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SENSITIVITY OF NEUTRAL THROUGHPUT TO GEOMETRY AND PLASMA POSITION IN THE TOKAMAK PHYSICS EXPERIMENT DIVERTOR REGION

DIVERTOR SYSTEMS

KEYWORDS: *fusion, divertor, TPX*

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Sufficient neutral atom and molecular throughput is essential for the steady-state operation of the proposed Tokamak Physics Experiment tokamak. To predict the throughput, the B2 edge-plasma fluid code and the DEGAS Monte Carlo neutral transport code were coupled globally. For the day 1 low-power (17.5-MW) operation condition, the recycling coefficient for both codes matched at 0.985, implying that for every 1000 ions striking the divertor plate, 15 are ultimately removed down the pump duct. The neutral molecular density was $2.52 \pm 0.15 \times 10^{19}/m^3$, giving a throughput of 92.6 ± 5.6 Torr·ℓ/s. Varying the scrape-off length for the plasma extending into the gap between the baffle and the plate from 0 to 2 cm decreased the throughput by a factor of >2. Moving the strike point away from the gap at first increases the throughput by lessening the pumping efficiency of the plasma in the gap. As the plasma is moved even farther away, the throughput drops due to a lack of source term for neutrals entering the pumped region. Illustrating the importance of moving the source term, moving the strike point away from the gap but retaining the original plasma in the gap lowers the throughput by a factor of 10. Altering the curvature of the baffle has little effect on the neutral solution.

I. INTRODUCTION

The Tokamak Physics Experiment (TPX) tokamak[1] will be the first major tokamak with pulse lengths longer than the pump-out timescales of the neutral gas. This steady-state operating mode cannot rely on conditioning between shots to turn the walls of the device into pumping surfaces. The first wall and divertor surfaces will be saturated with hydrogenic species. Particle control in the TPX high-recycling divertor will depend on the pumping system and on the detailed design of the divertor structure itself.

Particles leaking from the core will decrease the particle content of the plasma. These will be replaced primarily by particles injected via neutral beams. The volume of the TPX will be 20 m^3. Assuming a volume-averaged electron density of $5 \times 10^{19}/m^3$ and a global particle confinement time of $\tau_p^* = 0.4$ s, the main-plasma fueling requirement will be 2.5×10^{21} nuclei/s (Ref. 2). Since the standard method of decreasing the particle content (preshot wall conditioning) cannot affect the neutral throughput in a steady-state device, particle balance must be maintained by removal of neutral molecules through the pump ducts. To achieve a particle removal rate equal to the particle fueling rate, a throughput of 35.3 Torr·ℓ/s, corresponding to 1.25×10^{21} molecule/s, is required.

Figure 1 shows the two-dimensional cross-sectional slice of the lower divertor including the region below the baffle and the first stages of the pumping system. The sizes of the gap and position of the baffle structure were optimized to maximize throughput.[2] Doing so, the maximum throughput we found in our model was 92.6 ± 5.6 Torr·ℓ/s.

An additional possible source of particles is gas puffing. These neutrals would also need to be removed from the plasma. However, gas puffing increases the pressure in the scrape-off plasma and pump duct, which in turn increases throughput (which is proportional to pressure). Thus, the additional particle load introduced by puffing will not necessarily increase the maximum

