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MECHANISM OF FORMATION OF HOT ELECTRON COMPONENT IN THE INTERACTION BETWEEN AN ELECTRON BEAM AND A PLASMA

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Results are presented of an experimental investigation of the spectra of the oscillations excited by an electron beam in a plasma under conditions when a hot electron component appears. It is shown that the form of the oscillation spectra observed near the electron gun differ greatly from the form of the spectra measured in other regions of the plasma, where waves of the "whistler" type were observed. Absorption of waves of this type by the cold plasma electrons and by the hot-component electrons was observed. As a result of the generalization of the experimental results, a mechanism is proposed explaining the formation of the hot electron component. The component elements of this mechanism are the scattering of the beam electrons by electrostatic oscillations, capture of part of these electrons in the magnetic trap, and subsequent heating of the electrons by resonant interaction with the waves of the "whistler" type.

1. INTRODUCTION

In various experimental investigations of plasma heating[1-5] it was observed that under definite conditions there is produced a group of hot electrons with energy from several dozen keV to several MeV, exceeding by many times the voltage applied from the outside. These results have stimulated the study of collective processes, and in particular, the investigation of the hot component produced upon interaction of the electron beam with the plasma[6-9]. These and a number of investigations yielded the main macroscopic parameters of a plasma containing a hot electron component, but the mechanism whereby the latter is produced remained unclear. This was due, first, to the complexity of the phenomenon and, second, to the fact that the obtained experimental results yield only obviously integral characteristics and contain practically none of the data needed for the theory, foremost among which are the spectra of the excited oscillations.

From the very outset, there was no doubt that this phenomenon is connected with excitation of slow waves in the plasma, i.e., waves whose phase velocity is smaller than the velocity of light. It is known from the theory (see, for example,[10]) that these include oscillations of the electrostatic type with frequencies on the order of the plasma electron frequency ω_{0e} and electromagnetic waves with frequencies lower than the electron cyclotron frequency ω_{He}, which are frequently called also "whistlers."

In order to ascertain the mechanism whereby the hot electron component is produced, it is necessary to answer at least three fundamental questions.

1. What types of waves are excited by the beam in the plasma under conditions when the hot electron component is produced?
2. What type of waves transfer the energy to the hot electrons?
3. What distinguishes the small fraction of electrons receiving the larger energy from all others? In other words, what explains the fact that the density of the hot electron component is always many times smaller than the density of the plasma electrons?

The first question was the subject of[11-13]. It is shown in[11] that when the condition $\omega_{0e} \approx m\omega_{He}$ ($m = 1, 2, 3, \dots$) is satisfied, intense electrostatic oscillations are excited. It has turned out, however, that oscillations of this type do not propagate in the central region of the magnetic trap, but are localized near the place where the beam enters the plasma[12,13]. The entire remaining volume of the plasma is occupied by waves of the "whistler" type the intensity of which turns out to be smaller by at least one order of magnitude than the intensity of the electrostatic oscillations.

We present in this paper new experimental results and discuss them for the purpose of answering the still-unanswered questions, thus attempting to ascertain the mechanism whereby the hot electron, is produced when an electron beam interacts with a plasma.

2. EXPERIMENTAL RESULTS

The experimental setup, the diagnostic apparatus, and the data-reduction procedure were described in[12,13]. Principal attention, as before, was paid to an investigation of the spectra of the oscillations excited under the condition $\omega_{0e} \approx m\omega_{He}$ ($m = 2, 3$), i.e., when the density and temperature of the hot electron component were maximal. However, unlike the experimental conditions described in[12,13], the distribution of the intensity of the magnetic field near the electron gun varied in different experiments (Fig. 1). Figure 1 shows the location of the employed diagnostic apparatus, particularly the five high-frequency probes—four "electric" and one "magnetic" (loop). The signals from each probe were fed, through a branching system, to four receivers tuned to different frequencies within the investigated band. This has made it possible to observe the time correlation of the oscillation intensity at different frequencies. The plasma parameters (density $n_0 \approx (3-6) \times 10^{11}$ cm^{-3}) and the beam parameters (10 kV, 10 A, duration ≈ 600 μsec) were the same as before. In the experiments in which

