A PROOF OF PRINCIPLE EXPERIMENT OF LASER WAKEFIELD ACCELERATOR

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Abstract

The ultrashort super-intense lasers allows us to test a principle of the laser wakefield particle acceleration. The peak power of 30 TW and the pulse width of 1 ps produced by the Nd:glass laser system is capable of creating a highly-ionized plasma of a moderate density gas in an ultrafast time scale and generating a large amplitude plasma wave with the accelerating gradient of 2.5 GeV/m. The particle acceleration can be demonstrated by injecting a few MeV electrons emitted from a solid target by an intense laser irradiation.

1 INTRODUCTION

Super-high accelerating gradients for future accelerators can be achieved by the use of a plasma-based acceleration mechanism in which a plasma wave is driven by a laser pulse or a charged particle beam. It is known that the laser pulse is capable of exciting a plasma wave with a large amplitude and a relativistic phase velocity by means of beating two lasers or an ultrashort laser pulse [1]. This scheme came to be known as the Beat Wave Accelerator (BWA) for the beating laser driver or as the Laser Wakefield Accelerator (LWFA) for the short pulse laser driver. A salient feature of this scheme is to make use of material ionization or breakdown which limits the accelerating gradients for conventional accelerators. Experimental activities have focused on the BWA scheme so far, primarily because of the lack of super-intense ultrashort pulse laser.

The recent progress in ultrashort super-intense lasers allows us to test the principle of the LWFA. The intense short laser pulse with the peak power of 30 TW and the pulse width of 1 ps is delivered by the Nd:glass laser system in Osaka University. This laser can achieve $10^{17}-10^{18}$ W/cm^2 intensity which is strong enough to create a fully-ionized plasma in an ultrafast time scale due to the multiphoton ionization or the tunneling ionization process. In an appropriate density gas, a large amplitude of the wakefield is generated behind a laser pulse propagating through the plasma due to the ponderomotive force. According to a fluid model of the plasma dynamics, a phase velocity of the plasma wave is highly relativistic so that the wakefield can accelerate charged particles trapped by the plasma oscillation. The wakefield excitation can be diagnosed by acceleration of electrons produced by the intense laser irradiation on the solid target.

2 EXCITATION OF PLASMA WAVE

We consider electron density oscillations in a plasma excited by the impulse provided by an intense short laser pulse. For an unmagnetized, cold plasma of classical electrons and immobile ions, the linearized equations describing the motion of the plasma electron fluid are

$$m_e \frac{\partial \mathbf{v}}{\partial t} = \nabla(e\phi + \phi_{NL}), \qquad (1)$$

$$\frac{\partial n}{\partial t} + n_0 \nabla \mathbf{v} = 0, \quad \nabla^2 \phi = 4\pi e n, \qquad (2)$$

where $\mathbf{v}$ and n are the electron velocity and density perturbation; n_0 the unperturbed density; ϕ the electrostatic potential of the plasma; and ϕ_{NL} the ponderomotive potential defined by averaging the nonlinear force over $2\pi/\omega_0$, exerted on plasma electrons by a laser pulse with frequency ω_0. Thus the ponderomotive potential is $\phi_{NL} = -(m_e c^2/2)\mathbf{a}^2$, where $\mathbf{a} = e\mathbf{A}(r,z,t)/(m_e c^2)$ is the normalized vector potential of the laser field. Assuming that all of the axial and time dependencies can be expressed as a function of a single variable, $\zeta = z - v_p t$, with a phase velocity v_p of the excited plasma wave, the electrostatic potential during plasma oscillation is

$$\frac{\partial^2 \phi}{\partial \zeta^2} + k_p^2 \phi = -k_p^2 \phi_{NL}, \qquad (3)$$

where $k_p = \omega_p / v_p$ and $\omega_p = \sqrt{4\pi e^2 n_0 / m_e}$ is the plasma frequency. The solution is given by

$$\phi(r,\zeta) = k_p \int_{\zeta}^{\infty} d\zeta' \sin k_p(\zeta - \zeta') \phi_{NL}(r,\zeta'). \qquad (4)$$

The axial and radial wakefields are defined by $E_z = -\partial\phi/\partial\zeta$ and $E_r = -\partial\phi/\partial r$, respectively. Considering the bi-Gaussian profile of a laser pulse given by

$$|\mathbf{a}(r,\zeta)| = a_0 \exp\Big(-\frac{r^2}{\sigma_r^2} - \frac{\zeta^2}{2\sigma_z^2}\Big), \qquad (5)$$

where σ_z is the rms pulse length and σ_r is the rms spot size, the axial electric field become

$$\begin{aligned} eE_z = & \ (\sqrt{\pi}/4) m_e c^2 k_p^2 a_0^2 \sigma_z \exp(-2r^2/\sigma_r^2 - k_p^2\sigma_z^2/4) \\ & \times \big[C(\zeta)\cos k_p\zeta + S(\zeta)\sin k_p\zeta\big], \end{aligned} \qquad (6)$$

where

$$C(\zeta) = 1 - \mathrm{Re}\big[\mathrm{erf}(\zeta/\sigma_z - ik_p\sigma_z/2)\big], \qquad (7)$$
$$S(\zeta) = -\mathrm{Im}\big[\mathrm{erf}(\zeta/\sigma_z - ik_p\sigma_z/2)\big]. \qquad (8)$$

The maximum accelerating gradient is achieved at the plasma wavelength $\lambda_p = \pi\sigma_z$: $(eE_z)_{\max} = 2\sqrt{\pi}e^{-1} m_e c^2 a_0^2/\sigma_z$. As an example, the maximum accelerating gradient of the plasma wave excited by a 1.052μm laser with intensity of 10^{18} W/cm^2 and 1 ps pulse duration leads to 2.5 GeV/m at the plasma density of 2.415×10^{15} cm^{-3}.

