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PLASMA PHYSICS
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THERMAL DESORPTION MEASUREMENTS OF HYDROGEN-
ISOTOPE RETENTION IN ALCATOR -A

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ABSTRACT

Results are presented for deuterium retention measurements in type 304 stainless steel exposed in the edge plasma of the Alcator-A tokamak. Stainless steel samples, at 300K, with surface conditions characterized by Auger electron spectroscopy, were introduced into the limiter shadow region for exposure to deuterium plasmas, and then withdrawn into an appended UHV chamber for thermal desorption measurements. For unoxidized samples exposed at the vacuum vessel wall radius, $1 \times 10^{15} \text{Dcm}^{-2}$ was retained after exposure to high density ($\bar{n}_e = 3 \times 10^{14} \text{cm}^{-3}$) discharges. Exposure to consecutive series of N discharges produced retention proportional to $N^{1/2}$.

DISCLAIMER

Introduction

Recycling of the hydrogen working gas in tokamaks is fundamental to plasma behavior, directly affecting the density and temperature profiles and the plasma purity.^{1,2} The hydrogen retention properties³⁻⁵ of the wall (or limiters) is an important parameter of the recycling process. The trapping coefficient (or inversely, the re-emission coefficient), saturation level, and trapping strengths are retention properties which determine to what level the wall is a source or sink of hydrogen during the course of a discharge.

In this paper we present results of measurements of hydrogen retention in stainless steel samples exposed in the edge plasma of the Alcator-A tokamak. The trapped hydrogen is analyzed by thermal desorption mass spectroscopy following plasma exposure. The total hydrogen retention is measured to an accuracy of $\pm 10\%$ with a minimum detectable retention of $\sim 10^{13} \text{ cm}^{-2}$. Although lacking in the present study, detailed examination of the thermal desorption transients can yield information on hydrogen trapping mechanisms and the implantation profiles.⁶⁻⁸

2. Apparatus

The first wall of Alcator-A is a 304 stainless steel bellows, normally maintained near 77 K during tokamak operation. For the initial studies reported on this paper a 304 stainless steel sample at ambient (300 K) temperature was used. The sample is in the shape of a thin (0.005 cm) ribbon (1.9 cm x 0.64 cm)

stretched between two 0.24 cm copper rods, and carried at the end of a stainless steel carrier tube inside an air-actuated bellows. The bellows mechanism has a linear travel of 2.5 m allowing the sample to be withdrawn from the plasma-edge to an analysis chamber after exposure. Lines for thermocouples and for passing heating current through the sample run within the carrier tube isolated from ground. The 30 liter analysis chamber contains a quadrupole mass spectrometer⁹ for the thermal desorption measurements and an Auger electron spectrometer¹⁰ for characterizing the surface of the sample. A gas handling system with a capacitance manometer is connected to the analysis chamber for accurate measurement of the chamber pumping speed and calibration of the mass spectrometer. A turbomolecular pump, with a measured net pumping speed of 385 l/s for H_2 , pumps the chamber with sufficient speed that thermal desorption measurements can be considered within the high pumping speed limit;¹¹ i.e., the measured pressure rise in the chamber is proportional to the desorption rate. The mass spectrometer is operated at a sensitivity of 1 ampere per torr of H_2 which allows as few as 10^{12} atoms of hydrogen, released over a few seconds to be detectable. Base pressures in the low 10^{-9} torr range are obtained in the analysis chamber after a mild (450 K) overnight bakeout.

Sample temperature during heating or plasma exposure is measured with a platinum-rhodium thermocouple spot-welded to the sample ribbon.

3. Experiment

The sample probe is located on the tokamak midplane, 90° toroidally from the circular molybdenum limiter, in the electron streaming direction. The minor radius of the primary limiter is 10 cm. The next plasma boundary is determined by pairs of stainless steel "virtual limiters" located at 90° intervals around the torus, at a radius of 11.5 cm; the nominal wall radius is 12.5 cm. The sample could be introduced to a minimum minor radius of 10 cm. The long axis of the sample ribbon is normal to the midplane and the sample surface is oriented at a 30° angle with respect to the toroidal magnetic field.

