Development of Monochromatic X-ray Source using the Linac for FEL at Nihon University

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Abstract

An electron linac for FEL was constructed at Nihon University and the development of an X-ray source using the linac is in the planning stage. Since the maximum of electron beam energy is 125 MeV, Parametric X-ray Radiation (PXR), which has attractive characteristics such as the monochromaticity and the directivity, is one of the promising candidates of the X-ray generator. In order to estimate PXR as the X-ray generator, several numerical calculations were carried out under the condition that the electron beam energy is 125 MeV. According to the results of the calculations, PXR using the linac designed for FEL is not suitable for a continuous X-ray source because of the electron beam duty. It has, however, a possibility of an excellent pulse X-ray source with the high peak intensity and the energy tunability.

1 Introduction

At Laboratory for Electron Beam Research and Application (LEBRA) of Nihon University an electron linac was constructed for an FEL system and has been developed [1]. First operation of the linac was performed in 1998 and 90 MeV electron beams were obtained. Studies of the undulator radiation have been made in order to achieve lasing at 488 nm [2]. The spontaneous radiation and the FEL from the visible to the ultraviolet region are expected to be applied material and life science. These fields of study, however, also require an X-ray source with excellent performance. Since the electron beam energy of the LEBRA linac is limited to 125 MeV, it is difficult to realize a monochromatic X-ray source with the energy tunability using the conventional methods such as an undulator. Therefore, the radiation with the interaction between the relativistic electrons and the material with the periodic potential, such as crystal medium, should be considered as the process to generate X-rays [3]. In particular, the new type of the radiations, which is called Parametric X-ray Radiation (PXR), is attractive because of its monochromaticity and directivity. The theoretical calculations and the quantitative estimate of the radiation in the case of using the linac of LEBRA is carried out and discussed in this paper.

2 Performance of the Linac for FEL of LEBRA

The parameters of the electron linac of LEBRA are shown in Table 1 [4]. Since it was designed for FEL, it is superior in respect of the beam current and the macro pulse width. Its beam emittance is also relatively excellent. The maximum energy of the linac is 125 MeV, which is enough for the undulator radiation in the visible region. However, it is too low to generate X-rays with the conventional undulator.

Table 1: Parameters of the electron linac for FEL at Nihon University.

Beam energy	125 MeV
Beam current	
average during a macro pulse	200 mA
maximum at a peak	20 A
Width of a macro pulse	20 μs
Width of a beam bunch	3.5$\sim$10 ps
Energy dispersion	$<$ 0.5 %
Normalized emittance	50π mm mrad
Repetition of macro pulses	12.5 Hz
Maximum beam power	6.25 kW
Frequency of acceleration	2856 MHz
Klystron power	30 MW $\times$ 2

3 Parametric X-ray Radiation

The phenomenon called Parametric X-ray Radiation, which is generated by the interaction betwwen a relativistic charged particle and crystal medium, has been studied theoritically. Recently, several experimental results of PXR have been reported [5].

The incident electron and the emitted PXR satisfy the conservation of energy and momentum. The energy of PXR is written as,

$$\hbar\omega = \frac{\hbar c\,|\boldsymbol{g}\cdot\boldsymbol{v}\,|}{c-\boldsymbol{v}\cdot\boldsymbol{\Omega}}, \tag{1}$$

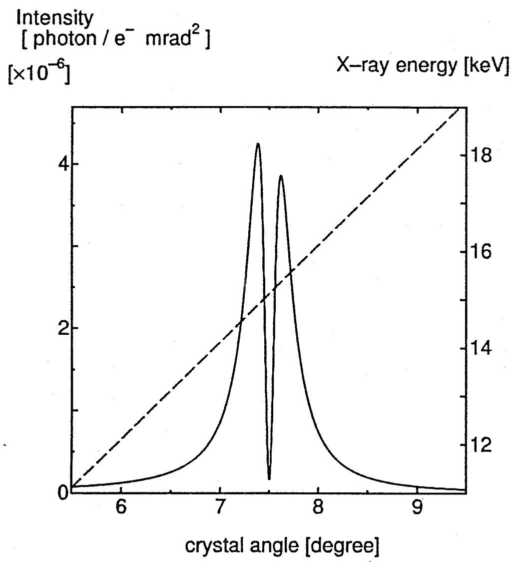

Figure 1: Calculation of PXR from (111) planes of a perfect Si crystal with 1 mm thickness. The solid line is the angular distribution of PXR and the dashed line is the PXR energy, where the electron energy is 125 MeV and the Bragg angle is 7.5°.

where $\boldsymbol{g}$ is the reciprocal lattice vector of a crystal, $\boldsymbol{v}$ is the electron velocity and $\boldsymbol{\Omega} = \boldsymbol{k}/|\boldsymbol{k}|$ ($\boldsymbol{k}$: the wave-vector of emitted PXR). Equation 1 means that the energy of PXR is tunable by controlling the crystal geometry.

