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Generation and use of parametric X-ray by LINAC

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Parametric X-rays (PXR) were generated in the 6~15keV region to examine the generation and use of PXR by LINAC. The target crystal was a Si single crystal, and the FWHMs of the PXR spectra were obtained at about 350eV by a Si-PIN photo diode detecter with 250eV FWHM at 5.9keV (^{55}Fe). The experiments found that it was possible to select a crystal rotaion angle, detection angle, crystal thickness, crystal material, and interference plane to enhance the PXR intensity. Moreover, in the experiment for use of PXR, the mass attenuation coefficient around the K-edge could be measured accurately in a narrow range with PXR. The results support that the PXR is a good monochromatic hard X-ray souce, where the energy can be countinuously changed.

KEY WORDS: parametric X ray, monochromatic X-ray, mass attenuation coefficient-edge

I. Introduction

When relativistic charged particles pass through a crystal, the crystal atom generates polarization radiation, and photons are emitted in the crystal. These photons are scattered and subject to interference by the orderly crystalline structure, and are emitted around the Bragg angle for X-ray diffraction[1),2)]. This phenomenon is called parametric X-ray radiation (PXR).

The PXR has several characteristics: it has good monochromatic X-rays; its energy can be continuously changed by rotating the crystal; the X-ray energy does not depend on the energy of the incident particles. Compared with other hard X-ray sources, the PXR can be generated by a small accelerator and simplified systems.

The use of PXR offers the following possibilities: one as a monochromatic hard X-ray source, and another as a determination of characteristics of a target crystal generating PXR by the information of spectrum, etc. Here the intensity of the PXR is an important factor. Therefore, this study was attempted to determine the X-ray attenuation in air at 8~15keV to improve the characteristics of the intensity and the energy of the generated PXR. Applications of PXR as a monochromatic X-ray source and for evaluating the properties of a target crystal were also examined by measuring the absorption coefficients of the materials with the K edge energy from a few to several tens of keV.

The factors that affect the PXR characteristic are the operating conditions of the accelerator (electron energy, electric current, pulse width, etc.), the target crystal (kind, thickness, material, crystal rotation angle, etc.), and the detector (detection angle, etc.).

II. Experimental Setup

The experiments were carried out with the 45MeV LINAC at Hokkaido University. The experimental set up is shown in **Fig. 1**.

The target crystal was a Si single crystal, and the (220) plane was mainly used for the PXR interference plane. The distance between target crystal and X-ray detector was 200cm and a Pb collimator with a 2mm×2mm×20cm hole was installed between the target and detector. The Si-PIN photodiode detector, which has a 13mm^2 sensitive region and 250eV of full width at half maximum (FWHM) at 5.9keV of ^{55}Fe, was adopted as the X-ray detector. The detector is installed in the Pb shielding box, which has a 2mm×2mm×10cm slit.

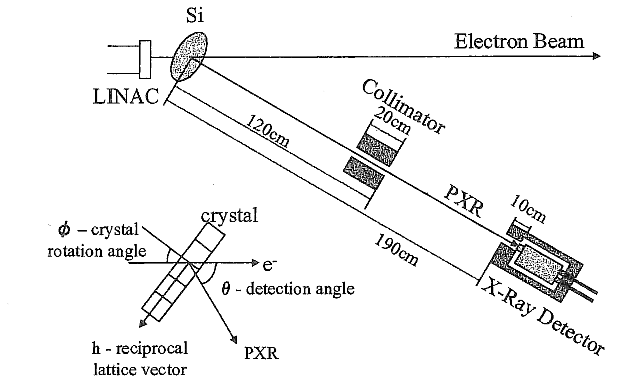

Fig. 1 The experimental setup.