Exposures were made at various radii, for different numbers of discharges, and at several plasma densities in deuterium plasmas. Within 100 seconds after the exposure, the sample was withdrawn into the analysis chamber where the trapped gas was desorbed by passing current, varying linearly from 0 to 10 amperes through the sample. The maximum sample temperature was 1023 K. The resulting sample temperature rises linearly from 400 K to 900 K in 7 seconds, then flattens to 1050°K over the next 6 seconds. We note that broad desorption peaks occurred at approximately 650 K and 900 K, although no attempt at spectrum analysis is made in this paper. The total retained deuterium per sample exposure was determined by integrating the desorbed gas pressure vs time curve recorded on a strip chart recorder.

4. Results and Discussion

Figure 1a shows Auger spectra of the sample surface after residing in the analysis chamber residual gas for 24 hours, and

then immediately after heating to 1023 K [Fig. 1b]. Carbon impurities and the oxide layer are completely removed from the stainless steel surface while traces of sulfur evidently diffuse to the surface from the bulk. These results are in agreement with the results of Mathewson and Achard¹² and indicate that an unoxidized surface is exposed to the plasma in this experiment. A spot check with Auger after plasma exposure, but before flashing, showed a decrease in sulfur coverage and very little increase in carbon and oxygen coverages.

Long exposure to 10^{-4} torr of D_2 , followed by pumpdown to 10^{-9} torr and flash heating, yields no perceptible desorption of D_2 . However, adsorbed layers that might exist in equilibrium at 10^{-4} torr would desorb during pumpout and not be observed.

Figure 2 shows the sample temperature reached during a single discharge for different sample positions. Ohmic power in the plasma, if uniformly radiated, can only account for about 10 K rise in sample temperature; however, Langmuir probe measurements¹³ of edge-plasma density and electron temperature (Fig. 3) show that no sample intercepts sufficient electron flux at $r \leq 11.5$ cm to account for the observed increase in sample temperature.

In Figure 4, the deuterium retention after single discharge exposures at different radii follows a trend similar to the edge-plasma density for $r > 11.5$ cm, indicating that plasma ions are responsible for a major fraction of the retained deuterium. For $r \leq 11.5$ cm, the retention is not expected to increase in the same proportion as the steep rise in plasma density that is observed at the virtual limiter radius (11.5 cm) because of the high diffusivity and ease of de-trapping of deuterium.

Wilson and Baskes^{6,7} have shown that thermal desorption measurements of 1 keV D^+ implants in type 316 stainless steel at 296 K are consistent with an activation energy of 0.61 eV for bulk diffusion, and trapping in a low binding energy trap (0.29 eV) distributed within the volume of the ion range at a concentration of ~1 atomic %. Thus, deuterium retention within the bulk of stainless steel, and that residing in the 0.29 eV traps should decrease rapidly with only moderate increases in temperature. In fact, a factor of ~20 decrease in retention has been measured¹⁴ for 304 stainless steel implanted with 10 keV D_3^+ at 425 K relative to the equivalent implantation at 300 K.

Figure 5 shows the deuterium retention after single discharge exposures at the nominal wall position ($r = 12.5$ cm) as a function of the line-average plasma density ($\bar{n}_e$). The retention appears linear up to $\bar{n}_e = 2 \times 10^{14} \text{ cm}^{-3}$. The turnover observed in the retention curve above $2 \times 10^{14} \text{ cm}^{-3}$ may represent a decrease in that fraction of incident flux which is composed of charge-exchange neutrals. The contribution of high energy (≥ 500 eV) charge exchange neutrals to the observed retention is evidently small because measurements¹⁵ of the charge exchange flux at 500 eV, 700 eV, and 2000 eV fall by a factor of two when $\bar{n}_e$ is increased from 1 to $2 \times 10^{14} \text{ cm}^{-3}$ and fall by an additional factor of eight, when $\bar{n}_e$ is increased from 2 to $3 \times 10^{14} \text{ cm}^{-3}$.

