PRAMANA
— journal of
physics

Vol. 63, No. 5
November 2004
pp. 1031–1037

Characteristics of a multi-keV monochromatic point x-ray source based on vacuum diode with laser-produced plasma as cathode

A MOORTI, M RAGHURAMAIAH, P A NAIK and P D GUPTA
Laser Plasma Division, Centre for Advanced Technology, Indore 452 013, India
E-mail: moorti@cat.ernet.in

MS received 28 January 2004; revised 23 April 2004; accepted 15 June 2004

Abstract. Temporal, spatial and spectral characteristics of a multi-keV monochromatic point x-ray source based on vacuum diode with laser-produced plasma as cathode are presented. Electrons from a laser-produced aluminium plasma were accelerated towards a conical point tip titanium anode to generate K-shell x-ray radiation. Approximately 10^{10} photons/pulse were generated in x-ray pulses of ∼18 to ∼28 ns duration from a source of ∼300 μm diameter, at $h\nu = 4.51$ keV (K_α emission of titanium), with a brightness of $\sim 10^{20}$ photons/cm^2/s/sr. This was sufficient to record single-shot x-ray radiographs of physical objects on a DEF-5 x-ray film kept at a distance of up to ∼10 cm.

Keywords. Multi-keV x-ray source; vacuum x-ray diode; laser plasma cathode.

PACS Nos 52.59.Px; 52.80.Vp; 07.85.Fv

1. Introduction

Generation of high brightness x-ray pulses of tens of picosecond to several nanosecond duration in multi-keV region has been of considerable interest for many potential applications. Although, currently available systems based on synchrotron radiation sources [1] present many interesting features, they are large, complex and expensive devices, which are often set up only as a central facility. This has motivated the development of alternative, less expensive and compact laboratory x-ray sources for some applications, which do not need all the distinctive features of the synchrotron radiation sources. Next, high-power lasers have been used to heat high-density plasma produced from solid targets to hundreds of electron volts temperature. However, they emit over a very broad range of spectrum consisting of line and continuum x-ray radiation [2,3].

Among the various other x-ray sources developed, e.g. pinch plasma devices (like x-pinch, θ-pinch, plasma focus), vacuum spark discharges etc., generation of high brightness x-ray pulses in multi-keV region using vacuum x-ray diodes has attracted considerable attention in the last several years. Powerful, repetitive flash x-ray systems have been developed using various high voltage pulsed power technologies, viz. cable transformers [4], Mark generators [5] and Blumelein technology [6–8]. Recently, vacuum x-ray diode sources have been reported using carbon nanotubes [9] and graphite nanofibre [10] field emitters. In addition, laser-driven vacuum x-ray diodes have been particularly attractive for the generation of short-duration x-ray pulses in a compact set-up which can be temporally synchronised with respect to the laser pulse. For instance, laser-driven photo-cathodes have been used to generate multi-keV x-ray pulses [11–13] of $\sim$10 ns–1 ps duration. However, the flux of x-ray photons generated is rather small, typically 10^4–10^7 photons/pulse.

Alternatively, electrons may also be extracted from plasma produced by focussing a pulsed laser beam on a metal cathode [13–15], which provides much higher flux of electrons than the photo-cathodes. Consequently, much larger number of x-ray photons can be obtained in a vacuum x-ray diode with laser-plasma cathode. Egbert *et al* [13] have reported five orders of magnitude higher x-ray flux ($\sim 10^9$ photons/pulse) in the plasma-cathode regime as compared to that in the photo-emission cathode mode ($\sim 10^4$ photons/pulse). However, they have not described characteristics of the x-ray emission in their work. Further, Wang *et al* [14] have shown that a high-quality electron beam can be generated from laser-produced plasmas with higher number of electrons as compared to that with photo-emission. Korobkin *et al* [15] have reported optimisation of various parameters of a vacuum diode x-ray source with laser-plasma cathode and obtained $\sim 10^{10}$ photons/pulse of Ti K-shell emission. However, no details about the spatial, spectral, and angular distribution characteristics were given. Since, vacuum diode x-ray source with laser-plasma cathode can provide a cheap, compact, multi-keV source for a variety of applications, viz. x-ray diffraction studies, flash radiography, and pump and probe type experiments involving lasers, their temporal, spatial and spectral characterizations are highly desirable to exploit their full potential for various applications.

