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PARTICLE AND ENERGY TRANSPORT IN THE PLASMA
SCRAPE-OFF ZONE AND ITS IMPACT ON LIMITER DESIGN

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ABSTRACT

The design of limiters for fusion devices depends critically on the transport properties of the plasma edge. Recent data from Langmuir Probe experiments and calorimeter probe experiments on the Poloidal Divertor Experiment (PDX) have provided information about the transport of particles and energy in the edge region of a plasma. These data have been used as input to a simple one-dimensional model in which the particle and thermal diffusion coefficients are permitted to be functions of the density and temperature. The transport coefficients deduced from the data are then applied to the cases of the TFTR device and a device like FED/INTOR to predict the optimum design for limiters or pump limiters. The results indicate the optimum limiter should have a concave shape when viewed from the plasma. The effect of the uncertainties in the deduced coefficients on the optimum design performance are also discussed.

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I. INTRODUCTION

The design of a limiter depends strongly on the profiles of density and temperature in the scrape-off zone since those quantities determine the energy and particle flows to the limiter. Recent Langmuir probe measurements¹ done on the Princeton Large Torus (PLT) and the Poloidal Divertor Experiment (PDX) have determined the temperature and density profiles for ohmically heated discharges. In addition, calorimeter probe measurements² have determined the variation of the energy flow in the edge under a variety of conditions. These data have been used as input to a simple one-dimensional transport model whose coefficients are adjusted to fit the data on the edge properties. These transport coefficients can then be used to predict the particle and energy fluxes in planned devices such as the Tokamak Fusion Test Reactor (TFTR) or the International Tokamak Reactor (INTOR). By varying the values of the coefficients, the effect of the uncertainty in the transport on a particular limiter design can be investigated. This is done for the INTOR pump limiter.

Section II describes the equations used to compute the edge temperature and density profiles. The fitting of the data from PDX is described in Sec. III. The results of the edge transport from PDX are applied to TFTR and INTOR in Sec. IV. Section V contains several general conclusions.

II. THE TRANSPORT MODEL

The transport of particles and energy in the edge region of a plasma has been considered by several authors.³⁻⁶ The method used here most

closely resembles that of Howe.⁵ The purpose of this model is to provide a method for rapid evaluation of limiter designs for devices such as TFTR and INTOR. The effects of neutrals in the edge region have been included because the neutrals strongly influence the properties of the edge region (see Refs. 7 and 8).

If the limiter scrape-off zone is described in a slab geometry, then the plasma transport equations in steady state can be written as

$$-\frac{d}{dx} D \frac{dn}{dx} = -\frac{n}{\tau_i} + S_e, \quad (1)$$

$$-\frac{d}{dx} \left(n \chi_e \frac{dT_e}{dx} \right) - \frac{d}{dx} \left(\frac{3}{2} T_e D \frac{dn}{dx} \right) = -\frac{2\gamma n T_e}{\tau_i} - Q_e^i + q_{ei}, \quad (2)$$

$$-\frac{d}{dx} \left(n \chi_i \frac{dT_i}{dx} \right) - \frac{d}{dx} \left(\frac{3}{2} T_i D \frac{dn}{dx} \right) = -2 \frac{\mu n T_i}{\tau_i} - Q_{cx} + Q_e^i - q_{ei}, \quad (3)$$

where

S_e = density source due to ionization of neutrals,

Q_e^i = energy loss to electrons due to ionization of neutrals (see Ref. 9),

Q_i^i = energy gain to ions due to ionization of neutrals,

Q_{cx} = energy loss to ions due to charge exchange, and

q_{ei} = electron ion coupling (see Ref. 10).

The terms involving neutrals were computed using the algorithm SPUDNUT.¹¹ The cross sections used in SPUDNUT were taken from Ref. 12. The coefficients γ and μ represent the effect of the sheath on the edge transport (see Ref. 13). The coordinate x is the distance into the

scrape-off from the last closed flux surface. The parallel confinement time is given by a connection length divided by a parallel velocity

$$\tau_{\parallel} = \frac{L}{v_{\parallel}} = \frac{\pi q R}{v_{\parallel}} \quad (4)$$

where $v_{\parallel}$ is given in Ref. 13. The connection length is only $\pi q R$ because the limiter is assumed to be toroidally symmetric, and an average particle needs to traverse only half of the minor circumference to reach the limiter. The flux surfaces are assumed to be circular in this model. The value of χ_1 was taken to be two to four times the neoclassical value.

