10. Recent Progress on Laser Acceleration Research

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Abstract

Recently there has been a tremendous experimental progress in ultrahigh field particle acceleration driven by ultraintense laser pulses in plasmas. A design of the laser wakefield accelerators aiming at GeV energy gains is discussed by presenting our recent progress on the laser wakefield acceleration experiments, the developments of high quality electron beam injectors and the capillary plasma waveguide for optical guiding of ultrashort intense laser pulses.

Keywords: Laser-plasma accelerators, Laser wakefield acceleration, Photocathode RF gun, Z-pinch capillary plasma waveguides

1. Introduction

A number of concepts of particle acceleration by laser fields have been proposed almost since the beginning of the laser evolution. Recently advance in generation of ultraintense short pulse lasers has brought about tremendous progress in experimental maturity of laser-driven particle accelerator concepts. Ultrahigh fields generated by focused laser pulses have evolved a great deal of particle acceleration concepts. The peak amplitude of the transverse electric field of a linearly polarized laser pulse is given by $E_L[\mathrm{TV/m}] \simeq 2.7 \times 10^{-9} I^{1/2}[\mathrm{W/cm^2}] \simeq 3.2 a_0/\lambda_0[\mu\mathrm{m}]$, where I is the laser intensity, λ_0 is the laser wavelength, and a_0 is the laser strength parameter given by $a_0 \simeq 0.85 \times 10^{-9} \lambda_0[\mu\mathrm{m}] I^{1/2}[\mathrm{W/cm^2}]$. Physically a_0 is equal to the normalized momentum of the electron quiver motion in the laser field.

A novel particle acceleration concept was proposed by Tajima and Dawson[1], which utilizes plasma waves excited by intense laser beam interactions with plasmas for particle acceleration, known as laser-plasma accelerators. In particular recently there has been a prominent experimental progress and a great interest in the laser wakefield acceleration (LWFA) of electrons since the first ultrahigh gradient acceleration experiment made by Nakajima et al. [2]. First-generation experiments have successfully shown that ultrahigh accelerating gradients higher than 10 GeV/m and relativistic electron acceleration up to more than 100 MeV with large energy spread. The second-generation experiments have aimed at a high energy gain of more than 1 GeV and high quality beam acceleration with a small energy spread. Here we present a design of the GeV laser wakefield accelerator experiments and our recent experimental progress for such second-generation experiments.

2. Electron Acceleration by Laser Wakefields

Plasmas can sustain ultrahigh electric fields, and can optically guide the laser beam and the particle beam as well under appropriate conditions. For a nonrelativistic plasma wave, the acceleration gradients are limited to the order of the wave-breaking field given by $eE_{WB}[\mathrm{eV/cm}] = m_e c\omega_p \simeq 0.96 n_0^{1/2}[\mathrm{cm^{-3}}]$, where $\omega_p = (4\pi n_0 e^2/m_e)^{1/2}$ is the electron plasma frequency and n_0 is the ambient electron plasma density.

In order to demonstrate the electron acceleration by laser wakefields, we have carried out the acceleration experiments using the table-top terawatt laser. The laser pulses with duration of 90 fs and the peak power of 2 TW produced by the Ti:Sapphire laser system at 790 nm wavelength were focused by a f/10 off-axis parabolic mirror in the acceleration chamber filled with a He gas. The measured focal spot radius was 13 μm. A single bunch electron beam with the energy of 17 MeV and the FWHM bunch duration of 10 ps from the RF linac at 10 Hz repetition rate is brought to a focus with the FWHM beam size of 0.8 mm. An electron pulse was synchronized to the laser pulses within the rms jitter of 3.7 ps. The energy gain spectra of accelerated electrons were measured for various He gas pressures and the laser peak powers as shown in Fig. 1. The maximum energy gain up to 300 MeV was observed for the peak power of 1.8 TW at 20 Torr[3].

