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Image Analysis of Plasma Induced by Focused IR Pulsed Laser

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Abstract: Plasma induced by focused laser beam is very essential especially in laser material interaction. Preliminary study leading to this research has been carried out. A Q-switch Nd:YAG laser was employed as a source of energy. The laser was focused using a wide-angle camera lens. The formation of plasma at the focal region was visualized perpendicularly using a CCD video camera interfaced to an image processing system. The dynamic expansion of the laser plasma was grabbed in conjunction with a high-speed photographic system. The observation results show that the plasma was formed in an ellipsoidal shape. The lateral width and the length of the plasma were found gradually increased with respect to the energy. However the intensity of the plasma beam was discovered as a nonlinear effect.

Keywords: Laser, plasma, image, lens, morphology.

1. Introduction

Plasma is ionized state [1]. In plasma, electrons have freely dissociated from their atoms, which then become positive ions in a process that occurs in the presence of photons. Thus plasma can conduct electricity, but in most other properties plasma behaves like a gas. Plasma is properly considered as a fourth state of matter, along with solids, liquids and gases [2]. Plasma can be created by heat, electricity or radiant energy, such as laser light. Two common examples of the existent of plasma are lightning and electrical spark. Additional examples are neon signs, the ionosphere in the outer earth atmosphere, the sun and in fact all stars are made completely of plasma, and thus 99% of the universe is plasma [3].

Light energy can create plasma when high power density is achieved, commonly between 10^{10} and 10^{12} Wcm^{-2} [4]. This high irradiance can be obtained when laser light is sufficiently condensed in time and space. Such a sudden event is known as optical breakdown. This process of optical breakdown can be demonstrated by focusing a Q-switched Nd:YAG laser [5]. The level of Q-switched laser irradiance necessary for initiating optical breakdown has electrical field strength in excess of 10^7 V/cm [6].

The mechanism responsible for optical breakdown by Q-switched Nd:YAG laser is due to the effect of pulse duration [7]. Q-switched pulses of several nanosecond duration cause ionization, mainly by focal heating of the target [8]. At the focal spot, temperatures in excess of several thousand degrees Celsius are achieved. The electric field strength and the heat at the focal spot are adequate to initiate ionization. Once the optical breakdown have been initiated the ionization, that is by starting free electrons, plasma grows through the mechanism of electron avalanche or cascade. The optical breakdown and the plasma formation are sudden events, or a high-speed phenomenon. Meaning that, to record such events need very sophisticated equipment and high-speed photography technique.

In this present paper we are going to report the experiment of plasma formation in air. The phenomena were grabbed by using an ultra high-speed photography technique with the aid of image processing system.

2. Experimental Setup

A Q-switched Nd:YAG laser with 1.06 μm wavelength and 8 ns pulse duration was employed as a source of energy. Lumonics HY200 Nd:YAG laser was focused using a short focal length of 28 mm camera lens. A wide-angle camera lens was chosen in order to avoid the aberration phenomenon.

The Nd:YAG laser was triggered externally by using an electronic trigger delay unit. The delay output of the laser was measured using a large area photodiode that is coupled with a broadband oscilloscope of Hewlett Packard 500 MHz. The output delay of Nd:YAG laser after been triggered was found as 180 μs. The electronic trigger delay unit was utilized to synchronize the signal of Nd:YAG laser and the CCD video camera. When the system was electronically triggered, the event was automatically grabbed and the image was displayed on the screen of the computer. The delay unit was designed so that the image can either be grabbed in real time mode or manually.

For the purpose of setting the optical alignment, the unit will normally set in real time mode. For recording

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performance, the unit was set to manual, and image acquisition will only grab as it commanded.

The luminous blue-white spark emission as indicated by the existence of optical breakdown was visualized and recorded by using a PULNIX TM-6EX couple charge device (CCD) video camera. The CCD camera then was interfaced using frame grabber to the personal computer. A Matrox Inspector digital image processing software version 2.1 was utilized to process and analyzed the grabbing image. The computer also controlled by the trigger delay unit. The whole set of optical and electronic system alignment is shown in Fig. 1.

