ON THE THEORY OF RADIATION AT LARGE EFFECTIVE COUPLING CONSTANT

S.P. Fomin*, **N.F. Shul'ga**

Akhiezer Institute for Theoretical Physics,

National Science Center "Kharkov Institute of Physics and Technology", 61108, Kharkov, Ukraine;

V.N. Karazin Kharkov National University, 61077, Kharkov, Ukraine

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A brief historical overview of one of the direction of investigations of high-energy particle interaction with matter at large values of the effective coupling constant is presented. The treatment is based on an example of ultra relativistic electron bremsstrahlung in an amorphous target and in a crystal when the coherence length is much greater than the particle free path in matter and when the multiple scattering can have a significant impact on the bremsstrahlung process. The comparison of the results of theoretical calculations with the data of recent experiments carried out in SLAC and CERN is given.

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1. INTRODUCTION

Petr Ivanovich Fomin, in addition to his wide erudition and profound knowledge in many areas of modern physics, had also subtle physical intuition, which allowed him, as he used to say, "to see an answer, even without solving a problem". One of examples of his physical sagacity is the work devoted to the analysis of the contribution of higher orders of perturbation theory in the coupling constant of quantum electrodynamics with respect to the problem of coherent bremsstrahlung in a crystal [1]. This work played an important role in the development of a new direction in the research of high energy particles interaction with matter at the large effective coupling constant. As it often happens in scientific investigations, this story began with a paradoxical experimental result, which had not an explanation by the existent theoretical concepts at that time.

Almost half a century ago the electron linear accelerator LUE-2 GeV was build and put into operation in Kharkov Institute of Physics and Technology. It was the largest linac in Europe at that time. In addition to electron beam, the gamma-quanta beams, preferably monochromatic and polarized, were very needed for carrying out research in nuclear physics. The coherent bremsstrhlung (CB) at relativistic electron passing through the single crystals at small angles to the crystallographic axes and planes was used for producing such a gamma-quanta beams. The theory of CB has been developed earlier in works of B. Ferretti [2], M.L. Ter-Mikaelian [3] and H. Uberall [4], and this technique had already been used successfully in some accelerator centers such as Frascati (Italy), DESY (Germany) and others.

Due to efforts of accelerator specialists, the relativistic positron beam with energies up to 1 GeV and small enough beam emittance, was also obtained by the end of the 60s. This made it possible to extend significantly the range of experimental research in nuclear physics at the LUE-2 GeV in Kharkov. By this time it was discovered the phenomenon of ion channeling in crystals [5-9]. It is interesting that this phenomenon was theoretically predicted by J. Stark in 1912 [6], and then rediscovered by M.T. Robinson and O.S. Oen in 1963 [5] almost accidentally in computer simulation of particle passage through a single crystal. This phenomenon is abnormally large penetration of positively charged ions moving along the densely packed by atoms the crystallographic axes or planes. The essence of the channeling phenomenon, as anomalous penetration, is the reduction of ionization losses of ions due to a significant decrease the probability of close encounters with the atoms of the crystal at the ion's "sliding incidence" and "full reflection" by the averaged field of positively charged atomic chains and planes of a crystal lattice in comparison with the scattering in an amorphous medium [5-9]. In one of the first reviews on this subject M.Thompson [9] pointed out that it would be interesting to investigate also the positron channeling in crystals.

Working in the positron beam-line group at Kharkov accelerator LUE-2 GeV young researcher V.L. Morokhovskii decided to check experimentally the availability of the orientation effect at the relativistic positron beam passing through a crystal. Without special equipment for the crystal orientation with the required accuracy ($\sim 10^{-4} rad$), he made the

*Corresponding author E-mail address: sfomin@kipt.kharkov.ua

"improvised goniometer" of original designed. The first measurements of orientation dependence of the bremsstrahlung intensity at electron and positron beams incident along the crystallographic axis in single silicon and niobium crystals showed a significant difference between the emission by electrons and positrons. This was contrary to the predictions existed at that time the CB theory, which was based on the use of the first Born approximation of quantum electrodynamics, that means using the first terms of the perturbation theory in the coupling constant of the interaction. The use of this approach was considered justified, since the coupling constant of electrons and positrons interaction with the Coulomb field of the atomic nucleus, $Ze^2 \approx Z/137$, much less than unity. The bremsstrahlung cross section in the first Born approximation is proportional to the particle charge in square, and, therefore, there is no dependence on the sign of the particle charge in this case, and thus, the electrons and positrons have to radiate alike.

What did the experiment showed? With the gradual reduction of the angle between the direction of the incident particle beam and a crystallographic axes there was observed the increasing of the intensity of gamma radiation for both electrons and positrons, according to the predictions of the CB theory. However, starting from a certain value of the orientation angle and with a further its reduction, the experiment showed a striking difference in the emission of electrons and positrons. The intensity of electron emission continued to increase, reaching a maximum at zero orientation angle, but the emission of positrons thus falls almost to zero, or at least below the level of radiation in the disoriented target and even lower than radiation on the electronic subsystem of a crystal. This looked as the positrons "not see" the atomic nuclei located in the crystal lattice points, and pass through a crystal practically without radiation!

From the beginning, these results were considered by colleagues with great disbelief. Fellow experimenters have expressed complaints about the method of measurements. There were serious objections from the theorists also. So, academician A.I. Akhiezer, author of the world famous book "Quantum Electrodynamics" [10], expressed doubts about the reliability of the results of this experiment, because the CB theory of Ferretti-Ter-Mikaelian-Uberall perfectly describes all available at that time experimental data on the coherent radiation of electrons in crystals, and according to this theory, the differences in the emission of electrons and positrons should not be. So, it was decided not to publish the results of these measurements.

Repeated checking and rechecking of "strange" results conducted with improved equipment and experimental method was followed, however, indicate a fundamental difference in the emission of electrons and positrons in aligned crystal. And V.L. Morokhovskii decided to discuss the situation with P.I. Fomin.

In those years, P.I. Fomin, was a scientific fellow of the theoretical department headed by A.I. Akhiezer. His scientific interests were mainly devoted to the problems of quantum electrodynamics at small distances (see, for example, his review [11] and references therein). As a "social duties", he was also the head of the seminar "The philosophical problems of natural science" for accelerator department fellows. This seminar, in contrast to most such events in those years, was quite informal and enjoyed great popularity among his listeners. P.I. Fomin, himself a philosopher by nature, fond of history of science, had an extensive personal library on the subject, preferring the original works of the great thinkers, their correspondence with colleagues, thus trying to understand the phenomenon of the "birth of a new knowledge". In addition, for some time, along with other KIPT theorists P.I. Fomin gave a course of lectures for the experimenters on current issues in high-energy physics [12], in which the coherent radiation in crystals was discussed, as well. Therefore, addressing the young researcher for advice to the P.I. Fomin was not accidental.

