A Phenomenological Model for H-Mode

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Abstract

A phenomenological model has been developed to clarify the role of the boundary configuration in the heat transport of the H-mode regime. We assume that the dominant mechanism of heat loss at the edge of the plasma is convection and that the diffusion coefficient (D_{edge}) at the edge of the plasma increases rapidly with plasma pressure, but drops to a low value when the temperature exceeds a certain threshold value. When particle refueling takes place without time delay, as in the case of a limiter discharge, the unfavorable temperature dependence of the D_{edge} prohibits even a modest rise of the edge temperature. In a divertor discharge, the particles lost from the closed surface are kept away from the edge region for a time comparable to or longer than the energy transport time in the edge region. Thus, rapid increase in the heat flux allows an excursion of the edge temperature to a higher value thereby reaching the threshold value of the H-transition.

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1. Introduction

It has been observed that global energy confinement (τ_E) decreases with increasing auxiliary input power in the normal limiter discharges[1] (L-mode). Recently, such a deterioration in τ_E has been significantly ameliorated in the so-called "H-mode" discharge of a poloidal divertor configuration.[2-4] However, the H-mode mechanism and the role of the boundary configuration in it have not been well understood even though there have been several attempts[5-8] to model the H-mode. In this note, we suggest a phenomenological model of the H-mode, particularly the role of the boundary configuration. The main objective of such a model is to suggest new experimental directions or approaches as well as to stimulate theoretical modeling.

2. A Phenomenological H-mode Model

Figure 1 uses ASDEX data to show edge temperature as a function of beam power for both divertor and limiter discharges. For the limiter discharge the increase in edge temperature is very modest, approximately $T_{edge} \propto P^{\alpha}$ with $\alpha <$ 1/5. The deterioration of τ_E in the edge region is much worse than that in the whole plasma region since the total stored energy scales as $P^{\sim 1/2}$. It appears that the low edge temperature "drags" down the core temperatures. In the divertor discharge, especially after the H-transition, a significantly high edge temperature was observed. As discussed in Ref. 9, high edge temperature seems to trigger formation of the H-mode discharge. (In the H-mode discharge, improvement in τ_E is mainly attributed to reduction of the thermal conductivity in the whole plasma.) Therefore, it is important to understand the difference in edge heat transport among discharges with various boundary configurations.

2.1 Assumptions of the Model

From the data in Fig. 1, one may simply conclude that edge thermal conductivity, the diffusion coefficient, or both increase rapidly with temperature and decrease to a lower value when the temperature exceeds a threshold value, as illustrated in Fig. 2. Since the recycling pattern appears to play an important role in the H-mode mechanism, we assume that convection is the dominant loss mechanism in the edge region during the L-phase (the pretransition phase).

$$Q = - 5TD_{edge} \nabla n \qquad (1)$$

where Q and D_{edge} are the heat flux and the diffusion coefficient at the edge, respectively. Here we define the edge region as a region within a few hydrogen mean paths from the outermost closed surface. Since τ_E in the limiter discharge is independent of $\bar{n}$ with fixed power, τ_E may be a function of the average plasma pressure ($\bar{n}\bar{T}$). Therefore, it is reasonable to assume that D_{edge} increases rapidly with nT_{edge} and drops to a lower value when the temperature exceeds a threshold value.

Such a special transport, however, must come from a property inherent in the edge. Otherwise, the high temperature gradient (pedestal) observed at the edge of the H-mode discharge should exist in the inner, high temperature region where almost no recycling takes place. Possible inherent edge properties are ones associated with the separatrix, such as high shear near the last closed surface and the special transport mechanism near the X-point.[6] If the observed improvement of τ_E in the scoop limiter (PDX)[10] and Ne injection (Z-mode ISXB)[11] experiments are modified manifestations of the H-mode regime, the above edge properties are not key ingredients in the H-mode mechanism.

The other conceivable edge property, which may be responsible for the assumed transport is the high density gradient at the edge. In a high density tokamak discharge, the density profile is nearly flat in the core region and a steep gradient exists at the edge where particle recycling takes place. This assumption is consistent with the fact that the H-mode does not exist in low density discharges, in which both ∇n and $\nabla \ln n$ are low due to deeper penetration of the recycled neutral hydrogen. It has been argued[11] that a higher density gradient caused by Ne impurity recycling may be responsible for the improvement in τ_E and τ_p on ISX-B (Z-mode) since the kinetic ballooning mode theory[12] predicts that two energy confinement regimes with different temperature scalings exist, depending on a plasma parameter proportional to ∇n. The line tying effect is also a possible edge property which may affect the edge transport. As discussed in Ref. 5, the line tying effect may appear in the scrape-off layer, which is connected to the wall through the field line when the temperature there exceeds a certain value. This may stabilize the instability that may be responsible for the edge transport. The effect may extend radially inwards by a radial wave length of the instability from the scrape-off layer.

