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Angular distribution and forward peaking of laser produced plasma ions

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Abstract

This paper represents the results of a study of angular distribution of laser produced ions (LPI) of Al, Cu, and Ag. The angular distribution is studied by CR-39 (SSNTD) and ion assisted sputtering experiments. A Q-Switched Nd:YAG laser (1.064 μm, 1.1 MW) with 10 mJ pulsed energy was used to produce the Ag ions, which were detected by CR-39 detector mounted at $-17.5°$, 0°, 17.5°, 30°, 60°, and 90° from the normal to the target placed at a distance of 9 cm from the target. Etched CR-39 detectors then observed under the Motic DMB Series optical microscope. A bunch of ions was detected along the normal of target due to self generated collimation of ions. This is termed as Forward Peaking of Laser Produced Ions. Similar results were also observed from sputtering of polished Al substrate by laser produced ions of Cu and Sputtering of polished Cu substrate by laser produced ions of Al. The surface morphology of the ion irradiated samples were observed under the Scanning Electron microscope (SEM) S 300 Hi-tech. Formation of a circular damage on the surface of the substrates by irradiation conforms the ions collimation along the normal or Forward Peaking of ions.

Keywords: Forward peaking; Laser produced Ions; Motic DMB series; SEM S300 Hi-tech; Solid state nuclear track detector (SSNTD); Sputtering

1. INTRODUCTION

Plasma emission from the target surface starts soon after the laser photon reacts with the target surface (Harilal *et al*., 2003), which is called laser produced plasma (LPP). When the laser radiation is absorbed by the solid surface, electromagnetic energy converts into electrical excitation and then into thermal energy, chemical energy, and mechanical energy to cause evaporation, ablation, excitation, plasma formation, and exfoliation. Evaporants form a plasma plume consisting of a mixture of energetic species including atoms, molecules, electrons, ions, clusters, micron-sized particles, and molten globules (Charisey *et al*., 1999). Ions accelerated from the surface of the target form a cone due to their angular distribution. The angular distribution of ions may also be described as the "half angle" of the distribution cone, $\theta_{1/2}$ is defined as the value of angle at which the flux is equal to half of its maximum (Charisey *et al*., 1999). Plasma near the surface of the target has the maximum density of atoms, ions, electrons, and vapors; this layer is called the Knudsen Layer, the plasma on this layer is also called vapor plasma. Within this layer, ions interact with each other and they also generate more ionization states by collisions (Harilal *et al*., 2003). From this layer, the plasma expands thermodynamically away from the target. As the plasma plume accelerates, its density decreases. The plasma frequency is proportional to the square root of the electron density (Hutchinson *et al.*, 2002). Thus, the plasma frequency will decrease with decreasing electron concentration. The layer or surface where the plasma frequency equals the frequency of incoming laser radiation is called the critical layer, and the electron concentration of this layer is called critical concentration (n_c). The plasma ions are angularly distributed with respect to energy and charge states due to the mutual interaction and collisions with neutral atoms ions or with nano particles.

The energy of emitted ions from Nd:YAG laser induced plasma was measured using CR-39/PM-355 (Rafique *et al*., 2003). The ion flux was forced more into the axial direction than compared to that in the radial direction. The maximum energy of ions was found to be 20 keV in the axial direction.

Laser produced plasma ions (laser ion source, LIS) can be divided into three groups with different energies, fast, slow, and thermal. Peterlongo *et al.* (1994) investigated ion emis-

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sion from the plasma produced with the pulsed ablation laser system (PALS) using ion collectors located at various angles. Ion collector signals showed the different groups of ions (slow, thermal, and fast ions), which justifies the angular distribution of ions.

Laska and Krasa (2001) reported on the properties of ions from LIS generated by different kind of lasers, at laser power densities from 10^9 W/cm^2 to 10^{17} W/cm^2, and the mechanism of ion generation was also discussed. It was found that LIS is an efficient source for various applications, depending on the laser parameters, and properties of the target material under study. LIS delivers ions of different atomic masses with multiple charge states having energies from 10 eV–100 MeV/s.