P.I. Fomin, familiarized with the essence of the problem, suggested that the dependence on the sign of the charge of the incident particle can occur in the following terms of the expansion in the coupling constant, and because it is a coherent interaction with the atoms of the crystal lattice, the correction may be not so small. First it is necessary to calculate the contribution of the second Born approximation, and then it will be clear what this is about. Carrying out these quite time-consuming calculations P.I. Fomin instructed his graduate students, one of the authors of the present article (N.F.S.), because at that time he was wholly absorbed in his ideas of spontaneous creation of the universe from a vacuum [13], as well as preparation for the defense of the doctoral thesis [14].

The results of the calculations showed that, indeed, in the second term in the coupling constant expansion the dependence on the sign of the particle charge appears. These results were published in 1971 in JETP letters [1] and, in fact, have been the starting point for the development of a new direction in the study of interaction of high-energy particles with matter at a large effective coupling constant. The article [1] is still cited in almost all the reviews and monographs on the subject, as a pioneer work. Following the publication of these results, both theoretical and experimental research in this area has gained impetus not only in KIPT, but in many other research centers as well.

In subsequent, a great number of theoretical and experimental investigations in this direction has been done in KIPT already without P.I. Fomin[1] (see, for example, reviews and monograph [15-17] and references therein). First, the detailed analysis of the

[1]P.I. Fomin shortly after defending his Doctoral thesis moved to Kiev to the Bogolubov Institute for Theoretical Physics, where he headed the department of the theory of gravity and elementary particles.

conditions of applicability of perturbation theory to the problem of coherent interaction of high energy charged particles with crystals was carried out. A number of new physical effects resulting from violation of these conditions were predicted. In particular, it was shown that in the case of small-angle particles passing to the crystal axis, instead of the normal coupling constant of charged particle interaction with the atomic field, Ze^2, there is an effective coupling constant, NZe^2, where N is the number of atoms in the crystal chain within the coherence length (N can reach hundreds or thousands). There is no small coupling constant is this case, and it requires the development of new approaches. Such approaches have been developed on the basis of the eikonal and the quasi-classical approximation of quantum electrodynamics and in the framework of classical electrodynamics [15-17].

Going beyond the Born approximation made it possible not only to describe the experimental results obtained previously for the radiation of electrons and positrons in oriented crystals, but led to a number of predictions of new effects associated with a large effective coupling constant of fast charged particles interaction with the strong external field, such as the crystal lattice field, etc. Among these effects, the coherent radiation of above-barrier and channeled electrons and positrons in crystals, the coherent production of electron-positron pairs and development of electromagnetic showers in crystals, coherent effects in multiple scattering of relativistic particles in straight and bent crystals and a number of others.

One of these effects, associated with a significant influence of multiple scattering on the bremsstrahlung of ultra relativistic electrons, namely, the suppression of radiation in a thin layer of matter was predicted and studied theoretically in [18-20]. In spite of the close physical nature with the formerly known Landau-Pomeranchuk-Migdal effect (the LPM effect) [21-23], this effect in its manifestations, however, is very different from the LPM effect. In recent $SLAC$ and $CERN$ experiments devoted to the studying the effect of multiple scattering on radiation [24-31], in addition to confirming the basic predictions of the theory of the LPM effect, the experimental confirmation of the existence of the effect of suppression of radiation in a thin layer of matter was also obtained. In [27-31] this effect was named as the Ternovskii-Shul'ga-Fomin effect (the TSF effect) after the names of the authors of the first theoretical papers, in which this effect was predicted and studied theoretically [18-20]. A brief review of the history of the theoretical prediction and experimental observation of this effect is the subject of this paper.

2. THE COHERENCE LENGTH OF BREMSSTRAHLUNG

The process of radiation of a relativistic electron develops in a large spatial region along the direction of particle motion, which is called the coherence length of radiation process. This length is determined by the expression [3,17,23,33]

$$l_c = 2\varepsilon\varepsilon'/m^2\omega \,, \tag{1}$$

where m is the electron mass, ε and $\varepsilon' = \varepsilon - \omega$ are the initial and final electron energies and ω is the photon energy. (We use the system of units for which the light velocity and the Plank constant are equal to unity.) The ratio between the coherence length and characteristic dimensions of the scattering potential determines the intensity and spectral characteristics of the bremsstrahlung.

For example, if at the motion of a fast electron along a chain of N-atoms in a crystal, the coherence length l_c is less than the distance between atoms in the chain, d, the radiation on these N-atoms can be regarded as independent. In this case, the total intensity of radiation is the sum of the intensity of the radiation on each individual atom, i.e. is proportional to N, as in the case of radiation in the amorphous medium, in which the atoms are arranged randomly.

If $l_c = d$, then the strong interference in the emission by an electron in subsequent interactions with atoms in the chain will takes place, and characteristic interference maxima will be observed in the emission spectrum at $\omega = 2\varepsilon\varepsilon'/m^2 d$ and multiples to its value. Such type of radiation is called the coherent radiation type B.

If the condition $l_c >> Nd$ is fulfilled, then the radiation will have a coherent character, and the total intensity of radiation at the N-atom chain will be proportional to N^2. In this case, the radiation at the N-atoms, with the $Z|e|$ charge of each, is equivalent to the radiation of one hypothetical atom with a charge of $NZ|e|$. The effective coupling constant is equal to NZe^2 and can be significantly greater than unit.

The concept of coherence length naturally arises in the description of bremsstrahlung in the framework of classical theory of radiation as well, but with the only difference being that the particle energy change during the radiation process does not take into account, i.e. $\varepsilon' = \varepsilon$ and therefore, the coherence length in classical electrodynamics is defined by expression

$$l_c = 2\gamma^2/\omega \,, \tag{2}$$

where $\gamma = \varepsilon/m$ is the Lorenz factor of an electron.

To demonstrate this, let′s consider the motion of a fast particle in a medium along a trajectory close to a rectilinear one. Such a particle radiates electromagnetic waves. In this case, the difference of phases $\Delta\varphi$ of the waves radiated by the electron under the angle ϑ to the momentum of the particle at the time moments t and $t + l/v$ is equal to

$$\Delta\varphi = \omega\frac{l}{v} - \vec{k}\cdot\vec{\Delta r}(l/v), \tag{3}$$

where $\vec{\Delta r}(l/v)$ is the distance passed by the particle in time l/v.

