Angular Distributions of EUV Generated by 5.7 MeV Electrons with Multilayer Mo/Si Structure

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Abstract. The article considers the dynamics of the changes in intensity and shape of angular distributions of backward transition radiation and quasi-monochromatic radiation of the periodic structure of a multilayer mirror in the vacuum ultraviolet region depending on the orientation of the target for electrons with energy of 5.7 MeV. It has been shown that the dynamics of the changes in intensity and shape of angular distributions of backward transition radiation and of periodic structure radiation observed after passing the radiation through an absorption edge filter displays opposite tendencies. These opposite tendencies may be used as an indicator in experiments aimed at detecting the effect of periodic structure radiation in the ultraviolet region of the analog of parametric X-ray in crystals.

Introduction

When relativistic electrons interact with a periodic structure of crystal or artificial structure known as a multilayer X-ray mirror, certain processes generating quasi-monochromatic radiation in directions determined by Bragg's law take place. Unlike crystals, the composition and period of the structure of the X-ray mirror can be made any at will, therefore artificial multilayer structures is more promising as radiators of X-ray and EUV radiation. The design and composition of such structures was studied and optimized well enough to control X-ray and EUV beams. But the use of such structures as radiators of quasi-monochromatic radiation is poorly studied.

In a number of theoretical works [1-4] it was shown that there are two mechanisms contributing to radiation. The first one is diffraction of photons of transition radiation formed on the input surface of the target (diffracted transition radiation, DTR). The second one is coherent polarization radiation of the periodic structure, whose mechanism is analogous to the one of parametric X-ray radiation (PXR) in crystals.

In our earlier works we investigated DTR and PXR in the X-ray photon energy range of 5-15 keV generated by electrons with energies of 500 MeV [2-4] and 15-33 MeV [5] in multilayer X-ray mirrors. It was shown in [2,3] that the main contribution to radiation is made by DTR.

We have recently done several experiments [6,7] in order to detect radiation connected with periodic structure of the target (periodic structure radiation, PSR) in the EUV region, which is analogous to DTR and PXR for the X-ray region.

The most promising result was obtained in Ref. [8], which contains a comparison of intensities of radiation generated by a polished layer of Mo (single layer target (SLT)) and by a periodic multilayer structure (PMS) consisting of 50 Mo/Si layers at oblique incidence of electrons (θ_o=45^o) with an energy of 5.7 MeV on targets surface. Radiation was detected at an angle θ_D =135^o, relative to the incident beam in the plane **vn** (**v** is the velocity vector of the electrons, **n** is the normal to the target surface). Significant excess of radiation yield from the PMS over radiation yield from the SLT observed in the experiment was linked to the observation of PSR contribution. However, experimentally observed increase in the intensity integrated over the spectrum in the case of PMS is not direct evidence of observing the PSR effect.

A trustworthy proof of PSR generation fact is observation of one of its fundamental properties, namely the dependence of the energy of generated photons E_γ on kinematic parameters of interaction process, such as the angle of electrons interaction with the surface of the target θ_0 and of radiation coming out of the target θ_D (1).

$$E_\gamma = \hbar \frac{2\pi\hbar}{d} \frac{\sin\theta_O}{\beta^{-1}-\sqrt{\varepsilon(\omega)}\,\cos\theta_D}, \qquad (1)$$

where $\beta=v/c$ is the relative velocity of electrons; d is the period of structure; $\varepsilon(\omega)=1-[a(1-\varepsilon(\omega)_A)+b(1-\varepsilon(\omega)_B)]/d$ is the permittivity averaged over the period of structure; $\varepsilon(\omega)_A$ and $\varepsilon(\omega)_B$ are the permittivities of substances A and B, θ_0 is the Bragg's angle, θ_D is the observation angle measured from the direction of electron beam motion. The present work considers a proposal for an experiment aimed at finding the effect of PSR based on the use of angular and spectral properties of radiation generated by PMS.

Methods and Approaches

The property of PSR described by equation (1) may be observed without direct measurement of the energy of photons by a spectrometric device. Quasi-monochromatic character of a PSR spectrum may be detected by investigating the overall intensity and changes in the shape of angular distributions measured for several typical orientations of the target θ_0. In this case radiation must pass through a filter whose absorption edge is close to the expected energy of the radiation under investigation. The experiment is planned to be carried out on an extracted electron beam having an energy of 5.7 MeV in an experimental setup based on the microtron M-5 at Tomsk Polytechnic University. The scheme of the experiment is shown in Fig.1. A detailed description of the experimental setup can be found in [8].

