Experiment of Laser Wake-Field Accelerator

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Abstract

Experiment of the laser wake-field accelerator (LWFA) is envisaged by using a short pulse, high power laser. The LWFA is a novel particle accelerator concept based on a large amplitude plasma wave excited by a short intense laser pulse. The accelerating gradient of wake-field is possible to exceed 2 GeV/m by focusing a 1.05 μm laser pulse of 1 ps duration and 30 TW power into a moderate density gas. The particle acceleration can be demonstrated by injecting a few MeV electrons emitted from a solid target irradiated by an intense laser. The experiment will be the first proof of principle of the LWFA.

1 INTRODUCTION

A breakthrough of achieving super-high accelerating gradients for future accelerators is 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 provided by the Nd:glass laser system. With the use of this laser we should be able to achieve a capability of $10^{17} - 10^{18}$ W/cm^2 intensity in 1 ps pulse duration. The intensity of this laser is strong enough to create a highly-ionized plasma in an ultrafast time scale due to the multiphoton ionization or the tunneling ionization process. In an appropriate gas pressure, 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 experiment will diagnose acceleration of relativistic electrons produced by the intense laser irradiation.

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

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

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

where 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

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

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

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

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

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

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

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

where

$$C(\zeta) = 1 - \mathrm{Re}\big[\mathrm{erf}(\zeta/\sigma_z - ik_p\sigma_z/2)\big], \quad (7)$$

$$S(\zeta) = -\mathrm{Im}\big[\mathrm{erf}(\zeta/\sigma_z - ik_p\sigma_z/2)\big]. \quad (8)$$

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

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

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

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

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

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

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

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

Thus equations of electron motion are

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

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

$$(\Delta E)_{\max} = \int_{-\infty}^{\infty} E_z(z)dz = \pi m_e c^2 \varepsilon_0 \cos\psi_s, \quad (14)$$

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,

$$(\Delta E)_{\max} \simeq 1.49 P(\mathrm{TW})/\tau_L(\mathrm{ps}) \quad \mathrm{MeV}, \quad (15)$$

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

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

$$eE_z/(m_e c\omega_p) \geq \gamma(1 - \beta_\phi\beta) - 1/\gamma_\phi, \quad (16)$$

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

$$\beta_\phi = \frac{v_p}{c} = \sqrt{1 - \frac{\omega_p^2}{\omega_0^2}}, \qquad \gamma_\phi = \frac{1}{\sqrt{1-\beta_\phi^2}} = \frac{\omega_0}{\omega_p}. \quad (17)$$

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 100 μm. For the use of production of an electron probing beam, a part of the laser pulse before compression is split and focused onto an aluminum target with a focal spot of 30 μm in diameter.

5 PLASMA

Although the optimum plasma density for the wakefield excitation is 2.4×10^{15} cm^{-3} for a 1 ps pulse, it is possible to generate a large amplitude plasma wave over a broad range of the electron density in the plasma. This feature is advantage of the LWFA scheme over the beat wave excitation which occurs only at the resonant density. Thus in the LWFA, there is no need to have highly homogeneous plasmas at fairly high densities in the long region.

The short pulse laser with intensity greater than $\sim 10^{15}$ W/cm^2 causes tunneling ionization of atoms in an ultrafast time scale ($\leq$ 10 fs). The ionization due to the intense laser field can be classified by the Keldysh tunneling parameter [3], $\kappa = \omega_0\sqrt{2m_e U_i}/(eE_0)$, where U_i is the ionization potential of the atom or ion and ω_0 and E_0 are the frequency and the strength of the electric field, respectively. In the regime of $\kappa < 1$, the ionization is described as a tunneling process, while the multiphoton ionization dominates in the region, $\kappa > 1$. The onset of tunneling ionization is predicted by a simple Coulomb-barrier model. The threshold intensity for the production of charge state Z [4] is given by