For high energies, the deviation of the particle trajectory from a rectilinear one is small. Since the scattering angle of the particle on the time interval $(t, t+\tau)$ is small, we find that

$$\vec{v}(t+\tau) \approx \vec{v}\left(1 - \frac{1}{2}\vartheta_\tau^2\right) + \vec{\vartheta}_\tau, \quad (4)$$

where $\vec{v} = \vec{v}(t)$ is the electron velocity and $\vec{\vartheta}_\tau$ is the scattering angle for the time τ. Here, $\vec{v} \cdot \vec{\vartheta}_\tau = 0$ and $|\vec{\vartheta}_\tau| \ll 1$.

Using relation (4), we find that

$$\vec{\Delta r}(l/v) \approx \vec{v}\frac{l}{v} - \frac{\vec{v}}{2}\int_0^{l/v} dt\, {\vartheta_t}^2 + \int_0^{l/v} dt\, \vec{\vartheta}_t. \quad (5)$$

If the scattering angle of a particle at the length l is sufficiently small, then we can keep only the first summand in (5). Then, the difference of phases (3) is

$$\Delta\varphi = \omega\frac{l}{v} - k\, l\cos\vartheta. \quad (6)$$

Defining the coherence length $l(\omega, \vartheta)$ as the length at which $\Delta\varphi = 1$ we find that

$$l(\omega, \vartheta) = \left(\frac{\omega}{v} - k\cos\vartheta\right)^{-1}. \quad (7)$$

The typical radiation angles of the relativistic electron are small in comparison with one; therefore, $\cos\vartheta$ in (7) can be expanded in small values of ϑ. Keeping only the first two terms of this expansion, we obtain

$$l(\omega, \vartheta) \approx \frac{l_c}{1 + \gamma^2\vartheta^2}. \quad (8)$$

While deducing (8), we also neglected dielectric properties of the medium, i.e., we assumed that $k = \omega/c$.

For $\gamma\vartheta \leq 1$, we have $l(\omega, \vartheta) \sim l_c$. Hence, the length at which the interference of waves radiated by the electron is essential is defined in order of magnitude by relation (2). This length is the coherence length of the radiation process in classical electrodynamics. In the region of small frequencies, where the recoil effect of radiation can be neglected $\omega \ll \varepsilon$, the length l_c coincides with the appropriate result (2) obtained on the basis of the quantum radiation theory.

If in the limits of the coherence length of the radiation process an electron interacts only with one atom of a medium then interference of the waves radiated by an electron at different atoms is not important for radiation. In this case the radiation spectral density is determined by the Bethe-Heitler formula [17,23,32]

$$\frac{dE_{BH}}{d\omega} = \frac{4t}{3X_0}\frac{\varepsilon'}{\varepsilon}\left(1 + \frac{3}{4}\frac{\omega^2}{\varepsilon\varepsilon'}\right), \quad (9)$$

where t is the target thickness, X_0 is the radiation length

$$X_0 = m^2/(4Z^2e^6 n * \ln(mR)), \quad (10)$$

n is the density of atoms in a medium and R is the screening radius of atomic potential.

The coherence length grows fast with particle energy increasing and with decreasing of emitted photon energy. Landau and Pomeranchuk paid attention to the fact that if in the limits of coherence length of radiation process an electron interacts with a large number of atoms, the radiation of low energy photons can be considered on the basis of the classical theory of radiation [17,21,23].

3. THE LANDAU-POMERANCHUK-MIGDAL EFFECT

Landau and Pomeranchuk showed in [21] that if the root-mean-square angle of electron multiple scattering $\bar{\vartheta}_{ms}$ at the distance of a coherence length l_c exceeds the characteristic angle of relativistic particle radiation $\theta_k \sim \gamma^{-1}$, where $\gamma = \varepsilon/m$ is the Lorentz factor of an electron, then the radiation power spectrum will be suppressed in comparison with the Bethe-Hietler result given by formula (9).

To describe the bremsstrahlung spectrum at $\gamma^2\bar{\vartheta}^2{}_{ms} \gg 1$ in the easiest way, Landau and Pomeranchuk use some significant simplifications at the averaging of radiation spectrum over multiple scattering of electrons in amorphous medium. The detailed analysis and corrections of their calculation scheme can be found in [17,23,34]. Thus, their final formula had only quantitative character.

$$\frac{dE_{LP}}{d\omega} = \frac{e^2}{2}\sqrt{\frac{3\omega q}{2\pi}}\, t, q = \bar{\vartheta^2}_{ms}/l_c. \quad (11)$$

Comparing (11) with Bethe-Heitler formula (9) we see that

$$\frac{dE_{LP}}{d\omega} \ll \frac{dE_{BH}}{d\omega}. \quad (12)$$

Thus, Landau and Pomeranchuk showed that character of high energy electron radiation in an amorphous medium has changed considerably at $\gamma^2\bar{\vartheta}^2{}_{ms} \approx 1$, e.g. in the region of electron energies and photon frequencies for which the mean square angles of multiple scattering in the limits of coherence length is compared with the square of the typical radiation angles of relativistic electrons ${\theta_k}^2 \approx \gamma^{-2}$. However the formula (11) has only qualitative character.

The quantitative theory of the multiple scattering effect on an electron radiation in an amorphous medium was offered by Migdal in [22]. This theory was based on the application of the kinetic equation method to the given task. Migdal obtained the following formula for a spectrum of electron radiation in an amorphous medium at $\omega \ll \varepsilon$

$$\frac{dE}{d\omega} = \left(\frac{dE}{d\omega}\right)_0 \cdot \Phi_M(s), \quad (13)$$

where $(dE/d\omega)_0$ is the spectrum of radiation without taking into account the multiple scattering influence on radiation (this value coincides with the corresponding result of Bethe and Heitler (9) with a logarithmic accuracy) and $\Phi_M(s)$ is the function, obtained by Migdal, which describes the influence of multiple scattering on radiation

$$\Phi_M(s) = 24s^2\left\{\int_0^\infty dt\, \coth t\, e^{-2st}\sin 2st - \frac{\pi}{4}\right\}. \quad (14)$$

The parameter s is determined by the expression

$$s = \frac{1}{2\sqrt{2}}\sqrt{\frac{\omega}{\omega_{LPM}}}\,, \qquad (15)$$

where

$$\omega_{LMP} = 16\pi Z^2 e^4 n\, m^{-4}\varepsilon^2\, ln(mR)\,. \qquad (16)$$

The value ω_{LMP} determines the range of gamma quanta energies, starting with which the multiple scattering influences radiation spectrum essentially.

The Migdal function is close to unity at $s > 1$, i.e. at $\omega > \omega_{LPM}$. The spectrum of radiation in this case coincides with the corresponding result of Bethe and Heitler (9).

