STABILITY IMPROVEMENT OF A LASER-ACCELERATED ELECTRON BEAM AND THE PULSE WIDTH MEASUREMENT OF THE ELECTRON BEAM

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Laser wakefield acceleration has the possibility to generate an ultrashort electron beam of the order of femtoseconds or less. In applications of these laser accelerated electron beams, stable and controllable electron beams are necessary. A high stability electron bunch is generated by laser wakefield acceleration with the help of a colliding laser pulse (optical injection). Stable and monoenergetic electron beams have been generated in the self-injection scheme of laser acceleration by using a Nitrogen gas jet target. The electron interaction with the laser field results in transverse oscillations of the electron beam. From the electron oscillation period dependence on the electron energy we find that the electron beam width is equal to 1.7 fs (rms).

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INTRODUCTION

Measurements and manipulation of ultrafast phenomena open up new science and applications. Femtosecond (1 fs=10^{-15} s) pulses can be used to initiate and control molecular dynamics on a few tens of femtoseconds timescale, and attosecond (1 as=10^{-18} s) pulses can be used to initiate and control quantum dynamics on attosecond timescales. Generation of ultrashort pulses is a key to exploring the dynamical behavior of matter on ever-shorter timescales. High-order harmonics of femtosecond laser pulses have been shown to be a source of a sub-femtosecond extreme-ultraviolet (XUV) pulse [1-4]. However, in order to observe several phenomena on ultrashort timescales, an ultrashort x-ray and an electron beam are necessary. Laser wakefield acceleration (LWFA) [5] based on the effect of plasma wave excitation in the wake of an intense laser pulse, has the possibility to generate an ultrashort electron beam of the order of femtoseconds or less. In experiments, it has been demonstrated that LWFA is capable of generating electron beams with high energy up to 1 GeV [6, 7] and high quality [8-11]: quasi-monoenergetic, low in emittance, and a very short duration [12]. In addition, the electron beam has a current density up to the kilo-amprere level. It has the possibility to be a source of a X-ray free-electron laser (XFEL) for a coherent X-ray source [13].

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. Several schemes of electron injection were proposed in order to provide more controllable regimes including tailored plasma density profiles [14, 15] and optical injection [16-21]. Experimentally, stable and controllable electron beams have been generated in the self-injection [22] and optical injection scheme [19-21]. Within self-injection, a laser pulse excites a wake wave and injects electrons into the wake. Within optical injection, the electrons are injected into the wakefield by an additional laser pulse [16-21]. Optical injection has an advantage in using a regular pattern wakefield excited by a driver laser pulse. In applications of the electron beam, it is necessary to characterize the electron beam. The important parameters are energy, energy spread, emittance, and pulse width. Among these parameters it is difficult, in particular, to measure the pulse width due to the ultrashort bunch length. 100 fs electron beams have been measured by using Coherent Transition Radiation (CTR) [23,24] and an electro-optical (EO) crystal [25]. An electron generates radiation at the boundary of materials. The radiation is called transition radiation. When the pulse width of the electrons is shorter than the period of the radiation, the radiation should be coherent. From the boundary in wavelength between the coherent and incoherent emission, the pulse width of the electrons can be calculated. However, the laser-accelerated electrons have a quasi-monoenergetic part (electron beam) and a broad-spectrum part (thermal electrons). The pulse width measured by CTR includes the total width of the electrons not only the electron beam. In order to observe the pulse width of the electron beam, the effect of the thermal electrons should be separated from the electron beam. In order to measure the pulse width of the laser accelerated electron beam by using a EO crystal, the crystal should be placed on the electron and laser axis near the laser focus point to get on electron beam with high charge density. The measured pulse width should be the total width not only the monoenergetic part. The radiation from the interaction between the crystal and the laser pulse should be noise. In addition, the crystal could be damaged by the laser pulse. In order to observe the pulse width of the electron beam, the effects of the thermal electrons and the laser pulse should be separated from the electron beam.

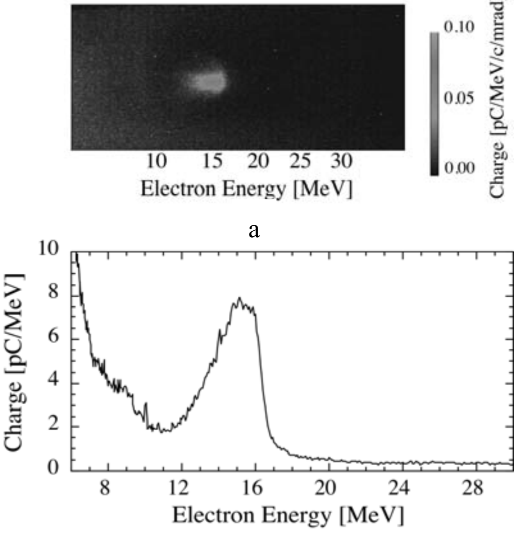
On the other hand, the electron beam oscillates in an electric field [26-29]. The electric field is caused by the laser pulse and/or a plasma wave. When the pulse length of the electron beam is shorter than the plasma wavelength and the electron beam is in the laser pulse, the energy spectrum is converted to the pulse width of the electron beam.