In this paper, we present various characteristics of a multi-keV, monochromatic, vacuum diode x-ray source with laser-plasma as the cathode. Electrons from laser-produced aluminium plasma were accelerated on to a conical point tip titanium anode. x-ray pulses of $\sim$18–28 ns duration, depending on the cathode–anode separation, were obtained from a source of $\sim$300 μm diameter, at $h\nu = 4.51$ keV (K_α emission of titanium). Approximately 10^{10} photons/pulse were generated, which correspond to a brightness of $\sim 10^{20}$ photons/cm^2/s/sr. Single-shot x-ray radiographs of small physical objects were recorded on a Kodak DEF-5 x-ray film using this source.

2. Experimental details

Figure 1 shows a schematic of the experimental set-up. The diode consists of a planar aluminium slab as a cathode and a point-tip (hemispherical shape of $\sim$300 μm diameter) anode of titanium, placed in a chamber evacuated to $\sim 2 \times 10^{-5}$ Torr. Anode was biased to +20 kV DC. Anode to cathode separation was varied in the range of 1 to 10 mm. An Nd : YAG laser beam (laser energy $\sim$2–40 mJ, pulse duration $\sim$20 ns, full-width at half-maximum (FWHM), and rep rate of 1 Hz) was focussed on the aluminium target to produce the plasma.

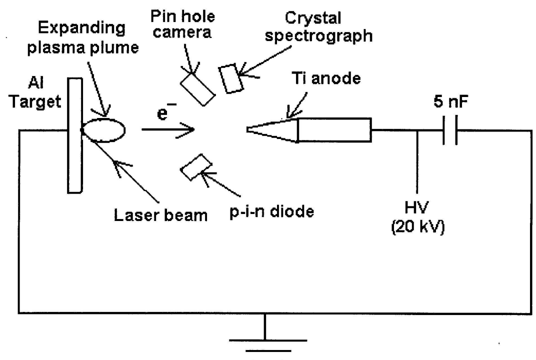

Figure 1. Schematic of the experimental set-up.

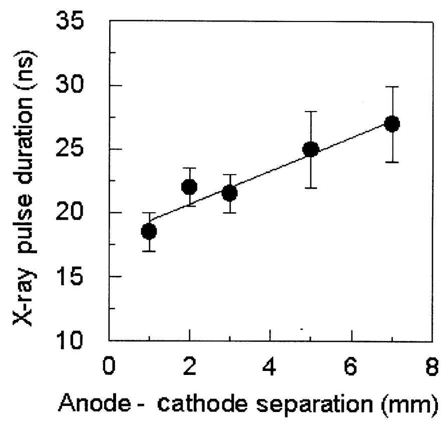

Figure 2. Dependence of the K_α x-ray pulse duration on the anode–cathode separation (laser energy = 25 mJ, anode voltage = 20 kV).

3. Results and discussion

Temporal profile of the x-ray emission pulse from the anode was monitored through a silicon p–i–n detector (Quantrad 100-PIN-250). The p–i–n detector was covered with a 100 μm thick beryllium foil and a 6 μm thick aluminium foil (overall cut-off energy ∼3.6 keV) to block any plasma radiation from entering the detector. Variation of the K-shell x-ray pulse duration (τ) with anode–cathode separation (d) for a fixed value of laser energy ∼25 mJ and anode voltage = 20 kV is shown in figure 2. It varies from ∼18 ns to 28 ns for anode–cathode separation from 1 mm to 7 mm. For the anode–cathode separation exceeding 7 mm, a hump started appearing in the rising part of the x-ray pulse. Typical x-ray pulses recorded for $d = 2$ mm and 10 mm are shown in figure 3.

The above observations may be understood as follows: The plasma is produced on the Al target by focussing laser beam, which expands towards the anode. Electrons from the sheath region of the expanding plasma are accelerated towards the tip of

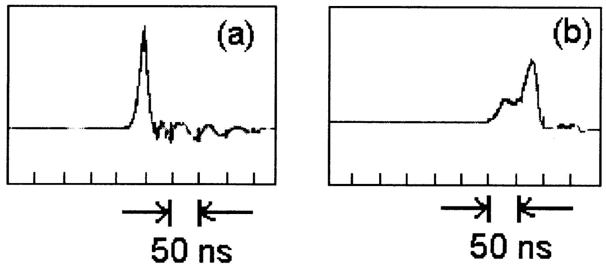

Figure 3. Typical temporal profiles of K_α x-ray emission. (**a**) $d = 2$ mm, (**b**) $d = 10$ mm.

