Pulsed Quasi-monochromatic x-ray source for radiography and x-ray absorption spectroscopy

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Abstract

Monochromatic and quasi-monochromatic x-ray backlighting is a proven diagnostic technique with many important applications in Inertial Confinement Fusion and related research work. The quasi-monochromatic x-ray source can also be used in the x-ray absorption spectroscopy. A quasi-monochromatic x-ray backlighting system in the spectral range of 7.9 – 9.4 Å (1.32 - 1.57 keV) range has been developed using Thallium Acid phthalate (TAP) crystal. This diagnostics is tunable in the wavelength range of 7 - 10 Å. In one setting it can cover a spectral range of 1.5 Å (ΔE = 0.25 keV). The x-ray radiograph spectral parameters were optimized using copper plasma. The temporal pulse duration was measured as 1.0 ns using indigenously developed fast x-ray vacuum bi-planar photodiodes (≈ 150 ps). The spatial resolution calculated was 50 μm which depends on the plasma source size.

Introduction:

During the last 20 years, x-ray radiography techniques have been successfully used as a dense plasma diagnostics tool in experiments such as Inertial confinement fusion (ICF), high current pinch discharge and high energy density physics [1]. The process of inertial confinement fusion takes place in a nanosecond time scale. The ICF related dynamic experiments require high energy, high resolution microscopy to probe the time dependent symmetry in the compression in Hohlraums [2]. Pulsed radiography with short duration (sub-ns to sub-ps) is required for such an application. Shorter the x-ray pulse duration, better will be the temporal resolution and hence the spatial resolution (minimizing the hydrodynamic smearing) of the radiograph. Pulsed radiograph produces more accurate measurements. Modeling of the implosion and the stability of the spherical shell are being done using the x-ray radiography of thin foil acceleration considering the thin foil as a small section of the spherical target [3]. In an opaque high/ mid Z material, it is not possible to get information about the shock characteristics inside the sample and then to directly measure the fluid (particle) velocities. The x-ray probing /backlighting also can be used to deduce information of other shock parameter such as density [4]. The shock velocity and fluid velocity can be measured simultaneously by using x-ray radiography along with x-ray streak camera [5].

The laser produced plasma can generate an intense monochromatic /quasi-monochromatic x-ray source using a curved / flat crystal spectrometer with a pulse duration of the order of hundreds of femtosecond to nanoseconds (Kα photons of low to mid Z targets depending on the laser pulse duration). Spherically bent crystals are used to select the probe wavelength and create the monochromatic image [6] and flat crystals are used for the quasi-monochromatic x-ray source [7]. Both radiographs are having merits and demerits. For example the bent crystals have the following advantages:

1. X-rays of particular wavelength (monochromatic), which satisfy the Bragg’s condition will be reflected and focused on a point on the circle.
2. High luminosity due to the focusing feature of the spherical surface.
3. Better spectral resolution can be obtained in the scheme when the radiation angle of incidence on the crystal surface is close to the crystal normal on the Rowland circle.

On the other hand, it has various disadvantages over the flat crystal spectrometer such as

1. The bending of the crystals is done with the mechanical arrangement which restrict the clear aperture of the crystal.
2. As mentioned above, high resolution can be achieved by choosing the angle of incidence close to normal, which limits the spectral range.
3. In bent crystal, the angle of incidence is close to the normal where maximum debris fluxes of the laser produced plasma are present which puts the crystal at the risk of maximum damage.
4. Alignment of the spherically bent crystal is more complicated than that of the flat crystal spectrometer and bending of the crystal by putting stress is also very critical. A mismatch in the strain can cause damage of the crystal.

Quasi-monochromatic x-ray backlighter can also be used in absorption spectroscopy. In the absorption spectroscopy, warm plasma is irradiated from behind, typically by broad band photon flux. The warm plasma absorbs radiation from the backlight at frequencies corresponding to the particular transitions. Thus, the absorption feature appear in the spectrum. Analysis of the absorption profile yields the number of ground state ions [8].

**Experimental set up:**

The experiment was devided into two parts. In the first part, a quasi-monochromatic x-ray backlighter system was developed using our existing 30 J/300 - 800 ps Nd: Glass laser system for the x-ray pulse generation. The laser system was operated at 15 J, and focussed onto the copper target for the generation of the charateric lines in the spectral range of 7.9 – 9.4 Å. Its various parameters were calibrated using the characterics values of the x-rays from the NIST data base library. After calibration, the copper target was replaced with gold target.

