Electron acceleration in imploded hollow cylinder

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Abstract. Energetic electrons were generated using a 3-mm-long plasma tube created by imploding a hollow polystyrene cylinder. The spectra of a comparatively high-density plasma ∼ 10^{19} cm^{-3} had a bump around 10 MeV. Moreover, electron energies in excess of 600 MeV have been observed. The results of numerical calculations indicate that the bump around 10 MeV is produced by multi-dephasing of accelerated electrons in the electron plasma wave.

1. Introduction

Recently, there has been a remarkable development in the field of high intensity and short pulse laser technology, namely a high-intensity focused optical beam can be used to generate relativistic electrons [1]. In a previous study, the energies of MeV-electrons generated by the relativistic optical interaction with plasmas were reported to have a continuous Maxwellian distribution [2]. A few years ago, several groups reported that monoenergetic beams can be generated by controlling the plasma density and the propagation conditions of the optical pump pulse [3, 4, 5, 6]. More recently, Leemans et al. succeeded in producing an over 1-GeV monoenergetic electron beam using a 3.3-cm-long gas-filled capillary discharge waveguide [7]. One of the critical issues of their study was the use of a plasma tube that was long enough to produce a 1-GeV monoenergetic beam. The long plasma tube acts like an optical fiber for the optical pulse, and a high-intensity laser pulse excites a laser wakefield in this long plasma.

In this article, we analyze the energy spectrum of the relativistic electrons produced by PW laser system with a plasma tube, which was generated with six beams of GEKKO XII (GXII) laser system. The spatial density distribution of the plasma tube was controlled by varying the total energy of GXII laser. This electron beam has an energy spectrum with a bump around 10 MeV. Moreover, employing a longer propagation distance might enable a broadband energy spectrum to be expanded to over 600 MeV, or even to ∼800 MeV. The results of a simple numerical analysis indicate that the formation of a bump in the energy spectrum is caused by multi-dephasing during propagation in the long plasma tube.
2. Experimental setup
The experiment was performed using the PW laser system at the Institute of Laser Engineering at Osaka University [8]. The plasma tube was created by imploding a hollow polystyrene plastic (CH) cylinder that was 3 mm in length, 700 µm in diameter and had a wall thickness of 14 µm. To implode this plastic cylinder shell, six beams of the GXII laser system irradiated the outer surface; this irradiation was kept as uniform as possible. The beams for imploding a plastic cylinder shell were frequency doubled using potassium dihydrogen phosphate (KDP) crystals, and were smoothed by random phase plates (RPP). The pulse had a full width at half maximum of 1 ns. The plasma tube, which consists of a central low-density region surrounded by an outer high-density region, is formed during the implosion. The temporal plasma density profile for laser acceleration was changed by varying the total energy of the implosion beams (E_{imp} = 1.9, 2.0 and 2.3 kJ). The pump laser beam from the PW laser system was injected 3.1 ns after the irradiation by the implosion beams. The PW laser system is a chirped-pulse-amplification (CPA) Nd:glass laser system having a central wavelength of 1.053 µm. In the experiment, the pump beam had a pulse energy of 100 J and a full width at half maximum of 700 fs at the target. In this study, the pump laser beam from the PW laser system was injected into three types of plasma tubes that had different densities in their central regions. The energy spectrum of electrons accelerated forward along the propagation axis of the pump beam was measured using an electron spectrometer (ESM) which uses a Fuji BAS-SR2025 imaging plate (IP) as a detector. The absolute calibration of the IP for electrons was performed [9, 10].

3. Experimental result
Figure 1(a) shows three spectral profiles of relativistic electrons generated for three different implosion energies. The spectrum for E_{imp} = 1.9 kJ has a broad energy spread, which is a characteristic feature of relativistic interactions between the ultra-intense laser pulse and plasmas. The electron spectra for E_{imp} = 2.0 and 2.3 kJ have an impressive feature, namely they have a bump around ~10 MeV in the continuous spectrum for comparatively high-density interactions, while there is no bump for E_{imp} = 1.9 kJ. The highest electron energy was obtained with an implosion energy of 1.9 kJ. As Figure 1(b) shows, the signal for E_{imp} = 1.9 kJ extends over 600 MeV and only merges with the background at energy of ~800 MeV.

4. Discussion
We now proceed to discuss the experimentally obtained electron spectra. We have performed a following simple numerical analysis in order to explain these spectra. In the experimental
conditions we used, the focused laser intensity could exceed $10^{18} \text{W/cm}^2$. Under such conditions the electron plasma wave can be excited. In our model, a simple sinusoidal wakefield, of which frequency is determined by the plasma density, is assumed to propagate in the propagation direction of the pump beam with an estimated phase velocity. The electric field of the laser wakefield ($E_{\text{lw}}$) is given by

$$E_{\text{lw}}(z, t) = E_{\text{wb}} \sin \left( \frac{\omega_p}{v_{\text{ph}}} z - \omega_p t - \phi \right),$$

