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Electron Acceleration by the TW-laser Pulse in the Underdense Plasma

K.Koyama, E.Miura, N.Saito, and M.Tanimoto

National institute of Advanced Industrial Science and Technology (AIST)

Tsukuba Central 2, Umezono 1-1-1, Tsukuba, Ibaraki, 305-8568, Japan

Plasmas produced by the super-intense and ultra-short laser pulses have a potential ability to accelerate electrons to the relativistic energy region in a short distance. Most of the experiments have been carried out in the self-modulated laser wake field acceleration (SLWFA) scheme in the electron density region lower than 10^{19} cm^{-3} by using the laser pulse duration of around 400 fs, because it is easy to excite the electron plasma wave to the large amplitude. The plasmas of the high electron density are favorable from the viewpoint of decreasing the threshold power of the relativistic self-guiding of the laser beam as well as enhancing the accelerating field unless instabilities arise. We performed the interaction experiments in the moderately underdense plasma ($>10^{20}$ cm^{-3}) by using the 100-fs laser pulses. In this paper, we briefly present the experiments and discuss about the stochastic acceleration model to explain the experimental results.

Intense output pulses of a Ti:sapphire laser (790nm) were focused on the sharply bounded uniform gas-jet targets. The peak power and the duration of the laser pulse were 1.8 TW and 100 fs (FWHM), respectively. The gas density of the target of 3.4×10^{19} cm^{-3} corresponds to the electron density of 2.7×10^{20} cm^{-3} for the Ar^{8+}-plasma. The average intensity in a focal spot of 12-15μm in a vacuum was 7×10^{17} W/cm^2, which was surrounded by a large halo with the intensity of 10^{15}-10^{16} W/cm^2. Figure 1(*a*) and (*b*) show a typical shadowgraph of the plasma taken just after the TW laser pulses passed through the gas-target and a time-integrated side-scattering image of the TW laser beam at the wavelength of

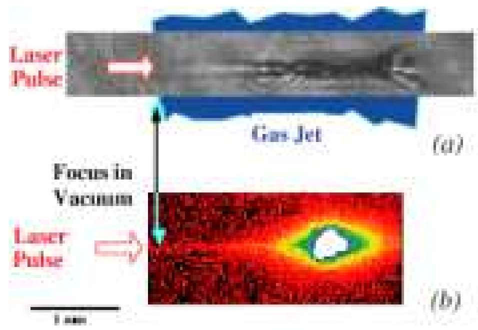


Fig.1 The typical shadowgraph (a) and the image of the side scattering (b) of the plasmas.

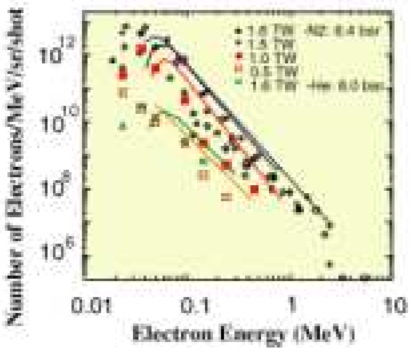
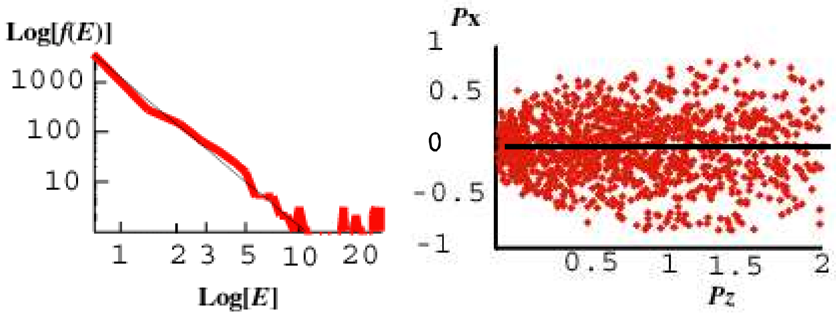


Fig.2 Energy spectra of electron beams measured at the forward direction.

