Proof-of-Principle Experiments of Laser Wakefield Acceleration

K. NAKAJIMA,[a] T. KAWAKUBO,[a] H. NAKANISHI,[a] A. OGATA,[a] Y. KATO,[b] R. KODAMA,[b] K. MIMA,[b] H. SHIRAGA,[b] K. SUZUKI,[b] K. YAMAKAWA,[b] T. ZHANG,[b] Y. SAKAWA,[c] T. SHOJI,[c] Y. NISHIDA,[d] N. YUGAMI,[d] M. DOWNER,[e] D. FISHER,[e] B. NEWBERGER,[e] and T. TAJIMA[e]

Abstract

The principle of laser wakefield particle acceleration has been tested by the Nd:glass laser system providing a short pulse with a power of 10 TW and a duration of 1 ps. Electrons accelerated up to 18 MeV/c have been observed by injecting 1 MeV/c electrons emitted from a solid target by an intense laser impact. The accelerating field gradient of 30 GeV/m is inferred.

PACS numbers: 52.35.Mw, 52.40.Nk, 52.75.Di

[a]National Laboratory for High Energy Physics, Tsukuba, Ibaraki, Japan
[b]Institute of Laser Engineering, Osaka University, Osaka, Japan
[c]Plasma Science Center of Nagoya University, Nagoya, Japan
[d]Utsunomiya University, Utsunomiya, Japan
[e]Institute for Fusion Studies, The University of Texas at Austin, Austin, Texas 78712

Recently there has been a great interest in laser-plasma accelerators as possible next-generation particle accelerators because of their potential for ultra high accelerating gradients and compact size compared with conventional accelerators. 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 ultra short laser pulse.[1] These schemes came to be known as the Beat Wave Accelerator (BWA) for beating lasers or as the Laser Wakefield Accelerator (LWFA) for a short pulse laser. Experimental activities around the world have focused on the BWA scheme using CO_2 and Nd:glass lasers,[2] primarily because of lack of intense ultra short pulse lasers until recently. A possible advantage in the BWA 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. In the meantime, the LWFA does not rely on the resonant excitation of plasma waves so that a fine-tuning of the plasma density is not absolutely necessary. Furthermore a new prospect of the LWFA are proposed, that is called "self-modulated-LWFA"[3] in which the self-modulation of the laser pulse is accompanied by the resonant excitation of wake fields behind the pulse. In the LWFA scheme, however, no experiment is reported on the wakefield excitation and its acceleration of particles to date. This letter reports a first experimental result on the laser wakefield acceleration and on evidence of self-modulated wakefield mechanism.

To estimate the amplitude of wakefields in a plasma excited by an intense short laser pulse, we employed a fluid model of the plasma dynamics, assuming a cold plasma of electron fluid and stationary ions. The momentum, continuity and Poisson's equations are linearized to result in a simple harmonic oscillator equation for the wave potential of the electron fluid driven by the ponderomotive force of the laser field. An analytical solution for the wake potential is obtained for transversely and longitudinally Gaussian pulse envelope.[4] The axial and radial wakefields are calculated from the wake potential resulted from the density oscillation with the plasma frequency $\omega_p = \sqrt{4\pi e^2 n_e/m_e}$ for the ambient density n_e of the plasma electrons. The maximum amplitude of the axial wakefield is achieved at the plasma wavelength $\lambda_p = \pi\sigma_z$: $(eE_z)_{\max} \simeq 1.3 m_e c^2 a_0^2/\sigma_z$, where σ_z is the rms pulse length and a_0 is the normalized vector of the laser field given by $a_0^2 = 0.73 \times 10^{-18} I \lambda_0^2$ for the peak intensity I in units of W/cm^2, the laser wavelength λ_0 in units of μm.

