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Abstract. We propose a new approach to avoid dephasing limitation of laser wakefield acceleration by manipulating the group velocity of the driving pulse using clustered plasmas. We demonstrated the control of phase velocity in clustered plasmas by third harmonic generation and frequency domain interferometry experiments. The results agree with a numerical model. Based on this model, the group velocity of the driving pulse in clustered plasmas was calculated and the result shows the group velocity can approach the speed of light *c* in clustered plasmas.

Keywords: dephasing length, group velocity, clustered plasma
PACS: 52.38.Kd, 41.75.Jv, 36.40.Gk, 36.40.Vz

INTRODUCTION

Table-top laser-driven wakefield accelerators can now produce quasi-monoenergetic electrons bunches with energy up to 1 GeV [1], offering excellent candidates for the next generation of high-energy accelerators. Higher energy gain demands longer acceleration length, which is limited by the Rayleigh length and dephasing length. Preformed plasma channel can guide the laser pulse to increase acceleration length up to the dephasing length L_d, above which the accelerated electrons outrun the plasma wave and slip into deceleration region. To increase dephasing length further in conventional plasmas requires decreasing plasma density below 10^{18} cm^{-3}, where plasma channels become difficult to form.

The limitation of the dephasing was shown theoretically to be relaxed by a proper plasma gradient [2] and a layered profile of the plasma density [3]. However, these methods bring engineering challenge and are difficult to implement. In addition, since the electrons become ultrarelativistic relatively easily, the phase velocity of the wake needs to approach the speed of light in vacuum *c* to achieve acceleration without dephasing, which can't be resolved by above methods. Here we propose a new approach to avoid dephasing limitation of laser wakefield acceleration by manipulating the group velocity of the driving pulse using clustered plasmas.

Intense laser interactions with clustered plasmas generate high-energy electrons and ions as well as X-rays. The quasi-free electrons in the clustered plasma give rise to unique optical properties [4]. After a pump pulse ionizes an atomic cluster, it becomes a bound nano-plasma, begins expanding, and contributes positively to the refractive index, eventually reaching a Mie resonance. However, real cluster targets are a mixture of clusters and monomers. The monomer plasma contributes negatively to the refractive index immediately after the pump pulse. By adjusting cluster mass fraction

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f_c and choosing appropriate delay Δt, we can control phase and group velocity in clustered plasmas.

Here we demonstrated phase velocity control of a delayed driving pulse through fs-time-resolved third harmonic generation (THG) [5] and frequency domain interferometry (FDI) experiments. A modified uniformly expanding cluster model [6] was used and compared with our experiment results. Based on this model, the group velocity of driving pulse in clustered plasma was calculated and the result shows the group velocity of the driving pulse can approach the speed of the light in vacuum c in clustered plasma.

PHASE VELOCITY IN CLUSTERED PLASMA: EXPERIMENT

Experiments were performed on an 800 nm, 10 Hz Ti:sapphire laser system. For THG experiment, illustrated in Figure 1a, 100 fs pulses were split into pump and probe beams. Pump pulses were frequency doubled (100 fs, 400 nm). Peak pump intensity was maintained at 10^{15} W/cm^2, while the probe intensity was varied over a range by a λ/2 plate and thin polarizer. A translation stage controlled pump-probe delay. The pump and probe intersected at a small angle (~2°) to separate FWM from THG. Clusters were formed in a room temperature pulsed supersonic gas jet (750 μm orifice, 11° half expansion angle) backed with 600 psi argon. For FDI experiment, illustrated in Figure 1b, the 400 nm pump intensity was maintained at 4×10^{15} W/cm^2 with beam diameter (1/e^2) of 40 μm. A Michelson interferometer was placed in the 800 nm arm to generate co-propagating probe and references at fixed temporal separation 1.6 ps. The probe and reference pulses were collinear with the pump and were focused onto the pumped region of the jet with beam diameter around 150 μm.