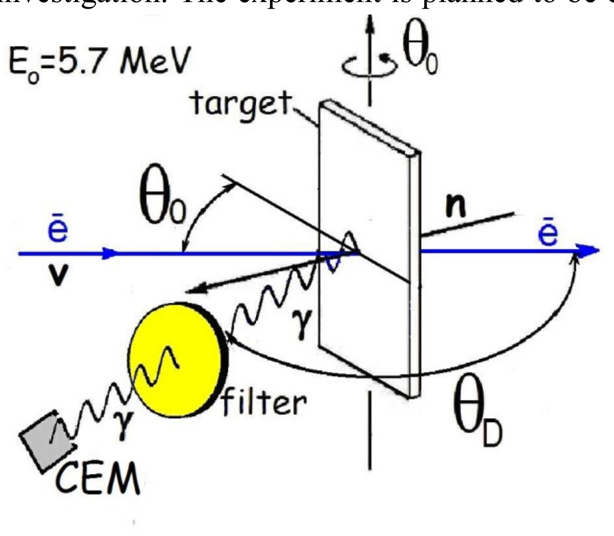

Fig.1 Scheme of the experiment.

A multilayer X-ray mirror with a period d=11.32 nm and an aluminum filter is planned to be used in the experiment. The period d and the energy of L-edge of absorption of the aluminum filter (E_L = 72.6 eV) determine the range of basic kinematic parameters θ_0 and θ_D, important for the investigation of spectral properties of the radiation. According to (1), angular distributions of radiation may be investigated in the range $50^o < \theta_D < 160^o$ for several values of the angle between the velocity vector and the target surface in the range $50^o < \theta_D < 160^o$.

A channel electron multiplier (CEM) (model "VEU-6" [9]) operating in the photon counting mode is going to be used for detection of radiation. According to the results of previous experiments [7,8] it is expected that the main experimental difficulty in identifying PSR is detecting the contribution of PSR against the background of backward transition radiation (BTR) formed on the input surface of the target and emitted in the same direction as PSR.

In order to analyze the contribution of BTR to measured values, let us consider BTR spectra for Mo (curve 1), Si (curve 2), SiO_2 (curve 3) calculated in the range between 5 eV and 100 eV shown in Fig.2 The spectra shown in Fig.2 were calculated at the maximum of horizontal profile of angular distribution generated at $\theta_0=67.5^o$. It is important to mention that the shape of spectral distribution

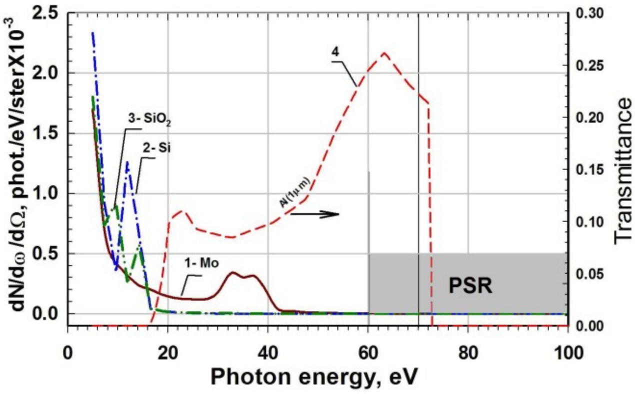

Fig.2. Spectral angular density of BTR at the maximum of the angular distribution at θ_0=67.5^o for three materials. Mo: curve 1, Si: curve 2, and SiO_2: curve 3. Curve 4 shows the photon transmittance through a 1 μm thick Al foil. The gray area indicates the expected PSR region.

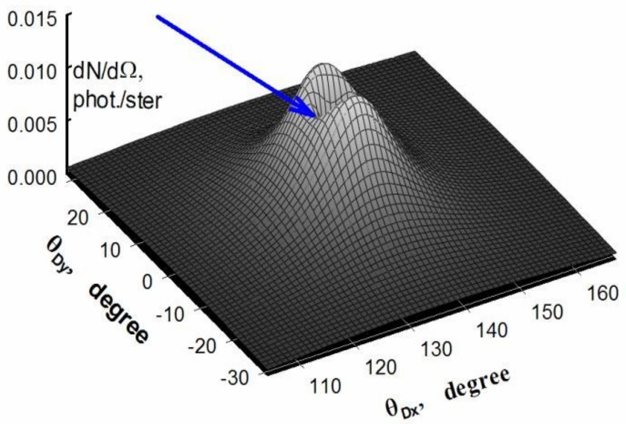

Fig.3. Angular density of the yield of BTR quanta in the energy range between 5 and 150 eV for Mo calculated by [10]. The arrow indicates the maximum of the horizontal angular profile $dN/d\Omega(\theta_{Dx}, \theta_{Dy}=0)$ chosen for calculating the spectra shown in Fig. 2.

of BTR is virtually independent of the direction of radiation inside the angular distribution cone. Curve 4 in Fig. 2 shows the transmittance of an aluminum filter having a thickness of 1μm. The database of optical constants "EPDL-97" [11] was used in the calculations. As can be seen from Fig.2, the main yield of BTR (curves 1,2,3) lies in the energy region E_γ <40 eV, while the energy of PSR photons generated by the periodic structure is in the range between 60 and 100 eV (the dark area in fig.2).

