A GEV LASER WAKEFIELD ACCELERATOR DRIVEN BY A T^3 LASER

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Abstract

Recently there has been a great progress in laser wakefield accelerators (LWFA) promising a compact high-energy accelerator with ultrahigh gradient particle acceleration of the order of 10 GeV/m. A compact terawatt laser system referred to as T^3 (table-top-terawatt) lasers is available for the LWFA as a laser driver providing intense ultrashort laser pulses with a reasonable repetition rate. Our current research is focused on achieving high energy particle acceleration to energies more than 1 GeV in a table-top scale owing to a channel-guided LWFA scheme by the use of 100 fs, 2 TW T^3 laser system.

1 INTRODUCTION

In conventional RF-driven accelerators the accelerating field gradient is limited to approximately 100 MV/m due to electrical breakdown on material surfaces. If we were to construct a 10-TeV accelerator by means of conventional technology, its size would exceed 100 km in length. Such scale of size gives rise to technological difficulties in stable acceleration and transport of particle beams. In order to produce ultra-high energy-particles required for high energy physics frontiers within a limited size, it would be necessary to innovate acceleration mechanisms capable of ultra-high-gradient particle acceleration as well as driving power sources. The state-of-art of klystrons for driving conventional RF linacs exists at the power level of 100 MW. On the other hand, the power level of lasers reaches to petawatts. Therefore, laser-driven particle accelerators have been conceived over the past decade to be the next-generation particle accelerators, promising super-high field particle acceleration[1]. Among a number of laser accelerator concepts proposed so far, laser wakefield accelerators have great potential to produce ultra-high-field gradients of plasma waves excited by an intense ultrashort laser pulse[2]. Recently wakefield excitation in a plasma has been confirmed by the use of a compact terawatt laser system so called T^3 lasers[3].

In this paper we present our current project of the LWFA test facility which is aimed at an energy gain of the order of GeV in a table-top size using a 100 fs, 2 TW T^3 laser system. A high energy gain can be achieved through a long-distance channeling propagation of intense short laser pulses. We report experimental results on propagation of ultrashort laser pulses in a plasma.

2 CHANNEL-GUIDED LWFA

The axial and radial wakefields are calculated from the wake potential resulted from the density oscillation with the plasma frequency $\omega_p = \sqrt{4\pi e^2 n_e/m_e}$ for the ambient density n_e of plasma electrons. The maximum amplitude of the axial wakefield is achieved at the plasma wavelength $\lambda_p = \pi\sigma_z$: $(eE_z)_{\max} \simeq 1.3 m_e c^2 a_0^2/\sigma_z$, where σ_z is the rms pulse length and a_0 is the normalized vector potential of the laser field given by $a_0^2 = 0.73 \times 10^{-18} I\lambda_0^2$ for the peak intensity I in units of W/cm^2, the laser wavelength $\lambda_0 = 2\pi c/\omega_0$ in units of μm, and the laser frequency ω_0.

Assuming a Gaussian beam propagation of the laser pulse at the peak power (P) in an underdense plasma ($\omega_0 \gg \omega_p$), the peak amplitude of the accelerating wakefield is

$$eE_z = \frac{\Omega_0 P}{\sqrt{\pi} m_e c^2}\Big(\frac{\lambda_0}{\lambda_p}\Big)\Big(\frac{k_p\sigma_z}{Z_R}\Big)\exp\Big(-\frac{k_p^2\sigma_z^2}{4}\Big), \qquad (1)$$

where Ω_0 is the vacuum resistivity (377Ω), λ_0 is the laser wavelength, $k_p = 2\pi/\lambda_p$, σ_z is the temporal $1/e$ half-width of the pulse and Z_R is the Rayleigh length, i.e. $Z_R = \pi R_0^2/\lambda_0$, where R_0 is the spot radius at the focus. 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; $\Delta W_{\max}[\mathrm{MeV}] \simeq 1.4 P[\mathrm{TW}]\lambda_0[\mu\mathrm{m}]/\tau_0[\mathrm{ps}]$, where τ_0 is the pulse duration in FWHM, $c\tau_0 = (2\ln 2)\sigma_z$. For the diffraction-limited case, the energy gain is at most 22 MeV for a 100 fs, 2 TW laser pulse.