3 ELECTRON ACCELERATION

Assuming the Gaussian beam optics, the intensity is expressed by

$$I(r,z) = \frac{2P}{\pi w^2(z)} \exp\Big[-\frac{2r^2}{w^2(z)}\Big], \qquad (9)$$

where P is the peak power of the laser pulse. The spot size $w(z)$ of the laser beam is

$$w(z) = w_0\big[1 + (z/z_R)^2\big]^{1/2}, \qquad z_R = \pi w_0^2/\lambda_0, \qquad (10)$$

where w_0 is the radius of the beam waist, z_R the vacuum Rayleigh length and λ_0 the wavelength of the laser. The longitudinal wakefield excited by a Gaussian laser pulse is written as

$$eE_z = \frac{m_e c^2 \varepsilon_0}{z_R[1+(z/z_R)^2]} \exp\Big(-\frac{r^2}{w_0^2[1+(z/z_R)^2]}\Big)\cos\psi, \qquad (11)$$

where $\psi = k_p z - \omega_p t$ and with the vacuum resistivity Ω_0 (377Ω),

$$\varepsilon_0 = \frac{\Omega_0 P}{\sqrt{\pi} m_e^2 c^4}\Big(\frac{\lambda_0}{\lambda_p}\Big) k_p\sigma_z \exp\Big(-\frac{k_p^2\sigma_z^2}{4}\Big). \qquad (12)$$

Thus equations of electron motion are

$$m_e\frac{d(\gamma\mathbf{v})}{dt} = -e\mathbf{E}, \qquad \frac{d\psi}{dt} = \omega_p\Big(\frac{v_z}{v_p} - 1\Big), \qquad (13)$$

where $\gamma = 1/\sqrt{1 - \mathbf{v}^2/c^2}$ and $v_z = dz/dt$.

The trapping condition of an electron with the energy $\gamma = E/m_e c^2$ and the velocity $\beta = v/c$ is given by

$$eE_z/(m_e c\omega_p) \geq \gamma(1 - \beta_\phi\beta) - 1/\gamma_\phi, \qquad (14)$$

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

$$\beta_\phi = \frac{v_p}{c} = \sqrt{1 - \frac{\omega_p^2}{\omega_0^2}}, \qquad \gamma_\phi = \frac{1}{\sqrt{1-\beta_\phi^2}} = \frac{\omega_0}{\omega_p}. \qquad (15)$$

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

$$(\Delta E)_{\max} = \int_{-\infty}^{\infty} E_z(z)dz = \pi m_e c^2 \varepsilon_0 \cos\psi_s, \qquad (16)$$

where ψ_s is the synchronous phase of the electron captured by the wave potential. As an example, a laser pulse at wavelength $\lambda_0 = 1.052\mu$m should be able to produce the maximum energy gain,

$$(\Delta E)_{\max} \simeq 1.49 P(\mathrm{TW})/\tau_L(\mathrm{ps}) \quad \mathrm{MeV}, \qquad (17)$$

where τ_L is the pulse width in FWHM, $c\tau_L = (2\ln 2)\sigma_z$.

4 LASER

The super-intense, ultrashort laser pulse is available at Institute of Laser Engineering, Osaka University [2]. A 1 ps laser pulse is amplified to a peak power of 30 TW by using the technique of chirped-pulse amplification with a 1.052 μm Nd:glass laser. A laser pulse of 130 ps duration is coupled to a single mode fiber of a 1.85 km length. A chirped pulse of 150 ps duration and 1.8 nm bandwidth at exit of the fiber is amplified to an energy of 41 J with a beam diameter of 14 cm. Finally the laser pulse is compressed to a pulse width of 1 ps by a pair of gratings. The output from the compression stage is focused into a vacuum chamber containing He gas with a focal spot size of 90 μm.

