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NEUTRAL TRANSPORT IN THE ALT-I LIMITER

BY

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ABSTRACT

The behavior of neutral atoms and molecules in the TEXTOR pump limiter ALT-I has been investigated with the aid of the 2-D Monte Carlo neutral transport code DEGAS. The code incorporates the full set of relevant collision processes (atomic and molecular), and it has a standard wall model which includes fast-neutral reflection and molecular desorption. The limiter has a narrow neck positioned in the toroidal direction, with an entrance at one end and a neutralizer plate set at an angle at the other end. Neutrals born at the neutralizer plate can make their way down a long, narrow duct into a pumping plenum. Both the width of the entrance duct and the width of the duct leading into the plenum can be varied in the experiment. The limiter was modeled with a 2-D geometry, which included corrections for 3-D effects. Among the quantities predicted by the code which are directly relevant to experiment include the neutral pressure within the plenum and along the duct leading into the plenum, the gettering rates, and the heat flux to the walls of the duct. These have been calculated for a variety of plasma parameters in

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the inlet, and the behavior with respect to variations of the duct widths has been studied. Because of the presence of the long duct separating the entrance chamber from the plenum, a high probability of ionization generally results, suggesting that a calculation allowing the plasma to adjust to the neutral sources might show a large amount of recycling.

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I. INTRODUCTION AND MODEL

The Monte Carlo neutral transport code DEGAS¹ has been used to model poloidal divertors²⁻⁴ and pump limiters.⁵ In this paper we use it to simulate the TEXTOR pump limiter ALT-I,^{6,7} a schematic top view of which is shown in Fig. 1. Ions enter through the opening at top left, flow across the chamber at a speed taken to be $[(T_e + T_i/m)]^{1/2}$ and, after acceleration across the sheath, strike the TiC-coated carbon neutralizer plate, which is set at an angle of 30° relative to the direction of plasma flow. Neutrals emitted from the plate can travel down a long duct into the pumping plenum.

The height (perpendicular to the drawing in Fig. 1) of both the inlet duct and the duct leading into the plenum is 30 cm. The width b_1 of the former duct can be varied up to a maximum of 3 cm, and the width b_2 of the latter duct can be set to either 7 cm or 13 cm. (The slabs which move are the lower face of the entrance duct and the left-hand side of the long duct, as seen in Fig. 1.) The outer shape of the plenum is two cylinders connected by a frustum. Encircling the larger cylinder near the frustum is a cylindrical array of Zr-V-Fe bulk getter modules (SAES St 1707), which has a total rated pumping speed of 18,000 l/s for H₂ at 300°C. Near the far end of the plenum is a small duct leading to a turbomolecular pump with a conductance-limited effective H₂ pumping speed of approximately 1000 l/s.

Reflections from the neutralizer plate and the stainless steel walls are modeled using the data of Eckstein and Verbeek.⁸ Neutrals implanted in the wall are assumed to diffuse to the surface and to desorb as wall-temperature molecules. Any atom which strikes a getter surface but which does not stick is taken to desorb as a cold molecule. The data⁸ apply to the case of normal incidence. Since the reflection coefficient increases with shallower incidence angle,⁸ the model may underestimate the frequency of reflection, and

thus the conductance of atoms down the long duct. Unfortunately, no experimental data exist for the conductance of atoms in the energy range ($E < 100$ eV) expected here, so the degree of the underestimate is unknown.

The code incorporates the relevant neutral/plasma processes such as charge exchange, electron-impact ionization, and dissociation.¹⁻⁴ Collisions between neutrals have not been considered, although at high plasma densities they might play a role within the inlet and near the top of the main duct.

Modeling an inherently 3-D device such as ALT-I with a 2-D code necessarily involves heuristic considerations. The rectangular ducts are most easily handled by the code by regarding the vertical dimension (normal to the plane of Fig. 1) as infinite. While the geometry of the plenum suggests a cylindrical treatment, it too was modeled like the ducts.

To account for 3-D effects, two corrections in the parameters were considered. First, the sticking probability σ appropriate to the bulk getter was adjusted so as to preserve the total pumping speed, i.e., to preserve the product σA , where A is the surface area. Given an effective area $2ha$, where $h=25$ cm and $a=30$ cm, one obtains an effective sticking probability $\sigma = 0.27$ for H_2 . The presence of the turbomolecular pump was modeled as an area with a sticking probability of 0.072; the width of this area was adjusted to make the effective area agree with the actual area. The sticking probability for atoms at the bulk getter was taken to be twice that of molecules. Atoms entering the duct to the turbomolecular pump were assumed to convert rapidly to molecules, and the effective atomic sticking probability was enhanced over the molecular sticking probability by the square root of the mass ratio. The calculated results are, in fact, insensitive to these choices for atoms, since within the plenum the density of atoms is usually two orders of magnitude less than the density of molecules.

