FEASIBILITY STUDY OF A LASER-DRIVEN HIGH ENERGY ELECTRON ACCELERATION IN A LONG UP-RAMP DENSITY

Minseok Kim, Seungwoo Lee, Jinju Kim, Inhyuk Nam*, Hyyong Suk†, GIST, Gwangju, Korea

Abstract

The density-tapered plasmas have been considered as a key source to overcome the dephasing problem, which is a very important energy saturation mechanism in laser wakefield acceleration (LWFA). In the most researches, the tapered plasma density is used after electron injection, but when no electron trapping happens, it may also support the high energy electron generation. For this purpose, we suggest a gas cell with long density gradient, which can be easily controlled by sending the gas with different pressures at two inlets. Therefore, by means of computational fluid dynamics (CFD) simulation, we confirmed that the long density-tapering can be created with the use of different backing pressures at each inlet, and we demonstrated the long up-ramp density gas cell increases the electron energies compared to the untapered density one in 2D particle-in-cell (PIC) simulation.

INTRODUCTION

Laser-driven wakefield acceleration (LWFA) can produce high energy electrons of an order of 1 GeV in cm-scale distance [1–4] and it has an enormous potential for applications such as table-top advanced accelerators, X-ray sources, etc [5, 6]. For this purpose, several types of plasma sources have been used, including supersonic gas jets, gas cells, and discharged capillaries. Supersonic gas jets are simple an easy to use, but generally they can not produce a stable and uniform density along the laser propagation direction. Compared with the supersonic gas jets, gas cells are known to be able to produce more stable and uniform gas density, which will result in more stable and uniform plasma density by an intense laser beam propagating in the gas. Therefore, gas cells are an important plasma source for laser wakefield acceleration and they have been used for numerous experiments so far. As far as we know, however, all gas cells were designed to have a uniform gas density along the laser propagation direction. In this case, the dephasing problem is inevitable and the accelerated energy is limited. This kind of dephasing problem is severe as the dephasing length is calculated to be a couple of centimeters for typical experimental parameters in LWFA. Hence, it will be much better if the dephasing problem can be avoided somehow.

In order to overcome the dephasing problem, the phase locking concept was proposed for LWFA and it can be realized by upward density tapering [7, 8]. Actually in recent years a couple of discharge-based capillary plasma sources were developed for this purpose [9, 10]. However, the most researches have focused on the density tapering effect after the electron injection. Since the density profile increased from the beginning can be generated rather in practice, the up-ramp density effect before the electron trapping is needed to study. For this purpose, we suggest a capillary gas cell with long density tapering. By sending the gas with different pressures at two inlets, the density gradient inside the gas cell can be easily formed and controlled. In this paper, we investigated the generation of gas density tapering over long distance by using three-dimensional (3D) CFD (computational fluid dynamics) simulation, and two-dimensional (2D) PIC (particle-in-cell) simulation was performed to confirm that such long up-ramp density can increase the electron energies.

