The paper "Fully quantum treatment of the Landau-Pomeranchuk-Migdal effect in QED and QCD" (B.G. Zakharov, 1996)

In the work [1] a formalism for calculation of the processes of the type $a \to bc$ in amorphous media at high energies (when the energies of the particles a, b and c are much bigger than their masses) induced by multiple scattering in the medium has been developed. In calculating of such processes one faces a problem of accounting for the Landau-Pomeranchuk-Migdal (LPM) [2, 3] effect related to large coherence length for $a \to bc$ transition at high energies. In this regime $a \to bc$ process involves interactions with many medium constituents. The problem becomes especially complicated in the non-abelian case when all the particles undergo multiple rescatterings in the medium. The approach [1] is applicable both in QED for ordinary materials (for instance, for the photon emission from electrons $e \to \gamma e$) and in QCD (for instance, for the gluon emission from fast quarks $q \to gq$ in a hot quark-gluon plasma or in a cold nuclear matter). The formalism is valid for any magnitude of the LPM suppression of the cross section. It accounts for accurately the Coulomb effects in multiple scattering and works both for infinite and finite-size matter. The spectrum in the Feynman variable $x_b = E_b/E_a$ has been expressed through the Green function of a two dimensional Schrödinger equation with an imaginary potential. This Green function describes the in-medium evolution on the light-cone $t = z$ (z is coordinate along the momentum of the initial fast particle a) in the transverse plane of the fictitious system $bc\bar{a}$ from point-like to point-like state. In the $bc\bar{a}$ system the particle $\bar{a}$ is located at the center of mass of the bc pair. In the above Schrödinger equation the coordinate z plays the role of time, and the Schrödinger mass equals $x_b(1 - x_b)E_a$, which is the reduced mass of the system bc in the impact parameter plane (where the role of masses are played by the particle energies). The imaginary potential is proportional to the product of the matter density and the cross section for interaction with a medium particle of the $bc\bar{a}$ system. The derivation is based on the representation of the wave function of each fast particle in the form of the product of the plane wave $\exp[E(t - z)]$ and a slowly varying "transverse" wave function $\phi(\vec{\rho}, z)$, which satisfies a two dimensional Schrödinger equation with mass $M = E$ (E is the energy of the particle). Each transverse wave function has been written through the relevant Green function. It allows one, after integrating over the variable $t - z$ in each vertex (which leads to the mass conservation $M_a = M_b + M_c$ in the vertexes $a \to bc$), to obtain the diagrammatic representation of the amplitudes in terms of the transverse propagators. Making use of the Feynman path integral representation for the transverse propagators one can obtain the cross section of the process $a \to bc$ in a path integral form in the transverse plane on the light-cone $t = z$. Of course, the functional integral for the amplitude cannot be calculated analytically. However, it turned out that for the cross section, after averaging over the medium states, all the functional integrations, except for the integration over the transverse distance between b and c, can be taken analytically similarly to the case of the functional integral for the electron density matrix [4]. And the remaining integral over the relative transverse vector $\vec{\rho}_b - \vec{\rho}_c$ gives the above mentioned Green function for the system $bc\bar{a}$. An important feature of the obtained diagrammatic representation for the cross section is that for the QCD case the calculation of the color factors becomes trivial.

An analysis of the LPM effect and the parton energy loss in QCD matter is of great interest both from general theoretic and phenomenological point of view. At the time of its publication the work was of special interest due to the interest in the radiative parton energy loss in the quark-gluon plasma, which was expected to be produced in future experiments on heavy ion collisions at RHIC and LHC. It has been expected that the energy loss of the fast quarks and gluons produced in hard processes as they traverse the quark-gluon plasma would suppress the hadron spectra at high transverse momenta (similarly to the reduction of radiation in a concrete nuclear reactor containment). Subsequently, it turned out to be case, and analyzing of the suppression of the high-p_T spectra (usually called "jet quenching") became one of the major methods in diagnostics of the QCD matter in heavy ion collisions at RHIC and LHC. The analysis [1] turned out to be the first consistent calculation of the radiative energy loss in QCD matter. The previous attempts [5–7] to calculate them, even in the soft gluon approximation, have not been successful. Practically simultaneously with [1] the induced gluon radiation in QCD matter was addressed in works [8], where only the regime of strong LPM effect and in the soft gluon approximation was studied. However, later on, it became clear that the calculations [8] contain conceptual errors, that were subsequently corrected in [9].