Once the temperature dependence of $\tau_{\parallel}$ is included explicitly in Eqs. (1), (2), and (3), the equations must be solved numerically. It is only slightly more difficult to make the heat conduction and particle diffusion coefficients functions of the density and temperature, i.e., $\chi = \chi_0 T^a n^b$ and $D = D_0 T^c n^d$. The resulting nonlinear second order equations were solved using an implicit scheme involving successive substitution.¹⁴ The boundary conditions are the particle loss rate ($\dot{N}$); total power flow (P) to the limiter; the ratio of T_1 to T_e ; ratio of the temperature gradients at the plasma edge; and the density, temperature, and neutral particle energy at the outer edge of the scrape-off (i.e., at the wall). Particles flowing to the limiter were returned as a volume source of neutrals. Simple exponential solutions plus a density and temperature pedestal were used as the initial guess for the iterative solution. For a typical case fifteen iterations were required for convergence. A nodal point spacing of 1 mm was found to be adequate

for most cases. The neutral profile was computed for each iteration but the nodal spacing was about 5 mm for the neutral calculation.

The density and temperature profiles resulting from the solution of Eqs. (1) and (2) can be used to compute the flow of particles and power to the limiter using the following equations:

$$\Gamma_i = n v_i \quad (5)$$

$$Q_i = 2\gamma T \Gamma_i. \quad (6)$$

Given the flux profiles, a shape for the pump limiter surface which has constant power density can be derived.¹⁵ This shape will be referred to as the optimum limiter shape.

III. ANALYSIS OF THE EXPERIMENTAL DATA

The experimental data¹ for the density and temperature profiles in the edge were fit using the following free parameters: the rate of particle loss ($\bar{N}$), the power flowing to the limiter (P), and the transport coefficients (χ_0 , a , b , D_0 , c , d). These were adjusted so as to minimize the mean square deviation of the calculated value from the data. It was assumed that $T_i/T_e = 1.5$ and the neutral energy was 3 eV. The best fit profiles are shown as a solid line with the experimental data in Fig. 1. The coefficients which gave the best fit are shown in Table I. The errors shown in Table I were determined using standard statistical methods. The fit was insensitive to T_i/T_e over the range 1 to 3, to the neutral energy over the range 3 to 10 eV, and the value of χ_2 over the range 200 to 1200 cm²/sec.

Once the temperature and density profiles have been determined, the profile of the energy flow to the limiter may be computed using Eq. (6). The result is a very nearly exponential decay with a characteristic length of $\lambda_E = 3.3$ cm. The calorimeter probe data² show $\lambda_E = 2.6$ cm for similar plasma conditions. This difference is not unexpected considering the data were not taken during the same discharges. This model also reproduces the general features of the data in Refs. 1 and 2 when the plasma conditions are changed. The parameters in Table I imply that $\chi_e = 4.5 \times 10^4$ cm²/sec and $D = 1 \times 10^4$ cm²/sec at the plasma edge. These values are similar to those typically used in computations of edge profiles.

IV. APPLICATION TO TFTR AND INTOR

Using the χ and D values which best fit the PDX data ($\chi_e = 4.5 \times 10^4$, $D = 1 \times 10^4$), this model predicts an energy scrape-off length of $\lambda_E = 1.5$ cm for TFTR. This is right in the center of the range used to design the TFTR bumper limiter. The predicted power density on the limiter agrees very well with that predicted by the analytic model of Schmidt¹⁶ if the same λ_E is used. Thus the present model agrees well with previous predictions for TFTR.

