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H–MODE THRESHOLD POWER SCALING AND THE ∇B DRIFT EFFECT*

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One of the largest influences on the H–mode power threshold (P_{TH}) is the direction of the ion ∇B drift relative to the X–point location, where factors of 2–3 increase in P_{TH} are observed for the ion ∇B drift away from the X–point. It is proposed that the threshold power scaling observed in single-null configurations with the ion ∇B drift toward the X–point location (P_{TH} ~ nB, where n is the plasma density, and B is the toroidal field) is due to the scaling of the magnitude of the ∇B drift effect. Hinton [1] and later Hinton and Staebler [2] have modeled this effect as neoclassical cross field fluxes of both heat and particles driven by poloidal temperature gradients on the open field lines in the scrape-off layer (SOL). The ∇B drift effect influences the power threshold by affecting the edge conditions needed for the L–H transition. It is not essential for the L–H transition itself since transitions are observed with either direction of B. Predictions of this model include saturation of the B scaling of P_{TH} at high field, 1/B scaling of P_{TH} with reverse B, and no B scaling of P_{TH} in balanced double-null configurations. This last prediction is consistent with the observed scaling of P_{TH} in double-null plasmas in DIII–D [3].

Neoclassical cross field fluxes

In the model by Hinton and Staebler [2], the ∇B effect is attributed to neoclassical cross field fluxes of heat and particles driven by poloidal temperature gradients on the open field lines in the SOL. In cylindrical geometry, the radial fluxes are given by:

$$q_{er} = \frac{5}{2} n_e \frac{cTe}{eB^2} \frac{B_\varphi}{r} \frac{\partial T_e}{\partial \vartheta} + q_{er}^A \tag{1}$$

$$q_{ir} = -\frac{5}{2} n_i \frac{cT_i}{eB^2} \frac{B_\varphi}{r} \frac{\partial T_i}{\partial \vartheta} + q_{ir}^A \tag{2}$$

$$\Gamma_{er} = \Gamma_{ir} = \frac{c}{eB^2} \frac{B_\varphi}{r} \left(\frac{\partial P_e}{\partial \vartheta} - en_e \frac{\partial \Phi}{\partial \vartheta} \right) + \Gamma_r^A \tag{3}$$

where q_{er} is the radial electron heat flux, q_{ir} is the radial ion heat flux, Γ_r is the radial ambipolar particle flux, and q_{er}^A, q_{ir}^A, and Γ_r^A are the anomalous fluxes which represent all other transport processes which are not included in the Coulomb collision treatment. A diagram showing the direction of the gradients and fluxes is shown in Fig. 1. Integrating poloidally, they find that the ratio of the classical heat flux to the anomolous heat flux can be large, on the order of ~0.5 for typical scrape-off layer conditions. The direction of the poloidally integrated flux is radially inward when the ion ∇B drift direction is towards the X–point and outward when the ion ∇B drift direction is away from the X–point.

Following the work of Mahdavi *et al*. [4], we have developed a 1D heat conduction model to estimate the poloidal gradients of T_e and T_i in the SOL. These gradients are peaked near the X–point

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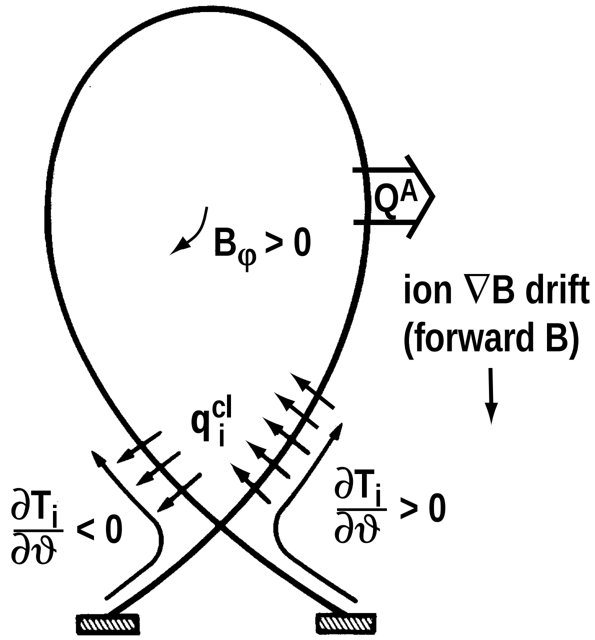