Figure 6 shows the deuterium retention as a function of exposure to a number (N) of discharges with $\bar{n}_e = 3 \times 10^{14} \text{ cm}^{-3}$. Again, the sample was exposed at the nominal wall position ($r = 12.5$ cm). Since the discharges occurred at regular time

intervals of eight minutes, the $n^{1/2}$ dependence shown by the data of Fig. 6 is proportional to a $t^{1/2}$ time dependence for the retention. This behavior is consistent with a simple diffusive model for the outgassing of deuterium,¹⁶ in which the same amount of deuterium ($\sim 1 \times 10^{15}$ Dcm⁻²) is implanted per discharge, which subsequently diffuses out at a rate proportional to $t^{1/2}$.

We note that the data of Fig. 6 shows no evidence of saturation of deuterium retention with discharge exposure (at least up to the maximum exposure of twelve discharges). However, based on low energy (0.1 - 1 keV D⁺) implantation studies in stainless steel at 300 K, saturation effects are not expected until the total retention is $\sim 10^{16}$ Dcm⁻².

5. Summary and Conclusions

We have presented the first results for deuterium retention measurements in type 304 stainless steel samples exposed to the edge plasma of the Alcator-A tokamak at room temperature. For flash-annealed (unoxidized) samples, typically 1×10^{15} Dcm⁻² was obtained immediately (1-2 min.) after exposure to a high density ($\bar{n}_e = 2 \times 10^{14}$ cm⁻³) discharge at the nominal wall radius of the vacuum vessel. From the radial dependence of the observed retention, and the linearity of the retention with plasma density from $\bar{n}_e = (0.8 - 2.0) \times 10^{14}$ cm⁻³, we conclude that ions in the edge plasma rather than charge exchange neutrals from the central plasma are the major source of implanted deuterium. An attempt to observe the retention saturate with exposure to a small number (12) of discharges yields results consistent with a constant implantation per discharge, followed by a simple diffusive release of the

trapped gas between discharges, with no evidence for saturation at a total retention of $4 \times 10^{15} \text{ cm}^{-2}$.

A sample that can be maintained at 77 K is currently under construction that should yield results more directly applicable to studying retention in Alcator's cold wall and provide an interesting contrast to the present work.

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 Fig. 1. Auger electron spectra of stainless steel (Type 304) samples: (a) as received, and (b) after flash heating to 1600K and cooling in the UHV analysis chamber.

Fig. 2. Sample temperature as a function of position within the Alcator vacuum vessel. The nominal radius of the vessel wall is 12.5 cm and the inner radius of the primary limiter is 10.0 cm. 793958

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 Fig. 3. Langmuir probe measurements of the plasma edge density for discharges with $\bar{n}_e = 3.5 \times 10^{14} \text{ cm}^{-3}$, (from Reference 13).

Fig. 4. Deuterium retention in 304 stainless steel after exposure to single high power discharges in Alcator ($\bar{n}_e = 3 \times 10^{14} \text{ cm}^{-3}$) as a function of exposure position.

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Fig. 5. Deuterium retention in 204 X stainless steel after exposure to single high power discharges as a function of (linear-averaged) plasma density. The sample was exposed at the nominal wall position (2.17 cm) and at various temperatures (298K).

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Fig. 6. Deuterium retention in 304 stainless steel as a function of exposure to high power discharges with $\bar{n}_e = 3 \times 10^{14} \text{ cm}^{-3}$. The sample was exposed at the nominal wall position (12.5 cm) and at ambient temperatures (20 C).

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