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Volume effect of laser produced plasma on X-ray emissions

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Abstract. An investigation of x-ray emission from Cu plasma produced by 1.054 μm Nd:glass laser pulses of 5 ns duration, at $2 \times 10^{12}-2 \times 10^{13}$ W cm^{-2} is reported. The x-ray emission has been studied as a function of target position with respect to the laser beam focus position. It has been observed that x-ray emissions from ns duration plasma show a volume effect similar to sub-nanosecond plasmas. Due to this effect the x-ray yield increases when target is moved away relative to the best focal plane of the laser beam. This result supports the theoretical model of Tallents and has also been testified independently using suitably modified theoretical model for our experimental conditions. While above result is in good agreement with similar experimental results obtained for sub-nanosecond laser produced plasmas, it differs from result claiming filamentation rather than pure geometrical effect leading to x-ray enhancement for ns plasmas.

Keywords. Laser produced plasmas; x-ray emissions; laser beam focus; filamentation.

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1. Introduction

Laser produced plasmas (LPP) of sufficiently high temperature of few hundred eV's are good sources of x-rays [1]. In the past there have been several attempts to optimize the x-ray emission as well to produce uniform elongated plasma for its application in x-ray lasing medium [2]. Many workers have shown in the past that the ideal focus need not be the most efficient soft x-ray source. Even though the power density is highest in the focus than in the regime. It was experimentally seen that the temperature of the plasma does not show much increase beyond certain limiting value of power density of the laser beam. And for lower power density, temperature increases linearly. This situation is most favourable for short laser pulses (sub-nanoseconds) as the plasma cloud above the focal spot does not expand laterally beyond the perimeter of the spot so the spot dimensions determine its volume. Hence within a certain distance from the ideal focus, dependence upon electron temperature is eliminated and x-ray yield is controlled by the plasma volume i.e. the diameter of the spot or the distance from the ideal focus for both line emission as well as for the continuum bremsstrahlung radiation. For ns duration LPP the situation will change due to the significant loss of energy due to lateral energy transport during tight focusing conditions compared to the defocus conditions. This will result in maintaining of nearly constant plasma temperature conditions during laser irradiation of the target under tightly focused to weakly focused geometry. In addition the plasma volume will increase under defocused condition as compared to focused condition even when there is lateral expansion of the ns duration LPP. It can be understood from the fact that the plasma corona region which is mainly responsible for conversion of laser light into x-rays will be larger in volume compared to best focus situation. The theoretical estimates of Tallents *et al* [3], based upon the simple scaling of electron temperature and plasma volume predict a pair of lateral maxima with a minimum in the focus on the curve of soft x-ray emission flux as a function of the target distance from the focus. Experimental results are in agreement with this model.

We have investigated this problem in the nanosecond regime of LPP. In this regime also, we find that x-ray emission from massive copper plasma produced by 5J Nd:glass laser of 5 ns pulse duration gives enhanced x-ray signal away from the best focus of the laser beam. The Langmuir signal gives the ion velocity, which does not show more than 10% variation over a distance of 2.5 mm from the best focal plane on either side.

