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Two-Dimensional Impurity Transport Calculations for a High Recycling Divertor*

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1. Abstract

Two dimensional analysis of impurity transport in a high recycling divertor shows asymmetric particle fluxes to the divertor plate, low helium pumping efficiency, and high scrapeoff zone shielding for sputtered impurities.

2. Introduction and Summary

Impurity transport in the INTOR divertor scrapeoff region has been studied with the ZTRANS 2-D Monte Carlo code. The calculations used input hydrogen plasma data from the Planet fluid code for the "realistic geometry" high recycling regime.[1] Helium, iron, oxygen, and tungsten transport were examined.

For the helium transport simulation, 10,000 ions were launched uniformly on the outer separatrix flux surface, representing the effect of outwardly diffusing helium. The resulting flux of helium to the outer collector plate is found to be highly peaked on the large major radius side of the plate center, where the plasma is cold ($T_e \lesssim 15$ eV). As a result, sputtering of the tungsten plate by helium is negligible. The helium pumping efficiency, however, is low with only 0.7% of the He current entering the scrapeoff region being pumped.

For iron launched from the first wall, representing the effect of sputtering by charge exchange neutrals, 10% are found to enter the plasma. Subsequently, iron in the plasma is readily removed by flowing to and condensing on the wall and divertor plate.

The transport of sputtered tungsten from the divertor plate (if any) was also examined. Tungsten ions were launched from the middle 5 cm of the plate at several vertical distances. Most or all return to the plate

3. Model

The ZTRANS code computes the transport of individual impurity atoms and ions in a fixed background DT plasma. The specified plasma parameters are N_e, N_i, T_e, T_i, V_{DT}, and E where the fluid velocity V_{DT} and the electric field E are directed along the magnetic field. All quantities are two dimensional functions of the poloidal coordinates. An ion in a charge state Z is assumed to have thermalizing collisions with the DT ions on a time scale τ_0. At each collision the ion acquires a parallel velocity $V_\parallel = V_0$ where V_0 is chosen from a normal distribution with zero mean and standard deviation $V_{th} = \sqrt{T_i/m_Z}$ with m_Z the impurity mass. Between collisions, the ion motion along the field line is subject to acceleration due to the electric field, and thermal and frictional forces with the plasma:

$$m_Z \frac{dV_\parallel}{dt} = Z\,|e|\,E + F_1 \qquad (1)$$

For the present work a quasi-fluid concept has been used to compute the thermal and frictional forces. In this concept the force on an individual ion, between thermalizing collisions, is chosen to be the same as the force on a thermalized impurity fluid. This latter force is given by Braginski[2] for impurity-electron collisions and by a disparate mass extention to the Braginski theory for impurity-ion collisions:[3]

$$F_1 = \frac{|e|}{m_Z}\left(.71\, Z^2 \nabla T_e + 2.21\, Z^2 \nabla T_i\right) + \frac{m_Z V_{DT}}{\tau_1} \qquad (2)$$

where the gradients are along the field line and τ_1 is the time constant for the frictional force. The present calculations use $\tau_0 = \tau_1 = 1/\nu$ where

$$\nu = \frac{4(2\Pi)^{1/2}\, N_i\, e^4 \log \Lambda}{3\,(4\pi\,\varepsilon_0)^2\, T_i^{3/2}} \sqrt{\frac{m_{DT}}{m_Z\,(m_Z + m_{DT})}}\; Z^2 \qquad (3)$$

is the Braginski collision frequency.

Between thermalizing collisions, the ion diffuses in the perpendicular direction by an amount Δ chosen from a normal distribution with zero mean and standard deviation $\sqrt{D\Delta t}$ where $D = D_{Bohm}$ is the local diffusion coefficient.

The charge state of the ion is determined from the local rate coefficients. The probability of an ion changing charge state in an interval Δt is:

$$p_o = 1 - e^{-\Delta t/\tau_2} \quad (4)$$

where

$$\tau_2 = \frac{1}{N_e \left[\langle\sigma v\rangle_I + \langle\sigma v\rangle_R\right]} , \quad (5)$$

$\langle\sigma v\rangle_I$ is the rate coefficient for ionization of an ion in charge state Z to Z+1 and $\langle\sigma v\rangle_R$ is the rate coefficient for recombination to the Z-1 state.

