Curved crystal spectrometer for the measurement of X-ray lines from laser-produced plasmas*

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In order to diagnose the laser-produced plasmas, a focusing curved crystal spectrometer has been developed for measuring the X-ray lines radiated from a laser-produced plasmas. The design is based on the fact that the ray emitted from a source located at one focus of an ellipse will converge on the other focus by the reflection of the elliptical surface. The focal length and the eccentricity of the ellipse are 1350 mm and 0.9586, respectively. The spectrometer can be used to measure the X-ray lines in the wavelength range of 0.2-0.37 nm, and a LiF crystal (200) ($2d$ = 0.4027 nm) is used as dispersive element covering Bragg angle from 30° to 67.5°. The spectrometer was tested on Shenguang- Ⅱ which can deliver laser energy of 60-80 J/pulse and the laser wavelength is 0.35 μm. Photographs of spectra including the 1s2p $^1P_1$-1s^2 $^1S_0$ resonance line(w), the 1s2p $^3P_2$-1s^2 $^1S_0$ magnetic quadrupole line(x), the 1s2p $^3P_1$-1s^2 $^1S_0$ intercombination lines(y), the 1s2p $^3S_1$-1s^2 $^1S_0$ forbidden line(z) in helium-like Ti ⅩⅪ and the 1s2s2p $^2P_{3/2}$-1s^{2}2s $^2S_{1/2}$ line(q) in lithium-like Ti ⅩⅩ have been recorded with a X-ray CCD camera. The experimental result shows that the wavelength resolution($\lambda/\Delta\lambda$) is above 1000 and the elliptical crystal spectrometer is suitable for X-ray spectroscopy.

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High-temperature and high-density plasmas can be produced by laser inertial confinement fusion (ICF), and the X-ray spectra emitted from the plasmas contain very abundant information, from which the electron temperature and density could be induced. The crystal spectrometer is a useful tool to investigate the dynamics of plasma formation and evolution, and it plays a significant role in the field of ICF [1-3]. During recent years, many spectrometers have been developed to measure X-ray spectra. However the crystal spectrometers have become the most important routine tool for plasma diagnosis due to its simple structure, convenient operation, and low cost. Recently the bent crystal spectro meters have been designed to measure X-ray in the Lawrence Livermore National Laboratory [4-6]. In this paper, we will describe an elliptically bent crystal spectrometer with a 0.9586 eccentricity, a 1350 mm-long focal distance, and a 30-67.5° Bragg angle. It employs a LiF ($2d$ = 0.4027 nm) crystal as the dispersive element and is equipped with an X-ray charge coupled device (CCD) camera as the detector. The spectrometer has been designed and fabricated for measuring soft X-ray spectra in the range of 0.2-0.37 nm, and has been applied for X-ray diagnostics of the laser-produced plasmas on the Shenguang-Ⅱ laser facility.

The optical system was designed in the elliptical geometry[7,8] as shown in Fig.1. The X-ray source is located at the front focal point and the X-rays reflected by the elliptically bent LiF crystal are focused at the rear focal point where an exit slit is positioned and a 20-μm-thick beryllium foil is placed in front of the exit slit to cut off the visible light and low-energy X-ray. Below the rear focal point, a X-ray CCD or streak camera can be applied to measure simultaneously spatially and temporally resolved X-ray spectra of a nanosecond source.

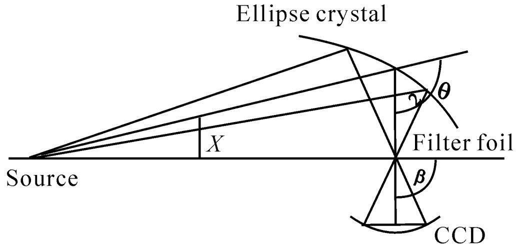

Fig.1 Diffraction geometry graph of elliptical crystal

In Fig.1, θ is the Bragg diffraction angle, and β is the spectral detection angle. According to the design of the

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spectrometer, the ellipse has an eccentricity of 0.9586 and a focal length (between the source and the center of the exit slit) of 1350 mm. The following expressions can be given by an elliptical equation.

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}=1, \tag{1}$$

$$c=\sqrt{a^2-b^2}, \tag{2}$$

$$e=\frac{c}{a}, \tag{3}$$

where a denotes length of the long semiaxis, b represents length of the short semiaxis, c indicates the semifocal length, and e is the eccentricity. Using $e = 0.9586$, $c = 675$ mm, in Eq. (2) and Eq. (3), we can obtain $a = 704.15$ mm and $b = 200.50$ mm.

Furthermore the Bragg angle θ for the reflection at the crystal and the spectral detection angle β for this given elliptical geometry can be related by the following relation [9],

$$\mathrm{tg}\theta=\frac{1-e\cos\beta}{e\sin\beta}. \tag{4}$$

The spectral resolution of the crystal instrument can be further deduced from the Bragg equation,

$$2d\sin\theta=n\lambda \quad (n=0,1,2,\cdots\cdots), \tag{5}$$

where $2d$ is the interplanar spacing, n is the diffraction order, and λ is the x-ray wavelength. Using Eq. (4) and Eq. (5), we obtain ($n = 1$)

$$\sin\theta=\frac{1-e\cos\beta}{\sqrt{1+e^2-2e\cos\beta}}, \tag{6}$$

and

$$\frac{\lambda}{2d}=\sin\theta=\frac{1-e\cos\beta}{\sqrt{1+e^2-2e\cos\beta}}. \tag{7}$$

Using Eq. (7),the wavelength and photo energy position as functions of β along the detection circle can be obtained. And the wavelength resolution could be improved by decreasing the value of β.