2.2 Effect of the Boundary Configuration on the Edge Temperature

With the assumptions described in Sec. 2.1, we attempt to explain the significant effect of the boundary configuration on the edge temperature. In the limiter discharge, enhancement in D_{edge} due to increase in T_{edge} does not change ∇n or n because the particles lost to the limiter are ionized immediately. It enhances the particle flux (D_{edge} ∇n) and hence suppresses the edge temperature. If $D_{edge} \propto (nT)_{edge}^{\sim 4}$, it is consistent with the experimental data in Fig. 1. With such unfavorable T-dependence, doubling the temperature, for example, requires an impractical level of high power.

What makes the difference in the edge temperature between the divertor and limiter discharges? As far as steady-state edge heat and particle transports are concerned, there should be no significant difference whether the plasma is limited by the mechanical limiter or by the separatrix because particles recycle 100% effectively in both configurations. (If a fraction of the recycled particles are pumped to the wall or limiter surface, gas puff usually compensates for the loss to maintain the plasma density.) However, in a dynamical phase, there is a significant difference. With added beam power, the D_{edge} in Fig. 2 increases, but the particles which escape from the edge region to the divertor region do not return to the main plasma immediately because they temporarily are trapped in the divertor region. This time lag allows excursion of the edge temperature to a high value because enhancement in $D_{edge}\nabla n$ is relatively low due to a temporary lack of particle refueling. The excursion becomes large when this time lag becomes comparable to the edge energy transport time. The dynamically elevated temperature may trigger formation of the H-mode discharge, in which the transport coefficients are substantially low. The particles returning from the divertor region to the main plasma after the transition contribute to an increase in the density of the main plasma.

To explain our model more clearly, we use a simple set of heat and particle balance equations in the edge and divertor regions.

$$3\,\frac{dNT}{dt} = Q - \frac{5NT}{\tau_{edge}} \tag{2}$$

$$\frac{dN}{dt} = \frac{N_D}{\tau_D} - \frac{N\delta}{\tau_{edge}} + \frac{N_o - N}{\tau_m} \tag{3}$$

$$\frac{dN_D}{dt} = \frac{N\delta}{\tau_{edge}} - \frac{N_D}{\tau_D} \tag{4}$$

where N, N_D are the total numbers of the particles in the edge region of the main plasma and in the divertor, respectively, τ_{edge} and τ_D are the particle confinement times in the respective region, T and Q are the temperature and heat flux in the edge region, and δ is the divertor efficiency ($\delta \approx 1$ for a well-established divertor and $\delta \approx 0$ for the limiter configuration). The third term in Eq. (3) represents the particle flux from the core region. We assume that

$$\tau_{edge} = \tau_{edge}^{0} \left\{\frac{N_o T_o}{N\ T}\right\}^{\alpha} \tag{5}$$

where N_o, T_o are the initial values for N and T, i.e., N(t=o) and T(t=o), respectively. The range of α is consistent with the observations in $2<\alpha<5$. We use normalized quantities, defined as $\tilde{Q} = Q\tau_{edge}^{o}/(5\ N_oT_o)$, $\tilde{t} = t/\tau_{edge}^{o}$, $\tilde{N}_* = N_*/N_o$, and $\tilde{T}_* = T_*/T_o$. For $\tilde{t} < 0$, $\tilde{Q} = 1$, $\tilde{T} = 1$, and $\tilde{N} = 1$. At $\tilde{t} = 0$, $\tilde{Q}$ is raised instantly to a constant value. For $t > 0$, $\tilde{T}$ and $\tilde{N}$ evolve as shown in Fig. 3 ($\tilde{Q} = 3$ for $t > +0$, $\alpha = 4$, $\tau_m/\tau_{edge}^{o} = 2$). For $\delta = 0$ (i.e., the limiter case), the increase in $\tilde{T}$ is very modest. On the other hand, for $\delta = 1$ (i.e., the divertor case) and $\tau_D/\tau_{edge}^{o} = 2$, the maximum achievable temperature ($\tilde{T}_{max}$) is about a factor of two higher than that of the case with $\delta = 0$. Higher temperature in the case $\delta = 1$ is mainly due to a drop in the density in the edge region because of temporary trapping of lost particles in the divertor region. If the particle transport from the core to the edge, expressed by the third term in Eq. (3), is not high, the high ∇n (which may be a critical condition as discussed earlier) is still maintained even if the density in the edge region decreases. (The location of the high ∇n moves slightly inward radially.)

