Comparative Study: Laser Produced Plasmas in cryogenic and non-cryogenic Liquid

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ABSTRACT: A Comparison between dynamics of Liquid Nitrogen and Water plasma is under taken. A Q-switched Nd: YAG laser (1064 nm, 9-14ns and 1.1 MW) is focused on the Liquid-Nitrogen-jet in air to generate plasma. The images captured by CCD based computer controlled image capturing system are analyzed by obtaining contours, intensity profiles etc. Intensity profiles show that the average intensity is same for both targets, where as intensity for Liquid Nitrogen plasma is little higher than Water plasma in central region. The central region of Liquid Nitrogen plasma is larger as compared to other (intermediate & outer) regions whereas in case of Water plasma all three regions (central, intermediate & outer) have comparable intensity ratio. In Liquid Nitrogen plasma intensity decreases abruptly from central to intermediate region, whereas in case of Water plasma intensity decreases gradually through different regions.

Keywords: Nd:YAG Laser, Laser Induced Plasma, Liquid Nitrogen jet, CCD imaging.

I. INTRODUCTION

The laser produced plasma has many applications like microscopy and lithography, PLD, medical industry etc. [1,2]. Conventional targets for LIP produce debris which may damage sensitive components positioned close to the plasma. Several methods have been designed to minimize the effect of debris. The amount of debris produced can be limited by replacing conventional solid targets with gas, liquid-droplet or liquid-jet targets. By choosing liquid or frozen microscopic droplets as target, this problem has also been shown to be negligible. Use of cryogenic liquids in the liquid-jet mode, it lowers the debris emission from droplet targets [1, 3-7].

Depending on the hydrodynamic properties of the liquid, the source may be operated either in the liquid-jet mode or the droplet mode. For application point of view, the liquid-jet mode is often preferable due to its higher stability and simpler triggering [8-10]. The drift in drop position is experimentally and theoretically shown to be due to a temperature induced increase in target liquid viscosity as a result of evaporation [11]. A cooled capillary nozzle arrangement allows long term operation and avoids previously reported jet instabilities [12].

Liquid metal jets as regenerative targets for hot and dense laser plasma generation has many applications [3]. Other liquid targets like water jet, methanol and ethanol were also used for optimization of target and nozzle size, laser energies and pulse durations on the source size of the plasma [13-14]. Tapered glass nozzles suitable for liquid jet target generation in laser plasma sources provides flexibility regarding nozzle diameter and pressure, thereby allowing optimization of the target size [15].

The plasma evolution and expansion may be analyzed by photography using different diagnostics but the easiest one is the analyzing the plume images. Different plasma characteristics have been studies. The results show that, the plasma area is linearly increased with focal length, which is in good agreement with beam waist concept. The plasma parameters that led to radiation emission have been studied by many scientists [16-22].

This paper reports the intensity variation in cryogenic liquid (Liquid Nitrogen) and Non-cryogenic liquid (Water) having different intermolecular forces strengths in air.

II. Experimental Setup

A liquid-jet (Liquid Nitrogen, Water) is obtained by employing a self fabricated stainless steel designed target delivery system. It is mounted on the six ports spherical stainless steel chamber. A Q-switched pulsed Nd:YAG laser (1064 nm, 1.1 MW, 9-14 ns) is irradiated on liquid target jet (diameter ~5mm) in air (1 atm). Laser spot size and laser power densities are 12 µm, 3 x 1012 W/m2 respectively. Several images (region=visible, λ=750-400nm) for Liquid Nitrogen jet and Water jet plasma ~105K are captured using CCD based computer controlled image capturing system. The schematic of experimental setup is shown in figure 1.

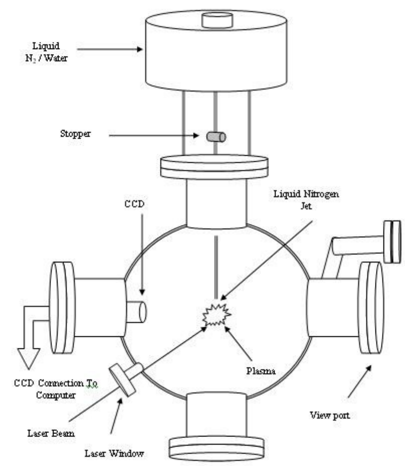


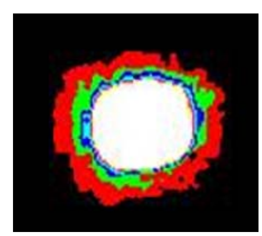
Figure 1: Schematic of Experimental Setup

III. Result and Discussion:

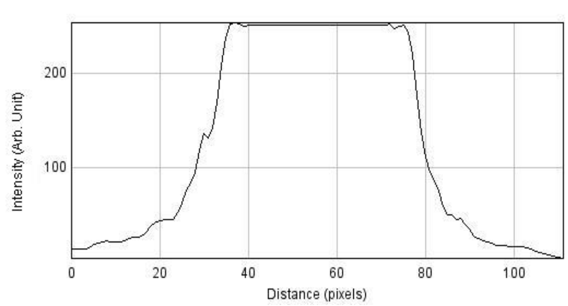
Several images for Liquid Nitrogen Jet Plasma and Water Plasma are captured using CCD based computer controlled image capturing system. Out of these images, five images for Liquid Nitrogen jet plasma and five images for Water jet plasma are selected.

One of five images along with intensity profile for Liquid Nitrogen jet plasma are shown in figures 2.

(a) Original Image of LN_2 Plasma



(b) Pseudo Color Image



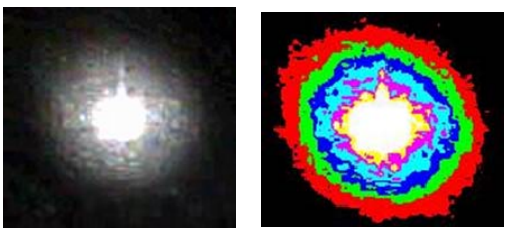
(c) 2 D Intensity Profile

Figure 2: Images of Liquid Nitrogen Plasma along with Intensity Profile.

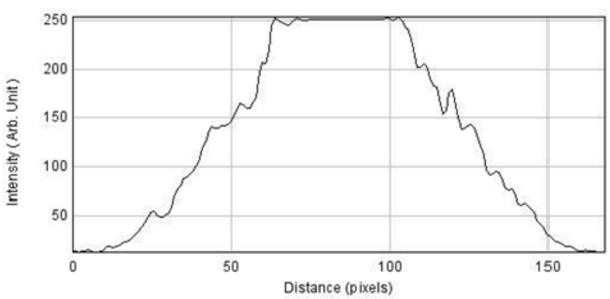
(Length of plasma = 17.0 mm, Peak Intensity = 250 Arb. Units)

The figure 2a is real image of Liquid Nitrogen jet plasma captured by CCD. The figure 2b is the pseudo colored image showing that region I (central region) is most dominant as compared to region II (intermediate region) and region III (outer region), which are very small in length and have very low intensities as compared to region I (central region). The figure 2c shows two dimensional intensity profiles for Liquid Nitrogen jet plasma.

One of the five images along with intensity profile for Water jet plasma shown in figures 3.



(a) Original Image of Water Plasma (b) Pseudo Color Image



(c) 2 D Intensity Profile

Figure 3: Images of Water Plasma along with Intensity Profile.

(Length of plasma = 32.0 mm, Peak Intensity = 255 Arb. Units)

The figure 3a is the real image of Water Jet plasma. The figure 3b shows the pseudo code image which reveals that region II (intermediate region) and region III (outer region) also have greater width and intensity as compared to Liquid Nitrogen jet plasma. In Water jet plasma intensity decreases almost uniformly through different regions as compared to Liquid Nitrogen jet plasma, where maximum intensity lies at the centre with maximum length. It means the region II (intermediate region) and region III (outer region) are very very small as compared to region I (central region) whereas in Water different regions have suitable ratio. The figure 3c shows two dimensional intensity profiles for Water jet plasma.

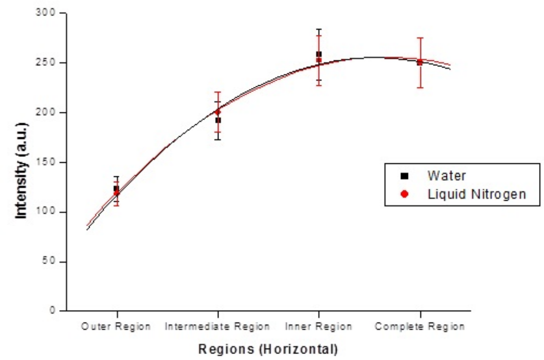


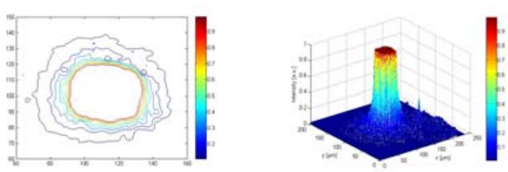
Figure 4: Comparison of intensity profile between Liquid Nitrogen jet plasma and Water jet plasma in different regions.

Figure 4 shows the comparison of intensity for outer region, intermediate region, inner region and complete image respectively. Comparison of intensity profiles for both Liquid Nitrogen Jet plasma and Water Jet plasma in figure 4 which shows that as a whole the intensity is same for both the targets, Whereas in central region intensity in Liquid Nitrogen plasma is little higher than that of Water plasma. In intermediate region Water has greater intensity as compared to Liquid Nitrogen Jet plasma. Similarly in outer region Liquid Nitrogen Jet plasma intensity is again higher than Water Jet plasma as shown in figures 4.

The intensity of plasma is related to the density gradient. Bright light is emitted as a result of photo-ionization, bremsstrahlung, recombination, excitation and de-excitation etc. As the plasma accelerates and expands, its density decreases. The plasma frequency is proportional the square root of the electron density [12]. Thus the plasma frequency will decrease with decreasing the electron concentration. During the expansion, the ambient air exerts resistive force over the plume expansion because as the plume expands then collision between plasma species and air molecules takes place so plasma species will lose their momentum and transfer their kinetic energy to the air molecules which in turn inhibit the further expansion [14, 18].

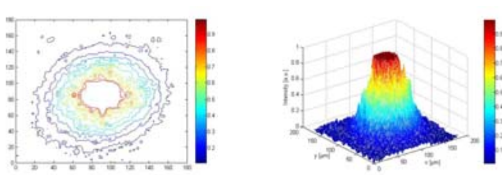
During the plasma expansion, the electrons are heated to maximum temperature so maximum absorption of laser takes place and intensity reaches at its maximum peak value due to high density and temperature. Also when the electrons are heated to maximum temperature they separate from ions and move in the forward direction [18-20]. Such charge displacement creates electronic sheath, which eventually accelerates the ions. Hence the ions are collimated beam. Electrons move due to coulomb forces and during this process there are also recombination, excitation, de-excitation, inverse bremsstrahlung [20].

The 3D intensity profiles and contours were also obtained for Liquid Nitrogen plasma and Water plasma shown in figures 2 and 3 to have further analysis as shown in figures 5 and 6.



(a) Contours **(b) 3 D Intensity Profile**

Figure 5: Contours of Liquid Nitrogen plasma along with 3 D Intensity Profile.



(a) Contours **(b) 3 D Intensity Profile**

Figure. 6: Contours of Water plasma along with 3 D Intensity Profile.

Figure 5a and 6a show Contours which provide the boundaries for different regions with decreasing intensity. Figure 5b and 6b shows intensity profiles with reference to the spatial volume. The curves are in agreement with analysis discussed earlier and in literature. At distance close to the target an intense continuous emission was observed. The emission spectrum is attributed to both the elastic collisions of the electron with the atoms and ions (free-free emission) and the recombination of the electron with the ions (free bound emission). [23]

From figures 5 and 6, it can be seen that in case of Liquid Nitrogen plasma most of the intensity is available in the centre and intensity regions are less in number if we compare it with the Water plasma. Also from three dimensional intensity profiles it is clear that the change in intensity from inner to outer region is much abrupt in case of Liquid Nitrogen Plasma whereas in case of Water Plasma, intensity decreases gradually. Heat transfers from inner region to outer region of Water plasma is much slower than in case of Liquid Nitrogen plasma, which may be due to strong intermolecular bonding and high boiling point of Water.

IV. Conclusion:

As a whole, intensity is same for both targets where as in central region intensity for Liquid-Nitrogen-jet plasma is little high er than Water-jet plasma. In case of Liquid Nitrogen plasma central region is most dominant as compared to intermediate and outer regions, which are very small in length as compared to central region. As well as outer regions have very low intensity as compared to central region. Whereas in case of Water-jet plasma intermediate and outer regions are also have comparable width and intensity as compared to Liquid-Nitrogen-jet plasma. In Water plasma, intensity decreases less abruptly through different regions as compared to Liquid-Nitrogen plasma, where maximum intensity occurs at center with maximum length. i.e. in Water-jet plasma different regions have comparable ratio and intensity decreases gradually but not abruptly.

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