In this experiment, the laser pulse is delivered by the Nd:glass laser system[5] capable of generating the peak power up to 30 TW with a pulse duration of 1 ps. This laser system is based on the technique of chirped pulse amplification.[6] A low energy pulse of 20 nJ with 130 ps duration from the mode-locked oscillator is passed through a single mode fiber of a 1.85 km length to produce a linear frequency chirp. The long linearly chirped pulse with 450 ps duration and a 4 nm bandwidth at exit of the fiber is split into two pulses each of which is amplified to the maximum energy of 40 J through each broad bandwidth amplifier-chain. One of amplified pulses with 200 ps duration and 2.8 nm bandwidth is compressed to 1 ps duration by a pair of gratings. The other uncompressed pulse is focused on the solid target to produce an electron beam.

The experimental setup is schematically shown in Fig. 1. The laser beam with a 140 mm diameter from the compression stage is focused by a 3.1 m focal length lens of $f/22$ 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.[7] With a 10 TW laser pulse focused into the He gas, the fully ionized plasma can be produced over more than 60 mm around the beam waist. The compressor grating-pair, the 10° mirror and the focusing lens are installed in the vacuum vessel connected to the vacuum chamber for the acceleration experiment. These vacuum chambers are 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 the 200 ps laser pulse. The p-localized laser beam with 140 mm diameter is 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. The peak intensity then exceeds 10^{16} W/cm^2 for 20 J irradiation. The target rod of 60 mm length is mounted on the plunger head inside the vacuum chamber. Hot electrons emitted from the target are injected into the waist of the 1 ps pulse laser beam through the 90° bending magnetic with appropriate edge angles so as to achieve double focusing of an electron beam. Since the electron beam length is 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 $\pm$100 ps. Electrons within momentum spread of 0.2 MeV/c are collimated at the focus. Electrons trapped by wakefields are accelerated in the beam waist of twice the Rayleigh length, $\approx$ 10 mm. The momentum of electron is analyzed by the dipole field of the magnetic spectrometer placed in the exit of the interaction chamber. The magnetic of the spectrometer is designed to form a Fowler-Hafner type spectrograph[8] with a bending angle of 90° and horizontal focusing. This spectrometer covers the momentum range of 5.6 – 19.5 MeV/c at the dipole field of 3.9 kG. The geometrical acceptance of the spectrometer is $\sim$ 0.01% of 4π solid angles over the interaction point. The momentum resolution of the spectrometer is typically 1.0 MeV/c per channel at the 3.9 kG bending field. Upon exiting the vacuum chamber of a vertical aperture 15 mm through a 100 μm thick Capton window, electrons are detected by the array of 32 scintillation counters placed at the image plane of the spectrometer. Each detector is assembled with a 3 mm thick, 10 mm wide, 60 mm long plastic scintillator coupled to a $\frac{1}{2}$-in. photomultiplier tube. Pulse heights of the detector are measured during 200 ns by the fast multichannel CAMAC ADCs gated by the trigger pre-pulse in coincidence with a laser pulse. The detector is sensitive to a single minimum ionizing particle. The noise level of the detector was less than 1 ADC count corresponding to approximately 2.5 mV pulse height. 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 background x rays are detected by 4 scintillation counters placed around the vacuum chamber to monitor electron intensity. The vacuum chamber is shielded by 4 mm thick lead sheets to reduce the flux of background x rays. The back of the detector is entirely surrounded by 50 mm thick lead bricks so that the background signal levels were reduced down to a few ADC counts.

In the beginning of this experiment, the electron production has been carried out by using only the 200 ps laser pulse. The momentum distribution of produced electrons was measured with the spectrometer for the injection bending field set to 0.5, 1, 2, and 3 MeV/c. The most of electrons were observed with the spectrometer set to 380 G for the injection bending field set to 340 G (1 MeV/c$\approx$ 0.6 MeV kinetic energy) as shown in Fig. 2. A number of electrons along with numerous x rays was produced above the pulse energy of 20 J. The observed signal levels above 2 MeV/c were as small as noise levels. The absolute number of produced electrons with momentum of 9.86 ± 0.24 MeV/c is estimated to be $\sim 5 \times 10^4$ in the interaction region. This result is consistent with the experimental data on the superthermal electron production in laser-plasma interaction.[9] The flux of electrons above 2 MeV/c ($\approx$ 1.6 MeV kinetic energy) is expected to be at most 10^{-4} lower than that of 1 MeV/c electrons.