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

The Gaussian pulse of Nd:glass laser with the peak intensity of 10^{18} W/cm^2 and the pulse length of $\tau_L = 1$ ps causes the onset of ionization at the leading front distant from the pulse peak by $2\tau_L$ in a hydrogen gas, and by $1.6\tau_L$ in a He gas. The tunneling ionization theory [5] gives the ionization rate for hydrogen atom,

$$W_H = 1.61\omega_{a.u.} \left[\frac{10.87E_{a.u.}}{E_0}\right]^{1/2} \exp\left[-\frac{2E_{a.u.}}{3E_0}\right], \tag{19}$$

where $\omega_{a.u.}$ is the atomic unit of frequency($= 4.1 \times 10^{16}$ s^{-1}) and $E_{a.u.}$ is the atomic field strength (5.1×10^9 V/cm). The laser with intensity of 4×10^{14} W/cm^2 can produce a fully ionized hydrogen plasma in ~ 1 fs. Thus an appropriate plasma density required for excitation of the plasma wave is produced by adjusting the filling pressure of gases without any elctric discharge device or pre-ionizing laser pulses.

6 DIAGNOSTICS

For the acceleration experiment, it is necessary to use elctrons of which energy are larger than the trapping codition corresponding to the amplitude of plasma waves. 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. It is known that a large amount of electrons with energy up to ~ 1 MeV are created in plasmas produced by irradiation of an intense laser pulse on solid targets. Extremely hot electron generation may be explained by the Raman instability or the resonance absorption of the laser radiation. According to experiments in CO_2 laser produced plasmas [6], electrons with energies up to 1.4 MeV were observed in a 5° wide cone about the target normal during a 300 ps risetime of the laser pulse with intensity of 10^{14} W/cm^2. A typical fluence was $\sim 10^7$ electrons/keV-str at an energy of 1 MeV. The theoretical simulation of the Raman forward scattering gives the instability threshold intensity of $\sim 10^{16}$ W/cm^2 for Nd:glass laser.

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 horizontal and vertical focusing is achieved by appropriate choice of the magnet edge angle. The spectrograph provides an electron beam with the image diameter of 30μm 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 must be injected along the axis of the main laser beam at the time delay within ~ 50 ps behind the laser pulse. The optimum delay is achieved 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 ~ 10 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 CONCLUSION

For application of the LWFA to high energy particle accelerators, some problems regarding the acceleration distance must be circumvented. The acceleration length is limited by a phase detuning between the plasma wave and the accelerated particles, an energy depletion of the pump laser and a stably transport distance of both laser and particle beams without diffraction and instabilities in plasmas. In this experiment, the primary limitation on the acceleration length is diffraction of the laser beam because of extremely underdense plasmas. The self-focusing effect of an intense laser pulse propagating in a plasma may prevent its transverse profile from spreading. The nonlinear excitation of plasma waves may prevent trapped particles from detuning to the phase velocity of the plasma wave. These nonlinear effects due to the superintense laser field are investigated along with the ultrafast ionization dynamics through this experiment.

8 REFERENCES

[1] T. Tajima and J.M. Dawson, "Laser Electron Accelerator", Phy. Rev. Lett, vol. 43, pp. 267-270 July, 1979.

[2] K. Yamakawa et al., "Prepulse-free 30-TW, 1-ps Nd:glass Laser", Opt. Lett., vol. 16, pp. 1593-1595 October, 1991.

[3] L.V. Keldysh, "Ionization in the field of a strong electromagnetic wave", Zh. Eksp. Teor. Fiz., vol. 47, pp. 1945-1957 November, 1964.

[4] B.M. Penetrante and J.N. Bardsley, "Residual energy in plasmas produced by intense subpicosecond lasers", Phys. Rev. A, vol. 43, pp. 3100- 3113 March, 1991.

[5] M.V. Ammosov, N.B. Delone and V.P. Krainov, "Tunnel ionization of complex atoms and of atomic ions in an alternating electromagnetic field", Zh. Eksp. Teor. Fiz., Vol. 91, 2008-2013 December, 1986.

[6] C. Joshi et al., "Forward raman instability and electron acceleration", Phys. Rev. Lett., vol. 47, pp. 1285-1288 November, 1981.