OVERVIEW AND PROSPECTS OF ADVANCED ACCELERATOR TECHNOLOGIES

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Abstract

Recently there is a great interest growing in advanced accelerator technologies based on laser and plasma acceleration mechanisms, which have a tremendous potential for applications to a wide range of sciences, not only basic sciences but also medical and industrial sciences. The novel particle acceleration technologies make it possible to produce unique high quality beams in a compact system, which are crucial for specific applications. In particular extraordinary evolution of ultraintense ultrashort pulse lasers can generate ultrahigh gradient accelerating fields of the order of 1 TeV/m in a plasma to accelerate electron beams well collimated with small emittance and femtosecond buch length up to 1 GeV in a 1 mm length of plasma.

INTRODUCTION

A number of concepts of particle acceleration by laser fields have been proposed almost since the beginning of the laser evolution in the early 1960s[1]. At the first workshop on Laser Acceleration of Particles in 1982 it is addressed that the realization that we seem to be near the end of the road for conventional accelerators has generated renewed interest in the possibility of accelerators with super-high accelerating fields[2]. In vacuum, intense focused optical fields can exceed a few TV/m at the laser intensity of 10^{18} W/cm^2. Such ultrahigh fields have evolved a great deal of particle acceleration concepts by ultraintense laser interaction with particle beams and plasmas.

A novel particle acceleration concept was proposed by Tajima and Dawson[3], 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 great experimental progress on the laser wakefield acceleration (LWFA) of electrons since the first ultrahigh gradient acceleration experiment made by Nakajima et al. [4]. Recent experiments have successfully demonstrated that the self-modulated LWFA mechanism is capable of generating ultrahigh accelerating gradient of the order of 1 TeV/m and of accelerating electrons up to the high energy well beyond 200 MeV in a few mm-scale interaction length[5]. These capabilities make it possible to realize a table-top accelerator and high energy frontier accelerators in a reasonable size and cost.

Among Asian countries, in particular Korea, Taiwan, China, India and Israel as well as Japan, rapidly increase facilities and researchers for research and development of advanced accelerator technologies to produce the outstanding outcomes and contributions to this field. Even in the world-wide community, the relevant advanced accelerator technologies is more or less on a starting level of their research and development. The Asian community has a great potential and opportunity for creating a cutting edge in this field. In this context this paper highlights rapid progress on the advanced accelerator technologies in the Asian community as well as the recent world-wide frontier, and to post prospects of the laser-driven accelerators in the TeV range.

LASER ACCELERATION IN VACUUM

The most prominent feature of laser acceleration concepts is the use of ultraintense laser fields, which is defined by the strength parameter a_0, where $a_0 \equiv eA_0/m_e c^2$ is the normalized peak amplitude of the laser vetor potential A_0, given by

$$a_0 \cong 0.85 \times 10^{-9} \lambda_0[\mu\text{m}] I^{1/2} [\text{W/cm}^2], \qquad (1)$$

where for the peak intensity I in units of W/cm^2, the laser wavelength $\lambda_0 = 2\pi c/\omega$ in units of μm, and the laser frequency ω. The peak amplitude of the transverse electric field of a linearly polarized laser pulse is given by

$$E_L[\text{TV/m}] \cong 3.2 a_0/\lambda_0 \simeq 2.7 \times 10^{-9} I^{1/2}. \qquad (2)$$

For example, the laser intensity of $I = 10^{18}$ W/cm^2 gives $E_L = 2.7$ TV/m.