III. Experimental Results

The PXR energy(E) and intensity(I) are expressed by the following equations[3)],

$$E = \hbar\omega = \hbar\frac{h\nu\sin\phi}{1-\beta\cos\theta} \quad (1),$$

$$\frac{dI}{d\Omega} = C\left(\frac{\omega\varepsilon_0}{c}\right)^2\left[\left(\frac{\omega\varepsilon_0}{c}\right)^2 - 2\left(\frac{\omega\varepsilon_0}{c}\right)h\sin\phi + h^2 - \left\{\left(\frac{\omega\varepsilon_0}{c}\right)\cos\theta + h\sin(\phi-\theta)\right\}^2\right] \Big/ \left[\left(\frac{\omega\varepsilon_0}{c}\right)^2\sin^2\theta + 2\left(\frac{\omega\varepsilon_0}{c}\right)h\sin\theta\right.$$

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$$\cos\phi + h^2\cos^2\phi + \left(\frac{\omega}{c\beta}\right)\left\{\gamma^{-2} + \beta^2(1-\varepsilon_0)\right\}\Bigg]^2 \quad (2).$$

where h is the reciprocal lattice vector of the target crystal, ω is frequency of photons, v is the velocity of electron, c is velocity of light, β is v/c, ε_0 is dielectric constant of crystal, ϕ is the crystal rotation angle, θ is the detection angle, and C is a constant. We know from these equations, the PXR energy and intensity are changed by the conditions of the accelerator, the crystal rotation angle, the detection angle, and the crystallographic plane that the PXR interferes with. However, because these parameters affect the PXR energy and intensity, the PXR energy and the intensity are correlated. The calculated results in **Fig 2** and **3** were obtained from Eq. (1) and (2).

Two types of experiments were carried out: one to examine improvements in the PXR intensity and energy characteristics, another to determine the use of PXR.

1. Dependence on the crystal rotation angle

The PXR energy and intensity depend on the crystal rotation angle. First, an experiment was carried out changing the rotation angle of the crystal. The experimental results are shown in **Fig. 2**.

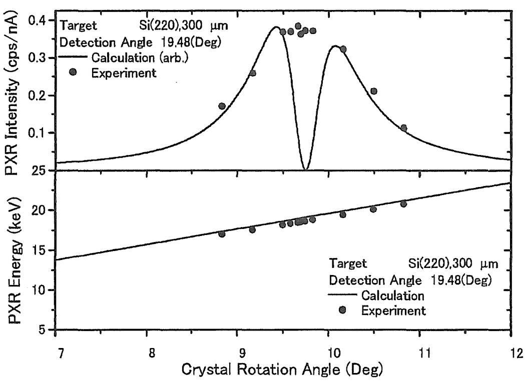

Fig. 2 Dependence on crystal rotation angle.

The PXR energy changed linearly with the crystal rotation angle; the PXR intensity has a maximum at the Bragg angle, and the experimental values agree well with the calculated results except that the experimental intensity result does not clearly resolve the double peaks. However, the intensity may have double peaks as indicated by the theoretical calculations. This may be due to the expansion of the crystal rotation angle and the detection angle caused by the spread of the electron beam. Assuming that the spread of the electron beam has Gaussian distribution, correction with method of moving average made the double peak a single peak and the single peak agreed with the exprimental results. This indicated that the spread of electron beam might cause the overlapping of the double peaks that exist in a narrow range. As other reasons the effects of the electron multiple scattering and crystal thickness are conceivable.

2. Dependence on detection angle

Here, we consider the case where the interference plane between the target crystal and PXR is fixed and the detection angle varies. Although the PXR energy and intensity can be changed by the crystal rotation angle, these changes, particularly the energy change, are very small. Thus, the dependence of the PXR on the detection angle was examined by changing the crystal rotation angle that satisfied the Bragg condition. **Figure 3** shows a typical result.

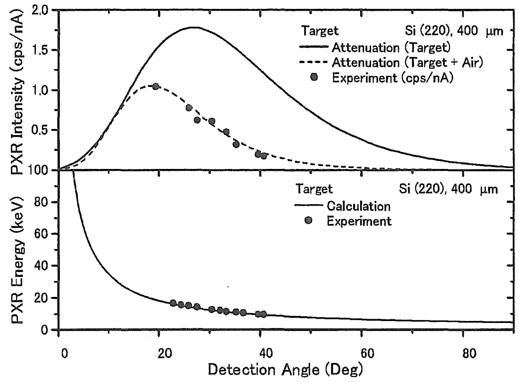

Fig. 3 Dependence on the detector angle.

