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INFLUENCE OF MULTIPLE SCATTERING ON BREMSSTRAHLUNG BY RELATIVISTIC ELECTRONS IN A THIN ORIENTED CRYSTAL

S.P. Fomin[1,2,3], I.V. Kyryllin[1,3], M.S. Malovytsia[1,3], S.M. Shulga[1], G. Kube[2], A. Novokshonov[2], S. Strokov[2], A. Fomin[4]
[1]NSC "Kharkiv Institute of Physics and Technology", Kharkiv, Ukraine;
[2]Deutsche Elektronen-Synchrotron (DESY), Hamburg, Germany;
[3]V.N. Karazin Kharkiv National University, Kharkiv, Ukraine;
[4]Irene Joliot-Curie Laboratory (IJCLab), Orsay, France
E-mail: spfomin@gmail.com

The effect of multiple scattering on the bremsstrahlung of ultra relativistic electrons on the lattice atoms of a thin oriented crystal is investigated. It is shown that when the condition of dipole mode of radiation is violated, a radiation suppression effect should take place. This effect is similar to the Ternovskii-Shul'ga-Fomin effect of radiation suppression in a thin amorphous target, but in the case of a thin oriented crystal the coherent bremsstrahlung is suppressed. The conditions for experimental observation of this effect at the DESY accelerator is discussed.

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INTRODUCTION

Landau and Pomeranchuk showed [1] that the multiple scattering of ultra relativistic electrons on the atoms of matter can lead to the suppression of bremsstrahlung compared to the predictions of the Bethe-Heitler theory [2]. This occurs when the RMS angle of multiple scattering of an electron on atoms within the radiation formation zone, or coherence length [3] exceeds the characteristic angle of the relativistic electron radiation $1/\gamma$, where γ is the electron Lorenz factor. A quantitative theory of this effect was later developed by Migdal [4], and now this phenomenon is known as the Landau-Pomeranchuk-Migdal (LPM) effect [5].

The experimental verification of the Migdal theory was carried out at SLAC for the electron beam energies up to 25 GeV, using a wide range of target thicknesses and kind of materials: from aluminum to uranium [6,7]. The results of this study generally confirmed the predictions of the Migdal theory of the LPM effect [4]. However, in the case of relatively thin targets, some discrepancies with the Migdal theory were observed.

In [8] it was shown that these discrepancies in the SLAC experiment were related to the suppression of bremsstrahlung in a thin layer of matter, a phenomenon theoretically predicted earlier in [9, 10].

A quantitative theory of the radiation suppression effect in a thin layer of matter was developed in [11, 12]. A detailed experimental study of this effect was carried out by the NA63 collaboration at the CERN SPS accelerator at electron energies up to 250 GeV [13,14]. After the experimental confirmation of the main predictions of the theory [8-12], this effect was named the Ternovskii-Shul'ga-Fomin (TSF) effect after the authors of the theoretical prediction.

Although both the LPM and TSF effects are of the same nature, namely the impact of multiple scattering on radiation, they give significantly different dependencies of the radiation spectral density on the emitted photon energy and, especially, on the target thickness.

Note that the TSF effect is a direct manifestation of radiation by so-called "half-naked" electron or an electron with non-equilibrium own Coulomb field (see [5, 10, 14].

Analogues of LPM and TSF effects should also occur when relativistic electrons pass through oriented crystals [5, 9, 10, 15], but in this case, coherent bremsstrahlung will be suppressed.

In the CERN experiment to study channeling radiation [16], the LPM effect was observed in a relatively thick crystal. An experimental study of the TSF effect in oriented crystals has not yet been carried out.

In this paper, the possibility of setting up an experiment to study the TSF effect in thin crystals at the DESY accelerators is examined. Preliminary analysis shows that the presence of a coherent effect in the scattering and radiation of relativistic electrons in the crystal makes it possible to observe the TSF effect at electron energies up to 6 GeV at the DESY II booster.

1. EFFECT OCCURRENCE CONDITIONS

The main condition for the occurrence of both the LPM and TSF effects is the violation of the dipole radiation regime, that is, the excess of the RMS angle of multiple scattering of an electron within the coherence length of radiation l_c [3] over the characteristic radiation angle of the relativistic electron $\theta_k \sim 1/\gamma$, i.e.

$$\gamma\theta_{ms}(l_c) > 1. \quad (1)$$

The coherence length of the bremsstrahlung increases rapidly with increasing electron energy and decreasing energy of the emitted gamma quantum [3]:

$$l_c \approx {2\varepsilon\varepsilon'}/{m^2\omega}, \quad (2)$$

where ε and ε' are the electron energy before and after radiation, m is the electron mass, ω is the energy of the emitted gamma quantum, $\varepsilon = \varepsilon' + \omega$ ($c = \hbar = 1$).