If $s \ll 1$,

$$\Phi_M(s) \approx 6s. \qquad (17)$$

The intensity of radiation in this case is much less, than the corresponding result of Bethe and Heitler. The formula (13) with the asymptotic (17) differs from the qualitative result (11) only by numerical coefficient. Considering the important Migdal's input to the theory of this effect it is now called the Landau-Pomeranchuk-Migdal effect (the LPM-effect).

The quantitative theory of the LPM-effect was developed by Migdal for a boundless amorphous medium [22]. This approach is quite applicable if the thickness of the target is rather big in comparison with a coherence length of radiation process $t \gg l_c$. However, at rather high energies of electrons and small energies of radiated photons the opposite condition can be realized:

$$l_c \gg t\,, \qquad (18)$$

i.e., if the coherent length of radiation is greater than the target thickens t. The radiation process in this case was studied on the basis of kinetic equation method [18], the classical theory of radiation [19,20] and the theorem of factorization for radiation cross-section in QED [35]. Here, we outline briefly the second one as the easiest way to analyze the physics of the multiple scattering effect on radiation is this case and to obtain the quantitative results and to compare them with the experimental results.

4. RADIATION IN A THIN LAYER OF MATTER

In classical electrodynamics the spectral angular density of radiation is determined by the formula (see [17,21,23])

$$\frac{d^2E}{d\omega do} = \frac{e^2}{4\pi^2}\left|\vec{k}\times\vec{I}\right|^2, \qquad (19)$$

where $\vec{k} = \omega\vec{n}$ is the wave vector in the direction of radiation $\vec{n}$ and

$$\vec{I} = \int_{-\infty}^{\infty} dt\,\vec{v}(t)e^{i(\omega t - \vec{k}\cdot\vec{r}(t))}. \qquad (20)$$

Here $\vec{v}(t)$ and $\vec{r}(t)$ are the velocity and the position vector of the electron at a moment of time t, and do is the element of solid angle near the unit vector $\vec{n}$.

Integrating (20) by parts, it is easy to show that

$$\vec{I} = i\int_{-\infty}^{\infty} dt\, e^{i(\omega t - \vec{k}\cdot\vec{r}(t))}\frac{d}{dt}\frac{\vec{v}(t)}{\omega - \vec{k}\cdot\vec{v}(t)}. \qquad (21)$$

This representation of $\vec{I}$ is rather convenient, since the integrand in (21) is different from zero only in the region of an external field, i.e. within the target, when the acceleration of the particle is nonzero.

For high energies, the typical angles of the particle scattering in the external field are small. Thus, the vector of the particle velocity $\vec{v}(t)$ can be represented in the form

$$\vec{v}(t) \approx \vec{v}\left(1 - \frac{1}{2}v_{\perp}^2(t)\right) + \vec{v}_{\perp}(t), \qquad (22)$$

where $\vec{v}$ is the initial velocity of the electron and $\vec{v}_{\perp}(t)$ is its transversal velocity in the external field, $v_{\perp}(t) \ll v$, $\vec{v}_{\perp}(t) \perp \vec{v}$. If, in the region of action of the external field on the particle, the phase factor of the exponent $\exp\left[i(\omega t - \vec{k}\cdot\vec{r}(t))\right]$ is small in comparison with unity, the exponent in (21) can be replaced by unity and

$$\vec{I} \approx i\left(\frac{\vec{v}'}{\omega - \vec{k}\cdot\vec{v}'} - \frac{\vec{v}}{\omega - \vec{k}\cdot\vec{v}}\right), \qquad (23)$$

where $\vec{v}$ and $\vec{v}'$ are the velocities of the electron before and after its interaction with the target.

Substituting this relation for $\vec{I}$ into (19), after integrating over solid angles of radiation do, we obtain the following expression for the spectral density of radiation:

$$\frac{dE}{d\omega} = \frac{2e^2}{\pi}\int d^2\theta\, f(\theta,t)\times \left[\frac{2\xi^2+1}{\xi\sqrt{\xi^2+1}}\ln\left(\xi+\sqrt{\xi^2+1}\right) - 1\right], \qquad (24)$$

where $\xi = \gamma\theta/2$, θ is the angle of particle scattering by the target and $f(\theta,t)$ is the distribution function over particle scattering angles θ depending on the target thickness t.

The formula (24) shows that at realization of the condition (18) the spectral density of radiation is determined only by the scattering angle of a particle and does not depend on the details of its trajectory in a target. Therefore, the formula (24) can be used when studying radiation of particles, both in crystalline, and amorphous targets. The difference between the processes of radiation in these cases is determined only by distribution function of scattered particles on angles.

The formula (24) has simple asymptotes at small and large values of a mean square angle of multiple scattering of particles by the target $\bar{\vartheta}^2{}_{ms}$:

$$\frac{dE}{d\omega} \approx \frac{2e^2}{3\pi}\gamma^2\bar{\vartheta}^2{}_{ms}, \quad \gamma^2\bar{\vartheta}^2{}_{ms} \ll 1,$$
$$\frac{dE}{d\omega} \approx \frac{2e^2}{\pi}\ln(\gamma^2\bar{\vartheta}^2{}_{ms}), \quad \gamma^2\bar{\vartheta}^2{}_{ms} \gg 1. \qquad (25)$$

In the amorphous target the value $\bar{\vartheta^2}_{ms}$ is proportional to the thickness t. Thus, if $\gamma^2\bar{\vartheta^2}_{ms} \ll 1$, the formula (25) transforms into the corresponding result of Bethe and Heitler (9). If $\gamma^2\bar{\vartheta^2}_{ms} \gg 1$, then according to (25), the linear dependence of dE/dw from L is replaced by a weaker logarithmic one. It means, that at realization of the condition $\gamma^2\bar{\vartheta^2}_{ms} \gg 1$ the effect of suppression of radiation as contrasted to the corresponding result of Bethe and Heitler takes place.

The root-mean-square angle of electron multiple scattering on atoms in an amorphous medium at the depth t is inversely proportional to the electron energy ε [23,36]

$$\sqrt{\bar{\vartheta^2}_{ms}(t)} = (\varepsilon_s/\varepsilon)\sqrt{t/X_0}\,[1 + 0.038ln(t/X_0)]\ ,$$
$$\varepsilon_s^2 = 4\pi \cdot m^2/e^2\ , \tag{26}$$

so, the target thickness l_γ, at which $\sqrt{\bar{\vartheta^2}_{ms}(l_\gamma)} = \gamma^{-1}$ does not depend on the electron energy ε and is determined by the target material only $l_\gamma \approx 0.15\% X_0$.