Figure 4 shows the maximum temperature ($\tilde{T}_{max}$) as a function of the input power [$\tilde{Q}$ (t > 0)] for various τ_D/τ_{edge}^{o} with fixed δ (= 1) and two different α. The case with $\tau_D/\tau_{edge}^{o} = 0.01$ also corresponds to the limiter case. If one assumes a threshold value of, e.g., $\tilde{T}_{max} = 2.5$ for the H-mode transition, our simple model becomes consistent with experimental observations. For the limiter discharge ($\tau_D/\tau_{edge}^{o} = 0.01$), the increase in the edge temperature with added input power is very small, far below the required value for the transition. On the other hand, in the case of the divertor discharge ($\tau_D/\tau_{edge}^{o} \gtrsim 0.5$), the edge temperature can exceed the threshold value. Our argument holds for a relatively wide range of the assumed value of α. Figure 5 shows dependence of the maximum temperature ($\tilde{T}_{max}$) on the divertor efficiency (δ) with $\alpha = 4$, $\tau_D/\tau_{edge}^{o} = 2.0$, and $\tilde{Q}$ (t > 0) = 3, 6. The maximum temperature ($\tilde{T}_{max}$) increases approximately linearly with δ. In Figs. 3, 4, and 5, we assume $\tau_m/\tau_{edge}^{o} = 2$, but the above argument still holds in the wide range of τ_m/τ_{edge}^{o} ($0.5 \lesssim \tau_m/\tau_{edge}^{o}$).

3. Discussion

Our simple model is consistent with various experimental observations, as described below.

3.1 Triggering the H-mode by Sawtooth Oscillations at Low Power

Experiments show that when input power is marginal, the H-transition is triggered by sawtooth oscillations. In our model, the rise of the edge temperature in the divertor configuration is due to the dynamical effect. If the input power is increased over a time scale much longer than τ_D, the difference between the configurations should disappear and the threshold temperature is not obtainable. However, in the tokamak discharge, the sawtooth oscillation causes a pulse of heat flow to the edge region, allowing an excursion of the temperature beyond the threshold value even if the input power into the discharge is raised very gradually. This may also be part of the reason why the H-mode was never obtained in the nonsawtoothing XB discharge of D-III.[3]

3.2 Dependence of the Power Threshold for the H-transition on the Divertor Configuration and Working Gas

A threshold value of the input power has been observed (typically ~ 2 MW, which is approximately 4-5 times the ohmic power for the 400 kA discharge in ASDEX, D-III, and PDX, and which corresponds to $\tilde{Q} \sim 4$ in our model). It has been observed that the threshold value depends on the divertor configuration and the working gas.[9] The threshold power depends on the value of τ_D/τ_{edge}^o, as shown in Fig. 4. The divertor configuration is parameterized by τ_D/τ_{edge}^o. The closed divertor has higher τ_D and hence higher τ_D/τ_{edge}^o, leading to a lower threshold value. It also has been argued that the compression ratio (P_{DIV}^o/P_{Main}^o) is a good experimental indicator of whether the H-mode regime is accessible.[4,13] (P_{DIV}^o and P_{Main}^o are the neutral pressures in the respective region.) Since $P_{DIV}^o \propto N_D$ and $P_{Main}^o \propto N_D/\tau_D$, the compression ratio is proportional to τ_D and thus τ_D/τ_{edge}^o. (Note that τ_{edge} depends on the edge plasma condition, independent of the boundary configuration.) Therefore, our model qualitatively explains the observed sensitivity of the compression ratio to the H-mode accessibility.

If τ_{edge}^{o} does not vary from the D^+ plasma to the H^+ plasma, τ_D/τ_{edge}^{o} for the H^+ plasma may be ~ 40% lower than that for the D^+ plasma because τ_D is expected to be proportional to the square root of the mass of the working gas. Thus, our model predicts a higher threshold value for the H^+ plasma if the divertor configuration is marginal. The ASDEX experiment[9] shows that the threshold value for the H^+ discharge is substantially higher than that for the D^+ discharge.

3.3 Differences Between ASDEX and D-III H-Modes

In the ASDEX,[2,9] the H-transition is very clear, accompanying a high pedestal in the temperature profile and a significant drop in the recycling signal. On other hand, the H-transition in the D-III XB configuration is modest and sometimes unclear.[3] This difference appears to be related to the substantial difference in τ_E between these devices. The τ_E in the ASDEX H-mode discharge, particularly during the quiescent phase between the "H_α-spike," is significantly higher than that in the D-III XB discharge. We believe that this difference in τ_E is not due to the small differences between the devices such as the plasma shape, the major radius, and the injection angle of the neutral beam, but may be due to the significant difference in the divertor configuration. In the ASDEX (a closed divertor), τ_D is approximately the ratio of the divertor volume to the conductance (from the divertor chamber to the main plasma region) and ~ 40 msec, quite long compared with τ_{edge} ~ 5 ~ 10 msec (~ a fraction of the τ_E). The higher value of τ_D is also independent of the edge plasma. On the other hand, in the expanded boundary of D-III, it is ~ 1 msec without the plasma plugging effect, which is too short for the H-transition. The τ_D is enhanced by the plugging of the recycled neutral with the divertor plasma. The plugging efficiency depends on the size of the divertor channel and the gap between the wall and the divertor channel. The plugging efficiency in D-III is estimated to be ~ 0.9 from the numerical calculation,[14] and thus τ_D is ~ 10 msec, which is long enough for the transition.