In the acceleration experiment the injection bending field was set to 1 MeV/c. Such electron production for each laser shot was identified from signal levels in x-ray monitoring detectors. The momentum distribution of electron signals was measured for 8 TW focused into a static fill of 50 mTorr of He gas as shown in Fig. 3(a). The electron density of a fully ionized plasma is $3.5 \times 10^{15}\,\mathrm{cm}^{-3}$ at this pressure. The spectrum of electrons measured at 50 mTorr is distinguished from the data measured for 7 TW injected into an evacuated chamber at 5.2×10^{-5} Torr. No energetic electrons above 2 MeV/c were observed when both the 200 ps pulse and the 1 ps pulse were injected in the evacuated chamber. The momentum spectra of accelerated electrons has been inferred by integrating equations of 3D electron motion as shown in Fig. 3(a). In a higher momentum tail of the spectrum, the simulation results are in good agreement with the experimental data points obtained for the 8 TW injection. The data obtained from the evacuated condition are also roughly in agreement with the momentum spectrum of injected electrons approximated by a Gaussian distribution as shown in Fig. 2. The simulation indicates that injected electrons were accelerated by the excited plasma wave of the peak accelerating gradient of 0.7 GeV/m. The number of electrons accelerated by the wakefield is estimated as an upper limit of Poisson processes with 95% confidence level from observed signal levels[10] as shown in Fig. 3(b). An estimate of the number of electrons accelerated up to higher momenta than 2 MeV/c results in ≈ 100, assuming the evacuated data as background.

In the high plasma density experiment we observed several data points contributed by electrons accelerated up to higher momenta than 5 MeV/c when He gas was filled by the gas-jet injector with the back-pressure of 7.8 atm. The pulsed gas pressure was calibrated to be 200 Torr for such back-pressure. This pressure corresponds to a fully ionized plasma density of $1.5 \times 10^{19}\,\text{cm}^{-3}$. The observed signals are shown in Fig 4(a). Significant signal levels were detected when electrons were injected. With no electrons injected, the detectable signal levels were as small as the background signals. It implies that there was no significant contribution to detectable signals due to self-trapping of the background plasma electrons and x-ray emissions in the plasma. The number of electrons accelerated is evaluated from the similar analysis to the low pressure data with 95% confidence level as shown in Fig. 4(b). It is estimated that about 100 electrons injected into the plasma are trapped and accelerated up to higher momenta than 5 MeV/c by the plasma wave. The distribution of accelerated electrons seems to be concentrated on the momentum range above 11 MeV/c. This suggests phase bunching mechanism somewhat appears in the same manner as the linear accelerator. The highest momentum of the accelerated electrons was 18.0 ± 0.8 MeV/c. The linear plasma fluid theory cannot predict the observe spectrum of accelerated electrons for a rather low power of 3 TW and such high plasma density. It is suggested that more efficient excitation of plasma waves may be caused by highly nonlinear effects. The self-modulation of a laser pulse has been predicted to excite accelerating electric fields in excess of 100 GV/m around such plasma density.[3] This prediction is based on two requirements: The pulse length is longer than the plasma wavelength, $L > \lambda_p = 8.5\,\mu$m, and the power is greater than the critical power for the relativistic self-focusing, $P \geq P_c \simeq 17(\lambda_p/\lambda_0)^2$ GW= 1.1 TW. Both the pulse length and the power were adequate to excite the self-modulation of a laser pulse in this experiment. In this plasma density, the acceleration length is limited to $\lambda_p(\lambda_p/\lambda_0)^2 \simeq 0.6$ mm by the detuning of accelerated electrons from the phase velocity of the plasma wave. Then we can infer the accelerating field gradient of 30 GeV/m.

