NOISE IN A TURBULENT PLASMA

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Results are presented of an investigation of the electromagnetic radiation from a plasma during turbulent heating by a current. It is demonstrated that the intensity of the radiation depends on the magnitude of the longitudinal electric field as well as on its distribution along the plasma column. The spectral composition of the radiation and its dependence on the plasma density in the trap is investigated. The degree of plasma turbulence is estimated on the basis of the magnitude of the diamagnetic effect and of the anomalous resistance.

THE plasma noise was investigated in the same setup which was previously used to study plasma heating in a direct discharge [1,2]. In the described experiments, the direct-discharge capacitance connected between the terminal electrodes of the titanium injectors was 2.60 or 0.8 μF and was charged to 15–30 kV; the discharge period was 7.5 and 4 μsec. Simultaneously with the noise investigations, we studied in the same experiments a number other plasma parameters. Oscillograms were obtained of the current and direct-discharge voltage, and the plasma diamagnetism and the bremsstrahlung x rays were measured. A single probe was used to obtain the distribution of the potential along the plasma column during the time of flow of the longitudinal current. The variation of the plasma density in the trap was measured with a phase meter with a raster sweep ($n_{cr} \approx 2 \times 10^{14}$ cm^{-3}). The microwave radiation was investigated in the range from 300 to 3×10^4 MHz with the aid of video receivers whose selective elements were low-Q resonators and waveguides biased to cutoff. At the same time, we studied the oscillations ($f = 4 \times 10^5$–10^7 Hz) observed on the current oscillograms.

GENERAL CHARACTERISTICS OF THE RADIATION

Comparison of the oscillograms of the longitudinal current and of the integral radio emission from the plasma in the wavelength range from 100 to 2 cm, obtained in a single experiment, shows that the radiation is observed so long as intense high-frequency oscillations are seen on the current and voltage oscillograms.

Figure 1 shows the oscillograms of the longitudinal current and of the radio emission from the plasma. Figure 1a corresponds to the case when the discharge-gap voltage is applied 8 μsec after turning on the plasma injectors. In this case the emission begins simultaneously with the appearance of the longitudinal current and lasts almost 10 μsec. If the voltage is applied to the discharge gap with a larger delay, then the duration of the emission becomes shorter. From a comparison of Figs. 1a and b it follows that when a voltage is applied 24 μsec after the start of the injector operation, the time during which the noise is emitted from the plasma decreases from 10 to 2 μsec. The duration of the aperiodic part of the current also decreases in this case from 10 to 2 μsec.

Comparison of the duration of the emission and the duration of the initial stage of the longitudinal current shows that they are related. It was established earlier [2] that the duration of the initial stage of the longitudinal current depends on the value of the plasma density in the trap at the instant when the direct discharge is turned on. Consequently, the decrease in the noise-emission duration can also be related with the increase in density. The fluctuations observed on the current oscillograms (Fig. 1a) show that the plasma oscillation spectrum is not limited to 3×10^8 Hz, and extends towards lower frequencies.

A detailed analysis of the longitudinal-current oscillograms shows that in a number of cases the initially disordered oscillations become periodic in the course of time. This is clearly seen on those oscillograms, which were plotted with the direct discharge turned on simultaneously with the plasma injectors, a condition under which the initial period of the discharge was the longest.

Figure 2 shows a series of oscillograms obtained with 15 kV applied to the direct-discharge capacitor, in a magnetic field of 3.3 kOe. The oscillograms were chosen for a case in which the delay in the start of the direct discharge varied negligibly from experiment to

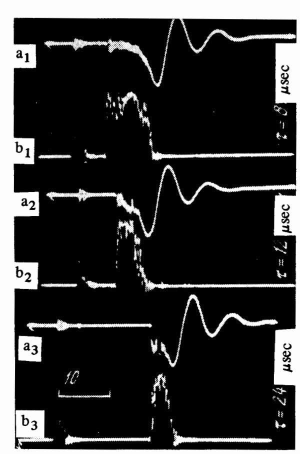


FIG. 1. Oscillograms of longitudinal current (a) and of integral radio emission (b) from a plasma (λ = 2 – 100 cm). The oscillograms were taken at 3 different times (8, 12, and 24 μsec) following the switching of the direct discharge and the switching of the plasma injectors. The magnetic field is H = 3.3 kOe. The current oscillograms show the hf oscillations. The oscillating-discharge period is 7.5 μsec.

