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Influence of atomic species on laser pulse propagation in underdense plasmas

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ABSTRACT

A 65 fs, intense ($\sim 10^{18}$ Wcm^{-2}) laser pulse incident on a supersonic, laminar gas-jet was investigated via 90° Thomson Scattering and interferometry diagnostics. In order to study the effect of atomic species on laser pulse propagation, the laser interaction with different gases (Nitrogen and Argon) was monitored. In the experimental conditions, both the atomic species resulted in similar electron densities, however, early diffraction of the laser pulse was observed in Argon gas, while, stable propagation of the pulse over several Rayleigh lengths was seen in the case of Nitrogen gas target. Features of the scattering region indicate a competition between optical diffraction and intensity dependent non-linear focusing of the pulse. The observations suggest that proper choice of the target is essential within the available laser pulse parameters, as it can enhance or spoil the propagation of laser pulse in plasmas.

1. Introduction

Recent advances in compact table-top terwatt laser systems has made available focused intensities greater than 10^{18} Wcm^{-2} in small scale laboratories and allowed a precise investigation into the non-linear laser-plasma interaction regime. The study of propagation of intense laser pulses in plasmas is relevant for a number of applications, such as particle acceleration, X-ray lasers and fast igniter scheme for inertial confinement fusion. For successful realization of these applications, the novel feature of these laser pulses, their peak intensity, must be maintained over long distances. Refractive defocussing, however, may limit the intensity which can be achieved by focusing these short pulses. Ionization of a gaseous medium by a laser pulse with Gaussian intensity distribution produces a maximum of the electron density along the laser propagation axis, which gradually decreases along transverse direction. This electron density distribution modifies the refractive index of the medium, which behaves as a diverging lens, i.e. it defocuses the laser pulse. Ionization induced defocussing effect has been widely investigated experimentally [1–4], theoretically [5,6] and numerically [7] in the past few years. In these studies, it was found that ionization induced refractive effect is more serious when high atomic number gas targets are used; and where subsequent ionization of the medium could create density gradients. Such density gradients refract the laser pulse and severely affect their propagation in plasmas.

This paper reports on experimental observation of stable propagation of modest power laser pulses in high atomic number gas target and at high backing pressure. The experimental result shows that stable propagation of laser pulses is possible even in high density gas target. The observation suggests that the nature of the target medium plays a crucial role in guiding the laser pulse. Proper choice of the target is essential within the available laser pulse parameters, as it can enhance or spoil the propagation of laser pulse in plasmas.

2. Experimental setup

The experiment was carried out at ILIL laboratory of Istituto Nazionale di Ottica (INO) with a Ti:Sapphire laser system, which delivers 800 nm, 65 fs laser pulse. A small part of the pulse was split, doubled in frequency (using a KDP crystal) and used as a probe pulse for interferometry. The main laser pulse was focused up to 10 μm spot using an F/6 off axis parabolic mirror. The experimental set up is illustrated in Fig. 1. The experiment was mainly devoted to optimize conditions for electron acceleration by varying the gas density and pulse duration. The gas density was controlled by changing the backing pressure of the nozzle,

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while the pulse duration required tuning of the gratings. By scanning the position of the best focus onto the gas-jet, the optimal conditions for electron acceleration was found. The probe laser pulse was used for Nomarsky modified interferometry [8] to obtain the electron density evolution. Thomson scattering diagnostic, which consists of an imaging system for the scattering region and a spectrometer (as shown in Fig. 1) was set to retrieve information on the laser propagation. A phosphor screen (LANEX) placed along laser propagation axis was used to detect the accelerated electron bunch. The electron acceleration studies were successful and reported elsewhere [9].