The spatial distribution of PXR is obtained by the perturbation theory and expressed by,

$$\frac{\mathrm{d}N}{\mathrm{d}\Omega} = \sum_{g(\neq 0)} \frac{\alpha L \omega^3 |\chi_g(\omega)|^2}{2\pi c v (c - \boldsymbol{v}\cdot\boldsymbol{\Omega})} \left| \frac{[(\omega/c^2)\boldsymbol{v} + \boldsymbol{g}] \times \boldsymbol{\Omega}}{|\boldsymbol{k}_\perp - \boldsymbol{g}_\perp|^2 + (\omega/v)^2 \gamma^{-2}} \right|^2 , \tag{2}$$

where L and $\chi_g(\omega)$ are thickness and the Fourier component of the dielectric function of the crystal respectively, $\boldsymbol{k}_\perp$ and $\boldsymbol{g}_\perp$ are the components of $\boldsymbol{k}$ and $\boldsymbol{g}$ perpendicular to $\boldsymbol{v}$ respectively. The relativistic factor γ means $\gamma = E/m_0c^2$, where E and m_0 are energy and rest mass of the incident charged particle respectively.

The energy and the intensity of PXR from (111) planes of a Si crystal with 1 mm thickness, which is placed with Bragg angle 7.5° and irradiated by 125 MeV electron beams, are shown in Fig. 1. Those were calculated as the functions of the angle between the crystal plane and the electron beam axis, where the emission angle of X-rays is fixed as 15° (twice of Bragg angle) and the collecting aperture for X-rays is 1 mrad^2. Figure 1 means that the PXR energy is almost linear to the crystal angle and the angular distribution has a dip at just the Bragg angle and two peaks under the ideal condition.

According to eq. (2), the integral intensity of the radiation has little dependency on the energy of the incident relativistic electron. The peak intensity of PXR, however, is depend on the electron energy since the spatial distribution has a width corresponding to the factor

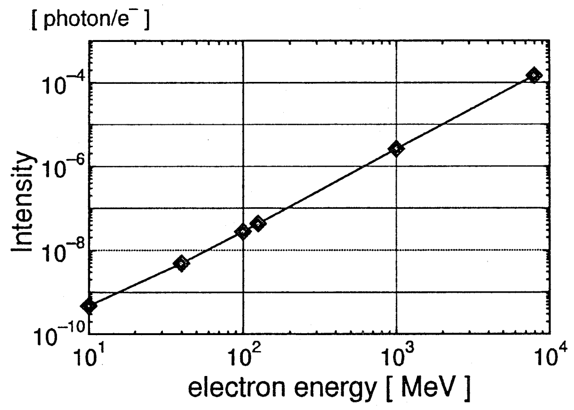

Figure 2: Dependency of the PXR peak intensity on the energy of incident electron. These were calculated under the condition that the crystal is 1 mm thick Si(111), the Bragg angle is 7.5° and the window aperture is 0.01 mrad^2.

γ. Figure 2 shows this dependency in the case of Si (111), where the Bragg angle is 7.5° and the collecting aperture is 0.01 mrad^2. Although higher energy electron beam has more advantage, a severe limitation, such as the critical wavelength of the synchrotron radiation, dose not exist in the case of relatively low energy electron beam. Therefore, PXR is attractive for a middle class electron accelerator as a generating process of X-rays.

One of the significant characteristics of PXR is that PXR energy can be tunable by controlling of the Bragg angle. Figure 3 shows the energy variation and the peak intensity of PXR which is generated by 1 mm thick Si(111) irradiated with 125 MeV electron beam. They are written as functions of the Bragg angle. As shown in Fig. 3, PXR is able to cover relatively wide range of X-ray energy and its intensity has little dependency on the Bragg angle. Those properties mean that PXR has the possibility of a monochromatic X-ray source with the energy tunability.

