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Abstract

Full Text

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Observation of Plasma Noise during Turbulent Heating

(Presented by Academician E. K. Zavoiskii, 7 IV 1969)

Introduction. In our previous publications ⁽¹⁾, experimental data were presented which indicate that turbulent heating of plasma by a direct-discharge current is a consequence of an ion-acoustic instability of the current. The theory of this variant of turbulent heating is set forth in ^(2, 3). However, until now there have been no measurements of the spectrum of plasma oscillations under conditions of turbulent heating in the frequency range of order

$\omega_{pi} = (4\pi ne^2/M)^{1/2}$, where, according to the theory, one should expect the maximum noise intensity. The difficulty in measuring such noise is that its wavelength is small—of the order of the Debye radius r_D . Under typical experimental conditions ($n_e \simeq 10^{13} \text{ cm}^{-3}$, $T_e \simeq 10^3 \text{ eV}$), r_D is $10^{-1} \div 10^{-2} \text{ cm}$. Therefore, although use of the direct measurement method—a Langmuir probe in the plasma—is possible ^(4, 5), the processing of the data is difficult and ambiguous, since in practice the size of the probe is more than an order of magnitude larger than the expected characteristic wavelength. In addition, such a probe may be surrounded by a dense plasma that screens the ion-acoustic oscillations.

Therefore, to detect ion-acoustic noise in the plasma, a magnetic probe with a loop diameter of $\sim 1 \text{ cm}$ was used. It is clear that such a probe cannot directly measure the longitudinal electric field of small-scale ion-acoustic oscillations. The magnetic probe was chosen on the assumption that processes of nonlinear transformation of ion-acoustic waves lead to the excitation in the plasma of weakly damped electromagnetic oscillations—whistlers—with a frequency of order ω_{pi} . The wavelength of such oscillations under our conditions is $3 \div 14 \text{ cm}$. This method has already been used in plasma experiments to detect Langmuir oscillations which, as a result of the nonlinear process of “coalescence,” give electromagnetic radiation at the frequency $2\omega_{pi}$ (see, for example, ^(6, 7)). But, in contrast to electromagnetic waves with frequency $2\omega_{pi}$, “whistlers” are proper oscillations of the plasma, existing in a broad frequency range. Therefore, accumulation of whistlers in a “plasma resonator” is possible not only at frequencies $\omega_1 + \omega_2$, corresponding to the coalescence of ion-acoustic oscillations with frequencies ω_1 and ω_2 , but also at difference frequencies $\omega_1 - \omega_2$, corresponding to scattering of ion sound as a result of whistler emission. These processes lead to accumulation of whistler energy $H_{\sim}^2/8\pi$ with frequency $\Omega \simeq \omega_{pi}$ according to the law:

Fig. 1. Oscillograms of rf signals from a magnetic probe. Experimental conditions: $n_0 = 9 \cdot 10^{12} \text{ cm}^{-3}$, $H = 7 \text{ kOe}$, $U = 24 \text{ kV}$

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$$\frac{d H_{\sim}^2}{dt 8\pi} \simeq \frac{w_{\sim}^2}{Mnc^2} \cdot \frac{\omega_{pi}^2}{\Omega}. \quad (1)$$

Here w_{\sim} is the energy density of ion-acoustic oscillations in the frequency region ω_{pi} . Landau damping for whistlers is small if their phase velocity along the magnetic field is greater than the mean thermal velocity of the electrons, $v_{Te} \ll \Omega/q$. This condition is satisfied if

$$\Omega \gg \frac{8\pi n T_e}{H^2} \frac{eH}{mC}. \quad (2)$$

Experimental setup and research methods. The experiments were carried out on the HPR-2 apparatus, the parameters and electrical circuit of which have been published in (8).

In the experiments described here, in addition to monitoring the concentration of charged plasma particles in the trap before and during the flow of current, measurements were made of the diamagnetism of the heated plasma, and the current through the plasma and the voltage on the direct-discharge capacitor were also oscillographed. The study of rf electromagnetic oscillations in the process of turbulent heating was carried out with a matched magnetic probe. In addition to rf electromagnetic oscillations, the probe also recorded changes in the azimuthal magnetic field of the current. The signals from the probe were fed to the plates of an I-2-7 oscilloscope with a bandwidth of $2 \cdot 10^9 \text{ Hz}$ and photographed. Subsequently, using an analog machine and a low-frequency spectrum analyzer of the ASChKh-1 type (range of analyzed frequencies 20 Hz-20 kHz; the output signal is proportional to the voltage at the input), Fourier analysis of these oscillations was performed.