It was recently shown (Umstadter *et al*., 2003) that when the electrons are heated to high temperature or accelerated to high velocities, they get separated from plasma ions. Such charge displacement creates an electrostatic sheath, which eventually accelerates the ions. In this case, ions beam are accelerated as a collimated beam. Target surface defects can play a major role in the species' kinetic energy distribution (Dickinson *et al*., 1991).

The results of angular distribution of LPP ions with respect to their thermal velocity and ionization states for Al target shows the same trend as for Pb target that was studied previously (Stepnov *et al*., 2003). In this paper, we discuss the angular distribution of LPI for Al and Cu with respect to their velocity.

It is well-known from the literature that the properties of plasma can be studied by X-ray spectroscopy. Rosmej *et al*. (2002) have studied plasma by spatially resolved X-ray spectroscopy. They have investigated the generation of fast ions at various laser installations with different flux densities and laser wavelengths. It was demonstrated that the fast ions generation in LPP can be achieved from a very low level of the averaged laser intensity at the surface of target. The time-of-flight mass spectrometry ion diagnostics and X-ray spectrographs give very close results for the energy distribution of the thermal ion components.

When plasma is produced in air by laser, it will interact with air. The interaction of air with LPI not only disturbs their angular distribution, but also disturbs the electron density. The dependence of electron density and temperature on the distance from the target surface and on the laser irradiation were shown (Ying *et al*., 2003). They also discussed how air takes part in the plasma evolution process and confirmed that the ignition of air plasma was by collisions between the energetic electrons and the nitrogen atoms through a cascaded process.

In this paper, we attempted to confirm the idea of self collimated ion beam in LPP of Al and Cu, which is called forward peaking. It is very useful for the generation of laser based ion sources, which can produce a collimated beam of ions due to forward peaking.

LPP can be used as an ions source. Ogawa *et al*. (2003) developed an ion source for generation of low charged heavy ions using low-power KrF excimer and frequency doubled Nd:YAG lasers.

2. EXPERIMENTAL SETUP

In the first experiment, the laser was focused on a polished 99.99% pure copper target, in air at 15° to the normal to the target, polished 99.99% pure Aluminum substrate was placed at a distance of 6 cm along the normal of the target. The Sample was then irradiated by 600 pulses of Nd:YAG (1.064 μm, 1.1 MW, 10 mJ) laser. Then a copper target was replaced by Aluminum target and Aluminum substrate was replaced by Copper substrate. A schematic arrangement is as shown in Figure 1a.

In the second experiment, laser was focused on Silver target of thickness of 40 micrometer, at 45° to the normal of the target, Silver target was irradiated by 600 laser pulses. Six CR-39 (SSNTDs) detectors were placed at −17.5°, 0°, 17.5°, 30°, 60°, and 90°, to the normal of the target in a vacuum chamber at a pressure of $\sim 10^{-6}$ Torr. The schematic of the experimental set up is exposure in the vacuum is shown in Figure 1b.

3. RESULTS AND DISCUSSION

LIP is generated when laser intensity increased the threshold breakdown intensity of the material. The concentration of the plasma species (electrons, ions, atoms, and vapor) is very high and very near to the surface of the target forming Knudsen layer. Within this layer, ions interact with each other and they also generated more ionization states by collisions (Harilal *et al*., 2003). From this layer plasma plume expands due to isothermal expansion until the termination of the laser pulse (Harilal *et al*., 2003). Electrons are much more mobile than ions and neutral atoms, but at the same time, electrons are restricted from escaping the plume, due to the strong space charge field, and collectively moving away from the ions (Charisey *et al*., 1999).

