LOSS MONITOR ON THE BASIS OF DIFFUSIVE RADIATION FROM ROUGH SURFACES

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Abstract

Diffusive Radiation is generated when a charged particle passes through a randomly inhomogeneous medium. Such a situation can be realized when a charged particle slides over a rough metallic surface. One of the important properties of DR is that the emission maximum lies at large angles from particle velocity direction. Therefore it can be used for detection of beam touch to the accelerators vacuum chamber wall in case when generated photons will be observed on the opposite side of the vacuum chamber. Such a diagnostics can be especially useful for monitoring of beam particle losses.

There is substantial interest in the development of different tools for beam diagnostics. Particularly, optical transition radiation is widely used for this goal [1, 2, 3]. With modern powerful optical detectors OTR based devices are very convenient. However there is also a problem with use of OTR. For relativistic particles, TR photons are emitted at very small angles $\theta \sim \gamma^{-1} \ll 1$. DR that we are going to discuss is free from such a shortage. In the present paper we consider the possibility of using of DR from rough surfaces for beam diagnostics.

A charged particle passing through a stack of plates placed in a homogeneous medium is known to be radiating electromagnetic waves. Radiation originates because of the scattering of electromagnetic field on the plates. Considering this problem theoretically it was shown [6, 7] that the spectral angular radiation intensity can be represented as a sum of single scattering I_0 and multiple scattering I_D contributions of pseudophotons

$$I = I_0 + I_D \tag{1}$$

where

$$I_0(\theta,\omega) = \frac{e^2}{2c}\frac{B(|k_0 - k cos\theta|)\sin^2\theta}{[\gamma^{-2} + \sin^2\theta k^2/k_0^2]^2}\frac{\omega^2}{k_0^4 c^2} \tag{2}$$

and diffusive contribution is determined as

$$I_D(\theta,\omega) = \frac{5e^2\gamma^2}{2\varepsilon c}\frac{L_z l_{in}(\omega)}{l^2(\omega)}\frac{\sin^2\theta}{|\cos\theta|} \tag{3}$$

Here L_z is the path of the particle in the medium, θ is the observation angle, $k_0 = \omega/v$, v is the particle velocity, $k = \omega\sqrt{\varepsilon}/c$, B is the correlation function of random dielectric constant field created by randomly located plates. Assuming that parallel plates with equal probability can occupy any point of z axis one finds correlation function as follows

$$B(q_z) = \frac{4(b-\varepsilon)^2)n\sin^2 q_z a/2}{q_z^2}\frac{\omega^4}{c^4}. \tag{4}$$

where $n = N/L_z$ is concentration of plates in the system, a is their thickness, b is their dielectric constant and ε is the average dielectric constant of the system. In Eq. (3), l and l_{in} are average elastic and inelastic mean free paths of photon in the medium. Inelastic mean free path is mainly associated with the absorption of electromagnetic field in the medium. Elastic mean free path is associated with the photon refraction on plates. It depends on the falling angle on plates. In the case when photon falls normally elastic mean free path is determined as follows

$$l = \frac{4k^2}{B(0) + B(2k)} \tag{5}$$

Note that just this quantity enters into spectral angular intensity Eq. (3). Eqs. (3, 5) are correct in the weak scattering limit $\lambda/l \ll 1$ and for observation angles $\theta = \pi/2 - \delta, \delta \gg (1/kl)^{1/3}$. Last restriction over angles appears because when $\theta = \pi/2$ pseudophotons are moving parallel to plates and no any refraction happens and the condition of weak scattering is failed. When the conditions of multiple scattering of electromagnetic field are fulfilled the diffusive contribution to the radiation intensity Eq. (3) is the main one because $I_D/I_0 \sim l_{in}/l \gg 1$. As it is seen from Eq. (3) the radiation intensity is determined by elastic and inelastic mean free paths of photon in the medium. It follows from Eq. (4) that when $ka \gg 1$, $B(2k)/B(0) \sim 1/(ka)^2 \ll 1$. Therefore in both cases $ka \gg 1$ and $ka \ll 1$ the photon mean free path has the form

$$l \sim \frac{k^2}{B(0)} \tag{6}$$

where $B(0) = k^4(b-\varepsilon)^2 na^2/\varepsilon^2$. Substituting this expression into Eq. (6) and taking into account that $k = \omega\sqrt{\varepsilon}/c$, we have

$$l \sim \frac{\varepsilon}{\frac{\omega^2}{c^2}(b-\varepsilon)^2 na^2} \tag{7}$$

Remind that ε is the average dielectric constant of the system which for a layered stack has the form:

$$\varepsilon(\omega) = nab(\omega) + (1 - na)\varepsilon_0(\omega) \tag{8}$$

Here ε_0 is the dielectric constant of a homogeneous medium into which plates with dielectric constant $b(\omega)$ and

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thickness a are randomly embedded. If a homogeneous medium is vacuum then $\varepsilon_0 \equiv 1$. The parameter na is the fraction of the plates in the system.

