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Development of online quasimonochromatic X-ray backlighter for high energy density physics studies

S CHAURASIA*, P LESHMA and D S MUNDA
High Pressure & Synchrotron Radiation Physics Division, Bhabha Atomic Research Centre, Mumbai 400 085, India
*Corresponding author. E-mail: pgshivanand@gmail.com; shibu@barc.gov.in

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Abstract. Monochromatic X-ray backlighting has been employed with great success in various laser plasma experiments including inertial confinement fusion (ICF) research. However, implementation of a monochromatic backlighting system typically requires extremely high quality spherically bent crystals which are difficult to manufacture and are also expensive. In this paper, we present a quasimonochromatic X-ray backlighting system using flat thallium acid pthalate (TAP) crystal. The detailed characterization of the system is discussed. The X-ray backlighter spectral range is caliberated using Cu spectrum in the spectral range 7–9 Å (1.38–1.77 keV). Gold plasma produces continuous X-ray spectrum (M band) in this range. The spectral, spatial and temporal resolutions of the system measured are 30 mÅ, 50 μm and 1.5 ns respectively. The spectral width of the X-ray pulse is 2 Å ($\Delta E = 0.39$ keV).

Keywords. X-ray backlighter; quasimonochromatic; crystal spectrometer.

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1. Introduction

X-ray backlighting refers to the technique of radiography of transient phenomena in high-density materials. It is a powerful method for measuring hydrodynamic evolution of materials subjected to external pressures, such as those created by X-rays [1–3] or laser ablation [4–6]. Material can be subjected to 10–20 Mbar shock pressure by laser ablation. When the backlighter is either monochromatic or spectrally resolved by the imaging instrument, information on the opacity or equation-of-state of a material can be obtained [7–9]. X-ray radiography is an important tool for diagnosing the dynamics, symmetry, stability and size of the laser-driven implosion. In opaque high/mean Z materials, it is not possible to get information about the shock characteristics of the sample and then measure fluid velocities directily. The X-ray probing also provides direct information of another shock parameter such as density

[10]. The shock velocity and fluid velocity (particle velocity) can be measured simulatenously by using X-ray radiography with X-ray streak camera [11]. It will allow precise and absolute measurement of equation-of-state (EOS) of the material. The requirements for probing the X-ray photons energy, spatial resolution of the set-up and the signal-to-noise ratio in the recorded images are stringent in order to yield quantitative measurements from the radiograph.The laser-produced plasma can produce an intense monochromatic/quasi-monochromatic X-ray source using a crystal spectrometer with very short pulse duration (say $K\alpha$ photons of low Z to mid-Z elements with a pulse duration of a few hundreds of femtoseconds to a few picoseconds) from a source of 10–20 μm size [10–16]. Thus, we can generate a monochromatic X-ray source with a spatial resolution of 10 μm and and a temporal resolution of a few hundreds of femtoseconds.

Generally, spherically bent crystals are used to select probe wavelength and create monochromatic image. This requires that the object under study be placed inside the Rowland circle to maximize resolution and have a direct line of sight with the object [12–16]. This puts the expensive crystal at a high risk of destruction when the plasma under study produces significant debris. The high-quality spherical crystals are extremely difficult to manufacture and can be very expensive. Furthermore, due to the high stresses induced by bending in two dimensions, large crystals are extremely impractical, necessitating a relatively small aperture for imaging. The X-ray backlighting has been successfully used to generate pulse radiographs with two-dimensional spatial resolution at a chosen time in the event history [17,18] or streaked radiographs with one-dimensional spatial resolution [19,20]. Pulsed radiographs have generally been recorded using pinhole imaging of an extended backlighter plasma or by projection of X-rays from small, quasi-point, backlighting plasma and in both cases limiting spectral resolution of the probe radiation has been achieved using appropriate combination of backlighting target materials and thin foil k-edge absorbing filters. In our case, we have extended the projection technique to include a Bragg crystal as a dispersive element by allowing quasimonochromatic probing of shocked material. Here, in this paper we present the development of simple quasimonochromatic X-ray backlighter using flat TAP crystal. The spectral width of the X-ray pulse is 2 Å ($\Delta E = 0.39$ keV).