A single crystal Thallium Acid Pthalate (TAP) (size of 50 x10 mm² with a thickness of 2 mm) with cleavage plane parallel to (001) plane and 2d=25.75 Å, was used to select quasi-monochromatic x-ray beam in the spectral range 7.9 – 9.4 Å (1.32 - 1.57 keV) of the gold plasma for the x-ray probing. After reflection from the crystal plane, the probe beam is incident on the detector (x-ray CCD camera of M/s Rigaku). The pixel size of the CCD camera is 13.5 µm x 13.5 µm. It can also accommodate Phosphor screen, MCPs and x-ray film based detection systems. Details of the spatial, spectral and temporal parameter measurement of the spectrometer are described below:

**Optimized Crystal spectrometer parameters**

The geometrical requirement to ensure maximum spatial resolution and spectral purity within the resolution element in the object can be achieved using schematic shown in Fig 1. The spatial resolution of the backlighter in the x and y direction are dependent on the source size ∆x and ∆y in the x and y direction neglecting the contribution of the refraction, diffraction and the hydrodynamic smearing. For ideal case ∆x = ∆y = 10 µm. Diffraction is negligible if λ/Δx < δθ , δθ where is crystal rocking angle. A typical value of δθ for TAP crystal is 0.45 - 1 mrad. Therefore, for diffraction to be negligible, λ should be less than 10 Å [9]. Hydrodynamic smearing depends on the compression velocity v of the target during radiograph frame time, Δt, and limits the effective spatial resolution on ≈ v.Δt. For a typical value of the particle velocity 5 x 10⁶ cm/s and Δt of the x-ray flash of about 500 ps, it put upper limit of 25 µm. In our case, we have laser focal spot of 80 – 100 µm. In our earlier publication, it has been shown that the focal spot can go down as low as to 40 µm due to self focusing of laser beam caused by non-linear processes involved in the plasma [10].
Spectral characteristics measurement

The spectral range and spectral resolution depend upon the crystal used (2d as well as size), the distance between the source and the detector (via crystal) and the orientation of the detector with respect to the x-rays incident on it. The spectral range i.e. $\lambda_{\text{min}}$ and $\lambda_{\text{max}}$ using Bragg’s condition as shown in Fig. 1 can be written as.

\[
\lambda_{\text{max}} = 2d \left( 2h + x_0 \right) / \left[ \left( 2h + x_0 \right)^2 + L^2 \right]^{1/2} \quad \ldots (1)
\]

\[
\lambda_{\text{min}} = 2d \left( 2h - x_0 \right) / \left[ \left( 2h - x_0 \right)^2 + L^2 \right]^{1/2} \quad \ldots (2)
\]

From equation (1) and (2), it is obvious that the spectral range of the spectrometer depends on the geometrical parameters of the arrangement as shown in Fig. 1. For a given d and fixed L, the spectral range can be changed by changing the distance $h$. Also, for a given d, spectral range ($\lambda_{\text{max}} - \lambda_{\text{min}}$) can be increased by reducing the source to detector distance. However, as described above this distance cannot be reduced arbitrarily as the plasma debris could damage the crystal. For a complete shadow of the entire object a source spectrum with a bandwidth $\Delta\lambda \approx 2\lambda\varepsilon t(1 - \varepsilon^2)^{1/2} / (ht)$, where $\varepsilon = \lambda_0/2d$, and $t$ = the target thickness, is required and typically $\Delta\lambda/\lambda_0 \approx 0.025$. Quasi-continuous M band emission observed in high Z laser irradiated targets such as gold (used by us) are possible candidates for such sources.

Spectral resolution is 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

\[
\Delta\lambda = \frac{2d}{\left[ 1 + (2h/L)^2 \right]^{3/2}} \left[ \delta \theta + \delta x / L[1+(2h/L)] \right] \quad \ldots (3)
\]

The first term in the square bracket in the above equation is a crystal dependent term and the second term is governed by the characteristics of the source and the detector. Further, it can be seen from equation (3) that the resolution $\Delta\lambda$ is small for large values of L and $h / L$. In our set up the spectral range is 7.9 – 9.4 Å (1.32 - 1.57 keV) with the spectral resolution of $\Delta\lambda = 30$ mÅ.