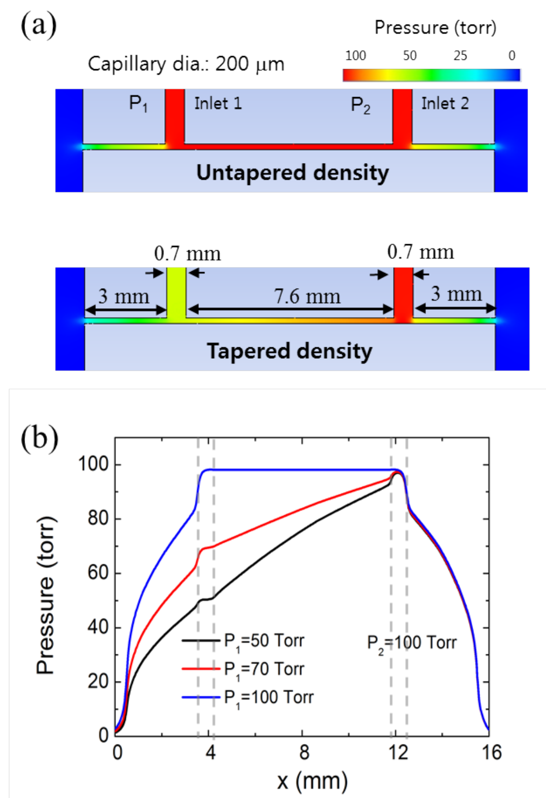

Figure 1: (a) Pressure distribution of a capillary depending on backing pressures at both inlets. When the different pressures are injected through each inlet, the density gradient is produced inside the capillary. (see lower figure) (b) The lineouts along the capillary axis with different P1 under the backing pressure of P2 = 100 Torr. The two dash lines indicate inlet positions.

* present address: SLAC National Accelerator Laboratory, Menlo Park, California, USA

† hysuk@gist.ac.kr

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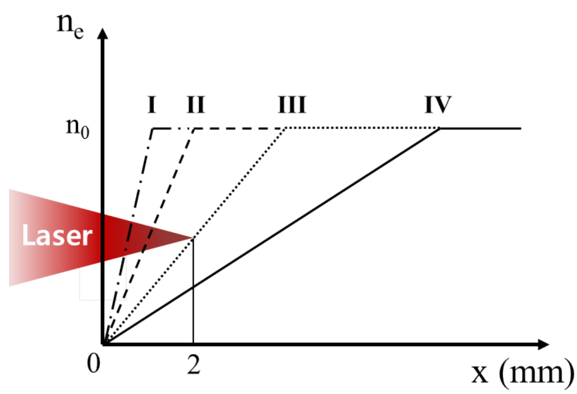

Figure 2: Schematic of the tapered plasma density profile for PIC simulation. Focal point of the laser pulse is fixed at x=2 mm and the up-ramp density distance d_R varies from 1 to 7 mm (I: $d_R = 1$ mm, II: $d_R = 2$ mm, III: $d_R = 4$ mm, IV: $d_R = 7$ mm).

CFD SIMULATIONS

We proposed a simple way to control the gas pressure gradient by injecting gas of different pressures at each of two inlets. In order to confirm the feasibility of controlling the gas pressure gradient between two inlets, we carried out 3D CFD simulations which is based on Navier-Stokes equations. The simulation is based on the standard $k - \epsilon$ turbulence model solved by the implicit density-based solver, and the fluid is regarded as an ideal gas (hydrogen) allowing for compressible flow. The gas species may affect the transient results in time, but in steady state we have to consider, there is no big difference. As shown in Fig. 1(a), the neutral gas is injected into the capillary through two inlets and the capillary is located in vacuum. To produce the pressure difference for smooth gas flow, the additional boxes of $3 \times 3 \times 3$ mm are added at both ends of the capillary as the outlets, which has a pressure of 1×10^{-4} Torr.

In this simulation, the gas pressure at inlet 2 is fixed to 100 Torr and the pressure at inlet 1 is changed from 50 to 100 Torr. The capillary hole diameter is 0.2 mm, and the inlet width and depth are 0.7 mm and 0.35 mm, respectively. The simulation result in Fig. 1(b) indicates that the gas density inside the capillary has a density gradient along the capillary axis and can be controlled by varying the gas pressures at each inlet. Furthermore, it is noticeable that there is the rather long density gradient from the capillary entrance (left outlet in Fig. 1(a)) to the intersection of capillary and inlet 2. Thus, the gas density is increased from the capillary entrance, and the gradient is related to the inlet 2 position and pressure. Such long up-ramp density may be used to optimize the condition of electron acceleration with tapered density profile.

