Measurement of integral diffraction coefficients of crystals on beamline 4B7 of Beijing Synchrotron Radiation Facility*

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(Received 12 April 2010; revised manuscript received 15 June 2010)

Integral diffraction coefficients of the crystal are the essential data of a crystal spectrometer which is extensively used to measure quantitative x-ray spectra of high temperature plasmas in kilo-electron-volt region. An experimental method has been developed to measure the integral diffraction coefficients of crystals on beamline 4B7 of Beijing Synchrotron Radiation Facility. The integral diffraction coefficients of several crystals including polyethylene terephthalate (PET), thallium acid phthalate (TlAP) and rubidium acid phthalate (RAP) crystals have been measured in the x-ray energy range 2100–5600 eV and compared with the calculations of the 'Darwin Prins' and the 'Mosaic' models. It is shown that the integral diffraction coefficients of these crystals are between the calculations of the 'Darwin Prins' and the 'Mosaic' models, but more close to the 'Darwin Prins' model calculations.

Keywords: integral diffraction coefficient, crystal, x-ray spectrum measurement, high temperature plasmas

PACS: 07.85.–m, 61.05.Cp, 52.70.–m **DOI:** 10.1088/1674-1056/20/1/010705

1. Introduction

X-ray spectra from high temperature plasmas have been of great importance in the studies of inertial confinement fusion (ICF), astrophysics, x-ray laser and atomic physics, as they were extensively used to determine temperatures and densities of the plasmas and study the atomic energy levels and process parameters.[1−8] Usually x-ray spectra have been measured with grating spectrometers,[9,10] filter and grazing-incidence mirror coupled x-ray diode arrays (called soft-x-ray spectrometers)[11] and crystal spectrometers.[4−8,12,13] Especially, crystal spectrometers are the main diagnostic equipments for the keV x-ray spectra with a high spectral resolution. In order to obtain quantitative x-ray spectra in the keV x-ray region, the integral diffraction coefficients of the crystal are the essential data of a crystal spectrometer.

Theoretically, two models have been developed to describe the diffraction of crystals.[14] One is called the 'Darwin Prins' model, which is for perfect crystals, and the other is the 'Mosaic' model for non-perfect mosaic crystals. However, the calculation results of the two models are quite different. Since the late 1960s, some experiments have been carried out to calibrate the integral diffraction coefficients of crystals using different laboratory x-ray sources, such as x-ray tubes and x-ray fluorescence sources.[15−18] Vierling *et al.*[15] measured the integral diffraction coefficient R for the (200) planes in LiF crystal using a double crystal spectrometer over the wavelength range 0.07–0.21 nm. It was shown that R was different for the three types of LiF crystals (cleaved, abraded and flexed LiF crystals) and lay between the calculations of the 'Darwin Prins' model and the 'Mosaic' model. Burek *et al.*[16] studied the diffraction coefficients for potassium acid phthalate (KAP), ethylenediamine-d-tartrate (EDDT) and ammonium dihydrogen phosphate (ADP) crystals, indicating that available sam-

