Thermal diffusion and eddy currents in a magnetized plasma

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Eddy currents accompanying the thermal diffusion of a plasma in a magnetic field have been observed and studied by direct measurements. The formation of regions of reduced density against the background plasma has been detected upon the appearance of diffusion currents.

1. A theoretical analysis[1,2] shows that the diffusive spreading of an inhomogeneity in a weakly ionized, magnetized plasma may involve the excitation of eddy currents, depending on the shape of the inhomogeneity. In this case the electrons diffuse along the magnetic field, the ions diffuse across it, and the current loop is closed by the background particles. In the case of a diffusion of this sort, which is frequently called "unipolar," the evolution times of the inhomogeneities are sharply lower than in the case of an ambipolar diffusion, in which the electron and ion fluxes are equal at each point. These times are on the order of the largest time determined by the electron longitudinal and ion transverse unipolar diffusion coefficients. The closing of the circuit for the currents through the background plasma results in a redistribution of the background particles, and it reduces the plasma density in certain regions.[2] This density decrease is a distinctive property of unipolar diffusion in an unbounded plasma.

In this letter we are reporting an experimental study of the thermal diffusion[1)] of a magnetized plasma during a local heating of electrons. In some earlier experiments[4] it had been found that during a local heating of the electrons of a magnetized plasma a density redistribution occurs at essentially the same rate as heat propagation. These indirect pieces of evidence indicated that a rapid thermal diffusion of plasma would be accompanied by a flow of eddy currents. Our purpose in the present study was to directly observe and study these eddy currents.

2. The experimental apparatus consists of a vacuum chamber 150 cm long and 80 cm in diameter. A helium plasma is produced by an rf pulsed discharge in a uniform magnetic field ($H = 200$ Oe) at a pressure of 10^{-2} torr. The local heating of electrons is produced by a current-carrying loop with a diameter of 1.5 cm, which is placed at the axis of the plasma column, which is ~40 cm in diameter. The rf heating pulse ($\omega = 2\times 10^8$ s^{-1}, $\tau_p = 2\times 10^{-4}$ s) is applied to the loop in the plasma decay stage. The time scale of the variations in the plasma density after the source is removed is $\tau_{N_e} = 10^{-3}$ s. The plasma electrons are heated at a density $N_e = 2\times 10^{12}$ cm^{-3} and at electron and ion temperatures $T_e \approx T_i \approx 0.4$ eV. Under these experimental conditions, the parameter values correspond to the relations

$$\nu_{em} < \nu_{ei} \ll \omega_{H_e} \ll \omega_{p_e}\ , \qquad m_e \nu_{ei} \ll M_i \nu_{im}\ ,$$

where ν_{em}, ν_{ei}, and ν_{im} are the electron-neutral, electron-ion, and ion-neutral collision rates, respectively; ω_{H_e} is the electron gyrofrequency; ω_{p_e} is the plasma frequency; and m_e and M_i are the electron and ion masses.

The spatial distributions of the electron temperature and the plasma density are determined with the help of movable Langmuir probes. A plane double probe[5] consisting of two metal disks 10^{-1} cm in diameter was fabricated for measuring the electron and ion diffusion fluxes. These disks were positioned parallel to each other, with their working surfaces facing in opposite directions. The distance between disks was 10^{-2} cm, considerably shorter than the length scales of the variations in the temperature and density of electrons. The two disks were held at the same potential with respect to the plasma. From the difference signal from the disks we determined the amplitude and direction of the electron or ion current in the plasma. The plane double probe was moved along the radius and the axis of the chamber.

3. When an rf voltage was applied to the loop, the quasistatic field from the antenna ($\omega \sim \nu_{ei}$) caused an ohmic heating of electrons. A thermal wave propagated away from the heat source along the magnetic field. Because of the nonuniform transverse heating, this wave took the form of a cone with its base facing the source.[4] Figure

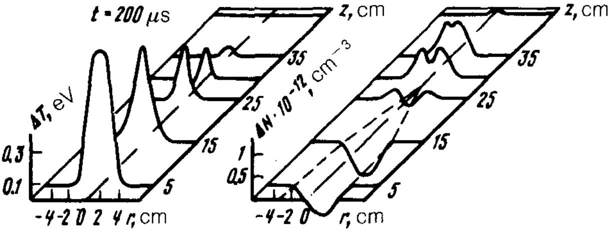

FIG. 1. Quasisteady spatial distributions of the electron temperature and the plasma density 200 μs after the heat source is removed. The source is at $z = 0$.

