DESTRUCTION OF THE ANOMALOUS SKIN LAYER IN A TURBULENT PLASMA

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Results of an experimental investigation of passage of a high-frequency probing electromagnetic signal ($f = 3 \times 10^8$ Hz) through a turbulent plasma are presented. The observed thickness of the skin layer of a turbulent plasma exceeds the theoretical thickness c/ω_{pe} by 16 times and the thickness of the dissipative skin layer by ~6 times. Increase of the thickness of the turbulent plasma skin layer is apparently due to the high frequency probing signal being carried into the plasma by Langmuir oscillations.

IN [1-3] are described results of investigations of turbulent plasma heating by a longitudinal current. The anomalous resistance, the intense electromagnetic radiation in a wide frequency band, and the appreciable plasma electron heating observed in these experiments were attributed to development of small-scale instabilities in the plasma.

Results of investigations of the noise of a turbulent plasma are given in [4]. The same paper, which deals with the absolute intensity of noise emitted in the region of double the plasma frequency $2\omega_{pe}$, presents estimates of the energy density of the plasma oscillations; the degree of turbulence is determined from the diamagnetism of the plasma and from the anomalous resistance. Unlike these experiments, there is given in [5] an estimate of the degree of turbulence of the plasma as determined from its own radiation and the Raman scattering of the electromagnetic waves in the microwave band.

In the experiments described below we investigated the influence of turbulence on the conditions of propagation of a weak high-frequency electromagnetic signal in a plasma. To perform this experiment, one of the plasma injectors (Fig. 1) was replaced with a stainless-steel electrode (the apparatus is described in [1,2]). In the center of the electrode there was an opening to admit a glass tube in which was placed a magnetic probe of 3 mm diameter, screened against the electric fields of the plasma. The probe measured the magnetic component of the high-frequency field parallel to the mirror-machine axis, and was located on the trap axis exactly under the transmitting loop. The transmitting loop was connected to a high frequency generator operating at $f = 3 \times 10^8$ Hz, modulated periodically by pulses with a repetition frequency $\sim 5 \times 10^5$ Hz and pulse duration

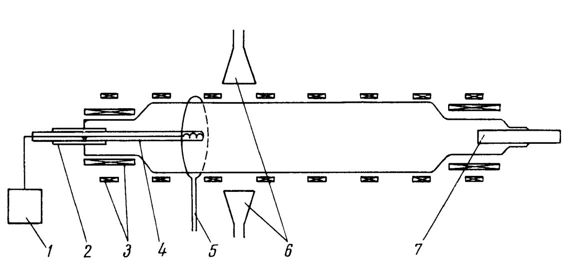

FIG. 1. Diagram of setup: 1 – resonator ($f_0 = 3 \times 10^8$ Hz) and detector head, 2 – direct-discharge electrode, 3 – magnetic-field coil, 4 – magnetic probe, 5 – transmitting loop, 6 – interferometer antennas, 7 – plasma injector.

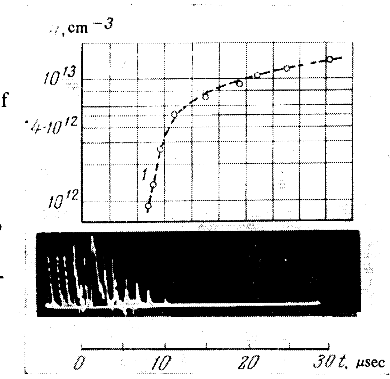

FIG. 2. Time variation of the plasma concentration and oscillogram of high-frequency sounding signal ($f = 3 \times 10^8$ Hz) on the receiving probe when the trap is filled with plasma by one injector. Experimental conditions: $H = 3$ kOe, $U_{dir} = 15$ kV.

1 μsec. The amplitude of the high-frequency field of the loop was 0.1 Oe.

The signal received by the probe was fed to a cavity tuned to 3×10^8 Hz, and was amplified after detection by the amplifier of the oscilloscope. Owing to the use of a cavity, it was possible to reduce greatly the power level of the high-frequency noise at the input to the detector head, but in this case the power of the noise radiated by the plasma was still comparable with the power of the probing signal fed to the receiving probe.

