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Recent Progress and Perspectives of Laser-Plasma Accelerators

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Abstract

Recent progress of laser-plasma accelerators has matured a concept of particle acceleration owing to plasma waves excited by laser or electron beams as a possible next generation particle accelerators promising ultrahigh accelerating gradients and a compact size. Four major concepts of laser-plasma accelerators, the plasma beat wave accelerator, the laser wakefield accelerator, the self-modulated laser wakefield accelerator and the plasma wakefield accelerator are reviewed on accelerator physics issues and experiments demonstrating basic mechanisms of their concepts. As a perspective to the future practical application, a design of 5TeV linear colliders based on the laser wakefield accelerator is discussed.

1 Introduction

A proposal of Tajima and Dawson has initiated a modern history of the plasma acceleration[1]. Their paper proposed two laser-based schemes, which are now called beat wave acceleration (BWA) and laser wakefield acceleration (LWA). Because lasers to meet the requirements of the LWA were hardly available on 1980's, the experimental studies of the BWA was started. Several years later, Chen proposed a scheme which uses particle beams instead of lasers in order to excite plasma waves[2]. This scheme is now called plasma wakefield acceleration (PWA). It was soon noticed that the beam-driven and laser-driven methods have physics much in common. It is this PWA which has first produced considerable amount of accelerated particles[3]. Following this, quite a few good experiments on the BWA have been reported successively[5, 6, 7]. Meanwhile, invention of the chirped-pulse amplifier (CPA)[8] has enabled us to use a high-power laser with pulse width around the wavelength of high-density plasma wave. Sprangle called attention to the LWA[9]. The first experiment of the LWA was made by KEK group, using the CPA laser at ILE[10]. Recently a wakefield of the order of 10 GeV/m in a plasma has been directly observed by the use of a compact terawatt laser system so called T^3 lasers[22].

The self-modulated laser wakefield acceleration (sm-LWA) has its roots in old Raman scattering. Russian group and NRL group have pointed that the mechanism is positively useful for acceleration, if it utilizes the recent high power lasers[11, 12]. The experiment by KEK demonstrated ultrahigh gradient electron acceleration of the order of 30 GeV/m, using a multiterawatt short laser pulse[13]. Recently experimental demonstration of the sm-LWA has been reported by several groups [14, 15, 16]. Although the sm-LWA can generate the accelerating field exceeding 100 GeV/m, this mechanism could be not applicable to a practical accelerator because of a short acceleration length limited by dephasing of accelerated electrons or depletion of pump pulses.

The first-generation studies on laser-plasma accelerators have succeeded in demonstrating the proof-of-principle experiments to prove ultrahigh field generation in a plasma and electron acceleration by plasma waves. It is of importance for practical applications to generate a high energy gain with a good beam quality as well as high gradient acceleration. The second-generation study has been started to aim at realization of high energy laser-plasma accelerators in the world-wide community. Their efforts are concentrated on overcoming two difficulties. The one is the development of optical guiding methods in plasmas to extend the acceleration length for laser-based schemes. The other is the development of spatial and temporal matching technologies of electron beams to be accelerated by plasma waves. The former issue is a topical subject on laser-plasma interaction physics. The latter issue includes a very low emittance, short-bunch electron source, such as a photocathode RF gun [29] and a plasma cathode driven by intense ultrashort laser pulses[30], and a femtosecond synchronization technology.

Next two sections of this paper summarizes principles of plasma accelerators and hitherto experiments. A perspective of high energy laser-plasma accelerators is discussed about accelerator physics issues and linear collider design based on LWA in Section 4.

2 Principles of Laser-Plasma Accelerators

The most promising characteristic of laser-plasma accelerators is their ability to support extremely high accelerating gradients. In conventional rf-driven accelerators, the accelerating gradients are limited to approximately 100 MV/m due to electrical breakdown on material surfaces. In ionized plasmas, one can generate electron plasma waves with electric fields of the order of the nonrelativistic wavebreaking field given by $E_0 = m_e \omega_p c/e$ or

$$E_0[\mathrm{V/cm}] \simeq 0.96 n_p^{1/2}[\mathrm{cm}^{-3}], \tag{1}$$

where $\omega_p = [4\pi n_p e^2/m_e]^{1/2}$ is the electron plasma frequency and n_p is the ambient electron plasma density. It means that the plasma density of $n_p = 10^{18}\mathrm{cm}^{-3}$ gives the acceleration gradient of 100 GeV/m.

