OPTIMUM SHAPES FOR PUMP LIMITERS

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ABSTRACT

The design of a pump limiter depends strongly on the details of the plasma scrapeoff zone. A model has been developed which allows the transport coefficients in the scrapeoff to be functions of n and T . This model has been used to predict scrapeoff profiles for FED/INTOR. The profiles are used to find and analyze limiter profiles. The results suggest the use of limiter shapes which curve toward the plasma.

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I. INTRODUCTION

The design of a pump limiter depends strongly on the profiles of density and temperature in the scrapeoff 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 shown edge densities of $\sim 10^{12} \text{ cm}^{-3}$ and temperatures of $\sim 10 \text{ eV}$ with longer than expected temperature scrapeoff lengths. Calorimeter probe measurements² on both PLT and PDX have also shown that the energy flux in the shadow of the limiter does not fall off like a simple exponential but shows a tail extending to the wall. Since the scrapeoff zone profiles used to design pump limiters for the Fusion Engineering Device (FED) and the International Tokamak Reactor (INTOR) have been simple exponentials,^{3,4} and those profiles are not in good agreement with the data, the inclusion of more exact terms in the plasma transport equations in the scrapeoff should result in improved pump limiter designs. The purpose of this paper is to examine the improvements that can be made in the modeling of the scrapeoff zone and determine the impact of such improved modeling on pump limiter designs for FED/INTOR.

Section II contains a brief discussion of the transport equations and their solution. The results of varying various parameters in the transport model are presented in Section III. The impact of the parameter studies on the pump limiter design is also given in Section III. Section IV contains some general conclusions concerning pump limiter design based on the results of the modeling.

II. THE PLASMA TRANSPORT EQUATIONS AND LIMITER SHAPE

If the limiter scrapeoff zone is described in a slab geometry (as Howe did for FED³), then the plasma transport equations can be written as

$$\frac{d}{dx} D \frac{dn}{dx} = \frac{n}{\tau_{||}} \quad , \quad (1)$$

$$\frac{d}{dx} (n \chi \frac{dT}{dx}) + \frac{d}{dx} (3TD \frac{dn}{dx}) = \frac{2\gamma nT}{\tau_{||}} \quad . \quad (2)$$

Where $n = n_e = n_i$, $T = T_e = T_i$, $\chi = \chi_e + \chi_i$, $\gamma = \gamma_e + 1$, and x is the distance into the scrapeoff. The enhancement of the electron energy flux due to the sheath potential is given by

$$\gamma_e = 1 + \frac{1}{4} \ln \frac{m_i T_e}{m_e T_i} \quad . \quad (3)$$

The parallel confinement time is given by a connection length divided by the sound speed or

$$\tau_{||} = \frac{L}{v_s} = \frac{\pi q R}{(k T_e / m_i)^{1/2}} \quad . \quad (4)$$

The connection length is only $\pi q R$ because the limiter is 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 extrapolation to noncircular shapes is left to Section IV.

Once the temperature dependance of $\tau_{||}$ is included explicitly in equations (1) and (2), the equations must be solved numerically, and it is only slightly more difficult to make the heat conduction and particle diffusion coefficients functions of the density and temperature also, 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.⁵ The boundary conditions are the particle loss rate ($\dot{N}$) and total power flow (P) to the limiter at the

plasma edge, and the density and temperature at the outer edge of the scrapeoff (i.e., at the wall). The simple exponential solutions plus a density and temperature pedestal were used as the initial guess for the iterative solution. For a typical case seven iterations were required for convergence. A nodal point spacing of 1mm was found to be adequate for most cases.

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

$$\Gamma_{\parallel} = nL/\tau_{\parallel} \quad , \quad (5)$$

$$Q_{\parallel} = 2\gamma T \Gamma_{\parallel} \quad . \quad (6)$$

Given the flux profiles, a shape for the pump limiter surface which has constant power density can be derived.⁶ If θ is the angle between the limiter surface normal and the x direction, and z the distance along the limiter surface, then the shape of the limiter is given by

$$\frac{dx}{dz} = \cot \theta \quad (7)$$

$$\sin \theta = \frac{Q_d}{Q_{\parallel}} \quad , \quad (8)$$

where Q_d is the design value of the constant power density. These equations were numerically integrated to find the limiter shape for a given power density.