Above calculations, derived from the geometrical arrangement were measured by focusing the laser pulse on the copper target. Strong emission lines from Cu XX and Cu XXI ions are reflected from the Bragg’s crystal and recorded on the x-ray CCD camera and corresponding spectral plot is shown in figure 2 in the spectral range 7.9 - 9.4 Å. For the calibration, we used wavelength $\lambda = 8.7 \, \text{Å} \,(2p^5 – 2p^4 4d), 9.106 \, \text{Å} \,(2s^2 \, 2p^6 – 2s^2 \, 2p^5 4d, \, ^1S – 1/2, 3/2)$, and $9.24 \, \text{Å} \,(2s^2 \, 2p^6 – 2s^2 \, 2p^5 4d, \, ^1S – 3/2, 5/2)$.

Fig. 1: Schematic diagram of the set up for the x-ray radiography and absorption spectroscopy studies. Thallium Acid Phthalate (TAP) crystal and gold M Band spectrum were used for the quasi-monochromatic x-ray source generation. In our detection system, the x-ray CCD camera size is 27 mm x 27 mm.
Temporal resolution for the x-ray backlighter is dependent on the pulse duration of the laser system used for x-ray generation. The temporal profile of the soft x-ray pulse generated in the spectral range of (0.8 – 1.56 keV) and (> 0.9 keV) using 5 µm Al and B10 filter respectively have been measured using x-ray vacuum bi-planar photodiode (VBPD) and 500 MHz scope (2.5 GS/s) as shown in Fig. 3. The delay between the two pulses is due to the difference in the length of the BNC cable. The x-ray pulse duration measured was approximately 1.0 ns for the laser pulse of duration 500 ps. The multiple peaks observed were due to electrical noise in the circuit. More accurate measurement can be made by coupling the x-ray streak camera with the crystal spectrometer. Earlier published data on the measurement of the x-ray pulse duration of M band spectrum using x-ray streak camera shows the pulse duration close to the laser pulse duration. The x-ray pulse duration can further go down to a few picosecond using ultra-short laser system.

In the second part, copper target was replaced with gold target. The gold plasma emits continuous M band spectrum in this spectral range. Laser energy of the single beam now increased to 20 J per laser pulse and then was converted into a two arm laser system with 10 J energy in each arm. One beam with 10 J/300 - 800 ps was focused in 80-100 µm diameter (focused intensity ~ 10^{14} W/cm^2) on a gold target to generate gold x-rays. Other laser beam interacts with the target under investigation for the dynamic studies. We have introduced various objects to be radiographed and also Al foil for the x-ray imaging and absorption spectroscopy. The time integrated absolute x-ray photon flux from the gold plasma on the CCD detector was calculated by taking account of filter transmission (in our case 3 numbers of B 10 filter, transmission > 95% for x-ray radiation > 1 keV) and the crystal reflection (20 - 30 % for the alkalimetal bi-pthalate crystal @ \lambda = 8.3 Å) [11]. The x-ray flux from the...
gold plasma measured at the detector was 2 µJ/Sr and total x-ray flux estimated was approximately 8.44 µJ/Sr.

The object to be radiographed was inserted in between source and monochromator crystal as shown in figure 1. The radiography of various targets of different thicknesses (t) were done. Depending on the target thickness, the magnification of the backlighter was fixed by changing the distance between x-ray source to object and object to detector. The object thickness t sets a restriction on the source to object distance (l) is for the maximum useful detector diameter (2x), given as

\[ l \geq \frac{t(L)}{x_0} \]

to record the whole object with a suitable source size. Thicker the object size, larger will be the source to object distance and hence lower the magnification. The minimum source to object distance is a few mm.

