GENERATION OF FEMTO-SECOND ELECTRON BEAMS FROM THE LASER WAKEFIELD ACCELERATION AT KERI

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Abstract

High power (> TW) lasers can be used to accelerate electrons to relativistic high energies over a very short distance (< 1mm). We have a research program on the laser wakefield acceleration at KERI (Korea Electrotechnology Research Institute), and the ongoing research activities and results are described in this paper.

INTRODUCTION

A high-power laser beam has an ultra-strong electric field, which is given by $E_{laser} = (2I/c\varepsilon_0)^{1/2}$. Here, I is the laser beam intensity and ε_0 is the electric permittivity of free space. For example, a laser beam of $I = 10^{18} W/cm^2$, which can be easily obtained from a modern table-top terawatt (T^3) laser system, has an electric field of 3 TV/m. However, the laser electric field is transverse, so it can not be used directly for efficient acceleration of charged particles. But direction of the laser electric field can be changed to a longitudinal direction if a laser pulse is sent through a plasma and a laser wakefield is generated. [1] Such a laser wakefield is so strong that it can accelerate electrons to relativistic high energies over a very short distance (< 1 mm). Hence, acceleration of electrons to high energies using lasers is of great interest.

There are various issues in laser and plasma-based advanced accelerator research. One of important tasks of plasma accelerators is how to generate high-energy electron beams with a small energy spread. For this purpose, we are going to conduct a series of experiments on the laser wakefield acceleration at KERI, where a T^3 laser system is used for laser plasma interactions. The first experiment of the plan is the self-modulated laser wakefield acceleration (SM-LWFA), in which the rather long (>> plasma wavelength λ_p) laser pulse is self-modulated into shorter pulses due to the Raman scattering instability and plasma electrons are self-injected into the acceleration phase. This is a simplest acceleration method in laser and plasma-based acceleration mechanisms. Hence, we start with this experiment due to its simplicity. However, it should be noted that SM-LWFA leads to a large energy spread (~ 100 %) as background plasma electrons are randomly injected. Thus, another experiment will be performed after the SM-LWFA experiment to achieve a smaller energy spread. In this paper we report the ongoing research activities and results, and the future plan is introduced a well.

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TABLE-TOP TERAWATT LASER SYSTEM

The laser system for the advanced accelerator research at KERI is a hybrid type of Nd:glass and Ti:sapphire, and the overall picture of the laser system is shown in Fig. 1. The oscillator (Time-Bandwidth GLX-200) is a glass laser that can produce 200 fs laser pulses at 76 MHz by using the so-called SESAM (Semiconductor Saturable Absorber Mirror) technology for stable fs mode-locking. The laser pulses are sent to the Ti:sapphire regenerative amplifier, where the laser pulse is stretched to 1.4 ns and then it is amplified by the Ti:sapphire rod pumped by the frequency-doubled Nd:YLF laser (Spectra-Physics Evolution-X. In this way the regenerative amplifier can produce laser pulses with an energy of 0.4 mJ/pulse at 500 Hz. The output from the regenerative amplifier is sent to three stages of Nd:glass amplifier system and the laser pulse is amplified to 2 J/pulse. And then this pulse is compressed by two gratings with an efficiency of 70 % and the pulse duration is reduced to 700 fs. Hence, 1.4 J/pulse is eventually sent to the laser-plasma interaction chamber.

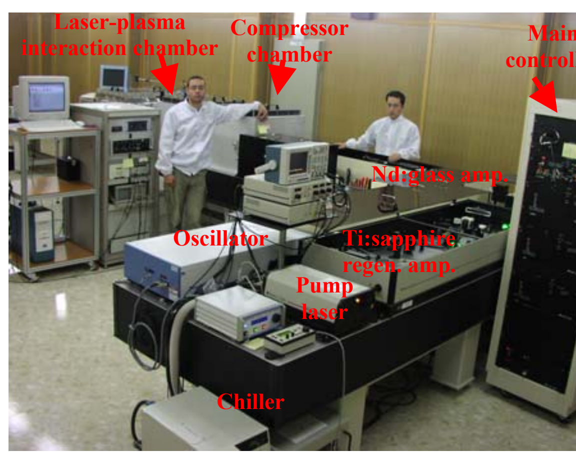

Figure 1: Overall picture of the laser system.