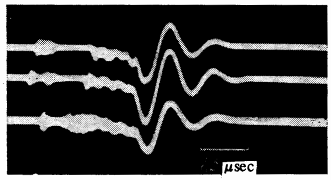


FIG. 2. Series of longitudinal-current oscillograms, showing the ordered hf oscillations. The initial voltage on the direct-discharge capacitance is U_{dir} = 15 kV, H = 3.3 kOe, $n_0 = 10^{12}$ cm^{-3}. The period of the longitudinal current is 7.5 μsec.

experiment. It is seen from Fig. 2 that the period of the high-frequency oscillations remains constant at ~2.5 μsec in all the current oscillograms. With increasing voltage on the direct-discharge capacitance, and with a constant magnetic field, the period of these oscillations becomes shorter, and with increasing magnetic field their period increases if the voltage on the direct-discharge capacitance is maintained constant from experiment to experiment. Figure 3 shows the period of the high-frequency current oscillations against the magnetic field.

With decreasing duration of the initial stage of the discharge, and also with decreasing direct-discharge capacitance, the periodicity of the current oscillations vanishes, in spite of the fact that the contribution of the energy to the discharge remains constant and equal to the contribution of the energy at the largest capacitance. In this case the current oscillograms reveal only irregular high-frequency oscillations.

A comparison of the current and plasma-emission oscillograms in the range from 300 to 30,000 MHz shows that the emission peaks correspond to fluctuation dips of the longitudinal current. This fact is illustrated in Fig. 4 by oscillograms of the longitudinal current and of the plasma emission at frequencies 800, 1000, 1200, and 1600 MHz.

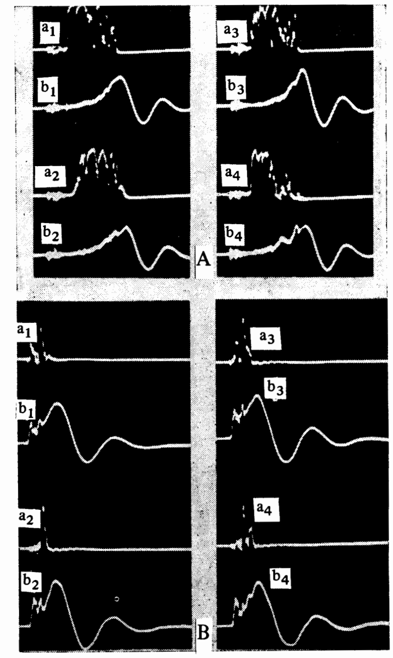


FIG. 4. Oscillograms of electromagnetic radiation from the plasma (a) and of the longitudinal current (b). The radiation is shown at the frequencies 8 × 10^8 Hz (a_1, b_1), 10^9 Hz (a_2, b_2), 1.2 × 10^9 Hz (a_3, b_3), and 1.6 × 10^9 Hz (a_4, b_4). We see that the radiation peaks correspond to dips in the longitudinal current. A – Direct discharge switched simultaneously with the plasma injectors. B – with 20 μsec delay.

POLARIZATION OF RADIATION

The polarization of the radiation was determined in the centimeter wavelength band (1 cm ≤ λ ≤ 1.44 cm). In this case, a conical antenna with a teflon focusing lens was connected with the aid of a rectangular waveguide to the detector head. In the experiments we compared the signals received at two positions of the electric vector of the antenna, parallel and perpendicular to the plasma-containing magnetic field. The experiments were performed in a magnetic field of 3 kOe at an initial plasma density in the trap 1.3 × 10^{13} cm^{-3}. The direct-discharge capacitance was charged to 15 kV.

For each antenna position we performed up to 20 experiments and determined the average signal for a particular polarization. Simultaneously with these measurements, we monitored the noise level from the same volume of the plasma and in the same frequency band, received by a similar receiver but for only one antenna polarization. Knowing the noise level at the monitor receiver, we could compare more accurately the emission intensities at different antenna polarizations. The results indicate that the radiation from the plasma in this frequency range is not polarized.