In conclusion we have demonstrated that electrons injected into a laser-produced plasma are accelerated by wakefields excited by a short laser pulse. We report the first test of the laser wakefield acceleration mechanism. The momentum spectra of accelerated electrons have been well predicted by simulation results in the linear wakefield regime. In the nonlinear regime we have observed more energetic electrons accelerated up to 18 MeV/c close to the detection limit of the spectrometer. The observation implies that instabilities associated with the relativistic self-focusing may cause excitation of enhanced wakefields.

Acknowledgments

The work was supported in part by the U.S. Department of Energy and NSF, and in part by the Ministry of Education of Japan and JSPS.

References

[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]C.E. Clayton *et al.*, Phys. Rev. Lett. **54**, 2343 (1985); N.A. Ebrahim, Phys. Canada **45**, 178 (1989); A.E. Dangor *et al.*, Phys. Scr. **T30**, 107 (1990); Y. Kitagawa *et al.*, Phys. Rev. Lett **68**, 321 (1992); F. Amironov *et al.*, Phys. Rev. Lett. **68**, 3710 (1992); C.E. Clayton *et al.*, Phys. Rev. Lett. **70**, 37 (1993).

[3]N.E. Andreev *et al.*, Zh. Eksp. Teor. Fiz. **55**, 552 (1992) [JETP Lett. **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]K. Nakajima, Phys. Rev. A **45**, 1149 (1992); K. Nakajima *et al.*, in *1992 Linear Accelerator Conference Proceedings*, ed. C.R. Hoffmann, Ottawa, August 1992, AECL-10728, Vol. 1, p. 332.

[5]K. Yamakawa *et al.*, Opt. Lett. **16**, 1593 (1991).

[6]P. Maine *et al.*, IEEE J. Quantum Electron. **QE-24**, 398 (1988).

[7]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).

[8]J.J. Livingood, *The Optics of Dipole Magnets* (Academic, New York, 1969), p. 66.

[9]S. Aithal *et al.*, Phys. Fluids **30**, 3825 (1987); C. Rousseaux *et al.*, Phys. Fluids B **4**, 2589 (1992).

[10]Particle Data Group, Phys. Rev. D **45**, III.39 (1992).

Figure Captions

1. Schematic of the experimental setup.

2. Momentum spectrum of electrons produced by the 200 ps laser pulse at the injection bending field set to 1 MeV/c. The solid line shows a fit to a Gaussian distribution.

3. Momentum spectra of accelerated electrons in a static fill of He gas at 50 mTorr and the evacuated chamber at 0.05 mTorr. (a) Observed signal levels of the detector. The solid line shows the momentum spectrum expected from the simulation of electron acceleration due to wakefields excited by a 8 TW laser pulse. The dashed line shows the spectrum of injected electrons. (b) The number of electrons accelerated up to higher momenta than 2 MeV/c. The values are estimated as upper limits of Poisson processes with 95% confidence level.

4. Momentum spectra of accelerated electrons for a He gas jet at the back-pressure 7.8 atm. (a) Observed signal levels of the detector. (b) The number of electrons accelerated up to higher momenta than 5 MeV/c with 95% confidence level. The solid line shows the spectrum with electrons injected at 1 MeV/c. The dashed line shows the data with no electrons injected.