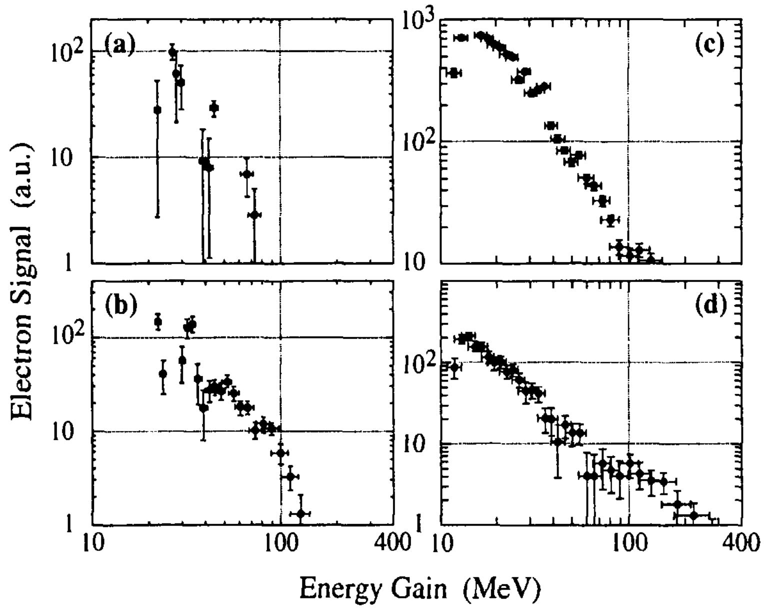

Figure 1: Measured energy gain spectra of accelerated electrons for (a) 3.4 Torr, P=0.9 TW, (b) 20 Torr, P=0.9 TW, (c) 2 Torr, P=1.8 TW, and (d) 20 Torr, P=1.8 TW.

The wakefield excitation has been confirmed by 2-D measurements of the plasma wave oscillation with the frequency domain interferometer. The measured density perturbation has shown the longitudinal wakefields of the order of ~ 10 GeV/m in good agreement with the accelerating wakefields expected theoretically. Measurements of the Thomson scattering image of the 1.8 TW pump laser in He gas plasma at 20 Torr have indicated that the strong self-guiding of the laser beam occurs over 2 cm in a plasma. We have also observed a jet-like formation generated with numerous energetic electrons transversely ejected from the central region of plasmas. The detail measurements have shown that an electron jet produced an outward electron flux with the maximum energy higher than 140 keV in a cylindrically homogeneous distribution around the laser propagation axis. This implies that energetic electrons are accelerated by the transverse wakefields higher than 140 MeV/cm, assuming a transverse acceleration length of 10 μm. Since the longitudinal wakefield is higher than the transverse wakefield for the laser focusing parameters, it is inferred that the maximum energy gain exceeds 280 MeV, which indicates a good consistency with the acceleration measurements.

3. GeV Laser Wakefield Acceleration

As an intense laser pulse propagates through an underdense plasma, the ponderomotive force expels electrons from the region of the laser pulse. This effect excites a large amplitude plasma wave (wakefield) with phase velocity approximately equal to the group velocity of laser pulse, given by $v_p = c(1-\omega_p^2/\omega_0^2)^{1/2}$, where ω_0 is the laser frequency. The maximum axial wakefield occurs at the plasma wavelength, $\lambda_p[\mu\text{m}] \simeq 0.57\tau$ in a plasma with the resonant electron density, $n_0[\text{cm}^{-3}] \simeq 3.5 \times 10^{21}/\tau^2$ in terms of a FWHM pulse duration τ [fs]. When a Gaussian driving laser pulse with the peak power P [TW] is focused on the spot size r_0 [μm], the maximum axial wakefield yields

$$(eE_z)_{max}[\text{GeV/m}] \simeq 8.6 \times 10^4 P\lambda_0^2/(\tau r_0^2 \gamma_0), \tag{1}$$

where $\gamma_0 = (1 + a_0^2/2)^{1/2}$ takes account of nonlinear relativistic effects, and $a_0 = 6.8\lambda_0 P^{1/2}/r_0$ for the linear polarization[4].

Table 1: Parameters of the GeV capillary-guided laser wakefield accelerators.

Energy gain [GeV]	0.5	1	5
Pulse duratuon τ [fs]	20	50	100
Peak power P [TW]	100	40	20
Spot radius r_0 [μm]	30	20	10
Laser strength parameter a_0	1.8	1.7	2.4
Plasma density [10^{18} cm^{-3}]	8.8	1.4	0.35
Accelerating gradient [GeV/cm]	1.9	0.7	0.55
Diffraction length [cm]	1.1	0.5	0.12
Dephasing length [cm]	0.4	5.5	56
Capillary length [cm]	No	1.5	10
Number of particles accelerated [10^9]	7	1.1	0.2

In order to achieve the acceleration energy gains of higher than 1 GeV in a single stage of cm-scale, it is necessary to extend the acceleration length limited by diffraction effects of laser beams. We propose the capillary-guided laser wakefield accelerators in which both the driving laser pulses and particle beams can be guided through Z-pinch capillary discharge plasmas of cm-scale. The parameters to test electron acceleration of GeV energies are shown in Table 1. The design of the laser wakefield accelerators is based on availability of the 10 Hz table-top ultrashort, ultrahigh peak power Ti:Sapphire laser with 20 fs and 100 TW developed at JAERI-KANSAI.

