PRAMANA
— journal of
physics

Vol. 55, Nos 5 & 6
Nov. & Dec. 2000
pp. 797–802


# Scaling of x-ray emission and ion velocity in laser produced Cu plasmas

Y B S R PRASAD[1], V K SENECHA[1], H C PANT[1], M P KAMATH[2], G S SOLANKI[2], P K TRIPATHI[2], A P KULKARNI[2], S GUPTA[2], R PAREEK[2], A S JOSHI[2], N SREEDHAR[3], SAMEER NIGAM[3] and C P NAVATHE[3]
[1]Plasma Physics Laboratory, [2]High Power Laser Lab, [3]High Power Laser Electronic Group, Laser Plasma Division, Centre for Advanced Technology, Indore 452 013, India
Email: yprasad@cat.ernet.in

**Abstract.** The x-ray emission from slab targets of copper irradiated by Nd:glass laser (1.054 $\mu$m, 5 and 15 ns) at intensities between $10^{12}$ and $10^{14}$W/cm$^2$ has been studied. The x-ray emissions were monitored with the help of high quantum efficiency x-ray silicon photo diodes and vacuum photo diodes, all covered with aluminium filters of different thickness. The x-ray intensity vs the laser intensity has a scaling factor of (1.2–1.92). The relative x-ray conversion efficiency follows an empirical relationship which is in close agreement with the one reported by Babonneau *et al*. The ion velocities were monitored using Langmuir probes placed at different angles and radial distances from the target position. The variation of the ion velocity with the laser intensity follows a scaling of the form $\Phi^{\beta}$ where $\beta \sim 0.22$ which is in good agreement with the reported scaling factor values. The results on the x-ray emission from Cu plasma are reported.

**Keywords.** Laser plasma; x-ray emission; conversion efficiency; ion velocities.

**PACS Nos 52.50 Jm; 52.25 Nr**

## 1. Introduction

X-ray emission studies from laser produced plasmas under different experimental conditions are being carried out in many laboratories [1]. The main purpose behind these studies is to optimize the x-ray emission in different x-ray energy ranges. The important benefits from this kind of optimization studies are in the fields of x-ray lithography, x-ray lasers etc. Another important area where this finds use is to determine suitable x-ray back lighting sources for probing the high density regions of laser produced plasmas which requires that the source has to be much brighter in the particular x-ray wavelength window compared to the self emission of the plasma being probed.

Different experimental methods are used to estimate the x-ray emissivity from laser produced plasmas. Absolutely calibrated bolormeters, time integrated and time resolved transmission grating spectrometers (TGS) are some of them. The x-ray diodes were also used to record the x-ray signals from the plasmas. With the help of suitable x-ray filters it

