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MAGNETOSONIC PLASMA HEATING IN A TOKAMAK

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In [1] we obtained experimentally for the first time excitation of magnetosonic resonance in a Tokamak plasma. We report here the results of experiments on magnetosonic plasma heating with the same setup ("TM-1-VCh").

As in the preceding experiments [1], the plasma was heated with a HF generator ($f = 21$ MHz) coupled to the plasma by a narrow loop. This loop was introduced into the liner either with or without quartz insulation. The discharge was produced in hydrogen or deuterium at a pressure $8 \times 10^{-5} - 8 \times 10^{-4}$ Torr.

The heating effect was determined by measuring the plasma pressure $n(T_e + T_i)$. The diamagnetic signal was determined from the reaction of the current in the circuit of the magnetic-field solenoid [2]. We measured simultaneously the average concentration of the charged particles with microwave interferometers at the wavelengths $\lambda = 3.8$ and 7.9 mm. The diameter of the plasma column was estimated by microwave chord sounding.

The diamagnetism produced when an HF pulse is applied is illustrated in Fig. 1, which shows the increase of $n(T_e + T_i)$ and the increase of $T = T_e + T_i$ under the influence of the magnetosonic wave absorbed by the plasma. The HF pulse duration was 400 μsec and was chosen to agree with the estimated energy lifetime $\tau_E \sim 300$ μsec for heating by current. The average charged-particle density at the instant when the HF pulse was turned on was 10^{13} cm^{-3} at an average plasma filament diameter 12 cm.

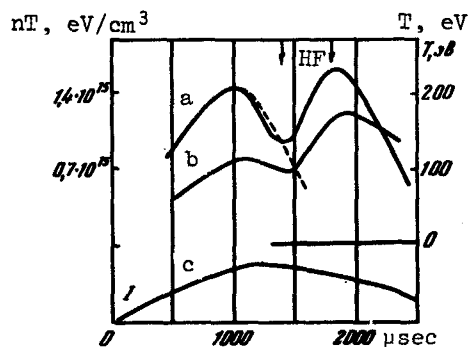

Fig. 1. a) Time variation of $n(T_e + T_i)$ in the presence (solid curve) and absence (dashed) of HF heating. b) Time variation of $(T_e + T_i)$. c) Oscillogram of current in plasma.

The energy content of the plasma in the Joule heating regime was 6 J in our experiment, the dissipation of the magnetosonic wave supplied more than 5 J to the plasma, and the total temperature doubled to approximately 200 eV. This effect corresponds to absorption of ~16 J of generator power ($P_{act} \simeq 40$ kW). The heating efficiency was thus 40%.

One of the most important problems connected with plasma heating is which of the particles, i.e., electrons or ions, absorb the energy of the magnetosonic oscillations. In our case, the ion temperature was determined by measuring the half-width of the C III impurity line ($\lambda = 4647$ Å). The maximum ion temperature was reached in this experiment at the end of the HF pulse and amounted to ~110 eV. According to [5], this value of T_i is an underestimate, since the C III lines are intense in the peripheral parts of the plasma filament.

A typical picture of the growth of the ion temperature following application of a long HF pulse is shown in Fig. 2. The nominal active power of the generator did not exceed 20 kW here. The upper curve of Fig. 2 shows the grid current of the HF generator. We see clearly that the power drawn increases in the vicinity of the magnetosonic resonance and correlates with the heating. For comparison, the ion temperature is shown here for two cases: with the HF power turned on (upper curve), and heating by current only (lower curve). Figure 3 shows the time variation of the ion temperature when the heating is by a shorter HF pulse ($\tau_{HF} \sim 750$ μsec). We see that T_i decreases with a characteristic time $\tau_i \sim 500$ μsec.

The agreement between the measured increments of nT and T_i indicate that the HF pulse heats mainly the ionic component. This is also confirmed by the fact that no noticeable change of the current or of the sonenoidal electric field was observed.