DEPENDENCE OF RADIATION ON THE MAGNETIC FIELD

In the experiments we compared the intensity of the noise radiated by the plasma at the initial stage of longitudinal current at 10^{10} Hz and in the range from 3 × 10^8 to 1.5 × 10^{10} Hz, varying the magnetic field from 1 to 9 kOe. The initial plasma density in the trap was 1.3 × 10^{13} cm^{-3}. The direct-discharge capacitance C = 0.8 μF was charged to 17 kV. After detection and amplification the signals were fed to the oscilloscope plates. Several oscillograms were obtained for each value of the magnetic field.

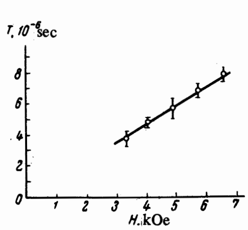


FIG. 3. Period of hf current oscillations vs. magnetic field. Experimental conditions U_{dir} = 15 kV, $n_0 = 10^{12}$ cm^{-3}. Discharge period 7.5 μsec.

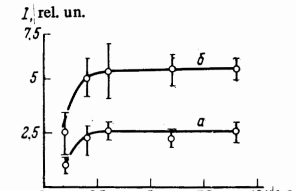


FIG. 5. Intensity of the noise from magnetic field: a – radiation at λ = 3.0 cm; b – radiation in the range from 100 to 2 cm. Experimental conditions: direct-discharge capacitance voltage 1.7 kV, initial plasma density in trap ~1.3 × 10^{13} cm^{-3}.

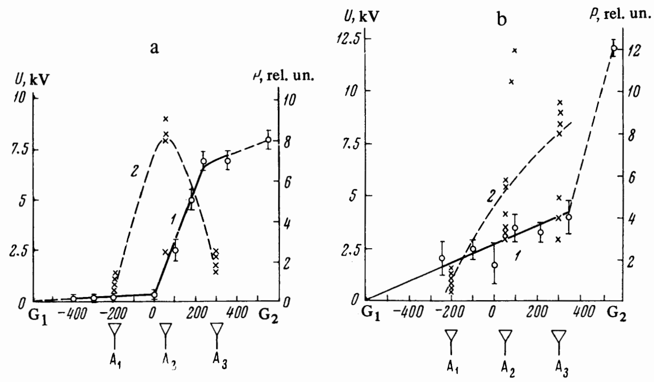


FIG. 6. Distribution of the noise intensity along the plasma (curve 2). The same figure shows the distribution of the potential (curve 1). The experimental conditions are the same (H_0 = 3.3 kOe, U_{dir} = 15 kV). As follows from the figure, the distribution of the noise intensity duplicates the distribution of the potential. The radiation has been measured with a waveguide biased beyond cutoff with $\lambda_{cr} \leqslant 1.44$ cm, $n \approx 10^{12}$ cm^{-3}. The abscissas show the distance (in mm) from the center of the setup. G_1 and G_2 – guns; A_1, A_2, A_3 – antennas. a – Direct discharge switched on 12 μsec after starting the plasma injectors, b – 20 μsec delay.

Figure 5 shows the averaged course of the radiation intensity as a function of the magnetic field for a frequency 10^{10} Hz (curve a). As follows from the plot, the radiation intensity remains constant starting with 3 kOe upwards. When the magnetic field is decreased to less than 3 kOe, a certain decrease in the intensity is observed. The same figure (curve b) shows the variation of the integral-radiation intensity in the range from 100 to 2 cm. A similar dependence is observed in this case, too.

DISTRIBUTION OF RADIATION ALONG THE PLASMA COLUMN

It was established earlier [2] that in a turbulent plasma there exists, from the instant of appearance of a longitudinal current, an appreciable potential drop along the discharge axis. The electric field measured in these experiments reached 500 V/cm and exceeded the critical Dreicer field [12] by many times. When the initial plasma density in the trap was increased, the magnitude and the character of the distribution of the electric field changed, but the electric field was 40–45 V/cm and was much higher than the critical value calculated even from the initial plasma temperature.