3. Results and discussion

Interferometry and Thomson scattering diagnostic provide useful support to gain information on laser pulse propagation in plasmas. Fig. 2 shows the interferogram and Thomson scattered image obtained using Nitrogen gas target. It is observed that the laser pulse propagates without any early diffraction, maintaining its radial extent and a long channel-like longitudinal propagation. The laser pulse envelope was Gaussian with some imperfection. The Rayleigh length of the pulse was around 60 μm. However, the length of the scattering region is greater than 300 μm, which is more than five times the Rayleigh length. A bright scattered region maintained over propagation length is also seen in the Thomson scattered image. Fig. 3 shows the interferogram and Thomson scattered image obtained using Argon gas target. Unlike the case of Nitrogen gas, divergence of the pulse is clearly noticed from interferogram. A gradual decrease in the intensity of the scattered radiation with the propagation of the pulse can also be seen in the Thomson image. These behaviours of laser pulse propagation in these two different gases were reproducible during the experiment. In the Thomson scattering image from Nitrogen gas, the noteworthy features in the scattered region were the periodic structure and intensity enhancement with propagation. As the light emitted from Thomson scattering is the product of the local laser intensity and the electron density [10], it gives combined information on laser intensity enhancement and electron density evolution. Electron density evolution can be estimated with optical interferometry and thus, Thomson scattering can provide some information about intensity evolution of the laser pulse. Such a method to characterize the ultraintense and ultrashort laser fields and to study the ultrafast dynamics of the electrons was proposed by Gao [11,12].

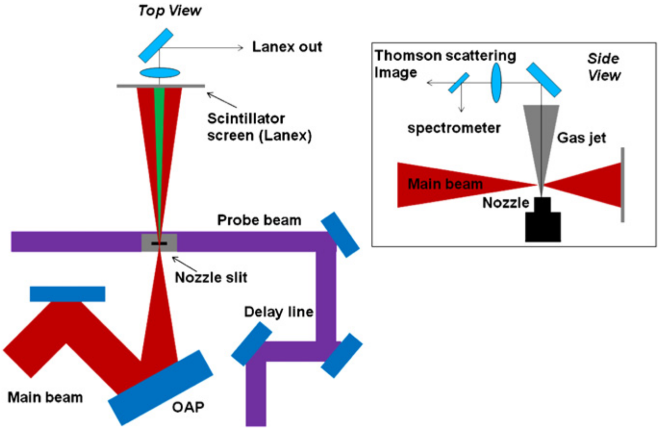

Fig. 1. Experimental set up scheme. On the left side the laser beam lines, and the diagnostics arrangement is shown. On the right side Thomson Scattering diagnostic is shown.

In the present work, the propagation issue of the laser pulse in Nitrogen and Argon gases has been focused upon. The different behaviours in the propagation of the laser pulses in these two gases can be understood from their ionization potentials. Figs. 4 and 5 illustrates the temporal profile of the laser pulse and ionization threshold [inset] for Nitrogen and Argon gases, respectively. At the intensities and time scales of currently available CPA laser pulses, the gaseous medium can be completely or partially ionized in a time shorter than a single wave period. The refractive index of the ionized medium or plasma can be given as

$$\eta(r,t) = \sqrt{1 - \frac{\omega_p^2(r,t)}{\gamma\omega^2}} \tag{1}$$

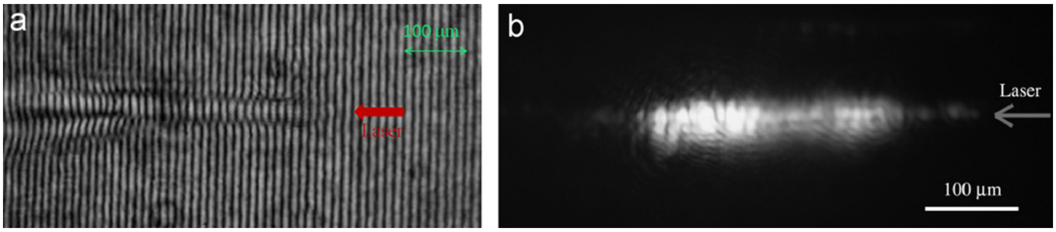

Fig. 2. (a): Interferogram obtained in case of N_2 at 35 bar. The interferograms are taken at $\geq$ 5 ps after the arrival of the main laser pulse. The interferogram shows a collimated propagation of the laser pulse over few hundreds μm indicating a competitive process against optical diffraction. Arrow in the figure indicates the direction of laser pulse propagation. (b): Thomson scattering image. It shows the intensity of the scattering region is almost same for initial part of the propagation and then increase as the pulse propagate further. The images also shows a quasi-periodic structure in the scattering region.