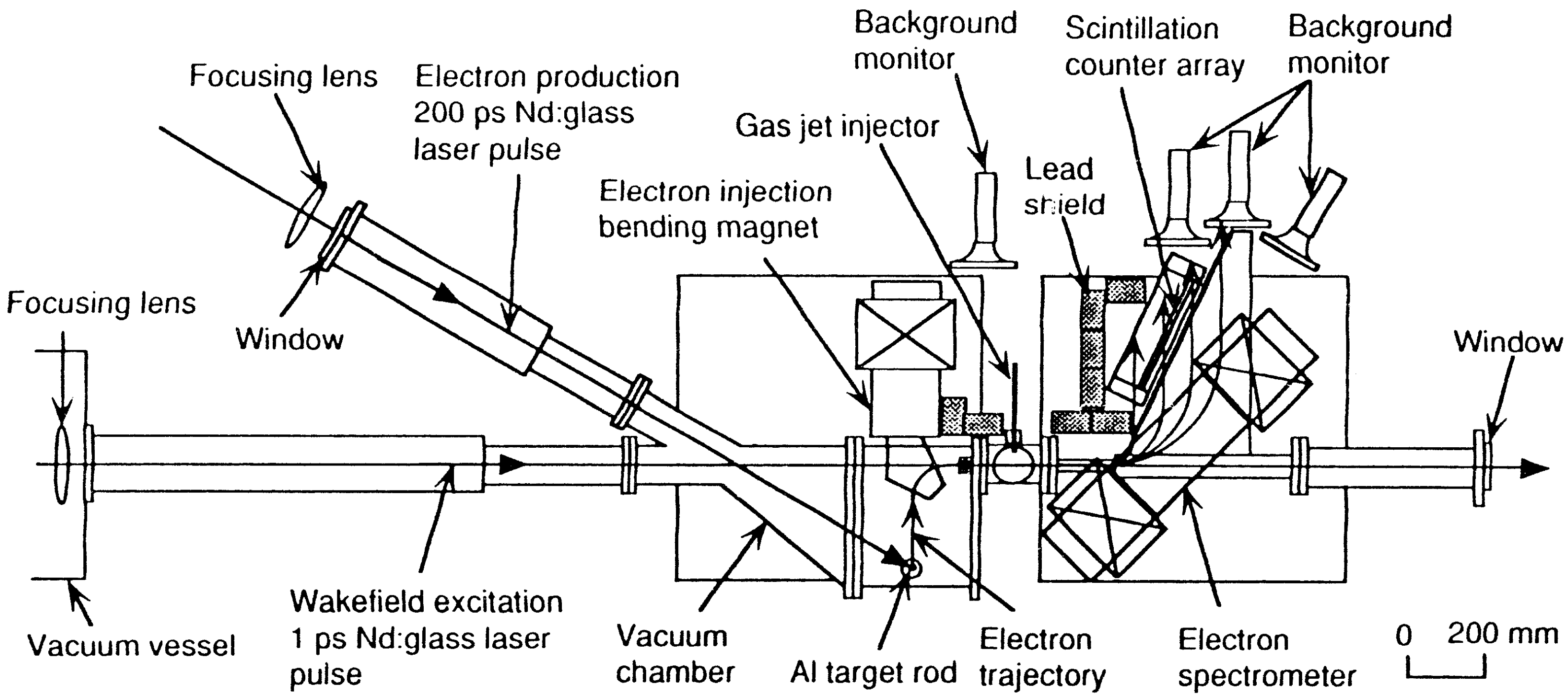

Fig. 1. Schematic of the experimental setup.