To be used for acceleration, the phase velocity of the plasma wave should be nearly equal to the particle velocity, which is the light velocity in light particles such as electrons. We have at least four methods to generate such waves. They are depicted in Fig. 1. Let us assume here that the test particles are electrons.

In the PWA, repulsion of plasma electrons against beams triggers plasma oscillations. The maximum wakefield amplitude excited by the drive electron beam with density n_b is given by

$$E_{max}/E_0 = n_b/n_p. \tag{2}$$

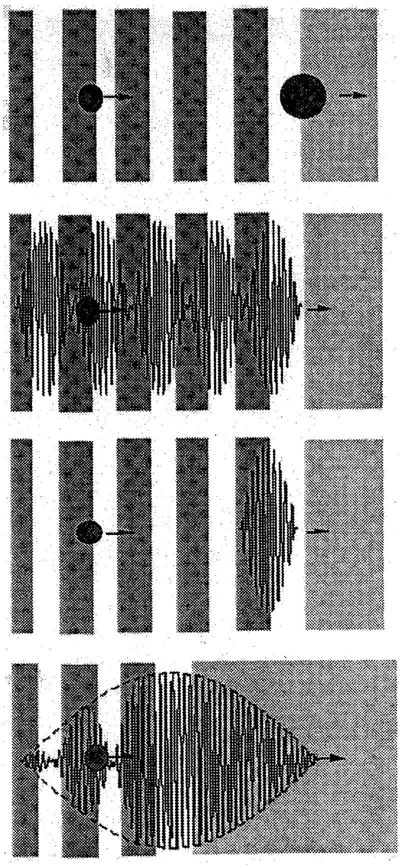

Fig. 1 Generation of plasma waves. Background intensity shows the plasma density, the balls show particles and solid lines show laser amplitudes.

The PWA is in principle a transformer converting high-current low-energy beams to low-current high-energy beams. Let us write the charge and energy of the primary and secondary beams as C_1, E_1, C_2, E_2. Because of the energy conservation, it is constrained by the relation $C_1E_1 > C_2E_2$. Moreover, if the bunch lengths of the two beams are infinite small, there is another constrain called transformer limit;.*i.e.*,

$$E_2/E_1 < 2. \tag{3}$$

It means that the energy gain of the secondary beam is less than twice of the energy of the primary beam.

In the BWA and LWA, the ponderomotive force of lasers triggers the oscillation. Difference between two methods is in that the BWA uses two lasers, of which frequency difference is equal to the plasma frequency, while the LWA uses a laser pulse with width nearly equal to the plasma wavelength. The fourth method, sm-LWA uses a laser with high power and long pulsewidth. The laser pulse excites the plasma wave, and is instead modulated by the plasma frequency. A parameter useful in discussing the ponderomotive force is the normalized vector potential defined as $a = eA/m_ec^2$. Its peak amplitude of a linearly polarized laser is given by

$$a_0 = 0.85 \times 10^{-9}\lambda[\mu\mathrm{m}]I^{1/2}[\mathrm{W/cm^2}], \tag{4}$$

where λ is the laser wavelength and I is the laser intensity. In the LWA, the maximum wakefield amplitude is given by

$$E_{max}/E_0 = a_0^2/(1+a_0^2)^{1/2}. \tag{5}$$

In the BWA, the maximum electric field at the saturation of the plasma wave is given by

$$E_{max}/E_0 = (16a_1a_2/3)^{1/3}, \tag{6}$$

where a_1 and a_2 are the normalized vector potentials of two lasers[18]. The mechanism of the sm-LWA is more complicated than the BWA and the standard LWA. It uses laser pulses which satisfies two requirements; first, the pulse width should be much longer than the plasma wavelength, and second, its power should exceed the critical power of the relativistic self-focusing of the laser P_c, where

$$P_c[\mathrm{GW}] = 17(\omega_L/\omega_p)^2, \tag{7}$$

with ω_L, the laser frequency.

