ISSN 0915-633X

NATIONAL INSTITUTE FOR FUSION SCIENCE

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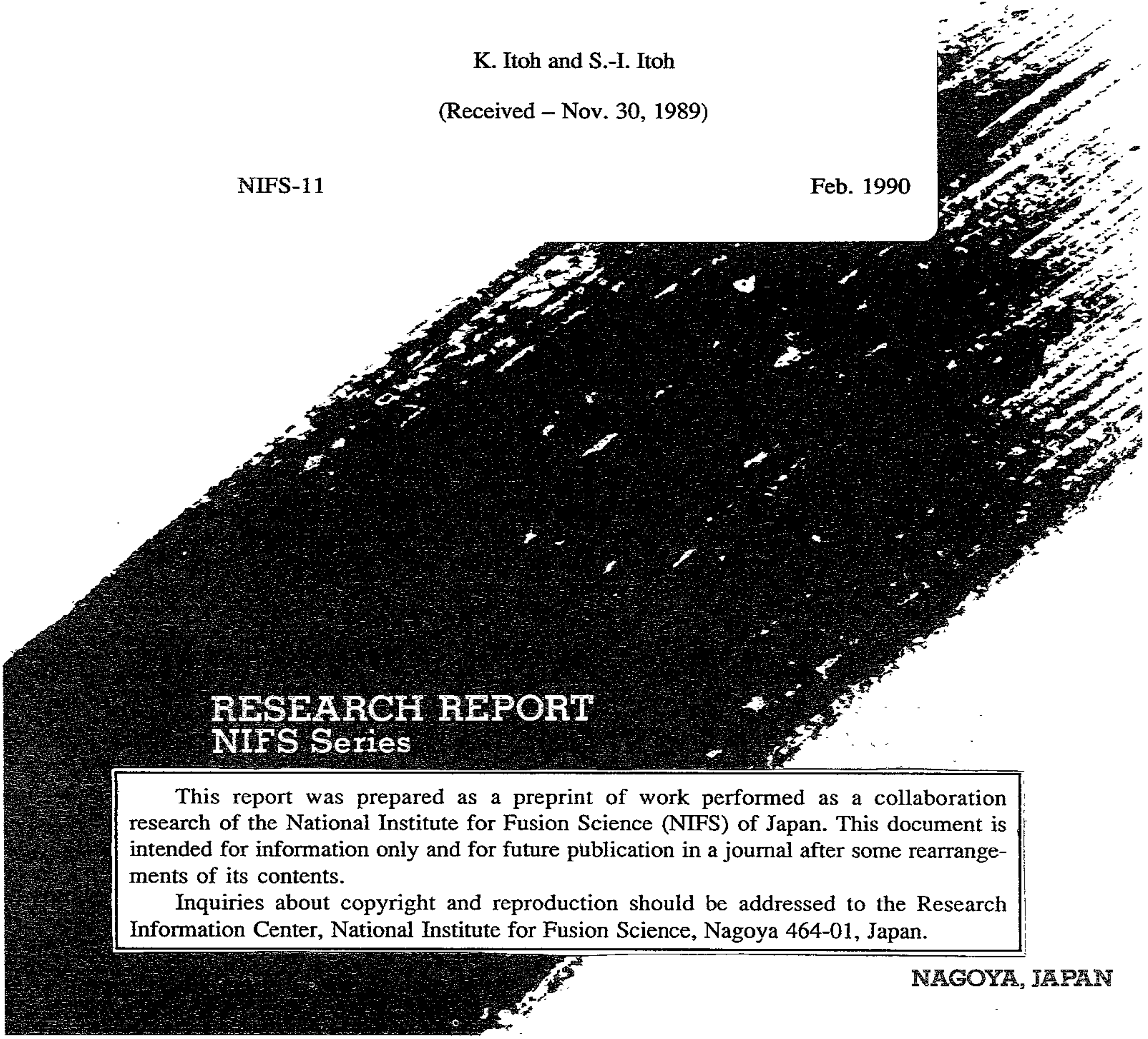
(Received – Nov. 30, 1989)

NIFS-11 Feb. 1990



RESEARCH REPORT
NIFS Series

NAGOYA, JAPAN

Effect of Confinement of SoL Plasma on Core Temperature Profile

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Abstract

The dependence of the core confinement on the edge plasma parameter is discussed in L-mode tokamaks. Employing the result of the transport analysis in the scrape-off layer, the boundary condition for the transport in the core plasma is expressed in terms of the heating power. Various forms of the dependences of the local thermal conductivity on the temperature and temperature gradient are examined. The power dependence of the edge temperature is found to be an origin of that the profile resiliency holds in a wide range of the heating power in L-mode tokamaks.