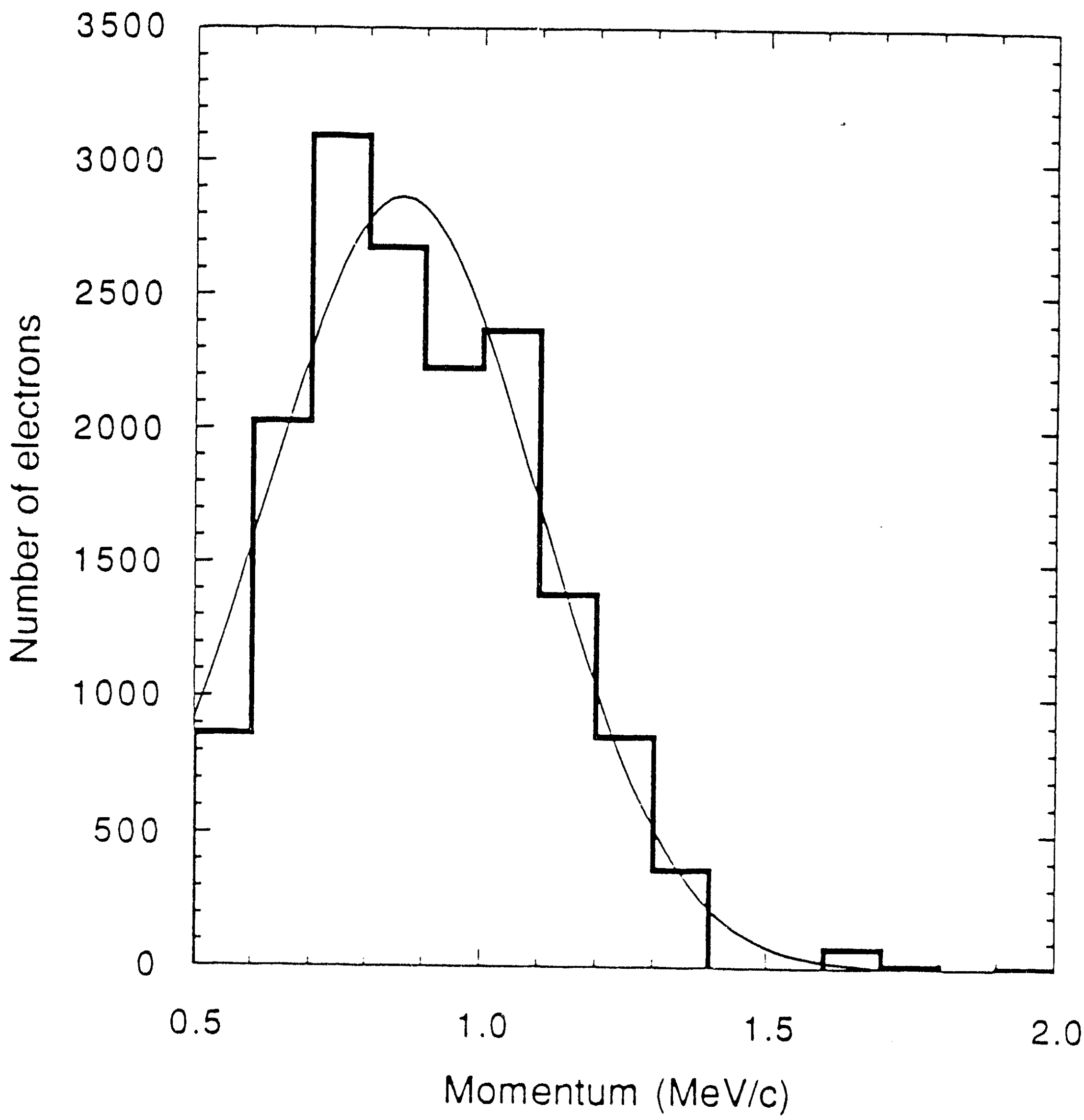

Fig. 2. Momentum spectrum of electrons produced by the 200 ps laser pulse at the injection bending field set to 1 MeV/c. The solid line shows a fit to a Gaussian distribution.

