Divertor Erosion Study for TPX and Implications for Steady-State Fusion Reactors

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Abstract

A sputtering erosion analysis was performed for the tilted plate divertor design of the proposed TPX tokamak. High temperature (~ 100 eV), non-radiative, steady-state compatible, plasma edge conditions were used as input to the REDEP erosion/redeposition code. For the reference carbon surface the results show a stable erosion profile, i.e., non-runaway self-sputtering, in spite of carbon self-sputtering coefficients that are locally in excess of unity. The resulting net erosion rates are high (peak $\approx 1\text{--}2.5$ m/burn-yr) but may be acceptable for a low duty factor experimental device such as TPX. Other surface materials were also analyzed, in part to obtain insight for fusion reactor designs using a similar plasma regime. Both medium and high-Z materials are predicted not to work, due to runaway self-sputtering. Beryllium is stable but has erosion rates as high or higher than carbon. A liquid metal lithium surface has stable sputtering with a zero-erosion potential and may thus be an attractive future material choice.

1. Introduction

The proposed Tokamak Physics Experiment (TPX) [1] is designed to develop the scientific basis for a compact steady-state tokamak fusion reactor. The design uses RF driven, non-inductive current drive to achieve steady state. It is known from previous studies e.g. [2] that non-inductive current drive may result in higher edge temperatures and hence more difficult plasma-surface interaction problems at the divertor. The higher edge temperature results from the need to minimize core plasma density to achieve acceptable current drive efficiency. The purpose of this analysis is to examine divertor erosion both specifically for the TPX needs, and to identify acceptable future solutions.

A key design issue for fusion is the choice of divertor facing material. Carbon has been selected in TPX because of its high temperature capability, present experimental familiarity, and its low core plasma radiation potential. While limiting erosion is important to any device, a high erosion rate may be tolerable in TPX because of the low ($\sim 0.2\%$) duty factor. However, this is not the case for a commercial or demo type D-T reactor. Likewise, tritium co-deposition in carbon growth regions is a secondary issue in the primarily non-tritium TPX, but can be highly significant in a D-T machine. For these reasons we examine a number of commonly proposed alternative surface materials, in the context of the TPX divertor plasma conditions.

2. Model

TPX is a compact tokamak with major radius 2.25 m, minor radius 0.5 m, and plasma current of 2.0 MA. A "tilted

plate" double null pumped divertor is used for power and particle control. The divertor design is shown in fig. 1. For this study the outer plate of an outer divertor is analyzed - this is the expected highest erosion area.

Fig. 1 TPX divertor geometry.

Plasma parameters from the UEDGE code solution of Rensink et al. [3] are used in the analysis. This solution is for a reference operating scenario with 18 MW of heating power (neutral beams, LH, and ICRF), and average core plasma density of $5 \times 10^{19} \text{ m}^{-3}$. Power into the scrape-off layer is assumed to be 12.5 MW, with separatrix density of $1.65 \times 10^{19} \text{ m}^{-3}$.

The (2-D) UEDGE plasma profiles are used as input to the REDEP[4-5] code. Some smoothing is done to conform to the fine-structure REDEP grid. The (pre-sheath) plasma profiles for the central 40 cm region along the divertor plate are shown in fig. 2. The distance parameter shown is in the direction from top to bottom. The sharp temperature drop near the bottom of the plate is due to the vertical orientation of the plate - neutrals recycling from near the top of the plate are directed radially inward toward the separatrix and private flux region. This enhances recycling near the separatrix and reduces the temperature near the separatrix strike point on the divertor plate. Although most TPX operation would use protium, we primarily analyze the D-D worst case. Trace plasma concentrations of oxygen (0.1%), helium (0.1%), and tritium (0.5%) are assumed. Additionally, a charge exchange D^0 flux, locally equal to 30% of the ion flux, with average energy proportional to the local ion temperature is used for the REDEP calculations. The calculations assume toroidal symmetry, and a constant poloidal field-to-surface angle of 15° .

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Fig. 2 Plasma parameters at the divertor; T_i = ion temp., T_e = electron temp., N_e = electron density, G_i = ion flux.

The REDEP code computes the sputtering, near-surface (~ 0 -3 cm perp. to the plate) transport, and redeposition of the surface material. The code solves for the self-consistent self-sputtering flux, and the impurity flux leaving the near-surface region. Sputtering fluxes are computed based on models of impact energy and angle for each particle species, at each divertor point. For TPX type conditions, redeposited carbon ions are predicted to impact the surface at an average elevation angle of $\sim 55^\circ$ [6]. This is predicted to enhance sputtering coefficients by about a factor of two over the normal incidence values, e.g. as shown in [7]. Of particular significance is the self-sputtering coefficient which for carbon can exceed unity.

Carbon chemical sputtering is computed as a function of surface temperature and incident D^+ and D^0 energy. The surface temperature along the divertor plate is assumed to vary linearly with plasma heat load. A maximum surface temperature of $T_{s\max} = 1000^\circ\text{C}$ is used as a reference, with minimum temperature of 100°C . The transport of chemically sputtered carbon is, in general very complex, involving the interaction of numerous hydrocarbon species [8]. For this study, a simplified transport model is used, based on the results of [8]. This model considers the emission, and transport of methane only. While this should be relatively accurate for this high edge temperature regime further, more detailed modeling of chemical sputtering is warranted.

In addition to physical and chemical sputtering, the code models carbon erosion due to the radiation enhanced sublimation (RES) process. The RES coefficients are given by the formula of [9], with the plasma transport computed based on thermal carbon emission.

A key assumption for carbon modeling is that the redeposited carbon sticks adequately to the surface and that the sputtering properties of the redeposited carbon films are the same as for the original graphite surface. As discussed in [10]

this is believed to be a reasonable interpretation of the present, limited data base for redeposited carbon. However, more data is clearly needed for thick redeposited films created at high flux rates and elevated substrate temperatures. Similar considerations apply to beryllium.

3. Results

3.1 Carbon - Reference Case

Fig. 3 shows the REDEP results for the reference case parameters. Both gross (sputtering only) and net (sputtering minus redeposition) erosion rates are shown. The net erosion rate is shown in two parts with different scale factors to show detail. Peak rates for this and other cases are listed in Table 1.

Fig. 3 Divertor erosion profile, carbon reference case.

The gross rate is significant in judging the issue of redeposited carbon integrity as well as the overall risk in relying on redeposition processes. The gross erosion profile is characterized by a wide region (0-25 cm) of modest erosion (≤ 10 cm/burn-yr), and by the narrower region shown with high erosion. The gross erosion rate is roughly proportional to the ion flux with fluctuations due to temperature and self-sputtering profiles. The peak gross rate of ~ 6 m/burn-yr occurs near the peak in ion flux at a point where the plasma temperature has not yet collapsed. After this point, the gross erosion falls off due to diminishing particle impingement energies.

The net erosion rate profile shows the following trends: 1) For the upper portion of the plate the net rate is approximately equal to the gross rate, i.e. there is low redeposition. This is due to the low electron density in this region which enables sputtered atoms to travel farther from the plate before being ionized. 2) Redeposition is higher towards the plate bottom due to the much higher plasma density. 3) The peak net erosion rate is about a factor of five less than the

Table 1 TPX/REDEP Analysis Summary

Divertor Plate Material	Other conditions	Maximum Gross Erosion Rate (cm/burn-yr)	Maximum Net Erosion Rate (cm/burn-yr)	Comments
Carbon	$T_s^{\max} = 1000^\circ\text{C}^*$	626	131	reference case
	1300 $^\circ\text{C}$	1340	243	significant radiation enhanced sublimation
	700 $^\circ\text{C}$	1020	150	
	100 $^\circ\text{C}$	356	99	shows effect of no chemical sputtering
Beryllium		1230	221	
Vanadium		∞	∞	runaway self-sputtering
Tungsten		∞	∞	runaway self-sputtering
Lithium		1310	234/0 **	

* maximum surface temperature

** rate without/with flow replenishment

peak gross rate. 4) There is a substantial region of net *growth* at the plate bottom. This is due to a transfer of material from top to bottom.

The carbon self-sputtering coefficient for this case varies along the divertor plate being about 0.7 at the top, peaking at just above unity at the maximum temperature point, and diminishing to ~ 0 at the bottom. A self-sputtering coefficient greater than unity imposes a risk of a runaway sputtering cascade. For this design, however, a significant amount of sputtered material at and near the peak is not locally redeposited but instead redeposited farther down the plate. This prevents a runaway self-sputtering cascade from developing. This result, while encouraging, is obviously dependent on uncertainties in the value of self-sputtering coefficients. To assess the sensitivity of the results to the latter, cases were run with all self sputtering coefficients multiplied by a constant factor, "K". An increase of 50% in self-sputtering coeffs., i.e. $K=1.5$, results in a $\sim 200\%$ increase in peak and $\sim 100\%$ increase in average erosion/growth rates. The profile is stable but on the verge of runaway. Conversely, a value of $K=1/1.5$ reduces the peak erosion by $\sim 40\%$.

3.2 Carbon - Other Cases

The maximum divertor surface temperature is an important design variable dependent on the cooling system parameters and on the coating thickness. To assess the sensitivity to this parameter REDEP runs were made for several values of $T_s^{\max}$ with all other conditions the same. The results are summarized in Table 1.

For $T_s^{\max} = 1300^\circ\text{C}$ both gross and net erosion rates increase substantially. This is primarily due to radiation enhanced sublimation which is negligible for the reference case but increases exponentially with surface temperature. RES is a particular concern for this high plasma edge temperature solution - at lower edge temperatures, e.g. $T_e = 50\text{ eV}$, surface temperatures as high as $\sim 1700^\circ\text{C}$ are tolerable [11]. Erosion also increases for a lower peak temperature of $T_s^{\max} = 700^\circ\text{C}$, due to higher chemical sputtering. This affects the gross erosion more than the net. The smaller effect on net erosion is due to the high redeposition fractions of the

slow moving chemically sputtered methane molecules compared to physically sputtered carbon atoms. The case of a low temperature surface was also analyzed to show startup condition results as well as to illustrate the effects of eliminating chemical sputtering altogether.

REDEP runs were also performed for plasmas with different hydrogen isotope compositions. (For simplicity in showing trends, the same D-D plasma profiles are used). For the D-D reference case, with a trace tritium content, the tritium co-deposition rate (in carbon growth regions of the divertor) is a relatively modest 1.2 Kg/burn-yr (total for the upper and lower outer divertor plates). However, for a 50-50 D-T plasma (representing a hypothetical post-TPX reactor) the co-deposition rate rises to a very high value of 202 Kg/burn-yr. The peak net erosion rate for this case is 228 cm/burn-yr or about twice as high as the D-D case. A P-P plasma yields a peak net erosion rate of 68 cm/burn-yr, or about half as much as the D-D case.

3.3 Other Materials

Fig. 4 shows REDEP results for a beryllium divertor surface. The erosion profiles are qualitatively similar to carbon. Peak erosion/growth rates (see Table 1) are about a factor of two higher than carbon. This is primarily due to higher D-Be sputtering coefficients, and secondarily to differences in sputtered impurity transport between beryllium and carbon.

Vanadium and tungsten surfaces were analyzed. Both materials are predicted to result in runaway self-sputtering. This is an expected result based on the high self-sputtering coefficients for this high plasma temperature regime, and on the higher local redeposition fractions of the medium and high-Z atoms compared to the low-Z materials.

Finally, a lithium surface was analyzed. As shown in Table 1 if lithium is considered as a static surface material its erosion is similar to beryllium. Since the surface can, in principle, be replenished by flowing liquid metal, however, the key result shown here is that there is no runaway.

Fig. 4 Divertor erosion profile, beryllium surface.

3.4 Plasma Contamination

In addition to erosion, the present analysis provides information on the potential for plasma contamination by sputtered impurities. For the low-Z materials, it is found that less than 1% of the sputtered atoms leave the near-surface region. This occurs because almost all of the sputtered material is confined to the near-surface region and redeposited at some point on the wall. Thus, although sputtering is high, impurity concentrations away from the divertor surface appear likely to be low.

4. Conclusions

This study has focused on an important plasma edge regime, namely one that may be most compatible with steady state operation. The erosion analysis performed for this regime shows potentially acceptable results for TPX but severe difficulties for future devices. TPX has a design goal of 5×10^5 s of total operation. For a tolerable sputtering erosion thickness for carbon of ~ 1 cm, and using the peak net erosion rate found for the reference case, the coating would last some 2.5×10^5 s. Considering that most shots are not D-D and accounting for some natural fluctuations in strike point position, we conclude that the carbon coating should roughly last the life of the machine. This assumes acceptable properties of the redeposited material. The potential for plasma contamination by sputtered carbon appears to be low. Thus, a carbon surface appears to be marginally adequate for the TPX mission. Results for beryllium are qualitatively similar. Although not analyzed for TPX, high erosion rates for carbon and beryllium were also found for a radiative divertor regime [12] for the ITER design. The basic problem for the low-Z materials is high hydrogen sputtering coefficients combined with relatively low local redeposition fractions.

As shown by the vanadium and tungsten simulations, both medium and high-Z materials are unacceptable for this regime due to runaway self-sputtering. In contrast, these appear good to excellent for a radiative regime [12].

In terms of extrapolation to a similar-plasma-regime, post-TPX, D-T burning reactor, a carbon surface appears to be highly undesirable due to high erosion and high tritium co-deposition rates. Beryllium use would eliminate all or most of the tritium co-deposition concerns. There is also somewhat less concern about the properties of redeposited beryllium films. On the other hand, the temperature limit of beryllium is more restrictive than carbon, and the erosion rate is about twice as high. (Disruption erosion is also worse for beryllium). For high duty factor operation the only feasible material identified here is a replenishable lithium surface. Of course, numerous other considerations besides erosion affect such a design choice, so the restriction to this one material may be a serious limitation.

In general, more data is needed on such erosion related issues as the properties of thick redeposited films, oblique incidence sputtering coefficients, and carbon chemical sputtering. Obtaining such data is, in fact, part of the TPX mission. Indeed, TPX, if built, would provide critical information on edge plasma conditions and plasma-surface interactions needed for fusion development.

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