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EFFECTS OF NEUTRAL BEAM INJECTION AND GAS PUFFING ON DEUTERIUM AND IMPURITY LEVELS IN THE SCRAPEOFF LAYER OF ISX-B

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Plasma-material interactions in the scrapeoff region of a tokamak have important effects on the overall performance of the machine. In order to prudently select the most appropriate materials for walls, limiters and armor plate, it is necessary to characterize the plasma that interacts with these surfaces and to understand what effect different modes of operation of the tokamak have on plasma characteristics. We have made a series of measurements on the ISX tokamak using deposition probe techniques to identify and quantify the impurities ($Z \geq 8$) in the limiter shadow, and to determine the temporal behavior of both impurity and plasma particles in this region. These measurements have been made under a variety of tokamak operating conditions, including both ohmic and neutral beam heated discharges. The results are interpreted in terms of edge conditions, impurity introduction, gas puffing, and the relative importance of wall and limiter contributions.

1. INTRODUCTION

One of the most critical areas for material performance in a tokamak is the region in which the plasma interacts with the physical boundaries of the machine, such as the limiter, armor plate, and first wall [1]. In order to effectively choose materials that can withstand the plasma edge, it is necessary to understand the conditions that exist there. In this work we report measurements of impurity and deuterium fluxes made in the scrapeoff layer of the ISX-B tokamak using time-resolved deposition probe techniques. Exposures were made for both ohmic and neutral beam injected (NBI) discharges and for discharges designed to test the effects of gas puffing on edge conditions. Since integrated deposition probe results may be dominated by instabilities, time-resolved measurements are necessary to delineate the individual effects of beam injection, gas puffing, or magnetohydrodynamic (MHD) activity. In all cases Rutherford ion backscattering and nuclear reaction analysis were used to determine quantitatively the materials retained on the samples.

Deposition probe techniques have been used previously to measure plasma edge parameters on the ISX tokamak. Time-resolved impurity measurements made on ISX-A [2] demonstrated a correlation between plasma instabilities and impurity fluxes in the edge that continues to be true in the present work. More recently, saturation type measurements [3] have been used to estimate impurity fluxes and deuterium fluxes and energies in ISX-B. Radial profiles of both impurities and deuterium in the ISX-B scrapeoff layer have also been made [3]. In combination with the present work, these results permit a reasonable picture of the ISX plasma edge region to be drawn.

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2. EXPERIMENTAL PROCEDURE

Silicon deposition probes were exposed to a variety of operating conditions in the plasma edge of ISX-B using a bellows sealed sample insertion system that allowed the samples to be positioned at any radius between the limiter and the outer wall. An electrically driven rotating shaft permitted multiple samples or time-resolved samples to be used. All exposures were made in the horizontal midplane of the tokamak at a toroidal position 120° from the limiters in the positive ion current direction. For the data presented here, an inner bar limiter of stainless steel and an outer mushroom shaped limiter of TiC coated graphite were in operation. Upper and lower bar limiters were also present, but were too far from the plasma centerline to have a significant effect on circular discharges. Exposures have been made for both ohmic and neutral beam injected discharges, and for discharges in which the fill gas puffing was programmed to determine its effect on the edge.

Single crystal silicon probes were used for impurity deposition so that the advantages of channeling could be utilized during Rutherford backscattering analysis, and amorphous silicon was used for H and D collection because of its superior trapping behavior for these isotopes. After being cut to size (19 x 7.8 x 0.4 mm), the samples were cleaned in organic solvents and acid, rinsed in distilled water, and air dried. This procedure resulted in the formation of a uniform oxide layer ($\sim 3 \times 10^{15}$ O/cm^2) that was relatively stable to further air exposure over periods of months. This was important because the samples were opened to the atmosphere between the time of tokamak exposure and the subsequent ion beam analysis.

Time-resolved exposures were made by mechanically rotating a cylindrical drum behind a protective aluminum shield. Samples attached to the drum were exposed to the plasma through a slot in the shield for only a specific period of time during the discharge. To insure adequate impurity deposition, the collection process was integrated over approximately 5 discharges. Time resolution for the present data was 15 ms.

After exposure the probes were transferred to a 2.5 MeV Van de Graaff accelerator where they were analyzed for impurity deposits using 2 MeV ^{4}He backscattering, and for retained deuterium using the D(^{3}He,p)^{4}He nuclear reaction. Details of the Rutherford backscattering (RBS) and nuclear reaction analysis (NRA) techniques have been described previously [2,3]. Both techniques yield quantitative results.

