MEASUREMENT OF THE PARAMETRIC X-RAYS WITH THE ROCKING CURVE METHOD*

Y. Hayashi†, M. Kando, H. Kotaki, K. Kawase, T. Homma, S. V. Bulanov,
Japan Atomic Energy Agency, Kyoto, 619 - 0215, Japan

Abstract

Parametric X-ray generation is one of the ways to obtain monochromatic X-rays. The parametric X-rays are suitable for various applications. Usually a single photon counting method is utilized for measurement of the parametric X-rays. Although this method has an advantage to obtain a clear energy spectrum, it is time consuming. With a rocking curve method, we measured 10 keV parametric X-rays generated in the 150 MeV electrons accelerated by the microtron accelerator with the Si crystal. The rocking curve method has an advantage in quick finding the parametric X-rays. As a result, we found the parametric X-rays peak. The intensity of the parametric X-rays generated by laser plasma electrons is estimated.

INTRODUCTION

Monochromatic X-rays sources are useful tools for such applications as the X-ray imaging. In 1985, Vorobiev discovered a new generation method of monochromatic X-rays: parametric X-rays [1]. The parametric X-rays are generated in the interaction between high energy electrons with a crystal. The mechanism of the X-rays generation is qualitatively explained as the diffraction of virtual photons. The scheme of the X-rays generation is similar to that of the X-ray diffraction. The radiation direction and the monochromatic energy of the X-rays are described by the Bragg equation. The energy of the X-rays is tunable by changing the angle between the incident electron beam and the crystal plane. This is a convenient method generating the monochromatic X-rays with the energy is less than 50 keV.

This method attracted substantial attention. Many people has been studied the generation mechanism of the parametric X-rays and proposed the formula of the X-rays intensity [2]−[4]. Feranchuk-Ivashin model (FI model) [4] and Nitta's equation [3] provide the examples of the studies. The parametric X-rays have been used in some laboratories [5]. At Nihon University, there is a facility for application of the parametric X-rays. An imaging of tetra fish was demonstrated with the parametric X-rays [6].

Recently 1GeV electrons were produced in the laser plasma interaction [7]−[9]. A broad energy spectrum of the laser plasma electrons can contribute to generate quasi-monochromatic X-rays, because the energy of the parametric X-rays weakly depends on the electron energy. The single photon counting method is not matched to measure the parametric X-rays using the laser plasma electrons. For single photon counting we must keep following condition ($\bar{N} < 1$ (photons / X-rays pulse), where $\bar{N}$ is mean value of photon numbers measured at X-rays pulse). The measurements of the parametric X-rays generated with the single photon counting method is time consuming. We propose a simple method to measure the parametric X-rays generation known as rocking curve method. The rocking curve method is the way that measuring X-rays dependence on the crystal rotation with at a fixed X-ray detector and injected electrons beam. If the intensity of the parametric X-rays is enough high, at a Bragg angle we can obtain a clear peak, which is due to the parametric X-rays.

In this paper, we indicated the experimental result applied the rocking curve method for the parametric X-rays generated by Si (111) thin crystal irradiated by 150 MeV electrons from electron accelerator. We estimate the intensity of the parametric X-rays generation using the laser plasma electrons.

EXPERIMENT

A schematic of our experimental setup is illustrated in Fig. 1. An electron accelerator microtron at Japan Atomic Energy Agency, was used as a source of a high-energy electron beam. The beam was guided by a beam transport system and irradiated into the crystal. The energy and the charge of the beam were 150 MeV and 20 - 30 pC / pulse, respectively.

A thin Si single crystal was prepared for the generation of parametric X-rays in the range of 10 keV. The surface of the crystal was parallel to the (111) crystal plate and its size was 70 mm x 70 mm x 0.1 mm. The crystal was set on motorized stages, which were at air condition. For the detection of the parametric X-rays, we used Si-PIN X-ray detector (Amptek XR-100CR) with an amplifier. The detector has 5 mm^2 of detection area. A beryllium filter (thickness: 12.7 μm) was set in front of the detector. The generation condition of parametric X-rays is described by the Bragg condition:

$$E_n = 12.4n/(2d_{hkl} \sin\theta_B), \quad (1)$$

where E_n is the energy of X-rays in keV, n is the positive integer, θ_B is the Bragg angle, $h, k,$ and l are the indices of atomic layer, and d_{hkl} is the distance between the atomic layer (hkl) in crystal. The parameter d_{hkl} is given by

* We thank S. Kondo and S. Kanazawa for operating and maintaining the electron accelerator.

† hayashi.yukio@jaea.go.jp

$$d_{hkl} = a/\sqrt{h^2 + k^2 + l^2}, \quad (2)$$

where a is the lattice constant (a = 0.543 nm for Si).