The Migdal theory of the LPM effect [4] describes radiation in an infinite amorphous medium, and therefore is suitable for describing the effect of multiple scattering on bremsstrahlung in relatively thick targets when $T > l_c$. To describe radiation in a thin target when $T < l_c$, the approach developed in [11,12] can be used.

For the TSF effect to occur, two conditions must be met simultaneously: the first is a "thin target" $T < l_c$, and the second the non-dipole radiation regime (1), i.e.

$$l_c > T > l_\gamma. \quad (3)$$

By solving the left side of this inequality with respect to the energy of the emitted gamma-quantum using expressions (2), we obtain

$$\omega < \omega_{TSF} \equiv 2\gamma^2/T, \quad (4)$$

where ω_{TSF} is the boundary energy of the gamma quantum, separating the regions of the spectrum of bremsstrahlung, in which two effects of radiation suppression are realized: TSF (at $\omega < \omega_{TSF}$) and LPM (at $\omega > \omega_{TSF}$). Recall that in both of these cases we are talking about a non-dipole radiation regime when condition (1) is satisfied, which in terms of the energy of gamma quanta can be represented as

$$\omega < \omega_{LPM} \equiv \frac{32\pi Z^2 e^4 n}{m^4}\varepsilon^2 \ln(mR), \quad (5)$$

where $Z|e|$ is the charge of an atomic nucleus, and R is the screening radius of the Coulomb potential of the atomic nucleus.

In this case, ω_{LPM} is the boundary energy of the gamma quantum, below which the non-dipole mode of radiation is realized, and both effects of radiation suppression of LPM and TSF can take place. The contribution of so-called dielectric suppression, or Ter-Mikaelian effect [3] is dominant in the soft part of the spectrum at

$$\omega < \gamma\omega_p. \quad (6)$$

When preparing an experiment to test the TSF effect in a crystal, it is necessary to select such a region of the spectrum of the emitted gamma quanta in which this effect could be observed most clearly and without interference with other mechanisms of radiation suppression. Simultaneous consideration of conditions (4) and (6) determines the optimal region of the radiation spectrum for observing the TSF effect as:

$$\gamma\omega_p < \omega < 2\gamma^2/T\ . \quad (7)$$

At the same time, the condition of non-dipole radiation must also be satisfied, i.e. the inequality (1), in which instead of θ_{ms} the RMS angle of coherent scattering of the particle in the crystal θ_{cr} should be used, and the coherence length l_c must be replaced by the crystal thickness T_{cr} according to condition (3). Thus, for radiation in a thin oriented crystal, the non-dipole condition has the form:

$$\gamma\theta_{cr}(T_{cr}) > 1. \quad (8)$$

For example, in the case of using a silicon crystal with the thickness of $T_{cr} = 10$ μm oriented along the <111> axis to the electron beam with the energy ε = 6 GeV condition (7) gives:

$$0.3\ \text{MeV} < \omega < 4\ \text{MeV}. \quad (9)$$

2. COHERENT EFFECT IN SCATTERING OF FAST ELECTRON IN CRYSTAL

Unlike in an amorphous substance, atoms in a crystal are arranged strictly periodically. If a relativistic charged particle moves along one of the crystal axes, then there are significant correlations in the interactions with atoms located along this axis that can lead to signifi-cant differences in electrodynamic processes in crystals compared to an amorphous medium.

Moving in the crystal at a small angle ψ to a crystal axis (axis z in Fig. 1), the relativistic electron periodically collides with atoms located along this axis. Due to weak scattering on each individual atom, the fast electron will move almost rectilinearly with only minor changes in the impact parameter during sequential collisions with the atoms of the chain. This means that all the atoms of a given chain will scatter the electron in the same direction. As a result, the mean square angle of electron scattering by the chain will be proportional to the square of the number of scattering atoms $N \sim 2R/\psi d$, where the shielding radius R determines the effective transverse size of the atomic chain and d is the distance between the atoms in the chain. This is fundamentally different from scattering on randomly located atoms of an amorphous target, where the electron mean square scattering angle is proportional to the number of atoms along its trajectory, i.e., the target thickness T [3].

