Oscillatory dissipation regime in a current layer

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A regime wherein the electron temperature of the plasma and the conductivity vary periodically with time was experimentally observed in a turbulent neutral θ-pinch layer. The experimental results are satisfactorily explained by using a simple physical model based on the quasilinear theory of ion-sound instability, with account taken of the energy losses.

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INTRODUCTION

The investigation of the dynamics of plasma heating in current layers is of importance for different models of solar flares, processes in the geomagnetic tail of the earth, and certain trends in controlled thermonuclear fusion. It is customarily assumed that the most effective dissipation mechanism comprises current instabilities. Certain features of the energy release in a neutral turbulent current layer were investigated experimentally.[1,2] It was shown that the plasma heating is connected with the anomalously low plasma conductivity σ, due to excitation of ion-sound turbulence. The bulk of the electrons is heated to temperatures 0.5–1 keV, and a small fraction is accelerated to energies 12 keV. The values of σ attainable in experiments during the initial stage of the dissipation process, the heating rate, as well as the features of the energy spectrum of the electrons[3,4] can be explained for current systems without energy loss on the basis of the quasilinear theory of ion-sound instability.[5,6]

For problems of astrophysics and controlled thermonuclear fusion, it is important to investigate the dynamics of plasma heating during later stages, when the heat loss and the particle accumulation and departure from the layer become substantial. In this paper we attempt to study the evolution of electron heating in a neutral layer at times when the influence of the thermal conductivity on the current dissipation in the layer is substantial, while the hydrodynamic motions along the layer can still be neglected. Experiments revealed under these conditions the existence of a dissipation regime in which the temperature and the noise level in the layer increase and decrease periodically. It will be shown by phenomenological estimates that these can be interpreted as relaxation oscillations about a definite dynamic equilibrium.

The feasibility in principle of realizing a regime with relaxation oscillations in a turbulent neutral layer with energy loss will be demonstrated in the following manner. We consider a plane current layer located between oppositely directed magnetic fields. The layer is infinite in the electric-field direction and has a finite width L along the magnetic force lines. We assume that the energy density W of the ion-sound waves in the layer is low enough and that we can confine ourselves to the quasilinear stage of the instability. We assume that the inequality $\nu_{\rm eff} \ll \omega_{He}$ is satisfied throughout in the neutral layer except for a small vicinity of the neutral line ($\nu_{\rm eff}$ is the effective frequency of the collisions with the ion-sound noise and ω_{He} is the electron cyclotron frequency). This inequality means that the electrons are magnetized and that their velocity distribution is almost isotropic in a reference frame connected with the current. The electronic growth rate is determined in this case by two quantities: by the current velocity v_d and by the effect of temperature T_e.[5] We assume in addition that $\omega_{He} \ll \omega_{pe}$ and that the influence of the magnetic field on the dispersion characteristics of the ion-sound oscillations can be neglected.

We characterize the energy losses by means of the reciprocal energy lifetime ν_E, which in the general case depends on the electron temperature T_c and on the noise energy density W. The neutral layer can then be in dynamic equilibrium T_{e*}, W_*, which corresponds to the vanishing of the right-hand side of the following equations:

$$n\frac{dT_e}{dt}=\frac{e^2n^2v_d^2}{\sigma(W,T_e)}-\nu_E(W,T_e)nT_e, \tag{1}$$

$$\frac{dW}{dt}=\gamma_e(T_e)W-\gamma(W); \tag{2}$$

$$\sigma(W,T_e)=ne^2/m\nu_{\rm eff},\quad \nu_{\rm eff}=\gamma_eW/mnv_dc_s\ [6].$$

Here $\gamma_e(T_e)=\mu\omega_{pe}(v_d/c_s-1)$ is the maximum growth rate of the ion-sound instability over the spectrum of the unstable waves; $\mu=m/M$ is the ratio of the electron and ion masses; $c_s=(T_e/M)^{1/2}$; γ is the maximum possible noise damping decrement for the given plasma system, and is assumed for simplicity to be independent of the electron temperature. We assume that the energy loss is due to the anomalous thermal conductivity along the magnetic field, and then

$$\nu_E=\varkappa/nL_{\rm eff}^2,\quad \varkappa=nT_e/m\nu_{\rm eff},\quad L_{\rm eff}\approx L/2.$$