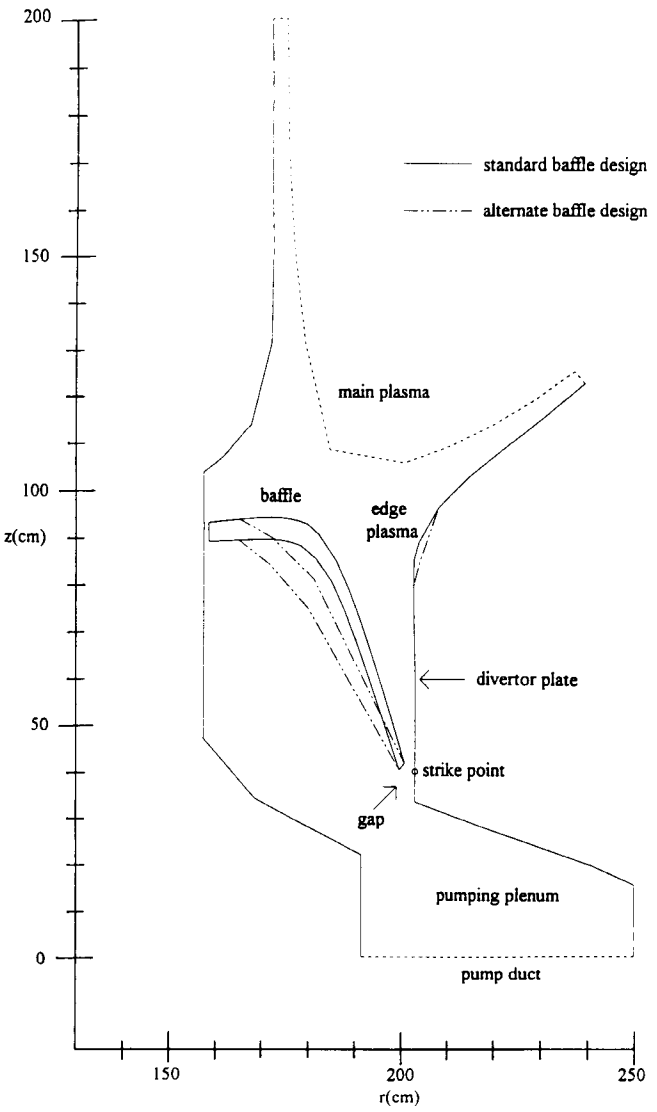


Fig. 1. The DEGAS-simulated region, with labels. The coordinate r is measured from the centerline of the device.

pumping speed needed in the TPX. This problem was not further addressed in the current work.

This paper utilizes the optimum geometry shown in Fig. 1 to investigate the operational parameters that could influence particle throughput. These parameters include moving the position of the strike point on the outer divertor plate, varying the scrape-off length of the edge plasma in the gap between the baffle plate and divertor plate, and simply closing off the pumps. Also investigated is a slightly altered baffle and first-wall design, shown as a dotted and dashed line in Fig. 1. Analysis of the changes in those parameters helps illustrate the trade-off between neutral molecules being lost back to the plasma through the gap versus the creation and loss of neutrals in the edge plasma before they have even entered the pumping plenum region.

II. MODEL

Two computer codes were used in this work. The B2 transport code[3] is a two-dimensional fluid model that solves the first three coupled moment equations: continuity, momentum balance (parallel component only), and energy balance. The source rate and location for new ions from the divertor plate are determined by specifying a local recycling coefficient along the boundaries of the simulation. In this work, the recycling coefficient was 1.00 at all surfaces except for the divertor plate, where it was treated as a variable with values ranging from 0.95 to 0.995.

The DEGAS code[4] is a three-dimensional Monte Carlo multispecies neutral transport code that contains extensive atomic physics including charge exchange, electron and ion impact ionizations, and molecular dissociations. Energy- and angle-resolved wall reflection coefficients include effects of surface roughness and are taken from fractal TRIM (Ref. 5). The DEGAS code follows neutral particles (atoms and molecules) in three dimensions but assumes symmetry in the toroidal direction; therefore, the geometry and plasma parameters need only be specified in two dimensions. The pumping ducts will be positioned discretely toroidally around the real device. Our simulation, which is a two-dimensional toroidal slice through the device, must somehow account for this. The bottom wall of our simulation is labeled "pump duct" in Fig. 1 because on the other side of this wall is the pump duct. The molecular transmission probability factor of a single duct was calculated to be 0.148. This number was calculated using the methodology used in Ref. 2, but with different numbers to reflect newer design dimensions. Since only 16% of the device actually has a pump duct there (in the annulus represented by our bottom wall), to account for the ratio of actual pumping surfaces positioned discretely toroidally around the device to the area at the toroidally symmetric simulation boundary, the transparency at the boundary was set to be 16% of 0.148.

The electron temperature and density profiles in the entire simulation space are shown in Figs. 2 and 3. These are outputs from B2 and inputs into DEGAS. The B2 run was characterized by an input power of 4.7 MW per outboard plate and a $1.65 \times 10^{19}/m^3$ density at the outboard midplane separatrix. For more detail, Fig. 4 shows the ion and electron temperatures, the ion flux, and the electron density (which is equal to the ion density) along the divertor plate. Explanation of stretching the orthogonal B2 grid to the nonorthogonal DEGAS grid can be found in Refs. 2 and 6. The plasma from the B2 simulation extends partially into the private flux region, to within about 2 mm of the baffle plate. The remainder of the scrape-off plasma is assumed to decrease exponentially (in both density and temperature) with distance from the B2-generated plasma. This additional scrape-off plasma is limited by the baffle except where it extends into the gap.

