Laser and Particle Beams (2008), *26*, 473–478. Printed in the USA.

doi:10.1017/S0263034608000487

Laser plasma interaction in copper nano-particle targets

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(RECEIVED 15 January 2008; ACCEPTED 24 June 2008)

Abstract

In this paper, we present the results of studies on ion emission characteristics of a laser plasma produced from a copper nano-particle layer of 1–3 μm thickness coated over polished surface of a solid copper target. Laser intensity of 10^{13}–10^{14} W/cm^2 was produced on the targets by a 2 J Nd:glass laser having a variable pulse duration of 300–800 ps. Nano-particle size was in the range of 15–25 nm. Ion emission from the nano-particle plasma was compared with plasma generated from a polished copper target. Ion emission from the nano-structured target was observed to depend on the polarization of the incident laser beam. This effect was stronger for a shorter laser pulse. X-ray emission was measured in the soft and hard X-ray region (0.7 to 8 keV) using various X-ray filters. A nano-particle coated target is found to yield a larger flux as well as velocity of ions as compared to polished target when the laser polarization is parallel to the plane containing target normal and detector axis. However, no X-ray enhancement has been observed in the wavelength range 1.5 to 20 Å.

Keywords: Ion emission; Laser-plasma interaction; Laser-plasma; Nano-particles

1. INTRODUCTION

Laser produced plasma is an intense source of X-rays and charged particles. The X-ray emission is observed over a broad spectral range since the bremsstrahlung emission is superimposed on the recombination radiation and line emission. Plasma generated by intense lasers is considered to be an extraordinary source of ions. Such an ion source is important due to its well defined material vaporization and deposition characteristics. Thus, it is extremely useful in ion implantation schemes with or without an additional ion accelerator. These laser plasma ion sources have been used at the front end in particle accelerators as well. Further, the emitted ions are also used as diagnostic tools in laser-plasma interaction experiments. The simplest of the ion diagnostics is based on an application of the time-of-flight (TOF) method, which makes it possible to measure the currents, the charge states and the energy spectra of ions, utilizing ion collectors (Krasa *et al.*, 2005). Our work on laser plasma interaction in the past few years has been focused on the study of several target designs involving composite as well as mixtures of materials having varying density and target surface structuring. The main aims of these experiments have been two fold. The first aim has been to study possible enhancement in X-rays in different spectral regions. Such studies have relevance while designing an intense laser plasma X-ray source for different applications, such as backlighting, opacity measurements, lithography etc. (Faenov *et al.*, 2007; Laska *et al.*, 2007*a*; Nickles *et al.*, 2007; Orlov *et al.*, 2007). Each of these applications needs a source of high brightness, but, in different spectral regions. The second aim has been to study ion emission from these targets, with a special emphasis on effect of various laser parameters such as laser intensity, pulse duration, polarization etc. Such a study is important for a well characterized laser based ion source (Laska *et al.*, 2007*b*, 2007*a*; Varro, 2007; Varro & Farkas, 2008; Wolowski *et al.*, 2007*a*, 2007*b*) In our earlier work, we reported our work on the laser interaction with Au-Cu alloy targets (Chaurasia *et al.*, 2007*b*; Gupta & Godwal, 2001), high Z doped polymer targets (Dhareshwar & Pant, 1993; Chaurasia *et al.*, 2007*a*), high Z (Au) coated targets (Dhareshwar *et al.*, 1986) and double layered targets. Other groups also have shown interesting results with such complex targets (Chakera *et al.*, 2003; Wolowski *et al.*, 2007*a*, 2007*b*; Dhareshwar & Chaurasia, 2007).