Thus, the condition of the suppression of radiation due to the multiple scattering effect $\sqrt{\bar{\vartheta^2}_{ms}(l_c)} > \gamma^{-1}$ (so-called non-dipole regime of radiation) can be written in the following form:

$$l_c > l_\gamma\,. \tag{27}$$

If $t < l_\gamma$, i.e. the target thickness t is less than $0.15\%\, X_0$, the spectral density of radiation for all possible emitted photon energies is defined by the Bethe-Heitler formula (9).

If $t > l_\gamma$, there are three possible regimes of radiation in this case depending on the energy region of emitted photon.

For the relatively hard part of emitted spectrum, when $l_c < l_\gamma$, we have a dipole regime of radiation describing by the Bethe-Hietler formula (9) too.

For the non-dipole radiation, $l_c > l_\gamma$, there are two regions, defined by the ratio between the coherence length l_c and the target thickness t, with quite different behavior of radiation spectrum. If the target thick enough, $t \gg l_c > l_\gamma$, the Migdal theory [22] of the LPM effect, which describes the suppression of radiation in a boundless amorphous medium, is applicable. For relatively thin target, $l_c \gg t > l_\gamma$ (intermediate case), the TSF mechanism of radiation [18,19] is realized.

The condition (27) determines the photon energy region, where the LPM effect is essential:

$$\omega < \omega_{LPM} = \frac{\varepsilon}{1 + \varepsilon_{LPM}/\varepsilon}\,, \tag{28}$$
$$\varepsilon_{LPM} = \frac{e^2 m^2}{4\pi} X_0 \approx 7.7\,TeV \cdot X_0\,(cm)\,.$$

It means that for ultra high electron energy ($\varepsilon \gg \varepsilon_{LPM}$) the whole radiation spectrum is suppressed due to the LPM effect: $\omega_{LPM} \approx \epsilon$.

If $\varepsilon \ll \varepsilon_{LPM}$, then $\omega_{LPM} \approx \frac{\varepsilon^2}{\varepsilon_{LPM}} \approx \frac{1600\gamma^2}{X_0}$.

The upper limit for the emitted photon energy for the TSF regime of radiation TSF follows from the TSF effect condition

$$l_c \gg t > l_\gamma\,. \tag{29}$$

It is defined by equality $t = l_c$ and can be written in the following form:

$$\omega_{TSF} = \frac{\varepsilon}{1 + \varepsilon_{TSF}/\varepsilon}\,, \tag{30}$$
$$\varepsilon_{TSF} = \frac{m^2 t}{2} \approx 6.6\,PeV \cdot t(cm)\,.$$

If $\varepsilon \gg \varepsilon_{TSF}$, one can use simpler expression for the TSF effect threshold $\omega_{TSF} \approx 2\gamma^2/t$.

Modification of character of electron radiation in a thin layer of substance happens under the same conditions, as in case of the LPM effect. However, the radiation spectral densities (13) and (24), essentially differ (the dependencies from t, ε and ω are different). It is related to the fact that the formula (24) is valid at realization of the condition $l_c \gg t$, whereas the formula (13), describing the LPM effect is valid at $l_c \ll t$.

In an amorphous target the function $f(\theta, t)$ is the Bethe -Moliere distribution function [36] which takes into account both single and multiple scattering of particle in a medium. Thus the formula (24) takes into account both single and multiple electron scattering in a target. At $t \to 0$, when we can neglect the influence of the multiple scattering on radiation, the formula (24) transforms into the corresponding result of the Bethe-Heitler theory. (We need to note that the Bethe-Heitler result is obtained with logarithmic accuracy in the Migdal theory.) The analysis of the formula (25) has shown [37,38] that the Bethe-Heitler result is also true at the condition $\gamma^2\bar{\vartheta^2}_{ms} \ll 1$.

If $\gamma^2\bar{\vartheta^2}_{ms} \gg 1$, as it was shown in [38], first several terms of the distribution of the formula (24) on the parameter a^{-2}, where $a = \gamma^2$, have the following form

$$\frac{dE}{d\omega} = \frac{2e^2}{\pi}\left[(\ln a^2 - C))\left(1 + \frac{2}{a^2}\right) + \frac{2}{a^2} + \frac{C}{B} - 1\right], \tag{31}$$

where C is the Euler constant, $B - \ln B = \ln(\chi_c^2/\chi_1^2) + 1 - 2C$, $\chi_c^2 = 4\pi n Z^2 e^4 t/(pv)^2$ and $\chi_1 = 1/pR$.

We want to emphasize that consideration of several terms of distribution in (31) is very important for comparing the theory predictions with the $SLAC$ experimental data [24-26].

The asymptotes (25) show that at $t \ll l_\gamma$ (that means $\xi \ll 1$) the formula (24) gives the Bethe-Hietler result with the linear dependence from the target thickness. In the opposite case, i.e. at $t \gg l_\gamma$, the formula (24) gives the only logarithmic increasing of radiation power spectral density with the target thickness increasing.

Such a strange behavior of radiation power (the scattering angle still increase linearly with thickness, but radiation no) can be explain by relativistic delay effect during regeneration of the own Coulomb field of relativistic electron after its scattering on a big angle $\sqrt{\vartheta^2{}_{ms}} > \gamma^{-1}$, and it can be treated as a radiation of the "half-bare" electron, i.e. the electron with non-equilibrium own Coulomb field (see [20,23,39] for detailed discussion). This logarithmic behavior will be changed for the linear one again when the target thickness reaches the value of coherence length for the given photon energy ω.

The quantum treatment of the TSF effects was done in [35,40-42] using different approaches and it is became an important for ultra high electron energy $\varepsilon \gg \varepsilon_{TSF}$), when $\omega_{TSF} \approx \varepsilon$ and the whole radiation spectrum is suppressed due to the TSF effect.

There are two additional factors that have essential influence on radiation process in matter, namely, the dielectric suppression (or the Ter-Mikaelian effect [33]) and the transition radiation from the target bounds [26,33]. Both these effects could be neglected, if we consider the photons energy higher than $\omega_0 = \gamma\omega_p$, where ω_p is the plasma frequency [33]. For tantalum target and the electron beam energy $\varepsilon = 150\,GeV$ this threshold is about $\omega_0 \approx 25\,MeV$.

The qualitative difference between the different regimes of radiation in amorphous matter, namely the BH, LPM and TSF regimes and their consequent changing clear demonstrates the thickness dependence of the radiation power spectrum $dE/d\omega$. The results of theoretical calculations of such dependence are represented in Fig.1.

