Particle and energy balance in magnetosonic heating of a plasma in the TO-1 tokamak

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A twofold action of magnetosonic oscillations on the state of a plasma in a tokamak is established; this action is manifest by heating of the ions through oscillation-energy dissipation, and in an additional increase of the energy content of the plasma as a result of the lowering of the anomalous electronic thermal conductivity.

As reported in[1,2], when the spectrum of the natural magnetosonic oscillations of the plasma pinch is excited in the TO-1 tokamak, an effective plasma heating is observed, manifest in an increase of the plasma diamagnetism, an increase of the ion temperature, an outward displacement of the pinch, and an increase of the current of the balance regulators. A study of the structure of the fields excited in the plasma and of the temporal waveform of the individual resonance maxima of the oscillation spectrum has shown that the absorption of the oscillation energy in the plasma greatly exceeds the absorption in the chamber walls.[3]

It is well known[4] that the loss of thermal energy from the plasma in tokamak installations is determined principally by the anomalous electronic thermal conductivity and exceeds by more than one order of magnitude the value predicted by the neoclassical theory.[5] At the same time, the experimental facts favor the assumptions of a Coulomb heat exchange between the electrons and the ions and of a neoclassical mechanism of ion thermal conductivity.[6] On the basis of these assumptions, let us discuss the particle and energy balance under conditions of magnetosonic heating of the plasma in the TO-1.

Figure 1a shows the dependence of the ion temperature on the sum P_{ei} of the power transferred to the ions from the electrons as a result of Coulomb collisions, and the power input P to the plasma from the HF generator. The power P_{ei} is given by the formula

$$P_{ei} = 0.4 \cdot 10^{-26} \int \frac{n_e^2}{\sqrt{T_i}} dV$$

(see, e.g., [6]), where T_i is the ion temperature, n_e is the plasma concentration, and the integral is taken over the entire volume of the plasma. The ion temperature was determined from the Doppler broadening of the line of the highly ionized impurity C V at the maximum of the high-frequency heating. The experimental points fit well the curve $T_i \sim (P_{ei} + P)^{2/5}$. Since the collision frequencies corresponded in the investigated discharge conditions to the region of the "plateau," in which the energy lifetime of the ions is $\tau_{E_i} \sim T_i^{-3/2}$ and the ion temperature should increase in proportion to the power input raised to the 2/5 power, we can conclude on the basis of Fig. 1a that the entire high-frequency power was consumed in the heating of the ion component of the plasma.

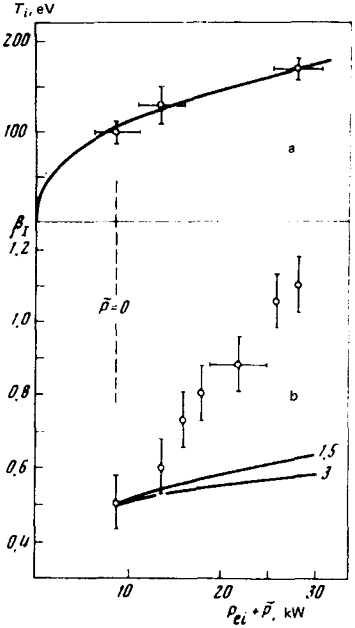

FIG. 1. Dependence of the ion temperature (a) and of the plasma energy content (b) on the total power input to the ions.

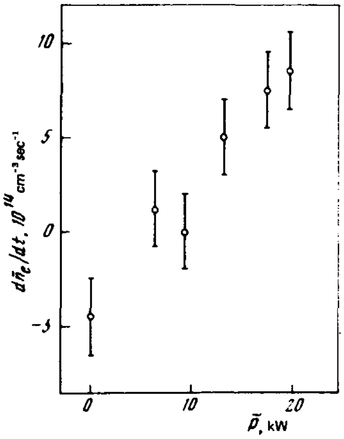

FIG. 2. Rate of change of the plasma concentration averaged over the diaphragm diameter vs the power developed by the high-frequency generator.

This conclusion seems to contradict the measurement results. Actually, if the entire HF power were to go to ion heating, then the expected relative increase of the energy content of the plasma should not be large, inasmuch as $T_e > T_i$ in the initial state. The solid curves of Fig. 1b show the variation of β_I (the ratio of the plasma pressure to the pressure of the poloidal magnetic field), due the increase increase in the ion temperature only for two initial values of T_e/T_i. The curves in the figure lie much lower than the experimental points, indicating that the energy content of the electronic plasma component increases. This fact can be attributed only to an increase in the energy lifetime of the electrons, since the plasma Ohmic-heating power changed during the course of the high-frequency heating by not more than 15—20%.