In order to choose optimal geometry of the electron beam interaction with the target let us consider the dynamics of changes in the intensity of angular distribution of BTR generated for several values θ_0 - 42.5^o, 47.5^o, 52.5^o and 57.5^o. Figs. 4 and 5 show the shapes of angular distribution of BTR for radiation in the energy range E_γ between 30 eV and 150 eV calculated on

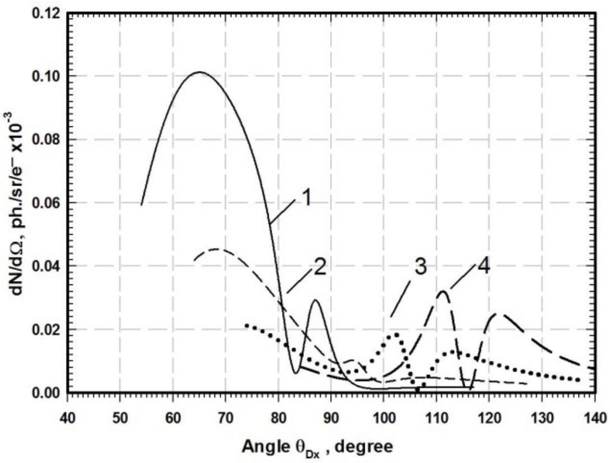

Fig.4 Angular distributions of EUV of BTR, which is emitted in the plane **vn**, calculated for SiO_2 and 5.7 MeV electrons. Curves 1, 2, 3 and 4 are calculated for θ_o = 42.5^o, 47.5^o, 52.5^o and 57.5^o, respectively.

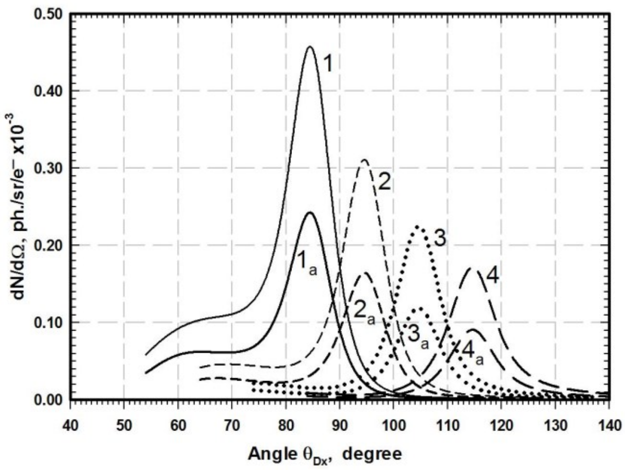

Fig.5 Angular distributions of EUV of BTR, which is emitted θ_{Dy}=1/γ to the plane **vn**, calculated for SiO_2 and 5.7 MeV electrons. Curves 1, 2, 3 and 4 are calculated for θ_o = 42.5^o, 47.5^o, 52.5^o and 57.5^o, respectively. Curves 1a, 2a, 3a and 4a show angular distributions of BTR taking absorption in the Al filter into account and are multiplied by factor of 5.

basis of approach [10]. Fig. 4 shows the case of radiation in the plane **vn**. Fig.5 shows the case of radiation at an angle $1/\gamma$ (γ =11.15 is Lorentz factor of electrons with an energy of 5.7 MeV) to the plane **vn**. BTR was calculated for a surface consisting of silicon oxide SiO_2, which is the top layer of SLT and PMS. It can be seen from figures 4 and 5 that complex evolution of angular distribution shape with the change of θ_o is observed for the radiation in the plane **vn.** Angular distribution of the radiation emitted at an angle $1/\gamma$ to the plane **vn** have a simpler shape and a clear tendency to change, which lies in increasing of intensity with an decrease in θ_o. The difference in the dynamics of the changes in angular distributions shown in Figs. 4 and 5 is due to polarization properties of the radiation. Therefore, in order to simplify the interpretation of experimental results, it is better to investigate the angular distribution of the radiation generated at an angle $1/\gamma$ to the plane **vn**. Curves 1_a, 2_a, 3_a and 4_a in Fig. 5 show angular distributions of BTR after passing through an Al filter having a thickness of 1 μm. It follows from Fig.5 that the general tendency of changing angular distributions after passing through a filter, i.e. the increasing of intensity with an decrease in θ_o, is still present.