With the aid of a long current-carrying loop it is possible to excite in a plasma a magnetosonic wave traveling towards the center, provided the frequency of the high frequency oscillations is lower than the lower hybrid frequency

$$f_{h2} = eH / 2\pi c\sqrt{Mm}.$$

Under the conditions of our experiment (magnetic field 3 kOe, deuterium plasma), the lower hybrid frequency is $f_{h2} = 1.3 \times 10^8$ Hz. It might appear that a high-frequency sounding signal $f = 3 \times 10^8$ Hz should experience skin effect at a length c/ω_{pe}. Actually, the conditions for the excitation of a direct magnetosonic were not very good, since we could not make the loop longer than 50 cm. The experiments were therefore performed first for the purpose of determining the conditions for the passage of the high-frequency signal from the loop to a laminar plasma.

To this end we determined with a microwave interferometer the time variation of the plasma density in the trap after the operation of the injector (Fig. 2). The obtained density was used to plot the dependence of the theoretical thickness of the skin layer c/ω_{pe} for differ-

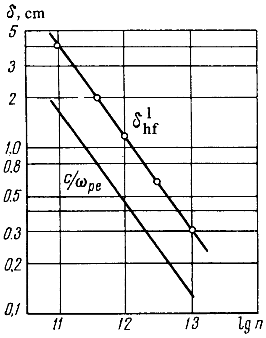

FIG. 3. Dependence of the theoretical thickness c/ω_{pe} and the thickness of the experimental skin layer δ^{l}_{hf} on the density of the laminar plasma in the trap.

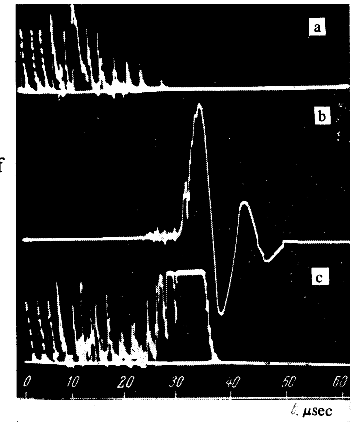

FIG. 5. Oscillograms of high frequency sounding signals ($f = 3 \times 10^{8}$ Hz): a – at the receiving probe without current, c – with current, b – oscillogram of longitudinal current. The oscillogram a shows the attenuation of the sounding signal without current. When $n \approx 10^{12}$ cm^{-3} (Fig. 2) the probe signal vanishes. Oscillogram c shows the increase of the signal of the probe during the time of the development of the instability of the longitudinal current at a concentration $n \approx 10^{13}$ cm^{-3} (according to Fig. 4).

ent values of the initial concentration. Simultaneously, the magnetic probe was used to register the high-frequency generator. With increasing plasma density, the amplitude of the high frequency signal on the probe decrease, and starting with a certain instant, the signal on the probe vanishes (Fig. 2). Knowing the value of the transmitted high-frequency signal without the plasma and its decrease with increasing density, we could experimentally determine the thickness of the skin layer δ^{l}_{hf} of the laminar plasma. In the experiments, δ^{l}_{hf} was obtained for a plasma cylinder of 4 cm radius. The radius of the plasma was determined from the readings of a microwave interferometer ($\lambda = 0.815$ cm) and a phase meter ($\lambda = 0.23$ cm) assuming a linear drop in the density. This radius coincides satisfactorily with the current radius of the plasma, obtained from measurements with magnetic probes.[2].

Figure 3 shows the dependence of the theoretical thickness of the skin layer c/ω_{pe} on the plasma density in the trap. The same figure shows the experimental value of the thickness of the skin layer. According to the data of Fig. 3, we determine the ratio of the thickness of the measured skin layer to the theoretical one. It turned out to be equal to three. Thus, in a laminar plasma the skin-layer thickness δ^{l}_{hf} calculated from the transmission of a high-frequency probing signal is $3c/\omega_{pe}$.

The coefficient preceding c/ω_{pe} characterizes the geometrical conditions of the penetration of the high-frequency signal into the plasma in the case of the relatively short loop. We assume that in a turbulent plasma with current this coefficient remains unchanged, that is, $\delta^{t}_{hf} = 3\delta_{t}$, where δ_{t} is the thickness of the skin layer when the signal is excited by a long loop in a turbulent plasma, and δ^{t}_{hf} is the thickness of the skin layer of the turbulent plasma, obtained from the transmission of the high-frequency probing signal.