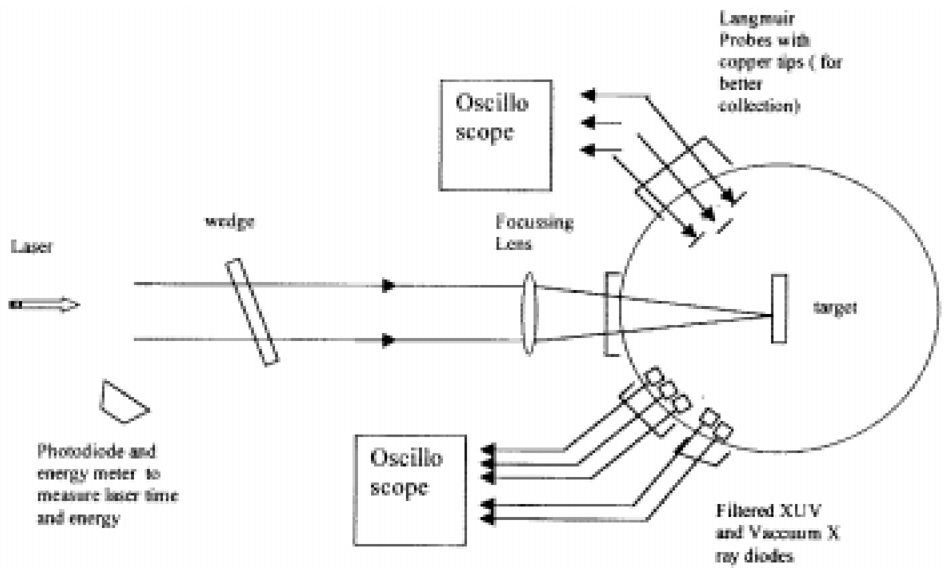


**Figure 1.** Experimental setup.

is possible to measure the x-ray emissions in different wavelength windows. This method is much simpler when compared to that of above two i.e. TGS and bolometers. In fact the availability of high sensitivity x-ray diodes with nearly theoretical quantum efficiencies and zero dead layers resulting in very good x-ray sensitivities making them highly suitable candidates for these studies.

Experiments were conducted in our laboratory with a Nd:glass laser system (1.054 $\mu$m) [2] to study the x-ray emission from Cu plasma at different laser intensities below $10^{14}$ W/cm$^2$. In this study x-ray diodes (UDT model XUV 5 Si photo diodes, for soft x-ray XUV) covering photons with energies between 6 eV and 12 keV corresponding to wavelength of 1 to 200 A were used to monitor the x-ray emissions. These detectors have low noise levels and extremely stable and high quantum efficiencies which are predicted by the simple expression $E_{\rm ph}/3.63$ eV over most of the XUV spectral range. The experimental results are presented in this present paper along with comparison with the results reported from other laboratories. The x-ray emisivity is expressed through the scaling of x-ray signal with laser intensity and the dependence of x-ray conversion efficiency on laser energy. In addition to these the ion velocity scaling with laser intensity was also studied and will be presented.

## 2. Experimental setup

Experiments were carried out with one beam of the Nd:glass high power laser system (1054 nm, 5–15 ns, 85 mm beam diameter). The laser energy was varied from few joules up to 60 J. A plano convex lens of focal length 500 mm $f/5.88$ was used to focus the laser beam on to slab targets. The schematic experimental setup is shown in figure 1. Copper slab targets were well polished to remove any non uniformities. The focal spot diameters are about 80–90 $\mu$m giving laser intensities between $10^{12}-10^{14}$ W/cm$^2$. The focal spot was optimized by taking low energy shots (few hundred mJ) at different lens positions and choosing the best focal position. The targets were mounted on a target positioning system consisting of three independent movements. The target can be moved in all $x, y, z$ directions with an accuracy of few microns in order to provide fresh target surface for each laser shot. This can be accomplished from outside with the help of a personal computer based control system. The high accuracy is required when a particular location on target has to be irradiated. The target was slightly rotated such that the target normal makes approximately few degrees angle with the laser axis. This is done in order to avoid reflection from target surface being fed back in to laser system. The chamber was evacuated to a vacuum of $10^{-5}$ mbar.

The x-ray spectrum was measured with the help of UDT XUV-5 x-ray silicon photo diodes combined with x-ray filters of aluminium material of different thickness (12 $\mu$, 24 $\mu$ and 48 $\mu$m with cutoff energies i.e., energy where the transmission reduces by $1/e$ factor at 4.12 keV, 5.34 keV and 6.78 keV respectively). In addition to these Si pin photo diodes, vacuum x-ray diodes [3] covered with aluminized polycarbonate foil (named B-10, with composition: aluminium 0.05 mg/cm$^2$, oxygen 0.0375 mg/cm$^2$ and carbon 0.15 mg/cm$^2$ with cutoff energy ($\sim$ 810 eV) and 12 $\mu$m aluminium foil were also used to monitor the x-ray emissions. The XUV diodes and vacuum diodes were placed in the horizontal plane $\sim$ 35 cm away from the plasma at angles of 45$^\circ$ and 22.5$^\circ$ with respect to the laser beam axis.