The intensity of the noise radiated by the plasma is expected to be related to the magnitude of the longitudinal electric field [3], and the change in the character of the distribution of this field should be reflected to some degree also in the intensity of the noise radiated by different sections of the plasma.

In experiments organized for this purpose, we investigated the radiation from the plasma in the wavelength range from 1 to 1.44 cm. One of the receiver antennas was placed near the center of the trap, and two others were shifted relative to the center of the trap by 20 cm in both directions. The antennas had teflon focusing lenses and received radiation from plasma cylinders ~5 cm high. The sensitivity of each receiver was calibrated beforehand.

In the first experiments, the direct discharge was turned on with a delay of 12 μsec relative to the start of the plasma-injector operation. The plasmoids reached the center of the trap within that time, but the plasma density in the central region does not exceed $(1-2) \times 10^{12}$ cm^{-3}, and was much lower than at the injectors. The variation of the noise amplitude along the plasma column, obtained for these conditions, shows that the maximum of the radiation intensity lies near the center of the trap, in the region of the maximum electric-field gradient.

If the direct discharge is turned on with a delay up to 20 μsec, then the maximum of the noise intensity shifts towards one of the plasma injectors (Fig. 6b). The shift of the intensity maximum is apparently connected with the asymmetry in the injector placement. (The plasma density is higher in the region of the injector that is installed in the vacuum-chamber tube with the smaller diameter, since the tube diameter is 35 mm, whereas the chamber diameter is 80 mm at the location of the second injector.)

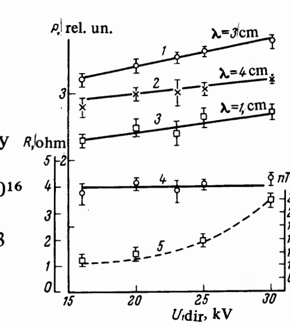
Figure 6 shows the radiation levels received by the antennas from different sections of the plasma, with the direct discharge turned on 12 μsec (a) and 20 μsec (b) after the injector operation; the figures show also the distribution of the potential along the plasma column. Comparison of the potential and radiation-intensity distributions along the plasma column shows that the noise intensity duplicates qualitatively the longitudinal electric-field distribution.

As indicated above, the maximum plasma concentration in the central part of the trap did not exceed 2×10^{12} cm^{-3} at the instant of noise reception (the direct discharge was turned on with a delay of 12 μsec). On the other hand, the upper limit of the radiation frequency was in the region of 2.5×10^{10} Hz and corresponded to the theoretically-predicted [4-6] plasma radiation at double the plasma frequency. Variation of the magnetic field in a wide range did not change the character of the radiation. Radiation at 2 ω_{pe} was observed by Demidov et al. [7]. As is well known [8-10], in systems with high Langmuir-oscillation levels it is possible to have nonlinear wave interaction that results in transformation of certain types of waves into others, so that a broad spectrum of plasma radiation can be observed, up to frequencies $2\omega_{pe}$. The energy radiated at the frequency $2\omega_{pe}$ is determined by the relation [11]

$$E_{2\omega_{pe}} \approx 30\omega_{pe}t\left(\frac{\omega_{pe}}{ck_0}\right)^3 \overline{W}_e \frac{\overline{W}_e}{mn_0c^2},$$

where $\overline{W}_e$ is the energy density of the plasma oscillations per unit volume, ω_{pe} the plasma frequency, m the

FIG. 7. Variation of noise intensity (curves 1–3), anomalous resistance (curve 4) and diamagnetic effect (× 10^{16} eV/cm^3) (curve 5) with voltage across the discharge gap. H_0 = 6 kOe, n_0 = 1.3 × 10^{13} cm^{-3}.



mass of the electron, n_0 the plasma density, and k_0 the characteristic wave vector and c the speed of light. In this experiment, the noise energy radiated at $2\omega_{pe}$ was $\sim 10^{-6}$ J/cm³. This enables us to estimate the energy density of the plasma oscillations under the assumption that $k_0 = 2\pi/\lambda_D$. For $n_0 = 10^{12}$ cm^{-3}, $\overline{E}_{2\omega} = 10^{-6}$ J/cm³, and $k_0 = 200$, we have $\overline{W}_e \approx 10^{-3}$ J/cm³.