2. Experimental set-up

The quasimonochromatic X-ray backlighter system has been developed with our existing 20 J/300–800 ps Nd:Glass laser system. We have converted 20 J laser beam into a two-arm laser system with 10 J energy in each arm. One beam with 10 J/300–800 ps was focussed in 80 μm diameter (focussed intensity $\sim 10^{14}$ W/cm^2) on a gold target to generate gold X-rays. Another laser beam was used to irradiate targets to be studied. The schematic of the set-up is shown in figure 1a. A TAP crystal cleavage plane parallel to 0 0 1 plane with $2d = 25.75$ Å, 50×10 mm^2 area and a thickness of 2 mm was used to select quasimonochromatic X-ray beam in the spectral range 7–9 Å (1.38–1.77 keV) for the X-ray probing. The crystal was placed at a distance of 165 cm from the target. The detector unit was mounted with a flange having a tapered angle of 18° and was connected to the vacuum chamber port flange. The crystal was mounted on a motorized z-stage which has a maximum movement of 12 mm. The vertical movements help us to choose a particular

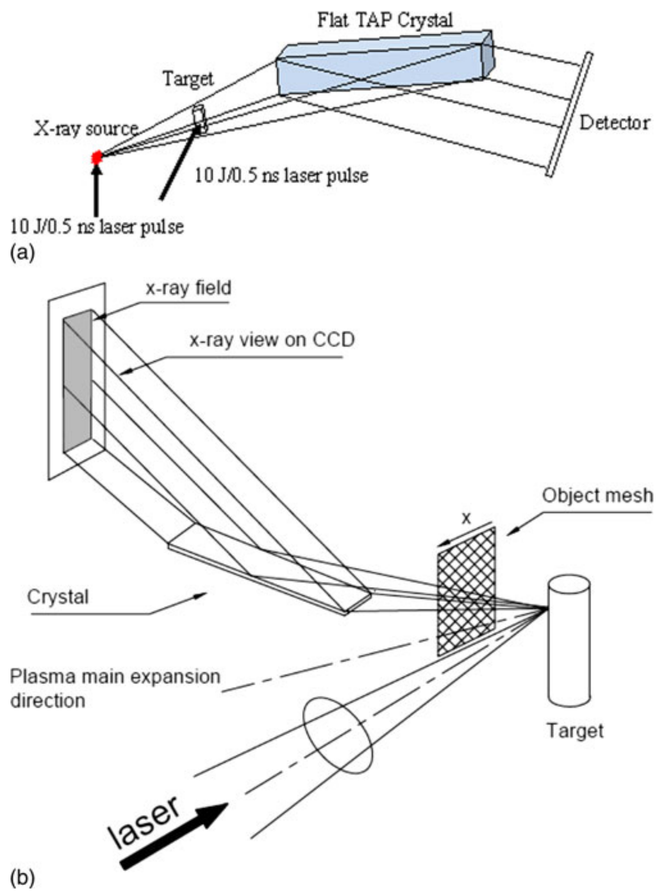

Figure 1. (**a**) Schematic of a quasimonochrmatic X-ray backlighter source. The crsytal used was thallium acid pthalate (TAP). The detector used were X-ray CCD camera and phosphor screen backed by an image intensifier tube. The laser beem was split into two, one on the target producing X-rays and other one onto the target to be probed. (**b**) Schematic diagram of the quasimonochromatic X-ray backlighting of SS mesh with flat TAP crystal.

