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Narrow band X-ray emission in the water-window spectral region from a laser heated gold copper mix-*Z* plasma

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ABSTRACT A laser plasma X-ray source of narrow spectral range in the water-window region, is reported using a 50–50 (atomic fraction) mixture of gold-copper mix-*Z* planar target. Plasma was produced using the second harmonic beam of an Nd:glass laser focused to an intensity $\sim 10^{13}$ W/cm^2 on the target. The spectrum of the plasma radiation transmitted through a free-standing 0.4 μm aluminium/0.9 μm vanadium X-ray filter foil was measured to lie in the narrow-band of 24–26 Å. This provides a debris-free X-ray dose of 2–3 mJ/sr which can be used for single shot X-ray imaging of live biological samples.

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1 Introduction

X-ray sources in the water-window region (23–44 Å) [1–9] are of particular interest for imaging of live biological samples with high contrast as in this range the water present in the sample offers very little absorption to the radiation compared to the other major constituents like carbon. Although a synchrotron radiation source (SRS) can be used for this purpose, an exposure of the order of few milliseconds is usually necessary. In comparison, laser produced plasmas, on account of their high peak brightness, can provide sufficient exposure in a single pulse of short duration (nanosecond or smaller). This facilitates imaging of the sample in a single shot. This is advantageous as it prevents any degradation of the resolution due to motion blurring [5], as well as radiation induced structural changes in the sample which manifest over a longer time scale. Thus a laser produced plasma X-ray source offers unique advantages over an SRS source in X-ray imaging of the live sample in the water-window spectral range owing to its smaller source size and high peak brightness in a short duration pulse. Hence, it is desirable to have efficient laser produced plasma soft X-ray source for the above application.

Laser irradiated gas and liquid jets [7–9] have been used to produce narrow band line emission in the water-window spectral region, and they are accompanied by little or no plasma-debris. However they have a rather poor conversion of laser energy to X-rays, although the use of high-Z solid targets and short wavelength lasers as the driver for producing a laser-plasma X-ray source of high conversion efficiency is well established [1, 10–14]. For instance, Eidmann and Schwanda [14] obtained an overall X-ray conversion efficiency of $\sim 70\%$ by irradiating a gold target with Nd:glass laser pulses (3 ns duration, 0.53 μm wavelength) at $\sim 10^{13}$ W/cm^2. More recently, novel targets have been explored such as nanostructure targets [5] and mix-*Z* targets [15–17] for enhancement of the X-ray emission. A debris-free X-ray radiation in the water-window spectral region can be obtained from these plasmas by using them along with either multi-layer X-ray mirror [2, 3] or narrow band X-ray filters. However the multi-layer mirrors in the water-window spectral range are rarely available. Moreover, they also increase the source to the sample distance due to the geometric requirements of the incidence angle. However, free-standing X-ray filters will have the advantages of a simple geometry and they are available with high transmission ($\gtrsim 10\%$) over a narrow spectral band.

X-ray imaging using broad-band radiation within the water-window spectral region (23–44 Å) may also lead to a poor contrast and a lower resolution in the recorded image. For example, X-ray transmission through a 1 μm thick protein sample changes by a factor of ~ 5 in going from 23 Å to 44 Å [18]. Such a large variation in the transmission will have a large change in the image contrast and also have a detrimental effect on the spatial resolution in the imaging [3, 18]. Moreover, the variation in the transmission of X-rays through a biological sample (even within the water-window range) may forbid precise quantitative analysis of the recorded X-ray images. It is therefore desirable that an X-ray source in the water-window range should have a narrow spectrum for live sample imaging. Furthermore, it is also desirable that this narrow spectrum is preferably nearer to the shorter wavelength end of the water-window spectral range, as the shorter wavelength X-rays have a higher penetration depth in the sample and provide a higher spatial resolution [1, 19]. Such a narrow spectral content X-ray source in the water window spectral range, especially from the laser irradiated mix-*Z* solid targets has not been reported in literature.

In this paper, we present a narrow band X-ray source in the water window spectral range at 25 Å ± 1 Å (i.e. 24–26 Å).