Even if τ_D is comparable to or longer than τ_{edge}, the improvement in τ_E in an open divertor such as the XB configuration may be limited as discussed below. Sudden significant improvement in the edge energy confinement after the H-transition, such as observed in ASDEX (clear H-transition) reduces the heat flow into the scrape-off layer by more than a factor of 10. This reduces the temperature of the divertor plasma and hence the plugging efficiency when the temperature goes below 10 eV. (Note that the ionization cross section of the neutral hydrogen becomes low when the electron temperature is below 10 eV.) For the XB configuration, which relies on plasma plugging to maintain high τ_D, sudden significant improvements in the edge energy confinement lead to rapid transfer of the particle from the divertor region to the main edge plasma and hence to a cooling of the edge plasma. Thus, a strong jump in the edge temperature after the transition may be limited by this mechanism resulting in a weak or unclear transition.

The effect of a sudden decrease in the heat flux on the divertor temperature can be estimated as follows. The heat flux to the divertor plate (Q_{plate}) is $Q_{plate} \propto n_w T_w{}^{3/2}$ where n_w and T_w are the density and temperature near the plate. Since $n_o T_o = n_w T_w$ where n_o and T_o are the density and temperature at the scrape-off layer of the main plasma, $Q_{plate} \propto (n_o T_o) T_w{}^{1/2}$. From the simple divertor theory,[15] in which the electron parallel thermal conduction is the dominant heat transport in the divertor region, T_o is insensitive to the plasma parameters, $T_o \propto Q^{2/7}$. Since particle density should be conserved even after the transition, n_o remains more or less unchanged. Therefore, $T_w \propto Q_{plate}^{10/7}$. If the heat flow ($Q_{plate}$) is reduced by even a small factor, T_w may go below 10 eV, resulting in a significant deterioration of the plugging efficiency.

3.4 Improved Energy and Particle Confinement in the Scoop-Limiter Experiment on PDX

In the scoop-limiter experiment on PDX, an improvement in energy and particle confinement has been reported.[10] It is also claimed that ~50% of the particle flux that escapes from the closed surface and enters the plenum of the scoop limiter, in which the particle can be kept a time that is substantially longer than τ_{edge}, corresponds to $\delta = 0.5$ in our model. Figure 5 shows the dependence of the peak edge temperature ($\tilde{T}_{max}$) on the divertor efficiency (δ) in our modeling. The transition may be possible, depending upon the assumed threshold value of the edge temperature.

3.5 Z-Mode (ISX-B)

It has been observed that a small amount of impurity injection (Ne) has improved τ_E and τ_p in an ISX-B neutral-beam-heated discharge. This may be a modified version of the H-mode discharge. In Ref. 11, it is argued that neon or oxygen neutrals can penetrate more deeply into the main plasma than can hydrogen neutrals. This results in a steep density gradient, which leads to a favorable transport.[12] This effect may be related to our model in the following way. ISX-B has no divertor configuration. However, recycled neon (neon ion plus 10 electrons) can be trapped in the main plasma region, just inside the edge region (because of its deep penetration) instead of outside the outermost closed surface. Note that we define the edge region as where hydrogen ionization takes place. The effective δ may be ~ 0.2 since

$Z_{eff} \sim 2$. This value of δ may be too small for the transition. Thus, it may require a special impurity transport in the edge region, i.e., fast neon transport in the edge regions relative to that of bulk ion transport in order to increase the value of δ. Our model predicts no improvement in τ_E when C and S_i impurities are used because the mean-free path of these impurities is shorter than that of hydrogen. This agrees with the experimental observations.[11]

4. Summary

Summarizing our phenomenological H-mode model, we assume that the dominant mechanism of heat loss at the edge of the plasma is convection. The diffusion coefficient (D_{edge}) at the edge of the plasma increases rapidly with plasma pressure, but drops to a low value when the temperature exceeds a certain threshold value. When particle refueling takes place without time delay, as in the case with a limiter discharge, the unfavorable temperature dependence of the D_{edge} prohibits even a modest rise of the edge temperature. In a divertor discharge, the particles lost from the closed surface are kept away from the edge region for a time comparable to or longer than the energy transport time in the edge region. Thus, rapid increase in the heat flux allows the excursion of the edge temperature to a higher value thereby reaching the threshold value of the H-transition.

