Elliptically-bent crystal spectrograph for X-ray diagnosis of laser-produced plasmas

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In order to measure spatially and temporarily resolved laser-produced plasma X-ray spectra in 0.2 − 2 nm region, a novel two-channel elliptically-bent crystal spectrograph has been developed. Dispersive elements are LiF, PET, Mica, and KAP crystals, which cover Bragg angles in the range of 30 − 67.5 degrees. Eccentricity and focal distance of twin ellipses are 0.9586 and 1350 mm, respectively. Spatially resolved spectrum is photographically recorded with an X-ray film or X-CCD camera in one channel, and temporarily resolved one is photographically recorded with an X-ray streak camera in another channel, thus spatially and temporarily resolved spectra can be simultaneously obtained. Spectral images were acquired with X-CCD and PET in SHENGUANG-II laser facility, and experimental results show that the spectral resolution of the spectrograph is about 0.002 nm.

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A large amount of high-temperature and high-density plasmas are produced in laser inertial confinement fusion (ICF). X-rays are radiated from laser-produced plasmas and used in spectral measurement and plasma diagnosis. Plasma state, such as electron temperature and density, can be determined through X-ray spectra[1,2]. Grating spectrographs were widely used to diagnose laser-produced plasmas and grazing incidence is adopted to increase grating reflectivity. However, collecting efficiency is low and it was difficult to obtain X-ray spectra below 2 nm[3,4]. We developed a novel two-channel elliptically-bent crystal spectrograph (ECS) with Bragg angle of 30 − 67.5 degrees in 0.2 − 2 nm region. Dispersive crystals are elliptically bent to increase spatial resolution. X-ray spectra are recorded with a film or CCD camera in one channel, with a streak camera in another, so spatial and temporal resolution can be obtained simultaneously.

The schematic of the ECS is shown in Fig. 1. X-ray source of the laser-produced plasma is located at the front intersecting focus of the twin ellipses, i.e., at the center of vacuum target chamber. Being diffracted by the elliptically-bent crystals, the X-rays are convergent at twin rear foci respectively. Space-resolved spectrum is recorded with an X-ray film or CCD camera in the lower channel, while time-resolved spectrum is recorded with an X-ray streak camera in the upper channel. Twin slits are located at the rear foci respectively. Two pieces of filter may be placed in front of the slits to cut off low-energy X-rays and stray light.

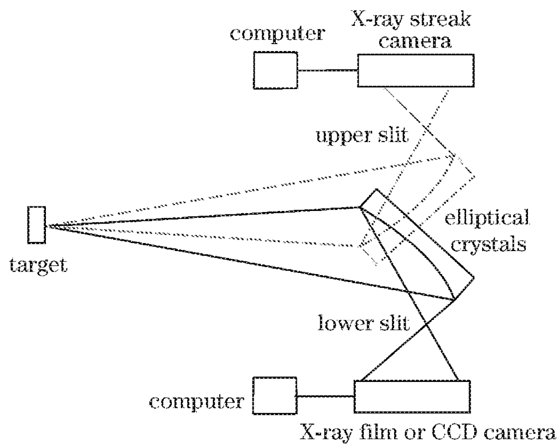

Fig. 1. Schematic of the ECS.

The two ellipses have identical geometric dimension, with eccentricity of 0.9586, focal distance of 1350 mm, Bragg angle of 30 − 67.5 degrees, arc length of 125.64 mm, spectral detection angle of 55.4 − 134.0 degrees, and optical path length of 1456.3 mm. As circle center of semicircular film camera is coincident with the rear focal point, optical distances through different Bragg angles are equal when the spectrum is recorded with film camera[5]. A piece of film is divided into three identical sections with light shield, so it can be used for three shots for one film setting. X-rays from the first focus are convergent at the second focus after they are diffracted by these crystals, thereby the ECS has self-focusing characteristics. Moreover, the twin elliptical substrates are partly overlapped in the transverse and longitudinal directions, so the spectrograph is reduced in size and weight.