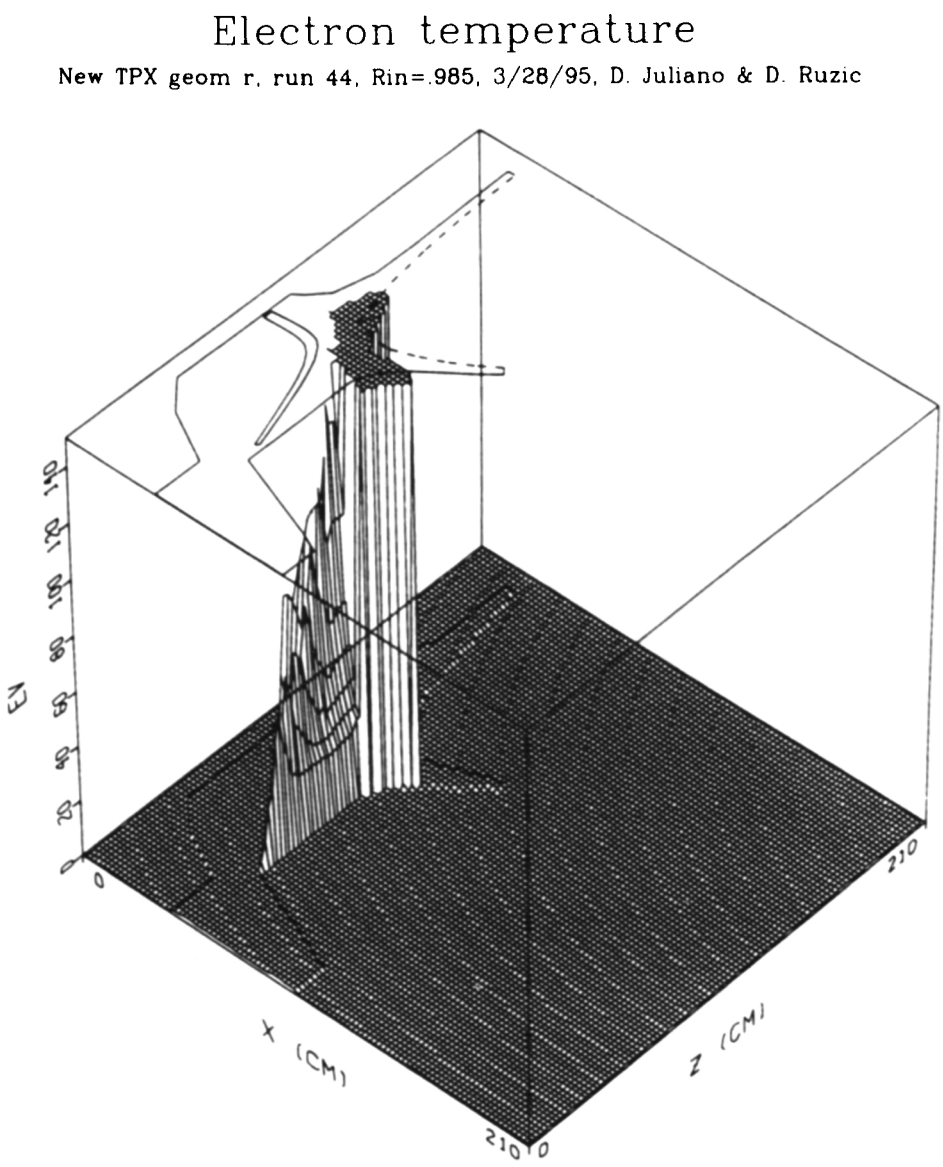


Fig. 2. The electron temperature from B2 as input into DEGAS, with the device ouline overlaid above.

