21PB-085

Quasi-monochromatic X-ray generation using laser-plasma electrons
レーザープラズマ電子を用いた準単色X線生成

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The interaction between an ultrashort pulse high-power laser and a high density gas jet can produce laser-plasma electrons the energies of which are higher than 10 MeV. We have a plan to generate quasi-monochromatic X-rays applying laser-plasma electrons. It is possible by use of high-energy electrons injection into a single crystal called as a parametric X-ray method. With the method, arbitrary X-ray energies are tunable by changing the incident angle of laser-plasma electrons and the position of X-ray detector. In the presentation, we discuss the feature of parametric X-ray generation and experimental scheme.

1. Introduction

An ultrashort pulse high-power laser is installed in various laboratories. When such laser is focused on a gas jet, laser-plasma ions and laser-plasma electrons are produced. Then the part of the laser-plasma electrons are accelerated to 10 - 1000 MeV by a laser wakefield [1].

It is interested to consider the application of high-energy laser-plasma electrons. We pay attention to the technique of quasi-monochromatic X-rays generation called as a parametric X-ray method [2]. In this method, quasi-monochromatic parametric X-rays are produced by the injection of high-energy electrons into a single crystal. Parametric X-rays generated with a linear electron accelerator are already applied to X-ray imaging [3]. We consider that laser-plasma electrons are also possible for parametric X-rays generation. According to the papers, laser-plasma electrons have short pulse duration of a few fs [4, 5]. For this reason, the combination of such electrons and parametric X-ray method makes it possible to generate quasi-monochromatic X-rays the pulse duration of which is shorter than 1 ps.

2. Estimation of parametric X-ray generation

The schematic view of parametric X-ray generation is shown in Fig. 1. An ultrashort pulse high-power laser focusing to a gas jet makes a laser-plasma and a laser wakefield. Since the part of the laser-plasma electrons feel the accelerated phase of the wakefield across long distance, the laser-plasma electrons the energies of which are higher than 10 MeV are radiated. The injection of these electrons into a crystal produces parametric X-rays.

According to the theory, the energy of parametric X-rays $E_{\hbar\omega}$ is given by [3, 6]

$$E_{\hbar\omega} = h \cdot c \cdot \sin\theta \ / \ [d_{hkl} \cdot (1 - \beta \cdot \cos\phi)], \quad (1)$$

where h is the Planck constant, c is the speed of light, d_{hkl} is the distance of a crystal plane, θ is the injection angle of incident electrons into the crystal plane, β is the electron velocity divided by the speed of light c, and ϕ is the angle between the incident electrons and the outgoing X-rays.

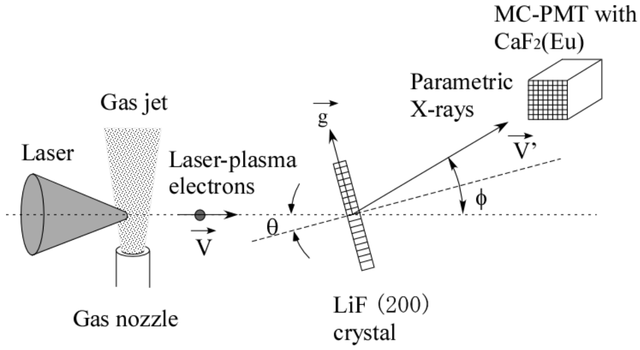

Fig.1. Schematic view of parametric X-ray generation with laser-plasma electrons.

Equation (1) indicates that if incident electrons possess the relativistic energies which correspond with $\beta \sim 1$, the arbitrary quasi-monochromatic energies of parametric X-rays are acquired easily by tuning of θ and ϕ. The equation resembles Bragg's law which is followed by X-ray diffraction. For the special case that $\beta \to 1$ and $\phi = 2\theta$, the equation is consistent with the law. Parametric X-rays and diffracted X-rays have the common extinction rule which determinates the existence of outgoing X-rays from a crystal. For instance, X-rays emission is prohibited for a LiF(110) crystal and permitted for a LiF(200) crystal in both cases .