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The source was produced by focussing the second harmonic of a glass laser to an intensity of $\sim 10^{13}$ W/cm^2 on a 50–50 (atomic fraction) copper-gold mix-Z target, filtered through a 0.4 μm aluminium/0.9 μm vanadium free-standing X-ray filter. The X-ray spectrum and the energy flux are measured at two angles viz. 45° and 85° from the target normal using a transmission grating spectrograph and calibrated xuv p–i–n diodes. An X-ray flux of 2–3 mJ/sr is obtained which should be useful for single shot X-ray imaging of live biological samples with high contrast.

2 Experimental set-up

Figure 1 shows a schematic of the experimental set-up. An Nd:phosphate glass laser providing 4 J, 3 ns (FWHM) laser pulses at $\lambda_L = 0.53$ μm after second harmonic conversion was used. Plasma was produced by focussing the laser beam using an $f/6$ plano-convex lens (focal length: 40 cm) on a planar strip of 50–50 (atomic fraction) mixture of gold and copper ($\sim 70:30$ by weight fraction). The focal spot diameter of the focused beam was 130 μm as measured from X-ray pin-hole pictures of the plasma emission. The laser intensity for these irradiation conditions was estimated to be $\sim 10^{13}$ W/cm^2. The 50–50 proportion of gold and copper mixture was chosen as it was found to be the optimum atomic composition for maximum soft X-ray conversion [17] and reduction in keV X-ray line emission [20]. The target was placed inside a plasma chamber evacuated to 10^{-5} Torr using a turbo molecular pump based (oil-free) vacuum system. The X-ray radiation from the plasma was transmitted through a free-standing 0.4 μm aluminium/0.9 μm vanadium foil (IRD). The computed transmission characteristic of this filter is shown in Fig. 2. It provides a high transmission over a narrow spectral band starting from $\lambda \sim 24$ Å (corresponding to the L-edges of vanadium) with a peak transmission of $\sim 9.4\%$, and its transmission increases rapidly for $\lambda \leq 12$ Å. However, as the above gold-copper mix-Z plasma emits a much lower intensity X-ray radiation for the latter spectral region [20], this X-ray filter is quite effective in obtaining a narrow-band radiation in the water-window.

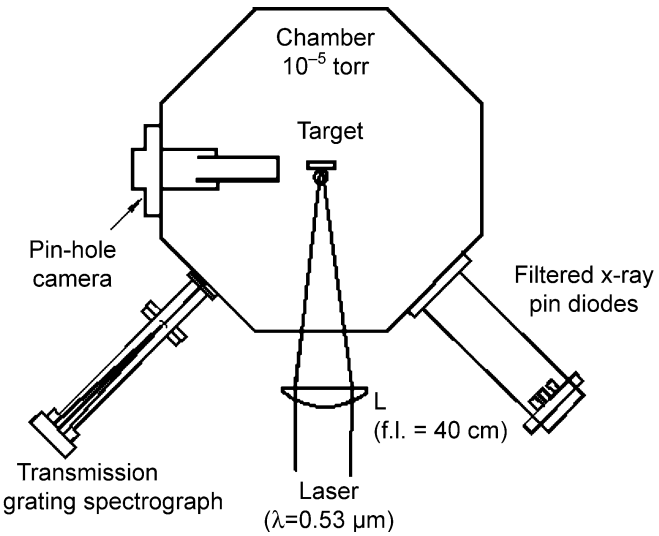

FIGURE 1 The experimental setup showing the plasma chamber and the diagnostics

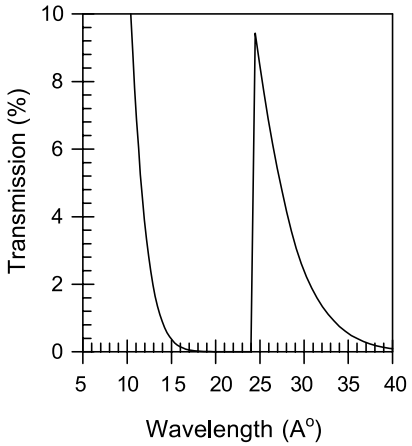

FIGURE 2 Computed filter transmission with X-ray wavelength for the 0.4 μm Al/0.9 μm V soft X-ray filter

