Drag effect in the electron-hole-phonon system of InSb: thermal quenching of luminescence in weak magnetic fields

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The spectra of the interband luminescence excited in InSb by two-photon pumping with a CO_2 laser were investigated at ~ 2 K. Strong quenching of the luminescence was observed in a relatively weak magnetic field (~ 1 kOe) directed along the wave vector of the exciting light. Such quenching was due to an increase in the temperature of the hole system. The magnetic field effect was absent when the orientation was transverse. A model was used to explain the observed behavior by manifestation of a mutual drag of quasiparticles in the electron-hole-phonon system. The phonons, which carry heat from the region of absorption of light to the "cold" bulk, drag holes and then the holes drag electrons due to the electron-hole scattering. A magnetic field of suitable orientation "magnetizes" the electron system and slows it down, which in the final analysis lowers the efficiency of cooling and is therefore responsible for an increase in the temperature of the system. The drag effect is possible because of the strong screening of the impurity scattering by nonequilibrium carriers.

Investigations of the luminescence emitted by semiconductors, used traditionally in studies of electron excitations, is nowadays employed increasingly to find information on the phonon system or on the interaction of electron excitations with phonons (see, for example, Ref. 1). This was also the task of the work reported below which represented an experimental and theoretical study of an unusual situation when a relatively weak magnetic field, which did not magnetize completely the electron-hole plasma in a semiconductor, nevertheless had a very strong influence on the temperature dependence of this plasma.

Our earlier experimental investigation of the polarization dependence of the luminescence emitted by InSb in a magnetic field[2] at high excitation rates revealed a strong quenching of the luminescence on application of a longitudinal (relative to the direction of excitation) magnetic field. However, there was almost no change in the luninescence intensity in a transverse magnetic field.

We shall show that a theoretical explanation of this effect is based on the concept of thermal quenching of the luminescence and that the magnetic field is a factor which influences the temperature of the excited region of a crystal. Since under these conditions heat is transported by phonons, it is clear that the influence of a magnetic field on the energy balance can be manifested only under the drag effect conditions. Since phonons interact mainly with holes and the magnetic fields used in our experiments do not affect significantly the motion of holes (although these fields may magnetize electrons), it is necessary to assume that mutual drag of electrons and holes by phonons takes place. The magnetic field decelerates electrons drifting from the excited region of a crystal to the cold bulk and this in turn slows down the drift of holes and, in the final analysis, lowers the efficiency of the phonon heat transport and increases the temperature of the system.

Under equilibrium conditions the drag effect should be suppressed because of the strong scattering of carriers by impurities. However, in the investigated situation the nonequilibrium density of electrons and holes is considerably higher than the impurity concentration, so that effective screening by nonequilibrium carriers reduces the role of the impurity scattering and, as demonstrated by estimates given below, facilitates the drag effect.

EXPERIMENTS

An investigation was made of the quenching of recombination radiation (luminescence) when InSb was subjected to a magnetic field parallel to the direction of excitation. The quenching effect was observed when the luminescence was collected along the direction of excitation and at right angles to this direction.

The experiments were carried out mainly on samples of n-type InSb with an equilibrium density $n_0 = 8\times 10^{13}\,\mathrm{cm}^{-3}$. These samples were either polished mechanically or etched in CP-4A. Nonequilibrium carriers were excited as a result of absorption of CO_2 laser radiation of 9.6 μm wavelength. The laser was Q-switched and it emitted pulses of 1 kW power, 300 ns duration, and 250 Hz repetition frequency. The laser radiation was focused on samples of 4×6 mm area and 1-mm thick which were inmersed directly in liquid helium at 1.8 K. A magnetic field was applied by a pair of superconducting coils. In view of the smallness of the two-photon absorption coefficient, homogeneous excitation of an electron-hole plasma (EHP) occurred in a cylindrical region of dimensions governed by the diameter of the focused beam and by the thickness of the sample. The luminescence investigated in the transmission geometry was recorded either directly with a photodetector or with a spectrophotometer. When the luminescence was collected at right-angles to the direction of excitation, it passed through the unexcited part of the semiconductor and suffered partial absorption. Therefore, the influence of a longitudinal magnetic field was manifested most clearly when the luminescence was collected along the direction of excitation and the main investigations were carried out in this particular geometry.

