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Time-resolved X-rays emission and laser to X-rays conversion efficiency of metallic targets

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Abstract— The laser to x-rays conversion efficiency of laser induced plasma has been investigated. Three metallic targets Al (13), Cu (29) and W (74) were irradiated with Nd: YAG laser (1064 nm) under vacuum ~10-4 torr. The x-rays emission is monitored by an X-rays detector (modified PIN photodiode) filtered with 10 µm Al sheet. The conversion efficiency as well as total x-rays energy is strongly atomic number dependent of target material. The measurements are also supplemented by the time-resolved x-rays emission behavior which exhibits variation in response to the atomic number.

Index Terms— Laser, vacuum, metal target, laser induced plasma, X-rays, conversion efficiency, PIN photodiode.

1. Introduction

Laser induced plasma X-rays have much importance in the field of research due to many applications in different fields like microscopic imaging [1], diffraction [2], X-ray laser pumping [3], microlithography [4],[5] and spectroscopy [6]. One of the primary objectives to produce such kind of X-rays is the conversion of laser energy into X-rays. Initially, the investigations were concerned with the conversion of laser energy to X-rays in the range which could possibly be used for lithography and radiography [7],[8],[9]. Recently, the emphasis has been shifted and the laser induced X-rays are used in a number of applications [10]. These X-rays can be used in controlled nano-machining of the materials [11]. In addition, the precision of nano-machining could be achieved upto the diffraction limit of the X-rays [12]. The laser induced X-rays have been used to investigate the stability as well as optical luminescence and low-dimensionality photoluminescent patterns from complex materials [13],[14]. The light storage devices containing nitride materials require their decomposition or instability by writing micro-metal lines on surface and for this purpose laser induced x-rays are the most efficient and emerging agents [15]. The irradiation of semi-fluorinated mono-layered materials with Soft X-rays affects the physical and chemical properties of materials [16]. The polymers can be used as light wave-guide by inducing modification in refractive index within the irradiated volume [17].
Therefore, it is of paramount importance to explore the laser to X-rays conversion efficiencies in order to utilize these X-rays.

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A comparative study of different wavelength lasers has demonstrated that the laser to X-rays conversion efficiency increases with shorter wavelengths [18].
Many authors [19],[20],[21],[22],[23],[24],[25] have studied the X-rays emission and efficiency of conversion of laser energy into X-rays. The measurements of the X-rays emission from different targets were performed using a variety of photo-detectors each suited for specific X-rays photon energy range covered with suitable filters.
This paper reports the investigations on the Nd:YAG laser induced plasma X-rays conversion efficiency from varying the target of different atomic numbers. Time-resolved behavior of the X-rays emission has also been discussed in this paper.

2. Experimental Setup

An Nd: YAG laser (1064 nm, 10 mJ, 9 ns, and ~1012 W/cm2) is tightly focused to irradiate Al (13), Cu (29) and W (74) 4N pure metal targets. In order to expose the targets under vacuum, the targets were attached on the translatory moving motorized mount placed in vacuum chamber. The laser beam was made to impinge on the surface of the target material using IR lens of focal length 17 cm to produce expanding plasma cloud in the vicinity of target.
The experiment was performed under vacuum ~ 10-4 torr, which is achieved by using turbo molecular pump. The X-rays emitted from these targets are detected by a properly biased and filtered PIN-photodiode (BPX-65), modified by removing TO-18 Window (with spectral range of 350 to 1100 nm wavelength) and covered with Al filter of 10 µm thickness. The peak spectral response of 10µm Al filter is presented in figure 1(a). Then after placing 10 micron thick Al filter the spectral response of the detector ranges from 100 eV to 60 KeV. The X-rays signals obtained from properly biased detector were stored using a 200 MHz digital oscilloscope. A schematic diagram of experimental setup is shown in figure 1(b).