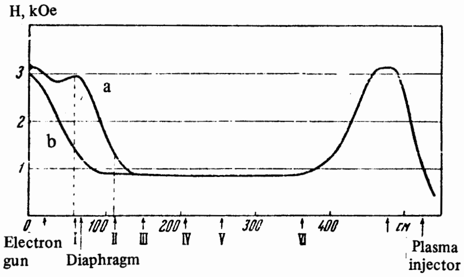

FIG. 1. Distribution of magnetic field intensity (a) and (b) along the axis of the apparatus and relative location of the diagnostic apparatus. I—probe No. 1, II—probe No. 2, III—8-mm radiointerferometer, IV—diamagnetic coil, V—probe No. 3, "magnetic probe," x-radiation receiver, VI—probe No. 4.

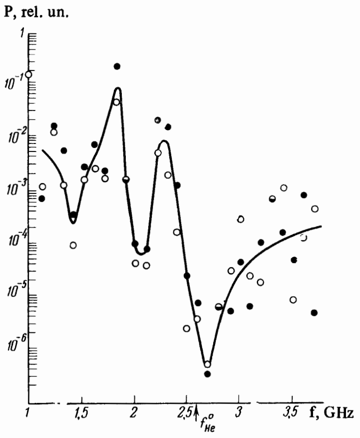

FIG. 2. Oscillation spectra obtained with the aid of probe No. 2, located at a radius of 7 cm. The frequency $f^0{}_{He}$ corresponds to the intensity of the main magnetic field. ○—$\omega_{0e} \approx 2\omega_{He}$, ●—$\omega_{0e} \approx 3\omega_{He}$, ◒—coinciding points.

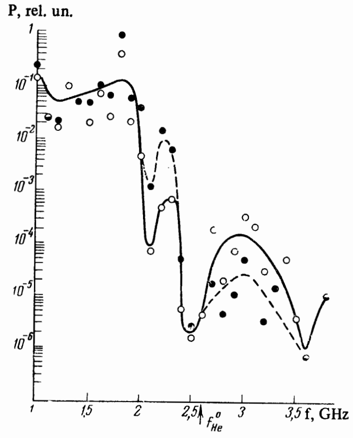

FIG. 3. Spectra of oscillations obtained with the aid of probe No. 3, placed at a radius of 6.5 cm. Most of the hot electrons were annihilated on this probe, which penetrated deepest into the plasma, and an x-ray pickup was aimed at this probe. ○—$\omega_{0e} \approx 2\omega_{He}$; ●—$\omega_{0e} \approx 3\omega_{He}$, ◒—coinciding points.

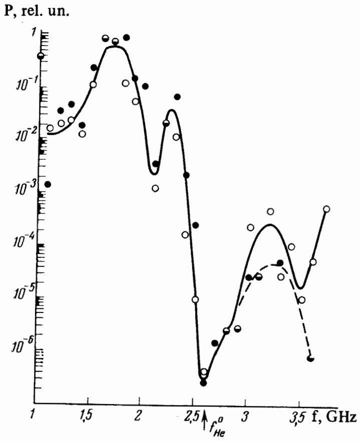

FIG. 4. Oscillation spectra obtained with the aid of a "magnetic" probe installed at a radius of 7 cm. ○—$\omega_{0e} \approx 2\omega_{He}$, ●—$\omega_{0e} \approx 3\omega_{He}$, ◒—coinciding points.

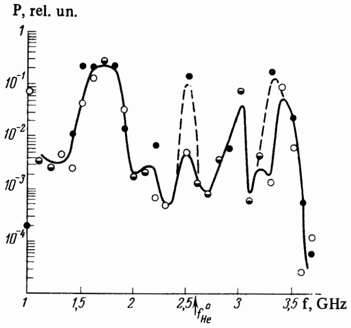

FIG. 5. Oscillation spectra obtained with the aid of probe No. 1 installed at a radius of 6 cm. ○—$\omega_{0e} \approx 2\omega_{He}$, ●—$\omega_{0e} \approx 3\omega_{He}$, ◒—coinciding points.

the field configuration b of Fig. 1 was used, the diaphragm closest to the electron beam was removed.