As the detection angle increased, the intensity increased to a maxmum at a certain detection angle and then decreased, while the energy continuously decreased as shown in the experiments and calculations. The experiments were carried out in air, and it is necessary to consider both attenuation of the X-rays in the crystal and air. Without the attenuation, the intensity would have become several tens of times the intensity with the attenuation, and indicated a maximum at about 50°. With the 400 μm crystal and (220) reflection, the intensity indicated a maximum near 20°. If the crystal thickness and PXR interference plane are changed, the maximum would appear at a different angle (energy).

3. Dependence on crystal thickness

Since the target crystal is the PXR source, thicker crystals increase the intensity of the source. However, at the same time, thick crystals attenuate the X-ray intensity. Further, electron multiple scattering and attenuation in the crystal affect the properties of the PXR monochromatcity.

We examined crystals of various thicknesses: 200, 300, 400, 500 and 625 μm Si (220), and the experimental results are shown in **Fig. 4**. It is found that with the thicker crystals, the intensity increases at higher energies. Thicker crystals also resulted in the larger FWHM. Therefore, when monochromaticity is important, thin crystals are preferable. Here, the FWHM of the 400 μm crystal showed the largest value. This crystal thickness was mainly used in the experiments at Hokkaido University. Since the electron beam has been controlled to hit a point, the quality of the crystal would have been deteriorated due to the lattice defects which might have been induced during the experiments.

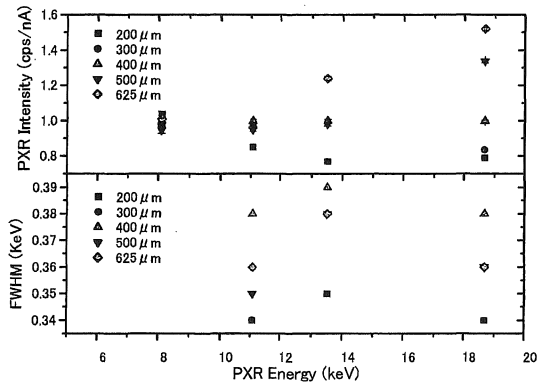

Fig. 4 Dependence on crystal thickness.

4. Dependence on separation of the crystallographic plane

When the PXR interference plane was changed, the PXR intensity and energy was also changed. A change in the PXR interference plane means that the distance between the two interference planes which the X-ray interfere with changes.

Fig. 5 shows the variation of the PXR energy and intensity with respect to a change of the distance between the two interference plane. The distance of interference plane of Si (220) and Si (400) are 1.92×10^{-10}m, 1.36×10^{-10}m respectively. If there is no attenuation, larger intervals of the PXR interference plane result in larger intensities and lower energies. However, when the PXR energy is lower, the effect of attenuation, especially in the target, becomes larger. Therefore, smaller intervals between interference planes result in larger intensities when the PXR energy is low.

The experiments and calculations indicate different results with respect to the intensity in **Fig. 5**. As this reasons for this it is conceivable that on the occasion of this experiment the alignment between collimator and slit was off, setting the crystal plane was not properly and photons which reached the detector decreased. Hereafter, it is necessary to carry out this experiment again carefully.

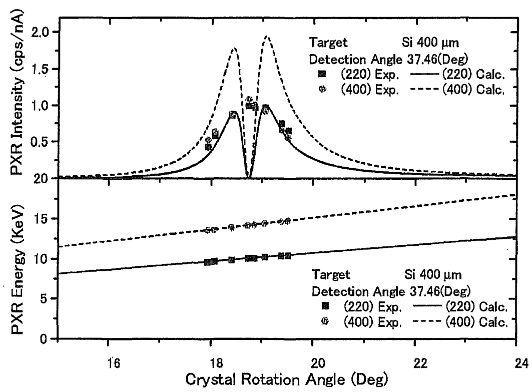

Fig. 5 Dependence on separation of crystallographic planes.

