Diagnostics of Laser Induced Spark in Air
Using Fast ICCD Photography

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Laser induced breakdown of air at atmospheric pressure is investigated using fast photography. The nanosecond pulses from the frequency doubled Nd:YAG laser is used to create the cascade type optical breakdown. Fast, side-on views of the plasma kernel are made by recording the overall visible emission from the air spark using a gated ICCD camera system. The two dimensional time resolved spontaneous emission images give not only its expansion dynamics but also its lifetime.

1. Introduction

When a powerful laser pulse is focused into air or onto a solid target, an intense spark or plasma is formed. This plasma may be used for variety of applications including elemental analysis based on plasma emission, production of soft and hard X-ray radiation, sample vaporization for spectroscopy, thin film deposition, inertially confined fusion and other applications. To understand the process of laser-induced breakdown it requires an understanding of the initial stages of various processes involved during laser-matter interaction, plasma formation, and its subsequent expansion. There are several techniques employed for diagnosing a laser created plasma which includes, optical emission spectroscopy, laser induced fluorescence, microwave and laser interferometry, Langmuir probe and Thomson scattering\(^1\). Photography and other imaging techniques add another dimension to plume diagnostics by providing two-dimensional snap shots of the three-dimensional plume propagation. This capability becomes essential for hydrodynamic understanding of the plume propagation and reactive scattering. Recently, with the advent of commercial intensified CCDs, it is possible to obtain nanosecond time resolution, high spatial resolution and high sensitivity\(^2-4\).

The laser focusing effects and subsequent spatial development of the initial plasma in air are investigated using fast photography. The focal lengths of the lenses used are 4cm, 8.5 cm, 15 cm and 25 cm.
2. Experimental details

The experimental arrangement for gated-ICCD photography is shown in figure 1. Pulses from the frequency doubled Nd: YAG laser (10 ns, maximum energy 600 mJ) are used to create an optical breakdown in air. The laser beam is attenuated using a combination of wave plate and cube beam splitter. While maintaining a fixed polarization state, the incident laser energy is systematically varied by adjusting relative angle of polarization. The breakdown is generated by focusing the laser beam using antireflection-coated lenses at atmospheric air. The energy of the laser is monitored using a laser energy meter (Ophir Model No. 10 A-P).

Fast photography of the laser spark is accomplished using an intensified CCD camera (PI.MAX, Model 512RB, Princeton instruments). The 512 x 512 square CCD pixel format (pixel size 19 µm X 19 µm) with 2 ns fast gating time makes this camera ideal for fast photography. A magenta subtractive dichotic filter is used for eliminating

Fig.1. Schematic of the experimental set-up used for imaging studies (WP – wave plate; R – reflector; BS – beam sampler; L – lens; F – filter; PTG – programmable timing generator)
532 nm stray photons reaching the camera. A Nikon lens is used to image the plume region onto the ICCD to form a 2-dimensional image of the plume intensity. A Programmable Timing Generator (PTG) is used to control the delay time between the laser pulse and the imaging system, and the overall temporal resolution of the delay between the laser pulse and the camera images is 1 ns. Since the camera and the pulse delay generator have an internal delay of 100 ns, we used the time variable trigger pulse from the laser power supply for triggering the PTG for obtaining images at earlier times. Calibration of the spatial scale is performed using two dimensional grid pattern placed at the location of the breakdown kernel.

3. Results and Discussion

The camera is installed to take pictures in a direction perpendicular to the laser beam propagation direction. Typical temporal evolution of the plasma kernel produced using \( f = 4 \text{ cm} \) lens is given in figure 2. The laser beam is incident from the left hand side. Each image in the figure is recorded from an independent breakdown event. All the images are normalized on a logarithmic scale. This gives a fast on-scale overview of the image. With linear scale, changes in intensity are mapped equally to the display color (gray) levels while with logarithmic scale, changes in intensity on the faint (dark) end are more pronounced. Since CCD detectors have three orders of magnitude more dynamic range than the computer display, this option can map both faint and bright signals most appropriately. The recorded breakdown images in the experiment are very reproducible, and the images show that the initial plasma expands or propagates opposite to the laser incident direction.

The laser spark is produced through an initial breakdown followed by growth and heating of the plasma during the reminder of the laser pulse after breakdown. After breakdown the plasma is heated to a point where it is opaque to the laser. During the plasma expansion, the heating of the cold gas is initially provided by UV emission from the hot plasma. When the region heated in this manner is sufficiently ionized, the absorption of the laser turns on dramatically through the inverse bremsstrahlung process. When the region has become quite hot, it heats the next cold region through UV
emission. The newly formed plasma also screens the plasma formed earlier from the laser radiation.

