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Design Considerations of Modular Pump Limiters for Large Tokamaks

T. Uckan
C. C. Klepper
P. K. Mioduszewski

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T. Uckan
C. C. Klepper
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ABSTRACT

Long-pulse (>10-s) and high-power (>10-MW) operation of large tokamaks requires multiple limiter modules for particle and heat removal, and the power load must be distributed among a number of modules. Because each added module changes the performance of all the others, a set of design criteria must be defined for the overall limiter system. The relationship between individual modules must also be considered from the standpoint of flux coverage and shadowing effects. This paper addresses these issues and provides design guidelines. Parameters of the individual modules are then determined from the system requirements for particle and power removal. Long-pulse operation of large tokamaks requires that the limiter modules be equipped with active cooling. At the leading edge of a module, the cooling channel determines the thickness of the limiter blade (or head). A model has been developed for estimating the system exhaust efficiency in terms of the parameters of the leading edge (i.e., its thickness and the design heat flux) in terms of given device parameters and the power load that must be removed. The impact on module design of state-of-the-art engineering technology for high heat removal is discussed. The choice of locations for the modules is also investigated, and the effects of shadowing between modules on particle and power removal are examined. The results are applied to the Tore Supra tokamak. Conceptual design parameters of the modular pump limiter system are given.

1. INTRODUCTION

Particle and power removal is an important issue in large tokamak fusion devices because of their long-pulse (>10-s) operation with high-power (>10-MW) plasma heating and extensive external plasma fueling [i.e., neutral beam injection (NBI), gas puff, and pellets]. In such devices, the particle recycling from the walls (liner/limiters) can reach 100% within a few seconds of the plasma discharge; this can cause density buildup and eventually lead to plasma disruption. One possible solution to this, as planned for the Tore Supra tokamak,[1] is to use a pump limiter system. A pump limiter can provide the exhaust capability needed for density control by removing a small percentage of the particles, which would otherwise be recycled. Single pump limiter modules have been used successfully on a number of fusion devices.[2] An axisymmetric pump limiter (toroidal belt) was installed on the TEXTOR tokamak,[3] and initial-phase test runs have already started. A pump limiter system, on the other hand, consists of several modules to handle the large power load and exhibits performance different from that of a single module. Since each added module changes the performance of the rest, design criteria need to be defined for the overall limiter system and then applied to module design. The relationship between individual modules must also be considered from the standpoint of flux coverage and shadowing effects.

In order to see the effect of the pump limiters on the device operation clearly, let us start with the equilibrium plasma density,[4]

$$N_e = \Phi_{\rm ext}\tau_p/[1-(R-\epsilon)] \ , \tag{1}$$

where $\Phi_{\rm ext}$, τ_p, R, and ϵ are the external fueling rate, the global particle confinement time, the particle recycling coefficient, and the pump limiter system exhaust efficiency, respectively. This relation demonstrates that the plasma density can be controlled very effectively with pump limiters having relatively low exhaust efficiency ($\epsilon \sim 0.1$) provided $R \approx 1$, which is the case for long-pulse devices. The required pump limiter exhaust efficiency is easily estimated from[4]

$$\epsilon = \Phi_{\rm ext}/(N_e/\tau_p) \ . \tag{2}$$

In this paper, we establish design criteria for the optimization of particle exhaust as a function of heat loads and the device parameters and then apply the results to study the performance of a system of modular pump limiters. First, we briefly review the characteristics and the basic parameters of a modular pump limiter.

The results are then applied to a modular system. The design considerations of this system are discussed in a model that gives the system exhaust efficiency in terms of the parameters of the device and the actively cooled leading edge. The model is then applied to the Tore Supra tokamak for estimating the conceptual design parameters of the pump limiter system.

2. MODULAR PUMP LIMITER FOR PARTICLE AND POWER REMOVAL

Figure 1 shows a schematic of a typical modular pump limiter and its parameters. The general physics of pump limiters have recently been discussed by Mioduszewski.[4] The basic principle of the pump limiter operation is as follows. Charged particles in the plasma scrape-off layer (SOL) that flow along the magnetic field lines enter the module from both the ion and the electron side, and they hit the neutralizer plate. As a result, a neutral gas with a pressure p_0 is formed in the pumping chamber; it can be exhausted with a pump that has an effective pumping speed of S_{eff}. The x-coordinate in Fig. 1 indicates the distance into the SOL from the last closed flux surface defined by the location of the module head. The rest of the notation on this figure is as follows:

- L_θ module poloidal extent,
- L_ϕ module toroidal extent,
- x_h module head thickness,
- d module leading edge diameter (which accommodates a cooling channel),
- Δ module throat entrance width.

We note that the module leading edge, where the particle flow is perpendicular, is subjected to a high heat flux—as much as 5 kW/cm^2 in large future tokamaks. Therefore, use of active cooling, as shown in this figure, is inevitable.

For these discussions, we assume that the SOL plasma parameters (e.g., the density, the electron temperature, and the particle and heat fluxes along the field line) all have exponential profiles in x with their respective e-folding scale (or characteristic) lengths, λ_n, λ_T, λ_Γ, and λ_q.