Figure 1 shows typical dependences of the integrated intensity of the luminescence emitted by a sample of n-type InSb with an equilibrium electron density $n_0 = 8\times 10^{13}$ cm^{-3} on the magnitude and direction of the magnetic field.

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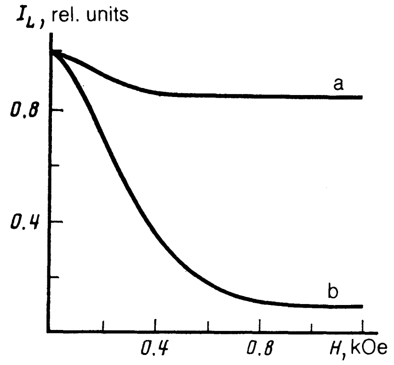

FIG. 1. Dependence of the integrated luminescence intensity I_L on the magnetic field applied to a sample of n-type InSb with an equilibrium carrier density $n_0 = 8\times10^{13}$ cm^{-3}: a) $\mathbf{H}\perp\mathbf{k}$; b) $\mathbf{H}\|\mathbf{k}$ ($\mathbf{k}$ is the wave vector of the exciting radiation).

Clearly, in a magnetic field $\mathbf{H}\|\mathbf{k}$, where $\mathbf{k}$ is the vector along the excitation direction, there was a strong quenching of the luminescence by a factor of ~ 10, whereas in a transverse magnetic field, $\mathbf{H}\perp\mathbf{k}$, the quenching effect did not exceed 15%. Similar results were also obtained for samples with higher equilibrium carrier densities (n_0 up to 10^{15} cm^{-3}) and also for lightly doped p-type samples, although the influence of a longitudinal magnetic field in the latter case was less.

A study of the luminescence emitted by InSb as a result of two-photon excitation with CO_2 laser radiation reported in Ref. 3 demonstrated that the luminescence spectrum consisted of a single line due to interband transitions. It was also established in Ref. 3 that under the conditions described above the EHP of the semiconductor had a temperature close to the temperature of the helium bath. An increase in the rate of excitation resulted in lasing; the width of the spectral line then decreased and the integrated intensity of the luminescence rose strongly. An estimate of the density of nonequilibrium carriers during emission of stimulated radiation under conditions close to those described above was given in Ref. 4: this density was $\sim 3\times10^{15}$ cm^{-3}.

The maximum quenching of the luminescence occurred specifically in the case of strong pumping when lasing was observed. The luminescence spectra were recorded in the absence of a longitudinal magnetic field and in a field $H\approx 1$ kOe applied to a sample with $n_0 = 8\times10^{13}$ cm^{-3} (Fig. 2). In a magnetic field the intensity at the spectral line maximum fell by a factor of ~ 20 and this increased strongly the line width. Such a change in the luminescence intensity and the spectral line width indicated that a transition from stimulated to spontaneous emission took place on application of the magnetic field. A further increase of the magnetic field to 10 kOe did not alter significantly the spectral line profile.

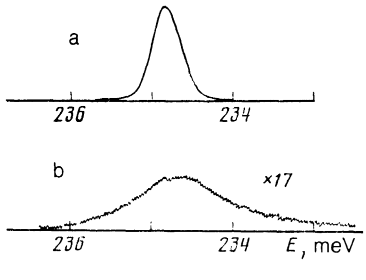

FIG. 2. Luminescence spectra of a sample of n-type InSb with an equilibrium carrier density $n_0 = 8\times10^{13}$ cm^{-3} in the absence (a) and presence (b) of a longitudinal magnetic field ($H = 1$ kOe).

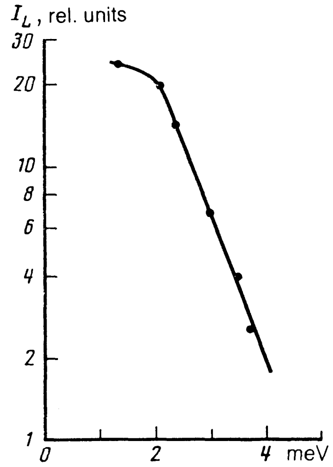

FIG. 3. Dependence of the integrated luminescence intensity I_L on the temperature of the helium bath containing a sample of n-type InSb with an equilibrium carrier density $n_0 = 8\times10^{13}$ cm^{-3}.

