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Heat Deposition on the Partial Limiter

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Abstract

The effect of the partial limiter in the outermost magnetic surface of toroidal plasmas is studied. The power deposition on the partial limiter and its effect on the temperature profile are analysed. Interpretation in terms of the perpendicular heat conductivity is also discussed.

keywords; edge plasma, limiter, heat deposition, cross field diffusion

Recently the study on the role of edge plasma for the global confinement has attracted attentions. The nature of the thermal conductivity near edge has been investigated on various devices. One of the experimental investigation is the application of the partial limiter. Intruding a partial limiter into the inside of the outermost magnetic surface, the heat deposition on it and its effect on the temperature profile are studied in the tokamak[1] and stellarators(helical systems)[2,3]. Employing the two dimensional transport analysis, we derive an analytical formula for the effect of the partial limiter. The interpretation of the result in terms of the edge thermal conductivity is also discussed.

We take a simple model of the partial limiter presented in Fig.1. The width of the projection of the limiter head on the magnetic surface, which is measured across the magnetic field, is denoted by d. The limiter is intruded to the distance h measured from the outermost magnetic surface. The outermost magnetic surface is determined by either the separatrix or fixed limiter with much larger area. The head of the limiter is assumed to be flat and coinside with magnetic surfaces. In the following we assume that the gyroradius is much smaller than d. The depth of the limiter is assumed to be much smaller than the minor radius, and we employ the slab geometry in the transport analysis. The x-axis is taken in the direction of the minor radius as x=a-r, where a is the minor radius of the outermost magnetic surface.

The heat flux onto the limiter is given by

$$P_{\|}(lim) = \int_0^h dx\ q_{\|} d \tag{1}$$

where $q_{\parallel}$ is the heat flux density along the magnetic field. Since we are working on the edge plasma, we assume that the parallel conductivity is given by the classical value in the collisional limit as[4]

$$q_{\|} = -\kappa_{\|} \nabla_{\|} T, \qquad \kappa_{\|} = \kappa_{\|0} T^{\frac{5}{2}} \tag{2}$$

where T is the electron temperature and $\kappa_{\parallel 0}$ is a numerical constant. Integrating the temperature along the field line, we obtain the temperature profile on the magnetic surface

$$T^{\frac{7}{2}} - T^{\frac{7}{2}}(on \ \ limiter) = \frac{7}{2\kappa_{\|0}} q_{\|} \ell. \tag{3}$$

where ℓ is the distance from the partial limiter along the field line. It is noted that the temperature gradient is localized on the flux tube near the limiter, so that the averaged temperature on the surface is approximated by the asymptotic value in the limit $\ell = S/2d$, where S is the area of the magnetic surface ($S = 4\pi^2 aR$, R is the major radius), as

$$T \simeq \left(\frac{7 S q_{\|}}{4 \kappa_{\|0} d} \right)^{\frac{2}{7}}. \tag{4}$$

The perpendicular heat flux to the outermost magnetic surface $P_\perp$, which is deposited on the fixed limiter (or going out of the separatrix) is given as

$$P_{\perp} = S \kappa_{\perp} \frac{\partial T}{\partial x}. \tag{5}$$

In deriving Eq.(5), we assume that ion and electron temperatures are close to each other. We also assume that the heating power is deposited near the axis of the plasma and not in the region of our interest. The radiation loss is neglected in order to keep the clarity of the argument. (The introduction of the radiation loss can be done by straightforward extension.) The total energy balance gives

$$S\frac{\partial}{\partial x}\kappa_{\perp}\frac{\partial T}{\partial x} = \frac{d^2}{S}\frac{4}{7}\kappa_{\|0}T^{\frac{7}{2}}. \tag{6}$$

The energy conservation relation, $P_{\perp}+P_{\parallel}=P_0$, is satisfied, where P_0 is the total heat transfer from core plasma to the magnetic surface defined by the partial limiter, r=a-h.

From Eq.(6), the temperature on the surface r=a-h, T(lim), and the heat flux to the limiter, $P(\mathrm{lim})=P_{\parallel}$, are solved. In principle, the perpendicular diffusivity can be affected by the introduction of the partial limiter. This effect has been observed, for instance, in the internal ring devices[5] through the formation of the convective cells. We here simply neglect this kind of process. The thermal conductivity may depend on the plasma temperature; hence the change of the temperature due to the partial limiter can change the transport coefficient. This influence is taken into account in this article.

