LASER WAKE FIELD ACCELERATION RESEARCH AT KERI

C. Kim*[†], G. H. Kim, J. U. Kim, I. S. Ko[†], H. J. Lee, and H. Suk
Center for Advanced Accelerators
Korea Electrotechnology Research Institute, Changwon, 641-120, Korea
[†]Department of Physics, POSTECH, Pohang, 790-784, Korea

Abstract

An overview of a plasma-based advanced acceleration study at Korea Electrotechnology Research Institute (KERI) is presented. In order to get a high acceleration gradient $(> 1 \text{ GeV/m})$, the laser wake field acceleration (LWFA) has been studied at KERI. In the research of the LWFA at KERI, the sharp density transition LWFA project and the self-modulated laser wake field acceleration (SM-LWFA) project are under way. For the sharp density transition LWFA, trapping and acceleration of electrons in a background plasma by using a sharp downward density transition is described with simulation results. For the SM-LWFA, the experimental plan with the parameter study is presented and experiment results of the gas jet characterization are described as a preliminary study.

1 INTRODUCTION

LWFAs have been high-lightened since they can be used to accelerate charged particles to a relativistic high energy over a short distance [1]. As a terra-watt laser pulse passes through a plasma, a wake field is generated behind the laser pulse and the laser wake field produces extremely strong electric field. The maximum electric field of the laser wake field is on the order of 100 GV/m when a plasma density of $n_0 = 10^{18} \text{ cm}^{-3}$ is used. This electric field is three orders of magnitude stronger than that of conventional radio frequency (RF) accelerators. Thus LWFAs are intensively studied around the world.

At KERI we started a research program for LWFA in 2002. The major goal of the research is to investigate the possibility of a table-top high-energy electron accelerator. In most plasma-based acceleration experiments, an external injection system is used for beam injection. Hence, a relatively big injector is required and it is hard to make the entire accelerator system to a table-top size that may be important in future accelerator applications. In addition to the big size problem, there is a difficulty of phase matching between the laser wake filed and the injected beam in the external injection system. This difficulty comes from the fact that the laser wake field wavelength is so short in LWFAs. Hence, the phase matching is problematic due to time jittering of the laser pulse and injected beam.

As an alternative choice, $self-trapping$ of electrons in a plasma can be used for injection [2]. In the plasma, there are plenty of electrons and it is known that some hot plasma electrons, which are generated by various mechanisms such as a transverse wake breaking, longitudinal wave breaking, etc., can be trapped by the wake field.

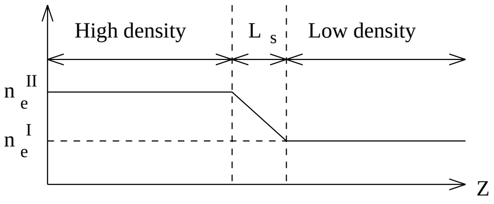

Figure 1: Density profile of an inhomogeneous plasma, in which L_s is the scale length of the density transition region and L_s is much smaller than the plasma wavelength λ_p in the sharp density transition laser wake field acceleration project.

In the laser wake field research at KERI, we are going to investigate the new self-injection mechanism that was recently proposed by Suk $et\ al.$ According to the proposed injection method, some background plasma electrons can be trapped and accelerated by the wake field when the wake field passes through a sharp downward density transition. In addition to this study, the SM-LWFA experiment is scheduled to be performed at KERI. In this paper, a brief overview of the LWFA projects at KERI is pesented.

2 LASER WAKE FIELD ACCELERATION STUDIES

2.1 Laser Wake Field Acceleration with a Density Transition

In the previous inhomogeneous density plasma LWFA self-injection methods, the plasma electrons are randomly trapped into the wake field and it leads a large energy spread of the electron beam. Furthermore, the accelerated electrons collide with plasma electrons remaining in the wake field and this scattering effect increases the beam emittance. To overcome these problem of the previous self-injection methods, a new self-injection scheme is proposed recently [3]. In this injection scheme, plasma electrons are

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* chbkim@postech.ac.kr

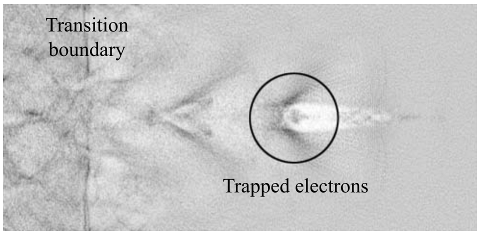


Figure 2: PIC simulation result of electron self-trapping at the sharp density transition. In this simulation, the transition length $L_s = 0$ and the plasma density ratio $n_e^I/n_e^{II} = 4/3$. Trapped electrons are shown in the circle.

fully ejected from the laser or electron beam path due to the laser ponderomotive force or space charge force and a nonlinear wake field is generated. When the wake field passes through a sharp downward density transition with $L_s \ll \lambda_p$, some plasma electrons are locally and transversely trapped into a wake field . This is due to the sudden increase of the plasma wavelength λ_p across the transition, and the injection occurs locally in the phase space. As a result, this internal injection scheme can lead to a rather small energy spread, which is important for beam applications.