Keywords: temperature profile, boundary condition, scrape-off layer

The importance of the edge plasmas for the core confinement has been widely recognized. One of the most striking is the appearance of the H-mode, which is characterized by the establishment of the transport barrier at the edge$^{1)}$. The other improved modes of tokamak discharge, such as Supershot^{2}, Improved Divertor Confinement (IDC)$^{3)}$, Improved Ohmic Confienemnt (IOC)$^{4)}$ and Improved L-mode (IL)$^{5)}$, are also associated with the particular care about the scrape-off layer (SoL) plasma in experiments. The modellings of the H-mode$^{6-8)}$ and IOC$^{9)}$ has shown the important roles of edge plasma parameters including neutral particles for the appearance of these improved confinement modes.

The edge parameters are also important for the L-mode plasma itself. One particlular aspect of the L-mode is the deterioration of the energy confinement time τ_E by the increment of the heating power$^{10)}$. The deterioration of τ_E with respect to the heating power can be explained by the temperature dependence of the thermal conductivity. However, the offset-linear fitting of τ_E has also been proposed$^{11)}$, which implies that the temperature dependence of the thermal conductivity is not enough to understand the core plasma transport. The thermal conductivity may also depend on the gradient scale length of the temperature. The other character of the L-mode is the fact that the electron temperature profile is resilient to a class under the various heating power. This has been partly understood by the model that the electron thermal conductivity is an increasing function of the minor radiuse$^{12,13)}$. The comparison of the experimentally observed profile with theoretical model has not been satisfactory.

In this article, we investigate an impact of the edge plasma parameter on the core plasma parameters. We find that the weak dependence of the edge temperature on the heating power is one of the origins of the L-mode scaling.

Let us take the model of the energy balance equation as

$$\frac{1}{r}\frac{\partial}{\partial r} r\kappa \frac{\partial}{\partial r} T + P = 0, \tag{1}$$

where r is the minor radius, P is the heating power and κ is the thermal diffusivity. We take the model of the thermal conductivity κ as

$$\kappa = \kappa_0 \left(\frac{T}{T_1}\right)^{\alpha} \left|\frac{a\nabla T}{T}\right|^{\beta}, \tag{2}$$

where α and β are numerical constant, a is the minor radius, and T_1 is a typical temperature of the core. The coefficient κ_0 may have a dependence on the parameter such as the magnetic field. In order to focus on the temperature dependence and to keep the analytic insight, we assume that κ_0 is constant over the plasma column. The energy balance equation can be written in the dimensionless form as

$$\frac{1}{x}\frac{d}{dx} x\kappa_0 \hat{T}^{\alpha-\beta}\left|\frac{d\hat{T}}{dx}\right|^{\beta+1} = -\frac{a^2}{T_1} P_0 h(x), \tag{3}$$

where $x=r/a$, $\hat{T}=T/T_1$, and the heating profile $P(r)$ is given as $P(r)=P_0h(r)$. This equation is integrated as

$$\hat{T}(x) = \left\{ \hat{T}(1)^{\frac{1+\alpha}{1+\beta}} + \frac{1+\alpha}{1+\beta}\bar{P}_0^{\frac{1}{1+\beta}} \int_x^1 dx H^{\frac{1}{1+\beta}} \right\}^{\frac{1+\beta}{1+\alpha}} \qquad (4)$$

where

$$\bar{P}_0 = \frac{a^2 P_0}{\kappa_0 T_1}, \qquad (5)$$

$$H(r) = \frac{1}{x}\int_0^x x dx\ h(x). \qquad (6)$$

This result shows that the positive value of α is one origin of the power degradation of the confinement. In the large power limit, $P_0 \to \infty$, the plasma temperature scales as $P^{1/(1+\alpha)}$, and the confinement time scales as $P^{-\alpha/(1+\alpha)}$. This nature holds, however, in the asymptotic limit. The range of the heating power, in which this scaling holds, depends on the boundary condition T(a). The power depndence of T(a) is necessary to be known. To show this fact more clearly, we choose the model of h(r)=1, which corresponds to the case of a broad heating profile. In this case, the temeprature profile is given as

$$\hat{T}(x) = \hat{T}(1)\left[1+ \frac{1+\alpha}{2+\beta}\{P_0\hat{T}(1)^{-1-\alpha}\}^{\frac{1}{1+\beta}}\{1-x^{\frac{2+\beta}{1+\beta}}\}\right]^{\frac{1+\beta}{1+\alpha}}. \qquad (7)$$

This result shows that the sensitivity of the temperature profile on the heating power depends on the P dependence of T(a).

We have performed the analysis on the plasma transport in the SoL regime by employing time-dependent and two-dimensional transport code(14). The transport coefficient in the SoL regime is assumed to be classical (parallel) and Bohm-like (perpendicular). The plasma profile in SoL is solved by specifying the heat and particle flow from the core plasma, P_{out} and Γ_{out}, respectively. The boundary conditions on the plasma-material interface (i.e., divertor plasma) are given by the Bohm sheath criterion. The motion of neutral particles is sloved by the Monte-Carlo technique. The precise description of the numerical computation and comparison with analytic study is given in Refs.(14-15).