III. RESULTS OF PARAMETER STUDIES AND LIMITER SHAPES

The baseline parameters for FED/INTOR which were used as a design basis in this study are shown in Table I. In this study χ and D were taken to be constant throughout the scrapeoff since there is very little experimental evidence that indicates what the density and temperature dependence of χ and D should be. The solution of the equations in Section II using the baseline parameters gives the density, temperature, particle and energy fluxes shown in Figure 1. Also shown is a typical simple exponential solution. It is evident from this graph that even the inclusion of $\tau_{||}$ being a function of T results in a considerable modification of the profiles in the scrapeoff. The long tails seen in this figure agree qualitatively with the experimental evidence. Figure 2 shows the limiter shape corresponding to a design energy flux of 160 W cm^{-2} resulting in limiter width (W) of 1.5m . The same shape in real space is shown in the inset in Figure 2, where the plasma edge is shown for reference. Limiter shapes having an optimum shape for 200 W cm^{-2} ($W = 1.1\text{m}$) and having a constant radius of curvature, and the same width and leading edge position (limiter surface normal to poloidal flux lines) as the two optimum shapes, were also considered. The radii of curvature were $R_L = 270 \text{ cm}$ ($W = 1.1\text{m}$) and $R_L = 207 \text{ cm}$ ($W = 1.5\text{m}$). In addition, limiters having $R_L = \infty$ (flat) with the same leading edge position but different width, were considered. Heat and particle flux profiles for the baseline case are shown in Figure 3 for the 1.5m wide optimum shape and for the corresponding constant curvature shape.

The range of variation in the baseline parameters which were considered in this study is shown in Table II. The designs corresponding to a width of 1.1m were analyzed for all of the cases in Table II. The 1.5m width design

was considered only for case A. For comparison to the simple exponential model, the e-folding length in the range $0 \leq x \leq 2$ cm is plotted versus x for case A in Figure 4. This is for comparison purposes only and it must be emphasized that the profiles computed in this study are not at all simple exponentials.

The peak power density on the surface of the limiter and the leading edge as a function of these parameter variations is shown in Figure 5 for $W = 1.5m$ and in Figure 6 for $W = 1.1m$. In the case of a flat limiter the curve labeled tip implies a width of the limiter which is less than that of the other two shapes, e.g., $W_{flat} = 0.76m$ for the $W = 1.1m$ case. The width of the limiter does not affect the peak surface heat flux for a given shape but does strongly affect the leading edge position and hence the tip heat load. With the exception of the variation with power to the limiter, the peak energy flux occurs on the limiter surface if the value of the parameter is less than the design value, and it occurs on the tip if the parameter is greater than the design value. In the case of power the variation in peak energy flux is in the same direction as the variation in the parameter with the interesting feature that the tip dominates at the lowest power.

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 Post,⁷ and Hefetz.⁸ The results of this optimistic pumped fraction are shown in Figure 7 for $W = 1.5m$ and Figure 8 for $W = 1.1m$. The results show that the pumped fraction is closely related to the tip heat load except in the cases of $D = \text{constant}$ when

it is nearly constant, and for decreasing power to the limiter when it increases strongly even though the tip heat load is decreasing.

IV. THE IMPACT ON PUMP LIMITER DESIGNS

The results of this study suggest several things in regard to the design of pump limiters. The use of flat limiters results in a very high peak surface energy flux (about 4 times the optimum shape). This is due to a significantly smaller wetted area. The differences between this study and the previous FED study⁹ are primarily in the power (80 MW versus 56 MW FED) and in the scrapeoff thickness $\lambda_E \sim 1$ cm vs. $\lambda_E \sim 8$ cm (FED). Part of the difference in λ is in the baseline where $\lambda_E = 2$ cm for FED. The remainder of the difference comes from the way λ is adjusted for the different flux surface spacings in the noncircular shape appropriate to FED/INTOR. In the FED study the ratio used was between the field line spacing at the position desired and the smallest spacing (at the outboard midplane). Since the models used to calculate λ all assume circular flux surfaces, it is more correct to take the ratio of the spacing at the position desired to the average spacing in the actual shape to adjust λ . Under this assumption the expansion for the FED case is a factor of 2, not a factor of 4. The net result is a factor of 4 change in λ which appears as $\sqrt{\lambda}$ in the power.³ This brings the present study into agreement with the previous FED study. In fact, for both FED and INTOR the field line spacing over the outer half of a limiter on the bottom of the machine is very close to the average, which implies the results of this study are directly applicable to FED/INTOR. The inner half of the limiter will have slightly lower peak fluxes due to the expansion of the flux surfaces.