2. Experimental details

Experiments were carried out using one beam of the four arms Nd:glass high power laser system (1.054 μm, 5 ns, 85 mm beam diameter) [4]. The laser energy was varied between 1–5 Joules. A plano convex lens, with f/5.8 was used to focus the laser beam on to a massive slab target of oxygen free copper. These targets were well polished to remove any non-uniformity on the surface. The focal spot diameters were measured and found to be $\sim$80 μm, giving laser intensities between 2×10^{12}–2×10^{13} W/cm^2. The x-ray spectrum was measured with the help of XUV PIN x-ray diodes covered with different x-ray filters of aluminum (12 μm, 24 μm and 48 μm thickness). In addition, two indigenously made vacuum x-ray diodes [5] covered with aluminized polycarbonate foil filter (named B-10, with composition: aluminum 0.05 mg/cm^2, oxygen 0.0375 mg/cm^2 and carbon 0.15 mg/cm^2 with cutoff energy i.e., energy where the transmission reduces by $1/e$ factor is $\sim$810 eV) and a 12 μm aluminum filters were also used to monitor the x-ray emissions. The x-ray and vacuum diodes were mounted at angles of 45° and 22.5° with respect to the target normal axis. In addition to these diodes Langmuir probes were used to get the information about the ion velocities. The Langmuir probes were kept at a distance of 18 cm and 50 cm at an angle of 22.5° with respect to the target normal and were connected to a PC based data acquisition system [6] which was used for recording the ion velocity profile in digitized form and perform calculations to obtain the ion velocities using the time of flight measurements. A polished copper tip attached to a simple BNC connector was used as Langmuir probes. The probe is kept at a proper bias so as to make it sensitive to ions; probe however is sensitive to radiations like x-rays and UV. The laser energy and the pulse duration were monitored using an energy meter and a bi-planar photo diode system [7] which is calibrated and kept oriented properly to look for the scattered laser photons from the wedge plate as shown in figure 1, schematic of experimental set-up.

The chamber was evacuated up to 2×10^{-5} torr. The target was mounted on a target positioning system controlled by three independent stepper motors. The target can be moved along x, y, z directions in order to provide fresh target surface for each laser shot. This was accomplished with the help of a personal computer controlled motorized $x-y-z$ movement unit.

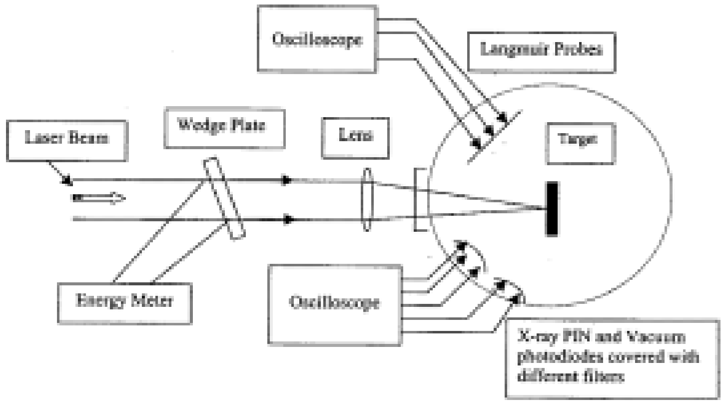

Figure 1. Schematic of experimental set-up.

3. Results and discussion

The x-ray emission monitored with x-ray PIN photodiodes and Vacuum photodiodes after covering them with x-ray filters, shows enhancement of x-ray signal by a factor of 1.7 when target is moved 1.5 mm away from the best focal plane of the laser beam.

Figure 2 shows the x-ray intensity as a function of target position with respect of laser beam focal plane $(x = 0)$ with x-ray intensity increasing in the direction of propagation of laser beam. The position of focal plane was determined with an uncertainty of ~400 μm. One can clearly see the increase in the x-ray intensity when target is moved within 2.5 mm range from the focal plane. It shows a minimum for the zero target position and shows a maximum at 1.5 mm on each side of the target. Ion velocity does not show a variation of more than 10% over the entire focal range of laser shots on copper target. Taken at its face value above results are in good agreement with the one reported by Chvojka *et al* [8] for x-ray emission from Al foil target irradiated with 1.315 μm laser beam of 50 J and 300 ps duration. Two sets of x-ray data taken with 15 J and 11 J constant energy shots clearly shows that two lateral maxima appear in the x-ray signal plotted against the target position relative to the best focus condition. The corresponding plasma temperature and density values derived using two-foil method shows nearly flat profile over the entire range of shots at different target positions relative to the best focus. Thus in the intensity range of around 10^{15} W cm^{-2}, results support the theoretical model of Tallents *et al* [3]. However they are different as per the results of A. Giulietti *et al* [9], showing x-ray and second harmonic yields to be correlated as a function of target position with respect to the laser beam focus. Although the x-ray emission is significantly enhanced but due to the filamentation of the laser light in the corona region, they rule out the possibility of any geometrical effect of focusing leading to the enhancement. The x-ray signal, which is recorded by them in 1–10 keV range using x-ray PIN diode covered by 8 μm Beryllium filter, shows maxima between -1 and -0.5 mm on one side and $+0.5$ mm on other side. While the two maxima at -0.5 mm and $+0.5$ mm are supporting our results and matching well with the Tallents and our model. However the second maxima at -1.0 mm is unexplained from our point of view. If we consider the fact that filamentation is the main reason for the x-ray

