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FED PUMPED LIMITER CONFIGURATION ISSUES*

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ABSTRACT

Impurity control in the Fusion Engineering Device (FED) is provided by a toroidal belt pumped limiter. Limiter design issues addressed in this paper are (1) poloidal location of the limiter belt, (2) shape of the limiter surface facing the plasma, and (3) whether the belt is pumped from one or both sides. The criteria used for evaluation of limiter configuration features were sensitivity to plasma-edge conditions and ease of maintenance and fabrication. The evaluation resulted in the selection of a baseline FED limiter that is located at the bottom of the device and has a flat surface with a single leading edge.

INTRODUCTION

Several recent conceptual designs for future tokamak reactors have included mechanical pumped limiters.[1-3] The purpose of the limiter is to establish the plasma edge and provide a mechanism to remove impurities (e.g., helium ash) from the plasma.

The Fusion Engineering Device (FED) pumped limiter, shown in Fig. 1, is a toroidally continuous flat plate located at the bottom of the device with a single leading edge. During the design definition phase of the FED, a physics task team was formed to address pumped limiter issues. The baseline limiter design incorporates several of the features, including a flat surface and single leading edge, identified by the task team.[4] Three key limiter design issues discussed in Refs. 1-4 are (1) poloidal location of the limiter belt, (2) poloidal contour of the limiter relative to the plasma, and (3) single- or double-edged blade. Each of these issues is discussed in this paper as it relates to the FED limiter design.

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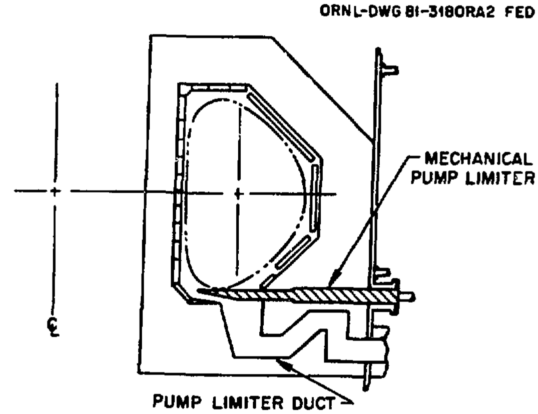

Fig. 1. Elevation view of FED pumped limiter

The plasma edge conditions for FED have a high degree of uncertainty. Nominal values of the plasma edge parameters and estimates of the uncertainty in these values, which were used for FED limiter performance calculations, are listed in Table 1. As discussed in Ref. 1, these conditions resulted in limiter lifetimes ranging from two months for the "worst-case" conditions to about four years for the "best-case" conditions.

Because of the high degree of uncertainty in plasma edge conditions, the sensitivity of the limiter performance to these conditions was an important factor in selecting configuration features. The sensitivity of the peak heat flux to the plasma edge conditions is discussed in the following sections of this paper. The peak particle flux to the limiter surface exhibits the same sensitivity as the heat flux. These two parameters, heat flux and particle flux to the limiter surface, determine the erosion lifetime of the limiter. Erosion lifetime is a critical issue[1-3] in selecting and designing impurity control devices (pumped limiters and magnetic divertors).

Table 1. There is a high degree of uncertainty in the plasma edge parameters

Parameter	Nominal value	Range of Uncertainty
Total particle transport heat load to limiter (MW)	56	5 to 56
Total flux of ions leaving plasma (s^{-1})	5×10^{23}	5×10^{22} to 5×10^{23}
Scrape-off layer e-fold distances (cm) (outboard mid-plane location)		
• Particle flux	3	0.75 to 12
• Heat flux	2	0.5 to 8
• Particle energy	6	1.5 to 24

The ability to adjust the particle pumping is also discussed in comparing limiter configuration features because the pumping requirement is uncertain, and pumping may significantly affect plasma performance. In addition to performance parameters, maintenance and fabrication differences between configurations and the impact of the limiter configuration on other subsystems were considered in selecting configuration features.

Poloidal Location

Three locations considered for a pumped limiter are shown in Fig. 2. The bottom location is more tolerant to uncertain plasma edge conditions. This feature is demonstrated in Fig. 3, which compares the sensitivity of the heat flux to changes in the scrapeoff e-fold distance for limiters at the 45° facet and bottom locations. The reason for the smaller leading-edge loads at the bottom location is the spreading of the magnetic flux surfaces in this region.

