ION HEATING IN A TURBULENT PLASMA

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Submitted 7 October 1967
ZhETF Pis'ma 6, No. 11, 951-953 (1 December 1967)

We investigated, using the TN-4 magnetic trap of the mirror type ("probkotron") described in [1], the heating of ions in a plasma turbulently heated by a current flowing along the magnetic axis of the mirror machine [1,2]. Unlike [2,3], we determined the average ion energy by a method based on simultaneous measurement of the energy E and momentum P of the flux of the plasma-ion charge-exchange neutrals. The average energy $\bar{E}$ of the neutrals was calculated from the formula

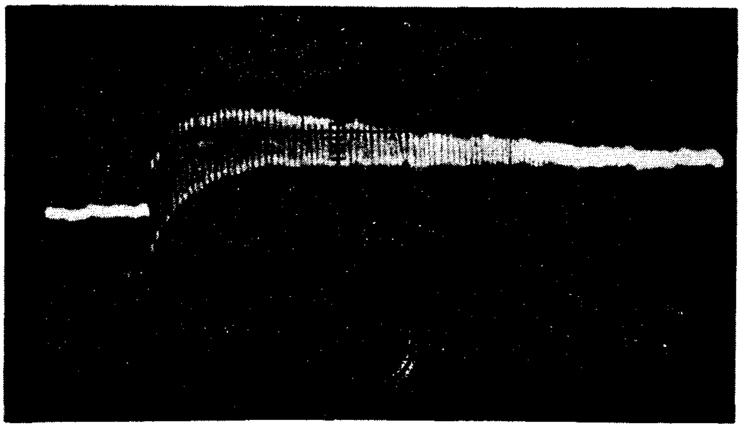
$$\bar{E} = \frac{M}{2}\left(\frac{2E}{P}\right)^2$$

and was assumed equal to the average energy of the plasma ions. To measure E and P we used a specially prepared capacitor microphone located behind the wall of the vacuum chamber, against an opening cut in the central part of the chamber. The microphone was protected against the plasma by three metallic grids. The microphone membrane was made of an aluminum strip 0.8 cm wide and 2.5×10^{-3} cm thick, coated on the internal side by an aluminum-oxide film and covered with lamp-black on the outside. Owing to the difference in the thermal expansion of the aluminum and its oxide, the membrane was deformed when heated by the neutral flux and the capacitance of the microphone changed. Calibration of the energy sensitivity of the membrane was effected by passing current through it and monitoring against a bolometer using a pulsed light source. The calibration was accurate and constant within 5%. The membrane cooling time constant was approximately 0.1 sec.

The momentum of the neutrals was measured with the same microphone. The flux of the plasma-ion charge-exchange neutrals imparted its entire momentum to the membrane within a time much shorter than the period of its natural oscillations, and produced damped oscillations of the membrane, and consequently a change in the microphone capacitance. The sensitivity of the microphone to momentum was determined by applying a potential difference between the membrane and the metallic grid closest to it (the grid was used to shield the microphone against the plasma). The accuracy and constancy of the momentum calibration were 2 and 5% respectively. The required absolute energy and momentum sensitivities of the microphone were chosen by means of preliminary experiments.

To simplify measurements of the microphone capacitance, the microphone was connected in the circuit of a 30 MHz generator, whose oscillations produced beats with oscillations of a standard generator. After converting the beat frequency into an amplitude, the signal was fed to the oscilloscope amplifier.

The figure shows a typical oscillogram of the readings of the microphone in the TN-4 setup. The initial stage shows the damped oscillations of the membrane, with frequency 0.64 kHz, due to the momentum of the neutral-particle flux, followed by slowly growing deviations caused by the deformation of the membrane as it becomes heated, through the lamp-black layers, by the neutral flux. It was found in the experiment that the average plasma ion energy is approximately 2 keV at a plasma hot-particle concentration $\sim 10^{13}$ cm^{-3}. These data are in qualitative agreement with the measurements of the plasma diamagnetism and with microwave measurements of its density.



Oscillogram of pickup measuring the momentum and energy of the ion charge-exchange neutral current. Sweep duration 110 msec. Magnitude of neutral momentum P = 2.1×10^{-3} g-cm/sec, energy E = 7.2×10^{4} erg, average plasma ion energy 2.4 keV at density $\sim 10^{13}$ cm^{-3}. Frequency of membrane mechanical vibrations 0.62 kHz.