This relativistic self-focusing is understood as following; The refraction index of the laser in a plasma is given by

$$N_R = [1-(\omega_p(r)/\omega_L)^2]^{1/2}. \tag{8}$$

In a strong laser field, the plasma frequency becomes smaller;

$$\omega_p(r) = \frac{\omega_{p0}(r)}{[1+a^2(r)]^{1/2}}, \tag{9}$$

where ω_{p0} is the ambient plasma frequency. Physically, this is due to the fact the electrons make relativistic oscillation transversely in the laser fields, which increases their relativistic mass. The large a on the laser axis thus gives small ω_p there. The refraction index distribution becomes such that the index is largest on the axis and decreases as r increases. This distribution focuses the laser.

In the linear regime, the plasma wave is a simple sinusoidal oscillation as far as the density perturbation is small; *i.e.*, $\delta n_p/n_p \ll 1$. In the nonlinear regime, the electric field becomes a sawtooth form associated with wave steepening and peaked density oscillation as shown in Fig. 2[17]. The nonlinear wave in which $\delta n_p/n_p \geq 1$ can be excited in the PWA using drive beams in which the electron density is higher than in the plasma;*i.e.* $n_b > n_p$. It is also possible in the LWA using a laser with high intensity; rigorously, if its normalized vector potential exceeds unity; $a_0 > 1$. The sm-LWA drives nonlinear wakefields even if $a_0 < 1$.

3 Acceleration Experiments

The hitherto obtained main experimental results are summarized in Table 1. The table gives only the first and best results of each method. A more comprehensive table is found in a review by Esarey[18].

Among the four schemes, the sm-LWA results in extremely large acceleration gradients. Figure 3 shows the RAL results. The laser with the power of 25TW was used. No electron was injected, so the results show plasma electrons trapped and accelerated by the laser field. The number of electrons accelerated was 10^8 and

Table 1. Experimental results of laser-plasma electron acceleration.

	energy gain/acceleration length	no. of particles	institution, year, ref.
PWA	200keV/40mm		ANL 89[3]
	20MeV/1m	$\sim 10^9$	KEK 92[4]
BWA	10MeV/3-7mm	$< 10^3$	ILE 92[5]
	28MeV/10mm	$< 10^4$	UCLA 93[6]
LWA	12MeV/10mm	$\sim 10^2$	KEK 93[13]
	300MeV/20mm	$\sim 10^2$	KEK/JAERI/Tokyo 96[19]
sm-LWA	18MeV/0.6mm	$\sim 110^2$	KEK/ILE 93[13]
	44MeV/0.3mm	$\sim 10^{10}$/MeV/sr	RAL 95[14]

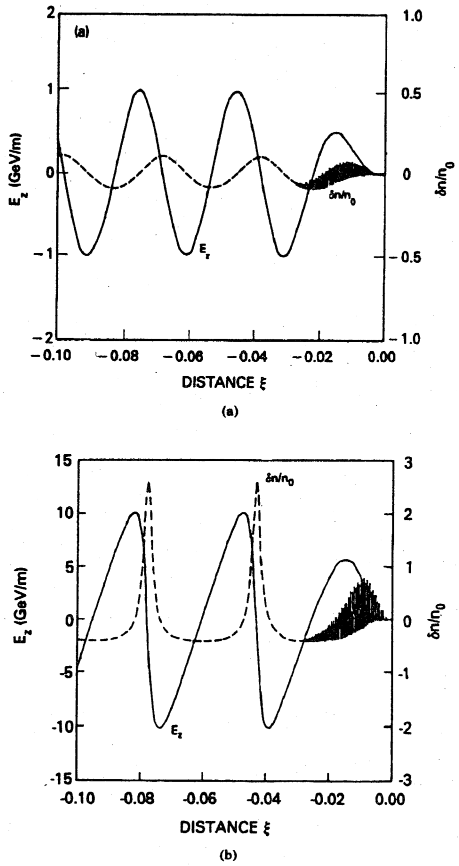

Fig. 2 Linear(a) and nonlinear(b) plasma wave and their fields. $a = 0.5$ in (a) and $a = 2$ in (b).

the normalized emittance was calculated as $5\pi\mu$m for electrons with energy around 30MeV. Recent report says that a new detector has found electrons with energy up to 100MeV.

