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THE OBSERVATION STUDY OF INFRARED LASER INDUCED PLASMA PLUME

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Abstract
The potential of laser-induced plasma is now becoming an important for fusion research in attempt to add the source of energy. Light energy can create plasma when high irradiance is focused. However, until today scientists and engineers still work hard to get the fusion energy into reality. Hence research is still going on to endeavor the knowledge and better understanding on laser plasma. In order to give some light on the problems, a fundamental study was carried to form the laser plasma. In this case, a high-power Q-switched Nd:YAG laser was employed to generate plasma. Camera lenses with various focal lengths were utilized to generate optical breakdown and initiate plasma plume on a cylindrical brass target. The plasma plume formation were visualized and recorded via CCD video camera. The recorded images were analyzed using Matrox Inspector version 2.1 and video test 5 softwares. The results obtained show that, the plasma area is linearly increased with focal length, which is in good agreement with the beam waist concept. Whereas, the length of plasma, related to the Rayleigh range was found quadratically change with focal length.

Keywords: Focal length, high speed imaging, laser plasma plume, Q-Switched Nd:YAG laser.

INTRODUCTION

When a high-power laser beam is focused onto a solid surface, it can cause the removal of material by melting, vaporization, plasma plume formation, sublimation and a number of nonlinear processes [Atwee *et al*. 2001]. Pulsed laser induced plasma has a very short temporal existence and is transient in nature, with a fast evolution of the characteristic parameters that are heavily dependent on irradiation conditions such as incident laser intensity and irradiation spot size [Harilal Bindhu *et al*. 1997]. The characteristics of the plasma plume are dependent on laser irradiance, target composition and atmospheric condition [Harilal Bindhu *et al*. 1997, Liu *et al*. 1999]. The study of laser induced plasma plays a fundamental role for diagnostic purpose in many applications, concerning laser-matter interaction as pulsed laser deposition [Giardini *et al*. 2000, Teghil *et al*. 2001, Cappelli *et al*. 2002, De Giacomo *et al*. 2002, Teghil *et al*. 2002], laser induce breakdown [Ali and Bidin 2003], welding, cutting and so on. In spite of the fact that, in the last 10 years, a large number of experimental

and theoretical works [Urbassek and Mitchel 1987, Singh and Narayan 1990, Chrisey and Huber 1994, Pant *et al.* 1998, Amoruso 1999, Di Trolio *et al*. 2000, Flemini *et al*. 2000] were devoted to the laser induced plasma generation and evolution, these processes are still not well understood. The interpretation of experimental results can be improved by theoretical modeling of the plume expansion. Many techniques were used for expansion of plasma produced by nanosecond lasers: by magnetic field [Pant *et al.* 1998]; increasing the output energy of laser [Ali and Bidin 2003], and/or focusing system consisting of two or more lenses [Eugene Gordon 2000]. The Dynamics and understanding of plasma plume expansion into ambient atmosphere is of special importance in pulsed laser deposition, nanocluster formation, and laser induced breakdown studies [Yalcin *et al*. 2005]. When a laser beam being focused to a point, all its energies are concentrated on one small point making the point to have a great energy, high temperature and high pressure [Bidin and Amar 2003].
High-speed photographic recording of expanding laser plasmas using framing image-converter cameras is a well established technique [Ready 1971, Hughes 1975]. More recently, the technique has been refined by the introduction of CCD (Charged Coupled Device) cameras which allow direct digital recording, thus greatly facilitating computer processing of the images as well as providing improved sensitivity. Such imaging devices have been widely used in the area of pulsed laser plasma plume formation. Despite the technique's ease of implementation, the retrieval of quantitative information characterizing the plume expansion from the imaged is usually complex. By narrowing down the spectral range of the imaged light to that of a know emission line, it becomes possible to track the evolution of the corresponding excited state. This can be carried out by placing a tuned interference filter in front of the camera, in which case, the measured intensities are integrated over the line profile [Whitty and Mosnier 1998]. However until today scientists and engineers still work hard to get the fusion energy into reality. Hence research is still going on to endeavor the knowledge and better understanding on laser plasma.
The objective of this paper is to generate the plasma plume by using various lenses with different focal lengths.