In this work, B2 and DEGAS are coupled globally. By examining the number of particles exiting through the limited conductance pump duct versus the number of input particles, a recycling coefficient can be found for a given geometry and plasma configuration. A recycling coefficient of 0.985 means that for every 1000 particles that strike the divertor plate, only 15 ultimately exit the device. In B2, the input recycling coefficient has a similar meaning. To converge the neutral and plasma solutions, five B2 simulations were run with different recycling coefficients as inputs. Each produced different plasma density, flux, and temperature profiles. Then DEGAS was run on each of these cases, and the global neutral recycling coefficient was found. Figure 5 shows the results. The recycling coefficient output by DEGAS is plotted versus the recycling coefficient used as an input for B2 for several different cases. The line where $R_{in} = R_{out}$ is shown. None of our cases were directly on this line, which would indicate that the recycling coefficient that went into B2 was the recycling coefficient gotten out of DEGAS. Thus, another case was run in which the results of two B2 runs (R_{in} = 0.98, R_{in} = 0.99) were averaged, giving an R_{in} that is the average of the B2 runs (R_{in} = 0.985). The global particle balance is consistent in this case. In the data shown in Figs. 2, 3, and 4, an R_{in} of 0.985 was used.

III. RESULTS

III.A. Throttling the Pump

Related to the discussion of recycling is the operational parameter of turning off, or valving off, the vacuum pumps during a run. This forces the recycling to

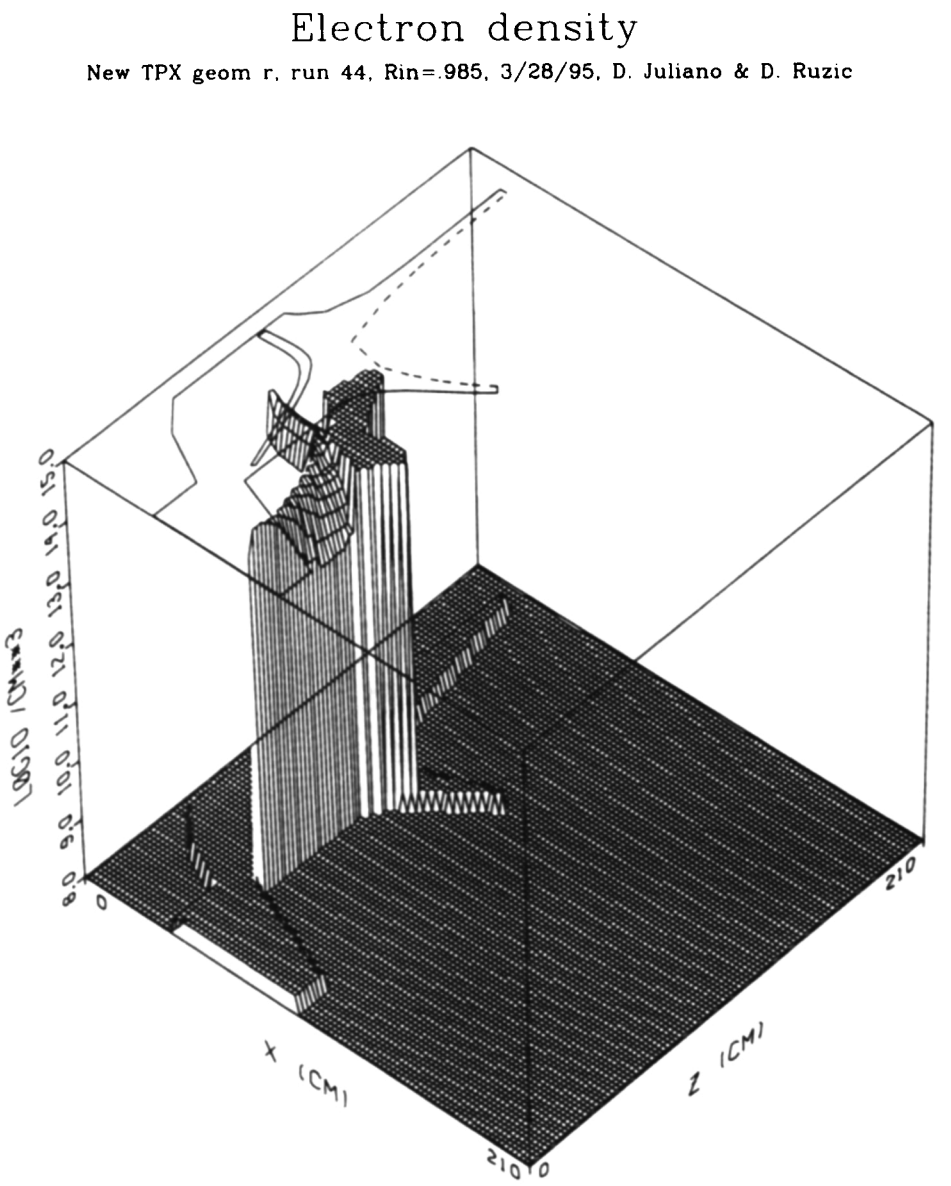


Fig. 3. The electron density from B2 as input into DEGAS, with the device outline overlaid above.