Additional advantages of the bottom location over other locations are:

1. The module is small and is therefore easier to remove and replace and occupies less space, leaving more room for breeding blanket modules, diagnostics, neutral beam ducts, ICRH launchers, etc.

2. The leading-edge position with respect to the plasma edge can be adjusted by changing the plasma major radius.

3. Limiter structure and vacuum duct can be decoupled; hence, the limiter can be replaced without removing a large duct structure.

A limiter located at the midplane potentially reduces the size of the toroidal field coils by allowing the shield sector to be symmetrical in the vertical direction. This would also permit symmetrical control coils and allow the lower control coils to be located closer to the plasma. However, the bottom location was selected over either the 45° location or midplane location because of its potential maintenance and plasma/limiter leading-edge position control advantages.

Shaped vs flat limiter

The heat flux ($\dot{q}$) to a toroidally continuous limiter surface facing the plasma is assumed to be given by:[5]

$$\dot{q} = \frac{\dot{Q}_T}{4\pi R \lambda_Q} e^{-x/\lambda_Q} \sin \theta \qquad (1)$$

where

$\dot{Q}_T$ = total particle transport heat load,

R = major radius distance to the limiter surface,

λ_Q = heat flux e-fold distance,

x = minor radius distance from the limiter surface to the plasma edge (Fig. 4), and

θ = angle of incidence between the limiter and a poloidal flux line (Fig. 4).

This simple expression for the decay of the heat flux in the scrapeoff layer assumes that the electron and ion heat conduction and cross-field diffusion coefficients are constant throughout the scrapeoff layer. Experimental evidence[6] indicates that these quantities are not constant. However, for the purpose of comparing limiter design features, the exponential decay relation should be adequate. A circular plasma is assumed for developing analytical expressions relating the various parameters in Eq. (1).