Second, the width b_2 of the long duct was adjusted to account for the enhanced conductance of a 2-D duct. For this purpose, the relevant conductances were evaluated by separate runs with DEGAS, and the effective width was determined by matching the conductances per unit height in two and three dimensions. As is shown in the Appendix, this results in a shrinking of the 7 cm duct to 5.93 cm and a shrinking of the 13 cm duct to 10.5 cm. These effective widths were used in the running of the code. (In the remainder of the paper, we continue to refer to the widths by their physical values of 7 cm and 13 cm.)

II. RESULTS

Runs were made with two choices of plasma temperature at the innermost limiter edge, $T_e = T_i = 10$ eV and $T_e = T_i = 25$ eV (chosen to bracket the ionization potential of hydrogen), and with four choices of ion density at this point: $n = 3 \times 10^{11} \text{cm}^{-3}$, $1 \times 10^{12} \text{cm}^{-3}$, $3 \times 10^{12} \text{cm}^{-3}$, and $1 \times 10^{13} \text{cm}^{-3}$. Discharges in TEXTOR during May 1983 indicate that central densities up to $2 \times 10^{13} \text{cm}^{-3}$ can be routinely produced.⁹ The density and temperature were assumed to drop exponentially across the scrape-off layer. Estimates for the e-folding lengths λ_n and λ_t are rather uncertain but one expects the former to be a few centimeters and the latter to be considerably longer, and therefore of minor importance. Since fits to PDX data^{10,11} suggest values of λ_n in the range 2-4 cm, the choice $\lambda_n = 3$ cm was used here. Furthermore, early measurements on TEXTOR yield an e-folding distance of 2 cm for the power.⁹ Combining this with λ_n , one obtains $\lambda_t = 9$ cm. In all cases the plasma was hydrogen.

A flight was terminated either when the neutral escaped back through the inlet duct or when its weight was decreased below 0.1 via ionization or

gettering. Typically, the flights continued for a very long time, since neutrals within the plenum tended to become trapped there. Computational time per flight increased with density, ranging from about 0.2 sec (on the CRAY) at the lowest density to about 1.5 sec at the highest. The number of flights was chosen to be 250, in order to produce a relative standard deviation in molecular pressure and density of about 10%.

Figures 2 and 3 show the ionization probability P_i , as a function of the ion density, for two values of the width of each duct ($b_1 = 1$ cm, 3 cm; $b_2 = 7$ cm, 13 cm). With fixed geometry, P_i shows the expected increase as a function of both density and temperature. With fixed plasma profiles, P_i decreases as the duct leading into the plenum is widened, since neutrals then have a better chance of leaving the inlet duct. Furthermore, P_i tends to increase as the inlet duct is widened, because the plasma volume becomes larger. Overall the ionization probability ranges from 0.053 at $T = 10$ eV, $n = 3 \times 10^{11} \text{cm}^{-3}$, $b_1 = 1$ cm, and $b_2 = 13$ cm, to 0.74 at $T = 25$ eV, $n = 10^{13} \text{cm}^{-3}$, $b_1 = 3$ cm, and $b_2 = 7$ cm.

The ionization probability is a measure of the degree of self-consistency of the calculation. Reionization may affect the plasma parameters, creating regions of high recycling near the plate.²⁻⁴ It is not known how large P_i must be to trigger this effect, and in practice the coupling of the neutrals code to the plasma code presents considerable difficulty. However, the results of Figs. 2 and 3 point toward the desirability of a self-consistent calculation at higher densities and temperatures. The results should be understood with this caveat in mind.

Pressure measurements are assumed to be made by attaching a thin tube and measuring the pressure at the far end of the tube, where the population is entirely molecular (at wall temperature). Atomic pressures were included in

the following way. Suppose the atomic density n at a point near the wall gives rise to a contribution n' to the molecular density at the end of the tube. From continuity one expects the relation

$$n(T/m)^{1/2} = 2n'(T_0/2m)^{1/2},$$

where T is the atomic temperature, T_0 is the wall temperature, m is the atomic mass, and the factors of two follow from the conversion of atoms to molecules. The resulting contribution to the molecular pressure at the end of the tube is then $p' = n'T_0$, or

$$p' = n(TT_0/2)^{1/2}.$$

This contribution usually amounts to no more than 15% near the top of the duct and less than 1% at the end of the duct and within the plenum.