5 PLASMA

The short pulse laser with intensity greater than 10^{15} W/cm^2 causes tunneling ionization of atoms in an ultrafast time scale ($\lesssim$ 10 fs). The onset of tunneling ionization is predicted by a simple Coulomb-barrier model. The threshold intensity [3] for the production of charge state Z of the atom or ion with the ionization potential U_i is given by

$$I_{\mathrm{th}} = 2.2 \times 10^{15} Z^{-2}(U_i/27.21)^4 \quad \mathrm{W/cm^2}. \qquad (18)$$

The ionization rate [4] for a hydrogen atom is given by ,

$$W_{\mathrm{H}} = 1.61\omega_{\mathrm{a.u.}}\Big[\frac{10.87E_{\mathrm{a.u.}}}{E_0}\Big]^{1/2}\exp\Big[-\frac{2E_{\mathrm{a.u.}}}{3E_0}\Big], \qquad (19)$$

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

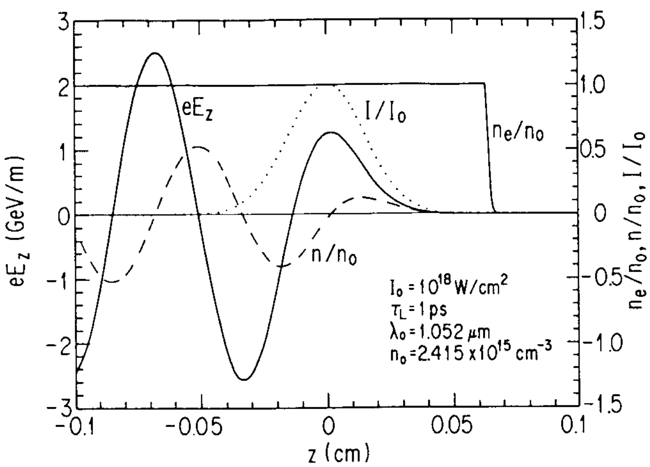

Figure 1: Evolution of the electron density n_e, the density perturbation n and the axial electric field E_z excited by a 1 ps Nd:glass laser pulse of the peak intensity 10^{18} W/cm^2.

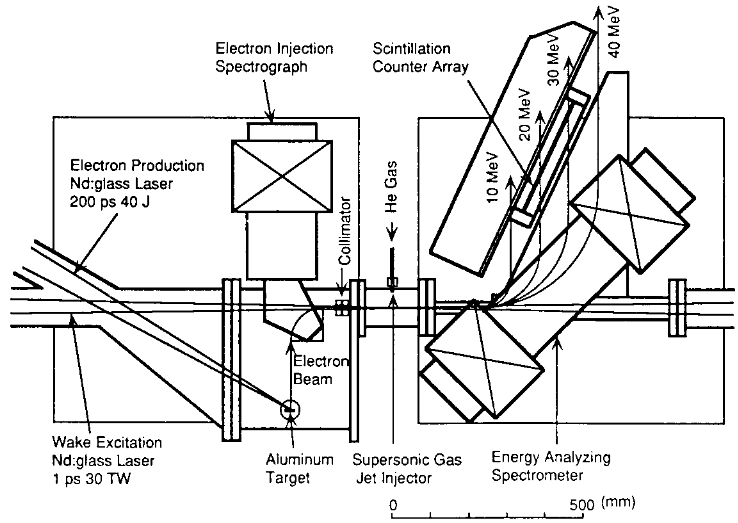

Figure 2: Experimental layout for electron acceleration

Fig. 1 shows evolution of the electron density of a hydrogen plasma with the initial atom density $n_0 = 2.415 \times 10^{15}$ cm^{-3}, the density perturbation and the axial electric field excited by a 1 ps laser pulse with the peak intensity $I_0 = 10^{18}$ W/cm^2.

6 DIAGNOSTICS

The diagnostic system is shown in Fig. 2. For the acceleration experiment, it is necessary to use elctrons of which energy are higher than the trapping condition. The minimum threshold kinetic energy trapped by the plasma wave potential is about 40 keV for excitation of a 10^{18} W/cm^2 intensity. A number of experiments have showed the generation of energetic electrons up to a few MeV by laser irradiation on solid targets. The recent experiment[5] observed emission of relativistic electrons up to an energy of $\sim$ 2.3 MeV from the exploding thin foil plasmas produced by CO_2 laser at intensity of 4×10^{14} W/cm^2. A typical fluence is $\sim 10^7$ electrons/keV-str at 1 MeV. Superthermal electron production may be explained by the Raman instability or the resonance absorption of the laser radiation. The Raman forward scattering occurs at the instability threshold intensity of $\sim 10^{16}$ W/cm^2 for Nd:glass laser. An electron probing beam is produced by a 40 J, 200 ps pulse focused onto an aluminum target.

In order to inject electrons emitted from the solid target into the laser wakefield in the waist of the laser beam, a dipole magnet is used to select the electron energy in the range of $0.2-3$ MeV. This spectrograph is placed between the solid target and the image point of electrons so that an electron beam with the image diameter of 50μm and the energy spread of 10% at 1 MeV by means of adjusting the collimator. A typical intensity of a pulsed probing beam leads to 10^6 electrons at 1 MeV. The electrons are injected along the axis of the main laser beam in a time delay by adjusting the optical path length of two laser pulses.

The electron acceleration occurs at the waist of the laser beam characterized by the Rayleigh length of 1 cm in the plasma chamber. The accelerated electrons are bent by the 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 4.3 kG. The electron detector is the array of 32 scintillation counters each of which is assembled with a 1 cm wide scintillator and a 1/2-in. photomutiplier. 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 1.3 MeV per channel.

7 REFERENCES

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