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A novel X-ray spectrometer for plasma hot spot diagnosis

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A R T I C L E   I N F O

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A B S T R A C T

A novel X-ray spectrometer is designed to diagnose the different conditions in plasmas. It can provide both X-ray spectroscopy and plasma image information simultaneously. Two pairs of elliptical crystal analyzers are used to measure the X-ray spectroscopy in the range of 2–20 keV. The pinhole imaging system coupled with gated micro-channel plate(MCP) detectors are developed, which allows 20 images to be collected in a single individual experiment. The experiments of measuring spectra were conducted at "Shenguang-II upgraded laser" in China Academy of Engineering Physics to demonstrate the utility of the spectrometer. The X-ray spectroscopy information was obtained by the image plate(IP). The hot spot imaging experiments were carried out at "Shenguang-III prototype facility". We have obtained the hot sport images with the spectrometer, and the signal to noise ratio of 30 ∼ 40 is observed.

1. Introduction

In the research experiment of inertial confinement fusion, it is important to develop implosion instability of high temperature plasmas [1–3]. In order to diagnose the conditions necessary for ignition, a set of high quality diagnostics is required. These include x-ray spectroscopy and other imaging detecting technology which can be applied to a variety of experimental platforms [4–7]. For example, electron densities and temperatures can be determined by detecting the ratios and broadenings of x-ray lines emitted from the imploded plasma [8–10]. Higher resolution images of objects in high energy density plasmas, which are non-transparent to certain diagnosis methods, such as electronic microscopy, could also be obtained with the x-ray imaging technique. Moreover, the x-ray self-emission from the imploded capsule is imaged to measure the symmetry of the implosion [11].

In this paper, we propose a novel X-ray spectrometer to diagnose the spectra and analyze the images of fusion hot spot, which includes using an elliptically geometric crystal to investigate the plasmas with high spectral resolution. In this way, we can measure X-ray spectra of many different types elements even with very low emission. Moreover, spectral range of 2–20 keV is covered with the high resolution crystal. The crystal spectroscopy consists of four elliptically bent crystals, and each spectral line reflected by the crystal emits to an IP. A thin beryllium (100 μm) between the spectrometer and the target, is mounted on an adjustment wheel to shield against plasma debris. The X-ray imaging instrument relies on the pinhole imaging systems, which are coupled with gated MCP detectors that could achieve the required temporal resolution. We could collect 20 images in each single experiment with the instrument.

2. Instrument design

The principles of a pair of elliptical crystal analyzers are illustrated in Fig. 1. A source placed at one focus is diffracted by the crystal according to the Bragg principle [12,13]. With different wavelengths and different points along the crystal, the x-rays are dispersed. All rays emitting from source, off crystals, through slit (at the second focus), and into the detectors were analyzed for calculating the spectral resolution and spectral range.

In the proposed geometry, the crystal is curved in the spectral direction on an ellipse with major and minor axes of a and b, respectively. $2c$ is the distance between the two foci of the ellipse, and $e = c/a$ is the eccentricity of the ellipse. The relationship among a, b, and c is demonstrated using the following equation,

$$a^2 = b^2 + c^2. \tag{1}$$

The critical parameters of the crystal analyzers are the ellipse's eccentricity e, distance between foci $2c$ and Bragg angle θ. Some parameters of the elliptically curved crystals, shown in Table 1, were

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Table 1
The parameters of the elliptically curved crystals.

Crystal	2d (nm)	e (mm)	a (mm)	b (mm)	θ	Energy (keV)
α-quartz(1010)	0.8512	0.96	468	128.55	27°–40°	2.3 –3.2
α-quartz(2023)	0.2749	0.98	459.18	91.38	18°–35°	7.9 –13.5
α-quartz(1011)	0.6687	0.985	456.85	78.83	14°–24°	4.5 –7.2
Si(111)	0.6271 0.6271	0.98	459.18	91.38	18°–35°	10.3–19.2 (n = 3) 3.4–6.4 (n = 1)

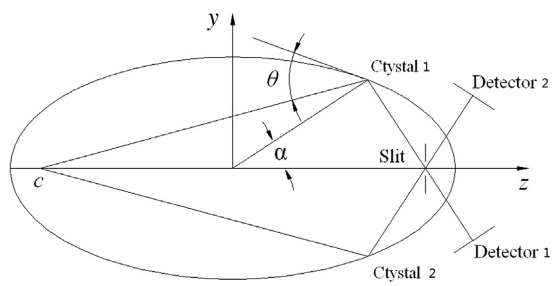

Fig. 1. The schematic of spectral detection system of elliptical curved crystal spectrometer.