SM-LWFA EXPERIMENT

As mentioned in Introduction, we started with the SM-LWFA experiment as it is a simplest mechanism in laser and plasma-based advanced accelerators. A schematic of the experimental setup for this experiment is shown in Fig. 2. The 2 TW (1.4 J/700 fs) laser beam is sent to the laser-plasma interaction chamber in which the laser beam is focused to a supersonic gas jet with a focused spot size of about 10 microns by the gold-coated parabolic mirror. The gas jet has a diameter of 1 mm and its neutral gas density profile was measured by the Mach-Zehnder interferometer. The measurement result shows that the density profile is almost Gaussian across the transverse direction and the neutral gas density is in the range of 10^{18} to 10^{19} cm^{-3}. Intensity of the focused laser beam is on the order of 10^{18} W/cm^2, so the electric field is strong enough to ionize He atoms to a plasma. When the intense laser beam with a duration of 700 fs interacts with the He plasma, some background plasma electrons are self-injected into the acceleration phase of a self-modulated laser wakefield. The accelerated electrons have an energy spread of 100 %, so the low energy and high energy electrons are redistributed when they propagate along the longitudinal direction. The low energy electrons have a very strong space-charge force and they diverge very rapidly. Our main interest is in the high energy electrons, so a collimator with a 2 mm diameter is setup to cut off the low energy electrons. The electrons, which passed the collimator, propagate through the integrating current transformer for charge measurement. After that, the electrons are sent to the dipole magnet and beam imaging plate (phosphor-based Kodak Lanex film) to measure energy and energy spread. In order to know the focused laser beam location and to view the longitudinal plasma images, two CCD cameras are installed at 90^o. The transmitted laser light is reflected by the 45^o thin Al foil and is sent to the spectrometer to measure the plasma density based on the Raman scattering method.

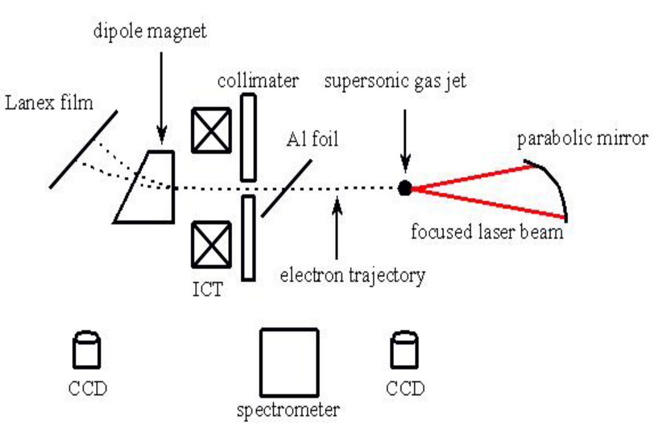

Figure 2: Schematic of the experimental setup for the self-modulated laser wakefield acceleration.

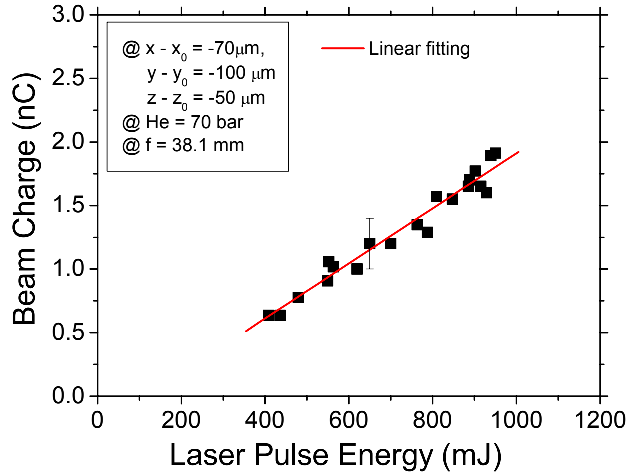

Figure 3: Plasma density profile used for the simulation.

For the experiment the beam charge was measured as a function of the laser beam energy. Figure 3 shows the result when the collimator was removed. Thus the charge is a total charge passing through the ICT (integrating current transformer). The result shows that the electron charge almost linearly increases as the laser energy increases. For this measurement we used a parabolic mirror with a focal length of 3.8 cm and a backing He pressure of 70 bars. Figure 3 shows that extension of the linear fitting does not pass the origin in the graph, so the result implies that there is a minimum threshold (laser) energy for electron beam generation.

The beam charge may be dependent on the plasma density. To investigate this issue the laser energy was fixed at 0.9 J and then the He gas backing pressure was varied from 20 bars to 70 bars. This measurement indicates that the beam charge increases almost linearly to the backing pressure that is linear to the gas density at the laser plasma interaction point.

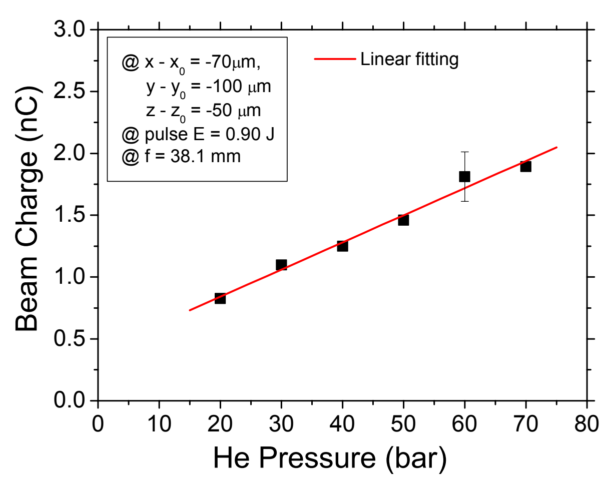

Figure 4: Electron beam charge as a function of the He backing pressure. This result implies that the beam charge is linearly proportional to the plasma density.