We confine ourselves to layer parameters such that the change of the dynamic equilibrium is "adiabatic" relative to the possible relaxation oscillations, i.e., the characteristic time of the variation of n, γ, and v_d is much longer than the period of the relaxation oscillations. Then, linearization of Eqs. (1) and (2) near the dynamic equilibrium, with allowance for the indicated dependences of the functions σ, ν_E, and γ_e on T_e and W, yields the following equation ($\tilde W$ is the deviation from the equilibrium value of W_*):

$$\ddot{\tilde W}+2\nu\dot{\tilde W}+\omega^2\tilde W=0. \tag{3}$$

This equation describes an oscillator with frequency $\omega = (\gamma\nu_{E*})^{1/2}$ and with a damping $\nu = 2\nu_{E*}$. At $\gamma \gg \nu_{E*}$, the quality factor of the relaxation oscillations is $Q = \omega/2\nu \gg 1$. Thus, weakly damped relaxation oscillations are possible near the dynamic equilibrium of the neutral current layer with energy loss and can result, first, from the "nonadiabatic" formation of the neutral layer, relative to the possible relaxation oscillations, and second, because of the nonadiabatic change of the external conditions, (e.g., of the value of the boundary magnetic field) for the current layer that is already in dynamic equilibrium.

The relaxation of the current layer is analogous to the periodic regimes of plasma systems with turbulence excited by fast particles, which were investigated in Refs. 7 and 8. It was shown there, within the framework of the quasilinear approximation, that periodic pulsations of the parameters appear near dynamic equilibrium with respect to the fast particles and the energy of the excited waves. The possibility of such a regime for a turbulent neutral layer was first indicated in Ref. 9.

1. EXPERIMENTAL RESULTS

A turbulent current layer with a zero magnetic-field line was produced with an installation of the θ-pinch type with opposing fields. To produce the magnetic piston we used a surge loop of diameter 16 cm and width $L = 30$ cm. The amplitude of the magnetic field of the piston was 1200 Oe, and the half-period was 1.3 μsec. The initial plasma parameters were $n = 10^{11}-10^{14}$ cm^{-3}, $T_{e0} \approx T_{i0} \approx 1-5$ eV, $H_0 = 100-600$ Oe, and the working gases were hydrogen and argon. A description of the apparatus and of the process of current-layer formation is given in Ref. 2. When a plasma with a frozen-in initial magnetic field of opposite direction is compressed by a magnetic piston, a cylindrical current layer that converges towards the axis of the apparatus is produced.

The temperature of the plasma in the course of the formation and evolution of the current layer was measured with a double potential probe against a floating potential. One of the electrodes was placed in the region of the current layer and the other in the unperturbed plasma on the axis of the plasma volume. The double potential probe is similar to that described in Ref. 10. This procedure can be used when the floating potential exceeds the potentials connected with the hydrodynamic motions of the plasma. Under the conditions of the described experiment, as shown by special measurements, it is possible to determine the plasma temperature with the aid of the potential probes if $T_e > 50$ eV (Ref. 11).

For a Maxwellian distribution function, the plasma temperature relative to the floating potential is given by

$$\varphi = \frac{T_e}{2e} \ln\left(\mu \frac{\pi}{2}\right).$$

The energy spectrum of the electrons was measured with a multichannel x-ray pickup with a detector based on a microchannel plate, which could measure the thermal part of the distribution function at $T_e \geqslant 300$ eV. The measurements have shown that the distribution function in the current layer is not Maxwellian.[4] Calculations show that the described floating-potential method of determining the temperature is correct for these spectra if the temperature is taken to mean the quantity connected with the average energy of the particles by the relation $T_e = (\frac{2}{3})\bar{\varepsilon}$. At $T_e \geqslant 300$ eV the temperature obtained by both methods under identical experimental conditions coincide. In the present paper, the x-ray pickup was used to estimate the hardness of the electron spectrum from the ratio of the signals from two channels that registered the bremsstrahlung of the plasma on a target specially placed in the plasma. The inputs of the channels were covered with absorbers: A_1— aluminum 7 μm thick; A_2 — polystyrene 24 μm thick.

Typical oscillograms of the signals from the potential probe (a) and from one of the x-ray pickup channels (b) are shown in Fig. 1. The figure shows also oscillograms of the magnetic signals. It is seen that a signal from the x-ray pickup as well as a large negative potential is registered in the current layer, whose position in the figure is shown by arrows. This is evidence of intense heating of the plasma in the layer.