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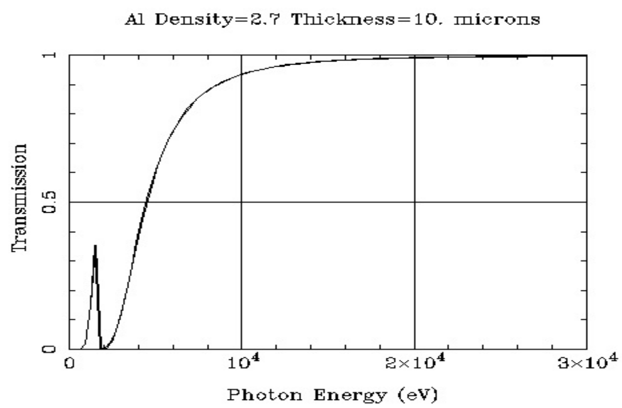

Fig. 1(a): Peak spectral response of 10 µm thick Al filter [26]

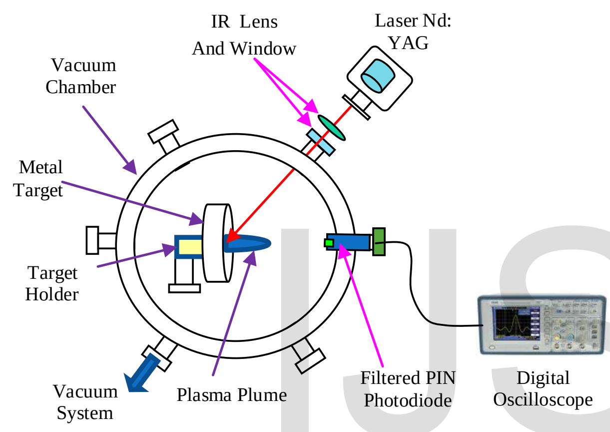

Fig. 1(b): A Schematic of experimental setup

3. Results and Discussion

Laser induced plasma emits different types of radiations including visible, ultraviolet, ions, electrons and X-rays. The most probable emission mechanisms to emit X-rays are Bremsstrahlung, line emission and recombination. The emission of X-rays shows an anisotropic behavior due to plasma opacity examined by radiations in different directions normal to the target. Actually, when the laser energy is absorbed by the material, the metal gets heated and breakdown occurs due to which low energy electrons are generated. The electrons are ionized and leave behind holes. Electrons being lighter particles move forward from ions with greater velocity and an electric field is set up due to the separation between electrons and ions. Due to the attractive force, the electrons decelerate and come back towards ions. Three processes may occur at this stage: i) loss in the electron energy due to deceleration while passing near the ions emitting Bremsstrahlung radiation or X-rays; ii) recombination of electrons with ions producing X-rays; iii) and a probability is that if already bound electrons lose energy by falling to a lower ionic energy states, then a discrete set of X-rays energy is emitted. The relative strengths of the emitted X-rays from either of the three processes depends on how the plasma was formed; typically, for plasma from low Z-material continuum or Bremsstrahlung emission dominates, while for a medium Z-material, line emission can be stronger. X-rays emitted from sufficiently high temperature plasma provided a convenient means for studying the dense plasma properties. The efficiency of conversion of laser energy into X-rays is determined by following mathematical relation [23]:

$$\eta = E_X / E_L \qquad (1)$$

Where E_X is the energy emitted by the plasma in X-rays region of the electromagnetic spectrum and E_L is the laser pulse energy. Both energies are calculated by the following relation.

$$E = \int_0^t (\frac{S^2 t}{R}) dt \qquad (2)$$

Where S is the signal voltage, t is the time duration and R is the load resistance used in biasing circuit.

X-rays emitted are detected by a filtered PIN-Photodiode (BPX-65) with a 10 microns Al filter. A typical Nd: YAG laser Pulse signal taken by IR detector having time duration of 14 ns is shown in fig. 2.

