Transition Radiation of Fast Electrons as a Broadband Vacuum-Ultraviolet Radiation Source

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Abstract—The characteristics of a possible radiation source in the vacuum-ultraviolet and soft X-ray range based on the transition radiation of electrons with an energy of about 100 keV are calculated. The possibilities of enhancing the radiation yield in the geometry of the glancing interaction of electrons with a target are analyzed. The possibility of creating a source with a yield on the order of 10^{-5} photon/(eV sr) per electron is demonstrated.

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INTRODUCTION

An important spectral range of electromagnetic radiation is the vacuum-ultraviolet region (VUR) which is used in various fields of science and practical applications. To date, a variety of VUR sources have been developed [1], the most powerful of which are synchrotrons and lasers based on free electrons. The main drawback of these sources is the high cost of their fabrication and maintenance which limits their availability.

A promising direction for the creation of VUR sources lies in the use of mechanisms for the generation of electromagnetic radiation implemented upon the interaction of relativistic charged particles with matter [2–5]; however, the applied use of such sources is limited due to significant costs. The main problem in this field is the small photoabsorption length of VUR which is comparable to the wavelength. This significantly reduces the effectiveness of the practical use of coherent mechanisms of radiation generation when a charged particle moves in matter.

In this context, attention is attracted to transition radiation (TR) occurring when a charged particle crosses the boundary between two media with different dielectric susceptibilities $\varepsilon(\omega)$ (ω is the energy of the quantum emitted). To date, this radiation has been studied in detail both theoretically and experimentally [6]. A feature of transition radiation is the significant yield in the range of VUR. In this range, TR was studied theoretically and experimentally in [5, 7], where the possibility of using this mechanism as a source of radiation was shown. In [8, 9], the results of the theoretical study of VUR were presented for the glancing geometry of the interaction of a charged particle with a planar target. It was shown that the yield of TR increases by tens times in comparison to the usual case, which is undoubtedly of interest in developing VUR sources on the basis of TR.

This paper presents the results of calculations of the characteristics of a VUR source based on TR in the geometry of glancing interaction with the plane of a target surface. The cases of transition-radiation generation upon the inlet or emission of particles from a target are considered. In these calculations, we use the relativistic system of units $\hbar = c = 1$.

CALCULATION OF THE TRANSITION RADIATION CHARACTERISTICS

Calculation of the spectral-angular characteristics of TR arising when a particle crosses a substance–vacuum interface at a sliding angle can be performed based on [8], using data on the dielectric susceptibility of the substance $\chi(\omega)$ [10]. These expressions take into account the longitudinal component of the electric field of the charged particle with allowance for the scattering of radiation at the substance—free space interface. Within the geometrical configuration shown in Fig. 1, the amplitude of the TR can be written in the following form

$$\mathbf{A}^{\mathrm{TR}} = \left(\mathbf{e}_{\perp} - n_{\perp}\frac{\mathbf{n}_{\parallel}}{n_{\parallel}^{2}}\right)A_1 + \mathbf{e}'A_2, \quad (1)$$

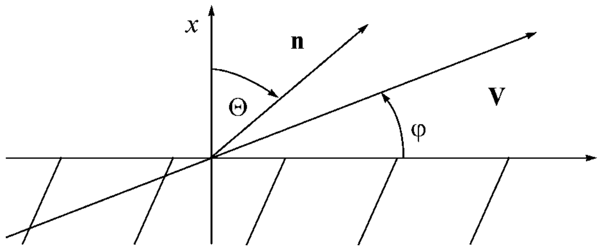

Fig. 1. Geometry of the emission process: **V** is the velocity of the emitted electron; **n** is the unit vector along the direction of propagation of the emitted quantum.

where $n_\perp$ and $n_\parallel$ are the components of **n** ($n_\parallel^2 = n_x^2 + n_y^2$), $\mathbf{e}' = \frac{[\mathbf{n}_\parallel \mathbf{e}_\perp]}{n_\parallel}$, $\mathbf{e}_\perp$ is the unit vector along the normal to the plane of the medium surface.