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This paper presents some interesting results observed in solid targets coated with a layer of nano-particles on top of a solid copper target. Ion emission in such a target is seen to behave in quite a different way as compared to a plane, polished copper target. Interaction of intense lasers with clusters and nano-particles has become a subject of intensive study in the recent times in which significant enhancement in soft and hard X-ray emission has been reported by several authors (Varro, 2007; Wolowski *et al.*, 2007*a*, 2007*b*; McPherson *et al.*, 1994; Ditmire *et al.*, 1997*a*, 1997*b*; Rajeev *et al.*, 2003, kulcsar *et al.*, 2000). Efforts have been taken by several groups to understand the laser absorption processes in clusters (Holkundkar & Gupta, 2007). It has been shown that laser absorption processes involved in the laser-plasma interaction have a strong effect on the ion emission characteristics also. Intense beams of energetic ions have been observed from nano-structured surfaces (Zweiback *et al.*, 1999). These reports have been concerning interaction of femtosecond pulses (100–800 fs, intensity -10^{15} to 10^{16} W/cm^2) with nano-structured surfaces. Extremely energetic (MeV) and highly stripped ions have been produced by intense laser interaction in noble gas clusters (Ditmire *et al.*, 1997*a*, 1997*b*). Free standing metal clusters (Ag, Pt) have been also used to generate highly charged and energetic ions (Koller *et al.*, 1999). There have been no reports so far on interaction of sub-nanosecond laser pulses with metallic targets having a surface layer of nano-particles. So, our present experiments have been performed to address some of these specific questions such as does the nano-particle layer behave in a different manner when exposed to sub-nanosecond (300–800 ps) laser pulse durations? Does the presence of such nano-particles have an effect on energy absorption processes? Could there be a difference in thermal conduction between free-standing metal clusters and a layer of metal nano-particles deposited on the surface of the bulk material?

These questions have motivated us to do some experiments with laser of several nanoseconds duration, wherein distinct differences have been seen (Hegazy *et al.*, 2007). So, it is not that the nano-particles are ablated in the very initial part of the laser pulse leaving uniform plasma to interact with the main part of the laser pulses. Simulations of these experimental conditions have been performed by other groups, wherein, the problem has been treated as a two layer problem. In this, a low density nano-particle layer is considered to be followed by the solid density layer. The results have shown a 10-fold increase in bremsstrahlung emission (wavelength range of 50–100 Å) for nano-particle layer which has 12.5% of the density of bulk target and 5-fold increase for a 25% density target. This has been explained on the basis of the deeper penetration of the laser radiation, leading to larger ablated plasma and therefore a higher bremsstrahlung emission.

2. EXPERIMENTAL DETAILS

In our experiments reported here, we have compared the X-ray and ion emissions from plasmas produced from 1 and 3 μm thick layers of copper nano-crystalline particles (15–25 nm) over a solid copper surface and an uncoated solid target. The laser used in these experiments is a 2 J/300 to 800 ps Nd:glass with a focused intensity in the range of 10^{12} to 10^{13} W/cm^2. Laser beam was made incident normal to the target plane. Laser was plane polarized and the electric field vector could be made either parallel (P_a) or perpendicular (P_e) to the plane containing the target normal and the axis of the ion collectors as shown in the experimental scheme in Figure 1. Targets were prepared by direct current (DC) magnetron sputtering technique, by which, copper nano-particles were deposited on the surface of a bulk copper target at relatively high pressure (∼20–200 mT) and low substrate temperatures (∼100–300 K). This technique is known to produce nano-crystalline films (Ayyub *et al.*, 2001). The average particle size can be controlled by proper choice of sputtering voltage, gas pressure, and substrate temperature. In the present case, the nano-crystalline copper sample was prepared by DC magnetron sputtering (at 325 V) from a 50 mm diameter copper target at 10^{-1} Torr pressure on a bulk copper substrate at 300°K. The average particle size (obtained from a measurement of the X-ray diffraction line broadening) was about 15–25 nm. Figure 2 shows the scanning electron microscope (SEM) picture of the copper nano-target layer coated on the bulk copper with the scale marking of 1 μm.