The temperature of the EHP, deduced from the short-wavelength edge of the luminescence line in a longitudinal magnetic field (curve b) was ~ 5 K, indicating that this magnetic field increased the EHP temperature.

This was supported by the results (Fig. 3) demonstrating that the integrated luninescence intensity varied with the temperature of the helium bath in the range from 1.8 to 3.7 K. It is clear from this figure that a change in this temperature by a factor of 2 altered the luminescence intensity by a factor of 20. Such thermal quenching of the luminescence of indium antimonide was primarily due to an increase in the phase volume in which the holes were distributed (Boltzmann distribution) on increase in temperature; this reduced the probability of recombination and lowered the gain.

A shutter placed in the direct vicinity of a sample could be used to stop the luminescence and to determine the size of the excited region of a crystal. It was found that the diameter of this region was not affected by the magnetic fields in which strong quenching of the luminescence was observed.

These experimental results led us to the following conclusions.

1. Luminescence quenching was a purely bulk effect and in no way related to the state of the surface of a sample.

2. The change in the integrated intensity and in the nature of the luminescence spectrum in a magnetic field demonstrated that the application of a magnetic field suppressed stimulated emission (lasing) so that spontaneous emission was observed.

3. The luminescence quenching effect was independent of the direction along which the luminescence was collected and this indicated that the influence of the magnetic field could not be reduced to some direct magnetooptic effects, such as the direct influence of the magnetic field on the gain or on the losses in the EHP.

4. Since an increase in the temperature of the helium bath produced the same luminescence quenching as the ap-

plication of a longitudinal magnetic field and the EHP temperature in a magnetic field, deduced from the luminescence spectrum, rose to ~5 K, the direct cause of the luminescence quenching in a magnetic field was an increase in the EHP temperature.

5. A strong difference between the degree of influence of the magnetic field on the luminescence intensity in longitudinal and transverse fields demonstrated the kinetic origin of the effect: the magnetic field had a considerable influence on the motion of the EHP charges in the radial direction.

6. The kinetic influence of a magnetic field was not due to confinement of the EHP: the dimensions of the active region were not affected by the application of a magnetic field.

THEORY

We shall begin by noting that although our measurements were carried out using pulses, the pulse duration exceeded all the characteristic times (lifetime, time taken to establish the electron temperature) of the investigated problem and a quasisteady state of the system can be considered theoretically.

Since, according to the experimental results, the magnetic field effect is clearly of kinetic origin, we shall begin by considering the characteristic kinetic parameters of the system using the known values of the concentration of impurity centers ($\sim 10^{14}$ cm^{-3}) and of the density of nonequilibrium carriers ($\sim 10^{15}$ cm^{-3} at excitation rates typical of our experiments). Bearing in mind that InSb is characterized by $m_e \sim 1.4\times 10^{-19}$ g and $m_h \sim 0.4\times 10^{-27}$ g, we readily find that the Fermi energy for electrons is $\varepsilon_{Fe} \sim 30$ K, whereas that for holes is $\varepsilon_{Fh} \sim 1$ K, so that the electron system is degenerate but the hole system is not. In estimating the relaxation times it is necessary to determine also the screening characteristics. In the case of electrons the screening radius can be estimated in the usual way and it amounts to $\sim 10^{-5}$ cm. As far as holes are concerned, the position is complicated by the fact that we cannot use the gas approximation: $T < e^2 n^{1/3}/\varepsilon_0$ (ε_0 is the permittivity); we shall return to this point later. At this stage we shall simply note that the screening radius of holes can obviously be greater than $n^{-1/3} \sim 10^{-5}$ cm. Therefore, the screening radius r_D has an upper limit of $\sim 10^{-5}$ cm. We can now estimate the relaxation time of carriers interacting with impurities and with one another. In the case of electrons ($\varepsilon_{Fe} > e^2 n^{1/3}/\varepsilon_0$) we can obtain the necessary estimates in the usual way employing a standard expression[5]

$$\tau = (2m)^{1/2}\varepsilon_0^2\varepsilon_F^{3/2}/\pi e^4 N\Phi(\eta),$$
$$\Phi(\eta) = \ln(1+\eta) - \eta/(1+\eta), \qquad (1)$$
$$\eta = 8m\varepsilon_F r_D^2/\hbar^2,$$