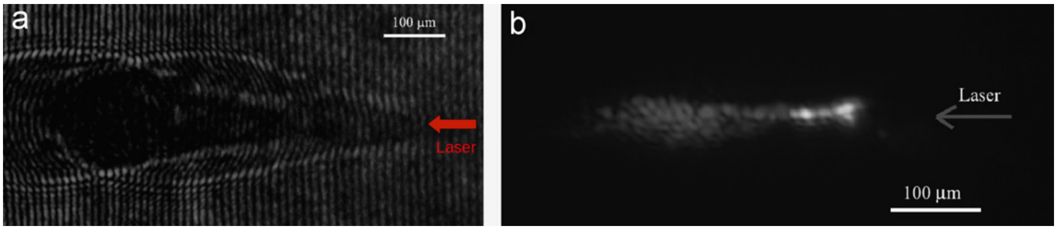

Fig. 3. (a): Interferogram obtained in case of Ar at 35 bar. The interferograms are taken at $\geq$ 5 ps after the arrival of main laser pulse. The interferogram shows the diffraction of the laser pulse. Arrow in the figure indicates the direction of laser pulse propagation. (b): Thomson scattering image. It shows a gradual decrease in the intensity of the scattering region.

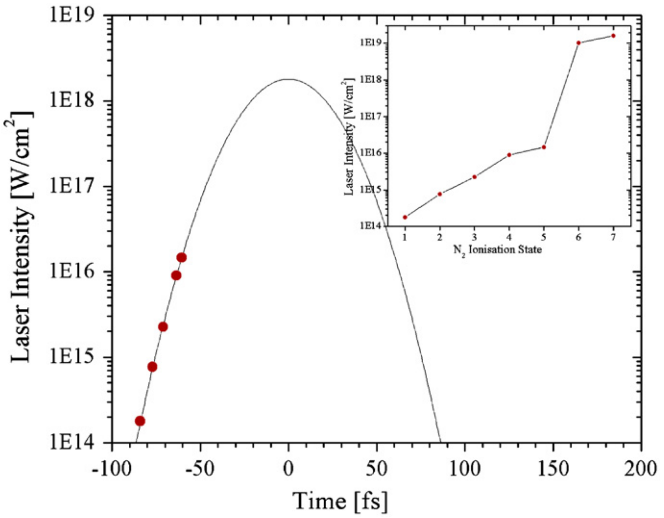

Fig. 4. The figure represents the temporal intensity profile of the laser pulse. Red dots on the curve represent different ionization levels for N_2 gas. Inset: Intensity vs ionization state for N_2 gas. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

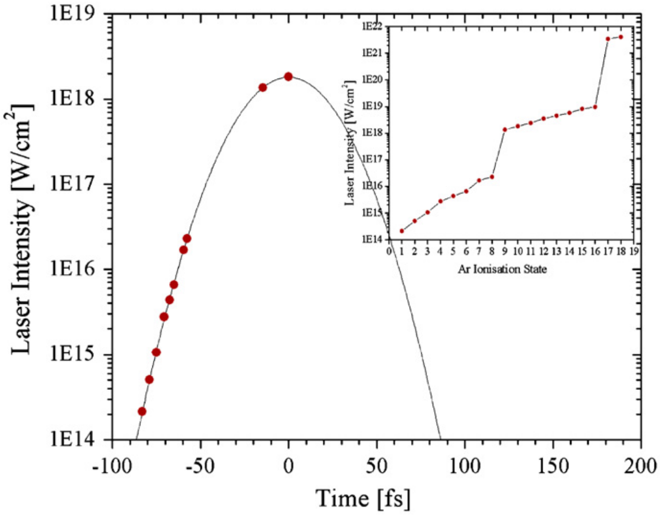

Fig. 5. The figure represents the temporal intensity profile of the laser pulse. Red dots on the curve represent different ionization levels for Ar gas. Inset: Intensity vs ionization state for Ar gas. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

where ω_p is the plasma frequency, ω is the laser frequency, $\gamma=\sqrt{1+a^2/2}$, and $a=eE/m\omega c$, E is the electric field of the laser pulse. During the ionization process, the uneven transverse electron density distribution could defocus the laser pulse. However, if the critical power threshold could be reached the pulse could undergo self-focusing [13]. In addition, at intensities $\geq 10^{18}$ Wcm^{-2} relativistic effects become significant, which modulates the refractive index of the plasma in a way exactly opposite to ionization process and causes the laser pulse to focus [14].

