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

K. Nakajima,[1] D. Fisher,[5] T. Kawakubo,[1] H. Nakanishi,[1] A. Ogata,[1] Y. Kato,[2] Y. Kitagawa,[2] R. Kodama,[2] K. Mima,[2] H. Shiraga,[2] K. Suzuki,[2] K. Yamakawa,[2] T. Zhang,[2] Y. Sakawa,[3] T. Shoji,[3] Y. Nishida,[4] N. Yugami,[4] M. Downer,[5] and T. Tajima[1]

[1]*National Laboratory for High Energy Physics, Tsukuba, Ibaraki, Japan*
[2]*Institute of Laser Engineering, Osaka University, Osaka, Japan*
[3]*Plasma Science Center of Nagoya University, Nagoya, Japan*
[4]*Utsunomiya University, Utsunomiya, Japan*
[5]*The University of Texas at Austin, Austin, Texas 78712*
(Received 25 July 1994)

A laser pulse with a power of ~3 TW and a duration of 1 ps has been focused onto a gas. Ultrahigh-gradient electron acceleration has been observed in the laser-produced plasma with a density of $\sim 10^{19}$ cm^{-3} when injecting 1 MeV/c electrons. The simulation of the laser-plasma interaction revealed the existence of ultrahigh-gradient wake fields excited due to self-modulation of the laser pulse and its electron acceleration, consistent with the experimental results.

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

Recently there has been great interest in the 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 wake field accelerator (LWFA). A possible advantage in the PBWA is efficient excitation of plasma waves due to the resonance between the beat frequency of the 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 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 the resonant excitation of wake fields behind an intense laser pulse modulated due to the highly nonlinear laser-plasma interaction.

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

In this experiment [6], the laser pulse was delivered by a Nd:glass laser system [7] capable of generating a 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 He gas to a spot size of 80 μm. A peak intensity of the order of 10^{17} W/cm^2 can be achieved so that a fully ionized plasma can be created on a fast time scale (≤ 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 the He^{2+} ion [8]. With a 3 TW laser pulse focused into the He gas, a fully ionized plasma can be produced over more than 20 mm around the focus. A compressor grating pair, a 10° mirror, and a 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 turbomolecular pumps. For creation of a low density plasma, the gas was statically introduced with a flow-controlled valve. For the high density plasma experiment, He gas was introduced with a 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

 0031-9007/95/74(22)/4428(4)$06.00

focused with a 1.6 m focal length lens to a spot size of 40 μm diameter onto an 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 electrons produced 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 the 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 wake fields are accelerated in the beam waist of twice the Rayleigh length ≈ 10 mm. The momentum of the electrons was analyzed by the dipole field of a 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 vertical aperture 15 mm through a 100 μm thick Capton window, electrons were detected by an 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 back side of the detectors was entirely surrounded by 50 mm thick lead bricks so that x-ray emission was not detected.

The injection momentum of the electrons was set to 1 MeV/c (≈ 0.6 MeV kinetic energy) in these experiments. The momentum distribution of the 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 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 the electrons was obtained from the momentum spectra measured for these pressures as shown in Fig. 1. The maximum energy gain is given by $\pi(eE_z)_{\max}Z_R$ with the maximum accelerating field $(eE_z)_{\max}$ assuming vacuum diffraction. The experimental data are in good agreement with the linearized 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 wake fields from decreasing due to a mismatch between the plasma-wave period and the laser pulse duration.

We envisaged acceleration experiments at much higher plasma density producing highly nonlinear laser-

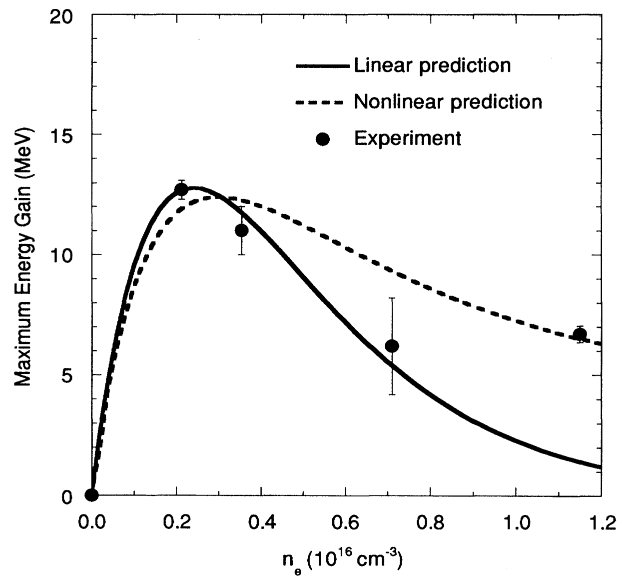

FIG. 1. The maximum energy gain of an injected electron as a function of the plasma density in comparison with theoretical predictions based on the linear fluid model (solid line) and the nonlinear fluid model (dashed line) for the 8 TW, 1 ps laser pulse [2].