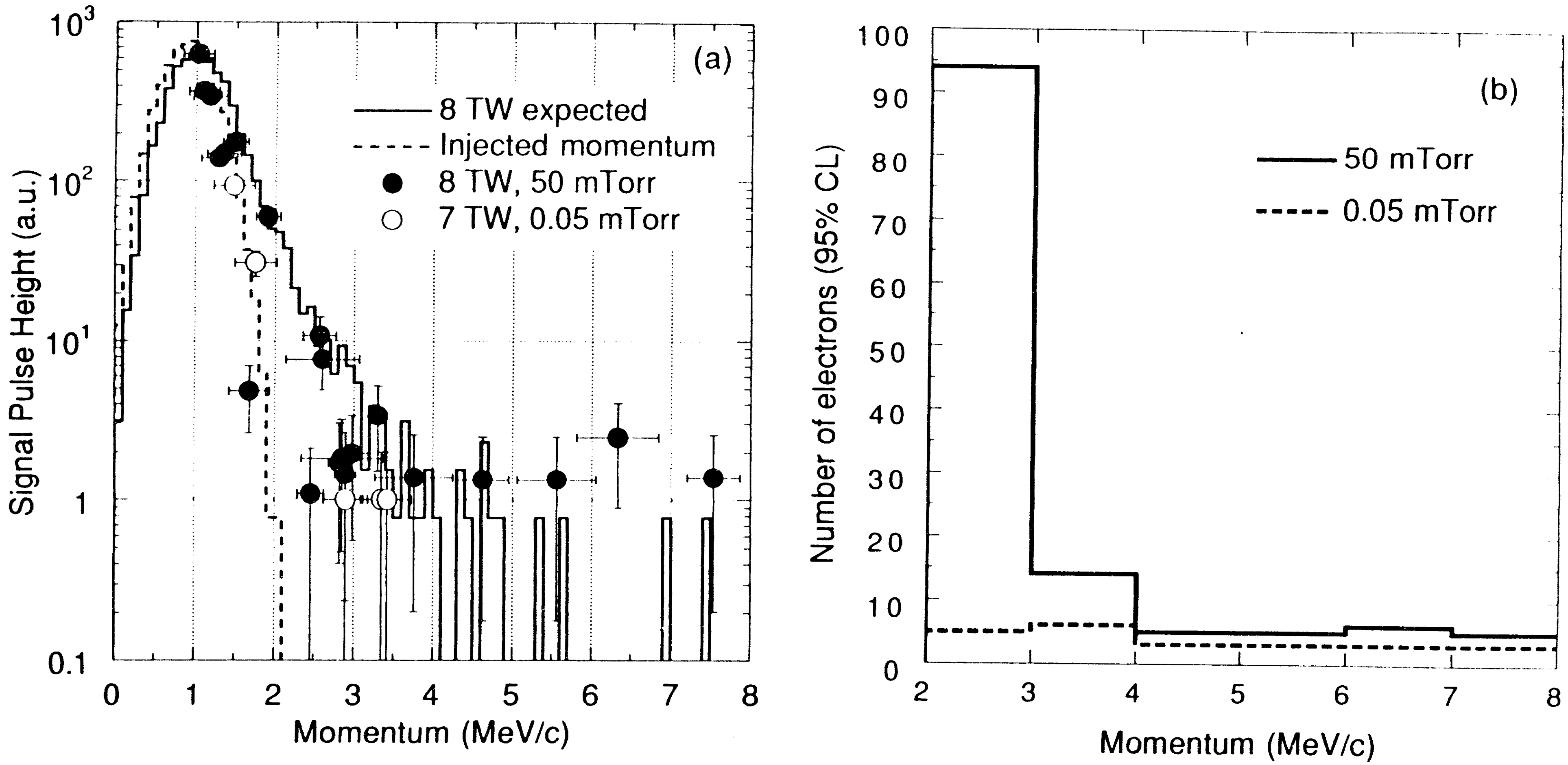

Fig. 3. Momentum spectra of accelerated electrons in a static fill of He gas at 50 mTorr and the evacuated chamber at 0.05 mTorr. (a) Observed signal levels of the detector. The solid line shows the momentum spectrum expected from the simulation of electron acceleration due to wakefields excited by a 8 TW laser pulse. The dashed line shows the spectrum of injected electrons. (b) The number of electrons accelerated up to higher momenta than 2 MeV/c. The values are estimated as upper limits of Poisson processes with 95% confidence level.

