TEMPERATURE LIMIT OF A GRAPHITE DIVERTOR SURFACE DUE TO PARTICLE EROSION

by

J. N. Brooks

MASTER

FUSION POWER PROGRAM

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ABSTRACT

The surface temperature limit of a graphite coated tokamak divertor due to particle erosion has been examined theoretically. The analysis uses models for physical sputtering, radiation enhanced sublimation, and redeposition phenomena. An upper bound on surface temperature is computed based on the necessary condition that self-sputtering be finite. The allowable graphite surface temperature is found to depend strongly on the plasma edge temperature, being limited to ≤ 1150 C for medium plasma edge temperatures (~ 150 eV).

1. INTRODUCTION

Graphite has been proposed as a high temperature material for fusion reactor surfaces, but particle erosion may limit its acceptable operating temperature. This limit may arise from radiation enhanced sublimation (RES), and physical self-sputtering. Since RES increases rapidly with surface temperature, it has been recognized that excessive erosion due to RES may seriously limit the operating temperature of graphite^(1,2). Physical self-sputtering itself may be unacceptably high for temperatures where the carbon surface no longer retains a significant hydrogen concentration⁽³⁾. A key factor in self-sputtering is the expected tokamak divertor boundary conditions that result in oblique angle particle impingement.

To provide an initial quantitative assessment of this issue, for fusion reactor design purposes, a simple point model of carbon erosion was developed. The model is based primarily on erosion/redeposition theory and analysis⁽³⁻⁵⁾ and uses the RES model of Bohdansky and Roth⁽⁶⁾. An upper bound on surface temperature is computed based on the necessary condition that self-sputtering (physical plus RES) be finite. Self-sputtering is computed using estimates for carbon ion charge states, sheath potential, and related parameters, for a low to medium plasma edge temperature regime. The computed bound on graphite surface temperature ranges from ~ 2000 C at low edge temperature (~ 30 eV) to ~ 1150 C for medium edge temperature (~ 150 eV), for reference parameter estimates.

2. CARBON EROSION MODEL

Phenomena related to particle erosion of a carbon divertor surface are shown schematically in Fig. 1. The divertor geometry is characterized by a near-tangential magnetic field; typically $\alpha \leq 5^\circ$. Plasma particles, primarily deuterium-tritium ions and neutrals, and helium ions, impinge on and sputter the surface. The divertor plate center receives the highest particle flux and has generally the worst erosion problem. The focus of the model will therefore be on the center region. For low to medium edge temperature plasma regimes, and for regions near the divertor center ($\pm \sim 10$ cm along the plate), sputtered carbon atoms are ionized close to the plate. Most of the ionized carbon flows back to the divertor due to momentum transfer with the incoming plasma and possible pre-sheath electric fields. The returning ions acquire a

PLASMA PARTICLE FLUX

$D^+, T^+, D^0, T^0, e^-, He^{+2}, C^{+N}$

Figure 1. Divertor erosion phenomena.

substantial energy in the sheath region and are redeposited on the surface causing self-sputtering. A sputtering cascade results which obviously must be finite for acceptable operation.

Particle erosion of carbon can result from physical sputtering, chemical sputtering, and radiation enhanced sublimation. For simplicity, these will all be referred to as sputtering. Physical sputtering results in energetic emission of carbon atoms at energies characteristic of the surface binding energy (~ 8 eV), while RES results in the thermal emission ($\lesssim .2$ eV) of carbon atoms^(1,2). Chemical sputtering involves the emission and transport of hydrocarbons (CH_4 , etc.) but can be treated simply as resulting in low energy sputtered carbon, for the present purposes. Because of the difference in sputtered energies, the low and high energy sputtered carbon needs to be modeled as separate species. There is also a small flux of highly ionized carbon ions from the plasma core, resulting from non-immediately redeposited sputtered carbon. This is generally less than 1% of the DT flux and will be ignored in the present calculations.

For a point on the divertor surface the total ("gross") flux of sputtered carbon of each species is given, for finite values of sputtered flux, by:

$$\Gamma_{Z_1}^{\text{GROSS}} = \Gamma_{\text{DT}} Y_{\text{DT}}^a + \Gamma_{\alpha} Y_{\alpha}^a + \Gamma_{Z_1}^{\text{GROSS}} R_1 Y_Z^a(E_1) + \Gamma_{Z_2}^{\text{GROSS}} R_2 Y_Z^a(E_2) \quad (1)$$

$$\Gamma_{Z_2}^{\text{GROSS}} = \Gamma_{\text{DT}} (Y_{\text{DT}}^b + Y_{\text{DT}}^c) + \Gamma_{\alpha} Y_{\alpha}^b + \Gamma_{Z_1}^{\text{GROSS}} R_1 Y_Z^b(E_1) + \Gamma_{Z_2}^{\text{GROSS}} R_2 Y_Z^b(E_2) \quad (2)$$

where Γ denotes a particle flux, Y is a sputtering coefficient, R is the fraction of sputtered particles that are redeposited, and E is the energy of the redeposited particles. The subscripts denote DT = deuterium-tritium, α = helium, Z = carbon, 1 = high energy (physically) sputtered carbon, 2 = low energy sputtered carbon. The superscripts denote a = physical sputtering, b = RES, c = chemical sputtering.

The solution to the simultaneous equations (1) and (2) are:

$$r_{Z_1}^{GROSS} = \frac{r_{DT} Y_{DT}^a + r_{\alpha} Y_{\alpha}^a + \frac{R_2 Y_Z^a(E_2) [r_{DT} (Y_{DT}^b + Y_{DT}^c) + r_{\alpha} Y_{\alpha}^b]}{1 - R_2 Y_Z^b(E_2)}}{1 - R_1 Y_Z^a(E_1) - \frac{R_1 R_2 Y_Z^a(E_2) Y_Z^b(E_1)}{1 - R_2 Y_Z^b(E_2)}} \quad (3)$$

$$r_{Z_2}^{GROSS} = \frac{r_{Z_1}^{GROSS} R_1 Y_Z^b(E_1) + r_{DT} (Y_{DT}^b + Y_{DT}^c) + r_{\alpha} Y_{\alpha}^b}{1 - R_2 Y_Z^b(E_2)} \quad (4)$$

The sputtered fluxes $r_{Z_1}^{GROSS}$, $r_{Z_2}^{GROSS}$ are both finite if the denominators of (3) and (4) are positive, giving the necessary conditions:

$$R_1 Y_Z^a(E_1) + \frac{R_1 R_2 Y_Z^a(E_2) Y_Z^b(E_1)}{1 - R_2 Y_Z^b(E_2)} < 1 \quad (5)$$

$$R_2 Y_Z^b(E_2) < 1 \quad (6)$$

Conditions (5-6) determine a surface temperature limit, given sputtering data, and values for the plasma related parameters R_1 , R_2 , E_1 , E_2 . Note that the non-self sputtering coefficients do not enter into conditions (5-6) but are of course important in determining whether the erosion rate is acceptable, though finite.

Specifically, the net erosion flux of carbon is given by the difference between the sputtered and redeposited fluxes:

$$r_Z^{NET} = r_{Z_1}^{GROSS} (1 - R_1) + r_{Z_2}^{GROSS} (1 - R_2) \quad (7)$$

In general, the values of R_1 and R_2 are close to unity, and an accurate determination of (7) requires a detailed spatial analysis, e.g. of the type provided by the REDEP computer code⁽⁴⁾. However, conditions (5-6) can be evaluated by using simpler estimates of the plasma related parameters. These are considered in the following section.

3. PLASMA BOUNDARY PARAMETERS

The sheath region can supply a high energy to the redeposited ions and is therefore critical to the erosion process. It has been shown^(7,8) that for oblique magnetic field geometries the sheath potential is essentially the same as the normal field case. The sheath width, however, is larger, being characterized by a high electric field in a region of several debye lengths from the surface, and a smaller electric field out to about the DT ion gyroradius. The fraction of the total potential difference that occurs in the debye region depends generally on the magnetic field angle⁽⁷⁾. Due to a combination of gyromotion and electric field acceleration light ions, including carbon, tend to impact the surface at non-normal incidence. In a recent sheath calculation for $\alpha = 5^\circ$ ⁽³⁾, it was found that the average carbon ion incident angle was $\sim 50^\circ$ from the normal, and that the potential drop in the debye region was about 50% of the total. This was for limiter type edge conditions ($T = 100$ eV, $5 \times 10^{18} \text{ m}^{-3}$). It is believed,⁽⁹⁾ but not yet verified, that similar parameters would apply to divertor conditions, i.e. with higher densities.

The energy of redeposited ions depends on their charge state and whether they have been accelerated through the full sheath potential. For a plasma with ion and electron temperatures, T_i , T_e , electron density N_e , at the divertor plate center, the mean free path for sputtered carbon is given by:

$$\lambda_i = \frac{V_o}{N_e \langle \sigma v \rangle}$$

where V_o is the sputtered atom velocity and $\langle \sigma v \rangle$ is the rate coefficient for electron impact ionization. Table 1 compares the mean free paths (ignoring density variations in the sheath and off-normal emission) with the two relevant sheath distances, for typical values of sputtered particle energies and plasma parameters.

Table 1. Ionization Mean Free Path for Carbon Compared to Characteristic Oblique-Angle Sheath Distances; for Plasma Parameters, $T_e = T_i = 100$ eV, $N_e = 10^{20} \text{ m}^{-3}$, $B = 5 \text{ T}$

Sputtered Particle Energy	Mean Free Path, λ_i	Ratio of Mean Free Sheath Path to Debye Region Width $\lambda_i/5\lambda_D$	Ratio of Mean Free Sheath Path to Gyro Region Width λ_i/r_{DT}
.15 eV	$1.5 \times 10^{-4} \text{ m}$	4	.5
8	1.1×10^{-3}	30	3

As shown in Table 1, ionization occurs well after the first sheath region for both species. Physically sputtered carbon is ionized outside of the entire sheath, while RES carbon particles are ionized at distances comparable to the full sheath width. Particles ionized within the sheath may travel outside of the sheath region before being turned around (by plasma collisions) and redeposited. Even assuming no further transport away from the sheath, however, we can conclude that both classes of sputtered particles will likely accelerate through all or most of the sheath potential.

The charge state of the redeposited ions depends on a complex transport process involving carbon ion collisions with the DT plasma. For physically sputtered carbon, average redeposited charge states of $K_1 \sim 3$ have been calculated⁽¹⁰⁾. For RES carbon, charge states are likely to be lower; precise values would require a detailed analysis. The minimum value of $K_2 = 1$ can be used as a best-guess value, at present.

4. RESULTS AND DISCUSSION

Based on the preceding considerations, a carbon surface temperature limit was computed by setting the left hand side of (5) to unity and solving for the surface temperature as a function of plasma temperature $T_e = T_i$. Redeposition fractions $R_1 = R_2 = 1$ were used, and except where otherwise noted, $\phi = 3kT_e/e$, $E_1 = K_1\phi$, $E_2 = K_2\phi$, $K_1 = 3$, $K_2 = 1$ were used as reference conditions.

Physical self-sputtering coefficients were computed as follows. A "pure" carbon yield was calculated by multiplying the measured self-sputtering yield given by Roth⁽¹¹⁾ for normal incidence by an angular factor given by the

formula of Yamamura et al⁽¹²⁾. An incidence angle of 50° from the normal was used for both carbon species. The resulting yield exceeds unity at an energy of about 1700 eV, a result in line with several TRIM code computations e.g. Ref. (13).

It is believed that a high hydrogen concentration (~ 40% H/C), expected in saturated carbon divertor surfaces for low enough surface temperatures, reduces the sputtering yields substantially from the pure carbon value. To approximately account for the reduction of self-sputtering coefficient due to a surface hydrogen concentration, the pure carbon yield was used in the reference calculation if it was less than or equal to 0.5, otherwise a value of $Y_Z^a = 0.5$ was used. This was found to give a reasonable agreement with the results found in a more detailed calculation⁽³⁾. A calculation using the pure carbon yield was also used made.

The Roth and Bohdansky⁽⁶⁾ RES coefficient for carbon, used in this work, has the form:

$$Y_Z^b(E) = f(E) e^{-0.78 \text{ eV}/T},$$

where $f(E)$ describes the incident particle energy dependence, and T is the surface temperature.

Figure 2 shows the results of these computations for low to moderate plasma edge temperatures, and for a surface temperature domain $\leq 2100^\circ\text{C}$. For the reference case, the carbon surface temperature is essentially not limited by self-sputtering for plasma temperatures less than about 30 eV. This is encouraging but of potentially limited significance because other surface materials, such as tungsten, would likely be used at low plasma edge temperatures instead of carbon (to achieve low DT sputtering). The carbon surface temperature limit decreases rapidly for $30 \leq T_e \leq 100 \text{ eV}$ and is fairly flat thereafter as the sputtering coefficients remain approximately constant.

The bottom curve of Fig. 2 is an important bounding case, and shows the effect of assuming that hydrogen has no effect on the carbon self-sputtering. For this calculation the pure carbon yield, calculated as described above, was used. This curve would apply to surface temperatures exceeding the temperature where hydrogen is driven out of the carbon surface. For example, if this is found to occur at 800 C, then the bottom

Figure 2. Carbon surface temperature limit as a function of plasma edge temperature; as determined by necessary conditions on self-sputtering.

curve of Fig. 2 would apply for $T_e \leq 150$ eV, while for $T_e > 150$ eV a temperature limit of 800 C, and this curve, provide upper and lower bounds, respectively.

The relative contributions of physical sputtering and RES to the temperature limit are shown by the curve of Fig. 2 with no physical sputtering. The effect of changes in the charge state K_2 , and the fraction of sheath energy acquired by the low energy sputtered carbon are also shown. These parameters make a substantial difference at lower plasma temperatures but not at medium temperatures where the sputtering coefficients flatten out. We conclude that an accurate assessment of the charge state and details of the RES carbon transport are important for low plasma edge temperatures, and relatively unimportant at medium temperatures.

Two qualifications on these results should be noted. Regarding sheath parameters, a high erosion/redeposition rate could itself affect the sheath and edge physics, e.g. by reducing the sheath potential (since ambipolarity is more easily maintained). This is, in theory, a weak effect (since the potential scales only logarithmically with the field-free ion boundary flux), but a self-consistent analysis would be required for better confidence. Secondly, the sputtering properties of a redeposited carbon layer are uncertain. Existing models are based on data from original carbon surfaces. Redeposited surface microstructure, binding energy, metal content, etc. could affect the sputtering properties. Data on high temperature, redeposited carbon surfaces is needed.

5. CONCLUSION

A surface temperature limit for a graphite divertor surface has been computed based on models of the erosion/redeposition process and on sputtering. The results indicate a potentially serious limitation on the surface temperature in the medium plasma edge temperature regime. One limit on surface temperature in this regime is set at the point where a surface hydrogen concentration no longer reduces physical self-sputtering. Another limit is set by radiation enhanced sublimation and physical self-sputtering at about 1150 C, for plausible estimates of the redeposited ion charge states and sheath potential. These are necessary conditions - sufficient conditions on surface temperature may be substantially lower. For the low edge temperature

regime (≤ 50 eV) the surface temperature limit is less restrictive although better information on charge state and sputtered ion transport is required for a precise assessment.

Key uncertainties are the materials properties of redeposited carbon, particularly off-normal sputtering coefficients, and plasma boundary related parameters for oblique angle divertor geometry.

6. REFERENCES

- (1) J. Roth, J. Bohdanský, and K.L. Wilson, J. Nucl. Mat. 111&112 (1982) 775.
- (2) J. Roth, J.B. Roberto, and K.L. Wilson, J. Nucl. Mat. 122&123 (1984) 1447.
- (3) J.N. Brooks et al., J. Nucl. Mat. 163-165 (1989).
- (4) J.N. Brooks, Nuc. Tech./Fusion 4 (1983) 33.
- (5) J.N. Brooks and M. Kaminsky, Fus. Tech. 6 (1984) 465.
- (6) J. Bohdanský and J. Roth, Proc. 5th Symposium on Fusion Technology (Soft), 1988, in press.
- (7) R. Chodura, Phys. Fluids 25 (1982) 1628.
- (8) A.B. DeWald, A.W. Bailey, and J.N. Brooks, Phys. Fluids 30 (1987) 267.
- (9) A.B. DeWald, Georgia Institute of Technology Personal Communication (1989).
- (10) C. Boley and J.N. Brooks, FED/INTOR/ICFW/82-16, Chap. VI, Georgia Institute of Technology 9 (1982).
- (11) J. Roth, J. Nucl. Mat. 145-147 (1987) 87.
- (12) Y. Yamamura, Y. Itikawa, and N. Itoh, IPPJ-AM-26 (Inst. Plasma Physics, Nagoya University).
- (13) W. Eckstein and J.P. Biersack, Z. Phys. B Condensed Matter 63 (1986) 109.

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