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Resonant diffusive radiation in random multilayered systems

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Abstract

We have theoretically shown that the yield of diffuse radiation generated by relativistic electrons passing random multilayered systems can be increased when a resonant condition is met. Resonant condition can be satisfied for the wavelength region representing visible light as well as soft X-rays. The intensity of diffusive soft X-rays for specific multilayered systems consisting of two components is compared with the intensity of Cherenkov radiation. For radiation at photon energy of 99.4 eV, the intensity of resonant diffusive radiation (RDR) generated by 5 MeV electrons passing a Be/Si multilayer exceeds the intensity of Cherenkov radiation by a factor of ≈60 for electrons with the same energy passing a Si foil. For a photon energy of 453 eV and 13 MeV electrons passing Be/Ti multilayer generate RDR exceeding Cherenkov radiation generated by electrons passing a Ti foils by a factor ≈130.

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1. Introduction

Recently radiation generated by relativistic electrons passing through periodic multilayer structures have received increased attention [1–3]. This has particularly been enabled by the availability of multilayers with periodicities in the nm scale. Yamada and Hosokava [2] demonstrated resonant transition radiation (RTR) [4–6] to be applicable as a radiation source in the wavelength region $\lambda < 1$ nm. This was achieved by 15 MeV electrons passing a periodic multilayer with 176 nm thick nickel layers as radiator and 221 nm thick carbon layers as a spacer. As the RTR intensity is proportional to $[\varepsilon_1(\omega) - \varepsilon_2(\omega)]^2$, where ε_1 and ε_2 are the dielectric constants of the multilayer components, a sharp increase can be expected around inner-shell absorption edges [1].

In the X-ray region the dielectric constant can be described by the plasma formula and usually is less than unity. However, in narrow region around absorption edges of some materials the dielectric constant can exceed unity. This means that the condition for Cherenkov radiation (CR) can be fulfilled even in the X-ray region. The intensity of CR is proportional to $\varepsilon(\omega) - 1$.

Bazylev et al. [7] demonstrated the generation of CR around the K absorption edge of C from 1.2 GeV electrons passing a carbon containing foil. More recently Knulst et al. [8] used 5 MeV electrons to generate CR around the Si L absorption edge ≈99 MeV and 10 MeV electrons to generate CR around L edges of V (512 eV) and Ti (453 eV).

Previously we showed that diffusive radiation (DR) generated by relativistic electrons passing a randomly distributed multilayer system can provide an alternative for a source with a high radiation yield [9]. Experimental evi-

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dence in favor of this mechanism was provided by Yuan et al. [10] who conducted experiments on radiation generated by relativistic electrons passing a system of microspheres, distributed randomly in a dielectric material. The observed strong dependence of the radiation intensity as a function of the particle energy could only be explained by the DR mechanism [11]. In this paper we discuss the influence of a resonance effect on the yield of diffusive radiation (RDR). As the resonant condition requires that n exceeds 1, this effect can for radiation in the soft X-ray region only be achieved around selected absorption edges representing an atomic inner-shell of an element. Our paper explicitly deals with the generation of resonant diffuse radiation around these inner-shell absorption edges. A complicating factor for this short wavelength region is that DR requires a low absorption to enable multiple scattering. Nevertheless we have shown that when a resonance condition is met related to the anomalous behavior of dielectric constant around an adsorption edge, the yield resulting from RDR exceeds the yield of CR in this soft X-ray region.

2. Initial relations

Let us consider radiation from a charged particle uniformly moving in a homogeneous medium with randomly embedded parallel foils in it. The origin of the radiation can be explained as follows. Each charged particle creates an electromagnetic field around it which is not yet photon but a pseudophoton. These pseudophotons are scattered on the inhomogeneities of dielectric constant and convert into real photons. We consider the radiation due to scattering of pseudophotons which includes also the conventional transition radiation (TR). We do not consider the bremsstrahlung and Cherenkov radiation which have different origin. We have shown [9] that the radiation intensity can be represented as a sum of two contributions. One is the contribution by single scattering and the another is the contribution caused by multiple scattering of pseudophotons. The single scattering contribution actually is TR from randomly spaced interfaces. However here we are interested in the contribution by multiple scattering [9], as it was shown that it leads to the diffusion of pseudophotons. As demonstrated in [9] a simplified expression for the yield for DR can be achieved by introducing a random multilayer system with Gaussian distribution of distances between the foils. It should be emphasised that other random systems are not excluded to be applicable. The statistical properties of the Gaussian distribution enters to the solution through the elastic mean free path of the photons.

