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Observation of Ultrahigh Gradient Electron Acceleration by a Self-Modulated Intense Short Laser Pulse

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ABSTRACT

Ultrahigh-gradient electron acceleration exceeding 30 GeV/m has been observed in an underdense plasma produced by an intense short laser pulse of 3 TW when injecting 1 MeV/c electrons. The simulation on laser-plasma interaction revealed existence of ultrahigh-gradient wakefields excited due to a self-modulated laser pulse.

PACS numbers: 29.17.+w, 52.35.Mw, 52.40.Nk, 52.65.+z

Recently there has been a great interest in generation of large-amplitude, relativistic plasma waves because of their potential for ultrahigh-gradient particle acceleration. It is known that the laser pulse is capable of exciting a plasma wave propagating at a phase velocity close to the velocity of light by means of beating two-frequency lasers or an ultrashort intense laser pulse [1]. Two schemes came to be known as the plasma

beat-wave accelerator (PBWA) and as the laser wakefield accelerator (LWFA). A possible advantage in the PBWA is efficient excitation of plasma waves due to resonance between the beat frequency of two lasers and the plasma frequency. On the other hand, a fine adjustment of the beat frequency with the plasma frequency is necessary. As a plasma wave builds up to a large amplitude, its amplitude saturates due to the nonlinear plasma oscillations and finally instabilities associated with ion motion disrupt coherent waves. The LWFA does not rely on resonant excitation of plasma waves so that a fine tuning of the plasma density is not necessary. To achieve efficient excitation of large amplitude plasma waves, alternative schemes have been proposed. The "pulse train-LWFA" [2] can resonantly drive nonlinear plasma waves with optimized pulse width and interpulse spacings. The "self-modulated-LWFA" [3] is accompanied by resonant excitation of wakefields behind an intense laser pulse modulated due to the highly nonlinear laser plasma interaction.

Excitation of wakefields and their electron acceleration have been recently reported in the experiments using a terawatt ultrashort laser pulse. Laser-induced wakefields has been first observed as a coherent far-infrared radiation from the laser-produced plasmas by H. Hamster et al. [4]. We demonstrated acceleration of electrons due to wakefields excited by an intense short laser pulse in a moderate density plasma [5]. We confirmed that electrons injected to the laser-induced wakefield were accelerated in the average field gradient of 0.7 GeV/m in the linear regime of plasma waves. We have made acceleration experiments in the nonlinear regime of plasma waves. This letter reports the first observation of electrons accelerated by ultrahigh accelerating field due to a self-modulated wakefield mechanism and results of the simulation analysis on laser-plasma interactions for the experiments in the nonlinear regime.

In this experiment [6], the laser pulse was delivered by the Nd:glass laser system [7] capable of generating the peak power up to 30 TW with a pulse duration of 1 ps at the wavelength of 1.052 μm. The laser beam with a 140 mm diameter was focused by a 3.1 m focal length lens into the vacuum chamber filled with a He gas to a spot size of 80 μm. The peak intensity of the order of 10^{17} W/cm^2 can be achieved so that a fully ionized plasma can be created in a fast time scale ($\leq$ 10 fs) due to the tunneling ionization process. The threshold intensity for the onset of tunneling ionization is 8.8×10^{15} W/cm^2 for He^{2+} ion [8]. With a 3 TW laser pulse focused into the He gas, the fully ionized plasma can be produced over more than 20 mm around the focus. The compressor grating-pair, the 10° mirror and the focusing lens were installed in the vacuum vessel connected to the vacuum chamber for the acceleration experiment. These vacuum chambers were evacuated down to $\sim 10^{-5}$ Torr with two turbo molecular pumps. For creation of a low density plasma, a gas was statically filled with the flow controlled valve. For the high density plasma experiment, a He gas was filled with the supersonic gas-jet injector. Electrons for acceleration are produced from an aluminum solid target irradiated by a 200 ps laser pulse. The $p-$polarized laser beam with a 140 mm diameter was focused with a 1.6 m focal length lens to a spot size of 40 μm diameter onto the aluminum rod of 6 mm diameter inside the vacuum chamber. The peak intensity exceeds 10^{16} W/cm^2 for 20 J irradiation. The absolute number of produced electrons with momentum of 0.86 ± 0.24 MeV/c was estimated to be $\sim 5 \times 10^4$ in the interaction region. Hot electrons emitted from the aluminum target were injected into the waist of a 1 ps laser pulse through the 90° bending magnet with appropriate edge angles so as to achieve double focusing of an electron beam. Since the electron beam length was as short as the 200 ps laser pulse duration, the optical path length of the 200 ps laser pulse is adjusted so that the 1 ps laser pulse should overlap with electrons at the focus within ± 100 ps. Electrons trapped by wakefields are accelerated in the beam waist of twice the Rayleigh length, $\approx$ 10 mm. The momentum of electron was analyzed