Fig. 1. Classical cross-field ion heat flux $\left(q_i^{cl}\right)$ for the ion grad-B drift towards the X–point. The anomalous energy flux (Q^A) is strongest on the outboard midplane.

region and $\partial T_i / \partial\vartheta \approx 2.5\ \partial T_e / \partial\vartheta$, consistent with experimental measurements of midplane temperatures of $T_e(0)$=80±20 eV, and $T_i(0)$=190±20 eV [5]. Assuming these gradients are the same for the inside and outside SOLs, the net cross field heat fluxes are given by the difference of 1/B on the inside and outside. Using the cylindrical approximation, this difference is given by

$$\left(\frac{B_o}{B_{out}} - \frac{B_o}{B_{in}}\right) = 2\varepsilon \sin\vartheta \tag{4}$$

where ε is the inverse aspect ratio.

Estimating the power flow across the separatrix due to these neoclassical cross field fluxes, we find:

$$\langle q_{er} \rangle S = 0.036\ \text{MW}$$

$$\langle q_{ir} \rangle S = -0.24\ \text{MW}$$

$$\left\langle \frac{5}{2}(T_e + T_i)\Gamma \right\rangle S = -0.088\ \text{MW}$$

for a net inward power of 0.26 MW. The bracket indicates a flux surface average and S is the plasma surface area. This power is comparable to the threshold power of approximately 1 MW, demonstrating that the magnitude of these neoclassical cross field fluxes can be significant with respect to aiding or inhibiting the L to H transition.

These fluxes are enhanced when the temperature near the X–point is reduced, for example, by divertor detachment. This situation can be approximated with this model by setting the X–point height equal to zero. In this case we find a net inward power of 0.64MW. This may still be an under estimate of the power due to these fluxes because we have assumed that the heat flux in the boundary layer is symmetrical for the inner and outer SOLs. Experimental observations and toroidal geometry considerations indicate that the heat flux is higher in the outer channel and this would further increase the inward magnitude of $\langle q_{\mathrm{ir}} \rangle$.

Another feature of this model is that it may explain the increase of P_{TH} at low density. As the density is reduced, heat flow along the boundary layer changes from being conduction limited to sheath flow limited. When this happens, the poloidal temperature gradient occurs almost entirely at the target plate. The lack of significant poloidal gradients near the core plasma reduces the neoclassical cross field fluxes and the ∇B effect is reduced.

∇B drift effect and the H–mode power threshold

The ∇B effect may be important to the L–H transition through its contribution to the edge pressure gradient from the inward radial fluxes of heat and particles. These fluxes act like a heat and particle pinch at the edge of the plasma and increase the edge pressure gradient. It is conjectured that the power threshold is actually a threshold for E_r which is related to the edge pressure gradient through the radial force balance equation [6]. By contributing to the edge pressure gradient, these fluxes reduce the power required to obtain H–mode. When the direction of the field is reversed, these fluxes act to decrease the edge pressure gradient and increase the threshold power. It is also possible that the ∇B effect could directly effect E_r through some other mechanism, but this discussion is beyond the scope of this paper.

In the present model, the cross field fluxes due to the ∇B drift effect are treated as an additional power flow across the separatrix given by

$$P_{\nabla B} \propto \varepsilon \frac{n}{r} \frac{T}{B} \frac{\partial T}{\partial \vartheta} S \tag{5}$$

where S is the plasma surface area (~rR). Depending on the direction of B, this term either adds to (ion ∇B drift toward the X–point) or subtracts from P_{SEP} to determine the threshold power for the L–H transition:

$$\left(P_{\nabla P}\right)_{TH} = P_{SEP} \pm P_{\nabla B} \tag{6}$$

where P_{SEP} is the power flowing across the separatrix and $\left(P_{\nabla P}\right)_{TH}$ is the power required to increase the pressure gradient to the threshold condition.

