A GEV LASER WAKEFIELD ACCELERATOR USING TABLE-TOP-TERAWATT LASER

K. Nakajima, M. Arinaga, T. Kawakubo, T. Kawamoto,
H. Nakanishi, and A. Ogata
KEK, National Laboratory for High Energy Physics
1-1 Oho-cho, Tsukuba-shi, Ibaraki-ken 305, Japan

Abstract

We propose an ultra-high accelerating gradient accelerator based on the laser wakefield acceleration mechanism driven by an ultra-short pulse laser with power of the order of TW. A state of the art of such high-power lasers makes possible to build compact high-intensity lasers known as a table-top-terawatt laser (T^3). We report the development for a compact accelerator capable of acceleration up to GeV energies using the multi-terawatt T^3 laser with a 100 fs pulse duration.

1 INTRODUCTION

The laser-driven particle accelerators have been conceived over a past decade to be a next generation particle accelerator promising super-high field particle acceleration[1]. Among a number of novel concepts proposed so far, recently there has been a great advance in laser-plasma accelerators with success in demonstrating ultrahigh gradient particle acceleration of order of GeV/m[2]. Thus much current interest has focused on development of a practical accelerator based on laser-plasma acceleration mechanism in performance of accelerators, not only accelerating field but beam intensity, emittance, repetition rate and so on.

Currently there have been two major schemes of laser-plasma accelerators: the plasma beat wave accelerator (PBWA) and the laser wake-field accelerator (LWFA). In the PBWA two-frequency lasers are optically mixed to produce laser beat waves. When the beat wave frequency is equal to the plasma frequency, beat waves drive plasma waves at a resonance density. In the LWFA, an intense ultrashort laser pulse excites wakefields in a plasma due to a nonresonant shock. Although both methods have limitations on particle acceleration, the LWFA has some advantages of simplicity, plasma control and instabilities. Moreover, recent technological availability of high power ultrashort-pulse lasers confers a benefit on the LWFA. Advance in laser technology has offered us compact terawatt laser systems referred to as T^3 (table-top-terawatt) lasers. The availability of T^3 lasers makes possible to build the accelerator system in a compact size with a reasonable repetition rate.

This report discusses limitations of the fundamental LWFA scheme on the energy gain and improved schemes to achieve multi-GeV acceleration by overcoming its limitations. We present the propoasal of the LWFA system aiming at a GeV energy gain in a table-top size.

2 ENERGY GAIN OF THE LWFA

Diffraction-limited LWFA

An intense short laser pulse excites a wake of plasma waves due to the ponderomotive force in an underdense plasma, $\omega_0 \gg \omega_p$, where ω_0 is the laser frequency, $\omega_p = (4\pi e^2 n_e/m_e)^{1/2}$ is the electron plasma frequency, and n_e is the ambient electron density. The plasma wave phase velocity is equal to the laser pulse group velocity in a plasma, given by $v_\phi = c\sqrt{1-\omega_p^2/\omega_0^2}$. Assuming a Gaussian beam propagation of the laser pulse with the peak power P in a fairly underdense plasma, the peak amplitude of accelerating wakefields is

$$eE_z = \frac{\Omega_0 P}{\sqrt{\pi} m_e c^2}\left(\frac{\lambda_0}{\lambda_p}\right)\left(\frac{k_p \sigma_z}{Z_R}\right)\exp\left(-\frac{k_p^2\sigma_z^2}{4}\right). \quad (1)$$

where Ω_0 is the vacuum resistivity (377Ω), λ_0 is the laser wavelength, $k_p = 2\pi/\lambda_p = \omega_p/v_\phi$, σ_z is the temporal $1/e$ half-width of the pulse, Z_R is the Rayleigh length, $Z_R = \pi R_0^2/\lambda_0$ and R_0 is the spot radius at the focus. Note that the accelerating field is propotional to P rather than $\sqrt{P}$ in conventional rf-driven accelerators. The maximum gradient is achieved at the plasma wavelength $\lambda_p = \pi\sigma_z$: $(eE_z)_{\max} = 2\sqrt{\pi}e^{-1}m_e c^2 a_0^2/\sigma_z$, where $a_0^2 = 0.73\times 10^{-18} I\lambda_0^2$, the laser intensity I is in units of W/cm^2 and λ_0 is in units of μm.