In the first run of experiments, the potential probe was used to measure the dependence of the floating potential in the layer on the lifetime τ of the layer at a fixed position of the probe inside the plasma volume ($r = 3.4$ cm, Fig. 2). The time interval τ was reckoned from the instant of the appearance of the null line of the magnetic field on the plasma-volume boundary to the instant of its arrival to the probe. At constant r, variation of τ was achieved by changing the velocity of the current layer with change of initial plasma density in the range $n = 3\times10^{11}-2\times10^{13}$ cm^{-3}.

As seen from the figure, the plots for the different values of the magnetic field are similar. Intense heating of the plasma begins with a certain delay relative to the start of formation of the current layer. The characteristic time of plasma heating in the layer amounts to 30–50 nsec. The heating time of the plasma increases with increasing initial magnetic field. The maximum plasma temperature is reached by the instant $\tau = 70-100$ nsec, which is close to the characteristic layer-formation time. According to the magnetic measurements, by that time the layer reaches a symmetrical state, (by that instant the amplitude of the piston magnetic field exceeds $2|H_0|$), after which the values of

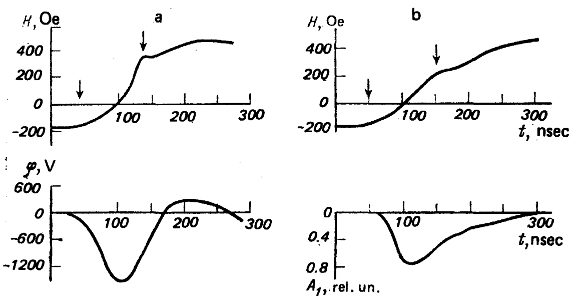

FIG. 1. Oscillograms of signals from the magnetic and potential probes and of the signal from the x-ray pickup, r is the distance from the probes to the axis of the volume: a) $H_0 = 260$ Oe, $n = 10^{13}$ cm^{-3}, $r = 5.3$ cm; b) $H_0 = 255$ Oe, $n = 3\times10^{13}$ cm^{-3}, $r = 5.8$ cm.

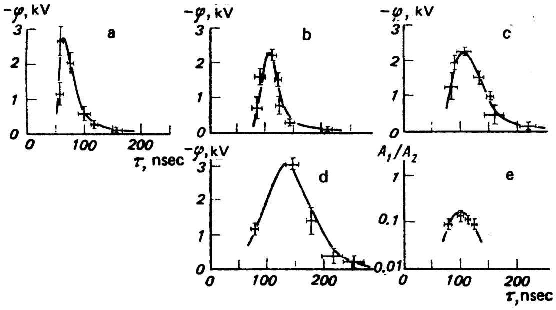

FIG. 2. Initial stage of plasma heating in the layer, $r=4.8$ cm; a) hydrogen, $H_0=160$ Oe; b) hydrogen, $H_0=250$ Oe; c) hydrogen, $H_0=340$ Oe; d) argon, $H_0=260$ Oe; e) hydrogen, $H_0=240-360$ Oe.

the magnetic field on the boundaries of the layer stabilize.[12] The thickness of the steady-state layer is $c/\omega_{pe} < \Delta < c/\omega_{pi}$.[2] With further increase of τ, as seen from Fig. 2, the value of the temperature in the layer, registered at a fixed radius, decreases. For hydrogen and argon the plots of $\varphi(\tau)$ are similar, although a smoother variation is observed for argon.

Figure 2 shows the ratio of the signals from two x-ray pickup channels, covered with different absorbers, as a function of τ. An increase of this ratio, which characterizes the hardness of the energy spectrum of the electrons, corresponds to an increase of the average particle energy. The ratio could be measured here only for those τ which correspond, in accordance with potential measurements, to the maximum heating of the plasma in the current layer. At $\tau > 130$ nsec and $\tau < 80$ nsec the ratio decreases abruptly because of the decrease of the sensitivity of the channel with a thick absorber with decreasing energy of the plasma electrons. Thus, measurements of the initial stage of the plasma heating in the turbulent current layer by independent methods yield identical results.