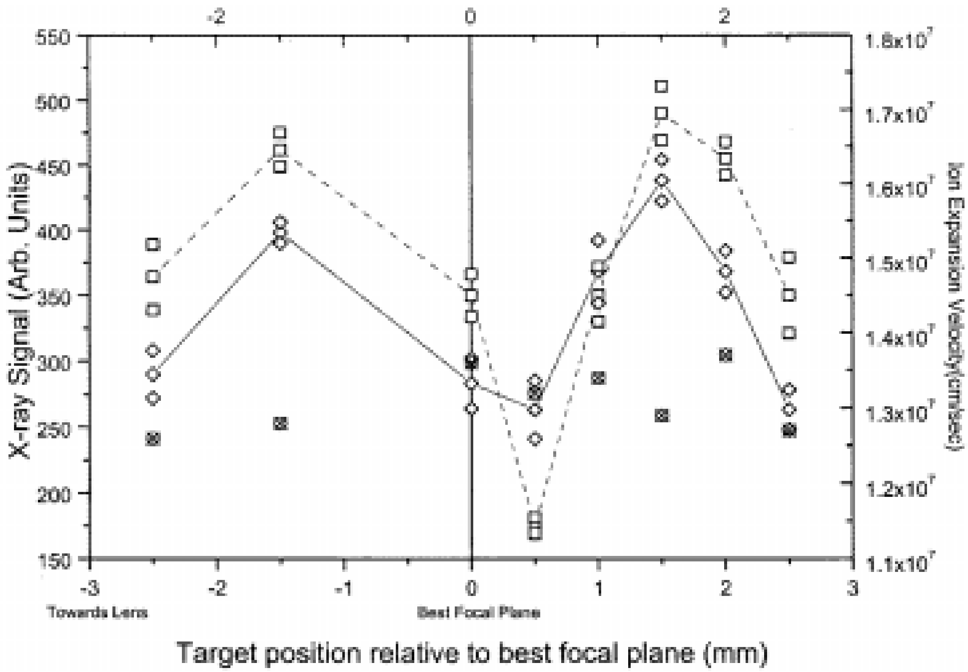

Figure 2. X-ray signal (in arbitrary units) recorded after irradiation solid copper target with 5 J, 5 ns laser beam of 1.054 mm wavelength as a function of target position with respect to the laser beam focal plane for (□-dash line) vacuum photodiode signal after covering it with B-10 filter and (⋄-solid line) for PIN diode signal after covering it with Al filter of 12 μm. The (⊗) data points represent plasma ion velocity as per values given on the right side Y-axis showing $\leq$ 10% variation.

enhancement then it should show itself by increase in the plasma temperature and fluctuation in the density in the off focus position. This has not been seen by them and as per Chvojka's result [8], which is at an intensity value one order higher compared with Giulietti [9] experiment, occurrence of filamentation leading to transient jump in temperature and density should have shown by itself in the temperature and density variations shown by Chvojka *et al* [8]. Further, how the filamentation is leading to smooth x-ray emission from LPP is not clear! Since, filamentation in the under dense plasma may generate sharp temperature and density gradients which will inhibit the energy transport by electron and nonlocal energy transport leads to fluctuation in the plasma [10] giving enhancement to the scattering and other loss mechanism which will result in poor energy deposition in the plasma. It is therefore necessary to repeat this experiment at different laser intensities and monitor the laser energy losses due to scattering and other parametric instabilities like SBS, SRS and TPD [11]. A more detailed experiment with simultaneous measurement of plasma temperature, density and scatterings along with measurement of SH emission and SBS and SRS emission and measure of lateral energy transport will give better insight into the physics of laser plasma interaction, filamentation and x-ray energy emission processes.