Our simple phenomenological model is somewhat speculative and needs to be studied for justification. Obviously, the main uncertainty of the model is the assumption concerning transport, described in Sec. 2.1. Nonetheless, it clearly suggests some future experiments:

1. In order to obtain the highest transport τ_E, the divertor configuration must be a "closed" one where particle confinement in the divertor region must be sufficiently long compared with the edge transport time, and must primarily depend on the divertor geometry, not on plasma plugging. The expanded boundary type poloidal divertor, which relies on plasma plugging, has lower τ_E. However, its advantage is its ability to control impurities due to a lower sputtering rate associated with a high density, cold divertor plasma and better impurity shielding capability. Furthermore, it is a simpler divertor configuration, which is an important consideration for future designs. An optimal configuration may be the expanded boundary type divertor with a tight baffle.

2. Active divertor recycling control, particularly before the transition, may help to increase the edge temperature. By adjusting the puffing rate or by pumping the particles in the divertor region, the optimal H-mode condition may be found.

3. Our model does not exclude an H-mode discharge in the limiter configuration. One realistic approach may be to use a thin blade pump limiter with high δ for only a short period just before the transition. After the transition, the plasma may be moved into contact with the normal limiter which can handle the heat flow. The major concern here is the impurity contamination associated with high edge temperature and better impurity confinement.

4. In our model, the "ergodic" or "island" divertor[16-19] could create a good H-mode discharge because the heat and particle fluxes can be guided into a small chamber. It is also expected to have a good impurity shielding function, which is required to maintain the H-mode discharge in a steady state. Furthermore, the required coil current for the ergodic divertor is small, and the system is, therefore, relatively simple.

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Figure Captions

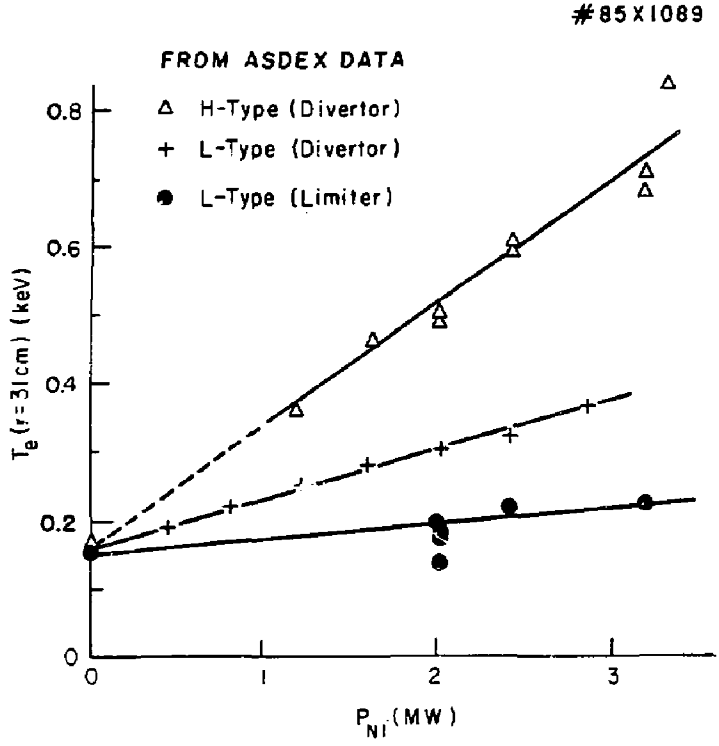
Fig. 1. Variation of edge electron temperature T_e with beam power P_{NI} in limiter, L- and H-type discharges (ASDEX). I_p = 380 kA; $\bar{n}_e = 3 \times 10^{13}$ cm^{-3} (H), $n_e < 2 \times 10^{13}$ cm^{-3} (L), and $n_e = 5 \times 10^{13}$ cm^{-3} (limiter). From Ref. 9.

Fig. 2. Temperature dependence of edge diffusion coefficient, which is consistent with the data in Fig. 1.

Fig. 3. Time evolution of edge temperature and density for both divertor ($\delta = 1$) and limiter ($\delta = 0$) configurations in our model. Power ($\tilde{Q}$) is raised instantly from $\tilde{Q} = 1$ to $\tilde{Q} = 3$ at $\tilde{t} = 0$. $\tau_D/\tau_{edge}^{o} = 2$, $\tau_m/\tau_{edge}^{o} = 2$, $\alpha = 4$.

