Energy-confinement features observed in experiments with the ohmic *H* mode in the TUMAN-3 tokamak

M. V. Andreĭko, L. G. Askinazi, V. E. Golant, V. A. Kornev,
S. V. Lebedev, L. S. Levin, G. T. Razdobarin, V. V. Rozhdestvenskiĭ,
A. S. Tukachinskiĭ, and S. P. Yaroshevich
A. F. Ioffe Physicotechnical Institute, Russian Academy of Sciences,
194021 St. Petersburg, Russia

(Submitted 8 December 1993)
Pis'ma Zh. Eksp. Teor. Fiz. **59**, No. 2, 94–97 (25 January 1994)

Some new features of energy confinement have been observed in the regime with reduced plasma transport during ohmic heating: the ohmic *H* mode. In particular, the energy confinement time τ_E depends strongly on the plasma current and the injected power, while it depends only weakly on the density. Both the absolute values of the energy confinement time and its dependence on the parameters correspond well to the empirical law (the scaling law) which describes the *H* regime in devices with intense auxiliary heating. The results found here indicate that the physics of the confinement in the *H* mode is the same in devices differing in geometry and in heating method. An unexpectedly long energy confinement time—30 ms—has been measured in the small TUMAN-3 device. This figure exceeds the prediction of the scaling law for an ohmically heated plasma by a factor of 15.

The various energy confinement regimes in tokamaks are classified by convention as the "ohmic regime," the "*L* regime," and the "*H* regime." Correspondingly, there are three types of scaling laws which describe transport properties (Table I). In particular, energy confinement in the ohmic-heating regime is described by scaling laws which are based on the assumption of a linear dependence on the average density and the safety factor. The dependence on the dimensions of the device is cubic. Some typical examples of this type of scaling are neo-Alcator scaling[1] and Merezhkin–Mukhovatov scaling.[2] If there is auxiliary heating, the energy confinement depends on the parameters in a very different way. In general, the expressions for the *L* regimes do not predict any significant dependence on the density or safety factor. Instead, the scaling laws predict a linear dependence on the current and an inverse proportionality to the square root of the heating power. The dependence on the dimensions is weaker (the exponent is 1 or 2). The types of scaling which are mentioned most often are the Goldston scaling[3] and the ITER89-P scaling.[4] The dependence of τ_E on the parameters in regimes with improved confinement with auxiliary heating (the *H* regimes) differ only slightly from the expressions mentioned above for the *L* regimes. The basic difference is in the absolute values of τ_E. In the *H* mode this time is generally twice as long. As an example we might cite the scaling law proposed for describing the *H* mode without edge-localized modes (ELMs) in the DIII-D and JET devices.[5] The difference in dependence on the parameters leads to a significant difference in the estimates of the energy confinement time for the ohmic-heating regime if the ohmic power is used as

TABLE I. Examples of scaling laws describing the confinement time in ohmic-heating regimes for *L* and *H* modes with auxiliary heating.

Scaling law (10^{19} m^{-3}, m, MA, MW, T, keV)	τ_E, ms
Neo-Alcator $7naR^2q^{\mathrm{cyl}}$	1.9
Merezhkin–Mukhovatov $1.1na^{0.25}R^{2.75}qk^{0.125}A_i^{0.5}/\langle T_e\rangle^{0.5}$	2.3
Goldston (*L* mode) $37I_pP^{-0.5}R^{1.75}a^{-0.37}k^{0.5}(A_i/1.5)^{0.5}$	10.7
ITER89-P (*L* mode) $48I_p^{0.85}R^{1.2}a^{0.3}k^{0.5}n^{0.1}B_T^{0.2}A_i^{0.5}P^{-0.5}F[f_s^{\alpha-s}f_q^{\alpha-q}]$	9.9
DIII-D/JET (*H* mode) $106P^{-0.46}I_p^{1.03}R^{1.48}$	15.6

the heating power in the last three expressions. Table I shows estimates of τ_E for an ohmic-heating regime with a current of 155 kA in the TUMAN-3 tokamak according to the various scaling laws.

The *H* mode in the ohmic-heating regime (the ohmic *H* mode) was first observed[6] in the DIII-D tokamak. The energy confinement time in this experiments was 1.2 times that predicted by the neo-Alcator scaling. In the experiments with the ohmic *H* mode in the TUMAN-3, a value of τ_E^{NA} higher by a factor of 2 to 4 was found.[7,8] It can thus be suggested that the transport laws in the ohmic *H* mode differ from those observed in the ohmic regime.