The oscillation by the laser field is a reference for the conversion. In this paper we present the result of the optical injection to generate a stable electron beam, and the pulse width measurement of the laser accelerated electron beam. The electron beam is in the laser field and is oscillated by the field. From the oscillation, we measure the electron pulse width of 1.7 fs (rms).

1. OPTICAL INJECTION

The experiments have been performed with a 3 TW linearly polarized Ti:sapphire laser [30]. The target is a supersonic helium gas jet flowing out of a rectangular nozzle with the size of 1.3 mm x 4 mm. The 70 fs driver pulse with 0.2 J energy is focused onto the helium gas jet. The peak irradiance, I_0, is 6.8×10^{17} W/cm^2 corresponding to a dimensionless amplitude of $a_0 = 8.5 \times 10^{-10}\ \lambda_0\ [\mu\text{m}]\ (I_0[\text{W/cm}^2])^{1/2} = 0.6$, where λ_0 is the laser light wavelength of 800 nm. The 70 fs injecting pulse with 10 mJ energy is focused onto a region at the beginning of a channel formed by the driver pulse at the angle of 135 degrees with respect to the driver pulse propagation. Its peak irradiance, I_1, is about 2.0×10^{16} W/cm^2, corresponding to a dimensionless amplitude of $a_1 = 0.1$.

The self-injection ceases at lower plasma densities, when the wake wave becomes more regular. In order to demonstrate the counter-crossing injection, we must use plasma with a density below the self-injection threshold. The threshold parameters are found by changing the plasma density and measuring accelerated electrons with the driver pulse alone. When the plasma density decreases from 4.10×10^{19} cm^{-3} to $n_e = 4.00 \times 10^{19}$ cm^{-3}, the reproducibility abruptly drops. For our parameters, the self-injection ceases at the plasma density below the threshold of 4.00×10^{19} cm^{-3}.



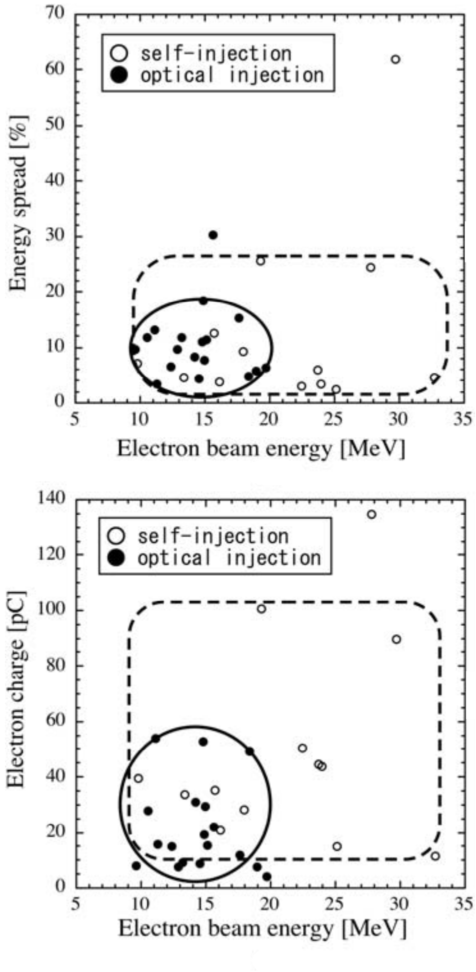
a

b

Fig. 1. A typical image of an energy distribution of the electron bunch obtained by the counter-crossing injection at $n_e = 3.95 \times 10^{19}$ cm^{-3} (a), and a projection of the image onto the energy axis (b)

Fig. 1 shows the energy spectrum of the accelerated electron bunch optically injected with the help of the injecting pulse for $n_e = 3.95 \times 10^{19}$ cm^{-3}. This density is below the self-injection threshold. The collision of the two laser pulses produces a quasi-monoenergetic electron bunch with 15 MeV peak energy, 7.8 % (1.2 MeV) rms energy spread, 30 pC charge, and 15 mrad divergence.