The excitation of magnetosonic oscillations in the plasma has led also to a jumplike increase of the derivative of the plasma concentration with respect to time. The dependence of dn_e/dt on the power developed by the high-frequency generator is shown in Fig. 2. As shown by optical measurements performed by N.N. Shvindt, this effect is not the consequence of an increase in the flux of the neutral particles into the plasma, since it is not accompanied by an increase in the intensities of the spectral lines of the hydrogen and of the impurities, an increase capable of explaining the observed change in the concentration of the charged particles. Measurements of the spectral lines were performed both in the exciter region and in the diametrically opposite section of the tokamak chamber. Thus, the observed behavior of the concentration offers evidence of an increase in the diffusion lifetime τ_D of the plasma.

The relative change $\Delta\tau_D/\tau_D$ can be estimated from the material-balance equation of the plasma $dn_e/dt = I - n_e/\tau_D$, where n_e is the plasma concentration averaged over the diaphragm diameter, I is the neutral-gas flux density, assuming that $\tau_D \gtrsim \tau_E$. In our case I is constant, $n_e = 10^{13}$ cm^{-3}, $\tau_{E_i} = 2.5$ msec, and $\Delta\tau_D/\tau_D \gtrsim 0.5$. We note that the total increase of the plasma concentration in the course of the HF heating amounted to 10—15%.

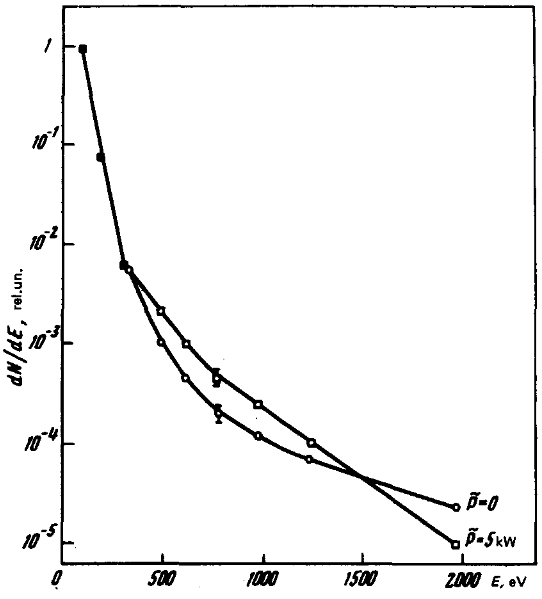

FIG. 3. Energy distribution of the charge-exchange atoms in the presence and in the absence of HF heating.

The action of the HF oscillations on the plasma was manifest also in a straightening of the high-energy tail of the ion distribution function, which differed noticeably from Maxwellian in the absence of the oscillations. This effect is illustrated by Fig. 3, which shows the energy spectra of the charge-exchange atoms.

On the basis of the presented results we can conclude that the magnetosonic oscillations exert a twofold action on the state of the plasma in the tokamak. First, the entire dissipated oscillation energy goes to heating the ionic component of the plasma. Second, the presence of oscillations leads to an additional increase of the energy content as a result of the decrease of the anomalous electronic thermal conductivity, and also to an increase of the diffusion lifetime of the plasma.

It should be noted that the stabilizing action of the magnetosonic oscillations on certain types of plasma instability, namely drift instability, was predicted theoretically[7] and confirmed experimentally in a Q machine.[8]

[1] N.V. Ivanov, I.A. Kovan, P.I. Kozlov, E.V. Los', V.S. Svishchev, and N.N. Shvindt, ZhETF Pis. Red. **16**, 88 (1972) [JETP Lett. **16**, 60 (1972)].
[2] N.V. Ivanov, I.A. Kovan, V.V. Siluyanov, and N.N. Shvindt, Atom. Energ. **36**, 374 (1974).
[3] N.V. Ivanov and I.A. Kovan, *ibid.*, in print.
[4] L.A. Artsimovich, ZhETF Pis. Red. **13**, 101 (1971) [JETP Lett. **13**, 70 (1971)].
[5] A.A. Galeev and R.Z. Sagdeev, Zh. Eksp. Teor. Fiz. **53**, 348 (1967) [Sov. Phys.-JETP **26**, 233 (1968)].
[6] L.A. Artsimovich, A.V. Glukhov, and M.P. Petrov, ZhETF Pis. Red. **11**, 449 (1970) [JETP Lett. **11**, 304 (1970)].
[7] A.A. Ivanov and T.K. Soboleva, Zh. Eksp. Teor. Fiz. **62**, 2170 (1972) [Sov. Phys.-JETP **35**, 1135 (1972)].
[8] L.A. Artsimovich, V.D. Rusanov, T.K. Soboleva, S.S. Sobolev, and N.M. Umrikhin, Paper at International Conference on Phenomenon in Ionized Gases, Prague, 1973.