The configuration of the magnetic field was changed in such a way that probe No. 1 (see, Fig. 1, field configuration b) turned out to be approximately in that region of the field where probe No. 2 was located (see field configuration a, Fig. 1); the latter (see field configuration b, Fig. 1) was in the region of the homogeneous field. The oscillation spectra obtained under these conditions are shown in Figs. 2—5. We see that the spectra obtained with the aid of probes No. 2 and No. 3 and the "magnetic" probe, all of them located in the region of the homogeneous field, are similar in many respects. These spectra have minima analogous to those described earlier in[13], at the frequency f^0_{He} = 2.6 GHz, the cyclotron frequency corresponding to the magnetic field intensity at the center of the trap, and at the frequency ~ 2.0 GHz. The scatter in the intensity of the oscillations at these frequencies hardly exceeds the limits of the measurement accuracy. The absolute intensity of the oscillations measured with the aid of these probes was of the same order. In all the spectra, the maximum intensity of the oscillations was observed in the frequency region 1.8 GHz.

The oscillation spectra of Fig. 5, obtained with the aid of probe No. 1, differ significantly both from the spectra obtained with the aid of probe 2 in the case of field configuration a (Fig. 1)[13] and from the spectra of Figs. 2—4, although certain attributes of the latter apparently still remain. This means that the dimensions of the plasma region in which the electrostatic oscillations were excited did not depend directly on the magnetic field intensity. Inasmuch as the electrostatic oscillations excited in the plasma by the beam were investigated in detail in a number of studies (see, for example[1,2,11]) we did not investigate them further, and paid principal attention to the singularities of the spectra of the electromagnetic oscillations.

We note first of all that the appearance of a minimum at the frequency f^0_{He} was not unexpected, since waves of the "whistler" type should be effectively

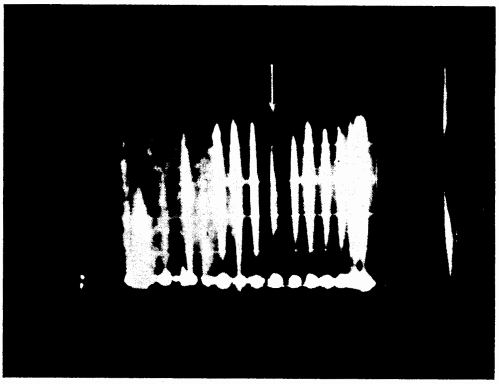

FIG. 6. Oscillogram illustrating the dependence of the oscillation amplitude on the main magnetic field. The minimum (marked with an arrow) corresponds to a field intensity 1 kOe; the receiver is tuned to 2.2 GHz. Three to five pulses were produced at each value of the field intensity.

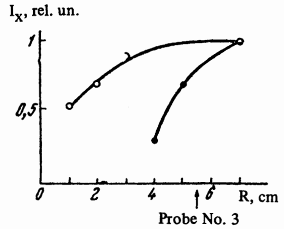

FIG. 7. Dependence of the x-ray intensity on the position of the probes relative to the plasma radius R. X-radiation with energy exceeding 15 keV, produced at probe No. 3, was registered. ○—probe No. 2 was moved and probe No. 4 was fixed at a radius 7 cm; ●—probe No. 4 was moved and probe No. 2 was fixed at a radius of 7 cm.

absorbed by the cold plasma electrons, (according to the theory, the phase velocity of such waves $v_{ph} \rightarrow 0$ as $\omega \rightarrow \omega_{He}$, where anomalous dispersion is observed). The nature of this absorption is analogous in many respects to the nature of an effect well known in optics, that of sharp increase of absorption in solids, liquids, and gases near the anomalous-dispersion frequencies.

