Setup for study of radiation in VUV region generated by 5.7 MeV electrons in a multilayer mirror

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Abstract. The experimental setup created for investigating the radiation in the vacuum ultraviolet (VUV) region generated by 5.7 MeV electrons in a multilayer X-ray mirror at different angles of the electron beam incidence on the X-ray mirror surface is described. The method proposed for parametric X-rays separation from the generated radiation is analyzed. The method is based on the K-edge effect of photon absorption in fluorine at transmission of generated radiation through a thin Teflon filter. The results of the first test measurements are discussed.

1. Introduction
It is known that in the spectrum of radiation generated by an electron beam in a periodic radiator, in contrast to a uniform flat one, the appearance of additional quasi-monochromatic components should be expected due to the radiation diffraction on a multilayer structure of the radiator. A number of studies [1–4] have experimentally shown that the artificial periodic structures (APS) and the crystals are suitable for generation of quasi-monochromatic X-ray radiation at passing charged particles through them. The mechanisms of radiation providing the main contributions to the generated radiation are transition x-ray radiation (TR) and bremsstrahlung (Br) with subsequent diffraction of their photons in the periodic structure of the radiator, as well as the mechanism of generation known as parametric x-ray radiation (PXR). PXR is coherent radiation for a given direction and the wavelength emitted by periodic structure excited by a relativistic charged particle. In the experiments, these types of radiation manifest itself as a number of coherent spectral peaks with the position, width and intensity depending on the mechanism of radiation. Further, for convenience, these types of radiation will be referred to be a general term – the coherent radiation from a periodic structure (CRPS).

In contrast to the crystals, the technology of artificial periodic structures, such as multilayer X-ray mirrors, allow to create a structure with the specified parameters, such as the atomic composition of the layers and the law of its distribution. One from the attractive features of such structures for the generation of radiation is that at least they have a greater efficiency of the generation of radiation in comparison with crystals [3], and therefore have a less destructive effect on the electron beam in the case of a thin radiator, that is important for possible further use of this electron beam for any additional applications or for the repeated penetration of the internal radiator for the radiation generation in circular accelerators.

X-ray emission from APS was previously observed in the photon energy range of 4–20 keV in the experiments at 500 MeV electron beam of the Tomsk synchrotron [1, 3] and at betatron internal beam
of 15–35 MeV electrons [4]. Since APS period is greater than that of the crystals, they can be used for radiation generation in soft X-rays and vacuum ultraviolet (VUV) ranges [5]. Currently, there is a gap in experimental studies of parametric radiation in the VUV range. However, this might serve as promising base of tunable VUV source for some applications.

In this paper the experimental setup created for investigating the radiation in the VUV region generated by microtron electrons in periodic structures is described. The results of the first test experiment carried out on the created setup are presented. In addition, the detailed discussion is provided for the method for extracting the parametric component of the total VUV radiation generated by electrons interacting with the APS. The first attempt of experimental observation of the parametric component in VUV radiation generated by electrons with energy of 5.7 MeV in APS is also described. The orientation dependences of the angular distributions of radiation generated both on the surfaces of a homogeneous thin plate and multilayer X-ray mirror were measured and compared.

2. Experimental setup
The experimental setup was established on the basis of the Tomsk microtron M-5. The scheme of the experimental chamber with a detection unit is shown in figure 1. The frequency of the accelerator is 25 Hz, the duration of the extracted electron beam is 0.4 μs. Electron beam diameter is defined by a collimator with the diameter of 3 mm and length of 60 mm located at the distance of 600 mm from the mirror. Monitoring the current of electrons accelerated up to 5.7 MeV is carried out by an induction sensor (IS) placed between the collimator and the radiator. VUV yield is measured by a channel electron multiplier (CEM) VEU-6. The detector is located in the median plane of the accelerator at the distance of 64 cm from the radiator and at an angle of 60° to the direction of the electron beam. Permanent magnets and diaphragms are set along the direction of VUV registration for cleaning the flow of the generated photons from electrons scattered by the target. CEM works in the counting

![Figure 1. Scheme of experimental chamber with a detection unit.](image-url)
mode. The measuring VUV system maintains linearity of photon registration at the loading of about 2 pulses during the electron dumping on the radiator. The registration system loading is checked during the experiment for every 100 repetitions of the accelerator. Figure 2 shows a typical [6] dependence of the efficiency of photon detection on the photon energy. Spectral range of detected radiation is additionally regulated with absorption filters installed before the CEM’s window. The absorbing filters are replaced by means of the turret mounted in front of the detector.