$$A_1 = \frac{e\, n_\perp V_\perp}{\pi\ n_\parallel} \frac{\chi}{(1 - \mathbf{n}_\parallel \mathbf{V}_\parallel)^2 - n_\perp^2 V_\perp^2} \times \frac{1}{1 - \mathbf{n}_\parallel \mathbf{V}_\parallel - V_\perp \sqrt{n_\perp^2 + \chi}} \times \frac{V_\perp \sqrt{n_\perp^2 + \chi}\left(n_\parallel^2 - \mathbf{n}_\parallel \mathbf{V}_\parallel\right) - n_\parallel^2\left(1 - V_\perp^2 - \mathbf{n}_\parallel \mathbf{V}_\parallel\right)}{n_\perp(1+\chi) + \sqrt{n_\perp^2 + \chi}}, \tag{2a}$$

$$A_2 = \frac{e\, n_\perp V_\perp}{\pi\ n_\parallel} \frac{\chi}{(1 - \mathbf{n}_\parallel \mathbf{V}_\parallel)^2 - n_\perp^2 V_\perp^2} \times \frac{1}{1 - \mathbf{n}_\parallel \mathbf{V}_\parallel - V_\perp \sqrt{n_\perp^2 + \chi}} \frac{n_y V_\perp V_x}{\chi n_\perp + \sqrt{n_\perp^2 + \chi}}. \tag{2b}$$

The spectral-angular distribution of radiation is given by:

$$\omega \frac{dN}{d\omega d\Omega} = \omega \frac{dN_1}{d\omega d\Omega} + \omega \frac{dN_2}{d\omega d\Omega} = |A_1|^2 + |A_2|^2.$$

It is not difficult to show that the TR yield decreases proportionally to the squared particle velocity upon decreasing energy of the charged particle, and the spectral-angular distribution of TR for the condition $V \ll 1$ can be presented in the form

$$\omega \frac{dN_1}{d\omega d\Omega} = \frac{e^2}{\pi^2}\left(\chi'^2 + \chi''^2\right) \times \frac{n_\perp^2 n_\parallel^2 V_\perp^2}{\left(n_\perp(1+\chi') + \beta'\right)^2 + \left(n_\perp \chi'' + \beta''\right)^2}.$$

$$\beta' = \frac{1}{\sqrt{2}}\sqrt{\sqrt{\left(n_\perp^2 + \chi'\right)^2 + \chi''^2} + n_\perp^2 + \chi'},$$

$$\beta'' = \frac{1}{\sqrt{2}}\sqrt{\sqrt{\left(n_\perp^2 + \chi'\right)^2 + \chi''^2} - n_\perp^2 - \chi'}.$$

The maxima of the angular distributions in this case are close to the angle of total internal reflection, defined by the equality $\cos(\Theta) = \sqrt{-\chi'}$, and their position does not depend on the orientation of the momentum of the emitted electron relative to the plane of the target. Figure 2 shows the calculation results for electrons with an energy of 50 keV ($V = 0.19$) emitted perpendicularly to the surface of a carbon target; the angle Θ' is counted from the beam axis in the reaction plane.

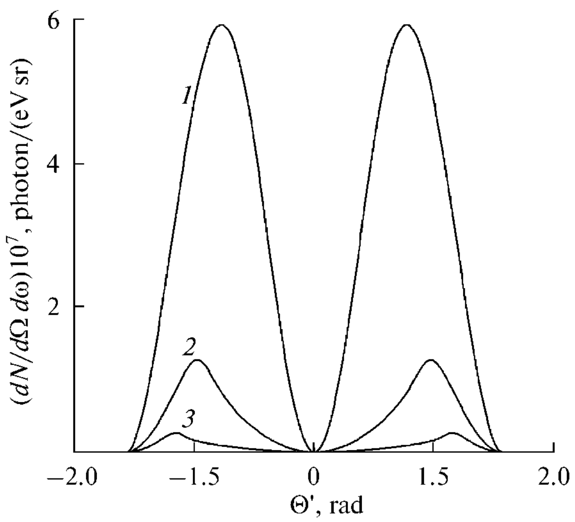

Fig. 2. Spectral-angular distribution of TR at normal emission of 50-keV electrons from a target at different photon energies: (*1*) 30; (*2*) 50; (*3*) 70 eV.

As a result of studying the possibility of increasing the yield of TR in the geometry of glancing interaction with the plane of the target surface, the effect of increasing the TR yield by tens times was discovered [8, 9]. This effect is explained by the combined action of two mechanisms of the formation of maxima in the angular distribution of TR. The first one corresponds to the case of total external reflection, when the maximum of the angular distribution is observed near the angle of total external reflection. The second mechanism is implemented due to reconstruction of the Coulomb field of the charged particle with increasing velocity. Figure 3 shows the curves obtained as a result of calculating the spectral-angular distribution of TR in the case of the effect of increasing angular density of TR in glancing interaction geometry.

It is worth noting that the degree of manifestation of this effect heavily depends on the values of χ' and χ''. To obtain the maximum angular density of TR, the condition $\sqrt{2}(1+\chi') \gg \sqrt{\chi''/|\chi'|}$ must be fulfilled. In the opposite case, the effect proves to be insignificant and the position of the maximum is determined to a great extent by the degree of transformation of the Coulomb field of the emitted electron.