A rough interface is a region with random fluctuations of dielectric constant that separates two homogeneous semi-infinite media. Suppose that $z = 0$ is the plane distorted by the roughness. The equation of rough surface is determined as follows

$$z = h(\vec{\rho}) \tag{9}$$

where h is a random function and $\vec{\rho}$ is a two-dimensional radius vector in the x, y plane. We suppose that the space $z > h(\vec{\rho})$ is occupied by the vacuum or air and the space $z < h(\vec{\rho})$ by a metal. Usually, for convenience, h is assumed as a gaussian stochastic process characterized by two parameters

$$< h(\vec{\rho}) >= 0 \tag{10}$$
$$< h(\vec{\rho}_1)h(\vec{\rho}_2) >= \delta^2 W(|\vec{\rho}_1 - \vec{\rho}_2|)$$

where $<$ ... $>$ mean averaging over the randomness, $\delta^2 =< h^2(\vec{\rho}) >$ is the average deviation of surface from the plane $z = 0$. Because of the translational invariance and isotropy the correlation function W depends on the quantity $|\vec{\rho}_1 - \vec{\rho}_2|$. It follows from Eq. (11) that $W(0) = 1$. Roughnesses at two points located far away from each other are uncorrelated therefore when $|\vec{\rho}_1 - \vec{\rho}_2| \to \infty$, W goes to 0. One can determine correlation length σ as a distance at which correlation function is essentially decreased. Frequently gaussian form for correlation function $W(\rho) = \exp(-\rho^2/\sigma^2)$ is used. The parameters δ and σ experimentally can be found using light scattering from rough surfaces [4]. Depending on the degree of treatment of the surface of a metal δ is of order of several ten angstroms and σ is of order of few hundred angstroms. Another parameter characterizing roughness that plays important role in radiation is the average of modulus of deviation from the reference plane $z = 0$, $R =< |h(\vec{\rho})| >$ [5]. Depending on the degree of treatment of the surface this parameter varies from $0.01\mu m$ to $5\mu m$.

When a charged particle slides over a rough surface it crosses randomly distributed hills and valleys. One can model these hills and valleys as randomly located plates and vacuum spacings between them. Correlation length of the roughness σ plays role of the thickness of the plates. An electromagnetic wave can travel through these hills provided that σ is smaller than the depth of skin layer in the metal. In the optical region this condition will be fulfilled for not very rough surfaces. Moreover if the hills are high enough $2\pi R \gg \lambda$ then one can assume that photon with wavelength λ is propagating through a random stack of parallel plates having one-dimensional randomness of dielectric constant.

For realization of diffusive mechanism of radiation absorption should be weak. This means that the plates should be very thin. Moreover, in metal case their thickness should be less than the depth of skin layer of metals, in order to the photons diffusively propagate over the system. In the optical region a metal skin layer is of order of several hundred angstroms. As was mentioned above for rough surfaces σ which plays a role of thickness is of order of a few hundred angstrom therefore an optical photon can diffuse through hills and valleys of a rough metallic surface. An experiment on radiation from $80\,keV$ energy electrons sliding over rough metallic surfaces was carried out many years ago[5]. An enhancement of radiation intensity compared to normal falling case was observed. Estimations of hill and valley sizes show that conditions for generation of diffusive radiation exist in the experiment [5]. Unpolarized character and spectral angular dependence of observed radiation intensity are well described by diffusive radiation intensity formulae [6]. Hence we think that in the experiments [5] the diffusive radiation was observed. The energy of a charged particle should be enough for penetration of the system with inessential variation of its velocity. In the experiments [5], keV energy electrons were used. For observation of diffusive radiation from protons their energy should be at least several *MeV* in order to penetrate through many hills when sliding over a rough surface. As it follows from Eq. (3) maximum of radiation lies in the region of large angles from particle velocity direction. Using Eq. (3) one can estimate the integrated over all angles number of emitted photons in the interval $\Delta\omega$ as