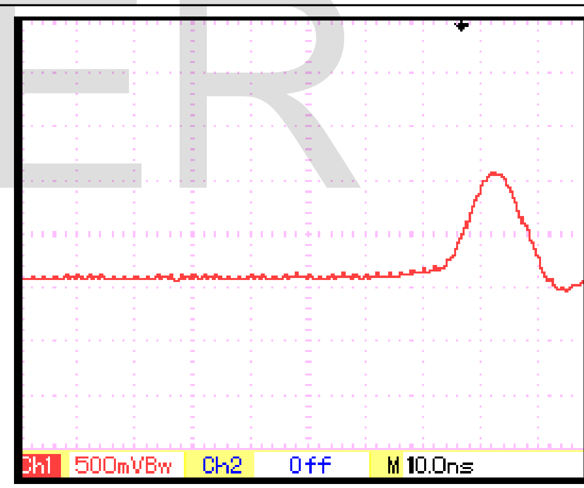

Fig. 2: An Nd: YAG laser signal profile

3.1. Signal from Al plasma

Fig. 3 shows the time resolved x-ray signal profile generated from Al plasma. The whole signal lasts for about 47 ns (line 1–line 2) which indicate the duration of X-rays burst. A very small disturbance at the beginning of the signal represent that only a few X-rays are generated due to the line emission because at early stages of the plasma formation the constituents of the plasma do not have such high density as well as the energy that they could undergo Bremsstrahlung or recombination.

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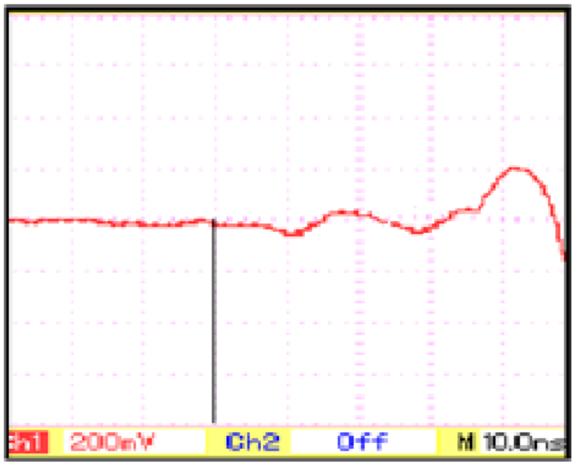

Fig. 3: X-rays signal from Al

With the passage of time, the plasma becomes hot and dense leading to the phenomena of Bremsstrahlung, line and recombination resulting in the enhancement of the X-rays emission after 37 ns from the beginning of signal, as indicated by the largest peak at the leading edge of the signal profile. Maximum voltage of this peak is 240 mV and the peak lasts for 10 ns (FWHM). The laser to X-rays conversion efficiency extracted from this signal is 0.86 %.

3.2. Signal from Cu plasma

Time resolved X-rays signal profile generated from Cu target is represented in figure 4. The whole signal lasts for about 46 ns (line 1–line 2) which yield the duration of X-rays emission. A disturbance at the start of the signal indicates the formation of plasma from which only a few X-rays are generated. After 34 ns a bigger peak appears indicating the emission of burst of X-rays. This peak appears due to formation of electron hot spots because of the stage plasma formation. The maximum voltage of this peak is 270 mV and the peak lasts for 12 ns (FWHM). The laser to X-rays conversion efficiency is calculated to be 1.04 %.

3.3. Signal from W plasma

Figure 5 shows the time resolved x-ray signal profile generated from W plasma. The duration of X-rays signal is 56 ns (line 1-line 2). Hot and dense plasma is formed after 46 ns leading to the formation of electron hot spots resulting in the enhancement of the X-rays emission. This increase in the X-rays emission is indicated by the largest peak at the leading edge of the signal profile.
The maximum voltage of this high intensity peak is 360 mV and time duration (FWHM) of this peak is 10 ns. Laser to X-rays conversion efficiency calculated from this signal is 2.8 %.