DEPENDENCE OF THE RADIATION ON THE LONGITUDINAL ELECTRIC FIELD

We compared in the experiments the amplitude of the signals received at a definite wavelength as the electric field in the plasma was varied. The minimum voltage applied to the direct-discharge electrodes was 15 kV. The experiments were made in a magnetic field of 6 kOe with initial plasma density 1.3×10^{13} cm^{-3}. The noise from the plasma was simultaneously received at four wavelengths: 1, 1.5, 3, and 4 cm. Additional measurements were made of the diamagnetic effects, and oscillograms were taken of the current and voltage of the direct discharge. The obtained oscillograms were used to plot the noise amplitude, the diamagnetic effect, and the anomalous resistance of the discharge as a function of the direct-discharge electrode voltage.

Figure 7 shows these curves. It is seen that the noise intensity increases linearly with increasing discharge voltage, while the diamagnetic effect increases with increasing longitudinal electric field somewhat more rapidly.

DEPENDENCE OF RADIATION ON THE PLASMA DENSITY

In our experiments, the trap was filled with plasma from injectors. After the operation of the injectors, the plasma concentration in the trap increased with time to 2.3×10^{13} cm^{-3}. We can use this circumstance to investigate the dependence of the radiation on the plasma density in a wide range. To this end it is sufficient to turn on the direct discharge simultaneously or with a delay relative to the injector start. It is necessary, of course, to trace the possible variation of the plasma concentration in the trap after the direct discharge is turned on. In our experiments, the plasma density was monitored with a phase meter operating at a wavelength 2.3 mm with a resolution time 0.3 μsec. The radiation was received simultaneously at several fixed frequencies with the aid of low-Q resonators ($f_0 = 6 \times 10^9$, 7.5×10^9, and 3×10^{10} Hz) with a waveguide biased beyond cutoff with $\lambda_{cr} = 1.44$ cm. In the same experiments, we obtained oscillograms with the current and voltage of the direct discharge and the diamagnetism of the plasma. Knowing the current and voltage of the discharge gap, we could plot the anomalous resistance as a function of the time.

Figure 8 shows in one time scale the variation of the plasma density in the central plane of the trap, the radiation from the plasma at wavelengths 3 and 4 cm, and the oscillograms of radiation obtained with the aid of the cutoff waveguide at $\lambda_{cr} = 1.44$ cm. The same figure shows the first half-cycle of the longitudinal current and the time variation of the anomalous resistance, calculated from the current and voltage oscillograms, and also an oscillogram of the plasma diamagnetic signal.

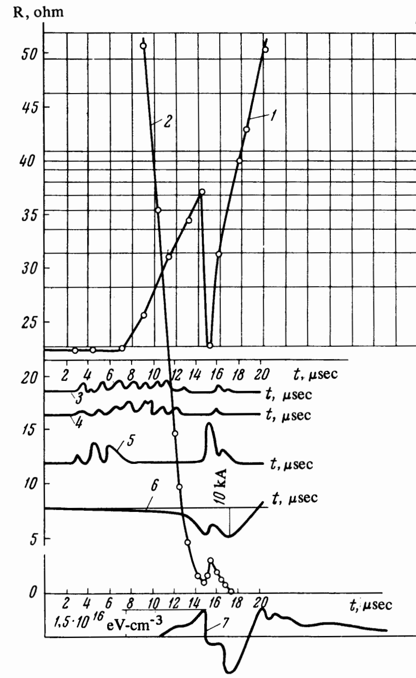


FIG. 8. Dependence of the radiation on the plasma density in the trap. Curve 1 – plasma density vs. time; 2 – anomalous resistance vs. time, obtained from the voltage and current oscillograms; 3 – radiation at $\lambda = 3$ cm; 4 – radiation at $\lambda_{cr} \leqslant 1.44$ cm; 5 – radiation at $\lambda = 4$ cm; 6 – oscillogram of first half-cycle of the current; 7 – oscillogram of diamagnetic effect. It is seen that radiation at $\lambda = 3$ cm and $\lambda \leqslant 1.4$ cm begins and ends simultaneously, but the 4 cm radiation ends somewhat earlier. The radiation at $\lambda = 3$ cm and $\lambda = 4$ cm corresponds to the radiation in the ω_{pe} region. At the instant of the density dip, the radiation appears again. A decrease in the concentration can be connected with the buildup of a large-scale instability. Experimental conditions: $H_0 = 3$ kOe, $U_{dir} = 16$ kV. The diamagnetic effect reaches 1.5×10^{16} eV/cm³, and the maximum density is $\sim 3 \times 10^{13}$ cm^{-3}.

