Optimization of x-ray line emission from copper plasma with laser focal spot

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Abstract: Laser produced x-ray are having variety of applications. X-ray emission from copper plasma produced by a sub-nanosecond Nd: glass laser have been studied as a function of distance of the target from the best focus position. Optimization of soft (0.7 – 1.56 keV) and hard x-ray (3- 5 keV) emission as a function of the laser focal position has been undertaken. The x-ray line emission in the spectral range of 7.7 Å - 9.6 Å range with respect to the laser focal position is important for applications and has been separately measured. It is observed that the maximum soft x-ray emission is away on both side of the best focus while hard x-ray shows peak close to best focus position. The line emission intensity variation with respect to focal position also exhibits the double hump variation with varying focal position. This indicates that the line emission is a strong function of plasma volume rather than laser intensity

Introduction: Intense XUV to soft x-ray emission from laser-produced plasma sources is currently of great interest for a variety of research investigations including inertial confinement fusion [1], x-ray backlighting [2] soft x-ray lithography [3] etc. In macroscopic application of x-ray source, x-ray line sources are proved to be the best sources to get better resolution and quantitative measurements. Many authors have recorded optimized ion emission [4, 5] and x-ray emission [6, 7] with the focal position variation. Application needs motivate the irradiation conditions to be optimized. X-ray emission has exhibited one [6, 8], two [9, 10], or even three [11] peaks when the laser focus position with regard to the target surface was varied. Two peaks in ions or x-ray flux can be explained by variation in output associated with threshold laser intensity and the varying plasma volume as the lens-target distance is changed [12]. Three or more peaks suggest filamentation or beam hot spots [13]. The optimization of line emission with the laser intensity has been done [14]. Here we have done the optimization of x-ray line emission intensity with the laser focal spot variation at fixed laser energy.

Experimental set-up: The experiments were performed with our home built Nd:glass laser system (λ=1.06μm) which is capable of producing 12J. The laser system used is consists of a commercial oscillator (100mJ/300-800 psec) followed by two 19 mm x 300 mm Nd:Glass amplifier pumped by six xenon filled flashlamps, two 38 mm x 300 mm and one 50 mm x 300mm Nd:Glass amplifiers pumped by twelve xenon filled flashlamps each. A spatial filter to remove non-uniformity and to expand the beam is placed in between the second and third stage amplifiers of the chain. Two Faraday Isolators protect from back reflection which can cause damage to the optics and laser oscillator. The laser system was operated in a single shot mode with maximum energy of 3.5 J per pulse and pulse duration of 500 psec. The high power laser was focused in a chamber evacuated to 4x10⁻⁵ mbar with intensity of the order of 10¹² to 9 x
10^{13} \text{ W/cm}^2. The laser was incident normal to the target. Diagnostics of the ion flux are based on time-of-flight methods (Ion collector). Silicon semiconductor diodes (XUV100, by UDT sensor) were used for x-ray flux measurement. An indigenously developed x-ray crystal spectrometer based on TAP crystal placed at 45° is used for the line emission studies of copper plasma. For online detection a combination of a phosphor screen (P 11 phosphor coated on fiber optic plate) and intensifier and its driving electronics is used. The detector unit was mounted with a flange having a tapered angle of 18° and was connected to vacuum chamber port flange. The target was fixed on motorized z-stage which is having a movement of 12 mm. The vertical movement helps us to measure the x-ray spectrum over a broad spectral range. By changing the crystal height, the spectrograph is able to cover a wavelength range of 7.1–10.3 Å, with a spectral resolution of 34 mÅ limited by the source size. Two aluminized polycarbonate foils (Alexander Vacuum Research, Inc., trade name: B-10) having 1/e cutoff of 0.9 keV were used to prevent any scattered light in the plasma chamber from coupling to the phosphor screen. In a single shot, the spectrometer can cover a spectral range of 1.8 Å. The crystal angle was adjusted at a fixed value so that it can generate the spectrum of the range of 7.7 – 9.5 Å on the useful area of the detector. To measure the soft x-rays, the AXUV detector cover with B10 filter (transmission >0.9 keV) was placed at angle (θ = 50°) with respect to target normal at a distance of 40 cm and other AXUV cover with 2 µm Al filter (transmission 0.7-1.56 keV and >2.1 keV) was placed at angle (θ = 85°) with respect to target normal at a distance of 36.2 cm. For harder x-ray measurement, detector cover with 12micron Ti filter (transmission 3.0 - 5 keV) was place at (45°) and at a distance of 65 cm.