Diffraction limits the laser-plasma interaction distance to $\simeq \pi Z_R$ Thus the maximum energy gain of relativistic electrons is obtained as $\Delta W = eE_z \cdot \pi Z_R$. For the optimum plasma density, $n_e = 1/\pi r_e \sigma_z^2$, where r_e is the classical electron radius, $\Delta W_{\max}[\text{MeV}] \simeq 1.4 P[\text{TW}]\lambda_0[\mu\text{m}]/\tau_0[\text{ps}]$, where τ_0 is the pulse duration in FWHM, $c\tau_0 = (2\ln 2)\sigma_z$. Note that the maximum energy gain is independent of the focusing property of the laser beam due to diffraction effects.

As an example, with a $P = 2$ TW, $\tau = 100$ fs, $\lambda_0 = 0.8$ μm laser pulse, the maximum accelerating gradient is $eE_{z\max} \simeq 2.1$ GeV/m at the plasma density of $n_e = 2.4\times 10^{17}$ cm^{-3} for the focus spot radius $R_0 = 30$ μm and $Z_R = 3.5$ mm. Thus the maximum energy gain is limited to $\Delta W_{\max} \simeq 23$ MeV.

Channel-guided LWFA

In order to increase the energy gain of electrons accelerated by wakefields, it is essential to propagate a short laser pulse in a plasma beyond the vacuum Rayleigh length limited by diffraction. The refraction index of a plasma is given by $\eta \simeq 1 - (\omega_p^2/2\omega_0^2)[n(r)/n_0]$, where $n(r)$ is the electron density profile. For refractive guiding of a laser beam, a radial profile of the refraction index must be $\partial\eta/\partial r < 0$ [3]. It has been conceived that short intense laser pulses can be optically guided without diffraction by plasma density channels with such a radial index profile as optical fibers. Optical guiding of a Gaussian laser pulse with a focal spot radius R_0 can be made through the plasma density channel with a parabolic electron density profile given by $n(r) = n(0) + \Delta n r^2/R_0^2$. If the channel density depth satisfies $\Delta n = 1/(\pi r_e R_0^2)$, propagation of a laser pulse occurs with a constant spot size, R_0, matched to the equilibrium radius. When the optical guiding can be accomplished by the preformed plasma density channel, the acceleration distance is limited due to detuning of accelerated particles from a correct acceleration phase of plasma waves and/or due to the pulse energy depletion of a laser pulse. A phase detuning distance is given by $L_\phi \simeq \lambda_p(\lambda_p/\lambda_0)^2$. The energy depeletion distance, in which the laser pulse loses a half of its total energy, is $L_d = (16/3\pi^{3/2})(\lambda_p/a_0^2 k_p \sigma_z)(\lambda_p/\lambda_0)^2$[4]. As the phase detuning distance is $L_\phi < L_d$ for $a_0^2 < (8/3\pi^{5/2})(\lambda_p/\sigma_z)$, the maximum energy gain is limited to be $\Delta W = (2/\pi)eE_z L_\phi$. When a matched optical guiding with an uniform envelope radius, $R_0 = (\lambda_p/\pi)(\Delta n/n(0))^{-1/2}$ is made, the energy gain is obtained as

$$\Delta W = \frac{2\Omega_0 P}{\sqrt{\pi} m_e c^2}\left(\frac{\Delta n}{n(0)}\right) k_p \sigma_z \exp\left(-\frac{k_p^2\sigma_z^2}{4}\right). \qquad (2)$$

For the plasma density of the channel axis, $n(0) = 1/(\pi r_e \sigma_z^2)$, the energy gain is given by $\Delta W[\mathrm{GeV}] \simeq 0.6P[\mathrm{TW}](\Delta n/n(0))$, where $\Delta n/n(0) = (\sigma_z/R_0)^2$.