5. An example of the Use of PXR

Based on the above findings, measurements of the mass attenuation coefficient near the K-edge energy was carried out to illustrate the applicability of PXR[4]. Here, the PXR is used as a monochromatic X-ray source to evaluate the properties of the target crystal by measuring the mass attenuation coefficients of the materials considered.

The mass attenuation coefficients were measured for Ni (ρ=8.902g/cm^3, 10 μm), and are shown in **Fig. 6**. **Fig. 6** shows that mass attenuation coefficients are measured accurately in the exceedingly narrow range near the K-edge with PXR.

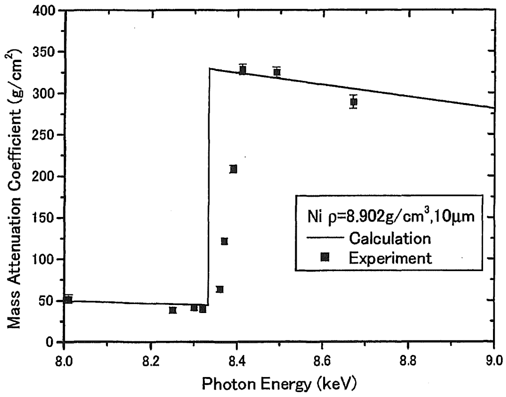

Fig. 6 Mass attenuation coefficient of Ni near the K-edge.

An enlarged spectrum is shown in **Fig. 7**. Comparing the spectra when passing through the material and the spectra without the material, it was not confirmed that the peak forms change. This indicates that the PXR monochromaticity is smaller at least in the measured energy interval (0.03keV). It is conceivable that the energy spread of PXR can be measured by narrowing the energy interval.

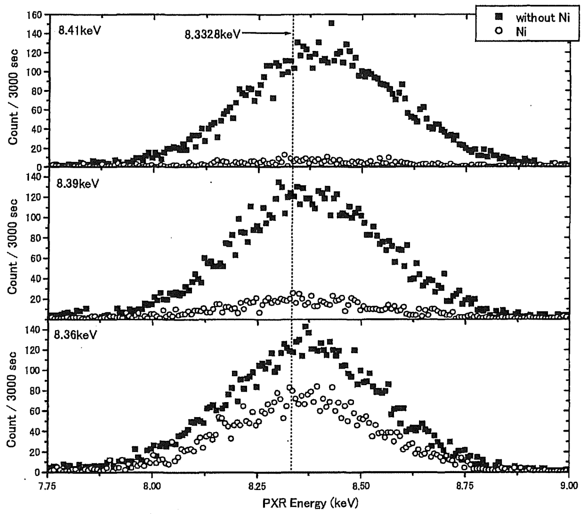

Fig. 7 Changes in the attenuation of PXR spectra after penetrating Ni.

IV. Conclusion

If PXR is applied as a hard X-ray source, the intensity of enhancement is important. To enhance the PXR intensity, it is enough to select a crystal rotation angle at about the Bragg angle, to fix the detection angle around 20° (for Si (200), 400 μ m), to set a thick target crystal, and to select the crystal material and plane fitting the large interference plane. The attenuation in crystal and air must be taken into account and it is necessary to establish the energy change.

It is essential to optimize these factors (intensity, energy, spread of energy, etc.) for specific applications with a PXR energy in the order of 10keV, there are only very small intensity differences with the crystal thicknesses of 200 to 625 μ m. Thus, from the PXR monochromaticity, a thin target crystal is preferable

As the mass attenuation coefficient near the K-edge could be measured accurately in a narrow range with PXR, the PXR is a good monochromatic hard X-ray source, which can continuously change the energy. However, theoretically there is no energy spread at the K-edge, while the experimental results show a spread of energy. This result may reflect the energy resolution of the system of measurement and the spread of the PXR energy.

Further, research will evaluate the spread of the PXR energy by measurement of the K-edge and also examine evaluate the crystal defect of the target crystal with the spread of the PXR energy.

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