The observed dependence of the plasma temperature in the layer on τ can be connected both with the temporal dynamics of the heating mechanism in the current layer and with the change of the initial plasma density at various τ. It should be noted that the change of n is negligible during the stage of the rapid initial plasma heating ($70 < \tau < 100$ nsec). The temporal evolution of the plasma temperature in the formed current layer at $\tau = 100$ nsec was investigated by measuring, as the layer moved towards the axis, the floating potential of the system at the instants that the layer passed over the potential pickups located at various radii of the plasma volume. To construct the plot, we used measurements in current layers with boundary magnetic field amplitudes $H_b = 270-315$ Oe and with initial plasma density $n = (5-10)\times 10^{12}$ cm^{-3}. It is seen that the plasma temperature in the layer varies with time nonmonotonically and oscillates with a period ~150 nsec. The average plasma temperature T_{av} in the layer decreases with time. During the first half-cycle, $T_{av} \approx 200$ eV, as follows from the mean value of the potential in the interval $\tau = 100-200$ nsec in Fig. 3. The nonmonotinic character of the dependence of the temperature on τ in Fig. 2 can also be attributed to the buildup of oscillations in the course of the temporal evolution of the current layer.

The plasma heating in the layer is connected with the development of small-scale instabilities that lead to an anomalously low value of the conductivity. Figure 3b shows the results of the measurements of the conductivity of the plasma in the course of evolution of the current layer. Near the null line of the magnetic field, Ohm's law for the current-layer plasma takes the simple form $j = \sigma E_\varphi$. The plasma conductivity in the current layer was determined from the results of measurements of the azimuthal electric field E_φ and of the current density

$$j \approx c\Delta H/4\pi\Delta r$$

with probes near the null line of the magnetic field. These measurements are described in detail in Ref. 3. It follows from Fig. 3b that the change of the plasma temperature in the layer is connected with the change of its conductivity. Since the plasma conductivity is connected with the turbulence level W/nT_e, it follows that the turbulence level oscillates during the evolution of the current layer.

2. PHENOMENOLOGICAL ESTIMATES

The experimentally observed oscillations are nonlinear. It follows from Fig. 3a that $\tilde{T}/T_{e*} \approx 0.5$ at $\tau = 150-350$ nsec. The oscillation current density is $W \sim T/\sigma$. The relative change of this quantity in this range of values of τ is approximately equal to 10. For nonlinear oscillations, in which the modulation of the noise energy density is $W_{max}/W_* \gg 1$ and the depth of the temperature modulation is $\tilde{T}/T_{e*} < 1$, Eqs. (1) and (2) can be written in the form

$$\frac{d\tilde{T}}{dt} = \nu_{E*} T_{e*} \left(\frac{W}{W_*} - \frac{W_*}{W}\right) \tag{4}$$

$$\frac{dW}{dt} = -\frac{\gamma}{2}\frac{\tilde{T}}{T_{e*}} W. \tag{5}$$

The values of W_* and T_{e*} correspond to the state of dynamic equilibrium. It is assumed that in the turbulent layer there is realized a quasilinear regime of ion-sound turbulence, and the characteristic time of variation of n, v_d and γ greatly exceeds the period of the relaxation oscillations.

From Eqs. (4) and (5) we can obtain the connection between the modulations of the noise energy level and the temperature. The energy density of the noise is maximal at $\tilde{T} = 0$ and

$$\tilde{T}/T_{e*} \approx (W_{max}/W_*)^{1/2}/Q. \tag{6}$$

It follows also from (4) that the noise energy-density oscillations leads the temperature oscillations in phase by one-quarter of the period. In addition, from Eqs. (4) and (5) at $W_{max}/W_* \gg 1$ we can obtain the period of the nonlinear oscillations

$$T_N = \frac{2}{\pi}\left(\frac{2\pi}{\omega}\right)\left(\frac{W_*}{W_{max}}\right)^{1/2} \ln\frac{4W_{max}}{W_*}, \tag{7}$$

where $2\pi/\omega$ is the period of the linear oscillations.

We define the average value of W_* as

$$W_* = (W_{min} W_{max})^{1/2}$$

and the modulation of the noise energy density in Fig. 3 is equal to $W_{max}/W_* \approx 3$. During one period of the oscillations in Fig. 3a the amplitude decreases by a factor 2.5, and consequently $\nu^{-1} \approx 2\pi/\omega$, while $Q \approx 3$. It is seen that the connection between the quantities $\tilde{T}/T_*$, $\tilde{W}/W_*$, and Q agree satisfactorily with Eq. (6).