2.1 PARTICLE EXHAUST

The particle exhaust efficiency of a pump limiter module is given by[5]

$$\epsilon_{\text{PL}} = \epsilon_{\text{MC}}\epsilon_{\text{R}}\epsilon_{\text{coll}} \ , \tag{3}$$

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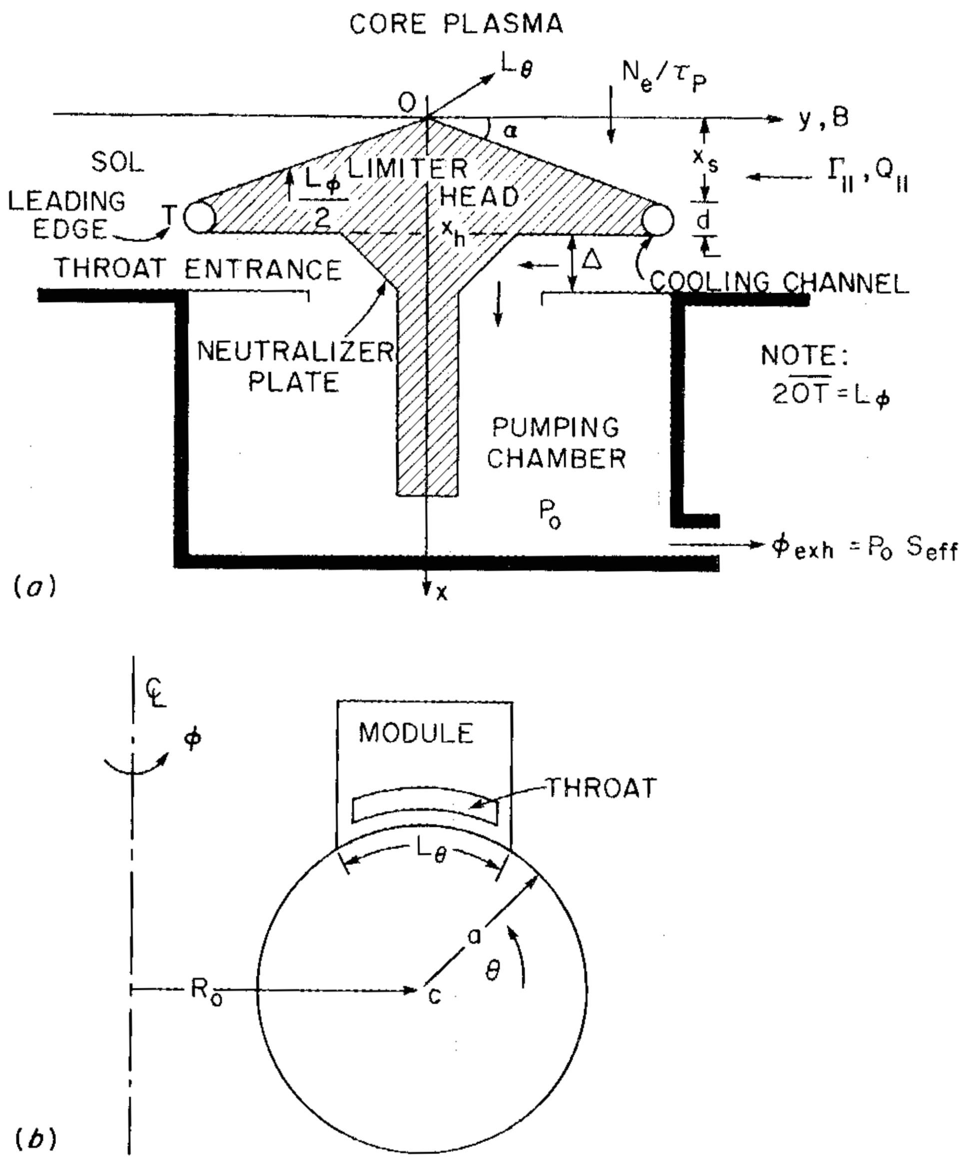

Fig. 1. (a) Schematic of a typical modular pump limiter and its characteristic parameters. (b) Location of the module in the tokamak plasma.

where $\epsilon_{\rm MC}$, $\epsilon_{\rm R}$, and $\epsilon_{\rm coll}$ are the module coverage, particle removal, and collection efficiencies, respectively. We briefly discuss $\epsilon_{\rm R}$ and $\epsilon_{\rm coll}$; $\epsilon_{\rm MC}$ is described in Appendix A.

The particle removal efficiency is a fraction of the total particle flux at the module throat that is actually exhausted by pumping, $\Phi_{\rm exh} = p_0 S_{\rm eff}$. The recent ALT-I modular pump limiter experiments carried out on TEXTOR[6] indicate $\epsilon_{\rm R}$ = 50–60%.

The particle collection efficiency shows the fraction of the total flux available for the module that actually enters the throat; it is given by[5]

$$\epsilon_{\rm coll} = \exp(-x_h)/\lambda_\Gamma)[1 - \exp(-\Delta/\lambda_\Gamma)] \ . \tag{4}$$

The throat entrance width should be at least a density scale length λ_n of the SOL for high collection. However, if it is too large, the particle backflow becomes high and the pressure buildup for efficient pumping cannot be established. For our discussions, we take $\Delta = \lambda_n$ and also assume $\lambda_T = 2\lambda_n$, as observed experimentally; this gives[5] $\lambda_\Gamma = (4/5)\lambda_n$. Thus, the module exhaust efficiency simply reduces to

$$\epsilon_{\rm PL} = (\epsilon_{\rm MC}/2.8)\exp(-x_h/\lambda_\Gamma) \ . \tag{5}$$

2.2 POWER REMOVAL

The total power received by the modular pump limiter $P_{\rm L}$ is the sum of the power to the module surface, to the leading edge, and to the neutralizer plate. It is shown[5] that $P_{\rm L}$ can be estimated from

$$P_{\rm L} = 2L_\theta Q_0 \lambda_q\{1 - \exp[-(x_h + \Delta)/\lambda_q]\} \ ,$$

where $Q_0 \equiv Q(x = 0)$ is the heat flux at the SOL boundary. Also, typically $(x_h + \Delta)/\lambda_q > 1$, where λ_q is the heat flux scale length of the SOL. Thus, we take

$$P_{\rm L} = 2L_\theta Q_0 \lambda_q \ . \tag{6}$$

Here again, for simplicity we use, for the rest of the discussions, $\lambda_q = (4/7)\lambda_n$, which is consistent with earlier assumptions on the SOL characteristic lengths.