4. High Quality Electron Beam Injectors

In order to produce a high quality electron beam with low momentum spread and good pulse-to-pulse energy stability, it is required that femtosecond electron bunches should be injected with the energy higher than trapping threshold and femtosecond synchronization with respect to a wakefield accelerating phase space which is typically less than 100 fs in a longitudinal scale and 10 μm in a transverse size. For the second-generation experiments of laser wakefield accelerators, we have developed an electron injection system consisting of a photocathode RF gun and a compact race-track microtron shown in Fig. 2. The injection system can deliver the electron beam with energy of 150 MeV, pulse length of 3 ps FWHM and charge of 0.5 nC. As results of beam tests of the Cu photocathode RF gun driven by 50 Hz UV (263 nm) laser pulses delivered from a compact all solid-state Nd:YLF laser system, we have obtatined its excellent performance producing the maximum beam chrage of about 3 nC with quantum efficiency of 1.4×10^{-4}, the normalized emittance of a few π mm mrad and the pulse length of 5 ps[5].

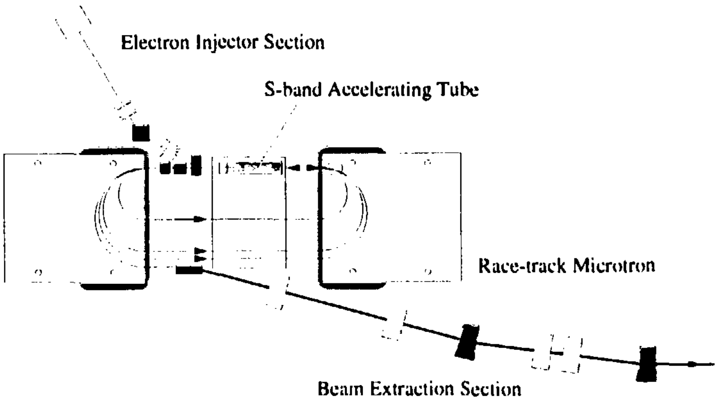

Figure 2: A schematic of the electron injection system.

5. Z-pinch Capillary Plasma Waveguides

We have presented the first direct observation of optical guiding of high intensity laser pulses over 2 cm through a plasma channel produced by an imploding phase of fast Z-pinch discharge in a gas-filled capillary[6]. A high current fast Z-pinch discharge generates strong azimuthal magnetic field, which contracts the plasma radially inward down to $\sim$ 100 μm in diameter. The imploding current sheet drives the converging shock wave ahead of it, producing a concave electron density profile in the radial direction just before the stagnation phase. The concave profile is approximately parabolic to out a radius of $\sim$ 50 μm, after which the density falls off. We have used a capillary with an inner diameter of 1 mm and a length of up to 2 cm, filled with helium. A high intensity Ti:Sapphire laser pulse (λ = 790 nm, 90 fs, $> 1 \times 10^{17}$ W/cm^2) was focused on the front edge of the capillary to a spot size of 40 μm in diameter. The transmitted laser beam profile at the exit of the capillary was observed through a band pass filter ($\Delta\lambda$ = 10 nm) with a CCD camera. Fig. 3 shows typical CCD images of the transmitted high intensity Ti:sapphire laser pulse profile through the capillary discharge plasma. These show clearly that a high intensity laser pulse could be guided through the channel over a distance of 2 cm corresponding to $\sim$ 12.5 Z_{R0}, where $Z_{R0} \sim$ 1.6 mm is the Rayleigh length of the laser beam.

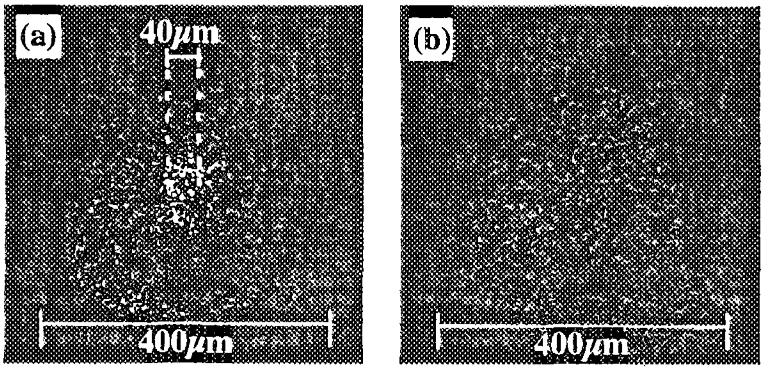

Figure 3: Typical CCD images of the transmitted a high intensity Ti:Sapphire laser pulse ($\sim 1 \times 10^{17}$ W/cm^2) through the capillary at an initial pressure of 0.9 Torr He; (a) t = 8.5 ns, (b) no discharge.

6. Conclusions

The laser wakefield acceleration experiments with a beam injection have accomplished electron acceleration up to 300 MeV. It is of importance for practical applications to generate a high energy gain with a high beam quality as well as high gradient acceleration. The high energy gain exceeding 1 GeV will be achieved by optical guiding by means of the capillary plasma waveguide, presently by which 2 TW, 90 fs laser pulses have propagated over 2 cm in the plasma channel with 20 μm radius. The high quality beam with a low energy spread and a low emittance will be injected by the 150 MeV microtron with the photocathode RF gun.

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