Experimental Studies on Pump Limiters*

P. Mioduszewski

MASTER

Fusion Energy Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830 USA

CONF-820545--13

DE82 017408

Abstract

Pump limiters are mechanical devices for He-ash removal, fuel particle control, and possibly impurity control. Different designs have been suggested by various authors over the past decade. However, the magnetic divertor concepts seemed to be more promising, mainly because of their remote plasma-material interactions. All of the characteristics of magnetic divertors have been proven experimentally, but the overall performance and complexity cause concern about their application to tokamak reactors. Consequently, it is time now to explore the potential of mechanical particle control devices, i.e. pump limiters. Because of the high recycling at the limiter, it is sufficient to exhaust only a small fraction, about 1-10%, of the limiter particle flux to remove e.g. He at its rate of production. Pump limiter experiments have been conducted so far on Alcator, PDX, Macrotron, and ISX. Depending on the experimental design, a pressure build-up of between 1 mTorr and 50 mTorr has been reported. The closed configuration pump limiters provide high collection efficiencies, but have to accommodate high power fluxes at the leading edge. An open configuration, on the other hand, avoids leading edges but provides only fairly low collection efficiencies. The pump limiter development program now calls for a full pump limiter to be implemented in a major tokamak device. Presently, full-size pump limiter experiments on PDX, ISX, and TEXTOR are in preparation.

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

1. Introduction

Removal of He-ash and impurities are vital necessities in burning fusion devices. Magnetic divertors and pump limiters/mechanical divertors have been proposed to accomplish this task. Magnetic divertors seem to be very attractive for impurity control, because the plasma boundary is determined by a magnetic limiter (separatrix), and the interaction of energetic plasma ions with material surfaces is removed into a separate chamber. Additional impurity control is provided by the shielding action of the scrapeoff layer. All of these favorable characteristics of divertors have been demonstrated experimentally. On the other hand, conceptual design studies of fusion demonstration devices - like the Fusion Engineering Device (FED) or the International Tokamak Reactor (INTOR) - have revealed that magnetic divertors add undesirable complexity and cost to the already complicated design. Therefore, the performance of simple mechanical divertors, which have been proposed at various stages of the tokamak development, ought to be explored experimentally to find out if they can provide practical alternatives to magnetic divertors.

2. Synopsis of the Mechanical Divertor/Pump Limiter Concept

The principal idea of a mechanical divertor/pump limiter was published, almost a decade ago, by Vershkov and Mirnov in 1973.^[1] They suggested, as an intermediate step, to control the impurity content in tokamaks by improving the limiter. To minimize the impurity evolution at the limiter, they proposed to design it in the form of a rotating ring to spread the deposited energy over a larger area. The authors proposed a "mushroom" cross-section of the limiter ring with titanium getter on the lateral walls to perform some plasma- and impurity unloading. The pump limiter concepts that emerged until today are basically variations of this original idea. In 1974 Kelley suggested a

combined "Toroidal Band Limiter and Pump for a Tokamak".^[2] This limiter consists of vertical bars around the outer vacuum chamber wall, and the surface behind it is freshly evaporated titanium. A more detailed proposal of a "Scrapeoff Limiter" for α -particle exhaust and wall originated impurity screening was given by Bieger et al.^[3] They based their discussion on reactor applications and estimated an unloading efficiency of 0.1. A similar design of a scrapeoff limiter was proposed by Schivell.^[4] The emphasis of this proposal is on impurity control in a contemporary device like PLT, with an extrapolation to TFTR.

First pump limiter designs that combine α -particle exhaust with adequate heat removal capabilities, for steady state operation, have been published by Conn et al.^[5] and by Brooks et al.^[6] In these designs the limiter surface facing the plasma has a convex curvature. This way the leading edges are removed a few centimeters behind the plasma edge and the power loads are reduced correspondingly. Fairly extensive conceptual design studies for pump limiter systems were conducted for the Fusion Engineering Device (FED)^[7] and for the International Tokamak Reactor (INTOR).^[8] The FED pump limiter has one leading edge and is based on the idea that the heat load there can be controlled by changing the plasma major radius. The performance of the FED pump limiter has been studied in terms of plasma behaviour^[7, 9] as well as material aspects.^[10, 11] While the analysis of α -particle exhaust as well as plasma behaviour indicates satisfactory performance, the main culprit from the materials standpoint is the surface erosion due to sputtering and vaporisation following plasma disruptions. Depending on the plasma model, limiter lifetimes between a few weeks and a few months have been estimated.^[7, 10, 11] The INTOR-work on pump limiters^[8] includes studies on the following issues: heat load, erosion, impurity control, and particle removal.

combined "Toroidal Band Limiter and Pump for a Tokamak".[2] This limiter consists of vertical bars around the outer vacuum chamber wall, and the surface behind it is freshly evaporated titanium. A more detailed proposal of a "Scrapeoff Limiter" for α -particle exhaust and wall originated impurity screening was given by Bieger et al.[3] They based their discussion on reactor applications and estimated an unloading efficiency of 0.1. A similar design of a scrapeoff limiter was proposed by Schivell.[4] The emphasis of this proposal is on impurity control in a contemporary device like PLT, with an extrapolation to TFTR.

First pump limiter designs that combine α -particle exhaust with adequate heat removal capabilities, for steady state operation, have been published by Conn et al.[5] and by Brooks et al.[6] In these designs the limiter surface facing the plasma has a convex curvature. This way the leading edges are removed a few centimeters behind the plasma edge and the power loads are reduced correspondingly. Fairly extensive conceptual design studies for pump limiter systems were conducted for the Fusion Engineering Device (FED)[7] and for the International Tokamak Reactor (INTOR).[8] The FED pump limiter has one leading edge and is based on the idea that the heat load there can be controlled by changing the plasma major radius. The performance of the FED pump limiter has been studied in terms of plasma behaviour[7, 9] as well as material aspects.[10, 11] While the analysis of α -particle exhaust as well as plasma behaviour indicates satisfactory performance, the main culprit from the materials standpoint is the surface erosion due to sputtering and vaporisation following plasma disruptions. Depending on the plasma model, limiter lifetimes between a few weeks and a few months have been estimated.[7, 10, 11] The INTOR-work on pump limiters[8] includes studies on the following issues: heat load, erosion, impurity control, and particle removal.

In addition to the purely mechanical pump limiters, several hybrid concepts have been suggested.[12, 13, 14] The general idea of these proposals is to add magnetic coils with simple configurations with which the scrapeoff plasma is changed in such a way as to achieve a distributed power load. In the present article we want to restrict the discussion to mechanical devices and, therefore, the interested reader is referred to the literature given above.

3. Pump Limiter Concepts

Pump limiters are special limiters which combine helium-ash exhaust and fuel particle control with heat removal. The particle exhaust is based on the following processes: The plasma particles in the scrapeoff layer flow along the magnetic field lines to the limiter- or neutralizer-plate surface, where a large fraction of the impinging ions is neutralized and reflected. For typical tokamak conditions ($T_i = 20-200$ eV at the edge) the reflection coefficient is around 0.5, the neutral fraction of the reflected particles is close to one, and their energy peaks near the incident energy.[15, 16] A fraction of the reflected neutrals- which are no longer confined by the magnetic field- is then directed into a pumping channel. For a crude estimate, neglecting plasma effects, we assume that the neutral pressure in the pumping channel increases until the influx of fast particles is balanced by the backflow of room-temperature neutrals. The achieved density compression in the pumping channel is then proportional to the ratio of the velocities of incident to backflowing particles, which is typically in the range of 10-100. This compression can be expected to be even higher if the limiter configuration is such that the backflow of neutrals is impeded by the incident plasma flow ("plasma plugging").

Under the assumption that the recycling at the limiter is between 0.9 and 1.0, a small fraction of only 1-10% of the recycling flux corresponds to the plasma fueling rate, or to the He-generation rate in a DT-burning plasma. Removing this small fraction of the limiter flux can, therefore, balance the total influx or generation rate of the respective species.

We will discuss here two types of pump limiters which are shown in Fig. 1 schematically. Characteristic of the configuration in Fig. 1(a) is the channel behind the limiter. Due to this channel, the backflow of neutralized particles into the plasma chamber is strongly impeded by the incident plasma flow ("plasma plugging"). A consequence of this design is a high heat load at the leading edges. This problem can be avoided with a configuration as shown in Fig. 1(b) in which no leading edges are exposed to the plasma flow. However, in this case the collection efficiencies are low. Only a fairly small fraction of the incident particle flux is scattered into the pumping duct and the backflow into the plasma chamber is assumed to depend largely on the pumping speed of the applied vacuum pumps. Pump limiter types represented by the configuration in Fig. 1(a) will be referred to as "closed pump limiters" and the one shown in Fig. 1(b) as "open pump limiters". In the following sections we will discuss both configurations in more detail.

3.1 Closed Pump Limiter

The closed pump limiter combines high particle collection efficiencies with straight forward design.^[17] The main problem with this concept seems to be the power dissipation at the leading edge. The design distance between the plasma edge and the leading edge of the limiter is a trade-off between high particle collection and manageable heat load, and depends on the actual scrapeoff lengths of particle- and power fluxes. If the e-folding lengths of particle- and power flux are known, the limiter surface can be optimized for constant power density.^[18] Assuming an exponential decay of the power

density $q(x)$ with e-folding length λ_q , constant heat flux on the limiter requires its projection on the limiter surface to be a constant:

$$q(x) = q_0 e^{-x/\lambda_q} \cos \phi = q_0 c = q_d \quad , \quad (1)$$

where ϕ is the angle between the incident flux and the limiter surface normal, x is the distance into the scrapeoff layer, and the product $q_0 c$ is the design heat load q_d . From Eq. (1) we derive the equation for the surface contour^[19] of a toroidal limiter, which is in cartesian coordinates

$$y(x) = \lambda_q (c^2 - 1 - \arctan c^2 - 1 - c^{-2} e^{-2x/\lambda_q} - 1 + \arctan c^{-2} e^{-2x/\lambda_q} - 1) \quad , \quad (2)$$

where the coordinate y is tangent to the poloidal cross section of the plasma. This equation is valid for $0 < x < -\lambda_q \ln c$; for $x_m = -\lambda_q \ln c$ the projection angle ϕ becomes zero and the flux is perpendicular to the surface. From the definition in Eq. (1) c is the ratio of the design heat load and the maximum heat flux q_0 at $x = 0$. If q_0 is expressed in terms of the total parallel power in the scrapeoff layer P_T , c turns out to be

$$c = \frac{4\pi R_0 \lambda_q q_d}{P_T} \quad . \quad (3)$$

The total power deposited on the shaped part of the limiter is then $P_L = P_T(1 - e^{-x_m/\lambda_q}) = P_T(1 - c)$. For the total power of e.g. $P_T = 3$ MW, radius $R_0 = 1.5$ m, and design heat load of $q_d = 2$ MW/m² the constant heat flux limiter contours have been plotted in Ref. [20] as a function of the scrapeoff length λ_q .

After optimizing the power deposition on the limiter, we now ask how much particle removal can be achieved with this design. If the particle flux had the same scrapeoff length as the power flux, the fraction of particles flowing behind the limiter would be $f = e^{-x_m/\lambda_q} = c$, which is typically in the range of 0.05-0.2. However, since the particle flux scales as $nT^{1/2}$, while the power flux scales as $nT^{3/2}$, we expect a shorter power scrapeoff for equal density- and temperature e-folding lengths. Assuming radial dependences of $n(x) = n_0 e^{-x/\lambda_n}$ and $T(x) = T_0 e^{-x/\lambda_T}$ the composite e-folding lengths for particle flux λ_T and power flux λ_q become

$$\lambda_T = \frac{2\lambda_n\lambda_T}{2\lambda_T + \lambda_n} \quad \text{and} \quad (4)$$

$$\lambda_q = \frac{2\lambda_T\lambda_n}{2\lambda_T + 3\lambda_n} .$$

For $\lambda_n = \lambda_T$ these equations yield $\lambda_q/\lambda_T = 3/5$. In ISX we found typically $\lambda_T = 2$ cm and $\lambda_q = 1.5$ cm for ohmic discharges, from which we can deduce $\lambda_n = 2.5$ cm and $\lambda_T = 5$ cm. For a constant power limiter this implies that the fraction $f = e^{-x_m/\lambda_T} = c \lambda_q/\lambda_T$ of the particle flux flows behind the limiter. For a typical $c = 0.1$ and the ISX-values for λ_q and λ_T we obtain $f = 0.18$, i.e. 18% of the particles are available for pumping while the fraction $(1-c) = 0.9$ of the power is deposited on the front of the limiter. This example shows (given the ideal case of exponential decay of power and particle flux) that a particle scraper can be designed which has sufficient particle removal efficiency and manageable heat load at the leading edge. In the real world, however, the fluxes might deviate substantially from exponential behaviour and the characteristic lengths are difficult to predict in advance and/or may change during operation. Therefore, it is worthwhile to explore

other possibilities of particle collection, an example of which is the open pump limiter as shown in Fig. 1(b).

3.2 Open Pump Limiter

To avoid the problem of uncontrolled high heat loads at the leading edge, an open pump

limiter based on ballistic particle collection only has been proposed.^[20] To illustrate the principle, and to derive the basic equations, we begin with a simple geometry, as indicated in the insert of Fig. 2. The resulting equations for the particle collection efficiency are then applied to limiter configurations with no leading edge, as shown in Fig. 3. To compute the total flux reflected into a given pumping channel, we make the following assumptions: (1) the incident particle flux falls off exponentially with outward radial distance into the scrapeoff layer; (2) the reflection coefficient is $R = 0.5$ over the entire energy range;^[15, 16] (3) the reflected particles have a cosine distribution; (4) the energy of the reflected particles is a substantial fraction of the incident energy; (5) the neutral fraction of the reflected particles is close to unity.^[15] Under these assumptions, and for the geometry indicated in Fig. 2, we have computed the fraction of the incident particle flux $\Gamma_i = \Gamma_0 e^{-x/\lambda_T}$ that is reflected into the pumping channel. Per unit length dz' of the pumping channel the collected flux $d\Gamma_{col} / dz'$ is

$$\frac{d\Gamma_{col}}{dz'} = \frac{R_0 \Gamma_0}{\pi} \iiint \frac{e^{-x/\lambda_T} y(x_0 - x) dx dy dz}{(y^2 + (x_0 - x)^2 + z^2)^{3/2}} . \quad (5)$$

As an example, we have assumed a limiter height of $x_0 = 3\lambda_T$ and plotted the ratio of the collected particle flux Γ_{col} to the incident flux Γ_i as a

function of pumping channel width b and scrapeoff length λ_T . For a typical case of $\lambda_q = 1$ cm and $b = 2.5$ cm the collected fraction is 0.1.

These calculations indicate that at least for favorable geometries open pump limiters can provide sufficient plasma exhaust. We now apply the same principles to realistic limiter geometries, as shown in Fig. 3. These configurations have no leading edges. The probability that a particle is scattered into a pumping channel of width b is a function of the aspect ratio A , the channel width b over the limiter-plate width y_0 . Under the same assumptions as above, the particle collection probability has been computed for a toroidal device of $R_0 = 1.3$ m, $a = 40$ cm and $\lambda_T = 2$ cm. For the configuration 3 (a) and an assumed $A = 0.33$ the computation yields a marginal 2.6%. By modifying the basic geometry such that a configuration similar to the one shown in Fig. 3(b) results, aspect ratios between 0.5 and 1.0 can be achieved, yielding collection probabilities of 4.2% and 8.5% respectively.

The basic configurations 3(a) and (b) may have two main problems: (1) the conductance between plasma chamber and pumping chamber is high and very large pumping speeds are required to inhibit backflow of the gas if no plasma effects are present; (2) for large devices and/or high density scrapeoff plasmas the mean free path of the reflected particles may become shorter than the path length from the reflection point to the pumping chamber. In the latter case particles get re-ionized and recycle back to the limiter rather than being removed. This situation can be improved by splitting up the limiter into several separate plates as shown in Fig. 3(c). In this "venetian blind" configuration no leading edges are exposed to the plasma flux, since the leading edge of one plate is in the shadow of the trailing edge of the next plate. This arrangement reduces the conductance between the pumping chamber and the main plasma chamber, and it provides short path lengths of the reflected particles.

4. Experimental Pump Limiter Studies

Experimental studies on specific aspects of pump limiters have been conducted on Alcator A,[21] Macrotron,[22] PDX,[23] and ISX-B.[24, 20] The first results are encouraging and have initiated further experiments as well as conceptual design studies for future machines. On Alcator-A the possibilities of particle removal with mechanical limiters were investigated by measuring the neutral density build-up near the regular molybdenum limiter. A schematic view of the experimental apparatus is shown in Fig. 4. In the poloidal plane of the limiter the toroidal vacuum vessel has three rectangular slots, at the end of which the pressure build-up is measured with fast response (≤ 5 ms) absolute pressure gauges. The vacuum response time for room temperature deuterium was 10-15 ms at the horizontal duct and about 100 ms at the top and bottom ducts. Typical plasma parameters during these experiments were $B_T = 6$ T, plasma current $130 < I_p < 200$ kA, plasma density $1 \cdot 10^{14} < \bar{n}_e < 5.5 \cdot 10^{14} \text{ cm}^{-3}$, and the discharge duration between 115 and 140 ms. The filling pressure before plasma initiation was 4 to 8×10^{-5} Torr and the working gases included either H_2 , D_2 , or He. The evolution of plasma density $\bar{n}_e$ and limiter port pressures are shown in Fig. 5, along with plasma current, loop-voltage and gas puff. The pressure build-up in the three limiter ports is represented by the bottom three traces. The top port, which is not intersected by any portion of the limiter, does not exhibit any pressure rise during the discharge, while the side and bottom ports show large pressure rises. The different time histories are explained by the respective vacuum response times. This indicates that the pressure rise is primarily due to particles directly reflected from the limiter, and the charge exchange flux does not contribute significantly. The maximum pressure rise, observed at the bottom port, is 29 mTorr of D_2 when $\bar{n}_e = 5.1 \times 10^{14} \text{ cm}^{-3}$. This is a factor of 5 to

10 higher than the pressure rise due to puffing cold gas into the torus without plasma. Pressure measurements in other ports where there are no limiters showed a behaviour similar to the top port in the limiter plane.

By plotting the peak neutral pressure as a function of line-average density, as shown in Fig. 6, it was found that the gas accumulation below $n_e = 2 \times 10^{14} \text{ cm}^{-3}$ was modest while it increased steeply between 2 and $5 \times 10^{14} \text{ cm}^{-3}$. A measure for the efficiency of a pump limiter is the ratio of the particle flux entering the pump port to the total charged particle flux leaving the plasma volume. In Alcator this efficiency was found to be 1.5-10.5% over the density range investigated with D_2 , while the surface area of the limiter port apertures to the total vacuum vessel wall area was only 0.15%.

The second pump limiter experiment we want to discuss here was performed on Macrotr, [22] and is also based on the collection of reflected particles. Typical plasma parameters for these experiments were: $B_T = 0.3 \text{ T}$, $I = 80 \text{ kA}$, $n_e = 10^{12}-10^{13} \text{ cm}^{-3}$, $T_e = 120 \text{ eV}$ and $T_i = 50 \text{ eV}$. Due to the low magnetic field the Macrotr plasma has a large scrapeoff thickness of about 10 cm. Pump limiter experiments have been carried out with a small probe (2.3 cm diameter) and a large area limiter (20 cm $\times$ 60 cm $\times$ 6 cm), the experimental arrangements of which are shown in Fig. 7. We will include the probe measurements in our discussion, while the more recent large area limiter results will be reported elsewhere. [25] The probe is capable of radial movement and the collection throat has either micro channels or an open end as shown in Fig. 7. Approximately 60 cm from the collection throat the pressure is measured with a cold cathode pressure gauge. The vacuum time constant for room temperature molecular hydrogen is 50 ms.

A typical set of data signals is shown in Fig. 8. The neutral pressure in the collection probe reaches about 5 mTorr with a time delay relative to the density corresponding to the response time of the tube. The pressure rise as a function of probe position is shown in Fig. 9. Also plotted is the incident particle flux as inferred from Langmuir probe measurements. The maximum observed pressure is 8 mTorr corresponding to molecular densities of $4-6 \times 10^{14} \text{ cm}^{-3}$, which is more than 100 times the local plasma density. The graph also reveals that the ratio of the pressure increase to the incident flux is a function of position. The insert of Fig. 9 shows a polar plot of the maximum pressure at a given radial position. The pressure obtained on the ion drift side is approximately twice that on the electron drift side. Empirical scaling of the pressure build-up as a function of density shows a stronger than linear dependence, i.e. $p \propto n^2$ for the open probe and $p \propto n^{1.5}$ for the channeled probe. The authors attribute this behaviour to plasma effects rather than ballistic collection only. The strong density dependence of the particle removal efficiency gives additional evidence of plasma effects. The particle removal efficiency is defined here as the ratio of removed particle flux to incident plasma flux, where the particle removal is deduced from the rate of pressure rise in the tube. The maximum observed removal efficiency was 0.17 at a plasma density $\bar{n}_e = 1.5 \times 10^{12} \text{ cm}^{-3}$.

In ISX-B studies are being performed to explore possibilities of designing pump limiters with sufficient particle removal but without leading edges and the related power removal problems.^[20] For this purpose a probe type pump limiter was built with a geometry simple enough to be modeled by the equations for particle collection efficiency given in Section 3.2. Figure 10 shows the experiment arrangement. The geometry of the collection probe is similar to the one shown in the insert of Fig. 2. The probe consists of two separate electrically isolated blades intercepting the scrapeoff plasma

perpendicularly. A certain fraction of the plasma particles reflected from one of the blades is collected by a tube (3.5 cm diameter, 80 cm length) at the outer end of which the pressure rise is measured with a response time of 50 ms for thermal hydrogen. By simultaneously measuring the ion saturation current to the limiter blade, a correlation between incident flux and pressure build-up is found which allows one to deduce a particle collection efficiency. Both limiter blades are equipped with thermocouples to measure the total energy deposition during the discharge. The particle collection efficiency of this arrangement is calculated according to Section 3.2 and is 0.1.

The plasma parameters during these experiments were: $B_T = 1.2$ T, $I_p = 170$ kA, and $\bar{n}_e = 2-4 \times 10^{13} \text{ cm}^{-3}$. A typical set of results is shown in Fig. 11, where the pressure, plasma density, and fueling rate are plotted. The pressure rise, ion saturation current and the average energy flux density to the limiter were measured as a function of radial distance from the plasma edge, defined by the main limiter. Figure 12 shows the measured profiles. All data were taken on the electron-drift side of the limiter. The total pressure rise is modest, compared to those seen in other machines, but, referring to the Macrotron results, (see insert of Fig. 9) one might suspect it to be a factor of two higher on the ion-drift side. Pressure, as well as power and particle flux profiles, reveal an approximately exponential decay up to 3 cm behind the plasma edge, with e-folding lengths of $\lambda_q = 1.5$ cm and $\lambda_T = 2$ cm. Plasma density and temperature at $r = a$ were measured by Thomson scattering to be $n_e = 2.5 \times 10^{12} \text{ cm}^{-3}$ and $T_e = 30-40$ eV. The corresponding profiles in the scrapeoff were calculated from the Thomson scattering values at the edge, the measured profiles of ion saturation current j_{sat}^+ and power flux q , and the equations $j_{sat}^+ = n_e (2kT_e/\pi m)^{1/2}$ and $q = \gamma(j_{sat}^+/e)kT_e$. The corresponding e-folding distances for density and temperatures were found to be $\lambda_n = 2.5$ cm and $\lambda_T = 5.0$ cm respectively.

efficiency of 10% reveals that the measured efficiency exceeds the computed one by about 50% at the highest incident flux. This enhancement is assumed to be due to "plasma plugging" effects. The experiment has also been modeled with a Monte Carlo code,^[26] and the results are in good agreement with the experimental data.

While the experiments discussed so far are basically open pump limiters the "scoop limiter" installed on PDX^[23] is of the closed pump limiter type and exhibits quite different behaviour. The PDX experiments were conducted in OH deuterium discharges with typically $B_T = 1.7$ T, $I_p = 300$ kA, $n_e = 3 \times 10^{13} \text{ cm}^{-3}$ and standard D configuration. It was found that in this configuration most of the energy flows within about 1 cm of the separatrix, while for distances of the order of 5 cm outside the separatrix the plasma density and temperatures are essentially constant.^[27] Since the pulse length (~ 1 s) was also short enough for inertia cooling, the emphasis of the scoop experiment was on particle collection rather than energy removal. The location of the scoop and the corresponding pressure gauges on PDX are shown in Fig. 15(a), while details of the scoop can be seen in Fig. 15(b). The plenum of the scoop is connected through a duct of 130 cm length and 2.5 cm diameter to the pressure gauges. The scoop was moved through the scrapeoff layer and the pressure rise measured as a function of position. The peak pressures for various line-integrated densities are plotted in Fig. 16 as a function of major radius. Although the plasma densities were modest during these experiments, the pressure buildup in the scoop is impressive. The peak pressure was found to increase exponentially with the line-integrated density $\int n dl$ of the main plasma which is consistent with other measurements on PDX,^[27] showing that $\int n dl$ in the divertor throat rises exponentially with $\int n dl$ measured on the plasma equator. Plotting the maximum achieved pressures as a function of the electron density in the scrapeoff plasma reveals a much

stronger than linear dependence, which indicates strong plasma plugging effects. This behaviour has been modeled successfully with Monte Carlo techniques to yield a trapping efficiency of about 90% and a neutral pressure scaling roughly with the square of the plasma density.[28]

5. Future Experimental Work

Full-size pump limiters are presently being prepared for PDX[29], ISX, and TEXTOR. All of these pump limiters are designed to take the full heat load and exhaust a substantial fraction of the plasma fueling rate. The PDX limiter is based on the scoop limiter experience except that the leading edge is somewhat more recessed behind the plasma edge to avoid excessive heat loads. Figure 17 shows an isometric view of the large scoop limiter assembly. The limiter surface facing the plasma is armored with graphite tiles, and the neutralizer plate consists of copper which is plated with 0.5 mm thick vanadium to reduce sputtering. Power deposition profiles indicate that the limiter should withstand total plasma powers of 1-2 MW. Gas pumping is achieved with Ti-gettering in the plenum chamber of the scoop.

For ISX two full-size pump limiter modules are under construction, one of which is shown schematically in Fig. 18. The main constraint for the design was that only 15 cm diameter ports at the bottom of the machine were available. Based on previous experience in ISX, two "mushroom"-shaped limiters of about 15 cm diameter have been designed. The two pump limiter units are about 180° apart from each other toroidally, and each one has an internal pumping speed of approximately 2000 l/s provided by Zr-Al getter pumps.[30]

One of the limiter modules has a gas puffing system through the centre of the mushroom shaped head. This will allow the comparison of fueling efficiencies by puffing hydrogen through the plasma edge or through the

limiter. By puffing impurity gases through the plasma edge or through the limiter, and monitoring the impurity radiation from the plasma spectroscopically, one will also get a measure of the impurity shielding efficiency of the scrapeoff plasma. The fraction of plasma particles removed with these two units was estimated to be 5-10% of the total incident flux, depending on the plasma plugging effect. Assuming recycling coefficients between 0.9 and 1.0, a substantial effect on the plasma density is expected.

6. Discussion

To compare the results of the performed particle collection experiments, the achieved pressures p and typical collection efficiencies ϵ_{col} are collated in Table I, along with the line averaged electron density $\bar{n}_e$ and the scrapeoff plasma parameters.

TABLE I

	Type	P [mTorr]	$\epsilon_{\text{col}}^{\#}$ = $\Gamma_{\text{col}}/\Gamma_{\text{inc}}$	$\bar{n}_e$ [10^{13} cm^{-3}]	$n_e(\text{SOL})$ [10^{13} cm^{-3}]	$T_e(\text{SOL})$ [eV]	λ_n [cm]
ISX-B	open	2	~ 0.1 ; l	4	0.2	30	2.3
		5(NBI)		9.5			
Macrotron ^[22,25,31]	open	8	~ 0.1 ; g	0.15	0.2	30	~ 10
Alcator-A ^[21,32]	open	29	~ 0.1 ; g	50	8	10	1.4
PDX ^[23,33]	closed	48	~ 1.0 ; l	4.3	0.3-1.0	10	$\geq \dagger$

[#] l = local collection efficiency

g = global collection efficiency

$\dagger n_e$ = const over 5 cm outside the separatrix

Except for a few NBI-discharges in ISX, all studies were performed in ohmically heated discharges. The achieved neutral pressure is the most obvious parameter for comparison. It is also a very practical parameter, because it determines the necessary pumping speed required to exhaust a given amount of gas. The second important parameter for characterization of the pump limiter performance is the "collection efficiency" $\epsilon_{col} = \Gamma_{col}/\Gamma_{inc}$. For the experiments listed in Table I the collection efficiencies were all determined in different ways and their numerical values are not directly comparable. However, we can distinguish two classes of experiments: (1) open pump limiter experiments with ϵ_{col} in the order of 0.1, and (2) a closed pump limiter with ϵ_{col} in the order of one.

For a rough estimate of the achievable pressure, we assume that the collected fast flux is balanced by the (near) thermal backflow. Actually, the slowing down process in the duct creates a non-thermal velocity distribution and the backflow is likely to contain considerable non-thermal components. In addition, the backflow of neutrals might be impeded by the plasma ("plasma plugging"), leading to higher pressure buildup. These complex processes, including plasma effects outside the collection duct, have been simulated successfully with Monte Carlo techniques to obtain more accurate estimates for pressure rises and collection efficiencies.[34, 35, 36]

The experiments performed on ISX and Macrotor are very similar. Nevertheless, the pressure measured in Macrotor is higher than in ISX by a factor of 4. How can this discrepancy be explained? Comparing the geometries of the two pump limiter probes reveals that the concave shape of the Macrotor probe is likely to be more favorable for particle collection than the flat ISX probe, which was designed for easy modeling of the collection efficiency. In addition, as measured on Macrotor and shown in

the insert of Fig. 9, the pressure can be higher on the ion drift side than on the electron drift side by a factor of two. This is not understood, but it is consistent with findings on TFR-600^[37] and other devices which show that deposition probes collect about three times more deuterium on the ion side than on the electron side. While the relevant Macrotror data are taken at the ion side, all ISX measurements correspond to the electron side. Thus, taking into account the orientation of the probe plus the shape of the collecting surface, the discrepancy in neutral pressure buildup might be explained.

Comparing the ISX and Macrotror results with the ones obtained in Alcator, we find that the pressure rise on Alcator is fairly high for an open pump limiter experiment. This is mainly due to the high density and short fall-off length in the scrapeoff plasma yielding high absolute fluxes.

The most impressive pressure rise was achieved in the "scoop limiter" on PDX. There are essentially two reasons why one would expect good performance of this closed pump limiter. First, the neutralizer plate has a favorable inclination with respect to particle reflection into the pumping chamber, while in open pump limiters this surface is directed, in contrary, toward the plasma chamber. Second, the path length from the neutralizer plate to the plasma chamber can be made long enough (cf. Fig. 15) to prevent backflow of neutral particles ("plasma plugging"). The PDX results confirm the anticipated high particle removal efficiency.

To evaluate the different types of pump limiters it is useful to establish some additional criteria. We define the "particle exhaust efficiency" $\epsilon = \epsilon_{col} \cdot \epsilon_t$ as the product of collection efficiency and trapping efficiency. The trapping coefficient ϵ_t accounts for the collected fraction that is actually trapped: $\epsilon_t = (\Gamma_{col} - \Gamma_{out}) / \Gamma_{out}$, where Γ_{out} corresponds to the backflow. For the particle scraper $\epsilon_t = 0.9$ is assumed,^[28] for

ballistic limiters ϵ_t is likely to be considerably less, and also dependent on the applied pumping speed. Thus, for favorable geometry we expect exhaust efficiencies close to one for closed pump limiters and of 0.1-0.2 for open pump limiters, but in either case only at the expense of extreme heat loads. To obtain a measure for the efficiencies that can actually be utilized, we define the "practical exhaust efficiency" ϵ' which is achievable with a limiter that is designed for tolerable heat loads. For the closed pump limiter with constant power load the practical collection efficiency was deduced in Section 3.1 to be $f = c \lambda_q / \lambda_r$. For $c = q_d / q_0$ and $q_0 = P_T / 4 \pi R_0 \lambda_q$ the practical exhaust efficiency at design heat load q_d and total limiter power P_T is

$$\epsilon' = \frac{q_d}{P_T / 4 \pi R_0 \lambda_q} \cdot \lambda_q / \lambda_r \cdot \epsilon_t \quad (6)$$

For short pulses the design load q_d can be chosen substantially higher than for steady state operation. Therefore, the efficiency according to Eq. (6) depends on the pulse length. Taking FED as an example for a steady state device with $P_T = 50$ MW, $q_d = 2$ MW/m², $R_0 = 5$ m, $\lambda_q = 0.02$ m, $\lambda_r = 0.033$ m, and $\epsilon_t = 0.9$, the practical exhaust efficiency is $\epsilon' = 0.15$. For the open limiter the practical exhaust efficiency cannot be computed with a simple analytical expression as in Eq. (6). Depending on the geometry, the collection efficiency is determined by rather complex integrals of the type given in Eq. (5). The design approach for this case would be to find the limiter shape with tolerable heat flux and compute the collection efficiency for this specific case. Although designs favorable for particle collection (as the one shown in the insert of Fig. 2) may provide between 0.1 and 0.2, realistic configurations with adequate heat

removal in steady state seem to have collection efficiencies of only 0.02 to 0.08. The trapping efficiency is likely to be considerably less than one. If pumping speeds are applied which are of the order of the conductance of the particle collection slot, one might expect $\epsilon_t = 0.5$. Thus, a conservative estimate of the exhaust efficiency is between 1% and 4%. The Alcator results seem to indicate better performance of open pump limiters, but in steady state operation the particle and associated power fluxes on the limiter have to be reduced to a tolerable level, which will then reduce the exhaust efficiency correspondingly.

7. Conclusions

Experimental studies with pump limiters, performed on present day tokamaks, show that the achievable neutral pressures are sufficient for effective particle exhaust. At the fairly high fluxes of today's pulsed devices, both open and closed limiters seem to provide the necessary collection efficiencies. Extrapolation to future steady state devices with considerably lower fluxes, however, indicates that closed pump limiters should have higher efficiencies, even at tolerable leading edge heat loads. One disadvantage of the closed pump limiter is that the plasma edge parameters have to be known in advance to design the limiter properly. This may be impossible. Furthermore, the edge plasma is likely to change in different operating regimes of the device. Overall, open pump limiters seem to have much lower efficiencies, but can be designed without leading edges, and have the further advantage that larger uncertainties in the plasma parameters can be accommodated.

A comparison of the performance of pump limiters and magnetic divertors should be based on the following criteria: particle exhaust, energy removal, impurity control, and complexity of design. The scoping studies performed

on present-day machines have provided encouraging results concerning particle exhaust. The next logical step is a full size pump limiter to demonstrate particle control. This should be followed by a pump limiter with particle control capabilities under long pulse energy removal conditions, i.e. for quasi steady state operation requiring active cooling. In the third stage of the pump limiter development which could also be part of the first and second stages we have to explore the impurity control capabilities. The potential for impurity control is not as obvious for pump limiters as it is for magnetic divertors, the primary reason being the interaction of the plasma with the limiters in the main discharge chamber. On the other hand, it has been shown recently that co-injected neutral particle beams drive impurities out of the plasma centre into the edge.^[38] A combination of beam driven impurity control and a pump limiter to skim off the edge impurities may be one possibility to achieve sufficient impurity control which has to be explored in the future.

Acknowledgements

I thank J. Sheffield and M. Saltmarsh for their encouragement and support of this work, and A. Wootton, P. Edmonds, H. Howe, and R. W. Conn for valuable discussions. I am also indebted to Charles Schultz for invaluable inspirations, and to Gail Robinson for not giving up one day before this paper was due.

References

1. V. A. Vershkov and S. V. Mirnov, "The Role of Impurities in the Present Tokamak Experiments," PPPL Matt-Trans 113 (1973), and Nucl. Fusion 14 (1974) 383.
2. G. G. Kelley, "Modification of the Belt Limiter Concept to Provide

for Purging of Impurities," ORMAK II/TTF Design Memo No. 17, Nov. 22, 1974.

3. W. Bieger, K. H. Dippel, G. Fuchs, and G. Wolf, Symposium on Plasma-Wall-Interaction, Jülich, 1976.
4. J. F. Schivell, "Method of Plasma Impurity Control Without Magnetic Divertor," PPPL-1342, June 1977.
5. R. W. Conn, I. N. Sviatoslavsky, and D. K. Sze, Proc. 8th Symposium on Engineering Problems in Fusion Research, San Francisco, 1979.
6. J. N. Brooks, C. C. Baker, H. C. Stevens, and C. A. Trachsel, *ibid.*
7. C. A. Flanagan, D. Steiner, G. E. Smith, Editors Fusion Engineering Device Design Description, ORNL/TM-7948, Dec. 1981.
8. U.S. Contribution to the Impurity Control Physics; INTOR Workshop, Phase 2A, Session IV, March 1982.
9. H. Howe, "Physics Considerations for the FED Limiter," ORNL/TM-7803, June 1981.
10. G. M. Fuller, Coordinator, FED First Wall/Limiter Workshop, Oak Ridge, April 30, 1981.
11. J. R. Haines, B. A. Cramer, J. P. Davisson, and H. C. Mantz, 2nd Topical Conference on Fusion Materials, Seattle 1981, to be published in J. Nucl. Materials.

12. Fusion Research Development Center, INTOR Workshop Report, Group 3, Impurity Control, Fueling and Exhaust, JAERI-M 8622 (1979).
13. T. Hino, "New Impurity Control Scheme by Ripple Limiter," JA-A16256, January 1981.
14. G. Fuchs, "A Scheme to Pump the Exhaust from a Fusion Reactor," Jül-1696, December 1980.
15. W. Eckstein and H. Verbeek, J. Nucl. Material 76 and 77 (1978) 365.
16. O. S. Oen and M. T. Robinson, J. Nucl. Material 76 and 77 (1978) 370.
17. J. A. Schmidt, Comments Plasma Phys. Cont. Fusion; 5, 6 (1980) 225.
18. J. A. Schmidt, TFTR Physics Report No. 12, PPPL, 1979.
19. P. Mioduszewski, "A Constant Heat Flux Plasma Limiter for TEXTOR," Jül-1681, October 1980.
20. P. K. Mioduszewski, P. H. Edmonds, and J. Sheffield, J. Vac. Sci. Technology, 20 (1982) 1284.
21. David O. Overskei, Phys. Rev. Lett. 46 (1981) 177.
22. S. Talmadge, R. W. Conn, A. K. Prinja, and R. J. Taylor, submitted to Phys. Rev. Letters.
23. R. Jacobsen, "Preliminary Particle Scoop Limiter Measurements in PDX," PPPL-1825, August 1981.

24. P. K. Mioduszewski, P. H. Edmonds, and J. Sheffield, Proc. of IAEA Tech. Committee Meeting on Divertors and Impurity Control in Tokamaks, Garching, July, 1981.
25. S. Talmadge, R. W. Conn, A Prinja, and R. J. Taylor, paper C4, this conference.
26. J. T. Hogan, paper F25, this conference.
27. D. K. Owens, Bull. APS Vol. 25, No. 8, 941, October 1980.
28. M. Petravic, D. Post, D. Heifetz, and J. Schmidt Phys. Rev. Lett. 48 (1982) 326.
29. R. Budny, unpublished.
30. SAES Getters, S.p.a. Milano, Italy, Document No. G77620 (1977).
31. S. J. Zweben and R. J. Taylor, "Edge Plasma Measurements on the UCLA Tokamaks," UCLA/PPG-543, March 1981.
32. L. Scatturo and B. Kusse, Nucl. Fusion 18 (1978) 1717.
33. R. Budny, to be published in J. Vac. Sci. Technology.
34. D. E. Post, M. Petravic, and D. Heifetz, paper D1, this conference.
35. A. K. Prinja, R. W. Conn, S. Talmadge, D. Heifetz, and D. Post, paper C5, this conference.
36. D. Heifetz, D. Post, J. Cecchi, and M. Ulrickson, paper C8, this conference.

37. G. Staudenmaier, P. Staib, and W. Poschenrieder, J. Nucl. Mater. 93 and 94 (1980) 121.

38. R. Isler et al., Phys. Rev. Lett. 4F (1981) 649.

Figure Captions

Fig. 1 Schematic of closed (a) and open (b) pump limiter configurations.

Fig. 2 Pump limiter based on ballistic particle collection: fraction of particles scattered into pumping channel.

Fig. 3 Pump limiter configurations without leading edges (a) basic design, (b) increased collection efficiency (c) "venetian blind" - version.

Fig. 4 Cutaway view of the Alcator-A pump limiter experiment (courtesy of D. Overskei).

Fig. 5 Temporal evolution of a typical deuterium discharge. The bottom three traces are the signals from the pressure gauges in the limiter ports (courtesy of D. Overskei).

Fig. 6 Maximum neutral pressure in the limiter bottom port of Alcator as a function of peak line-average density (courtesy of D. Overskei).

Fig. 7 Experimental arrangement of pump limiters in Macrotor (courtesy of S. Talmadge).

Fig. 8 Typical set of raw data of Macrotor pump limiter experiment (courtesy of S. Talmadge).

Fig. 9 Peak pressure and incident ion flux as function of position in

Macro-tor. The insert shows a polar plot of the pressure (courtesy of S. Talmadge).

Fig. 10 Schematic of pump limiter scoping studies on ISX-B.

Fig. 11 Pressure rise, line-average electron density, and fueling rate of pump limiter experiment on ISX-B.

Fig. 12 Pressure rise, ion saturation current density, and average power deposition as function of radial position in ISX-B.

Fig. 13 Peak pressure as a function of line-average density for OH- and NBI-discharges in ISX-B.

Fig. 14 Collected particle flux deduced from equilibrium pressure as a function of incident flux on ISX-B.

Fig. 15 (a) Schematic of the PDX pump limiter experiment

(b) Design of the scoop limiter (courtesy of R. Jacobsen).

Fig. 16 Peak pressure in the PDX scoop limiter as a function of major radius for different line-integrated densities (courtesy of R. Jacobsen).

Fig. 17 Isometric view of the large PDX scoop limiter (courtesy of R. Budny).

Fig. 18 Full-size pump limiter module to be installed on ISX-B.

(a) CLOSED CONFIGURATION

(b) OPEN CONFIGURATION

V_L (3v/d)

I_p (52 kA/d)

$\bar{n}_e$ ($8 \times 10^{13} \text{ cm}^{-3}/d$)

D_2 INJECTION
PRESSURE ($100 \mu/d$)

LIMITER
PORT
PRESSURES
($5 \mu/d$)

TOP
SIDE
BOTTOM

$t=0$

$t(20ms/d)$

13 msec/div

PRESSURE, ION SATURATION CURRENT, POWER DEPOSITION

ORNL-DWG 82-2518

FED

81X0264

ORNL-DWG 82-2513 FED