In a comparison of the oscillograms of the oscillations and of the x-rays it was noted that the appearance of the minimum at frequencies near 2 GHz is connected with the presence of intense x-radiation. Moreover, were we to use in the reduction of the oscillograms not the oscillation intensity corresponding to the maximum x-ray intensity but the maximum intensity of the oscillation during the pulse, then this minimum would be missing from Figs. 2—4. However, in order to verify conclusively that the appearance of such a minimum is not an apparatus effect or an error in the reduction of the oscillograms, we plotted the oscillation amplitude against the intensity of the main magnetic field. To relate the oscillation amplitude with the intensity of the x-ray intensity we used the following simple scheme. A voltage proportional to the current in the coils of the main magnetic field was applied to the input of the horizontal-deflection amplifier of a type S1-18 oscilloscope; the signal to the vertical amplifier came from a receiver tuned to 2.2. GHz and connected to probe No. 3. The amplified x-ray signal was applied to the supply of the cathode-ray beam. Under these conditions, the oscillations on the oscilloscope screen were registered only if the intensity of the x-rays was higher than the established threshold. Figure 6 shows the oscillogram obtained in this experiment and reveals a minimum of the oscillation amplitude, which shifts as expected towards larger magnetic fields. Thus, the minimum observed on the spectra at the frequencies $f < f_{He}^0$ is confirmed also by the dependence of the oscillation intensity on the intensity of the main magnetic field.

Measurements of the range of distribution of the oscillation intensity at the field configuration a (Fig. 1) revealed one more property of the hot electron component, a property of importance for the understanding of the entire mechanism. It turned out that insertion of probe No. 2 into the plasma, up to the beam radius (≈ 2 cm), had little effect on the intensity of the x-radiation produced by the hot electrons striking probe No. 3, whereas when probe No. 4 was inserted into the plasma only 1—2 cm deeper than probe No. 3, the intensity of the x-rays was greatly reduced (Fig. 7). This means that the bulk of the hot electrons is reflected at the very start of the magnetic mirror, without reaching probe No. 2. The latter is possible in the case when only the perpendicular velocity component of the hot electrons increases mainly during the time of heating.

3. DISCUSSION OF RESULTS

I. As is well known, a monoenergetic beam of electrons moving with velocity v_1 along an external magnetic field excites in a plasma electrostatic oscillations with an increment

$$\gamma \sim (n_1 / n_0)^{1/3} \omega_{0e},$$

where n_1 is the beam density and n_0 is the plasma density ($n_1 \ll n_0$). Under the conditions of our experiment ($n_1 \sim 10^9$ cm^{-3}, $n_0 \sim 5 \times 10^{11}$ cm^{-3}) the characteristic length of the buildup of these oscillations $L \sim v_1/\gamma$ amounted to several centimeters. However, as a result of the reaction of the oscillations on the beam, its distribution function becomes plateau-like and the excitation of oscillations of this type ceases. Apparently, the spreading of the beam accounts for the fact that the electrostatic oscillations are excited only near the entrance of the beam into the plasma.

The excitation of electromagnetic waves by a beam of electrons moving along an external magnetic field H_0 was investigated theoretically in[14]; it is shown that the waves excited with the largest increments are those oblique relative to H_0. However, it followed from the experiment that waves with vectors k almost parallel to H_0 were also excited quite effectively[12]. To obtain this result, the hypothesis was advanced that waves of the "first line" type are excited by those beam electrons which obtain a transverse velocity component when they interact with the electrostatic oscillations. (The appearance of a perpendicular velocity component of the beam electrons following interaction with a plasma was observed, in particular, in[15].) In order to justify such an assumption, the problem of excitation of waves of this type with $k \parallel H_0$ by a smeared-out electron beam was solved.