The described pickup was used to study ion heating in the turbulent plasma under two modes. In the first, the mirror machine was filled with plasma from one or two titanium guns located in the magnetic mirrors, and turbulent heating of the plasma was produced by current after 15 - 100 μsec. In the second case, the mirror machine was first filled with plasma from one gun, and 15 - 50 μsec later the second gun operated and turbulent heating was produced with different time delays relative to the start of its operation. In both cases we measured considerable heating of the plasma ions. In the second variant, however, when the delay τ ranged from 2 to 4 μsec, much greater heating of the ions was observed. The average ion energy reached in this case 5 - 8 keV, and the ion energy per running centimeter of plasma column exceeded, after heating by the current, the initial energy stored in the capacitor of the second gun. It follows therefore that the strong heating of the ions was not the result of simply deceleration of the plasmoid from the second gun, but occurred only when a rapid plasmoid, with velocity in the range $v = L/2\tau \simeq (3 - 5) \times 10^{7}$ cm/sec passed through the plasma (L - length of the mirror machine).

This phenomenon can be explained within the framework of a theory that relates the anomalous resistance of the plasma with ion-sound current instability [4]. Whereas the bulk of the turbulent-plasma ions can be heated by relatively weak nonlinear effects, the ions of a plasmoid moving through a plasma at a velocity larger than the speed of ion sound can become heated by linear Landau damping of the oscillations excited by the electron current. The rate of such heating is high and may be comparable with the rate of heating of the electrons by an electric field.

From the condition for the existence of ion-sound instability it follows that the energy density $n'T_i'$ of the hot ionic plasma component can exceed the energy density nT_e of the electrons, but not more than by a factor $(T_i'/T_e)^{5/2}(mu^2/T_e)^{1/2}$ (u - current velocity).

Since the electrons are cooled more rapidly than the ions, owing to their larger mobility along the magnetic field, the energy density stored in the ions during the heating time may turn out to be larger than that in the electrons.

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[2] M. V. Babykin, P. P. Gavrin, E. K. Zavoiskii, et al., ibid. 47, 1597 (1964) [20, 1073, (1965)].
[3] M. V. Babykin, E. K. Zavoiskii, L. I. Rudakov, et al., ibid. 43, 1976 (1962) [16, 1391 (1963)].
[4] L. I. Rudakov and L. V. Korablev, ibid. 50, 220 (1966) [23, 145 (1966)].

CURRENT OSCILLATIONS IN n-Ge DOPED WITH MANGANESE

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Submitted 7 October 1967
ZhETF Pis'ma 6, No. 11, 954-956 (1 December 1967)

By now a large number of investigators reported observation of current oscillations in germanium and silicon. In some cases these oscillations were due to the occurrence of negative volume differential conductivity and moving electric domains. These phenomena were observed at temperatures much higher than room temperature. In a number of cases the negative conductivity and the current oscillations were connected with injection through the contacts.

In the experiments described below, we observed current oscillations with large amplitude in n-type germanium doped with manganese. These oscillations are apparently not connected with injection in the contacts, are observed near room temperature and in weak fields, and it seems to us that they have an origin different than that indicated above.

The compensating impurity in our samples was antimony, whose concentration was chosen such as to make the electrons fill completely the lower level of the manganese ($E_V + 0.15$ eV) and fill partially the upper level ($E_c - 0.37$ eV). It must be noted that if the antimony concentration was made larger than twice the manganese concentration, there were no oscillations.

Figure 1 shows the current-voltage characteristics of two samples differing in length by a factor of 2, and having approximately the same impurity concentration. The manganese concentration was $\sim 10^{14}$ cm^{-3}, and the degree of filling of the upper level of manganese by electrons was close to unity. The curves were plotted under conditions when the resistance of the sample exceeded the load resistance. The measurements were made in a

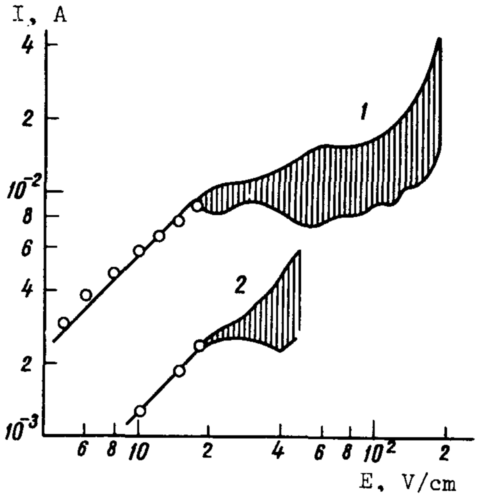

Fig. 1. Current-voltage characteristics for two samples: 1 - 5 mm long, 2 - 2.5 mm long.