This is the basis for the space charge acceleration model for the ions in the plume. The coulomb's attraction of the ions by electrons that nearly escape at the plume boundary, producing a space charge field that tend to accelerate the ions according to their charge (Bykovskii *et al*., 1974). The space charge of electrons is also called the plasma sheath, which is responsible for ions acceleration along the normal of the target. Ions accelerated from the target surface (Ablation Layer) form a cone. This cone formation is due to the angular distribution of the ions; angular distribution of ions may also be called the "half angle" of the distribution cone, $\theta_{1/2}$, that is, defined as the value of the θ at which the flux is half of its maximum (Charisey *et al*., 1999).

Numerous studies have shown that the angular distribution of the laser-generated flux is often (but not always) much more strongly forward peaked than the flux obtained from small area effusive sources operating under collisionless conditions. This forward peaking phenomenon for depo-

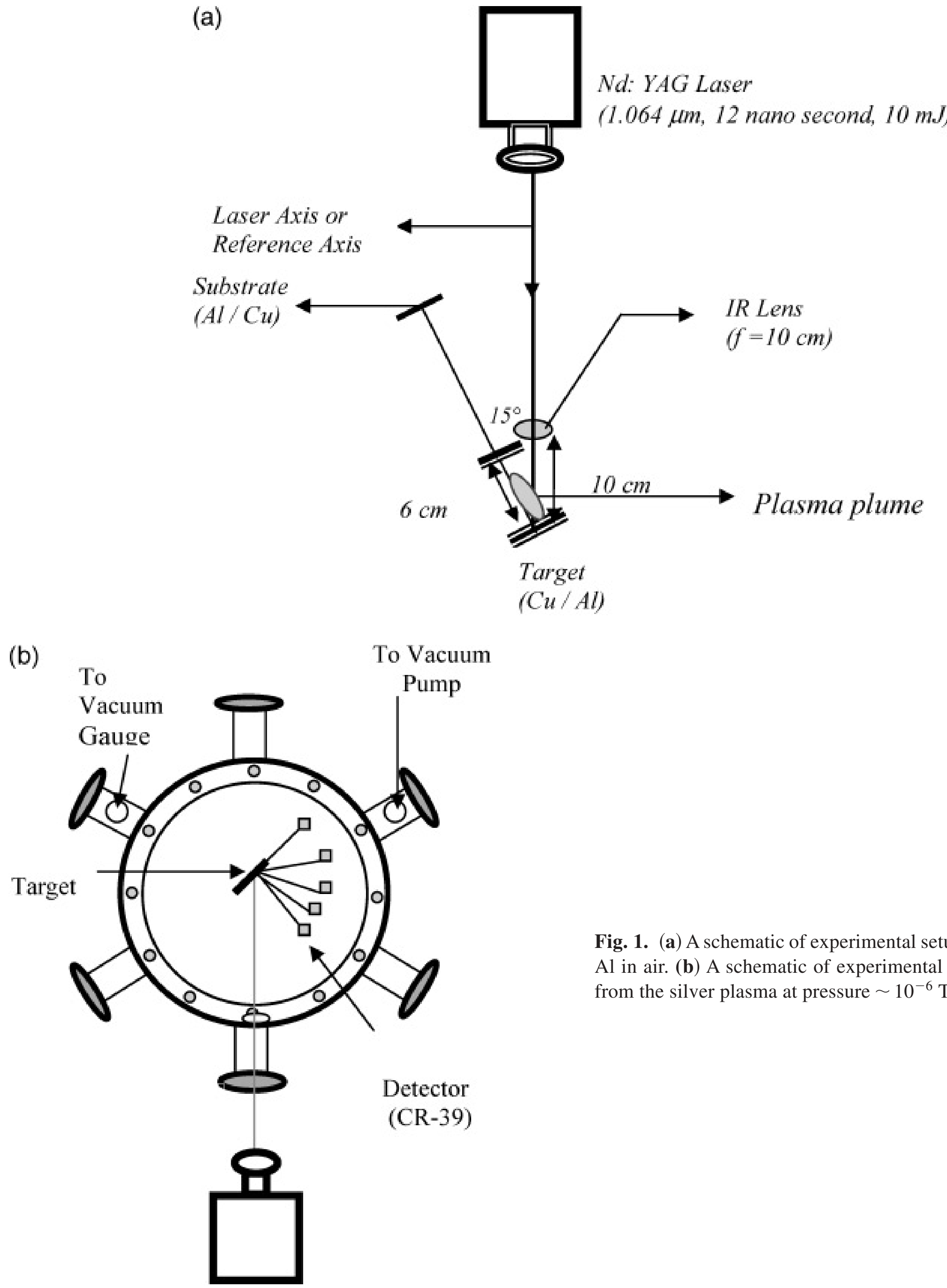

Fig. 1. (**a**) A schematic of experimental setup for ion irradiation of Cu and Al in air. (**b**) A schematic of experimental arrangement for ion detection from the silver plasma at pressure $\sim 10^{-6}$ Torr.

sition in a vacuum arises due to collision of plume species among themselves (Charisey *et al*., 1999). But in the presence of the ambient gas at low pressure or in air (1 atm) the scattering of ions by gas atoms must be considered.

The same results were obtained in silver ion detection experiment; a bunch of ions can be seen very clearly at the detector placed at 0° to the normal of the target as shown in the Figure 2. The ion bunch is measured to be 0.4 mm in diameter. It was also clear from the detector analysis that ions in the bunch was of the order of same average energy with high concentration and higher energy. So ions of greater energy moves along the normal of the target surface. A graph of the ion flux with respect to the angle is shown in the Figure 3.