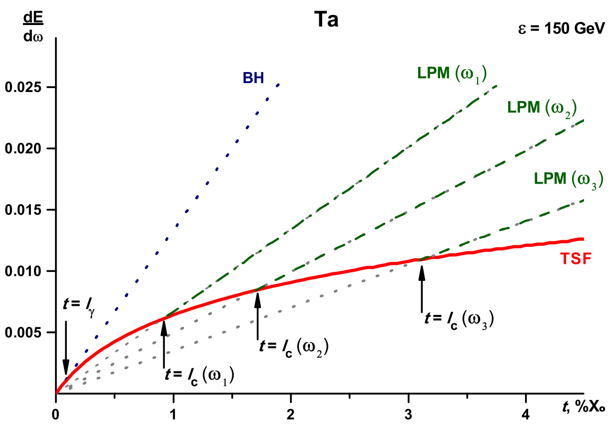

Fig.1. *The radiation power spectrum of* $150\,GeV$ *electrons in tantalum target via target thickness* t $(\%\,X_0)$. *The detailed description of curves is given in text*

For $t < l_\gamma$, i.e. when the target thickness t is too small that the multiple scattering of relativistic electrons in target is not enough to fulfill the condition (27), the radiation process has a dipole character and the radiation power spectrum is described by the Bethe-Hietler formula (9). The soft part of the Bethe-Hietler spectrum ($\omega \ll \varepsilon$) does not depend on ω and describes by a very simple formula $dE_{BH}/d\omega = 4t/3X_0$. The corresponding curve is presented in Fig.1 by dashed straight line "BH".

At the target thickness increasing the condition $t = l_\gamma$ could be fulfilled, and at this point the dipole regime of radiation is changed for the non-dipole that leads to suppression of radiation comparing with the Bethe-Hietler formula predictions. For relatively soft photons, for which $l_c \gg t$, the radiation power for this part of radiation spectrum is determined by the formula (31) that means the TSF regime of radiation with a logarithmic dependence on the target thickness t (solid line "TSF" in Fig.1). As it follows from eq. (31) $dE_{TSF}/d\omega$ does not depend on the emitted photon energy ω , however, the validity condition of the TSF regime (29) depends. It means that for different ω_n the transition from the TSF to LPM regime of radiation takes place at different values of target thickness $t_n = l_c(w_n)$. In Fig.1 there are three such points market by arrows for different photon energies ω_n , namely $\omega_1 = 150$, $\omega_2 = 350$ and $\omega_3 = 800\,MeV$. There are also three different dot-dashed lines "LPM", which are calculated using the Migdal formulae (13) and (14) for these values of photon energy respectively. Thus, changing the target thickness one can consequently observe three different mechanisms of radiation of relativistic electron in amorphous target such as the BH, TSF and LPM.

5. THE EXPERIMENTAL STUDIES OF THE LPM AND TSF EFFECTS

Besides the theoretical interest, the LPM effect is relevant in a variety of physics areas, ranging from the design of calorimeters for the LHC to ultra high energy cosmic rays. Many nuclear effects, including the "colour transparency" suppression of nuclear reactions, are closely related (see, e.g., [26] and references therein).

The first experiments on detection of the LPM effect were conducted using of cosmic rays [40,41] and secondary electron beams with the energy of $40\,GeV$ on the protons accelerator of IHEP (Protvino, Russia) [42]. Because of the insufficient statistics of measurements these experiments could only deal with qualitative confirmation of the LPM effect existence.

The detailed experimental investigation of the LPM effect was carried out only 40 years after its prediction. This experiment was carried out in 1993-95 on SLAC accelerator at the electron energies 8 and $25\,GeV$ [24-26]. In this experiment (SLAC E-146) there were measured the spectra of bremsstrahlung in the region of relatively small energies of gamma-quanta ω (from $200\,keV$ up to $500\,MeV$) for targets produced from different materials (from carbon to uranium) and in a rather wide interval of target thickness t (from $0.1\,\%$ up to $6\,\%$ of radiation lengths X_0).

The analysis of the data obtained showed a good agreement between the predictions of the Migdal theory of the LPM effect and the experiment for relatively thick targets and not very low photon energies. For theoretical description of experimental data at the photon energy region from several MeV and below it was necessary to take into account the superposition of several effects, such as the LPM effect, the Ter-Mikaelian effect (or "dielectric suppression"), transition radiation (see [26]). However, even after that for the case of golden target of 0.7% of radiation length thickness there was a significant disagreement between theory and experiment. Such "unexpected" behavior of the radiation spectrum at low frequencies was named in [24] as "edge effect" and there was an attempt to exclude it by subtraction procedure, because "no satisfactory theoretical treatment of this phenomenon" (see [24]) was found for that moment. Actually, they found out the Ternovskii article [18], in which the Migdal theory of the LPM effect developed for boundless amorphous medium was improved for the finite target thickness case. However, when they tried to use the Ternovskii formula to describe the "edge effect", they obtained the excess of the Bethe-Heitler result [32] instead of the expected suppression, and they wrote in [24] that this formula gives "unphysical result". The discrepancy observed in SLAC experiment stimulated a new wave of theoretical investigations of the multiple scattering effect on radiation (see [34,35,37,38,40-45]).

In [37] it was shown that the deviation from predictions of the Migdal theory observed in [24-26] takes place when the target thickness t is small in comparison with the coherence length of radiation process l_c, and the "unphysical result" obtained by the Ternovskii formula in [24] is connected with the usage of the asymptotic formula for a mean-square angle of multiple scattering, which is not applicable for the SLAC experiment E-146 conditions.

The most demonstrative example of the presence of different mechanisms of radiation at the SLAC E-146 experiment gives by measurements of radiation spectrum from golden target of different thicknesses represented in Fig.2.

The quantitative theory of the radiation suppression effect in a thin layer of matter was developed later in [34,35,37,38,40-42] using different approaches. The results obtained in these works are in a good agreement with the SLAC experimental data for the thin golden target (see, for example, reviews [23,26]). However, it was the only one explicit manifestation of this effect during the SLAC experiment E-146 and it took place in a relatively narrow photon energy region for 25 GeV electrons. That is why it was necessary to carry out a special experimental investigation of this effect at higher electron energy that gives a wider photon energy region for observation of this effect and, that is even more important, to study the thickness dependence of radiation intensity in a thin-target case, which is essentially differ from the BH and LPM regime of radiation (see [26]). The higher energy of electron beam gives also a possibility to separate the radiation spectrum regions, where the influence of the above mentioned different mechanisms of radiation is overlapped.

A new experimental study of the LPM and analogous effects at essentially higher electron energies (up to $\varepsilon = 287\,GeV$) was carried out recently at CERN by the NA63 Collaboration (see [20,21] and also [27-31]).

