GENERATION OF SMALL ENERGY SPREAD ELECTRON BEAM FROM SELF-MODULATED LASER WAKEFIELD ACCELERATOR

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Abstract

Laser and plasma based accelerators have been studied for a next generation particle accelerator. However, there are some problems to solve for real applications and small energy spread is one of them. In this work, we introduce a method to control the energy spread. From a basic theory and simulations, it is found that the transverse density distribution of an electron beam is changed from a Gaussian to a Maxwell-Boltzmann distribution, and the longitudinal density profile becomes a trumpet-shape, as the electron beam propagates in vacuum. From this electron dynamics, a collimator is installed to remove the small energy electrons and it is shown that the electron beam energy spread can be controlled with the collimator.

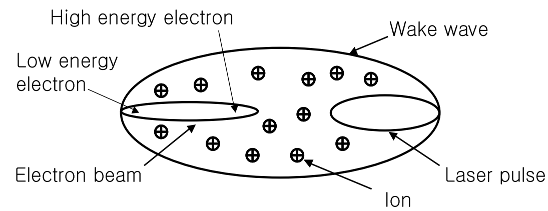

Figure 1: Schematic view of the electron beam inside wake wave. When a laser pulse passes through a plasma, a wake wave is generated and an electron beam can be accelerated inside the wake wave. Note that, in the frame of the wake wave, the electron beam just passes through the ion plasma.

INTRODUCTION

In the last thirty years, the experimental study of laser plasma accelerators has been made great progress for the beam energy and a generation of 200 MeV electron beam is already achieved [1]. Naturally, the quality of the electron beam becomes most important matter. For most applications, a high quality electron beam is required. However, electron beams from laser plasma accelerators have been observed to have a large energy spread, so that the small energy spread is a hot issue in the laser plasma accelerator research. Recently, the monoenergetic features of the electron beam are observed in the electron energy spectrum, when the plasma density is just above a threshold required for the wave breaking. These features are observed consistently in the electron energy spectrum, although the energy of the beam was observed to vary from shot to shot [3]. In addition, the evolution of electron spectra with experimental parameters indicates that using a laser pulse shorter than the plasma period is beneficial for high quality, monoenergetic electron accelerations [4].

In this study, we introduce an alternative method to reduce the energy spread of the electron beam, which is generated from a self-modulated laser wakefield accelerator. As shown in above, most of studies have been focused on the generation of a small energy spread electron beam. However, if it is possible to remove small energy electrons from a large energy spread electron beam, it will be another method to obtain a small energy spread. In an experiment of the self-modulated laser wakefield accelerator, it is reported that the energy spectrum of the electron beam is made of hot components in the center and colder components in the outer part. This indicates that the very fast electrons are more collimated than the less energetic ones [5]. Thus, if a collimator is installed on the electron path, one can block the low energy part to reduce the energy spread of the electron beam.

This study starts from a model of the electron beam inside the wake wave. By using the simple model, the electron dynamics of the electron beam is described in and outside the plasma. A two-dimensional particle in cell (PIC) simulation is also tried to confirm this theoretical result, and the theory and the simulation results show a good agreement. Next, we designed an experiment to removed small energy part of the electron beam, which is generated from the self-modulated laser wakefield accelerator. The experimental result shows that the small energy electrons can be removed effectively by using a small aperture collimator.

BASIC THEORY

Figure 1 is a schematic view of the electron beam which is accelerated by the plasma wakefield. When the laser pulse passes through the plasma, the wake wave is generated along the laser pulse. If the wake wave is stronger than the wave breaking threshold, background electrons can be injected into the wake wave. The phase velocity of the wake wave is almost same with the laser velocity in the plasma, so that the electron inside the wake wave can be accelerated to a high energy. Note that the electron inside the wake wave just passes through the ion plasma because the ion motion is negligible owing to its heavy mass. Thus, one can simplify the electron beam in the wake wave as an electron beam in the background ion plasma. The potential

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of the ion plasma which has a density n_i is given by

$$\phi = \frac{q n_i r^2}{4\epsilon\gamma^2}, \tag{1}$$

where the Poission's equation is used. From the Boltzmann relation, one can write down the electron density distribution as

$$n(r) = n(0)\exp\left(-\frac{q^2 n_i r^2}{4\epsilon k_B T_\perp \gamma^2} - \frac{q\phi_s(r)}{k_B T_\perp}\right), \tag{2}$$

where k_b is the Boltzmann constant, $T_\perp$ is the transverse temperature, and $\phi_s(r)$ is the space-charge potential. The first and second term represent a focusing force of the ion plasma and defocusing force of the space-charge effect, respectively. Inside the plasma, the space-charge effect is negligible. By setting $\phi_s(r) = 0$, one can obtain the Gaussian density distribution

$$n(r) = n(0)\exp\left(-\frac{q^2 n_i r^2}{4\epsilon k_B T_\perp \gamma^2}\right). \tag{3}$$