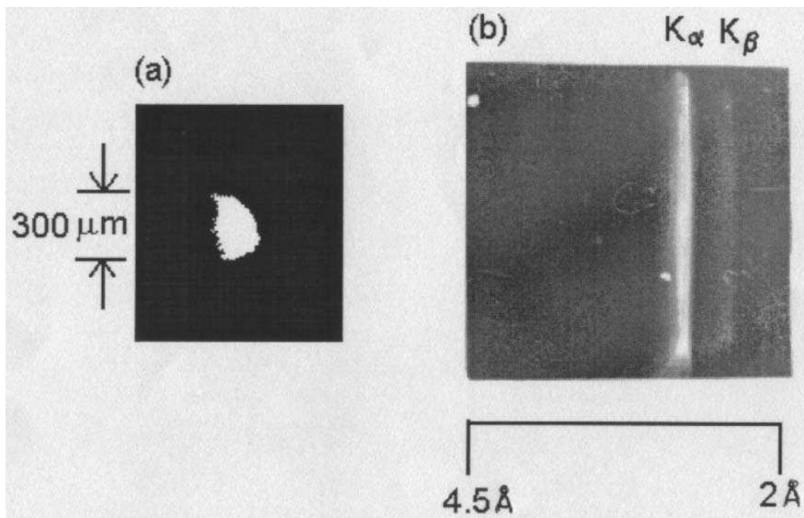

Figure 4. (**a**) Spatial profile of the K_α x-ray source, (**b**) x-ray emission spectrum from titanium anode. K_α: 4.51 keV (2.75 Å), K_β: 4.93 keV (2.51 Å).

the conical Ti anode and lead to generation of characteristic K-shell x-ray radiation. The x-ray emission from the anode starts with the formation of plasma on the cathode and stops with the shortening of the diode gap with the arrival of the plasma boundary at the anode. At this stage high current flows in the diode and anode voltage falls rapidly. Hence, the time duration of the x-ray emission from the anode is determined by the time taken by the plasma boundary to reach the anode, which is proportional to the anode–cathode separation. In figure 2, the dependence of pulse duration on the anode–cathode separation fits to a linear relation, τ (ns) $= 1.5d$ (mm) + 17.5. Further, for the anode–cathode separation exceeding 7 mm, a hump started appearing in the rising part of the x-ray pulse. This may be due to the fact that at larger anode–cathode separation, the extraction field reduces, and hence initially only faster groups of electrons present in the plasma are accelerated towards the anode, which are responsible for the hump in the rising part of the x-ray pulse. Subsequent expansion of the plasma leads to further extraction of the plasma electrons, contributing to the rest of the x-ray emission pulse.

The x-ray source (anode tip) was imaged using an x-ray pinhole camera. The diameter of the pinhole used was 50 μm, and the camera magnification was 2.5. The image was recorded on a Kodak DEF-5 x-ray film. Figure 4a shows a spatial profile of the K_α x-ray source. The image recorded is oblong in shape as the pinhole camera looked at an angle of 45° with respect to the anode axis. From the densitometer traces of the image, the source size was determined to be $\sim$300 μm, consistent with the size of the tip of the anode.

A crystal spectrograph was set up using penta erythritol (PET) (plane – 0 0 2, $2d = 8.742$ Å) to record the x-ray emission spectrum from the anode. The spectrograph covered a range from 2 Å to 4.5 Å with a spectral resolution of 0.025 Å. Kodak DEF-5 x-ray film was used as the detector. Figure 4b shows the x-ray spectrum consisting of a strong K_α line ($E_\mathrm{x} = 4.51$ keV, $\lambda = 2.75$ Å) and a weaker K_β line ($E_\mathrm{x} = 4.93$ keV, $\lambda = 2.51$ Å) of titanium. The intensity ratio of the K_α to K_β line was measured to be $\approx 40:1$. Next, the K_α line intensity was about 80 times higher than the background.