In addition to these diodes Langmuir probes were used to get the information about the ion velocities. The Langmuir probe were kept at a distance of 10/50 cm at angle of 22.5$^\circ$ and were connected to a PC based data acquisition system [4] which grabs the ion velocity profile and calculates the ion velocities. A polished copper tip attached to a simple BNC connector was used as Langmuir probe. The probe is sensitive for the em radiation like x-rays and UV and also for charged particles like ions and electrons. The laser energy and the pulse duration were monitored using energy meter and photo diodes.

## 3. Results and discussion

The x-ray intensity values at different laser energies are plotted in logarithmic scale in figure 2 for 12, 24 and 48 $\mu$m thick aluminum filters. Since the time duration of the laser pulse and the focal spot dimensions are constant through out the experiment the scaling between the laser intensity and x-ray intensity can be expressed in the form of a power law variation given as

$$I_x = \Phi^\alpha$$

where $\Phi^\alpha$ the laser flux in W/cm$^2$, $I_x$ is the intensity of x-rays falling on the detector and $\alpha$ is the scaling coefficient.

From the figure 2 the scaling coefficient $\alpha$ is found to be varying between 1.2–1.92. The diode after the 48 $\mu$m are mainly sensitive for the harder component of x-rays whose slope is 1.92. The drop in the hard x-rays is abrupt with the fall in the laser intensities. This can be understood in terms of rapid decrease of x-ray emissivity in this energy range when the laser flux is below $\sim 10^{12}$ W/cm$^2$ [7].

The scaling of the relative x-ray conversion efficiency as a function of laser intensities are shown in figure 3 for different thickness of aluminium filters. They are in agreement

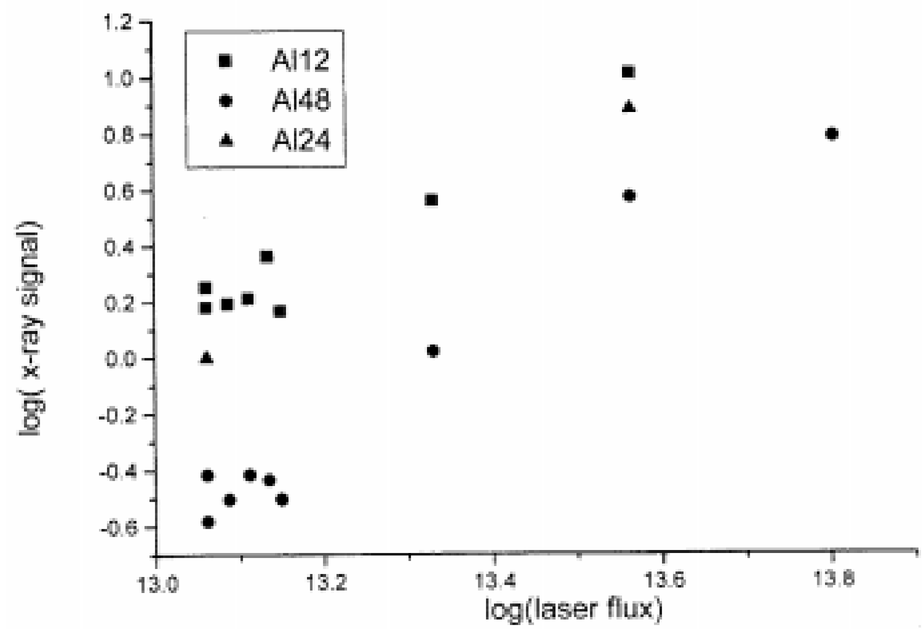


**Figure 2.** Scaling between laser flux and the x-ray signal for aluminium 12, 24, 48 micron filters with copper target.