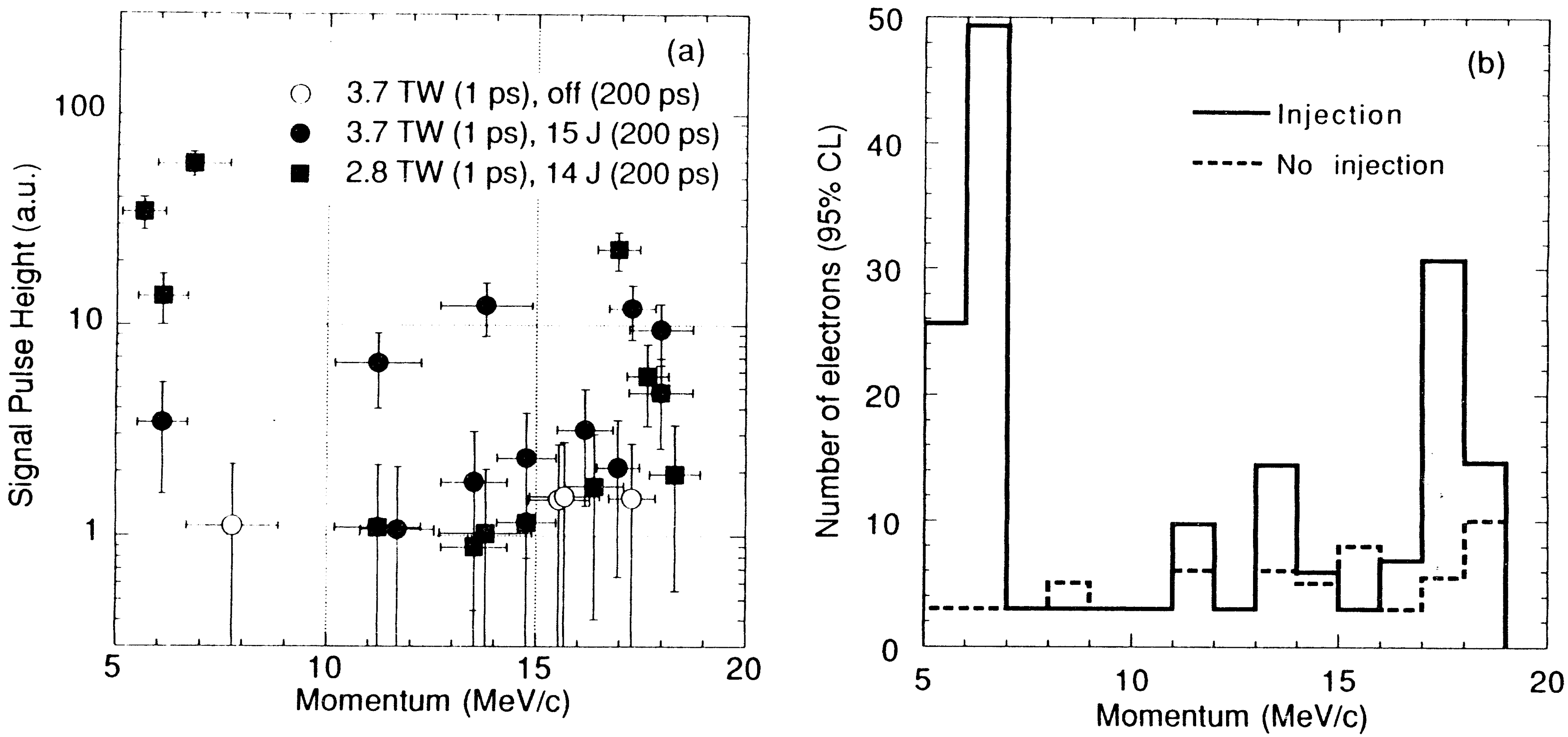

Fig. 4. Momentum spectra of accelerated electrons for a He gas jet at the back-pressure 7.8 atm. (a) Observed signal levels of the detector. (b) The number of electrons accelerated up to higher momenta than 5 MeV/c with 95% confidence level. The solid line shows the spectrum with electrons injected at 1 MeV/c. The dashed line shows the data with no electrons injected.

DATE FILMED

7/7/94

END

4