Angular dependences of ion number density for different charge states, average velocity, and its spread were measured by time-of-flight method by Stepnov *et al*. (2003); ion charge state distribution shows high charge and low charge state groups at normal expansion direction. Ions in these groups have different average expansion velocity and longitudinal velocity spread. Angular distribution of high charge states is narrower than that of low charge state ion group,

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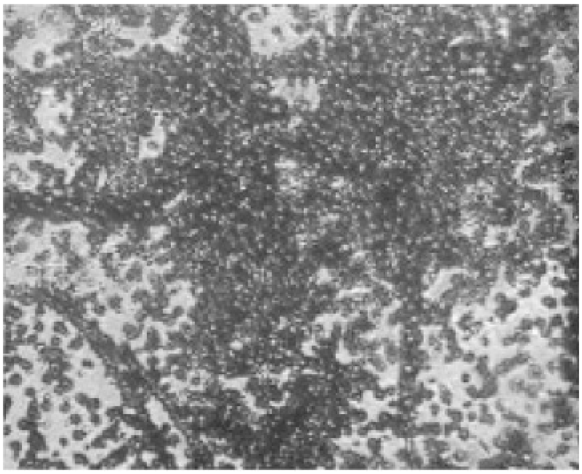

Fig. 2. Detector at 0° showing very clearly the bunch of ions.

maximum yield of low charge states occur at some angle from normal.

Forward peaking is always a result of plasma plume regardless of conditions under which the plasma is produced, in air or in vacuum (Rafique *et al.*, 2003). This was confirmed by the laser produced plasma ions sputtering experiments in air. In these experiments, circular damage of 0.1 mm and 0.14 mm in diameter were observed on the surface of Cu and Al substrates, respectively, those were placed along the normal of the target as shown in the Figures 4 and 5. Thus a collimated beam of plasma ions of greater energy formed along the normal of the target.

At the edge of the Knudsen layer, a bunch of ions of higher concentration might be formed, that is, then accelerated away from the target, due to adiabatic expansion of plasma. During its flight away from the target, ion concentration decreases due to diffusion and scattering by mutual interaction, or with electrons or atoms of plasma that resulted in angular distribution of plasma plume. When this bunch of ions reaches the critical layer, where laser plasma interaction is maximum due to same frequency of both plasma and laser. Electrons might gain energy by inverse bremsstrahlung and accelerated backward due to ponderomotive forces of laser radiation. This phenomenon is responsible for cascade ionization, which results in angular distribution, and thermodynamical expansion of the plasma plume. These effects decrease the concentration of bunch of ions. Further decrease in ion concentration is due to the plasma decay (recombination or attachment) and scattering with ambient gas if present.