The temperature at the boundary of the core plasma was found to scale as[15)]

$$T(a) \propto P_{out}^{1/2} \, \Gamma_{out}^{-1/4} \quad . \tag{8}$$

The particle confinement time τ_p, which satisfies the relation $\Gamma_{out}=V_p n/\tau_p$, ($V_p$ is the plasma volume and n is the average density,) has also power dependence. Assuming that

$$\tau_p \propto P^{-\gamma} \tag{9}$$

we have

$$T(a) \propto P^{1/2-\gamma/4} \quad . \tag{10}$$

From Eq.(10), we see that the power dependence of $T(a)^{(1+\alpha)}$ is close to P^1 if α is of the order of unity. This condition is independent of β. From Eq.(7), the ratio of T(0) to T(a) is given as

$$\frac{T(0)}{T(a)} = \left[1 + \frac{1+\alpha}{2+\beta} \{P_0 \hat{T}(1)^{-1-\alpha}\}^{\frac{1}{1+\beta}} \right]^{\frac{1+\beta}{1+\alpha}} \tag{11}$$

and is a weak function of the heating power, except the case of β $=-1$. (The situation of $\beta=-1$is physically irrelevant.)

This can be seen from the present experimental results more clearly. Let us take the value of $\gamma=0.5$ after the experiments[16]. For instance, for the case of $\alpha=3/2$, which corresponds to the model of the trapped particle drift turbulence[17], $T(a)^{(1+\alpha)}$ scales as $P^{15/16}$. Since the power dependences of two terms in the right hand side of Eq.(7) is close to each other, the temperature profile keeps a similar shape for the wide range of the plasma profile. Namely, in Eq.(11), the second term in the bracket of the right hand side is proportional to $P^{1/16}$ ($\beta=0$) and is almost independent of the heating power. If β is positive, the index become smaller than 1/16. This means that the shape of the plasma temperature has only weak dependence on the absolute value of the heating power. This fact is attributed to the "weak profile consistensy" in experiments. The asymptocic nature such as $T\propto P^{0.4}$ holds for the wide range of the experimental parameters.

Let us compare this result with the model including the critical temperature gradient. This kind model assumes such that the thermal transport becomes very large if $|a\nabla T/T|$ exceeds a critical value. This may be a physics base of the "profile consistency Ansatz" in terms of a local transport coefficient. In the beginning of the proposal of this Ansatz, the profile consistency has been largely discussed in relation with the MHD activity in plasma associated with the current profile. However, under some condition, the microscopic picture can also predict such a nature of κ (e.g., for the class of η_i modes). We here discuss the role of the boundary condition in this situation without specifying the origin of the critical gradient.

Assume that the thermal conductivity becomes very large if the gradient scale exceeds the criterion, say $|a\nabla T/T| > f$. Then the profile is restricted to near by of the state

$$\frac{d}{dx} \ln \hat{T} = -f \tag{12}$$

if the heating power is strong in Eq.(1). This equation is rewritten as

$$T(r) = T(a)\exp\{\int_r^a f\, dx\} . \tag{13}$$

The absolute value of the temperature is determined by the boundary value, because the shape of the profile is fixed to the specific form. In this limit, i.e., thermal conductivity has a stiff dependence on the gradient, the edge plasma temperature determines the global energy confinement time itself. We notice that this result is obtained by taking the limit of $\beta \to \infty$ of Eq.(4) and replacing a by a/f in Eq.(2). The profile resiliency holds in the presence of the critical temperature gradient. However, as is shown in Eq.(11), the sensitivity of the profile to the heating power is weak even in the case of much smaller value of β.

In summary, we studied the effect of the edge plasma temperature on the global confinement time as well as on the temperature profile. We choose two different models of the transport coefficient. One has a moderate dependences on temperature and temperature gradient, Eq.(2). The power dependence of the edge plasma temperature is taken into account. It is found that this power dependence causes the result that the profile similarity holds over a wide range of heating power. The other model of κ is assumed to have a very stiff dependence of κ on the gradient. In such a limit, the shape is determined by the critical gradient length independently of the edge parameter; the absolute value of T is solely dictated by the edge plasma temperature. In either case, the dependence of T(a) on the heating power is close to that of the core temperature, T(0).

It is noted that the off-set linear scaling is not derived by this kind of consideration. For the first model of κ, T(0) and T(a) depend on the similar power law. The second model of κ, i.e., that with the critical temperature gradient, is often referred to the offest linear scaling. This is because the confinement characteristics is expected to change at the power level where $|a\nabla T/T|$ first approaches to the critical value f. However, Eqs.(10) and (13) indicate that the asymptotic dependence of temperature on heating power, P, shows a fractional power. Internal energy does not increase linearly with P, provided that the density is fixed. Therefore, if the off-set linear scaling is a better expression of the experimental results, the consideration on the other mechanism (e.g., fast particle effects and so on[18]) would be necessary to explain it. The investigation of the edge condition and comparison with experiments are as important as those for the core transport itself, and requires further research.

Authors acknowledge discussion with Dr. N. Ueda on numerical simulation of the SoL/divertor plasma. This work is partly supported by the Grant-in-Aid for Fusion Research of MoE Japan.

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