by the dipole field of the magnetic spectrometer placed in the exit of the interaction chamber. This spectrometer covers the momentum range of 5.6 – 19.5 MeV/c at the dipole field of 3.9 kG. The momentum resolution of the spectrometer is typically 1.0 MeV/c at this range. Upon exiting the vacuum chamber of a vertical aperture 15 mm through a 100 μm thick Capton window, electrons were detected by the array of 32 scintillation counters placed at the image plane of the spectrometer. The detectors were sensitive to a single minimum ionizing particle. The noise level of the detector was smaller than the signal pulse height of 2.5 mV. The probability of counting a cosmic ray in coincidence with a laser shot is estimated to be less than 10^{-8} for each detector. The vacuum chamber was shielded by 4 mm thick lead sheets to reduce the flux of background x rays. The backside of the detectors was entirely surrounded by 50 mm thick lead bricks so that x-ray emission were not detected.

The injection momentum of electrons was set to 1 MeV/c ($\approx$ 0.6 MeV kinetic energy) in these experiments. The momentum distribution of electron signals was measured for 8 TW focused into a static fill of He gas at various pressures ranging from a vacuum pressure of 0.05 mTorr to 160 mTorr. The electron density of a fully ionized plasma corresponds to 3.5×10^{15} cm^{-3} at a He pressure of 50 mTorr. The maximum energy gained by electrons was obtained from the momentum spectra measured for these pressures as shown in Fig. 1. The maximum energy gain is given by $\pi Z_R \cdot eE_z$ with the peak accelerating field E_z, assuming vacuum diffraction. The experimental data are in good agreement with the linearlized theory in the low plasma densities. In plasma densities higher than 10^{16} cm^{-3}, however, the linear theory fails to predict the measured data. This indicates that nonlinear behaviors of plasma waves prevent excitation of wakefields from decreasing due to mismatch between the plasma-wave period and the laser pulse duration.

We envisaged acceleration experiments at much higher plasma density producing highly nonlinear laser-plasma interactions. It has been suggested that the self-modulation of a laser pulse is induced to break up into multiple-pulses, which resonantly excite a large wakefield [3]. The self-modulation instability is driven by two requirements: The pulse length is longer than the plasma wavelength, $L > \lambda_p$ and the power is greater than the critical power for the relativistic self-focusing, $P \geq P_c \simeq 17(\lambda_p/\lambda)^2$ GW, where λ is the laser wavelength. These conditions are fulfilled with a laser power of 1 TW for the plasma density of order of 10^{19} cm^{-3}. To achieve such a high plasma density, a He gas was filled by the gas-jet injector with the back-pressure of 7.8 atm in this experiment. The pulsed gas pressure was calibrated to be 220 Torr corresponding to a fully ionized plasma density of 1.5×10^{19} cm^{-3}. Significant level of signals was detected when electrons were injected as shown in Fig. 2. With no electrons injected, the detectable signal levels were as small as the background signals, which were contributed from self-trapping of the background plasma electrons. It is estimated that about 100 of electrons injected into the plasma are trapped and accelerated up to higher momenta than 5 MeV/c. The highest momentum of the accelerated electrons was 18.0 ± 0.8 MeV/c. The linear plasma fluid theory fails to predict the observed spectrum of accelerated electrons in such high density plasma for a rather low laser power. It implies that more efficient excitation of plasma waves may be caused by highly nonlinear effects. At this plasma density, the acceleration length is limited to $\lambda_p(\lambda_p/\lambda)^2 \simeq 0.6$ mm by detuning of accelerated electrons from the phase velocity of the plasma wave. Thus we can infer the peak accelerating field gradient of 30 GeV/m.