An impurity particle changes charge if a uniformly distributed random number K_1, $0 \le K_1 \le 1$, satisfies $K_1 \le P_o$. If a particle changes charge, the charge is recombination if a second randomly chosen number K_2, $0 \le K_2 \le 1$, is

$$K_2 \le \frac{\langle\sigma v\rangle_R}{\langle\sigma v\rangle_R + \langle\sigma v\rangle_I} \quad (6)$$

Otherwise, the change is ionization. The rate coefficients are computed from the atomic physics code of Hulse.[4]

The outer scrapeoff zone geometry is shown in Fig. 1. Boundary conditions used are as follows. For simulating impurity outflux from the plasma, ions are launched uniformly along the outer separatrix flux surface, from the top of the plasma to the x-point. These ions have an initial charge state of Z=2 for helium and Z=8 for oxygen. For simulating newly ionized sputtered neutrals, ions are launched either near the wall or divertor plate with an initial charge state of Z=1.

For a species other than helium, a history terminates if the particle hits the wall or divertor plate where it is assumed to stick. If a (non-helium) particle enters the plasma, it is launched as described above. For helium a history terminates if the particle (1) enters the plasma, or (2) is pumped. Helium impinging on the (stainless steel) first wall or (tungsten) divertor plate is reflected/desorbed as a neutral. Probability distribution functions for the reflected energy are taken from the He backscattering data in Ref. [5]. The reflected angular probability distribution is taken as cosine of the elevation angle (referred to the surface normal) and uniform in the azimuthal angle. Helium entering the plenum region near the outer collector plate is pumped with a 10% probability, otherwise it randomly reenters the divertor region as a neutral. Finally, particles crossing from the large major radius side of the scrapeoff to the small radius side, at the plasma top, are treated as reentering the plasma.

Neutral helium atoms are tracked by a standard Monte Carlo process until ionized, at which time they are followed by the above described procedure for ions. Electron impact ionization of neutral helium is by far the dominant physical process although charge exchange could be simulated if needed for different plasma regimes e.g., with much higher hydrogen neutral densities.

4. Results

The ZTRANS simulations are summarized in Table 1. The helium flux to the divertor plate and the helium density in the scrapeoff zone are shown in Fig. 1-2. The helium impingement energy is below the threshold for He $\rightarrow$ W sputtering except for about $\pm$ 1.5 cm from the plate center where the He flux is low. For iron and oxygen, the flux to the plate (not shown) is also concentrated on the outboard side. The tendency of impurities to impinge on the cold plasma field line regions for a high recycling regime is in accordance with the 1-D analysis of Neuhauser, et al.[6] The highly asymmetric character of the flux, found here in the 2-D analysis, is apparently due to the significant difference in poloidal field line structure on the two sides of the divertor plate bounded by the separatrix.

The helium flux and density are calibrated numerically by requiring that the helium current pumped is equal to the α-particle production rate. The predicted pumping efficiency is low but may still be adequate for maintaining a reasonable helium density in the plasma; this issue needs further assessment. The helium density is fairly constant in the top half of the outer scrapeoff. The density peaks near the divertor plate due to high local recycling. The helium density varies from about 5% of the DT density on and near the separatrix to $\sim$ 30% near the first wall.

The results for iron and tungsten transport appear to be favorable for the high recycling regime. The scrapeoff zone has a shielding efficiency of $\sim$

90% for wall sputtered iron. Of the iron entering the plasma and subsequently diffusing out, the removal rate is high, ~ 20%.

For tungsten launched at ~ .7 cm from the plate, which is about the maximum mean free path for ionization of sputtered W° atoms, for the plasma conditions predicted in Ref. [1], all ions return to the plate. This is in accordance with previous predictions of the REDEP computer code.[7] Even for ions launched ~ 3 cm from the plate, most return. This is a favorable result but is still subject to numerous uncertainties in the models.

