ENHANCEMENT OF THE ELECTRON ENERGY BY USING A LINEARLY TAPERED DENSITY IN THE LASER WAKEFIELD ACCELERATION

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Abstract

Due to the capability of making a compact accelerator and the ability to generate an ultra-short bunch electron beam, a laser wakefield acceleration (LWFA) is widely studied. In LWFA, a dephasing effect is the main limitation of the electron energy. To overcome the dephasing effect and increase the electron energy, we studied the linearly tapered density. Experimental results show that with linearly tapered density, we could increase the electron energy with the same laser power.

INTRODUCTION

By using an ultra high power femtosecond laser and plasma, it is possible to accelerate the electron to high energy in short distance, which is called a laser wakefield accelerator (LWFA) [1,2]. When the high intensity laser propagates inside the plasma, a plasma wakewave is generated due to the Ponderomotive force. Acceleration field generated by this wakewave, the electron can be accelerated. The acceleration field strength is almost thousand times higher than the conventional RF linac, a compact electron accelerator can be made. LWFA scheme also generate a femtosecond electron bunch due to the narrow acceleration region. Such short electron bunch can be used to time resolved x-ray probing experiment.

In LWFA, the acceleration length is limited due to the dephasing effect, which means that the electron accelerated high energy can go out from the acceleration phase to deceleration phase. The dephasing length is determined by the plasma density (dephasing length $\mu\ n_e^{-3/2}$). Due to this dephasing effect, the energy of the electron is determined by the electron density of the plasma. To overcome the limitation of the energy due to the dephasing, a tapered density as an acceleration medium is proposed. In which the plasma density increases along the laser propagation direction [3]. In this work, we studied the effect of the tapered density on the energy.

EFFECT OF THE TAPERED DENSITY

In LWFA, a plasma density is an important parameter, because the density determines the maximum acceleration field strength limited by the wavebreaking, given as $E_{\max}[\mathrm{V/m}] = 0.96\sqrt{n_e[\mathrm{cm}^{-3}]}$, and the dephasing length given as $L_d = l_p(w/w_p)^2$, where l_p the plasma wavelength, w laser frequency, and w_p the plasma frequency [4]. The maximum electron energy is determined by the plasma density because the electron energy can be estimated by the product of the field strength and the acceleration length.

If the plasma density increases along the laser propagation direction, the plasma wavelength decreases. The size of the acceleration region decreases due to the size of the plasma wavelength. The laser position is almost the same because the group velocity of the laser does not change much. The overall effect of the density increment is that the region of acceleration (acceleration phase) go ahead compared with the uniform density. Using this effect, the electron can be accelerated in longer distance. The acceleration field strength also increases along the laser propagation direction. Due to these effects, the electron can be accelerated higher energy by using a tapered density.

EXPERIMENT AND RESULTS

The effect of the linearly tapered density was studied by using a square nozzle and a high power femtosecond laser. To generate a linearly tapered density structure, a square shape nozzle was made. The measured gas density profile shows that the gas density linearly decreases along the normal direction of the nozzle. Simply tilting the nozzle, the gas density along the laser propagation direction increases linearly because the distance between the laser and the nozzle linearly decreases. The size of the nozzle out is 3 mm long and 1 mm wide. The gas density was controlled by the back pressure of the gas nozzle and the laser beam height from the nozzle.

Figure 1 shows the experimental setup. A 20 TW laser was used. The pulse duration of the laser was 40 fs which was measured by using a single shot autocorrelator before the experiment. For the experiment, the laser energy was 500 mJ. The laser beam was focused using on axis parabolic mirror with f/#=17.

The plasma density was measured by using a biprism interferometer for each laser shot. A small part of the laser beam was used for the interferometer. The frequency was converted to second harmonic frequency by using a BBO crystal. The delay between the laser pulse and the probe light was controlled by the optical delay line of the probe light. In the experiment the delay was set as the main pulse is at the edge of the nozzle.

A Lanex film was used to measure the electron beam position. The fluorescence light from the Lanex film was imaged on the ICCD camera. For the electron energy measurement, a permanent magnet was inserted between the Lanex and the nozzle. The magnetic field of the magnet was 1 T. After the magnet, an integrated current transformer (ICT) was used to measure the bunch charge.