Fig. 1. Oscillograms of rf signals from a magnetic probe. Experimental conditions: $n_0 = 9 \cdot 10^{12} \text{ cm}^{-3}$, $H = 7 \text{ kOe}$, $U = 24 \text{ kV}$.

Measurement results. In (8, 9) it was shown that in a plasma with finite turbulent conductivity there are strong current fluctuations with characteristic frequencies of 5-20 MHz. The amplitude of these fluctuations exceeds the magnitude of the rf signals under study by tens of times. In spectral analysis, the frequency spectrum of the low-frequency oscillations may be very extended. It is therefore necessary to separate these frequencies from the sought frequencies $\sim \omega_{pi}$, which arise as a result of the nonlinear transformation of ion-sound oscillations into whistlers.

Figure 2

Figure 2: Figure 2

Under the chosen experimental conditions ($H = 7 \div 14$ kOe, $U = 18 \div 33$ kV, and $n_0 = 2 \cdot 10^{12} \div 2 \cdot 10^{13}$ cm $^{-3}$), the “low-frequency” instability appears $0.3 \div 0.4$ μ s after the start of the discharge. To exclude the influence of this instability on the frequency spectrum of the rf oscillations, Fourier analysis was carried out over the first $0.15 \div 0.2$ μ s. Figure 1 shows oscillograms of rf oscillations measured with a magnetic probe at a sweep speed of 10^8 cm/s. In this case the photographs were taken sequentially. Oscillogram 1 corresponds to $0 \div 0.1$ μ s, and oscillogram 2 to $0.1-0.2$ μ s from the moment the current appears in the plasma. The oscillograms show rf oscillations that modulate the low-frequency component corresponding to the rise of the current.

Figure 2 shows oscillograms of signals from the output of the spectrum analyzer, illustrating the frequency spectrum of the rf oscillations (a spectrum similar to that shown in Fig. 1, 2 was analyzed). At the top, for control (Fig. 2, 1), the frequency spectrum of periodically repeating rectangular pulses is given; their analysis was performed under the same conditions. It follows from Fig. 2 that, with increasing initial density of charged plasma particles in the trap (n_0 increases from $2 \cdot 10^{12}$ cm $^{-3}$ (Fig. 2, 2) to $2 \cdot 10^{13}$ cm $^{-3}$ (Fig. 2, 4)), the upper boundary of the spectrum shifts toward higher frequencies. On these same oscillograms it is evident that rather broad lines are distinguished in the spectra of the rf oscillations (the line width is of the order of the frequency).

To construct the true energy spectrum from these oscillograms, a number of additional calculations must be carried out. First,

it is necessary to take into account the transfer characteristic of the entire measuring path in the range of frequencies under study and, secondly, to take into account that the signal on the screen of the AChKh-1 analyzer is proportional to the voltage, not to the power of the harmonics.

Fig. 2. Oscillograms of the frequency spectra of hf oscillations after Fourier analysis

Figure 3 gives the energy Fourier spectra of the hf oscillations with the above corrections taken into account. The spectra were constructed for three values of the initial concentration n_0 of charged plasma particles in the trap: $1.6 \cdot 10^{13}$ cm $^{-3}$ (1), $9 \cdot 10^{12}$ cm $^{-3}$ (2), $2 \cdot 10^{12}$ cm $^{-3}$ (3), at one and the same magnetic field ($H \simeq 7$ kOe) and the same initial voltage on the capacitor of the direct discharge ($U = 24$ kV). It is seen that, as n_0 decreases, the upper boundary of the spectrum shifts toward lower frequencies (cf. 1 and 3). Estimates show that the frequency shift is proportional to $\sqrt{n_0}$. In addition, on these curves two groups of lines stand out, one of which lies somewhat below the plasma ion frequencies, while the other lies near $2\omega_{pi}$. In Fig. 3 one also sees a considerable increase in the intensity of the harmonics on the low-frequency side of the spectrum.

This increase is monotonic in character, and its boundary shifts when n_0 is changed. Control experiments carried out in magnetic fields $H = 14$ kOe, with the other initial plasma parameters unchanged, show that the position of the spectral lines does not depend on the magnetic field. Increasing the voltage on the capacitor of the direct discharge leads to an increase in the intensity of the hf electromagnetic oscillations. Figure 4 illustrates this dependence. It is seen that increasing the discharge voltage by a factor of 2, from 16 to 32 kV, leads to an increase in the energy density of the hf oscillations by a factor of 4, from 10^{-3} to $4 \cdot 10^{-3}$ erg/cm³; at the same time the energy density of the heated plasma, measured under these same conditions, changes from $5 \cdot 10^3$ to $2 \cdot 10^4$ erg/cm³. Investigation of the distribution of the intensity of the hf oscillations over the diameter of the plasma current column shows that the oscillation intensity remains approximately constant inside it and falls off somewhat faster than r^{-1} outside the plasma current cord.

