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REDEPOSITION OF THE SPUTTERED SURFACE IN LIMITERS*

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REDEPOSITION OF THE SPUTTERED SURFACE IN LIMITERS[*]

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Abstract

Erosion of the surface coating of a pumped limiter by sputtering may be a critical life-limiting issue for future tokamak reactors. Redeposition of the sputtered material, however, may extend the coating life significantly. This subject has now been studied through the use of a code which models the redepositon of sputtered material which gets ionized in the scrape-off layer. The code also treats the transfer of wall-sputtered material to the limiter. The code uses models of the plasma density and temperature in the scrape-off zone, sheath potential, sputtering coefficients, spatial distribution of the sputtered atoms, and electron impact ionization coefficient for the sputtered atoms. The studies were made for "high flux" and "low flux" edge conditions corresponding to FED and STARFIRE limiters and assumed plasma-edge parameters. The results indicate that substantial redeposition from the scrape-off layer ionized neutrals occurs in the cases considered.

Introduction

A computer code has been developed which models sputtering and redeposition of limiter coating materials. Midplane pumped limiter designs, such as that proposed for STARFIRE,[1], and bottom limiter configurations, such as that proposed for FED,[2] have been investigated.

The code calculates the sputtering yield at each point along the limiter surface. Neutral sputtered atoms ejected from the surface flow in the scrape-off zone and undergo electron impact ionization. The ionized atoms then tend to return to the limiter, following a trajectory with guiding center motion along the field line passing through the point where the ionization occurred.

Near the limiter surface the returning, singly ionized, sputtered atoms gain energy when accelerated across the sheath potential. Upon impacting the limiter surface, additional sputtering is initiated. In this calculation several iterations on this sputtering redeposition process are carried out until a convergent sputtered particle source term is calculated at each spatial mesh point on the limiter surface. The two-dimensional calculation follows the trajectories of all sputtered atoms through the scrape-off region so that the redistribution of the limiter surface coating can be determined.

The results obtained should be useful in providing an initial understanding of the sputtering-redeposition processes for limiter systems. The model is by no means complete but the trends predicted should be useful in subsequent designs of pumped limiter systems.

We find that the redeposition process is an important consideration in determining the expected life of pumped limiter systems. For beryllium-coated limiters as proposed for the STARFIRE design, and for carbon-coated limiters, as proposed for FED, the net erosion rate calculated is significantly below that predicted when the redeposition process is not considered. In fact, when these tokamak systems are operated with plasma impurity species concentrations near 1%, we find that net limiter coating buildup is predicted over most of the limiter surface. This results because self-sputtering yields for both carbon and beryllium are less than unity.

Model Description

In this section the sputtering-redeposition model is described using the STARFIRE limiter system as a reference case. Modifications required to perform the analysis of the FED limiter are presented below.

Figure 1 defines the general limiter geometry. The leading edge of the limiter defines the beginning of the scrape-off zone. The limiter is divided into a number of intervals corresponding to equal spacing in the x-direction. A set of equally spaced intervals are also constructed in the y-direction so that the region above the limiter is covered with a spatial grid. The plasma particle energy and density are assumed to decrease exponentially with distance from the plasma edge, i.e. as $e^{-x/\delta}$. The particle density and temperature e-folding distances and the plasma-edge conditions used here for the reference calculations are listed in Table 1 for STARFIRE and FED. (the actual STARFIRE design used a higher edge temperature and this case will be treated later.

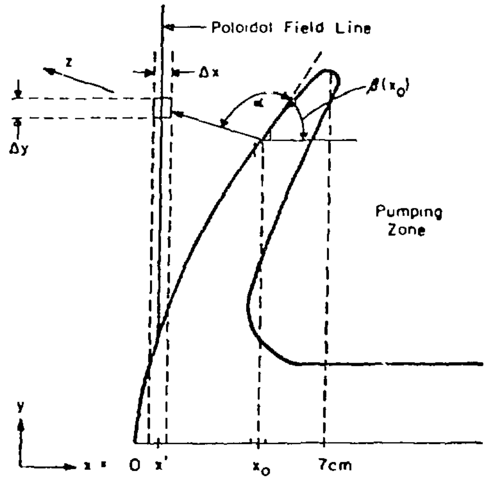

Fig. 1. STARFIRE limiter schematic and coordinate system.

In this model one poloidal field line is associated with each x-interval and extends above the limiter surface passing through elements of the spatial

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Table 1. Reference Case Values of Model Parameters for the Scrape-off Region Plasma and Limiter

Parameter	STARFIRE	FED
Limiter location	midplane	bottom
Particle e-folding distance, δ_p (cm)	5.0	12.0
Temperature e-folding distance, δ_T	10.0	24.0
Edge temperature (eV)	100	100
Edge density ($10^{19}/m^3$)	1.0	1.0
Active limiter area (m^2)	85	22.0
Particle current to the limiter (10^{22}/s)	4.3	50.0
Limiter coating material	beryllium	carbon

grid. Charged particles flow in towards the limiter surface. The plasma flux to the limiter consists of deuterium, tritium, and beryllium ions, and electrons. (Helium is not treated for simplicity.) The greater mobility of the electron component of the plasma results in the formation of a negative sheath over the entire limiter surface. A sheath potential of $e\phi = 3kT(x)$ is assumed where $T_e = T_i = T(x)$ is the local plasma temperature at a distance x from the plasma edge. Due to the presence of this sheath, incoming ions are accelerated toward the limiter and strike the surface at near-normal incidence.

With the particle and energy fluxes to the limiter as specified above, the source flux of sputtered atoms, SZ(x), from the limiter surface of location x is calculated using the sputtering model of Smith[3] for D-T self-sputtering of beryllium. All atoms sputtered from the lmiter are assumed to have a velocity V_0, corresponding to an energy of 1 eV and are assumed to be ejected in a neutral charge state. A symmetric sinusoidal distribution is used to describe the directional dependence of the sputtered particle motion so that

$$S_0 = SZ(x_0)\,\frac{\sin[\alpha + \beta(x_0)]\,d\alpha}{2\cos[\beta(x_0)]} \qquad (1)$$

represents the soruce current of sputtered neutral beryllium atoms moving in a direction defined by α that are produced on a portion of the limiter surface associated with the increment Δx about location x_0. In this expression $\beta(x_0)$ is the angle of inclination of the limiter surface at x_0 and α is the ejection angle of the sputtered atom with respect to the limiter surface as shown in Fig. 1. This sputtered atom source, represents the predicted surface erosion if no redeposition takes place.

The angular distribution of sputtered atoms is divided into 30 intervals, $\Delta\alpha = \pi/30$. The source term of sputtered neutrals for each direction α provides the initial condition for the following balance equation:

$$\frac{d\Gamma_z(z)}{dz} = \frac{d[N_z(z)V_0]}{dz} = -N_z(z)N_e(z)\langle\sigma v(z)\rangle i \qquad (2)$$

where $\Gamma_z(z)$ is the current of sputtered neutral atoms at a distance x away from x_0, moving in a direction defined by α, N_e and N_z are the electron and neutral beryllium atoms densities respectively and $\langle\sigma v(z)\rangle_I$ is the rate coefficient for electron impact ionization. In these calculations, rate coefficients reported by Bell, at al.[4] have been used.

The solution to Eq. (2) is easily obtained and one finds that the attenuation of this neutral particle current can be written as:

$$\frac{d\Gamma_Z(z)}{dz} = \frac{-S_0}{\lambda(z)}\exp - \left\{\int_{x_0}^{z} \frac{dz'}{\lambda(z')}\right\} , \qquad (3)$$

where $\lambda(z)$, the neutral atom mean-free path, is given by $N_e(z)\langle\sigma v(z)\rangle_i/V_0$. For every element of the two-dimensional spatial grid the number of beryllium atoms ionized in that region of space, $\Delta x\Delta y$, is calculated by numerical integration of Eq. (1). The integration is carried out for all directions α, and the procedure repeated to include source contributions from each spatial interval, Δx, on the limiter surface.

Once ionized, sputtered beryllium atoms become tied to field lines in the vicinity of the ionizing collision. Subsequent couloub collisions with the incoming plasma should quickly force the ionized beryllium atoms back to the limiter, for plasma temperatures of $\lesssim$200 eV. For higher temperatures, the plasma-to-beryllium momentum transfer depends on the assumed collisonality in the scrape-off zone and there is some chance that beryllium ions could flow around the torus with some diffusion. For the symmetric limiter cases discussed here, particles undergoing no diffusion would merely hit the other side of the limiter from their birth side resulting in the same redeposition profile as if they were forced back immediately. The effect of diffusion would be to spread out the redistribution profile but initial analysis indicates that this effect is small. Consequently, to first order, all ionized beryllium atoms can be treated as moving with the scrape-off region plasma and following the field lines in that zone back toward the limiter surface. The steady-state return current of beryllium atoms to a particular interval, Δx, located at x' on the limiter surface is calculated by summing the ionization rate of beryllium atoms in the appropriate grid regions, in the scrape-off zone, i.e. those grid regions intercepted by the magnetic field line associated with the limiter location x'. For STARFIRE, this summation is simply in the y-direction, since field lines are nearly verticle in the region of the midplane limiter. For the bottom limiter in FED this summation, as well as the numerical integrations required, is more difficult due to the complicated magnetic field structure in the scrape-off region of that system.

Before returning to the limiter surface, singly ionized beryllium atoms are accelerated across the sheath region. Upon impact, these cause additional self-sputtering of the coating. Due to the short times involved newly ionized beryllium atoms will probably remain in the single charged state before returning to the limiter but this point needs further analysis. At this point in our calculation, the source flux of sputtered neutral beryllium atoms is revised to reflect this source term enhancement.

For materials such as iron, which have self-sputtering yields greater than unity, this return process could lead to a runaway situation. The physical sputtering yields for the coating materials considered here, beryllium or carbon, are less than unity. For these materials then, an iteration is performed on the calculation just described until the source term converges to a steady-state form. This converged source defines the total number of atoms sputtered.

Once convergence is established, the difference between the final sputtered atom source flux and the redeposited flux at each spatial interval is used to determine the net limiter coating erosion or buildup rate as a function of position along the limiter surface.

Erosion on the STARFIRE Limiter

A mechanical pumped limiter system located on the outboard portion of the torus at the plasma midplane is used to provide impurity control in STARFIRE. A coating of beryllium is provided to prevent sputtering of the underlying structural material and to keep the high-Z impurity content of the plasma to a minimum.

Plasma parameters characterizing the STARFIRE scrape-off zone (Table 1) are provided as input to our sputtering-redeposition code. The net beryllium erosion rate calculated is shown in Fig. 2 for three different beryllium impurity ion concentrations in the plasma. For an impurity-free plasma, Curve a, substantial erosion of the limiter tip is predicted. On the other hand, the rest of the limiter suffers no erosion and in fact has a slight buildup. Actually the plasma will contain some beryllium from various sources. These sources are: (1) beryllium sputtered from the limiter that is not immediately redeposited; (2) charge-exchange sputtered beryllium from the first wall; and (3) beryllium intentionally added to the plasma from an external source, e.g. with the D-T fuel stream.

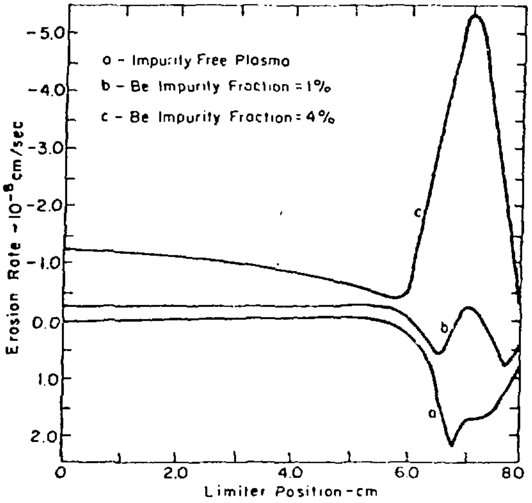

Fig. 2. Beryllium coating erosion rate on the STARFIRE limiter.

A beryllium impurity fraction in the plasma provides for additional deposition of beryllium at all points on the limiter. Calculations were made for this case assuming that the beryllium deposition flux on the limiter is proportional to the D-T particle flux. The deposition rate is strongest then at the limiter tip where the maximum flux occurs. Curve b of Fig. 2 shows the net beryllium coating redistribution that results if a beryllium impurity fraction of 1% is maintained in the plasma. The impurity deposition at the tip nearly compensates for the erosion observed in the impurity-free case. For a beryllium impurity concentration of 4%, a net beryllium coating buildup is predicted over the entire limiter surface. This is shown in Curve c.

Sensitivity Analysis

One uncertainty in the above analysis lies in the specification of the energy spectrum used to represent neutral atoms sputtered from the surface. For the reference calculations, a representative value of U_0 = 1 eV was used for the energy of all sputtered neutrals. (This corresponds to a value of about one-half of the beryllium surface binding energy.) In order to determine how the redeposition calculation is effected if the average sputtered neutral ejection energy is significantly different from this value, the calculations were repeated using values of U_0 = 0.1 and 10.0 eV. The net erosion rates calculated are shown as Curves a and b of Fig. 3, respectively. The variation in the neutral atom mean-free path for the three values of U_0 considered is shown in Table 2. When U_0 = 0.1 eV neutral particle migration is severely limited. Sputtered atoms are redeposited on surface elements not far from their point of origin. Consequently, very few of these atoms are lost due to migration into other portions of the system. A plasma impurity concentration of 1% produces a net coating buildup over the entire limiter surface. When U_0 is taken as 10 eV, the neutral atom mobility is increased (see Table 2). The total amount of beryllium available to maintain the limiter coating decreases as atoms migrate to other surfaces inside the torus or into the pumping plenum. A substantial erosion rate is predicted near the tip of the limiter where the sputtered atom source term is largest. However, this erosion can probably be eliminated by maintaining a higher beryllium concentration in the plasma.

Variations in plasma edge conditions were also investigated. The sputtered atom source term is effected by variations in both plasma edge density and temperature. We find that the converged source term maintains roughly the same spatial form as the edge temperature and density are varied. The maximum value of the converged source flux, which always occurs at the limiter tip, is listed in Table 2 for several combinations of plasma edge temperatures and density. This value provides a relative measure of the amount of material redistributed per unit time. With the source term determined, the redeposition profiles shown in Fig. 3 are easily understood if one again examines the mobility of the sputtered neutrals. Mean-free paths for sputtered neutral atoms at the leading edge and near the limiter tip are listed in Table 2 for the combinations of plasma edge temperature and density considered.

FED Limiter Analysis

The sputtering-redeposition calculation described above was modified to allow analysis of the FED limiter. This mechanical limiter is located at the bottom of the D-shaped plasma as shown in Fig. 4. A two-dimensional map of the more complicated scrape-off region magnetic field structure for this system was constructed using magnetic flux profiles reported by Strickler.[5] Carbon is the limiter coating material considered here and consequently is also the major plasma impurity species.

Once again, sputtering yields are calculated using the model of Smith, and electron impact ionization rate coefficients reported by Bell, et al., are used to calculate the neutral sputtered carbon atom mean-free path in the two-dimensional region above the limiter. Parameters describing the FED scrape-off region plasma and limiter system are listed in Table 1.

The results of the analysis are shown in Fig. 5. The erosion for the case where no redeposition takes place, for an impurity-free plasma and for a plasma

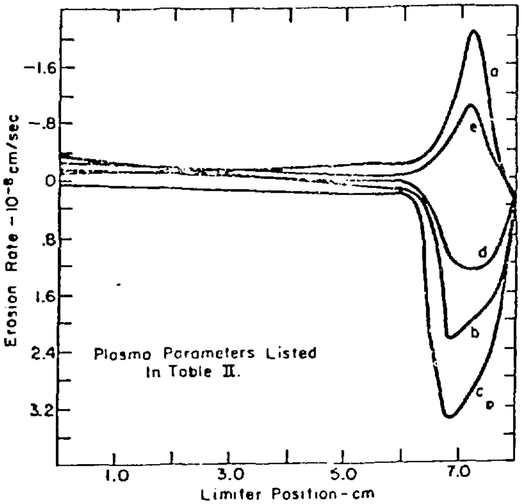

Fig. 3. Coating erosion on the STARFIRE limiter.

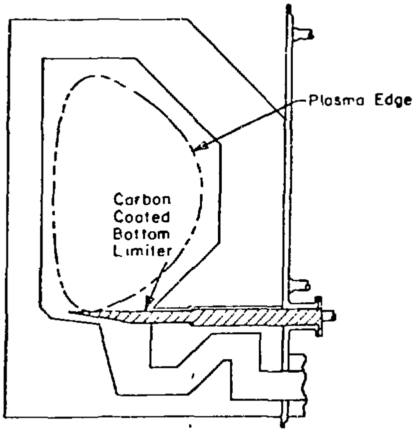

Fig. 4. FED bottom limiter - baseline design.

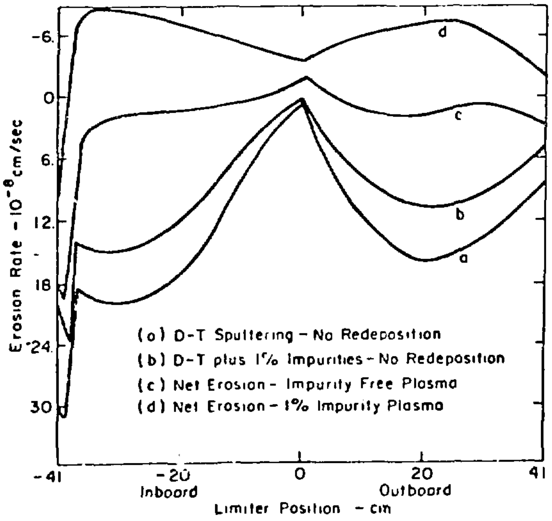

Fig. 5. Carbon coating erosion rate on the FED Limiter

Table 2. Model Parameters for Fig. 3 Curves

Designation	a	b	c	d	e
U_0, eV	0.1	10.0	1.0	1.0	1.0
T_{edge}, eV	100	100	100	1000	1000
N_{edge}, $10^{19}/m^3$	1.0	1.0	1.0	0.1	0.1
$\dot{S}Z(x = 7\ cm)$, $10^{11}\ m^{-2}s^{-1}$	8.5	7.8	7.5	4.9	7.2
$\lambda(x = 0)$, cm	0.14	1.4	4.6	5.9	0.59
$\lambda(x = 7\ cm)$, cm	0.47	4.7	1.5	9.5	0.95

containing a 1% carbon atom impurity concentration are shown as Curves a and b, respectively. As in STARFIRE, curvature effects produce maximum erosion on the limiter tip. The results of the redeposition calculation for these two cases are shown as Curves c and d, respectively. Significant erosion still occurs at the limiter tip in each case. For a 1% plasma impurity content, limiter coating growth rates as high as 1 μm/h of operation are predicted on the central portions of the limiter. This value translates to a coating growth rate of 1 cm over the four-phase, ten-year operating scenario proposed for FED. On the limiter tip, erosion rates in excess of 1 μm/h are predicted. It appears though that tip erosion might be eliminated by adding carbon to the plasma and/or by transfer from the wall to the limiter. Note though that chemical sputtering, an important erosion mechanism for carbon coated limiter systems, has not been considered in the present model.

Conclusions

Redeposition of sputtered material will prolong limiter life expectancy beyond that originally anticipated. Limiter designs, however, have not been optimized with respect to these calculations. Redeposition may be a mixed blessing since the coating may grow to be too thick. Limiter coating erosion/deposition rates near zero over much of the limiter surface might be achievable by controlling the plasma impurity content and by modifying limiter geometry. (See also Ref. 7 for a discussion of this option.) Other mechanisms for controlling limiter coating thickness may become apparent as more detailed studies are carried out.

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