

Laser Wakefield Accelerator Experiments Using 1ps 30TW Nd:glass Laser

K. Nakajima, H. Nakanishi, T. Kawakubo, A. Ogata
KEK, National Laboratory for High Energy Physics, Tsukuba, Ibaraki, Japan

Y. Kitagawa, H. Shiraga, R. Kodama, T. Zhang, K. Suzuki, Y. Kato
Institute of Laser Engineering, Osaka University, Osaka, Japan

Y. Sakawa, T. Shoji
Plasma Science Center, Nagoya University, Nagoya, Japan

Y. Nishida, N. Yugami
Department of Electric and Electronic Engineering, Utsunomiya University, Utsunomiya, Japan

T. Tajima
Institute for Fusion Studies, The University of Texas at Austin, Austin, Texas, USA

Abstract

The peak power of 30TW and the pulse width of 1ps produced by the Nd:glass laser system is capable of creating a highly-ionized plasma of a moderate density gas on an ultrafast time scale and generating a large amplitude plasma wave with an accelerating gradient of the order of GeV/m. We are going to demonstrate particle acceleration injecting electrons of a few MeV emitted from a solid target by intense laser irradiation.

1 INTRODUCTION

Recent progress in ultrashort super-intense lasers allows us to test the principle of the Laser Wakefield Accelerator (LWFA) [1]. An intense, short laser pulse with peak power of 30TW and pulse width of 1ps is delivered by the Nd:glass laser system GMII in Osaka University. This laser achieves $10^{17} - 10^{18} \text{W/cm}^2$ intensity, strong enough to create a fully-ionized plasma on an ultrafast time scale by the tunneling ionization process. In a plasma with appropriate density, a large amplitude of wakefield is generated behind the laser pulse propagating through the plasma due to the ponderomotive force. The phase velocity of the plasma wave is highly relativistic so that the wakefield can accelerate charged particles trapped by the plasma oscillation.

In these experiments, a chamber is filled with H_2 or He gas beforehand, whose pressure mates with the optimum plasma density for acceleration if it is completely ionized. Two $1.052\mu\text{m}$ Nd:glass laser beams are injected into the chamber. One with 200ps duration and 200GW peak power bombarded a solid target to produce test electrons whose energy ranges to the order of MeV. The other, with 1ps duration and 30TW peak power, ionizes the gas

and excites wakefields in the resultant plasma in synchronism with the first laser. Energy change of the test electrons caused by the wakefield is measured by an energy analyzer.

We have not yet conditioned the 1ps laser to attain the full power. Consequently, no conclusive demonstration of the acceleration has not yet observed.

2 THEORETICAL PREDICTIONS

We assume the Gaussian beam optics, in which the laser beam has the wavelength λ_0 , the peak power P , the radius $w_0(z)$ at the waist and the vacuum Rayleigh length z_R . The linear model with an unmagnetized, cold plasma of classical electrons and immobile ions gives the longitudinal wakefield excited by the Gaussian laser pulse as[2]

$$eE_z = \frac{m_e c^2 \epsilon_0 \cos(k_p z - \omega_p t)}{z_R [1 + (z/z_R)^2]} \exp\left(-\frac{r^2}{w_0^2 [1 + (z/z_R)^2]}\right), \quad (1)$$

with the vacuum resistivity $\Omega_0 = 377\Omega$, the plasma frequency ω_p , $k_p = \omega_p/v_p$ with a phase velocity of the plasma wave v_p , and

$$\epsilon_0 = \frac{\Omega_0 P}{\sqrt{\pi} m_e^2 c^4} \left(\frac{\lambda_0}{\lambda_p}\right) k_p \sigma_z \exp\left(-\frac{k_p^2 \sigma_z^2}{4}\right), \quad (2)$$

where σ_z is the rms pulse length. The wakefield is maximum when the plasma density gives the relation $\lambda_p = \pi \sigma_z$.

The maximum energy gained by an electron with velocity equal to the phase velocity of the plasma wave is obtained by integrating the axial wakefield along the laser beam axis,

$$(\Delta E)_{\text{max}} = \int_{-\infty}^{\infty} E_z(z) dz = \pi m_e c^2 \epsilon_0. \quad (3)$$

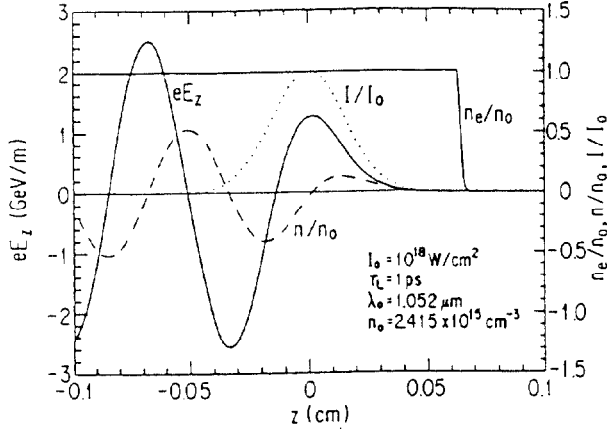


Figure 1: Evolution of the electron density n_e , the density perturbation n and the axial electric field E_z excited by a 1 ps Nd:glass laser pulse of the peak intensity 10^{18} W/cm^2 .