For the Bragg condition, 10 keV X-rays are produced at the angle of 2 θ_B (= 22.8 deg.) from the injected beam. Therefore the detector was fixed at the angle of 22.8 deg. from the electrons beam and at 900 mm from the crystal surface. The detector has high detection efficiency to 10 keV X-rays (close to 100 %), and low efficiency to X-rays with the energy higher than 100 keV [10]. The detector with a copper collimator was surrounded by radiation shielding made of lead, brasses, and plastic blocks. The crystal angle to the electron beam was placed by using a He-Ne laser, which was co-aligned with the beamline. The signal of the detector and a trigger signal from the microtron were observed with a digital oscilloscope. The trigger signal prevented the detector from detecting such noise signal from natural radiation.

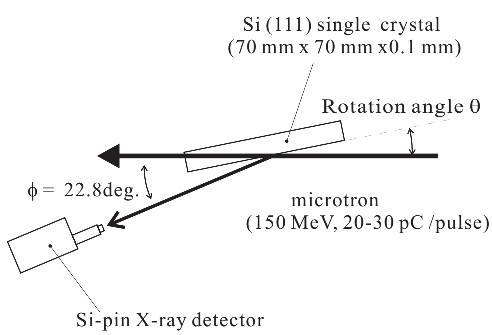

Figure 1: Experimental setup.

RESULTS AND DISCUSSION

Measurement with Rocking Curve Method

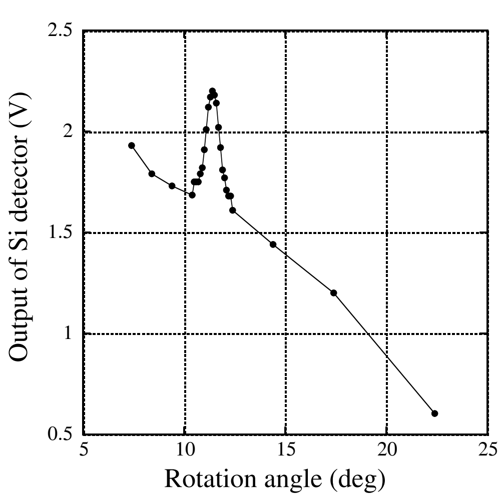

Figure 2: X-ray measurement with rocking curve method.

The parametric X-rays generated by the Si (111) crystal was measured with rocking curve method. Figure 2 illustrates the result of the curve. The rotation angle θ was changed from 7.4 deg. to 22.4 deg. At each angle, the measurement was repeated 100 times and the mean value was shown in the figure. The curve consists of a broad part and a sharp peak around the Bragg angle (θ_B = 11.4 degree). Since this angle is consistent to the condition for generating the 10 keV parametric X-rays, we consider that the peak is mainly due to the 10 keV parametric X-rays. Therefore we conclude that the rocking curve method is suitable for measurements.

The observed FWHM of the peak is approximately 0.82 deg. This value is larger than the ideal width, which is equal to $(1/\gamma)$ rad = 0.20 deg. Since the X-ray flux was too high under our experimental conditions, the detector indicates nonlinear output. This makes the FWHM value larger. The crystal plane was not flat, because the crystal folder held only the edge part of the crystal. This also makes the width of the peak broader. The broad part of the energy spectrum is caused by bremsstrahlung X-ray from the crystal, Mylar film (used as X-ray window for the experimental chamber), and air.

Dependence between the rotation angle and intensity indicates that main component of the bremsstrahlung X-ray is generated by the interaction of the electron beam with the crystal. Since increasing the angle corresponds to a decrement of the distance of the electron beam passing through the crystal, increasing the angle makes the intensity of the bremsstrahlung X-ray weaker.

According to the Feranchuk-Ivashin model, the generation condition of the parametric X-ray slightly differs from the Bragg condition, and the intensity of the parametric X-rays $dI_{hkl}/d\Omega$ is given by [4, 5]:

$$dI_{hkl}/d\Omega \propto |S_{hkl}|^2 \times g(\theta_x, \theta_y, \gamma, \omega_p/\omega), \quad (3)$$

$$S_{hkl} = \begin{cases} 4f[1 + \exp\{-\pi i(h+k+l)/2\}] \\ (\text{ all the indices } h, k, \text{and } l \text{ are odd (even)}), \\ 0 \text{ (else)} \end{cases} \quad (4)$$

$$g(\theta_x, \theta_y, \gamma, \omega_p/\omega) = \frac{[{\theta_x}^2 \cos^2(2\theta_B) + {\theta_y}^2]}{[{\theta_x}^2 + {\theta_y}^2 + (1/\gamma)^2 + (\omega_p/\omega)^2]^2}. \quad (5)$$

Here Ω is the solid angle, θ_x (θ_y) is the deviation from the Bragg direction in the plane (perpendicular to the plane), S_{hkl} is the crystal structure factor, f is the atomic scattering factor, γ is the Lorenz factor, ω_p is the plasma frequency of the crystal, and ω is the photon frequency.

Equations (3) - (5) indicate that not only 10 keV (the plane (111)) but 30 keV ((333)) and 40 keV ((444)) X-rays are also permitted to generate at the angle $\theta = \theta_B$ = 11.4 deg. The parametric X-ray generation from the plane (222) is forbidden ($S_{222} = 0$ in Eq. (4)). Since the Si detector has detection efficiency to 30 keV and 40 keV X-ray, the peak at the Bragg angle in Fig. 2 also included these harmonic X-rays.