3. RESULTS AND DISCUSSION

3.1 Neutral Beam Injection

The temporal behavior of the principal impurities collected 2.5 cm behind the limiter radius during six 1.1 MW neutral beam injected discharges in ISX-B is shown in the bottom section of Fig. 1. The plasma parameters for these discharges were: toroidal field, B_t = 1.31 T; plasma current, I_p = 160 kA; and electron density, $\bar{n}_e = 4.4 \times 10^{13}/cm^3$. Oxygen was the most abundant impurity observed, with more than an order of magnitude greater deposition than iron, the most common metallic element. Chromium and nickel (not shown) were present in approximately the same ratios to iron as in 304 stainless steel, the wall material in ISX-B and also the material of the inner bar limiter. The small amount of titanium on the probe must have come from the TiC coated POCO graphite limiter. A sharp increase is observed in all impurity levels at the onset of neutral beam injection. Even though the effect may occur indirectly, such as through variations in plasma position, it is clear that edge impurity fluxes are increased by neutral beam injection by a factor of 2-3 for oxygen and ~7 for metallic elements. The initial peak in impurity levels has been observed in all time-resolved probe data from ISX [2] and is believed to be due to unstable operation immediately following breakdown.

Impurity deposition as a function of time is compared with MHD level, density, and gas puffing rate in Fig. 1. The 40 keV neutral hydrogen beam was co-injected into the deuterium plasma from 80 to 180 ms. Beam power during injection exceeded ohmic heating power by a factor of ~4. The increase in impurity levels with the onset of NBI is clear, but an increase in MHD activity is also apparent at this time. This correlation between MHD activity, as measured by magnetic loops, and the level of metallic impurities in the plasma edge is found in all our results. (See Fig. 4 and Ref. 2) In general, a correlation can also be found between MHD activity, and thus impurity levels, and in-out shifts in the plasma position. An outward shift could conceivably lead to increased deposits on our probe, since impurity levels have been shown to decrease with increasing minor radius beyond the limiter [3]. This is not felt to be an important factor in our results, since comparable deposits have been measured on the probe for both inward and outward shifts. However, small changes in the location of the plasma column about its central

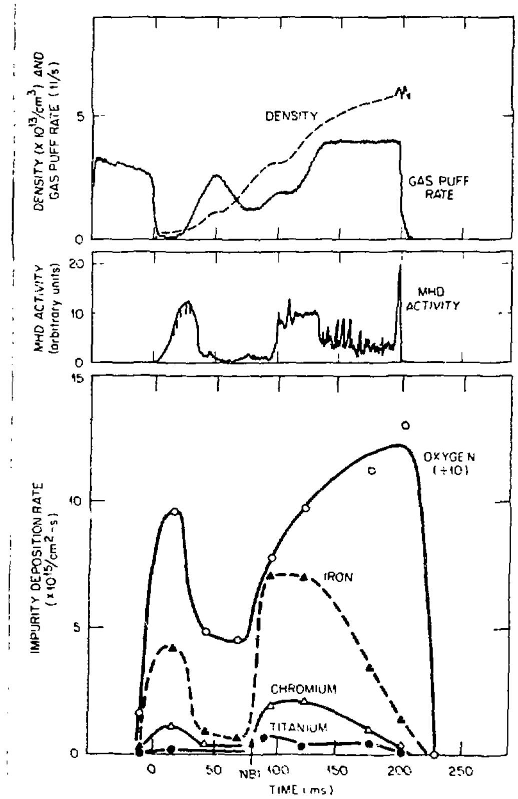

Figure 1: Comparison of time-resolved impurity deposition rates with MHD activity, plasma density, and gas puff rate for 1.1 MW neutral beam injected deuterium discharges in ISX-B. The arrow indicates the start of 100 ms NBI.

position may be responsible for increased impurity levels in the edge as a result of increased contact between the plasma and limiter-like projections inside the vacuum vessel.

At 150 ms both MHD and iron levels have begun to decrease, even though the neutral beam injection is still firing. This reduction in both MHD and iron levels may be due to the increased gas puffing that begins at ~120 ms for the purpose of maintaining plasma stability during injected discharges. For ohmic shots the puffing rate during this part of the discharge is lower, yet stable operation is obtained. Appropriate gas puffing appears to be able to maximize plasma stability while minimizing the introduction of metallic impurities into the plasma.

Oxygen behaves differently during the later stages of these injected discharges, (See Fig. 1) with edge levels continuing to build until the end of the discharge. They are relatively unaffected by the gas puffing rate. This is in agreement with other experiments on saturation behavior of impurities [3] and isotopic exchange [4] in ISX that suggest different mechanisms are responsible for the introduction of iron and oxygen into the plasma edge. In particular, chemical effects may be important in oxygen introduction, while physical processes such as sputtering and arcing are dominant in the case of metals.