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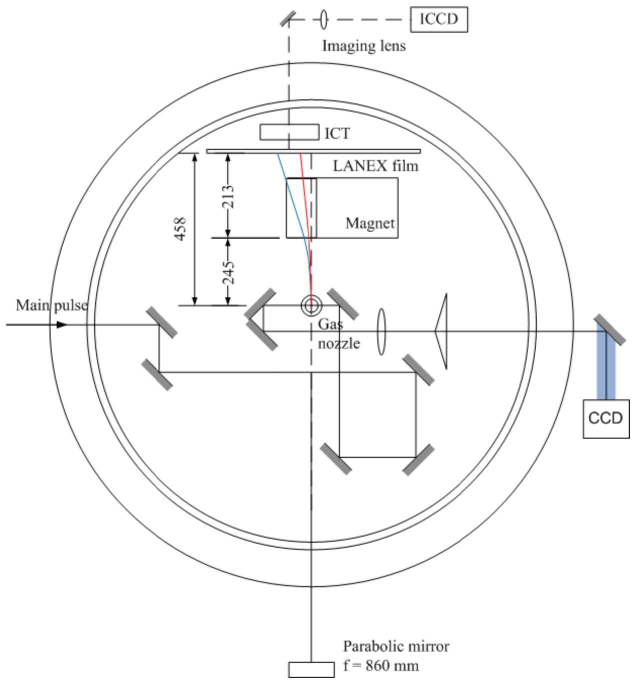

Figure 1: Experimental setup.

The measured electron beam position and the energy is shown in Fig. 2 with parallel and tilted nozzle geometry. In Fig. 2, a) and c) show the electron beam position without magnet. The laser position is at the zero of the coordinate. Circles with cross in Fig. 2 a) and c) show the position of the electron beam with the same experimental condition. The position of the beam center was calculated by the geometric center as

$$x_c = \int xI(x,y)\,dxdy \Big/ \int I(x,y)\,dxdy\,.$$

The distance between the Lanex and the nozzle was 460 mm. The pointing stability of the electron beam was with parallel nozzle was 16 mrad in horizontal direction and 7 mrad in vertical direction. With tilted nozzle, the pointing stability was 5 mrad in horizontal direction and 6.6 mrad in vertical direction.

Figure 2 b) and d) show the measured electron energy with parallel and tilted nozzle respectively. The laser position is also at the zero of the coordinate. The measured energy shows that with the same laser power, the electron energy increases by simply rotating the nozzle.

The measured electron density profiles for each case in Fig. 2 are shown in Fig. 3. With tilted nozzle, the plasma density increases by 10^{19} cm^{-3} in 1 mm. With parallel nozzle, the density increases due to the gas density change but the change of the density is only 4×10^{18} cm^{-3} in 1 mm. The tilted angle of the nozzle for this case is 25 degree. The measured plasma density shows that the density profile can be easily changed by the tilting angle of the nozzle.

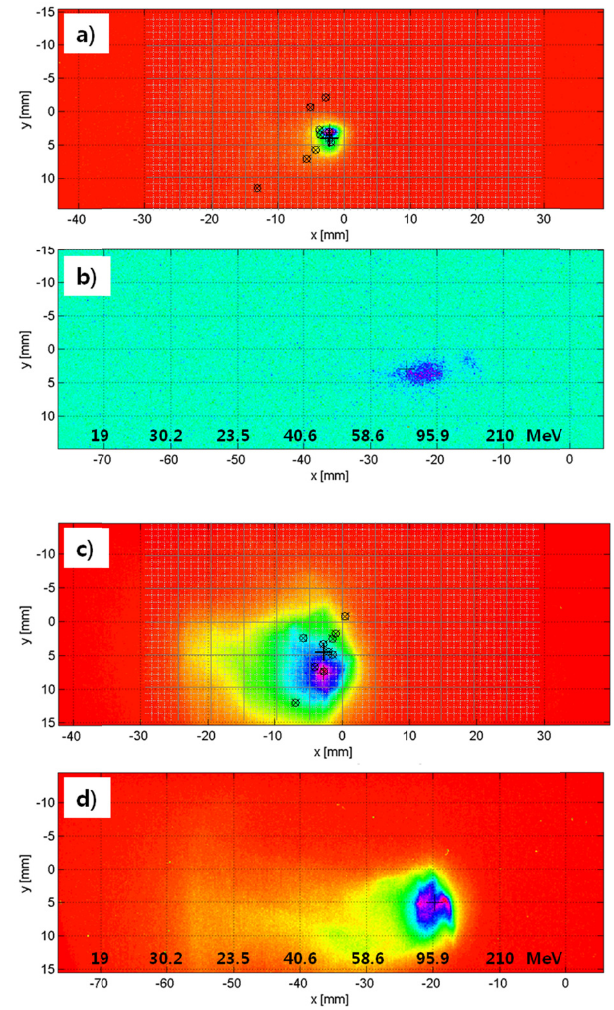

Figure 2: Electron beam position and energy. With parallel nozzle, Electron beam pointing and energy. a) and c) show the electron beam position with parallel and tilted nozzle respectively. b) and d) show the measured electron energy with parallel and tilted nozzle respectively. In a) and c), the circles with cross show the beam position with the same experimental condition.