In solving this problem it was assumed that the plasma is cold and unbounded, the beam distribution function $F(v_{\parallel}, v_{\perp})$ is Maxwellian with respect to the longitudinal and transverse velocities, and the thermal velocity v_{1T} of the beam particles is of the order of its directional velocity v_1. The expressions obtained in[14] were used for the dielectric tensor of the plasma with the beam. The dispersion equation for the electromagnetic waves is of the form

$$N^4 - 2\varepsilon_{11}{}^0 N^2 + (\varepsilon_{11}{}^0)^2 + (\varepsilon_{12}{}^0 + \varepsilon_{12}{}')^2 = 0, \qquad (1)$$

where N is the refractive index, ϵ_{11}^0 and ϵ_{12}^0 are the components of the dielectric tensor of the cold plasma, and ϵ_{12}' is the contribution made by the beam to the component ϵ_{12}. These components are written in the form[7,14]

$$\varepsilon_{11}{}^0 = 1 - \frac{\omega_{0e}{}^2}{\omega^2 - \omega_{He}{}^2}, \qquad \varepsilon_{12}{}^0 = -\frac{i\omega_{0e}{}^2\omega_{He}}{\omega(\omega^2 - \omega_{He}{}^2)},$$

$$\varepsilon_{12}{}' = -\frac{\sqrt{\pi}}{2}\frac{\omega_{0e1}^2}{\omega^2}\frac{\omega - kv_1}{\sqrt{2}kv_{1T}}W(z), \qquad (2)$$

where k is the wave number and ω_{0e1} is the plasma frequency of the beam. The function W(z) is given by

$$W(z) = e^{-z^2}\left(\pm 1 + \frac{2i}{\sqrt{\pi}}\int\limits_0^z e^{t^2}\,dt\right), \qquad z = \frac{\omega - \omega_{He} - kv_1}{\sqrt{2}kv_{1T}}. \qquad (3)$$

Using the assumption that $v_{1T} \sim v_1$, it is easy to simplify expression (3) and reduce it to the form

$$W(z) \approx \pm 1 + \frac{2iz}{\sqrt{\pi}}. \qquad (4)$$

In expressions (3) and (4) the plus sign means that the wave moves in the same direction as the beam electrons, and the minus sign is used in the opposite case. To simplify the solution, it is also assumed that the oscillation frequency is close to the cyclotron frequency, i.e., $\omega \approx \omega_{He}$. As a result, expressions are obtained for the increment and the frequency of the maximally excited wave (wave number $k_{max} \approx \omega_{He}/v_1$):

$$\gamma_{max} \approx 3\cdot 10^{-2}\frac{\omega_{0e1}^2\omega_{0e}{}^2}{\omega_{He}{}^3}\left(\frac{v_1}{c}\right)^4, \qquad (5)$$

$$\omega_{max} \approx \omega_{He}\left[1 - 0.6\left(\frac{\omega_{0e}}{\omega_{He}}\frac{v_1}{c}\right)^2\right], \qquad (6)$$

where c is the velocity of light.

It is seen from these expressions that the waves that build up move in the same direction as the beam; ω_{max} is always somewhat smaller than the cyclotron frequency. However, if we substitute in (5) the parameters of our experiment, then the increment turns out to be utterly insufficient to be able to attribute experimental results to such a mechanism. Consequently, there exists a stronger mechanism for the excitation of waves of the "whistler" type. It may be based, for example, on the modulation of the beam at the frequencies of the electrostatic oscillations. The appearance of such a modulation in the beam as it emerges from the plasma was observed experimentally in[16].

Another mechanism that can, in principle, lead to energy transfer from the electrostatic oscillations to the electromagnetic ones is the nonlinear interaction of the oscillations.

II. It can be concluded from the aggregate of our experimental results that the hot electronic component is produced during the course of the interaction between the resonant electrons and waves of the "whistler" type. Let us list briefly the results that allow us to make this statement:

1. The region of localization of waves of this type coincides with the plasma region (axial and radial) where the hot electrons are registered. The electrostatic oscillations are excited mainly outside this region.

2. A correlation was observed between the intensity of the x-radiation and the intensity of the waves of the "whistler" type with frequencies $\omega \lesssim \omega_{He}$. It was established that the waves of this type are excited not by the hot-component electrons but by the beam electrons.