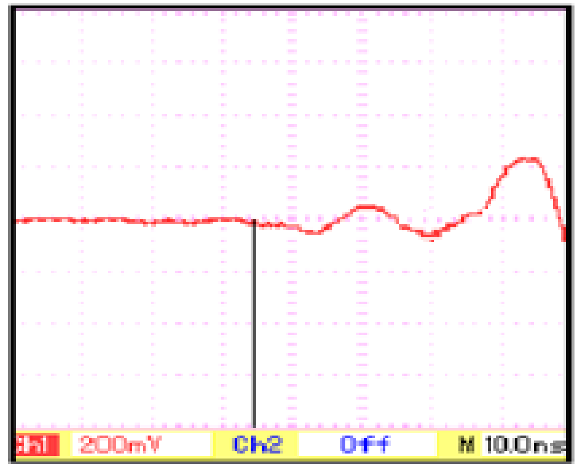

Fig. 4: X-rays signal from Cu

Fig. 5: X-rays signal from W

A comparison of the time resolved X-rays signals from Al, Cu and W (as from fig. 3,4,&5), it is observed that disturbances for Al signal appears few ns earlier than Cu and W which shows that the initiation of plasma formation starts earlier due to low melting point of Al. The time duration of X-rays emission for W (56 ns) is longer with the highest peak intensity (350 mV) than Al (41 ns, 245 mV) and Cu (45 ns, 265 mV) which shows that W is better source of X-rays.

A number of signals were taken for Al, Cu and W X-rays sources. The average value of peak voltage, time duration and hence energy were taken to calculate the average laser to X-rays conversion efficiency. The data obtained from these calculations is listed in Table 1.

Table 1 depicts that Aluminum having low atomic number emits lowest energy X-rays with less intensity as compared to Cu and W. Copper is a stronger emitter of X-rays both in terms of intensity and energy as compared to Al. Tungsten emits highly energetic X-rays with largest intensity due to high atomic number and melting point. This is because of the generation of much stronger electric field at the W surface as compared to Al and Cu. This stronger field is capable of producing more hot and dense plasma. Moreover, the X-rays emission duration is longer for W as compared to Al and Cu. The generation of more hot and dense plasma for longer period of time is the obvious reason for the greater laser to X-rays conversion efficiency in case of W. The variation of average energy of X-rays and average conversion efficiency of emitted X-rays with atomic number is presented in a graph in fig. 6.

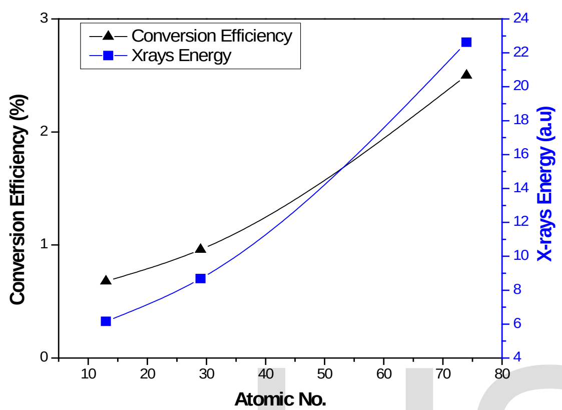

Fig. 6: Variation in X-ray energy and average conversion efficiency with atomic number.

It is obvious from Table 1 and fig. 6 that the energy and the laser to X-rays conversion efficiency are higher for metallic target with greater atomic number. The effect of atomic number on the X-rays emission could be explained by the fact that higher the atomic number of the target, the nucleus becomes more positive which results in greater force of attraction on the nearby electrons. Thus, the production of the X-rays by the Bremsstrahlung process is more efficient and the energy of the beam increases [27]. Basically as the atomic number of the target material increases, the efficiency of the production of Bremsstrahlung radiations increases, and the high-energy photons increase in number more readily than the low-energy photons.

TABLE 1
Parameters obtained from X-rays signals

Target Material	Atomic No. (Z)	Average Peak voltage (mV)	Average peak current (mA)	Average Time duration (ns)	Energy of X-rays E_X (a.u)	Conversion Efficiency η (%)
Al	13	245	4.79	41	6.16	0.68
Cu	29	265	5.18	45	8.68	0.96
W	74	350	6.84	55	22.62	2.50

4. Conclusion

The atomic number of the target material strongly influences the time-resolved behavior of X-rays in terms of initiation of the X-rays burst and emission duration. The conversion efficiency strongly depends on the target material mainly on the atomic number due to the transition probability (Line emission, Bremsstrahlung and recombination) involved in the X-rays emission and emission time duration.

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