Can Wall and Limiter Erosion be Eliminated in Fusion Reactors?*

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Introduction

Pump limiter designs, while generally simpler than magnetic diverters have two primary problems: wall erosion and the resultant plasma impurity concentration. In principle, these problems can both be solved by artificially maintaining an impurity density of low-Z materials in the plasma edge region which should enable impurity deposition on the limiter and walls to exactly compensate erosion while at the same time producing negligible radiation loss from the plasma. In this paper we outline a proposed method of in-situ maintenance of pump limiters for tokamak reactors and describe how this system could be operated, perhaps under steady-state conditions.

Pump Limiters

The most detailed analysis of pump limiters has been done as part of the STARFIRE¹ and FED² design effort. In the STARFIRE design the limiter was placed along the outside circumference of the machine and in the FED the limiter was a flat plate intersecting the bottom edge of the plasma. While both of these locations offer ease of mechanical access and other advantages, we consider here a limiter along the inside (small R) wall of the vacuum chamber. This limiter system would utilize the inner wall surface to define a plasma edge and absorb thermal power and the top and bottom edges could be used in a pump limiter scheme. This design is shown in Fig. 1.

Among these are: 1) The power output of the reactor is related to major radius by the relation

$$P = (B_T^4) \left( \frac{\text{Vol}}{R^4} \right) (AR) = 1/R$$

where $B_T$ is the toroidal field, $R$ is the major radius and $A$ the plasma cross section, and the geometric parameters of the reactor are fixed. Thus, removing the inner scrape off between the plasma and the wall produces a significant benefit in fusion power output. 2) The thermal heat load of the plasma can be spread over a large area and the local power deposition can be minimized. 3) The inner wall of the vacuum chamber will have to be designed to withstand disruptions so it is undesirable to design another area to withstand the steady-state heat loads. 4) The inner wall provides a surface least sensitive to toroidal field ripple. 5) Neutron shielding problems are no worse than other designs (perhaps somewhat better than the STARFIRE where additional shielding was required on the outer wall). 6) The limiter utilizes the region of the plasma where the field lines are spread farthest apart and the local power density can be made lowest. An additional feature of this system is that alpha pumping efficiency is greatest when the plasma shape is optimized and a production is maximized. The parameters of the limiter environment are shown in Table 1.

### Table 1

<table>
<thead>
<tr>
<th>Assumed Limiter Environment</th>
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<tbody>
<tr>
<td>Ion Flux</td>
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<tr>
<td>Ion Temperature (Limiter Radius)</td>
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<tr>
<td>Flux e Folding Length</td>
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<tr>
<td>Temperature e Folding Length</td>
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<tr>
<td>Limiter Geometry</td>
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<td>Pump Ports</td>
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### In-Situ Low-Z Coatings

Low-Z coatings have been proposed for the first wall limiter systems of reactors by a number of people. If sputtering is assumed to be the dominant source of impurity introduction (chemical sputtering arcing and thermal description are assumed negligible) then the equilibrium impurity density ratio $n_Z/n_H$ can be found in terms of the edge particle confinement times $\tau_H$ and $\tau_Z$, and sputtering yield $S_{HZ}$, $S_{ZZ}$. This relation is

$$\frac{n_Z}{n_H} = \frac{\tau_Z}{\tau_H} \frac{S_{HZ}}{1 - S_{ZZ}}$$

where the critical density ratio for ignition has been shown to be roughly

$$\frac{n_Z}{n_H} = \frac{\tau_Z}{\tau_H} \frac{S_{HZ}}{1 - S_{ZZ}}$$

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for light ions. Assuming the impurity density ratio is constant throughout the plasma, these relations imply the constraint on the self-sputtering coefficient that

$$S_{zz} < 1 - \left(\frac{T_z}{T_H}\right)^2 (S_{H2} + Y).$$

The addition of other sources of impurities (chemical sputtering, arcing, etc.) further reduces the allowable range of $S_{zz}$. Defining a yield due to other effects

$$Y = \frac{\text{injected impurities}}{\text{exiting H ions}},$$

we obtain

$$S_{zz} < 1 - \left(\frac{T_z}{T_H}\right)^2 (S_{H2} + Y). \quad (1)$$

It has been shown using simple approximations of sheath potential, electron and ion temperatures, ionic charge, etc. that ignition should be possible for C, Be and B walls at all plasma edge temperatures, but for heavier walls only with plasma edge temperatures less than roughly 50 eV. Chemical sputtering may be troublesome for B and C however, and neutrons react strongly with common isotopes of B. Thus this study assumes that He would be the most desirable coating material.

The primary mechanical problem caused by the plasma is the high erosion rate due to the bombardment of plasma ions. This erosion rate must be matched in an operating reactor by an equal redeposition rate, otherwise the impurities would build up in the plasma. Calculations have shown that erosion is the dominant effect where the plasma is hot and dense and deposition dominates where the plasma temperature is coldest (see Fig. 2). This produces a net flow of surface material from regions where the limiter/wall sees plasma ions near the maximum in sputtering yields ($r \sim$ small), to regions where lower temperature ions hit the wall ($r \sim$ large). In order to balance erosion it is necessary to raise the local impurity density in the plasma to artificially enhance the redeposition rate where erosion dominates. This can be achieved by doping the edge regions of the plasma with impurities. The amount of material required for recoating is a function of minor radius. A rough estimate of the mass required is given by the difference between the curves in Fig. 2.

It seems reasonable to assume that material deposited from the plasma should have similar properties to material from which erosion is taking place. This assumption is equivalent to the assumption that the self-sputtering rate $S_{zz}(E)$ is continuous as it goes through one, since deposition will occur where $S_{zz}$ is less than one and erosion will occur when $S_{zz}$ is greater than one. Most parameterizations of $S_{zz}$ assume this continuity.

In low duty cycle machines (i.e., almost all existing plasma devices) it is very difficult to control the surface composition of walls and limiters due to real and virtual leaks and outgassing of all components. In reactors and other high duty cycle machines however, it should be possible to control the surface composition rather easily. The low temperature of plasma at radii near the wall implies that plasma impurity deposition will dominate erosion at this radius. The primary source of plasma impurities will be in the region where the hottest plasma contacts the wall and the nature of the impurities introduced at this point should be under control if the surface composition (and injected impurity composition) can be controlled.

**Pump Limiter Structure**

The proposed geometry for the pump limiter is shown in Fig. 3. The inner wall of the device is curved to conform closely to the plasma shape, thus reducing the local heat deposition and erosion. Since it is doubtful that the wall can conform too closely to the plasma, whose shape cannot be constant, it will be desirable to move the plasma around slowly to bring it in contact with the wall at different places.

![Fig. 3](https://example.com/fig3.png)
The pump ducts (top and bottom) are similar to those of other designs, with some modifications. Vanes have been inserted into the ducts and each duct accepts plasma from one direction only. The alignment of the vanes is parallel to the direction of the local magnetic field and they extend out in front of the pumping duct itself. The vanes serve three purposes: they prevent back diffusion of high pressure gas across field lines, they provide mechanical support, and they provide a structure within which the surface recoating apparatus can be mounted. Back diffusion could be a problem since the distance d to the plasma perpendicular and parallel to field lines (i.e. plasma flow) is related by the ratio

\[ \frac{d_z}{d_t} = \frac{B_t}{|B_T + B_p|} \approx 0.1 \]

The vanes permit easy access to the front edges and all other parts of the limiter and could easily be designed to accommodate equipment to inject pellets, powders, gasses (such as H\textsubscript{2}O\textsubscript{2}), or wires into the plasma.

The high heat load on the limiter surface itself would provide a very uniform environment for locating injection apparatus, but the vanes should provide sufficient space for additional cooling equipment, together with injection equipment. Maintenance of this equipment would be difficult but could be done by withdrawing the pump limiter module. Redundancy would be the most obvious solution to the injection/maintenance problem.

Recoating Techniques

Recoating is primarily a problem in the region where the hot plasma contacts the wall. By spreading this surface out and making it accessible from the outside, it should be possible to minimize the erosion rate and make recoating much easier. This could be done by methods shown in Fig. 4. Material could be injected from the limiter edge with the plasma either on the median plane or offset up or down. Thus, it would be possible to cover the entire surface at frequent intervals during a long burn pulse. Ideally the point of impurity injection should be close to the location where recoating is required, however dimensions of the plasma and the difficulty of operating impurity injectors in the inner wall make it necessary to use plasma diffusion to carry impurities some distance (\(~1.6\) m in FED/INTOR) to recoat the wall on the median plane. This reduces the recoating efficiency somewhat, as injected impurities can diffuse into the plasma rather than going to the wall.

Under normal operating conditions, it seems likely that the lip of the limiter will not be eroded, since this edge will be located at a minor radius greater than the cross-over point (11 cm) in Fig. 2. Likewise, the wall surface around the outer (large R) surface of the vacuum chamber will be dominated by redeposition and should require little attention.

It can be shown (Ref. 5 and 7) that a considerable fraction of material sputtered into the plasma is quickly returned to the surface from which it was sputtered. This is due to the fact that roughly half of the material introduced into the plasma will immediately start diffusing outward. This effect reduces the effective sputtering yields (both S\textsubscript{Z} and S\textsubscript{P}) by roughly a factor of two. Likewise, any fraction of the material injected into the limiter region for surface recoating material injected into the limiter region for surface recoating will go into the body of the plasma. Thus Eq. (1) can be satisfied if the injected impurity coefficient Y is comparable to S\textsubscript{Z}. Estimates of whether ignition would be possible are complicated by a large number of factors from relative concentrations of impurities in the center and edge of the plasmas, physical sputtering yields, chemical sputtering, sheath potentials, etc.; nevertheless, the simplest models show that ignition is likely even with sufficient material injected into the edge region to prevent erosion.

Conclusion

We have described a pump limiter system which is compatible with in-situ recoating of the limiter surface. The recoating could be done during normal tokamak operation. We have shown how this system is compatible with most of the constraints of fusion reactor operation and might provide a significant advantage over magnetic diverters and other pump limiter geometries.

References

7. J. Brooks, "Redeposition of a Sputtered Surface in Limiters," see these Proceedings.