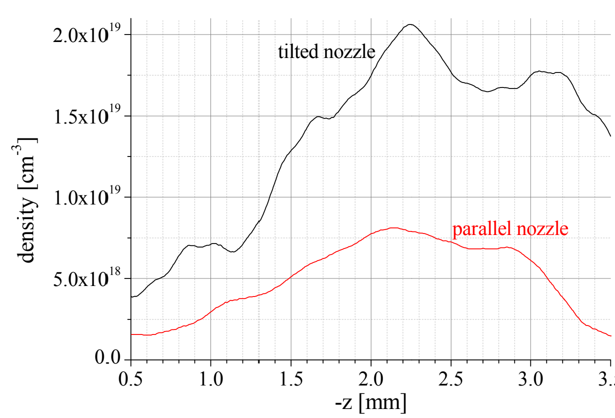

Figure 3: Cross section of the measured plasma density.

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Table 1: Summary of Data

	Parallel nozzle		Tilted nozzle	
	average	deviation	average	deviation
Charge [pC]	74.6	± 24	124	± 13
Density [10^{18} cm^{-3}]	7	± 0.8	19	± 1.3
Energy [MeV]	67	50 ~ 100	77	90 ~ 67
x_c [mm]	-4.5	± 3.3	-2.9	± 2.3
y_c [mm]	4.0	± 3.9	4.6	± 3.7

The back pressure was 30 bar for parallel nozzle and 50 bar for tilted nozzle. The low density with tilted nozzle was 5×10^{18} cm^{-3}, the back pressure for the parallel nozzle was reduced to compare the low density plasma.

For each condition, the beam position and the energy were measured in 10 consecutive shots. The overall results summarized in Table 1. The average value is the average over 10 experiments and the deviation means the standard deviation. In Table 1, the bunch charge was only measured with magnet which means that only high energy electron bunch was measured. The density value in Table 1 is the average value in 2 mm range. The bunch charge and the electron energy increase with tilted nozzle.

To simulate the plasma condition dependence on the electron energy, a two dimensional particle in cell code (XOOPIC) was used to simulate the density structure effect on the electron energy [6].

Two different density profiles were used. One is uniform plasma density where the density is 4×10^{19} cm^{-3} and the other is the linearly tapered density profile. For tapered density profile, the density increases by 10^{19} cm^{-3} in 1 mm. The electron energy in acceleration distance in shown in Fig. 4. With uniform density, the electron is accelerated in longer distance. With tapered density, the electron is accelerated shorter distance but the energy is higher than with the uniform density. As mentioned above, with linearly tapered plasma density, the acceleration field strength is higher than with uniform plasma density. So the electron can be accelerated in higher energy. The simulation and the experimental results show that with linearly tapered plasma density, the electron can be accelerated in higher energy with the same laser parameter.

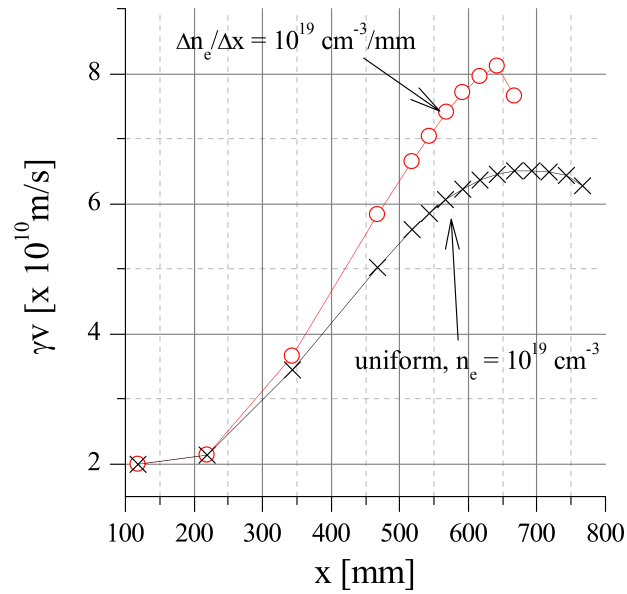

Figure 4: Electron energy in acceleration distance. (2D simulation results.) Open circle shows the electron energy with linearly tapered density and cross shows with parallel nozzle.

CONCLUSION

In conclusion, the effect of the linearly tapered density structures on the electron energy is studied. To generate the linearly tapered plasma density profile, the nozzle was simply tilted so the distance between the nozzle and the laser changes linearly along the laser propagation direction. The measured plasma density shows the linearly tapered density can be easily generated by this geometry. The experimental and simulation results agree that with linearly tapered density, the energy of the electron increases. The measured beam properties indicate that the electron energy can increase by using a linearly tapered density. The bunch charge also increases with the tapered density. A PIC results show that the electron can be accelerated higher energy with the tapered plasma density because of the higher acceleration field with the tapered density.

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