An important feature of TR in the geometry of glancing interaction is an increase in the yield of radiation in a wide range of spectrum. Figure 4 shows the calculation results for the ratio of the TR yield in

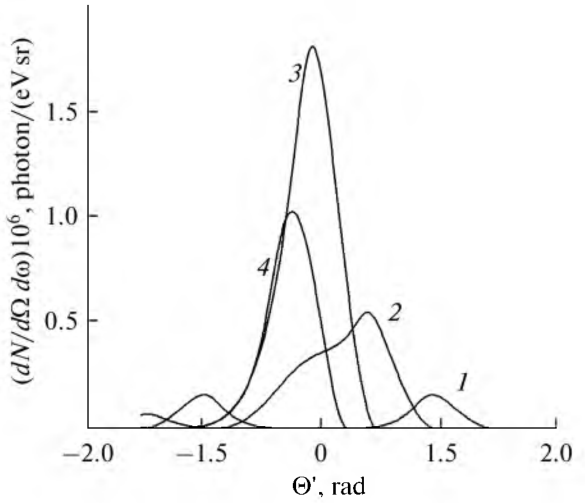

Fig. 3. Effect of increasing the angular density of the TR upon the emission of 200-keV electrons from a carbon target at different angles: (*1*) 90°; (*2*) 60°; (*3*) 30°; (*4*) 15°. The photon energy is 50 eV.

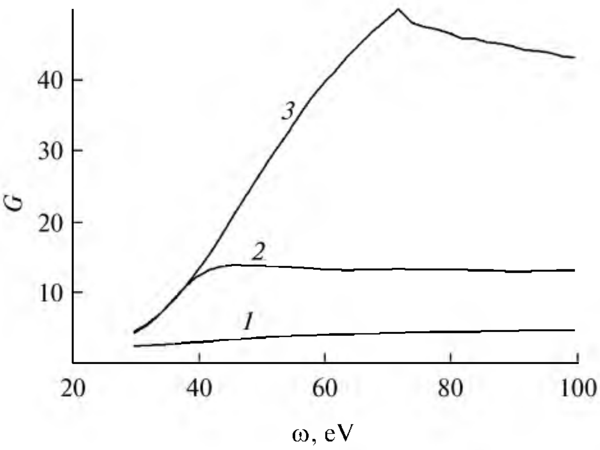

Fig. 4. Ratio of the TR yield in glancing interaction geometry to the yield corresponding to electron emission from a carbon target in the normal direction at different energies: (*1*) 100; (*2*) 300; (*3*) 500 keV.

glancing interaction geometry to the yield for the case of normal particle emission. For each photon energy, the angles of incidence and observation were chosen individually in the distribution maximum

$$\left(G(\omega, V) = \frac{dN_1}{d\omega d\Omega}\bigg|_{\varphi=\varphi^{opt}} \bigg/ \frac{dN_1}{d\omega d\Omega}\bigg|_{\varphi=\frac{\pi}{2}}\right).$$

TRANSITION RADIATION AS THE SOURCE OF VACUUM ULTRAVIOLET RADIATION

The transition-radiation model under the glancing interaction of charged particles with the surface of a target predicts the possibility of increasing the TR

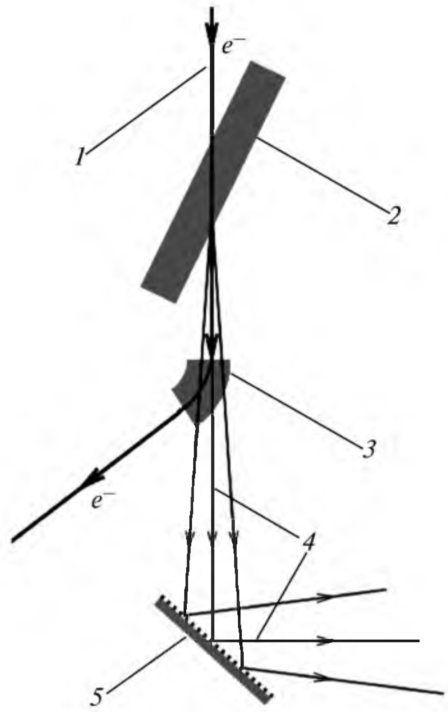

Fig. 5. Scheme of a possible source of VUR based on transition radiation at glancing interaction: (*1*) electron beam; (*2*) target; (*3*) magnet; (*4*) VUR; (*5*) diffraction grating.

yield by tens times (Fig. 4). In combination with the simplicity of implementation, this makes it possible to create a source of VUR based on this mechanism. The important characteristics of sources of radiation are the quantum yield and spectral range of emission.