3. MODULAR PUMP LIMITER SYSTEM

The power load in large tokamaks with $P_{\rm heating} \geq 10$ MW requires multiple pump limiter modules. Let us assume for our model calculations that the system consists of N identical modules that can remove particles with an exhaust efficiency ϵ. Furthermore, the limiters must handle a power load that is taken to be $P_T = (0.5\text{–}0.7)P_{heating}$.

The pump limiter system exhaust efficiency can be estimated as

$$\epsilon = N\epsilon_{PL} = (N\epsilon_{MC}/2.8)\exp(-x_h/\lambda_\Gamma) \ .$$

Here we also assume a full flux coverage system, $N \geq N_f$, where $N_f = \text{Integer}(1/\epsilon_{MC})$, as discussed in Appendix A. In this case, we achieve the highest exhaust efficiency possible:

$$\epsilon = \exp(-x_h/\lambda_\Gamma)/2.8 \ . \tag{7}$$

For $N > N_f$, the modules are said to be shadowing[5] each other, since there is more than one module in the flux tube defined by a module that is under consideration.

The system power handling can be calculated from the power received by each module,

$$P_L = 2L_\theta Q_0 \lambda_q(\text{eff}) \ , \tag{8}$$

where (from Appendix C)

$$\begin{aligned} \lambda_q(\text{eff}) &\equiv (1/2L_\theta)\sum_j (W_j^{+,-}\lambda_j^{+,-}) \\ &= \lambda_q(C_1 + C_2 N_f/N) \ , \end{aligned} \tag{9}$$

with j = (ion side, electron side) and $C_1 = \sqrt{2} - 1$, $C_1 + C_2 = 1$. Thus, the total power removed by N modules becomes simply

$$P_T = NP_L \ . \tag{10}$$

These N modules should be placed in the device so as to attain the expected optimum performance. This means that, from the particle removal point of view, the modules must be located to minimize shadowing. In our discussions, we assume a symmetric limiter configuration by considering an even number of modules that are placed in equal numbers at the top and the bottom of the device. In this case, the toroidal and the poloidal separations between the modules are $\phi_s = 4\pi/N$ and $\theta_s = \pi$, respectively.

As we discuss below, the actively cooled leading edge of the module has an impact on the amount of power that can be removed from the system safely, that is, without exceeding the maximum design value for the heat flux of the cooling channel at the leading edge. The design of limiter modules is always a compromise between a thin blade for high particle exhaust and a leading edge that is sufficiently recessed to be in a region of tolerable heat flux.

4. DESIGN CONSIDERATIONS

The maximum value of the heat flux, $Q_n(\max)$, and its location, x_m, for a circular cooling channel of diameter d for the leading edge of the pump limiter module, as shown in Fig. 2, are given by[5]

$$Q_n(\max) = Q_0 \exp(-x_m/\lambda_q) \cos\phi_m \ , \tag{11}$$

$$x_m = x_h - (d/2)(1 + \sin\phi_m) \ , \tag{12}$$

where

$$\sin\phi_m = [1 + (\lambda_q/d)^2]^{0.5} - (\lambda_q/d) \ . \tag{13}$$

With the present engineering technology[7,8] a typical design heat flux value for an actively cooled leading edge is $Q_n(\max) = 3$–$5\ \mathrm{kW/cm^2}$. This is possible with

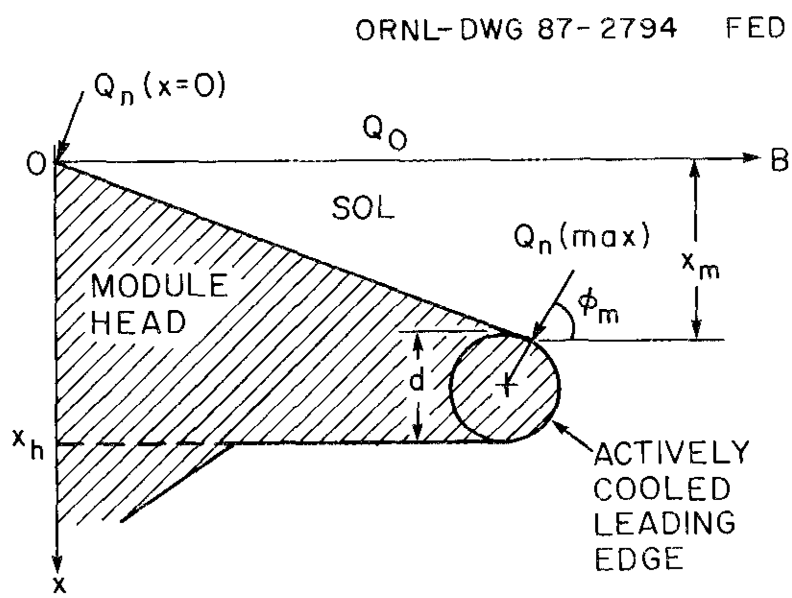

Fig. 2. Module head with an actively cooled leading edge with a diameter d, showing the maximum heat flux $Q_n(\max)$, its location x_m, and ϕ_m.