Fig. 2 compares the stability of the self-injection and the counter-crossing injection mechanism. The experiments of the counter-crossing injection were conducted for $n_e = 3.95 \times 10^{19}$ cm^{-3}. The self-injection has been seen for $n_e = 4.40 \times 10^{19}$ cm^{-3}, which is the optimum density for self-injection to generate quasi-monoenergetic electron beam. These results show that the counter-crossing injection has higher stability than the self-injection. Fig. 2 shows a wide scatter of the self-injection points, with several at large values, while the optical-injection points are clustered nearer to the lower left of each plot.



a

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Fig. 2. The stability of the self-injection and the countercrossing injection. The stability of the countercrossing injection is higher than that of the self-injection

2. PULSEWIDTH MEASUREMENT

A quasi-monoenergetic electron beam is generated in the self-injection scheme by using a Nitrogen gas target around the plasma density, n_e, of 4.0×10^{19} cm^{-3} assuming 5 ionizations of N_2. The quality of the electron beam is stable [31], because the laser pulse is guided a long distance in a channel produced by cascade onization due to the low ionization threshold [22]. By using the electron beam, a pulse width is measured.

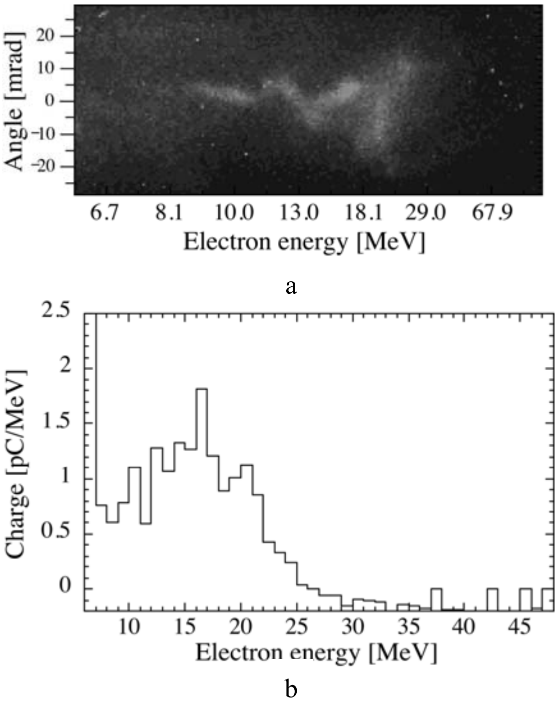

Fig. 3. Typical image of an electron beam in energy space (a), and a projection of the image onto the energy axis (b) for the laser pulse of S-polarization at $n_e = 4.4 \times 10^{19}$ cm^{-3}. The electron beam has peak energy of 17 MeV and a charge of 17.0 pC

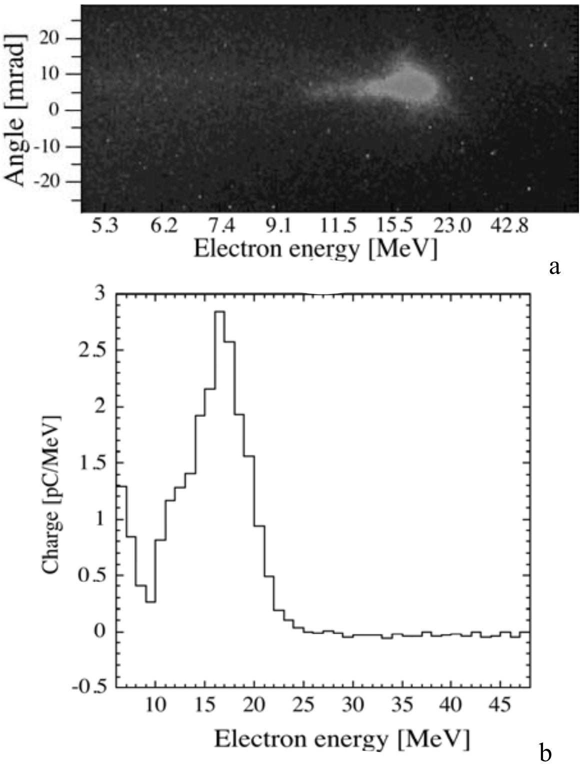

Fig. 4. Typical image of an electron beam in energy space (a), and a projection of the image onto the energy axis (b) for the laser pulse of P-polarization at $n_e = 4.4 \times 10^{19}$ cm^{-3}. The electron beam has peak energy of 17 MeV and a charge of 19.3 pC

The experiments have been performed with a Ti: sapphire laser system at the Japan Atomic Energy Agency (JAEA) named JLITE-X [30]. The laser pulse, which is linearly polarized, with 130 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 pulse width of the laser pulse, τ, is 40 fs. The peak irradiance, I_0, is 7.3×10^{17} W/cm^2 in vacuum corresponding to a dimensionless amplitude of the laser field $a_0 = 0.6$.