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 wake field [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 laser power of 1 TW for a plasma density of the order of 10^{19} cm^{-3}. To achieve such a high plasma density, He gas was introduced by the gas-jet injector with a 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}. A 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 the 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 a high density plasma for a rather low laser power. This implies that the 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 the accelerated

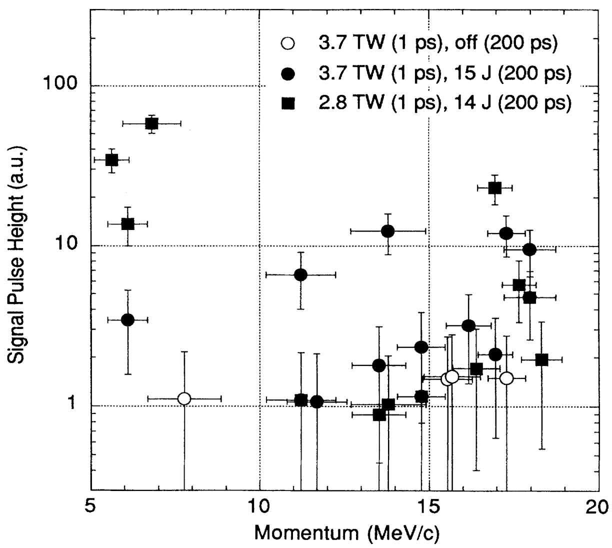

FIG. 2. Observed momentum spectra of accelerated electrons for a He gas jet at the back pressure 7.8 atm.

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 the details of laser-plasma interactions, we have made simulation analyses for these experiments. Recent analyses of intense short laser pulses in plasmas indicate that modulation can occur due to 1D forward Raman scattering at an early propagation distance [9,10]. In this limit, the ratio of the growth rate of 1D forward Raman scattering, Γ_{1D}, to that of self-modulation due to 2D effects, Γ_{2D}, is estimated to be $\Gamma_{1D}/\Gamma_{2D} = (k_p^4 R^2/2k_0^2)^{1/3}$, where $k_p = 2\pi/\lambda_p$, $k_0 = 2\pi/\lambda$, and R is the laser spot radius at focus [10]. Since this ratio is ~ 2 for our experiments, pulse modulation is expected to proceed predominantly in the 1D manner. The simulation reveals the self-consistent 1D evolution of a laser pulse and wake fields driven by its propagation in a plasma, based on a modified fully relativistic PIC (particle in cell) code. Figure 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 the created plasma compared to the expected vacuum focal intensity [11]. Modulation of the pulse appears after traveling 0.8 mm and remains during a propagating distance of 1.5 mm. The amplitude of the wake field after traveling 1.5 mm is shown in Fig. 4. Note that the maximum amplitude of the accelerating field exceeds 30 GV/m, predicting observation of high energy electrons accelerated by the ultrahigh gradient in the high density experiments. A long run of the simulation over the propagation distance of $1.5Z_R$ indicates that electrons with an initial momentum of 1 MeV/c are accelerated up to 25 MeV/c in wake fields of

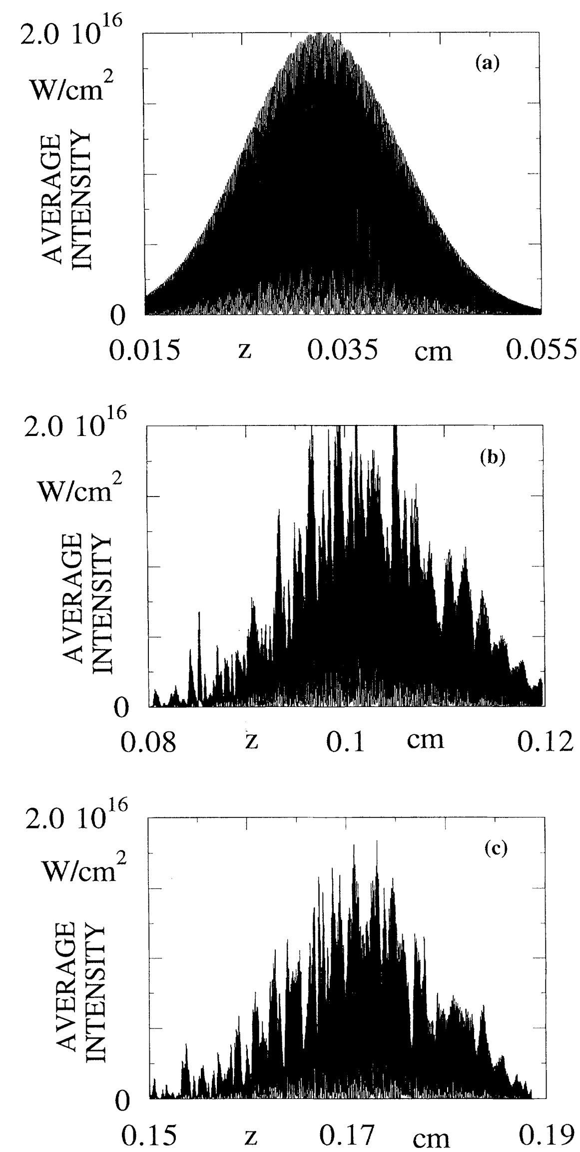

FIG. 3. Simulated temporal intensity profiles of the laser pulse with the initial peak intensity of 2×10^{16} W/cm^2 for the plasma density of 1.5×10^{19} cm^{-3} at successive traveling distances of (a) 0, (b) 0.8, and (c) 1.5 mm.

