Ohmic heating in the Tuman-3 tokamak in a weak magnetic field

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The energy confinement time in the ohmic-heating regime is found over a broad range of plasma currents with intense sawtooth oscillations in the density and other parameters. Distinctive features of the ion heating are discussed. The effect of trapped-particle drift on the density profiles is discussed.

The small aspect ratio of the Tuman-3 tokamak ($a = 24$ cm, $R = 55$ cm) gives the ohmic-heating regime several distinctive features.[1,2,4] It allows high-current ohmic discharges with a low safety factor $q < 3$ in magnetic fields which are weak in comparison with the usual tokamak fields. Under these conditions the quantity $\bar{\beta}_T$ can reach high values. Furthermore, at relatively low ion temperatures the ion-collision parameter[1] ν_i^* reaches a low value. In low-q regimes, there are intense sawtooth oscillations in the plasma density and in several other parameters.[3] In this letter we report a study of the ohmic-heating regime in the Tuman-3 over a broad range of the plasma current,

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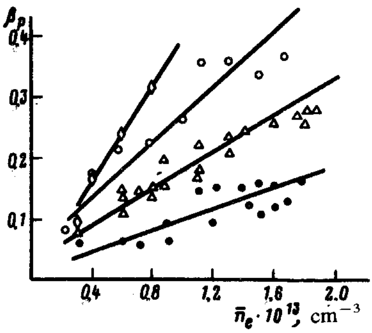

FIG. 1. β_p vs $\bar{n}_e$ for various ohmic-heating regimes. ◇—$I_p \simeq 32$ kA, $B_T \approx 1.8$ kG, $q \simeq 2.9$; ○—$I_p \simeq 60$ kA, $B_T \simeq 2.8$ kG, $q \simeq 2.4$; △—$I_p \simeq 95$ kA, $B_T \simeq 4.3$ kG, $q \simeq 2.3$; ●—$I_p \simeq 150$ kA, $B_T \simeq 6.4$ kG, $q \simeq 2.2$.

$30 \leqslant I_p \leqslant 170$ kA, for magnetic fields in the range $1.5 \leqslant B_T \leqslant 7$ kG with $q \sim 2.2$–2.9 $(q = 5a^2 B_T / R I_p)$.

The chamber is cleaned before the experiments by a low-temperature induction discharge in oxygen. An oxygen discharge has proved effective in removing carbon compounds from the chamber. The effect of cleaning in oxygen for 3–5 h is considerably greater than the effect of conditioning for many days in hydrogen and cleaning by a glow discharge in an inert gas. To remove the oxygen after the cleaning we use an induction discharge in hydrogen. The oxygen cleaning results in a significant improvement in the MHD stability of the ohmic regime and some decrease in the torus loop voltage.

Figure 1 shows $\bar{\beta}_p$, the average value over the cross section of the torus found from diamagnetic measurements, as a function of the density averaged along a diameter for various values of the plasma current $(30 \leqslant I_p \leqslant 150$ kA) and of the toroidal field. As I_p is increased from 50 to 150 kA, the axial electron temperature determined by the Thomson-scattering method increases from 150 to 500 eV. The loop voltage U_p is 1.8–2.5 V, and the corresponding effective charge is $Z_{\text{eff}} < 1.5$. Despite the several important distinctive features of the ohmic-heating regime, which we have already mentioned, we see the linear density dependence of $\bar{\beta}_p$ which is typical of tokamaks. In operation with $I_p \simeq 30$ kA and $I_p \simeq 60$ kA, we determined $\bar{\beta}_p$ up to the maximum densities, $\bar{n}_e \sim 8 \times 10^{12}$ cm^{-3} and $\bar{n}_e \sim 2 \times 10^{13}$ cm^{-3}. With $I_p \simeq 60$ kA and $B_T \simeq 2.8$ kG, the value $\bar{\beta}_p \simeq 0.4$ which we reached corresponds to the high value $\bar{\beta}_T \simeq 1.3\%$ for ohmic heating. The average energy confinement time determined from the data in Fig. 1 does not depend appreciably on the plasma current. At the density $\bar{n}_e \simeq 8 \times 10^{12}$ cm^{-3} we find $\tau_E \sim 1.2$–1.6 ms for the various regimes. The values of τ_E correspond roughly to Alcator scaling, $n_e \chi_e = (n_e a^2)/6\tau_E \sim 5 \times 10^{17}$ cm$^{-1} \cdot$s^{-1}. Significantly, the intense sawtooth oscillations described in Ref. 3 and observed again in the present experiments are not seen in the signal from the diamagnetic loop.

