Physics of Divertors and the Scrape-off Layer

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Abstract

Simple models are discussed which are useful in determining the relative importance of various processes in the scrape-off and divertor regions on the performance of divertors. First a model for plasma-wall-divertor interaction based on simple impurity balance considerations is described. Results obtained with this model show how steady-state impurity concentrations depend on typical divertor characteristics, such as unload efficiency, shielding efficiency and neutral backflow from divertor. In the second part expressions for these quantities are derived for a density profile in the scrape-off layer that results if plasma diffusion across the magnetic field is balanced by parallel flow along the field to the divertor. The dependence of these divertor characteristics on various plasma parameters in the scrape--off layer is discussed and numerical examples are given for the case of a poloidal divertor.

I. Introduction

Theoretical predictions of the various processes in the scrape-off and divertor regions and of the performance of divertors on tokamak plasmas have been made from a variety of points of view. The work by Hinton and Hazeltine /1/ and by Daybelge and Bein /2/ is based on neoclassical kinetic theory, whereas Boozer /3/ starts from the two-fluid equations. In the following we shall discuss simple zero-dimensional divertor models which, though not describing all the relevant processes correctly, are useful in developing an understanding of the relative importance of these processes in determining divertor operation (see also /4/ and literature cited therein).

In the first part we describe a model for plasma-wall-divertor interaction that is based on a zero-dimensional impurity balance equation and discuss results obtained with this model. In the second part the density profile in the scrape-off layer as derived from a one-dimensional diffusion equation is used to calculate various parameters (e.g. unload efficiency, shielding efficiency) that determine the performance of a divertor.

II. Plasma-Wall-Divertor Interaction

The operation of a divertor is specified by three main characteristic parameters:

- unload efficiency U,
- backstreaming ratio R_H, and
- shielding efficiency S.

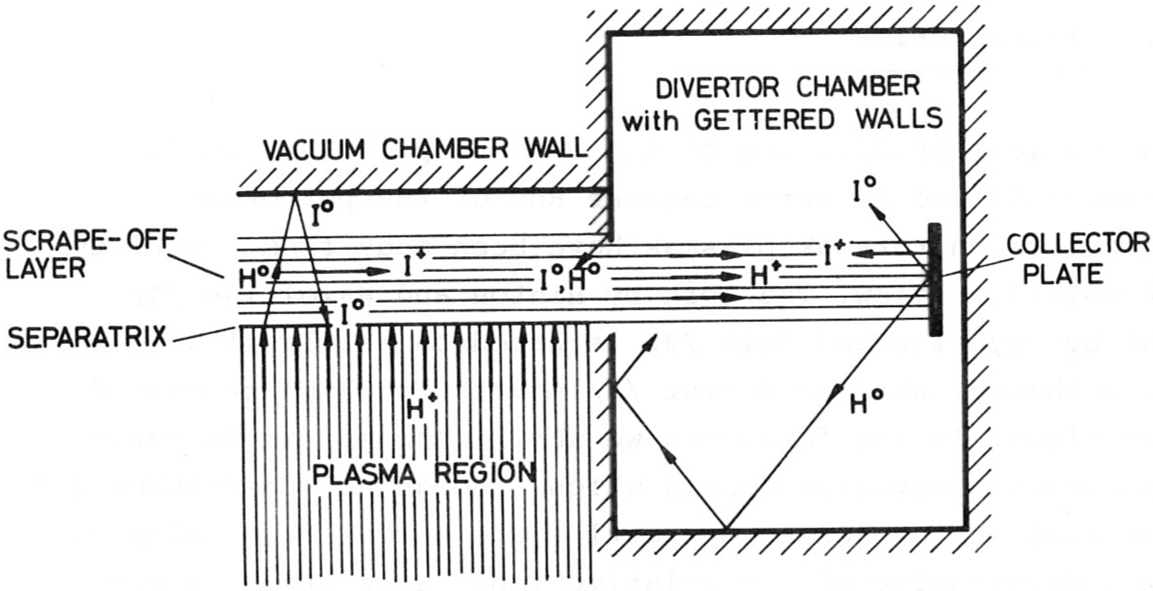

Fig. 1: Idealized representation of processes in the scrape-off and divertor regions.

A simplified representation of the processes in the scrape-off and divertor regions (see Fig.1) leads to the following impurity balance equation:

$$\dot{n}_I = \frac{n_H}{\tau_H} \Big\{ (1-U)(Y_H^L + \gamma_H \; Y_H^W)(1-S) + U\left[Y_H^D \, s_i \, \eta (1-s_f) + R_H \, \gamma_{H_2} \; Y_H^W \, (1-S)\right] + (1-R_H) \sum_m \alpha_m \, \gamma_m \, Y_H^W \, (1-S) \Big\} + \frac{n_I}{\tau_I} \Big\{ (1-U) \; Y_I^L \; (1-S) \; + U \; Y_I^D \; s_i \, \eta (1-s_f) - 1 \Big\} .$$

Here n and τ denote particle densities and confinement times, Y sputtering yields and γ the number of fast cx neutrals which bombard the wall per neutralized plasma ion. The subscripts H, H_2 and I relate to hydrogen atoms, hydrogen molecules and impurities, respectively, whereas the indices L, W and D indicate sputtering from the limiter, the wall and the collector plate.

The first line of the above equation describes the build-up of impurities caused by the part of the plasma impinging on the divertor slits. The second line represents the contribution by the plasma that enters the divertor and sputters the collector plate. A fraction $S_i\,\eta$ of the sputtered material becomes ionized in the plasma in front of the plate (S_i) and reaches the plasma chamber along the field lines (η). Part $(1 - S_f)$ of this fraction diffuses into the plasma. Of the neutralized gas, part R_H flows back into the plasma chamber and leads to cx sputtering. The third line of the equation describes the build-up of impurities connected with refuelling. Here α_m denotes the fraction that a specific refuelling method contributes to the total particle flux. The last line finally represents the contamination due to sputtering by impurity ions from the plasma. The impurity balance equation can be written in the form

$$\dot{c}_I = \frac{H}{\tau_p} + c_I \frac{I - 1}{\tau_I} ,$$

where $c_I = n_I/n_H$ is the relative concentration of impurity ions. The coefficient H describes all contributions to the contamination that are due to sputtering of the limiter and collector plates by plasma ions (including self-sputtering by metal ions) and of the wall by cx neutrals. The coefficient I describes the corresponding contributions due to sputtering by metal ions from the plasma.

This equation has the solution

$$c_I = \frac{H}{1 - I} \cdot \frac{\tau_I}{\tau_p} \left[1 - \exp - \left((1 - I) \frac{t}{\tau_I} \right) \right] .$$

For $I < 1$, which is usually the case, the impurity concentration, after a time of the order of the impurity confinement time τ_I, reaches the stationary value

$$c_{I,stat} = \frac{H}{1 - I} \cdot \frac{\tau_I}{\tau_p} .$$

Ion- CX- Sputtering	Unload Divertor U=1	Shielding Divertor S=1	No Backflow from Divertor R_H=O	No Divertor U=S=O
$Y_H^L \quad + \quad \gamma_H \, Y_H^W$	O	O	(1-U) (1-S)	1
Y_H^D	$S_i \eta (1-S_f)$	$\eta (1-S_f)$	$S_i \eta (1-S_f)$	O
$\gamma_{H_2} \, Y_H^W$	$R_H (1-S)$	O	O	O
$\sum_m \alpha_m \gamma_m \, Y_H^W$	$(1-R_H)$ (1-S)	O	(1-S)	$(1-R_H)$
Y_I^L	O	O	(1-U) (1-S)	1
Y_I^D	$S_i \eta (1-S_f)$	$\eta (1-S_f)$	$S_i \eta (1-S_f)$	O

Table 1

To obtain a better insight into the importance of the various factors which describe the plasma-wall-divertor interaction it is worthwhile to consider some limiting cases, e.g. 100 % unload divertor ($U = 1$), 100 % shielding divertor ($S = 1$), no backflow from divertor ($R_H = 0$) and no divertor at all ($U = S = 0$). Table 1 gives a survey of the resepctive contributions to impurity build-up in these cases. The sums of the first four lines of each column yield the coefficients H, the last two lines the coefficients I.

Zero-dimensional balance equations for plasma and impurity densities as described above are very useful for determining - at least in a qualitative way - how the various divertor characteristics influence the impurity level.

The following examples, which are taken from W.M.Stacey et al. /5/, show numerical simulations of the steady-state impurity build-up in a tokamak reactor. In this study two modes of divertor operation are compared: the "unload" divertor (with characteristic parameters $U = 0 \div 1$, $S = 0.05$) and the "shielding-unload" divertor ($S = 0.5 \div 1$, $U = 0.85$). Sputtering yields characteristic of iron were used and wall recycling of the DT mixture and of the impurities was assumed to be 0.95 and 0.05, respectively. The cx neutrals from the plasma were assumed to have a temperature $T_{np} = 2 \cdot T_{edge}$, those from the scrape-off layer $T_{ns} = \frac{1}{2} \cdot T_{edge}$, T_{edge} being the ion temperature at the edge of the plasma.

The steady-state impurity concentrations plotted in Figs.2 and 3 are normalized and have to be multiplied with the relative particle confinement times. Figures 2a and b show results for the unload divertor, and Figs.3a and b for the shielding-unload divertor. In the case of the unload divertor the wall-sputtered impurity concentration is quite sensitive to the unload efficiency at large values of U (Fig.2a) and to the plasma-edge temperature (Fig.2b), but only moderately

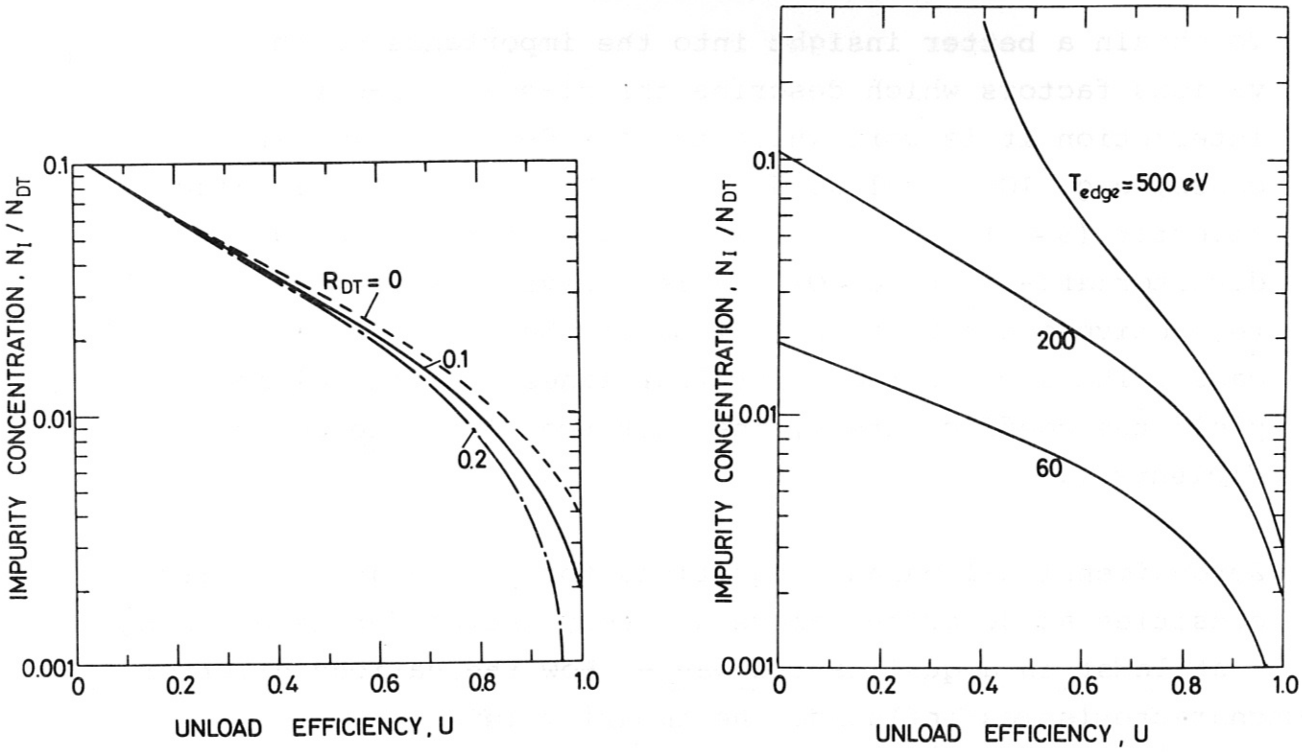

Fig.2: Normalized wall-sputtered impurity concentration as a function of unload efficiency U, with
a) backstreaming ratio R_{DT} (S = 0.05, T_{edge} = 200 eV) and
b) plamsa-edge temperature T_{edge} (S = 0.05, R_{DT} = 0.1 as parameters.

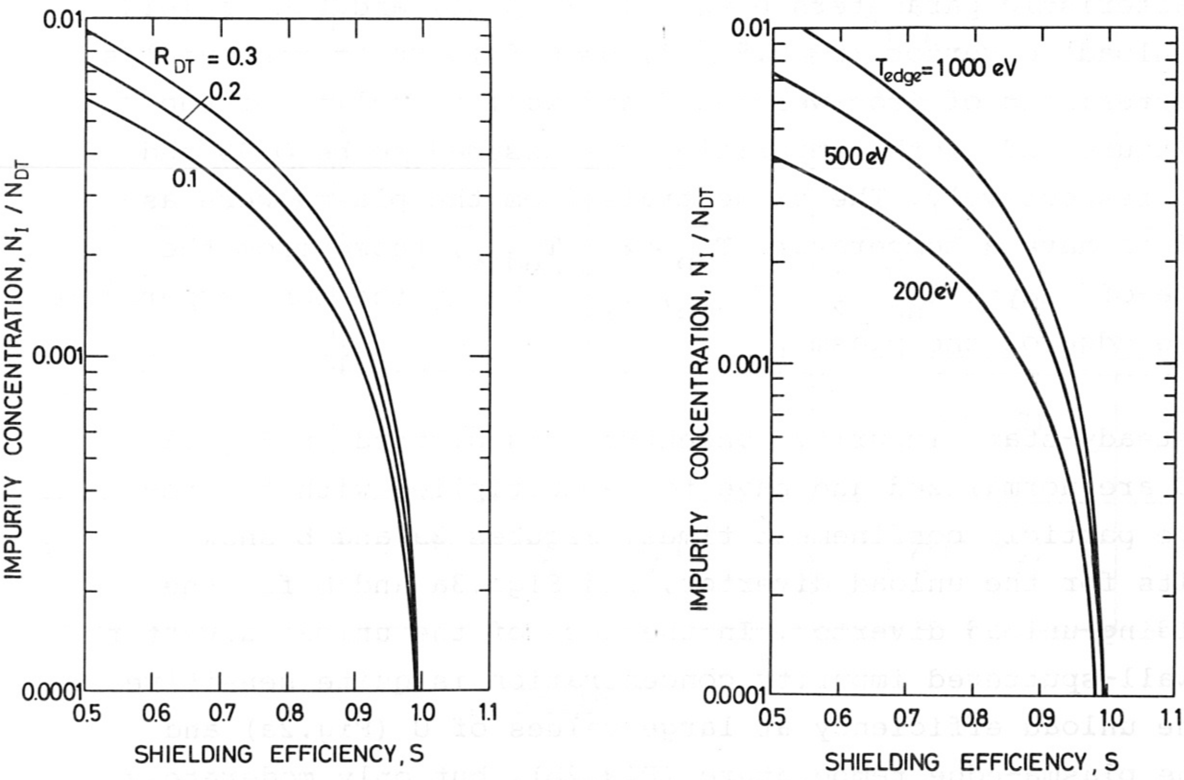

Fig.3: Normalized wall-sputtered impurity concentration as a function of shielding efficiency S, with
a) backstreaming ratio R_{DT} (U = 0.85, T_{edge} = 500 eV) and
b) plasma-edge temperature T_{edge} (U = 0.85, R_{DT} = 0.2) as parameters.

sensitive to the backstreaming ratio (Fig.2a). For the shielding-unload divertor the impurity concentration is extremely sensitive to the shielding efficiency at large values of S (Figs.3a and b). In general, the results show that a shielding-unload divertor has a greater potential for achieving a very low impurity concentration than an unload divertor.

III. Scrape-off Layer

1. Density profile

Various models have been proposed to describe the processes in the scrape-off layer. In the case that particle transport is governed by diffusion one usually considers a simple one-dimensional model in which plasma diffusion across the magnetic field (perpendicular diffusion coefficient $D_{\perp s}$) is balanced by particle flow parallel to the field lines into the divertor (particle loss time $\tau_{\parallel}$). In this model the two-dimensional effect of particle flow to the divertor is simulated by an absorption term in the particle continuity equation, which is then of the form

$$\frac{d}{dx}\left(D_{\perp s}\frac{dn}{dx}\right) = \frac{n}{\tau_{\parallel}} - n\, n_n \langle \sigma v \rangle_i \, .$$

The second term on the right-hand side, which describes ionization in the scrape-off zone, should be small for a working divertor and will be neglected in the following.

Assuming that $D_{\perp s}$ and $\tau_{\parallel}$ are constant across the scrape-off region, the density profile is given by

$$n = n_s \exp(-x/\Delta),$$

where $\Delta = (D_{\perp s}\,\tau_{\parallel})^{1/2}$

and $n_s = \frac{\bar{n}\,a}{2\tau_p} \frac{\Delta}{D_{\perp s}} = \frac{\bar{n}\,a}{2\tau_p} \left(\frac{\tau_{\parallel}}{D_{\perp s}}\right)^{1/2}$

are the width of the scrape-off layer and the plasma density at the seapratrix $(x = 0)$, respectively.

Apart from quantities that relate to the confined plasma (plasma radius a, average plasma density $\bar{n}$ and particle confinement time τ_p), the density profile in the scrape-off layer depends only on $D_{\perp s}$ and $\tau_{\parallel}$. According to one's prejudices about the relevant physics in the scrape-off layer, various choices for these quantities can be made.

a) Ambipolar flow with ion sound speed

In the "ion sound model" it is assumed that an electric sheath is formed in front of the neutralizer plates causing ambipolar plasma flow into the divertor with a flow velocity of the order of the ion sound speed, v_s. In this case $\tau_{\parallel}$ is simply given by

$$\tau_{\parallel} = L/v_s,$$

where L is the geometrical path length into the divertor.

This situation holds for divertors with no magnetic mirrors, e.g. for poloidal divertors with stagnation lines on the large major radius side. In a slightly modified way it also applies to divertors with magnetic mirrors (e.g. double inside poloidal divertor, bundle divertor) if the plasma in the scrape-off layer is collisional enough to maintain an isotropic velocity distribution, i.e. if particles are scattered by collisions into the loss-cone in a time shorter than their transit time into the divertor. In this case, however, only those particles that are not trapped (roughly a fraction $1 - (\frac{a}{R})^{1/2}$ for an inside poloidal divertor) contribute to the particle flux to the divertor, and the width of the scrape-off layer becomes correspondingly larger.

b) Mirror confinement

The situation is different if there is a mirror in front of the divertor and the scrape-off plasma is fairly collisionless. In this case a considerable fraction of the particles in the scrape-off layer is trapped (a fraction $\simeq (\frac{a}{R})^{1/2}$ for an inside poloidal divertor) and the particle flux to the divertor is determined by the rate at which collisions scatter these trapped particles into the loss-cone. In this "mirror confinement model" the particle loss time is approximately equal to the scattering time of trapped particles into the loss-cone, i.e.

$$\tau_{\parallel} = \tau_{90^{\circ}} \log M,$$

where $\tau_{90^{\circ}}$ is the 90° scattering time for the ions and M is the mirror ratio.

In practice, the anisotropic velocity distribution caused by the divertor loss-cone may be unstable to several microinstabilities, thus enhancing the scattering frequency and preventing a classical mirror confined scrape-off plasma.

One of the most important objectives of existing (DIVA, DITE) and forthcoming (ASDEX, PDX) divertor tokamaks is to investigate the scaling of certain quantities characteristic of a scrape-off layer (e.g. particle flow velocity, heat transport rate, density scale-length) and to compare it with the proposed models. So far experiments on FM 1 /6/ and DIVA /7/ indicate that the flow velocity into the divertor is about one-third the ion sound speed. The observed widths of the scrape-off layers in DITE /8/ and DIVA /7/ are consistent with the ion sound model and a perpendicular diffusion coefficient corresponding to 0.1 to 0.5 times Bohm diffusion. In DIVA the diffusion coefficient was also shown to have the functional dependence expected for Bohm diffusion (over a factor of 5 in parameter range) /9/.

2. Unload efficiency

If the density profile in the scrape-off layer is known, the unload efficiency of the divertor can be calculated from the relation

$$U = 1 - \exp\,(-W/\Delta'),$$

where W is the effective width of the divertor entrance slit and Δ' the density scale-length in the scrape-off layer projected into the divertor throat, i.e. $\Delta' = (B_p/B_p')\cdot\Delta$, B_p' being the poloidal field in the divertor throat and B_p the average poloidal field.

For $W/\Delta' = 4$, for example, a value that is easily attainable in most divertor designs, one gets $U \simeq 0.98$, i.e. most of the outstreaming plasma goes into the divertor.

3. Neutral gas return from the divertor

The wide divertor entrance slit postulated by a high unload efficiency has to be compared with the requirement that only a small fraction of the neutral gas that is generated in the divertor by neutralizing the incoming plasma should return to the main vacuum chamber. The latter requirement calls for high pumping speeds that can only be achieved by getter pumps. If possible, the getter pumping should be supplemented by trapping of plasma ions in the neutralizer plates.

The fraction of neutral gas that returns from the divertor, the backstreaming ratio R_H, is then given by

$$R_H = \frac{C(1 - f_p)}{C + P} ,$$

where C is the conductance of the divertor throat, f_p the trapping efficiency of the neutralizer plates for plasma ions, and $P = f_n A$ the pumping speed (f_n is the intrinsic pumping speed, and A the area of the gettering surfaces).

4. Shielding efficiency

The shielding process in the scrape-off layer consists of two steps: first the impurity atom has to be ionized and then the ion has to be swept into the divertor. In order to shield the plasma core against wall-originated impurities the ionization process has to take place so far away from the separatrix that the impurity ions cannot diffuse into the confined plasma during their flight into the divertor.

In the following, we shall assume that the inward diffusion is sufficiently slow for all the impurity ions to be swept into the divertor. With this simplification the shielding efficiency is equal to the ionization probability

$$S_i = 1 - \exp - \left[\frac{\langle \sigma v \rangle_i}{v_I} \int_0^\infty n dx \right] ,$$

where $\langle \sigma v \rangle_i$ is the ionization rate and v_I the radial velocity of the incoming impurity atom.

As far as the scrape-off plasma is concerned, the ionization probability depends only on the area density $\int_0^\infty n dx$. Furthermore, since it can be assumed that the impurity atoms all come off the wall with the same energy kT_I, the ionization proba-

bility is larger for heavier impurities ($v_I = (kT_I/m_I)^{1/2}$).
It is interesting to note that the area density of the scrape-off layer

$$\int_0^\infty n dx = n_s \Delta = \frac{\bar{n}a}{2\tau_p} \cdot \tau_{\parallel}$$

depends only on the sojourn time of particles in the scrape--off region, $\tau_{\parallel}$ (apart from quantities that relate to the confined plasma). For $\tau_{\parallel} = L/v_s$ (ion sound model) and a fixed type of divertor (which determines L and M) the area density and hence the ionization probability depend only on the electron temperature in the scrape-off layer, T_e ($\int_0^\infty n dx \propto T_e^{-1/2}$).

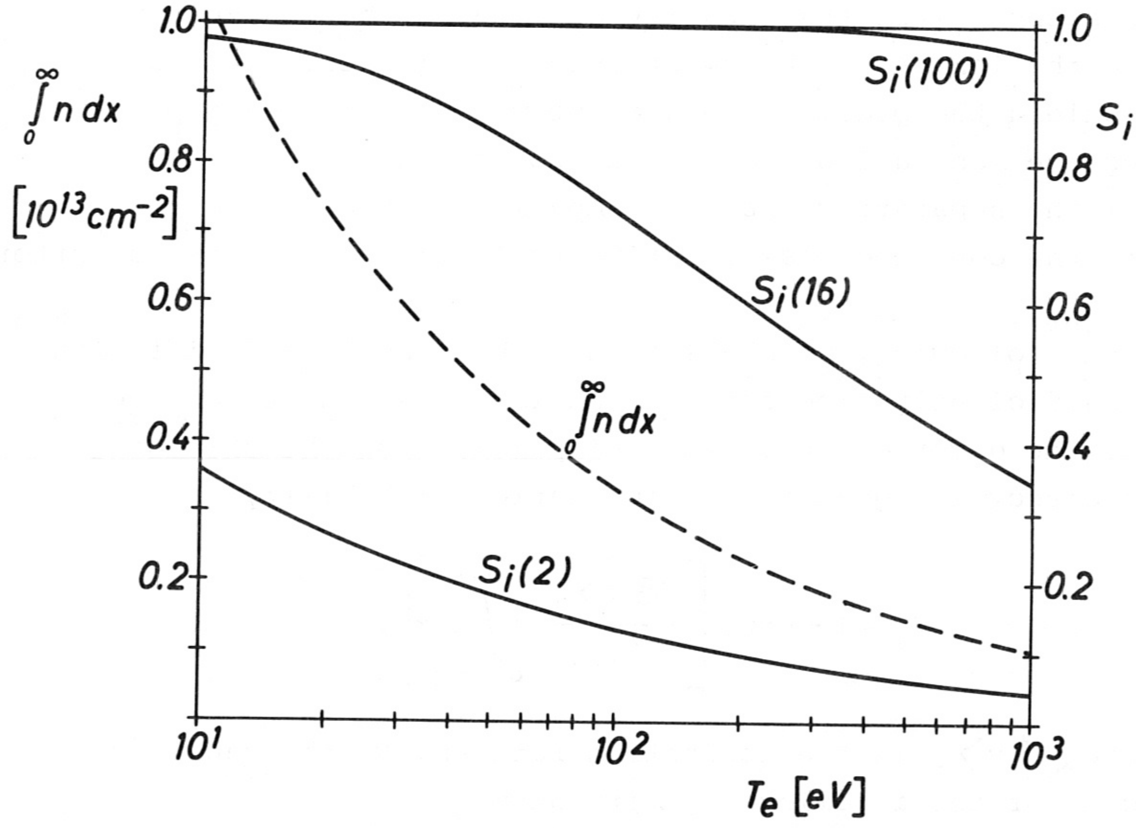

Fig.4: Area density $\int_0^\infty n dx$ and ionization probabilities for hydrogen $S_i(2)$, oxygen $S_i(16)$ and heavy impurities $S_i(100)$ as a function of the electron temperature in the scrape-off layer, T_e, for a poloidal divertor of ASDEX-size.

Figure 4 shows these dependences for a poloidal divertor of the geometry, dimensions and plasma parameters planned for ASDEX. In this example the impurities were assumed to have a radial velocity corresponding to 1 eV and values of 3×10^{-8}, 1×10^{-7} and 3×10^{-7} cm^3/s were used for the ionization rates of hydrogen ($S_i(2)$), oxygen ($S_i(16)$) and heavy impurities ($S_i(100)$), respectively.

Let us finally mention some possibilities of improving the shielding efficiency of the scrape-off layer.

- As we have seen above, it is advantageous to keep the electron temperature in the scrape-off layer as small as is compatible with effective ionization of the impurities. (A low edge temperature, of course, also helps to keep sputtering rates, and hence, the influx of impurities, small (see Figs. 2b and 3b).
- A longer path length into the divertor (e.g. as in the bundle divertor) increases the ionization probability. But this also increases the sojourn time of the impurities in the scrape--off layer and therefore the distance they diffuse into the plasma before reaching the divertor.
- Increasing the density in the scrape-off layer, e.g. by gas puffing, is certainly beneficial. This effect is believed to account for the improved plasma purity observed in tokamak experiments using gas puffing such as Alcator and Pulsator.
- A novel method of improving the shielding efficiency is the proposal /10/ to enhance the diffusion coefficient at the plasma edge by ergodization of the magnetic field lines. This is accomplished by superposing resonant helical fields on an axially symmetric tokamak equilibrium. It is claimed that this increases the area density by a factor of ten over that expected for an ordinary poloidal divertor.

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