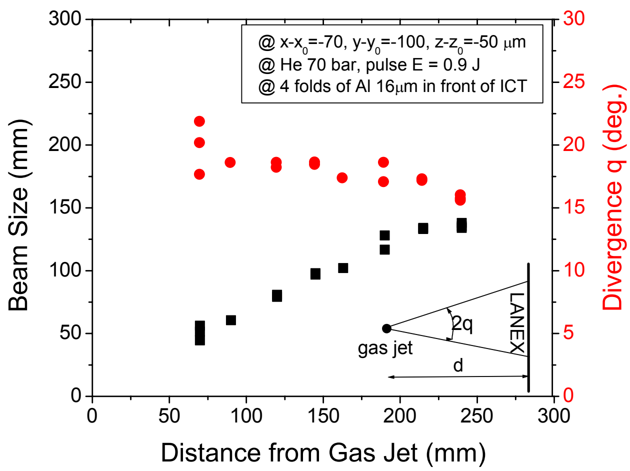

Figure 5: Measurement of a beam size as a function of the distance from the gas jet.

Figures 3 and 4 show that the beam charge per pulse is a few nC. The beam duration would be around the laser pulse duration that is 700 fs. Based on these parameters the peak current is estimated to be on the order of kA. But the beam diameter at the exit of the gas jet will be less than the plasma wavelength λ_p (~ 10 µm) and the energy of the electrons will be in the range of MeV. Hence, the electron beam is severely space charge dominated. For this reason the beam is expected to diverge very rapidly as it propagates. This is confirmed in Fig. 5, where the beam size is measured as a function of the propagation distance from the gas jet. Figure 5 indicates that the generated electron beam diverges at the angle of about 30 °, in which the large angle is caused by low energy electrons. Our measurement result shows that the energy of particles is reduced sensitively as the measurement position moves outward.

MONOENERGETIC ELECTRON-BEAM GENERATION

Generation of qusi-monoenergetic electron beams is a hot issue in the advanced accelerator community as it is very important. Several ideas were proposed to produce such beams using lasers. [2-4] One of them is to use a sharp downward density transition. According this idea, some background plasma electrons can be self-trapped by the laser wakefield when an intense laser beam pulse propagates through a sharp downward density transition. At the transition the wavelength of the wake wave increases suddenly so that some background plasma electrons are self-injected into the acceleration phase of the wakefield. This is illustrated in Fig. 6, where the laser pulse length satisfies the condition $c\tau = \lambda_p$. Here c is the light speed in free space and τ is the laser pulse duration. Figure 6 indicates that the trapped electrons at the transition can gain energies to higher than 100 MeV and the high energy electrons are well bunched.

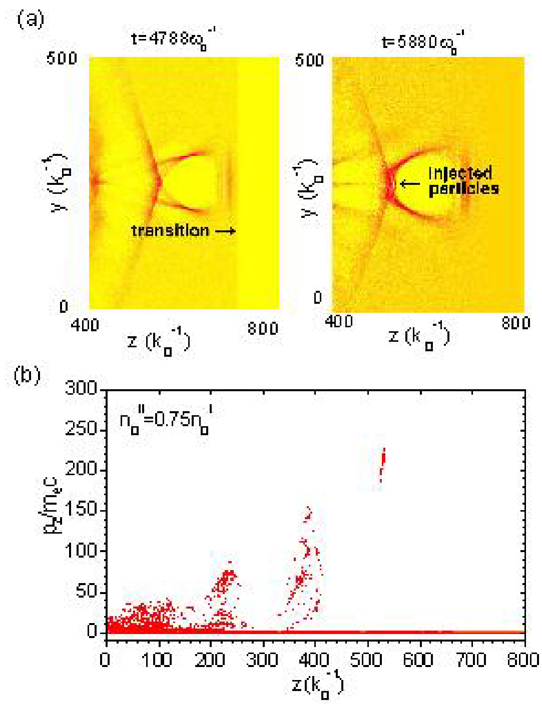

Figure 6: Simulation results for the self-trapped electrons at the density transition when the ratio of the low density to the high density is 0.75; (a) phase space plot (z, y) of plasma electrons at different moments and (b) phase space plot (z, p_z) of the plasma electrons at $t = 5880\omega_0^{-1}$. Here ω_0 is the laser frequency and $n_0^{\,l} = 5\times10^{18}$ cm^{-3}.

SUMMARY

Some of ongoing research activities at KERI were briefly introduced. One of them is the self-modulated laser wakefield acceleration. The result shows that we generated MeV-level high-energy electrons with a few nC per bunch and the electron beam is highly space-charge dominated, so the beam expands explosively as it propagates. This beam has an energy spread of 100 % naturally. In order to produce beams with a small energy spread, we are going to perform the density transition experiment after the self-modulated laser wakefield acceleration experiment.

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