Calculation of Parametric X-rays using the Laser Plasma Electrons

In this section, we discuss the calculation of the intensity of the parametric X-rays generated with laser plasma produced electrons. Typically, the energy spectrum of the laser plasma electrons is a superposition of monochromatic peak and relativistic Maxwellian distribution. Since the parametric X-rays generated by the monochromatic distribution can be easily calculated by Eqs. (3) - (5), we consider the parametric X-rays generation by the relativistic Maxwellian with electron temperature T_h (MeV).

By combining the Maxwellian with Eqs. (3) - (5), we find the parametric X-rays intensity $dI'_{hkl}/d\Omega$ is

$$\frac{dI'_{hkl}}{d\Omega} = \frac{4NK|S_{hkl}|^2}{3\sqrt{\pi}} {T_h}^2 H, \quad (6)$$

$$H \equiv \int_0^\infty \frac{\eta^{1.5}\exp(-\eta)({\theta_{xT}}^2\cos^2(2\theta_B) + {\theta_{yT}}^2)}{({\theta_{xT}}^2 + {\theta_{yT}}^2 + (.511/\eta)^2 + {W_T}^2)^2} d\eta, \quad (7)$$

$$\eta \equiv E/T_h,\ \theta_{xT} \equiv \theta_x \times T_h, \quad (8)$$

$$\theta_{yT} \equiv \theta_y \times T_h, W_T \equiv (\omega_p/\omega) \times T_h, \quad (9)$$

where N is the total number of the electrons, E is the electron energy in MeV, and K is the constant.

With Eqs. (6) - (9), the parametric X-ray intensity dependence on the temperature can be calculated. Figure 3 shows the result of the peak intensity of 10 keV parametric X-ray using Si (111) crystal. The plasma frequency of the Si crystal, $\hbar\omega_p$ is 31 eV. The peak intensity of the parametric X-ray increases with increasing the temperature T_h. The peak intensity of the parametric X-ray is proportional to the square of the temperature T_h for $T_h \leq 10$ MeV, and is saturated around $T_h \sim 100$ MeV. From this result, the laser plasma electrons with the temperature $T_h \sim 100$ MeV is enough high for 10 keV parametric X-ray production. Nowadays, 1 GeV range laser plasma electrons can be generated [7] - [9]. We consider it is possible to measure the parametric X-ray generated by the laser plasma electrons with the rocking curve method.

CONCLUSIONS

We measured the X-ray energy spectrum generated by the electrons and the Si (111) crystal with the rocking curve method. The sharp peak, which is due to the parametric X-ray, can be observed at the Bragg condition. We consider the rocking curve method is suitable for quick observing the parametric X-ray. The intensity of the parametric X-ray by using the laser plasma electrons was estimated. We found that the electron temperature $T_h \sim 100$ MeV is enough high for the efficient parametric X-ray generation. In the future, we plan to measure the parametric X-ray generated by laser plasma electrons and Si crystal with the rocking curve method.

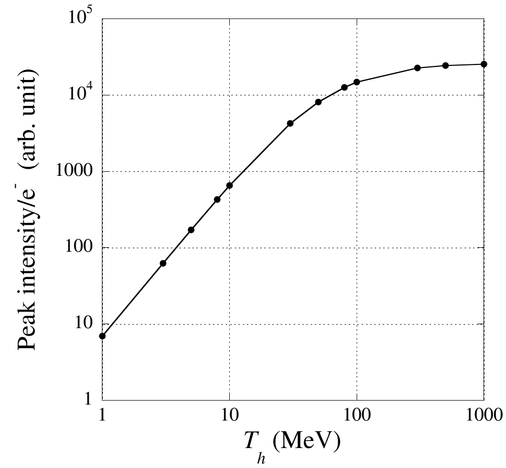

Figure 3: X-ray intensity dependence on electron temperature T_h.

REFERENCES

[1] S. A. Vorobiev *et al.*, JETP Letters 41 (1985) 1.

[2] V. G. Baryshevsky and I. D. Feranchuk, J.Phys. (Paris) 44 (1983) 913.

[3] H. Nitta, Phys. Lett. A 158 (1991) 270.

[4] I. D. Feranchuk and A. V. Ivashin, J.Phys. (Paris) 46 (1985) 1981.

[5] K. Chouffani *et al.*, Nucl. Instr. and. Meth. In Phys. Res. B 173 (2001) 241.

[6] Y. Hayakawa *et al.*, Nucl. Instr. and. Meth. In Phys. Res. B 266 (2008) 3758.

[7] J. Faure *et al.*, Nature 431 (2004) 541.

[8] C. G. R. Geddes *et al.*, Nature 431 (2004) 538.

[9] S. P. D. Mangles *et al.*, Nature 431 (2004) 535.

[10] http://www.amptek.com/xr100cr.html.