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Using Surface Probes and Laser-Induced Fluorescence

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Plasma Edge Studies in ISX-B and EBT-S
Using Surface Probes and Laser-Induced Fluorescence*

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1. Introduction

Surface and plasma edge studies in the ISX-B tokamak and EBT-S bumpy torus at ORNL have recently emphasized in situ measurements using surface deposition probes and laser-induced fluorescence. These studies have been designed to characterize ion and impurity fluxes in the plasma edge, determine erosion rates and impurity introduction mechanisms, and explore relationships between plasma operating conditions and surface and edge conditions. In this paper, we summarize recent results of plasma edge experiments on ISX-B and EBT-S using surface probes and laser-induced fluorescence, and present the corresponding picture of surface and plasma edge phenomena in these devices.

2. Experimental

The surface probe experiments involve for the most part the use of high-purity Si wafers, in single crystal form for impurity collection and amorphous (by self-ion bombardment) for deuterium trapping. The samples are mounted on a rotating drum which allows multiple and time-resolved (15 ms) exposures, and are inserted into the plasma edge region using a vacuum transfer system. Exposed samples are analyzed (1-3) for heavy impurities using Rutherford ion backscattering (RBS), for light impurities using RBS in the channeling geometry, and for deuterium using the $D(^3\text{He},p)^4\text{He}$ nuclear reaction. Deuterium energies are inferred from deuterium depth profiling (1), trapping vs. fluence behavior (1,4), near surface lattice damage (5), and transmission through limiting apertures (6). The sensitivity of these techniques is $\sim 10^{13}$ atoms/cm² for heavy impurities, $\sim 10^{15}$ atoms/cm² for light impurities and deuterium, and ~ 100 Å for depth profiling. Auger electron spectroscopy has also been used to characterize impurities in ISX-B (7) and EBT-S (8).

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Laser-induced fluorescence experiments have been performed using pulsed dye lasers to excite neutral Fe in ISX-B (9-11) and neutral Al in EBT-S (12). In these experiments, impurity densities in a given atomic state are determined from the intensity of laser-induced fluorescence following saturation pumping of the appropriate atomic transition. Velocity distributions are determined from the variation in fluorescence intensity while tuning narrow bandwidth laser light through the Doppler broadened absorption spectrum of the atoms. The technique is plasma-independent, has excellent space and time resolution, and allows detection of neutral atoms released from surfaces. Impurity release mechanisms can be investigated from velocity measurements. Sensitivities of $10^6 - 10^7$ atoms/cm² and 10^5 cm/sec have been demonstrated for neutral impurities in ISX-B and EBT-S (9-12).

3. ISX-B Results

Typical edge parameters for non-gettered, ohmic discharges in ISX-B are shown in Table I. These data are from surface probe measurements (1-4) with the exception of the neutral iron density which was determined using laser-induced fluorescence (9,10).

Ion behavior. The ion temperature and circulating ion flux 2 cm into the limiter shadow were determined from the best fit to recently revised (13) trapping vs. fluence curves for deuterium implantation in silicon. The saturation behavior of the deuterium trapping in the surface probes suggests a Maxwellian energy distribution and is not consistent with a monoenergetic distribution (4). Previous estimates (1,5) of edge temperature in ISX-B assuming monoenergetic incidence are closer to 100 eV including the sheath potential, but would be lower for a broad energy distribution. The sheath potential does not significantly influence the Maxwellian estimate since the high energy tail of the Maxwellian (which determines the high fluence behavior of the saturation) is not substantially shifted. The 20 eV edge ion temperature is consistent with recent Langmuir probe (14) and Thomson scattering (15) measurements of the edge electron temperature in ISX-B ranging from 10 to 40 eV. The circulating ion flux is in excellent agreement with the ion saturation current (3×10^{18} /cm²-s) to a biased probe at the same minor radius (15). The ion flux scrapeoff length as determined from the surface probes is also in agreement with the 1.9 cm 1/e decay length of the ion saturation current (15).

Neutral fluxes. Surface probe measurements at the wall position facing the plasma and away from the limiter indicate a substantial low-energy hydrogen outflux of $2 \times 10^{16}/\text{cm}^2\text{-s}$ at ~ 30 eV. This result is consistent with global outflux estimates in ISX-B assuming a confinement time of ~ 20 ms. The probe measurements also indicate a high energy tail in the neutral outflux consistent with charge exchange measurements (16) at higher energy. Recent efforts (17) to extend calibrated charge exchange measurements in ISX-B to lower energies suggest a neutral outflux of $\sim 5 \times 10^{15}/\text{cm}^2\text{-s}$ for $E > 35$ eV. This result is not inconsistent with the surface probe measurements since the neutral flux is rising with decreasing energy in this regime.

Impurity introduction. The principal impurities in ISX-B are oxygen, carbon, and the components of stainless steel. Limiter material is substantially less prevalent in the plasma edge than wall material. Oxygen is typically 1% of the plasma edge density, with iron and carbon a factor of ten lower. Approximately 1% of the edge iron density is not ionized. The flux scrapeoff length for iron is comparable to the hydrogen length. The total iron density in the edge is approximately a factor of ten higher than the plasma iron density as determined from optical measurements (18) under similar conditions. This result suggests efficient removal of impurities in the limiter shadow.

