High resolution X-ray spherically bent crystal spectrometer for laser-produced plasma diagnostics

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A new high spectral resolution crystal spectrometer is designed to measure very low emissive X-ray spectra of laser-produced plasma in 0.5−0.9 nm range. A large open aperture (30×20 (mm)) mica (002) spherically bent crystal with curvature radius $R = 380$ mm is used as dispersive and focusing element. The imaging plate is employed to obtain high spectral resolution with effective area of 30×80 (mm). The long designed path of the X-ray spectrometer beam is 980 mm from the source to the detector via the crystal. Experiment is carried out at a 20-J laser facility. X-ray spectra in an absolute intensity scale is obtained from Al laser-produced plasmas created by laser energy of 6.78 J. Samples of spectra obtained with spectral resolution of up to $E/\Delta E \sim 1500$ are presented. The results clearly show that the device is good to diagnose laser high-density plasmas.

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Recent advances in laser technology have made it possible to create high-density, highly ionized, and nonequilibrium plasmas. They are far from thermal equilibrium so that they are expected to be a good medium for X-ray lasers sources[1]. The crystal spectrograph has become one of the most valuable tools to diagnose laser-produced plasma. The Johann configuration has the advantages that the whole spectral range is recorded simultaneously and all the photons, which contribute to a spectral line, are reflected from the entire crystal. Therefore, it can obtain high luminosity, good spatial resolution, and very good spectral resolution[2,3]. Blasco *et al.* employed a large open aperture (30×10 (mm)) mica crystal with the radius of curvature $R = 100$ mm as the dispersive and focusing element, charge-coupled device (CCD) as the detector, and obtained simultaneous high spectral ($\lambda/\Delta\lambda$: $1000 - 5000$) and spatial ($40 - 80$ μm) resolution[4]. Sinars *et al.* indicated that spherically bent focusing spectrometers with one- or two-dimensional spatial resolution (FSSR) were commonly used to obtain spectra with $\lambda/\Delta\lambda > 1000$ from laser and exploding-wire plasmas[5].

The focusing spectrometer with FSSR concept is shown in Fig. 1. X-rays from the source are dispersed from the crystal according to the Bragg condition[6],

$$n\lambda = 2d \sin\theta, \tag{1}$$

where d is the distance between planes in the crystal, θ is the grazing angle relative to the crystal planes, λ is the reflected wavelength, n is an integer representing the order of the reflection.

After reflecting from the crystal, spectrally selected beams are formed in the meridional plane. Due to astigmatism, these beams are focused at different points in the meridional and sagittal planes. The positions of these points are given in the sagittal plane by

$$1/a + 1/b_{\rm s} = (2\cos\varphi)/R, \tag{2}$$

and in the meridional plane by

$$1/a + 1/b_{\rm m} = 2/(R\cos\varphi), \tag{3}$$

where $b_{\rm s}$ and $b_{\rm m}$ are the distances from the crystal to the points of sagittal and meridional beam focusing, R is the radius of curvature of the crystal, and $\varphi = 90^\circ - \theta$ is the angle of incidence (from normal incidence) of the incoming radiation.

To achieve the best possible spectral resolution and the best possible intensity in the image, the film or the CCD must exactly placed at the distance $b_{\rm s}$ from the crystal in accordance with Eq. (2). The X-ray detector must be placed on the Rowland circle in order to obtain good spectral resolution. It follows that, in order to obtain good spatial resolution perpendicular to the detector dispersion plane, the source must be set up at a distance[4]

$$a = R\cos\varphi/\cos 2\varphi, \tag{4}$$

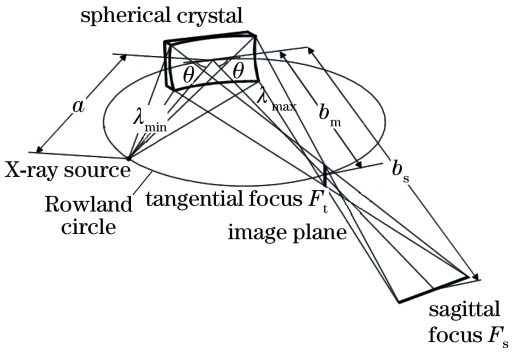

Fig. 1. Focusing properties of a spherically curved crystal. a is the distance from the source to the crystal.

and the distance between the crystal and the detector is

$$b = b_{\rm s} = R\cos\varphi. \tag{5}$$

Focusing on the Rowland circle can be achieved only for the central ray (the ray passing through the center of the crystal face) with a wavelength that matches the Bragg equation at the source position a. Radiation with other wavelengths within the spectrograph bandwidth limits indicated by the limiting rays in Fig. 1, $\lambda_{\rm min}$ and $\lambda_{\rm max}$, will be focused on the straight line connecting the source and the detector plane. However, for a small source, the shift of the focal position from the Rowland circle does not decrease the spectral resolution significantly[7].