*Project supported by the Foundation of National Key Laboratory of High Temperature and Density Plasma Physics (Grant No. 9140C6804020704), the National Natural Science Foundation of China (Grant No. 10874156), and one of the authors, Gan Xin-Shi, was also partially supported by the School of Physical Science and Technology in Sichuan University, China.
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ples of KAP were reasonably uniform and the measured R for KAP crystals was reproduced with the Darwin–Prins formula. The integral coefficient R for KAP was known to be 20 percent without calibration if the KAP was transparent and unabraded. But calibrations on EDDT and ADP must be carried out over the entire wavelength range of interest. Gilfrich *et al.*[17] measured the integral diffraction coefficients using a single crystal spectrometer for a number of crystals commonly used. The measured integral diffraction coefficients for a variety of crystals were between the calculations of the 'Darwin Prins' model and the 'Mosaic' model and in good agreement with the calculations of a reasonably sophisticated theory of crystal diffraction only when the appropriate parameters necessary for the calculation are available. Kestenbaum[18] studied the x-ray diffraction from highly oriented pyrolytic graphite over the energy range 2.0–8.0 keV using a commercial Norelco vacuum x-ray spectrometer. The measured R exhibited an energy dependence which closely followed that predicted for an ideally imperfect graphite crystal. However, the measured R was a factor of 1.5 less than the calculated value. Therefore, the experimental calibration for each real crystal is quite necessary to obtain its actual integral diffraction coefficients. For the previous experiments two experimental methods have been used to measure the integral diffraction coefficients.[15−18] One is the double crystal spectrometer and the other is the single crystal spectrometer. For the double crystal spectrometer, the first crystal acting as monochromator should be as perfect as possible and also should be of the same material as the crystal to be examined. As unpolarised x-rays became polarised after being reflected by the monochromator a polarisation correction was made to the measured integral diffraction coefficient R according to the polarisation property of the monochromator, which could cause an uncertainty in R. For the single crystal spectrometer, no monochromator was used. X-ray source mainly came from monochromatic x-rays of the characteristic lines of the target materials. But it also includes a small fraction of continue background x-rays which also added some uncertainty into the measured R. However, in the previous experiments the x-ray tube or x-ray fluorescer was used as an x-ray source. These x-ray sources can provide monochromatic radiations only at a series of limited energy points that depend on the target materials. Recently a medium-energy x-ray experimental beamline (4B7) was developed on Beijing Synchrotron Radiation Facility (BSRF). As the synchrotron radiation is a continue x-rays over a large energy range beamline 4B7 provides the mono-chromatic x-rays in the whole energy range 2000–6000 eV using the Si crystal as monochromators. The mono-chromatic x-rays from beamline 4B7 are good x-ray sources for crystal diffraction coefficient measurement.[19] However, the mono-chromatic x-rays from beamline 4B7 are polarised.[20,21] In the present article, an experimental method is proposed to measure the integral diffraction coefficients of crystals on the beamline 4B7. The integral diffraction coefficients of several crystals including polyethylene terephthalate (PET), thallium acid phthalate (TlAP) and rubidium acid phthalate (RAP)

crystals are obtained and compared with the results from the 'Darwin Prins' and the 'Mosaic' model in the x-ray energy range 2100–5600 eV.

2. Experimental arrangement

The experimental arrangement is shown schematically in Fig. 1. Beamline 4B7 was extracted from the 4B7 bending magnet of the synchrotron radiation storage ring on BSRF, and reflected by a planar mirror in the front part of the beamline at first. The electron energy was 2.5 GeV and the electron current ranged from about 30 mA to 80 mA in the experiment. As synchrotron radiation is an electromagnetic radiation with consecutive wavelengths and emitted in the tangent direction of the electron trajectory. A double-crystal monochromator was used to obtain the monochromatic x-rays with photon energies ranging from 2000 eV to 5600 eV in the beamline. The divergence of the monochromatic x-ray beam was about 0.5 mrad in the horizontal direction and about 0.37 mrad in the vertical direction. The monochromatic x-ray beam passed through the centre of a calibrating chamber. The sample crystal was located on a stage in the centre of the calibrating chamber, and a Si detector (AXUV-100G) was arranged on another stage. Both the sample stage and the detector stage can be rotated around an axis. The rotation axis is perpendicular to the incident x-ray beam and passes through the centre of the chamber. The sensitive surface of the Si detector was 10 mm×10 mm. A 2 mm (horizontal)×1 mm (vertical) silt was positioned 400 mm in front of the sample crystal in the monochromatic x-ray beam to limit the x-ray spot size. Therefore, the Si detector received the whole beams of the

incident or the diffracted x-rays by the crystal. The incident x-ray intensity was measured by moving the crystal out of and placing the Si detector in the x-ray beam. While the diffracted x-ray intensity measurement was made by locating the sample crystal in the incident x-ray beam and positioning the Si detector in the reflected x-ray beam.

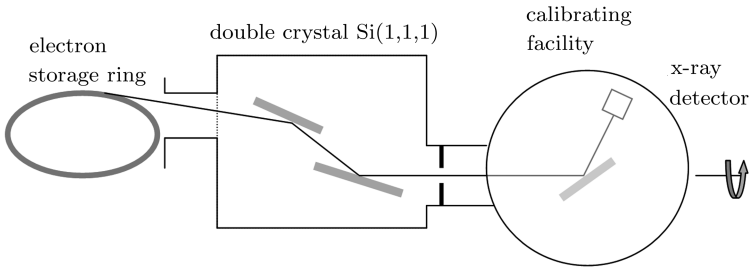


Fig. 1. Schematic of the experimental arrangement for the integral diffraction coefficient measurement of crystals on beamline 4B7 of BSRF.