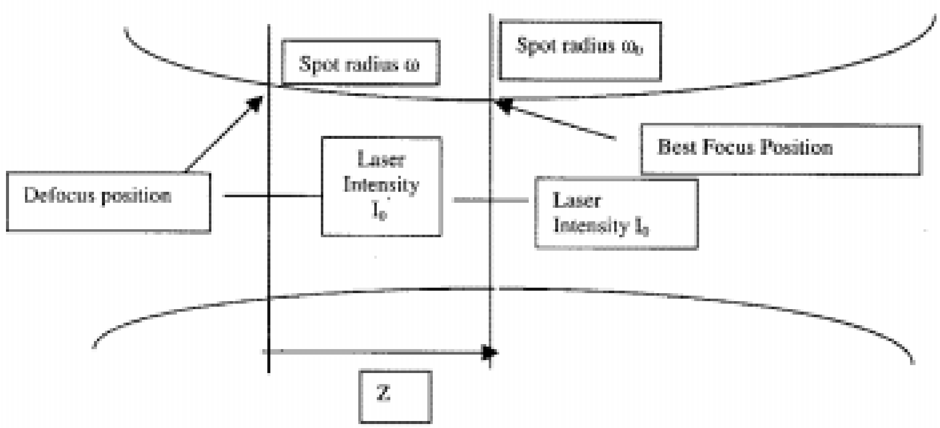

Figure 3. Representation of a Gaussian beam at the focal plane of a long focal length lens system.

4. Theoretical model

Tallents [3] had put forward a model for x-ray production, which can be used to predict the optimum conditions for x-ray emission. The basic assumption of the model is that there is very little variation in the plasma temperature and the laser energy absorbed by the plasma vary minimally with laser intensity.

For a Gaussian beam

$$I(\omega) = I_0 \mathrm{e}^{-2(\omega/\omega_0)^2}, \tag{1}$$

$$\omega^2 = \omega_0^2 \left[1 + \left(\frac{Z}{Z_R}\right)^2\right]. \tag{2}$$

Rayleigh range $Z_R = (\pi\omega_0^2/\lambda)$

Spot Dia. $= \pi\omega_0$

$$I_0' = \frac{I_0 \pi \omega_0^2}{\pi\omega^2} = I_0 \frac{\omega_0^2}{\omega^2}. \tag{3}$$

We define I_{th} as the threshold intensity at which we have the hot plasma giving x-ray emission and temperature in plateau region

$$I(r_{\mathrm{th}}) = I_0 \cdot \mathrm{e}^{-2(r_{\mathrm{th}}/\omega)^2}. \tag{4}$$

At defocus position $I_0 = I'$, therefore

$$I_{\mathrm{th}} = I_0' \cdot \mathrm{e}^{-2(r_{\mathrm{th}}/\omega)^2} \tag{5}$$

$$\left(\frac{r_{\mathrm{th}}}{\omega}\right)^2 = \frac{1}{2} \ln \frac{I_0'}{I_{\mathrm{th}}} \quad \text{or} \quad r_{\mathrm{th}}^2 = \frac{\omega^2}{2} \ln \frac{I_0'}{I_{\mathrm{th}}}.$$