The plot of the plasma density in the trap shows a density dip corresponding to a dip in the longitudinal current (curve b). The two dips can be attributed to the occurrence of large-scale instabilities that lead to escape of the plasma from the trap.

As seen from the figure, the noise from the plasma starts almost simultaneously at all the indicated frequencies, but the radiation at $\lambda = 4$ cm terminates somewhat earlier than the radiation at $\lambda = 3$ cm when the plasma density is increased. The radiations at $\lambda = 3$ cm and $\lambda \leq 1.44$ cm stops almost simultaneously, when the plasma density reaches $(2-3) \times 10^{12}$ cm^{-3}. This average density may be somewhat overestimated, since we took the plasma diameter to be the current diameter, which was equal to 8 cm under the conditions of this experiment. Actually, however, this diameter can be somewhat larger, and accordingly, the average density n can be smaller. With decreasing average plasma density during the time of the current flow, the electromagnetic radiation appears again at the same frequencies when the plasma density reaches the same value. The anomalous resistance, dropping from ~ 50 to 1 ohm, rises again and reaches 3 ohms at that instant of time (Fig. 8, curve 2). The diamagnetic effect of the plasma observed during the time of the first passage of the current through zero, was 1.5×10^{16} eV/cm² at a density 3×10^{13} cm^{-3}. We chose a mode with a density dip in order to investigate the character of the noise, but this mode is not optimal for heating purposes.

To produce optimal heating, it is necessary to have a relatively uniform distribution of the plasma density along the trap. Under these conditions, the duration of the aperiodic part of the discharge current decreases to 1.5–2 μsec, for equal energy contributions to the discharge, the diamagnetic effect increases in comparison with the preceding experiment by a factor of 2.

DISCUSSION OF RESULTS

1. We have established that the radiation from the plasma lies in a wide range of frequencies, from 10^8 to 3×10^{10} Hz.

2. The radiation from the plasma is not polarized.

3. When the magnetic field is varied, the radiation intensity and its frequency spectrum remain practically unchanged.

4. A study of the distribution of the radiation intensity along the plasma column shows that the greatest intensity corresponds to the maximum longitudinal electric-field gradient.

5. Both the intensity of the radiated noise and the plasma heating increase with increasing longitudinal electric field.

6. The frequency spectrum of the radiation shifts towards higher or lower frequencies with increasing or decreasing plasma density. This correspondence between the variations of the density and of the frequency of the radiated noise occurs at plasma densities up to $3-5 \times 10^{12}$ cm^{-3}.

We shall attempt, using this set of experimental facts, to draw certain conclusions concerning the probable mechanisms of instability excitation and to estimate the degree of turbulence during the time of flow of the longitudinal current.

In our earlier papers [1,2,9] we have discussed the possible mechanisms of plasma heating by a strong longitudinal current. We have shown that the observed heating can be attributed to excitation of current or ion-sound instability in the plasma. It was indicated at the same time that under certain conditions there is produced in the near-cathode region of the plasma a beam of electrons, and two-stream instability can develop [12]. In the case when two-stream instability develops, the deceleration length of the electron beam in the plasma amounts to [13]

$$\lambda = 10^{-8} \frac{E}{j} \sqrt{n} \ \text{cm}, \tag{1}$$

where E is the beam-electron energy in eV, j the current density in the beam in A/cm^2, and n the plasma density. At distances larger than several beam deceleration lengths λ, the current already carries the main bulk of the plasma electrons. Therefore, if the conditions $u > c_e$ are $u > c_s$ are satisfied (c_e—thermal velocity of the plasma electrons, c_s—velocity of ion sound), either current or ion-sound instability should be produced within the volume of the plasma. Accordingly, the effective collision frequency is in this case [2]