X-ray emission has been studied in a spectral range of 0.7 keV to 8 keV (1.5 to 20 Å) using three different types of detectors. Semiconductor detectors (100PIN250 from Quantrad and UDT XUV 100) as well as a seven channel array of, indigenously developed, fast response (75 ps) bi-planar vacuum diodes were used for this purpose. A 5 μm thick nickel and 12 μm thick titanium filters were used to cover the semiconductor detectors, whereas, a 6 μm thick polycarbonate film, B10 film, 2 μm, 5 μm, and

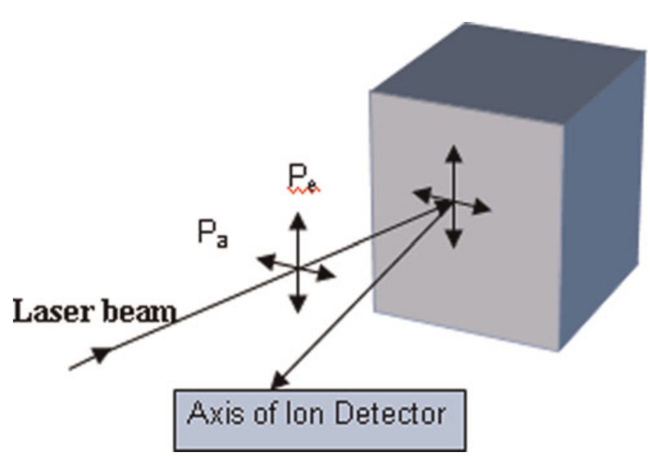

Fig. 1. (Color online) Experimental schematic.

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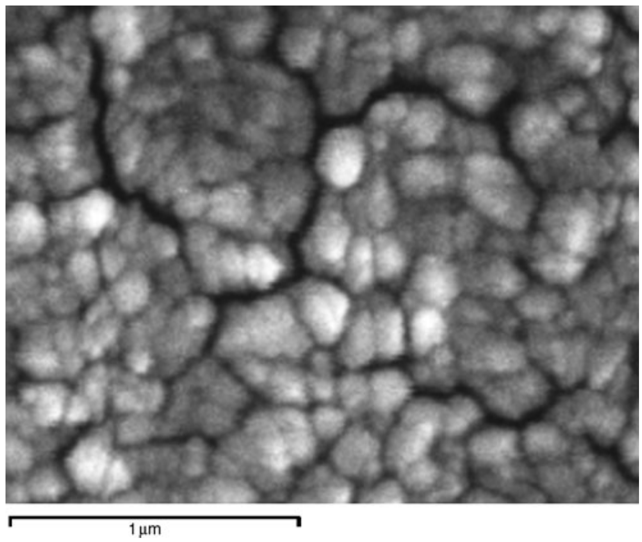

Fig. 2. SEM picture of copper nano-particle layer, showing the particle size to be about 15–25 nm.

12 μm aluminum filters were also used for the fast bi-planar diodes. X-ray transmission of all the filters used is shown in Figure 3. The seven channel bi-planar X-ray diode array is shown in Figure 4. These photodiodes had gold coated copper cathode with a quantum efficiency of 10^{-1} (electrons/photons) and were designed to give a 50 Ω impedance and fast rise time. Ion flux and ion velocity was measured by TOF method using an array of ion collectors placed at angles 13°, 30°, and 45° with respect to target normal.

3. RESULTS AND DISCUSSIONS

It is observed that the behavior of plasma generated from copper nano-particle coated targets is different from that of a plain copper target. Figures 5 and 6 show the Langmuir probe signal amplitudes versus laser energy for plain and nano-particle coated copper targets for a 500 ps and 320 ps pulse duration at the various detection angles. Laser pulse polarization is P_e. It is observed that the number of ions ablated in nano-particle coated targets is lower than in copper targets at all laser energies. The difference is seen to be higher for shorter pulse duration of 320 ps as compared to 500 ps. This is obvious since we are comparing the amplitudes at a given laser energy. The shorter pulse duration therefore will have higher intensity. Figure 7 shows the variation of signal amplitude with laser energy for P_a polarization of laser pulse for a 500 ps laser pulse. Here we observe the reverse. The number of ions is higher in case of nano-particle