Discussion of the experimental results. The experimental results obtained are in agreement with the theory of turbulent heating based on the ion-acoustic instability of the current ^(2,3), and with theoretical considerations on nonlinear wave transformation given in the Introduction*.

According to the theory ^(2,3), the frequency spectrum of ion-acoustic oscillations should have a sharp maximum near the frequency ω_{pi} . The energy density $w \sim$ of the ion-acoustic oscillations is related to the electric field E_0 acting in the discharge by the relation:

$$w \sim \left(nT_e \frac{E_0^2}{8\pi} \frac{M}{m} \right)^{1/2}, \quad (3)$$

* At the time of noise registration, the measured ratio of the current velocity to the mean thermal velocity of the electrons is ~ 0.1 . Therefore an instability with the characteristic frequency $\sqrt{m/M} \omega_{pe}$ is excluded.

with the help of which the estimate formula (1) can be rewritten in the form

$$\frac{d}{dt} \frac{H_{\sim}^2}{8\pi} \simeq \omega_{pi} \frac{T}{mc^2} \frac{E_0^2}{8\pi}. \quad (4)$$

The maximum in the observed spectrum at the frequency $\simeq 2\omega_{pi}$ can be explained by the nonlinear effect of coalescence of ion-acoustic oscillations with frequency ω_{pi} . The large width of the $2\omega_{pi}$ line may be connected with the fact that whistles are generated in regions of the plasma with different concentration. Frequencies below ω_{pi} may appear as a result of radiation of a whistle by an ion-acoustic oscillation with frequency ω_{pi} . In such processes, whistles with frequency $\ll \omega_{pi}$ may be generated if the width of the ion-sound spectrum is not very small.

Fig. 3. Energy spectrum of rf oscillations with corrections taken into account

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Fig. 4. Spectral density of “whistle” energy versus voltage across the discharge gap

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Formula (4) can be used to estimate the magnitude of the energy density of the whistles. Under typical experimental conditions, when the longitudinal electric field in the plasma is $E_0 = 0.7$ CGSE, and $n_0 = 10^{13}$ cm⁻³, nT of the plasma is equal to $5 \cdot 10^3$ erg/cm³. For an observation time $t = 0.1$ μs, from formula (4) we obtain $H_{\sim}^2/8\pi = 2 \cdot 10^{-3}$ erg/cm³, which is in good agreement with the experimental value $\simeq 10^{-3}$ erg/cm³ (see Fig. 4). The same formula explains the increase of $H_{\sim}^2/8\pi$ obtained in the experiment when the applied voltage is increased.

Thus, in our experiments it has been shown that, during turbulent current heating in a plasma, ion-acoustic noises with frequency ω_{pi} are excited. Their intensity is sufficient to explain the anomalous resistance of the plasma on the basis of the theory^{2,3}.

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CITED LITERATURE

1. M. V. Babykin, P. P. Gavrin, E. K. Zavoisky, L. I. Rudakov, V. A. Skoryupin, *Conf. on Plasma Physics and Controlled Nuclear Fusion Research*, Culham, England, IAEA, Vienna, Austria, 2, 1966, p. 327; *ZhETF*, **52**, 643 (1967).
2. L. I. Rudakov, L. V. Korablev, *ZhETF*, **50**, 220 (1966).
3. E. K. Zavoisky, L. I. Rudakov, *Atomic Energy*, **23**, 417 (1967).
4. S. G. Alikhanov et al., III International Conference on Research in Plasma Physics and Controlled Thermonuclear Reactions. International Atomic Energy Agency, CN-24/A-1, Novosibirsk, 1968.

5. N. F. Perepelkin, S. D. Fanchenko, DAN, **189**, No. 2 (1969).
6. B. A. Demidov, S. D. Fanchenko, *JETP Letters*, **2**, 533 (1965).
7. Yu. G. Kalinin et al., ZhETF, **55**, 115 (1968).
8. Yu. G. Kalinin, D. N. Lin et al., ZhETF, **56**, 462 (1969).
9. D. N. Lin, V. A. Skoryupin, ZhETF, **53**, 463 (1967).

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