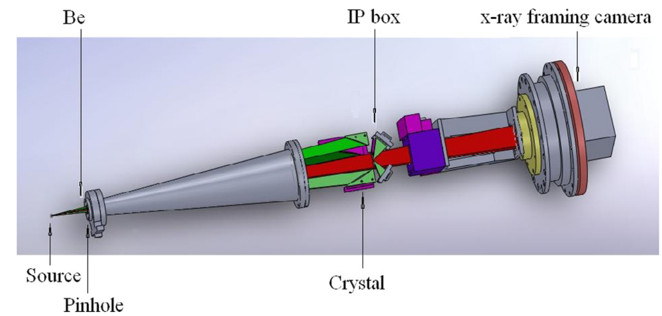

Fig. 2. CAD design of the pre-alignment configuration of the spectrometer.

calculated according to Eqs. (1) and $e = c/a$. Four curved crystal analyzers (α-quartz(1010), α-quartz(2023), α-quartz(1011) and Si(111)) have the same working distances 2c (900 mm). Using various crystals in elliptical configurations, we could measure radiation in almost the entire range of 2–20 keV [14,15]. Unlike many commonly used crystals reflecting only to one single reflection order, Si(111) can efficiently reflect several reflection orders, allowing us to record spectra over energy ranges: 3.4–6.4 keV in the first diffraction order of the Si(111) crystal, 10.3–19.2 keV in the third order of reflection. However, the second order is very weak and can be neglected.

If we define a sweep angle α in Fig. 1 such that $z = a\cos\alpha$ and $y = b\sin\alpha$, then a relation can be derived between α and θ [16]:

$$\sin\alpha = \frac{\sqrt{1-e^2}}{e}\cot\theta. \tag{2}$$

Using the Eq. (2), $e = c/a$ and $y = b\sin\alpha$, we finally find that

$$y = b^2/(c\tan\theta). \tag{3}$$

Then, From Eq. (1), it follows that

$$x = a\sqrt{1-(y/b)^2}. \tag{4}$$

We could calculate the coordinate figures of the ellipse and manufacture the crystal analyzers according to Eqs. (3) and (4).

3. Spectrometer configuration

A computer-aided design (CAD) model of the spectrometer is illustrated in Fig. 2. It uses the elliptically bent crystals as well as the X-ray framing camera, and it allows us to record X-ray spectra simultaneously with the images of X-ray sources. Elliptical crystal arrangements have some advantageous attributes for broadband X-ray spectroscopy of extended sources. In this structure, the X-ray source (hot spot) is placed at the far focus of the ellipse. Reflected by the elliptical crystal, X-rays focus on the near focus. In order to reduce unwanted radiations, a slit is needed in front of the detector. The ellipse of channel is rotated above the axis (z-axis) of the instrument by 2.1° and X-rays reflected by each crystal are detected on an IP. Four crystal analyzers are placed around the main beam axis (the axis of pinhole imaging) to measure spectra, as shown in Fig. 3.

The fusion experiment lasts about 1 ns per shot and MCP detectors are used for two-dimensional time-resolved X-ray imaging. Temporal gating on hundreds of picosecond time scale is achieved by propagating

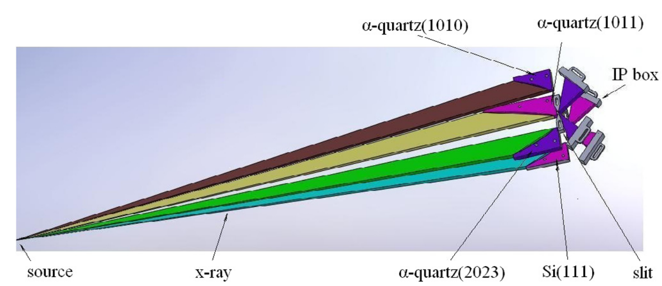

Fig. 3. Schematic view of four crystal analyzers. Radiated from a point source is analyzed at different energies with different IPs.

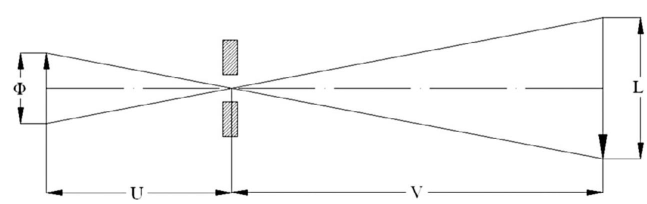

Fig. 4. Schematic diagram of pin-hole imaging.

a subnanosecond high voltage pulse across metal strip lines coated onto the MCP surface. The image is formed with the pinhole apertures, which is described in Fig. 4. A pin-hole with a diameter of D is located at a distance U from the object and a distance V from the image, where $L/\Phi = V/U$. The collection solid angle can be obtained by $\Omega = \frac{\pi D^2}{4U^2}$.

4. Measurement

The spectrometer was tested at Shenguang-II upgraded laser facility. Two pairs of elliptically curved crystals were used to make spectroscopy measurements of heated Au target. The high resolution X-ray spectra were taken using a 50 mm Fuji IP detector. With an access door, we could have easy access to insert the IP before the shot and remove them after the shot. The slits reduce the field of view of the detector to suppress background from Compton scattering, and it also suppress fluorescence from structures in the target chamber. The Be foil mounted in front of the spectrometer acts as a K-edge filter to further improve the signal to background ratio. This filter can also optimize the signal level