As seen from Fig. 4, in case of Nitrogen gas the rising edge of the laser pulse ionize the medium up to the 5th level in the early time of interaction, and most of the pulse propagates without further ionization. Within the intensity level of the focused pulse, during their interaction with laser electric field the ionized electrons could acquire relativistic quiver velocity, and gave rise to an increasing γ factor in Eq. (1). In this condition, a competition between optical diffraction and relativistic self-focusing took place and lead to a collimated propagation of the laser beam. This process became weak when the laser energy depleted significantly or when non-linear effects saturated. Instead, if the pulse peak intensity was comparable to the value suitable for partial ionization of the gas, as shown in Fig. 5 in case of Argon gas, ionization severely affected the pulse propagation. The laser pulse energy was mainly exhausted in ionizing the neutral gas medium and might not have reached a condition suitable for relativistic self-focusing. In such a case, ionization induced refractive effects remained strong enough to defocus the pulse.

The above argument is also supported by deconvolution of electron density from interferograms, which shows similar plasma density in both the gases. In spite of this fact, a quasi-stable propagation was observed in Nitrogen gas, while, defocussing effects remained dominant in Argon gas. Figs. 6 and 7 shows the electron density obtained from the interferogram recorded in case of Nitrogen and Argon gases, respectively. Due to poor

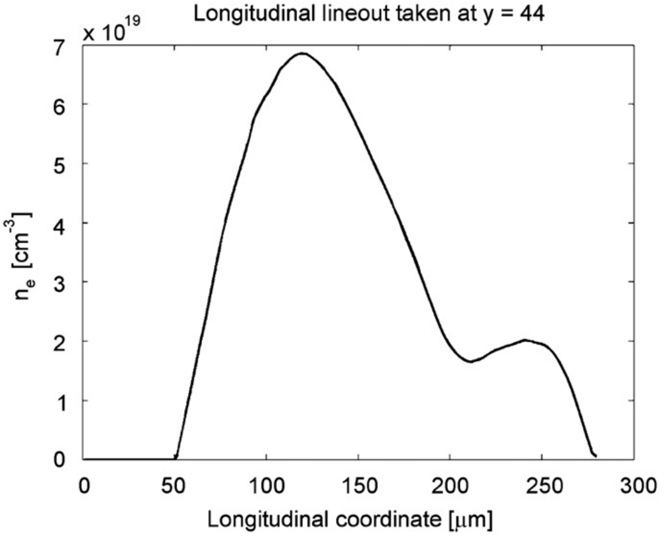

Fig. 6. Electron density evolution obtained from interferogram in case of Nitrogen gas.

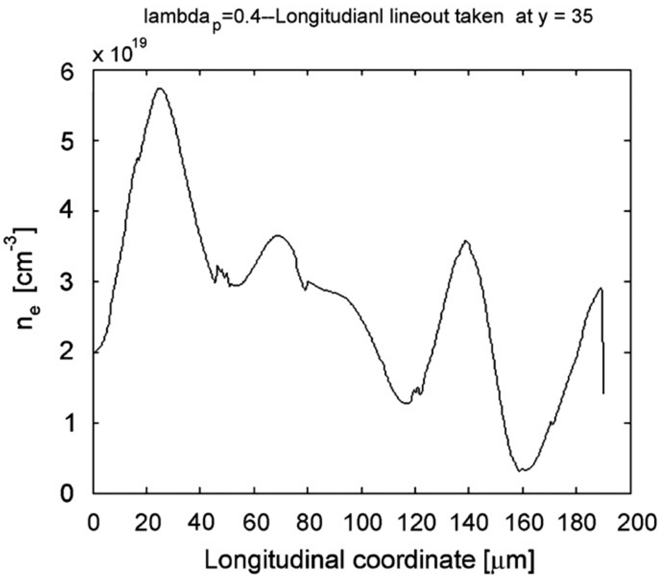

Fig. 7. Electron density evolution obtained from interferogram in case of Argon gas. Due to not good quality of interferogram and overlapping of the two images in Nomarsky interferometry, analysis of the interferogram is quantitative.