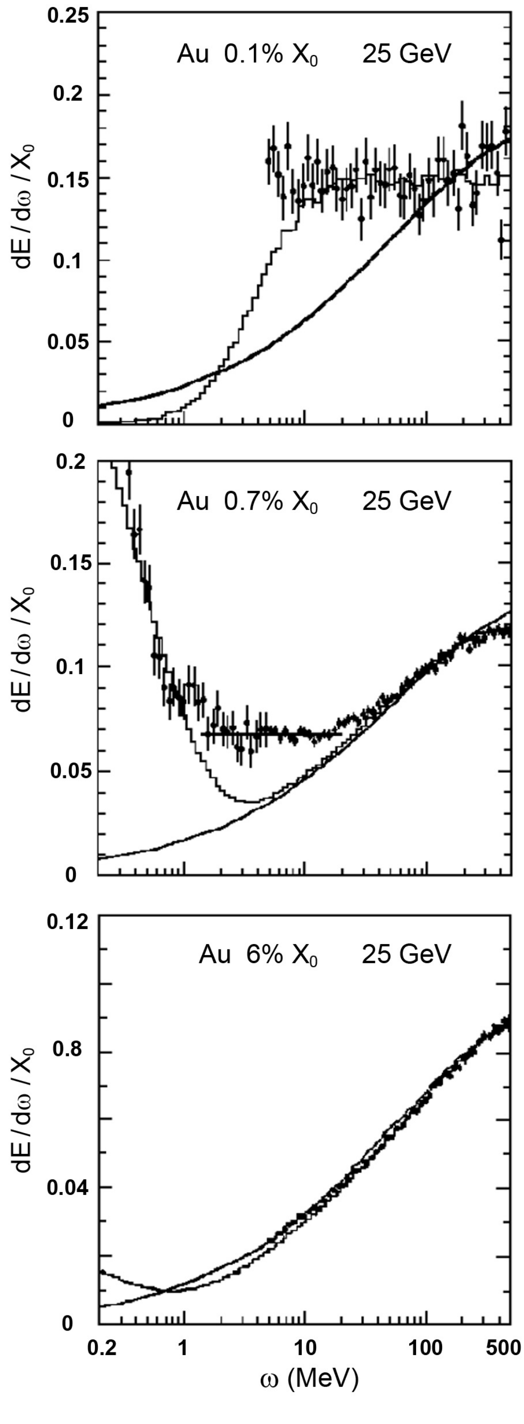

Fig.2. *Radiation spectra of 25 GeV electrons in the golden targets of thickness 0.1, 0.7 and 6% of radiation length X0. The solid curves in these figures correspond to the results of calculations under the Migdal formula (13), histograms are the results of the Monte-Carlo simulation of radiation spectrum including dielectric suppression and transition radiation [26], straight line is the result of calculations using formula (31)*

The results of measurements for Ir, Ta and Cu targets with thicknesses about 4% of the radiation length showed good agreement with the Migdal theory of the

LPM effect [22]. The effect of suppression of radiation in a thin target, named in these papers as the Ternovskii-Shul'ga-Fomin (TSF) effect, was also considered, however, the photon energy region, in which the TSF effect could be observed for chosen target thicknesses, was below the energy threshold of measured photons $\omega_{min} = 2\,GeV$ for both experiments [27,28]. The condition for the successful observation of the TSF effect in radiation spectrum was realized later in CERN for 206 and 234 GeV electrons radiation in Ta targets of 5...10 μm thickness [29].

Finally, the most important measurements for demonstration of the TSF effect essence, namely the logarithmic thickness dependence of radiation intensity in a thin target, were successfully carried out recently by the CERN NA63 collaboration [30]. In spite of all difficulties connected with a very complicate experimental installation and by operating with a set of very thin targets of several micrometers thickness, this experiment gave a conclusive proof of the suppression effect of relativistic electron radiation in a thin layer of matter predicted many years ago [18,19] and per se it gave the unique demonstration of the space-time evolution of the radiation process in matter as an example of radiation of ultra relativistic electron with non-equilibrium own Coulomb field [20,23,32].

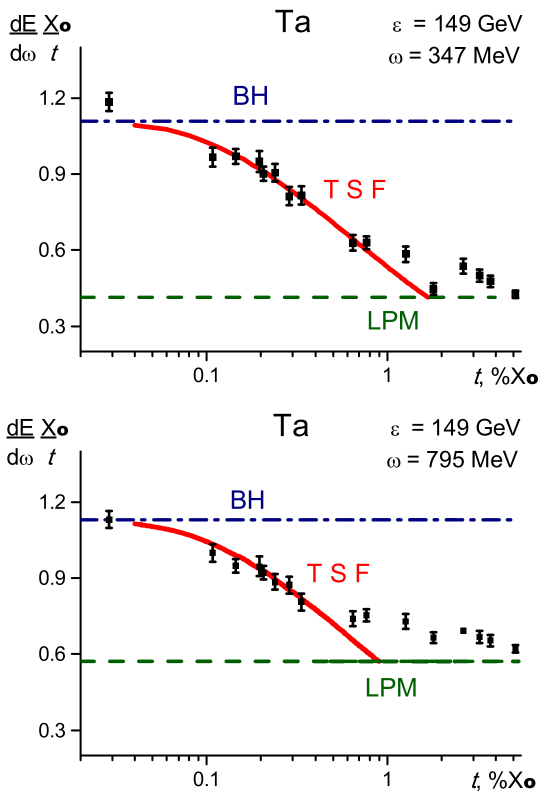

Fig.3. *The radiation power per unit length for 149 GeV electron radiation in tantalum target via target thickness t ($\%\,X_0$). The detailed description of curves is given in text*

The comparison of experimental data with the results of calculations using different approaches presented in [29,30] shows a good not only qualitative, but also quantitative agreement. In this short paper we present the comparison of the results of our calculation with the experimental data [30] only for two values of the emitted photon energy $\omega = 347$ and 795 MeV (Fig.3). Following [30] we present here the radiation power spectrum per unit length, i.e. as $dE/d\omega$ multiplied by X_0/t. In these units the linear dependence of the radiation power spectrum for the BH (dot-dashed line) and LPM (dashed line) regimes of radiation are the constants (see Fig.3). The curves TSF shows the logarithmic behavior of the radiation power spectrum in the intermediate region $l_c > t > l_\gamma$ for given ω.

