Improved confinement by lower-hybrid heating in the FT-2 tokamak

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A transition to a regime of improved confinement has been seen, for the first time, in experiments involving lower-hybrid heating, in which there is a substantial heating of ions and electrons at sufficiently high densities. The improvement in confinement occurs after the rf heating pulse. A slowing of the recycling of hydrogen at the periphery of the discharge and a broadening of the current-density profile play important roles here.

Spontaneous and induced transitions to improved confinement of energy and particles in the discharge have attracted much interest in recent research on the physical processes which occur in tokamak plasmas. Situations of this sort arise when there is a divertor configuration and also in ordinary limiter discharges, both with auxiliary heating and in ohmic-discharge plasmas.[1,2] The occurrence of the same effects, such as a density increase, a sharp decrease in the emission in a hydrogen (or deuterium) line, and a decrease in MHD activity, indicates that a common mechanism may be operating in this transition when different methods are used to achieve the improved confinement. Results obtained at the FT-2 tokamak with auxiliary lower-hybrid (LH) heating may be of interest for reaching an understanding of these physical processes.

The experiments were carried out at fairly high densities in a regime of electron and ion heating, without current drag. A characteristic feature of these experiments was the onset of improved confinement after the rf pulse ended. A detailed study of this regime was carried out at the FT-2 tokamak [$R=55$ cm, $a=8$ cm, $B=22$ kG, $I_p=22$ kA, $t_{pl}=40$ ms, $\bar{n}_e=(1.8-2.8)\times10^{13}$ cm^{-3}]. An rf power up to 120 kW at a frequency 920 MHz in a pulse of length 3 ms was launched in the plasma by a two-wave grill from the outer side of the torus[3] ($N_\parallel=2-4$). During the rf pulse, it was observed that the density rose (20–30%), that high-energy ion tails were generated, and that the bulk of the electrons and ions were heated. In these experiments, in the ohmic-heating (OH) regime, the central ion and electron temperatures were $T_e\simeq600$ eV and $T_i\simeq100$ eV. The increment in the ion temperature, ΔT_i, was found from the charge exchange of neutral hydrogen to be ~100 eV at a 30-kW input power. This increment increased linearly up to $\simeq400$ eV at 120 kW (at a density $\bar{n}=2.4\times10^{13}$ cm^{-3}). The increase in the electron temperature, ΔT_e, was determined from the soft x-ray emission to be $\simeq200-300$ eV; it varied slightly with the power.[4] Figure 1 illustrates the results with some basic oscilloscope traces of the discharge for $P_{rf}=80$ kW; Figure 2 shows the changes in the total diamagnetic signal as the rf power is varied. We see that after the rf pulse is turned off the emission in the $H\beta$

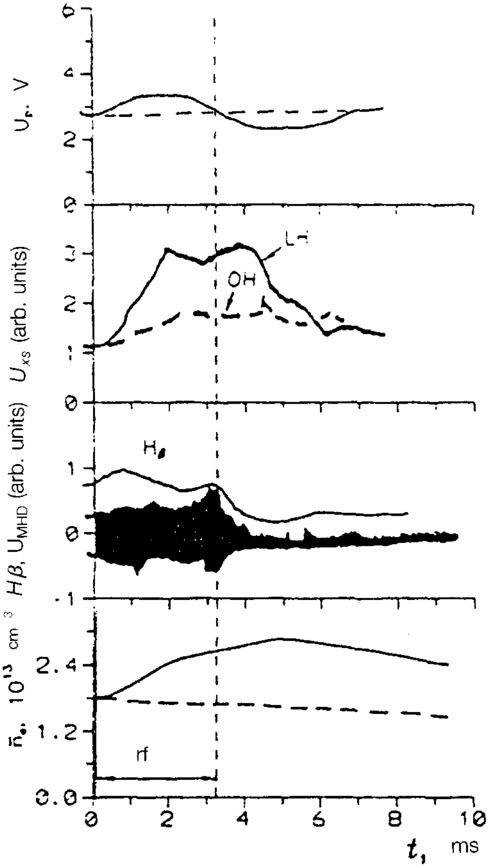

FIG. 1. Oscilloscope traces of the discharge. $P_{rf}=80$ kW. U_p—Plasma loop voltage; U_{xs}—soft x-ray signal along a central chord; $H\beta$—emission in the $H\beta$ line along the 4.5-cm chord; U_{MHD}—signal from the magnetic probes; $\bar{n}$—average density.

line falls off with an increase in the average density; there is also a sharp decrease in the MHD activity and a slight decrease in the voltage U_p. The level of the diamagnetic signal, which increases during the rf pulse, remains the same or even rises a bit further over a few milliseconds after the rf heating is turned off. These results on the change in the internal energy are confirmed by measurements of the electron and ion temperatures (Fig. 3) and of the density (which was measured by a seven-channel 2-mm interferometer).

