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Abstract

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PHYSICS

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STUDY OF THE DEPENDENCE OF PLASMA RESISTANCE ON THE ELECTRIC FIELD STRENGTH

(Presented by Academician E. K. Zavoiskii, July 4, 1966)

The prospects for heating plasma in closed magnetic traps by a current along the magnetic field depend strongly on the magnitude of the specific electrical conductivity σ of the plasma under various conditions. The power of Joule heating, other conditions being equal, is evidently proportional to the square of the electric-field strength E_θ along the circumference of the closed trap. It is equally evident that increasing E_θ is advantageous only provided that the active resistance of the plasma cord does not thereby become too large in absolute magnitude (or too small in comparison with the inductive resistance).

The widely known experiments on Joule heating of plasma ("Tokamak," "Stellarator-C") were carried out at $E_\theta \ll E_{\text{crit}}$, where ⁽¹⁾

$$E_{\text{crit}} \simeq 2 \cdot 10^{-12} n/T. \quad (1)$$

At $E_\theta \ll E_{\text{crit}}$, complete agreement is observed between the conductivity and the value determined by collisions of the current-carrying electrons with ions and neutral atoms. Below we shall call this value the **ordinary conductivity**.

According to the theory ⁽¹⁾, which does not take collective interactions into account, at $E_\theta > E_{\text{crit}}$ one might expect free acceleration of all plasma electrons without their heating, i.e., zero active resistance of the plasma cord. Meanwhile, in a number of theoretical papers ⁽²⁻⁵⁾, the possibility was considered of heating, and consequently also of anomalous active resistance, of a collisionless plasma as a result of the manifestation of collective interactions.

In studies under the program for the creation of a plasma betatron, it was found that at $E_\theta \gg E_{\text{crit}}$ free acceleration of electrons in a plasma with density 10^{10} cm^{-3} either is not observed at all or is interrupted in a time of less than 10^{-7} sec (see ^(6,7)).

In ⁽⁸⁾ it was shown that, at field strengths considerably exceeding E_{crit} , the active resistance of an annular plasma cord with density 10^{12} cm^{-3} proved to

Fig. 1

Figure 1: Fig. 1

Fig. 2

Figure 2: Fig. 2

be much greater than the value of the ordinary resistance and could be ascribed only to the manifestation of collective interactions. These results were confirmed in ⁽⁹⁾. In experiments on the stellarator ⁽¹⁰⁾, a jump in the active resistance of the plasma was demonstrated when the field strength passed through the value E_{crit} . Anomalous active resistance of the plasma at $E > E_{\text{crit}}$ was also observed in straight discharges ^(11,12).

The purpose of the present work was to study the dependence of the effective plasma conductivity σ_{eff} on the electric field E_{θ} over a broad range of variation of the electric field. In a toroidal discharge chamber made of quartz (major diameter 50 cm, minor diameter 8 cm), plasma with density $10^{11} \div 10^{12} \text{ cm}^{-3}$ was created by the injection method. A system of 20 magnetic coils, uniformly distributed along the perimeter of the torus, produced a quasistationary confining magnetic field with strength up to 10 kG (at the center of the magnetic coil). By switching the coils, the field H_{θ} could be made either almost uniform along the perimeter of the torus (regime

of a uniform field), or having the spatially periodic configuration shown in Fig. 1 (the regime of a strongly corrugated field). The first regime corresponded to the conditions of previously performed experiments

Fig. 1

^(8,13). The second regime, according to ⁽¹⁴⁻¹⁶⁾, is possibly capable of ensuring equilibrium and stability of the plasma cord. A vortex electric field E_{θ} at a frequency of 200 kHz was applied along the perimeter of the torus. In this case the current-voltage characteristic of the discharge was measured, the microwave radiation of the plasma in the range of the electron plasma frequency ω_{pe} was recorded, and, with the aid of probes, the current distribution over the transverse section of the plasma cord was investigated.

Fig. 2

From the oscillograms of the current and voltage of the bypass the active resistance of the plasma cord was calculated at the moment of the first current maximum. Then, from the known transverse section of the current cord, the averaged plasma conductivity σ_{eff} was determined.

The results obtained in the uniform-field regime are presented in Figs. 2a and 3. Figure 2a shows the dependence $\sigma_{\text{eff}}(E_{\theta})$ in the range $E_{\theta} = 0.2 \div 50 \text{ V/cm}$ for a plasma with density 10^{12} cm^{-3} . At small values of E_{θ} the conductivity

Fig. 3

Figure 3: Fig. 3

corresponds to the ordinary conductivity of a preliminary plasma, and beginning from a certain threshold field value $E_{\text{thr}} \simeq 0.4$ V/cm the conductivity drops sharply. With a further increase of E_θ by a factor of 10-15, a plateau is observed on the curve $\sigma_{\text{eff}}(E_\theta)$, and then, apparently, a new decrease of the conductivity begins. The value of E_{thr} , in order of magnitude, agrees well with the value E_{crit} calculated from formula (1). This conclusion is confirmed by the experimental results presented in Fig. 3. Figure 3a shows oscillograms of the current in

the plasma (1), of the field E_θ (2), and of microwave radiation (3) in the case $E_\theta < E_{\text{thr}}$; in Fig. 3b—the same in the case $E_\theta > E_{\text{thr}}$. It is seen that, when the field passes through the values E_{thr} , the current changes from inductive to active and microwave radiation appears.*

Figure 2b shows the dependence $\sigma_{\text{eff}}(E_\theta)$ in the regime of a strongly corrugated field. Although the accuracy of the absolute calibration of σ_{eff} in this case is low because of the nonconstancy of the transverse cross section of the current cord along the perimeter of the torus, the good agreement of the general character of the curves in Fig. 2 is striking. At the same time, probe measurements showed that in the first case the current cord touches the outer wall of the discharge chamber, whereas in the second it has a cross-sectional diameter 2–2.5 times smaller and is separated from the walls by more than 1 cm (at the place indicated by the dotted line in Fig. 1).

Fig. 3

The results obtained may be summarized as follows:

1. At small electric-field strengths E_θ , the effective conductivity of the plasma in our experiment corresponds to the ordinary conductivity of the initial plasma.
2. When the critical value of the Dreicer field is exceeded, the effective conductivity drops abruptly, in full agreement with the results of works ^(10,11), and there is evidence of the buildup of plasma oscillations.
3. With a further increase of the electric-field strength by a factor of 10-20, a plateau is observed on the curve of the dependence of the plasma conductivity on the field strength, after which, apparently, a second decrease of the conductivity occurs.
4. The magnitude of the anomalous active resistance of the plasma in the region of large fields is in good qualitative agreement with that measured on the previously described apparatus ^(8,13).
5. It is significant that the transition from a practically homogeneous confining magnetic field to a strongly corrugated one did not substantially

change the general character of the dependence of the anomalous active resistance of the plasma on the electric field.

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* The appearance of microwave radiation in the range ω_{pe} when the field E_θ exceeded the value E_{crit} was observed on the C-1 stellarator (¹⁷).

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