LiF, PET, Mica, and KAP[6,7] crystals are adopted as dispersive elements for the ECS. X-rays will be diffracted by these crystals when they arrive at their surfaces. According to the Bragg diffraction equation

$$m\lambda = 2d \sin\theta, \qquad (1)$$

where $2d$ is crystal lattice constant, θ is Bragg diffraction angle, m is diffraction order number, λ is X-ray wavelength, and geometrical parameters, we obtain the range of Bragg angle covered by the ECS being 30 − 67.5 degrees. Using Eq. (1), diagnostic range of X-ray wavelengths is calculated and shown in Table 1 for the first order spectrum.

Table 1. Diagnostic Range of X-ray Wavelength

Crystal	hkl	2d (nm)	Diagnostic Range of X-Ray Wavelength (nm)
LiF	(200)	0.403	0.20 – 0.37
PET	(002)	0.874	0.44 – 0.81
Mica	(002)	1.984	0.99 – 1.83
KAP	(1010)	2.663	1.33 – 2.46

The spectrograph was used in experiments in SHENGUANG-II laser facility. Laser beam with wavelength of 0.35 μm was focused on a planar Au target with energy of 260 J, and pulse width of 960 ps and X-rays are radiated from laser-produced plasmas. Elliptically-bent PET is used as dispersive element, space-resolved spectrum is recorded with an X-ray CCD camera. The X-ray CCD camera is a two-dimensional detector with 1340×1300 planar array, the size of each pixel is 20 × 20 μm^2. A spectral photograph recorded with the X-CCD camera is shown in Fig. 2, and cross-section graph of intensity versus pixel along x-axis is shown in Fig. 3.

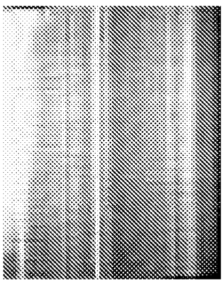

Fig. 2. The photograph of X-ray spectrum.

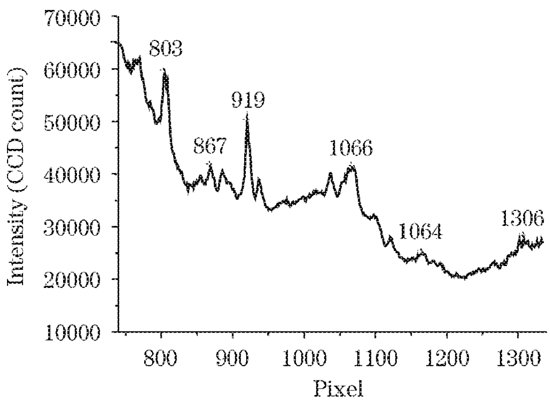

Fig. 3. Cross-section graph of intensity versus pixel.

Table 2. Calculated X-Ray Wavelength for PET

Pixel Position	X-ray Wavelength (nm)	Experimental Data of Tragin[8] (nm)	Transition
803	0.6352	0.6353	$8f$-$4d$
867	0.6454	0.6450	$8f$-$4d$
919	0.6474	0.6468	$7d$-$4p$
1066	0.6778	0.6783	$6p$-$4s$
1164	0.6919	0.6924	$6p$-$4s$
1306	0.7097	0.7098	$7f$-$4d$

The X-ray wavelengths are calculated by using Matlab 6.1 software and shown in Table 2. The maximal wavelength error is 0.0006 nm by comparing with the experimental results of N. Tragin *et al.*[8]. Two spectral lines whose wavelengths are 0.6454 nm and 0.6474 nm can be resolved; it indicates that the resolution of the spectrograph is about 0.002 nm. The distance from X-ray source to photocathode plane of the streak camera is fairly long up to 1.46 m, vacuum level did not reach to 3×10^{-3} Pa, so we did not measure time-resolved spectrum with the streak camera in case of damage.

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