# High-resolution X-ray focusing concave (elliptical) curved crystal spectrograph for laser-produced plasma

**Shali Xiao (肖沙里)[1], Yingjun Pan (潘英俊)[1], Xianxin Zhong (钟先信)[1], Xiancai Xiong (熊先才)[1], Guohong Yang (杨国洪)[2], Zongli Liu (刘宗礼)[2], and Yongkun Ding (丁永坤)[2]**

[1] *The Key Laboratory of Optoelectronic Technology and System, Ministry of Education, Chongqing University, Chongqing 400044*

[2] *Research Center of Laser Fusion, China Academy of Engineering Physics, Mianyang 621900*

Received May 9, 2004

The X-ray spectrum emitted from laser-produced plasma contains plentiful information. X-ray spectrometer is a powerful tool for plasma diagnosis and studying the information and evolution of the plasma. X-ray concave (elliptical) curved crystals analyzer was designed and manufactured to investigate the properties of laser-produced plasma. The experiment was carried out on Mianyang Xingguang-II Facility and aimed at investigating the characteristics of a high density iron plasma. Experimental results using KAP, LIF, PET, and MICA curved crystal analyzers are described, and the spectra of Au, Ti laser-produced plasma are shown. The focusing crystal analyzer clearly gave an increase in sensitivity over a flat crystal.

*OCIS codes:* 300.6560, 350.5400, 340.0340.

The use of lasers for creation of plasmas has been suggested as a means of achieving controlled thermonuclear fusion. Since then the ensuing concept of inertial confinement fusion (ICF), and other applications of laser-produced plasma, has been extensively studied[1,2] as well as properties of plasmas in general.

The crystal spectrograph, with both natural and artificial crystals, has become one of the most important routine tools for plasma diagnosis due to its simple structure, convenient operation, and low cost[3]. Compared with grating spectrographs, crystal spectrographs have higher collecting efficiency and better resolution.

Abundant spectra of highly charged ions from laser-produced plasmas have been obtained by using various crystal spectrographs. K, L, and M spectra of many elements have been used for determining electron temperature and electron density. The crystals used in these works include PET $2d = 0.874$ nm, MICA $2d = 1.984$ nm, KAP $2d = 2.663$ nm, and LIF $2d = 0.403$ nm.

The focusing of X-rays by concave (elliptical) bent crystals takes place either in the dispersion plane or perpendicular to it. X-ray spectrographs of concave type are suitable for high-resolution diagnosis if the crystal bending is sufficiently accurate. The mechanical design of concave curved crystal spectrograph is shown in Fig. 1.

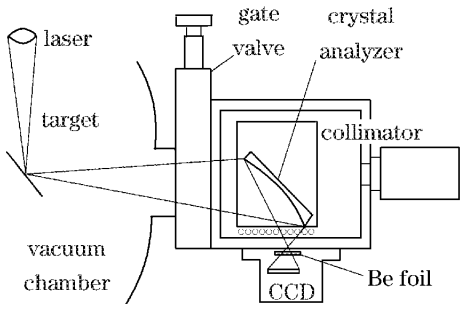


Fig. 1. Schematic diagram of the concave crystal spectrograph.

This arrangement provides complete isolation between the detector and the target chamber. The gate valve is held in the flange of the chamber port. The experimental chamber is allowed vented to atmosphere while maintaining high vacuum in the CCD detector.

The spectrograph has 1.35-m focal length and for these measurements, PET, LIF, KAP, and MICA crystals are bent onto an elliptical substrate with eccentricity $\varepsilon = 0.9586$. The analyzer is mounted onto ball bearing slide and its displacement is assured by a refaced screw with a 0.5-mm pitch. To block out visible and ultraviolet (UV) portions of the spectrum, we placed one Be foil (0.2 mm) at the entrance to the spectrograph. This foil was subject to occasional damage from target debris; therefore, we checked and replaced it at appropriate intervals.

Some advantages of the concave (elliptical) curved crystal spectrograph may be summarized as follows: the ray emitted from a focus (front) of elliptical will flock together on the other focus (back) by the reflection on the elliptical surface. Through the aperture set on the back focus, the X-ray will shoot on the detector of electronic position-sensitive[4] or photographic and go on record. It has self-focusing characteristics[5].

To determine X-ray yields, we needed accurate measurements of the X-ray spectrum produced by each source. The spectra varied not only with target material, but also with the laser parameters (wavelength, pulse energy, and focus). A curved (KAP, PET, LIF, and MICA) crystal spectrograph recorded X-ray spectra with 90° relative to the laser axis and 45° to the target normal direction. The Princeton Instrument Versa Ray 1300F (1340×1300 imaging array, 20×20 $\mu m^2$ pixels) was used as a high-resolution detection system. The detector was a front-illuminated charge-coupled device (CCD) chip. The system was sensitive enough that all spectra recorded in these experiments were produced by a single laser pulse. A photograph of the concave crystal spectrograph is shown in Fig. 2.

Concerning the spectral resolution $\Delta\lambda$ achievable in this kind of spectrograph, it is limited by three factors[6].

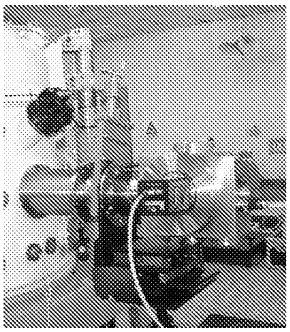

Fig. 2. The concave crystal spectrograph on Xingguang-II Facility.