THEORY

Prior to the investigation it is better to have some knowledge about the Gaussian beam and ions behavior at the focal region. First, let's find the relationship between the plasma and focal length. Consider the beam has been focused at target illustrated in Fig. 1.
The cone angle 'θ' with regards to the lens has aperture of 'a' and focal length 'f' can be written as:

$$\tan\theta = \frac{a}{f} \qquad (1)$$

However, it is assumed that 'θ' is much smaller; such as

$$\tan\theta \approx \theta = \frac{a}{f} \qquad (2)$$

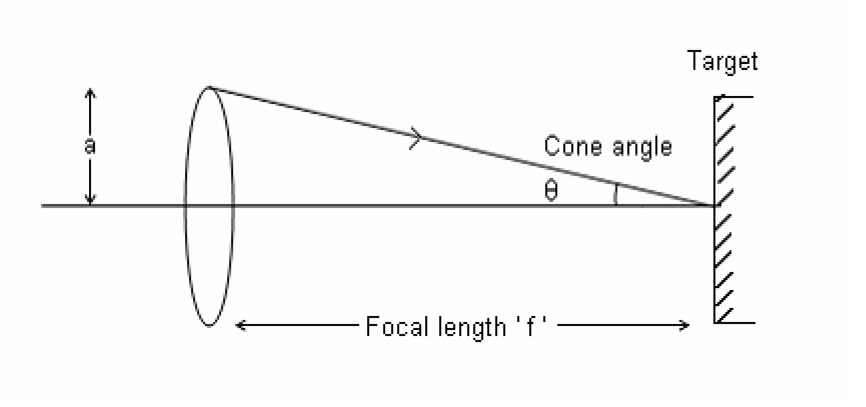


Fig. 1: The generation of plasma related to focal length.

The beam waist at the focal point is written as [Milonni and Eberly 1988];

$$\theta = \frac{\lambda}{\pi\omega_o} \quad (3)$$

Substituting Equation (2) in (3) it is obtained that

$$\omega_o = \frac{\lambda \, \mathbf{f}}{\pi \, \mathbf{a}} \quad (4)$$

where 'λ' is wavelength of laser beam of 1.064 μm, and 'a' is the aperture of the camera lens which remains constant in the experiment as 11 mm. Hence the beam waist is proportional to the focal length.

Theoretically the beam waist is determined the Rayleigh range 'z_o' as shown in Fig. 2 which means that the laser beam is energetic enough to cause damage when interact with the target or ionize the air molecules and other impurities in the region.

So it can be written as:

$$\mathbf{z_o} = \frac{\pi\omega_o^{\,2}}{\lambda} \quad (5)$$

If one substitutes Equation (4) into (5), one has

$$\mathbf{z_o} = \left(\frac{\lambda}{\pi \, \mathbf{a}^2}\right)\mathbf{f}^2 \quad (6)$$

This last equation indicates that the Raleigh region has a quadratic relationship with the focal length.

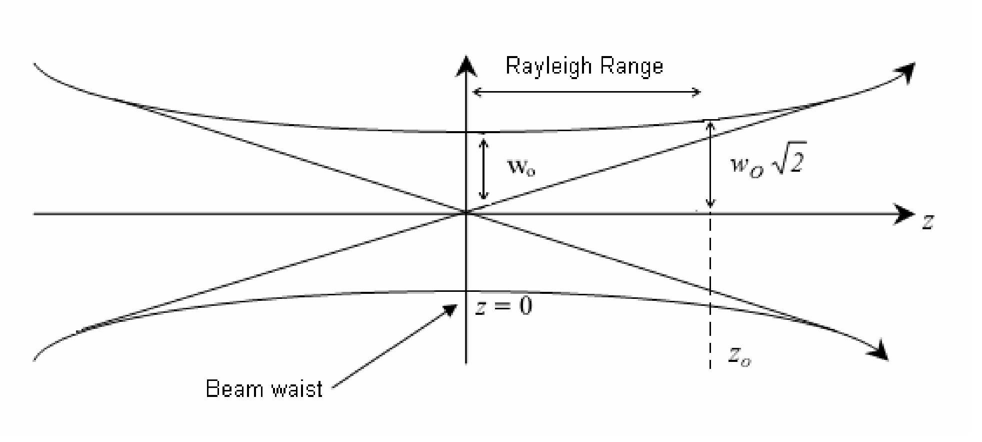


Fig. 2: Rayleigh range and beam waist.

