Fast pulsed electric field created from the self-generated filament of a femtosecond Ti:Sapphire laser pulse in air

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Abstract

We present an experiment demonstrating the generation of fast pulsed electric field from a plasma column created in air as a result of the interaction of N₂ and O₂ molecules with a 220 fs laser pulse. By first measuring the distribution of N and O and then by measuring the net charge present at different positions in the focal region, we determined that this plasma column has an intrinsic dipole moment, which generates these pulses. The origin of this dipole moment was attributed to longitudinal separation of electrons due to ponderomotive acceleration of electrons created through multiphoton ionization of N₂ and O₂ molecules.

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1. Introduction

Recently, some research groups [1–3] devised a simple method to measure the pulsed fields created as a result of the interaction of a focused laser pulse in air. In their studies, the emphasis was upon the interaction of long laser pulses (μs, ns and 700 ps), where the ionization of the molecules and generation of plasma is due to the acceleration of electrons through inverse bremsstrahlung followed by inelastic collisions with molecules. When the density of the carriers in the interaction region exceeds a threshold value [4] there will be avalanche ionization which creates a high density plasma. The conclusion of Refs. [1–3] is that the plasma created by this ionization process is not locally neutral and therefore the interaction volume possesses a dipole or quadrupole moment. By placing an antenna in the vicinity of the interaction volume, they were able to measure the field created by this charge distribution.

Naturally, the next step would be to extend these type of studies to the case of a plasma created through the interaction of short laser pulses with air because the ionization mechanism is different. It is thus expected that the produced plasma will have characteristics different from the plasma created by long laser pulses. It is known that the characteristic time for the collisions in air is ~ 1 ps [4], so in the case of pulses with duration around 100 fs, the collisional ionization followed by avalanche will not

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have an appreciable contribution in the generation of the plasma and it will be dominated by multiphoton ionization (MPI) of the molecules. These characteristics enables us to determine the origin of multiple electric moments, a task which in the case of long laser pulses has not been established [1–3]. Motivated with this expectation, we measured the pulsed electric field produced in the vicinity of the plasma column which is created during the propagation of a focused 220 fs Ti:Sapphire laser pulse in air. Our measurement indicates that the plasma column possesses a dipole moment. This might be explained by the theoretical findings of Goreslavsky and Narozhny [5]. According to their calculation, the electrons created inside the short pulse through the MPI will be accelerated backward resulting in an effective separation of electrons and positive molecular ions.

2. Experimental setup and results

The experimental setup is presented schematically in Fig. 1(a). The plasma column is created in air by focusing a 220 fs Ti:Sapphire laser pulse through a 1.5 m lens and is faintly visible to the naked eyes in a range of about 20 cm spanning the focal region. We place the dielectric shielded inner core of a 50 Ω coaxial cable at a distance of 0.5 cm from the plasma column (see Fig. 1(b)) and the signal detected by this antenna is sent to a 1 GHz oscilloscope having a 50 Ω input impedance (Tektronix 7834). As shown in Fig. 2 (top panel), the duration of the signal is less than 1 ns (which is the detection limit of our oscilloscope). However, if we did not care about impedance matching, we would get a signal as shown in Fig. 2 (lower panel) with a digital 500 MHz oscilloscope. This later signal is similar to what we presented elsewhere [6] using various types of detectors including capacitor plates, parallel wires with or without bias voltage, etc. The signal was interpreted as charges being collected by these plates (or wires) which spanned across the filament. A similar signal and explanation has later been reported in Ref. [7]. However, the current experiment clearly shows that the signal is electric in nature.

By measuring the amplitude of the signal as a function of distance from the geometrical focus of the lens, the dependence of the signal on the propagation distance can be determined. Fig. 3 shows the results for the case of 36 mJ pulses focused by a 100 cm focal length lens (Fig. 3(a)) and by a 150 cm focal length lens (Fig. 3(b)). Because the distance between the wire detector and the plasma column is small, we conclude that the detected field distribution shown in Fig. 3 corresponds in fact to the net charge distribution in the plasma column. In other words, if a positive net charge is suddenly created in the region near the wire, it will induce a current in the wire which will give a positive signal $S(t)$. If a negative net charge is created near the wire, then the
induced current will be in the opposite direction and the signal will be negative. This experimental measurement of the net charge distribution is the first step to make in order to fully reconstruct the positive and negative charge distributions in the plasma column. The next step consists of measuring the positive ions distribution. The knowledge on the distribution of the positive ions in this column could then allow us to fully reconstruct the electron distribution.

Recently, our group has developed a technique to determine the distribution of the $N^+_q$ ions by detecting the photoemission coming from the plasma column. The details of this measurement technique is discussed elsewhere [8]. Briefly, in the process of the MPI of $N_2$ molecules, some excited $N_2$ molecules and $N^+_q$ molecular ions created in the interaction region relax by emission in the second positive band system of $N_2$ and in the first negative band system of $N^+_q$. The strength of the photoemission signal integrated over all emission frequencies is proportional to the number of the created $N^+_q$ ions. Note that apart from the $N^+_q$ ions, $O^+_q$ ions are also created at any point in the column at such high intensities because the ionization potential of $O_2$ (12.1 eV) is lower than that of $N_2$ (15.6 eV) [9]. However, we cannot directly measure the density of these because no detectable $O_2$ or $O^+_q$ emission lines exists in the frequency range detected by our experimental setup. Anyhow, we expect that the local concentration of $O^+_q$ ions is proportional to the $N^+_q$ ions so that the overall positive ion distribution is the same as the $N^+_q$ ions distribution multiplied by a scaling factor. Thus we will use the $N^+_q$ ions distribution on an arbitrary scale to represent the overall positive ions distribution. In Fig. 4, we present the measured distribution of the $N^+_q$ ions in a plasma column created by focusing 36 mJ laser pulses with a 100 cm and a 150 cm lens.