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 30 mÅ limited by the source size. After reflection from the crystal plane, the probe beam was incident on the detector system. The detector system is capable of accommodating X-ray film, MCP, phosphor screen and the X-ray CCD camera. In the present experiments, we have used a P-11 phosphor screen backed by image intensifier tube and M/s Rigaku make X-ray CCD camera. The pixel size of the CCD camera is 13.5 μm $\times$ 13.5 μm and granular size of the phosphor on fibre-optic plate with 6 μm and fibre diameter is about 3.2 μm. The magnification of the diagnostics could be adjusted from 4 to 25 by changing the distances between X-ray source to target and target to detector which is required to record an event (laser-compressed target) of ~150–200 μm size. The delay between the X-ray probe pulse and main pulse on the target was achieved by providing an optical delay between the two laser beams. The delay between the X-ray probe pulse and main laser pulse on the target could be varied from 1 ns to 10 ns with temporal resolution of a few tens of picosecond. For the test purpose, we have replaced targets with the SS Mesh of ~80 μm diameter and spacing between the two wires ~350 μm as shown in figure 1b.

3. X-ray backlighter parameters

The X-ray backlighter for studying material under laser-driven shock required optimization of the spectral, spatial and temporal resolutions. The spectral resolution of the backlighter depends on the source or slit size (δx), X-ray source-to-detector distance (L) and perpendicular distance of the X-ray source from the crysal (h). Spectral resolution was determined by the size of the emitting region and by the rocking angle of the crystal. If we consider ideally monochromatic X-rays from a source, they will, after Bragg reflection from a crystal, fall on a detector and appear as a broad spectral line of certain wavelength interval $\Delta\lambda$. This interval $\Delta\lambda$ can be expressed as [21]

$$\Delta\lambda = \frac{2d}{[1+(2h/L)^2]^{1/2}}[\delta\theta + \delta x/L[1+(2h/L)^2]]. \tag{1}$$

The first term within the square brackets of the numerator in the above equation is the crystal-dependent term. It is the half width of the rocking curve (crystal reflection curve). A perfect crystal when all planes are parallel will have sharp rocking curve and thus a small value of $\delta\theta$. For a TAP crystal it is about 0.45 mrad [22] and the second term is governed by the characteristics of the source and the detector. By substituting the values of $\delta\theta$ and δx in eq. (1), the spectral resolution of the spectrometer was calculated as 30 mÅ. Thus, the resolving power $\lambda_0/\Delta\lambda$ for a given centre wavelength could be calculated. The resolving power of the spectrometer in our case was about 400.

The spatial resolution of the X-ray backlighter probe beam is dependent on the X-ray source size or the slit width of the slit used in front of the X-ray source. A slit is used in the plane of incidence to get two-dimensional imaging of X-ray source with spatial resolution in a direction perpendicular to the direction of dispersion. The slit is placed anywhere between the X-ray source and the object to be radiographed. If u is the distance between the slit and the source and v is that between the slit and the detector, the transverse magnification M_{L} of the X-ray source is equal to v/u. The spatial resolution of the spectrograph is basically governed by the slit width. For a magnification M_{L}, the spatial resolution from geometrical considerations comes to be

$$(1+M_{\mathrm{L}}^{-1})\Delta s, \tag{2}$$

where Δs is the source size or the slit width. The spatial resolution of the X-ray backlighter in the present case was 50 μm (size of the focussed beam at an intensity above 10^{14} W/cm^2 [23]) which will be further reduced to 25–30 μm by using a gold wire of diameter of 25 μm.

Temporal resolution for the X-ray backlighter depends on the pulse duration of the laser system used for X-ray generation. The temporal profile of the X-ray pulse generated in the spectral range of 0.8–1.56 keV has been measured by using 2 μm thick Al filter with X-ray biplanar photodiode [24]. The X-ray pulse durations measured were 1.5 ns and 4 ns respectively for 300 ps and 800 ps laser pulse duration as shown in figures 2a and 2b. The X-ray pulse duration can further go down to a few ps using ultrashort laser system.

