Consistency of the electron temperature profiles during ECR heating in the T-10 tokamak

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The electron temperature profiles during ECR heating in the T-10 tokamak have been calculated numerically. A model is proposed for the heat flux on the basis of canonical profiles of the current and the plasma pressure. The calculated temperature profiles agree with the experimental profiles for various magnitudes and profiles of the ECR heating power.

Recent experiments in the T-10 tokamak[1,2] with central and noncentral ECR heating indicate that the effective local thermal conductivity $\kappa_{\text{eff}} = -\Gamma/(\partial T_e/\partial r)$ depends strongly on the profile of the ECR power deposition (Γ is the electron heat flux). In this letter we report a numerical simulation of those experiments on the basis of a model which makes use of the concepts of "canonical" profiles of the current and the plasma pressures.[3,4]

Let us compare the results of experiments involving central heating (pulse No. 45439) and noncentral heating (pulse No. 45443) at a given current $I = 200$ kA and at a given average density $\bar{n} = 3.0\times 10^{13}$ cm^{-3}. The solid lines in Fig. 1 are experimental $T_e(r)$ profiles in the ohmic regime (OH) and during ECR heating (ECRH). In pulse 45439, heating was carried out at the center by three gyrotrons with a total absorbed power $P = 630$ kW. In pulse 45443, a single gyrotron heated the plasma at the center, while four heated it at a radius ~ 17 cm. The total power in this case was $P \sim 850$ kW (~ 200 kW at the center and ~ 650 kW at a radius of ~ 17 cm). It can be seen from this figure that the absolute values and profiles of $T_e(r)$ differ only slightly. The local values of the gradient $\partial T_e/\partial r$ also differ only slightly. On the other hand, the power deposited within a plasma cylinder of radius $r = 10$–12 cm has values differing by a factor of three. The values of κ_{eff} differ by a corresponding factor. Since the local values of the parameters $(n(r), T_e(r), \partial T_e/\partial r)$ are approximately the same, these

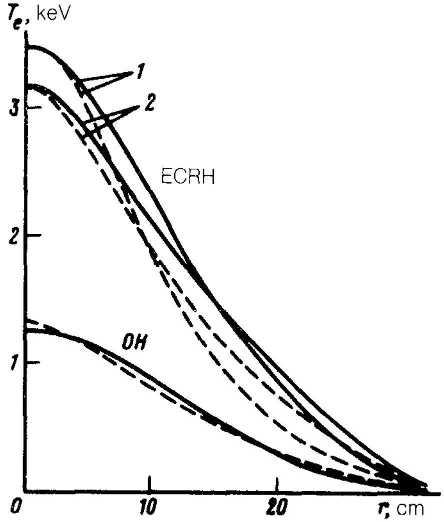

FIG. 1. Comparison of the results of the simulation (dashed curves) and experimental profiles (solid curves) of the electron temperature in the ohmic region (OH) and for two different profiles of the ECR heating power (ECRH). 1—Central heating (pulse No. 45439); 2—noncentral heating (pulse No. 45443). The data refer to the end of the heating pulse, which was 100 ms long.

changes in κ_{eff} could not be determined by a functional dependence of κ_{eff} on the local parameters. There is an effect associated with the overall $T_e(r)$ profile.

To describe the evolution of the electron temperature, we use the following simple model. The density $n = n(r,t)$ and the ion temperature $T_i = T_i(r,t)$ are assumed to be known from experiments. The system of energy-balance equations is written in this case as[5]

$$\frac{3}{2}\frac{\partial}{\partial t}(nT_e) = -\frac{1}{r}\frac{\partial}{\partial r}(r\Gamma) + Q_{\text{OH}} + Q_{ei} + Q_{EC} + Q_{rad},$$

$$\frac{\partial \mu}{\partial t} = \frac{c^2}{4\pi}\frac{\partial}{\partial r}\left(\frac{1}{\sigma r}\frac{\partial}{\partial r}(r^2\mu)\right). \tag{1}$$

Here $\mu = 1/q$; q is the safety factor; Q_{OH} is the Joule power; Q_{ei} is the exchange between electrons and ions; Q_{EC} is the power of the ECR heating; and Q_{rad} is the loss due to radiation and ionization. The distributions $Q_{\text{EC}}(r,t)$ and $Q_{\text{rad}}(r,t)$ were taken from experiments.

A specific feature of the model involves the choice of the flux Γ. We chose it to be a sum

$$\Gamma = \Gamma_A + \Gamma_B, \tag{2}$$

where Γ_A reflects the global electron-confinement characteristics, while Γ_B conveys the effect of the $T_e(r)$ profile or of other parameters.

To describe the global characteristics, we use the T-11 scaling, assuming

$$-\Gamma_A = \kappa_A \frac{\partial T_e}{\partial r}, \quad \varkappa_A = \varkappa_e^{\text{T-11}} + \varkappa_e^{neo} , \tag{3}$$

where $\kappa_e^{\text{T-11}} = 10^{20}(T_e^{1/2}/qR)(r/R)^{1.75}$ $\text{cm}^{-1}\cdot\text{s}^{-1}$ (T_e is in eV), and κ_e^{neo} is the neoclassical thermal conductivity.