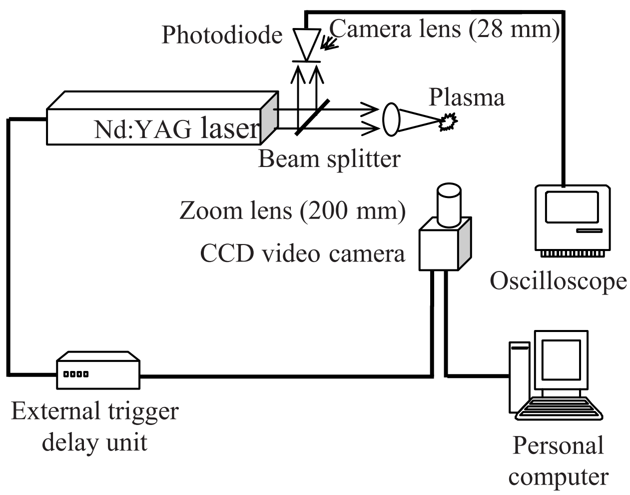


Fig. 1 Experimental setup to diagnose the laser plasma by using high-speed photographic technique and interface with image processing system.

Direct measurement through the Inspector software can be done, if a calibration has been made prior to the process. By taking an image of known dimension, like a negative film and millimeter ruler as shown in Fig. 2, the calibration can be performed by using a Calibration button in the Inspector software. The ruler was employ for the purpose of calculating magnification factor, while the negative film was used to indicate the position of breakdown. During alignment the laser was focused right at the center of the film.

The plasma formation was studied by varying the output energy of the Nd:YAG laser. The energy was verified by changing the oscillator voltage of the laser.

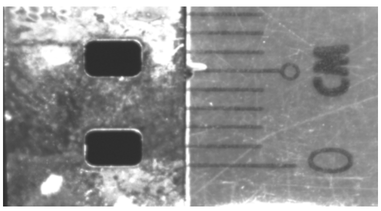


Fig. 2 Used film and millimeter ruler for magnification calibration process.

The energy corresponds to each oscillator voltage was measured by using the digital power meter. The energy responsible for generating breakdown was identified by the appearance of electrical spark emission at the focal point.

3. The Digital Image Processing

The pictures of plasma formation were grabbed at different laser energies. The typical results from these observation studied are shown in Fig. 3.

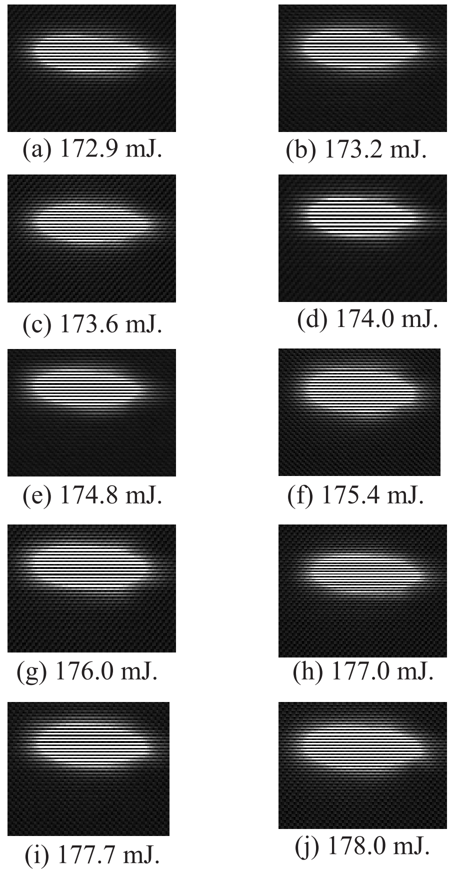
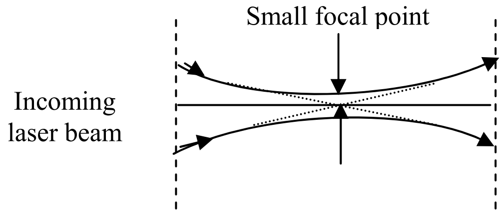


Fig. 3 Plasma formation at different laser energies.