The absolute flux at the detector (X-ray CCD camera) was measured by taking the calibrated e-h pair production value for 1 photon in the spectral range of 1.38–1.77 keV. The X-ray flux from the gold plasma measured at the detector was 2 μJ/Sr. The absolute

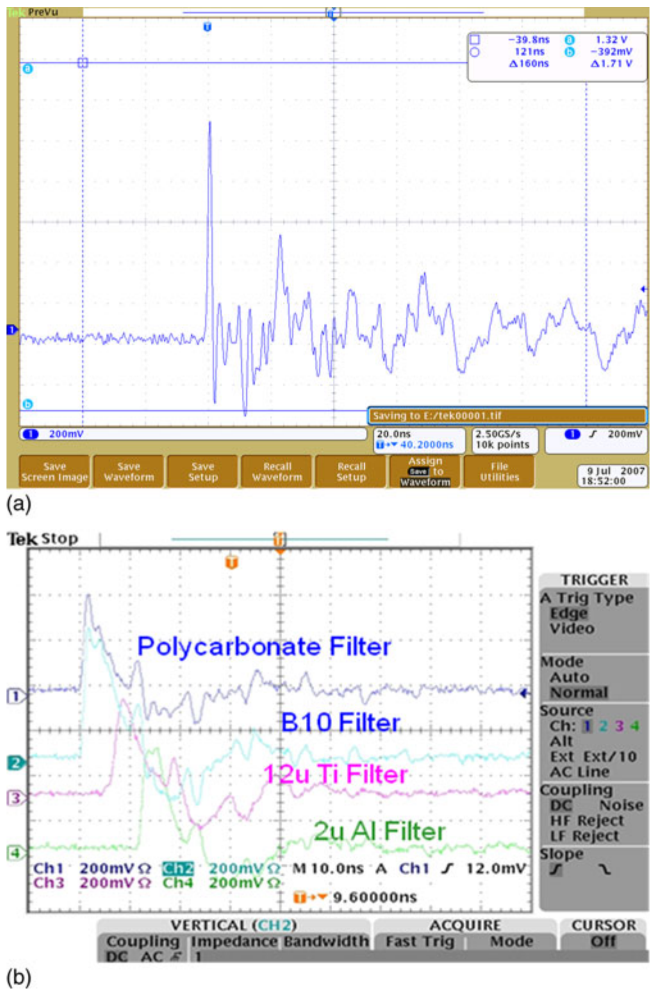

Figure 2. X-ray probe pulse measured using X-ray biplanar photodiode with 150 ps rise time and 500 MHz (2.5 GS/s) oscilloscope. (**a**) 1.5 ns X-ray pulse generated with laser of 300 ps pulse duration in the spectral range 0.7–1.56 keV and (**b**) 4 ns X-ray pulse generated with laser of 800 ps pulse duration in the spectral range 0.8–1.56 keV. In figure 2b, X-ray pulse duration was measured in other spectral range also using 6 μm thick polycarbonate, B10 and 12 μm thick titanium filters.