As can be easily seen from Fig. 1, the true scattering angle of the particle θ is related to the azimuthal scattering angle by the relation

$$\theta = 2\psi \sin\frac{\varphi}{2}. \quad (10)$$

For the case of a sufficiently thin crystal, when the azimuthal scattering angle φ is significantly less than unity, it follows from (10) that $\approx \psi\varphi$. This means that not only the azimuthal scattering has a coherent character, $\langle\varphi^2\rangle \sim N^2$, but the mean square of the true electron scattering angle $\langle\theta^2\rangle$ is also proportional to N^2.

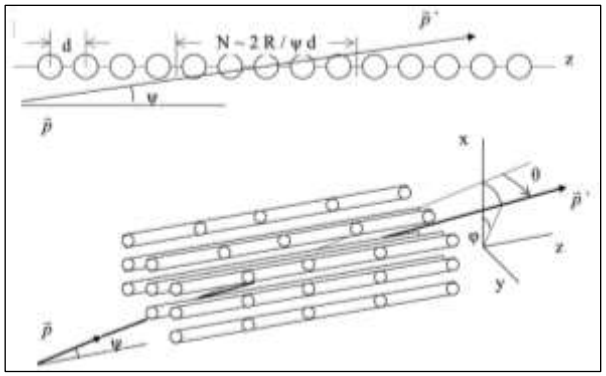


Fig. 1. Scattering of fast charged particles by crystal atomic chains of a crystal

However, with increasing crystal thickness, the RMS azimuthal scattering angle $\langle\varphi\rangle$ reaches the value π, which leads to the closure of the "azimuthal scattering ring", and further growth of the true scattering angle $\langle\theta^2\rangle$ occurs mainly due to incoherent scattering on thermal vibrations of atoms in crystal lattice nodes. Therefore, a significant (several-fold!) excess of coherent scattering angles in a crystal over conventional

multiple scattering in an amorphous target manifests itself only for relatively thin crystals (see direct comparison in Fig. 5 of [17]).

Thus, due to the coherent scattering effect in a thin crystal, it becomes possible to observe the TSF effect at lower electron energies compared to amorphous targets.

There is also an additional option in the case of a thin crystalline target that simplifies the experimental observation of the TSF effect. Instead of the very difficult experimental study of the dependence of radiation intensity on the target thickness, as it was successfully done in [14] for amorphous targets, in the case of a thin crystal one can observe the suppression of radiation by the transition from the dipole radiation mode to the non-dipole one studying the orientation dependence of the coherent radiation intensity.

Fig. 2 shows the results of computer simulation of the passage of an electron beam with the energy of 6 GeV through a silicon crystal of 10 μm thick with the beam incident at various angles ψ relative to the crystallographic axis ⟨111⟩. The value of the incident angle ψ presented in units of the Lindhard angle [18] reads

$$\psi_L = \sqrt{4Ze^2/\varepsilon d}, \quad (11)$$

which defines the characteristic angular scale of orientational effects for the fast charged particles in a crystal.

Relativistic electrons with $\psi < \psi_L$ can be captured to the axial channeling regime of the motion that means a finite motion in the averaged field of the nearest atomic chain [18]. The value of ψ_L for 6 GeV electrons passing through the Si crystal along the ⟨111⟩ axis is approximately $\psi_L \approx 0.16$ mrad.

The ring-shaped angular distributions of scattered particles at $\psi < \psi_L$ in Fig. 2 are a manifestation of the so-called "doughnut scattering effect", which was probably first observed in experiments on the scattering of protons and alpha particles by a thin crystal in [19].

However, the "doughnut scattering effect" occurs not only for channeled particles, but also for above-barrier, moreover both negatively and positively charged particles, since it is a consequence of coherent azimuthal scattering described above.

Above-barrier particles moving in the crystal at angles $\psi \gtrsim \psi_L$ successively collide with different chains of atoms located along the crystallographic axis, experiencing strong coherent azimuthal scattering on each chain. This leads to the fact that each subsequent collision with a chain of atoms will occur with a practically random impact parameter in the plane (x, y), despite the strict ordering of the arrangement of atomic chains in the lattice, which form close-packed crystalline planes.