In order to elucidate details of laser-plasma interactions, we have made the simulation analyses for these experiments. The simulation reveals the self-consistent 1-D evolution of a laser pulse and wakefields driven by its propagation in a plasma. The simulation is based on a modified fully relativistic PIC (particle in cell code), which

uses the set of Maxwell equations and advancing 'macro-electrons'. This code has been modified to have the simulation box move at any velocity so as to keep the long term evolution of a laser pulse watched without using an extremely long simulation grid. Fig. 3 shows a series of temporal evolutions of the intensity profile with an initial peak intensity of 2×10^{16} W/cm^2, assuming the transmission ratio of about 20 % due to defocusing of the laser beam in a created plasma compared to the expected vacuum focal intensity [9]. Modulation of the pulse appears after traveling 0.8 mm and remains during propagating a distance of 1.5 mm. The amplitude of wakefield after traveling 1.5 mm is shown in Fig. 4 (a). Note that the maximum amplitude of the accelerating field exceeds 30 GV/m, predicting observations of high energy electrons accelerated by the ultrahigh gradient in the high density experiments. The wave number spectrum of the transmitted light is shown in Fig. 4 (b). We can see the largest peak of the initial laser frequency and only a slight amount of the Raman shifts at $k \pm k_p$, the plasma wave number k_p apart from the laser wave number k. It is suggested that a self-modulation of the laser pulse enhances the wakefield excitation by a factor of 10 to 100 times larger than the linear wakefield. Contradicting the earlier theoretical predictions [3], the self-modulation of a short intense laser pulse may be induced by 1-D effects rather than 2-D effects with much lower power than a critical power for the relativistic self-focusing. It seems that the ultrahigh wakefield is not directly driven by the Raman forward scattering instability.

In conclusion we have observed that electrons injected into a laser-produced plasma are accelerated by an ultrahigh gradient wakefield induced due to a short laser pulse. We found that the linear theory can predict the wakefield behavior only in the low density plasma of which wavelength is about twice the pulse width. In the weak nonlinear regime where the plasma wavelength is approximately equal to the pulse width, the measured field is not so depressed as the linear prediction. In the highly nonlinear regime, we observed more energetic electrons accelerated by the ultrahigh accelerating field of 30 GeV/m. The PIC simulation revealed that such a large amplitude of the wakefield was generated due to the self-modulation of an intense short laser pulse in the same parameters as the experiment. It is not conclusive that the self-modulation of a laser pulse and its ultrahigh wakefield excitation are directly resulted from the relativistic self-focusing of the laser beam or the Raman instabilities. From an applied point of view, however, this mechanism may allow a novel micro-size accelerator for 100 MeV energies.