where N is the impurity concentration ($N = N_i$) or the density of holes ($N = n$). Calculations carried out using the system (1) give $\tau_{eh} \sim 0.5\times 10^{-12}$ s and $\tau_{ei} \gtrsim 10^{-11}$ s. Bearing in mind that the electrons are degenerate and holes are not, we can estimate τ_{he} from

$$\tau_{he} \sim \tau_{eh}(\varepsilon_{Fe}/T).$$

A calculation of the relaxation time of holes interacting with impurities is complicated by the circumstances mentioned above. If we ignore them and assume that the relevant cross section is $\sigma_{hi} \lesssim r_D^2$, we obtain order-of-magnitude estimates: $l_{hi} \gtrsim (\sigma_{hi} N_i)^{-1} \sim 10^{-4}$ cm and $\tau_{hi} \sim (l/v_h) \gtrsim 10^{-10}$ s. We note that since typical momenta of electrons $p_e \sim (m_e \varepsilon_{Fe})^{1/2}$ and holes $p_h \sim (m_h T)^{1/2}$ are of the same order of magnitude (for the experimentally found values of ε_{Fe} and T), the electron-hole scattering ensures effective momentum relaxation. It should also be noted that because of the screening of impurities by nonequilibrium carriers ($n \gg N_i$) the values of τ_{ei} and τ_{hi} are much larger than under equilibrium conditions.

It follows from our estimates that in the case of indium antimonide at helium temperatures when carriers interact with phonons the scattering by the deformation potential predominates over the piezoacoustic scattering.

The scattering of carriers by phonons is described by the usual expression

$$\tau^{-1} = \Lambda^2 (2m)^{3/2}\varepsilon^{1/2} p N_0(\hbar q \sim p)/2\hbar^4 \pi w \rho, \qquad (2)$$

where Λ is the deformation potential, w is the velocity of sound, ρ is the density of the investigated crystal, and N_0 is the equilibrium phonon distribution function.[1)] We therefore have $\tau_{hp} \sim 2\times 10^{-10}c\sim \tau_{hi}$ and $\tau_{ep} \sim 0.5\times 10^{-8}$ s. The scattering of phonons by carriers is described by

$$\tau_{pe}^{-1} \approx \frac{\Lambda^2}{\rho w^2}\frac{m}{\hbar^2}\left(\frac{3n}{\pi}\right)^{1/3}\frac{w}{v_F}\,\omega \sim 10^{-5}\omega, \qquad (3)$$

$$\tau_{ph}^{-1} \approx \frac{\Lambda^2}{\rho w^2}\left(\frac{\pi}{2}\right)^{1/2}\frac{n m^{1/2}}{T^{1/2}}\,\omega \sim 10^{-3}\omega \gg \tau_{pe}^{-1}. \qquad (4)$$

We can use these estimates to analyze the general picture of the kinetic effects in the investigated system. The newly generated high-energy electrons rapidly "dump" their energy because of the scattering by holes accompanied by the transformation of heavy holes into light ones[6]: the characteristic relaxation time is $\sim \tau_{eh}$. This situation applies up to energies $\sim \varepsilon_{Fe}$. The subsequent establishment of an equilibrium slows down because of the low effectiveness of the energy relaxation process for the usual electron-hole scattering and, therefore, the electron temperature is finally established in a time $\sim \tau_{eh} m_h/m_e$ ($> \tau_{hh}$). The last stage of the process is the establishment of an equilibrium with the phonon system in a time $\sim \tau_{hp}$. Since the times characteristic of the experimental situation ($\lesssim r_0/w, r_0^2/D_{e,h}$, where r_0 is the diameter of the active region and D is the diffusion coefficient) are much longer than the relaxation times discussed above, we can assume that our system is under local equilibrium conditions and we can describe it by a coordinate-dependent temperature.

We can easily see that in this situation the conduction of heat is mainly by phonons (this is primarily due to the large phase volume). Therefore, the influence of a magnetic field on the temperature of the system can only be via the scatterers, which in the case of phonons are primarily holes. However, we note that $\tau_{he}^{-1}(\sim 0.5\times 10^{11}\,\text{s}^{-1}) \gg \tau_{hi}^{-1}$ and for magnetic fields typical of our experiments we have $\Omega_h \tau_{he} \ll 1$. Therefore, just this estimate is sufficient to show that the system of holes cannot be magnetized (the role of the hole-hole collisions will be discussed later). In the case of the electron system the typical values of H which induce the observed effect are precisely of the order of those in which the condition $\Omega_e \tau_{eh} \gtrsim 1$ begins to be satisfied. However, we have seen already that the interaction of phonons with electrons can be ignored. On the basis of the above discussion we can explain the observed behavior only if we allow for the interaction of all the components of the system, i.e., of electrons, holes, and phonons.