The sharp density transition LWFA has been studied numerically with the OSIRIS code that is a fully relativistic and electromagnetic 2-D PIC (particle-in-cell) code [4]. A simulation result for $L_s = 0$ is shown in Fig. 2, where the density ratio n_e^I/n_e^{II} is 4/3. As shown in the figure, the wake wave is generated behind the laser pulse and an electron-free ion cavity is produced. When the wake wave passes through the downward density transition, some plasma electrons are transversely injected into the acceleration phase of the wake field as shown in the figure. As time goes on, the electrons are separated clearly from the background plasma electrons. In the beginning the trapped electrons have low energies, but they are accelerated rapidly to a relativistic energy by the ultrastrong wake field. As the energy increases, the space charge effect is reduced so that the electron beam size decreases gradually. The simulation shows that the trapped electrons can gain an energy of about 10 MeV. The ultimate energy of the electrons is limited by diffraction of the drive laser in this case as the laser beam size increases by $\sqrt{2}$ over a distance of the Rayleigh range.

This kind of trapping and acceleration mechanism is scheduled to be verified experimentally at KERI. For this experiment, we are going to use a terra-watt Nd:glass laser system and a plasma in the range of $n_e \sim 10^{16}$ cm^{-3}. The accelerated electrons will be diagnosed to yield the beam energy, energy spread, emittance, beam size, charge, etc. For these measurements various diagnostic techniques and tools will be developed. Before this experiment is performed, a SM-LWFA experiment will be conducted first. Now preparations for the SM-LWFA experiment are under way and the experiment is scheduled for next year after characterizations of the terra-watt laser are finished. The experimental plan is presented in the next section.

Table 1: Parameters for the self-modulated laser wake field acceleration experiment

Laser power P_l	2 TW
Laser pulse width τ_l	700 fs
Laser wavelength λ_l	1.053 μm
Plasma wavelength λ_p	10.5 μm
Plasma density n_e	1×10^{19} cm^{-3}
Maximum elecric field $\vec{E}_z$	$\sim$ 300 GeV/m
Expected beam energy	$\sim$ 10 MeV

2.2 *Self-Modulated Laser Wake Field Acceleration Studies*

As mentioned above, we have the SM-LWFA project in addition to the sharp downward density transition project. Experience and equipments obtained from this experiment will be valuable for the next experiment. The experimental setup of the SM-LWFA is very similar to the sharp density transition LWFA and an experimental setup can be used for two projects with a minimum modification. Most equipments of the experimental setups, which include the terra-watt laser system, the electron extraction beamline, and the diagnostic system for the electron beam, etc., are common. The only difference is the plasma generation part. In the downward density transition LWFA experiment, two relatively low density plasmas with a sharp density transition are needed. On the other hand, a homogeneous density plasma is used for the SM-LWFA.

In the SM-LWFA, a rather long single (≤ 1 ps) ultra high intensity ($\geq 10^{18}$ W/cm^2) laser pulse is used to produce a train of laser wake field. In this case, the laser pulse is much longer than λ_p so that the laser pulse is split into many laser pulses due to the Raman scattering instability. These laser pulse train excites the laser wake field resonantly. If the laser power P_l is somewhat larger than the critical power P_c, the so-called relativistic self-focusing occurs and this helps the laser beam propagate over a long distance. This phenomenon happens if the following condition is met : $P_l > P_c \simeq 17(\lambda_p/\lambda_l)$ GW, where λ_l is the laser wavelength. These condition is fulfilled with the laser power of 1 TW for the plasma density of the order of 10^{19} cm^{-3} [2]. In this high density regime, the laser pulse undergoes the self-modulation instability which causes the pulse to break up axially into multiple pulses at the plasma period and these multiple pulses excite a large amplitude wake field resonantly. This large amplitude causes longitudinal and transverse wave breakings. As a result, some plasma electrons are injected into the acceleration phase of the wake field and they are accelerated to a high energy.