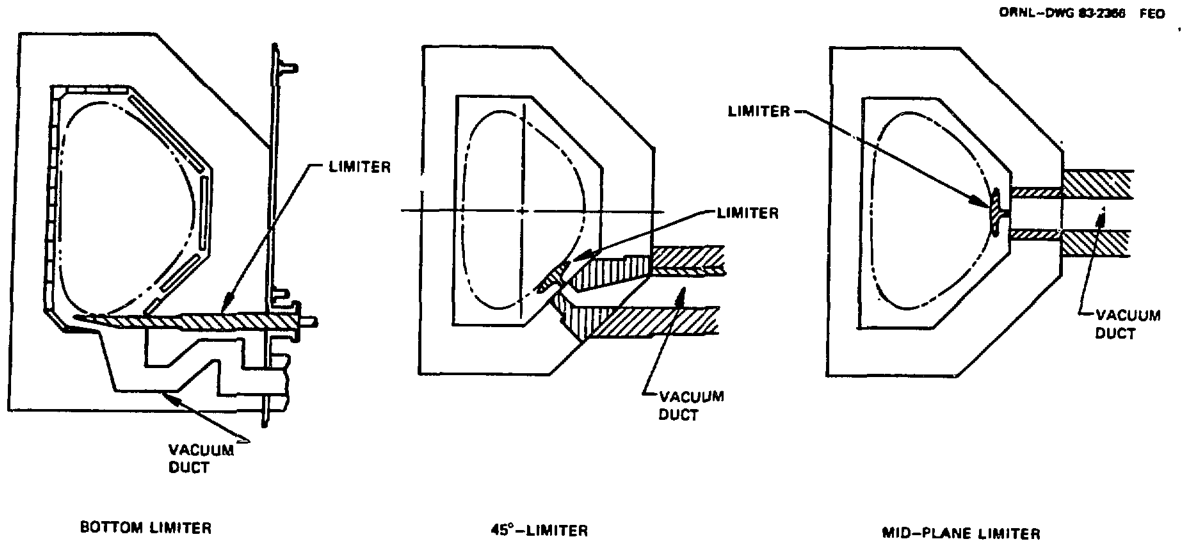

Fig. 2. Options for FED limiter location

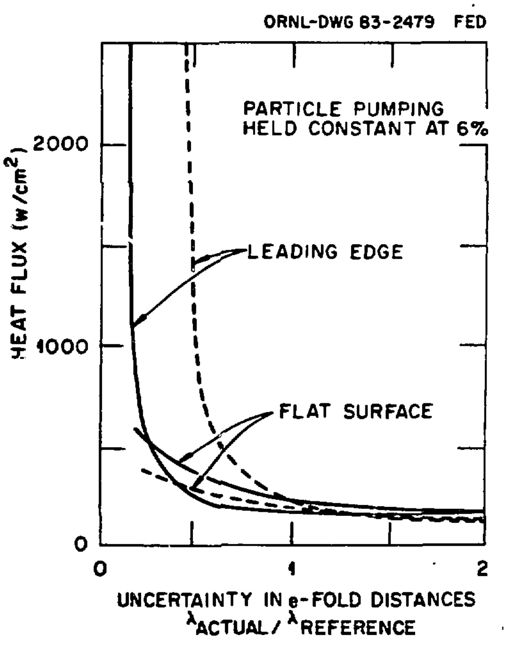

Fig. 3. Bottom location is less sensitive to changes in plasma edge conditions

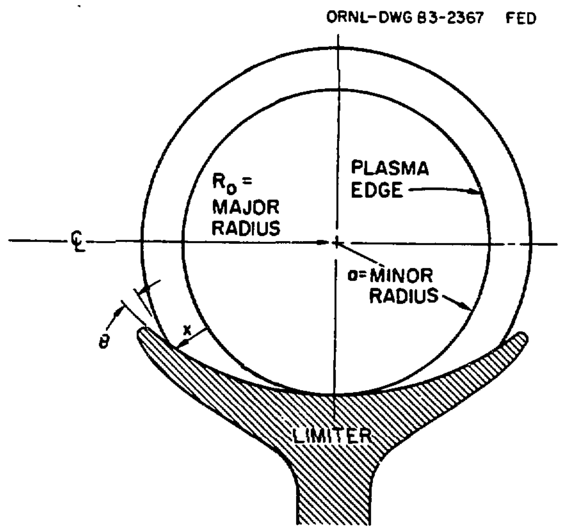

Fig. 4. Configuration of plasma relative to limiter surface

To obtain a constant design value heat flux ($\dot{q}_d$) along the limiter surface, the limiter must be shaped such that the angle θ as a function of x (distance into the scrapeoff) is

$$\theta(x) = \sin^{-1}\left(\frac{4\pi R\lambda_Q \dot{q}_d}{\dot{Q}_T} e^{x/\lambda_Q}\right) . \qquad (2)$$

A limiter contoured according to Eq. (2) is referred to as a contoured or shaped limiter.

In the following paragraphs, we distinguish between the reference (or design) values (subscript r) and actual values (subscript a) of the heat fluxes and e-fold distances. The reference value is the value predicted for baseline plasma edge conditions. Thus, the reference heat flux ($\dot{q}_r$) is expected for the baseline heat flux e-fold distance of λ_{Q_r}. The actual heat flux ($\dot{q}_a$) corresponds to the e-fold distance λ_{Q_a} actually present in the operating device. For FED, the uncertainty in λ_Q has been estimated to be a factor of 4 (see Table 1). The sensitivity of the heat flux to variations of λ_Q was examined for both shaped and flat limiters.

Using Eqs. (1) and (2), the ratio of the actual heat flux to the reference heat flux for a shaped limiter is given by

$$\frac{\dot{q}_a}{\dot{q}_r} = \left(\frac{\lambda_{Q_r}}{\lambda_{Q_a}}\right) e^{x/\lambda_{Q_r}\left[1 - (\lambda_{Q_r}/\lambda_{Q_a})\right]} . \qquad (3)$$

If $\lambda_{Q_a} < \lambda_{Q_r}$, then the maximum value of $\dot{q}_a/\dot{q}_r$ occurs as $x \to 0$ and is

$$\left(\frac{\dot{q}_a}{\dot{q}_r}\right)_{max} = \frac{\lambda_{Q_r}}{\lambda_{Q_a}} . \qquad (4)$$

Therefore, for a shaped limiter, if the actual value of the e-fold distance is a factor of 4 less than the reference value, then the maximum heat flux is 4 times greater than the reference heat flux.

