# PROOF OF PRINCIPLE EXPERIMENTS OF LASER WAKEFIELD ACCELERATION

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*Abstract*

Particle acceleration due to the laser wakefield has been demonstrated by the Nd:glass laser system providing a short pulse with a power of 10 TW and a duration of 1 ps. Electrons accelerated by plasma waves have been observed when injecting 1 MeV/c electrons emitted from a solid target by an intense laser impact. The accelerating field gradient of 0.7 GeV/m has been achieved.

## 1 INTRODUCTION

Recently there has been a great interest in laser-plasma accelerators as possible next generation particle accelerators because of their potential for ultrahigh 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 ultrashort 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 ultrashort pulse lasers till 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 necessary. In the LWFA scheme, however, no experiment is reported on the wakefield excitation and its acceleration of particles to date. This reports the first experimental results of electron acceleration due to the laser wakefield.

## 2 EXPERIMENTAL SETUP

In this experiment [4], the laser pulse was delivered by the Nd:glass laser system capable of generating the peak power up to 30 TW with a pulse duration of 1 ps [5].

This laser sytem is based on the technique of chirped pulse amplification. 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 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 1.8 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 $\mu$m. 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 $8.8 \times 10^{15}$ W/$cm^2$ for $He^{2+}$ ions [6]. 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. For creation of a plasma, a gas was statically filled with the flow controlled valve.

Electrons for acceleration were produced from an aluminum solid target irradiated by the amplified 200 ps laser pulse. The $p-$polarized laser beam with 140 mm diameter is focused with a 1.6 m focal length lens to a spot size of 40 $\mu$m 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 magnet 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
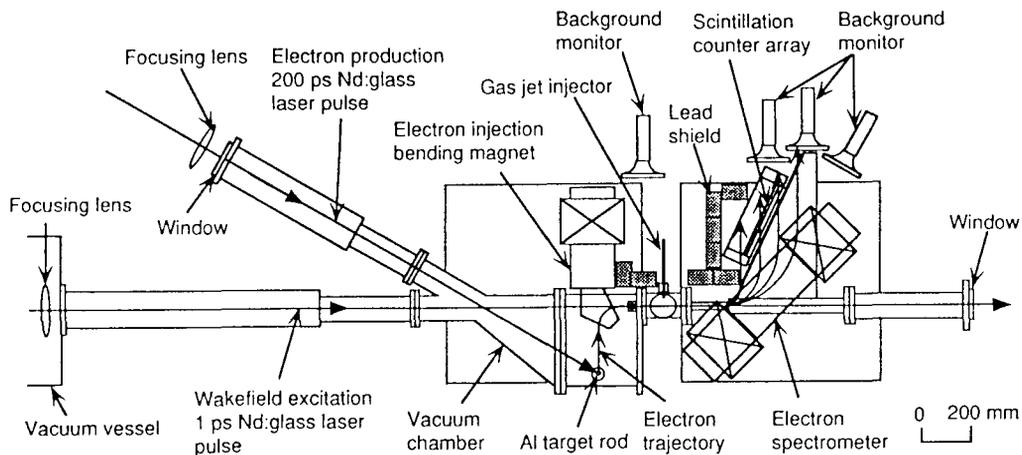
Figure 1: Schematic of the experimental setup.



Figure 2: Momentum spectrum of electrons produced by a 20 J laser pulse with a duration of 200 ps.

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, ≈ 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 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 per channel at the 3.9 kG bending field. Upon exiting the vacuum chamber of a vertical aperture 15 mm through a 100 $\mu$m thick Capton window, electrons are detected by the array of 32 scintillation counters placed at the image plane of the spectrometer. The detector is sensitive to a single minimum ionizing particle. The noise level of the detector was less than 1 ADC count. 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.

## 3 ELECTRON PRODUCTION

In the beginning of this experiment, production of electrons for acceleration 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 ≈ 0.6 MeV kinetic energy) as shown in Fig. 2. A number of electrons along with numerous x rays were produced above the pulse energy of 20 J. The observed signal levels above 2 MeV/c were as small as noise levels. The
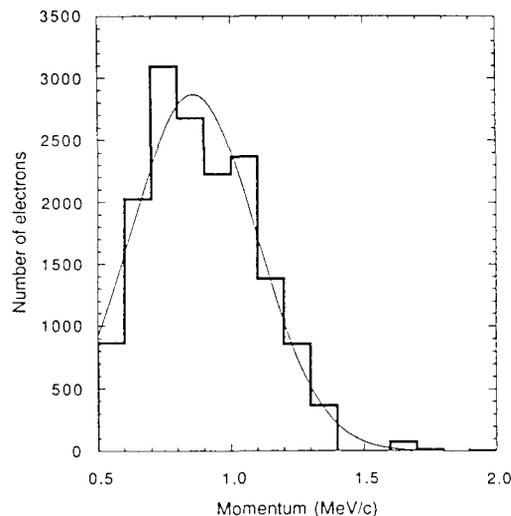
absolute number of produced electrons with momentum of 0.86 ± 0.24 MeV/c was estimated to be ∼ 5 × $10^4$ in the interaction region. This result is consistent with the experimental data on the superthermal electron production in laser-plasma interaction [7]. The flux of electrons above 2 MeV/c ( ≈ 1.6 MeV kinetic energy) is expected to be at most $10^{-4}$ lower than that of 1 MeV/c electrons.