The magnification of the diagnostics could be adjusted from 4 to 60 by changing the distances between x-ray source to target and target to detector (which is required to record an event (laser shocked target) of size approximately 150 to 200 µm). The x-ray radiograph of S. S. wire, S. S. mesh and 20 µm Al foil have been recorded. Figure 4a shows the optical microscope image of the 400 µm thick S S wire whose x-ray radiography record is shown in figure 4b. The magnification of the system in this case was approximately x16. 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 the spectrograph is 240 : 1. Such a pulse x-ray radiograph will provide very high resolution during the dynamic imaging of a fast moving object. A high resolution optical microscope image and x-ray radiograph of mesh with wire diameter about 86 – 90 µm and spacing between two wire of about 340 – 350 µm as measured is shown in figure 5 a & b. The x-ray intensity plot of the x-ray radiation along the X-axis and Y-axis are shown in figure 5c and d. The magnification of the radiograph was approximately 33X. Figure 6a shows the photograph of the target holder mounted with Al foil. Also in this figure the direction of laser pulse and the x-ray pulse are shown by arrows in white and red colours respectively. Figure 6b shows the x-ray radiograph of the 20 µm thick Al foil mounted on step holder marked in yellow circle. Figure 6c shows the intensity plot of the x-ray radiograph of 20 µm thick Al foil. The magnification of the system was set approximately x60 due to smaller size of the foil.

Fig. 4. (a) Photograph of 400 µm diameter Stainless Steel wire measured with high resolution optical microscope. (b) Pulsed X-ray radiography of wire using gold plasma as x-rays source in the spectral range 7.9 – 9.4 Å. (c) Transmitted intensity plot of the radiographed image of the S. S. wire. The intensity plot shows that the wire thickness from the radiographed image is 6769 µm indicating the magnification of the system is approximately 16 X.
by laser plasma, the spatial ion density is the key

Fig. 5: (a) Image of S. S. Mesh of diameter 80 µm and spacing approx 400 µm recorded with high resolution microscope. (b) Pulsed X-ray radiograph of the S. S. Mesh using laser plasma produced x-ray source in the spectral range 7.9 – 9.4 Å and pulse duration approximately ~1.0 ns. Plot (c) & (d) show the intensity distributions of x-ray radiation along the x-axis and y-axis with respect to the spatial position. The magnification of radiograph is approximately 33X. The detection system used in this measurement is x-ray CCD camera.

Absorption spectroscopy:

The online point projection radiography / point projection absorption technique was developed to characterize the number of different backlighters covering the spectral range of interest to study the basic hydrodynamic behaviour of the package (multilayered targets) and identify the heated material absorption features seen in the radiograph. Absorption spectroscopy can be used to obtain important information of atomic structure, such as photoionization cross section and double excited states. In the research of x-ray laser produced

Fig. 6: (a) Photograph of the Al foil mounted on target holder. (b) X-ray radiograph of the circled portion of the Al foil with target holder and (c) intensity plot of x-ray imaged 20 µm thick Aluminum foil of width 2 mm with respect to position. The magnification of the system was approximately 60.
parameter which can’t be directly measured by emission spectroscopy but can be measured by absorption spectroscopy.

The opacity of the discrete transition can be written as [12]

$$\mu(\lambda) = \frac{\pi e^2}{mc^2} f_{ik} \lambda^2 N_i L\phi(\lambda)$$

...(4)

where \(m\) is the mass of electron, \(c\) is the velocity of light, \(e\) is the charge of electron, \(f_{ik}\) is the absorption oscillator strength, \(\phi(\lambda)\) is the normalised line profile, \(N_i\) is the ion density on the ith level of transition and the integral is taken along the equivalent absorbing plasma column \(L\). Opacity of the plasma at a particular wavelength can be measured by measuring the transmitted intensity \(I(\lambda)\) and incident intensity \(I_0(\lambda)\) using point projection set up and the relation \(\mu(\lambda) = \ln[I_0(\lambda)/I(\lambda)]\). Here, in \(I(\lambda)\) the contribution of stray light and self emission from the absorbing plasma were subtracted. Once the value of \(\mu(\lambda)\) is known one can estimate density \(N_i\) of the expanded plasma using equation (4) at a particular time and space.