We do not know at present how the T and $\partial T/\partial\vartheta$ terms of $P_{\nabla B}$ scale. For a rough approximation, we assume a constant SOL pressure (nT = constant) and, equating P_{SEP} with the power flowing in the SOL, $P_{SEP} \sim KT^{5/2}\, \nabla T$, we approximate $\partial T/\partial\vartheta \sim P_{SEP}^{2/7}$. Using the double-null DIII–D results from [3] for $\left(P_{\nabla P}\right)_{TH}$ we then construct a scaling for P_{SEP},

$$P_{SEP}(\mathrm{MW}) = r(\mathrm{m})\left(5.7 - 4.35\frac{P_{SEP}^{2/7}(\mathrm{MW})}{B(\mathrm{T})}\right) \tag{7}$$

A plot of this function is shown in Fig. 2. At sufficiently high B, P_{SEP} saturates and the B scaling no longer applies. At low B, the power goes to zero for the forward B direction. This is the region where ohmic H–mode is observed. When the second term is comparable to the first term, the scaling of P_{SEP} is roughly linear with B. In the reverse B case, the power increases at low B, and decreases at high B. Because so many different factors contribute to the scaling of $P_{\nabla B}$, it is difficult to obtain a simple scaling of P_{SEP}, and the above model should only serve as an example or guide.

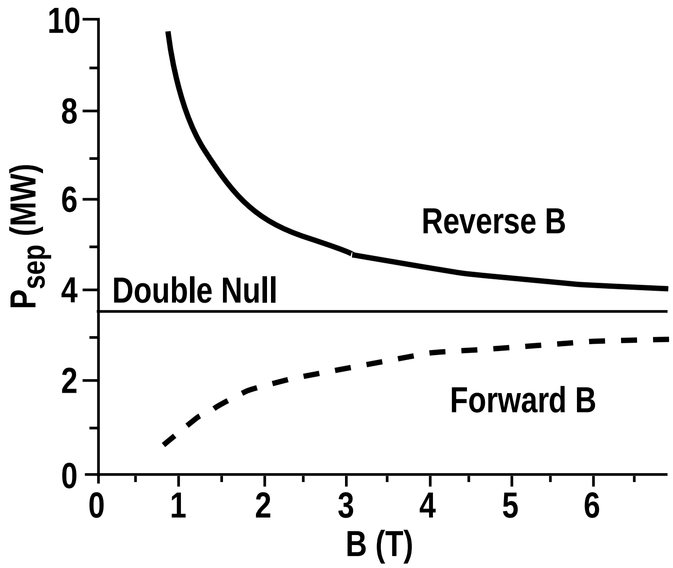

Fig. 2. Simplified scaling of P_{SEP} for both directions of B.

Conclusions

Using a simple 1D analysis of heat flow in the SOL to determine the poloidal gradient, $\partial T/\partial\vartheta$, the inward power flow across the separatrix due to neoclassical cross field fluxes is estimated. This power can be significant and it influences the H–mode power threshold, lowering it when the ion ∇B drift direction is toward the X–point, and raising it when the ion ∇B drift direction is away from the X–point. The existence of a density threshold for H–mode is also explained by this model.

A simple scaling relation of the neoclassical cross field fluxes with basic plasma parameters is developed. It shows that the B scaling of the H–mode power threshold can be explained by these neoclassical cross field fluxes. Predictions of this model include saturation of the B scaling of P_{TH} at high field, 1/B scaling of P_{TH} with reverse B, and no B scaling of P_{TH} in double-null configurations. This simple model predicts $P_{TH} \approx 12$ MW for ITER, which is far below the value of 150 MW obtained from a power law fit to the ITER threshold database [7].

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