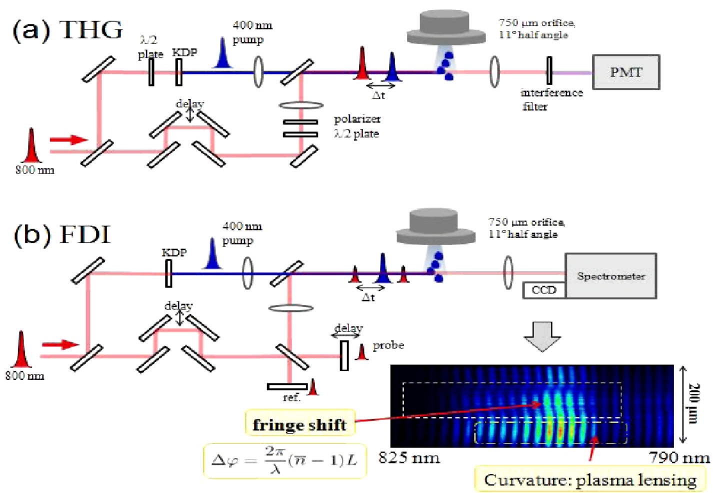

FIGURE 1. (a) Experimental schematic of THG experiment. (b) Experimental schematic of FDI experiment.

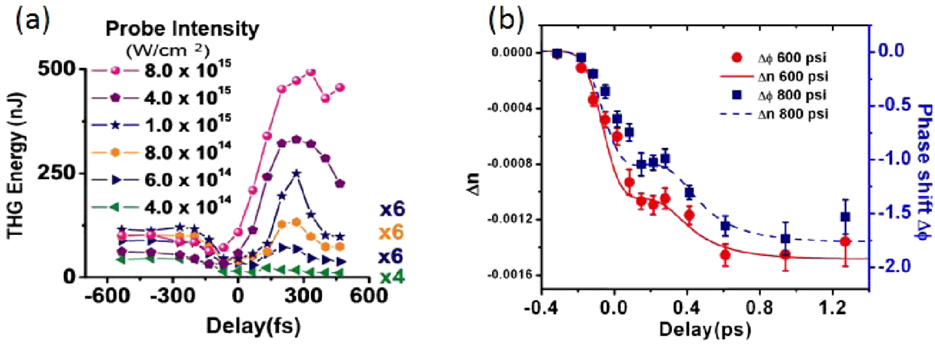

FIGURE 2. (a)THG from the probe vs Δt, for various probe intensity. (b) Time evolution of the phase shift and refractive index with theoretical fit.

Figure 2a illustrates results of third-harmonic generation (THG) by an 800 nm probe pulse polarized parallel to the pump, as a function of pump-probe delay Δt. For $I_{\text{probe}} > 10^{15}$ W/cm^2 a sharp enhancement at $\Delta t \sim 300$ fs is observed. This enhancement is attributed to the resonantly-enhanced $\chi^{(3)}$ and increase of the coherence length due to partial recovery of the refractive index as the clustered nano-plasmas expand.

FDI measurement gives the direct measurement of the fs-time-resolved refractive index of the target. As shown in Figure 2b, we observed a decrease in index from $n = 1$ to $n \approx 0.999$ at $\Delta t \sim 0$, immediately after the ionizing/heating pulse forms a monomer plasma. At $\Delta t \approx 300$ fs, however, we observed a transient recovery of n back toward unity, as clusters expand to a Mie resonance condition. The continuing drop is followed after the resonance as clustered plasmas are disassembling into monomer plasma.

The effects shown above strengthen with increasing cluster fraction. For the measurements shown above, monomers evidently dominated the cluster target. In fact we determined cluster mass fraction f_c from the FDI measurement. The essence of our method is that the negative index contribution of monomer plasma appears immediately after ionization by the pump, whereas the positive contribution of clustered plasma becomes significant only after clusters expand to a Mie resonance condition, enabling separation of monomer and cluster densities in the time domain, as shown in Fig 2b. We adopted a modified uniformly expanding cluster model [6] in the theoretical fit. This model starts failing as the density within the cluster falls below the critical density and the cluster starts to disassemble. As a remedy, we introduced an empirical exponential decay factor $\exp(-t(t-t_0)/\tau)$ into the modeled n_c, with $t_0 \approx 300$ fs and $\tau \approx 200$ fs. By fitting measured n_{total} (t) to this model, we find:

$$f_c = 0.25 \pm 0.03 \text{ at 600 psi,}$$

$$f_c = 0.35 \pm 0.04 \text{ at 800 psi.}$$

Higher cluster mass fraction will be critical to complete recovery of refractive index to unity and make the group velocity approach c as we will discuss later.