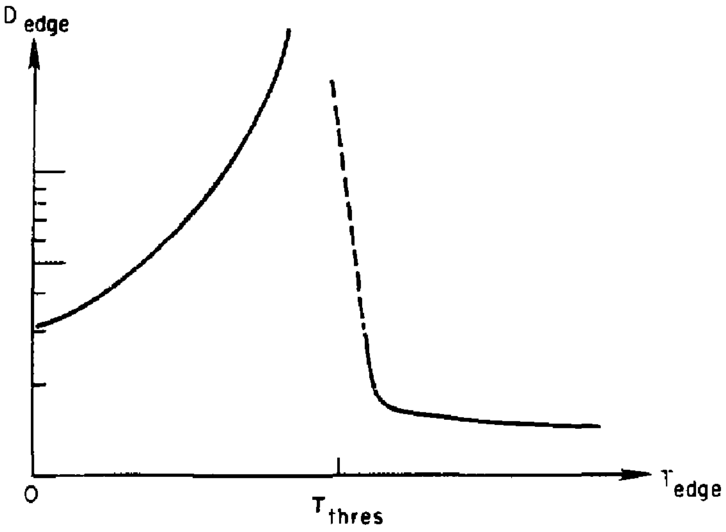
Fig. 4. The maximum temperature ($\tilde{T}_{max}$) as a function of power [$\tilde{Q}$ ($\tilde{t} > 0$)]. $\tilde{T}_{max}$ is defined in Fig. 3. $\tau_m/\tau_{edge}^{o} = 2$, $\delta = 1$.

Fig. 5. Dependence of divertor plugging efficiency (δ) on $\tilde{T}_{max}$. $\tau_D/\tau_{edge}^{o} = 2$, $\tau_m/\tau_{edge}^{o} = 2$, $\alpha = 4$.



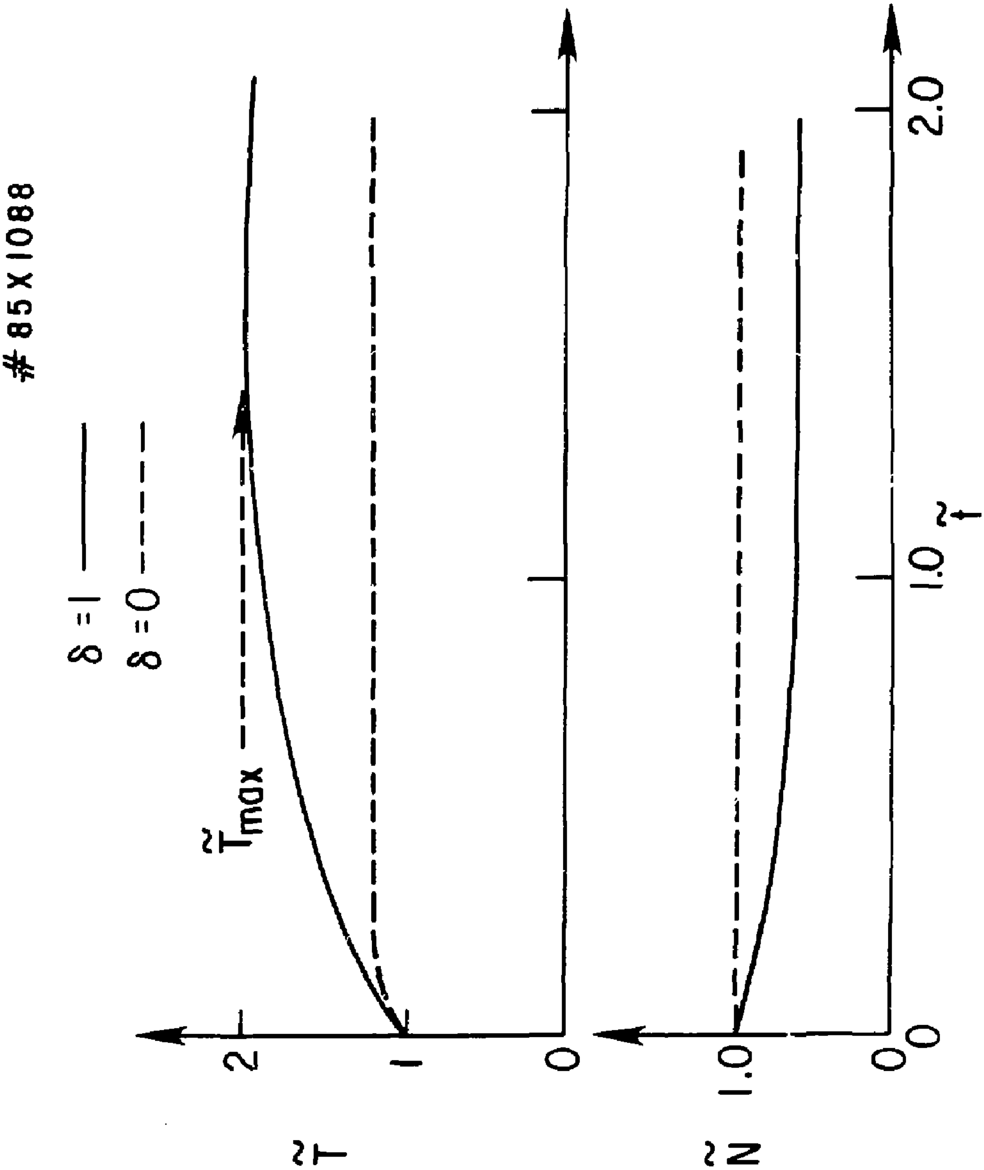
#85X1089
FROM ASDEX DATA
Δ H-Type (Divertor)
+ L-Type (Divertor)
● L-Type (Limiter)
T_e (r = 31 cm) (keV)
0.8
0.6
0.4
0.2
0
0
1
2
3
P_{NI} (MW)