$$\nu_{\text{eff}} = \omega_{pe} \frac{\overline{W}}{nT_e} \alpha, \tag{2}$$

where $\alpha \approx 1$, $\overline{W}$ is the oscillation energy density per unit volume, and the resistivity ρ is connected with ν_{eff} by the relation

$$\rho \approx 10^{13} \frac{\overline{W}}{nT_e\omega_{pe}}. \tag{3}$$

Relations (2) and (3) provide estimates of $\overline{W}$ and of the degree of plasma turbulence $\overline{W}/nT_e$, since n, T_e, and ρ are measured simultaneously in the experiments.

Let us examine the experimental results shown in Fig. 8. During the initial stage of the discharge (at the instant t = 6 sec) the current is ~1.5 kA, the plasma density is ~10^{12} cm^{-3}, and its diameter is 8 cm. The current velocity of the electrons in the plasma, calculated from these data, is 1.8×10^8 cm/sec, and the initial plasma temperature, obtained from the diamagnetic measurements, is 5 eV. Thus, current instability can set in during this stage of the discharge. The resistance of the discharge at this instant of time is ~50 ohm. One can assume, of course, that the current carries a small group of particles during this stage of the discharge. The energy of such motion of the electrons of a given group cannot exceed the voltage drop applied to the electrodes. Therefore the velocity of the electrodes which carry the current can be only smaller than 7×10^9 cm/sec, and the number of the particles in the group is not smaller than 3×10^{10} cm^{-3}. The deceleration length of these electrons, in accordance with formula (1), is ~5 cm (for n = 10^{12} cm^{-3} and j = 30 A/cm^2).

Turning to Fig. 8 (curves 3 and 4) we see that intense noise is radiated from the plasma during that time, with a frequency spectrum bounded from above by the quantity $2\omega_{pe}$. Although in the case of current instability there are directly excited frequencies on the order of or smaller than $\omega_{pe}(m/M)^{1/3}$, owing to the nonlinear interaction of the waves in the plasma there can occur oscillations of higher frequencies, as well as electromagnetic radiation up to frequencies ~$2\omega_{pe}$. This radiation can occur also as a result of merging of two Langmuir oscillations produced in the region of the electrodes when the electron beam is decelerated. Plasma heating during this initial stage of current flow is insignificant; as shown by the measurements of the diamagnetic effect, it does not exceed 2–5 $\times 10^{14}$ eV/cm^3.

With increasing plasma heating, the conditions for the buildup of the current instability are violated. Indeed, at the instant of time t = 12 μsec (Fig. 8), when the electromagnetic radiation from the plasma ceases, $nT_e = 5 \times 10^{15}$ eV/cm^3, u = 1.3×10^8 cm/sec, and only ion-sound instability can develop in the plasma. Actually, as follows from Fig. 8 (curve 7), the plasma heating continues, the rate of heating increases appreciably, and the diamagnetic effect reaches 1.5 $\times 10^{10}$ eV/cm^3.

The entire process can be repeated if the development of the large-scale instability results in a drop of the concentration and a partial cooling of the plasma, as is apparently the situation in the case shown in Fig. 8. The final diamagnetic effect reaches 1.5 $\times 10^{16}$ eV/cm^3, and the plasma density in the trap is 3×10^{13} cm^{-3}.

Knowing the anomalous resistance and the diamagnetic effect, as well as the time variation of the plasma density for the experiments shown in Fig. 8, it is possible to estimate the oscillation energy density per unit plasma volume. For three values of the anomalous resistance (50, 10, and 1.6 ohm) we have, in accord with formula (3): $W \approx 10^{-5}$ J/cm^3 for R = 50 ohm, $W \approx 6 \times 10^{-5}$ J/cm^3 for R = 10 ohm, and $W \approx 3 \times 10^{-5}$ J/cm^3 for R = 1.6 ohm. The degree of plasma turbulence W/nT_e, calculated at the same three points, ranges from 10^{-3} to 10^{-2}.

In conclusion, the authors thank E. K. Zavoĭskiĭ and L. I. Rudakov for continuous interest and help with the work.

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