TRANSPORT COEFFICIENTS OF THE PLASMA IN THE TOKAMAK TM-3 APPARATUS

G. A. Bobrovskii, N. D. Vinogradova, E. I.Kuznetsov, and K. A. Razumova

Submitted 10 January 1969
ZhETF Pis. Red. 9, No. 5, 269 - 273 (5 March 1969)

In previously published papers [1,2], plasma containment was characterized by the energy lifetime τ_ε. The value of τ_ε is governed by the total rate of energy loss and yields no information on the concrete loss mechanism. Actually, the plasma can lose energy 1) together with the charged particles, 2) with the thermal conductivity (ionic or electronic), and 3) with line and continuous emission, and also with the fast neutral atoms produced as a result of charge exchange of the cold gas by the hot ions. We have estimated separately each type of loss, which is accordingly characterized by the times of diffusion (τ_D), thermal conductivity (τ_H), and radiation + charge exchange (τ_r), respectively.

The experiments were performed with the TM-3 apparatus [1] under macroscopically stable discharge conditions in hydrogen. The value of τ_ε was determined from the diamagnetic effect and from the current-voltage characteristics of the discharge. To measure the rate of charged-particle loss we measured, besides the electron density (by radio interferometry) also the rates of ionization of the hydrogen atoms by determining the absolute intensities of the hydrogen Balmer lines [3]. The energy flux incident on the liner wall with the radiation and with the fast neutrals was registered with a semiconductor thermocouple. The value of τ_H could be calculated from the relation $1/\tau_\varepsilon = 1/\tau_D + 1/\tau_H + 1/\tau_r$.

It is of interest to compare the experimentally observed quantities with two limiting cases: 1) the maximum loss rate determined by the Bohm formula, and 2) the minimum rate determined by the classical transport coefficients. In comparing the experimental integral characteristics with the theoretical local ones, difficulties are encountered because of the lack of reliable information on the concentration and temperature gradients. In all the calculations we have assumed arbitrarily that the radial distributions of all the quantities are described by Bessel functions of zero order, and used the temperature and concentration values averaged over the cross section. In this case

$$\tau_D = a^2/(2.4)^2 D; \qquad \tau_H = a^2 n/(2.4)^2 \kappa,$$

where a is the plasma radius, assumed equal to the diaphragm radius, and D and κ are the diffusion and thermal conductivity coefficients. Thus, although the accuracy of the lifetime measurement is not worse than 30%, we cannot expect an accuracy better than 200 - 300% in the comparison of the experimental and theoretical quantities.

The theory developed by Galeev and Sagdeev in [4] yields different expressions for the transport coefficients, depending on the frequency ν_e of the collisions between the electrons.

I. Region of trapped particles, $\nu_e < \nu_1 = (v_{Te} H_\phi / a H_z)\varepsilon^{3/2}$ (H_z and H_ϕ - intensities of longitudinal and azimuthal magnetic fields, respectively, v_{Te} - thermal velocity of the electrons, ε - a/R, and R - major radius of torus). In this region, the diffusion coefficient is

$$D \simeq n\varepsilon^{1/2}/H_\phi^2 Te^{1/2}.$$

II. Transition region, $\nu_1 < \nu_e < \nu_2 = \nu_1 \varepsilon^{-3/2}$; $D \simeq (Te^{3/2}/H_\phi H_z)\varepsilon^2/a$.

III. Region where the trapped particles no longer play any role: $\nu_e > \nu_2$. $D \approx n\varepsilon^2/H_\phi^2 T_e^{1/2}$.

The thermal-conductivity coefficient $\kappa = \gamma D n$ (where γ is a numerical coefficient) turns out to be larger in our experiments for the ionic component.

Figure 1 shows the results of the measurements of the diffusion loss of the plasma and the theoretical values calculated for the same parameters. The figure shows also the loss rates calculated by Bohm's formula. All the experimental data were taken for the end of a rectangular current pulse, where the plasma characteristics can be regarded as finally established. The abscissas represent the ratio ν_e/ν_1. In the entire considered range of ν_e/ν_1, the experimentally measured loss rate is 5 - 10 times larger than the value expected from classical theory. The Bohm loss rate exceeds the experimental diffusion rate by 15 - 100 times and the experimental rate of loss with thermal conductivity by 10 - 30 times. Since the ion-ion collisions remain quite frequent at low concentrations, owing to the low ion temperature, all the considered regimes pertain, from the point of view of classical heat conduction, to the transition region. Figure 2 shows the measured and theoretically calculated reciprocal lifetimes with respect to heat conduction as functions of the electron concentration. In the experiment, τ_H characterizes the energy flux from the entire plasma, and not only from the ionic component, so that we chose for the theoretical calculation an expression having a similar meaning:

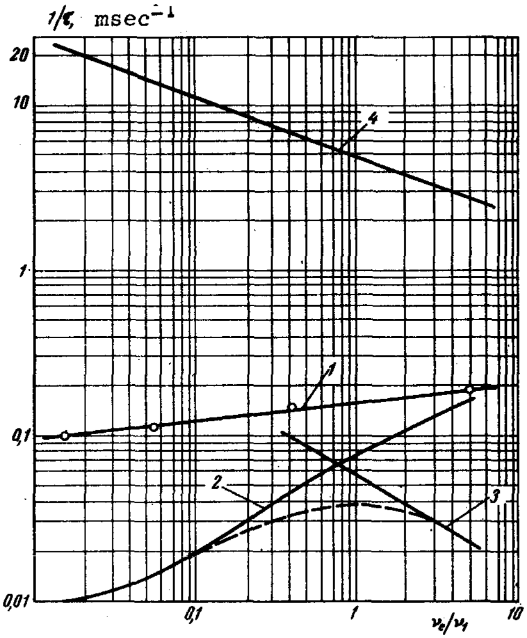

Fig. 1. Reciprocal lifetime with respect to diffusion vs. ν_e/ν_1: 1 - experiment, 2 - theory in region I, 3 - theory in region II, 4 - rate of Bohm diffusion. Dashed - proposed transition from one region to the other.