Lawson-Woodward theorem

Particle acceleration in vacuum can eliminate the difficulties associated with gas and plasmas where the accelerating field is limited due to the gas breakdown and the plasma wave-breaking besides suffering from beam-gas and plasma collisions and laser-plasma instabilities[6]. A major shortcoming of laser-vacuum acceleration is attributed to the phase velocity of the electric field in the accelerated direction of particles greater than the vacuum speed of light c for a focused laser beam. Consider the electric field of the Hermite-Gaussian TEM$_{lm}$ mode, assuming the propagation of a nearly plane wave. Since a Gaussian laser field propagating in the z direction is transversely bounded, the finite longitudinal component of the electric field is obtained as $E_z = -(1/ik)\nabla_\perp \cdot \mathbf{E}_\perp$ that can accelerate electrons in z direction, where k is the wavenumber. The phase velocity of the electric field along the propagation axis is given by

$$v_{ph} = c\left[1 - \frac{l+m+1}{kZ_R(1+z^2/Z_R^2)}\right]^{-1} > c, \qquad (3)$$

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where $Z_R = \pi w_0^2/\lambda_0$ the Rayleigh length, w_0 the minimum spot radius at focus, $\lambda_0 = 2\pi/k$ the wavelength, $\omega = ck$ the frequency. Therefore relativistic electrons with the longitudinal velosity $v_z \simeq c$ will slip in phase with respect to the accelerating field E_z and eventually decelerate. Although acceleration occurs over a slippage distance $Z_s \simeq \pi Z_R$, if an highly relativistic electron interacts over an infinite region ($z = -\infty$ to ∞), a net energy gain is zero resulting from deceleration canceling out acceleration. This is pointed out by the Lawson-Woodward theorem assuming that the region of interaction is infinite, no static electric or magnetic field is present, and nonlinear effects (e.g., ponderomotive, and radiation reaction forces) are neglected[7]. In order to make a nonzero net energy gain, one or more of these assumptions must be violated.

A variety of Vacuum Laser Acceleration

A number of laser acceleration concepts in vacuum have been proposed by the use of a finite interaction geometry, the external fields, and the ponderomotive force to overcome the L-W theorem. Since the essential physics of this theorem is based on an assumption that the phase velocity of a laser field near the focal region is greater than c, Kong and Ho presents the acceleration scheme called CAS (Capture Acceleration Scenario), in which relativistic electrons injected with small incident-angle relative to the laser propagation direction are not expelled by the laser beam, but are captured and significantly accelerated in the strong laser field region[8]. Taking into account of the distributions of the longitudinal electric field and the phase velocity for a linearly polarized Gaussian beam, they find that acceleration channels exist for a focused laser beam propagating in vacuum, where the wave phase velocity less than c combined with strong axial electric field make it as a wave guide tube of a conventional accelerator. Relativistic electrons injected into this acceleration channel can be trapped in the acceleration phase and remain in phase with the laser field for sufficient long duration, thereby receiving considerable energy. The energy gain is primarily due to the axial electric field, and the maximum energy gain can be roughly estimated by $\Delta W[\mathrm{MeV}] \approx 0.19 a_0 k w_0$. The laser intensity should be strong enough ($a_0 \geq 4$), and the electron incident angle θ is sufficiently as small as $\tan\theta \sim 0.12$. The optimum incident electron momentum is sensitive to the laser beam width, and should be in the range of 5-20 MeV. The 3D particle simulation shows that the energy gain can reach the order of GeV with $a_0 = 100$.

As the relativistic strong laser field of $a_0 \gg 1$ increases , the longitudinal accelerating force exerted on an electron is proportional to a_0^2 , whereas the transverse quivering force is just linearly proportional to a_0. This is essence of the relativistic ponderomotive acceleration that dominantly produces energetic particles in interaction of ultraintese laser fields with particle beams and plasma. The studies of electron acceleration in vacuum by a relativistic laser ponderomotive force has made great progress in recent years both theoretically [9, 10, 11, 12, 13] and experimentally [14, 15]. When a high intense laser beam is focused on free electrons in vacuum, the electrons oscillate in the laser polarization direction and are pushed in the laser propagation direction by Lorentz force. As a result, the electrons are accelerated to the laser propagation direction. However, the electrons are scattered in the radial direction because the Gaussian beam (TEM_{00} mode) has a large transverse gradient of the ponderomotive potential [9]. In order to avoid the transverse scattering, Stupakov and Zolotorev [12] proposed to use superposition of the higher order Hermite-Gaussian modes in addition to the fundamental mode, by which the electrons are accelerated and confined around the propagation axis of the laser pulse. The final electron energy after interaction with a laser pulse is approximately given by $\gamma_f \approx a_0^2/2$.

Kong and Kawata et al. proposed that superposition consisting of the TEM_{10} and TEM_{01} mode can accelerate an electron bunch longitudinally and at the same time confines it transversely in the superposed ponderomotive potential of an intense ultrashort laser pulse[13]. They find that electrons are effectively accelerated by the longitudinal ponderomotive force, keeping electrons trapped transversely inside a laser pulse by the transverse ponderomotive force up to a remarkable energy such as ~ 1.2 GeV for the laser intensity $I = 2 \times 10^{20}$ W/cm^2.

Masuda and Nakajima found that the electron scattering can be suppressed by the longitudinal components of the TEM_{00} mode when the laser pulse is tightly focused to small spot size comparable to the laser wavelength. If the longitudinal components are ignored, the electrons are never focused even for the higher order modes as shown in Fig. 1. The trapping effect by the higher order mode comes from partially the existence of the longitudinal field. As a result of optimizing a focusing spot size, the energy gain of accelerated electrons with the initial energy γ_0 can be given by $\Delta\gamma_f \approx 3\gamma_0 a_0^2/8$. The numerical simulations imply that the relativistic ponderomotive acceleration can produce a high quality electron beam characterized by extreme short

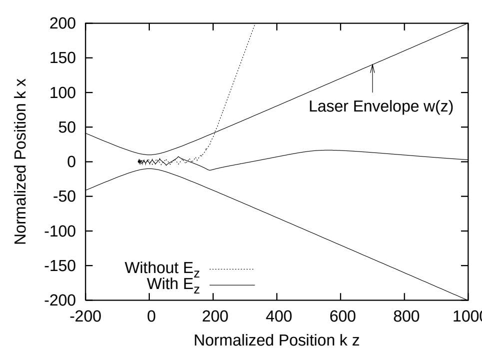

Figure 1: Typical trajectories of an electron accelerated by the fundamental Hermite-Gaussian mode, TEM_{00}, with the peak laser field $a_0 = 10$ for the cases with and without the longitudinal electromagnetic fields.

bunch duration of 900 attoseconds, the energy spread less than 1 %, and the normalized tranverse emittance less than 10 π mm·mrad.

Experiments of Vacuum Laser Acceleration

Although experimental tests on vacuum laser acceleration concepts are a proof-of-principle stage, recently some promising results have been obtained from the inverse free electron laser (IFEL) concept. Kimura et al. have demonstrated mono energetic laser acceleration of trapped microbunch electrons for the first time by using a staged IFEL scheme consisting of two undulators, a phase control chicane and a 200 MW CO_2 laser of 10.6 μm wavelength at the BNL-ATF[16]. In this experiment, the first IFEL is used to create microbunches, which are accelerated by a second IFEL using a tapered undulator. They successfully produce a high quality microbunch electron beam with a net energy gain of $>$ 7 MeV, an energy width of $\sim 0.86\%$ (FWHM) and a 1μm microbunch length.

Huang et al. plan to make a proof-of-principle experiment for structure-loaded vacuum acceleration to test a particle acceleration by TEM_{01} mode with a multistage laser-driven linear accelerator structure composed of a 16-stage ZnSe lens-array. In this accelerator structure, the phase control can be achieved by varying the refractive index of each lens as a function of temperature. The estimated energy gain will be 250 keV with the maximum accelerating gradient of 132 MV/m[17].

LASER ACCELERATION IN STRUCTURE

Structure-based accelerator concepts are considered as scaling down of the conventional RF accelerating structure to an optical wavelength according to a scaling law of the microwave accelerators, which describes that a shorter wavelength of the structure can produce a higher accelerating gradient with given input power. A straightforward scaling down of metallic structure used in the microwave frequency range results in extremely short attenuation length of the accelerating wave, that is a short acceleration length, because of a large ohmic loss in metal for the optical frequency range. In order to overcome shortcomings of small structures in the optical range, Lin proposed the dielectric waveguide accelerator (DWA) made of a hollow straight metal waveguide lined with dielectric that has the effect of slowing down the phase velocity just as a periodic disc of the RF linac structure[18]. Schächter proposed the optical Bragg accelerator composed of a series of concentric dielectric layers of a quarter wavelength thickness with high interaction impedance of the order of 2000Ω[19]. A Bragg structure provides a typical group velocity of $0.5c$ and the accelerating gradient of the order of 2 GV/m. Ogata pointed out that propagation of a laser wave in a hollow metallic waveguide with tube radius smaller than laser wavelength can generate an accelerating field referred to as a surface plasmon polariton. The accelerating gradient of plasmon accelerator is given by $E_z = \alpha\sqrt{P}/k_p$, where α is constant depending on material, P the laser power, and k_p the plasmon wavenumber. As an example, in a silver waveguide with radius of 227 nm, a 1 MW laser power at 344 nm wavelength can produce the energy gain of 195 keV in the acceleration length of 4.35 μm with the accelerating gradient of 45 GeV/m. The acceleration length can be improved by cooling the material down to 10 K so that the energy gain increases up to 277 MeV in a 6.16 mm acceleration length.

Lin also proposed the photonic band gap crystal accelerator using a photonic crystal, which is an artificial periodic lattice in one, two, or three dimensions, where the multiple scattering of the electromagnetic wave makes a forbidden band gap in which propagation of EM waves is prohibited[18]. For an accelerator application, a 2D photonic crystal consisting of array of vacuum holes in silicon with vacuum guide, which only fundamental mode within gap are confined and let all other higher order modes leak out to reduce instabilities. A defect in a perfect photonic lattice can guide the mode if the frequency falls within the band gap. The accelerating gradient of PBG accelerator is limited by the damage threshold of the material to 0.38 GeV/m at 1 μm wavelength.

LASER ACCELERATION IN PLASMAS

Plasmas provide some advantages as an accelerating medium in laser-driven accelerators. 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 gradient

$$E_0[\text{eV/cm}] = m_e c\omega_p \simeq 0.96 n_e^{1/2}[\text{cm}^{-3}], \qquad (4)$$

where $\omega_p = (4\pi n_e e^2/m_e)^{1/2}$ is the electron plasma frequency and n_e is the ambient electron plasma density. It means that the plasma density of $n_e = 10^{18}$ cm^{-3} can sustain the acceleration gradient of 100 GeV/m.

As an intense laser pulse propagates through an underdense plasma, $\omega_p^2/\omega^2 \ll 1$, the ponderomotive force associated with the laser pulse envelope 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. When a Gaussian laser pulse with the peak power P [TW] is focused on the spot size r_0 [μm], the maximum axial wakefield yields

$$(eE_z)_{\text{max}}[\text{GeV/m}] \simeq 8.6 \times 10^4 P\lambda_0^2/(\tau r_0^2 \gamma_L), \qquad (5)$$

where $\gamma_L = (1 + a_0^2/2)^{1/2}$ takes account of nonlinear relativistic effects, and $a_0 = 6.8\lambda_0 P^{1/2}/r_0$ for the linear polarization[20]. Kotaki measured the longitudinal wakefield amplitude measured at the laser intensity $I = 8.4 \times 10^{17}$ W/cm^2 ($a_0 \simeq 0.6$) with the frequency domain interferometer in a gas jet plasma of which the electron density was 7×10^{17} cm^{-3} as shown in Fig. 2[21].

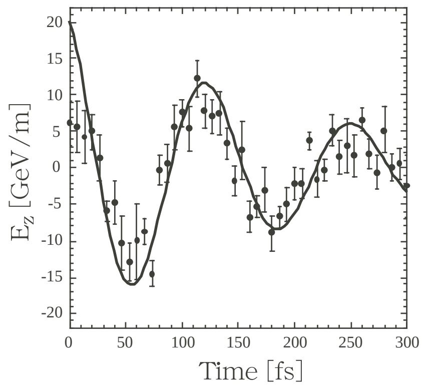

Figure 2: The longitudinal wakefield amplitude measured at the laser intensity $I = 8.4 \times 10^{17}$ W/cm^2 ($a_0 \simeq 0.6$) and the electron plasma density 7×10^{17} cm^{-3} with the frequency domain interferometer in a gas jet plasma. The solid curve shows a fit of the wakefield with oscillation period of 130 fs.

Laser Wake-Field Accelerators

Assuming a Gaussian beam propagation of the laser pulse with the peak power P in an underdense plasma ($\omega \gg \omega_p$), the effective acceleration length can be limited to a diffraction length $L_{dif} = \pi Z_R$. For a properly phased electron, the maximum energy gain is given by

$$\Delta W_{dif}[\text{GeV}] \simeq 0.85 P[\text{TW}]\lambda_0[\mu\text{m}]/(\gamma_L \tau[\text{fs}]). \quad (6)$$

Note that the maximum energy gain is independent of the focusing property of the laser beam due to diffraction effects in the limit of $a_0^2 \ll 1$. For example, the maximum energy gain of the LWFA driven by the laser pulse with $\lambda_0 = 0.8\mu$m, $P = 2$ TW, $\tau = 100$ fs, and $r_0 = 10\mu$m is limited to $\Delta W_{dif} = 12$ MeV by the diffraction length $L_{dif} = 1.2$ mm.

In order to achieve the acceleration energy gains 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. Zigler et al. demonstrated optical guiding of intense lasers in range of 10^{18} W/cm^2 up to 6 cm (hundreds of Rayleigh lengths) in plasma channels produced by capillary discharge in vacuum[22]. Hosokai et al. demonstrated the optical guiding of 2 TW, 90 fs laser pulses over 2 cm through a plasma channel produced by an imploding phase of fast Z-pinch discharge in a gas-filled capillary[23]. Based on success of the optical guiding, Nakajima proposed a 10 GeV capillary-guided laser wakefield accelerator in which both the driving laser pulses and particle beams can be guided through the capillary discharge plasmas of cm-scale[26]. A 10 GeV energy gain in a single stage acceleration will be achieved with a 20 cm long plasma waveguide driven by a 20 TW, 100 fs laser pulse in the plasma density of $n_e = 3.5 \times 10^{17}$ cm^{-3} without wave-breaking. The maximum number of electrons capable of accelerating with 100% energy spread is estimated to be $N_{\max} \sim 2 \times 10^8$.

Experimental Progress

In the past decade the worldwide experiments of laser-plasma particle acceleration have boosted their frontier of particle beam energy and intensity. FIg. 3 shows evolution of the electron beam energy frontier achieved in the laser and plasma acceleration experiments in chronological order. One can see that the experimental results indicate

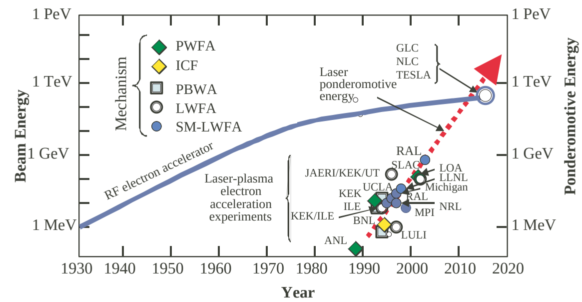

Figure 3: Evolution of the electron beam energy frontier of the RF electron accelerators (solid line) and the maximum electron energy plots achieved by the worldwide laser and plasma accelerator experiments. The dotted line shows evolution of the focused laser intensities represented by the ponderomotive energy.

a rapid increase of electron energies accelerated by laser-driven plasma-based concepts, whose rate is three to four orders of magnitude over the past ten years in coincidence with increase of the laser ponderomotive energy. A recent laser electron acceleration experiment carried out by using 160 J, 650 fs (~ 250 TW) pulses of the Vulcan Petawatt laser at RAL demonstrated the highest energy laser acceleration at the maximum energy of 650 MeV with 100% energy spread, whose energy spectra can be characterized by a power law rather than a Maxwellian distribution. This highest energy electrons are observed for a focused laser intensity of 3×10^{20} W/cm^2 ($a_0 \approx 15$).

The electron acceleration experiment carried out with 100 TW laser at JAERI-APRC observed enormous beam current of the order of Mega Ampere in the relativistic energy region (> 1 MeV). A 20 TW, 23fs laser pulse was focused onto a gas jet to produce the peak intensity of 2.3×10^{19} W/cm^2 ($a_0 \approx 3.3$). Kando et al. measured the electron energy spectra extending up to the maximum energy of 40 MeV, which are fitted to a power law given by $E^{-\alpha}$, where E is the electron energy and $\alpha = 3.7$. Measurement of the electron charge was 5 nC per shot for > 1 MeV electrons and ~ 50 nC per shot for the total number of charge, which means that a 20% of the laser pulse energy was converted to the energetic electrons. Since the numerical simulation indicated production of an electron bunch with 10 fs duration, it was inferred that the peak current of the accelerated electron bunch was 0.5 MA, which is three magnitude larger than that of the conventional accelerator beams.

Table 1: A conceptual design of 1 TeV Laser Micro Collider.

Center of Mass collision energy	1 TeV
Initial beam energy	50 MeV
Number of particles per bunch	10^{10}
Laser wavelength	0.8 μm
Laser spot size	10 μm
Repetition frequency	10 Hz
Required peak intensity	4.2×10^{22} W/cm^2
Required peak power	660 PW
Required pulse energy	8 kJ for 10% efficiency
Luminosity	2×10^{35} cm^{-2}s^{-1}

PROSPECTS OF ADVANCED ACCELERATOR TECHNOLOGIES

Fig. 3 implies that if a pace of evolution of the laser power continues or more efficient acceleration technology is discovered, the energy frontier accelerators may be superseded by laser accelerators in the next decade in the TeV energy range. Over the past ten years, laser intensities have increased by more than four orders of magnitude to reach the laser peak power of 1 PW and the intensities of the order of 10^{20} W/cm^2[27]. A straightforward extention of the laser peak power obviously reaches the order of Exawatt range in the next decade. It is known that such enormous laser power can be realizable by utilizing the most powerful lasers, such as NIF and LMJ projects[28], where extreme high power lasers consisting of hundreds of beams have potential to produce tens of EW in a 100 m square factory size, which would be much smaller than the next linear colliders. Based on availability of Exawatt class lasers and the past experimental results on laser-plasma acceleration, a laser-driven collider, called as a Laser Micro Collider, that can generate 1 TeV collision energy may be conceived. This collider scenario is based on ponderomotive acceleration and focusing of electron and positron beams at a single interaction with plasma or beams, that is, by no use of multiple staging or cascading like an conventional linear collider. Table 1 shows a conceptual design of 1 TeV Laser Micro Collider.

SUMMARY

During the past decade, the advanced accelerator technologies based on laser and plasma made tremendous progress, associated with the ultraintense laser technology and the frontier material science. The world-wide laser and plasma acceleration experiments boosts their energy frontier up to nearly 1 GeV in a 1 mm plasma with extreme high gradient accelerating fields of the order of 1 TeV/m, and its intensity frontier of accelerated electron beams up to the range of Mega Ampere with extreme short bunch duration of the order of femtoseconds. An extreme high quality and bright beam will be realized by photonic crystal accelerators or vacuum laser acceleration with optical phase control technologies.

Now there are rapidly growing interests and research activities in novel and advanced accelerator technologies related to laser and plasma in the Asian community, in particular Korea, Taiwan, China, India and Israel as well as Japan. We have prospects full of promise for the advanced accelerator technologies to create breakthrough and revolution to a wide range of sciences.

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