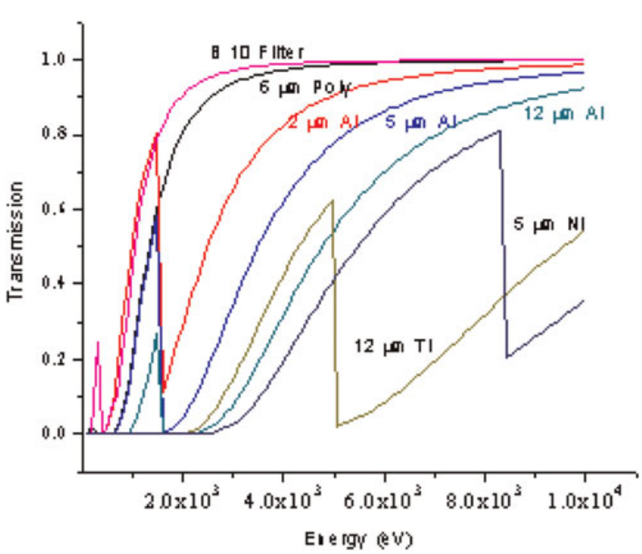

Fig. 3. (Color online) Filter transmission.

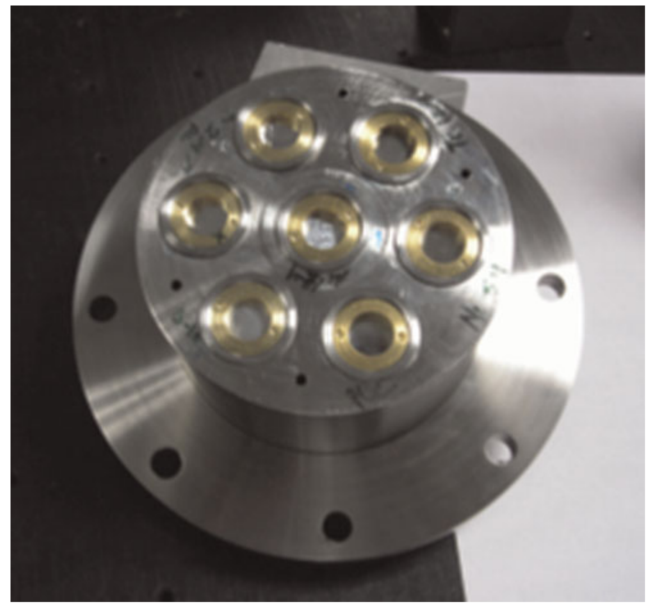

Fig. 4. (Color online) Seven channel fast response X-ray diode.

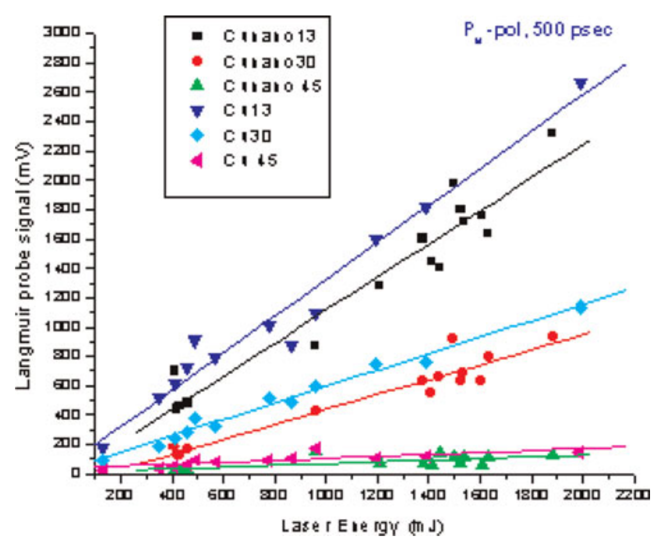

Fig. 5. (Color online) Ion amplitude versus laser energy for 500 ps, P_e nano-target compared with plain polished target.