The energy lifetime, which is $\tau_E^{\mathrm{OH}}=0.8$ ms in the ohmic regime, decreases with increasing power during the rf heating. At $P_{rf}=100$ kW it reaches $\tau_E^{\mathrm{LH}}=0.5$ ms. In the post-heating stage (PLH), this lifetime increases sharply to $\tau_E^{\mathrm{PLH}}=2$ ms. This effect was observed over a broad range of the source power level (40–140 kW). This lifetime agrees with that calculated from the Merezhkin–Mukhovatov scaling, the neo-Alcator scaling, and the Kaye–Goldstone scaling. In the post-heating stage, the increased lifetime is nearly independent of $\bar{n}$, as in the Kaye–Goldstone scaling and the DIIID–JET scaling. A density dependence arises when the radiative loss, measured by a bolometer, is taken into account. In this case the lifetime increases with increasing density, reaching 3 ms at $\bar{n}=3\times10^{13}$ cm^{-3}.

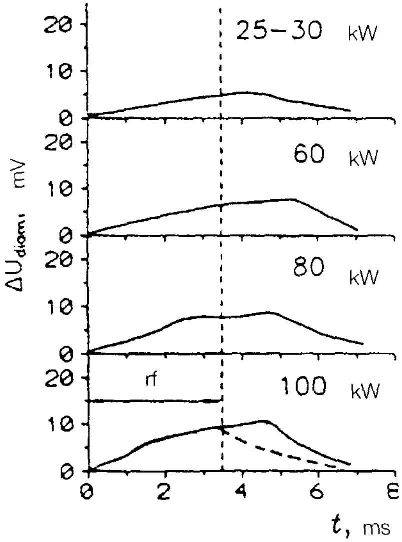

FIG. 2. Change in the total diamagnetic signal as the power level is changed. The dashed curve corresponds to a case in which improved confinement did not occur.

Efforts to achieve a stable state lasting more than 5 ms in the post-heating stage were hampered by the small dimensions of the tokamak and by the absence of a feedback in the plasma equilibrium. However, in those cases in which it was found possible to achieve this stable state, through a preliminary adjustment of the control fields and the injection field H_2, the duration of the stable post-heating state increased to 15–20 ms. In this case we sometimes observed some surges similar to ELMs (edge-localized relaxation modes) in the $H\beta$ spectral line. The ELMs are locally trapped peripheral modes, which often arise in the so-called H regime, i.e., a state of the plasma with improved confinement of particles and energy.[1] The onset of these ELMs results in some decrease in the density in the discharge (Fig. 4).

Moving on to a discussion of the observations, we should mention that several experimental and theoretical studies (e.g., Refs. 5–7) indicate that the confinement of particles and energy in a tokamak plasma depends strongly on the current-density profile.

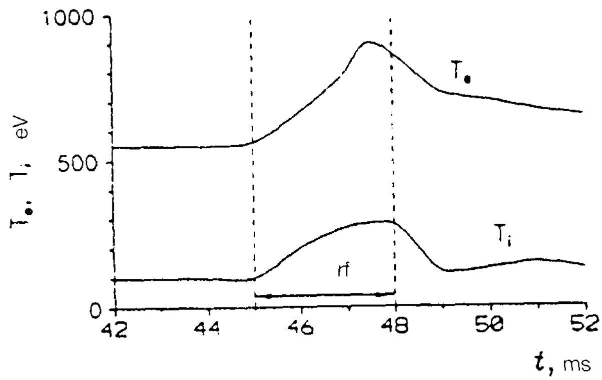

FIG. 3. Time evolution of the central electron and ion temperatures.

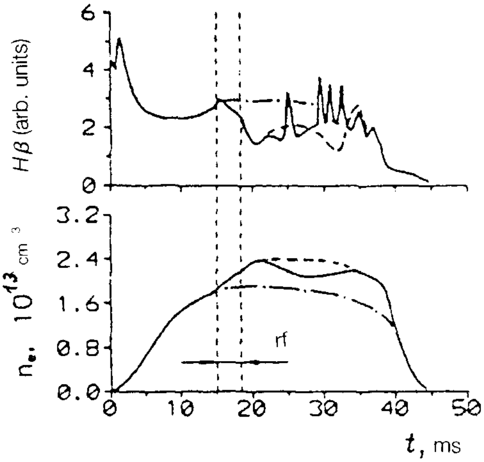

FIG. 4. Correlation between the density decay and the surges in the $H\beta$ line (ELMs). Dashed curve—Case without ELMs; dot-dashed curve—ohmic discharge.