The 1ps, 30TW laser pulse at wavelength $\lambda_0 = 1.052 \mu\text{m}$ should be able to produce the maximum energy gain of 45MeV.

The trapping condition for an electron with energy γ and velocity $\beta = v/c$ is given by

$$eE_z/(m_e c \omega_p) \geq \gamma(1 - \beta_\phi \beta) - 1/\gamma_\phi, \quad (4)$$

where β_ϕ is the phase velocity of the plasma wave and γ_ϕ is the relativistic factor of its phase velocity defined as

$$\beta_\phi = \frac{v_p}{c} = \sqrt{1 - \frac{\omega_p^2}{\omega_0^2}}, \quad \gamma_\phi = \frac{1}{\sqrt{1 - \beta_\phi^2}} = \frac{\omega_0}{\omega_p}. \quad (5)$$

The trapping and the acceleration occur at the waist in the Rayleigh length. The minimum threshold kinetic energy to be trapped by the plasma wake is about 40keV for excitation of a 10^{18} W/cm^2 intensity.

The present experiments utilizes the ability of tunneling ionization of a short pulse laser. The phenomenon on an ultrafast time scale ($\leq 10\text{fs}$) is distinct when the intensity is greater than 10^{15} W/cm^2 . The onset of tunneling ionization is predicted by a simple Coulomb-barrier model. The threshold intensity [4] for the production of charge state Z of the atom or ion with the ionization potential U_i is given by

$$I_{th} = 2.2 \times 10^{15} Z^{-2} (U_i/27.21)^4 \text{ W/cm}^2. \quad (6)$$

The ionization rate [5] for a hydrogen atom is given by ,

$$W_H = 1.61 \omega_{a.u.} \left[\frac{10.87 E_{a.u.}}{E_0} \right]^{1/2} \exp \left[-\frac{2E_{a.u.}}{3E_0} \right], \quad (7)$$

where $\omega_{a.u.}$ is the atomic unit of frequency ($4.1 \times 10^{16} \text{ s}^{-1}$) and $E_{a.u.}$ is the atomic field strength ($5.1 \times 10^9 \text{ V/cm}$).

Fig. 1 depicts the evolution of electron density in hydrogen plasma with initial atomic density $n_0 = 2.415 \times 10^{15}$

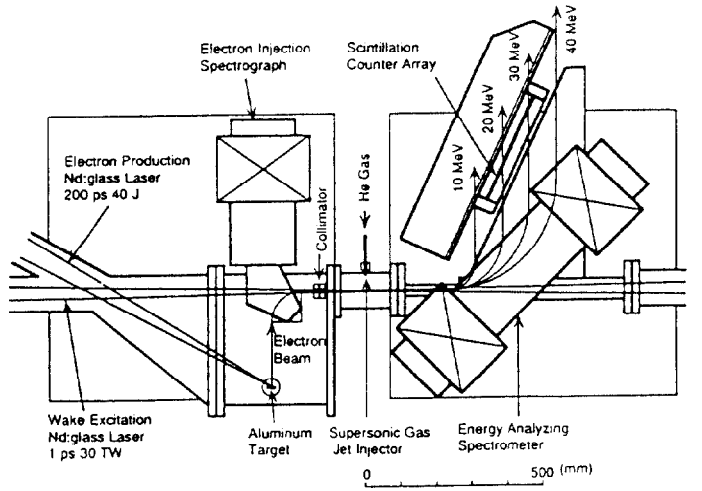


Figure 2: Experimental layout for electron acceleration.

cm^{-3} , the density perturbation and the axial electric field excited by a 1 ps laser pulse with the peak intensity $I_0 = 10^{18} \text{ W/cm}^2$.

3 EXPERIMENTAL APPARATUS

The chamber is filled with H_2 or He gas beforehand with static pressure to mate with the optimum plasma density for acceleration when completely ionized. It is also possible to feed the gas pulsively in synchronous with the laser pulse. Two $1.052 \mu\text{m}$ Nd:glass laser beams are injected into the chamber. One bombards a solid target to produce test electrons whose energy ranges to the order of MeV. The other with 1ps duration and 30TW peak power ionizes the gas and excites wakefield in the resultant plasma in synchronism with the first laser. The energy change of the test electrons caused by the wakefield is measured by an energy analyzer.

The lasers are almost linear polarized. They are processed as follows[3]. A primary Nd:YAG laser pulse of 130ps duration is coupled to a single mode fiber of 1.85km in length. The beam is split into two at the exit of the fiber, each has 200ps duration and 1.8nm bandwidth. One is amplified and used for the electron production. The other is also amplified to an energy of 41J with a beam diameter of 14cm, and it is finally compressed to a pulse width of 1ps by a pair of gratings. The output from the compression stage is focused into a vacuum chamber containing H_2 or He gas with a focal spot size of $\sim 100 \mu\text{m}$. Because the wavelength for maximum gain in the amplifiers (1053nm) is different from the central wavelength of the chirped pulse (1052.3nm), the spectrum of each of the two amplified pulses is shifted downwards.