According to the theory of multiple scattering on atomic chains of a crystal, developed in [20], the mean square angle of multiple scattering of electron (positron) $\langle\theta_{cr}^2\rangle$ exceeds the corresponding mean square of the scattering angle in an amorphous medium of the same thickness $\langle\theta_{am}^2\rangle$ by a factor

$$\frac{\langle\theta_{cr}^2\rangle}{\langle\theta_{am}^2\rangle} \approx \frac{R}{8\psi d}. \quad (12)$$

Significant correlations between successive collisions of a fast charged particle with atomic chains are possible at $\psi \gg \psi_L$. If it also turns out that the angle between the particle momentum and the direction of one of the crystallographic planes is less than the critical angle of planar channeling [18], then such a particle can be captured in the planar channeling mode and move along this crystallographic plane for some time.

The capture of a small part of the particle beam in the planar channeling mode is also possible at $\psi \ll \psi_L$. This is manifested in Fig. 2 in the form of a violation of the azimuthal symmetry in the angular distributions of scattered electrons at $\psi = 0; 0.25; 0.5\ \psi_L$. A much more obvious manifestation of this kind of "star" occurs in the angular distributions of positively charged particles that have passed through a thin crystal, because the planar channeling mode is much more stable for them than for negative ones [18].

By integrating over the azimuthal scattering angle φ of the two-dimensional angular distributions of scattered electrons by φ and θ shown in Fig. 2, we obtain the corresponding one-dimensional angular distributions of electrons $f(\theta)$ over the true scattering angle θ, which are necessary for determining the intensity of the electron beam radiation in the crystal.

Fig. 3 shows the obtained angular distributions of scattered electrons $f(\theta)$ for different orientation angles of the crystal ψ relative to the incident particle beam

From Fig. 3 it is evident that at $\psi = 3\ \&\ 5\ \psi_L$ the overwhelming majority of the scattered electrons is within the characteristic cone of radiation of the relativistic particle $\theta_k \sim 1/\gamma$. This means that the bremsstrahlung of these electrons will have a dipole character.

With decreasing angle ψ already at $\psi = 2\ \psi_L$ a noticeable part of the scattered electron beam leaves the characteristic radiation cone, that leads to a violation of the dipole character of the radiation for almost half of the beam particles. With a further decrease in the crystal orientation angle relative to the direction of the incident electron beam, a large part of the beam is scattered at an angle greater than $1/\gamma$, which means that the bremsstrahlung of these electrons will have a significantly non-dipole character.

Due to the high efficiency of coherent scattering in a thin crystal (see (12)) the conditions (8) for observing the TSF effect can be realized in a crystal at significantly lower electron energies than in an amorphous target.

3. TSF EFFECT IN A THIN CRYSTAL

The spectral density of radiation in a thin target ($T \ll l_c$), is defined by the formula (2.70) from [5]:

$$\frac{dE}{d\omega} = \frac{2e^2}{\pi} \int d\theta\, f(\theta) \left[\frac{2\xi^2+1}{\xi\sqrt{\xi^2+1}} ln\left(\xi + \sqrt{\xi^2+1}\right) - 1 \right], \quad (13)$$

where the parameter $\xi = \gamma\theta/2$ is the radiation dipole parameter (1) multiplied by 1/2, $f(\theta)$ is the angular distribution function of scattered electrons.

If $\xi \ll 1$, then the expression in square brackets for the integrals in equation (13) after expansion in a series in the small parameter ξ will be equal to $4\xi^2/3$, which leads to the following result for the spectral density of radiation in the dipole approximation, i.e. when $\gamma\theta < 1$:

$$\frac{dE}{d\omega} = \frac{2e^2}{3\pi}\gamma^2 \int \theta^2 f(\theta) d\theta. \quad (14)$$

If the opposite inequality $\xi \gg 1$ is satisfied, then the expression in square brackets for the integrals in equation (13) after expansion in a series in the small parameter $1/\xi$ gives the result $\ln(4\xi^2)$ that leads to the following expression for the spectral density of radiation:

$$\frac{dE_{TSF}}{d\omega} = \frac{2e^2}{\pi} \int \ln(\gamma^2\theta^2) f(\theta) d\theta. \quad (15)$$

Note that the spectral density of radiation in a thin target (13) does not depend on the energy of the emitted photon, but only on the parameter ξ. This means that the characteristics of the radiation do not depend on the details of its scattering history within the target and are completely determined by the final scattering angle of the particle when leaving the target. Therefore, this formula can be used to describe radiation in a thin target of any type: an amorphous plate, a thin crystal, a plasma clot, or a bunch of charged particles in an accelerator.