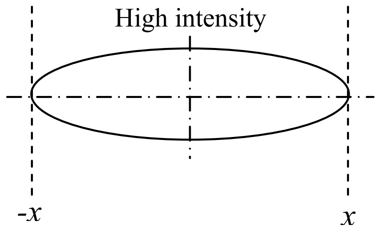
The original images of laser plasma grabbed by this system are in the form of ellipse. This is because the plasma was observed from the horizontal view of the laser beam such as shown in Fig. 4.

Each image was composed of a bright at the center and surrounded by blurring area. The blurred area was appeared because the dynamic growth of plasma formation. The blurred image becomes obvious when the breakdown was formed due to the higher laser energy, shown in Fig. 3 (g) - (j).

Using the image analysis provided in the Inspector that is by using a Morphological application, the black lines appearing in plasma region can be mapped out. The process was done by choosing dilation operation in the Morphological windows. In this process, two objects, which are separated by less than three pixels at any point, will become connected (merged into one object) at that point [9].



(a) Gaussian beam profile.



(b) Intensity distribution on the x-axis.

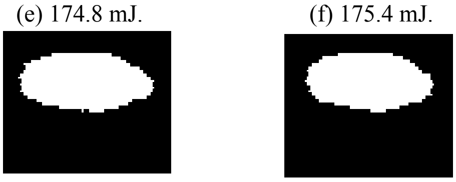
Fig. 4 The distribution of plasma beam along the x-axis.

Secondly, by choosing an appropriate threshold value, the blurred edges appearing on the image can be mapped out. In this particular process, the threshold value is setup at pixel of 128. This process is called *binary contrast enhancement* [10]. The same procedure was applied to each frame on Fig. 3. After all images had been processed, the alteration images are shown in Fig. 5.

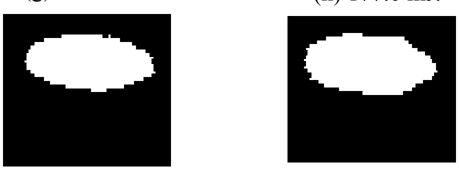
(a) 172.9 mJ. (b) 173.2 mJ.

(c) 173.6 mJ. (d) 174.0 mJ.

(e) 174.8 mJ. (f) 175.4 mJ.



(g) 176.0 mJ. (h) 177.0 mJ.



(i) 177.7 mJ. (j) 178.0 mJ.

Fig. 5 The altered laser plasma image by using Morphological and Threshold applications.

Advantages offered for such alteration figure is the accuracy in measuring the size of plasma. The dimensions of plasma in length and wide could be measured accurately in compared to prior images. The size of the plasma was measured from each frame in Fig. 5. The obtainable sizes of plasma were plotted with respect to the laser energies. The graph of plasma size against the oscillator voltage is shown in Fig. 6.

The curve of the graph in Fig. 6 shows that, the size of the plasma increased gradually with respect to the delivered energy. At the end of the curved, the fluctuation occurred. This is possibly due to the instabilities of the laser output when operated at higher energy. The fluctuation becomes apparently in the diameter of the plasma, such as shown in the lower curve of Fig. 6.

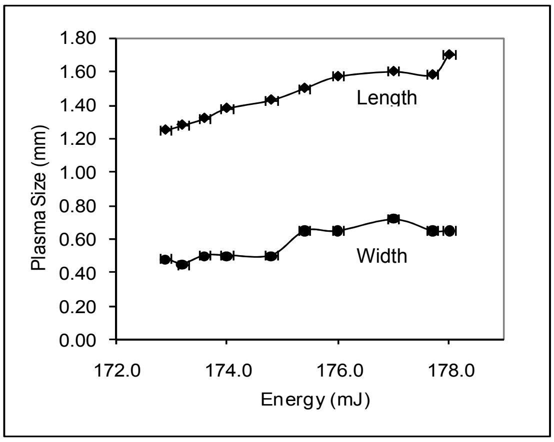


Fig. 6 The size of laser plasma as a function of laser energy.

Other aspect that could be considered in diagnostic of the plasma is its intensity distribution across the plasma region. In this matter, Fig. 3 is again utilized in order to obtain the information.

Using the image processing analysis, certain command is choose to analyze the profile across the beam (taken on wide section). The intensity profile for each frame in Fig. 3 is shown in Fig. 7.