Angular distribution of the K-shall x-ray emission from the anode tip was also studied. Kodak DEF-5 x-ray film was kept in two separate curved cassettes (covered by aluminised polycarbonate x-ray filters to block any visible radiation), in the form of an arc of radius 13 cm with the anode tip at the centre. The first cassette covered an angular range from 20° to 50° and the second from 60° to 90°, with respect to the axis of the anode tip. The film was exposed to K-shell x-rays in multiple shots. Densitometer trace of the exposed film was taken to measure optical density (OD) at different angles. Exposure (E) on the film at different angles was calculated from the relation, $E = 10^{\mathrm{OD}/\gamma}$, where the value of gamma (γ) for the x-ray film was measured to be 0.25, using the standard step filter technique. Angular distribution obtained for K-shell x-ray emission is shown in figure 5. It is observed that maximum emission is in the forward direction and the intensity reduces with an increase in the angle (θ). For a flat tip anode the K-shell x-ray radiation received at an angle θ with respect to the symmetry axis of the cathode is dependent on the solid angle the anode presents to the observer. The observed radiation is thus expected to fall off with angle as $\cos\theta$. But in our case the tip of the anode has a semi-spherical shape and therefore the observed angular distribution is comparatively more isotropic. A solid line curve corresponding to $\cos^{0.5}\theta$ is shown as an approximate fit to the experimental data.

Brightness of the source was derived from the measured signals of the p–i–n diode using its known response of 0.2 C/J. At a laser energy of 25 mJ, for a diode gap of $\sim$3 mm and anode potential of 20 kV, $\sim 10^{10}$ photons/pulse were generated. Using 300 μm as the diameter of the source and a pulse duration of $\sim$22 ns, the brightness of this K-shell x-ray radiation source is estimated to be $\sim 10^{20}$ photons/cm^2/s/sr. This would provide an x-ray flux of $\sim 10^7$–10^8 photons/cm^2 at 3 to 10 cm from the anode tip, which is sufficient to record a single-shot exposure on Kodak DEF 5 x-ray film [16]. A single-shot x-ray radiograph of a copper wire mesh, kept in contact with the film at a distance of 3 cm from the source is shown in figure 6. For distances larger than 10 cm, higher sensitivity x-ray detectors like back-thinned charge coupled device (CCD) camera can be used.

The above method of x-ray generation has several advantages when compared to the other vacuum diode x-ray sources. By producing plasma on the cathode, dis-

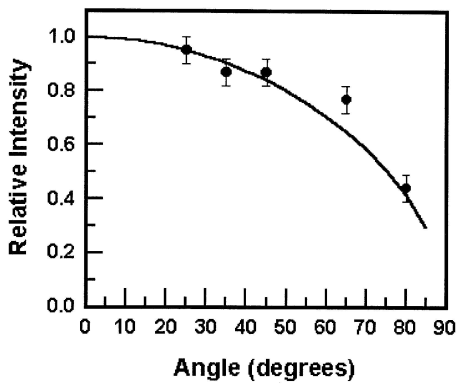

Figure 5. Angular distribution of the x-ray emission from the anode tip. The solid curve represents a $\cos^{0.5}\theta$ distribution.

charge can be initiated at much smaller electric fields as compared to that required for a field emission based diode. The field emission cathodes [17] require ultrahigh vacuum and an electric field exceeding 10^7 V/cm to achieve an electron current density of $\geq$10 A/cm^2. Next, although an explosive emission cathode [17] based x-ray tube (wherein the electron source is the plasma produced by explosion of the cathode micro-edges under the application of a high voltage pulse) may provide a higher current density, the lower threshold voltage for stable electron emission is $\sim$50 kV. The latter devices are thus generally suitable for the production of higher energy x-rays. Alternatively, x-rays of photon energy ranging from a few keV to tens of keV can be generated from the laser-driven vacuum diodes by using different anode materials and applying corresponding optimum accelerating voltages. This also leads to an improvement in the line to continuum intensity contrast of the x-ray emission from the anode. This is because the optimum voltage for maximum contrast for the K-shell emission lies between three to six times the threshold voltage required for excitation of the particular line radiation [18]. Further, as mentioned earlier, the source is particularly useful for pump and probe type experiments involving lasers, as the x-ray pulse can be temporally synchronised with respect to laser pulse. Finally, one can have a compact system, as the laser energy required for the operation of the diode is a few milliJoules only, which can be delivered by a small size pulsed YAG laser.