The multilayer structure of the X-ray mirror radiator consisted of 400 pairs of W and B₄C layers with period \( d = 1.8 \) nm is placed on Si substrate with a thickness of 35 μm. The horizontal and vertical dimensions of the radiator used in the first experiment were 6 and 9 mm, respectively. The radiator was placed in the vacuum chamber on the end of the vertical holder. Vertical movement of the holder and its rotation around vertical axis allowed setting the radiator on the trajectory of the electron beam and changing the orientation angle \( \theta_0 \) of electron incidence on its surface. Collection of information, its processing and control of the radiator attitude was carried out with the use of the specialized units of the computer-running CAMAC through a special program.

3. On study of CRPS and TR

According to our previous experiments, a back transition radiation (BTR) generated by electrons on the input Si-plate surface is effectively recorded with CEM. BTR yield is mainly located in the spectral range of 10 – 50 eV. BTR is also generated on the input surface of APS. The measured orientation dependences (OD) of BTR generated in APS and Si plate are shown in figure 3, curves 1 and 2, respectively. The figure shows that ODs measured for homogeneous Si plate and for multilayer structure are largely identical. Minima in the centers of the ODs are at the angle \( \theta_0 = \theta_B = \theta_D / 2 \) that corresponds to symmetric Bragg orientation of the radiator relative to the electron beam and a collimated detector. Maxima in both ODs are located symmetrically with respect to the dips in its centers. Angular distance \( \Delta \theta_0 \) between the ODs peaks is comparable to the value of \( \gamma^{-1} = 89.6 \) mrad, where \( \gamma \) is the Lorentz factor of accelerated electrons. In studies involving the detection of CRPS generated in APS, back transition radiation was seen as a background which should be taken into account at determining the contribution of a CRPS quasi-monochromatic component. To detect CRPS in the VUV range it was chosen the method based on the property of CRPS described by the dependence (1) defining the relation between photon energy \( E_\gamma \), angle \( \theta_0 \) of photon emission and angle \( \theta_0 \) of the electron incidence on the radiator layers.
\[ E_\gamma = \hbar \omega = \frac{2\pi \hbar c}{d} \frac{\sin \theta_o}{\beta^{-1} - \sqrt{\varepsilon(\omega)}} \cos \theta_p, \]  

where \( \beta = v/c \) – relative velocity of the electrons; \( d \) – period of APS;  
\[ \varepsilon(\omega) = 1 - \left[ a (1 - \varepsilon(\omega)_w) + b (1 - \varepsilon(\omega)_c) \right] / d \] – dielectric constants averaged over the period \( d \);  
\( \varepsilon(\omega)_w \) and \( \varepsilon(\omega)_c \) – dielectric constants of tungsten and carbon.

The principle of the method for finding the parametric X-rays is illustrated in figure 4. For discussion we used CRPS orientation dependence, curve 1, with its shape being typical for the crystals. Curve 4 represents the dependence of angular position of CRPS spectral peak on angle \( \theta_o \) for the structure with a period of 1.8 nm, angle of photon emission \( \theta_o = 60^\circ \) and electron energy of 5.7 MeV. The use of a thin-foil filter from the material with the absorption edge in the range of investigated energies will lead to a significant distortion of the specific shape of the CRPS angular distribution. A similar method with the use of a thin nickel foil was used in [7] to estimate the "natural" width of the spectral line of parametric X-ray radiation produced by a Si crystal in the region of photon energy of about 8 keV. In our case, the radiation energy in the center of the CRPS angular distribution, according to the formula (1), is about 600 eV. Therefore, it is advisable to use a filter containing fluorine, for example, Teflon \((C_2F_4)_n\) film or LiF crystal. The \( K \) absorption-edge energy of fluorine \( E_K = 688.37 \) eV. In addition to the absorption of radiation near the \( K \) edge, the 1 \( \mu \)m thick filter provides almost complete suppression of transition radiation in the range of 10–50 eV.
Orientation dependence of CRPS at using the thin \((C_2F_4)_n\) filter will be compared with orientation dependence at using another filter which has no absorption edge in the investigated range of photon energies, for example, polyethylene \((C_2H_4)_n\) filter. The coefficients of radiation transmission through \((C_2H_4)_n\) and \((C_2F_4)_n\) filters with a thickness of 1 μm, calculated using the database [8], are shown in figure 5.