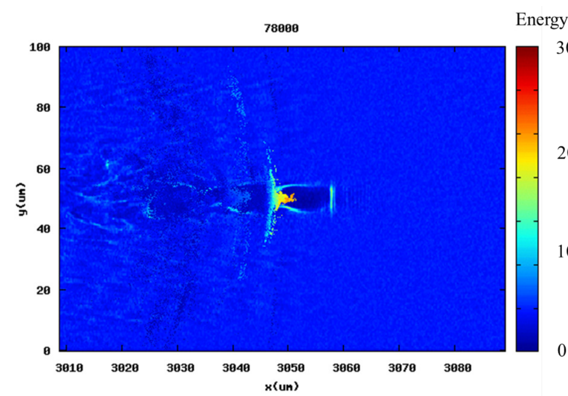

Figure 3: Electron bunch accelerated to high energy (~300 MeV) by a tapered plasma density profile.

2D PIC SIMULATIONS

Since the feasibility on the electron energy enhancement by tapered density have been established by many groups, the proposed capillary gas cell is clearly able to act as a plasma source to overcome the dephasing problem. Thus, the 2D PIC simulation was performed to investigate the effect of density gradient when the maximum density n_0 is constant. Figure 2 illustrates the schematic of the tapered plasma density profile for simulation. For simulations, we used a laser pulse with normalized vector potential $a_0 = 1.3$, focal spot size ω_0 (FWHM) = 20 μm, and central wavelength $\lambda_0 = 0.8$ μm. The laser is focused on $x = 2$ mm, while the up-ramp density distance d_R, which is defined by the distance from $n_e = 0$ to $n_e = n_0$ reaching at first, varies 1 to 7 mm. The window size is 80×100 μm, which has grid size $dx = \lambda_0/20$, $dy = \lambda_0/2$ and the number of particles, $N_p = 16$ per cell (super macro particles: 2.5×10^9) were used. In this PIC simulation, although the laser and plasma parameters are not matched with resonant condition in the bubble regime ($c\tau \sim \lambda/2$), the laser pulse length shrinks to the plasma wavelength without any laser power loss during the propagation through the plasma column. It can be described by the forced laser wakefield acceleration regime (F-LWFA), which occurs by combination of self-phase modulation, front Raman scattering instability, and so on [11]. Thus, the electron is self-injected and accelerated in the plasma with rather long laser pulse.

In the range of less than 1 mm ramp distance, no difference of electron energy was found because electrons are trapped in the bubble after d_R and the trapped electrons propagate through the uniform plasma density. When d_R is larger than 2 mm, the electrons are self-injected before $n_e = n_0$ and experience higher accelerating field due to the up-ramp density profile, so that high energy electron beams were generated (see Fig. 3). The energy increase rate is much higher as the plasma density is high as shown in Fig. 4(b), but the peak energy with same ramp distance is still larger under low plasma density than high density. This energy enhancement can be explained by increased dephasing length as in Fig. 4(a). Although the trapping time of electrons into

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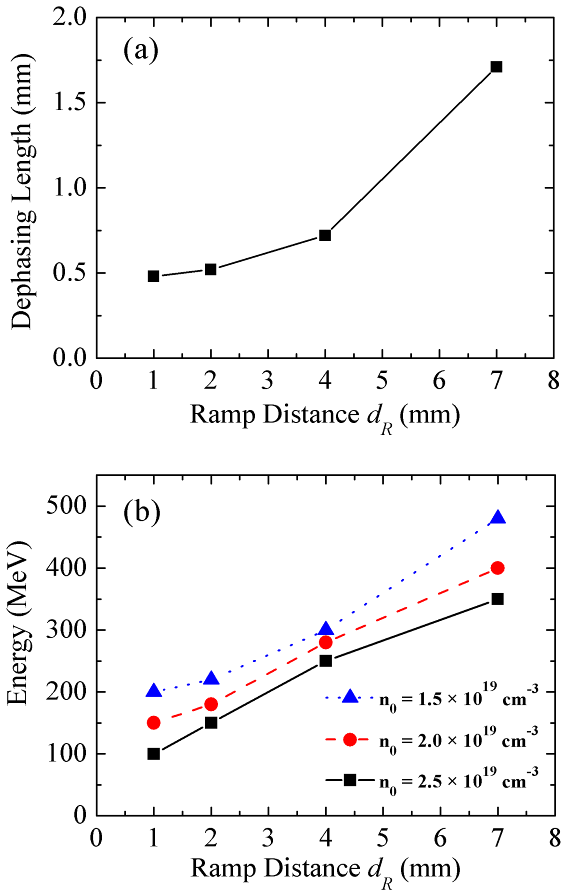