The electron beam oscillates in the electric field of the laser pulse. In phase space, we can see the electron oscillation by the electric field [32]. The oscillation is a reference in order to convert the energy spectrum to the pulse width. Fig. 3 shows the typical image of an energy distribution at $n_e = 4.4 \times 10^{19}$ cm^{-3} when the laser pulse has S-polarization (vertical polarization). Using the sensitivity of the phosphor screen, calibrated with the help of a conventional electron accelerator, we estimate that the total charge of the monoenergetic electron beam is about 17 pC. Electron oscillations are observed in energy space. The oscillation has an angle of 16 mrad. The electric field of the laser pulse is parallel to the direction of the oscillation. The amplitude of the electron oscillation by the laser field, $A_{e\text{-}laser}$, is defined as $A_{e\text{-}laser} = a_0/\gamma$, where γ is the Lorentz factor of the electron beam. From the experimental parameters, the estimated amplitude of the oscillation by the laser pulse is about 16 mrad. The maximum amplitude of the experimental data is 16 mrad. The result has good agreement with the calculated amplitude. When the laser pulse has P-polarization (horizontal polarization), no electron oscillation is observed as shown in Fig. 4. 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 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) of the electron is 1.5-cycles of the laser beam at a wavelength of 800 nm. The pulse width is 1.7 fs (rms) (12 % of the period of the plasma wave).

CONCLUSIONS

In order to improve the stability of laser-accelerated electron beam, optical injection experiments have been performed. The generated electron beam shows that the optical injection is one of techniques to generate a stable electron beam. Stable and monoenergetic electron beams have been generated in the self-injection scheme of laser acceleration by using a Nitrogen gas jet target. In the image of the energy spectrum, the electron oscillation by the laser field is observed. The energy spectrum can be converted to the electron pulse width. The result of the 0.64-cycles oscillations indicates a 1.7 fs (rms) pulse width for the electron beam. The peak current is 10 kA. The technique of the measurement is the direct observation of the pulse width of the electron beam.

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ПОВЫШЕНИЕ ВОСПРОИЗВОДИМОСТИ ПАРАМЕТРОВ ПУЧКОВ ЭЛЕКТРОНОВ, УСКОРЯЕМЫХ В ЛАЗЕРНОЙ ПЛАЗМЕ, И ИЗМЕРЕНИЕ ДЛИТЕЛЬНОСТИ ЭЛЕКТРОННОГО ПУЧКА

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В процессе ускорения кильватерными волнами возможна генерация сверхкоротких электронных пучков фемтосекундной длительностью. Для приложений требуются электронные пучки с воспроизводимыми и котролируемыми параметрами. Оптическая инжекция, использующая сталкивающиеся лазерные импульсы, обеспечивает высокую воспроизводимость параметров пучков ускоренных электронов. Моноэнергетические пучки электронов с воспроизводимыми параметрами были получены при «самоинжекции» в кильватерную волну в экспериментах, использующих в качестве мишени струю азота. Взаимодействие электронов с излучением лазерного импульса приводит к поперечным осцилляциям электронного пучка. Анализ наблюдаемой в эксперименте зависимости периода осцилляций от энергии электронов позволяет найти длительность электронного пучка, равную 1.7 фс.

ПІДВИЩЕННЯ ВІДТВОРЮВАНОСТІ ПАРАМЕТРІВ ПУЧКА ЕЛЕКТРОНІВ, ЩО УСКОРЮЮТЬСЯ В ЛАЗЕРНІЙ ПЛАЗМІ, ТА ВИМІРЮВАННЯ ТРИВАЛОСТІ ЕЛЕКТРОННОГО ПУЧКА

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В процесі прискорення кільватерними хвилями можлива генерація надкоротких електронних пучків фемтосекундної тривалості. Для додатків потрібні електронні пучки з відтворюючими і котролюючими параметрами. Оптична інжекція, що використовує зіштовхуючі лазерні імпульси, забезпечує високу відтворюваність параметрів пучків прискорених електронів. Моноенергетичні пучки електронів з відтворюваними параметрами були отримані при «самоінжекції» в кільватерну хвилю в експериментах, в яких в якості мішені використовувалася струмінь азоту. Взаємодія електронів з випромінюванням лазерного імпульсу призводить до поперечних осциляцій електронного пучка. Аналіз спостерігаючої в експерименті залежності періоду осциляцій від енергії електронів дозволяє знайти тривалість електронного пучка, яка дорівнює 1.7 фс.