The baseline parameters used in the study of the INTOR pump limiter are as follows: $R_0 = 5.3$ m, $a_0 = 1.52$ m (equivalent round), $q_{Lim} = 3$, (equivalent round), $P_{Lim} = 80$ MW, and $\dot{N} = 3.2 \times 10^{23}$ /sec. In the studies that were done the baseline values for χ and D were taken to be $\chi_1 = 800$ cm²/sec, $D = 1 \times 10^4$ cm²/sec, and χ_e varying like $1/n$ with χ_e

at $x=0$ being approximately $3 \times 10^4 \text{ cm}^2/\text{sec}$. Figure 2 shows the profiles of n , T_e , T_i , and the various neutral particle terms for the baseline case. The density plateau seen in this case is due to the fact that T_e is always greater than 15 eV where the electron ionization cross section is slowly varying with T_e . If either P is lowered or $\dot{N}$ is raised, this plateau disappears because T_e is less than 15 eV for a significant portion of the scrape-off zone. This plateau substantially eases the helium ash removal problem because of the large densities at the entrance to the pump channel.

The optimum limiter shape for a surface heat flux of 200 W/cm^2 was calculated using the method discussed in Ref. 15. This shape is taken as the baseline for all comparisons. The peak surface heat flux on this shape as a function of χ_e is shown in Fig. 5. It is seen that the leading edge power density increases as χ_e becomes larger than the design value whereas the limiter surface power increases if χ_e is smaller. Since the increase in peak power for smaller coefficients is so dramatic, it is important to know the shortest scrape-off length for which a limiter must be designed. The width of the limiter for a given shape does not affect the surface heat load but does strongly affect the leading edge load. The advantage of curving the limiter toward the plasma is a factor of 2 to 4 reduction in the heat load. The anticipated range of scrape-off lengths will determine whether the optimum shape or a simpler curved shape is the best choice. It should be noted that the TFTR limiter curves toward the plasma, but not with the optimum shape.

The fraction of the particles getting behind the limiter (and hence pumped) can be computed from the particle flux profiles if the leading edge position is taken to be the entrance to the pumping channel. This pumped fraction is optimistic because effects of recycling and density buildup near the neutralizer plate are not in this simple model. Proper estimates of the pumping require computations such as those of Heifetz.^{17,18} The results of this optimistic pumped fraction are between 8 and 30 percent, and even with the correction for recycling, this should be adequate for helium ash control.

IV. CONCLUSIONS

A simple computational model has been created which gives reasonable agreement with experimental data on the profiles of density, temperature, and energy in the edge region of a plasma. This model has been used to predict the heat and particle fluxes to limiters in TFTR and INTOR. The results for TFTR agree well with previous predictions. The electron temperature in the edge has a strong influence on the density profile. The cold edge scenario ($T_e < 50$ eV) results in the worst case for pumping, but the removal of helium ash is still adequate. The neutral particles in the edge tend to broaden the density profiles and compress the temperature profiles. In addition, the neutrals tend to reduce the impact of a change in transport coefficients on a given design, compared to a computation that ignores neutrals. The predicted fluxes depend quite strongly on the transport coefficients and more experimental data on such profiles would be very useful. This is particularly true of data taken during strong auxiliary heating.

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FIGURE CAPTIONS

FIG. 1 a) Fit to the PDX density data. The solid curve is the best fit to the data shown. The fit parameters are in Table I.

b) Fit to the PDX temperature data. The solid curve is the best fit to the data shown. The fit parameters are in Table I.

FIG. 2 a) Profiles of terms resulting from the neutral particle calculation for the baseline INTOR case.

b) The temperature and density profiles for the baseline INTOR case which correspond to the neutral profiles in a).

FIG. 3 The effect of varying x_e on the peak energy flux to the surface (a) and the leading edge (b) of a limiter having optimum shape (200 W/cm²).

Table I - Best Fit Parameters for the PDX Data

$$P = (1.6 \pm 0.5) \times 10^4 \text{ W}$$

$$\dot{N} = (1.4 \pm 0.5) \times 10^{21}/\text{sec}$$

$$\chi_{eo} = (9 \pm 3) \times 10^{16}$$

$$a = 0 \pm 0.25$$

$$b = -1 \pm 0.5$$

$$D_0 = (1 \pm 0.3) \times 10^4$$

$$c = 0 \pm 0.25$$

$$d = 0 \pm 0.25$$

$$\chi_i = 800 \text{ cm}^2/\text{sec}$$

$$a = 0$$

$$b = 0$$

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Figure 1

Figure 2

Figure 3

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