Let us now consider the example of DTR in terms of changes in angular distributions calculated on basis of Ref. [3]. Fig. 6 shows angular distributions of DTR emitted at an angle $\theta_{Dy}=1/\gamma$ to the plane **vn**. The distributions are calculated for a multilayer X-ray mirror consisting of 50 pairs of Mo/Si layers with a period d=11,32 nm. Each pair consists of a silicon layer with a thickness a=7.92nm and a Mo layer with a thickness b=3.4 nm. Model calculations of both DTR and BTR are performed with the use of optical constants database "Henke" [11]. Curves 1, 2, 3 and 4 are calculated for θ_o equal to 42.5°, 47.5°, 52.5° and 57.5°, respectively. According to expression (1), peak position in a radiation spectrum inside a DTR cone depends on θ_D and θ_o. In Fig. 6 curves 1_a and 4_a represent the dependences of the energy of DTR photons on the angle θ_D close to θ_D =2θ at the peak of the spectrum. The dash-dot line shows the energy of L-edge of radiation absorption for aluminum (E_L=72.6 eV). After DTR passes through an Al filter, radiation yield will be suppressed for quanta having an energy $E_\gamma > E_L$. Therefore, it should be expected that with a decrease in θ_o a general decrease in radiation yield will be observed for DTR. The calculated angular distributions of

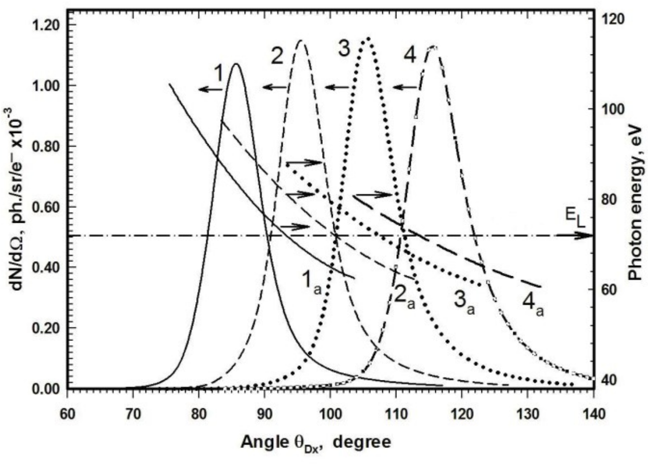

Fig.6 Angular distributions of DTR emitted at an angle $1/\gamma$ to the plane **vn**, which are calculated for PMS and electrons with an energy of 5.7 MeV. Curves 1a, 2a, 3a and 4a show the dependence of the energy of photons at the peak of DTR spectrum on θ_D. Curves 1-4 and curves 1a- 4a are calculated for θ_o equal to 42.5°, 47.5°, 52.5° and 57.5°, respectively. The dash dot line shows the energy of aluminum L-edge of absorption.

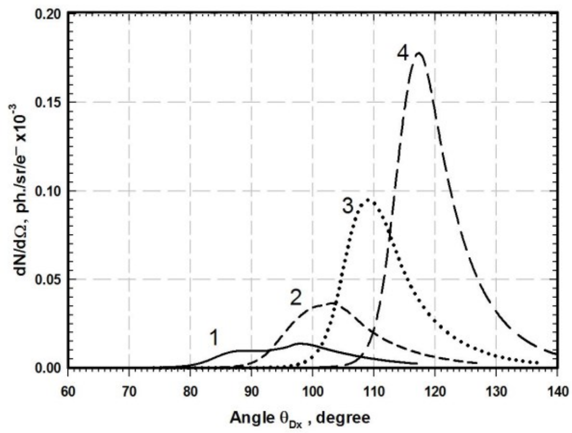

Fig.7 Curves 1, 2, 3 and 4 show the same information as figure 6 but with taken into account the absorption of DTR by 1 μm aluminum filter.

DTR after passing through an Al filter with a thickness of 1μm are presented in Fig.7 by curves 1-4 for angles θ_o = 42.5°, 47.5°, 52.5° and 57.5° respectively.

Summary

The comparison of tendencies in intensity changes of angular distribution for BTR and DTR shown in Fig.5 and Fig.7 proves that they are quite opposite to each other. This fact may be used in an experiment for identifying a particular type of radiation. Unlike the technique described in [8], where the proof of PSR detection is based on comparing the intensities of radiation generated by a single-layer and a multilayer targets, the method considered above is more trustworthy. It excludes the dependence of radiation intensity on such factors as, for example, target surface roughness.

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