5. Discussion

The impurity transport is dependent on second order quantities of the DT fluid computation such as fluid velocity and electric field. Additional fluid calculations with, for example, finer grids, and different divertor plate orientations are required for a better assessment of the helium pumping issue. A single-particle force computation based on Fockker-Planck/Braginski theory is being developed and will be used in further simulations. This will permit comparison with the quasi-fluid force computation.

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Table I. ZTRANS Results Summary

Helium Transport

- 10,000 ions launched from plasma, uniformly launched on outer separatrix field line.
- 4% hit divertor plate, prior to recycling.
- 0.7% are pumped.
- 99.3% return to plasma.

Iron Transport

- 5000 ions launched uniformly near outer first wall.
- 10% enter plasma.
- 4% hit divertor plate.
- 96% return to wall.
- Average charge states vary from 5 near the divertor to 11 near the plasma.

Oxygen Transport

- 5000 ions launched from plasma, uniformly launched on outer separatrix field line.
- 13% hit divertor plate.
- 87% hit first wall.
- Average charge states vary from 5 near the divertor to 8 near the plasma.

Tungsten Transport

Case A

- 5000 ions launched near center of divertor plate, at a distance ~ 0.7 cm above plate.
- All return to plate, none enter plasma.

Case B

- 5000 ions launched near center of divertor plate, at a distance of ~ 3.0 cm above plate.
- 9% enter plasma.
- 95% return to divertor plate.
- 5% hit first wall.
- Average charge states vary from 4 near the divertor to 12 near the plasma.

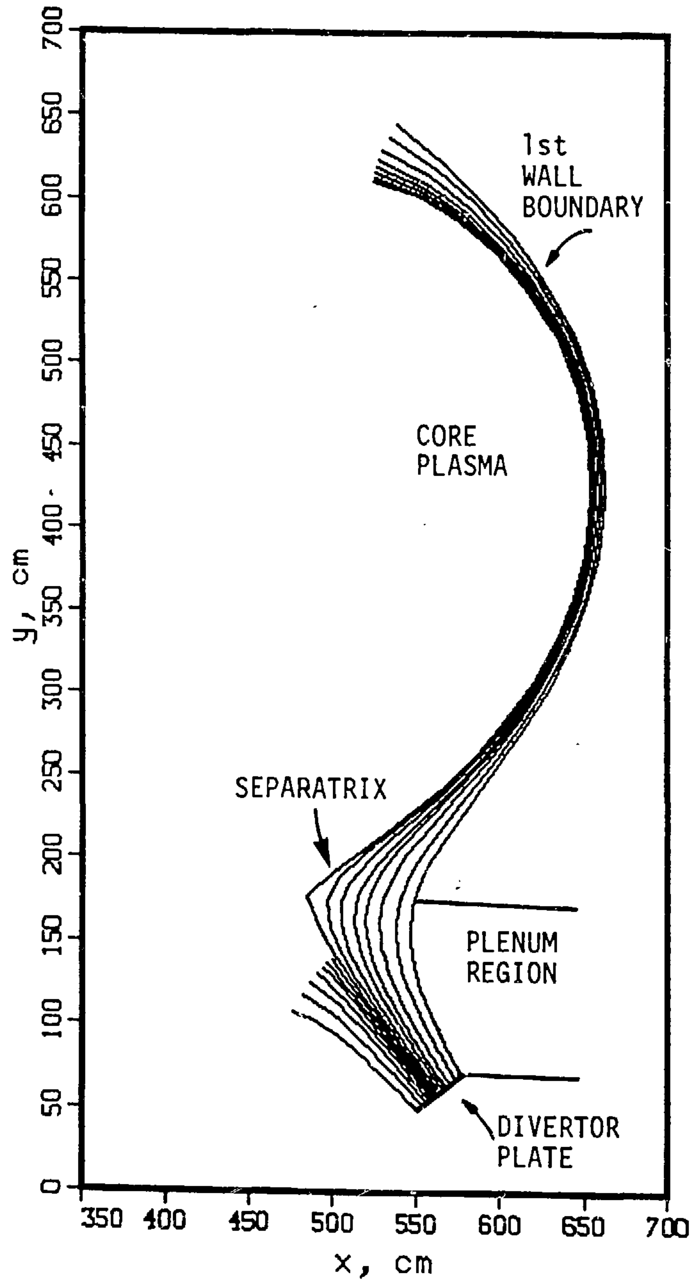

FIG. 1 Outer Scrapeoff Zone Geometry - Poloidal Field Lines and Associated Regions.

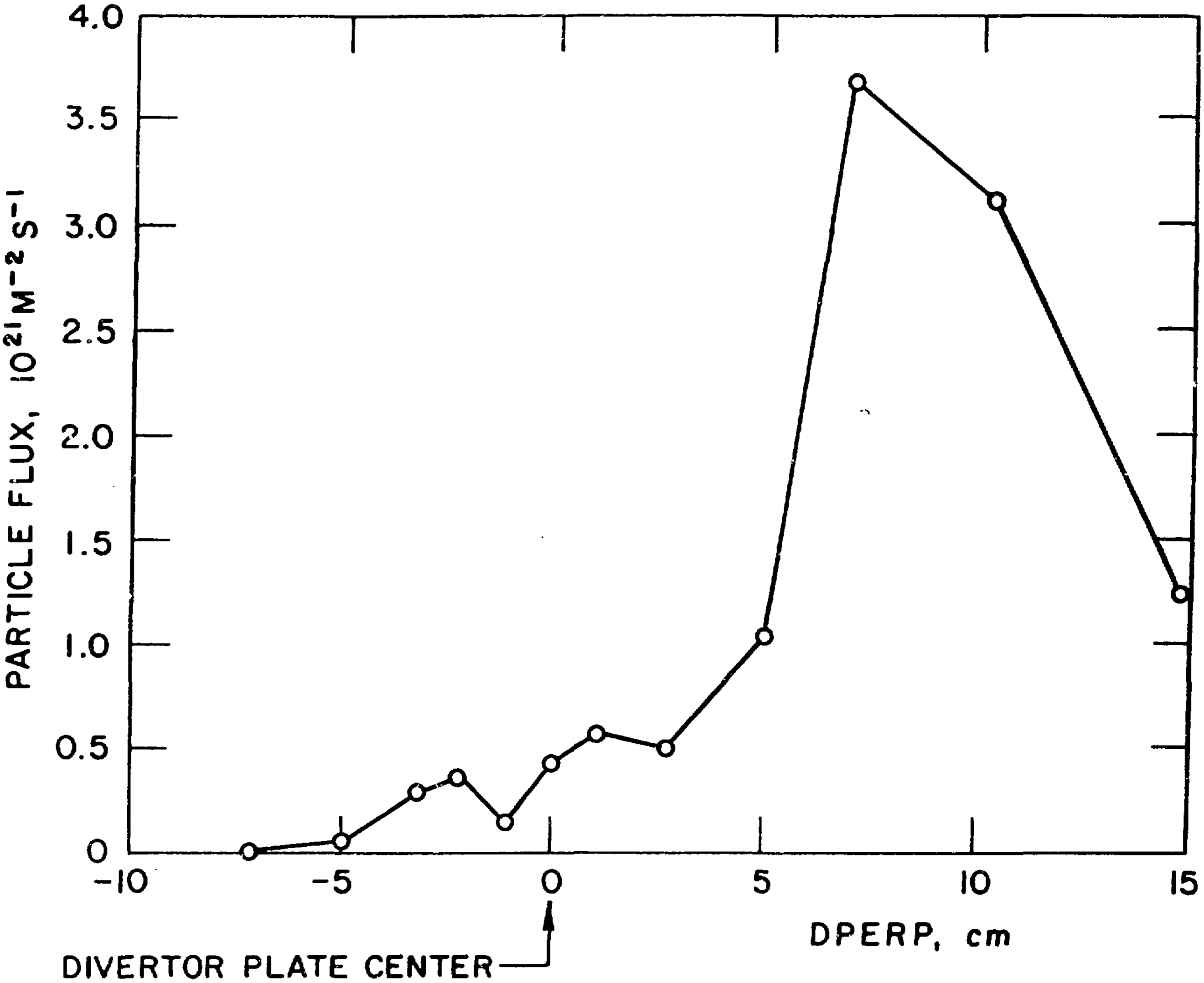

FIG. 2 Helium Flux to the Divertor Plate.
DPERP = Coordinate Perpendicular to the Separatrix Field Line.

