Preliminary experimental results on ion cyclotron heating in the TO-2 tokamak

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Experimental results on the heating of a hydrogen plasma at the fundamental ion cyclotron frequency in the TO-2 tokamak are reported. Under certain conditions, described here, a pronounced absorption of the fast magnetosonic wave and a volume heating of the plasma are observed.

An effective heating of a hydrogen plasma at the fundamental ion cyclotron frequency has been observed in the TO-2 tokamak.[1] The experiments were carried out in a divertor-free regime, with the separatrix lying near the chamber surface. The only element bounding the plasma was an open rf antenna. This antenna was in the central cross section of one of the toroidal sections of the device and consisted of a stripline 35 mm wide extending around the plasma column from the side of the weak toroidal field. The antenna was shielded from the plasma by two lateral limiters with radial slits. The distance between the limiters was 90 mm, and the diameter of their apertures was 270 mm. The radiating surface of the antenna lay 15 mm from the plasma boundary in the shadow of the limiters and spanned an angle of 150° in the poloidal direction. The plasma was heated by an oscillator at a frequency of 18.35 MHz at a power level up to 0.5 MW. The oscillator operated in the single-pulse regime.

Experiments were carried out in a toroidal magnetic field of 1.2 T, which corresponds to the case in which the cyclotron-resonance zone is at the center of the plasma column in macroscopically stable discharge regimes in hydrogen lasting $\cong$100 ms at a plasma current up to 35 kA. The ion temperature was measured by a single-channel electrostatic neutral-particle analyzer with a solid target.[2] This analyzer had high sensitivity over a broad energy range and could operate continuously during the discharge pulse. The flux of neutrals was analyzed along the direction of the major radius of the torus (in the equatorial plane) in a cross section in the section of the device opposite the antenna.

The solid curves in Fig. 1 are oscilloscope traces of some of the discharge characteristics during the injection of an rf power $P_{rf} \cong 25$ kW, beginning at 40 ms into the discharge. Shown here from top to bottom are the discharge current I_d, the discharge voltage U, the current (I) in the device which regulates the equilibrium along the major radius, the average plasma density $\bar{n}_e$, the constant component (I_0) of the grid current of the rf oscillator with the plasma and in its absence (dashed curve), and the flux density (J) of charge-exchange neutrals at an energy of 0.5 keV.

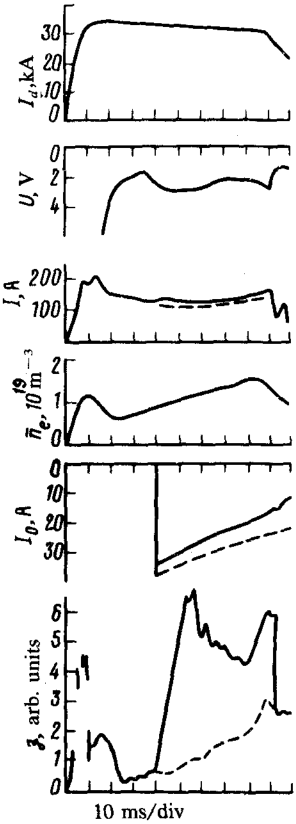

FIG. 1.

We see from these traces that the injection of the rf power changes the regulator current I, implying an increse in the plasma pressure, and also changes the analyzer signal J, implying an increase in the ion temperature (the behavior of these signals in the absence of the rf pulse is shown by the dashed curves). The loop voltage U and the plasma density $\bar{n}_e$ do not change. Furthermore, the rf heating is not accompanied by any significant changes in the spectral lines of light impurities (e.g., CIII and CV), integrated over the cross section. The input power was monitored by observing the decrease in the grid current of the oscillator with respect to the open-circuit current. This change in the current I_0 demonstrated, in particular, that the rf power was injected continuously into the plasma over time and that there was no oscillator loading of a mode nature.