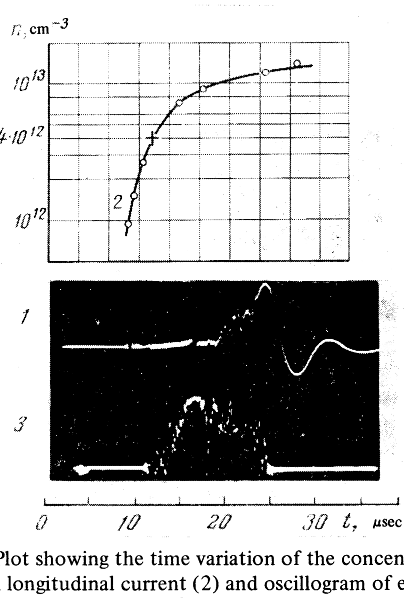

FIG. 4. Plot showing the time variation of the concentration of a plasma with longitudinal current (2) and oscillogram of emission from the plasma at frequency 3×10^{8} Hz (3). An oscillogram of the longitudinal current is also shown. The period of the current is 7.5 μsec, $H = 3$ kOe, $U_{dir} = 15$ kV.

Figure 4 shows the variation of the plasma density in the trap in the case of flow of strong current (2), the current oscillogram (1), and the oscillogram (3) of the noise radiated by the plasma at a frequency 3×10^{8} Hz. Figure 5 shows oscillograms of the time variation of the high-frequency signal amplitude of the probe without a longitudinal current (a) and with a longitudinal current (c). From the oscillogram of Fig. 5a and the time variation of the plasma density in the trap (Fig. 2, curve 1) we see that the signal stops at a density $\sim 10^{12}$ cm^{-3}. In a plasma with a longitudinal current, the time of signal passage is longer and apparently terminates with termination of the current instability. From comparison of Figs. 4, 2, and 5c it follows that at a concentration $\sim 1.0 \times 10^{13}$ cm^{-3} the probe signal reaches a value equal to the signal without the plasma. It is impossible to trace the signal at larger concentrations, since the noise level (see Fig. 4, curve 3) exceeds the levels of the sounding signal. From the oscillograms 5c and 5b we see that in the second and third half-cycles of the high-frequency current the signals do not reach the probe. The presented oscillograms offer evidence that the passage of the high-frequency signal is connected with the turbulence of the plasma due to the instability of the current.

Performing calculations similar to those made in the determination of the experimental skin layer, and assuming that $\delta^{t}_{hf}/\delta_{t} = 3$ and the plasma radius is $R = 4$ cm, we obtain the average thickness of the skin layer of the turbulent layer $\langle \delta_{t} \rangle$. For $|f(0)| = 1$, where $f(0) = 1/J_{0}(kR)$ [6] and $k = (1 + i)/\delta_{hf}$, we have $R/\delta_{hf} = 0.5$. Hence $\langle \delta_{t} \rangle \approx 3$ cm. This skin-layer thickness is approximately 18 times larger than c/ω_{pe} in a laminar plasma of the same density.

The observed effect, whereby the skin layer in a turbulent plasma is increased by a factor ~ 18, can hardly be attributed to the large effective electron collision frequency ν_{eff} in the turbulent plasma. The effective collision frequency calculated from the resistance for the point $\rho = 1.5$ ohm-cm, $n = 10^{13}$ cm^{-3}, for which the thickness of the skin layer of the turbulent plasma was obtained, is $\nu_{eff} = 7 \times 10^9$ sec^{-1}. Although this frequency exceeds the angular frequency of the sonic signal by almost four times, it cannot explain such a large thickness of the skin layer in the turbulent plasma. Indeed, the width of the dissipative skin layer $\delta_{dis} = (c/\omega_{pe})(\nu_{eff}/\pi f)^{1/2} \approx 0.5$ cm, and is only approximately three times larger than c/ω_{pe}.

Another possible explanation of the effect is given by Vedenov, Gordeev, and Rudakov [7]. According to them, broadening of the skin layer is possible as a result of the transport of the electromagnetic signal to the interior of the plasma by the Langmuir oscillations. The skin layer of the turbulent plasma $\langle \delta_t \rangle$ is determined in this case by

$$\langle \delta_t \rangle = \frac{c}{\omega_{pe}} \left(1 + \xi \frac{3\omega_{pe}^2 c_e^2}{8\pi^2 c^2 f^2} \right)^{1/2},$$

where $\xi = W/nT_e$ characterizes the degree of turbulence of the plasma. Thus, we can estimate ξ by determining $\langle \delta_t \rangle$. Under the conditions of the given experiment ($n = 10^{13}$ cm^{-3}, $c_e \sim 3 \times 10^9$ cm/sec, $\delta_t = 3$ cm), the degree of turbulence of the plasma is $\sim 6 \times 10^{-2}$.

In conclusion, the author is grateful to E. K. Zavoĭskiĭ for continuous interest and for the idea of performing the experiment, and L. I. Rudakov and M. V. Babykin for valuable advice and a discussion of the experimental results.

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