As the monochromatic x-rays from the beamline 4B7 are polarised,[20] in order to determine the integral diffraction coefficients of sample crystals, measurements were made for two diagnostic orientations, which we called vertical and horizontal diagnostic orientations, respectively. First, for the vertical diagnostic orientation measurement, the dispersive plane of the sample crystal was in the vertical plane, and the measured integral diffraction coefficient of the crystal is denoted as $R_{\rm v}$. Then, the whole diagnostic chamber was rotated quickly by 90° around the incident x-ray beam for the horizontal diagnostic orientation measurement. The dispersive plane of the sample crystal was in the horizontal plane, which was also parallel to the electron orbital plane, and the measured integral diffraction coefficient is denoted as $R_{\rm h}$ for the horizontal diagnostic orientation measurement. The intensities diffracted by the sample crystal for the two diagnostic orientations are, respectively, expressed as

$$I^{\rm v}_{\rm obs} = I_{\rm h}R_{\rm s} + I_{\rm v}R_{\rm p}, \tag{1}$$

$$I^{\rm h}_{\rm obs} = I_{\rm h}R_{\rm p} + I_{\rm v}R_{\rm s}, \tag{2}$$

where $I_{\rm v}$ and $I_{\rm h}$ are the x-ray intensities with electric field vector normal and parallel to the electron orbit, respectively; $R_{\rm s}$ and $R_{\rm p}$ represent the integral diffraction coefficients for the crystal to S-polarised x-rays (electric field vector of the incident x-ray is perpendicular to the incident plane of the crystal) and P-polarised x-rays (electric field vector of the incident x-ray is in the incident plane of the crystal), respectively. Dividing both sides of Eqs. (1) and (2) by the incident x-ray intensity I_0, we obtain the following equations:

$$R_{\rm h} = R_{\rm p}\eta_{\rm h} + R_{\rm s}\eta_{\rm v}, \tag{3}$$

$$R_{\rm v} = R_{\rm s}\eta_{\rm h} + R_{\rm p}\eta_{\rm v}, \tag{4}$$

where $R_{\rm h} = I^{\rm h}_{\rm obs}/I_0$, $R_{\rm v} = I^{\rm v}_{\rm obs}/I_0$, $\eta_{\rm h} = I_{\rm h}/I_0$, and $\eta_{\rm v} = I_{\rm v}/I_0$.