The laser wakefield electron acceleration has been carried out by KEK/JAERI/U. Tokyo group[19], using a 2 TW, 90 fs laser pulse synchronized with 17 MeV RF linac electron beam injector at the repetition rate of 10 Hz. They observed high energy electrons accelerated over 100 MeV up to 300 MeV by the wakefield of $\sim$ 15 GeV/m excited over a few cm long underdense plasma as shown in Fig. 4.

One drawback of laser accelerators is their short acceleration length. Acceleration length is limited by the shortest among the three below. First is the diffraction length or the depth of focus of the laser. It means that the acceleration is possible only around the focal

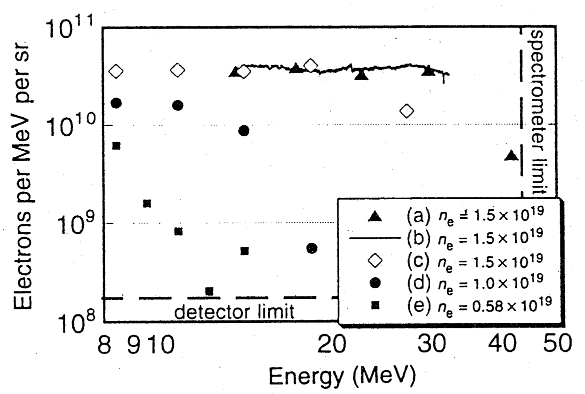

Fig. 3 The electron energy spectrum measured for a laser power of $\sim$ 25 TW in the RAL experiments.

point. If we loose the focus, the acceleration length can be lengthened, but the acceleration gradient becomes weak so that the energy gain cannot be increased. A parameter which expresses this length is the Rayleigh length

$$L_R = \pi(2\sigma_r)^2/\lambda_L \qquad (10)$$

where σ_r is the rms waist size of the laser.

The second is the dephasing length. It is the distance accelerated electrons outstrip the laser wakefield, given by

$$L_{ph} = \lambda_p^3/\lambda_L^2. \qquad (11)$$

This limit is caused because the group velocity of a laser in a plasma is given by $v_g = c[1 - (\omega_p/\omega_L)^2]^{1/2}$, which is smaller than the light velocity.

The third is the pump-depletion length in which the laser loses its power and cannot pump wakefields any more. One expression of this length given by Bulanov, *et al.*[20] is

$$L_{pd} = \frac{8}{3}\frac{\lambda_p}{\pi^{2/3}a^2k_p\sigma_z}\left(\frac{\lambda_p}{\lambda_L}\right)^2. \qquad (12)$$

The standard LWA is limited by diffraction, while the sm-LWA is often limited either by the dephasing or by the pump depletion.

The dephasing length and the pump-depletion length are long enough as far as we use plasmas with moderate density, so our effort has been paied to exceed the limit of the diffraction. One way is to go into the regime in which the relativistic focusing is possible. However, another way in the nonrelativistic regime has

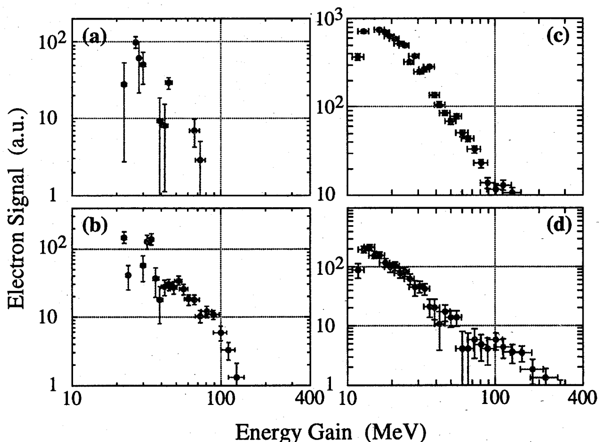

Fig. 4 LWA experimental results by KEK/ JAERI/ U. Tokyo. Energy gain spectra of accelerated electrons for a) 3.4 Torr, P=0.9 TW, b) 20 Torr, P=0.9 TW, c) 2 Torr, P=1.8 TW, and d) 20 Torr, P=1.8 TW.