At first, we neglect the temperature dependence of $\kappa_{\perp}$ in order to have the insight. The equations (3)-(6) have characteristic values for the distance h and temperature T(lim) as

$$h_* = S\kappa_{\perp}^{\frac{7}{9}}\left[\frac{7}{4\kappa_{\|0}d^2}\right]^{\frac{2}{9}} P_0^{-\frac{5}{9}} \tag{7}$$

and

$$T_* = \left[\frac{7P_0^2}{4\kappa_{\|0}\kappa_\perp d^2}\right]^{\frac{2}{9}}. \tag{8}$$

Normalizing T(x) to T_* and x to h_*, Eq.(6) can be rewritten as

$$\frac{d^2}{dy^2}\hat{T} = \hat{T}^{\frac{7}{2}} \qquad (y = x/h_*,\ \hat{T} = T/T_*). \tag{9}$$

The fraction of the energy to the wall and partial limiter is given as

$$P(lim) = P_0 - P(wall) \tag{10}$$

$$P(wall) = \left[\frac{d}{dy}\hat{T}(x=0)\right] P_0. \tag{11}$$

Equation (9) is solved with the boundary conditions

$$dT/dy=1 \qquad \text{at } y=h, \tag{12}$$

and

$$T(0)=0 \qquad \text{at } y=0. \tag{13}$$

Figure 2 illustrates the normalized temperature at the limiter head and the partition of the power to the partial limiter and wall. At the distance $h=h_*$, the partial limiter has substantial influence on the temperature profile and power deposition.

The critical depth h_* depends on plasma parameter as well as on geometrical parameters. It is noted that it depends on the cross field transport coefficient $\kappa_\perp$ as $\kappa_\perp^{7/9}$. As the diffusivity increases, the critical depth increases. In order to compare this dependence, the T-dependence of $\kappa_\perp$ must be retained. Writing the T-dependence in the power law,

$$\kappa_\perp = \kappa_A T^{\frac{\alpha}{2}} \tag{14}$$

where κ_A is a numerical constant, we find that h_* scales as

$$h_* = S\kappa_A^{\frac{7}{9+\alpha}} \left[\frac{7}{4\kappa_{\|0} d^2}\right]^{\frac{2+\alpha}{9+\alpha}} P_0^{\frac{\alpha-5}{9+\alpha}}. \tag{15}$$

The h-dependence of P(lim) also provides the key to know $\kappa_\perp$. In the small limit of h, we have

$$P(lim) \sim \kappa_{\|0} d^2 \left(\frac{h}{S}\right)^{\frac{9+\alpha}{2+\alpha}} \left(\frac{P_0}{\kappa_A}\right)^{\frac{7}{2+\alpha}}. \tag{16}$$

By studying the h-dependence of P(lim), the temperature dependence of the thermal conductivity can be studied. It is also noted that in such study to estimate α, the P_0 dependence of P(lim) must be consistent with the use of the same value of α.

In summary, we derived an analytic formula to estimate the effect of the partial limiter on the temperature profile and power flow near the edge. The critical depth, which depends on the conductivity as well as on the geometry of the limiter, was found. Beyond this distance, $h>h_*$, the intrusion of the partial limiter affects the flow of the energy and the temperature profile. This distance depends on the cross field transport coefficient. If $\kappa_\perp$ becomes large, h_* increases. In the experiments on stellarators(helical systems), the effect of the partial limiter is known to be small. This implies that the cross field diffusivity is large in the region of investigation. This, however, does not directly mean that the closed magnetic surfaces disappear and that the field lines are connected to the wall. Either the diffusion due to the magnetic braiding or those caused by the electromagnetic fluctuations can enhance the cross field transport and hence reduce the effect of the partial limiter. The careful analysis on the partial limiter experiments, as illustrated in this article, would provide a touch stone to study the anomalous transport near the edge.

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Figure Captions

Fig.1 Schematic geometry of the analysis. Poloidal cross section (a), and magnetic surface on the limiter head (b).

Fig.2 Normalized depth of the limiter head and the temperature on the magnetic surface at limiter head (a). The partition of the power to the partial limiter, P(lim), and that to the wall, P(wall), are shown in (b).

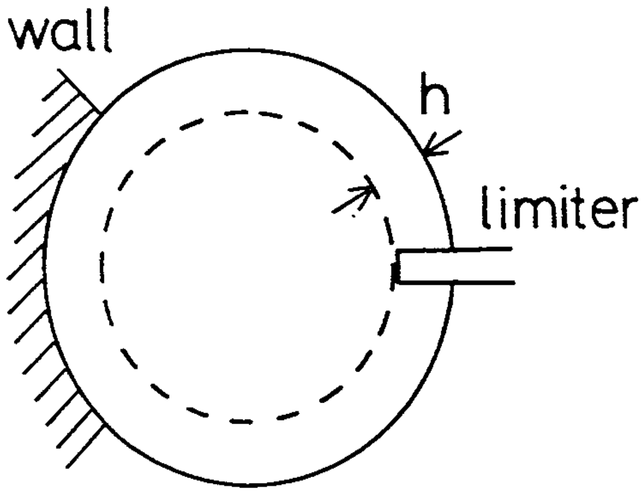


Fig. 1(a)