1.000 everywhere. Particles cannot exit. This was simulated by running a B2 solution with $R_{in} = 1.00$ on all surfaces and a DEGAS solution using that plasma and allowing no molecules or atoms to exit through the pump duct entrance. Figure 6 plots the molecular density at the duct entrance versus the input recycling coefficient. Note that only the cases marked by the solid boxes have a globally consistent neutral and plasma treatment. The effect of valving off the pump is to increase the neutral density by 51 ± 12%; however, this figure does not include systematic uncertainty, only statistical uncertainty. The points plotted in Fig. 6 do not follow a smooth curve. The data represented by dark boxes are more likely to be accurate, however, because the global recycling is consistent.

The density n at the end of the duct is directly related to the throughput Q by

$$Q = S_D(nk_BT) \ ,$$

where S_D is the pumping speed measured at the bottom of the pump duct. The pumping speed of a single duct S_D was found to be 7380 ℓ/s, giving a Q for the $R_{in} = 0.985$ case of 5.79 ± 0.35 Torr·ℓ/s. There are 16 pumps in the proposed design, so the total throughput would be 92.6 ± 5.6 Torr·ℓ/s.

III.B. Varying the Scrape-Off Length

The plasma density drops exponentially as a function of distance perpendicular to the separatrix. In this paper, the scrape-off length L is defined to be the distance

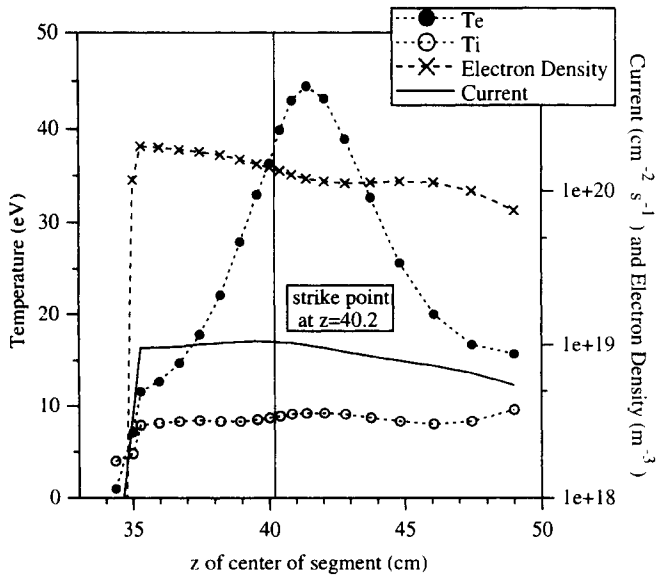


Fig. 4. Plasma parameters along the divertor plate, with the strike point at $z = 40.2$ marked. The coordinate z is that shown in Fig. 1.

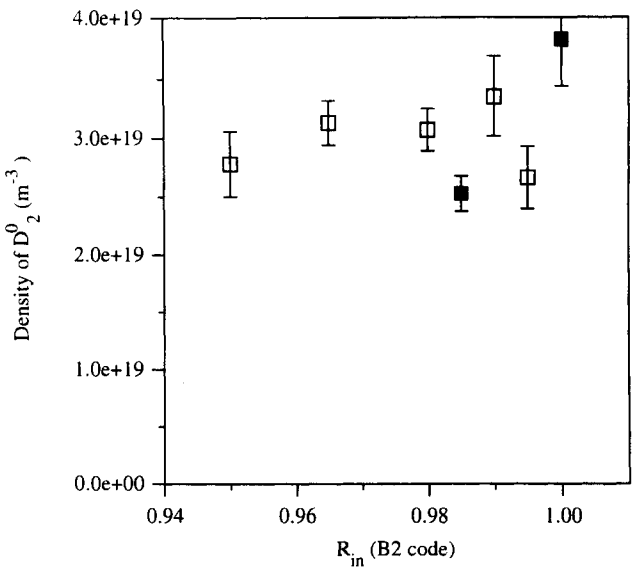


Fig. 6. Density of D_2^0 as a function of R_{in}, with the solid boxes designating runs in which recycling was consistent ($R_{out} = R_{in}$).