The intensity of parametric X-rays generation is calculated with a formula [6]. It is assumed that the energy spectrum of high-energy laser-plasma electrons follows Maxwell distribution with electrons temperature T_e , and the parametric X-rays are produced by the interaction between the laser-plasma electrons and a 1 mm thin LiF(200) single crystal. The parameters are θ = 0.15 rad and the temperature T_e =30 or 100 MeV.

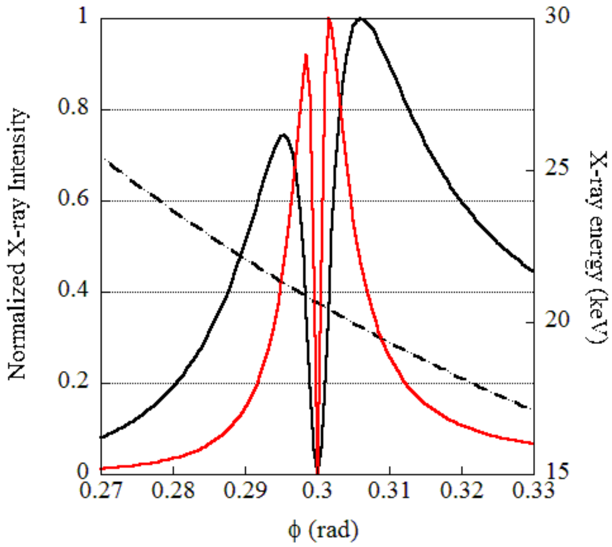

Fig.2. Calculation of parametric X-ray generation. X-ray generation is estimated with θ = 0.15 rad and a LiF(200) crystal. X-ray intensity at T_e=30 MeV (black line), X-ray intensity at T_e=100 MeV (red line), and X-ray energy (broken line).

The result of the parametric X-rays production is shown in Fig. 2. The X-ray energy becomes lower with increasing ϕ. At each electron temperature T_e, the X-rays intensity has two peaks at angles $\phi = \phi_{peak} \sim 2\theta = 0.3$ rad, and drops drastically at $\phi = 2\theta$. These are completely different from the feature of usual X-ray diffraction as the intensity of diffracted X-rays has single peak at $\phi = 2\theta$. Moreover, the peak angles ϕ_{peak} and the directivity of the parametric X-rays depend on electron temperature T_e. When the temperature increases, the angles ϕ_{peak} get closer to 2θ and the directivity becomes higher. In general, conversion efficiency from electron number to the photon number of parametric X-rays is almost constant to high-energy electrons. Therefore for the higher intensity of parametric X-rays generation, higher electrons temperature is required.

3. Discussion about experimental plan

An experimental setup is also shown in Fig. 1. Parametric X-rays are radiated from a crystal. However, undesirable bremsstrahlung X-rays generation also occurs by interaction between the crystal and laser-plasma electrons. A LiF(200) single crystal with 1 mm thickness is prepared. This crystal contributes the production of the bremsstrahlung X-rays lower because of its low effective atomic number.

Parametric X-rays can be observed with a multi-channel photo multiplier tube (MC-PMT) coupled with a 1mm thin CaF_2(Eu) scintillator. In the MC-PMT a lot of photo multiplier tubes are arranged in the state of 2-dimensional matrix. This enables to measure the directivity of the X-rays. The MC-PMT is also suitable to detect the energy spectrum of parametric X-rays. Since the energies of parametric X-rays are the function of angle ϕ, X-ray attenuation rate with an additional X-ray filter depends on the angle ϕ. Therefore X-ray energy spectrum is obtained with a comparison of the MC-PMT signals with and without the filter.

3. Summary

We propose the generation of arbitrary quasi-monochromatic X-rays with the combination of laser-plasma electrons and parametric X-ray method. The estimation of parametric X-rays production explains that the directivity of the X-rays becomes higher with increasing electron temperature T_e. The intensity of the X-rays has two peaks at $\phi_{peak} \sim 2\theta$. The features of prepared LiF crystal and MC-PMT for our experiment are also discussed.

By using laser-plasma electrons with the pulse duration of a few fs, it is possible to generate parametric X-rays the pulse duration of which is shorter than 1 ps. We expect that such X-rays are applied to ultrafast time-resolved X-ray diffraction in the future.

Acknowledgments

This work was supported by JSPS KAKENHI Grant Number 26390115.

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