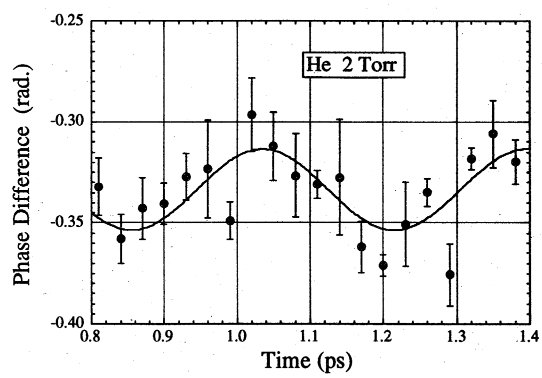

Fig. 5 Measurement of the plasma density oscillation excited by a 1 TW pump power in a He gas of 2 Torr. The solid curve shows a fit of the plasma wave with oscillation period of 360 fs.

already been adopted in industry. It is the principle of an optical fiber, in which lasers can propagate without diffraction. Refraction index of an optical fiber has a transverse distribution, in which the index is maximum at the core center, and low at the clad. If we could produce similar index distribution in a plasma along the laser axis, the laser would propagate without diffraction. The refraction index in a plasma has already been given in eq.(8). A plasma density distribution minimum at the laser axis will realize the index distribution suitable for laser propagation. Such an optical channel has been successfully produced by Durfee and Milchberg[21]. They used another laser to produce the channel. This laser pulse, focused by an axicon optics, prepared a shock-driven axially extended radial profile in plasma density distribution. The main laser, injected at the proper timing, was guided by the preformed channel for 24 times of the Rayleigh length.

The plasma wave excited by the LWA has been recently observed independently by two groups[22]. They measured the plasma electron density oscillation with the frequency domain interferometry technique. KEK/JAERI/U. Tokyo group also measured the plasma wave oscillation with the frequency domain interferometer to make confirmation of wakefield excitation by an ultrashort laser pulse in an underdense plasma[19]. Figure 5 shows the electron plasma wave measured at 2 Torr for the pump peak power of 1 TW. The measured density perturbation was $\langle \delta n/n_e \rangle \sim 15\%$ corresponding to the longitudinal wakefield of ~ 2 GeV/m. This measured amplitude is in good agreement with the accelerating wakefield of 2.2 GeV/m theoretically expected for 1 TW.

Although the PWA has ever attained smaller acceleration gradient than the laser drivers, it is limited neither diffraction nor dephasing. In order to obtain high energy gain in the PWA, it is essential to overcome the transformer limit. Three methods are proposed; The first is the use of driving beams consisting of multiple bunches[23]. Experiments by this method are planned at INP[24]. The second is the use of a single properly shaped driving beam. A triangular-shaped beam which has a linear rise over a length $L_b = N\lambda_p$ followed by a rapid termination gives the transformer ratio πN[25]. This experiment is planned at SLAC[26]. The third is to go to non-linear regime. If the beam density n_b exceeds the plasma density n_p, the beam blow out all the plasma electrons and a nonlinear wave with large amplitude is caused[27]. The experiments are planned at ANL[28]. High-current high-density beams are essential as drive beams in these experiments. The three experiments will use such good beams in order to attain 0.1-1GeV/m acceleration gradient.