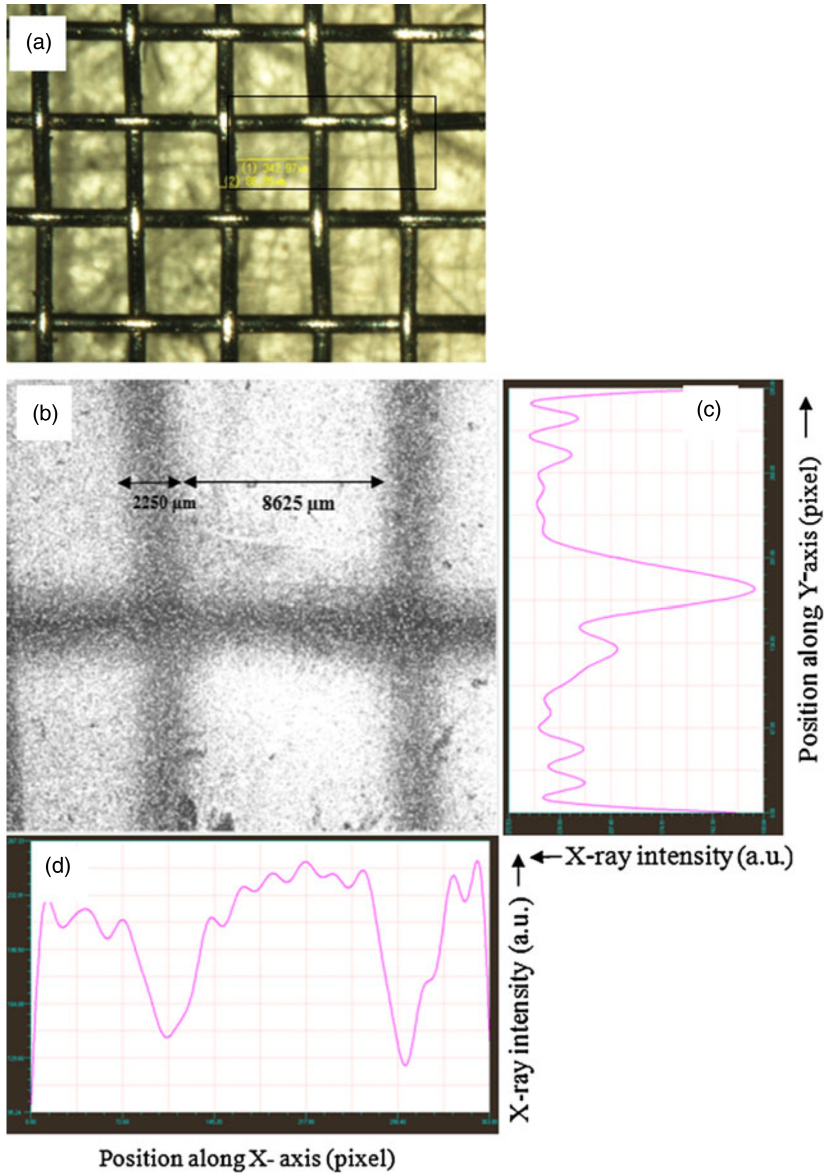

Figure 3. (**a**) Image of the SS mesh of 80 μm diameter and ∼400 μm spacing recorded with high resolution microscope. (**b**) Pulsed X-ray radiograph of the SS mesh using laser plasma produced X-ray source in the 7–9 Å spectral range and ∼1.5 ns pulse duration. Plots (**c**) and (**d**) show the intensity distributions of X-ray radiation along the x- and y-axes with respect to the spatial position. The magnification of the radiograph is set to 25×. X-ray CCD camera is the detection system used in this measurement.