Figure 4: (a) The dephasing length depending on the ramp distance d_R (b) PIC simulation results with peak energy as a function of ramp distance for $n_0 = 1.5 \times 10^{19} cm^{-3}$, $n_0 = 2 \times 10^{19} cm^{-3}$, and $n_0 = 2.5 \times 10^{19} cm^{-3}$.

the bubble is delayed as d_R is large, the dephasing length is extended and it can support the electron acceleration to high energy.

SUMMARY

In conclusion, a new capillary gas cell with tapered density has been presented by using a CFD simulation code. The density gradient can be obtained and controlled by varying the pressures at two inlets. In addition, the CFD simulation results showed a long up-ramp density profile is formed from the entrance of the gas cell to the second inlet. From PIC simulations, we demonstrated that this long density tapering can be used to increase the electron energy. These results indicate the proposed capillary gas cell can support the electron acceleration to high energy in high density range.

REFERENCES

[1] W. P. Leemans *et al.*, "GeV electron beams from a centimetre-scale accelerator", *Nat. Phys.*, vol. 2, no. 10, pp. 696-699, 2006.

[2] C. E. Clayton *et al.*, "Self-Guided Laser Wakefield Acceleration beyond 1 GeV Using Ionization-Induced Injection", *Phys. Rev. Lett.*, vol. 105, no. 10, p. 105003, 2010.

[3] X. Wang *et al.*, "Quasi-monoenergetic laser-plasma acceleration of electrons to 2 GeV", *Nat. Commun.*, vol. 4, no. 1988, 2013.

[4] N. A. M. Hafz *et al.*, "Stable generation of GeV-class electron beams from self-guided laser-plasma channels", *Nat. Photonics*, vol. 2, no. 9, pp. 571-577, 2008.

[5] K. Nakajima, "Compact X-ray sources: Towards a table-top free-electron laser", *Nat. Phys.*, vol. 4, no. 2, pp. 92-93, 2008.

[6] M. Kando *et al.*, "Electron acceleration by a nonlinear wakefield generated by ultrashort (23-fs) high-peak-power laser pulses in plasma", *Phys. Rev. E*, vol. 71, no. 1, p. 015403, 2005.

[7] T. Katsouleas, "Physical mechanisms in the plasma wakefield accelerator", *Phys. Rev. A*, vol. 33, no. 3, p. 2056, 1986.

[8] S. V. Bulanov *et al.*, "Physical mechanisms in the plasma wake-field accelerator", *Plasma Phys. Rep.*, vol. 23, no. 4, pp. 259-269, 1997.

[9] D. Kaganovich *et al.*, "Variable profile capillary discharge for improved phase matching in a laser wakefield accelerator", *Appl. Phys. Lett.*, vol. 75, no. 6, pp. 772-774, 1999.

[10] S. Abuazoum *et al.*, "Linearly tapered discharge capillary waveguides as a medium for a laser plasma wakefield accelerator", *Appl. Phys. Lett.*, vol. 100, no. 1, p. 014106, 2012.

[11] Z. Najmudin *et al.*, "Self-modulated wakefield and forced laser wakefield acceleration of electrons", *Phys. Plasmas*, vol. 10, no. 5, pp. 2071-2077, 2003.