DENSITY TRANSITION MEASUREMENT FOR THE ELECTRON INJECTION IN LASER WAKEFIELD ACCELERATOR

Jaehoon Kim, Seung Hoon Yoo, and Jong Uk Kim, Korea Electrotechnology Research Institute, Ansan, 426170, Republic of Korea.

Abstract

The electron injection into the acceleration phase of the laser wakefield accelerator(LWFA) is the key issues for the stable operation of the LWFA. For the controlled electron injection, a sharp downward electron density transition is one candidate. When the laser pulse pass the sharp electron density transition, the electron from the high density region is injected into the acceleration phase. For this injection scheme, a very sharp electron density transition, the distance of the density change must be shorter than the plasma wavelength, is needed. A shock structure of plasma generated at the gas target is one candidate for such a sharp electron density transition structure. To find out the feasible condition of the density structure, the electron density was measured by an interferometer with different time. A 200 ps, 300 mJ laser was used to generated plasmas. A frequency doubled femto-second laser was used as a probe beam of the interferometer. The measured electron density structure which is compared with a 2D PIC simulation, indicates that the feasible condition can be generated 1.2 ns after the laser pulse. This electron density structure will be used for the laser wakefield acceleration experiments.

INTRODUCTION

When a ultra high power propagate through plasma, the electrons are expelled out from high laser intensity region due to the Ponderomotive force. The electron density structure generates the plasma wave which propagates with the laser pulse. If the laser pulse length is close to the plasma wavelength, the electron density structure can accelerate electrons known as plasma wakefield accelerator.[1] If the electron is injected at the acceleration phase, that electron will be accelerated at high energy in very short acceleration distance. The acceleration phase region in space is very narrow, the accelerated electron bunch is very short, shorter than the plasma wavelength. By this laser wakefield acceleration, we can generate a femtosecond electron bunch. The x-ray pulse duration from this short electron bunch is also a few femtoseconds [2] which can be used as high time resolution material probing.

To generate a ultra short and mono energetic stable electron beam, the electron must be injected at the acceleration phase of the plasma wakefield especially at the first wakewave cavity. The main issue of the plasma wakefield acceleration is the injection scheme. Many injection schemes were proposed. One of the injection schemes is using a sharp electron density transition [3]. In this scheme, the wakewave passes through very sharp downward electron density transition structure. At the density transition position, the electron at the high density region is injected to the acceleration phase of the wakewave. For this scheme, a very sharp electron density transition, density change length less than the plasma wavelength, structure is needed.

A feasible candidate to generate such a sharp density transition is using a shock structure of plasma channel[4, 5]. There can be a very sharp electron density transition at outsize wall of the plasma channel because of the shock structure generated at boundary between plasma and the neutral gas. The peak electron density at the boundary is higher than the inside because the electron is piled at the boundary. After ionization of the residual neutral gas, we can get the sharp downward electron density transition at the plasma channel boundary.

The density transition length of the plasma channel is finite. The actual scale length must be measured and the effect of the finite scale length must be studied. In this work, the effect of the finite transition scale length is studied by a one-dimensional particle in cell code, and the electron density structure of the plasma channel was studied with an interferometer. The time evolution of the electron density transition scale length was measured.

DENSITY TRANSITION CONDITION FOR THE ELECTRON TRAPPING

When the plasma wakefield passes the region of the electron density transition, the electron at the higher density region is injected into the acceleration phase of the wakefield. The previous calculation indicates that the physical dimension of the electron density change must be shorter than the plasma wavelength[6,7]. If the density change length is longer than the plasma wavelength, there is no effect of the density transition.

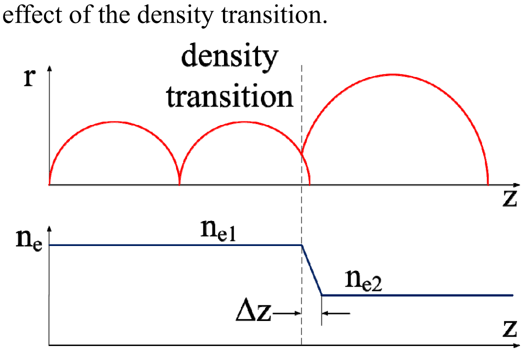

Figure 1:. Schematic diagram of the electron injection using density transition.

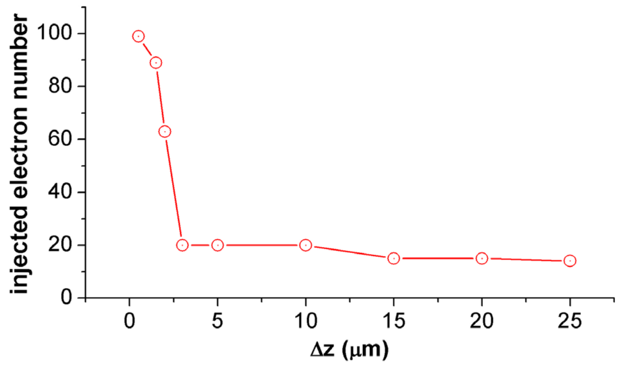

Figure 2: Injected electron number with different scale length. Unit of the electron number is arbitrary.