Figure 2 shows the results of an analysis of the corresponding traces at a slightly higher power level $P_{\rm rf}$. The central ion temperature T_i, determined from the slope of the energy spectrum between 0.3 and 1.5 keV, was obtained over several discharge pulses with reliably reproducible characteristics. In this energy interval the ion distribution functions with and without the rf pulse exhibit no distortions of any sort and are Maxwellian. For the regime described above, the ion heating efficiency is 2 eV/kW at a plasma density of 10^{13} cm^{-3}. Also shown in Fig. 2 is the increase in the plasma

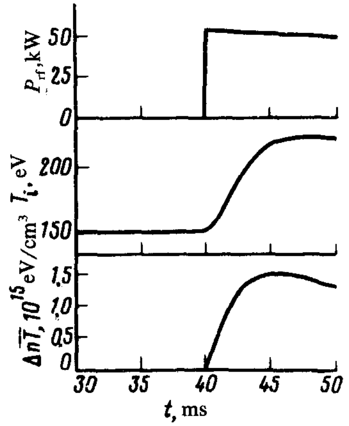

FIG. 2.

pressure, $\Delta\ \overline{nT}$, determined from the change in the equilibrium-regulator current. This change can be explained only in terms in an increase in the sum plasma temperature, since the injection of the rf power did not change the plasma density, as mentioned above. The increase, $\Delta\ (T_i + T_c) \cong 150$ eV, is nearly twice the increase in the ion temperature, indicating that the plasma electrons are heated.

The electron temperature had not yet been measured directly in these experiments. There is, however, evidence that the central electron temperature increases: the significant decrease in the intensity of the CV line in the axial part of the plasma column during the rf heating. This effect is illustrated by Fig. 3, which shows Abel-converted profiles of the intensity of the CV(2271 Å) line along the minor radius at a time 45 ms into the discharge with the rf pulse (solid curve) and without it (dashed curve).

These results thus demonstrate an effective volume heating of the hydrogen plas-

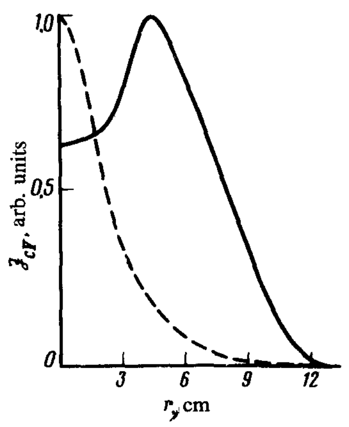

FIG. 3.

ma at the fundamental ion cyclotron frequency, without any significant effect on the plasma purity or confinement.

Why is it that, despite experiments in this frequency range dating back to the early 1970s, there has been no previous observation of the heating of a plasma with a single ion species at the frequency $\omega = \omega_{ci}$ in a tokamak? We believe the reason is that in none of the previous experiments of which we are aware were two conditions satisfied simultaneously: First, the wave frequency must be equal to the ion cyclotron frequency near the axis of the plasma column. Second, the transmitting antenna must be outside the cyclotron zone on the side of the weak toroidal magnetic field. Under these conditions, only a fast magnetosonic wave can be excited in the plasma volume; this wave propagates freely through the cyclotron zone and, after many passages, forms discrete natural modes. When the antenna is on the inner side of the torus, a fast magnetosonic wave is again excited, but there is a simultaneous excitation of a broad spectrum of slow modes, which are absorbed at the plasma periphery and do not reach the cyclotron-resonance zone. Since these waves have different polarizations, they do not convert into each other efficiently, so that the radiation resistance of the antenna (or the power injected into the plasma) is determined primarily by either the magnetosonic waves in the case of outer excitation or slow waves in the case of inner excitation.

The TO-2 experiments directly contradict the general belief that there is only a weak absorption of the fast magnetosonic wave at the fundamental ion cyclotron frequency: This absorption is in fact extremely strong. According to probe measurements, the quality factor of the natural modes does not exceed 50 and is independent of the longitudinal wave number K_z. This circumstance explains why there are no oscillations in the oscillator load. It may be that the strong cyclotron absorption observed here stems from an increase in the left-hand circularly polarized field of the fast magnetosonic wave due to the nonuniformity of the magnetic field and the actual ion drift trajectories in the tokamak. The effect of a rotational transform on the absorption of a fast magnetosonic wave at the frequency $\omega = \omega_{ci}$ for definitely untrapped ions was studied in Ref. 4. However, our experimental results contradict a conclusion reached there—that there is a surface power dissipation for modes with azimuthal number $m \neq -1$.

In conclusion we note that ion heating in a hydrogen plasma at the frequency $\omega = \omega_{ci}$ has been observed previously in the L-2 stellarator,[3] in experiments in which one of the present authors participated. However, the complicated magnetic field geometry of that stellarator has so far made it impossible to reach the definite conclusion that there is a direct cyclotron absorption of a fast magnetosonic wave.

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