Apart from the 10% statistical error, the pressure tends to be uniform within the plenum. Considered as a function of plasma density, at a fixed temperature and geometry, it has the behavior $p = p_0 (n/10^{12}\text{cm}^{-3})^\alpha$. The parameters p_0 and α for the various cases are given in Table I. The exponent α is less than unity, and it is smaller for the high-temperature cases (i.e. those with higher ionization) than for the low-temperature cases. In a self-consistent calculation one would expect the exponent to be increased, since if n_t and n_p are the plasma densities at the throat and plate, respectively, one would have $n_p \propto n_t^b$, with $b > 1$. Thus the pressure would be expected to vary with density in the throat according to $p \propto n_t^{b\alpha}$.

The H_α power, integrated over the inlet, is found to depend on plasma density according to $w(n) = w_0(n/10^{12}\text{cm}^{-3})^\beta$, with the parameters w_0 and β

listed for the various cases in Table 1. As expected the power increases with T and b_1 and decreases with b_2 . However, the results may be very rough, in that they are based on the assumptions that atoms reach coronal equilibrium within the inlet and that a reflected atom does not change its internal state.

Since the pressure is approximately uniform within the plenum, the molecular gettering rate can be computed from the pressure given above. Expressed in molecules/cm²-sec, it is $r = 1.42 \times 10^{21} \sigma p(\text{Torr})$. With $T = 25$ eV, $b_1 = 3$ cm, and $b_2 = 13$ cm, the rate at the bulk getter ranges from 1.95×10^{16} /cm² sec (at $n = 3 \times 10^{11}$ cm⁻³) to 3.54×10^{17} /cm² sec (at $n = 10^{13}$ cm⁻³).

Figures 4 and 5 show how the pressure in the main duct decreases with distance away from the neutralizer plate, for various geometries. In Fig. 4, the width of the inlet is held fixed and results are given for the two choices of duct width b_2 . The pressure is seen to increase as the duct is narrowed. In Fig. 5, b_2 is fixed, and the pressure increases as the inlet becomes narrower. In both of these figures, the rather high pressures (10^{-3} to 10^{-2} Torr) obtained at the higher plasma densities indicate that gas-phase scattering would be appreciable.

Another quantity accessible to experiment is the power delivered to the walls of the main duct. Figure 6 shows the code results for the power on the left wall (as viewed in Fig. 1), at $T = 25$ eV and for two choices of the plasma density. The results have large scatter because the power is carried mostly by fast atoms, for which statistics are poor. The first segment, which is the most probable target for fast atoms leaving the neutralizer plate, experiences a heat flux of several watts per square centimeter (at $n=10^{13}$ cm⁻³), but the smoothed flux diminishes exponentially with distance along the duct. The relative displacement of the two graphs in Fig. 6 confirms the expected linear dependence on the plasma density. In addition,

the results at 10 eV are consistent with the expected $T^{3/2}$ dependence on the plasma temperature. As the width of the main duct is decreased, the target presented by the first wall segment loses part of its solid angle to the inlet duct, and so one would expect the heat flux to decrease somewhat. This is borne out by the results at 25 eV and, to a lesser extent, at 10 eV. As the inlet duct is narrowed the same argument would predict an increased heat flux, but the drop in ion current itself would tend to decrease the heat flux. According to the calculations at 10 eV the heat flux increases somewhat as b_1 is narrowed, while at 25 eV it decreases.

Because of the large ionization probability, high recycling may be observed in ALT-I as it has thus far been described. Two methods of further enhancing the ion density at the plate have been included in the experiment. First, gas can be puffed into the plasma through a valve located halfway across the lower throat. Dissociation followed by ionization of the gas will then reduce the electron temperature and increase the ion density in the throat. Second, the neutral density in the throat can be increased by closing a baffle near the far end of the duct leading into the plenum, thereby stopping all pumping.

DEGAS cannot predict the recycling behavior of ALT-I because it does not include the effects of neutrals on the plasma. However, it can compute the total reionization rate S when gas puffing or duct baffling is present and compare these methods of enhancing the recycling. Let $R = (I + S)/I$ be the recycling coefficient, with I the ion current entering the throat. At a density of $3 \times 10^{12} \text{ cm}^{-3}$ and temperature of 10 eV, and with $b_1 = 3 \text{ cm}$ and $b_2 = 7 \text{ cm}$, R was 1.31 for the base case, 2.67 when gas was puffed into the throat at the rate of 10^{21} molecules/sec, and 1.70 with a baffle present. At $T = 25 \text{ eV}$ the respective values of R were 1.54, 2.97, and 1.92. At both

temperatures, gas puffing and duct baffling are thus seen to have similar effects.

III. CONCLUSIONS

We have presented calculations of the ionization probability, the pressure within the plenum, the gettering rates, the pressure drop along the main duct, the heat flux to the walls of the main duct, and the H_{α} power for a variety of assumed plasma parameters and for pertinent choices of the duct widths. The effects of duct baffling and gas puffing also have been considered. When experimental results become available, it will be interesting to compare them with the predictions of the code. This also may give an idea of the importance of the plasma reaction to the neutral sources.

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APPENDIX

Here we consider the issue of adjusting the width of the long duct (length = 83 cm) to account for the enhanced conductance of a 2-D duct. For a rectangular duct of height a , width b , and length l , the conductance has the form

$$C = \frac{1}{4} \bar{v} a b K(a/l, b/l),$$

where $\bar{v} = (8T/\pi m)^{1/2}$ and, in the absence of energy loss to the wall, the transmission probability K is a function of geometry only. For a duct in two dimensions, the height becomes large compared to the other dimensions and K becomes a function of b/l only

$$C' = \frac{1}{4} \bar{v} a b' K_{2D}(b'/l),$$

where primes distinguish this from the previous case.

To model the actual 3-D duct, one equates the conductances per unit height and solves this equation for the effective width b' . In the present case, this equation was solved numerically by making use of transmission probabilities constructed via duct simulations with DEGAS. The two needed values of K for $a=30$, corresponding to $b = 7$ cm and $b = 13$ cm, were found to be 0.156 and 0.227, respectively. The function $K_{2D}(r)$ has the limiting form $r \ln(1/r)$ as $r \rightarrow 0$, and for $r > 0.1$ it has been tabulated by Clausing.¹² When $b = 7$ cm, one needs values in the intermediate range, which were evaluated with DEGAS. The resulting width is $b' = 5.93$ cm. When $b = 13$ cm, one can interpolate in Clausing's table, and the result is $b' = 10.5$ cm.

TABLE I. Parameters in the fits $p(n) = p_0(n/10^{12}\text{cm}^{-3})^\alpha$ and $w(n) = w_0(n/10^{12}\text{cm}^{-3})^\beta$, where p is the pressure at the far end of the plenum, w is the total H_α power, and n is the ion density at the innermost layer within the entrance duct.

<u>T = 10 eV</u>					
$b_1(\text{cm})$	$b_2(\text{cm})$	$p_0(10^{-4}\text{Torr})$	α	$w_0(\text{W})$	β
3	7	0.947	0.90	0.197	2.16
3	13	1.14	0.92	0.122	2.34
1	7	1.29	0.90	0.0284	2.89
1	13	1.43	0.88	0.0712	2.11

<u>T = 25 eV</u>					
$b_1(\text{cm})$	$b_2(\text{cm})$	$p_0(10^{-4}\text{Torr})$	α	$w_0(\text{W})$	β
3	7	1.21	0.76	0.433	1.91
3	13	1.37	0.83	0.405	1.80
1	7	1.68	0.79	0.0839	2.40
1	13	1.74	0.81	0.167	1.93

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FIGURE CAPTIONS

- FIG. 1. Top view of ALT-I, as employed in DEGAS calculations. Dashed lines indicate zone boundaries.
- FIG. 2. Probability of ionization at $T = 10$ eV, for various duct widths and plasma densities.
- FIG. 3. Probability of ionization at $T = 25$ eV, for various duct widths and plasma densities.
- FIG. 4. Pressure drop along the main duct, for two values of the width of this duct. The horizontal coordinate is the distance from the far edge of the inlet. The straight lines indicate the best linear fits.
- FIG. 5. Pressure drop along the main duct, for two values of the width of the inlet. The straight lines indicate the best linear fits.
- FIG. 6. Heat flux on the left wall of the main duct (as viewed in Fig. 1), as a function of distance down the duct. The straight lines indicate the best linear fits.

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FIG. 1

FIG. 2

FIG. 3

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FIG. 4

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FIG. 5

FIG. 6

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