The effect of the density transition length on the electron injection is studied using 1D particle in cell simulation code, XOOPIC[7]. The electron density at high electron density region is 2×10^{19} cm^{-3} and the low density region is 1×10^{19} cm^{-3}. The laser power is 1.25×10^{19} W/cm^2.

Figure 2 shows the calculated number of the injected electrons with different transition length. The number of injected electron decreases abruptly if the transition length is longer than 2 μm. If the transition length is longer than 2.5 μm, the electron injection by the density transition is not effective. For this electron density range, the density transition length must be shorter than 2 μm. the electron density in this region, the density

GENERATION OF DENSITY TRANSITION USING PLASMA SHOCK

To realize the sharp density transition structure, a plasma shock structure was measured. A high power Ti:sapphire laser was used for the experiments. The output power of the system is 20 TW. The laser system consists of an oscillator, a stretcher, a regenerative amplifier, a multi pass amplifier, and vacuum compressor. The laser system uses chirp pulse amplification (CPA). The oscillator generates 20 fs, 5 nJ pulse at 80 MHz. This pulse is stretched to 200 ps by the stretcher. The low energy laser pulse is amplified by a regenerative amplifier up to 1.5 mJ and than amplified up to 1.2 J by a 4-pass main amplifier. After the multi-pass amplifier, the laser beam split in two parts by a beam splitter with 40 % transmission as shown in Fig. 3. The low energy beam, pre-pulse, is used to generate plasma. The high energy beam is compressed to 40 fs pulses. A small fraction of the compressed pulse was converted to second harmonic frequency by a BBO crystal and used as a probe beam for the interferometer. The time delay was measured the gas nozzle position. The evolution of the plasma shock structure was measured by changing the optical delay of the pre-pulse. Figure 3 shows the schematic diagram of the experiment.

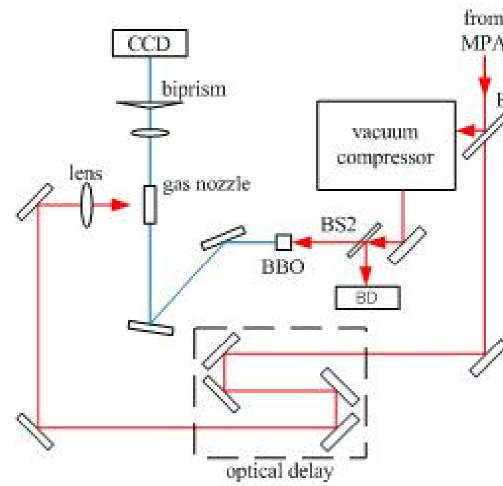

Figure 3: Schematic diagram of the experiment.

A biprism interferometer is used to measure the electron density of the plasma. The interferometer consists of an imaging lens, a biprism, and a CCD camera. The apex angle of the biprism is 178º. The magnification of the imaging lens is 6. The phase due to the plasma was recovered by Fourier transform method from the measured interferogram. An Abel inversion was applied to measure the electron density structure.

The time delay between the pre-pulse and the probe pulse is adjusted by the optical delay of the pre-pulse from 0.5 ns to 2.5 ns.

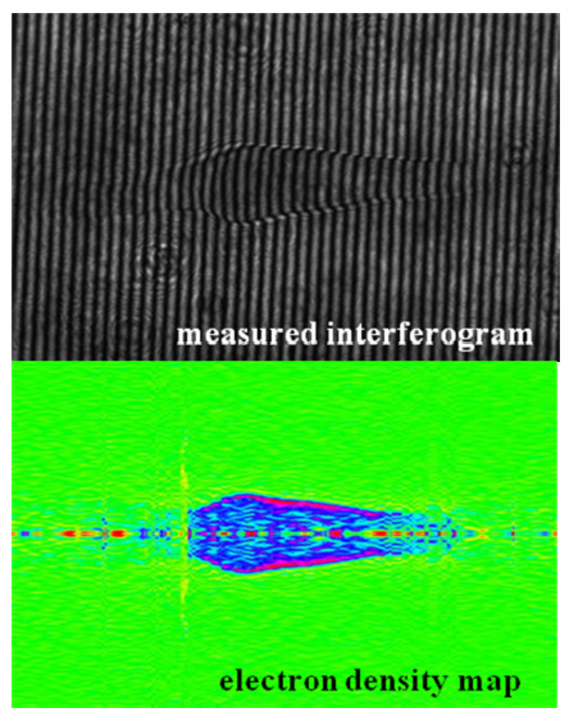

Figure 4: Electron density structure. Upper panel shows the measured interferogram and lower panel shows density map. Laser direction is from right to left.

The pre-pulse is focused on the center of gas nozzle by a lens with focal length 300 mm. The nozzle size is 4 mm long and 1 mm wide. The pre-pulse direction is along the short nozzle side. The neutral gas density is controlled by the back pressure of the gas nozzle and measured using an interferometer before the experiment. For this experiment, helium gas was used.