a leading edge made from a swirl tube cooling channel covered with graphite tiles that are brazed in vacuum. To examine the effect of $Q_n(\max)$ on the module design in terms of particle and power removal, we combine Eq. (11) with Eqs. (7)–(10) and obtain

$$F \equiv (3a/q)[Q_n(\max)\lambda_q/\epsilon^{1.4}P_{\rm T}] \tag{14}$$

$$= \exp[0.5(d/\lambda_q)(1+\sin\phi_m)]\cos\phi_m/[C_1(N/N_{\rm f})+C_2] \ . \tag{15}$$

Here we have used the fact that

$$N_{\rm f}L_\theta = (2\pi a/q) \ , \tag{16}$$

due to full flux coverage (see Appendix A). In Fig. 3, we display Eq. (15) for various values of λ_q/d and $N/N_{\rm f} = 1$, 1.5, and 2. For given device and pump limiter system requirements, the parameter F defined by Eq. (14) becomes known. Using the

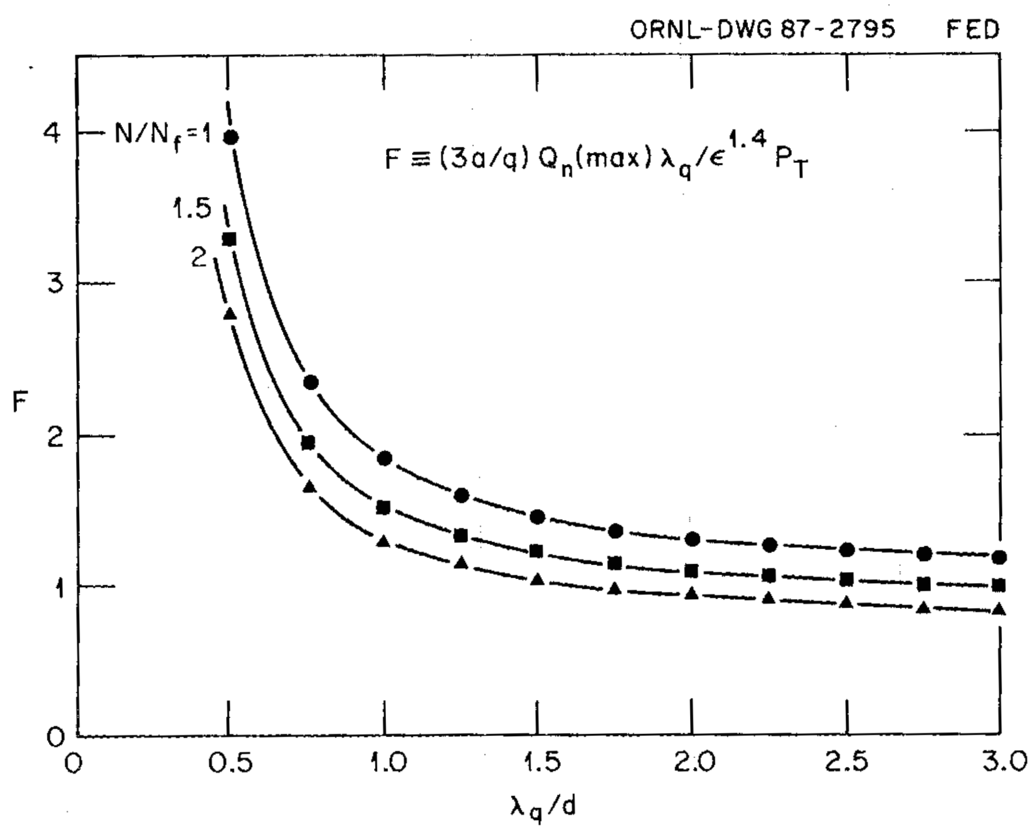

Fig. 3. Equation (15), $F \equiv (3a/q)[Q_n(\max)\lambda_q/\epsilon^{1.4}P_{\rm T}]$, as a function of λ_q/d for various values of $N/N_{\rm f}$.

value in the figure, we can establish possible realistic values of the cooling channel diameter, d, and the number of modules needed, N. Then the module head thickness is obtained from Eq. (7) as

$$x_h = -\lambda_\Gamma \ln(2.8\epsilon) \ . \tag{17}$$

The toroidal extent of the module L_ϕ is computed from the design heat flux $Q_s \equiv Q_n(x=0)$ at the limiter surface at the SOL boundary. From Fig. 2, we see that

$$L_\phi = 2Q_0(x_h - d)/Q_s \ . \tag{18}$$

The present design surface heat flux value is typically[9] Q_s = 300–500 W/cm^2.

5. APPLICATION TO THE TORE SUPRA TOKAMAK

We apply the model calculations to the Tore Supra tokamak[1] for estimating the conceptual design parameters of the modular pump limiter system. The Tore Supra fusion device is a large tokamak with a major radius R_0 = 2.35 m, a minor radius a = 0.75 m, a toroidal field B = 4.5 T produced by superconducting magnets at 4.2 K, and a maximum plasma current I_p = 1.7 MA. The typical discharge duration is expected to be 30 s; auxiliary plasma heating consists of 7 MW of NBI and a total of about 20 MW of ion cyclotron heating (ICH) and lower hybrid heating (LHH). It is expected that, during full-scale operation of the device, heating power of up to P_{heating} = 12 MW will be delivered by two of the three heating techniques. Tore Supra will also use pellet injection for core plasma fueling to permit operation at high plasma density ($\approx 10^{20}$ m^{-3}).

The large external sources ($\Phi_{\text{ext}} \approx 40$ torr·L/s) resulting from NBI and pellet fueling must be accommodated. In Tore Supra, the expected plasma efflux $N_e/\tau_p \approx 2.5 \times 10^{22}$ s^{-1} for a global particle confinement time of τ_p = 0.1 s, and this external fueling must be exhausted by the pump limiters to maintain particle balance. Thus, the overall required exhaust efficiency of the pump limiter system from Eq. (2) becomes $\epsilon \approx 10\%$.

Using typical SOL plasma scale lengths for Tore Supra,[5] λ_n = 3 cm, λ_Γ = 2.4 cm, and λ_q = 1.75 cm, and taking d = 2 cm for the module leading edge given the present technology of high heat flux removal, we find from Fig. 3 the value of F = 1.58. Furthermore, from Eq. (14), for a = 75 cm and q = 3, as calculated from Eq. (B.5) for an edge safety factor $q(a)$ = 2.5, we get

$$Q_n(\mathrm{max})/\epsilon^{1.4} P_T = 1.5 \times 10^{-2} \ , \quad \text{for } N = N_f \ , \tag{19a}$$

$$= 1.3 \times 10^{-2} \ , \quad \text{for } N = 1.5N_f \ , \tag{19b}$$

$$= 1.1 \times 10^{-2} \ , \quad \text{for } N = 2N_f \ . \tag{19c}$$

Furthermore, we need to remove a total power of $P_T = 6$ MW. Taking $Q_n(\mathrm{max}) = 3$ kW for the module leading edge,[9] we find from Eq. (19b) a system exhaust efficiency $\epsilon = 10\%$ with $N = 1.5N_f$; this may be an optimum case in terms of the number of modules needed. We take the poloidal extent of the module to be the vertical port dimension, $L_\theta = 40$ cm. Then, from Eq. (16), we find that a minimum of $N_f = 4$ modules is needed to have a full flux coverage system. Since the total number of modules for our case is $N/N_f = 1.5$, six modules are required to produce a symmetric pump limiter configuration.

The module head thickness is estimated from Eq. (17) by using $\epsilon = 10\%$ and $\lambda_\Gamma = 2.4$ cm, and we find that $x_h \approx 3$ cm. The toroidal extent of the module can easily be calculated from Eq. (18), with Q_0 taken from Eq. (8) and $\lambda_q(\mathrm{eff}) = 1.4$ cm, which is calculated from Eq. (9). We obtain $Q_0 = 8.9$ kW/cm^2. In turn, $L_\phi = 40$ cm, which is the vertical port size of the device, for $Q_s = 500$ W/cm^2.

These $N = 6$ modules are placed at the top and the bottom of Tore Supra in equal numbers, $N/2$, separated toroidally by $\phi_s = 120°$, as shown in (θ, ϕ) space in Fig. 4. In this figure, a flux tube defined by module 1, which is obtained by using Eq. (B.2), is also shown. We see that this module is partially shadowed by modules 4 and 6, as we expected, since $N > N_f$ for this case. Figure 5 is a perspective view of the planned vertical pump limiter module.[10] The module head is 40 by 40 cm and is made of copper cooling swirl tubes with 3-mm-thick graphite brazed armor protection. The leading edge of the module is expected to handle up to 3 kW/cm^2 of heat flux removal. The titanium getters in the pumping chamber can provide a pumping speed of 25,000 L/s. The limiter is designed to remove 1 MW of power. The head thickness is expected to be around 3 cm.

Experiments scheduled to start in early 1988 on the Tore Supra tokamak will provide the necessary data base for the performance of the modular pump limiter system needed for future fusion devices.

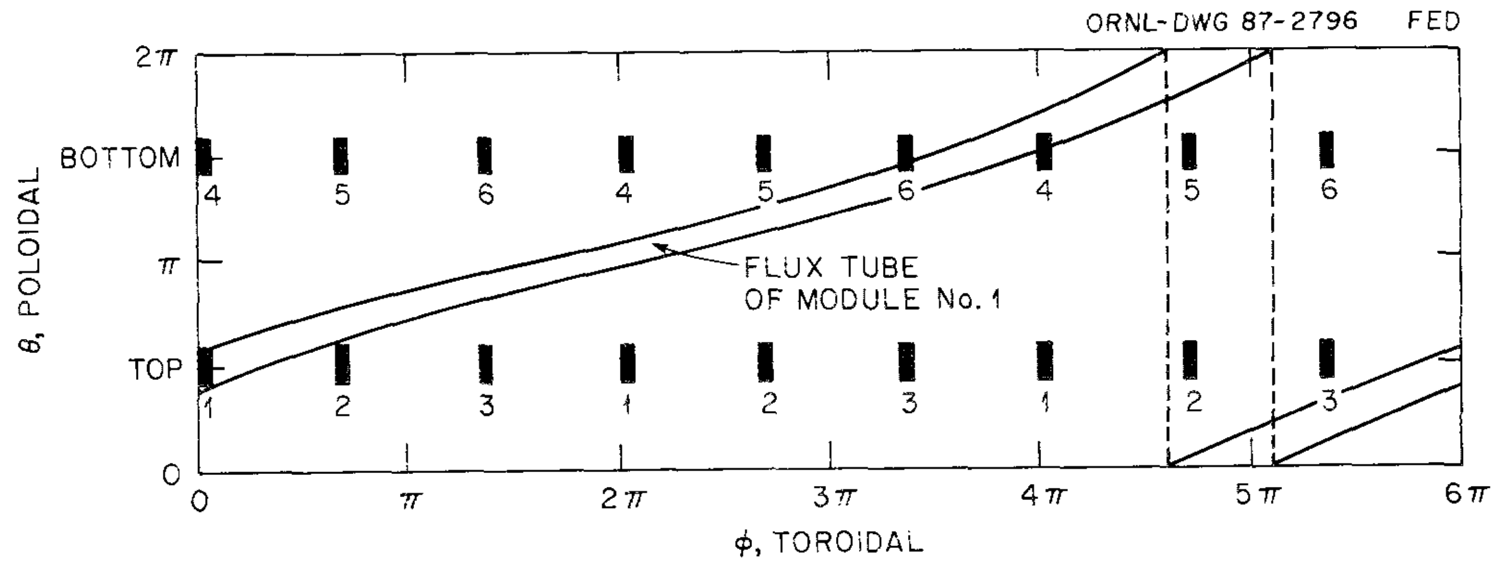

Fig. 4. Location of $N = 6$ modules in Tore Supra. Modules are placed at the top and bottom of the tokamak and 120° apart toroidally. A flux tube defined by module 1 is also shown. As expected, since $N > N_f = 4$, there is some shadowing between modules 4 and 6.

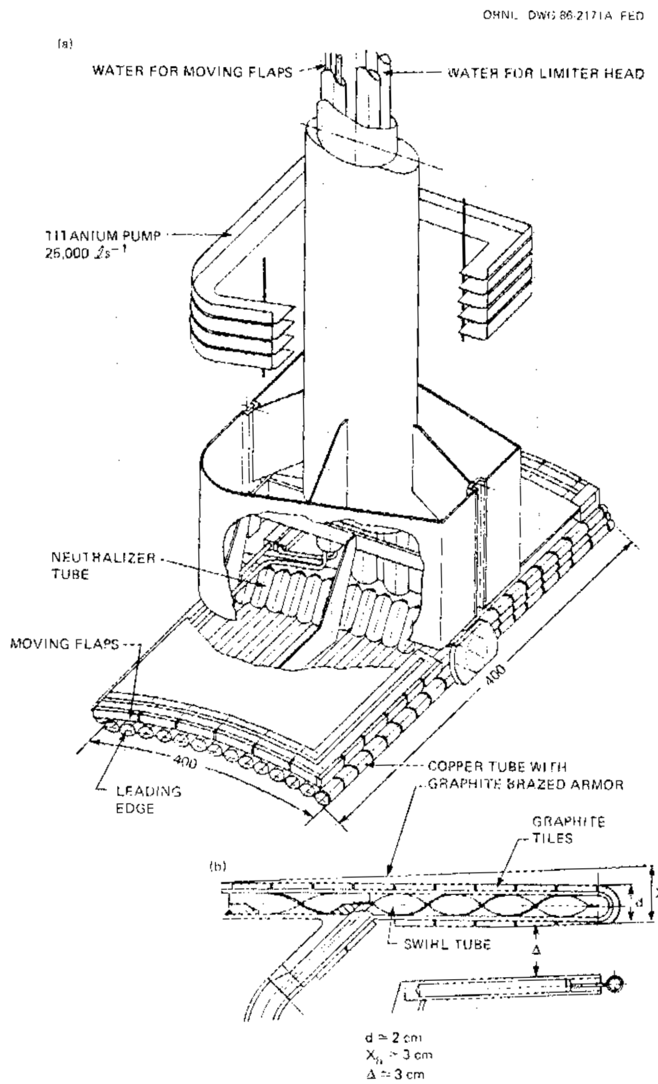

Fig. 5. (a) Perspective view of the planned vertical pump limiter module of the Tore Supra tokamak (Ref. 10). (b) The module head, including the leading edge, is made of copper cooling tubes with graphite brazed armor protection.

6. DISCUSSION

In this paper, we have discussed a pump limiter system with a number of modules that can handle a large amount of plasma heating for future tokamak fusion devices with extensive external fueling sources. We have developed a pump limiter model for estimating the design parameters of the module in terms of the parameters of an actively cooled module leading edge for a given exhaust efficiency and the power load that must be removed. The choice of module locations was also discussed, and the effects of shadowing between modules on particle and power removal were briefly examined. The results were then applied to the Tore Supra tokamak, and conceptual design parameters of the pump limiter system were presented.

As the long-pulse operation of tokamak fusion devices with large amounts of auxiliary plasma heating power and extensive plasma fueling becomes more common, use of some technique for particle and power removal is certainly inevitable. In this work, we have discussed a modular pump limiter system as one solution to this problem. In this regard, we are hopeful that engineering technology for high heat removal will soon achieve the routine application phase that we would like to have for the limiters.

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Appendix A

PUMP LIMITER MODULE FLUX COVERAGE ON TOKAMAKS

When a pump limiter module is placed in a tokamak edge for particle control, only some fraction of the total flux becomes available to the module. This fraction, the module flux coverage efficiency, is given by

$$\epsilon_{MC} = [\Gamma_\perp(x=0)A_\perp(\text{module area})] \times [\Gamma_\perp(x=0)A_\perp(\text{plasma area})]^{-1} .$$

In this equation, $\Gamma_\perp(x = 0)$ is the outward particle flux at the limiter location, $A_\perp$(plasma area) $= (2\pi a)(2\pi R_0)$ is the plasma surface area, and $A_\perp$(module area) is the area of the flux tube defined by the module in terms of (θ, ϕ) space as shown in Fig. A.1 and is given by

$$A_\perp(\text{module area}) = aR_0 \int_{\theta_1}^{\theta_2} d\theta \int_{\phi(\theta_1)}^{\phi(\theta_1+2\pi)} d\phi(1+\delta \;\cos\theta) , \qquad (A.1)$$

with $\delta \equiv a/R_0$, and we recall that here

$$\int_{\phi(\theta_1)}^{\phi(\theta_1+2\pi)} d\phi = [\phi(2\pi+\theta_1) - \phi(\theta_1)] = 2\pi q ,$$

where q is given by Eq. (B.5) in Appendix B. Carrying out the q integration in Eq. (A.1), we find

$$A_\perp(\text{module area}) = 2\pi q R_0 L_\theta [1 + 2(a\delta/L_\theta)\cos\theta_0 \sin(0.5L_\theta/a)] ,$$

where θ_0 is the poloidal midplane location of the module as shown in Fig. 6. Finally, the module flux coverage simply becomes

$$\epsilon_{MC} = (qL_\theta/2\pi a)[1 + 2(a\delta/L_\theta)\cos\theta_0 \sin(0.5L_\theta/a)] , \qquad (A.2)$$

and in the case of a large-aspect-ratio tokamak, $R_0/a \gg 1$, this reduces to

$$\epsilon_{MC} = qL_\theta/2\pi a . \qquad (A.3)$$

Equation (A.3) also defines the miminum number of modules N_f that will provide full flux coverage in a given device, $N_f\epsilon_{MC} = 1$, or

$$N_f \equiv \text{Integer}(1/\epsilon_{MC}) \approx 2\pi a/qL_\theta . \qquad (A.4)$$

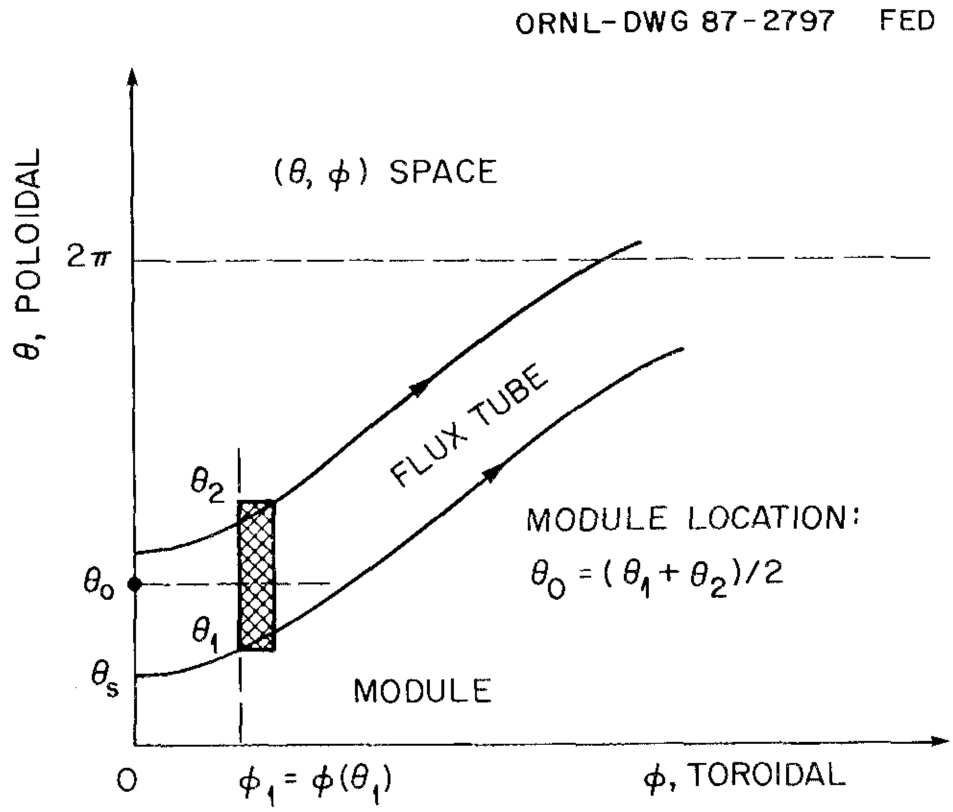

Fig. A.1. Area of the flux tube defined by the module in (θ, ϕ) space that is used for calculating the module flux coverage in Appendix A.

Appendix B

FIELD LINE MAPPING

In order to understand relationships, such as shadowing, between modules in a device, we need to perform the magnetic field line mapping starting from each module. The usual field line equation at the edge is

$$a d\theta / B_p = R_0(1 + \delta \cos\theta) d\phi / B_\phi \ ,$$

where B_p and B_ϕ are the poloidal and the toroidal magnetic fields, respectively. Rearranging this relation, we get

$$d\phi/d\theta = q(a)/[f(\theta)(1 + \delta\cos\theta)^2] \ . \tag{B.1}$$

Here, $q(a)$ is the "cylindrical edge safety factor" and $f(\theta) \equiv (1 + \delta\Lambda\cos\theta)$, with $\Lambda \equiv \beta_p + l_i/2 - 1$, which is the so-called Shafranov shift given in terms of the poloidal plasma beta β_p and the normalized plasma internal inductance l_i (≈ 1 on average). The integration of Eq. (B.1) gives the equation of the field line starting from the poloidal location of θ_s, Fig. A.1. For a typical β_p of 0.5,

