High-density ohmic heating in the TUMAN-3 tokamak

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An operating mode with an unusually high density has been observed in the course of a study of the possibility of raising the plasma density in experiments with magnetic compression and a second current increment. The plasma properties in this mode are reported. The results are compared with ordinary ohmic heating.

Several experiments have been carried out to produce and study high-density operating modes in the TUMAN-3 tokamak.[1] Such modes have attracted interest because of the importance of the limiting-density problem[2,3] and also because of the possibility of increasing the energy confinement time if an ALCATOR-like scaling holds. There are clear indications[4,5] that the peripheral plasma plays an important role in the physical effects which limit the density in a tokamak. Magnetic compression[6] or a rapid current increase after the current reaches its quasisteady value[7] can have a strong effect on the periphery.

In the series of experiments which we are describing here, the magnetic compression along the minor radius and the current rise were accompanied by a simultaneous additional injection of gas. Figure 1 shows some typical oscilloscope traces of the evolution of the plasma properties in such experiments. The magnetic field doubles over a time of 3.5 ms, while the plasma current increases by about 40% over 4 ms. Shown at the bottom of this figure are the model program used in the density control system and the experimental behavior of the density. The maximum increase in density found in the series of experiments was a tripling, from 1.4×10^{13} to 5.2×10^{13} cm^{-3}, over a time of 15 ms. The properties of the operating mode with the high density, which we will call the "high density mode" (*HDM*), and the properties of the original ohmic-heating mode are listed in Table I. The average density reached here is twice the previous limit in this device and is 0.85 of Greenwald's empirical limit,[2] which is the record high for modes without auxiliary heating and without pellet injection.

We will simply list and illustrate the basic properties of the plasma in this new state, since we do not have room in this letter for a detailed description of the physical processes accompanying the transition to the *HDM*. First, the density achieved here is apparently not the maximum density possible, since no cutoff occurred in the discharge, and the density increase was limited by the capabilities of the gas injection system used in these experiments. In addition, the level of the radiative loss does not indicate that a limit is being approached. As can be seen from Fig. 2a, this loss in-

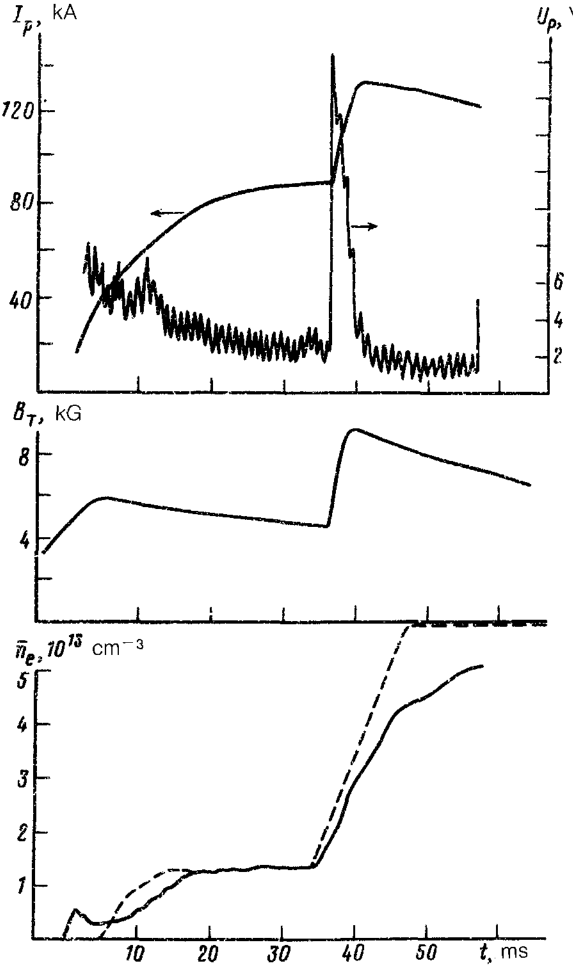

FIG. 1. Plasma current, loop voltage, longitudinal field, density, and (dashed line) model program for the density control system in a discharge with an increase in $\bar{n}_e$ during magnetic compression and a second current rise (*HDM*).

creases with increasing density, but even with $\bar{n}_e = 5.2\times10^{13}$ cm^{-3} the radiative loss is half the ohmic power deposited. Furthermore, there is no catastrophic increase in the effective charge (Fig. 2b). Second, the *HDM* is characterized by intense sawtooth oscillations of the temperature, according to observations The amplitude and period of these oscillations in the discharges with the higher densities are larger than in discharges with lower values of $\bar{n}_e$. The typical behavior of the intensity of the soft x radiation calculated from these results on the electron temperature and the average power is show in Fig. 3. The time evolution of J_{sxr} reveals a spontaneous increase in the oscillation amplitude and a simultaneous decrease in the intensity 8–10 ms after the beginning of the density increase. The apparent reason for this evolution of J_{sxr} lies in a termination of the redistribution of the current density profile and in a corresponding broadening of the region with $q(a) < 1$ (we had observed a similar effect earlier,[5] but calculations of the current diffusion are necessary in order to confirm this