The series of experiments which we are reporting here was undertaken in order to determine how τ_E depends on various parameters of the plasma in the ohmic mode. The experiments were carried out after a "boronization" of the walls of the discharge chamber; that process significantly increases the ranges of densities and currents which can be achieved.[9] A comparison of the results obtained before and after the boronization presents a unique opportunity to evaluate the effect of the injected power on the confinement in a regime without auxiliary heating at fixed values of I_p, B_T, $\bar{n}$, R, and a.

Experiments were carried out in a boronized chamber at the following values of the discharge parameters: $R_0=0.53$ m, $a_l=0.22$ m, $B_T \leqslant 0.7$ T, $I_p \leqslant 160$ kA, $\bar{n}_e \leqslant 5\times10^{19}$ m^{-3}, $T_{e0} \leqslant 0.7$ keV, and $T_{i0} \leqslant 0.2$ keV. The boronization resulted in the following improvements in the plasma characteristics (these values are typical for the procedure): The impurity concentration was reduced by a factor of 2 to 8, the effective plasma charge was reduced by a factor of 1.5 to 2.0, the intensity of the soft x radiation was reduced substantially (by a factor of 10), and the limiting density was increased 50%. In addition, some new effects were observed. In the ohmic *H* mode, about 20% of the total current was of a noninduction nature (a bootstrap current). Although the injected power was lowered by the boronization, the electron tempera-

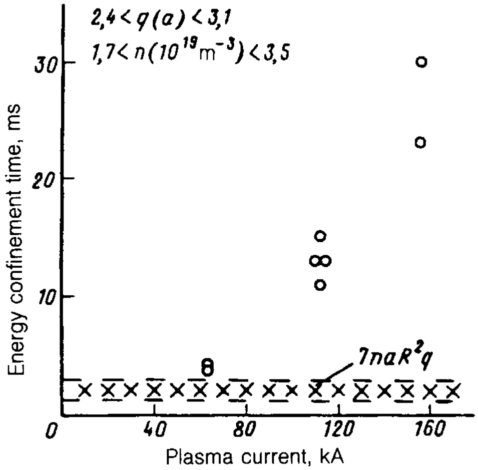

FIG. 1. Energy confinement time versus the current. The hatched region corresponds to the predictions of neo-Alcator scaling with $\bar{n}=(1.7\text{–}3.5)\times10^{19}\ \mathrm{m}^{-3}$ and $q=2.4\text{–}3.1$.

ture changed only negligibly. That result is evidence of an improvement of the energy confinement in the plasma.[9]

In the boronized chamber, it was possible to raise the current in the plasma to 160 kA. Under these conditions the ohmic *H* mode was initiated by a pulsed increase in the rate of injection of the working gas, as in some earlier experiments.[7] Measurements of the energy confinement time in the ohmic *H* mode with currents of 63, 112, and 155 kA in the plasma showed that τ_E depends strongly on I_p (Fig. 1; in this series, the concentration ranged from 1.7×10^{19} to $3.5\times10^{19}\ \mathrm{m}^{-3}$, and the safety factor from 2.4 to 3.1). This behavior contradicts the neo-Alcator scaling and is similar to the scaling laws predicted for plasmas with auxiliary heating. At the maximum current the experimental energy confinement time was 30 ms, which is 15 times τ_E^{NA}.

The energy confinement time was studied as a function of the injected power and the density in a regime with a current of 112 kA. The significant decrease in the loop voltage as a result of the boronization made it possible to produce discharges with identical values of the basic plasma parameters (I_p, B_T, $\bar{n}$, R, and a) at various values of the injected power. The plasma loop voltage and, correspondingly, the injected power decreased by a factor of 2 after boronization in this regime.[9] Despite the decrease in power, the plasma temperature remained essentially constant in the ohmic *H* mode at the same density. That result is evidence of a significant increase in the energy confinement time. Figure 2 shows τ_E as a function of the density. The points in this figure, which correspond to conditions after the boronization, lie considerably above those obtained in a chamber which had not been boronized. This figure also shows that the dependence of τ_E on the density is extremely weak. Shown for comparison here is the prediction of neo-Alcator scaling. The results which have been found are not an adequate basis for accurately determining how the energy confinement depends on the power and the density, but they definitely indicate that the behavior of τ_E in the ohmic *H* mode is different from the ohmic-heating scaling and is similar to the scaling for a plasma with auxiliary heating.