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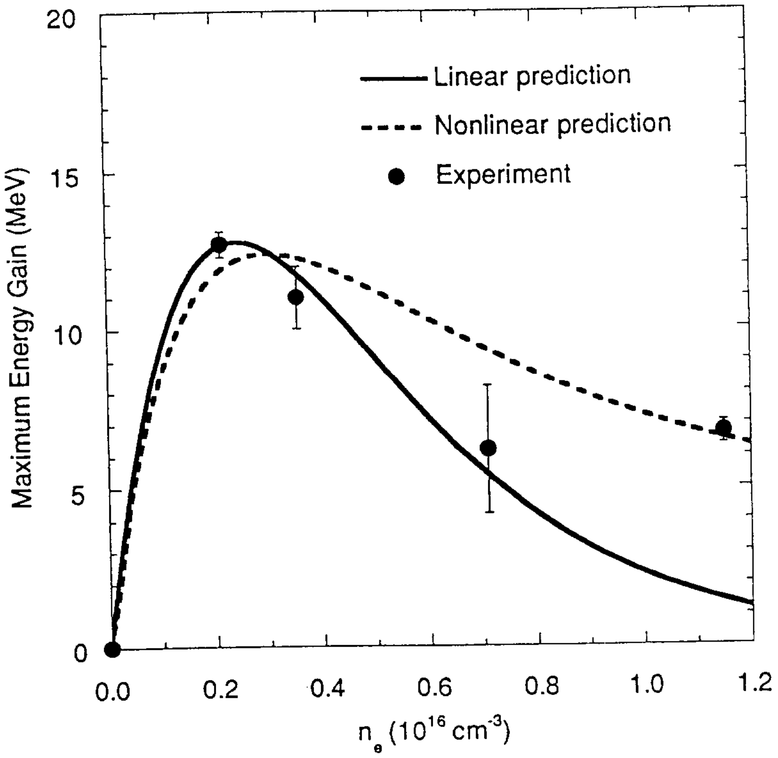

Fig. 1. The maximum energy gain of an injected electron as a function of the plasma density in comparison with theoretical predictions based on the linear fluid model (solid line) and the nonlinear fluid model (dashed line) for the 8 TW, 1 ps laser pulse.

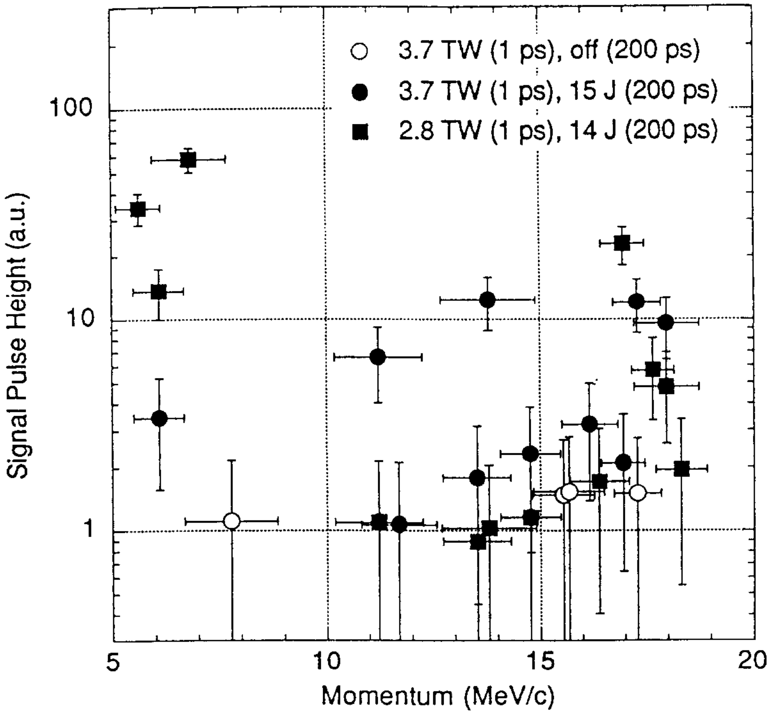

Fig. 2. Observed momentum spectra of accelerated electrons for a He gas jet at the back-pressure 7.8 atm.