![Figure 5. Coefficients of radiation transmission through 1 μm polyethylene and 1 μm Teflon filters, curves 1 and 2, respectively, in dependence with the photon energy.](image)

Figure 4 also shows the changes in the shape of CRPS orientation dependence at the radiation penetration of the polyethylene and Teflon filters, curves 2 and 3, respectively. As seen, the radiation intensity in the right peak is reduced by about 1.5 and 7.2 times at transmission of radiation through polyethylene and Teflon filters, respectively. Left maximum of intensity in OD is reduced by about 2 times in both cases. When using the Teflon filter, a stronger suppression of the right maximum is sustained, approximately 3.6 times higher as compared to the left one, which can be easily seen in the experiment. Thus, the analysis of the calculations allows us to conclude that by observing the predicted differences in OD, it will be possible to detect the presence of quasi-monochromatic components in the investigated radiation, the nature of which can be explained by a CRPS mechanism. Note that the calculated ODs submitted by curves 2 and 3 have the additional maxima on its left sides due to the influence of the absorption edge of carbon – a component of both filters. Their position \(\theta_0 = 12.5^\circ\) corresponds to the energy of generated radiation of 291 eV, according to formula (1).

4. Test measurements
The first experiments for testing the setup and on the monochromatic component separation in the radiation generated in the layered structure were carried out according to the above considered method.

![Figure 6. Orientation dependence of radiation yield from APS detected with CEM after transmission of radiation through the absorption filters. Curves 1 and 2 – for the filters consisted of single and double Teflon films with thickness of 1.7 μm. Curve 3 – smoothed difference between the yield values shown by curves 1 and 2.](image)

Measurements of the orientation dependences of the radiation were done with the use of the absorbing filters made of Teflon films. Figure 6 shows the orientation dependence obtained with using a 1.7 μm
Teflon filter, curve 1, which has a double-maximum form and a strong enough background substrate, with its intensity increasing with the decrease of angle $\theta_0$. Curve 2 in figure 6 shows the orientation dependence obtained using a double-film Teflon filter with a full thickness of 3.4 $\mu$m, which has not component of a double-maximum form. Curve 3 in figure 6 shows difference between the yield values shown by curves 1 and 2. The ratio of intensities of the OD maxima, curve 3, is about 2/3, instead of the expected value of 1/7. It means that the predicted peculiarities of the radiation angular distribution due to selective absorption of the Teflon filter are not observed. Double-peak form of the orientation dependence is preserved, and the expected suppression of the right peak is absent.

![Figure 7](image)

**Figure 7.** Same as in figure 4. Curve 2 – for polyethylene filter with thickness of 2 $\mu$m, curve 3 – for a combined (1 $\mu$m Teflon + 1 $\mu$m polyethylene films) filter.

One of the possible reasons for the result is that one-film filter used in the experiment has pores through which a soft transition radiation falls into the detector. This conclusion is supported by the fact that after installing the filter consisting of two identical 1.7 micron Teflon films, the peaks in OD were not observed (curve 2 in figure 6). Hence, the second Teflon filter completely absorbed soft transition radiation. Therefore, a composite filter consisting of thin polyethylene and Teflon films should be used because the dual-filter ensures the mutual overlap of the pores in the filters that can reliably suppress soft background of transition radiation. Figure 7 presents the orientation dependences of the radiation from a multilayer structure, calculated for the case of using the composite filters. Curve 2 – for the composite 2 $\mu$m polyethylene filter consisted of two films with thicknesses of 1 $\mu$m, curve 3 – for a combined (1 $\mu$m Teflon + 1 $\mu$m polyethylene) filter. As can be seen, the use of an additional filter does not violate the principle of the method. The asymmetry of the peaks of the orientation dependence is retained (the ratio of about 1/7). Although, the radiation yield will be lower by a factor of about 2. Another possible reason may be that the shape of the orientation dependence can be different from that used to discuss the method of separating the monochromatic component in the radiation generated in the layered structure, curve 1, figure 4. Our effort to calculate OD for x-ray mirror with using the existing theories has given ambiguous results.

5. Conclusion
The first test experiments have shown that the created experimental setup is workable. However, the analysis of the experimental results after testing the method for the observation of CRPS provided several suggestions for its improvement. First, it is necessary to reduce background induced by bremsstrahlung formed on the chamber walls by electrons scattered by the target at large angles. To this end, the radiator-to-detector distance should be increased. Narrower diaphragms for tighter collimation of radiation might also be useful. Secondly, it is also necessary to improve quality of the filters in order to exclude influence of its imperfections on experimental results. For further experiments it will be made a set of more perfect filters for different regions of the radiation cone. Finally, for the ultimate justification of the method of CRPS observation it is necessary to have the exact theoretical form of the CRPS orientation dependence. Unfortunately, the existing theories give
conflicting results so far. But, in any case, CRPS component will be seen due to a “jump” in the
distribution of radiation passed through a K edge filter because of the relation between photon energy
and direction of its emission given by equation (1).

Acknowledgments
This work was partly supported by the Russian Foundation for Basic Research, project 10-02-00942,
“The nonuniform photonic crystal as a new source of coherent submicrofocus X-rays from relativistic
electrons”.

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