The main condition for the applicability of formula (13) is the smallness of the region in which the scattering of the incident particle occurred, compared to the coherence length of the radiation l_c (2). All information about the nature of the "scatterer" is carried by the function $f(\theta)$.

If a thin amorphous plate is used as a target, then the Bethe-Moliere function (see, e.g. [5]) must be put into formula (13) as the distribution function of scattered electrons $f(\theta)$. In this case, if the condition $\xi \ll 1$ is met, formula (14) yields the dipole radiation result, that is, the Bethe-Heitler result [2], at which the radiation spectral density is proportional to the mean square value of the scattering angle, i.e. the target thickness.

If $\xi \gg 1$, then the effect of suppression of radiation in a thin layer of matter, or the TSF effect [8-12], will take place, when the radiation intensity has only a logarithmic dependence on the target thickness. As already noted, this effect was studied in the course of an experimental study by the CERN collaboration NA63 at the SPS accelerator [13, 14].

In the case under consideration in the article of scattering of 6 GeV electrons by a silicon crystal of 10 μm thickness at different angles of the electron beam incidence relative to the axis ⟨111⟩, the angular distribution function $f(\theta)$ of the electrons scattered by the crystal is presented in Fig. 3 by the corresponding curves for each incidence angle ψ.

The results of calculation of the orientational dependence of the radiation spectral density based on formula (13) and the mentioned above results of computer simulations of the electron scattering in Si crystal are shown in Fig. 4 by the solid red line.

The green dotted curve "T-M" in the Fig. 4 corresponds to the results of the Ter-Mikaelian theory of coherent bremsstrahlung in a crystal [3], based on the use of the first-Born approximation. The use of this approximation actually means neglecting the curvature of the particle's trajectory in the field of the crystal lattice, which leads to a formal divergence of the radiation intensity due to the unlimited growth of the number of atoms in the chains with which the electron effectively interacts when the angle ψ tends to zero (see Fig. 1).

This approach is acceptable when the relativistic electron motion is far from the channeling regime, i.e. when $\psi \gg \psi_L$.

Taking into account the curvature of the electron trajectory in an atomic chain field at $\psi \sim \psi_L$ when calculating the passing of a relativistic electron through a crystal eliminates this divergence, as it is shown by the blue dashed curve "Dipole" in Fig. 4.

Additional suppression of radiation due to intense scattering of a particle occurs when the scattering angle of a particle in the limit of the bremsstrahlung coherence length l_c exceeds the characteristic radiation angle of a relativistic particle $1/\gamma$. This effect is an analogue of the TSF effect of suppression of radiation in a thin amorphous plate firstly discovered in the SLAC experiment E-146 [7, 8] and then studied in details in the CERN experiment NA63 [13, 14]. However, in the case of an oriented crystal, suppression of coherent bremsstrahlung occurs (the solid red line TSF in Fig. 4), which significantly exceeds the usual bremsstrahlung in an amorphous target, described by the Bethe-Heitler theory [2], even being significantly suppressed by the TSF effect. The results of calculations according to the Bethe-Heitler theory is shown in Fig. 4 with the green dot-dashed line "B-H".

CONCLUSIONS

The analysis of the conditions for the manifestation of the TSF radiation suppression effect in a thin oriented crystal, carried out in this work, shows that there is a fundamental possibility of its experimental observation and study on the test beam of the DESY II booster synchrotron at an electron energy of 6 GeV. This radiation suppression effect is expected to be observed in the gamma-quantum radiation spectrum range of 0.3 MeV < ω < 4 MeV.

At lower energies of the emitted quanta, a stronger polarization mechanism of radiation suppression, the so-called Ter-Mikaelian effect [3], will take place.

In the harder part of the radiation spectrum, when the coherence length becomes less than the target thickness, a transition should occur from the TSF radiation suppression to the LPM mode [16] and then to the dipole mode of coherent bremsstrahlung which is represented in Fig. 4 by the dotted blue curve "Dipole".

According to condition (7), the spectral region of the TSF effect manifestation significantly expands with increasing electron energy.