That means that in a real system the randomness created by the parallel foils should fulfill the requirement to treat the dielectric constant as Gaussian distributed random function. For a large number of foils $N \gg 1$, in the wavelength range $\lambda \ll l$ (where l is the photon mean free path in the normal to the foils direction, for more details see [9]) diffusion contribution to the radiation intensity is the main one and given by the formula

$$I(\omega,\theta) = \frac{5e^2\gamma_m^2(\omega)L_zL^2\sin^2\theta}{2\varepsilon(\omega)cl^3|\cos\theta|}, \tag{1}$$

where ε is the average dielectric constant of the system

$$\varepsilon = \varepsilon_0 + na(\varepsilon_f - \varepsilon_0). \tag{2}$$

Here ε_0 and ε_f are dielectric constants of the medium and the plate, respectively, a is the thickness of the foils, $\gamma_m = (1 - v^2\varepsilon/c^2)^{-1/2}$ is the Lorentz factor of the particle in the medium, L_z is the system size in the z direction (we assume that the particle is moving in this direction) and L is the characteristic size of the system. The formula (1) has a clear physical meaning [12]. The quantity $e^2\gamma_m^2L_z/c$ is the total number of pseudophotons in the medium, $1/l$ is the probability of the photon scattering and L^2/l^2 is the average number of pseudophoton scatterings in the medium. Eq. (1) is correct provided that $\gamma_m^2 \gg ak$, where $k = \omega/c$ is the photon wavenumber. Taking into account that γ_m^2/k is the coherence length (radiation formation zone) [12] this condition means that many foils can be placed in a coherence length. Note that at the resonance point where $\gamma_m \to \infty$, the condition $\gamma_m^2 \gg ak$ is automatically fulfilled. This regime differs from those one which is usually explored in the periodical multilayered systems [4,5] where an enhancement of photon yield appears as a result of constructive interference.

Note that Eq. (1) is correct provided that $|\cos\theta| \gg (\lambda/l)^{1/3}$. This condition is caused by the fact that parallel to foils pseudophotons are not diffusing so why the theory is not applicable for very large angles. For the derivation of Eq. (1) we have neglected the absorption of the electromagnetic field. However a weak absorption $l_{in} \gg l$ (where l_{in} is the photon absorption length) can be taken into account in the following way [13] and also [11]. When $L > \sqrt{ll_{in}}$ the length $\sqrt{ll_{in}}$ becomes an effective size of the system and one should substitute L^2 by ll_{in} in Eq. (1), to obtain

$$I(\omega,\theta) = \frac{5e^2\gamma_m^2(\omega)L_zl_{in}(\omega)\sin^2\theta}{2\varepsilon(\omega)cl^2|\cos\theta|}. \tag{3}$$

Note that absorption introduces an extra frequency dependence in radiation intensity. In Section 4 we will investigate the photon mean free paths in the medium more detail.

3. Resonant emission

As is seen from Eqs. (1) and (3) the intensity of diffusive radiation is proportional to the square of particle Lorentz factor in the medium γ_m^2

$$\gamma_m^{-2} = 1 - \frac{v^2\varepsilon}{c^2} = 1 - \frac{v^2}{c^2}[\varepsilon_0 + (\varepsilon_f - \varepsilon_0)na]. \tag{4}$$

It follows from Eqs. (1), (3) and (4) that when v is such that $\gamma_m^{-2} = 0$ (resonant condition) the radiation intensity drastically increases. When $\gamma_m \to \infty$ the radiation intensity also becomes infinite. However physically this is impossible. This infinity arises because in theoretical consideration we assumed the system size infinite. However in reality