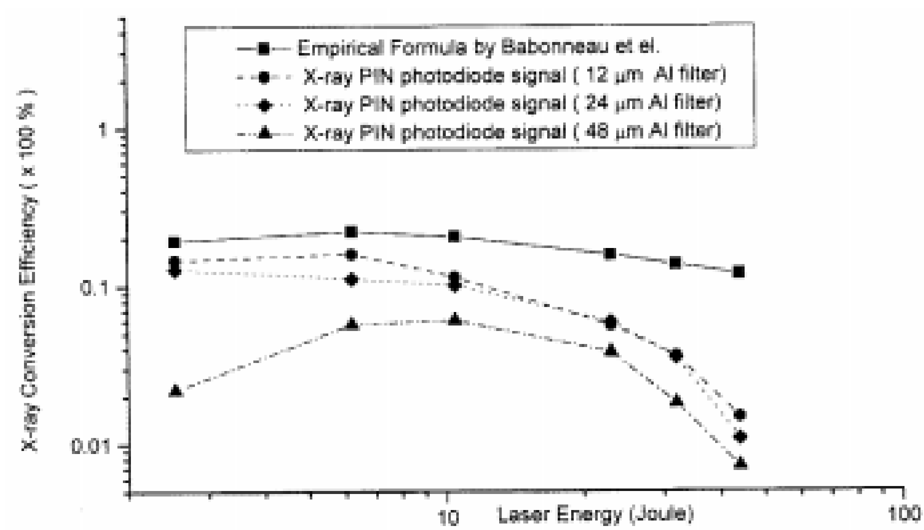


**Figure 3.** The relative conversion efficiency as a function of laser energy.

with those value reported by Gilbert *et al* [5]. The graph also shows the empirical analytical formula between the x-ray conversion rate versus different parameters of the interaction by Babonneau *et al* [6] expressed as

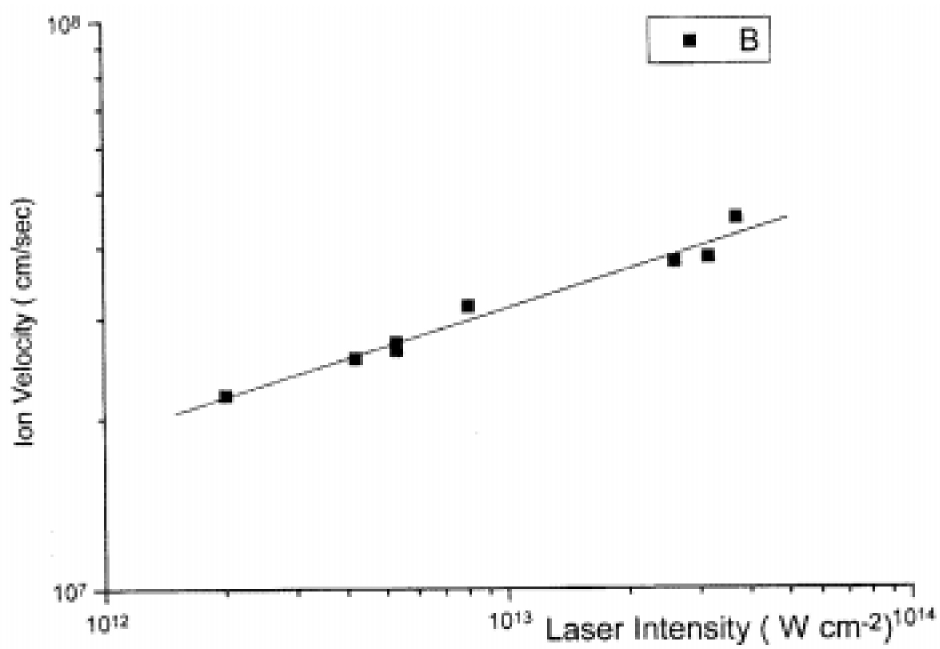


**Figure 4.** Ion velocity scaling as a function of laser intensity.

$$\zeta_x = \frac{E_x}{E_L} = 6.3 \times 10^{-4} Z \lambda^{-0.48} \Delta t^{0.33} \left( \frac{I_0}{I + I_0^2} \right)^{0.46},$$

where $I_0 = \Phi\lambda^2/4 \times 10^{13}$, here

$E_x$ = the emitted X-ray energy
$E_L$ = the incident laser energy
$\Phi$ = the incident laser flux (intensity) in W/cm$^2$
$\lambda$ = the laser wavelength in $\mu$m
$\Delta t$ = the laser pulse duration in ps.

The range of validity of this expression is $\Delta t \geq 500$ ps and $\lambda \leq 1.06$ $\mu$m.