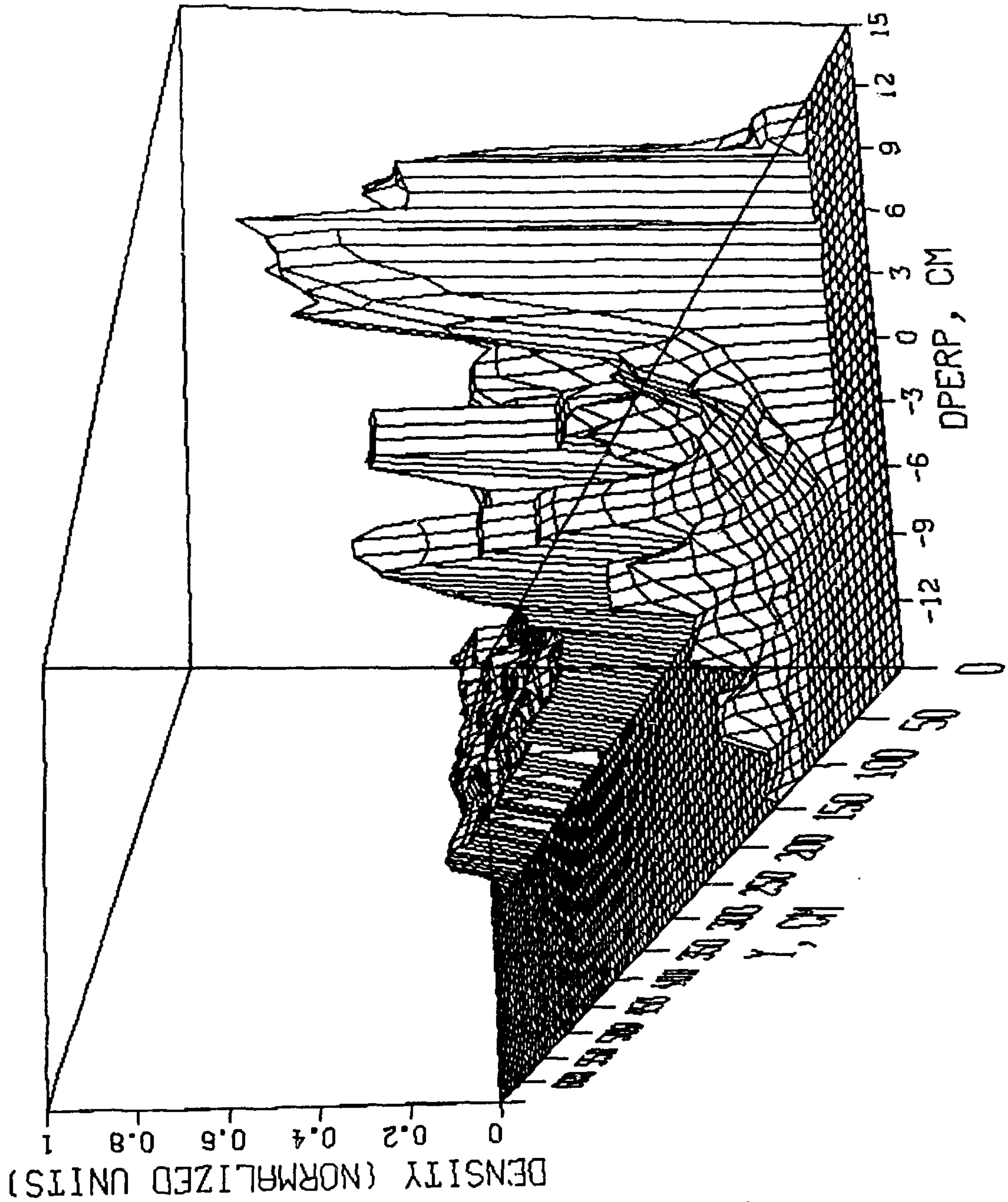

FIG. 3 Helium Density in the Outer Scrapeoff Region.
Normalization Constant = 1.5 X 10^{19} m^{-3}.