The X-ray spectrum was measured using a transmission grating spectrograph. For recording the spectrum over a large spectral range, a transmission grating of 2000 lines/mm was used along with UFSh-4 XUV sensitive film, with a spectral resolution of ~ 3 Å. The spectrum of the radiation transmitted through the narrow-band X-ray filter was recorded using a transmission grating of 5000 lines/mm along with a microchannel plate (MCP) detector [21]. The output of the MCP was imaged onto a 12-bit digital CCD camera (SamBa EZ 140 Sensovation) connected to a personal computer. In this mode, the spectral resolution was ~ 1 Å. Next, the X-ray conversion from the plasma was determined using xuv p–i–n diodes (AXUV-HS5, IRD) mounted at 45° and 85° from the target normal. These xuv p–i–n diodes have a linear response [22] of ~ 0.28 C/J from ~ 10 keV down to ~ 10 eV and therefore they are well suited for sub-keV X-ray intensity measurements. They were kept at a large distance (~ 169 cm) from the plasma X-ray source to avoid saturation due to the large X-ray flux. The X-ray yield in the narrow band spectral region of 24–26 Å using the 0.4 μm aluminium/0.9 μm vanadium filter was measured.

3 Results and discussion

X-ray emission from a mix-Z plasma recorded using a transmission grating spectrograph (with 2000 lines/mm grating) is shown in Fig. 3. This spectrum was derived from the recorded densitometric trace using a deconvolution procedure described in [13]. The mix-Z plasma has a peak emission around 25 Å and it decreases rapidly below 20 Å. Figure 4 shows the X-ray emission transmitted through the 0.4 μm aluminium/0.9 μm vanadium filter, as recorded using the grating spectrograph (with 5000 lines/mm grating) in the direction of 45° from the target normal. The filtered spectrum has a peak at ~ 25 Å and has a spectral transmission between 24–26 Å at FWHM, in agreement with the computed transmission curve shown in Fig. 2. Thus the X-ray radiation after passing through the above filter has a narrow spectral width which is useful for the imaging of live biological samples as discussed earlier. Next, the X-ray yield in the above spectral

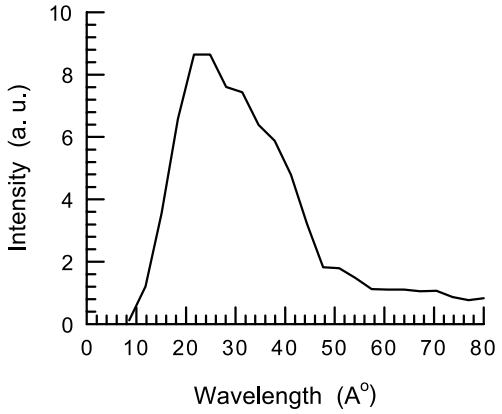

FIGURE 3 X-ray spectrum from gold-copper mix-Z plasma

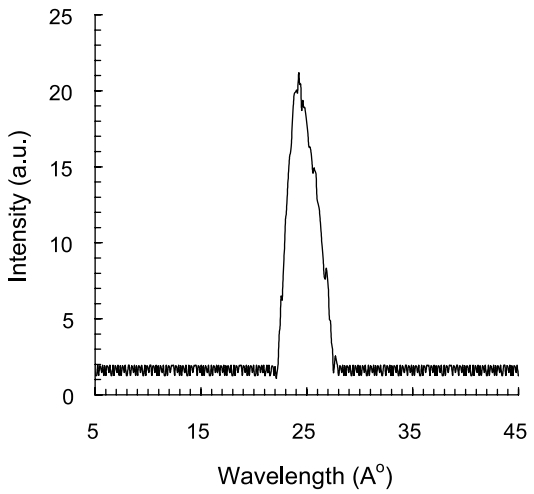

FIGURE 4 X-ray spectrum from gold-copper mix-Z plasma, transmitted through the 0.4 μm aluminium/0.9 μm vanadium filter

range actually incident on the detector (or a sample) is derived from the measured p–i–n diode signal using the response value of the detector of ~ 0.28 C/J. The X-ray yield per unit solid angle ($E_x/\mathrm{d}\Omega$) at a laser intensity of $\sim 10^{13}$ W/cm^2 for the 24–26 Å spectral range in the direction of 45° and 85° w.r. to the target normal is determined to be ~ 3 mJ/sr and ~ 1.9 mJ/sr respectively. For a sample placed at a distance of ~ 10 mm from the source, this corresponds to an X-ray dose of ~ 3 mJ/cm^2 and ~ 1.9 mJ/cm^2 respectively.

