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Spectrum measurements for picosecond laser produced X-ray sources*

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Abstract: In this paper, a transmission curved crystal spectrometer is developed . The transmission curved crystal spectrometer employs a quartz crystal with radius of 200 mm covering the measuring range of 8 keV to 60 keV. We have applied the spectrometer to measure X-ray sources driven by picosecond laser both at XG-III and the SGII-Updated laser facility. The characteristic Kα and Kβ line emissions from Cu, Mo, Ag, and Zr were measured. Specifically, the L-shell emissions from Au targets irradiated by the picosecond lasers with different pulse duration were compared. The spectra show good signal-to-noise ratio, which indicates the spectrometer is suitable for the diagnostic of picosecond laser produced X-ray sources.

Key words: laser plasma diagnosis, X-ray spectrum, transmission curved crystal spectrometer, laser-produced plasma

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X-ray pulse sources produced by laser beam are playing a more and more important role in time-resolved ultrafast X-ray imaging and spectroscopy in high energy density physics experiments[1-3]. X-ray pulse source usually acts as a backlight in Compton radiography[4] of implosion targets in inertial confinement fusion. The temporal resolution of radiography depends on the duration of X-ray pulse sources, while the measurable density relies on the energy of X-ray pulse sources. Line emission X-ray pulse sources could be employed in time-resolved X-ray Bragg diffraction to probe the lattice dynamics of shocked metals. Short duration of the X-ray pulse source is helpful to the measurement of more intermediate phases.

Therefore, to get results with better temporal resolution, X-ray sources with higher energy and short duration are more desirable. Nanosecond laser of 1ns pulse length and 10^{15} W/cm^2 intensity could generate X-ray sources with energy below 10 keV and several ns pulse length. And the dominant emission is the He-α line from He-like ions. Picosecond laser with a pulse length of $<$20 ps and intensity $>10^{17}$ W/cm^2 allows the generation of cold Kα sources above 10 keV with pulse length $<$ 100 ps[5]. Fast electrons are created when a picosecond laser interacts with a thin solid target. Then those fast electrons transfer in the target and collide with the atoms. The core electrons of atoms may be knocked out by the fast electrons, thus inner shell transitions generate characteristic line emission, including Kα and Kβ photons. Picosecond laser produced X-ray sources have the advantages of short pulse duration, small source size and high brightness. Consequently, they offer promises in ultra-fast diagnostic, such as instantaneous radiography and dynamic diffraction.

X-ray sources produced by picosecond commonly have a broad energy range from few keV to MeV, high photon flux above 10^{10} photons·keV^{-1}·sr^{-1}, and fast electrons followed. Precise measurement of the X-ray sources produced by laser beam is significant for their application. Many efforts have been made to provide spectra to characterize the laser produced plasma, which caused the invention of single-photon counting CCD[6], transmission (or reflection) curved (or flat) crystal spectrometer[7-10], and non-dispersive X-ray spectrometer with filter[11]. Among those equipments, transmission curved crystal spectrometer is the most widely used due to its wide energy coverage and high spectral resolution.

This paper will focus on the spectra measurement of picosecond laser produced X-ray sources via transmission curved crystal spectrometer. At first, we review the design of the transmission curved crystal spectrometer which can cover the energy range of 8−60 keV. Then we present the experimental results of the picosecond laser produced X-ray source performed at the

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XG-III laser facility and the SGII-Updated laser facility.

1 Instrument design

A transmission curved crystal spectrometer was designed and constructed to measure photons from 8 keV to 60 keV, covering the Kα lines from Cu to W. Fig.1 shows the schematic of the transmission curved crystal spectrometer. The transmission curved crystal spectrometer utilizes a cylindrical curved quartz transmission crystal to spread incoming X-ray according to its energy. The cylindrical curved quartz transmission crystal is α-quartz (d=0.668 7 nm) [10-11] of 10 mm in height, 60 mm in length, 200 μm in thickness and 200 mm in bent radius.