EXPERIMENTAL SETUP

A Q-switched Neodymium-doped Yttrium Aluminum Garnet (Nd:YAG) with chemical formula of $Nd:Y_3Al_5O_{12}$ solid state laser was employed as a source of energy. The fundamental wavelength of the beam was 1064 nm with pulse width of 10 ns. The laser was operated repetitively at the rate of I Hz with maximum pulse energy of 289 mJ. The laser beam was focused using camera lens to avoid aberration at the focal point. The intense hot radiance due to this aberration will create multi-breakdown along the focal depth. Hence camera lens is preferable compare to conventional lenses. In order to verify the size of plasma, various focal lengths are provided. The shorter focal length 28 mm provided by a wide angle of Soligor camera lens. Another series of focal length which including of 35, 50, 75, 85 and 100 mm was conducted by other Soligor camera. The laser was focused on a brass cylinder target with diameter of 13.09 $\pm$ 0.02 mm and length of 0.4 $\pm$ 0.02 mm. The target was hold vertically via the incoming beam. A Pulnix CCD camera was used to visualize and permanently record the plasma formation which interfaced to a personal computer. Matrox Inspector 2.1 software was utilized to process and analyzed the image. Neutral density filter with optical density of 3 was employed to avoid over exposure to the camera. The camera was aligned horizontally to plasma formation to protect from damaging. The experiment was carried in air under atmospheric pressure at room temperature. The laser energy was kept constant at 198 mJ. The emitted energy has an absorption length of several millimeters in the hot plasma, but only a fraction of millimeter in the surrounding. This can be observed in the real field as the plasma plume get larger along the beam axis and limitedly spreading in vertical axis. The whole experimental arrangement is depicted in Fig. 3.

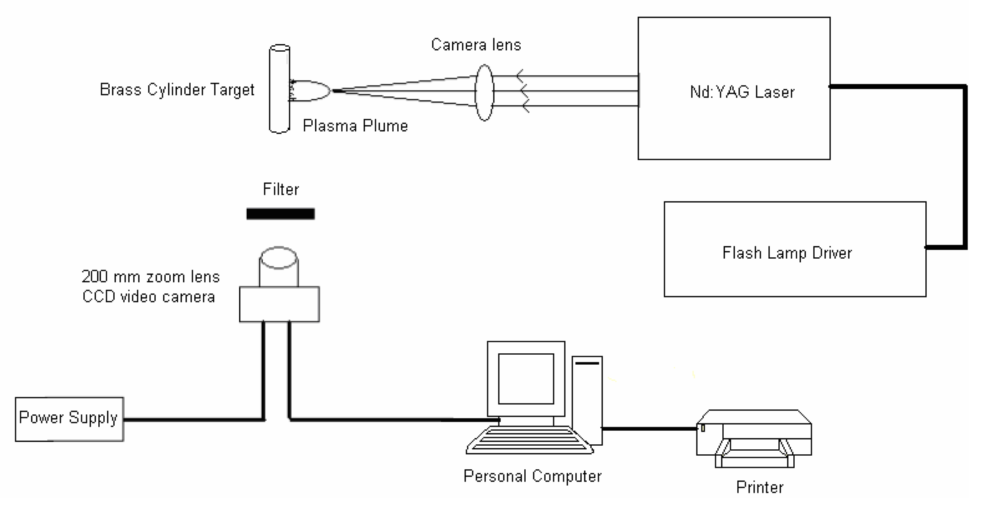
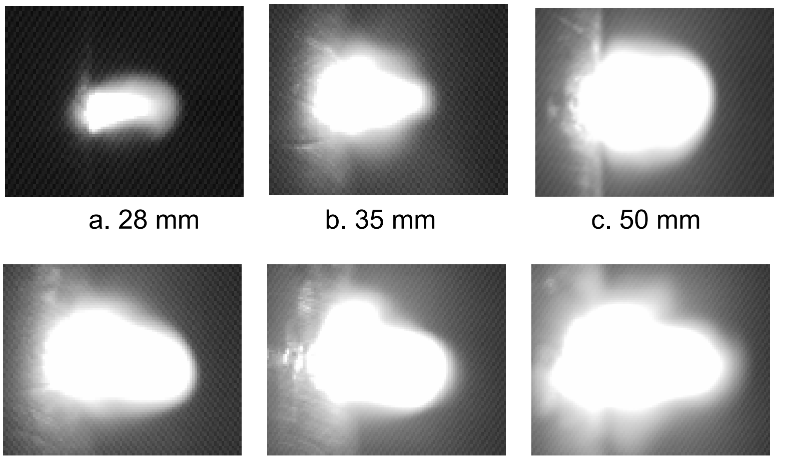