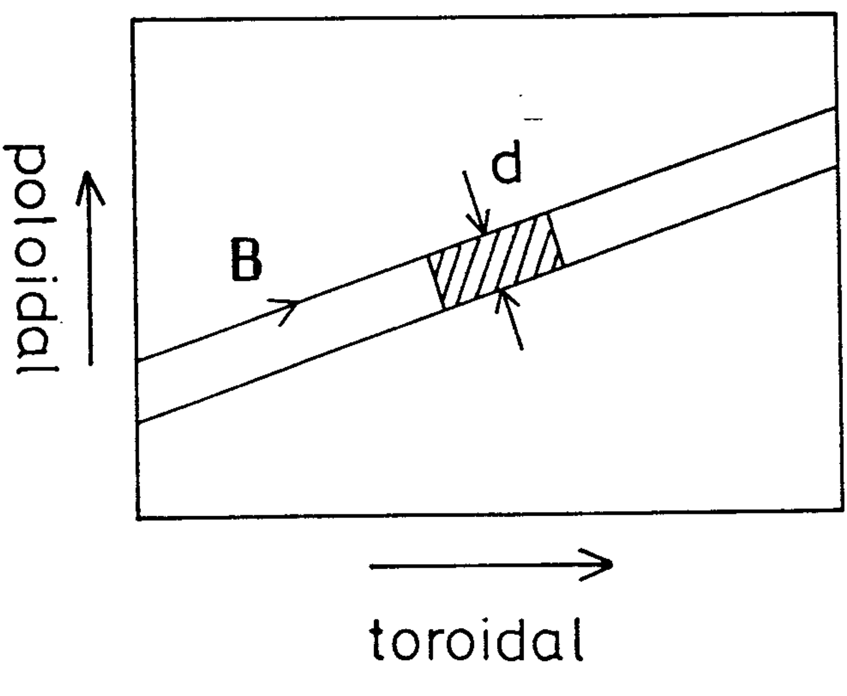
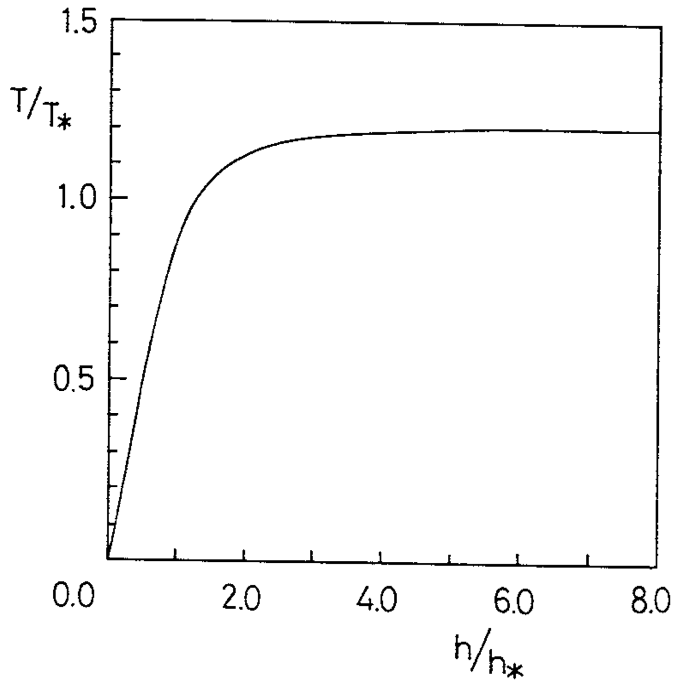


Fig. 1(b)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T/T*
1.0
0.5
0.0
2.0
4.0
6.0
8.0
h/h*

Fig. 2(a)

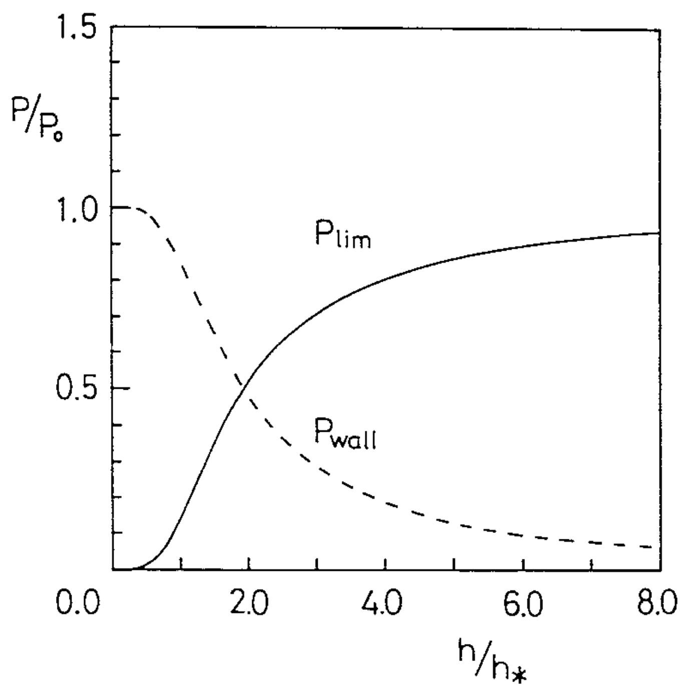
1.5
P/P₀
1.0
0.5
0.0
2.0
4.0
6.0
8.0
h/h*
Plim
Pwall

Fig. 2(b)