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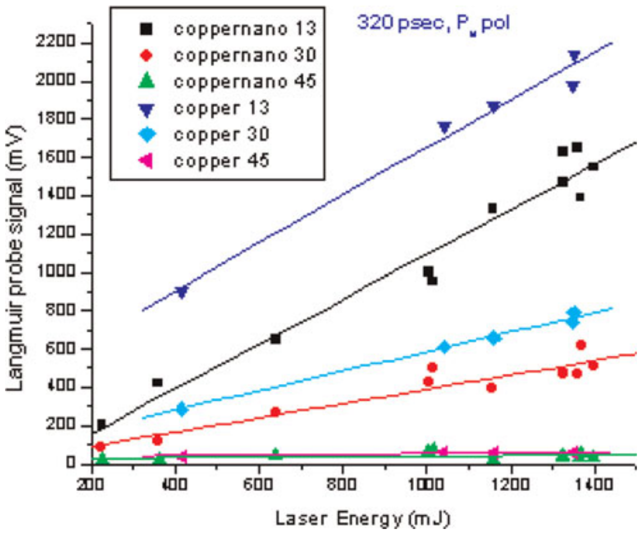

Fig. 6. (Color online) Ion amplitude versus laser energy for 320 ps for P_e for nano-targets and plain polished target.

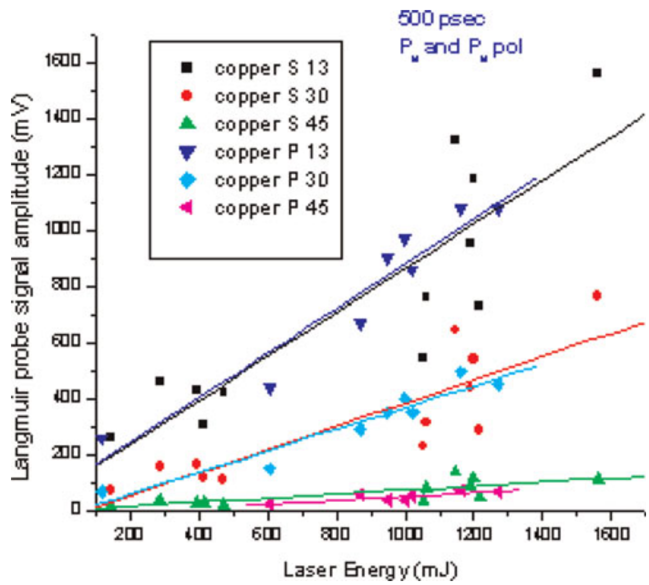

Fig. 8. (Color online) Ion amplitude versus laser energy for 500 ps laser pulse for both P_a and P_e in a plain polished copper target.

coated copper target. However, there is no observable difference in amplitude for P_a and P_e polarizations for a plain copper target as seen in Figure 8, which in fact is as expected, since the laser is normally incident. This shows that the material from the nano-particle coated targets is dependant on the orientation of the electric vector of the plane polarized laser pulse. The number of ions ablated is higher when the electric vector lies in the plane containing the target normal and the ion collector axis. It is the opposite for the perpendicular orientation of the electric field vector. Also, when the polarization is P_a, ablated ion numbers are higher compared to plain polished copper targets. Similarly, in Figure 9, the ion velocity is plotted versus laser energy for a P_a polarization. It is also observed to be higher for nano-particle coated copper targets as compared to plain copper at all laser energies. Ion amplitude and ion velocity was similarly higher for a 3 μm thick layer of nano-particles.

Such asymmetric emission of high energy electrons in the hydrodynamic expansion of large xenon clusters irradiated by intense laser fields has been reported (Kumarappan *et al.*, 2003). Electron yield was observed to be more than three times for the polarization parallel to the plane containing the target normal and the detector axis. These results have been explained on the basis of the force that the light field exerts on the polarization charge that is induced on the surface of the cluster. Most of these studies have been made with laser pulses in the duration range of 100 to