We have evidence (e.g., the inductive changes in the loop voltage) that the current channel is modified in the course of a lower-hybrid experiment. The voltage U_p increases somewhat during the rf pulse. This increase can be attributed to a contraction of the current channel as the result of a cooling of the periphery. This cooling is caused by a sharp increase in the hydrogen flux from the chamber wall and from the limiter, which is in turn a consequence of bombardment by fast ions. When the rf heating is turned off, the conditions favor a lower level of recycling at the periphery. This circumstance is manifested by a decrease in the emission in the $H\beta$ line. Substantial changes also occur in the central region of the discharge. According to spectrometric and x-ray measurements, there is an additional ionization of impurities ($O^{+6} \rightarrow O^{+7,+8}$), and the $Z_{\rm eff}$ profile acquires a peak, during the rf pulse. Estimates show that at $P_{\rm rf} = 100-120$ kW the value of $Z_{\rm eff}$ at the center reaches 5.5, although the average value found from the conductivity changes from $Z_{\rm eff}^{\rm OH} = 2.5$ to $Z_{\rm eff}^{\rm LH} = 4$. After the lower-hybrid heating is turned off, the central channel cools down. This cooling, while a high value $Z_{\rm eff}(0) \sim 5.5$ is retained, should lead to a decrease in the conductivity at the center of the plasma and to an "expulsion" of some of the current to the periphery.

These qualitative arguments have found support in calculations carried out with the Astra code, which had been used previously to analyze an experiment at the Tuman-3 tokamak.[2] The results of this simulation are shown in Fig. 5. Because of the increase in j and grad$j$ in the region of the $q = 2$, 3 resonant surfaces, we can explain the suppression of the large-scale oscillations with $m \sim 1$. This effect, along with the cessation of the bombardment of the wall by fast ions, should tend to reduce the recycling at the periphery and to improve the thermal insulation. In addition, the broadening of the current profile and the conversion of this profile to a shape which is stabler with respect to the growth of small-scale oscillations with $m \gg 1$ should lead to a suppression of these modes and, correspondingly, to a decrease in the internal transport of heat and particles.[5,7] The improvement in the thermal insulation in the post-heating stage also explains the repeated increase in the central ion temperature from 100 to 150 eV in Fig. 3. This value is close to the value $T_i^A = 160$ eV found from the Artsimovich formula. The initial value

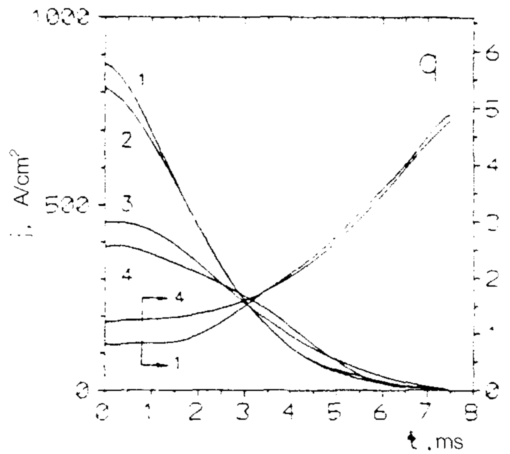

FIG. 5. Distribution of the safety factor q and of the current density j as found from the transport code. 1—Before the rf heating; 2—at the end of the rf pulse; 3,4—1 and 3 ms, respectively, after the end of the rf heating.

$T_i \leqslant 100$ eV during the ohmic heating indicates that a narrow $T_e(r)$ profile is initially established in small tokamaks because of the strong influence of the wall (a cooling). The result is an "underheating" of the ions. The slowing of the recycling caused by turning off the lower-hybrid heating, like a broadening of the current profile, makes it possible to achieve in a small tokamak a regime characteristic of large devices.

In summary, a substantial increase in the energy and particle confinement time has been observed in an experiment in which there was an effective heating of electrons and ions by lower-hybrid waves. This increase occurred after the heating pulse was turned off. We attribute the improvement in the thermal insulation to a broadening of the current-density profile and to a slowing of the hydrogen recycling at the periphery of the discharge.

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