790nm, respectively. The smooth channeling was terminated by an abrupt transition to a complex filamentation in the regime of the high electron density of $n_e \geq 2\times10^{19}$ cm^{-3} as well as the high laser power of $P_L \geq 1$ TW. A distance to the transition of the propagation mode was 0.8-1.2 mm. The side-scattering image consisted of a slender, pale and straight filament and a following extremely bright region, which corresponded to the smooth channeling and the part of the complex filamentation in the shadowgraph, respectively. In case that the plane of the polarization of the TW laser was parallel to the direction of the observer, the scattered light from the slender part became very weak, while the intensity of the bright part was unchanged. In the region of the low laser power or the low electron density, neither the transition to the complex filamentation nor the bright scattering was observed. A divergence of the high-energy electron beam of 6-8°FWHM was measured by using a scintillator detector. The direction of the electron beams fluctuated in the angle of 15-20°FWHM around the optical axis from shot to shot. Energy spectra measured by using an electron energy analyzer in the forward direction along the laser beam seem to have a power-law of $E^{-3.5}$ reaching the maximum electron energy of 2 MeV as shown in Fig.2. The maximum number of the high-energy electrons was estimated to be $(1.3\pm0.6)\times10^{11}$/sr/shot from the electron current measured by using a Faraday cup. The quality of the electron beam was evaluated by measuring widths of penumbrae of metal bolts placed at various angles from the laser axis. The apparent length of the electron source is estimated to be approximately 4 mm, which is longer than the plasma length of 3 mm. Emissions of high-energy electron beams seemed to correlate with the appearance of the transition feature of the laser pulse propagation. Obvious shifted component of the scattered spectrum giving evidence of the electron plasma wave was not observed in the forward direction.

It is hard to expect that the SLWFA could be driven in the moderately underdense plasma because of the short dephasing length of 1μm which is limited by the large difference of the phase velocities between the pump and the scattered light. In order to explain the electron acceleration in the present experiment, we theoretically analyzed the potential stochastic acceleration of electrons based on the random phase jump of the laser field in the disturbed plasma channel apart from the wakefield accelerations. Supposing that initial conditions of the electron motion are introduced by a series of m-times phase jumps of oscillation in the coherent laser field, the maximum kinetic energy of the electron is $E_{max}=\gamma_{max}-1=2\mathrm{m}^2a_0^2$, where a_0 is the normalized vector potential of the laser field. In order to introduce a realistic number of phase jumps, we assume that the phase jumps obey the probability function of $p(z)=(1/\lambda)\exp(-z/\lambda)$, where λ is the mean free path of the phase jump. The mean number of the phase jump is expressed to be $\mathrm{m}_0=z_p/\lambda$, where z_p is the length of the plasma filament. The power law spectrum of electron energy was well reproduced by introducing the probability function of the phase jumps ($\mathrm{m}_0=2$) and the self-generated magnetic field (≈2MG) induced by the forward drifting electrons of the relatively low energy as shown in Fig.3(*a*); besides,



(*a*) (*b*)

Fig.3. The energy (*a*) and momentum (*b*) distributions of the 4000 electrons. The average jump number is m_0=2. The field strength is a_0=0.7. The self-generated magnetic field is taken account.

the small divergence angle of the beam was reproduced by taking account of the pinch effect due to the magnetic field induced by the electron current as shown in Fig.3(*b*). If the number of phase-jump is fixed or the self-generated magnetic field is not taken account, the energy spectrum forms the Maxwellian distribution. For estimating the strength of the self-generated magnetic field, it is assumed that the electron current in the plasma is induced by the drifting electron-clouds with the velocity of $v_d = \left(\frac{a_0^2}{4 + a_0^2} \right) c$ and is limited by the value of the Alfven current.

In conclusion, the power law spectra of high-energy electrons reaching 2 MeV were obtained from the moderately underdense plasmas produced by focusing the 1.8-TW laser pulses on the gas-jet targets. The collective acceleration may hardly be expected under our experimental conditions. The stochastic acceleration model taking account of the random phase disturbance of the coherent laser field and the self-generated magnetic field has shown the efficient acceleration even in the weakly relativistic region of a_0<1.

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