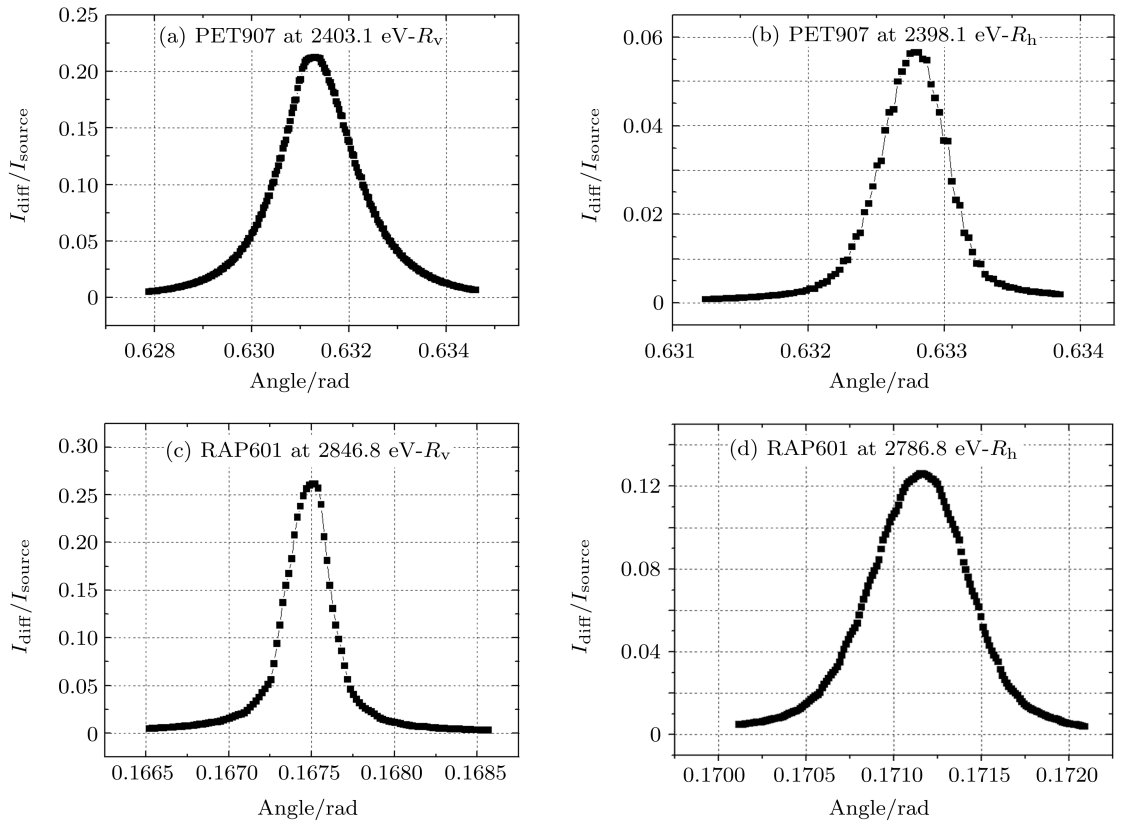
In order to obtain the integral diffraction coefficient $R_{\rm h}$ and $R_{\rm v}$, the rocking curves of the crystal were measured first. According to the definition of the rocking curve, the standard method to measure the crystal rocking curve is to measure the reflection curve of the crystal by scanning the incident angle at a fixed wavelength. Then the integral diffraction coefficient of the crystal can be obtained from the integrated rocking curve. But the width of the rocking curve is too small (about 10^{-4} rad). The angle adjustment precision of the apparatus which was mounted in the diagnostic chamber is limited, while the angle adjustment precision of the monochromator is very high. Therefore, in this experiment we measured the integral diffraction coefficient by scanning the wavelength at the fixed incident angle θ_0 as proposed in Ref. [19]. As the electron current in the electron storage ring decayed with time, the x-ray intensities decreased in the beamline during the measurements of x-ray source and the diffracted x-ray intensity. A Ni grid detector was located in the beamline during the whole measurements to monitor the x-ray source intensity. The signal outputs of the Ni grid detector were used to correct the x-ray source intensity and the diffracted x-ray intensity.

From Eqs. (3) and (4) and the equation $\eta_{\rm h} + \eta_{\rm v} = 1$, we obtain the integral diffraction coefficient of the sample crystal to the un-polarised x-rays

$$R_{\rm c} = \frac{R_{\rm p} + R_{\rm s}}{2} = \frac{R_{\rm v} + R_{\rm h}}{2}. \tag{5}$$

3. Experimental results and discussion

Five crystals (two PET crystals, two RAP crystals and one TlAP crystal) have been calibrated in this experiment. The typical measured rocking curves of $R_{\rm v}$ and $R_{\rm h}$ for the three types of crystals are shown in Fig. 2. It is shown that the peaks and widths of the rocking curves of $R_{\rm v}$ and $R_{\rm h}$ are quite different at the same x-ray energy point even for the same crystal. The width difference comes from the different divergence of the x-ray beam in the vertical and horizontal directions. But, besides the different divergence, the peak difference also results from the x-ray polarisation and different diffraction efficiencies of the crystal to S- and P-polarised x-rays.[14] The integral diffraction coefficients $R_{\rm h}$ and $R_{\rm v}$ have been obtained by integrating the rocking curves over the Bragg angle θ. The energies of the rocking curves of $R_{\rm v}$ and $R_{\rm h}$ are not exactly the same. Therefore, we fitted the measured $R_{\rm h}$, and obtained the $R_{\rm h}$ at the same photon energy points as those where $R_{\rm v}$ was measured. The results are presented in Tables 1–3. For the PET crystal (No. 501001030906), $R_{\rm v}$ is larger than $R_{\rm h}$ in the whole x-ray energy range 2100–5600 eV. The ratio of $R_{\rm h}$ to $R_{\rm v}$ increases from 0.1 to about 1.0 as the x-ray energy increases. As is well known, the integral diffraction coefficients of PET crystals to S-polarised x-rays are larger than those of P-polarised x-rays,[14] which means the x-ray intensity $I_{\rm h}$ is larger than $I_{\rm v}$ during the calibrating experiment of the PET crystal (No. 501001030906). For the other PET crystal (No. 501001030907), the two RAP crystals and the one TlAP crystal, their ratios of $R_{\rm h}$ to $R_{\rm v}$ increase to about 1.0 as the x-ray energy increases to about 4000 eV. Their ratios of $R_{\rm h}$ to $R_{\rm v}$ are even larger than 1.0 as the x-ray energy increases further from about 4000 eV. Therefore, the values of x-ray intensity $I_{\rm h}$ are larger than the values of $I_{\rm v}$ in an x-ray energy range from 2100 eV to about 4000 eV, but the ratios of $I_{\rm h}$ to $I_{\rm v}$ are smaller than 1.0 as x-ray energy increases further to 5600 eV during these experiments. Also shown in Tables 1–3 are the uncertainties of the integral diffraction coefficients $R_{\rm h}$ and $R_{\rm v}$. The uncertainties of the measured $R_{\rm h}$ and $R_{\rm v}$ mainly come from the uncertainties of the incident x-ray intensity and the diffraction x-ray intensity and the uncertainties of the Ni grid monitor signals.[21]