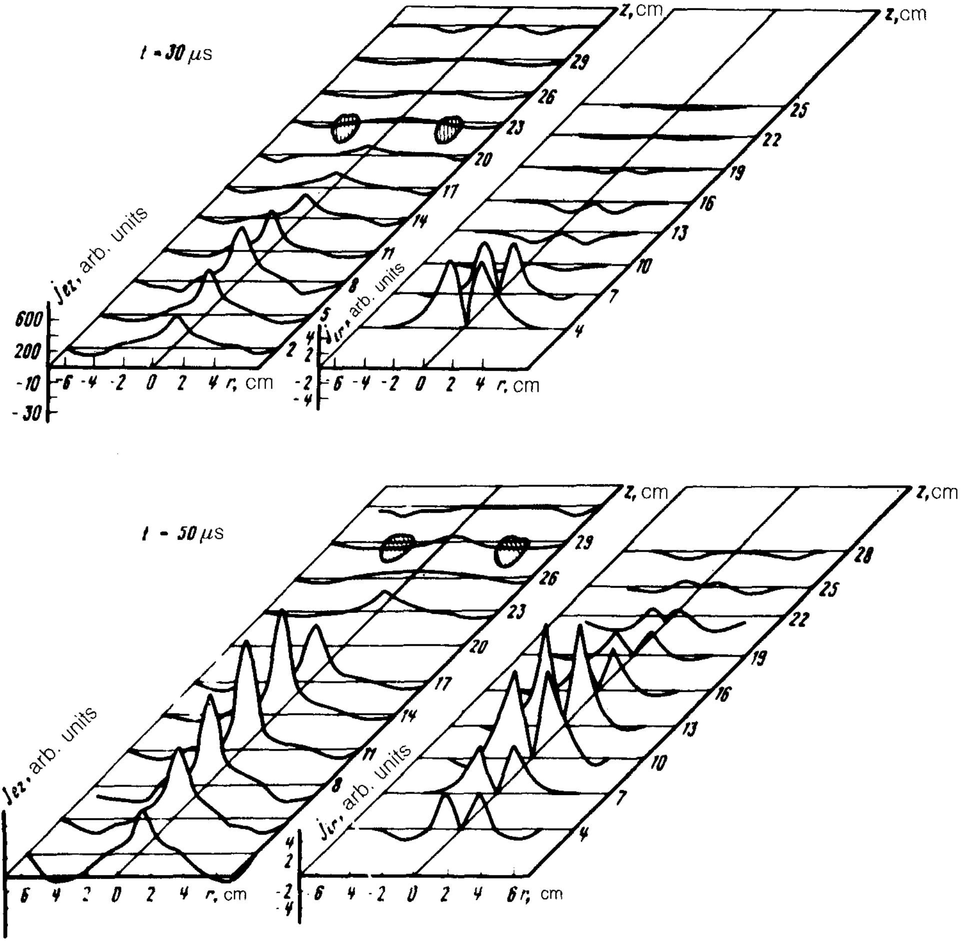

FIG. 2. Spatial distributions of the electron and ion current densities in the plasma in the course of thermal diffusion. a—30 μs after the heat source is applied; b—50 μs after the heat source is removed. The hatched regions are the observed depletion regions.

1 shows the quasisteady distribution of the electron temperature and of the perturbation of plasma density at the end of the heating pulse. The time scale for the thermal-diffusion redistribution of the density is 10^{-4} s. Such a short time, in comparison with the time scale for purely ambipolar diffusion across or along the magnetic field, corresponds to a longitudinal outflow of plasma with the electron thermal-diffusion coefficient.

The measurements with the plane double probe revealed that the changes caused in the plasma density in the magnetic field by the gradient of the electron temperature were accompanied by the formation of eddy currents. Figure 2 shows the results of these measurements, as spatial distributions of the electron current density along the magnetic field and of the ion current density across it. Along the axis, the electron current is directed away from the heat source, and a countercurrent of electrons is observed in the background plasma. Estimates show that the magnitudes of the direct and return currents of electrons are essentially the same (the axisymmetric distribution is taken into account).

The ion current near the source is directed across the magnetic field away from the heating region, and the return current of background ions is observed in those cross sections along the z axis where the direct electron current decreased. The maximum magnitude of the longitudinal electron current along the axis of the system corresponds to the maximum diffusion velocity ($v_{e\,\mathrm{diff}} \sim v_{T_e}^2/\nu_{ei} \vee T_e/T_e$, where v_{T_E} is the electron thermal velocity; Fig. 2).

As was noted earlier, a characteristic feature of unipolar diffusion is the formation of depletion regions in the background plasma. In an effort to observe these regions we used a miniature microwave probe[6] which made possible local measurements of relatively small density perturbations (its sensitivity was $\delta N/N \geqslant 5\times 10^{-3}$). The results of these measurements are shown by the hatched regions in Fig. 2, a and b. These regions correspond to plasma depletion regions with $\delta N/N \sim 10^{-2}$.

After the heat source was turned off, the electron temperature decreased over a time on the order of 3×10^{-5} s. A diffusive flow of plasma density back toward the original state occurred. The measurements showed that the directions of the electron and ion currents were the opposite of those during the thermal diffusion.

In summary, the direct measurements carried out in these experiments have shown that the thermal diffusion of a plasma in a magnetic field during the local heating of electrons is accompanied by the excitation of eddy currents, which flow through the perturbed and background plasma. The time scales of the changes in the plasma density are determined by the unipolar transport coefficients. The results of these experiments may be of assistance in interpreting results on the nonlinear interactions of intense radio waves with the ionospheric plasma.

[1)] Eddy currents in a plasma may also have a strong effect on the thermal-diffusion process.[3]

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