Effect of Beam Waist on Shock Properties of Laser-Induced Plasmas in Air by the Photoacoustic Probe Beam Deflection Method

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A plasma induced by focusing in air at atmospheric pressure a 7 ns Nd:YAG laser at 1.06 µm was studied by the photoacoustic probe beam deflection method. This technique is used for the first time to study shock waves from laser induced plasmas in air. We have studied the effect of beam waist on energy deposition. Our results indicate no appreciable effect on the shock wave properties of laser-induced plasmas formed with different focal distance in the range from 2.5 cm to 20 cm at µs time scale. The technique was found to be versatile, economic and simple to implement giving essential information for the shock wave evolution generated from plasmas produced by different methods.

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Laser-induced plasmas (LIP) have been proposed as a good analog of lightning1. The properties of LIP has been carefully evaluated with respect to its spectral properties2, temperature and density evolution3, optical emission4, focal size5, and stable products6-7. Unlike the usual spark-gap discharges, LIP is not contaminated by spark electrodes3, does not lose energy by heat transfer to the electrodes6, does not generate corona discharges along electrodes, and there is no shift from spark to glow discharge at low pressures. Nitric oxide plays an important role in atmospheric photochemistry and in global biogeochemical cycles and hence is an essential part of the determination of global climate8. Thus the rate of production of nitrogen oxides by natural and anthropogenic sources has been of great interest in recent years. It has been suggested that lightning is a major natural source of NOx, although there is considerable uncertainty over both the magnitude and the mechanism of NOx. It is expected that the production efficiency of nitric oxide, PNO, by lightning will be proportional to the rate of energy dissipated by lightning activity. Furthermore, it is generally believed that PNO is independent of input energy. Chameides suggested on theoretical grounds however that P does vary with input energy9. Recently it has been demonstrated that the production of nitric oxide, linearly depends with peak current of arc discharges10. There seems to be two possible scenarios to vary input energy in LIPs: (1) Modifying laser input energy using a focal length lens; and (2) Changing the focal length of the focusing lens at a constant laser input energy. The first approach is expensive since it requires a laser attenuator to avoid distortion of laser beam. The aim of this paper is to study the properties of LIP using different beam waists to evaluate the second alternative of varying input energy.

Experimental

A schematic diagram of the experimental set up is shown in figure 1. The plasma was produced by focusing in air a 1.06 µm beam with a pulse width of 7 ns from a high power Nd:YAG laser operating at 10 Hz (Surelite II, Continuum) using 2.5 cm diameter plano-convex lens of different focal distances. The beam diameter of the impinging laser was constant at 9 mm. The plasma was formed at the Mexico City atmospheric pressure, 770 mbar; room temperature was maintained constant at 19(±1)°C. The lens was mounted on a micrometric translation stage to vary the position of the plasma in the x-axis. The energy of the laser pulse was varied from 25 to 500 mJ using a high power attenuator (Newport, model 935-10) and was measured before the focusing lens by means of a calibrated beam splitter and after the plasma by a two-head energy meter (LabMaster Ultima with crystalline pyroelectric sensors: LM-P10i y LM-P10 from Coherent).

The probe beam was a 1 mW HeNe laser emitting at 633 nm with a diameter of 630 µm (U-1301, Newport,) that was mounted on a translation stage to vary its position perpendicular to the lens movement in the y-axis. The beam deflection was detected by a fast response photodiode, with a rise time ≤ 200 ps (model 877, Newport) and registered by a 500 MHz digital
oscilloscope (TDS 524A, Tektronix) triggered with an external pulse from the power supply of the Nd:YAG laser. The signals were stored in a PC with a GPIB interface for subsequent analysis. In order to avoid detection of laser scattered light (1.06 µm) and plasma emission, the photodiode was covered with an interference filter. Deflection signals were gathered from the average of 25 or 100 acquisitions for the shock and thermal expansion waves, respectively.

**Results**

The movements of the lens in the x-direction and the probing beam in the y-direction enable us to map the shock in two dimensions. The location of the shock wave in the x-axis varies with laser energy and focal lens used. For comparison purposes, the origin of the coordinates was defined by the location of the shock wave at 3 µs and 300 mJ in the direction of the laser beam. The regions before this point were defined as negative x-coordinates. Figure 2 shows two typical deflection signals of the shock waves produced by the laser-induced plasma. The peaks at the first nanoseconds are due to an incomplete blocking of the light at 1.06 µm. In the first microseconds the expanding plasma and the shock wave coexist spatially and temporally. As the probing laser approaches this region separation between the shock and thermal waves is smaller; however close to the plasma region, several new deflection signals arise due to changes in refractive index caused by the plasma itself overlapping with those produced by the shock and thermal expansion waves. These new signals restrict the accurate monitoring of the evolution of the expanding shock wave at time intervals ≤ 0.5 µs. As the probing laser is moved far away from the plasma region, the shock wave deflection amplitude decreases without a loss in sensitivity to its detect the temporal position. On the other hand, the thermal wave deflection amplitude decreases considerably making it impossible to map it further than 1.5 ms after plasma ignition. The shock wave deflection signals are highly reproducible determined by the laser stability energy that was within ± 3%.