In order to increase the energy gain, it is essential to propagate a short laser pulse in a plasma beyond the vacuum Rayleigh length limited by diffraction. Optical guiding of a Gaussian laser pulse with a focal spot radius of 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 uniform spot size (R_0). When the optical guiding can be accomplished through the plasma density channel, the acceleration distance is limited due to detuning of accelerated particles from a correct acceleration phase of plasma waves. As a phase detuning distance is limited to be $L_\phi \simeq \lambda_p(\lambda_p/\lambda_0)^2$, the maximum energy gain is given by $\Delta W = (2/\pi)eE_z L_\phi$. For the plasma density at 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 $\Delta n/n(0) = (\sigma_z/R_0)^2$. In the channel-guided LWFA, the maximum energy gain exceeds 5.5 GeV at the dephasing length of ~ 50 cm for a 100 fs, 2 TW laser pulse in the optimized plasma density channel ($n(0) = 2.4 \times 10^{17}$ W/cm^2, $\Delta n/n(0) = 4.6$). We can obtain the energy gain exceeding 1 GeV with propagation distance of 10 cm in the plasma channel.

3 LWFA PROJECT

3.1 LWFA Test Facility

We have developed the LWFA test facility to achieve GeV energies based on the channel-guided LWFA scheme. The test accelerator setup comprises the T^3 laser system, the RF linac beam injector, the electron transport beamline, the laser-plasma interaction chamber, the energy analyzing spectrometer and the optical diagnostic system. The main parameters of the test facility are summarized in Table 1. The facility has been constructed at Nuclear Engineering Research Laboratory in the University of Tokyo. In this facility we plan to execute experiments on laser-plasma interaction for observing wakefields and a femto-second X-ray generation through Thomson scattering as well as laser wakefield acceleration.

Table 1: Parameters of LWFA Test Facility

Laser	Ti:sapphire T^3 Laser
Wavelength	790 nm
Peak power	>2 TW
Pulse energy	>200 mJ
Pulse duration	100 fs
Repetition rate	10 Hz
Focal spot radius	$\sim 10\mu$m
Intensity	$\sim 1.3\times 10^{18}$ W/cm^2
Electron injector	RF Linac
Energy	15 MeV
Bunch length	~ 10 ps
Charge/bunch	>100 pC
Emittance	$\sim 10\pi$ mm-mrad
Beam size at focus	$\sim 10\mu$m
RF frequency	2856 MHz
Repetition rate	10 Hz
LWFA	Channel-Guided LWFA
Plasma density	$n(0) = 2.4\times 10^{17}$ cm^{-3}
Plasma wavelength	$\sim 70\mu$m
Density depth	$\Delta n = 1.1\times 10^{18}$ cm^{-3}
Channel radius	$\sim 10\mu$m
Channel length	~ 10 cm
Accelerating gradient	~ 18 GeV/m
Energy gain	>1 GeV

3.2 T^3 Laser System

We have constructed the Ti:sapphire T^3 laser system on a 2×4 m^2 table based on the chirped-pulse amplification (CPA) technique at 790 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 70 fs duration at a repetition rate of 80 MHz to deliver an output power of 0.75 W at 790 nm. The seed pulse from the oscillator is stretched to 320 ps in a four-pass grating arrangement with a reflective telescope. A stretched pulse is amplified to ~ 5 mJ in the Ti:sapphire regenerative amplifier (RGA) pumped at 10 Hz by 35 mJ, 6 ns pulses of a Q-switched Nd:YAG laser at 532 nm. The output from the regenerative amplifier is further amplified to > 400 mJ through a multipass pre-amplifier and a multipass main amplifier. Both faces of a Ti:sapphire crystal are pumped with two frequency-doubled pulses of 100 mJ for a pre-amplifier and 1.3 J for a main amplifier from a Q-switched Nd:YAG laser which produces a total energy of 1.6 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 a peak power of 2 TW. Since we have succeeded in producing the maximum output energy of 600 mJ at the main amplifier, we can generate the maximum peak power of 3 TW at 10 Hz with the transmission efficiency of 50% in the compressor.

3.3 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 energy is 0.2 MeV for an accelerating gradient of 18 GeV/m at a plasma density of $n_e = 2.4 \times 10^{17}$ cm^{-3}. We use the RF linac at NERL as an electron injector. This linac, driven at 2856 MHz RF frequency, produces 15 MeV elctron beam pulses with a bunch length of 10 ps containing 1.5 nC at the repetition rate of 10 Hz. An electron bunch is synchronized to wakefields excited by a 100 fs laser pulse with the phase locked control of the mode-locked oscillator. The phase locked loop maintains synchronization of the oscillator repetition period (79.3 MHz) with every 36th RF period of the linac (2856 MHz). We have measured a timing of the laser pulse and Cherenkov radiation from the electron beam with the streak camera. Experimental results indicate that synchronization between two pulses will be achieved within 10 ps.