The amount of deuterium retained in amorphous silicon samples exposed to the same sequence of beam injected discharges is shown in Fig. 2. Since the number of data points from amorphous material is limited, the damage to single crystal samples has also been plotted to give a more complete picture. Single crystal damage in silicon has been shown to be indicative of incident deuterium fluence and energy [5]. As was the case for heavy impurities, we see a sharp increase in retained deuterium coincident with the neutral particle injection. In these discharges hydrogen beams were fired into a deuterium plasma so that the observed rise in trapped deuterium is due to increases in plasma density and energy, and not to escaping high energy beam particles. The damage distribution, however, shows the influence of both hydrogen and deuterium. The damage data indicates relative rates during the discharge and should not be compared on an absolute basis with the retained deuterium values.

3.2 Gas Puffing

In order to clarify the effects of gas puffing on both plasma and impurity fluxes in the boundary layer, time-resolved measurements were made during a series of shots in which the fill gas was puffed twice during the discharge. In a typical ISX discharge, a "super puff" of ~0.3 tl of operating gas is injected into the tokamak at ~40 ms. This pulse serves to minimize MHD instabilities, as well as to increase plasma density and temperature. For our measurements, a second identical pulse of gas was injected at ~120 ms, so that its specific effect on the edge could be observed. The resulting levels of deposited oxygen and iron for 5 discharges are shown in Fig. 3. Chromium, nickel, and titanium were present in amounts comparable to the beam injected case. The plasma operating conditions for these exposures were; B_t = 1.3 T, I_p = 170 kA and

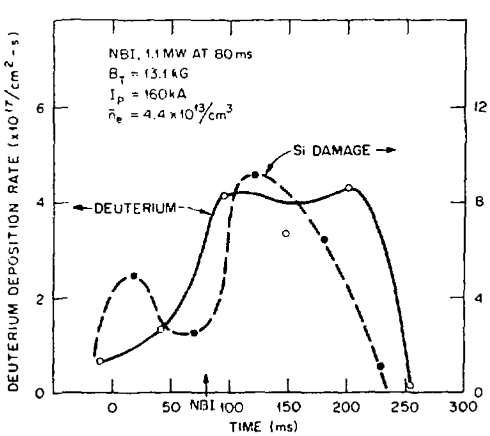

Figure 2: Deuterium retention (a Si) and single crystal silicon damage rates as functions of time for six 1.1 MW neutral beam injected deuterium discharges in ISX-B. The arrow indicates the start of 100 ms NBI.

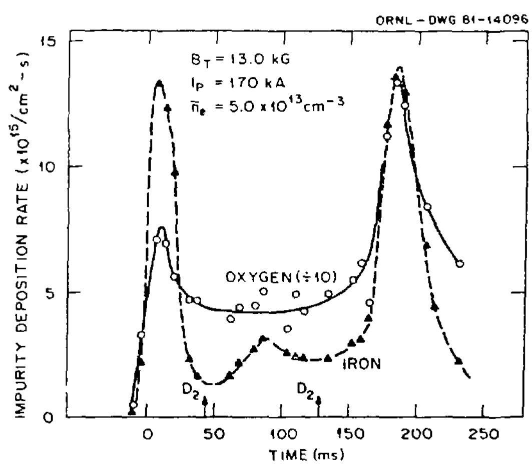

Figure 3 Impurity deposition rate as a function of time for five ohmic deuterium discharges in ISX-B with 0.3 tl gas puffing at 40 and 120 ms (arrows).

$\bar{n}_e = 5.0 \times 10^{13}/cm^3$. The increased impurity flux immediately after breakdown is again apparent for both oxygen and iron, as is a marked peaking at the end of the discharge when the plasma disrupts. Both these effects have been previously reported [2]. In all our measurements impurity levels have been observed to reach a minimum in the region of the first "super puff", as they do here. This minimum is probably the result of increased plasma stability rather than a direct effect of the gas puffing. This idea is supported by the results of the second gas puff which has only a limited effect on impurities, producing no significant change in the oxygen level, and only a small decrease in the iron. The lack of effect on oxygen is in agreement with the NBI result, while the minimal effect on iron is probably due to the stable, low MHD operation during this part of the discharge which cannot be quieted by additional puffing. Note that the slight peaking in iron flux just prior to 100 ms is also a time of incipient MHD activity (Fig. 4). Both effects are eliminated during the second deuterium puff. It would appear that gas puffing can minimize edge metallic impurity levels only to the extent that it can maintain a stable, low MHD plasma.

Far more pronounced effects of the gas puffing are seen in the plasma-edge deuterium flux as illustrated at the bottom of Fig. 4. Here both surface damage and deuterium retention in single crystal silicon are plotted as functions of time and compared with MHD level, density, and gas puffing rate. Since trapping behavior differs between single crystal and amorphous material, the absolute deuterium levels should not be directly comparable to those of Fig. 2.