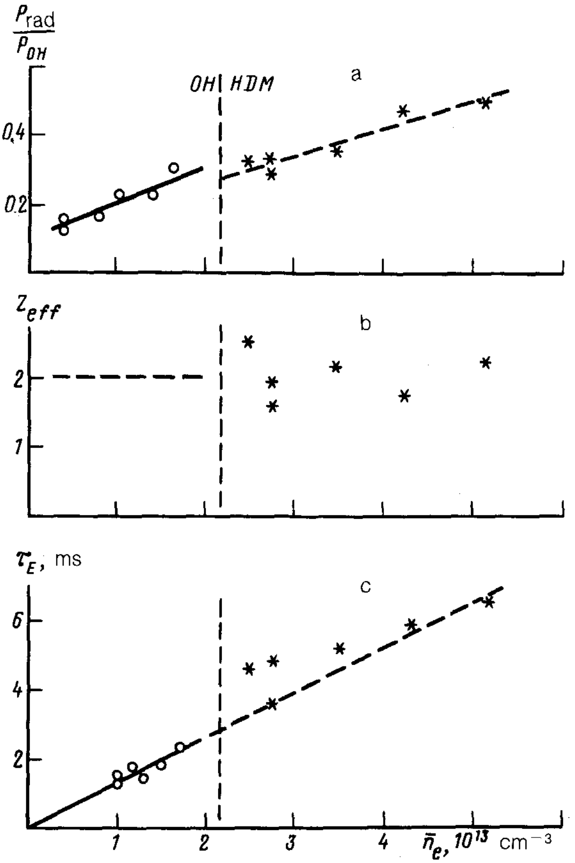

FIG. 2. a—Fraction of energy lost by radiation; b—effective charge; c—energy confinement time, all as functions of the density in the ohmic-heating mode (*OH*) and the high-density mode (*HDM*).

hypothesis). The increase in the amplitude of the sawteeth is accompanied by a simultaneous and essentially complete halt to the density increase.

Measurements of the energy confinement time in the *HDM* are of particular interest, since a saturation of the linear dependence $\tau_e(\bar{n}_e)$ toward the limiting density has been observed in several experiments.[7,8] Figure 2c shows the results of the τ_E measurements in the TUMAN-3 during ordinary ohmic heating and in the *HDM* at approximately equal values of the safety factor $q(a)$ (here we are ignoring dW/dt; the effect is to slightly reduce the value of τ_E^{HDM} at $t<45$ ms, while the temperature and the density are rising; Fig. 3). The time $\tau_E^{HDM}(\bar{n}_e)$ thus does not reach saturation at high densities. It may reach a value slightly above the value found through an extrapolation of the linear dependence typical of ohmic heating with a low density in the TUMAN-3. Estimates of the particle confinement time found through an analysis of the balance equation with a source found from the D_a emission show that τ_p in the *HDM* is ≈ 15 ms and thus 5 or 6 times that in the ohmic-heating mode.

Another conclusion which can be drawn from these experiments is that the par-

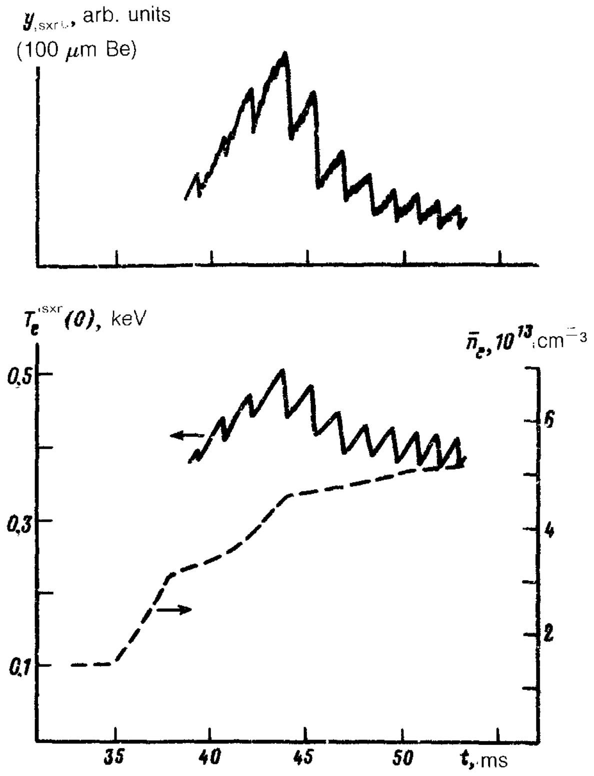

FIG. 3. Time evolution of the intensity of the soft x radiation from the plasma, calculated by the multiple-absorber method, the central temperature, and the average density in a discharge in the *HDM*.

ticular method used to form the plasma column has a strong effect on the maximum density achievable in the column. The linear dependence $\tau_E(n_e)$ in the *HDM* up to the maximum density is evidence of the transition to a mode with improved confinement, as has been observed in the *ASDEX*[8] and the *DIII-D*.[10] In the *HDM*, the particle confinement time increases to a level 1.5 times that found through an extrapolation of $\tau_p \sim \bar{n}_e$.

TABLE I. Plasma properties in the *HDM* and the *OH*.

	I_p kA	B_T kG	q^{cyl}	$\bar{n}_e$ 10^{13}cm^{-3}	T_{eo} keV	T_{io} keV	τ_E ms	τ_p ms	Z_{eff}	β_T^{max} %	$\bar{\beta}_T$ %	β_p
OH	94	4,5	2,7	1,4	0,4	0,11	1,5	2,5	2,0	1,9	0,4	0,15
HDM	120	6,7	3,2	5,2	0,5	0,17	6,5	15	2,2	3,5	0,9	0,44

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