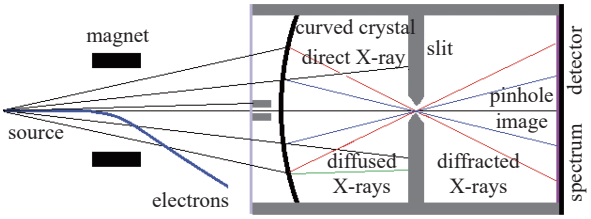


Fig. 1 Configuration of the transmission curved crystal spectrometer

X-rays from the source are incident into the crystal and only a part of them satisfying the Bragg diffraction condition would be diffracted effectively. The Fuji MS-type image plate was chosen for the spectrometer detector to measure the time-integrating X-ray spectrum. The image plate is scanned using a Typhoon 7000 image plate scan at a spatial resolution of 25 μm. The distance between the X-ray source and the crystal is 300 mm, while that between the crystal and the detector is 200 mm which equals to the radius of the curved crystal. Therefore, the spectrometer can cover the energy range of 8−60 keV. By varying the distance between the X-ray source and the crystal, the energy range could be adjusted.

To get pure diffraction signal, much work have be done in the design to reduce background noise since background noise in laser produced plasma X-ray sources is expected to be significant, especially in experiment with picosecond laser. The background noise is mainly caused by the direct X-rays, the diffuse X-rays and high energy particles including electrons[12]. An entrance aperture plate made of lead is installed in front of the curved crystal so that only the working region of the curved crystal could be irradiated by direct X-rays. Since all the diffracted X-rays would be focused on the axis, a lead slit is located at the focus to block the direct X-rays. To protect the spectrometer from diffusing X-rays, the spectrometer is covered with lead shields. Charged particles could be bended by magnets in front of the spectrometer. In addition, a CH slice with thickness of 1 mm is applied to protect the crystal from the fragments of targets.

In the alignment, the curved crystal mount is adjusted so that the curved crystal is aligned to the spectrometer axis. A diode laser is mounted at the spectrometer and also aligned to the spectrometer axis. By moving the whole spectrometer in x, y and z, the laser beam is incident onto the X-ray source. Adjust the distance between the spectrometer and the source, then we would have accomplished the alignment of the spectrometer with respect to the X-ray source.

Quantitative measurement of X-ray spectra requires calibration of the instrument ’s throughput. Thus the absolute sensitivity calibration of the transmission curved crystal spectrometer is in plan. In this work, we use XOP code to get the theoretical diffraction efficiency of the bent crystal according to the Takagi-Taupin model.

2 Testing at laboratory X-ray tube

Before fielding the transmission curved crystal spectrometer on laser facility, a demonstration experiment was carried out at a laboratory X-ray tube to verify our design. The X-ray tube was operated at 40 kV and 2 mA and positioned 300 mm away from the curved crystal. Fig.2 shows the typical spectral image from molybdenum (Mo) anode X-ray tube measured by the transmission curved crystal spectrometer. A pinhole image of the X-ray tube is located at the center of the spectral image, which provides information of source size and spatial distribution. Two spectra appear at the two flanks of the detector and the two

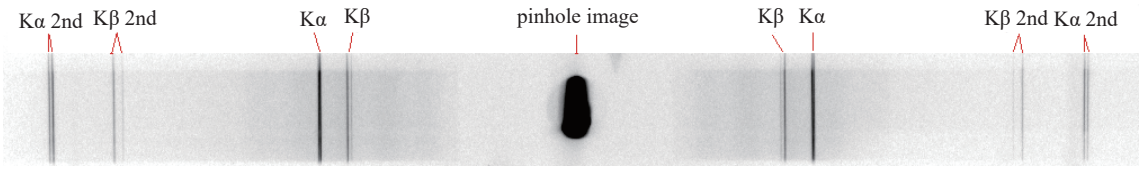


Fig. 2 Typical spectral image acquired from the molybdenum anode X-ray tube

spectra are symmetric about the central axis of the spectrometer. The 1st order and 2nd order diffraction of Mo Kα1, Kα2, Kβ1 and Kβ2 line emissions are visible.

As we know, the molybdenum anode X-ray tube generally has four strong line emissions composed of Kα1, Kα2, Kβ1 and Kβ2, among which the Kα1 line is the strongest. Thus we identify the strongest line emission as Kα1 line emission located at 17.479 keV and calibrate the energy. Fig.3 shows the molybdenum spectra summed over the spectral image shown in Fig.2 (only the energy range of interest). The two lower energy line emissions in the spectrum are measured at 17.48 keV and 17.38 keV which are consistent with Kα1 at 17.479 keV and Kα2 at 17.374 keV. And the higher energy line emissions are measured at 19.61 keV and 19.95 keV which are consistent with Kβ1 at 19.608 keV and Kβ2 at 19.965 keV. It is obvious that the resolving resolution of second-order diffraction of Mo Kα is much better than that of first-order.