The images taken at different times mirror the temporal displacement of the plume front and hence give the velocity of the plume. At initial times (< 4 ns) the plasma expansion is found to be spherical in nature. As time evolves, the plasma expands more in the axial direction (laser propagation direction) than in the lateral direction. The expansion velocities of the plasmas are measured from the time evolution of the images and the estimated velocities of the plasmas in the initial stages are $1.1 \times 10^7$ cm s$^{-1}$ in the axial direction and $5 \times 10^6$ cm s$^{-1}$ in the lateral direction. The size of the kernel also grows with time and stagnates after 10 ns. The length of the kernel is estimated from data with more than 95% of the maximum intensity. At 10 ns the image size is 2.48 mm.
Fig. 3: The temporal evolution of the plume intensity taken from the images with time elapsed after the onset of the plasma formation.

long with a diameter of 1.62 mm. Figure 3 represents the temporal evolution of the maximum plume intensity (taken from the image) with time elapsed after the onset of plasma. It is observed that the emission intensities of the plasma increase up to a certain time and then decrease with time.

At times greater than 10 ns, the dimension of the radiating region appears to be constant. However, a complex feature begins to form in the time frame, especially at later times. The 3-dimensional plasma intensity plot of the ICCD image at 400 ns is given in fig. 4 illustrating the complex feature of the plume. When the initial plasma expands, opposite to the expansion direction, the surrounding gas moves inward toward the center of the hot kernel. The dumbbell shape of the kernel shows more asymmetric nature with higher focal length lenses. Figs. 5-7 give the images of the time evolution of laser produced spark recorded at the same condition described above using f = 8.5cm, 15 cm and 25 cm lenses respectively. The spatial property of the kernel is found to be varying
with increasing focal length of the lens used. As focal length increases, the focal spot size as well Rayleigh range also increases. The local laser irradiance across focal area is a function of the reciprocal of the laser-beam size. If the incident energy is higher than breakdown threshold then the breakdown can be initiated earlier at a location before the pulse reaches the focal point. It is to be expected that the region of ionization will extend away from the focus, towards the focusing lens until the peak of the laser pulse has passed. This is simply the result of the breakdown condition being fulfilled over a large volume. This effect is often described as a ‘breakdown wave’. Fig. 7 shows asymmetric plasma boundary expansion, the velocity being greatest towards the lens. This backward movement of the plasma kernel results from the building of a laser supported radiation wave that travels against the laser beam, where as the opposite side, screened by the absorbing plasma, is no longer fed by the laser energy and relaxes through deexcitation of the ionized species\textsuperscript{5}. The observed shift ceases $\sim 10$ ns from the onset of the plasma, which corresponds to the end of the laser pulse. At this stage the plasma emission intensity reaches its maximum value, from which it decays in times as short as a few hundreds of nanoseconds (fig.3).

To have a better understanding on the effect of laser energy on the backward movement of the kernel, the images of air spark are taken at different laser energy levels.
Fig. 5. Time evolution of laser produced air spark created by focusing pulses from a frequency doubled ND:YAG laser in air using $f = 8.5$ cm lens. The time marked in the images corresponding to the time after the onset of plasma formation. All images are normalized on a logarithmic scale.

Fig. 6. Time evolution of laser produced air spark (lens used $f = 15$ cm, other conditions are similar to figure 5).
Fig. 7. Time evolution of laser produced air spark (lens used $f = 25$ cm, other conditions are similar to figure 5).

The plasma kernel is found to be advancing in the backward direction (direction of the focusing laser beam) as the focal length of the lens as well as laser energy increases. The spatial structure of energy deposition at the focal volume is given in fig. 8 along with recorded images of the air spark at different energy levels (using $f = 25$ cm lens). At low energies the kernel is located at the focal spot itself. But as laser energy increases the kernel moves backwards. The higher the incident energy, the farther the initial plasma moves away from the focal point. If the laser energy is within the threshold range the induced plasma should appear very close to the focal point. With $f = 25$ cm lens, the center of the plasma kernel is found to be moved a distance $3.77$ mm as the laser energy increases from $20$ mJ to $350$ mJ.
4. Summary

Time resolved spatial features of the UV-VIS radiation of the plasma kernel generated by laser induced optical breakdown in air are investigated using fast photography. The shape of the kernel turns out to be spherical at early times and a complex feature at later times. The temporal evolution of the plasma emission shows a rapid growth of intensity till the end of laser pulse following by characteristic decay in intensity, which extends a few microseconds. The kernel position is found to move toward the laser beam with increasing laser energy. This backward axial movement is high when we use higher focal length lenses. Fast photography with ICCD sensitivity is extremely useful for studying these hydrodynamic effects. Emission spectroscopy along a particular line-of-sight is less useful without previous knowledge of the hydrodynamics.
Reference:


