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FARADAY SCREEN SPUTTERING ON TPX

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MASTER

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FARADAY SCREEN SPUTTERING ON TPX

David A. Ehst

1. Introduction

The TPX design [Reierson] stipulates that the ion-cyclotron resonance frequency (ICRF) antenna must have a Faraday screen (FS). We consider here possible low Z coatings for the screen, as well as sputtering behavior of the Ni and Ti substrates. The theory of rf-induced sputtering has been developed in [Perkins; Myra; D'Ippolito 1991], and we follow those theoretical approaches.

Our emphasis will be on both impurity generation as a possible source of increased Z_{eff} , and also on actual erosion-lifetime of the materials under worst case conditions.

2. Tokamak and Antenna Conditions

The Tokamak Physics Experiment (TPX) is planned for a major radius of 2.25 m, aspect ratio of 4.5, elongation of ~ 1.8 , with strong triangularity, and a toroidal current of 2.0 MA at full vacuum field of 4.0 T at the plasma center. The machine and rf system analyzed here have the parameters described at the conceptual design review (CDR) [Neilson] and in a detailed antenna design report [Swain].

The CDR identified ten operating scenarios in Chpt. 3 and an additional set of regimes in Chpt. 5. In all, a wide range of plasma parameters must be considered: central electron densities (10^{20} m^{-3})

$$0.42 \leq n_{\text{eo}} \leq 1.72 ;$$

average densities (10^{20} m^{-3})

$$0.30 \leq \bar{n}_{\text{eo}} \leq 1.35 ;$$

central electron temperatures (keV)

$$5 \leq T_{e0} \leq 21 ;$$

and an equal ion temperature, $T_i \simeq T_e$. The CDR (Chpt. 5) has $Z_{\text{eff}} = 2.0$ with a majority ion fraction of $f_D = n_D/n_i = 0.95$ and minority boron content $f_B = n_B/n_i = 0.05$. A similar Z_{eff} would result from a carbon impurity of $f_c \simeq 0.035$. The ICRF system [Swain] operates at fixed frequencies 45, 61, or 77 MHz and will initially provide 8-12 MW of heating power (two ports $\times$ 6 straps) for 1000s. An upgrade (3 ports) could provide 18 MW. Plasma heating with ICRF can be achieved with either 0° ("monopole") or 180° ("dipole") toroidal phase differences, strap-to-strap. Efficient current drive, for the specified toroidal distance between straps, requires phase differences $\simeq 30^\circ$ - 70° , depending on T_{e0} .

Impurities generated by ICRF may originate from various sites. The near-screen rf fields liberate antenna-Faraday screen (FS) atoms, while the radiated waves may travel over some distance to interact with other plasma-facing components (PFC), such as the divertor or limiters. Fortunately, TPX is adequately large and hot so the radiated rf power is mostly absorbed within the plasma, i.e., without long-range interactions with the PFC. Our calculations with the RIP code [Ehst 1987] show, for example, with a target plasma of $\bar{n}_e = 0.74 \times 10^{20} \text{ m}^{-3}$ and $T_{e0} = 12 \text{ keV}$ that 40% of the rf power is absorbed in the first pass through the plasma when $n_{11} = 5.0$. Since the fast wave group velocity is mostly radial, very little rf power is expected to travel toroidally away from the antenna. Hence, rf interactions should be confined to the near-screen location during high temperature plasma operations.

The ambient plasma conditions near the FS depend on the antenna position relative to the plasma and to other PFC materials. Figure 1 is a side view of the TPX and plasma; plasma is confined within the separatrix while the antenna is located outboard, between the poloidal limiters and symmetric about the midplane. In fact, the poloidal limiters, ripple plates, and toroidal limiter/stabilizers define a frame around the three ICRF ports, as shown in the "flattened" view in Fig. 2. Note the poloidal limiters are a long toroidal distance apart (135° in angle) and do not constitute close-fitting "guard limiters" for the FS. The poloidal limiter horizon is fixed at 20 mm beyond the separatrix at the midplane (forming a common scrape-off layer), but the FS elements are a variable distance further out, which creates a private scrape-off layer (PSOL)

within this wide limiter frame. The antenna is planned to have a horizontal stroke of 10 cm, which allows the PSOL width to vary from zero to 100 mm. For further clarification, Figs. 3 and 4 show the individual cooling tubes in the banks that form the FS, and Fig. 5 is a detail which illustrates the tube geometry and the common and private scrape-off layers. Although the PSOL width is variable we take a nominal value, $\Delta x_{\text{SOL}} = 20$ mm in our erosion analysis. The cooling tube OD is $2p = 15.8$ mm and the gap between tubes is $g = 4.3$ mm.

Behavior of rf-induced sputtering differs between the gaps and the front face directly facing the PSOL. For simplicity we arbitrarily declare the 45° region of tube surface in the gap to be a gap surface and the front ($2\times$) 45° to be front face; both surfaces are considered flat in the theory. The incident angle of the Tokamak magnetic field, $\underline{B}$, intersecting these surfaces is crucial to estimating the sputtering rates. As shown in Fig. 4, the tubes are designed to align with the diagonal pitch of $\underline{B}$ expected during normal operation. However, the mismatch, θ , in the gap can never be eliminated in practice, and we expect typically $5^\circ \leq \theta \leq 15^\circ$. The front face is more complicated. Figure 6 shows that in principle the $\underline{B}$ curvature could exactly match the FS front face, making the mismatch, α , exactly zero. In reality this is not possible; in order to avoid $\underline{B}$ connections from the FS to external PFC, we assume the FS tube bank is concave (more toroidal curvature than $\underline{B}$), similar to the second-generation A_1 antennas on JET [Bures]. Thus, in Fig. 6, the central tube bank is assumed to be offset a further distance Δx_{SOL} from the separatrix than the edges of the outer tube banks. For definiteness we stipulate a central offset 4 mm (many ion Larmor radii) larger than the edges. Following the analysis in [D'Ippolito 1991] our FS geometry would then result in $\alpha = 0.5^\circ$ at the very front. Moving into the gap, the circular geometry continuously changes and increases the mismatch until it approaches θ deep in the gap.

The TPX antenna has a total $N_{\text{FS}} = 52$ tubes arrayed poloidally. Calculations in [Swain] indicate a line voltage $V_l = 30$ kV will generate a strap voltage $V_a = 26\text{-}29$ kV over the 45-77 MHz range, and this results in a voltage drop [Perkins] of $V_g = 2V_a/N_{\text{FS}} = 1000\text{-}1120$ V, across each gap in the FS. At the front face a $\underline{B}$ line may connect FS tubes several gaps apart, so a larger relative voltage is generated; from the FS geometry we infer [D'Ippolito 1991] that typically a field line connects $\mu^* = 7$ tubes, and in the worst case, $\mu_{\text{max}} = 13$ tubes.

The operating lifetime and radiation fluence to the antenna are specified in [Reiersen]. The total plasma operation is $\tau_H = 3 \times 10^6$ s in proteum and $\tau_D = 2 \times 10^6$ s in deuterium; the latter operations result in the best performance and highest power fluxes on the FS. The maximum lifetime neutron production is 4×10^{22} neutrons (mainly from DD reactions), and, dividing by the PFC area in TPX, the resulting fluence is about 9×10^{20} neutrons/m².

3. Antenna Materials — Coating Options

Most metals and ceramics exhibit 5-30% changes in properties only after neutron exposure greater than 10^{23} /m², so we expect radiation damage to be minimal for the antenna. Table I lists the unirradiated properties of material candidates for antenna fabrication. We assume the FS tube structure is Ti (1.65 mm wall thickness); this is plated with a Ni subcoating (25 μ m thick). The outer coating is the first line of defense against plasma damage, and we consider various low Z materials: B, B₄C, BN, and two forms of carbon — graphite (G) and diamond-like carbon (DLC). Graphite properties are quite variable, especially if we consider that G may naturally coat the FS as a form of soot deposited due to divertor plate erosion. Likewise, sputtered and redeposited boron compounds will have changed stoichiometry and density compared to the as-fabricated materials. So the table is meant to be merely representative of typical properties.

Table I
Antenna Materials Properties (at 250°-400°C except where noted)

Property	Units	Ti	Ni	B	B ₄ C	BN	G	DLC
Thermal conductivity	W·m ⁻¹ ·K ⁻¹	10	65	50	12-20	~35	~80	1000
Atomic density	10 ²⁹ m ⁻³	0.563	0.898	1.41	1.36	1.09	0.898	1.40
Thermal expansion	10 ⁻⁶ K ⁻¹	9	13	5	4.8	5.5	3-7	0.8 (RT)
Electrical resistivity	$\Omega \cdot m$	2×10 ⁻⁶	2.6×10 ⁻⁷	100	≤10 ⁻³	10 ² -10 ¹⁰	10 ⁻⁵	10 ¹⁰

The operating temperature limits for these materials are set by various criteria (melting, thermal creep, phase change, decomposition, etc.) but are generally $\sim 1000^{\circ}\text{C}$. This is consistent with the requirement that the FS be bakeable at 350°C . Based on the coolant flow rates specified in [Swain] we estimate the hottest surface temperatures to be $\sim 425^{\circ}\text{C}$, at the FS location exposed to 2.3 MW/m^2 of ripple-lost ions (during 24 MW of beam heating). So all coating options meet temperature requirements.

Thermal expansion coefficients of all coatings except DLC are reasonably well matched to the tube structure (Ti); the Ni interface is compliant and should permit a good bond between structure and coating.

Coatings of B_4C on the DIIID FS have not shown reliable adhesion [Freeman]. In contrast, boron is known to adhere well to Ni [Cochran], but it attacks and embrittles Ti. Of course, any cracking or flaking of the coatings will allow hydrogen access to the Ti, leading to possible embrittlement (3-5 atom % H in Ti in equilibrium at 400°C and 10^{-3} Pa). Likewise, any porosity of the B_4C or BN compounds will invite H permeation to the Ti. In this sense G and DLC may be superior as they tend to absorb H, preventing migration to the structure.

Extreme hardness is typical for B, B_4C , cubic BN, and DLC, but this property is not a significant factor in the selection process.

Electrical resistivity is of some interest. Good insulators (BN and DLC) are immune to unipolar arcs, but the alternatives are acceptable, as arcing tends to diminish with operating time. More significantly, rf-induced sputtering was eliminated on Phaedrus-T by the use of thick insulators which covered the guard limiters surrounding the ICRF antenna. These insulators effectively reduced the sheath potential below the sputtering threshold on Phaedrus-T. Following the analysis of [Majeski] we estimate that for TPX the FS sheaths have a surface resistivity $R_s = \sqrt{T_e m_D} / (0.6 n_D e^2) \simeq 0.01 \Omega \cdot \text{m}^2$ when $n_D = 1 \times 10^{18} \text{ m}^{-3}$. Effective reduction in sheath potential is achieved if both the dc resistivity, $R_{DC} = \eta d$, and the ac impedance, $R_{AC} = d / (\omega \epsilon)$, are much larger than R_s ; here d is the coating thickness, η the volume resistivity, ϵ the permittivity, and ω the rf angular frequency. Three coating materials — B, B_4C , G — fail the dc test, as $R_s \geq R_{DC}$. The two good insulators, with dielectric constants of 4.0 for BN and 5.7 for DLC, both pass the dc test but result, at the 77 MHz

frequency, in $R_{AC} \sim 0.01 \Omega \cdot m^2$ for $d = 200 \mu m$. These two options thus are marginally effective in reducing sputtering, unless a coating thickness $d \geq 1 mm$ is used. Therefore, while hardly decisive, the BN and DLC coatings may offer modest advantages in reduced sputtering relative to B, B_4C , G.

The three boron compounds may be applied by plasma spray or CVD methods. There is no domestic supplier of B_4C coatings in the U.S., but considerable industrial capability should be available for DLC and B coatings. Cubic BN is presently difficult to apply as a thin film to large surface areas, such as the FS.

The appendix presents physical sputtering curves used to model the coating erosion, but a supplemental note must be added respecting chemical sputtering. Graphite displays a ten-fold increase in sputtering erosion as the material temperature increases from $400^\circ C$ to $600^\circ C$. Compared to G, DLC is expected to display less chemical sputtering. Also, B_4C displays increased chemical sputtering around $200^\circ C$ [Stacey]. It would seem prudent thus to apply an additional erosion factor of two or so to both G and B_4C materials, considering the high temperature operation of the FS coatings.

4. Near-Screen Plasma Conditions

The fast wave propagates in TPX at local densities $n_e \geq 2 \times 10^{18} m^{-3}$, although efficient coupling obtains with even lower densities right in front of the FS. Without ICRF, [Neilson] expects an H-mode separatrix density $n_s \simeq 0.2 n_{e0}$, and DIIID has seen $n_s \simeq 0.5 \bar{n}_e$ during strong ELM activity. For AT operating modes this implies $n_s \leq 0.6 \times 10^{20} m^{-3}$. In the common SOL and the PSOL an exponential decay of density is expected, so at the front face of the FS the density is $n_a = n_s \exp(-D/\lambda_n)$. Reported values of λ_n in experiments vary, e.g., with L- and H-mode, and with dipole vs. monopole ICRF operation [Neilson; Bures; D'Ippolito 1993]; we select a typical $\lambda_n = 1.5 cm$. Since $D = 2.0 cm + \Delta x_{SOL}$ is variable, it is possible to reduce n_a to very small values. Moreover, good coupling [Swain] is possible at $n_a = (1.0 - 13.) \times 10^{18} m^{-3}$. Measured n_a values [Doyle; Bures] vary with ICRF power and with confinement mode but are typically $\sim 1 \times 10^{18} m^{-3}$. Furthermore, TPX simulations [Neilson] predict $n_a < 4 \times 10^{18}$ for $\Delta x_{SOL} = 0.0$ (case #23).

We choose n_a as a parameter in our analysis; in front of the screen we consider both

$$n_a = 1. \times 10^{17}, 1. \times 10^{18} \text{ m}^{-3} .$$

In the gap the density is thought to be very low; we take this value also to be an input parameter to our analysis and consider both

$$n_g = 1. \times 10^{16}, 1. \times 10^{17} \text{ m}^{-3} .$$

The electron temperature varies rather slowly in the SOL. At the separatrix, T_{es} varies from ~ 40 eV to ~ 1000 eV for H-mode on different machines (DIII-D, ASDEX, JT60-U), and $T_{es} = 180$ eV is a typical value expected for TPX [Neilson]. On large machines $\lambda_T \sim 3\text{-}4$ cm is reported; and if we set $D = 2 \text{ cm} + \Delta x_{SOL} = 5 \text{ cm}$ we find

$$T_{ea} = T_{es} \exp(-D/\lambda_T) \simeq 20 \text{ eV} .$$

This estimate is close to experimental values in the SOL on various machines and agrees with the TPX predictions [Neilson] from B2 runs (case #5). However, JET data [Bures] show T_{ea} increases with ICRF power, roughly in accord with the explanation given in [Perkins]. We choose ad hoc for our analysis an expression which is a reasonable match to expected results

$$T_{ea} = 30 \text{ eV} + 20 \text{ eV} [V_g/(1120 \text{ V})]^2 ;$$

that is, $T_{ea} \rightarrow 50 \text{ eV}$ at the highest power (high voltage limit) operation of the antenna.

Sputtered neutrals may be ionized near the FS and may be accelerated back to the FS. The self-sputtered ions and the C minority (from the divertor) typically are multiply charged since $T_{ea} \lesssim 50 \text{ eV}$, and we posit that the average charge state will be $Z = 3$.

Although the impurity content will vary during TPX operations, for simplicity we will assume the plasma contains 95% deuterium and a single minority, viz., carbon, with $f_c = n_c/n_i = 0.05$.

The final preliminary to the erosion analysis is an estimate of sputtering from charge-exchange neutral hydrogen, which forms a lower limit to our calculations. Calculations with DEGAS [Ruzic] for TPX indicate for case #23 that the neutral D flux to the PFC is

$$\Gamma_0 = 9.3 \times 10^{19} \text{ m}^{-2} \cdot \text{s}^{-1} , \quad (1a)$$

with an average energy of $E_0 = 96 \text{ eV}$. We take these values to be typical of TPX performance.

5. RF-Induced Sputtering

As stated, the lower limit to sputtering is from charge-exchange neutrals, the surface atoms (species j) being liberated with a current density

$$\Gamma_{oj} = \Gamma_0 Y_{oj} C . \quad (1b)$$

The sputtering coefficients Y_{oj} (Appendix) are evaluated for deuterium at 45° incidence at E_0 for simplicity; and the factor C accounts for shadowing of the FS surface deep in the gap. From the geometry in Fig. 5 we set

$$C = \begin{cases} 1.0 & , \text{ front face (ff)} \\ 0.26 & , \text{ gap (g)} \end{cases} \quad (1c)$$

In the following analysis, ion-induced sputtering yields are estimated according to the theory in [D'Ippolito 1991], and we consider the gap and front face separately.

5.1 Gap Erosion

Sputtering depends on both the energy, E_i , and angle, Ψ_i , at which the incident ions strike the surface. The original theory [Perkins] of rf-induced sputtering demonstrated that the plasma near the FS rectifies the rf fields, providing a time-averaged dc electric field which accelerates ions near the FS into the surface.

Numerical modeling [Myra] indicates the accelerating potential in the gap sheath is, for $n_g \geq 10^{16} \text{ m}^{-3}$,

$$V_{sh} = (0.3 V_g) + 3 T_{ea} . \quad (2)$$

The ion impact energy is $E_i = Z_i e V_{sh}$, where $Z_i = 1$ for deuterons and $Z_i = 3$ for C and self- sputtering.

Depending on density and accelerating voltage the ions are either magnetized or not. The relevant parameters are: the ion Larmor radius,

$$\rho_{vj} = c_{vj} / \Omega_j \quad (3)$$

where Ω_j is the cyclotron frequency near the FS, and the accelerated ion speed is

$$c_{vj} = \sqrt{e Z_j V_g / m_j} ; \quad (4)$$

and the magnetic sheath width,

$$\Delta_m = (e V_g / T_{ea})^{3/4} \lambda_{De} , \quad (5)$$

where λ_{De} is the Debye length. For a B mismatch of θ (radians), the impact angle [Myra] is approximately

$$\Psi_j = \tan^{-1} \left[\theta + (\rho_{vj} / \Delta_{mj}) \right] . \quad (6)$$

[The angle Ψ in the appendix is the complement of Ψ .] Higher gap (antenna) voltages produce more oblique incidence, with concomitant higher sputtering compared to normal incidence. Heavier ions have a more normal incidence than light ions.

The ion incident flux depends on the majority ion sound speed in the presheath

$$c_s = \sqrt{T_{ea} / m_D} \quad (7)$$

and we allow T_{ea} to increase with V_g as discussed earlier. Then, for a small impurity content, the D and C fluxes are

$$\begin{cases} \Gamma_D = f_D n_g c_s \sin \theta \\ \Gamma_C = f_C n_g c_s \sin \theta \end{cases} \quad (8a)$$

$$\quad \quad \quad (8b)$$

For conservatism we assume a rather bad mismatch, $\theta = 15^\circ$, in the calculations which follow. For these conditions we find typically $\Gamma_D \simeq 1 \times 10^{20} \text{ m}^{-2} \text{ s}^{-1}$ in TPX with $n_g = 1 \times 10^{16} \text{ m}^{-3}$.

The gross erosion rate in the gap is the sum of charge-exchange, deuteron, and C^{+3} contributions, Eqs. (1) and (8)

$$\Gamma_{gj}^{(gr)} = \Gamma_{oj} + \Gamma_{Dj} + \Gamma_{Cj}, \quad (9)$$

with $\Gamma_{Dj} = \Gamma_D Y_{Dj}(E_D, \Psi_D)$ and $\Gamma_{Cj} = \Gamma_C Y_{Cj}(E_C, \Psi_C)$. For low Z coatings the sputtering yields and particle transport are all similar; moreover, sputtered ions are unlikely to return to their place of origin so self sputtering and redeposition are not significant for the low Z coatings. The net erosion rate for low Z materials, which is thus also given by Eq. (9), is plotted in Fig. 7 for locations deep in the gap between FS tubes. The right-hand ordinate converts the net gap erosion into practical units based on an atom density of $1 \times 10^{29} \text{ m}^{-3}$ (see Table I for other materials).

If the low Z coating should evaporate, spall or crack, the underlying metals, Ni or Ti, will be exposed to rf-induced sputtering, so a separate analysis was performed for these materials exposed in the FS gap. These heavier atoms have shorter mean free paths for ionization and so are more likely to return to the gap surface than the coating atoms. Also their self-sputtering is larger, so the net erosion may be more severe than the gross erosion. Following [D'Ippolito 1991], the net gap erosion is a modification of Eq. (9),

$$\Gamma_{gj}^{(net)} = \frac{\Gamma_{gj}^{(gr)} l_g}{1 - (Y_{jj} / Y_{cr}^g)} \quad (10)$$

Here $Y_{jj}(E_j, \Psi_j)$ is the self-sputtering coefficient. I_g is the probability that a sputtered neutral will escape the gap before being reionized, and Y_{cr}^g is a critical self-sputtering value which would lead to run-away (avalanche) self-sputtering. The functions I_g and Y_{cr}^g are highly uncertain in that they depend intimately on geometry and plasma transport in the gap vicinity. For the geometry of Fig. 5 we evaluated Eq. (10), and the results for Ni and Ti are displayed in Figs. 8 and 9. By our estimates $Y_{cr}^g \gtrsim 10$ for $10^{16} < n_g < 10^{17}$, while $Y_{jj} \lesssim 2-3$ for Ni and Ti at $E \lesssim 3000$ eV, so avalanche breakdown may not be a serious issue in the gap.

5.2 Front Face Erosion

The analysis here is similar to the gap except for three geometry-related effects [D'Ippolito 1991]. First, the accelerating sheath voltage is higher for field lines connecting non-adjacent tubes; we consider a typical value

$$\Delta V = \mu V_g = 7 V_g .$$

Then Eq. (2) is modified by replacing V_g with ΔV . [Theory and experiment indicate that dipole phasing nearly reduces ΔV to zero for the proper screen symmetry, but for our analysis we consider the worst case — long term operation in a current drive phasing — such that the usual "monopole" theory applies.] Next, the B angle of incidence, α , is different from the gap. As stated above, $\alpha \simeq 0.5^\circ$ at the very front of a tube but increases further into the gap. We assume $\alpha = 3^\circ$ is typical, which is within a factor of ~ 5 of 0.5° and 15° (the "worst case" mismatch θ value). Thus, Eq. (8) is used for the front face, but with θ replaced by α . Finally, the PSOL and front face geometry determine redeposition and possible self-sputtering problems, but differently from the gap problem. With the appropriate modifications, then Eq. (10) is used, replacing the gap values with I_{ff} and Y_{cr}^{ff} .

For the low Z coatings we computed I_{ff} and Y_{cr}^{ff} for the three possible constituent species, B, C, and N. We find I_{ff} is close to unity and $Y_{jj} \ll Y_{cr}^{ff}$, and gross and net local erosion are essentially the same for all species (see Fig. 10). For Ni and Ti, self-sputtering is near the peak values ($Y_{NiNi} \simeq 4$ at $E_{Ni} = 3$ eV, $\Delta V = \mu V_g = 7 V_g$ and $V_g = 1000$ V), and Y_{cr}^{ff} values are rather modest ($\sim 5-7$ at $n_a = 1 \times 10^{18} \text{ m}^{-3}$). Hence, especially at the highest voltages, self-sputtering considerably enhances the erosion rate. This is seen in Figs. 11 and 12, where both the gross and net local

erosion rates are displayed for Ni and Ti on the front face. Evidently Ni surfaces pose the most likely threat for runaway self-sputtering, but the effect is minimized with low density ($n_a < 10^{18} \text{ m}^{-3}$) at the FS and by operating below the maximum line voltage (corresponding to $V_g \approx 1000 \text{ V}$). Nevertheless, the uncertainties in estimating sputtered Ni return fluxes to the screen translate to uncertainties in our confidence in the results, such as Fig. 11.

5.3 Extrapolation to Other Conditions

Slight changes in the β angle can affect the gap erosion. As shown by Eq. (8), $\Gamma \propto \sin \theta$, so the gap erosion can be greatly reduced by achieving $\theta < 15^\circ$. Near the front face we recall that α could be larger than the "typical" 3° value used in the illustrations of Figs. 10-12; again $\Gamma \propto \sin \alpha$.

Also, as shown by Eq. (8), Γ is proportional to the local density in the gap and at the front face. The figures actually show only a factor ≈ 5 change in Γ as the local density varies an order of magnitude (due to compensating changes in impact angle, Ψ , which affect the sputtering coefficients); the figures can accordingly be approximately extended to other densities.

Also, Eq. 8 shows that $\Gamma_D \propto f_D$ and $\Gamma_C \propto f_C$. In our calculations $f_D = 0.95$ and $f_C = 0.05$, so 5% of the incident ions are minority carbon. Yet, the sputtering due to C is typically ~ 20 times larger than that due to D, so each species contributes roughly the same amount of the total erosion. Hence, if TPX actually had $f_C = 0.10$ we would expect a 50% increase in erosion relative to the values plotted.

5.4 Plasma Pollution

The total influx of screen atoms, j , averaged over the full FS, is found by adding the gap and front face contributions, $\bar{\Gamma}_j = [\Gamma_{gj}^{(net)} A_g + \Gamma_{ffj}^{(net)} A_{ff}] A_{FS}^{-1}$, where A_g and A_{ff} are the areas participating in gap and front face erosion, and A_{FS} is the total screen area. Table II shows $\bar{\Gamma}$ for the various materials, assuming $n_g = 1 \times 10^{16} \text{ m}^{-3}$, maximum voltage (1 kV), and worst alignment ($\theta = 15^\circ$). The low Z coatings and bare Ti represent impurity current densities of order a few times $10^{19} \text{ atoms m}^{-2} \text{ s}^{-1}$. This prediction is roughly similar to measured values for the JET FS with various coatings [D'Ippolito 1991].

Table II
Faraday Screen Impurity Production ($n_g = 1. \times 10^{16} \text{ m}^{-3}$; $\alpha = 3^\circ$)

Material Front Face Density (10^{18} m^{-3})	B/C/N		Ni		Ti	
	1.0	0.1	1.0	0.1	1.0	0.1
$\bar{\Gamma}$ ($10^{20} \text{ m}^{-2} \cdot \text{s}^{-1}$)	.70	.22	3.2	.66	.74	.22
T (10^{20} s^{-1})	1.5	.48	6.6	1.4	1.5	.46

Table II also exhibits the total impurity production rate,

$$T_j = 2 A_{FS} \bar{\Gamma}_j ,$$

where we have, for this illustration, assumed two ports are occupied by powered ICRF antennas. This source is the particle flux leaving the FS. Much less enters the confined plasma, as the poloidal/toroidal limiters are a sink in the PSOL, and the divertor should remove most impurities crossing the poloidal limiter horizon (see Fig. 5). For comparison, REDEP analysis for TPX indicates the divertor plates generate a carbon source rate of 4×10^{20} atoms per second which leave the near-surface region of the graphite tiles. Hence, from Table II, we feel the powered antennas will generate impurities at a rate, at most, comparable to the high power divertor influx. Of course, full coverage with Ni or Ti would probably be undesirable due to the high Z of these atoms. Small exposed areas of Ni or Ti will have a negligible contribution to the plasma impurity content.

5.5 Antenna Erosion Lifetime

Although TPX will operate longer in proteum than deuterium, the proton sputtering coefficients are typically a factor of two to four smaller than for deuterium. Also, poorer performance with proteum plasma will typically reduce the ion flux to the FS, relative to deuterium operation. We figure the erosion rate is dominated by

deuterium operations, and we estimate, for surface material j , the total FS erosion loss, δ_j , as

$$\delta_j = 1.25 \dot{\delta}_j \tau_D ,$$

where $\dot{\delta}_j$ is given, e.g., in Figs. 7-12, and $\tau_D = 2 \times 10^6 \text{ s} \approx 560 \text{ h}$. Table III summarizes the eroded thickness for the full life of TPX, assuming exposed areas of the various materials. The maximum erosion loss follows directly from the figures and assumes worst case conditions. More likely the FS will have only partial duty under the worst conditions. For example, antenna alignment frequently may be better ($\theta < 15^\circ$), density may be lower ($n_a < 10^{18} \text{ m}^{-3}$ where $\alpha = 3^\circ$), and low power ICRF would often occur with $V_g < 1 \text{ kV}$. The last row of Table III identifies the estimated material loss with the indicated reduction factors.

Table III
Erosion Loss Over TPX Lifetime (mm)

Material Location (gap; front face)	BN,G		B, DLC, B₄C		Ni		Ti	
	g	ff	g	ff	g	ff	g	ff
Max. loss (constant worst case)	0.39	2.08	0.28	1.49	0.93	14.3	0.57	5.02
Reduction factor	1/2	1/5	1/2	1/5	1/2	1/5	1/2	1/5
Likely loss (typ. operation)	0.20	0.42	0.14	0.30	0.47	2.9	0.28	1.00

Due to their lower atom densities we expect both BN and G to erode more quickly than either B, DLC, or B₄C. Also, the gap erosion is less than half that of the front face for these materials. For B, DLC, or B₄C we would desire a ~140 μm coating in the gap and ~300 μm coating at the front face. Nickel erodes extremely fast — several millimeters would erode if the bare metal were exposed to 560 h of high power operation. As planned for TPX only ~25 μm of Ni is sandwiched between the low Z coating and the FS structure, so, if the Ni were exposed via some removal of the

coating, it could itself be removed rather quickly, thus exposing the Ti structure. The Ti is most readily removed if exposed on the front face; a total ~1.0 mm could be lost through rf-induced sputtering if exposed for the full 560 h. This could jeopardize the FS survival, thinning the 1.7 mm tube wall such that thermal creep could lead to failure.

These calculations concern the worst case — an area of the FS which experiences net loss of material. Most experiments, however, typically find the FS is quickly covered with a layer of (G) material from high-power divertor/limiter operation. While such a process may provide a protective coating with successive, short pulsed operation of tokamaks, it will be prudent to provide the requisite ~140-300 μm coatings, specified above, to guard against erosion of areas which, in steady state ($\geq 1000\text{s}$ pulses) could escape protective deposition of G.

6. Disruption Erosion

We calculated G erosion (ablation), due to TPX worst-case thermal disruptions — 11 MJ/m² released to the FS in 0.1 ms. Simulations with the DESIRE code [Ehst 1993] predict ablation depths of ~3-6 μm , while, under similar conditions, plasma gun experiments in the U.S. and Russia result in 3-7 μm of loss. Hence, about forty to a hundred full power disruptions would be required directly to the FS in order to remove ~300 μm of a low Z coating.

7. Conclusions

Regarding the FS design we desire:

- alignment of the screen angle to minimize θ during high power operation;
- indenting the screen so the central tubes (Fig. 6) have Δx_{SOL} about 4 mm larger than the edges (implying an accurate knowledge of the separatrix flux surface, including toroidal ripple);

- retaining the option of laterally moving the antenna so Δx_{SOL} (Fig. 5) can vary from zero to ~ 8 cm, thus minimizing density at the FS without losing coupling;
- including a density diagnostic to monitor n_a .

Concerning low Z coatings:

- B_4C coating capability is not readily available in the U.S., and experience with FS coatings has not been as good as desired (flaking, nonuniform thickness);
- cubic BN is difficult to apply over large areas;
- graphite (G) has modest erosion rates which may, however, be enhanced by chemical sputtering;
- diamond-like-carbon (DLC) and B appear most attractive;
- B has the lowest Z of the coatings studied, although its microstructure will change and a B_xC_y compound may form after exposure to divertor-generated carbon and long term sputtering; B has an electric resistivity which is temperature dependent and may lead to local hot spots in thin rf coatings;
- under severe conditions ($n_a > 10^{18} \text{ m}^{-3}$), DLC has insulator properties which help to reduce the sheath potential, and the physical and chemical sputtering of DLC is reduced compared to G.

Coatings should be applied with care:

- a thickness of $\sim 50\text{-}150 \mu\text{m}$ is desired in the gap, and a thickness of $\sim 300 \mu\text{m}$ is needed on the front face;

- adequate gap protection would be promoted by coating the tubes prior to assembly, rather than attempting to coat the whole tube bank after the FS is assembled.

We found that Z_{eff} of the plasma will be barely affected by rf-induced sputtering if these low Z coatings are used. A small breach of the coating will expose Ni, which is a localized source of moderate Z impurity. Of more concern, if Ti is exposed to the plasma then long term self-sputtering may severely erode and thin the Ti coolant tube, leading to potential failure.

Our modeling includes myriad assumptions and depends on details of neutral and plasma transport in a complicated geometry. As such our lifetime calculations should be considered only a preliminary survey of this issue. One conclusion is evident, however. Operation of a FS is not likely for more than $\sim 10^3$ hours by our assessment. Other designs (antenna operation without a FS; or folded waveguides) may be superior for true steady state reactor conditions.

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Figure 1. TPX boundary geometry.

Figure 2. View of antenna/PFC from plasma.

Figure 3. Antenna/screen side view.

Figure 4. Faraday screen and current straps; the tokamak magnetic field defines an angle mismatch θ to the screen tube orientation.

Figure 5. Geometry detail of the screen tubes and the common and private scrape off layer.

Figure 6. Plan view of antenna with screen at a distance ΔX_{SOL} from poloidal limiter horizon.

Figure 7. Gap-net local erosion ($I = \text{B,C,N}$): $\theta = 15^\circ$, 5% C^{+3} ; two different gap densities.

Figure 8. Same as Fig. 7, except for exposed Ni.

Figure 9. Same as Fig. 7, except for exposed Ti.

Figure 10. Front face-net local erosion (I = B,C,N): $\alpha = 3^\circ$, 5% C⁺; two different front face densities.

Figure 11. Same as Fig. 10, except for exposed Ni; curves with diamonds are gross erosion, ignoring self-sputtering/avalanche.

Figure 12. Same as Fig. 11, except for Ti; net and gross erosion are similar.

APPENDIX

Physical sputtering data is displayed for C, Ni, and Ti in Figs. A1-A6 for normal incidence by D, light ions and self sputtering [Eckstein]. The large variations in experimental results, typified by D sputtering of C in Fig. A1, are due to differences in surface roughness, preparation techniques, contaminants, etc.

Within the large scatter of experimental results we found by comparison that all the low Z coatings sputter similarly, so, for $I = C, B, BN, B_4C$, we model the $D \rightarrow I$ sputtering coefficient as

$$Y_{DI} = S_{DC} A_1(\psi)$$

where $S_{DC}(E)$ is the normal incidence values for carbon (Fig. A1) as a function of ion energy, E . For $E < 1000$ eV we set $S_{DC} \equiv 0.03$. A fit to the angular dependence plotted in [Eckstein] is

$$A_1 = 1.0 + 4.7 (\psi/90^\circ)^{2.8} .$$

[All our $A(\psi)$ fits assume $\psi \leq 70^\circ$.]

Minority C and self-sputtering of low Z materials we find is also well represented by a single function,

$$Y_{CI} = S_{CC} A_2(\psi)$$

where S_{CC} is the dashed curve in Fig. A2, and we find

$$A_2 = 1.0 + 6.3 (\psi/90^\circ)^{3.4} .$$

For the metal surfaces (assuming the Ni or Ti are eventually exposed) we model

$$\begin{cases} Y_{DNI} = S_{DNI} A_3(\psi) \\ Y_{DTI} = S_{DTI} A_3(\psi) \end{cases} .$$

The experimental (dashed) curves are used for D normal incidence (Figs. A3 and A5), and we use

$$A_3 = 1.0 + 7.2 (\psi/90^\circ)^{3.4} .$$

Carbon sputtering data are not available, but a study of various light ion impacts on Ni, Cu, and Ti suggests

$$\begin{cases} Y_{\text{C Ni}} = 6 S_{\text{He Ni}} A_3 (\psi) \\ Y_{\text{C Ti}} = 6 S_{\text{He Ti}} A_3 (\psi) \end{cases} .$$

For metal self sputtering, which is large, we set

$$\begin{cases} Y_{\text{Ni Ni}} = S_{\text{Ni Ni}} A_4 (\psi) \\ Y_{\text{Ti Ti}} = S_{\text{Ti Ti}} A_4 (\psi) \end{cases} ,$$

where the angular enhancement is fairly mild,

$$A_4 = 1.0 + 3.3 (\psi/90^\circ)^{2.4} .$$

Neutral sputtered atoms are emitted at an average speed characterized by the sublimation energy of the solid materials [Matsunami]; we select the mean energies to be $T_n(\text{eV}) = 2.9, 3.7, 4.0, 2.2,$ and 2.4 for the five elements, respectively, B, C, N, Ni, and Ti.

Sputtered neutrals are re-ionized near the FS and a fraction may return to the surface. We evaluate the electron ionization rate assuming a local $T_e = 50$ eV,

$$\langle \sigma_{ei} v \rangle (10^{-13} \text{ m}^3 \cdot \text{s}^{-1}) = 1.6, 0.87, 0.62, 1.3, \text{ and } 2.1$$

for respectively B, C, N, Ni and Ti.

Experimental Data

Target	Projectile	Angle	Symbol	$E_{th}(eV)$	$Q(\text{atoms/ion})$
C/*	H	0	□		
C/*	D	0	◇		

Calculated Data

Target	Projectile	Angle	Symbol	$E_{th}(eV)$	$Q(\text{atoms/ion})$
C	H	0	■	27.3	0.0271
C	D	0	◆	24.3	0.0601
C	T	0	●	22.4	0.0684

Figure A1. Energy dependence of sputtering yield of C by H, D, and T; normal incidence (Ref. [Eckstein]).

Target: C

Experimental Data					
Target	Projectile	Angle	Symbol	$E_{th}(eV)$	$Q(\text{atoms/ion})$
C/*	He	0	$\triangle$	30.2	0.387
C/*	O	0	∇		
C/*	H ₂ O	0	$\triangleright$		
C/*	¹² C	0	$\square$	35.0	1.20
Calculated Data					
Target	Projectile	Angle	Symbol	$E_{th}(eV)$	$Q(\text{atoms/ion})$
C	He	0	$\blacktriangle$	25.4	0.169
C	¹² C	0	$\blacksquare$	44.0	0.620
C	O	0	$\blacktriangledown$	100.	0.990

Figure A2. Same as Fig. A1, but for C by ⁴He, C, and O.

Target: Ni

Experimental Data

Target	Projectile	Angle	Symbol	$E_{th}(eV)$	$Q(\text{atoms/ion})$
Ni	H	0	□	51.4	0.0420
Ni	D	0	◇	29.9	0.121
Ni	Ni	0	▷	32.5	14.0

Calculated Data

Target	Projectile	Angle	Symbol	$E_{th}(eV)$	$Q(\text{atoms/ion})$
Ni	H	0	■	53.2	0.0420
Ni	D	0	◆	30.8	0.110
Ni	Ni	0	▷	33.9	16.7

Figure A3. Same as Fig. A1, but for Ni by H, D, and Ni.

Target: Ni

Experimental Data					
Target	Projectile	Angle	Symbol	$E_{th}(eV)$	$Q(atoms/ion)$
Ni	He	0	Δ	16.8	0.499
Ni	O	0	∇	48.5	1.69
Ni	Ne	0	$\square$	15.1	5.07

Calculated Data					
Target	Projectile	Angle	Symbol	$E_{th}(eV)$	$Q(atoms/ion)$
Ni	3He	0	∇	28.4	0.372
Ni	He	0	$\blacktriangle$	24.3	0.432
Ni	Ne	0	$\blacksquare$	22.7	4.73

Figure A4. Same as Fig. A1, but for Ni by 3He , 4He , O, and Ne.

Target: Ti

Experimental Data

Target	Projectile	Angle	Symbol	$E_{th}(eV)$	$Q(\text{atoms/ion})$
Ti	H	0	□	69.2	0.0157
Ti	D	0	◇	33.2	0.0542

Calculated Data

Target	Projectile	Angle	Symbol	$E_{th}(eV)$	$Q(\text{atoms/ion})$
Ti	D	0	◆	33.9	0.0754
Ti	Ti	0	▶	40.4	4.63

Figure A5. Same as Fig. A1, but for Ti by H, D, and Ti.

Target: Ti

Experimental Data					
Target	Projectile	Angle	Symbol	$E_{th}(eV)$	$Q(\text{atoms/ion})$
Ti	He	0	Δ	35.9	0.234

Calculated Data					
Target	Projectile	Angle	Symbol	$E_{th}(eV)$	$Q(\text{atoms/ion})$
Ti	He	0	$\blacktriangle$	21.2	0.295
Ti	Ne	0	$\blacksquare$	22.0	3.00

Figure A6. Same as Fig. A1, but for Ti by ^4He and Ne.

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