If the space-charge effect is not negligible, i.e. on the boundary of the plasma and vacuum, one has to solve Eq. (2) with a numerical method. It is well known that the results is given by the Maxwell-Boltzmann distribution [6]. Especially, when $T_\perp = 0$, the beam is laminar and the density profile is uniform inside the beam, that is

$$n(r) = \begin{cases} n_0 & \text{for } 0 \le r \le a_0 \\ 0 & \text{for } r \ge a_0, \end{cases} \tag{4}$$

where a_0 is the beam radius at zero temperature. $T_\perp \neq 0$ means that there are focusing force from outside of the electron beam. Inside the plasma, electrons struggle against the focusing force from the ion plasma and their $T_\perp$ is increased, so that the electron density distribution is given by a narrow Gaussian. After electrons are ejected from the plasma, electrons are spread out by the space-charge effect and their $T_\perp$ is cooled down. Eventually, the electron density distribution is changed to a wide Maxwell-Boltzmann distribution at $T_\perp \simeq 0$.

In addition, there are small and high energy electrons in the electron beam, simultaneously, so that the beam size of small energy electrons are bigger than that of high energy electrons. It should be mentioned that if the beam size increases two times, then the electron density decreases four times, because the electron number should be conserved. Thus, in the case of high energy electrons, the beam size is small but the electron density is high, and vice versa for small energy electrons. Note that if all electrons are integrated to the longitudinal direction, one can find that the high energy electrons are gathered in the small center area with a high density, and small energy electrons are scattered to outside with a low density. Under this condition, if a small aperture collimator is installed, just center electrons can pass the aperture and others cannot. By following this way, one can remove small energy electrons effectively, and a small energy spread electron beam will be obtained.

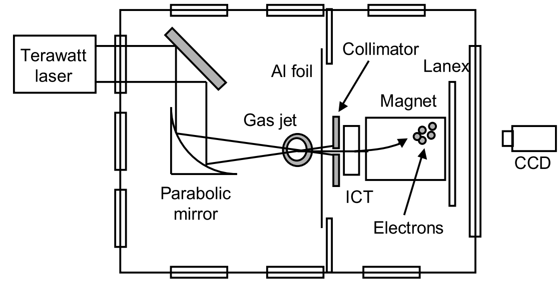

Figure 2: Experimental setup for the energy measurement. A 2 TW laser pulse is focused on the neutral gas to generate an electron beam. The electron beam passes through a collimator and comes to an ICT and a dipole magnet. After the dipole magnet, electrons hit a LANEX film and a scintillated image is taken by a CCD camera.

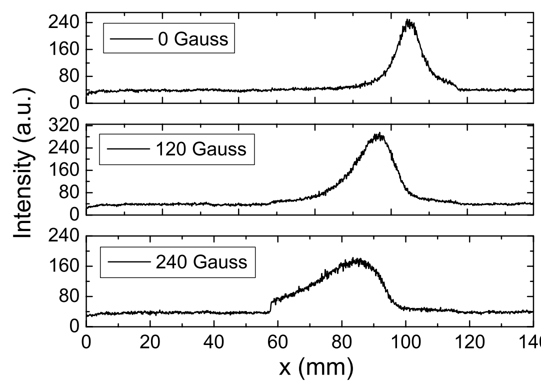

Figure 3: Electron density profiles under various magnetic fields. As the magnetic field increases, the electron trajectory is bent further. Note that the energy spread is not 100% but a small one.

EXPERIMENT RESULTS

An experimental scheme for the energy spread measurement is shown in Fig. 2. After the electron beam is generated from the laser and plasma interaction, it comes to the electron beam diagnostic system. First of all, an aluminum foil (16 μm) blocks the laser beam and removes thermal electrons from the plasma. After the foil, an 1 mm diameter Al collimator (5 mm thickness) is installed at 9 cm from the gas jet to remove small energy electrons. Next, an ICT and an electric dipole magnet are installed for the charge and the energy measurement of the electron beam. Finally, the electron beam hit the LANEX film and their scintillating image is taken by a 12 bit CCD camera behind the LANEX film.