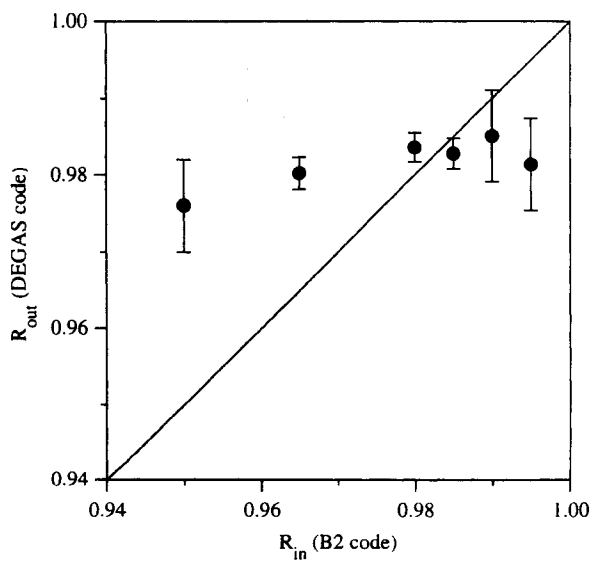


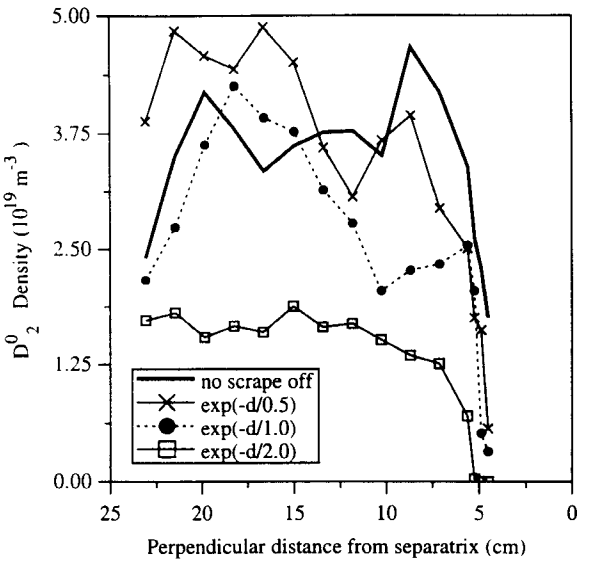
Fig. 5. The value R_{out} from DEGAS versus R_{in} from B2, with $R_{out} = R_{in}$ line drawn in. The two codes give consistent recycling for $R = 0.980$.

perpendicular to the separatrix at which the plasma density has dropped by a factor of $1/e$. The scrape-off length at the edge plasma has been estimated at 1 cm (Ref. 7). This number has some uncertainty and could be influenced by radio-frequency fields or other alterations of the edge electron temperature. In this work, four values of L were used: 0.0 (i.e., no scrape-off layer, just an abrupt transition from plasma to no plasma), 0.5, 1.0, and 2.0 cm.

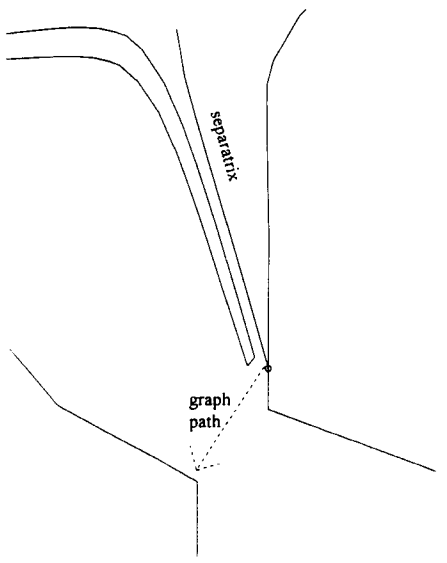
An important effect of the scrape-off layer is the ability of the plasma in the gap to ionize neutrals that pass through it, whether from the divertor plate above the gap or from the pumping plenum below the gap. The scrape-off layer decreases exponentially as a function of distance perpendicular to flux lines. The scrape-off distance was varied to see the effects this would have on the pumping ability of the plasma in the gap and, hence, on the throughput. The ionizing effect of the scrape-off layer in the gap can be seen in Fig. 7a, where the neutral density is plotted as a function of distance into the gap. The actual chord through the plasma is shown in Fig. 7b. As expected, when the plasma extended farther into the pump duct, it pumped more effectively on the neutrals, lowering the density at the exit plane and reducing the recycling. Figure 8 shows this result quantitatively. Note that a large scrape-off length of 2 cm can decrease the density at the duct entrance and hence the throughput by a factor of >2 compared with a small or nonexistent scrape-off layer.

III.C. Varying the Strike Point Location

The position of the strike point also has an important effect on the density and throughput, as can be seen in Fig. 9. For these simulations, the entire plasma was shifted vertically by the indicated offset. As the strike point is moved up from the base case, the density at the duct (and therefore the throughput) increases. This occurs because the weak plasma that extends through the gap into the 2-cm-wide region between the baffle and the divertor plate is decreased, so the plasma pumping of the neutrals in the pumping plenum decreases. Of course, neutrals heading directly up



(a)



(b)

Fig. 7. (a) Density of D_2^0 for different scrape-off models, graphed along a path approximately perpendicular to the separatrix. (b) Part of the simulated region, with the separatrix labeled and the graph path shown by a dotted arrow.

through the gap into the main plasma will be ionized by the scrape-off plasma wherever it is. But neutrals heading toward the bottom of the divertor plate, for example, will only pass through the gap before hitting the wall and (possibly) heading back down to the plenum. For such neutrals, the size and intensity of the scrape-off layer can make the difference between ionization (recycling) and eventual escape through the pump. Thus, when the strike point is raised, the weaker plasma in and near the gap gives neutrals in the plenum

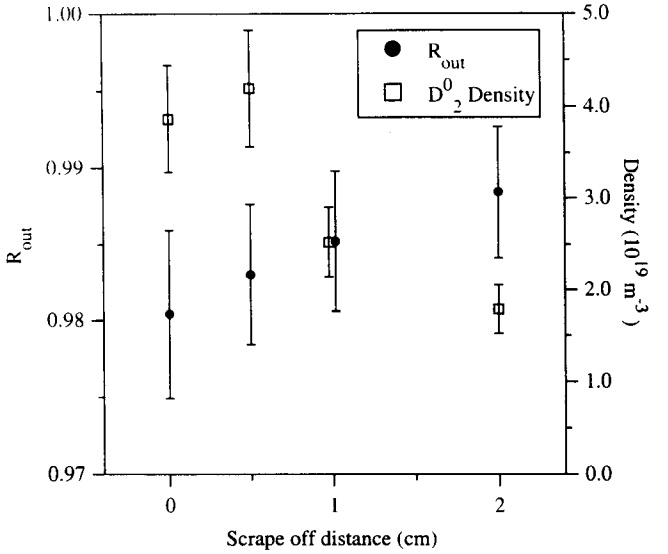


Fig. 8. The value R_{out} and density of D_2^0 averaged along the pump duct boundary shown in Fig. 1 for different scrape-off models.

a lesser chance of being ionized. Therefore, the density in the plenum and the throughput increases. At first this effect is only partially offset by the fact that fewer neutrals ever make it into the pumping plenum from the (now) more distant strike point. As the strike point is moved up farther, the density does decrease due to fewer neutrals being able to get into the pumping plenum in the first place. As the strike point is moved farther from the gap, fewer neutrals ever make it down through the gap. This effect is not mitigated by the fact

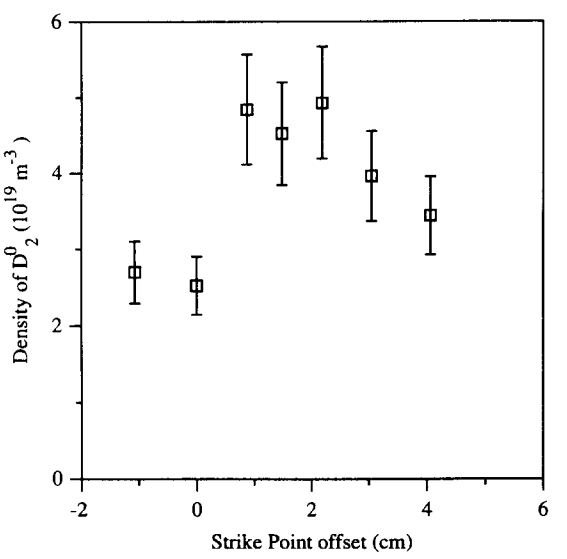


Fig. 9. Density of D_2^0 averaged along the pump duct boundary shown in Fig. 1 for different positions of the strike point.

that the scrape-off layer is also moving up because the decrease in pumping efficiency of the scrape-off layer is only in effect for the first 2 cm of movement. At this point, the plasma has been removed from the gap region so that neutrals hitting the divertor plate from the side don't have to travel through any scrape-off layer. Those that are heading back up into the plasma through the gap will be ionized independent of the plasma distance. Thus, moving the strike more than 2 cm up the divertor plate only reduces the neutral source term, and the density of neutral molecules in the pumping plenum decreases.