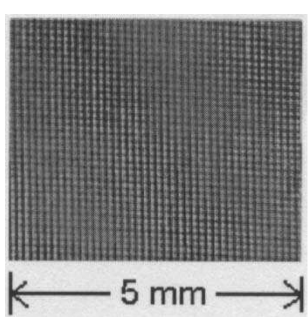

Figure 6. Single-shot x-ray radiograph of a copper wire mesh recorded using the K_α x-ray source. The wire thickness and grid seperation of the wire mesh is $\sim$60 μm each.

4. Conclusion

An experimental study of the characteristics of K_α x-ray generation in a vacuum x-ray diode with laser-produced plasma as an electron source has been carried out. This includes study of the pulse duration, spectrum, spatial and angular distribution of the emitted radiation. The source provides $\sim 10^{10}$ photons/pulse predominantly of $h\nu \sim 4.51$ keV, with an estimated brightness of $\sim 10^{20}$ photons/cm^2/s/sr. Single-shot x-ray radiographs of a copper wire mesh have been recorded at a distance of several centimetres using this source.

References

[1] Herman Winick (Ed.), *Synchrotron radiation sources: A primer* (World Scientific, Singapore, 1994)
[2] J A Chakera, V Arora, S Sailaja, S R Kumbhare, P A Naik, P D Gupta, N K Gupta and B K Godwal, *Appl. Phys. Lett.* **83**, 27 (2003)
[3] S Sailaja, P A Naik and P D Gupta, *IEEE Trans. Plasma Sci.* **29**, 960 (2001)
[4] A Khacef, R Viladrosa, C Cachoncinlle, E Robert and J M Pouvesle, *Rev. Sci. Instrum.* **68**, 2292 (1997)
[5] C N Boyer, G E Holland and J F Seely, *Rev. Sci. Instrum.* **69**, 2524 (1998)
[6] C B Collins, F Davanloo and T S Bowen, *Rev. Sci. Instrum.* **57**, 863 (1986)
[7] J J Coogan, F Davanloo and C B Collins, *Rev. Sci. Instrum.* **61**, 1448 (1990)
[8] M Zakaullah and J Worley, *J. Appl. Phys.* **88**, 1251 (2000)
[9] G Z Yue, Q Qiu, B Gao, Y Cheng, J Zhang, H Shomoda, S Cahng, J P Liu and O Zhou, *Appl. Phys. Lett.* **81**, 355 (2002)
[10] T Matsumoto and H Mimura, *Appl. Phys. Lett.* **82**, 1637 (2003)
[11] S E Dorenzo, W W Moses, S C Blankespoor, M Ito and K Oba, *IEEE Trans. Nucl. Sci.* **41**, 629 (1994)
[12] I V Tomov, P Chen and P M Rentzepis, *Rev. Sci. Instrum.* **66**, 5214 (1995)
[13] A Egbert, B N Chichkov, C Fallnich, S Zimmermann and A Reinhold, *Opt. Eng.* **41**, 2658 (2002)
[14] X J Wang, T Sang, H Kirk, T Srinivasan-Rao, J Fischer, K Batchelor, P Russell and R C Fernow, *J. Appl. Phys.* **72**, 888 (1992)
[15] Yu V Korobkin, I V Romanov, A A Rupasov, D A Fedin, A S Shikanov, A Moorti, M Raghuramaiah, J Upadhyay, S R Kumbhare, S Sailaja, V Arora, P A Naik and P D Gupta, *Laser and Particle Beams* **17**, 499 (1999)
[16] P D Rockett, C R Bird, C J Hailey, D Sullivan, D B Brown and P G Burkhalter, *Appl. Opt.* **24**, 2536 (1985)
[17] R B Miller, *Introduction to the physics of intense charged particle beams* (Plenum, New York, 1982)
[18] F Jamet and G Thomer, *Flash radiography* (Elsevier, Amsterdam, 1976)