In order to study effects of different focusing lenses on LIP, we map the shockwave envelop at a given time when the deflection signals are clearly separated from those generated from the plasma for various lenses. Figure 3 shows that for lenses with a focal distance from 2.5 cm to 10 cm, there was not a significant difference in their shape in the x and y axis. The same pattern was observed in the other axes since the plasma has a cylindrical geometry. Only for a 20 cm lens that was a longer elongation of the shock wave envelop. The shock wave velocities on the four coordinates did not differ appreciably although the shock wave propagates faster in the direction of the lens. Figure 4 gives the average shock wave velocity as a function of the focal lens. Due to the high reproducibility of shock wave, the error bars are smaller than the symbols shown. Although there is a clear trend on shock wave and focal length, the differences are not that significant if one considers that the area or the volume of the beam waist is directly proportional to focal distance or to the square of the focal distance, respectively. In our case the beam waist varied nearly an order of magnitude, which should be reflected in a strong variation on the shock wave velocity.
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under the shock wave envelop increases with laser energy. and instead a multiple small plasmas were formed. The area stable plasma was not produced at high laser energy (500 mJ) plasma was not reached. For long focal distance (20 cm) inside the lens and consequently the threshold to produce the LIP was not produced by low laser energy (50 mJ) at 2.5 cm focal length as this lens is very thick absorbing more energy V

Fig 4. Average shock wave front velocity as a function of the focal distance of the focusing lens used to produce LIP at 300 mJ per pulse.

Despite the differences observed in the shock wave shapes given in figure 2, the area under these envelopes is essentially independent on the lenses used except for the lens of 2.5 cm focal distance where the area is slightly smaller, about 16% (see figure 5). Nevertheless, one would expect a change of about 100 % for each lens used.

Figure 5 also shows this variation for different laser energy. LIP was not produced by low laser energy (50 mJ) at 2.5 cm focal length as this lens is very thick absorbing more energy inside the lens and consequently the threshold to produce the plasma was not reached. For long focal distance (20 cm) a stable plasma was not produced at high laser energy (500 mJ) and instead a multiple small plasmas were formed. The area under the shock wave envelop increases with laser energy.

Discussion

Our results clearly demonstrate that the focal distance of the focusing lens has not a strong effect on the shock wave generated from the LIP. This finding seems to be in apparent disagreement with the expected variation of the beam waist by varying the focal length of the lens used. Since the beam waist is directly proportional to focal length, and if the laser energy is deposited at different spot sizes, one would expect that the shock wave would consistently decrease by increasing focal distance. The answer to this controversy comes from the mechanism of electric breakdown itself. Electric breakdown occurs because the electric field at the focus exceeds the dielectric strength of air and not because of selective absorption of laser radiation by an atom or molecule. At atmospheric pressure, a cascade ionization develops when a few seed electrons absorb energy from the beam by inverse bremsstrahlung. The plasma grows towards the focusing lens; this asymmetric development has been explained by four different mechanisms: 1) when the laser energy flux exceeds the breakdown threshold, breakdown begins at the focus at the arrival of the first photons of the temporal Gaussian beam profile. When the majority of the photons arrive the breakdown threshold occurs at several points of the focusing column before the focal point causing a breakdown wave propagation towards the focusing lens; 2) the heated gas in the absorbing layer expands and sends out a shock wave in all directions; across the shock wave the gas is heated and ionized so that the zone of light absorption and energy release in the gas is displaced behind the shock front in direction towards the laser beam; 3) the gas ahead of the absorbing layer is ionized and becomes capable of light absorption by absorbing the thermal radiation which is emitted from the highly heated region of the gas behind the absorption wave front; and 4) a self-focusing effect occurs with short pulse and high energy density lasers, resulting in a non-uniform heating mechanism and development of high-density plasma filaments which grow towards the laser during the pulse. The relative importance of these mechanisms depends on several factors such as pulse width, energy density, laser wavelength, chemical nature of irradiated material and gas density. Since the plasma begins to form in a point near the focal point and then grows towards the focusing lens, the focal waist of the lens has little effect on the evolution of the shock wave. Consequently, the focal distance of lenses used to produce LIP with lasers are not important. During this work it was clear that the lenses with a focal distance of 2.5 cm were rapidly damaged by the laser. Therefore, we recommend to use a focal distance between 5 to 10 cm without an appreciable change in the properties of the LIP. For long focal distance, the stability of the plasma is severely affected and so we do not recommend to work with such lenses. Changing the beam waist is not an alternative for varying the linear energy deposition in LIP.

The photoacoustic probe beam deflection method used in this paper to study shock wave evolution in the microsecond time scale is extremely simple to implement and can be used at a longer time scale to study the expansion of the thermal waves once the plasma has decayed. In addition, the shock wave evolution from LIP has been modeled using a 3-D adaptive grid code solving the gas dynamic equations together with a system of rate equations for atomic/ionic and molecular species in perfect agreement with experimental data obtained by this experimental method. The results obtained in this work have been independently reproduced with more sophisticated optical methods such as shadowgrams or schlieren photography in our laboratory.

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