3. The heating feature contributing to the prolonged containment of the hot electrons in the magnetic trap after the beam is turned off, namely the predominant increase of the number of electrons having a perpendicular velocity during the heating process, is in good agreement with the spatial orientation of the vector of the electric field ($\mathbf{E} \perp \mathbf{H}_0$ for waves with frequencies $\omega \lesssim \omega_{He}$), and with the feature of the propagation of waves of the "whistler" type in a plasma (the effect of total internal reflection[12]).

4. Absorption of waves of the "whistler" type by cold plasma electrons and by hot-component electrons was observed.

At the plasma and neutral-gas densities reached in our experiment, there was practically no wave absorption in pair collisions between the particles. Collisionless absorption, as is well known, is produced by resonant particles whose velocity is close to the phase velocity of the wave ("Landau damping"). From the dispersion relation describing the propagation of waves of the "whistler" type in a cold unbounded plasma, and from the condition of the resonance of the electron and the wave it is easy to obtain an expression for the electron-velocity component $v_{\parallel}$ along $\mathbf{H}_0$[12]:

$$v_{\parallel} = c\frac{\omega_{He}}{\omega_{0e}}\left(1 - \frac{\omega}{\omega_{He}}\right)^{3/2} \qquad (7)$$

where ω is the frequency of the wave. It is seen from this, in particular, that the cold electrons ($\bar{v}_{\parallel} \approx 0$) can draw energy only from waves whose frequencies are close to ω_{He}, causing the appearance of a minimum near this frequency. Starting from the fact that the absorption of the waves by hot electrons also appears in the form of the minimum, it can be concluded that the distribution function of the electrons of a hot component with respect to $v_{\parallel}$ has a maximum at a certain value $\bar{v}_{\parallel} \approx 2 \times 10^9$ cm/sec. We note that in our case the approximation of an unbounded plasma ($k_{\perp} = 0$) is apparently not too crude, since for $k_{\parallel} > k_{\perp}$ waves with frequencies $\omega \lesssim \omega_{He}$, owing to the large refractive index; is determined by the transverse dimension of the plasma.

III. To explain the experimental results, the hypothesis was advanced earlier in a number of papers (particularly[7,15]) that the hot electronic component consists mainly of beam electrons that acquire an appreciable perpendicular velocity component as a result of interaction with the electric oscillations and are captured in the magnetic trap. Our experimental data can also be easily explained by starting from such an assumption. Indeed, the appearance of a maximum on the distribution function at $\bar{v}_{\|} \approx 2 \times 10^9$ cm/sec ($\bar{v}_{\|}$ is only one-third the initial beam velocity $v_1 = 6 \times 10^9$ cm/sec) can be easily explained by starting from the well known laws governing the capture of particles injected from the outside into a magnetic trap, and the aforementioned singularities of the propagation of electrostatic and electromagnetic oscillations in a plasma. We shall not discuss here this simple reasoning, and produce only the corresponding estimate of the density and temperature of the hot electron component.

The density of the hot electrons n_2 can be estimated with the aid of the expression

$$n_2 = \eta I \tau_1 / V, \tag{8}$$

where I is the beam current, V is the volume occupied by the hot electronic component, τ_1 is the lifetime of the hot electrons in the trap, determined in our case by the rates of diffusion across the magnetic field, and η the coefficient of capture of beam electrons in the trap. All the quantities with the exception of η were determined by us experimentally and amounted to $I = 10$ A $= 6 \times 10^{19}\ \text{sec}^{-1}$, $\tau_1 \approx 5 \times 10^{-6}$ sec (delay between the turning on of the beam and the appearance of the x-radiation under conditions $\omega_{0e} = 2.3\,\omega_{He}$), $V = 5 \times 10^4\ \text{cm}^3$, and $n_2 \approx 5 \times 10^8\ \text{cm}^{-3}$ (from diamagnetic and x-ray measurements). Substituting these values in (8), we obtain $\eta \sim 0.1$, which is perfectly reasonable.