4 Perspectives of Laser-Plasma Accelerators

Beam loading is understood as the reverse process of the PWA[31]. In PWA, a bunch of particles leaves a plasma wave behind. The amplitude of the wakefield is given by $E_z = eN/(\epsilon_0 \pi r_0^2)$, where r_0 is the radius of the field. This equation gives $N = \epsilon_0 \pi r_0^2 E_z/e$. Suppose that a test bunch with these N particle is injected into this wakefield E_z. The test bunch consumes all the energy of the wave and leave a quiet plasma behind. The N then gives the estimate of the maximum number of accelerated particles with 100% energy spread.

It should be noted that this number N is not very large if we assume the use of typical T^3 lasers. The standard LWA will attain $E_Z = 1$GeV/m and $r_0 = 50\mu$m, which gives eN =70pC or $N = 10^8$, at 100% energy width. The pulse power of a laser is given by laser energy divided by pulse duration. Such a laser has certainly large pulse power, but the TW output was attained by reducing the denominator down to 100fs range. High energy is necessary to obtain large current.

An inconspicuous feature of the plasma accelerators, compared with the high acceleration gradient, is its high bunch frequency and short bunch length. Specifically, the bunch frequency becomes equal to the plasma frequency, which is in the $10^{12} - 10^{15}$Hz range if plasmas in the density range of $10^{15} - 10^{20}$cm^{-3} are used. Such features may be useful in radiation generation. Plasma waves have a property bunching continuous beams, just as the rf waves have.

Emittance of the plasma accelerators is decided by their injectors. The rf laser cathode is regarded as the best injector at the present, because it gives not only good emittance but also high current and short bunch length. In addition, the laser cathode makes the synchronization easy between test beams and laser beams to drive the plasma waves. An rf laser cathode developed by BNL/SLAC/UCLA collaboration has a normalized emittance around $\sim 1\pi\mu$m[29].

The most serious problem of laser-based accelerators is the poor efficiency of lasers. The efficiency from wall-plug power to microwaves of conventional linacs is about 25%; *i.e.*, the efficiency of a klystron power supply has $\sim$ 80%, that of a klystron itself is $\sim$ 50%, that of a waveguide is $\sim$ 90%, and the structure efficiency is $\sim$ 70%. To the contrary, the efficiency from the wall-plug power to the laser power is below $\sim$ 0.1% in present T^3 lasers. It is expected that the use of laser diode arrays will improve this value up to the order of $\sim$ 10%. The efficiency from laser power to the plasma wakefield is below $\sim$ 25% in linear scheme. It could exceed $\sim$ 50% if we go to nonlinear regime. The efficiency from wall-plug power to plasma waves is thus below $\sim$ 2.5% in the linear regime using the diode laser pumping to be developed, which is 1/10 of that of conventional rf linacs.

Table 2. Linear collider design based on LWA.

Collider parameters	
Energy	5TeV (2.5TeV$\times$ 2.5TeV)
Luminosity	10^{35}cm^{-2}sec^{-1}
Bunch length	$\sim$ 1pm($=\beta^*$)
Emittance	1pm (round beam)
No. of electrons per bunch	10^7
Bunch frequency	40kHz
Disruption parameter	25
Beamstrahlung percentage	30%, $\delta_B = 0.3$
Upsilon parameter	10^3
Luminosity enhancement	3
Average beam power	0.25MW
LWA parameters	
Plasma density	10^{17}cm^{-3}
Acceleration length	1m
Energy gain per stage	10GeV
Number of stages	500
Laser power per stage	40kW
Laser energy per stage	1J
Average laser power	20MW

As an example of applications to high energy accelerators, a 5 TeV linear collider design based on the standard LWA is described in Table 2[32]. First assumed were wall-plug power, luminosity and the percentage of beamstrahlung. Because of the poor efficiency of the laser, the number of particles per bunch must be small. Their solution is small emittance, small final-focus beam size and short bunch length, all of which are on the order of pm. Each accelerator of the colliders has a laser-rf injector, a linac for pre-acceleration and 250 stages of laser wakefield accelerators. Each stage is 1m long, and has 10 GeV energy gain. The length is approximately equal to the dephasing and pump-depletion lengths. Two laser beams are fed to each stage, one of which create an optical channel, and the other is guided in the channel.

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