For the experimental level W_{max}/W_*, in accordance with (7), the period of the oscillations is

$$T_N \approx 2\pi/\omega = 2\pi (\nu_{E*}\gamma)^{-1/2}.$$

At dynamic equilibrium we have $\gamma = \gamma_{e*}$, and γ_{e*} can be expressed in terms of ν and σ_*. We then obtain the relation between the period of the oscillations and the damping time:

$$Q = {}^1/_2 (\pi\mu\sigma_*/2\omega)^{1/2}.$$

Substituting here the experimental values (see Fig. 3) $2\pi/\omega = 150$ nsec and $\sigma_* = (\sigma_{min}\sigma_{max})^{1/2} = 7\times 10^{12}$ sec^{-1}, we obtain $Q \approx 2.6$ and $\nu \approx 120$ nsec, in satisfactory agreement with the observed value of the damping.

The observation of oscillatory regimes is possible under the condition that the period of the oscillations is at least half the lifetime of the layer, as determined by the duration of the current pulse in the surge coil. In contrast to hydrogen, this condition is not satisfied for argon. It appears that this is the cause of the less gently sloping decrease, compared with hydrogen, of T_e with increasing τ in Fig. 2d.

Another necessary condition for the observation of relaxation oscillations is non-adiabaticity of the formation of the layer. It follows from Figs. 2 and 3 that the time of plasma heating and of the increase of the noise level during the initial stage is 70–100 nsec. This is much shorter than the period of the relaxation oscillations and consequently this condition can be regarded as satisfied.

From the definition

$$\nu^{-1} = 1/2\nu_{E*} = e^2 n L^2_{\text{eff}}/2\sigma_* T_{e*}$$

we can obtain an estimate for the effective cooling length L_{eff}. At $T_{e*} = T_{\text{av}}$ 200 eV we obtain $L_{\text{eff}} = 20$ cm $\approx L/2$; this confirms the assumption that the heat loss in the neutral layer is due to the finite width of the layer. Using the value of the L_{eff} we can determine

$$(v_d/c_s)_* = \sigma_* (M T_{e*})^{1/2}/n e^2 L_{\text{eff}}.$$

For the experimental values $(v_d/c_s)_* \approx 5$, this is close to the values measured in the front of an aperiodic-profile collisionless shock wave propagating across the magnetic field.[10]

In the neutral layer near the null magnetic-field line, in a region with characteristic dimension $(\rho_e\Delta)^{1/2}$ (ρ_e is the Larmor radius of the electron in the magnetic field at the boundary of the layer), the condition for the magnetization of the electrons is violated, and described the model of relaxation oscillations is no longer valid. Under the experimental conditions the contribution of this region to the total energetics of the layer is small. This region is, however, apparently the source of the accelerated electrons registered over the entire thickness of the layer. These electrons have no preferred direction of motion and their energy content is small.[3]

We examine now the applicability of the quasilinear approximation to ion-sound instability. The criterion is usually derived from the condition that the nonlinear decrement γ_N, which describes the scattering of ion sound by the ions, is small compared with the electron decrement γ_e. In our case it is necessary to make this condition stronger and stipulate that γ_N be less than the lowest frequency ν in the dynamics of the relaxation oscillations. Indeed, it is easy to show that if the term $\gamma_N W$ is nonlinear in Eq. (2), then this is reflected in the appearance of an additional damping of the relaxation oscillations in Eq. (3), with a damping frequency of the order of γ_N. Therefore, to neglect the nonlinear decrement γ_N in the dynamics of the relaxation oscillations, we must satisfy the condition $2\nu > \gamma_N$ or, using the definitions of ω and Q, we can write this condition as follows:

$$\gamma_{e*} \approx \gamma > \gamma_N Q^2. \tag{8}$$

According to Ref. 6, we can estimate the nonlinear decrement at

$$\gamma_N \approx 10^2 \omega_{pi} \frac{T_i}{T_e} \theta^2 \frac{W}{nT_e},$$

where θ is the relative current-direction angle in which the directions of the wave vectors of the unstable ion-sound noises are concentrated. From (8) we obtain

$$\frac{W_*}{nT_{e*}} = \frac{E\mu^{-1/2}}{(4\pi n T_e)^{1/2}} \frac{c_s}{v_d} < 10^{-2}\mu^{1/2} \frac{v_d}{c_s} \frac{T_e}{T_i} \theta^{-2} \frac{1}{Q^2}. \tag{9}$$

Estimating the lower bound of the right-hand side of (9) $[T_e/T_i \approx (v_d/c_s)_* \approx 5,\ \theta \approx 1]$ and putting $Q^2 \approx 10$, we have the condition $(W/nT_e)_* < 10^{-3}$. We calculate $W_*/nT_{e*} = \omega_{pe}/4\pi\sigma_* \approx 10^{-3}$ from the experimental condition. Thus, the criterion (9), with allowance for the possible increase of the parameter $T_e/T_i\theta^2$ compared with $(v_d/c_s)_*$, can be regarded as satisfied under the experimental conditions.