**Result and Discussion:** X-ray spectrum are measured using x-ray diodes covered with filter foil which transmit soft and hard x-rays and line emission is studied using crystal spectrometer. Variations in soft x-ray and hard x-ray flux with target position are shown in figure 1. It can be seen from the figure, the soft x-ray flux decreases as the best focus is approached. However, at the centre of the dip, a small peak is also seen in the soft x-ray flux. The hard x-ray flux is seen to start increasing as move towards the best focus and shows a peak emission at the position close to -1 mm from best focus. The plots in figure 1are observed to be asymmetric with respect to the best focus position '0 mm'. X-ray signal is seen to be slightly higher on the ‘-’ side, that is when the lens-target distance is greater than the focal length of the lens.

The double hump variation in soft x-ray flux in figure 1 has been seen by several other authors as well [6, 12].This has been ascribed as being due to the effect of a decreasing volume as we move towards the focus. The small peak at the centre of the dip of soft x-ray plot has been reported by some authors as a three peak structure. It has been ascribed due to higher ionization states being produced close to the focal plane, where the laser intensity is highest. However, the trend of variation for hard x-rays is quite different. Hard x-rays show a single peak close to -1 mm where the soft x-ray shows dip. The reason for this shift of maximum slightly away from the best focus position has been explained by other authors as well [10, 15, 16]. This peaking is always observed in the ‘-’ positions where the laser focus is in front of the target. In such geometry, laser beam filamentation could take place leading to a sharp increase in hot electron flux in the plasma, which further results in a corresponding increase in hard x-ray flux. Thus as we move the target closer to the focus, there is a combination of x-rays emitted due to bremsstrahlung and due to hot electrons caused by the non-linear processes. This combined effect together with the reduction in plasma volume causes the fall and rise in x-ray flux.

The emissions of hard x-rays from laser produced plasmas are connected with the presence of hot electrons with high temperature as a result of non-linear laser processes occurring within the plasma. The various theoretical and empirical scaling laws for the hot electron temperature are of the form [17].
\[ T_H = A \left( I \lambda^2 \right)^{\alpha}, \quad \ldots (1) \]

where \( \alpha \) varies from 1/3 to 2/3 and \( A = \frac{10^{15}W.cm^{-2}.\mu m^{-2}}{10keV} \). At our best focus position with \( I \lambda^2 = 10^{14}W.cm^{-2}.\mu m^{-2} \), we expect hot electron temperatures from equation (1) of typically only 3 keV. The increasing intensity with the movement of target towards the focus leads to the production of hot electrons with \( T_H \) up to 3 keV, which in turn results in the emission of hard (3 – 5 keV) x-rays.

The line emission of copper plasma recorded in the spectral range 7.7 – 9.6 Å using TAP crystal is shown in figure 2. An interesting observation of line emission with respect to laser focal position has been seen. The line emission intensity with respect to laser focal position is plotted in figure 3. From the figure it is clear that the intensities of the x-ray lines in the spectral range 7.7 to 9.6 Å emitted from copper follows the same trend as the soft x-rays measured by x-ray diodes. It is clear that the line emission x-ray yield is strong function of the laser focal position. From the above figure it is also cleared that x-ray yields in ‘-’ focal position is more than the ‘+’ position which is describe earlier and it is more pronounce than the soft x-ray measured with diodes.

Figure 1. Effect of focal position on soft using B10 (■) and 2 micron Al (●) filter and hard x-ray using 12 micron Ti filter (▲).
Conclusion: Optimization of soft (0.7 – 1.56 keV) and hard x-ray emission as a function of the laser focal position has been undertaken. The x-ray line emission in the spectral range of 7.7 Å - 9.6 Å range with respect to the laser focal position is important for applications and has been separately measured. The double hump structure observed in the soft x-ray emission measured with x-ray diodes covered with Al filter having x-ray transmission in the range of 0.7 – 1.56 keV and B10 filter having transmission range > 0.9 keV and hard x-ray emission in the range of 3 - 5 keV using 12 µm titanium filter have been measured. The double hump emission of soft x-rays with varying focal position can be explained as being due to the plasma
volume change with focal position and the hard x-ray variation as being due to nonlinear processes increasing at best focus intensity. The line emission intensity variation with respect to focal position also exhibits the double hump variation with varying focal position. This indicates that the line emission is a strong function of plasma volume rather than laser intensity.

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