In the absorption spectroscopy set up, first we replaced the gold target with the Aluminium (Al) target. The emission spectroscopy of the Al plasma was recorded and labelled as shown in figure 7a. The x-ray lines such as the He\(_0\) line (resonance line 1S2P \(1\)P\(_1\) – 1S\(_0\)), the inter-combination line (IC) (1S2P \(3\)P\(_1\) – 1S\(_2\) 1S\(_0\)), the di-electronic satellite (DS) (1S2P \(2\)D – 1S2P \(3\)P) lines and the K\(_\alpha\) lines from cold atoms of the Al at the wavelength \(\lambda = 7.7575\) Å, 7.8069 Å, 7.8471 Å and 8.3476 Å are present in the set spectral range 7.9 to 9.4 Å. Then the gold target was used to generate continuous x-ray spectrum in the same spectral range. A 20 µm thick Al foil was mounted in the path of the x-ray radiation and radiographs as shown in the figure 7b. To record the absorption spectroscopy of the Al plasma, the Al target was irradiated with the second laser beam. The delay between the x-ray probe pulse and main pulse on the object (Al) was achieved by providing an optical delay between two laser beams. The delay between the x-ray probe pulse and main laser pulse on target could be varied from 1 ns to 10 ns with temporal resolution of a few tens of pico second. In this case, the delay between the the x-ray probe pulse and main laser pulse on target was set to 3 ns. In figure 7c dark lines are shown as the absorption of continuous x-ray source at the wavelength close to the He\(_0\), IC and DS lines. The low intensity of the absorption lines and the distance from the Al target to the absorption lines can be explained as follows. The plasma expands opposite to the laser beam direction. After 3 ns, the ions with the energy levels 1S\(_0\), 1S\(_2\), 1S\(_3\), 1S\(_0\), 1S2P \(1\)P \(3\)P may have expanded to a certain distance from the Al target initial position and rarified before being exposed to the x-ray source. From the emission spectroscopy it can be seen that transition probability (oscillator strength) for the transition 1S2P \(1\)P\(_1\) – 1S\(_2\) 1S\(_0\), 1S2P \(3\)P\(_1\) – 1S\(_2\) 1S\(_0\), and 1S2P \(2\)D – 1S2P \(3\)P are high and hence in the case of absorption we can see absorption lines corresponding to these line i.e., 1S\(_2\) 1S\(_0\) - 1S2P \(1\)P\(_1\), 1S\(_3\) 1S\(_0\) - 1S2P \(3\)P\(_1\), and 1S2P \(2\)D-1S2P \(3\)P. This is the first observation made in our set up. Further work will be done with higher energy and better resolution.

**Conclusion**

A pulsed quasi-monochromatic x-ray radiograph of M- band spectrum of gold plasma has been developed. The x-ray spectral range of the radiograph is set to 7.9 – 9.4 Å (1.32 - 1.57 keV). The spectral width of the quasi monochromatic source was set to 1.5 Å (\(\Delta E = 0.25\) keV). The spectral resolution of the system measured using copper plasma was 30 mÅ. The x-ray pulse duration was measured using fast x-ray bi-planar photodiodes and 500 MHz scope as 1.0 ns for the laser pulse duration of 500 ps which is higher than earlier reported pulse duration measured with x-ray streak camera. The spatial resolution of the backlighter is approximately 50 µm depending on the laser focal spot size. The magnification could be varied from...
4 to 60. The x-ray radiography of the following have been presented in this paper: (1) S. S. mesh of wire diameter of 86-90 µm and separated by a distance of 342 µm, (2) S. S. wire of diameter of 400 µm and (3) 20 µm thick, 2 µm wide Aluminium foil. Absorption spectroscopy of the Al plasma has been measured using gold quasi-monochromatic x-ray pulse. Absorption lines corresponding to 1S\(^2\) \(^1\)S\(_0\)-1S\(^2\) \(^1\)P\(_1\), 1S\(^2\) \(^1\)S\(_0\)-1S\(^2\) \(^3\)P\(_1\), and 1S\(^2\) \(^2\)P\(_2\)-1S\(^2\) \(^2\)D transitions have been recorded.

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**Figure 7** (a). Emission spectrum of Al plasma recorded with TAP crystal spectrometer. (b) Radiography of the 20 µm Al foil using M band spectrum of gold plasma in the spectral range 7.6 to 9.4 Å with the blocked laser beam on target (c) absorption spectrum of the Al plasma exposed to the x-rays of the M band spectrum of gold plasma and (d) Intensity plot of the x-rays transmitted through Al plasma. Emission line of He\(_α\), IC and DS are closely matched with the absorption spectrum shown with blue arrows. Al plasma was irradiated 3 ns prior to the generation of x-ray pulse from the gold plasma.
the smooth operation of the laser system and for the electronics support.

References: