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REDUCTION OF RECYCLING BY PUMPING AT THE PDX LIMITER

By

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REDUCTION OF RECYCLING BY PUMPING AT THE PDX LIMITER

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ABSTRACT

We have installed two arrays of Zr-Al getters adjacent to the PDX limiter to affect the pumping of neutrals formed in this region. The projected area of the getters is approximately 0.4% of the plasma area, and the measured H_2 pumping speed is 16,000 l/sec. During ohmic discharges, the getters reduced the electron density decay time from 340 to 180 msec. This result, combined with H_a data indicates that the recycling coefficient decreases by 10% or more.

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I. INTRODUCTION

The concept of the pumped limiter¹ shows considerable promise as a solution to a number of potential fusion reactor problems, including impurity control, hydrogenic recycling control, and helium ash removal.² Pumped limiters figure prominently in the design considerations for FED³ and Starfire.⁴ This has occasioned several recent experiments on pumped limiter phenomena. A comprehensive review of these investigations is given by Mioduszewski.⁵ For background we include herein a brief overview of previous results.

In initial experiments Overskei⁶ measured the neutral pressure build-up behind the Alcator-A limiter and concluded that the limiter effectively removed up to 20% of the atoms injected during a discharge. Jacobsen attributed the observed pressure rise in a PDX scoop limiter to the effect of plasma plugging.⁷ In work on an ISX-B prototype pumped limiter⁸, pressure measurements were correlated with ion saturation current measurements to infer the importance of ballistic effects. Pumped limiter experiments on Macrotor have utilized small probes⁹ as well as large area structures.¹⁰ Pressure measurements indicated particle removal efficiencies of 10-15%. In addition to these efforts, pumped limiters for PDX,¹¹ and TEXTOR¹² are currently in fabrication.

In previous experiments, the pumped limiters have been essentially passive structures with emphasis placed on inferring collection efficiencies from pressure rise measurements. In the present work, we have installed two arrays of Zr-Al alloy bulk getters adjacent to the PDX outer moveable limiter. We present data complementary to the previous results in that we have observed changes in plasma parameters due to this concentrated pumping near the limiter. In particular, we have observed

variations in the electron density decay rate and H_{α} brightness as functions of the distance between the plasma/limiter interface and the getter arrays. We conclude from these data that the getters reduce the particle recycling coefficient by $\sim 10\%$. Unlike previous gettering experiments¹³ wherein Ti was sublimated over a large area of the vacuum vessel, the bulk getter arrays used in these experiments have a projected area of only 0.4% of that of the plasma.

In Section II we discuss details of the getter array construction and operation, along with the plasma conditions during the experiment. Results are presented in Section III and discussed in Section IV within the framework of a simple ballistic model.

II. EXPERIMENTAL CONDITIONS

A. Getters

The getter arrays utilize SAES Zr-Al alloy (St101®) bulk getter modules.¹⁴ The modules are corrugated structures of Zr-Al powder ($\sim 80 \mu\text{m}$ thick) press-bonded to both sides of a constantan substrate which is heated resistively. The Zr-Al alloy pumps hydrogenic species reversibly, while impurities (C,N,O) are permanently chemisorbed. Following an atmospheric exposure, the pumps are activated by heating to 700°C for 45 minutes to diffuse surface impurities into the bulk. Activation can be repeated until the total concentration of impurities reaches $\sim 10 \text{ Torr-l/g}$, after which the hydrogenic pumping speed begins to degrade significantly. The pumps are operated typically at 400°C where both impurities and hydrogenic species are pumped. Regeneration of absorbed hydrogen, which must be performed before reaching the embrittlement concentration of 20 Torr-l/g, is effected by raising the

getter temperature (typically to 700°C) to increase the equilibrium pressure of the hydrogen, which is then removed by the other vacuum system pumps.

Two arrays, each comprising eight Zr-Al modules, were installed adjacent to the PDX outer moveable limiter as shown in Fig. 1. The support structure vertical sides extend 4 cm beyond the face of the getters. The modules are connected in series electrically and are instrumented with a number of thermocouples, the signals of which are averaged for the temperature feedback control. A detailed description of the arrays is given by Sredniawski et al.¹⁵

The measured H₂ pumping speed of the arrays in the PDX vessel was 16,000 l/s following activation. The measured pumping speed of the turbomolecular pumps was 3500 l/s. As is typical for PDX operation, Ti was sublimated in the lower dome region to improve the base pressure and the general plasma behavior. The associated pumping speed was $\sim 10^5$ l/s. Visual observation during a subsequent vacuum opening confirmed that the region of deposition was localized to the lower dome and well-removed from the region of the outer vessel wall. It is thus expected that the effects of the Ti gettering were constant with respect to variations in plasma position and did not affect the results presented here.

B. Plasma Conditions

Data were obtained from circular, nondiverted, ohmically heated H discharges. Except as noted, plasmas were run on the outer graphite limiter only. As shown in Fig. 2, the plasma major radius R_0 was varied from 143 cm to 154 cm. The toroidal field current was held constant to produce a toroidal field B_T varying from 16.7 kG at $R_0 = 143$ cm to 15.5 kG

at $R_0 = 154$ cm. The plasma minor radius, a , was held constant at 41 cm. The outer limiter radius $R_L = R_0 + a$ thus varied from 181 cm to 195 cm, with the getter vertical support structure extending to 198 cm and the getter front surface at 202 cm (see Fig. 2). The plasma current was feedback stabilized to provide a 300 kA flattop, and the loop voltage was 1.2 V for the entire major radius scan. The average electron density $\bar{n}_e$ was feedback controlled to $1.5 \times 10^{13} \text{ cm}^{-3}$. At 0.4 s the gas feed was terminated to facilitate measurement of the density decay rate. The bolometer profiles were unchanged during the R_0 scan and showed no central peaking of the radiation. The total radiated power during the current flattop was ~ 0.4 of the ohmic heating input. The getters were activated for all of the data reported in Section III.

III. RESULTS

Figure 3 shows the time evolution of $\bar{n}_e$ for two limiter positions: $R_L = 195$ cm and $R_L = 188$ cm. The former case, for which the plasma edge is 7 cm from the getter surface, shows a much faster density decay rate after 0.4 s (when the gas feed valve was closed), as compared to the latter case where the plasma-limiter interface is further removed from the getter. In Fig. 4, the density exponential decay time at $t = 0.4$ s given by

$$\tau_p^* = n_e / (dn_e/dt) \Big|_{t=0.4s} \quad (1)$$

is plotted over the range $184 \text{ cm} \leq R_L \leq 195$ cm. From $R_L = 184$ cm to $R_L = 189$ cm, τ_p^* appears to have little dependence on R_L . From $R_L = 189$ cm to $R_L = 195$, τ_p^* decreases by a factor of ~ 1.9 . τ_p^* was also measured for

discharges with $R_0 = 143$ cm using the top and bottom moveable limiters with the outer limiter removed at $R_L = 195$ cm. We expect that the getters would have a negligible effect on the density decay rate in this case, since the neutrals are formed well away from the vicinity of the getter. These τ_p^* measurements are equal, within experimental uncertainty, to those obtained using only the outer limiter with $R_0 = 143$ cm. Thus, it would appear that even using the outer limiter, the effect of the getter is insignificant for $R_L < 188$ cm.

Measurements of the H_α brightness B on the midplane around the torus at $t = 0.3$ s are plotted in Fig. 5 for $R_L = 195$ cm and $R_L = 184$ cm. The data include a small correction for the changing major radius. As expected, both curves show a peaking in the region of the outer limiter. The peaking of the $R_L = 195$ cm data is somewhat more pronounced. The area under the $R_L = 184$ cm curve is ~ 1.7 times that for $R_L = 195$ cm.

Measurements were also made of the rate of gas flow as the plasma major radius was changed. Some increase of this quantity with R_L was observed; however, it is not possible to interpret this quantitatively owing in part to large fluctuations in the data, and in part to the fact that only a small (~ 0.3) and variable fraction of the total gas input actually goes into the discharge.¹⁶

Following the TFR group derivation,¹⁷ we can relate τ_p^* to the global plasma particle lifetime τ_p , and the recycling coefficient β , using

$$\tau_p^* = \tau_p / (1 - \beta) \quad . \quad (2)$$

The conventional interpretation¹⁸ of the H_α brightness is that for constant $\bar{n}_e$, $B \sim \tau_p^{-1}$. This, coupled with the observed change

in τ_p^* , would suggest that β decreases strongly as the plasma is moved closer to the getter. In fact, it is likely that β depends more on an "edge" particle confinement as opposed to τ_p in Eq. (2) which is the global confinement time. β thus has a more complicated functional dependence and may increase with β . Consistent with this interpretation is the qualitative argument that the observed decrease in recycling with increasing R_L reflects a decrease in the neutral density due to the getter pumping. The increased peaking of B for $R_L = 195$ cm is also consistent with localized pumping. The constant plasma density is maintained by an increase in the H_2 source which may be sufficiently distributed toroidally and poloidally so that the resulting small increase in the midplane H_u brightness is not observed.

We can thus obtain a conservative lower bound on the variation of β with R_L by assuming τ_p is constant and equal to a typical value of 0.035 s. Then from Eq. (2) and Fig. 4, we find that β varies from 0.90 at $R_L = 188$ to 0.81 at $R_L = 195$.

IV. DISCUSSION

In this section we estimate the fraction of particles which the getter would collect based on a simple ballistic model. A more detailed numerical calculation is planned.

Following Mioduszewski et al.⁸ we assume that neutrals are formed when the plasma ions collide with the limiter (or other surface). The production rate of neutrals is proportional to the particle flux incident on the limiter. This flux Γ is given by¹⁹

$$\Gamma = \Gamma_i \sin \theta \quad , \quad (3)$$

where Γ_1 is the particle flux along field lines in the edge region and θ is the angle between the field line and the direction normal to the limiter surface. Γ_1 is given by

$$\Gamma_1 = \Gamma_0 \exp(-(r-a)/\lambda) \quad , \quad (4)$$

where Γ_0 is the particle flux along field lines at the plasma edge, r is the distance from the magnetic axis to the point on the limiter, a is the plasma minor radius, and λ is the particle scrape-off distance.

The neutrals are assumed to be emitted with a $\cos \phi$ dependence where ϕ is the angle between the emission direction and the limiter surface normal. Since the limiter has a rail configuration we assume the neutrals are emitted as a line source. To estimate the pumped flux we require the effective sticking probabilities for neutral atomic hydrogen. The measured effective sticking probability for H_2 on the corrugated Zr-Al surface is 0.25. In general the value for atomic species will be higher. For the present estimate we take it to be 0.5.

Taking into account the detailed shape of the limiter and the solid angles which the getters subtend, and using the value of $\lambda = 3$ cm, measured under similar conditions,²⁰ we have estimated the fraction of particles which the getters would pump. For $R_L = 184$ cm, the estimate is 0.03. As R_L is increased, however, we find no significant change in the estimate. We further note that from the typical measured edge density and temperature²⁰ the estimated neutral-mean-free path (25 cm) is the same order as the mean distance from the limiter to the getter.

As an alternative we consider the ballistic collection of the particles which strike the vertical sections of the getter support

panels. As mentioned previously, these protrude to a major radius of 198 cm. The panels are mounted asymmetrically so that the plasma particles will encounter the vertical supports on the limiter side of the two arrays before reaching the vertical supports toroidally downstream from the limiter. The mean distance from these structures to the getter is much less than the estimated neutral-mean-free path. The incident flux beyond $R = 198$ cm is proportional to $\exp \{-(198-R_L)/\lambda\}$. We estimate that the solid angle factor is 0.5 and that the sticking coefficient is 0.5. The resulting expression for the pumped fraction, $(1-\beta)$ is given by

$$(1-\beta) \sim 0.1 + 0.25 \exp \{-(198-R_L)/\lambda\} \quad (5)$$

The term 0.1 follows from the observation that $\beta = 0.9$ in the region where the getter has no effect. Taking $\lambda = 3$ cm, the expression in Eq. (5) is found to give a good fit to the τ_p^* behavior in Fig. 4.

V. SUMMARY

We have installed Zr-Al pumping arrays adjacent to the outer limiter in PDX. We observe that as the plasma is moved closer to the getter arrays, the density decay time τ_p^* and H_α brightness decrease. We interpret these observations as a decrease in the recycling of at least 10%. We find that the data are in general agreement with estimates made assuming the getters pump neutrals produced ballistically on the getter panel structure.

VI. ACKNOWLEDGMENTS

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FIGURE CAPTIONS

- FIG. 1. Photograph of the Zr-Al arrays installed in PDX adjacent to the outer moveable limiter.
- FIG. 2. Schematic of the experimental arrangement. The sides of the getter support structure extend to $R = 198$ cm.
- FIG. 3. Time evolution of the line average electron density $\bar{n}_e$ for plasmas with $R_L = (R_0 + a)$ being 195 cm and 188 cm. The gas feed valve was closed at $t = 0.4$ s.
- FIG. 4. Graph of the density decay time τ_p^* vs. limiter radius R_L . The line shown represents a visual fit to the data.
- FIG. 5. Graph of H_α brightness as a function of toroidal angle with the limiter at 0° for $R_L = 184$ cm and 195 cm. Measurements were made on the midplane at $t = 0.3$ s. The approximate extent of the getters is shown.

Fig. 1

Fig. 2

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Fig. 3

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Fig. 4

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Fig. 5

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