The decreases in damage and deuterium flux that occur with each of the gas puffs is obvious. Unfortunately, saturation measurements, which can be used to estimate both energy and fluence to the probe, are not compatible with this time-resolved technique. Previous saturation studies on comparable discharges [3] at this radius have given estimates of deuterium energy on the order of 100 eV and fluence of $\sim 10^{17}$ D/cm^2-discharge. In the present work we are collecting primarily ions traveling parallel to B_t and the factor of two reduction in retained flux during puffing implies that the ion density has decreased by 2, that the average ion energy has decreased by $\sqrt{2}$, or, more likely, that a combination of these effects has taken place. In either case the deuterium flux in the edge has been "cooled" by the gas puffing. That is, there are fewer ions carrying less energy to a limiter-like surface.

3.3 Sources of Heavy Impurities

The principal heavy impurities found in the plasma edge of ISX-B were oxygen, iron, chromium, nickel and titanium. Oxygen is present in the oxide layer on the interior of the vacuum vessel, as well as in the more prevalent residual gases, H_2O and CO, while iron, chromium and nickel

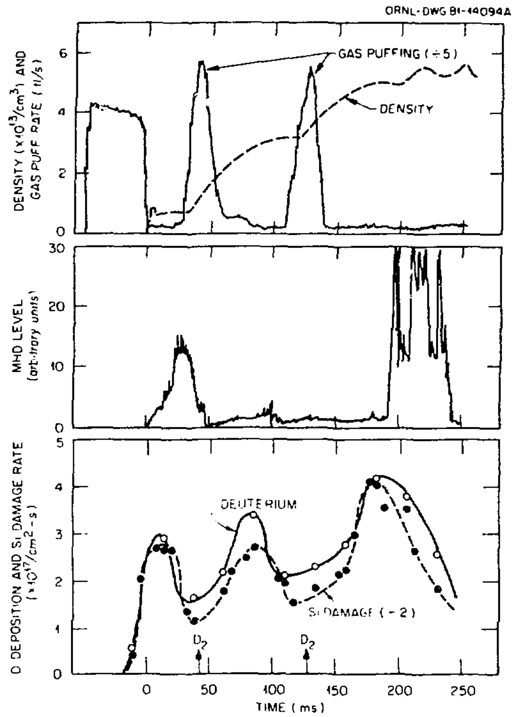

Figure 4: Comparison of deuterium deposition and single crystal silicon damage rates with MHD activity, plasma density, and gas puff rate for ohmic deuterium discharges in ISX-B with 0.3 tl gas puffing at 40 and 120 ms.

come from the stainless steel liner and the inner bar limiter. The smaller amounts of titanium (Fig. 1) must originate in the TiC coated outer limiter, since no Ti gettering had been used in ISX-B prior to these exposures. The level of titanium relative to that of stainless steel (<0.1) indicates that the limiter is not the primary source of metallic impurities during either ohmic or beam injected operation. It should be noted that after many hundreds of discharges, limiter material will be distributed throughout the machine, and the limiter itself will be covered with substantial amounts of iron from the walls [6]. This does not alter the conclusion that the walls and secondary limiters dominate the TiC limiter as a source of heavy impurities when the plasma is centered. Isler et al. [7] have recently used spectroscopic techniques to demonstrate that Ti XI radiation from an estimated position of 0.7 of the minor radius in ISX-B is strongly dependent on plasma position, increasing sharply as the plasma column is shifted from the centered position to a position 3 cm outside of center. However, other observations of Fe lines, both with TiC and stainless steel limiters, lead them to the conclusion that the wall is the principal source of impurities. On the basis of impurity levels measured during H to D changeover experiments in ISX-B, Roberto et al. [4] suggest that the dominant mechanism for metallic impurity introduction is charge exchange neutral sputtering of the walls. The present data are in agreement with these conclusions.

4. CONCLUSION

The impurities found in the plasma edge of ISX-B were oxygen from the wall and residual gases, stainless steel (Fe, Cr and Ni) from the vacuum vessel, and titanium from the TiC limiter. The relative amounts of iron and titanium indicate that the wall, and not the limiter, is the principal source of metallic impurities. Spectroscopic [7] and isotopic exchange [4] experiments suggest that charge exchange neutral sputtering of the wall may be the principal introduction mechanism for metals. As a result hydrogen sputtering behavior should be a major consideration in the selection of wall materials. Time-resolved impurity depositions showed a marked increase in impurity levels with the onset of 1.1 MW neutral beam injection. This increase was partially compensated for by increased gas puffing rates used in beam injected discharges. Impurity levels in the edge were found to correlate well with both MHD activity and instabilities in plasma position, reaching levels 2 to 5 times higher during breakdown and the disruptive end of a discharge than during the steady state portion. This points out the importance of transients and disruptions in impurity introduction and plasma-wall interactions. Finally, it was observed that gas puffing can effectively cool the plasma edge and, by minimizing instabilities, lower the level of impurities.

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