Thus, excitation of magnetosonic waves in a toroidal plasma with current leads to heating of the plasma. The maximum absorption in a deuterium plasma, as illustrated in Figs. 1 and 3, corresponds to excitation of a natural radial oscillation mode. At concentrations below the resonant value, absorption of HF energy at the asymmetrical radial mode m = 1 was observed. The plasma Q determined from the widths of the resonance maxima fluctuates in the range 6 - 15 and reaches a maximum at the maximum values of nT ensured by the Joule heating (near the current maximum). These effects agree well with the notions concerning the decays of magnetosonic waves [3].

Thus, the experiments with the deuterium plasma ($\omega \gtrsim \omega_{Hi}$) can be attributed to the decay of the initial magnetosonic wave into an "electrosonic" wave $\omega \sim kv_{Ti}$ and a drift wave $\omega_* \simeq (kcT_i/eH)(\nabla n/n)$, which ensures a low decay threshold, a plasma Q $\sim$ 10, and preferred heating of the ions. The produced drift waves with $k\rho_{Li} \sim 1$ should not lead to a noticeable diffusion of the plasma, owing to the short wavelength. The long-wave drift oscillations, which are capable of producing additional diffusion and heat conduction, are stabilized by the mag-

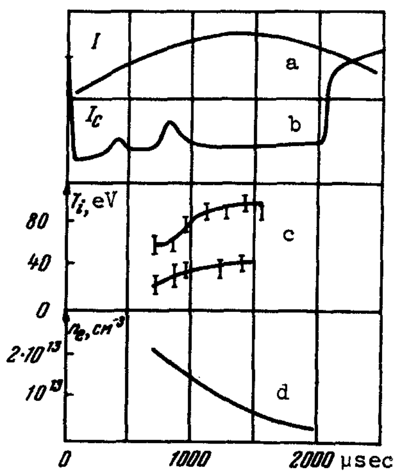

Fig. 2

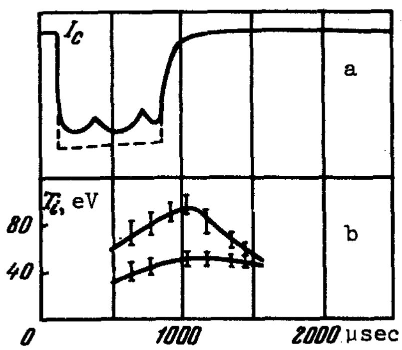

Fig. 3

Fig. 2. a) Oscillogram of HF generator grid current; b) oscillogram of current in plasma; c) ion temperature with (upper curve) and without (lower curve) HF heating; d) time variation of electron concentration.

Fig. 3. a) Oscillogram of HF generator grid current; b) ion temperature, with (upper curve) and without (lower curve) HF heating.

netic sound [4] and this should increase the lifetime. Indeed, the particle lifetime τ_n was increased by application of the HF.

The magnetosonic heating was produced under the conditions $\omega \gtrsim \omega_i$ (hydrogen) and $\omega \gtrsim 2\omega_i$ (deuterium), when no ion-cyclotron waves were excited. At $\omega < \omega_i$ we observed effective excitation of ion-cyclotron waves, in which case the HF power absorption was somewhat lower.

Consequently, the experiments have demonstrated the following:

1. Plasma can be heated by magnetosonic waves; the absolute increase of nT reaches 1.5 and $T_i + T_e$ is increased by 1.5 - 1.8 times in comparison with heating by current.

2. The heating took place mainly in the ionic component. T_i could become several times larger than the T_i obtained by Joule heating and could exceed T_e.

3. The lifetime τ_i was approximately double τ_E.

4. The energy absorption did not decrease when the plasma was heated, and the optimum corresponded to $(nT)_{max}$ in Joule heating.

5. The HF heating displaced the plasma filament, thus confirming the qualitative estimate of nT from the diamagnetic signal.

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DC VOLTAGES INDUCED BY MICROWAVE IRRADIATION IN SUPERCONDUCTING POINT JUNCTIONS

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One of the most pronounced manifestations of the nonstationary Josephson effect is the occurrence of current steps on the current-voltage characteristics (CVC) of Josephson junctions under the influence of electromagnetic radiation. Stepped CVC were observed many times in all types of weak superconducting junctions, such as tunnel, point-contact, and thin-film bridge junctions. Such characteristics result from the occurrence of an alternating Josephson current in the dc-biased junction, and its interaction with the external electromagnetic field.