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 $\sim 10\mu$m through a beamline consisting of a permanent quadrupole doublet, triplet and a triple focusing magnet. The RF linac and the beamline are separated with a 20μm thick titanium window from the interaction chamber to maintain ultrahigh vacuum in the electron injector.

3.4 Diagnostics

Plasma fluorescence and channeling propagation of a laser pulse can be imaged onto a charge-coupled-device (CCD) camera with the microscope objectives. Measurements of frequency and amplitude of excited plasma wakefields is performed by the frequency domain interferometry technique[3] with a frequency-doubled probe pulse generated by a KDP crystal from a fraction of the incident pulse.

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 $0-10$ 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 LASER PROPAGATION EXPERIMENTS

In order to achieve electron acceleration more than 1 GeV, It is essential to propagate ultrashort laser pulses with intensities higher than the fully ionizing threshold through distances much greater than Rayleigh length. We have investigated the propagation of ultrashort terawatt-power laser pulses in gases. In gas filled vacuum hamber, a plasma is produced through tunneling ionization due to an intense laser field higher than the threshold intensity of 9×10^{15} W/cm^2 for He^{2+} ionization. In vacuum the laser pulse focuses to a peak intensity of 1.5×10^{18} W/cm^2 for a peak power of 2.4 TW using a f/10 off-axis parabolic mirror with a focal length of 480 mm. The vacuum chamber was filled with helium (He), argon (Ar) and nitrogen (N_2) at pressures of $10^{-3} - 760$ Torr. Fluorescence and side scattered laser light from the plasma region were imaged onto a CCD camera to measure plasma length.

The fluorescence image showed a narrow long spark channel ranging 60 mm at 20 Torr of He for 2.5 TW. A magnified image of fluorescence was projected to a CCD camera through the microscope objective to measure the density distribution of the plasma channel. The diameter of the channel was 300μm in FWHM along the axis. A side projected image of the channel showed a flat or a double-peak profile as the laser peak power increases toward more than 1 TW and and the gas pressure increases toward more than 100 Torr. A hollow tube structure of the channel was clearly seen over more than 25 mm at 760 Torr of He for 2.5 TW. The forward scattered laser light was imaged onto a CCD camera coupled to the microscope objective through a 10 nm FWHM interferential filter to measure a focused spot size along the propagation axis. In vacuum at the pressure of 3×10^{-4} Torr, the measured spot size along the axis was in good agreement with the theoretical beam envelope for the Gaussian beam propagation without regard to the laser power. When the gas pressure increases toward more than 100 Torr, the spot size decreases down to the smaller size than the expected Gaussian propagation over the range of a few cm as the laser power increases toward more than 1 TW. At 2.5 TW in 760 Torr He gas, we observed a hollow tube structure of plasma region with a clear density depletion of 100μm diameter.

It is known that relativistic self-focusing in a homogeneous medium occurs for incident laser powers exceeding the critical power, given by $P_c = 17(\omega_0^2/\omega_p^2)$ GW. Relativistic self-focusing should take place at $P > P_c = 0.56$ TW in 760 Torr fully ionized He plasma ($n_e = 5.4 \times 10^{19}$ cm^{-3}). A long-range channeling of the laser pulse arose over 50-70 Rayleigh lengths from relativistic self-focusing and self-channeling. Furthermore we found elctron trajectories accelerated due to wakefields in N_2 gas. Trajectories were observed as a transverse jet for more than 0.5 TW in the pressures higher than 50 Torr.

5 CONCLUSIONS

We have been advancing the project on the LWFA development to obtain electron acceleration exceeding 1 GeV in a table-top size by the use of a 2 TW, 100 fs T^3 laser system and a 15 MeV RF linac injector. We have tested synchronization of the ultrashort laser pulse with the electron beam. We have demonstrated relativistic self-channeling propagation of high intensity ultrashort laser pulses and wakefield excitation in the channel. The electron acceleration experiment will be pursued through channel-guided wakefield excited by intense ultrashort laser pulses synchronized with injected electron pulses.

6 REFERENCES

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