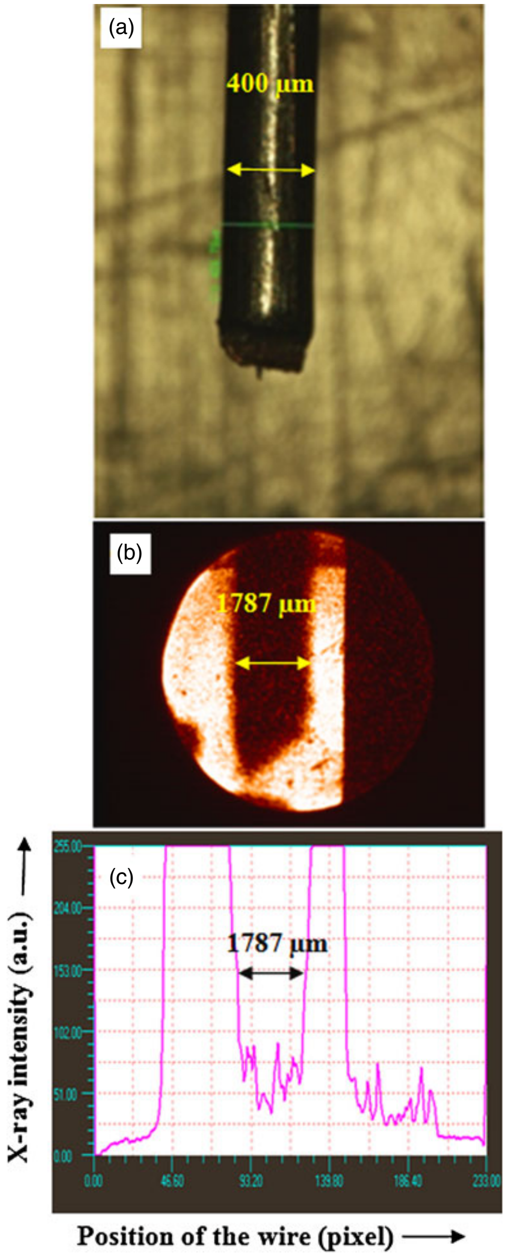

Figure 4. (**a**) Photograph of the 400 μm diameter SS wire measured with high resolution microscope. (**b**) Pulsed X-ray radiography of the wire using gold plasma as the X-ray source in 7–9 Å spectral range. Detection system used in this measurement is phosphor screen backed by image intensifier tube. The magnification of the radiograph is set to 4.5×. (**c**) Intensity plot of the radiograph image of the SS wire using PROMISE software. The wire diameter measured was 277 (pixel) $*$ 6.54 μm (size of one pixel) = 1786.65 μm.