The optimum shape which gives a flat heat flux profile requires very precise machining of the limiter surface and alignment with the magnetic field if its full benefit is to be realized. The constant radius shape is much

easier to machine and construct but has about twice the peak heat flux for the base case. However, the peak heat flux increases less rapidly on the surface of the constant curvature shape than the optimum shape as the transport coefficients are reduced from the baseline. The tip heat load depends only on the distance the tip is from the plasma and is independent of the shape of the surface. Thus, the choice of optimum versus circular shape depends on the anticipated range of variation in the baseline parameters. Processes which cause perpendicular diffusion will fill in the dip in the power density on the circular shape and reduce the peak power since the wetted area increases. Since both the optimum and circular shapes curve toward the plasma, it is important to investigate the effect of plasma shift on the tip heat load. Figure 9 shows the peak power density on the tip of the limiter as a function of the shift in plasma position for the circular case (the optimum shape gives similar results). It is seen that a shift of about 2.5 cm doubles the tip heat load. Thus, if the benefits of the limiter curving toward the plasma are to be realized, then the horizontal position control must be very good.

A model has been developed which allows easy evaluation of the impact of baseline parameter variations on pump limiter designs. The results of the study indicate about a factor of 2 to 4 advantage of a limiter shape which curves toward the plasma over a flat limiter. Experimental data concerning the scrapeoff properties of a plasma running off an axisymmetric limiter would provide very important information for the design of FED/INTOR pump limiters.

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TABLE I. FED/INTOR Baseline Parameters

$$R_o = 5.3 \text{ m}$$

$$a_o = 1.52 \text{ m (equivalent round)}$$

$$q_{lim} = 3 \text{ (equivalent round)}$$

$$P_{lim} = 80 \text{ MW}$$

$$\dot{N} = 3.2 \times 10^{23}/\text{sec}$$

$$D = 1 \times 10^4 \text{ cm}^2/\text{sec}$$

$$\chi = 3 \times 10^4 \text{ cm}^2/\text{sec}$$

TABLE II. Range of Parameters Considered

Case	χ (cm ² /s)	D (cm ² /s)	$\dot{N}$ (s ⁻¹)	P (MW)	q
A	7.5×10^3	$\chi/3$	3.2×10^{23}	80	3
	1.5×10^3	↓			
	6×10^4				
	12×10^4				
B	3×10^4	2×10^3			
	↓	4×10^3			
		8×10^3			
		1.6×10^4			
		3.2×10^4			
		6.4×10^4			
C	5×10^3	↓			
	1×10^4				
	2×10^4				
	4×10^4				
	8×10^4				
	16×10^4				
D	3×10^4	1×10^4	2×10^{24}	80	3
			1×10^{24}		
			1×10^{23}		
			5×10^{22}		
E			3.2×10^{23}	80	1
				↓	2
					4
					5
					F
40	↓				
20					
10					

Figure Captions

- Fig. 1. Profiles of n , T , heat flux Q , and particle flux Γ are shown for the baseline parameters with D and x constant and $\tau_{||} = \tau_{||}(T)$. A simple exponential is shown for comparison.
- Fig. 2 The limiter shape corresponding to 160 w/cm^2 (constant). The inset shows the real shape of such a limiter next to the plasma.
- Fig. 3 The power and particle fluxes to the constant power shape (a) and to a constant curvature shape (b) having $r_L = 207 \text{ cm}$.
- Fig. 4 Values of λ_p and λ_E in the region $0 \leq x \leq 2 \text{ cm}$ for comparison to previous calculations.
- Fig. 5. The variation of peak energy flux to the surface (a,b,c) and leading edge (d) of a limiter having (a) the constant power (160 w/cm^2) shape, (b) constant curvature ($R_L = 207 \text{ cm}$), (c) flat shape ($R_L = \infty$), with χ for $D = \chi/3$ (case A, Table 2).
- Fig. 6. The variation of peak energy flux to the surface (a,b,c) and leading edge (d) of a limiter having (a) constant power (210 w/cm^2) shape, (b) constant radius ($R_L = 270 \text{ cm}$), (c) flat shape ($R_L = \infty$) for cases A to F in Table II (1-6 respectively).
- Fig. 7. An optimistic estimate (see text) of the fraction of particles pumped for a leading edge position corresponding to the constant heat flux shape (160 w/cm^2) for case A in Table II.
- Fig. 8. The fraction pumped for the shapes and cases shown in Figure 6.
- Fig. 9 The leading edge energy flux as a function of the major radius shift of the plasma.

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Figure 1

Figure 2

Figure 3a

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Figure 3b

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9