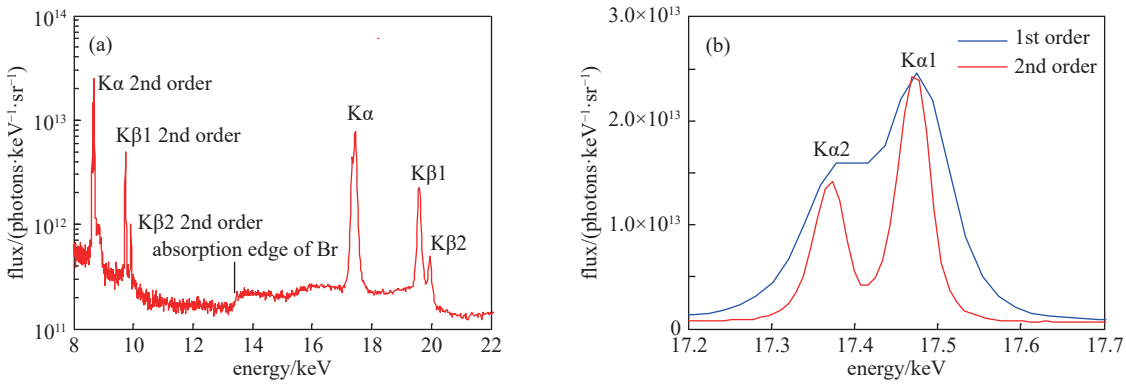


Fig. 3 Molybdenum spectra summed over the spectral image

It is noticed that there is an absorption mutation edge at 13.474 keV which is the absorption edge of Br in fact. The Fuji MS-type image plate consists of an X-ray sensitive material made from BaF(Br, I):Eu^{2+} and have absorption edges of Br (13.474 keV), Ba (37.44 keV), and I (33.170 keV)[13-14]. Those absorption edges only can be seen when the background noise is very low.

3 Experimental results and discussion

The experiment was performed on the XG-III laser facility and the SGII-Updated laser facility. XG-III is a high-intensity laser facility located at Research Center of Laser Fusion which can generate femtosecond, picosecond and nanosecond beams[15]. The picosecond beam of XG-III usually transfers about 150 J in a duration time of lower than 1 ps. At SGII-Updated laser facility, a short pulse beam with 500 J in energy and 10 ps in duration is constructed besides 8 long nanosecond pulse beams. For all experiments in our work, a single short picosecond laser beam is focused to a metal target, and the designed transmission curved crystal spectrometer is used to measure the X-ray spectra from the target.

Fig.4 shows the emission spectrum from Cu, Mo, Ag and Zr measured by the transmission curved crystal spectrometer. All the measured line emissions are shown in table 1. The measured spectra of Cu are shown in Fig.4(a). The Kα peak, line emissions from He-like state and H-like state are marked. Furthermore, the peaks located at 9.7 keV and 9.8 keV are also evident. Those peaks are line emissions from highly ionized Cu atoms. Since line transition in highly ionized Cu atoms are observed, it is verified that Cu plasma with sufficient temperature reaches the He- or H-like states.

X- ray spectra of Mo and Ag are shown in Fig.4(b) and (c), respectively. The Kα and Kβ lines of Mo and Ag are observed at the expected energy range. In addition, strong line emissions were also observed in the Mo spectrum at 8.72 keV and 8.77 keV, and in the Ag spectrum at 11.17 keV and 11.09 keV. Those two line emissions agree well with the second order diffraction of Mo Kα lines and Ag Kα lines respectively.

For Zr target it was expected that two lines would be observed in the region of 15.775 1 keV and 15.690 9 keV corresponding to the Kα1 and Kα2 transition, respectively. A peak is measured at 15.77 keV and 15.69 keV respectively, as shown in Fig.4(d). The Kβ energy peak measured is 17.63 keV.