Fig. 1



D_{edge}
0
T_{thres}
T_{edge}

Fig. 2



85X1088
$\delta = 1$
$\delta = 0$
$\tilde{T}_{max}$
$\tilde{T}$
2
1
0
$\tilde{N}$
1.0
0
0
1.0
2.0
$\tilde{t}$

Fig. 3

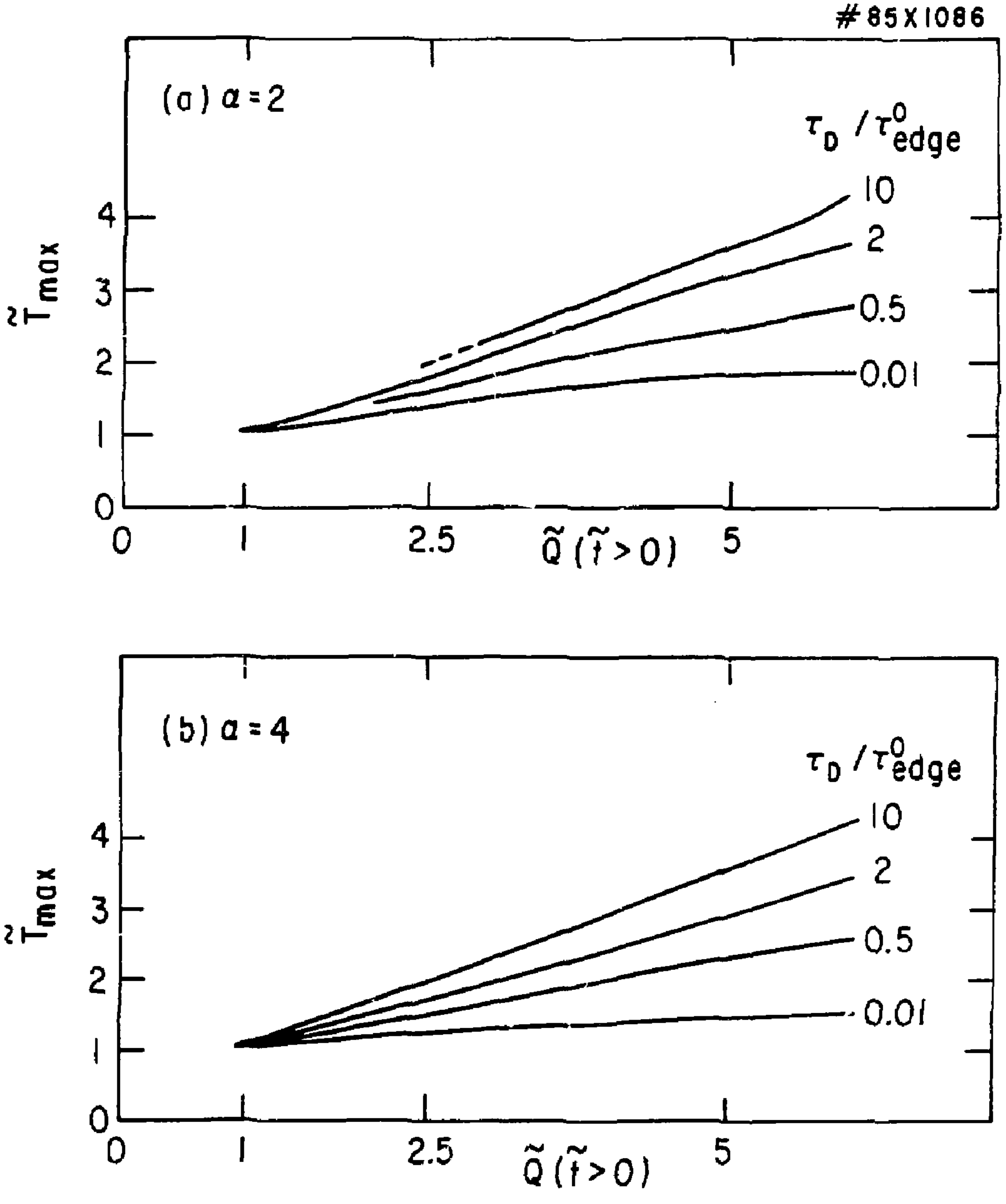
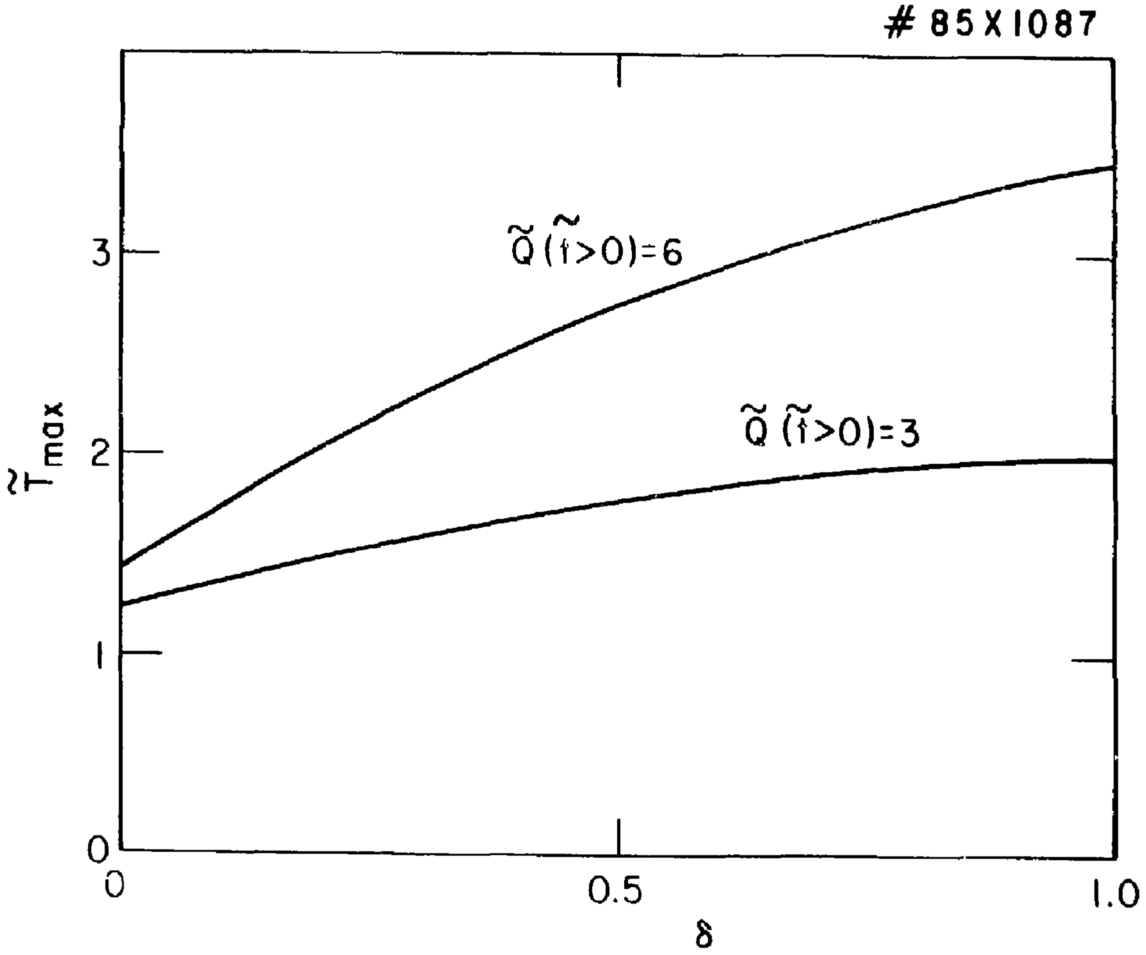

#85X1086
(a) α=2
τ_D / τ⁰_edge
10
2
0.5
0.01
T̃max
0
1
2
3
4
0
1
2.5
5
Q̃ (t̃>0)
(b) α=4
τ_D / τ⁰_edge
10
2
0.5
0.01
T̃max
0
1
2
3
4
0
1
2.5
5
Q̃ (t̃>0)

Fig. 4



85X1087
$\tilde{T}_{max}$
0
1
2
3
0
0.5
1.0
δ
$\tilde{Q}(\tilde{t}>0)=6$
$\tilde{Q}(\tilde{t}>0)=3$

Fig. 5

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