This expression gives the x-ray energy values that are spectrally integrated and hence, higher than our experimental results, which are for different energy ranges depending on the filter thickness. But the variation of relative x-ray conversion efficiency with laser intensity is in good agreement with that of Babonneau *et al* [6].

The efficiency of x-ray conversion is increasing with the laser intensity up to ~5*10$^{13}$ W/cm$^2$ after which the conversion exhibits saturation tendency over some intensity range and after this the conversion actually drops. This can be explained in terms of reduced laser absorption at higher laser intensities due to energy losses in other non linear processes like SBS, SRS and resonance absorption which are threshold processes.

Chaker *et al* [7] have reported peak conversion efficiencies around 8% for copper targets both in sub-keV energy range (0.1–0.75 keV) and keV range (0.75–2.0 keV) when the laser intensity $\Phi \sim 1 \times 10^{13}$ W/cm$^2$ for 1.06 micron laser. Figure 4 also shows that the changes in the conversion efficiency are much drastic after the A1-48 $\mu$m filter compared to that of A1-12 $\mu$m. This is due to the fact that cutoff energy for the 12 $\mu$m filter is much higher (higher transmission levels over wide x-ray wavelength range) as compared to 48 $\mu$m filter. The kind of drastic reduction in the x-ray conversion appears to be directly related with rapid decrease of emissivity of Cu below the temperature 300 eV [7]. Thus in order to obtain substantial conversion in the kV range, it is necessary to have a minimum temperature and thus to provide a laser irradiance of $\Phi \geq 10^{13}$ W/cm$^2$.

The scaling of ion velocities with laser intensity is shown in figure 4 on logarithmic scale. The signal from the probe contains the fast component due to x-rays and other radiation from the plasma and a slow ion pulse. The x-ray pulse is taken as time fiducial and the ion velocities are calculated. The data acquisition system [4] looks for ion current peaks and calculates the ion velocities. The ion velocity is a direct measure of plasma temperature. The ion velocities in the intensity range $10^{13}$–$10^{14}$ W/cm$^2$ scales as

$$V_i \propto \Phi^{\beta},$$

where $V_i$ is the ion velocity and $\beta$ is the scaling factor.

The scaling constant is ∼0.22 which is well in agreement with the values that are reported from other laboratories.

## 4. Summary and conclusions

The results from laser plasma interaction experiments in the form of x-ray conversion efficiencies vs laser intensity for different x-ray wavelength windows and scaling of ion velocity with laser intensity are presented here for copper slab targets. The x-ray intensities are scaling as $I_x \propto \Phi^{\alpha}$ where $\alpha$ is varying between (1.22 and 1.92). The scaling between the ion velocities and the laser intensity can be expressed as $V_i \propto \Phi^{0.22}$.

Main aim of our present series of studies is to optimize the x-ray emission under different experimental conditions. One of our main interest is to study the effect of macro particles i.e. clusters of different dimensions on the x-ray emissivity. These results will be presented in near future.

## References

[1] R Kodama, K Okada, N Ikeda, M Mineo, K A Tanaka, T Mochizuki and C Yamanaka, *J. Appl. Phys.* **59**, 3050 (1986)

[2] A S Joshi *et al*, *Fusion Engg. Design* **44**, 67 (1999)

[3] V N Rai, M Shukla and H C Pant, *Pramana – J. Phys.* **52**, 49 (1999)

[4] N Sreedhar, S Nigam, Y B S R Prasad, V K Senecha and C P Navathe, *Indian J. Engg. Mater. Sci.* **7**, 122 (2000)

[5] K M Gilbert, J P Anthes, M A Gusinow and M A Palmer, *J. Appl. Phys.* **51**, 1449 (1980)

[6] D Babonneau, D Billon, J L Bocher, G Di Bona, X Fortin and G Thiell, *Laser interaction and related plasma phenomena* edited by Heinrich Hora and George H Miley (Plenum Press, 1984) vol. 6

[7] M Chaker, H Pepin, V Bareau and B Lafontaine, *J. Appl. Phys.* **63**, 892 (1988)