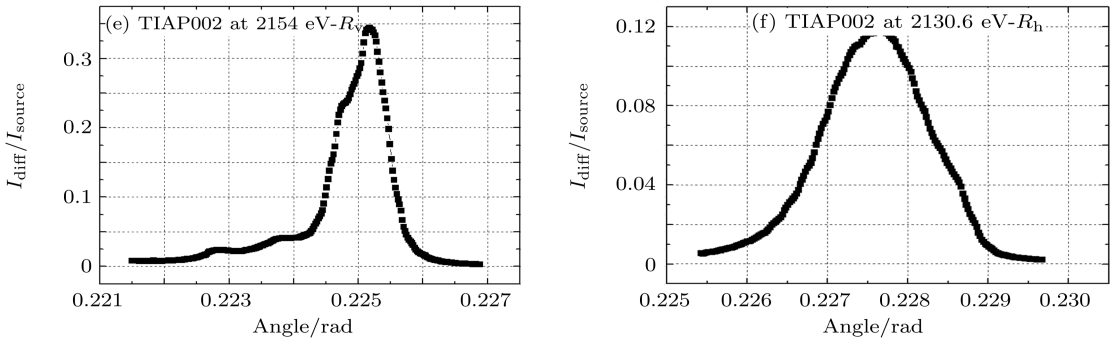


Fig. 2. Typical measured rocking curves of R_v and R_h for the three types of crystals.

Table 1. Experimental results of R_v and R_h for two PET crystals.

PET501001030906			PET501001030907		
E/eV	R_v /10^{-4} rad	R_h/10^{-5} rad	E/eV	R_v /10^{-4} rad	R_h/10^{-5}rad
2108.6	2.093±0.008	2.08±0.01	2104.9	4.436±0.018	2.29±0.07
2409.4	1.397±0.007	3.84±0.01	2403.1	4.574±0.018	3.92±0.12
2707.3	1.541±0.006	6.24±0.01	2699.8	3.881±0.016	6.87±0.21
3004.4	1.323±0.004	6.86±0.01	2994.8	3.73E±0.015	10.74±0.32
3301.6	1.213±0.004	7.37±0.02	3292.9	3.176±0.013	15.18±0.46
3608.7	1.110±0.004	7.78±0.02	4306.8	1.492±0.006	27.92±0.84
3915.5	1.028±0.002	8.19±0.01	5503.2	0.777±0.003	29.04±0.88
4316.5	0.952±0.002	8.47±0.01	–	–	–
4719.2	0.924±0.002	8.55±0.01	–	–	–
5118.4	0.911±0.003	8.51±0.02	–	–	–
5531.2	0.898±0.003	8.44±0.02	–	–	–

Table 2. Experimental results of R_v and R_h for two RAP crystals.

RAP403002990601			RAP403002990602		
E/eV	R_v /10^{-4} rad	R_h/10^{-5} rad	E/eV	R_v /10^{-4} rad	R_h/10^{-5} rad
2181.8	1.129±0.034	7.74±0.23	2149.0	1.042±0.032	6.68±0.20
2846.8	1.015±0.031	9.26±0.28	2458.6	1.102±0.035	7.72±0.23
3461.8	0.963±0.029	9.45±0.28	2791.0	1.009±0.030	8.84±0.27
3825.6	0.969±0.030	9.47±0.29	3113.4	0.997±0.030	9.18±0.28
4623.6	0.945±0.029	9.48±0.29	3414.2	0.970±0.029	9.24±0.28
–	–	–	3694.6	0.986±0.030	9.15±0.27
–	–	–	4050.4	0.892±0.027	9.70±0.29
–	–	–	4510.6	0.872±0.026	9.95±0.30
–	–	–	4946.8	0.858±0.027	10.27±0.31
–	–	–	5302.0	0.886±0.026	10.68±0.32
–	–	–	5727.5	0.848±0.025	10.14±0.31

Table 3. Experimental results of R_v and R_h for TlAP crystal.