The above measured X-ray fluence in the water-window spectral region is sufficient for single shot X-ray imaging of live biological samples on a high sensitive X-ray photoresist [19, 23, 24]. Transmission of a 1 μm thick protein sample for the above spectral range of 25 Å ±1 Å would change [18] only by ±10%. Thus there will not be any serious degradation of the contrast and resolution in the image. The corresponding X-ray exposure in the direction of 85° from the target normal lying in the water-window region (24–26 Å) is smaller by a factor of ~ 1.6, but it is accompanied by negligible target debris. In general, debris deposition on the filter can damage it and substantially alter/degrade its transmission characteristics over time. A free-standing sub-micron (0.3 μm thick) formvar filter [25] can be placed in front of the narrow band 0.4 μm aluminium/0.9 μm vanadium filter to protect it from the plasma debris. The former being inexpensive and easy to make, can be replaced as and when required and has a large transmission (> 70%) in the narrow spectral range of 24–26 Å.

It may be useful to know the X-ray conversion efficiency of the laser heated mix-Z plasma. Estimation of X-ray yield integrated over the full solid angle of emission from a planar target would require a knowledge of the angular distribution of the X-ray emission from the plasma. In plasmas produced from a planar target, the angular distribution of the radiation intensity is usually fitted to a form $I_\theta = I_0 \cos^n \theta$, where I_0 is the intensity in the direction of the target normal, θ is the angle between the direction of observation and the target normal, and 'n' is the scaling exponent whose value lies in the range $0 < n < 1$ [13]. The two limiting values (0, 1) represent isotropic and Lambertian distribution respectively. In the present case, measurements of X-ray emission in the 24–26 Å spectral region were performed at two angles viz. 45° and 85° from the target normal. Using the above generalised expression for angular emission from the plasma, and the ratio of the X-ray yield $E_x(45)/E_x(85)$ (i.e. the ratio of X-ray yield measured at 45° and 85° from the target normal), one can derive the value of the scaling exponent 'n' in the above spectral region. A value of ~ 0.23 of the scaling exponent 'n' is determined from the above. From this value of the scaling exponent, the X-ray conversion of the plasma in the 24–26 Å spectral range, integrated over a full solid angle, turns out to be $\sim 4.9\%$. Even for the two limiting cases of $n = 1$ (Lambertian distribution) and $n = 0$ (isotropic distribution), the X-ray conversion of the plasma in the 24–26 Å spectral range would be $\sim 3.9\%$ and 5.5% respectively. This high conversion efficiency of the high atomic number mix-Z plasma provides sufficient X-ray flux for single shot X-ray imaging.

4 Conclusion

In conclusion, a narrow band laser-plasma X-ray source in the 24–26 Å wavelength range lying in the water window spectral region is presented. The source was produced using a 50–50 (atomic fraction) copper-gold mix-Z target. Use of a free-standing narrow band 0.4 μm aluminium/0.9 μm vanadium X-ray filter makes the setting up of the source easy and its operation convenient for applications. An X-ray yield of ~ 3 mJ/sr is observed in the direction of 45° from the target normal in the narrow spectral range of 24–26 Å. This can be useful for single shot X-ray imaging of live biological samples in the water-window spectral region.