Fig. 3: Experimental setup to generate plasma plume.

RESULTS AND DISCUSSION

The typical results obtained from this observation are shown in picture of Fig. 4. The plasma plume images are arranged in the increasing order of focal length of the camera lens. The bright image is indicating the plume of plasma. The vertical line at the left side of each individual picture indicates the position of brass target. The plume of plasma is small with short focal length and getting larger with longer focal length.



a. 28 mm b. 35 mm c. 50 mm

d. 75 mm e. 85 mm f. 100 mm

Fig. 4: Plasma plume at various focal lengths.

Almost all images in Fig. 4 are accompanied with the blurry area. This blurry area is possibly due to diffusivity of heat and the scattering of ions and electrons. Immediately after the laser was focused right on the top surface of the brass, the particles were removed. These debris or the impurities were enhanced the ionization and lower the breakdown threshold. The way, the particles splash out determined the shape of the plasma formation. The removal particles, the electrons and the positive ions from air molecules are mutually interacted with each other together with the incoming beam. The *Bremstrahlung Effect* due to photons absorbing the electrons and the *Inverse Bremstrahlung* due to the recombination of the electrons and positive ions are responsible to cause the release of photons or fluorescence. The incandescent of the heats produced from the high temperature and photons librated from the plasma region subject to induce blurry area. The *Brillouin Scattering* and stimulated *Brillouin Scattering* due to the shockwave involved in expanding and forming heavy dense plasma region.

All the mechanisms involve in the interaction which cause ions disrupt on the target and responsible to expand and scattered the plume of plasma formation. The momentum of photons when impact on the target, also induce vibration which also contribute to cause the blurry part of the plasma. It also needs to note that plasma plume is dynamically expanding phenomenon, so due to the high speed motion also subjected to induce blurry image. As a result the combination of all these mechanisms, interaction, vibration and motion cause the image of plasma to become blur. This is obvious especially when the tested lens has the longest focal length such as shown in Fig. 4(f), which is taken with 100 mm focal length.

It is clearly observed that the plasma plume expand when the focal length is increased. Quantitatively, the plasma area and dimension were measured precisely via the Matrox Inspector software. The collected data were used to plot graph such as shown in Fig. 5.