The maximum value of $\dot{q}_a$ for $\lambda_{Q_a} > \lambda_{Q_r}$ occurs at the leading edge, which is the location where θ, defined by Eq. (2), reaches 90°. The heat flux at the leading edge is discussed later in this paper.

The maximum heat flux for a limiter that has a flat surface facing the plasma is

$$\dot{q}_m = \frac{\dot{Q}_T}{4\pi R} (ea\lambda_Q)^{-1/2} \qquad (5)$$

(assuming $x \ll a$). Using Eq. (5), the sensitivity of the maximum heat flux ratio $(\dot{q}_a/\dot{q}_r)_{max}$ to changes in the e-fold distance is

$$(\dot{q}_a/\dot{q}_r)_{max} = \left(\frac{\lambda_{Q_r}}{\lambda_{Q_a}}\right)^{1/2} . \qquad (6)$$

The maximum heat flux ratio for the shaped limiter was shown in Eq. (4) to be directly proportional to the ratio of the reference e-fold distance to the actual e-fold distance. The flat limiter is therefore less sensitive [Eq. (6)] to uncertainties in λ_Q. An actual heat flux e-fold distance that is a factor of 4 less than the reference e-fold distance results in a factor of 4 increase in the maximum heat flux for a shaped limiter and only a factor of 2 increase for the flat limiter. Note, however, that the shaped limiter might be designed to have a reference heat flux that is lower than that for a flat limiter.

Since the heat flux at the leading edge is determined by pumping requirements (does not depend on the limiter shape), the maximum heat flux experienced by a shaped limiter will be greater than or equal to the leading-edge flux. The reference or design value of the leading-edge heat flux could be chosen as the uniform heat flux used in designing a shaped limiter. For FED, with a pumping requirement of 5% of the particles leaving the plasma, the leading-edge heat flux is 170 W/cm^2. The maximum heat flux on the flat surface facing the plasma is 240 W/cm^2. Therefore, a shaped limiter with the heat flux on the surface facing the plasma designed to be equal to the reference leading-edge heat flux would reduce the heat flux by 30%. The benefit of a lower value of the heat flux for the shaped limiter at the reference plasma edge conditions can be lost if the actual conditions are different. For example, if the actual e-fold distance is less than one-half the reference e-fold distance, then the heat flux on the shaped limiter will be greater than on the flat limiter.

Single- vs Double-Edged Limiter

A toroidally continuous limiter can have either one or two leading edges relative to the poloidal component of the velocity of a charged particle. A double-edged limiter allows pumping of particles passing in either poloidal direction; a single-edged limiter allows only particles passing in one poloidal direction to be pumped. The advantage of a double-edged limiter is that, for the same pumping requirement, a double leading-edge design has a lower leading-edge heat flux. An alternate way of stating this advantage is that for the same heat flux at the leading edge, twice as many particles are pumped by the double-edged design. The advantage of a single leading edge relates to adjustment of the leading-edge conditions. Using a shaped limiter precludes adjustment. Pumping adjustability applies only to single-edged, flat limiter configurations.

The location of the leading edge is determined by the pumping requirement, usually specified as some fraction f_p of the total particles leaving the plasma. The fraction of particles that passes behind the leading edge (f_{LE}) is not precisely the fraction of particles pumped (f_p), because not all particles passing behind the limiter are pumped; some can escape back to the plasma. However, estimates for the FED limiter configuration[1] have shown that the pumping efficiency for particles that enter the slot behind the leading edge is quite high ($\sim$90%). For purposes of comparison, we specify f_{LE}, but it should be noted that the actual requirement is to provide some value of f_p.

The effect of moving the plasma, relative to the leading edge, on the leading-edge conditions (heat flux and fraction of particles pumped) is presented in Fig. 5 for limiter configurations with one or two leading edges. For a value of f_{LE} equal to 0.10 and the plasma at its reference position ($y = 0$), the leading-edge heat flux on the double-edged limiter is only 35% of the heat flux at the leading edge of the single-edged design. However, the amount of pumping or leading-edge heat flux can be significantly increased or reduced for the single-edge design by moving the plasma edge relative to the leading edge. For example, moving the plasma, relative to the single leading edge, by ±5 cm changes the fraction of particles (f_{LE}) passing behind the single-edged limiter from about 7% to 13%, compared with 10% at the reference plasma/limiter location. For this same adjustment (±5 cm), the leading-edge heat flux varies by about ±40% of the value of the heat flux at the reference location. For a limiter located at the bottom of the device, this movement can be achieved by either changing the plasma major radius (the method proposed for FED) or moving the limiter in or out radially.