The form of the spectrum is mainly determined by the values of χ' and χ'', for which the dependence on the photon energy has a smooth character far from the photoabsorption edges. This allows us to count on the creation of a broadband VUR source. Figure 5 shows the scheme of a possible source with the broadband TR signal monochromator. As the monochromator, it is advisable to use a diffraction grating, which makes it possible to change the spectrum of the source signal by turning the grating without altering the position of detector.

Figure 6 allows us to estimate the yield of TR corresponding to the discussed effect .The figure shows the spectral TR distributions which are analogous to Fig. 4 without normalization to the yield of TR at normal particle emission ($\Delta\Omega$ is the radiation collimation angle). We can see that the typical TR yield in the range of VUR has a magnitude on the order of 10^{-5} photon/(eV sr) per electron at an electron energy of about 100 keV.

Obviously, when a charged particle is emitted from a target its radiation is influenced by multiple scattering in the medium, so that the angular distribution of the transition radiation is broadened and its amplitude

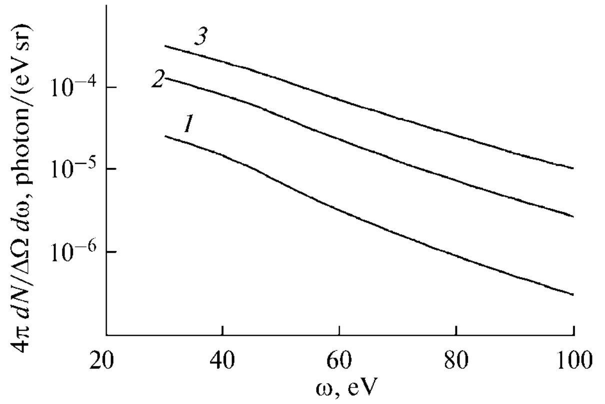

Fig. 6. TR yield in glancing interaction geometry for different energies of emitted electrons: (*1*) 100; (*2*) 300; (*3*) 500 keV.

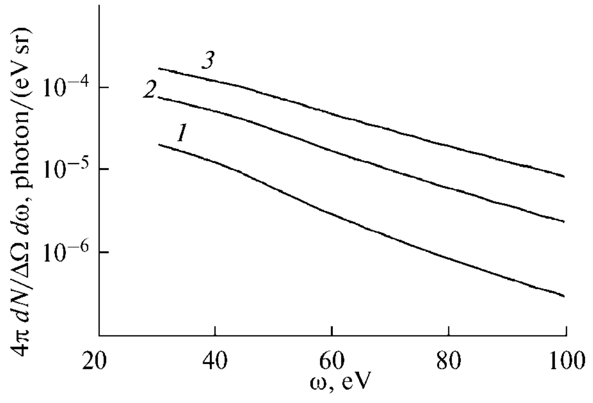

Fig. 7. TR yield in glancing interaction geometry in the case of inlet electrons of different energy: (*1*) 100; (*2*) 300; (*3*) 500 keV.

decreases. Most notably this influence is evident in the range of electron energies on the order of 100 keV.

The effect of multiple scattering can be reduced when using the two most simple methods. The first one assumes the use of heavy particles, for example protons. In this case, the energy of the protons will be sufficient to disregard the effect of multiple scattering, provided that the velocity of the protons is equal to that of the electrons. This approach has a significant drawback related to the need to obtain heavy particles of large enough energy, which is technically difficult. The second and simpler possibility of reducing the effect of multiple scattering is the use of TR geometry when the particle enters the target. Films with a thickness on the order of the photoabsorption length of transition radiation can be used as targets. For diamond-like carbon films, the photoabsorption length lies in the range of 30–100 eV and is on the order of 10 nm. Figure 7 shows the spectra of TR which are analogous to those given in Fig. 6 in the case when the particle enters the target.

CONCLUSIONS

Calculations of the spectral-angular characteristics of the source of VUR based on the transition radiation of charged particles with an energy on the order of 100 keV were performed. The results showed the possibility of obtaining a radiation yield of about 10^{-5} photon/(eV sr) in the spectral range of 30–100 eV. A diamond-like carbon film was considered as the radiator. It follows that the relative change in the yield of TR upon charged-particle entrance or emergence from the crystal is insignificant. This allows one to use the TR generated when the particle enters the target to implement a source of radiation with the minimal impact of multiple scattering on the characteristics of the TR. The scheme of the source shown in Fig. 5 can be successfully used for practical implementation. The energy range of charged particles of about 100 keV is undoubtedly convenient due to the wide use of electron beams of this energy in transmission electron microscopy. Moreover, the proposed radiation source can be implemented on ring accelerators in the mode of multiple particle passage through a target with subsequent monochromatization, as was recommended in [11].

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