The repetition rate of the laser system is less than once per hour. The pair of gratings, a focusing lens and the setups of Fig. 2 are contained in the chamber and evacuated to $\sim 10^{-9} \text{ torr}$. The laser power and the time structure

can be measured at the exit of the plasma chamber by a calorimeter and a streak camera with 0.6ps time resolution, respectively. In the course of optical alignment and timing adjustment, the source Nd:YAG laser is used at the pulse rate of 5Hz. The alignment used a metal sphere with a radius of 100 μ m, which was placed at the point to be focused and whose image was observed by a CCD camera from the end windows. The direction and the position of a final mirror were adjusted so that the sphere hides the laser beam completely.

The test electrons with energy satisfying the trapping condition are produced by irradiating a solid target by the 40J, 200ps laser. The electron production may be explained by the Raman instability or resonance absorption of the laser radiation[6]. In order to inject electrons emitted from the target into the laser wakefield at the waist of the laser beam, a dipole magnet is used to select the electron energy in the range of 0.2 – 3MeV. This spectrograph is placed between the target and the image point of electrons, as shown in Fig. 2. The electrons are injected along the axis of the main laser beam. The time delay between two laser beams are adjusted by the optical path lengths of two laser pulses. It takes account of the time-of-flight of the electrons, which amounts to 1.8ns for electrons of 1.5MeV/c. The test electrons are thus selected both by the spectrograph and the time-of-flight.

The acceleration occurs at the waist of the laser beam characterized by a Rayleigh length of 25mm in the plasma chamber. The test electrons are bent by an angle of 90° in the dipole field of the spectrometer placed in the exit of the plasma chamber. This spectrometer covers the energy range of 10 – 45 MeV at the dipole field of 4.3kG. The electron detector is an array of 32 scintillation counters each of which is assembled with a 1cm wide scintillator and a 1/2-in. H3165 photomultiplier. Shields of lead blocks and plates were necessary to reject background noise. The pulse heights of the detector array are measured by the fast multichannel CAMAC ADCs gated in coincidence with the laser pulse. The energy resolution of the spectrometer is 1.3MeV per channel.

4 EXPERIMENTAL RESULTS

No conclusive demonstration of the acceleration has not yet observed. We have not yet transmitted the full power of the 1ps laser to the plasma chamber.

As the target to produce test electrons, an aluminum rod and a gold plate were tried, but no substantial difference was found. The maximum electron energy was around 1MeV. The increase of the laser energy increased not the energy but the number of electrons. The energy spectrum of test electrons from the aluminum target produced by the 200ps, 25.9J laser beam is shown in Fig. 3.

We had prepared optical plasma diagnostics to measure the plasma density, the Stark broadening[7], the blueshifting of the incident laser spectrum[8], *etc.*. However, sufficient light intensity for such diagnostics has not obtained

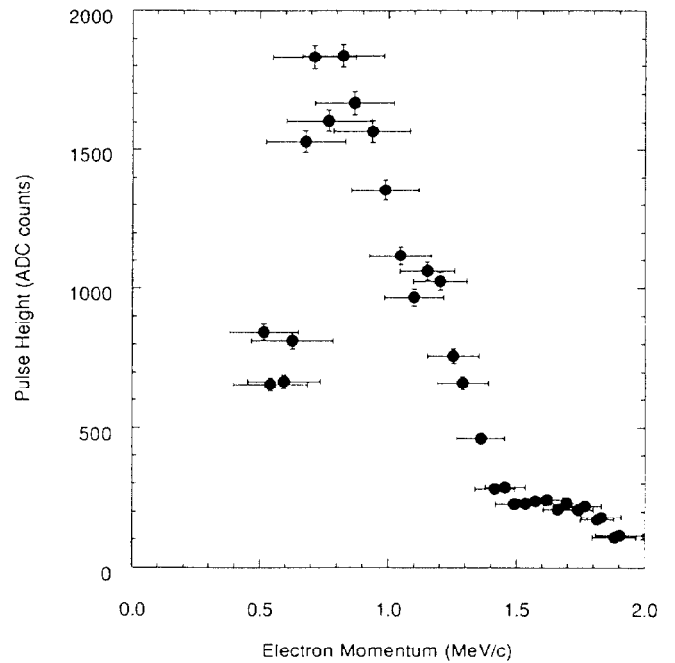


Figure 3: Energy spectrum of test electrons.

from the plasma. We have to calculate the plasma density from the gas pressure at the present.

We have tried acceleration experiments using the 1ps laser beam with power less than 5TW. It is found that the energy spectra of electrons are certainly different with and without the existence of the test electrons; i.e., with and without the operation of the 200ps laser. However, because of the poor signal-to-noise ratio of the energy spectra, we refrain from publishing the results. The ratio has been predicted by the simulation which numerically integrates the two-dimensional equation of motion. It gives the probability of the electron trapping in this range of laser power to be $< 10^{-4}$. We expect that the 1ps laser with the designed power will give clear results.

5 REFERENCES

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