This interaction may be associated with the electron-phonon drag effect. We can postulate that the phonon flux responsible for heat transport from the heated region to the cold volume drags the holes interacting with it and the holes then are scattered strongly by electrons which are dragged in turn. If the impurity scattering is sufficiently weak, then such mutual drag increases considerably the effective thermal conductivity. The application of a magnetic field which magnetizes electrons slows down the electron component and, in the final analysis, reduces the transfer of heat to the cold bulk.

As pointed out already, a quantitative analysis is complicated by a strong hole-hole interaction. In the case of electrons it is possible to employ the usual kinetic (transport) equation, because both the semiclassical ($\hbar/\varepsilon_{Fe}\tau_{ei} \ll 1$, $\hbar/\varepsilon_{Fe}\tau_{eh} \ll 1$),) and the gas ($\varepsilon_{Fe} > e^2 n^{1/3}/\varepsilon_0$) approximations are valid. Therefore, at least in the case of holes the latter inequality is not satisfied so that we cannot describe the hole-hole (and hole-impurity) interaction by the usual collision integral. The motion of individual holes resembles other oscillations in the wells of a potential relief due to the interaction with other holes and impurities (against the background of the negative charge of a degenerate electron gas). It should be noted that estimates indicate that the situation is then outside the range of validity of the semiclassical description: the characteristic spatial scale of such oscillations $\Delta x \sim (\varepsilon_0 T/e^2 n)^{1/2}$ satisfies the condition $p_h \Delta x \gtrsim \hbar$ (the frequency of such oscillations then obeys $\Delta x m_h/p_h \gg \Omega_h$, which stresses the "nonmagnetization" of the hole system). However, we can see that phonons nevertheless interact with individual holes, since $q_p(\sim 2p_h/\hbar) > (\Delta x)^{-1}$. This applies also to the interaction with electron excitations ($p_e \Delta x \gtrsim \hbar$). This circumstance makes it possible to describe the scattering of electrons and phonons by holes using the relaxation times estimated above.

Bearing in mind that the times needed for the establishment of a local equilibrium (τ_{eh}, τ_{hp}, and τ_{ph}) are much shorter than the characteristic transport times (hydrodynamic conditions), we can describe the nonequilibrium state entirely by introducing local drift velocities V_{de}, V_{dh}, and W_d and then the collision integrals can be estimated from

$$I_{eh} = \frac{f_e^-}{\tau_{eh}} - \frac{\mathbf{p}_e \mathbf{V}_{dh}}{\tau_{eh}} \frac{\partial f_{0e}}{\partial \varepsilon},$$

$$I_{ph} = \frac{N^-}{\tau_{ph}} - \frac{N_0(\omega + \mathbf{q}\mathbf{V}_{dh}) - N_0(\omega)}{\tau_{ph}},$$

where $f^- = f - f_0$; $N^- = N - N_0$; f_0 and N_0 are local equilibrium functions so that the kinetic equations for electrons and phonons become

$$\frac{e}{c}[\mathbf{vH}] \frac{\partial f_e^-}{\partial \mathbf{p}} + \frac{f_e^-}{\tau_{eh}} + \frac{f_e^-}{\tau_{ei}} - \frac{(\mathbf{p}_e \mathbf{V}_{dh})}{\tau_{eh}} \frac{\partial f_0}{\partial \varepsilon} = 0, \quad (5)$$

$$\mathbf{w}\nabla N + \frac{N^-}{\tau_{ph}} - \frac{(\mathbf{q}\mathbf{V}_{dh})}{\tau_{ph}} \frac{\partial N_0}{\partial \omega} = J, \quad (6)$$

J is a source due to the electron-hole system:

$$J \sim (T_h - T_p)/\tau_{hp},$$

where $T_h - T_p \ll T_p$; in turn, T_h and T_p are found from the energy balance of the electron-hole system allowing for the arrival of energy due to relaxation of high-energy particles.