As was pointed out in Refs. 1 and 2, the ion temperature in the Tuman-3 does not change as the toroidal field is increased, while it falls off slightly with increasing density. Similar results were obtained in the experiments which we are describing here,

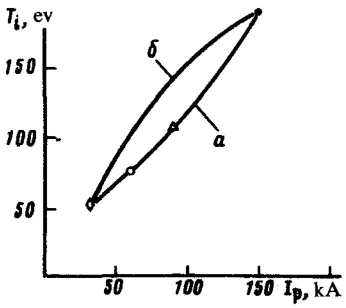

FIG. 2. Behavior of the ion temperature with increasing plasma current for regimes with $q < 3$. ◇—$B_T \simeq 1.8$ kG, $\bar{n}_e \simeq 4\times 10^{12}$ cm^{-3}; ○—$B_T \simeq 2.8$ kG, $\bar{n}_e \simeq 8\times 10^{12}$ cm^{-3}; △—$B_T \simeq 4.3$ kG, $\bar{n}_e \simeq 1\times 10^{13}$ cm^{-3}; ●—$B_T \simeq 6.4$ kG, $\bar{n}_e \simeq 1.2\times 10^{13}$ cm^{-3}. a: Experimental. b: $T_i = 6\times 10^{-7}(B_T I_p \bar{n}_e R^2)^{1/3}$.

with the improved cleaning of the chamber. In view of the small values $\nu_i^* < 1$, these two circumstances indicate that trapped particles play a definite role in the ion energy balance. Figure 2 shows the ion temperature at the center of the plasma column as determined from the spectrum of charge-exchange atoms as a function of the plasma current for regimes with $q < 3$. The increase in the temperature differs from the behavior $T_i = 6\times 10^{-7}(I_p B_T \bar{n}_e R^2)^{1/3}$, shown in the same figure.

The intense sawtooth oscillations of the density observed in Ref. 3 in the central part of the discharge (the amplitude of the oscillations reaches 30% of $\Delta n_0/n_0$) can be explained well in terms of the high velocity of the neoclassical trapped-particle pinch, which can reach[5] $v_{\text{neo}} \sim 10^3$ cm/s. Increasing the safety factor by raising the toroidal field at a fixed plasma current suppresses internal disruptions. In this regime, the trapped-particle pinch should cause a pronounced peaking of the radial density profile. Figure 3 shows radial density profiles measured with an eight-channel 2-mm interferometer. The density profile at the low values $q \simeq 2.4$ is averaged over time (over the oscillation period). With increasing safety factor, there is a significant contraction of the profile in the central region. The density profile at the periphery remains broad. A

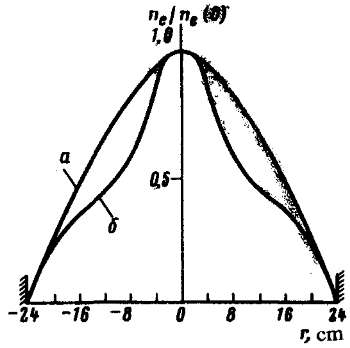

FIG. 3. Profiles of the reduced density for regimes with low and high safety factors. $I_p = 60$ kA. a—$q = 2.4$; b—$q = 4.7$. $\bar{n}_e = 1\times 10^{13}$ cm^{-3}.

numerical simulation of transport processes is presently being carried out to reach an understanding of the particle balance in a regime with a large safety factor.

In summary, a high value of the average parameter $\bar{\beta}_T$ (at $B_T \sim 3$ kG, $\bar{\beta}_T \sim 1.3\%$; the average is over the plasma cross section) has been achieved in the ohmic-heating regime in the Tuman-3 tokamak. The small aspect ratio ($R/a = 2.3$) is responsible for the low value of the collisionality parameter even at comparatively low temperatures ($\nu_i^* < 1$ over a large part of the plasma cross section). Also associated with the small aspect ratio is the greater influence of neoclassical effects on the plasma behavior, particularly the peaking of the radial density profile at high q and the high amplitude of the density oscillations in the low-q regime (with $\Delta n_0/n_0$ ranging up to 30%). Despite these distinctive features, the energy confinement in experiments with a weak magnetic field exhibits the scaling characteristic of the typical ohmic-heating regimes in tokamaks.

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