The temperature of the hot electronic component can be estimated by using the results of[17], where quasilinear-theory equations were obtained with allowance (phenomenological) for the correlation time of the microfields in the plasma. In particular, stochastic heating of the electrons by the random field of electromagnetic waves propagating along the external magnetic field was considered, and it was shown that in this case the field energy goes over mainly into the transverse energy of the electrons. Therefore, taking into account only the change of the distribution function F with respect to the transverse velocities and assuming that $\omega \approx \omega_{He}$, it is easy to obtain from Eq. (8) of[17] an equation in the form

$$\frac{\partial F}{\partial t} = \frac{\pi e^2 E^2 V_\omega}{4 m_e^2}\left(\frac{\partial^2 F}{\partial v_\perp^2} + \frac{1}{v_\perp}\frac{\partial F}{\partial v_\perp}\right), \tag{9}$$

where e and m_e are the charge and mass of the electron, E is the intensity of the electric field of the wave,

$$V_\omega = \frac{1}{2\pi}\int_{-\infty}^{\infty} U(t)\, e^{-i\omega t}\, dt, \tag{10}$$

and U(t) is the correlation function.

The parameter introduced to describe the behavior of the function U(t) is the correlation time τ_2, which coincides in order of magnitude with the time of the resonant interaction of the electron with the wave. Since the longitudinal component of the electron velocity remains practically unchanged in the interaction between electrons and waves of the "whistler" type, deviation from resonance should occur for other reasons, for example because of pair collisions or in an inhomogeneous external magnetic field. In a plasma of density 10^{11}—$10^{12}\ \text{cm}^{-3}$, the latter circumstance is decisive, and we therefore assume that τ_2 equals the travel time of the electron between mirrors.

The form of the function V_ω depends weakly on the concrete form of the correlation function. For example, if we choose

$$U(t) = \begin{cases} 1 & \text{if} \quad 0 < t \leqslant \tau_2 \\ 0 & \quad\quad t > \tau_2 \end{cases}, \tag{11}$$

then we obtain $V_\omega = \tau_2/2\pi$. In the case when $U(t) = \exp(-t/\tau_2)$, we have $V_\omega = \tau_2/\pi$. Since the magnetic trap used in our experiment had a relatively long homogeneous-field section, it seems more correct to choose the correlation function in the form (11).

In many experiments (see, for example,[7]) it has been shown that the distribution function of the hot electrons is Maxwellian. Therefore Eq. (9) should be satisfied by a function in the form

$$F = C\frac{1}{T_\perp(t)}\exp\left[-\frac{m_e v_\perp^2}{2T_\perp(t)}\right], \tag{12}$$

where $T_\perp(t)$ is a "transverse" temperature and C is a normalization constant. Substituting (12) in (9), we obtain

$$T_\perp(t) = T_0 + \frac{e^2E^2\tau_2}{4m_e}t, \tag{13}$$

where T_0 is the initial temperature of the electrons captured in the trap. Obviously, during the course of heating the electron temperature increases only in the time $t \sim \tau_1$ when the stationary state is established, i.e.,

$$(T_\perp)_{max} = T_0 + \frac{e^2E^2\tau_1\tau_2}{4m_e}. \tag{14}$$

Let us substitute in (14) the parameters of our experiment. Assuming that for resonant electrons $E \approx 15$ V/cm (starting from the width of the maximum of absorption and the field intensity given in[12]), $\tau_1 \approx 5 \times 10^{-6}$ sec, $\tau_2 \approx 10^{-7}$ sec, and $T_0 \approx 10^3$ eV, we obtain $(T_\perp)_{max} \approx 40$ keV, which is in good agreement with the quantity (20—40 keV) obtained from measurements with the aid of x-ray absorbers.

As follows from the measured spectra of the oscillations, particularly from Figs. 2—4, the minima of the absorption, connected with the hot component and the plasma electrons, coalesce. It is therefore possible that the electrons of the Maxwellian "tail" of the plasma also contribute to the hot electron component. However, elementary estimates show that the number of electrons with velocity $v_{\|} \approx 2 \times 10^9$ cm/sec in a plasma with temperature ~ 10 eV is so small that their contribution cannot be appreciable.