Figure 4 shows the measured electron density. The upper panel shows the measured interferogram and the lower panel is recovered density map. A fast Fourier transform method was used to reconstruct the phase map. Using this phase structure from the interferogram, the density structure was recovered by an Abel inversion.

Figure 5 shows the cross section of the electron density along vertical direction in Fig. 4 measured with different time delay. The density transition length is very short just after the laser pulse. The electron density structure is almost flat top shape because He is fully ionized by the pre-pulse. After laser pulse, the plasma expands into neutral gas. At the boundary of the plasma and neutral gas, a strong shock structure is generated. Electrons are piled at the boundary of the plasma and channel structure is generated as shown in Fig. 5 at time delay 1.2 ns. The electron which was inside the plasma channel was piled at the boundary, the peak electron density was also increased. At the boundary, the helium atom is ionized by the plasma electron and the radiation from the plasma. The electrons in the plasma also diffuse into the gas medium. The density change scale length becomes longer. Long after the laser pulse as 1.0 ns, the peak electron density start decreasing.

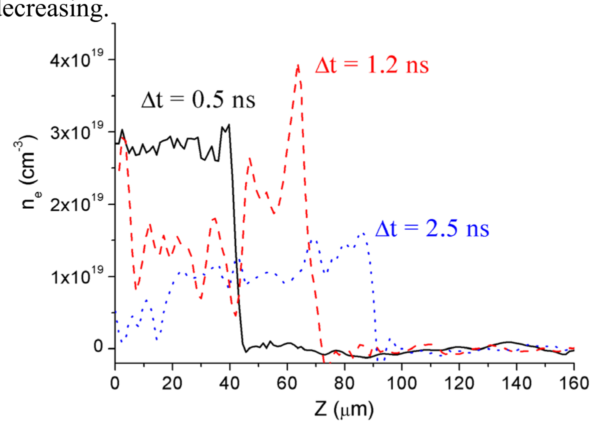

Figure 5: Cross sectional view of the density transition structure at the different time.

Figure 6 shows the peak electron density at the boundary between the plasma and the neutral gas and the density transition length. The peak electron density was slightly increased early in time after that the peak intensity was decreased. For the electron trapping condition, the peak density must be higher than the uniform plasma density. The neutral helium gas density is 1.5×10^{19} cm^{-3}, the plasma density is 3×10^{19} cm^{-3}. The peak intensity must be higher than this density. As in Fig 6, the channel density satisfies this condition only early in time. From the measured data, the feasible time delay between pre- and main- pulse is 1.2 ns.

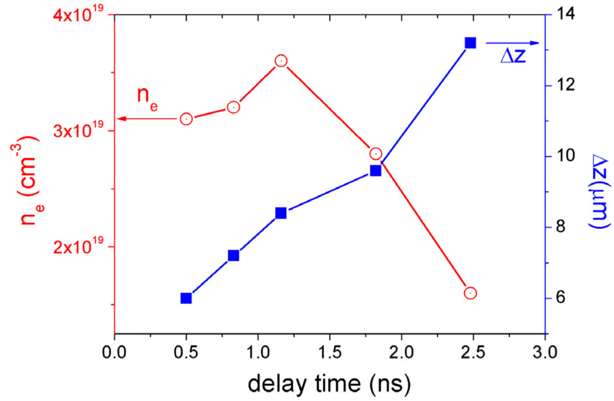

Figure 6: The measured density structure at different time. Open circle show the peak density at the boundary of the plasma. Closed square line shows the density transition length.

CONCLUSION

The effect of the density transition length to the electron injection process is investigated using one-dimensional PIC code. The simulation results indicate that the transition length must be less than 2 μm for the electron injection. To generate such a sharp density transition structure, a plasma shock structure was investigated. The time evolution of the shock structure indicates the feasible condition for the density transition electron injection scheme was generated 1.2 ns after the laser pulse. This results will be used for the laser wakefield accelerator with density transition trapping.

REFERENCES

[1] T. Tajima and J. M. Dawson, "Laser wakefield acc", Phys. Rev. Lett. 43, 267 (1979).

[2] P. Catravas, E. Esarey, and W. P. Leemans, "Short bunch length electron x-ray", Meas. Sci. Technol. 12, 1828 (2001).

[3] H. Suk, N. Barov, and J. B. Rosenzweig, Phys. Rev. Lett. 86, 1011 (2001).

[4] J. U. Kim, N. Hafz, and H. Suk, Phys. Rev. E 69, 026409 (2004).

[5] J. Kim, et al, J. Kor. Phys. Soc. 51, 397 (2007).

[6] H. Suk, H. J. Lee, and I. S. Ko, J. Opt. Soc. Am. B, 21, 1391 (2004).

[7] S. H. Yoo, J. Kim, J. U. Kim, M. S. Hur, and S. J. Hahn, Jpn. J. Appl. Phys., 48, 016002(2009)