The approaches to the radiative energy loss [10, 11] developed after the work [1] are less general. The formalism [10] accounts for only few first rescatterings of the fast partons in the soft gluon approximation, and applies only to a small size plasma. The formulas of [10] can be obtained from the formalism [1] by a simple expansion in the medium density. The formulas of [11], derived within the thermal field theory in the momentum representation for an infinite plasma, can be reproduced within the formalism [1] using the imaginary potential evaluated through the gluon polarization tensor [12]. However, contrary to [11] the approach [1] works also for a finite size plasma with a varying density. Thus today the formalism [1] still appears to be the most powerful method for calculation of the radiative energy loss in the QCD matter.

It worth noting that at the time of carrying out the analysis [1] there was also considerable interest to the LPM effect in QED stimulated by the first high-precision measurement of the effect for the photon emission from electrons at SLAC [13]. The well known approach by Migdal [3] based on the Fokker-Planck approximation has uncertainties that are much bigger than the accuracy achieved in the experiment [13]. Within the approach [1] the Fokker-Planck approximation corresponds to replacement of the exact Green function by the oscillator one. An analysis beyond the oscillator approximation within the formalism [1] carried out in [14, 15] demonstrated agreement with the SLAC data [13] and with the later data from CERN SPS [16] at the level of the radiative corrections.

The formalism [1] was the theoretical basis of the well known ASW (Armesto, Salgado and Wiedemann [17]) approach to jet quenching. The formulation in terms of the path integral and diagram technique dealing directly with the probability of the radiative processes given in [1] turns out to be very convenient for the study of the jet modification in the quark-gluon plasma accounting for the multiple gluon emission [18, 19]. This study is of great importance for physics of heavy ion collisions at energies of the RHIC, LHC and future colliders, and is now under active development.

[1] B.G. Zakharov, JETP Lett. **63**, 952 (1996).
[2] L.D. Landau and I.Ya. Pomeranchuk, *Dokl. Akad. Nauk SSSR* **92**, 535, 735 (1953).
[3] A.B. Migdal, *Phys. Rev.* **103**, 1811 (1956).
[4] B.G. Zakharov, Sov. J. Nucl. Phys. **46**, 92 (1987)
[5] M. Gyulassy and X.N. Wang, Nucl. Phys. B**420**, 583 (1994).
[6] X.N. Wang, M. Gyulassy, and M. Plümer, Phys. Rev. D**51**, 3436 (1995).
[7] R. Baier, Y.L. Dokshitzer, S. Peigné, and D. Schiff, Phys. Lett. B**345**, 277 (1995).
[8] R. Baier, Y.L. Dokshitzer, A.H. Mueller, S. Peigné, and D. Schiff, Nucl. Phys. B**483**, 291 (1997); *ibid.* B**484**, 265 (1997).
[9] R. Baier, Y.L. Dokshitzer, A.H. Mueller, and D. Schiff, Nucl. Phys. B**531**, 403 (1998).
[10] M. Gyulassy, P. Lévai and I. Vitev, Nucl. Phys. B**594**, 371 (2001).
[11] P. Arnold, G.D. Moore, and L.G. Yaffe, JHEP **0206**, 030 (2002).
[12] P. Aurenche and B.G. Zakharov, JETP Lett. **85**, 149 (2007).
[13] P.L. Anthony, *et al.* (E-146 SLAC Collaboration). Phys. Rev. Lett. **75**, 1949 (1995); Phys. Rev. D**56**, 1373 (1997)
[14] B.G. Zakharov, JETP Lett. **64**, 781 (1996); Phys. Atom. Nucl. **62**, 1008 (1999).
[15] B.G. Zakharov, JETP Lett. **78**, 759 (2003).
[16] H.D. Hansen, U.I. Uggerhøj, C. Biino et al., Phys. Rev. Lett. **91**, 014801 (2003).
[17] N. Armesto, C.A. Salgado, and U.A. Wiedemann, Phys. Rev. D**69**, 114003 (2004).
[18] Y. Mehtar-Tani, C.A. Salgado, and K. Tywoniuk, JHEP **1210**, 197 (2012).
[19] J.P. Blaizot, F. Dominguez, E. Iancu, and Y. Mehtar-Tani, JHEP **1301**, 143 (2013).