It is possible to separate quite distinctly the main factors under the influence of which there is produced a hot electron component in our experiments on the interaction of electron beams with a plasma:

1. Excitation of electrostatic oscillations near the electron gun.
2. Scattering of beam electrons by these oscillations and excitation of waves of the "whistler" type.
3. Capture of part of the scattered electrons in the magnetic trap.
4. Heating of these captured electrons and their diffusion across the magnetic field following interaction with waves of the "whistler" type.

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[1] I. F. Kharchenko, Ya. B. Faĭnberg, R. M. Nikolaev, E. A. Kornilov, E. I. Lutsenko, and N. S. Pedenko, Nucl. Fusion, p. III, 1962.

[2] L. D. Smullin and W. D. Getty, Proc. Conf. of Plasma Physics and Controlled Nuclear Fusion Research, Culham 1965, II, Vienna, 1966, p. 815.

[3] R. V. Neidigh, I. Alexeff, G. E. Guest, W. D. Jones, D. C. Montgomery, D. J. Rose, and W. L. Stirling, Conf. Proc., Novosibirsk, 1968, II, Vienna, 1969, p. 693.

[4] M. V. Babykin, P. P. Gavrin, E. K. Zavoĭskiĭ, S. L. Nedoseev, L. I. Rudakov, and V. A. Skoryupin, Zh. Eksp. Teor. Fiz. **42**, 1597 (1964) and **52**, 643 (1967) [Sov. Phys.-JETP **20**, 1073 (1965) and **25**, 421 (1967)].

[5] R. A. Dandl, J. L. Dunlap, H. O. Eason, P. H. Edmonds, A. C. England, W. J. Herrman, and N. H. Lazar, Conf. Proc., Novosibirsk, 1968, II, Vienna, 1969, p. 435.

[6] R. A. Demirkhanov, A. K. Govorkov, A. F. Popov, G. L. Kharasanov, Proc. Conf. etc. Pros. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Culham, 1965, II, Vienna, 1966, p. 801.

[7] L. P. Zakatov, A. G. Plakhov, D. D. Ryutov, and V. V. Shapkin, Zh. Eksp. Teor. Fiz. **54**, 1088 (1968) [Sov. Phys.-JETP **27**, 583 (1968)].

[8] A. I. Karchevskii, A. P. Babichev, Yu. A. Muromkin, and V. N. Bezmel'nitsyn, ibid. **53**, 1195 (1967) [**26**, 701 (1968)].

[9] B. S. Akshanov, Yu. Ya. Volkolupov, and K. D. Sinel'nikov, Zh. Tekh. Fiz. **36**, 595 (1966) [Sov. Phys.-Tech. Phys. **11**, 446 (1966)].

[10] V. D. Shafranov, in: Voprosy teorii plazmy (Problems of Plasma Theory), No. 3, Atomizdat, 1963.

[11] M. Seidl and P. Sunka, Nucl. Fussion **7**, 237 (1967).

[12] A. N. Krakhov, Zh. Eksp. Teor. Fiz. **56**, 792 (1969) [Sov. Phys.-JETP **29**, 431 (1969)].

[13] A. N. Krakhov, Third Europ Conf. on Contr. Fusion and Plasma Phys., Utrecht, Netherlands, rep. No. 42, 1969.

[14] K. N. Stepanov and A. B. Kitsenko, Zh. Tekh. Fiz. **31**, 167 (1961) [Sov. Phys.-Tech. Phys. **6**, 120 (1961)].

[15] J. Cabral, H. J. Hopman, F. G. Insinger, and W. Ott, Conf. Proc., Novosibirsk, 1968, II, 749, 1969.

[16] A. K. Berezin, Ya. B. Faĭnberg, L. I. Bolotin, G. P. Berezina, in: Vzaimodeĭstvie puchkov zaryazhennykh chastits s plazmoĭ (Interaction of Charged-particle Beams with a Plasma), Kiev, 1965.

[17] F. G. Bass, Ya. B. Faĭnberg, and V. D. Shapiro, Zh. Eksp. Teor. Fiz. **49**, 329 (1965) [Sov. Phys.-JETP **22**, 230 (1966)].

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41