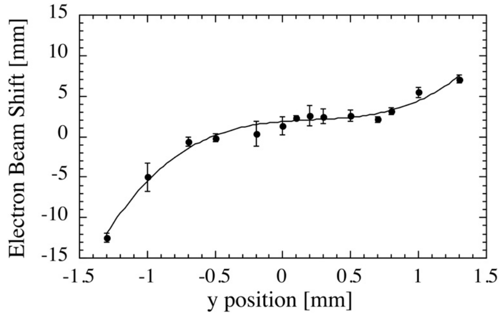

Figure 1: Control of the self-injected electron beam. The horizontal axis, y, is the difference of the laser axis from the center of the gas-jet. $y = 0$ means that the laser pulse passes through the center of the gas-jet. When the laser pulse is focused to the center of the gas-jet, the electron beam is generated near the laser axis. By controlling the gas-jet position, the direction of the electron beam can be controlled.

Direction Control

For applications of the laser accelerated electron beam, the electron beam position should be controlled. The gas-jet nozzle has a circular shape of 3-mm-diameter. For the experiment, we fix the distance between the laser focus position and the surface of the gas-jet position. In order to control the electron beam direction, we move the gas-jet position transverse to the laser propagation direction and gas-jet direction. The electron beam position is measured with a scintillating screen and a CCD camera. Figure 1 shows the result of the direction control. The electron beam bends away from the gas-jet. The electron beam follows the laser pulse. The laser pulse bends due to the plasma density distribution when the laser pulse is focused on the side of the gas-jet. As a result, the electron beam bends away from the gas-jet. The fluctuation is very small. It is possible to control the direction of the electron beam by changing the gas-jet position.

Profile Manipulation

In order to manipulate the profile of the electron beam, the polarization of the laser pulse is controlled by a half wave plate. Our experimental condition is $\tau = 40$ fs and $n_e = 2.0 \times 10^{19}$ cm^{-3}. From the plasma density, the period of the plasma wave is 24 fs. The profile of the laser accelerated electron beam in the first bucket of the wake wave can be manipulated, because the beam is in the laser pulse [10]. Profiles of the electron beams are shown in Fig. 2. The spatial profile of the electron beam shows an elliptical shape with its major axis parallel to the electric field of the laser pulse. The electrons oscillate in the laser pulse due to the electric field. This result shows that the electron beam profile can be controlled by the laser polarization and the quasi-monoenergetic electron beam is in the first bucket of the wake wave.

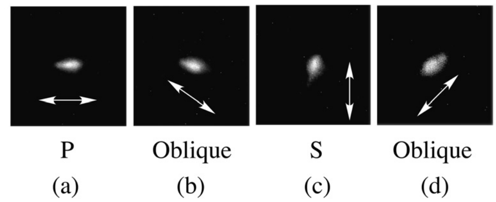

Figure 2: Typical profiles of the electron beams, the direction of the electric field in the laser pulse, and the polarization of the laser pulse. The profile can be manipulated by the laser polarization. The shape depends on the electric field of the laser pulse.

Observation of Electron Oscillation

The electron beam oscillates in the electric field of the laser pulse [10, 11] and the transverse wakefield excited by the laser pulse [12, 13]. Figure 3 shows a typical image of an energy distribution at $n_e = 2.2 \times 10^{19}$ cm^{-3} when the laser pulse has S-polarization (vertical polarization). Electron oscillations are observed in energy space. The oscillation has an angle of 16 mrad. When the laser pulse has P-polarization, no electron oscillation is observed. If the electron bunch is shorter than the half of the plasma wavelength, the electron energy spectrum can be converted to the electron pulse width. The electron oscillation is caused by the laser field or the transverse wakefield. In order to observe electron oscillation without the laser field, we decrease the plasma density. Here, the plasma wavelength is $\lambda_p = 2\pi c/\omega_p$ and the plasma frequency is $\omega_p = \sqrt{4\pi n_e e^2/m_e}$. When we decrease n_e, λ_p becomes long and the electron beam moves away from the laser pulse. At $n_e = 1 \times 10^{18}$ cm^{-3}, the electron oscillation is observed with the angle of 0.7 mrad when the laser pulse has P-polarization. The direction of the electron oscillation is perpendicular to the direction of the electric field of the laser pulse due to the P-polarization of the laser pulse. The oscillation is caused by the transverse wakefield.