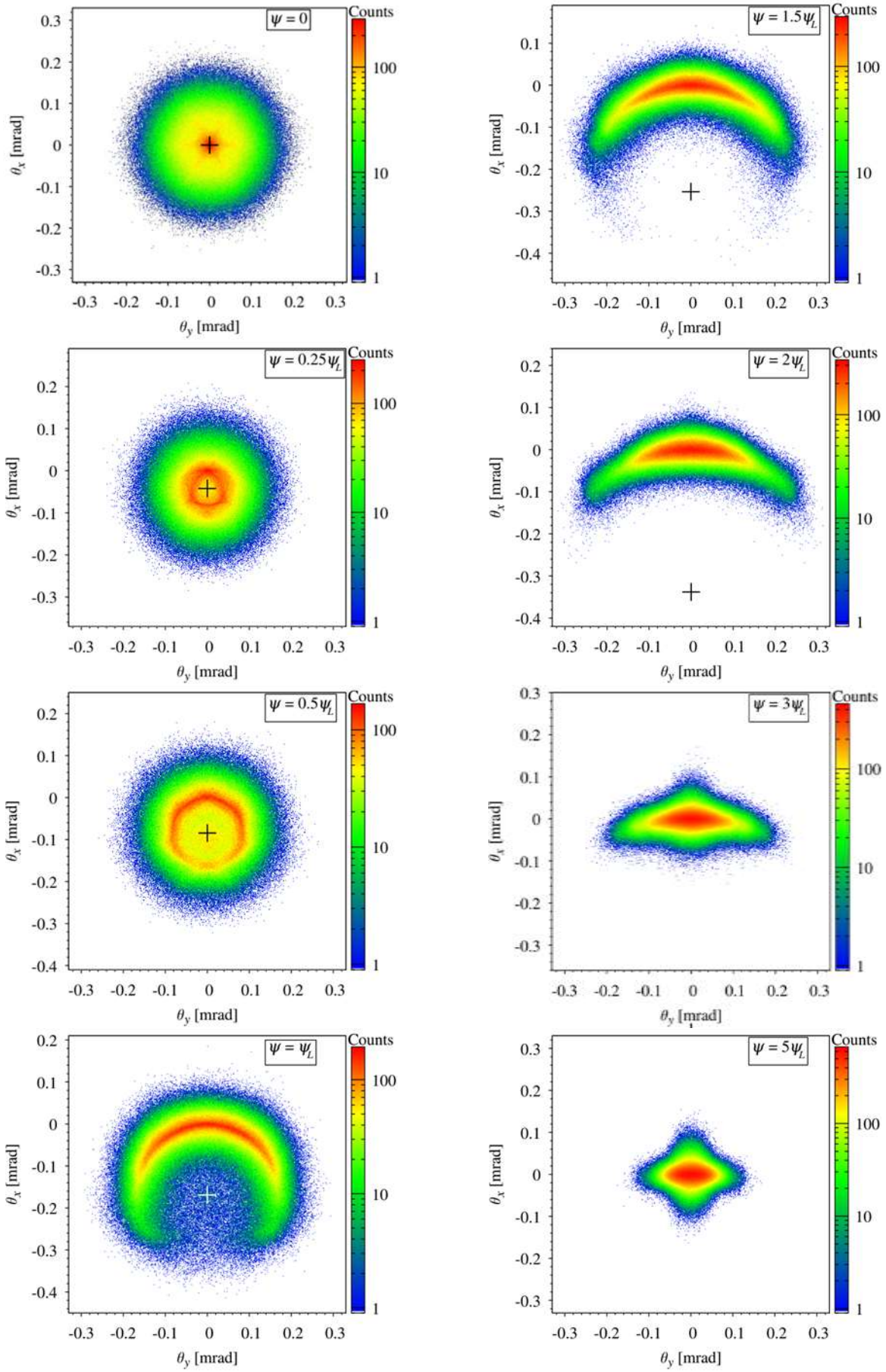


Fig. 2. The results of computer simulation of the angular distribution of scattered 6 GeV electrons impinged the Si crystal of 10 μm thickness at different initial angle ψ to the axis ⟨111⟩. The initial direction of impinged electron beam is $\theta_x=\theta_y=0$. The direction of the crystallographic axis ⟨111⟩ is indicated in the figures by cross