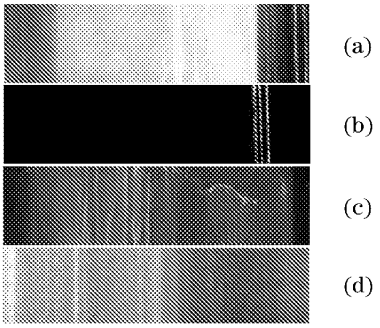


Fig. 3. The spectral photographs of KAP (a), LIF (b), MICA (c), and PET (d).

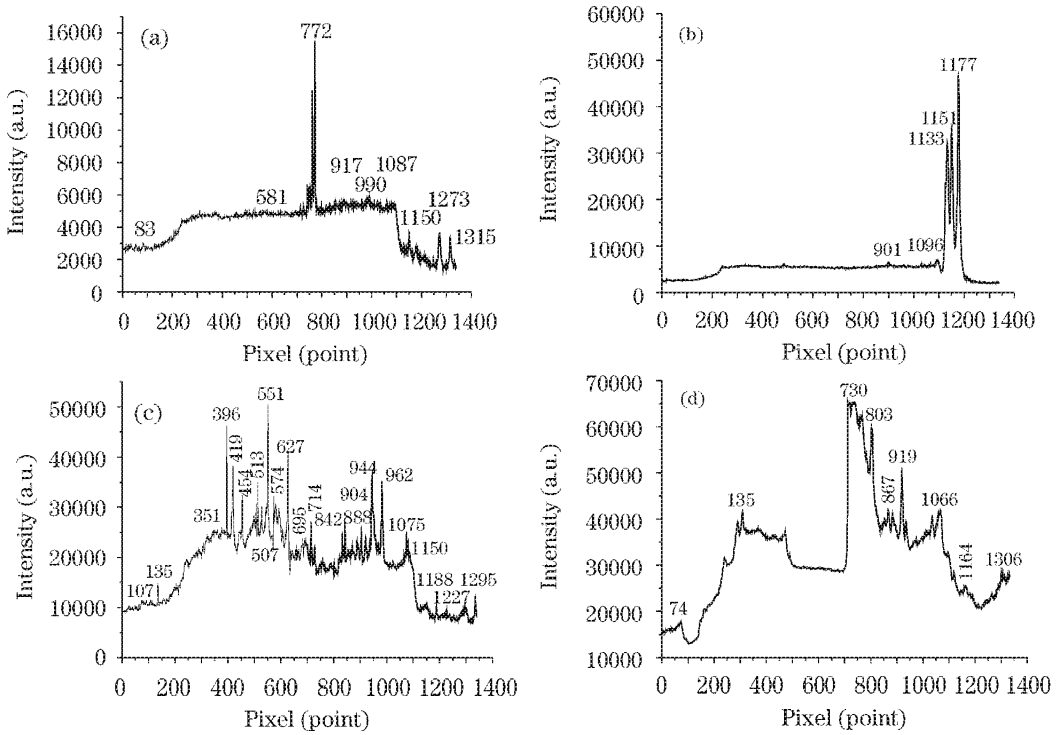


Fig. 4. Intensity versus pixel curves for KAP (Ti target, (a)), LIF (Ti, (b)), MICA (Au, (c)), and PET (Au, (d)).

The first one is the intrinsic resolution connected to the crystal rocking angle $\Delta\theta$,

$$\lambda/\Delta\lambda = \tan[\arcsin(\lambda/2d)]/\Delta\theta, \quad (1)$$

where usually $\Delta\theta \approx 10^{-4}$ rad as the order of magnitude. The second one is due to spectral dispersion $D$ and the finite pixel size $\Delta x$. The final one is source size $\phi$ (the laser focal spot diameter) which yields

$$\Delta\lambda = \phi/[D\cos(\theta + \theta_F)]. \quad (2)$$

We have used a PET crystal with a sufficiently small rocking angle and high reflectivity. Under these conditions it is easy to verify that the spectral resolution is $\lambda/\Delta\lambda$=1000. Compared with the case of a flat crystal, the photon flux is increased by about one order of magnitude. For other crystals, the results are similar. The obtained spectral photographs are shown in Fig. 3 and cross-section graphs of intensity versus pixel along $x$-axis are shown Fig. 4.

This work was supported by the National "863" Project of China. S. Xiao's e-mail is xiaoshali@cqu.edu.cn.

## References

1. D. A. Haynes, C. F. Hooper, R. C. Mancini, D. K. Bradley, J. Delettrez, R. Epstein, and P. A. Jaanimagi, Rev. Sci. Instrum. **66,** 755 (1995).
2. J. G. Lunney and J. F. Seely, Phys. Rev. Lett. **46,** 342 (1981).
3. A. A. Hauer, N. D. Delamater, and Z. M. Koenig, Laser Particle Beams **9,** 3 (1991).
4. K. Tohji and Y. Udagawa, Phys. Rev. B **36,** 9410 (1987).
5. X. C. Xiong, X. X. Zhong, S. L. Xiao, G. H. Yang, and J. Gao, Chin. Opt. Lett. **2,** 27 (2004).
6. M. Koenig, J. M. Boudenne, P. Legriel, A. Benuzzi, and T. Grandpierre, Rev. Sci. Instrum. **68,** 6 (1997).