TlAP501002041002		
E/eV	R_v /10^{-4} rad	R_h/10^{-4} rad
2154.0	3.67±0.11	1.901±0.060
2464.7	1.405±0.042	0.959±0.028
2791.0	1.729±0.052	1.332±0.040
3109.9	1.637±0.049	1.422±0.042
3339.4	1.601±0.048	1.507±0.045
3656.5	1.557±0.047	1.493±0.045
3954.2	1.553±0.047	1.534±0.046
4363.2	1.492±0.045	1.555±0.047
4835.1	1.464±0.044	1.547±0.047
5280.7	1.315±0.040	1.530±0.046
5709.8	1.355±0.041	1.479±0.045

The intensity monitor signals were used to correct the incident x-ray intensity and the diffraction x-ray intensity due to the decrease of the electron current with time in the electron storage ring during the measurement of the rocking curves. The integral diffraction coefficients of the three types of crystals to un-polarised x-rays in the x-ray region 2100–5600 eV were determined from the measured integral diffraction coefficients $R_{\rm h}$ and $R_{\rm v}$ through using Eq. (5) as shown in Fig. 3. The vertical errors in Fig. 3 come mainly from the measurement uncertainties of $R_{\rm v}$ and $R_{\rm h}$. Also presented are the calculations of the 'Darwin Prins' model and the 'Mosaic' model. The measured integral diffraction coefficients for the two PET crystals are quite different from each other. The integral diffraction coefficient for the PET crystal (No. 501001030907) is about 2.3×10^{-4} rad, which lies between calculations from the two model. But for the PET crystal (No. 501001030906), the integral diffraction coefficient is about 1.0×10^{-4} rad that is quite close to the calculation from the 'Darwin Prins' model. Therefore, for two crystals, even of the same type, their integral diffraction coefficients are quite different due to the difference in surface roughness or inner structure. For the two RAP crystals, the integral diffraction coefficients are almost the same, about 9.5×10^{-5} rad and also very close to the calculations from the 'Darwin Prins' model. For the TlAP crystal, except for the two energy points on lower energy side, the integral diffraction coefficients keep almost constant around 1.5×10^{-4} rad and are also in good agreement with the calculations from the 'Darwin Prins' model.

As the measured integral diffraction coefficients of the three types of crystals to un-polarised x-rays are very close to the calculations from the 'Darwin Prins' model except for the one PET crystal, these crystals are almost perfect crystals in surface and inner structure. Using the calculations of relative diffraction coefficient R from the 'Darwin Prins' model for perfect crystals and the measurements of integral diffraction coefficient $R_{\rm c}$, the integral diffraction coefficients of the several crystals to P-polarised and S-polarised x-rays were obtained. The results are shown in Fig. 4. For both the RAP and TlAP crystals, the differences in integral diffraction coefficients to P-polarised and S-polarised x-rays are very small in the energy range 2100–5600 eV. However, the integral diffraction coefficients of the PET crystal to S-polarised x-rays are much larger than those to P-polarised x-rays especially on the lower side of energy range 2100–5600 eV. This characteristic of PET crystal can be used to measure the polarised x-ray spectrum in the x-ray spectroscopy or may make the PET crystal used as a polariser to obtain the almost linearly polarised x-ray source from the un-polarised or weakly polarised x-rays in the energy range 2100–5600 eV.