In order to determine the mechanism of the electron oscillation at $n_e = 2.2 \times 10^{18}$ cm^{-3} when the laser pulse has S-polarization, we compare the oscillation by the laser field and the transverse wakefield. First we assume that the electron oscillation is caused by the laser field. The electric field of the laser pulse is parallel to the direction of the oscillation. From the experimental parameters, the estimated amplitude of the oscillation by the laser pulse is about 16 mrad. This is similar to the experimental results. When the laser pulse has P-polarization, the image of the energy distribution has no oscillation, because the direction of the oscillation by the laser field is parallel to the energy axis. The oscillation depends on the laser polarization. The fact, that the electric field of the laser pulse is parallel to the direction of the oscillation, is one piece of the evidence that the electron oscillation is caused by the laser field. The wave structure of the energy spectrum depends on the laser frequency. The pulse width (FWHM)

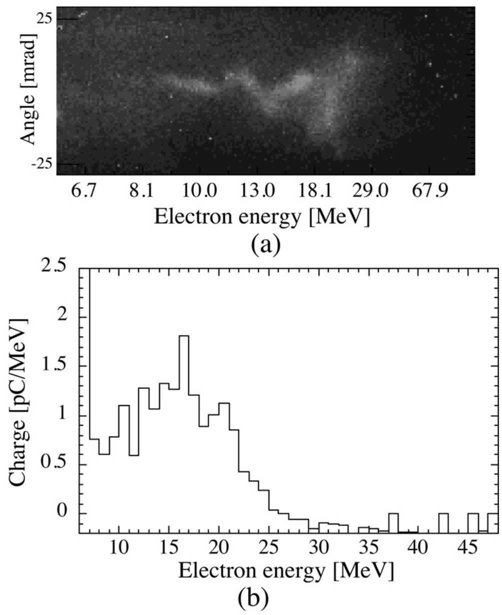

Figure 3: A typical image of the electron beam in the energy distribution (a) and a projection of the image onto the energy axis (b). The electron oscillation can be observed when the laser pulse has S-polarization. The oscillation corresponds to the laser frequency.

of the electron is 1.5-cycles of the laser beam at a wavelength of 800 nm. The pulse width may be about 4 fs (20% of the period of the plasma wave) if the oscillation is caused by the laser field. A three-dimensional particle-in-cell simulation result of the electron beam oscillation in the laser field has been already published [11]. Next we assume that the oscillation is caused by the transverse wakefield. The frequency of the oscillation by the transverse wakefield is $\omega_\beta = \omega_p/\sqrt{2\gamma_0\beta_0}$ [12, 13], where ω_p is the plasma frequency, $\gamma_0 = \omega_0/(\sqrt{3}\omega_p)$ is the injection energy, $\beta_0 = \sqrt{1-1/\gamma_0^2}$ is the injection speed of the electrons, and ω_0 is the laser frequency. The output angle of the electrons, $\theta(\gamma)$, is [13]

$$\theta(\gamma) = -\frac{\theta_0}{\pi}\frac{(\gamma_0\beta_0)^{1/4}}{(\gamma\beta)^{3/4}}\sin\left[\frac{E_0}{E_z}(\sqrt{2\gamma\beta}-\sqrt{2\gamma_0\beta_0})\right], \tag{1}$$

where E_z is an accelerating field, $eE_0 = m_e c\omega_p$ is the wave-breaking field, and $\theta_0 = \pi\omega_p r_0/(2c)$. The estimated output angle by the equation and the experimental data at $n_e = 1\times10^{18}$ cm^{-3} is 2 mrad at the electron energy of 20 MeV. The estimated length of the electron oscillation is 3 times longer than the plasma wavelength. It is difficult to observe the oscillation by the transverse wake with our parameters. There are contradictions if the oscillation is caused by the transverse wakefield.