One effect not included in our model is the change in scrape-off layer plasma due to neutrals recycled by it. The effect of adding cold neutrals to the scrape-off plasma would probably be equivalent to reducing the scrape-off distance. The additional neutrals might significantly increase the plasma density, however, leading to greater neutral currents from adjoining wall segments. Although our model includes neutral currents from wall segments adjoining the scrape-off plasma, these currents are consistent with an unperturbed scrape-off plasma. An increased neutral source in the gap in the form of these currents could mitigate or even reverse the decrease in throughput due to scrape-off plasma pumping.

The throughput is affected by two competing factors: Plasma pumping on the neutrals decreases the density, but the plasma striking the divertor is the source of neutrals. These two competing factors are further illustrated in Fig. 10, which shows the recycled neutrals divided into two categories: those that are recycled before they ever make it through the gap, and those that are recycled after passing through the gap into the pumping plenum, bouncing around, and returning to the plasma. As the strike point is moved up away from the gap, the fraction of neutrals recycled before leaving the gap increases, while the fraction of neutrals recycled after returning to the plasma decreases.

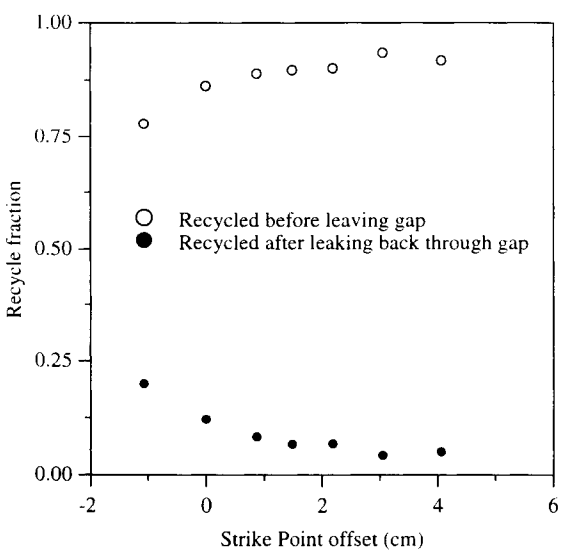


Fig. 10. Recycling of neutrals divided into two parts: particles recycled in the edge plasma before the gap, and particles recycled after escaping into the plenum and leaking back into the gap.

A more dramatic illustration of these competing effects is a case in which the strike point was moved up 2.19 cm, making the source of neutrals farther from the gap, but the plasma in the gap was left unchanged, so the scrape-off layer pumping remained the same. The result was that the density (and thus throughput) was decreased by a factor of 10.

III.D. Variation in Baffle Geometry

A small change to the geometry of the divertor structure was proposed and has recently been adopted. This involved pulling the baffle back away from the separatrix and making the divertor plate above the strike point curve more gently away from the strike point region to minimize plasma-surface interactions on these structures. The modified geometry is shown by the dashed lines in Fig. 1.

These changes to the geometry have a negligible effect on recycling and throughput. The density with the new design is 20% lower than for the old. However, the uncertainty is also 20%, so the geometries have equal densities to within our uncertainty.

The geometry change has little effect because it changes neither the source of neutrals, which is primarily near the strike point on the divertor plate, nor the removal of neutrals, which is primarily done by the plasma pumping in the gap.

IV. CONCLUSIONS

Throughput is strongly affected by the scrape-off distance and strike point position. A larger scrape-off layer increases recycling, decreasing throughput. According to our model, if moving the strike point removes the scrape-off plasma from the gap, throughput will increase. A model with self-consistent scrape-off plasma and currents would be needed to verify this effect. Such a model will be the subject of future research. If there is no scrape-off plasma in the gap, raising the strike point decreases throughput by reducing the number of neutrals that ever make it into the plenum. To the extent that we tested it, the alternate baffle model considered in this paper does not significantly change throughput.

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