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REFERENCES

1 I.C.E. Turcu, J.B. Dance *X-rays from Laser Plasmas: Generation and Applications* (Wiley, Chichester, 1999)
2 L.B. Da Silva, J.E. Trebes, R. Balhorn, S. Mrowka, E. Anderson, D.T. Attwood, T.W. Barbee Jr., J. Brase, M. Corzett, J. Gray, J.A. Koch, C. Lee, D. Kern, R.A. London, B.J. MacGowan, D.L. Mathews, Science **258**, 269 (1992)
3 M. Richardson, K. Shinohara, K.A. Tanaka, Y. Kinjo, N. Ikeda, M. Kado, Proc. SPIE **1741**, 133 (1992)
4 A.D. Stead, R.A. Cotton, J.G. Duckett, J.A. Goode, A.M. Page, T.W. Ford, J. X-ray Sci. Technol. **5**, 52 (1995)

5 T. Nishikawa, S. Suzuki, Y. Watanabe, O. Zhou, H. Nakano, Appl. Phys. B **78**, 885 (2004)
6 E.A. Gibson, A. Paul, A. Wagner, R. Tobey, D. Gaudiosi, S. Backus, I.P. Christov, A. Aquila, E.M. Gullikson, D.A. Attwood, M.M. Murnane, H. Kepteyn, Science **302**, 95 (2003)
7 P.A.C. Jannson, U. Vogt, H.M. Hertz, Rev. Sci. Instrum. **76**, 043 503 (2005)
8 H. Fiedorowicz, A. Bartnik, R. Jarocki, M. Szczurek, T. Wilhein, Appl. Phys. B **67**, 391 (1998)
9 L. Rymell, M. Berglund, H.M. Hertz, Appl. Phys. Lett. **66**, 2625 (1995)
10 H. Nishimura, F. Matsuoka, M. Yagi, K. Yamada, S. Nakai, G.H. McCall, C. Yamanaka, Phys. Fluids **26**, 1688 (1983)
11 R. Popil, P.D. Gupta, R. Fedosejevs, A.A. Offenberger, Phys. Rev. A **35**, 3874 (1987)
12 T. Mochizuki, T. Yabe, K. Okada, M. Hamada, N. Ikeda, S. Kiyokawa, C. Yamanaka, Phys. Rev. A **33**, 525 (1986)
13 S. Sailaja, P.A. Naik, P.D. Gupta, IEEE Trans. Plasma Sci. **29**, 960 (2001)
14 K. Eidmann, W. Schwanda, Laser Part. Beams **9**, 551 (1991)
15 T.J. Orzechowski, M.D. Rosen, H.N. Kornblum, J.L. Porter, L.J. Suter, A.R. Thiessen, R.J. Wallace, Phys. Rev. Lett. **77**, 3545 (1996)
16 D. Colombant, M. Klapisch, A. Bar-Shalom, Phys. Rev. E **57**, 3411 (1998)
17 J.A. Chakera, V. Arora, S. Sailaja, S.R. Kumbhare, P.A. Naik, P.D. Gupta, N.K. Gupta, B.K. Godwal, Appl. Phys. Lett. **83**, 27 (2003)
18 J. Fletcher, R. Cotton, C. Webb, Proc. SPIE **1741**, 142 (1992)
19 J.A. Chakera, S.R. Kumbhare, P.D. Gupta, J. X-ray Sci. Technol. **8**, 135 (1998)
20 V.A. Arora, J.A. Chakera, P.A. Naik, S.R. Kumbhare, P.D. Gupta, N.K. Gupta, J. Appl. Phys. **100**, 033 306 (2006)
21 S. Sailaja, V. Arora, S.R. Kumbhare, R.A. Joshi, P.A. Naik, P.D. Gupta, Opt. Laser Technol. **38**, 46 (2006)
22 G.C. Idzorek, R.J. Bartlett, Proc. SPIE **3114**, 349 (1997)
23 T. Tomie, H. Shimizu, T. Majima, T. Kanayama, M. Yamada, E. Miura, Proc. SPIE **1741**, 118 (1992)
24 A.C. Cefalas, P. Argitis, Z. Kollia, E. Sarantopoulou, T.W. Ford, A.D. Stead, A. Marranca, C.N. Danson, J. Knott, D. Neely, Central Laser Facility Annual Report 1996/97, p. 12
25 A. Chowdhury, P.A. Naik, P.D. Gupta, Sadhana **24**, 551 (1999)