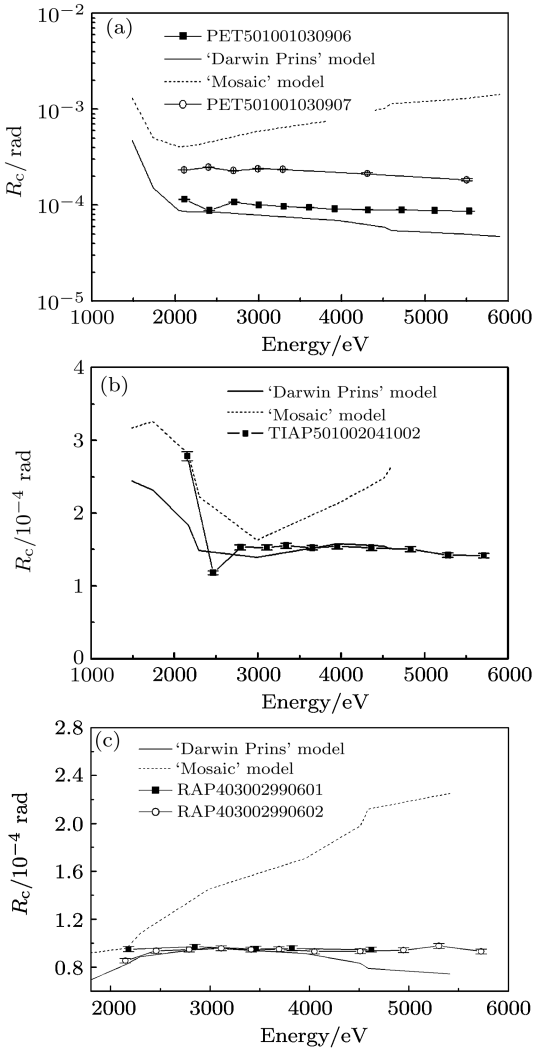
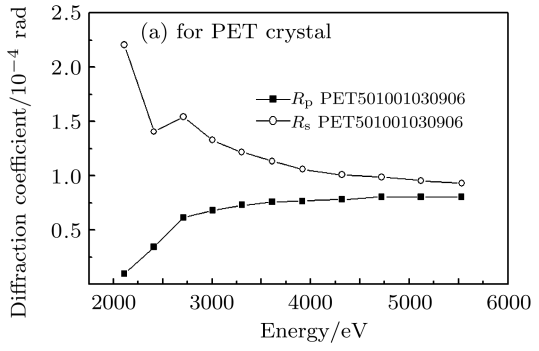


Fig. 3. Comparison between the measured integral diffraction coefficients of the three types of crystals to un-polarised x-ray in the energy range 2100–5600 eV and the calculations from the two models.



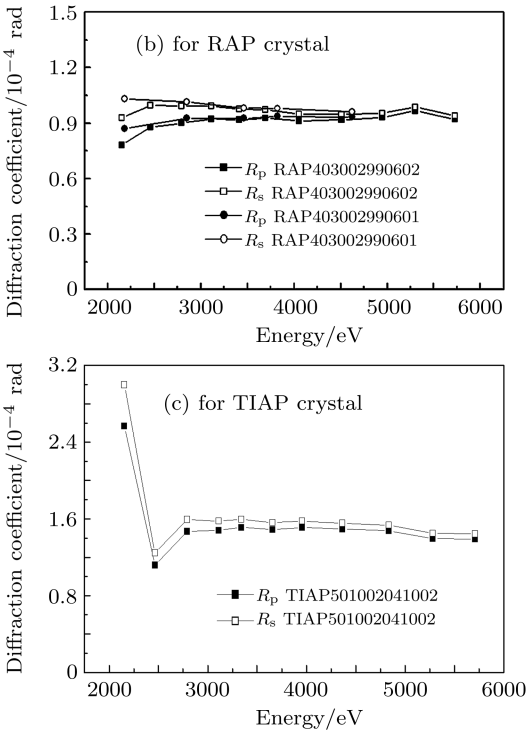


Fig. 4. Measured integral diffraction coefficients of the three types of crystals to P-polarised x-rays and S-polarised x-rays in the energy range 2100–5600 eV.

4. Conclusion

An experimental method has been proposed to measure the integral diffraction coefficients of crystals on beamline 4B7 of BSRF. The integral diffraction coefficients of several crystals to un-polarised x-rays, including two PET, one TlAP and two RAP crystals have been measured and obtained in the x-ray energy range 2100–5600 eV. Except for one of the PET crystals, for which the measured integral diffraction coefficients are between the two model calculations, the integral diffraction coefficients for other PET, TlAP and RAP crystals used in this experiment are quite close to the calculations from the 'Darwin Prins' model and far below the calculations from the 'Mosaic' model. For these crystals, using the calculated relative diffraction coefficients from the 'Darwin Prins' model and the measured integral diffraction coefficients, the integral diffraction coefficients of these crystals to P-polarised and S-polarised x-rays, have also been obtained. However, this experimental method can be used to calibrate other crystals. The experimental results of the integral diffraction coefficients of these calibrated crystals will be extensively used in quantitative diagnostics of x-ray spectra in the fields of inertial confinement fusion, astrophysics, x-ray laser and atomic physics in future.