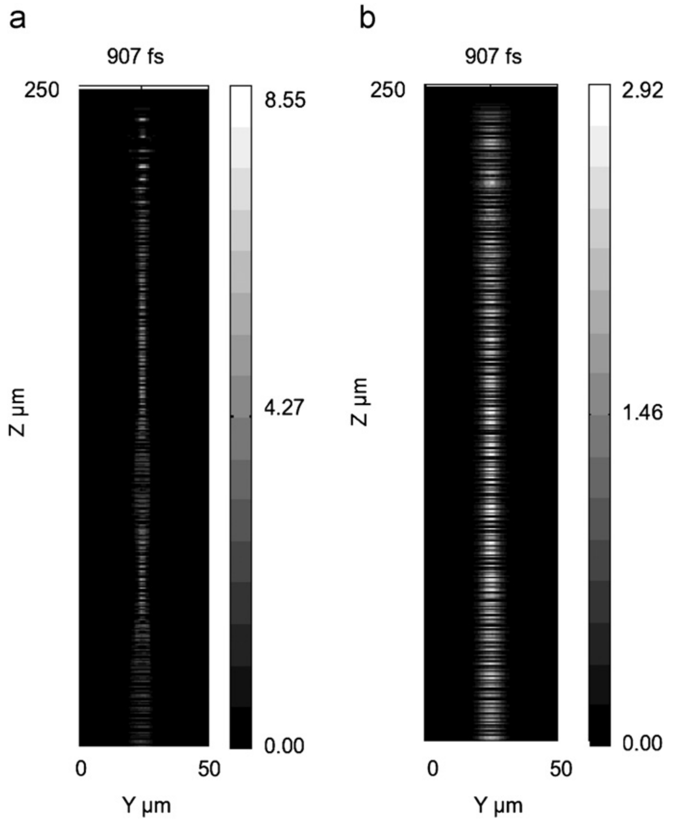

Fig. 8. Numerical calculation of laser pulse propagation in underdense plasma. (a) Intensity evolution of the pulse in pre-plasma density obtained from interferogram. (b) Intensity evolution of the pulse in with pre-plasma density less than that obtained from interferograms.

quality and overlapping of the two images in the interferogram, analysis was little difficult and quantitative.

To analyze the propagation of laser pulse in underdense plasma, preliminary simulation using a relativistic particle-in-cell code (PSC) was done. The code assumes fully ionized medium. The pre-plasma assumption was partially valid for Nitrogen gas where rapid ionization took place in the early stage of its interaction with laser pulse. The pre-plasma density was set close to the maximum electron density that could be reached with Nitrogen gas. Fig. 8 shows the intensity evolution of the pulse as it propagates in pre-formed, underdense plasma. The code reproduced similar features as seen in the Thomson image obtained from Nitrogen gas. Fig. 8(a) shows the self-focusing of the pulse. With propagation, the pulse experienced oscillating focusing. This may be due to an interplay between non-linear focusing and defocussing effects. The oscillating focusing can be correlated with the quasi-periodic structure present in the Thomson images. When the pre-plasma density was set quite below the value obtained from interferogram for Nitrogen gas, the pulse did not display any strict focusing behaviour. This is shown in Fig. 8(b). It suggests that at power and electron density level as in the case of our experiment, self-focusing of the pulse is possible. The absence of any such focusing behaviour of laser pulse in case of Argon gas implied that ionization induced defocussing effect prevented the stable propagation of the pulse.

Regarding to the assumption of pre-formed plasma in the code, the effect of ionization on intensity distribution during propagation of the pulse was not considered. However, it was obvious that when pulse was involved in ionizing the medium; energy depletion would become more significant. This might prevent the pulse to reach the critical power threshold for self-focusing. In addition, the continuous ionization of the medium, as in the case of Argon gas, would further affect the spot size of the pulse due to refraction induced defocussing. In such a case, both power and intensity might significantly be reduced and would result in non-stable propagation of the laser pulse.

4. Conclusion

To summarize, the effect of different atomic species on stable laser pulse propagation in plasmas has been studied experimentally. It was observed that stable propagation of the laser pulses can be achieved in higher atomic number gas target. Choice of target is essential and may help in choosing suitable regime for specific applications. It was observed that relativistic effects start taking place once the ionization process saturates partially or completely. These features are consistent with the ionization and relativistic non-linear effects in laser plasma interaction. A more detailed investigation of this process is in progress and will be the subject of future publication.

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