First, the electron energy distribution is measured under various magnetic fields and their results are shown in Fig. 3. As the magnetic field increased, the electron density profile is shifted to the left. By measuring the shift of

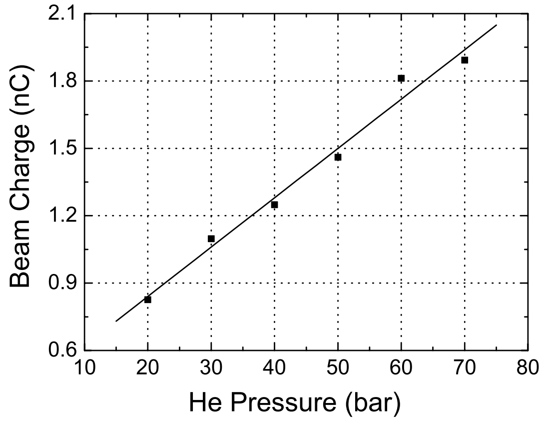

Figure 4: Total beam charge as a function of He gas pressure. The laser power is 1.4 TW.

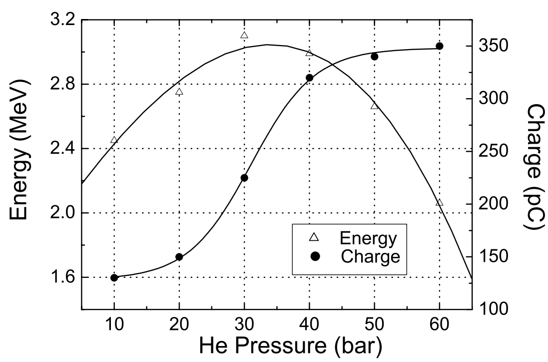

Figure 5: Measured energy and charge of the electron beam versus helium gas pressure. The electron beam energy reaches its maximum at 30 bar and decreases after that. On the other hand, the electron beam charge is saturated at the high pressure.

the maximum peak, the energy of the electron is calculated to 1.6 MeV. Note that, at 240 Gauss, the electron distribution is asymmetric and the large number of electron is bent lesser than the others. This means that the majority number of electrons have high energies and the energy spread is relatively small, comparing with 100% energy spread of other SM-LWFA cases. This result shows that one can remove small energy electrons effectively by using a small aperture collimator, and the energy spread can be controlled by changing the aperture size.

As a next experiment, we measured the charge of the electron beam under various gas pressures. First, the total charge of the whole electron beam is measured at various He pressure and the result is shown in Fig. 4. The result shows that the total beam charge is proportional to the gas pressure. Next, the same experiment is repeated with an 1 mm diameter collimator and the result is shown in Fig. 5. In addition to the beam charge, the energy of the electron beam is measured as well. Note that the charge is saturated after 50 bar. On the other hand, the energy of the electron beam shows a maximum value at 30 bar and decreases again after that. This result can be explained by the electron and wake wave detuning. In an one-dimensional cold plasma model, the maximum wave breaking electric field is given by $E_{max} = m_e\omega_p c/e$, so that the energy of the accelerated electron beam is increased when the density of the plasma is increased. At the same time, there is a limitation for the maximum energy of the electron beam because of the electron and wake wave detuning, and the dependence of the maximum energy gain is proportional to $1/n_e$ [2]. In short, at low gas pressures, the electron energy increases according to the gas pressure increase. However, after the optimum gas pressure, the electron inside the wake wave travels longer distance than the detuning length, and the electron energy begins to decrease. If the electron energy decreases, the beam size becomes bigger than the size at the maximum energy. Thus, even though the total charge of the whole electron beam is increased, the charge after the collimator will be saturated.

SUMMARY

In this study, we investigated a method to reduce the energy spread of the electron beam which is generated from a self-modulated laser wakefield accelerator. From a simple theory and a simulation, it is found that the electron density distribution is changed from a narrow Gaussian to a wide Maxwell-Boltzmann, as the electron beam is ejected from the plasma to vacuum. In addition, when the electron beam propagates in vacuum, small energy electrons are spread out faster than high energy electrons, and the density of small energy electrons are drop down as the beam size increases. Thus, if all electrons are integrated to the longitudinal direction, high energy electrons can be found in the center and small energy electrons can be observed from outside. From this electron dynamics, an experiment is designed to block the small energy part of the electron beam by using a collimator. The experiment result shows that the small energy electron is removed effectively, and the energy spread can be controlled with a simple collimator.

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