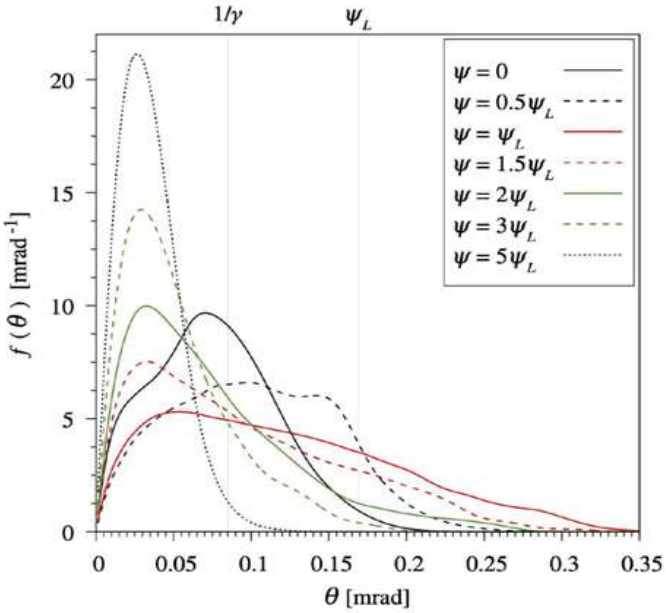


Fig. 3. The angular distribution function f(θ) of scattered 6 GeV electrons impinged the Si crystal of 10 μm thickness at different initial angle ψ to the axis ⟨111⟩

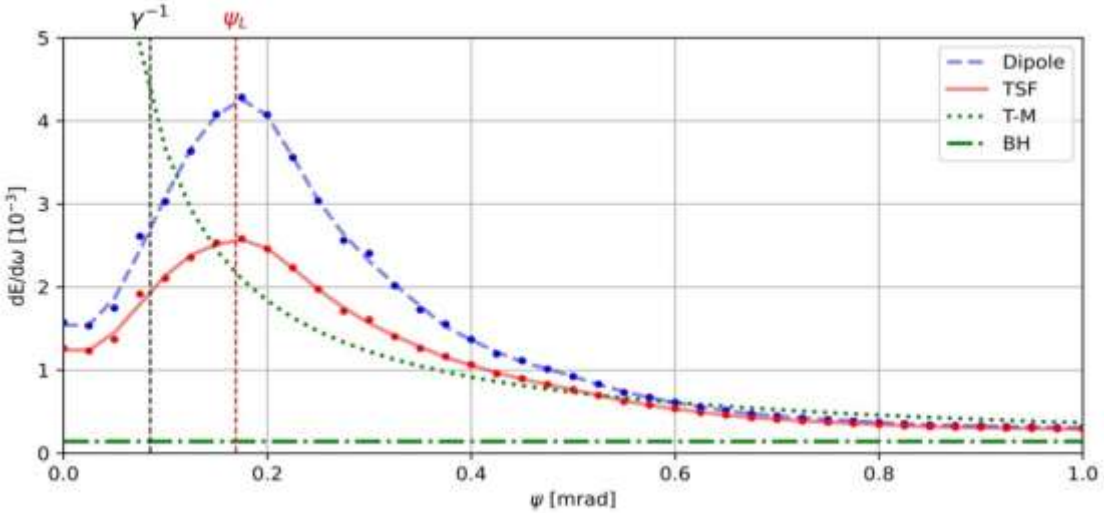


Fig. 4. Orientation dependence of the spectral density of coherent radiation of 6 GeV electrons in 10 μm thick silicon crystal when the beam falls at an angle ψ to the axis <111>. (Details in the text)

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ВПЛИВ БАГАТОРАЗОВОГО РОЗСІЯННЯ НА ГАЛЬМІВНЕ ВИПРОМІНЮВАННЯ РЕЛЯТИВІСТСЬКИХ ЕЛЕКТРОНІВ У ТОНКОМУ ОРІЄНТОВАНОМУ КРИСТАЛІ

С.П. Фомін, І.В. Кириллін, М.С. Маловиця, С.М. Шульга, Г. Кубе, А. Новокшонов, С. Строков, А. Фомін

Досліджено вплив багаторазового розсіювання на гальмівне випромінювання ультрарелятивістських електронів на атомах решітки тонкого орієнтованого кристала. Показано, що при порушенні умови дипольного режиму випромінювання має місце ефект пригнічення випромінювання. Цей ефект подібний до ефекту Терновського-Шульги-Фоміна пригнічення випромінювання в тонкій аморфній мішені, але у випадку тонкого орієнтованого кристала пригнічується когерентне гальмівне випромінювання. Обговорюються умови експериментального спостереження цього ефекту на прискорювачі DESY.