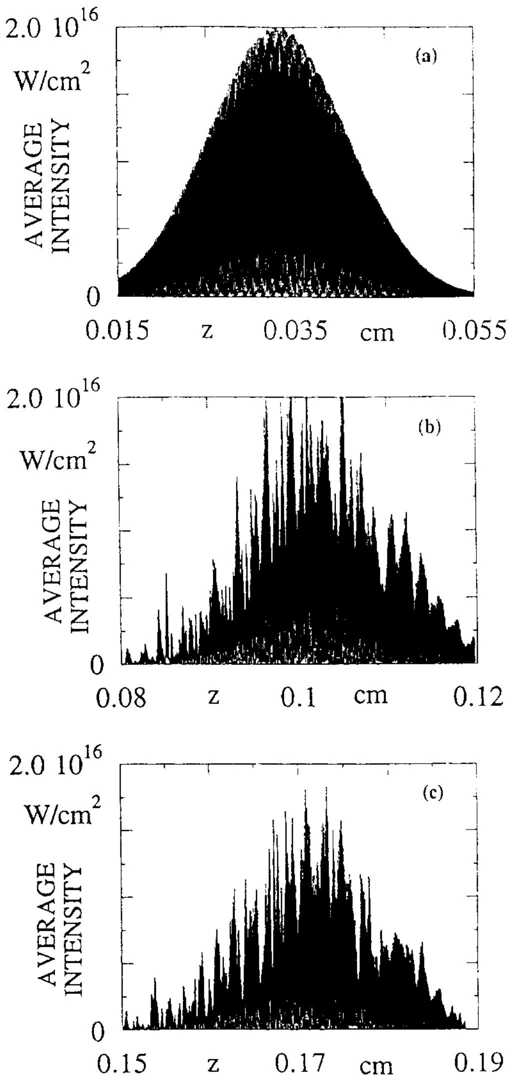

Fig. 3. Simulated temporal intencity profiles of the laser pulse with the initial peak intensity of 2 × 10^{16} W/cm^2 for the plasma density of 1.5 × 10^{19} cm^{-3} at successive traveling distances of (a) 0 mm, (b) 0.8 mm and (c) 1.5 mm.

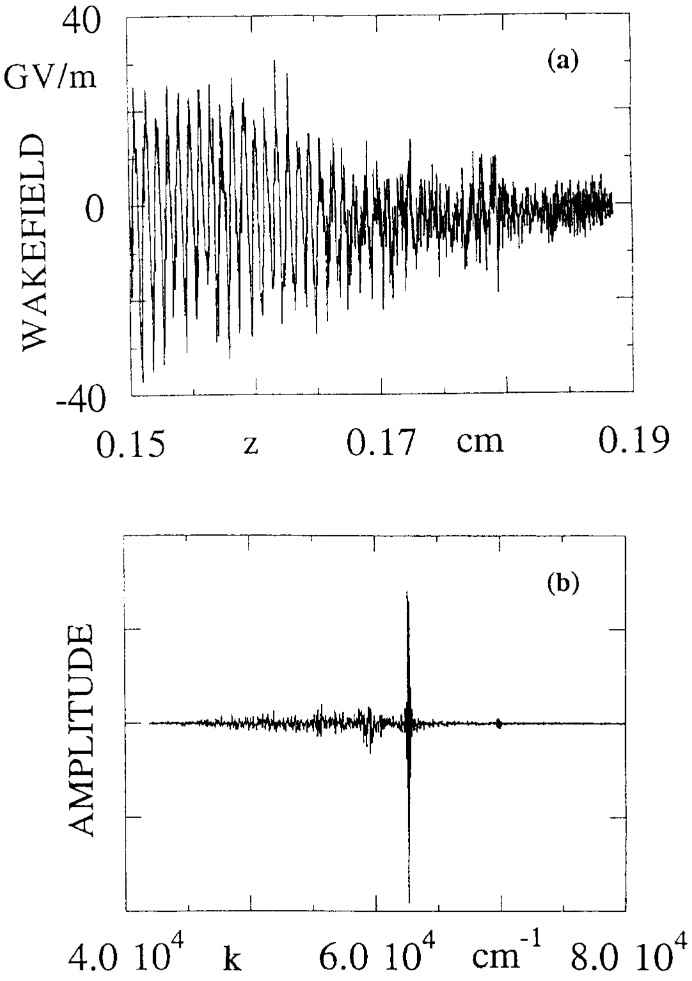

Fig. 4. Simulation results of (a) the accelerating wakefields and (b) the wave number spectrum of the laser pulse after traveling 1.5 mm for the same initial pulse intensity and plasma density as Fig. 3.