It should be noted that in Eq. (6) the probability of the phonon-hole processes τ_{ph}^{-1} differs significantly from zero only at phonon frequencies ω lower than the limiting value $\omega_l \sim (w/\hbar)(2m_h T)^{1/2}$.

In the case of holes we can write down the hydrodynamic equation of viscous flow which essentially represents the law of conversation of momentum:

$$\frac{W_d - V_{dh}}{\tau_{hp}} + \frac{V_{de} - V_{dh}}{\tau_{he}} = \frac{V_{dh}}{\tau_{hi}}. \quad (7)$$

Here, the terms on the left-hand side (to within a factor m_h) describe the force exerted on the hole liquid by phonons and electrons (per one hole), whereas the right-hand side represents the friction force exerted by impurities. It should be noted that the value of τ_{hi} (describing a viscous force per one hole) can be regarded as a phenomenological parameter. We shall assume that in a rough estimate we shall employ the relaxation time estimated above without allowance for the hole-hole interaction.

It follows from Eqs. (5)–(7) that

$$\mathbf{w}\nabla N + N^-/\tilde{\tau}_p = J,$$

$$\frac{1}{\tilde{\tau}_p} = \frac{1}{\tau_{ph}} \left\{ 1 - \left[1 + \tau_{hp} \left(\frac{1}{\tau_{hi}} + \frac{1}{\tau_{he}} \left[1 - \frac{1}{\Omega_e^2 \tau_{eh}^2 + 1} \right] \right) \right]^{-1} \right\}.$$

The order of magnitude of the temperature T in an overheated region of radius r_0 can be estimated from the energy balance condition:

$$C(\hbar\omega_l) D(\omega_l) \frac{T}{r_0} 2\pi r_0 \sim \pi r_0^2 I,$$

where I is the rate of arrival of energy in the phonon system (per unit volume),

$$D(\omega_l) \sim \frac{w^2}{3} \tilde{\tau}_p(\omega = \omega_l, T), \qquad C(\hbar\omega_l) \approx C(T = \hbar\omega_l),$$

$C(T)$ is the specific heat of the phonon system, and $\omega_l = \hbar^{-1} w (2m_h T)^{1/2}$. We can easily see that in the limit $\Omega_e \tau_{eh} \to 0$ if $\tau_{hp} \ll \tau_{hi}$, we have

$$\tilde{\tau}_p^{-1} \sim \tau_{ph}^{-1} (\tau_{hp}/\tau_{hi}),$$

i.e., the drag effect increases considerably the diffusion coefficient D and, therefore, lowers the temperature T. However, if $\Omega_e \tau_{eh} > 1$, then allowing for the inequality $\tau_{he} < \tau_{hi}$, we find that $\tilde{\tau}_p \sim \tau_{ph}$. A more detailed analysis shows that an increase in the magnetic field when the range $\Omega_e \tau_{eh} \sim \tau_{he}/\tau_{hi}$ is reached increases the temperature at which $\Omega_e \tau_{eh} \sim \tau_{he}/\tau_{hp}$ reaches saturation.

CONCLUSIONS

1) The luminescence quenching effect is observed in InSb on application of a magnetic field directed along the wave vector of the exciting light. This effect is practically absent in the transverse configuration. The strongest

quenching is observed under excitation conditions sufficient to cause emission of stimulated radiation (lasing).

2) The effect is of kinetic nature and the direct reason for the quenching is an increase in the temperature of the electron-hole system in the presence of a magnetic field.

3) The proposed theoretical model explains the observed phenomena by a contribution of the mutual drag of electrons and holes by phonons. A longitudinal magnetic field slows down the drift of electrons in the direction of the cold volume and this in turn slows down the drift of holes and in the final analysis lowers the amount of heat carried by phonons to the cold volume. The drag is possible because of the effective screening of impurities by nonequilibrium carriers. The proposed model is in qualitative agreement with the experimental results.

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[1)]Estimates show that the time needed to establish a local equilibrium is much shorter than the characteristic transport times, so that the regime can be regarded as hydrodynamic and the distribution function as of equilibrium type. Naturally, the distribution of the temperature in the hot region is inhomogeneous, but in order-of-magnitude estimates we can use some characteristic temperature.

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