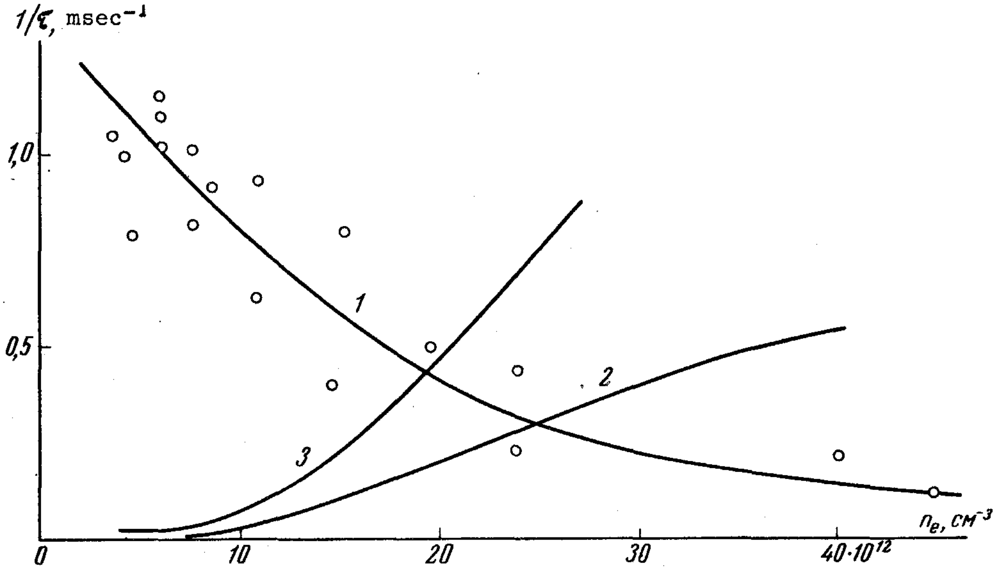

Fig. 2. Reciprocal lifetime with respect to heat conduction vs. n_e: 1 - experiment, 2 - theory, 3 - rate of energy transfer from electrons to ions in Coulomb collisions.

$$\tau_H = (a^2/(2,4)^2 \kappa)(n_e(T_e + T_i)/T_i).$$

At low concentrations, the experimentally measured $1/\tau_H$ is much larger than the theoretical one, but at $n_e \sim 3 \times 10^{13}$ the two values coincide.

It should be noted that the greater rate of loss from the plasma at low concentrations cannot be attributed to ionic thermal conductivity within the framework of classical theory, for in Coulomb collisions the energy transferred from the electrons to the ions is too low (see curve 3 of Fig. 2). The classical electronic thermal conductivity is also small. A plasma with low concentration apparently is characterized by the presence of nonclassical processes. The anomalous resistance observed under these conditions [5] may also be evidence of the development of instabilities.

On the other hand, we have assumed throughout that there are no impurities in the plasma. The presence of an appreciable impurity content at low electron densities can greatly increase the classical transport coefficients.

The fact that at sufficiently large concentrations the rates of energy loss from a real plasma agree with the calculated ones cannot, likewise, serve as evidence of the existence of classical transport coefficients, since the functional relations predicted by the theory are not observed. Only the absence of a dependence of the transport coefficients on the longitudinal magnetic field agrees with the theory. It is probable that both the classical mechanisms and the instability are equally responsible for the loss, thus greatly hindering the interpretation of the experimental results.

The authors thank L. A. Artsimovich, A. A. Galeev, B.B. Kadomtsev, and V. S. Mukhovatov for useful discussions and interest in the work.

[1] L. A. Artsimovich, G. A. Bobrovskii, S. V. Mironov, et al., Atom. Energ. 22, 259 (1967).
[2] L. L. Gorelik et al. Plasma Physics and Controlled Nucl. Fusion Res., Vienna, 2, 647 (1966).
[3] E. I. Kuznetsov, Atom. Energ. 25, 315 (1968).
[4] A. A. Galeev and R. Z. Sagdeev, Zh. Eksp. Teor. Fiz. 53, 348 (1967) [Sov. Phys.-JETP 26, 233 (1968)].
[5] G. A. Bobrovskii et al., Paper at II European Conference on Plasma Physics, Stockholm, 1967.

PULSED PARAMETRIC GENERATION IN DISTRIBUTED SYSTEMS

A. I. Vesnitskii, L. A. Ostrovskii, V. V. Papko, and V. N. Shabanov
Institute of Nuclear Physics, Gor'kii State University
Submitted 14 January 1969
ZhETF Pis. Red. 9, No. 5, 274 - 277 (5 March, 1969)

Distributed parametric generators of electromagnetic radiation were first realized in optics [1]. In view of the large dimensions of the resonant system (compared with the wavelength), it is possible to generate in such systems in principle, just as in lasers, radiation with a large discrete spectrum - at a number of modes simultaneously. An important factor in this case is the possibility of controlling the process by means of mode synchronization, which leads, in particular, to the production of short pulses. However, these phenomena have not yet been observed in parametric generators.

We present here the results of an experimental investigation of multimode parametric