Planned parameters for the SM-LWFA experiment are listed in Table 1. The laser power is 2 TW and the laser

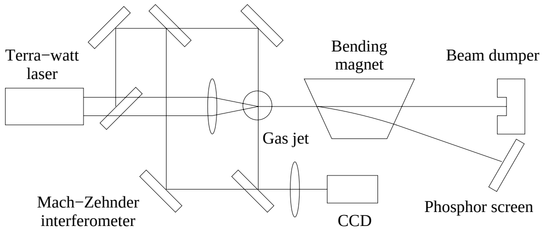
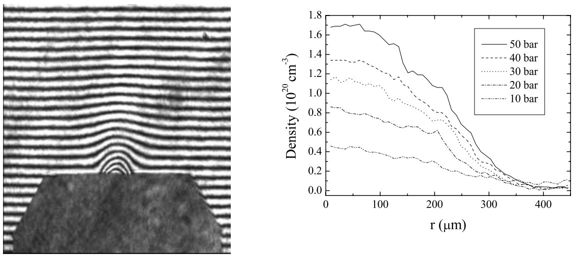


Figure 3: Schematic diagram of the experimental setup planned for the self-modulated laser wake field accelerator. The direction of the gas flow is perpendicular to the paper.

pulse width is given by 700 fs. To produce the self-modulated laser wake filed, the plasma wavelength is decided to be 10.5 $\mu\mathrm{m}$ which is 1 / 20 of laser pulse width, and the plasma density is determined to be $1 \times 10^{19}\ \mathrm{cm}^{-3}$ from the plasma wavelength. Under these conditions, maximum electric field of the wake field is calculated to 300 GeV/m and the expected energy of the electron beam is about 10 MeV.

Fig. 3 is the schematic diagram of the experimental setup planned for the SM-LWFA. A 2 TW, 700 fs laser pulse is produced from a Nd:Glass laser by the chirped pulse amplification method. The laser pulse is focused on the plasma which is made by the laser ionization of the neutral gas ejected from the gas jet and produces high energy electrons by the self-modulated laser wake field. The accelerated electron beam is bent when it pass through a bending magnet and separated from the laser pulse. Finally the electron beam hits the phosphor screen and parameters of electron beams such as the beam size, the emittance, and the energy can be measured. In the same time, small portion of the laser is split by the beam splitter and put into a Mach-Zehnder interferometer for the diagnostics of the laser produced plasma.

As a preliminary study, neutral gas densities is measured for the laser produced plasma generation. N_2 gas are ejected from a gas jet with various gas pressure and the fringe pattern of each pressure is obtained with a Mach-Zehnder interferometer. Measurement results are shown in Fig. 4. Fig. 4 (a) is the fringe pattern of N_2 gas. The gas pressure is 50 bar and the background pressure is 5.9×10^{-1} Torr. Diameter of the nozzle is 500 $\mu\mathrm{m}$ and the nozzle has a cylindrical symmetry. With these fringe pattern images, the density profiles of N_2 gas are calculated with Abel inversion [5]. The calculated neutral gas density is $1.7 \times 10^{18}\mathrm{cm}^{-3}$ at the center of the nozzle surface when the gas pressure is 50 bar. As shown in Fig. 4 (b), the neutral gas density has a Gaussian profile to the nozzle radius direction and exponentially decay to the direction of the gas flow.



(a) (b)

Figure 4: Neutral gas density from gas jet. (a) is the fringe pattern of N_2 gas. The gas pressure is 50 bar and the background pressure is 5.9×10^{-1} Torr. The diameter of nozzle is 500 $\mu\mathrm{m}$. (b) is calculated densities of N_2 gas at each backing pressure. The density profile is Gaussian to the nozzle radius direction.

3 SUMMARY

Since 2001, the LWFA has been studied at KERI. The main goal of this research is to investigate the possibility of a plasma-based table-top high energy accelerator. For this goal, the sharp density transition LWFA will be tested experimentally. Before the experiment, extensive PIC simulations have been performed. The simulation results show that a significant amount of plasma electrons can be trapped and accelerated to over 10 MeV by the wake field. In addition, the SM-LWFA project is under way. Experimental setups for these two projects have lots of common features and can be used for both of them with minimum modifications. These two LWFAs are based on self-trapping mechanisms by the wave-breaking and their results will be complementary to each other for the analysis of the self-trapping mechanisms. For the SM-LWFA, the parameter study was achieved for the experiment and the gas jet characterization was performed for laser-produced plasma generations. Based on the basic laser-plasma interaction experience, the SM-LWFA experiment and the sharp density transition LWFA experiment will be conducted in the near future.

4 REFERENCES

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