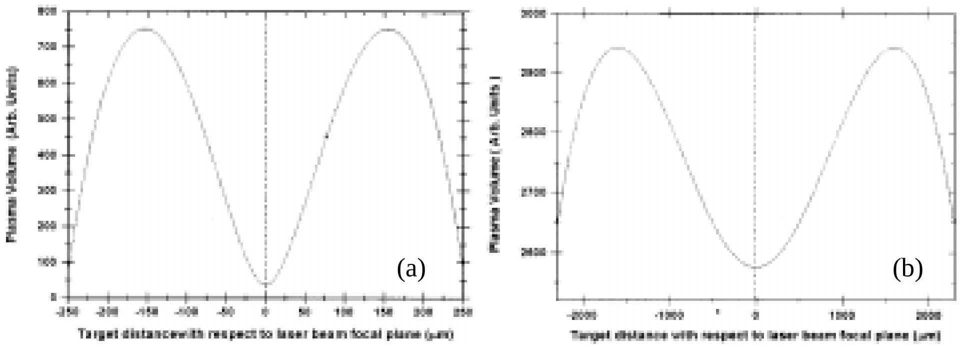

Figure 4. The X-ray flux that is directly proportional to the focal spot radius $r_{\rm th}^2$ is plotted against the target position with respect to the best laser beam focal plane. Negative values on x-axis imply that the point of laser focus is in front of the target surface, while positive values imply that the point of laser focus is behind the target surface. Results are for copper target (**a**) for Tallents data points and (**b**) for our own experimental parameters.

Put for ω and I_0' from eqs (2) and (3)

$$r_{\rm th}^2 = \omega_0^2 \left[1 + \left(\frac{Z}{Z_R}\right)^2\right] \ln\left[\frac{I_0}{I_{\rm th}} \frac{1}{\left[1+\frac{Z}{Z_R}\right]^2}\right].$$

For constant laser power and $I_{\rm th}$ being constant for a given material, therefore

$$\frac{I_0}{I_{\rm th}} = k,$$

$$r_{\rm th}^2 = \omega_0^2 \left[1 + \left(\frac{Z}{Z_R}\right)^2\right] \ln\left[\frac{k}{1+\left(\frac{Z}{Z_R}\right)^2}\right].$$

Since the volume of the hot expanding plasma is given by

$$V = \pi \cdot r_{\rm th}^2 \cdot x,$$

where x is the length of the plasma, which is proportional to the incident energy. As the energy is more or less constant for an experiment $V \propto r_{\rm th}^2$ and V varies as $r_{\rm th}^2$ as

$$\omega_0^2 \left[1 + \left(\frac{Z}{Z_R}\right)^2\right] \ln\left[\frac{I_0}{I_{\rm th}} \frac{1}{\left[1+\frac{Z}{Z_R}\right]^2}\right].$$

Thus if we plot the x-ray flux in terms of $r_{\rm th}^2$ as a function of target position relative to the best focus as shown in the figure 4a and 4b, we get after putting the appropriate values of focusing parameters, a plot which reproduces the graph of Tallents model and also the graph for our experimental parameters which matches well with the position of the two maxima in the experimental data curves.

5. Conclusion

The measurement of x-ray emission from the laser produced copper plasma formed by focussing of nsec laser beam with varying size of focal spot seems to confirm the basic assumption of model by Tallents *et al* [3] and also corroborates the experimental result of Chvojka *et al* [8] at sub-nanosecond laser pulse and Giulietti *et al* [9] at nsec laser pulse duration. The presence of two maxima in the x-ray signal plotted against the target placement distance with respect to the laser beam focal plane confirms the volume effect to be responsible for enhancement in the x-ray yield. Thus supports the model of Tallents [3] even in nanosecond LPP, independently confirms the experimental result of Chvojka [8]. This is also in agreement with the experimental results Giulietti *et al* [9] for ns LPP, except that they see prominent enhancement of x-ray signal when laser beam is focused in the front side of the target and it is correlated with second harmonic emission and thus related to filamentation in the plasma corona region. A more comprehensive experiment is called for to understand the role of lateral energy transport, filamentation and plasma volume in order to optimize the x-ray yield from LPP of nanosecond duration at varying laser intensities.

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