Differentiating Eq. (5), we obtain

$$\frac{\mathrm{d}\theta}{\mathrm{d}\lambda}=\frac{1}{2d\cos\theta}. \tag{8}$$

Clearly, the spectral resolution is mainly determined by the spacing of the diffracting planes according to Eq. (8), and it is also affected by other factors including the resolution of the crystal, the size of the source and the resolution of the detector.

The elliptically crystal spectrometer is mainly composed of the dispersive elements, the vacuum configuration, the spectral detectors, and the three-dimensional (3D) micro-adjustment devices(Fig.2). In our case, the dispersive element was LiF crystal, the elliptical substrate was manufactured by using a computer-controlled milling machine to guarantee the elliptical surface satisfaction with the designed elliptical equation. And the LiF crystal was fixed on the elliptical surface with one kind of special slow-solidifying-rate epoxy resin. The exit slit was mounted on the bottom of the housing and its width was adjusted between 0.1 and 1 mm through the side access port. A piece of filter foil was placed in front of the exit slit. The spectral detector was a X-ray CCD for measuring space resolution. The crystal spectrometer was bolted onto a 200-mm-diameter port of the Shenguang-Ⅱ target chamber through the adapting flange.

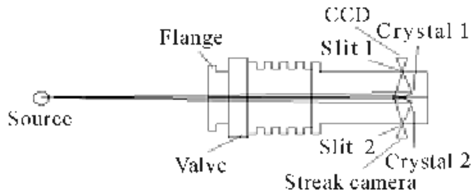

Fig.2 Structural sketch of curved crystal spectrometer

The experiment was performed inside the Shenguang-Ⅱ target chamber. One laser beam with a 0.35-ìm wavelength, a 800-ps pulse width, and a 60-80-J energy was focused on a 100-ìm-thick Ti planar target. The X-ray radiated from laser-produced plasmas was used as the light source. And the elliptically bent LiF crystal was utilized as the dispersive element. The emission spectrum of Ti plasmas was recorded by the X-ray CCD camera, which has a large detection area (26.8 mm×26 mm, 1340×1300 pixels and 20 μm×20 μm pixel size).

The X-ray spectral photograph emitted from Ti plasmas is shown in Fig.3. Using a program written in MATLAB based on Eqs. (4) and (5), we have identified the bright lines as

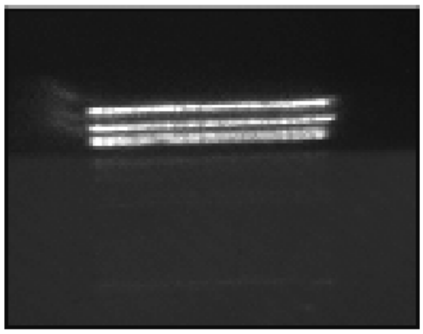

Fig.3 Spectra of Ti laser-produced plasma

shown in Fig.4. And we have used them for the wavelength calibration.

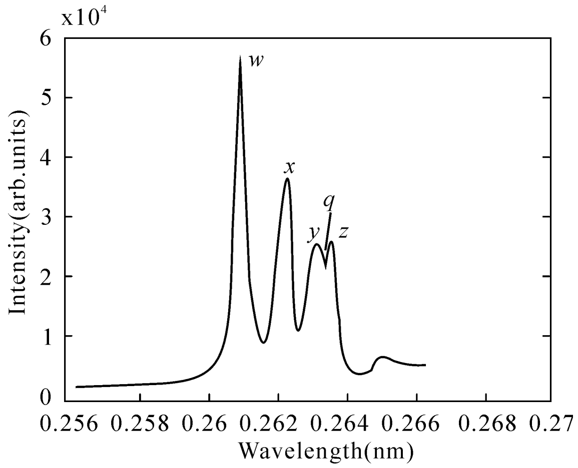

Fig.4 X-ray spectrum intensity

Tab.1 summarizes the results of our measurements. Various Ti XXI transitions are identified and listed in Tab.1. The experimental results have shown that the calculated spectral resolution ($\lambda/\Delta\lambda$) approximates 1077.

Tab.1 Ti XXI transitions wavelength resolution of spectra

Counts	Wavelength (nm)	Transition	Label	Resolution
94	0.2610	ls2p $^1p_1$-ls^2 $^1S_0$	*w*	1077
120	0.2619	ls2p $^3p_2$-ls^2 $^1S_0$	*x*	840
137	0.2625	ls2p $^3p_1$-ls^2 $^1S_0$	*y*	-
140	0.2628	ls2s2p $^2p_{3/2}$-ls^{2}2s $^2S_{1/2}$	*q*	-
146	0.2637	ls2p $^2S_1$-ls^2 $^1S_0$	*z*	-

Based on the elliptical focusing geometry, a crystal spectrometer has been designed. The important optical para meters have been discussed in this paper. Also, the target-shooting experiment has been performed at the Shenguang-Ⅱ laser facility for testing the spectrometer, and the X-ray spectrum of Ti plasmas was successfully recorded by a X-ray CCD camera. The X-ray wavelength and resolution of Ti plasmas have been calculated. The spectral resolution is better than 1000 and the elliptical crystal spectrometer is suitable for diagnosing laser-produced plasmas.

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