For numerical calculations we used the original Fortran code based on the same formulas as the calculations of the SF curves presented in figures in [29,30]. Following [30] we took into account the multiphoton effect by corresponding normalization on the BH radiation spectrum. The results of our calculations give a little excess (about 10%) over the results presented in [29,30] by SF curves in all figures, thereby they have a good agreement with experimental data (see, for example, Fig.3). The essential discrepancy observing around the point $t = l_c$ is easily explainable by the fact that the Migdal theory of the LPM effect is applicable at $t \gg l_c$ while the eq.(24) for the TSF regime of radiation is derived for $t \ll l_c$. In the intermediate region ($2l_c > t > l_c/2$) we have a smooth transition between these two regimes.

To summarize (Fig.4), the bremsstrahlung power spectrum level has been computed in the t, l_c and l_γ parameter space for a fixed electron energy $\varepsilon = 200\,GeV$ and tantalum target. The relative areas of applicability of different mechanisms of radiation at high energy region are shown in Fig.4, which is taken from the H.Thomsen's PhD dissertation [31]. The above discussed bremsstrahlung regimes: Bethe-Heitler (BH), Landau-Pomeranchuk-Migdal (LPM) and Ternovskii-Shul'ga-Fomin (TSF) are in the plot bordered by black lines. The abscissa shows the foil thickness in units of the multiple scattering length l_γ, while the ordinate shows the formation length, also in units of l_γ. Following the definition of considerable multiple Coulomb scattering within the formation length, only the BH regime is located below $l_c/l_\gamma < 2$. This regime is also present for very thin target, $t/l_\gamma < 1$. The diagonal line illustrates the characteristic threshold between the TSF and LPM regimes $t = l_c$. Generally, the matching between the TSF and LPM regimes is not complete, as this transition is not described by any analytical expression. Moving along a horizontal line in the figure corresponds to the thickness dependence for a fixed value of ω, while a vertical line gives the photon energy dependence for a fixed thickness. The direction of growing ω is indicated by the vertical arrow, $l_c \sim 1/\omega$. The special LPM photon energy dependence, $\sim \sqrt{\omega}$, is distinct. Also, the logarithmic thickness dependence in the TSF regime is very different from the linear one in the case of

BH and LPM. The plot is for illustration purposes only and encapsulates the tendencies shown in Fig.4.

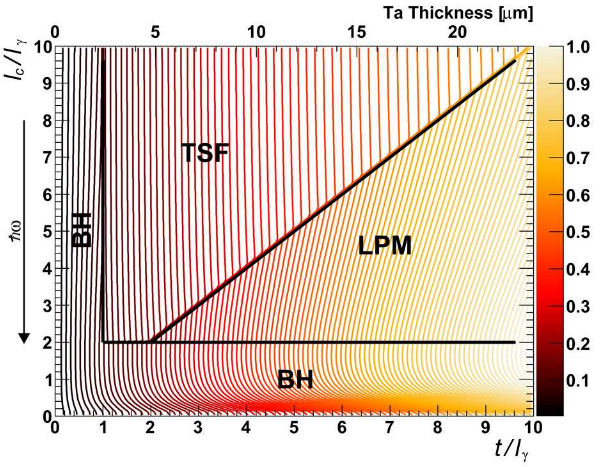

Fig.4. The bremsstrahlung power spectrum level (in arbitrary units) in the t, l_c and l_γ parameters space [31]. The contour lines trace lines of equal bremsstrahlung yield. Upper horizontal axis shows the equivalent tantalum thickness

As it was shown later in [43] the non-dipole regime of radiation changes essentially not only spectrum of emitted gamma quanta, but also their angular distribution. In [44] it was proposed to use special features of angular characteristics of non-dipole coherent radiation in a thin crystal for production of the intensive photon beams with high degree of linear polarization.

This idea is based on the fact that the non-dipole regime of radiation, when the scattering angle becomes bigger than the characteristic angle of radiation of relativistic electron γ^{-1}, gives a possibility to avoid a mixture of the radiation emitted under the different (more than γ^{-1}) angles. Using the photon collimators with angular width about γ^{-1} one can organize the space-angular separation of photons emitted by electrons that were scattered at essentially different directions.

6. CONCLUSIONS

We have shown only a small part of the results obtained while developing the new methods of description of high energy electron radiation out of the condition of applicability of the Born approximation. It was demonstrated that on the basis of developed methods it is possible to describe the effects connected to the large effective coupling constant, and to obtain not only qualitative, but also quantitative results.

One of the most interesting physical result obtained using developed approach, which was recently confirmed by SLAC and CERN experiments, is the effect of suppression of the radiation of ultra relativistic electrons in a thin layer of matter [30,45]. The experimental observation of logarithmic dependence of radiation yield from the target thickness [30] is the first direct demonstration of the suppression of radiation effect for a relativistic electron with non-equilibrium own Coulomb field (TSF effect), which was predicted and theoretically studied in [18-20]. This effect is an example of the interaction process with a large effective coupling constant, and it should have its analog also in QCD at quark-gluon interaction.

The theoretically predicted special features of angular distribution of radiation and its polarization at the TSF-effect condition [44,45] are proposed for a new experimental study at SLAC and CERN.

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К ТЕОРИИ ИЗЛУЧЕНИЯ В УСЛОВИЯХ БОЛЬШОЙ ЭФФЕКТИВНОЙ КОНСТАНТЫ СВЯЗИ

С.П. Фомин, Н.Ф. Шульга

Представлен краткий исторический обзор одного из направлений исследований взаимодействия частиц высокой энергии с веществом при больших значениях эффективной константы связи. Рассмотрение ведется на примере тормозного излучения ультрарелятивистских электронов в аморфной мишени и в кристалле в случае, когда длина когерентности излучения значительно превышает длину свободного пробега частицы в веществе и многократное рассеяние оказывает существенное влияние на процесс тормозного излучения. Проведено сравнение результатов теоретических расчетов с данными недавних экспериментов, выполненных в СЛАК и ЦЕРН.

ДО ТЕОРІЇ ВИПРОМІНЮВАННЯ В УМОВАХ ВЕЛИКОЇ ЕФЕКТИВНОЇ КОНСТАНТИ ЗВ'ЯЗКУ

С.П. Фомін, М.Ф. Шульга

Представлено короткий історичний огляд одного з напрямків досліджень взаємодії частинок високої енергії з речовиною при великих значеннях ефективної константи зв'язку. Розгляд ведеться на прикладі гальмівного випромінювання ультрарелятивістських електронів у аморфній мішені у випадку, коли довжина когерентності випромінювання значно перевищує довжину вільного пробігу частинки в речовині й багатократне розсіювання впливає на процес гальмівного випромінювання. Проведено порівняння результатів теоретичних розрахунків з даними недавніх експериментів, виконаних у СЛАК і ЦЕРН.