Despite of the difference between the experiment and the theoretical estimates presented above, a comparison of the two can be made, but with certain limitations. In the theoretical model we neglected for simplicity the hydrodynamic motions and the change of the layer thickness in the course of the relaxation oscillations. The characteristic time of the hydrodynamic motions can be naturally estimated at $\tau_2 2\Delta/c_A = H_b/(4\pi n M)^{1/2}$. The time τ_Δ of broadening of the layer due to the diffusion can be determined from the equation

$$d\Delta/dt = c^2/4\pi\sigma_*\Delta.$$

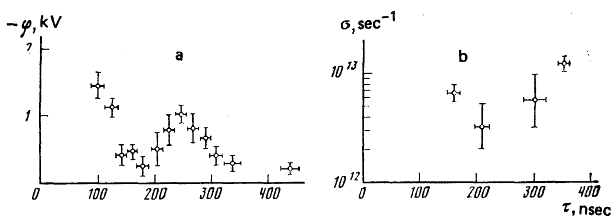

FIG. 3. Dependences of the floating potential and of the conductivity in the layer on the time: a) $n = (5-10)\times 10^{12}$ cm^{-3}; b) $n = (1-2.5)\times 10^{13}$ cm^{-3}.

Under the conditions of the experiment the inequalities $\omega\tau_2 > 1$ and $\omega\tau_\Delta > 1$ are satisfied with a small margin. This is apparently the reason for the variation of the equilibrium parameters in the course of the oscillations, and in particular for the already mentioned cooling of the plasma in the layer with time.

In the theoretical estimates we have also assumed that the ion-sound-noise damping decrement γ does not depend on the temperature T_e and changes little over the period of the relaxation oscillations. A reasonable power-law dependence of the decrement γ on T_e (with an exponent of the order of unity) manifests itself, as can be easily seen from (1) and (2), in the determination of the frequency of the relaxation oscillations by a factor of the order of unity. Therefore the dependence of γ on T_e does not play a principal role in the accuracy of the presented phenomenological estimates. As for the slow variation of γ, which is not connected with the temperature dependence, we can make the following remark. During the initial stage of the layer-formation process, when the boundary layer H_b rises with time, the noise level is high and there are no thermal losses. Under these conditions there can be realized in the current layer a self-similar regime of ion-sound instability, in which the damping of the noise by the group of "hot" ions compensates for the buildup with the growth rate γ_e, and a ratio $v_d/c_s \approx \mu^{-1/4}$ is established.[5,6] According to the phenomenological estimates, $(v_d/c_s)_*$ in the state of dynamic equilibrium is also close to $\mu^{-1/4}$. It can be assumed that the damping decrement of the noise is determined as before by the group of hot ions produced during the initial stage and changes little during the period of the relaxation oscillations.

CONCLUSION

Experiment has thus revealed, in the produced turbulent neutral layer, periodic time variation of the plasma parameters such as the electron temperature and the conductivity. This phenomenon is satisfactorily described by a relaxation-oscillation picture based on the quasilinear theory of ion-sound turbulence, with account taken of the energy losses due to the thermal conductivity along the magnetic force lines. Similar oscillations can be a common phenomenon for a plasma systems with turbulent heating, in which the characteristic growth time of the noise is much less than the time of the energy losses. It should be noted that the vibrational character of the evolution of the noise level, which controls the plasma resistance and consequently the electric field intensity, should manifest itself not only in the temperature oscillations, but should lead also to bursts in the acceleration of the particles and in the emission of electromagnetic waves. Since such bursts are typical of many plasma phenomena observed in the laboratory and in outer space, the results of this paper may be useful for their interpretation.

We make now a remark of importance from the point of view of current-flow models of solar flares. Let the energy losses decrease rapidly with increasing temperature T_e. Such an anomalous behavior of the energy losses can exist in a neutral layer on the sun at a predominant value of the radiation losses.[13,14] In this case the oscillations (3) can be unstable, i.e., $\nu \sim -\nu_e$. This means that there is no dynamic equilibrium in a current layer with such parameters, but oscillations of the values of the current layer that stabilize on a nonlinear level should exist, i.e., there should exist an undamped vibrational regime of the current layer.

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