CONCLUSIONS

Laser-plasma interaction generates an electron beam in the self-injection scheme. The ellipsoidal profile of the quasi-monoenergetic electron beam is rotated in such a way that the major axis of the ellipsoid follows the laser polarization axis. This result also indicates that the quasi-monoenergetic electron beam is in the first bucket of the wake wave. In the image of the energy spectrum, 1.5 periods of the electron oscillation is observed. As a control of the electron beam, we have succeeded in controlling the electron beam direction by changing the gas-jet position.

REFERENCES

[1] T. Tajima and J. M. Dawson, Phys. Rev. Lett. 43 (1979) 267; E. Esarey, *et al.*, IEEE Trans. Plasma. Sci. 24 (1996) 252; E. Esarey, *et al.*, Rev. Mod. Phys. 81 (2009) 1229.

[2] W. P. Leemans, *et al.*, Nature Phys. 2 (2006) 696; K. Nakamura, *et al.*, Phys. Plasmas 14 (2007) 056708; N. Hafz, *et al.*, Nature Photonics 2 (2008) 571.

[3] S. P. D. Mangles, *et al.*, Nature 431 (2004) 535; C. G. R. Geddes, *et al.*, Nature 431 (2004) 538; J. Faure, *et al.*, Nature 431 (2004) 541; A. Yamazaki, *et al.*, Phys. Plasmas 12 (2005) 093101; E. Miura, *et al.*, Appl. Phys. Lett. 86 (2005) 251501; M. Mori, *et al.*, Phys. Lett. A 356 (2006) 146; B. Hidding, *et al.*, Phys. Rev. Lett. 96 (2006) 105004.

[4] M. Mori, *et al.*, Phys. Rev. ST Accel. Beams 12 (2009) 082801.

[5] S. V. Bulanov, *et al.*, JETP Lett. 53 (1991) 565; S. V. Bulanov, *et al.*, Phys. Rev. Lett. 78 (1997) 004205; A. Pukhov and J. Meyer-ter-Vehn, Appl. Phys. B 74 (2002) 355; A. Zhidkov, *et al.*, Phys. Plasmas 11 (2004) 5379.

[6] Y. Fukuda, *et al.*, Phys. Lett. A 363 (2007) 130.

[7] S. V. Bulanov, *et al.*, Phys. Rev. E 58 (1998) R5257; H. Suk, *et al.*, Phys. Rev. Lett. 86 (2001) 1011; C. G. R. Geddes, *et al.*, Phys. Rev. Lett. 100 (2008) 215004.

[8] D. Umstadter, *et al.*, Phys. Rev. Lett. 76 (1996) 2073; E. Dodd, *et al.*, Phys. Rev. E 70 (2004) 056410; E. Esarey, *et al.*, Phys. Rev. Lett. 79 (1997) 2682; C. B. Schroeder, *et al.*, Phys. Rev. E 59 (1999) 6037; E. Esarey, *et al.*, Phys. Plasmas 6 (1999) 2262; P. Zhang, *et al.*, Phys. Plasmas 10 (2003) 2093; H. Kotaki, *et al.*, Phys. Plasmas 11 (2004) 3296; G. Fubiani, *et al.*, Phys. Rev. E 70 (2004) 016402; X. Davoine, *et al.*, Phys. Rev. Lett. 102 (2008) 065001; J. Faure, *et al.*, Nature 444 (2006) 737; H. Kotaki, *et al.*, Phys. Rev. Lett. 103 (2009) 194803; C. Rechatin, *et al.*, Phys. Rev. Lett. 103 (2009) 194804.

[9] M. Mori, *et al.*, Laser Phys. 16 (2006) 1092.

[10] S. P. D. Mangles, *et al.*, Phys. Rev. Lett. 96 (2006) 215001.

[11] K. Nemeth, *et al.*, Phys. Rev. Lett. 100 (2008) 095002.

[12] S. Kiselev, *et al.*, Phys. Rev. Lett. 93 (2004) 135004; A. Rousse, *et al.*, Phys. Rev. Lett. 93 (2004) 135005; K. Ta Phuoc , *et al.*, Phys. Plasmas 12 (2005) 023101; S. P. D. Mangles, *et al.*, Appl. Phys. Lett. 95 (2009) 181106.

[13] Y. Glinec, *et al.*, Europhys. Lett. 81 (2008) 64001.