Especially, $b_{\rm m} = b_{\rm s}$ occurs if $\theta = 90°$. If θ is in the range of $80° - 90°$, however, a spherical crystal can be used with a relatively small amount of astigmatism to obtain micron-scale spatial resolution. Thus, in this range, there is little difference in the performance of spherically bent crystal[5]. If $\theta > 45°$ and $\theta \neq 90°$, $b_{\rm m} \neq b_{\rm s}$ occurs in other words, the X-ray radiation from a small source is magnified after passing a spherical bent crystal.

The magnifications in the meridional and sagittal planes are

$$M_{\rm m} = \frac{b_{\rm m} - R\sin\theta}{R\sin\theta - a}, \tag{6}$$

$$M_{\rm s} = b_{\rm s}/a. \tag{7}$$

The focal lengths of the crystal in the horizontal and vertical directions $f_{\rm m}$ and $f_{\rm s}$ depend on R and φ as[8]

$$f_{\rm m} = \frac{aR\sin\varphi}{2a - R\sin\varphi}, \tag{8}$$

$$f_{\rm s} = \frac{aR}{2a\sin\varphi - R}. \tag{9}$$

As a reflection-type analyzer, mica has a significant layer d structure, excellent thermal and chemical stability. The crystal structure is monoclinic[9]. Mica has higher purity and transparency in the visible region. We chose spherically bent mica crystals with a minimum radius of curvature (R = 380 mm). The size of the spherically bent mica crystal is 30 × 20 (mm). It has very good reflectivity at reflection orders of 1, 2, 3, 4, 5, 7, 8, 11, 12, and 13[10]. Since the lattice space of mica crystal in the first order of diffraction is $2d = 1.994$ nm, it becomes possible to cover a very wide spectral range from about 0.12 to 1.9 nm[4].

The physical experiment was carried out using the spherical spectrometer at the 20-J laser facility of Research Center of Laser Fusion, China Academy of Engineering Physics. The angle between the laser beam and the normal line of the central target surface is about 45°. The imaging plate is employed to obtain a high spectral resolution and a narrow spectral bandwidth with an effective area of 30 × 80 (mm). The designed optical path of the X-ray spectrometer beam is 980 mm from the source to the detector via the mica crystal.

The laser energy is about 6.78 J in an exploding Al target experiment. The intensity distribution of diffracted beams on the crystal surface is shown in Fig. 2.

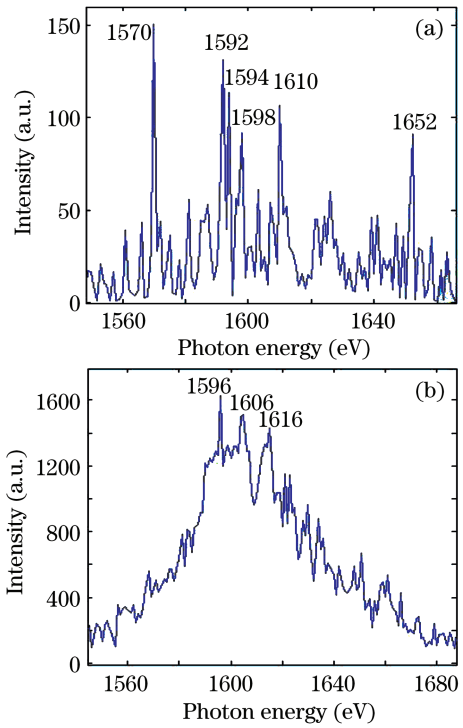

Fig. 2. Spectral intensity distribution. (a) Intensity versus photon energy in the horizontal plane for the spherically bent mica crystal spectrometer; (b) intensity versus photon energy in the perpendicular channel for the flat PET crystal spectrometer.

Table 1. Wavelength Resolution of Spectra

Intensity	Photon Energy (eV)	Bragg Angle (deg.)	$E/\Delta E$
150.3	1570	52.39	1570
131	1592	51.37	1337
113.5	1594	51.28	1328
91.83	1598	51.10	1165
106.8	1610	50.58	1007
91.33	1652	48.84	1101

A central wavelength of 0.776 nm (the Al XII transition) emitted from a point source with the full-width at half-maximum (FWHM) Gaussian spectral profile[11] of 1 eV is assumed for the calculation. The large size of our spherically bent crystal makes it possible to measure spectra over a wide spectral range of $0.5 - 0.9$ nm in the second diffraction order of the mica crystal. Thus, in one experiment we can simultaneously record spectra of all lines of Al ions, from He-like to Li-like lines. The spectral resolution $E/\Delta E$ up to 1500 is limited only by the imaging plate detector (see Table 1). However, there is a spectral resolution of $E/\Delta E \approx 50 - 100$ for the flat pentaerythritol (PET) crystal under the same condition.

In conclusion, the Johann geometry[12] and spectral characteristics of a spectrometer based on a spherical bent crystal are presented. A ray tracing approach is used to determine the geometry, dispersion, magnification, and luminosity. These features make spherical crystal spectrometers ideal to obtain high-resolution spectra even from low radiance plasmas.

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