ORNL-DWG 83-2368 FED

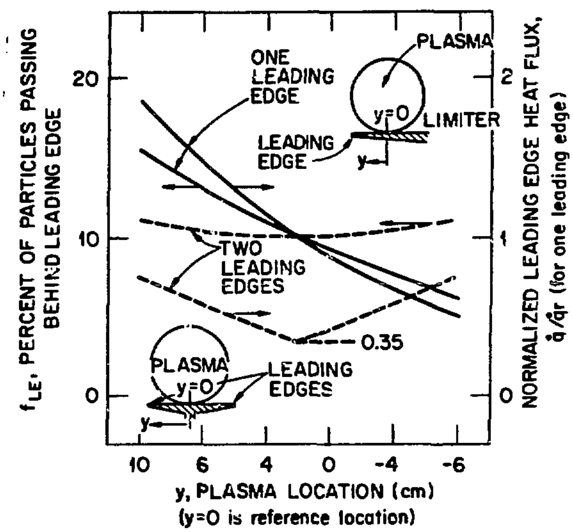

Fig. 5. Impact of plasma location on leading-edge conditions

Pumping for two leading edges is insensitive to this type of movement. Movement toward one leading edge increases the pumping at that leading edge but decreases the pumping at the other leading edge by about the same amount.

The heat flux sensitivity for a contoured limiter that has two leading edges is shown in Fig. 6. It was assumed that this limiter is contoured to maintain a constant heat flux on the surface facing the plasma that is equal to the value at each of the leading edges. Leading edges were located to meet a pumping requirement of 5% of the particle flux at the plasma edge. Sensitivities for single-edged limiters with a flat surface and a contoured surface are shown in Fig. 6 for comparison.

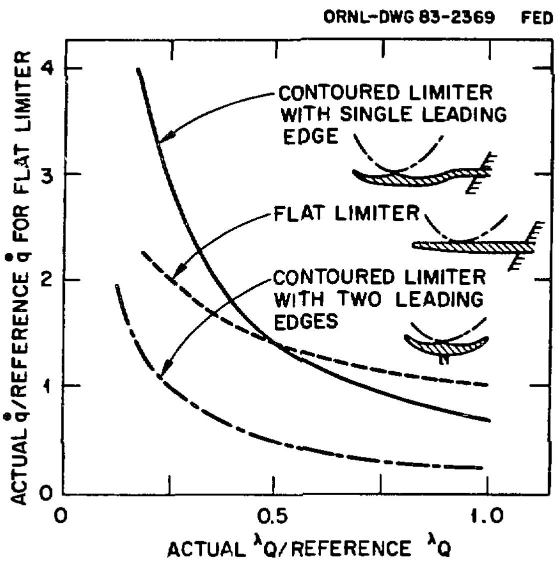

Fig. 6. Contoured limiter with two leading edges has lowest heat flux

Although a contoured limiter is more sensitive to changes in λ_Q than a flat limiter, the heat flux for the double-edged, contoured limiter is still a factor of 2 lower than the value for the flat limiter at the largest estimated uncertainty of $\lambda_{Q_a}/\lambda_{Q_r}$ = 0.25. Therefore, using the contoured limiter with two leading edges results in reduced heat fluxes compared with the flat limiter. However, since the heat fluxes on a flat, single-edged limiter can be accommodated, the flat, single-edged configuration was selected for FED because of its pumping adjustability, fabrication, and maintenance advantages.

CONCLUSIONS

Poloidal location, shape of the surface facing the plasma, and number of leading edges were the major FED limiter configuration issues considered in this paper. The configuration selected for the FED baseline pumped limiter is located at the bottom of the device and has a flat surface with a single leading edge. This design offers maintenance and fabrication advantages over other configurations studied. Because of the limited understanding of plasma edge conditions and possible need for pumping adjustment, further design complications such as a curved surface or two leading edges are not warranted.

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