The structure of Γ_B is chosen on the basis of the following considerations. According to Ref. 3, the simplest canonical profile $T_e^0(r)$ under the condition $Z_{\text{eff}}(r) = \text{const}$ is $T_e^0(r) = T_e^0(0)(1 + r^2/a_T^2)^{-4/3}$, where a_T is the current radius, given by $a_T = a\sqrt{q_0/(q_a + q_0)} \approx a/\sqrt{q_a - 1} \approx a/\sqrt{q_a}$. The function $T_e^0(r)$ satisfies the homogeneous differential equation $dT_e^0/dr + k_T T_e^0 = 0$, where $k_T = 8r/3a_T^2 \times (1 + r^2/a_T^2)^{-1}$. The "stiffness" of the canonical profile, i.e., the extent to which the local plasma parameters are "tied" to it, increases with increasing β_p, according to Ref. 3 (or in approximately this manner, in accordance with the behavior of the ratio $\bar{n}/I$). We accordingly set

$$-\Gamma_B = \varkappa_B [\bar{n}/I]\left(\frac{\partial T_e}{\partial r} + k_T T_e\right) . \tag{4}$$

Here $[\bar{n}/I]$ is the dimensionless number which we find if we express $\bar{n}$ in units of 10^{13} cm^{-3} and the current I in units of MA. The dimensionality of the parameter κ_B is that of a thermal conductivity. To preserve the global behavior, we set $\kappa_B = \alpha\kappa_e^{\text{T-11}}(a_T/2)$, where α is a constant on the order of unity. The term $k_T T_e$ in (4) represents a thermal pinch. With $T_e(r) = T_e^0(r)$ and $\Gamma_B = 0$, we have $\kappa_{\text{eff}} = \kappa_A$. If the expression in parentheses in (4) is positive in some region, i.e., if the thermal pinch prevails here, then we have $\kappa_{\text{eff}} < \kappa_A$, and the electron energy confinement is improved in this region.

The dashed line in Fig. 1 shows results calculated from model (1)–(4); here $\alpha = 1$, and $a_T = a/\sqrt{q_a}$. Figure 2 shows profiles of $\kappa_{\text{eff}}(r)$ for the two pulses under

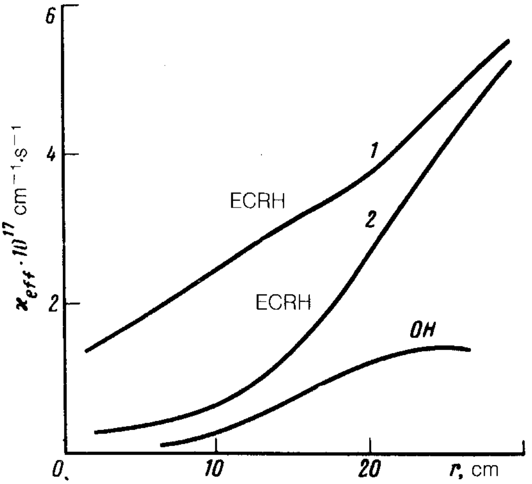

FIG. 2. Effective electron thermal conductivity for the heating regimes shown in Fig. 1.

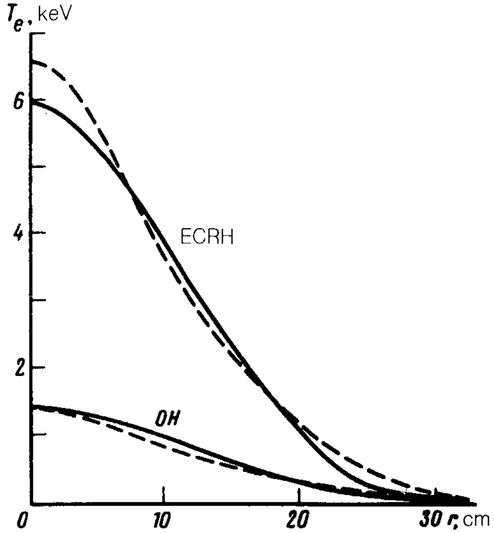

FIG. 3. Comparison of the results of the simulation (dashed lines) with experimental profiles of $T_e(r)$ in a regime with a high ECR heating power (solid lines) ($P = 1.9$ MW).

consideration. In the central part of the plasma column, the values of κ_{eff} differ by a factor of nearly four in the cases of relatively similar profiles $T_e(r)$. This "self-adjustment" of the model, which reflects the actual self-organization of the plasma, occurs because of the incorporation of effects associated with the canonical profile $T_e(r)$. A corresponding result is obtained when the behavior of $T_e(r)$ is tied to the canonical profile of the pressure.

To test this model, we carried out calculations at a high heating power, $P = 1.9$ MW; these results are shown in Fig. 3 (for pulse No. 45750). In this pulse, the ECR zones for the two groups of seven and three gyrotrons were positioned nearly symmetrically with respect to the center of the plasma column. The discharge current was the same ($I = 200$ kA), and the average density at the end of the heating pulse was $\bar{n} = 2.4 \times 10^{13}$ cm^{-3}. It can be concluded from these results that the model proposed here gives a completely satisfactory description of the results of ECRH experiments at the T-10 tokamak over broad ranges of both the heating power and the profile of this power.

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[1] V. V. Alikaev, A. A. Bagdasarov, N. L. Vasin *et al.*, Fiz. Plazmy **13**, 3 (1987) [Sov. J. Plasma Phys. **13**, 1 (1987)].
[2] V. V. Alikaev *et al.*, in Proceedings of the Eleventh International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Kyoto, 1986, IAEA-CN-47/A-II-4, 1986.
[3] Yu. V. Esipchuk and B. B. Kadomtsev, Pis'ma Zh. Eksp. Teor. Fiz. **43**, 573 (1986) [JETP Lett. **43**, 740 (1986)].
[4] N. L. Vasin, Yu. V. Esipchuk, K. A. Razumova, and V. V. Sannikov, Fiz. Plazmy **13**, 109 (1987) [Sov. J. Plasma Phys. **13**, 63 (1987)].
[5] Yu. N. Dnestrovskiĭ and D. P. Kostomarov, Matematicheskoe modelirovanie plasmy (Mathematical Modeling of Plasmas), Nauka, Moscow, 1982.

Translated by Dave Parsons