where $\omega_p$ is the plasma frequency, $v_{\text{ph}} = c(1 - \omega_p^2/\omega_0^2)^{1/2}$ is the phase velocity of the electron plasma wave ($\omega_0$ is the laser frequency), and $\phi$ is the initial phase. The wake amplitude was assumed to reach the wave-breaking limit $E_{\text{wb}} = 30 \sqrt{n_e/n_{17}} \text{GV/m}$, where $n_e$ is the plasma density. The initial relativistic electrons were assumed to have a Maxwellian energy distribution $f(\epsilon) \propto \exp(-\epsilon/k_B T_e)$, where $\epsilon$ is the kinetic energy of electrons and $k_B$ is Boltzmann constant. The initial temperature ($T_e$) of the Maxwellian electron beam was determined by ponderomotive potential energy estimated from the irradiation intensity. This thermal electron beam was injected into the sinusoidal wakefield equivalently for the various initial phases ($0 \leq \phi < 2\pi$).

We calculated the energy spectrum of the accelerated electrons for a uniform density distribution along the propagation axis. The relativistic effect was taken into account for solving an equation of motion for the electrons. For estimating the average plasma density, we observed the implosion dynamics using x-ray backlight streaked imaging. The density profile of a tentative plasma tube was evaluated by comparing an x-ray backlight streaked image obtained in the experiment and the calculated results obtained using the one-dimensional (1D) hydrodynamic code ILESTA-1D [11]. The densities of the central region of the plasma tube shown in Figure 2 were evaluated by this method. When the plasma density is $3.7 \times 10^{19} \text{cm}^{-3}$, the calculated spectrum has a bump around 10 MeV as shown in Figure 2(a). This spectrum corresponds to the experimentally obtained spectrum for $E_{\text{imp}}=2.3 \text{kJ}$ which has a bump at 10 MeV. From this simple calculation, we noticed that the bump corresponds to the energy that is between the energy determined by the phase velocity and the maximum energy by the dephasing length. The maximum energy determined by the dephasing length is given by $\gamma_{\text{max}} \sim \epsilon E_{\text{wb}} L_{dp}$, where $L_{dp} = \frac{1}{2} \gamma_{\text{ph}}^2 \lambda_p$ is a dephasing length, $\gamma_{\text{ph}} = 1/\sqrt{1 - (v_{\text{ph}}/c)^2}$ is a roelntz factor of the phase velocity and $\lambda_p$ is a wavelength of the electron plasma wave. When the plasma densities are $9.0 \times 10^{18}$, $2.0 \times 10^{19}$ and $3.7 \times 10^{19} \text{cm}^{-3}$, the energies determined by the phase velocity are 1.3, 1.8 and 2.7 MeV,
and those by the dephasing length are 180, 78 and 42 MeV, respectively. This fact gives us the following physical picture. A laser wakefield is an electron plasma wave that alternately has an acceleration phase and a deceleration phase. If the electrons have almost the same velocity as the phase velocity of the electron plasma wave, they can be trapped and accelerated by the wakefield in a manner similar to Landau damping. Once these electrons have completed the acceleration phase, they enter the deceleration phase and begin to be decelerated. This process is called dephasing, and the propagation distance until the commencement of deceleration is referred to as the dephasing length. When the plasma density is $3.7 \times 10^{19} \text{ cm}^{-3}$, the dephasing length is estimated to be $74 \mu \text{m}$. If the length of the wakefield plasma is much greater than the dephasing length, as was the case in our experiments, then the electrons trapped by the wakefield are alternately accelerated and decelerated. Therefore, these electrons are concentrated at the energy that is intermediate between the energy based on the dephasing length and that based on the phase velocity. Moreover, the calculated spectra for lower density plasmas also show a similar tendency as the experimentally obtained ones, as Figure 2 shows. The period of the electron plasma wave for $3.7 \times 10^{19} \text{ cm}^{-3}$ is 18 fs, while the pulse width of the pump beam is 700 fs. Thus a self-modulated wakefield is thought to be excited. Finally, it should be noted that 800-MeV electrons cannot be explained by our simple calculation as shown in Figure 2(b). The majority of fast electrons are thought to be generated by stochastic acceleration [12]. An high-power intense laser pulse might be disturbed by the nonlinear interaction of the intense laser field with plasmas. In this case, the intense laser pulse has stochastic phase disturbances, or is in the presence of a stochastic field. The electrons can be accelerated to high energy by this stochastic field. In this mechanism, the acceleration length is not limited by dephasing since coherent interaction such as the wakefield is not demanded.

In summary, we have performed laser acceleration experiments using a 3-mm-long plasma tube. The energetic electron spectrum had a bump around 10 MeV. Moreover, electron energies in excess of 600 MeV have been observed. We have performed a simple numerical calculation to explain the origin of this bump. A bump was obtained at about 10 MeV in our calculation when the plasma density was $3.7 \times 10^{19} \text{ cm}^{-3}$. The calculation results indicate that multi-dephasing in the electron plasma wave causes the formation of this bump during propagation in a long plasma tube.

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