In a recent experiment, Au wires were irradiated by a short pulse laser. Fig.5 shows the obtained L-shell emission

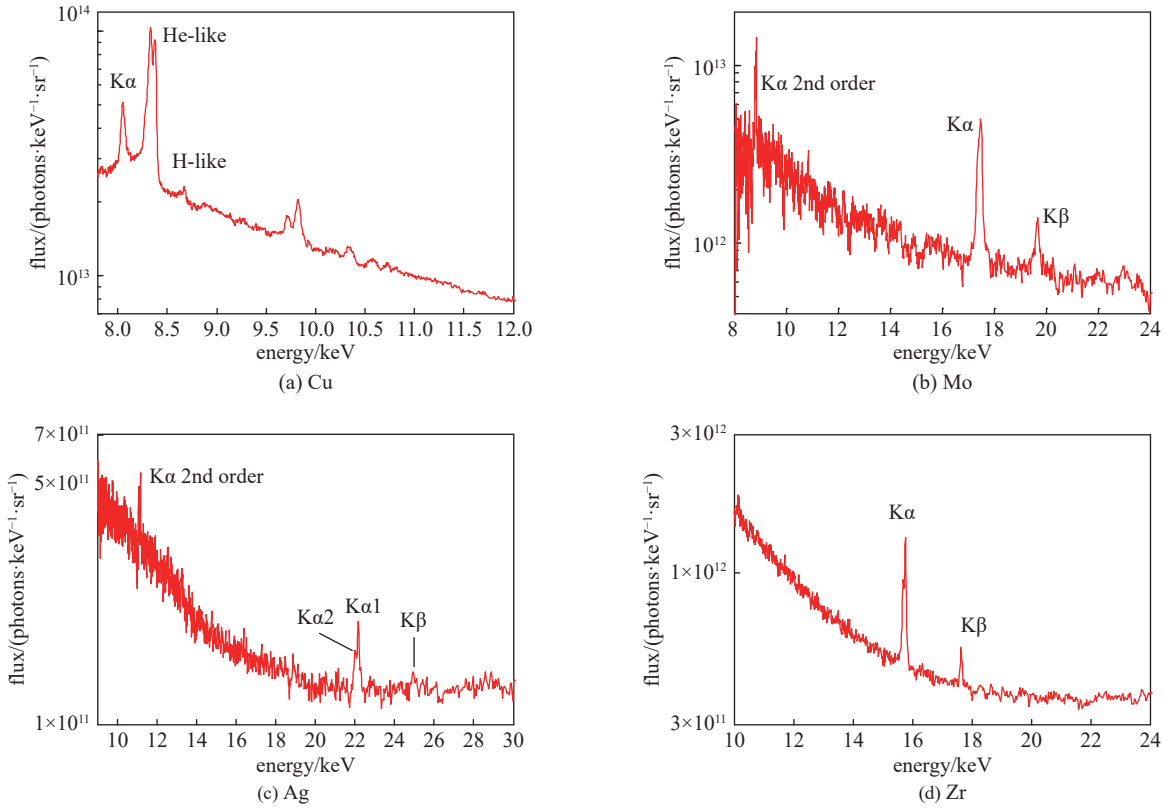
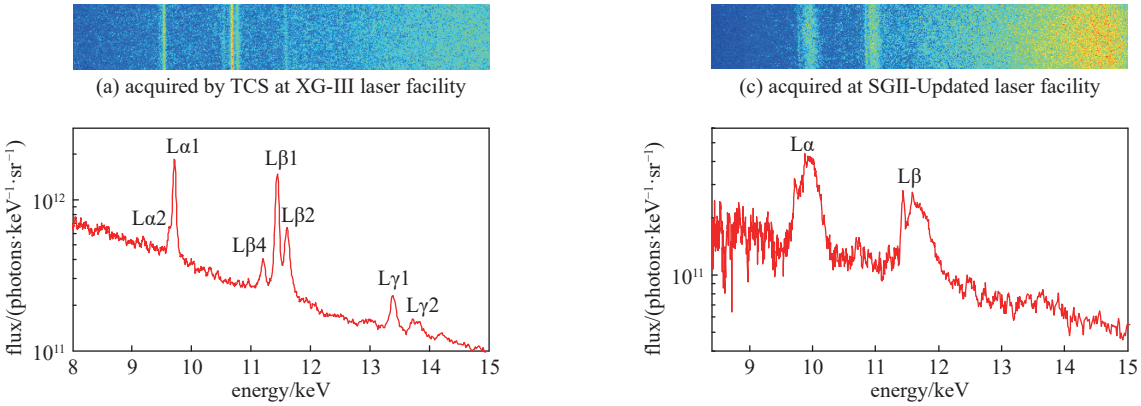