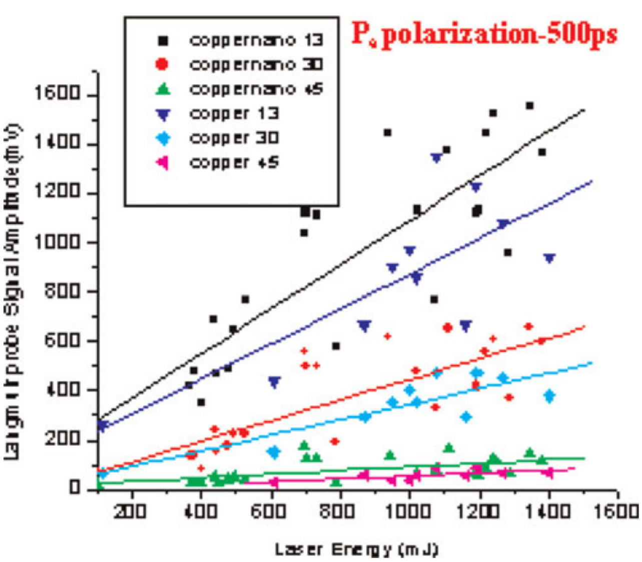

Fig. 7. (Color online) Ion amplitude versus laser energy for 500 ps laser pulse for P_a compared for nano-target and plain polished target.

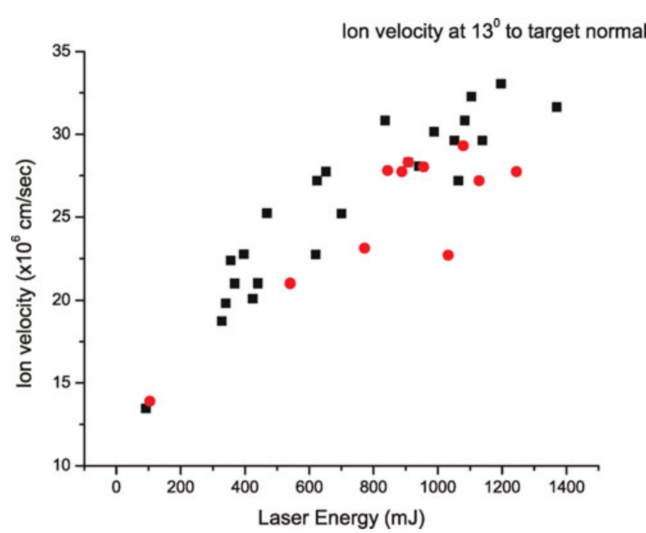

Fig. 9. (Color online) Ion velocity versus laser energy for 500 ps laser pulse for P_a. Copper (●) and nano-particle coated copper (■).

https://doi.org/10.1017/S0263034608000487 Published online by Cambridge University Press

2000 fs and laser intensity range of 10^{15} to 10^{16} W/cm^2. Copper nano-particles could be considered to behave like clusters with asymmetric surface charge polarization. In such a situation, one can expect asymmetric emission of ions. These are the first results reported on asymmetric charged particle emissions from metal nano-particles, to the best of our knowledge. In our experiments, we are using a laser pulse duration three orders of magnitude larger in an intensity range (10^{13}–10^{14} W/cm^2) which is two orders of magnitude lower than what has been reported by other authors.

Comparison of X-ray emission from the solid and nano-particle coated targets was done using both semiconductor diodes and fast response seven channel diode array. It is observed that there is no significant difference between the two types of targets. This could be due to the fact that we are observing X-ray emission in a rather narrow spectral range and more in the harder part of the spectrum. No measurements were made in the soft X-ray region in which the simulations have predicted an enhancement of X-ray emission by some authors (Hegazy *et al.*, 2007). Also, these authors proposed the enhancement of X-ray emission due to lowering of density in nano-targets. The effect of density is seen only when the target density is 12 to 25% of solid density. However, in targets that we have used, the average density of the nano-particle layer is 50% of solid density and it cannot be lowered further. Perhaps, this is the reason as to why we have not been able to observe significant enhancement in the case of nano-targets.

4. CONCLUSIONS

Interaction of a sub-nanosecond (320 ps and 500 ps) laser pulse of intensity 10^{13} to 10^{14} W/cm^2 with a 1–3 μm thickness layer of copper nano-particle (particle size in the range of 15–25 nm) on the surface of a polished, plane solid copper target has been studied. A nano-particle coated target is found to yield a larger flux of ions as compared to polished target when the laser polarization is parallel to the plane containing target normal and detector axis. Ion velocity is also observed to be higher in nano-particle coated targets in this case. However, no X-ray enhancement has been observed in the wavelength range 1.5 to 20 Å.

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