~ 30 GV/m as shown in Fig. 5. We find this simulation reproduces the momentum distribution of accelerated electrons observed in the experiment.

In conclusion, we have observed that electrons injected into a laser-produced plasma are accelerated by ultrahigh-gradient wake fields induced due to strong interaction of a short intense laser pulse with plasmas. We found that the linear theory can predict the wake field behavior only in the low density plasma of which the wavelength is about twice the pulse width. In the weak nonlinear regime where the plasma wavelength is approximately

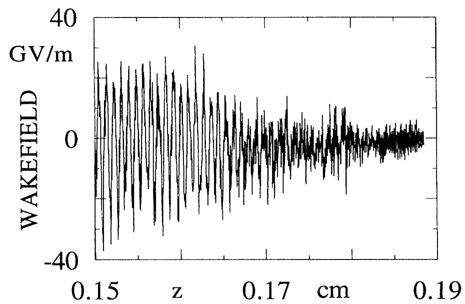

FIG. 4. Simulation results of the accelerating wake fields after traveling 1.5 mm for the same initial pulse intensity and plasma density as Fig. 3.

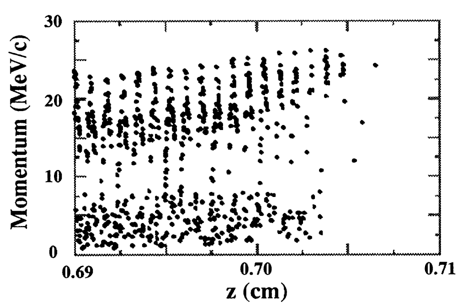

FIG. 5. Simulated momentum distribution of accelerated electrons with an initial momentum of 1 MeV/c as a function of propagation distance.

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 wake field was generated due to the self-modulation of an intense short laser pulse through Raman instabilities and that the acceleration of electrons occurred in wake fields so as to reproduce the observed momentum distribution.

The authors would like to acknowledge support from Professor H. Sugawara and Professor Y. Kimura at the National Laboratory for High Energy Physics (KEK) and the approval of this work and the technical support from Professor S. Nakai and the laser group at the Institute of Laser Engineering in Osaka University. This work was partly supported by JSPS, NSF, U.S. DOE grants and Grant-in-Aid from Ministry for Education, Science and Culture of Japan.

[1] T. Tajima and J.M. Dawson, Phys. Rev. Lett. **43**, 267 (1979); L.M. Gorbunov and V.I. Kirsanov, Zh. Eksp. Teor. Fiz. **93**, 509 (1987) [Sov. Phys. JETP **66**, 290 (1987)]; P. Sprangle *et al.,* Appl. Phys. Lett. **53**, 2146 (1988).
[2] K. Nakajima, Phys. Rev. A **45**, 1149 (1992); D. Umstadter, E. Esarey, and J. Kim, Phys. Rev. Lett. **72**, 1224 (1994); S. Dalla and M. Lontano, Phys. Rev. E **49**, R1819 (1994).
[3] N.E. Andreev *et al.,* Zh. Eksp. Teor. Fiz. **55**, 551 (1992) [Sov. Phys. JETP **55**, 571 (1992)]; E. Esarey *et al.,* Phys. Fluids B **5**, 2690 (1993); T.M. Antonsen, Jr. and P. Mora, Phys. Rev. Lett. **69**, 2204 (1992).
[4] H. Hamster *et al.,* Phys. Rev. Lett. **71**, 2725 (1993).
[5] K. Nakajima *et al.,* Phys. Scr. **T52**, 61 (1994).
[6] K. Nakajima *et al.,* in Proceedings of the 1992 Linear Accelerator Conference, Ottawa, 1992, edited by C.R. Hoffman (Report No. AECL-10728, 1992), Vol. 1, p. 332.
[7] K. Yamakawa *et al.,* Opt. Lett. **16**, 1593 (1991).
[8] M.V. Ammosov, N.B. Delone, and V.P. Krainov, Zh. Eksp. Teor. Fiz. **91**, 2008 (1986) [Sov. Phys. JETP **64**, 1191 (1986)]; B.M. Penetrante and J.N. Bardsley, Phys. Rev. A **43**, 3100 (1991).
[9] T.M. Antonsen, Jr. and P. Mora, Phys. Rev. Lett. **69**, 2204 (1992); W.B. Mori *et al.,* Phys. Rev. Lett. **72**, 1482 (1994).
[10] E. Esarey *et al.,* Phys. Rev. Lett. **72**, 2887 (1994).
[11] P. Mont *et al.,* J. Opt. Soc. Am. B **9**, 1579 (1992).