The results of the above mentioned experiments support the formation of bunch of ions very initially in the plasma plume, but its concentration decreases due to scattering, recombination, mutual interaction of ions and plume angular distribution.

4. CONCLUSION

It is concluded that a bunch of ions of high concentration in the plasma plume moves along the normal to the target surface in the form of collimated beam called forward peaking. During its flight away from the target surface, its

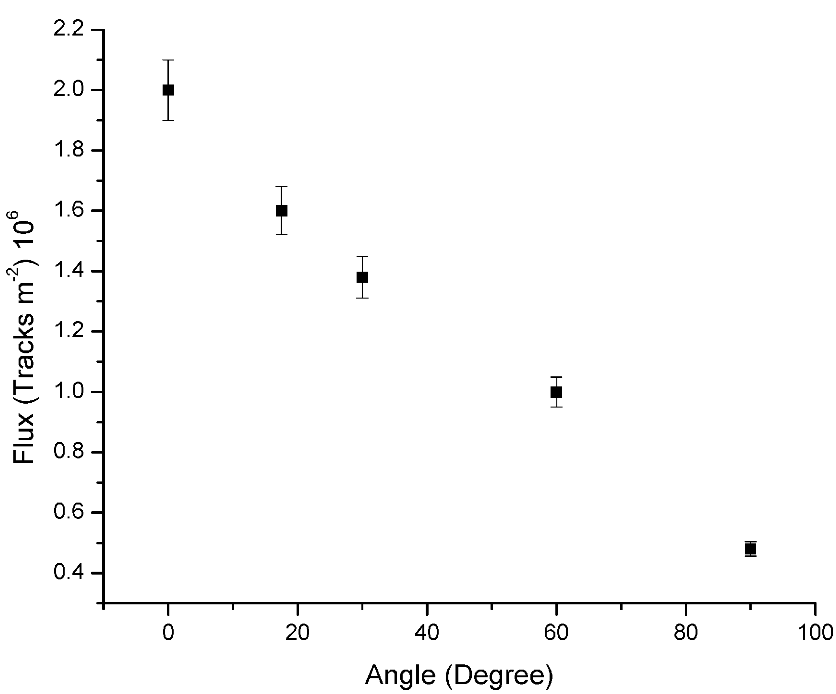

Fig. 3. Graph of angular distribution of silver ions flux.

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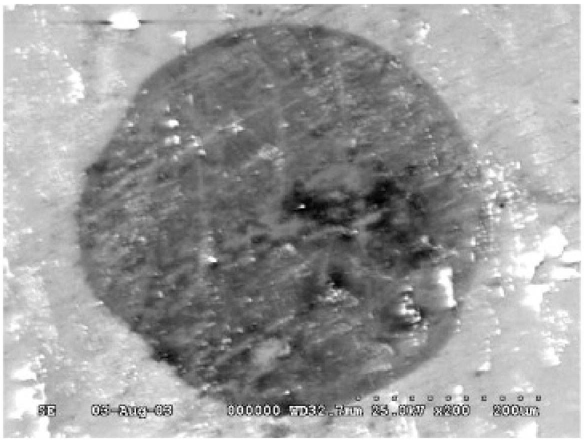

Fig. 4. SEM Micrograph of Al surface at magnification × 200 of the circular region of radius 230 μm, circular damage is a result of forward peaking of ions.

Fig. 5. SEM Micrograph of irradiated Cu surface at magnification × 400 showing the damaged circular region of radius 114.28 μm, which is also due to forward peaking.

concentration decreases due to diffusion or scattering of ions in the end.

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