Acknowledgement

We are grateful to the Beijing Synchrotron Radiation Laboratory for the experiment.

References

[1] Hauer A A, Delamater N D and Koenig Z M 1991 *Laser Part. Beams* **9** 3

[2] Aschke L and Depierreux S 2000 *J. Quant. Spectrosc. Radiat. Transfer* **65** 23

[3] Foord M E and Glenzer S H 2000 *J. Quant. Spectrosc. Radiat. Transfer* **65** 231

[4] Yang J M, Zhang J Y, Ding Y N, Peng Y L, Li J M, Zheng Z J, Yang G H, Zhang W H and Li J 2003 *Phys. Plasmas* **10** 4881

[5] Yang G H, Zhang J Y, Zhang B H, Zhou Y Q and Li J 2000 *Acta Phys. Sin.* **49** 2389 (in Chinese)

[6] Zhang J Y, Yang J M, Xu Y, Yang G H, Yan J, Meng G W, Ding Y N and Wang Y 2008 *Acta Phys. Sin.* **57** 985 (in Chinese)

[7] Yang J M, Hu Z M, Zhang J Y, Zhu T, Zhao Y, Wen T S, Wang Z B, Ding Y N, Wei M X, Yang G H and Zhang B H 2008 *Phys. Plasmas* **15** 112704

[8] Zhao Y, Yang J M, Zhang J Y, Liu J S, Yuan X and Jin F T 2009 *Rev. Sci. Instrum.* **80** 043505

[9] Yang J M, Ding Y N, Yi R Q, Wang Y M, Zhang W H and Zheng Z J 2001 *Acta Phys. Sin.* **50** 1723 (in Chinese)

[10] Yang J M, Ding Y N, Zheng Z J, Wang Y M, Zhang W H, Zhang J Y, Liu J Y, Shan B, Gao S C, Ren Y L and Liu X Q 2003 *Acta Phys. Sin.* **52** 1427 (in Chinese)

[11] Li S W, Yi R Q, Jiang X H, He X A, Cui Y L, Liu Y G, Ding Y K, Liu S Y, Lan K, Li Y S, Wu C S, Gu P J, Pei W B and He X T 2009 *Acta Phys. Sin.* **58** 3255 (in Chinese)

[12] Yang J M, Zhang J Y, Ding Y N, Yang G H, Jin F T, Yuan J M, Li J and Wang Y 2007 *High Power Laser and Particle Beams* **19** 1483 (in Chinese)

[13] Yang J M, Zhang J Y, Wu Z Q, Yang G H, Yan J, Ding Y N, Li J and Zheng Z J 2007 *High Power Laser and Particle Beams* **19** 1639 (in Chinese)

[14] Henke B L, Gullikson E M and Davis J C 1993 *At. Data Nucl. Data Tables* **54** 181

[15] Vierling J, Gilfrich J V and Birks L S 1969 *Appl. Spectrosc.* **23** 342

[16] Burek A J, Barrus D M and Blake R L 1974 *Astrophys. J.* **191** 533

[17] Gilfrich J V, Brown D B and Burkhalter P G 1975 *Appl. Spectrosc.* **29** 322
[18] Kestenbaum H L 1973 *Appl. Spectrosc.* **27** 454
[19] Gan X S, Yang J M, Yi R Q, Zhang J Y, Zhao Y D, Zhao Y, Cui M Q and Deng A H 2007 *High Power Laser and Particle Beams* **19** 1827 (in Chinese)
[20] Zhao J 2006 *The Studies of the Transmitting Characteristics of BSRF—Beamline 3B3 and Spectro-Crystals in Soft X-ray* (Ph. D. dissertation) Beijing: Institute of High Energy Physics, Chinese Academy of Sciences (in Chinese)
[21] Yang J M, Gan X S, Cui M Q, Zhao Y, Zhu T, Zhao Y D, Sun L J, Zheng L, Yan F, Hu Z M, Wei M X, Zhang J Y and Yi R Q 2010 *Nucl. Instrum. Methods Phys. Res.* A **615** 100