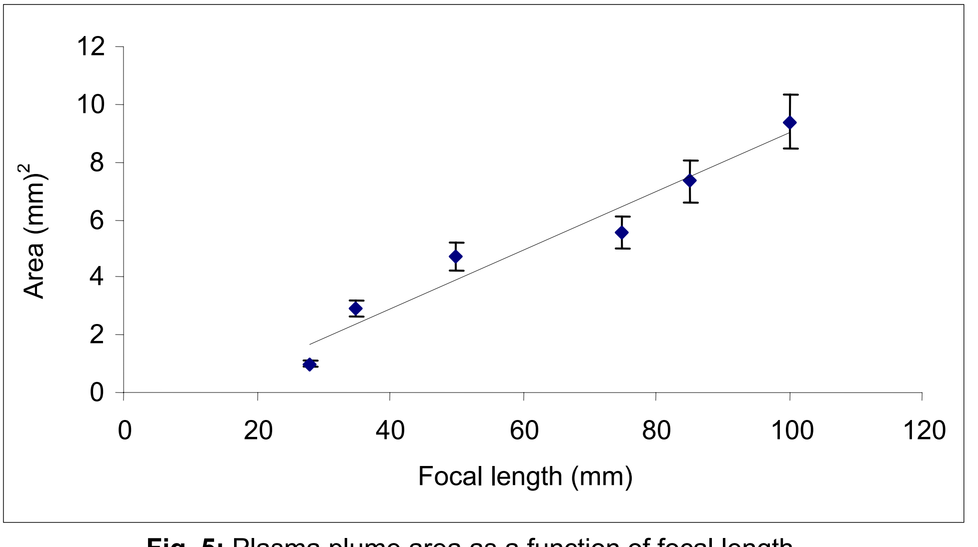


Fig. 5: Plasma plume area as a function of focal length.

Obviously the plasma area is proportional to the focal length. This result is in good agreement with the equation (4). In practice, the beam waist could be measured through the area of the beam spot at the focal point. It can influence the damaged area on the target or the area of the plasma formation. However the plasma area is of course much greater than the beam waist. Beam waist is the parameter of laser beam, the source used to initiate the plasma. The plasma is the production of high energy effect and strong electric field at the focal point. The supersonic wave soon become acoustic wave cause the charges and the removable particles diffused and spreading out of the focus point region, which cause the plasma also become much greater than the size of beam waist.

The plasma dimension in term of length and width is measured accurately via the Matrox Inspector software. The data collection is used to plot graph such as shown in Fig. 6. Curvature graph obtained indicate that plasma size is almost quadratic change which the focal length. This result again shows the similarity with the Rayleigh theory of equation (6).

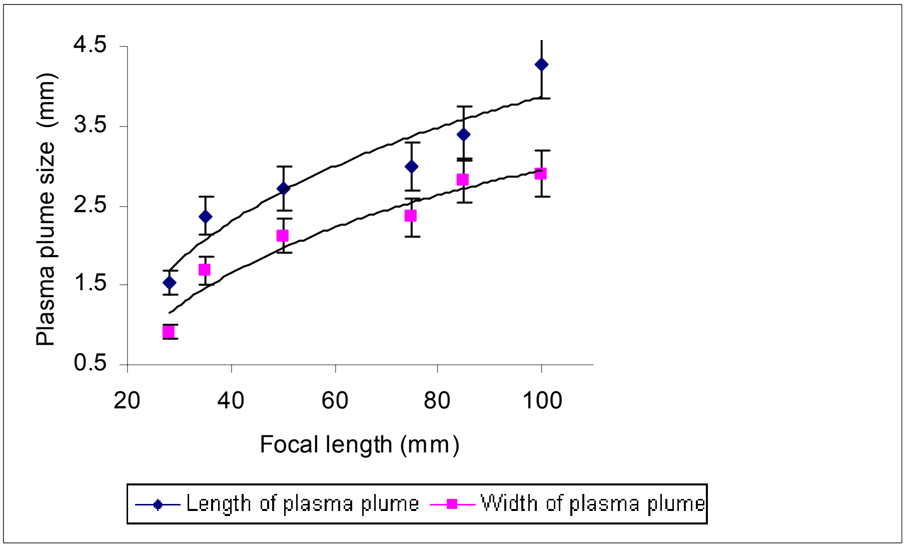


Fig. 6: Plasma plume size with respect to the focal length.

It is likely to note that, the Rayleigh range is representative of the length of plasma. Nevertheless the length of the plasma is larger than the theoretical value of the Rayleigh length. This is because the gross interaction occurred in between the removable particle, electrons and ions. The scattering, reflection, absorption diffusion and emission of photon in the plasma region, actually combined together to cause the plasma length as well as the width of plasma much greater than the original Rayleigh range and the beam waist themselves.

CONCLUSION

The infrared IR Nd:YAG laser induced plasma plume was successfully studied. The laser beam was focused using variable lenses on a cylindrical brass target. The formation of plasma plume area was observed linearly increased with the focal length. The result was found in good agreement with theory of Gaussian beam. The plasma length was obtained quadratically change with focal length. This experimental result was also approved by the Rayleigh theory. Thus the plasma formation depends on the lens to focus the laser beam. In this particular study it is observed that the longer the focal length the greater the plasma formation.

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