$$N_{ph} \sim \alpha \frac{L_z l_{in}}{l^2} \frac{\Delta\omega}{\omega} \tag{11}$$

where α is the fine structure constant. The angular part and γ^2 give contribution of order unity except the case of ultrarelativistic particles. It follows from Eq. (11)that the gain of photon yield compared to transition radiation from one interface case is of order $L_z l_{in}/l^2$. Let us estimate this ratio. The inelastic mean free path of the photon in a random stack can be estimated as follows:

$$l_{in} \sim \frac{\lambda}{\pi f Imb(\omega)} \tag{12}$$

where $f \sim na$ is the fraction of plates in the system. Taking into account that $|b| \gg \varepsilon \sim 1$, for the elastic mean free path one gets from Eq. (7)

$$l \sim \frac{\lambda^2}{4\pi^2 b^2 f a} \tag{13}$$

Diffusive photons are absorbed in the system. Only those escape the system that are created on the particle path of order l_{in}. Therefore when estimating the number of emitted from surface photons one should substitute L_z by l_{in} in Eq. (11). Therefore using Eqs.(11-13), for the number of emitted diffusive photons from a rough surface at the frequency interval $\Delta\omega \sim \omega$, we obtain the following estimate

$$N_{ph} \sim \alpha \left(\frac{4\pi b^2 \sigma}{Imb\lambda} \right)^2 \tag{14}$$

Note that in all equations above b is the real part of dielectric constant of metal. It follows from Eq. (14) that the photon yield does not depend on the averaged distance between hills [5]. It depends on the ratio σ/λ. Radiation intensity increases on the roughness σ increasing. Maximum intensity is achieved for short length waves. These characteristic features were observed in the experiment [5]. Taking the following reasonable values for a metal $b^2 \sim 10$, $Imb \sim 0.1$, $\sigma \sim 100A^o$, $\lambda \sim 4000A^o$ one has $N_{ph} \sim 10$. Thus the photon yield significantly exceeds the transition radiation yield $N_{tr} \sim 1/137$[8]. Note that even for very smooth surfaces $\sigma \sim 100A^o$ the effect is significant. Such a large photon yield allows to use the diffusive radiation for touch beam diagnostics at electron and proton accelerators.

To create a reliable instrument of beam diagnostics based on diffusive radiation corresponding signal from rough surface should be subtracted from background electromagnetic radiation. This background can be created by other mechanisms of radiations in the same spectral range (diffractive radiation, bremsstrahlung and etc). Also very important is to be sure that the detected signal is generated by the beam touch of the selected place in vacuum chamber. As a DR radiator, a special movable area with surface roughness greater than that in vacuum chamber can be prepared. Motion of this area can be realized in longitudinal or tangential directions with shifts comparable with area sizes. Signal of radiation detector modulated with the frequency of motion subtracted from permanent background supplies the specific DR contribution. The frequencies of kHz range can be applied. Another possibility is the more slow motion of area in radial direction. In this case one must watch on the signal intensity in fixed positions of area. Very promising can be idea to create the DR generator area with variable roughness. For this purpose the piezoelectric effect can be used. One can imagine a stack from piezo and non piezo but metal foils of different thickness. The face of such a stack serve as generator of DR. In case of electrical potential loading at stack the geometrical parameters of stack will change and corresponding modulations in detected signal should be registered. Optimal for DR detection system can be imagined section of vacuum chamber with double tap directed in opposite direction. In one tap a few tens square mm DR radiator can be placed and in opposite the DD detectors must be placed. The important advantage of DR usage is that the DR is emitted at large angles relative to the beam propagation direction. This allows to realize a very simple scheme of DR detection in orthogonal direction on the opposite side of the vacuum chamber. For this purpose existing taps in vacuum chamber can be used to minimize distance between the source of radiation and detector. Situation completely differ in traditional wire scanner technique where the detector of secondary particles/radiation are placed at few meter beam downstream. To extract the DR signal from background in vacuum chamber the motion of DR radiator can be used. Very promising is modulation of DR radiator parameter by piezoelectricity. Proof-of-concept experiment in this case do not need great expenditures and can be realized by usage of standard optical detectors.

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