$$\phi/q = [T(\delta,\theta) - T(\delta,\theta_s)] - [G(\delta,\theta) - G(\delta,\theta_s)] \ , \tag{B.2}$$

where

$$T(\delta,\theta) \equiv 2\tan^{-1}\{[(1-\delta)/(1+\delta)]^{0.5}\tan(0.5\theta)\} \ , \tag{B.3}$$

$$G(\delta,\theta) \equiv \delta(1-\delta^2)^{0.5}\sin\theta/(1+\delta\cos\theta) \ , \tag{B.4}$$

$$q \equiv q(a)/(1-\delta^2)^{1.5} \ . \tag{B.5}$$

Appendix C

ESTIMATE OF λ_q(eff)

Let us assume that we have a limiter system with full flux coverage, $N > N_f$, and therefore have shadowing between the modules, as shown in Fig. C.1. The power received by module k either from the ion drift (+) or from the electron drift (−) side for the shadowed zone j is given by Eq. (6),

$$P_j^{+,-} = Q_0 W_j^{+,-} \lambda_j^{+,-} \ , \tag{C.1}$$

where $W_j^{+,-}$ and $\lambda_j^{+,-}$ are the poloidal width and the heat flux scale length of the shadowed zone, respectively. Then the total power of the module k becomes

$$P_L(k) = \sum_j P_j^{+,-} \ , \tag{C.2}$$

with j = (ion side, electron side). If we define

$$\lambda_q(\text{eff}) \equiv (1/2L_\theta)\sum_j (W_j^{+,-}\lambda_j^{+,-}) \ ,$$

then Eq. (C.2) becomes

$$P_L(k) = 2Q_0 L_\theta \lambda_q(\text{eff}) \ . \tag{C.3}$$

It is shown that if two modules partially shadow a third one, as in Fig. C.1, then[5]

$$\lambda_q(\text{eff}) = \lambda_q(C_1 + C_2 N_f/N) \ , \tag{C.4}$$

where $C_1 = \sqrt{2} - 1$, $C_1 + C_2 = 1$, and λ_q is the heat flux scale length of the nonshadowed zone.

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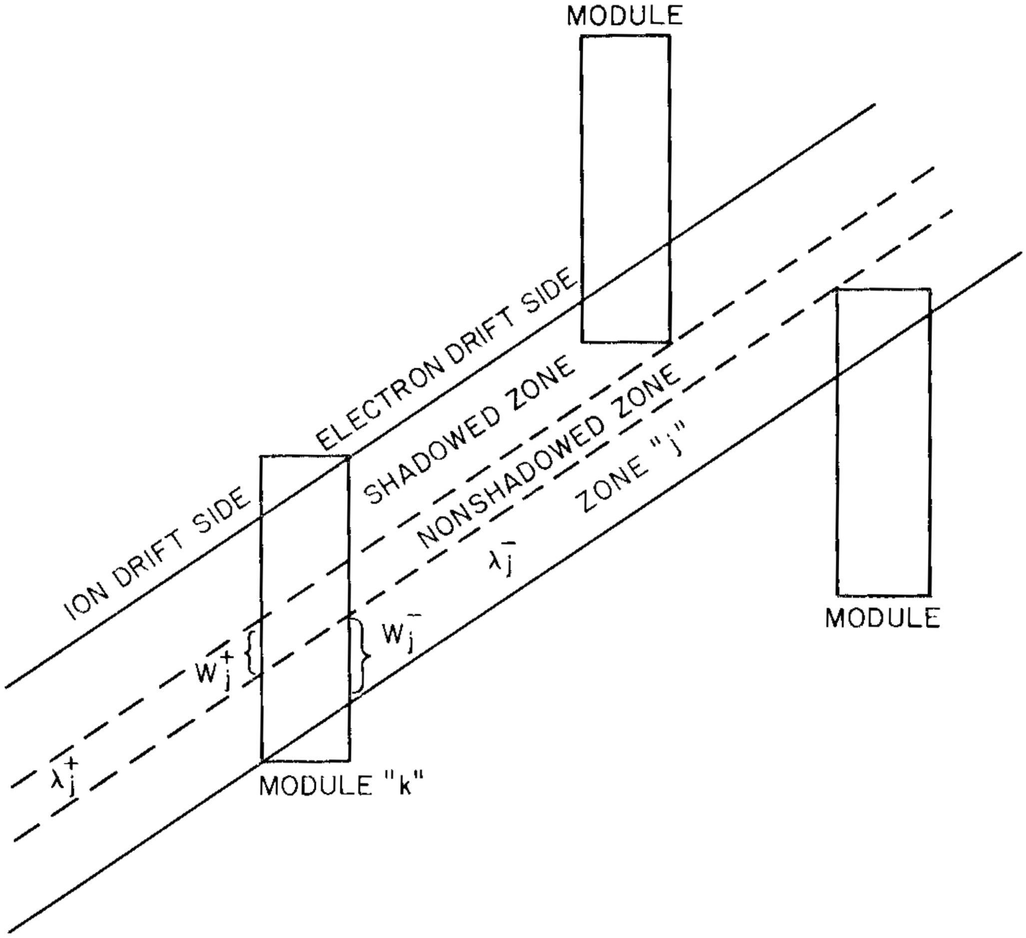

Fig. C.1. Typical shadowing case where three modules partially shadow each other (used for estimating the power received by module k in Appendix C).

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