An unexpectedly good agreement was found in a comparison of the behavior

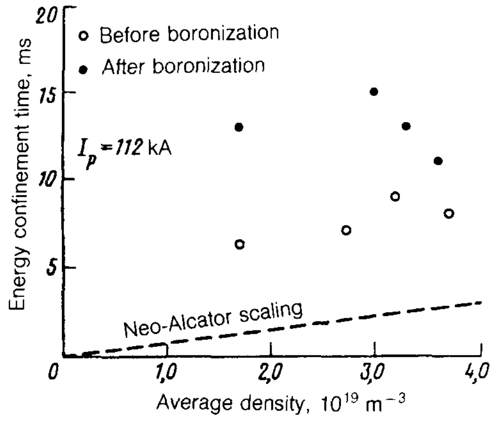

FIG. 2. Energy confinement time versus the density in a regime with a current of 112 kA. ○—Before "boronization"; ●—after.

observed experimentally with the scaling predicted for the *H* regime without ELMs. This comparison was carried out with the DIII-D/JET scaling,[5] which was proposed for plasmas in large devices (DIII-D, JET, and ASDEX) with intense auxiliary heating. We see in Fig. 3 that the points for the TUMAN-3 lie near the approximation for the three tokamaks. These results are evidence that the physics of the confinement in the *H* regime is the same, regardless of the heating method and the dimensions of the device. We should also mention the geometric simplicity of the TUMAN-3 tokamak, in which these results were obtained. The TUMAN-3 does not have a divertor, and the plasma cross section in it is defined by a circular limiter.

The behavior of τ_E as a function of the parameters observed in the ohmic *H* mode raises the hope that the confinement can be improved further after upgrading the TUMAN-3 tokamak. The current I_p can then be increased to 200 kA. It can also be predicted that τ_E will increase significantly when the DIII-D, JET, and ASDEX

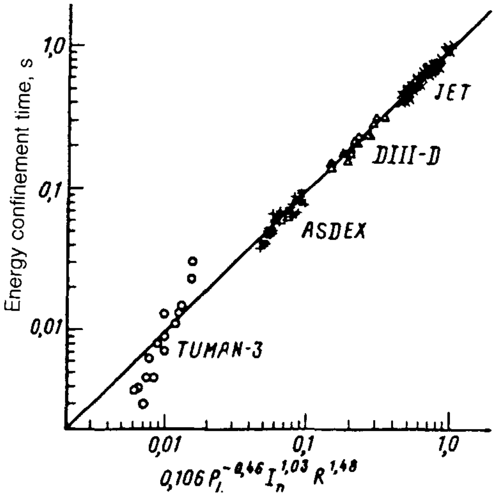

FIG. 3. Energy confinement time as a function of the predictions of the DIII-D/JET scaling proposed for the *H* mode without ELMs.

tokamaks are operated in the ohmic *H* mode, since in this case the injected power will be severalfold lower than in the case with auxiliary heating.

This study had financial support from the Russian Basic Research Foundation (Project Code 93-02-3342).

[1] B. Blackwell *et al. Proc. IX IAEA Conf. on Plasma Phys. and Contr. Nucl. Fusion Res.*, Baltimore, 1982 (Vienna, 1983), Vol. II, p. 27.

[2] V. G. Merezhkin and V. S. Mukhovatov, JETP Lett. **33**, 446 (1981).

[3] R. J. Goldston, Plasma Phys. and Contr. Fus. **26**, 87 (1984).

[4] P. N. Yushmanov, Nucl. Fus. **30**, 1999 (1990).

[5] D. P. Schissel *et al.*, Nucl. Fus. **31**, 73 (1991); T. C. Simonen *et al.*, Preprint GA-A20711, 1991.

[6] D. P. Schissel *et al.*, *Proc. 16th Conf. on Contr. Fusion and Plasma Phys.* (Venice, 1989), Vol. 13B-I, p. 115.

[7] L. G. Askinazi *et al.*, *Proc. 17th Eur. Conf. on Contr. Fusion and Plasma Phys.* (Amsterdam, 1990), Vol. 14B-I, p. 411.

[8] M. V. Andrejko *et al.*, *Proc. XIV Conf. on Plasma Phys. and Contr. Nucl. Fusion Res.*, (Wurzburg, 1992 (Vienna, 1993), Vol. I. p. 485.

[9] L. G. Askinazi *et al.*, *Proc. 20th Eur. Conf. on Contr. Fusion and Plasma Phys.* (Lisboa, 1993), Vol. 17C-IV, p. 1509.

Translated by D. Parsons