GROUP VELOCITY IN CLUSTERED PLASMA: CALCULATION

In the uniform density model, the dielectric constant inside the cluster is given by

$$\varepsilon_c = 1 - \frac{\omega_{p,c}^2}{\omega^2(1 + i\nu/\omega)}. \tag{1}$$

The collision frequency ν and ion mass are empirically modified to fit temporal evolution of cluster polarizability. The modified collision frequency is chosen as $\nu/\omega = 15/T_e^{1/4}$. The polarizability of the clustered plasma is

$$\gamma_{probe} = \frac{\varepsilon_c - 1}{\varepsilon_c + 2} R^3. \tag{2}$$

The refractive index n_{ph} is given by

$$n_{ph} = 1 + 2\pi n_c \,\mathrm{Re}(\gamma_{probe}) - \frac{\omega_{p,m}^2}{2\omega^2}. \tag{3}$$

The group index can be written as

$$n_g = n_{ph} + \omega \frac{\mathrm{d}n_{ph}}{\mathrm{d}\omega} = n_{ph} + 2\pi n_c \,\mathrm{Re}\{\frac{6R^3\omega_{p,c}^2}{(\varepsilon_c + 2)^2 \omega^2 (1 + i15/T_e^{1/4})}\} + \frac{\omega_{p,m}^2}{\omega^2}, \tag{4}$$

from which we calculated group velocity.

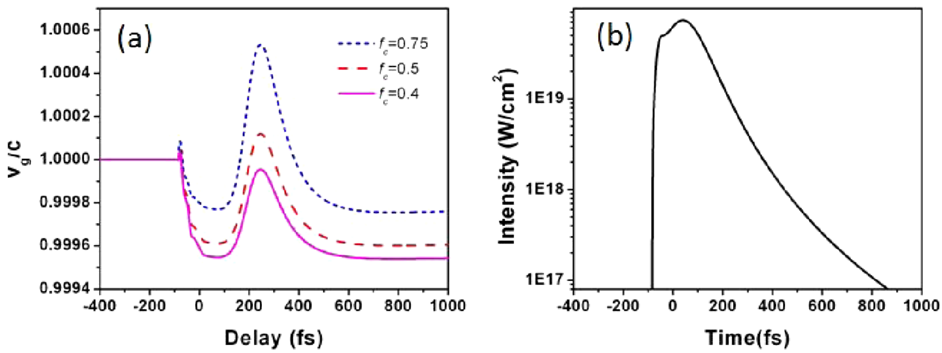

FIGURE 3. (a)Time evolution of the group velocity for various f_c. (b) The maximum probe intensity that can be applied without removing all the electrons.

Figure 3a shows the time evolution of the group velocity of a driving pulse in the clustered plasmas for various cluster fraction f_c with a pump intensity $I_{pump}=10^{15}$ W/cm^2. Group and phase velocity behave similarly. The group velocity reaches a peak at Mie resonance and approaches c with cluster fraction $f_c \sim 0.5$. Figure 3a also shows v_g becomes larger than c at resonance. This doesn't violate the ideas of special relativity. The definition of the group velocity has to be modified near an absorption line, because pulse reshaping occurs [7]. The clustered plasma can withstand a driving pulse up to relativistic intensity. As shown in Figure 3b, the peak intensity to strip all the electrons out of the clusters exceeds 10^{19} W/cm^2.

In addition to controlling the refractive index, clusters also provide a source of self-injected electrons. It has been reported [8] that relativistic electrons up to 58 MeV were generated as the electrons expelled from the clusters are injected and gain their energy by direct laser acceleration, although this result was achieved without cluster pre-expansion and index manipulation.

CONCLUSION

In this study, we have demonstrated control of the phase velocity of the driving pulse in clustered plasmas by choosing the delay and the jet parameters. We have calculated the group velocity dynamics based on a simple model which has yielded the phase velocity correctly. The simulation shows the group velocity would approach c at a moderate cluster fraction $f_c \sim 0.5$. Once the group velocity approaches c, we can increase the dephasing length greatly and even completely remove dephasing limitation of laser wakefield acceleration. Clusters also provide an effective source of injected electrons. These two advantages combined make clustered plasma an attractive candidate for laser-driven acceleration.

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