From the distribution of the positive ions (Fig. 4) and the net charge (Fig. 3) we can calculate the electron distribution in the plasma column by subtracting the net charge distribution from the $N^+_q$ ions distribution. As discussed above, the entire positive ion distribution is proportional to that of $N^+_q$. This allowed us to scale the net charge distribution in such a way that the calculated number of electrons equals the number of positive ions. The resulting curves shown in Figs. 5 and 6 demonstrates that in the plasma column, the positive charges and the electrons are separated in the longitudinal direction. The mass of the positive charges being much larger than that of the electrons, our observation implies that it is the electrons that have been displaced through their interaction with the laser pulse.

Fig. 5 corresponds to the case of a 100 cm focusing lens, which is too short to create a long filament in air, so the $N^+_q$ ions distribution is roughly symmetric. In the case of a 150 cm lens (Fig. 6), the situation becomes different. As can be observed from Fig. 4, the distribution of $N^+_q$ ions in this condition differs from that using a 1 m focusing lens in two respects. Firstly, the position of the maximum of the
positive charge distribution has been shifted towards the focusing lens. This is the manifestation of the phenomenon of self-focusing and is consistent with the prediction of the moving focus model [10]. Secondly, after the focusing point, in the case of 150 cm lens the rate of decrease of the ions density with propagation distance slows down. This is the so-called filamentation phenomenon [11–18]. Contrary to the difference between the two focusing conditions, the phenomenon of charge separation is present in both cases, which implies the universality of the charge separation phenomenon.

This phenomenon might be explained using the theoretical findings of Goreslavsky and Narozhny [5]: Assuming that the ionization mainly occurs in the peak of the pulse, most of the electrons in the plasma column will acquire a kinetic energy equal to the ponderomotive potential $U_p = F^2/4\omega^2$, where $F$ and $\omega$ are the peak electric field and the frequency of the laser (in atomic units), respectively. At our working intensity of $\sim 7 \times 10^{14}$ W/cm$^2$, $U_p \sim 42$ eV. Electrons with this amount of energy will move backward and will be decelerated very rapidly by the combined action of the restoring force of the positive ions and by collisions. It is expected that the electrons will be brought to rest and will undergo a strongly damped oscillatory motion at the plasma frequency $\omega_p = ((4\pi ne^2)/m)^{1/2}$, where $n$ is the density of molecules in air, $e$ is the charge of the electron and $m$ is its mass. In our case where the gas at atmospheric pressure is totally ionized, $n \sim 10^{19}$/cm$^3$ and $\omega_p \sim 10^{14}$. Even though the exact dynamics of the motion is beyond the scope of the present paper, qualitatively it is expected that the fast oscillation will not be detected by our detection system with a response time of $\sim 10^{-9}$ s. We are currently studying the characteristics of this electromagnetic pulse at long distances because we believe it could find some applications in technologies such as LIDAR.

In this article we intended to report only the new experimental observations. There are some questions worth mentioning about those results. The most important of these are: (a) What is the dependence of the charge separation on the experimental parameters such as intensity, confocal parameter, etc. The main difficulty with this is the fact that the mean free path of an electron in a fully ionized medium such as the plasma column we are dealing with is not available. (b) What is the dependence of the strongly damped oscillatory dynamics that occurs after the laser pulse has separated the charges on the same experimental parameters. This aspect of the phenomenon could provide some insight about the temporal shape of the electric pulse we are detecting, which would be very interesting. More advanced theoretical work on these two aspects of the longitudinal charge separation phenomenon would be crucial if one wants to use this electromagnetic pulse for some applications.
3. Conclusion

We have observed a fast electric pulse due to the charge separation in a plasma column created by focusing a 220 fs pulse with a 100 cm and a 150 cm lens in air. We demonstrated that by measuring the field near the plasma column (hence, net charge distribution) using an antenna and then comparing it to the positive ion distribution, we can fully reconstruct the electron distribution in the plasma column, providing us the experimental evidence that a net charge separation due to ponderomotive acceleration occurs. The interesting aspect of this charge separation is that when laser pulse has passed, the laser-induced dipole moment will oscillate because of the strong electrostatic restoring forces that accelerates the electrons toward the positive ions. This oscillation of the electrons produces an electric pulse with a duration less than 1 ns.

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References

[6] International workshop on ultrafast intense laser pulse propagation and its applications (by invitation only), sponsored by ARO and DREV, June 19–20, 1998, Laval University, Quebec City. The following principal investigators and representatives together with some of their colleagues and/or students were invited: I. Ahmad, C.M. Bowden, S. Cameron, S.L. Chin, D. Faubert, A.L. Gaeta, Y. Gamal, V.P. Kandidov, B. LaFontaine, J. Lavery, G. Mourou, A. Mysyrowicz, R. Sauerbrey, E.M. Wright.