Fig. 4 Typical line spectra from high-*Z* materials

Table 1 Energies of the observed line emissions

target material	lines	theoretical energy/keV	measured energy/keV
Cu	Kα1	8.0478	8.048
	Kβ1	8.9053	—
	He-like $2p^3P_1$	8.3470	8.332
	He-like $2p^1P_1$	8.3920	8.375
	H-like $2p_{1/2}$	8.6660	8.667
	H-like $2p_{3/2}$	8.6990	
			9.716
			9.822
Mo	Kα1	17.4793	17.480
	Kα2	17.3743	
	Kβ1	19.6083	19.680
Ag	Kα1	22.1629	22.170
	Kα2	21.9903	22.010
	Kβ1	24.9424	24.950
Zr	Kα1	15.7751	15.770
	Kα2	15.6909	15.690
	Kβ1	17.6678	17.630

spectroscopy of Au using the transmission curved crystal spectrometers. In Fig.5(a), the L-shell lines spectral image is shown acquired during the irradiation of an Au wire with a short pulse laser with 100.3 J in energy and 0.879 ps in duration at the XG-III laser facility. Fig.5(b) shows the L-series spectrum of Au wire summed over the spectral image in Fig.5(a). We can see seven independent line emissions in the spectrum. The two line emissions at left side of the spectrum are measured at 9.625 keV and 9.712 keV, which are consistent with Lα1 at 9.7133 keV and Lα2 at 9.628 keV. At the middle, three Lβ emissions are



(a) acquired by TCS at XG-III laser facility

(b) the spectral image in figure (a)

(c) acquired at SGII-Updated laser facility

(d) the spectral image in figure (c)

Fig. 5 Obtained L-shell emission spectroscopy of Au using the transmission curved crystal spectrometers

observed at the energies of 11.44 keV (Lβ1, 11.442 3 keV), 11.61 keV (Lβ2, 11.584 7 keV), and 11.2 keV (Lβ4, 11.204 8 keV). Two Lγ line emissions are also seen at 13.38 keV (Lγ1, 13.381 7 keV) and 13.72 keV (Lγ2, 13.709 7 keV).

In Fig.5(c), small region of interest from the Au L-shell lines spectral image is shown, which is acquired during the irradiation of an Au wire with a short pulse laser with 463.89 J in energy and 11.14 ps in duration at the SGII-Updated laser facility. Fig.5(d) shows the L-series spectrum of Au wire summed over the spectral image in Fig.5(c). The line emissions are broadened obviously in Fig.5(d) which indicates that the target is heated to a sufficient temperature by the short pulse laser with 11.14 ps in duration.

4 Conclusion

In conclusion, we have shown a successful method to characterize picosecond laser produced X-ray sources. The development and experiments of transmission curved crystal spectrometer have been described. High quality spectra from Cu, Mo, Ag, and Zr were measured at XG-III laser facility and SGII-updated laser facility, covering the energy from 8 keV to 60 keV. The experiments results show that the transmission curved crystal spectrometers are suitable for the diagnostic of picosecond laser produced X-ray sources. In future work, the efficiency calibration of the transmission curved crystal spectrometer and absolute measurement of Kα yield will be made.

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皮秒脉冲激光产生的 X 射线源能谱精密诊断

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摘 要： 针对皮秒脉冲激光产生的 X 射线能谱精密诊断需求，提出了一种晶体谱仪，该谱仪使用曲率为 200 mm 的透射式石英弯晶作为色散元件，测谱范围可覆盖 8～60 keV。使用该谱仪在星光 III 和神光 II 升级装置进行了应用，成功获得了铜、钼、银等元素的特征线能谱，以及金的 L 壳层特征线，测量获得的能谱信噪比较高，显示了谱仪在测量皮秒激光产生的 X 射线能谱上的良好性能。

关键词： 激光等离子体诊断；X 射线能谱；透射弯晶谱仪；激光等离子体