As an example, the matched optical guiding of a spot size, $R_0 = 15\mu$m for a 100 fs laser pulse can be made by the channel density depth of $\Delta n/n(0) = 2.1$ at $n(0) = 2.4 \times 10^{17}$ cm^{-3}. As a phase detuning distance is ~ 0.5 m, the energy gain of 2.5 GeV is achieved with $P = 2$ TW. The maximum amplitude of accelerating wakefields at the channel axis is $eE_z \simeq 8$ GeV/m within the energy depletion distance of $L_d \simeq 0.9$ m.

3 LWFA TEST FACILITY AT KEK

T^3 laser system

We have been constructing the T^3 laser system based on a Ti:sapphire based chirped-pulse amplification (CPA) technique at 800 nm. The oscillator is a mode-locked Ti:sapphire laser pumped by a cw-argon-ion laser at a power of 6 W. It produces pulses of less than 80 fs duration at a repetition rate of 81.6 MHz to deliver the output power of 0.75 W at 800 nm. The seed pulse from the oscillator is stretched to ~ 300 ps in a four-pass grating arrangement with the reflective telescope. A stretched pulse is amplified to ~ 5 mJ in the Ti:sapphire regenerative amplifier (RGA) pumped at 10 Hz by 100 mJ, 6 ns pulses of a Q-switched Nd:YAG laser at 532 nm. The output from the regenerative amplifier is further amplified to > 340 mJ in a four-pass power amplifier. Both faces of a Ti:sapphire crystal are pumped with two frequency-doubled pulses from a Q-switched Nd:YAG laser which produces the total energy of 1.5 J at 532 nm. The amplified pulse is compressed in a two-pass grating configuration to ~ 100 fs with an energy of > 200 mJ, corresponding to the peak power of 2 TW.

Electron beam injector

It is necessary for the LWFA to inject the electron beam with an appropriate initial energy so that electrons can be trapped and accelerated by relativistic wakefields. The minimum and maximum trapping energy are 0.9 MeV and 1360 MeV, respectively, for the accelerating gradient of 8 GeV/m at the plasma density of $n_e = 2.4 \times 10^{17}$ cm^{-3}. Thus the injection energy of electron beam should be higher than 1 MeV.

We use the RF linac for medical research as an electron injector. This linac driven at 2856 MHz RF frequency produces 10 MeV elctron beam pulses of a $\sim 1\mu$s duration with the peak current of ~ 300 mA at the repetition rate of 10 Hz. An electron pulse consists of a train of bunches with 350 ps separation, each of which has 10 pC (6×10^7) electrons. An electron bunch is synchronized to wakefields excited by a 100 fs laser pulse within timing jitter of 3 ps with the phase locked control of the mode-locked osillator. The phase locked loop maintains synchronization of the oscillator repetition period (81.6 MHz) with every 35th RF period of the linac (2856 MHz).

In order to accomplish correct synchronization of the electron bunch with an acceleration phase of the wakefield, the FWHM bunch length must be less than 100 fs. Such an ultrashort electron bunch may be produced from a RF photoinjector driven by femtosecond laser pulses at the UV wavelength. These pulses can be obtained through BBO crystals as third harmonic generation of Ti:sapphire laser pulses splitted from the output of the RGA. Then we can achieve the best synchronization with the wakefield.

An injected electron beam must spatially overlap with wakefields of which amplitudes are distributed inside the laser radial profile. Since the focusing force of the radial wakefield exists at $r < R_0/2$, the electron beam should be focused to the diameter less than a half laser spot size. An electron beam from the injector is brought to a focus in an interaction chamber with the rms beam size of $\sim 15\mu$m through a beamline consisting of a quadrupole triplet magnet and two quadrupole doublets.

Accelerator setup and diagnostics

The test accelerator setup is composed of the RF linac (RF photoinjector), the electron transport beamline, the laser-plasma interaction vacuum chamber, the energy analyzing spectrometer and the optical diagnostic system. A schematic is shown in Fig. 1.

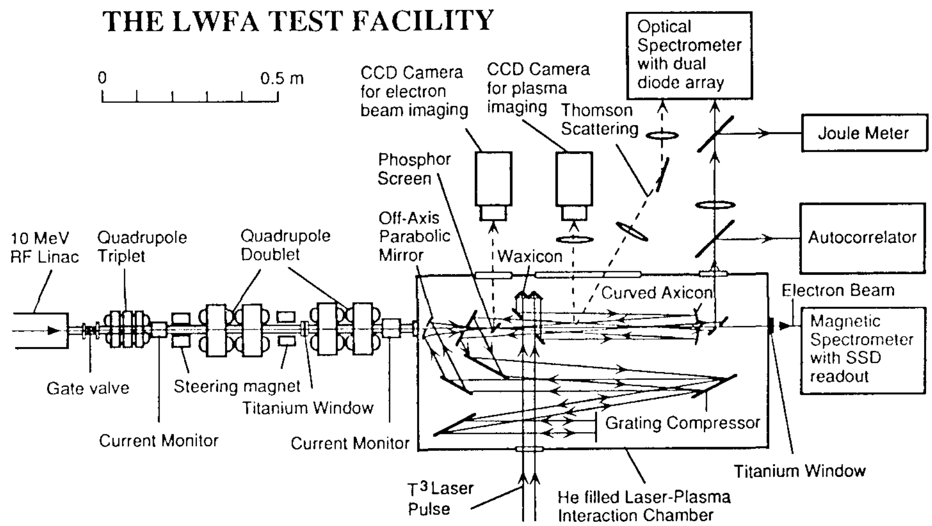

Figure 1: Plan view of the LWFA test facility.

In order to propagate and focus high power pulses, the grating compressor is installed into the interaction chamber which is evacuated and refilled with a Helium gas to prevent self-focusing and damage on the gratings. In the He filled interaction chamber, a plasma is produced by tunneling ionization due to an intense laser field of 5.6×10^{17} W/cm^2, higher than the threshold intensity of 9×10^{15} W/cm^2 for He^{2+} ionization. The RF linac and the beamline are separated with a titanium window from the interaction chamber to maintain ultrahigh vacuum in the electron injector.

In the diffraction-limited LWFA, the driver laser pulses are simply focused in the interaction chamber with an off-axis paraboloid. In the channel-guided LWFA, the plasma density channel must be preformed by a prepulse before exciting wakefields. A possible method to generate refractive index structure is the use of shock waves produced by a laser-induced gas breakdown[5]. The long laser pulses with relatively low intensity of $10^{13} \sim 10^{14}$ W/cm^2 induce the gas-breakdown through various ionization processes to drive a shock wave in the ion density, which develops a depression in the plasma density on axis behind the shock at the local ion sound speed, $c_s \sim 5 \times 10^6$ cm/s for a He plasma at a $\sim$ 100 eV electron plasma temperature. The uncompressed pulses ($\sim$ 300 ps) from the T^3 laser are passed in a $\sim$ 30 Torr He gas to preform a favorable plasma density channel. After some delays ($5 \sim 6$ ns), the output pulses from the grating compressor are focused onto the end of the channel to be guided.

Plasma fluorescence and channeling propagation of a laser pulse can be imaged onto a charge-coupled-device (CCD) camera with the microscope objectives. In order to measure frequency and amplitude of excited plasma wakefields, Thomson scattering measurement is performed at an angle of 60 degrees with a longer probe pulse at $\lambda = 0.8\mu$m derived from the output pulses of the power amplifier. A wavelength shift is expected to be $\Delta\lambda \sim 10$ nm for the plasma density of 2.4×10^{17} cm^{-3}. The energies of accelerated electrons are measured with the magnetic spectrometer consiting of two dipole magnets and three silicon strip detectors to measure a beam position and profile. The dipole field of 4 kG and the detecor position resolution of 0.25 mm allow for measuring particle energies in the range of $0 \sim 10$ GeV with resolution of 0.2 MeV. If we measure a position and profile of accelerated electrons at the entrance, the center and the exit of the spectrometer, we can precisely decide the energy, the energy spread and the emittance of the accelerated electron beam.

4 CONCLUSIONS

We present a proposal of the LWFA to obtain electron acceleration more than 1 GeV in a table-top size by the use of a 2 TW, 100 fs T^3 laser system and a 10 MeV RF linac injector. We will first focus on experiments to search for a stable optical guiding technique, following completion of the T^3 laser system. Then we install the RF linac injector or the RF photoinjector in future to carry out acceleration experiments on the diffraction-limited LWFA and the channel-guided LWFA.

5 REFERENCES

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