4 Estimate of PXR using the linac of LEBRA

In order to realize an X-ray source, quantitative estimates of the generated radiation is required. In particular, the properties of available X-rays such as the spectrum and the intensity are interesting. Table 2 shows the numerical estimate of PXR available with 125 MeV linac of LEBRA. Those calculations were carried out with respect to (111) planes of a Si crystal with a thickness of 1 mm. The crystal is placed so that the Bragg angle should be 7.5°. As shown in Table 2, the energy dispersion and the intensity of PXR are depend on the collecting aperture of the measurement system for X-rays. The intensity of PXR has to be traded off for the better energy resolution. The optical system for collecting X-rays and the secondary monochromator should be developed in order to improve the performance of the X-ray beam. Because of the asymmetry of PXR, the systems would be

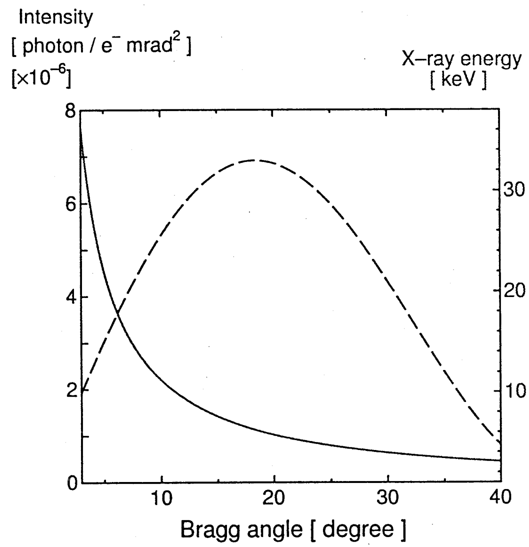

Figure 3: Energy (solid line) and peak intensity (dashed line) of PXR are expressed as functions of the Bragg angle, where the crystal is 1 mm thick Si(111) and the incident electron energy is 125 MeV.

more complex than those for the usual X-ray diffraction.

Although the average intensity of PXR is not excellent because of the low beam duty of the linac, the peak intensity is comparable to that of the bending magnet radiation using the GeV class synchrotron. Therefore, the X-ray source as an application of PXR is suitable for works that require pulse X-rays.

The divergence of the electron beam, which is used for generating PXR, has to increase after passing through the crystal. It is not problem, however, since the electron beam is used once and dumped in the case of the linac. Thus the linac is more suitable for this radiation phenomenon than the ring accelerator. In the future used electron beams could applied to generate positrons. The thermal load of the target crystal due to the electron beam is also not severe since the beam duty of the linac is relatively low. Moreover, the load of the spectroscopic and the transport systems for X-rays would be light because of the intrinsic monochromaticity and directivity of PXR.

5 Conclusion

The 125 MeV linac for FEL of LEBRA has the possibility of the monochromatic and energy-tunable X-ray source using PXR as the fundamental process to generate X-rays instead of the synchrotron radiation. Since the X-ray source using the linac would be pulse one, it should be applied taking account of this property. For the application of PXR to the X-ray source it is necessary to investigate the linearity of PXR intensity for the number of the incident electrons at high beam current. The study of the dependency upon the kind of the target crystal medium is also important since PXR is strongly depend on the atomic scattering factor. The detail characteristics of PXR should be studied experimentally and the optical system for X-rays should be also developed in order to realize the X-ray source.

Table 2: Characteristics of PXR available using the 125 MeV linac of LEBRA. These were calculated in the case of Si (111) with 1 mm thickness, where the Bragg angle is 7.5°.

Directivity of emission	4.3 mrad
Energy dispersion	0.75 % (1 mrad^2)
	0.075 % (0.01 mrad^2)
Intensity within 1 mrad^2	
peak at a micro bunch	5.7×10^{14} [photon/s]
avarage in a macro pulse	5.7×10^{12} [photon/s]
avarage (12.5 Hz)	1.4×10^{9} [photon/s]
Intensity within 0.01 mrad^2	
peak at a micro bunch	5.3×10^{12} [photon/s]
avarage in a macro pulse	5.3×10^{10} [photon/s]
avarage (12.5 Hz)	1.3×10^{7} [photon/s]
Thermal load of the crystal due to electron beam	~35 W

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