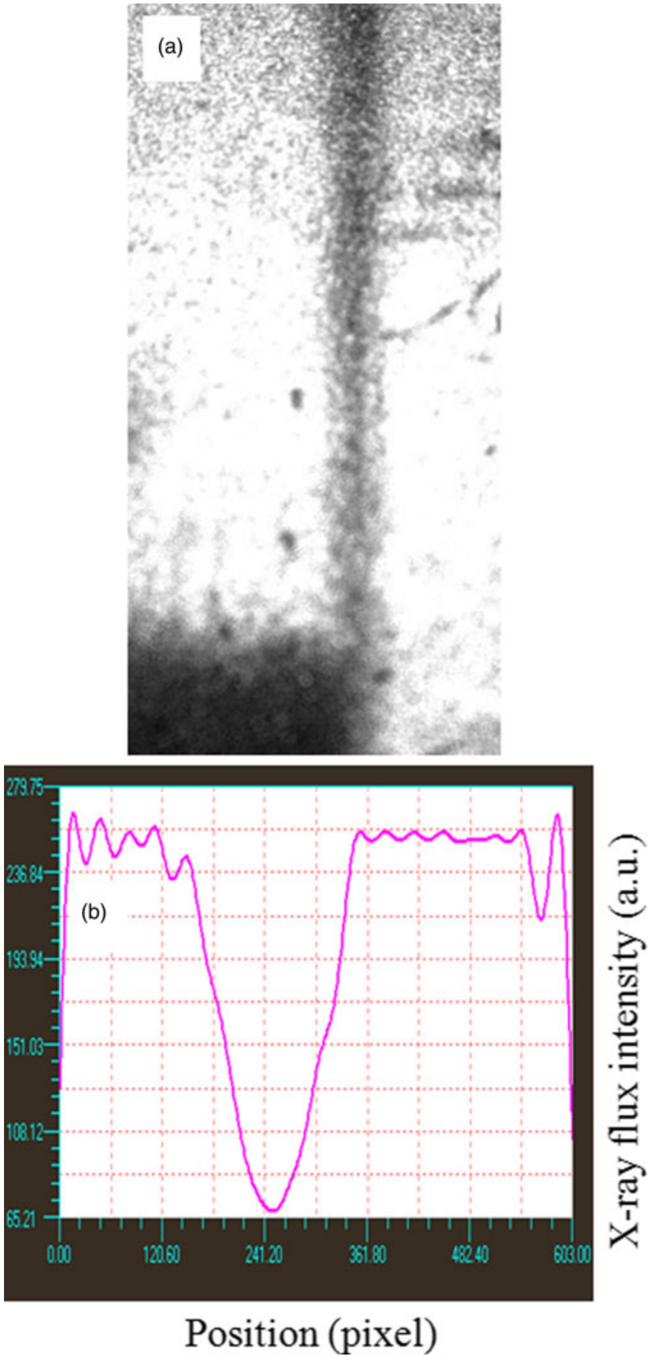

Figure 5. (**a**) X-ray radiograph and (**b**) intensity plot of X-ray imaged 20 μm thick aluminum foil of 2 mm width with respect to position.

flux of the X-ray from the X-ray source can be estimated by taking into account the filter transmission (in our case three B10 filters, transmission $> 95\%$ for X-ray radiation > 0.9 keV), crystal reflection (for alkali metal bi-phthalate crystal at $\lambda = 8.3$ Å) $= 20$–30% [22] and the quantum efficiency of the X-ray CCD detector at this wavelength. The total X-ray flux estimated is $\sim 8.44\ \mu$J/Sr. This result is in agreement with our earlier measured flux using silicon X-ray photodiodes [25].

4. Result and discussion

The quasimonochrmatic X-ray probe beam was generated by focussing a laser pulse on gold material. The pulse duration of the X-ray probe beam depends on the laser pulse duration. The X-ray pulse duration was measured using a fast vacuum biplanar photodoide of 150 ps rise time and 500 MHz oscilloscope. Figures 2a and 2b show 1.5 ns and 4 ns soft X-ray pulse durations for the laser pulse of durations 300 ps and 800 ps respectively. In figure 2b, the X-ray pulse durations in the soft X-ray spectral range (>0.8 keV), (>1 keV) and hard X-ray regime (3.2–5 keV) were also recorded by the biplanar photodoide covered with B10, 6 μm thick polycarbonate and 12 μm thick titanium filters respectively. The spectral range and the spectral resolution of the radiograph were calibrated with copper plasma. For X-ray backlighting, the copper target was changed with the gold target. As a preliminary test, we have done X-ray radiography of the SS mesh as shown in figure 3a. The magnification of the radiograph was set to $\times 25$ as mesh wire diameter was very small. The wire diameter of the mesh was about 86–90 μm and spacing between two wires was about 340–350 μm as measured by the high resolution microscope as shown in figure 3b. The X-ray intensity plot of the X-ray radiation along the x- and y-axes are shown in figures 3c and 3d. Figure 4a shows the X-ray imaging of the 400 μm thick SS wire whose optical microscope record is shown in figure 4b. The magnification of the system in this case was fixed to $\times 4.5$. The intensity plot of the X-ray radiation along the x-axis is shown in figure 4c. From figure 4c, it can be seen that the radiograph has very high signal-to-noise ratio. The signal-to-noise ratio of this spectrograph is 240 : 1. Such a pulse X-ray radiograph will provide very high resolution during the dynamic imaging of the very high speed moving object. Figure 5 shows the X-ray radiograph of the 20 μm thick Al foil mounted on the step holder.

5. Conclusion

A quasimonochromatic X-ray backlighter with 4–25 magnification in the 1.38–1.77 keV X-ray energy range ($\Delta E = 0.39$ keV) (corresponding wavelength range 7–9 Å) has been developed. The X-ray pulse duration was measured from 1.5 ns to 4 ns depending on the laser pulse duration from 300 ps to 800 ps. The spectral resolution of the system measured using copper plasma was 30 mÅ. The spatial resolution of the backlighter was approximately 50 μm depending on the laser focus spot size. It will be further reduced to 25 μm in future experiment by focussing laser pulse on 20–25 μm gold wire. The X-ray radiography of the following are presented in this paper: (1) SS mesh having a wire diameter of 86–90 μm and separated by a distance of 342 μm, (2) SS wire of 400 μm diameter and (3) 20 μm thick, 2 μm wide aluminium foil.

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