## 4 ACCELERATION EXPERIMENTS

In the acceleration experiment the injection bending field was set to 1 MeV/c. The momentum distribution of electron signals was measured for a peak power of 8 TW focused into a static fill of 50 mTorr He gas as shown in Fig. 3. The electron density of a fully ionized plasma is $3.5 \times 10^{15}$ 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 $5.2 \times 10^{-5}$ Torr. No energetic electrons above 2 MeV/c
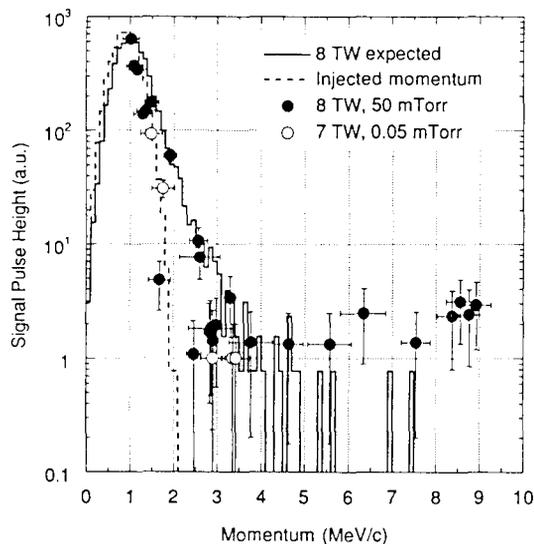
Figure 3: Momentum spectra of accelerated electrons in a static fill of He gas at 50 mTorr.



Figure 4: The maximum energy gain as a function of the plasma density in comparison with theoretical predictions

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 3-D electron motion. In a higher momentum tail of the spectrum, the simulation results are in good agreement with the experimental data points obtained for 8 TW injection. The simulation indicates that injected electrons were accelerated by the excited plasma wave with the peak accelerating gradient of 0.7 GeV/m. An estimate of the number of electrons accelerated up to higher momenta than 2 MeV/c results in $\sim 100$, assuming the evacuated data as background.

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 maximum energy gained by electrons was obtained from the momentum spectra measured for these pressures as shown in Fig. 4. The maximum energy gain is given by $\pi Z_R \cdot eE_z$ with the peak accelerating field $E_z$, assuming vacuum diffraction of the Rayleigh length $Z_R$. 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 nonlinear cold fluid model can 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.

## 5   CONCLUSIONS

We report the first test of the laser wakefield acceleration mechanism. We have demonstrated that electrons injected into a laser-produced plasma were accelerated by wakefields excited by a short laser pulse. The momentum spectra and the maximum energy gain of accelerated electrons have been well predicted by the linear fluid model in the low density plasma. The maximum accelerating gradient of the wakefield was estimated to be 0.7 GeV/m. In the higher plasma density no depression of wakefields was observed due to nonlinear effects.
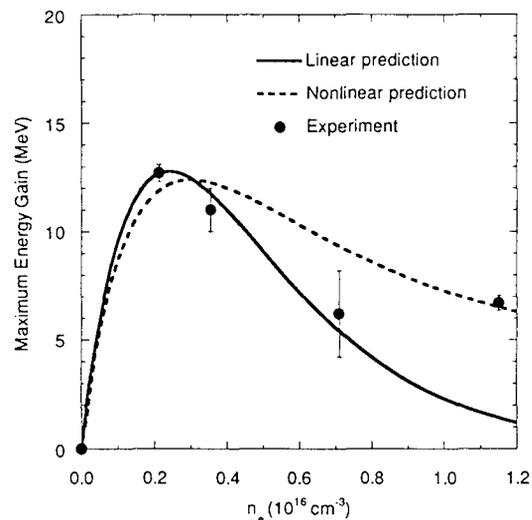
## 6   REFERENCES

[1] T. Tajima and J.M. Dawson, Phy. 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] 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**, 551 (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 et al., in 1992 Linear Accelerator Conference Proceedings, edited by C.R. Hoffmann, Ottawa, August 1992, AECL-10728, Vol. 1, p. 332.

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

[6] 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).

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