The peak intensity in arbitrary unit from each profile was taken and plotted as a function of energy. The relationship between the two parameters is shown in Fig. 8. Initially the graph shows that, the intensity of the plasma is gradually increasing with the increasing of energy. The minimum intensity is obtained when the supplied energy is 173.2 mJ. The graph then start to fluctuate when the energy is increasing higher and finally decreased drastically as the energy reach at the highest value.

The nonlinear phenomenon of laser plasma intensity is generally cause by the light wave which is coupled with electron plasma wave. Thus the coupling generates a spatial variation in the electric field intensity, which can enhance the ion density fluctuation via the ponderomotive force. Hence, there's a feedback loop, and instability can result.

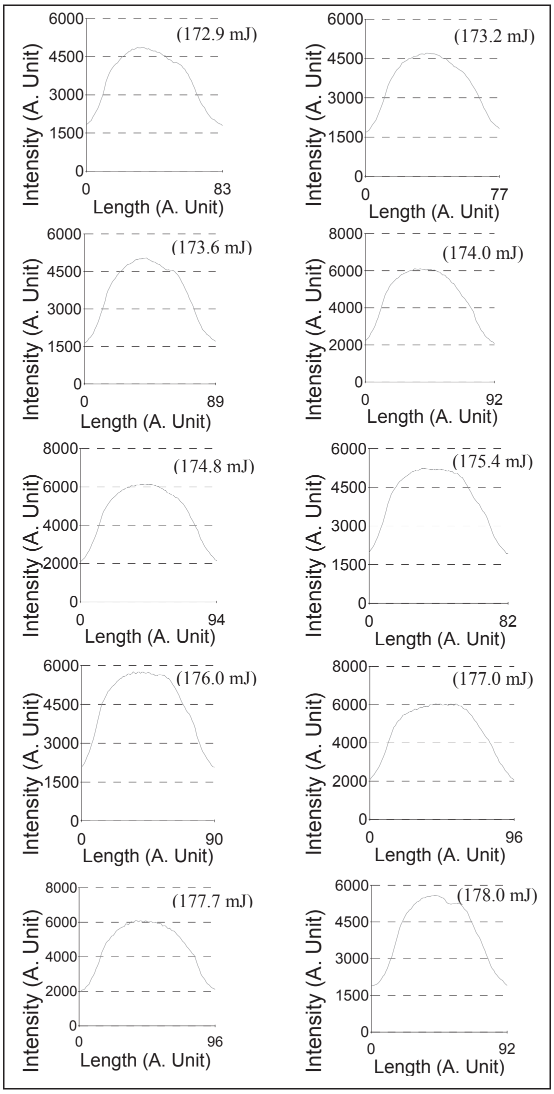


Fig. 7 The intensity profile of each frame in Figure 3.

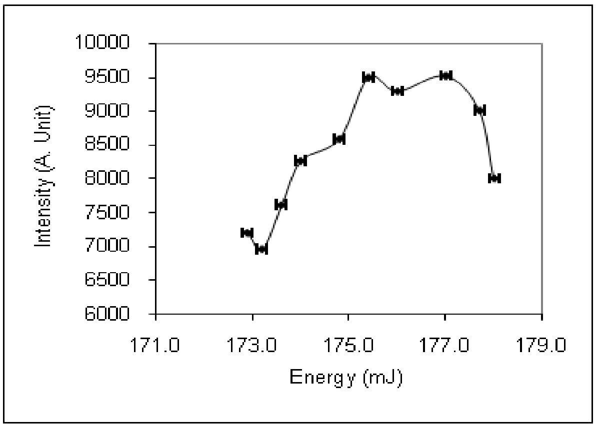


Fig. 8 The intensity of the plasma as a function of energy.

4. Conclusion

The plasma can be generated by focusing a Q-switched Nd:YAG laser in the air. Diagnostic of the laser plasma was carried in conjunction of high-speed photography technique with the aid of image processing system. The contrast of the image can be altered by using a binary morphological processes and binary contrast enhancement. The plasma size was found greater at higher energy. On the other hand the intensity of the plasma is unpredictable. From the experiment, we notice that there are instabilities in plasma expansion. The nonlinear force of the laser source mostly causes this phenomenon, besides the plasma beam also is unstable.

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