Heavy impurity densities increase approximately a factor of three for deuterium as compared to hydrogen discharges in ISX-B, but oxygen densities are unchanged (19). This suggests that physical sputtering is responsible for heavy impurity introduction and a chemical process is responsible for oxygen release. The low density of limiter material in the plasma edge suggests that wall sputtering is the dominant heavy impurity introduction mechanism. The measured neutral deuterium flux to the wall can account for the circulating iron impurity flux in the edge assuming a sputter yield of 10^{-3} (4). The sputtered iron flux is $\sim 3 \times 10^{12}/\text{cm}^2\text{-s}$ which is more than ten times the redeposited flux away from the limiter. This indicates net erosion of the wall with removal of impurities by impact with the limiter. Plasma shifting experiments (20) have also shown that the wall is the primary heavy impurity source in ISX-B.

The erosion of thin films in the plasma edge as determined by RBS measurements (3) suggests substantial sputtering at the limiter radius by incident oxygen and deuterium ions. The expected sputter erosion of the

TiC coating on the ISX-B outer limiter is not observed (21), which indicates that impurity transport to the limiter may be comparable to the release rate. This is consistent with the edge erosion and impurity flux results in Table I. Substantial near surface iron concentrations have been observed on TiC limiters following extended operation in ISX-B (22).

Plasma effects. A number of surface probe experiments have been performed to investigate the relationship between plasma operation and edge conditions. In Fig. 1, time-resolved edge impurity fluxes are shown for ISX-B discharges with neutral beam injection. A substantial increase in impurity introduction is associated with the onset of beam heating. Edge temperature, as indicated by deuterium damage and retention in silicon probes, increases by a factor of two during 1.1 MW of neutral injection (2). Gas puffing experiments (2) show that edge ion temperatures can be reduced by a factor of two by cold gas input, but that the corresponding direct influence on impurity introduction is small. Surface probe measurements during isotopic exchange in ISX-B are consistent with spectroscopic and residual gas analysis (RGA) results which indicate a rapid initial plasma changeover with an extended tail over several discharges associated with diffusion from the bulk (19).

4. EBT-S Results

Typical edge parameters for EBT-S operation at $\sim 5 \times 10^{-6}$ Torr and 100 kW of microwave heating are shown in Table II. These data are from laser-induced fluorescence (12) and surface probe (6,8) measurements.

Ion fluxes. The ion temperature and circulating ion flux 1.5 cm from the center midplane of an outer cavity wall in EBT-S were determined from the profile of transmitted deuterium ions collected on an amorphous silicon surface probe located behind an aperture (6). The spatial distribution of retained deuterium on the probe was measured using the $D(^3\text{He}, p)^4\text{He}$ nuclear reaction and is shown in Fig. 2. The substantial deposition of deuterium at positions well beyond the aperture radius indicates that the average ion gyroradius was at least comparable to the 3.4 mm aperture radius. The solid curve in the figure represents a calculation (including saturation effects) of the expected transmission profile for a 20 eV Maxwellian with a 3 kT sheath potential. At this energy, the retained deuterium in the probe is consistent with an incident flux of $10^{17}/\text{cm}^2\text{-s}$. This leads to an edge ion density of $\sim 10^{11}/\text{cm}^3$ in reasonable agreement with the estimated

edge electron density from the ionization length of sputtered aluminum determined by laser-induced fluorescence (12) and from spectroscopic measurements (23).

Impurity introduction. Erosion and redeposition at the center midplane of an outer cavity wall in EBT-S were monitored using laser-induced fluorescence (12) and Auger analysis of surface probes (8). This location in EBT-S corresponds to an erosion ring where field lines intercept the aluminum walls. The velocity distribution of neutral aluminum atoms released from the wall as determined by laser-induced fluorescence (12) is shown in Fig. 3. This distribution is typical of sputtering and greatly exceeds thermal velocities even at the melting temperature of aluminum. The sputtered aluminum flux (12) is in good agreement erosion rates inferred from the saturation coverage of aluminum deposited on a stainless steel surface probe (8). Hydrogen ion fluxes and energies (6) in the edge are much too low to account for the sputtered aluminum, and self-sputtering is expected to be the dominant aluminum release mechanism. The surface probe measurements (8) indicate that aluminum redeposition in the erosion ring is three-fourths of the release rate.

5. Summary

Surface probe and laser-induced fluorescence measurements in ISX-B and EBT-S have made significant contributions to the understanding of plasma edge characteristics and plasma-surface interactions in these devices. Where comparison is possible, these techniques have led to results which are consistent with plasma diagnostics. Charge-exchange neutral sputtering and self-ion sputtering have been identified as the dominant heavy impurity release mechanisms in ISX-B and EBT-S, respectively. The parameters listed in Table I and II represent substantial progress toward understanding edge phenomena in these devices.

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Table I. Typical ISX-B edge parameters as inferred from surface probe and laser-induced fluorescence measurements. The data are for non-gettered, ohmic plasmas with $\bar{n}_e \approx 4 \times 10^{13}/\text{cm}^3$ and $I_p \approx 150$ kA.

2 cm outside limiter radius

Ion density	$2 \times 10^{12}/\text{cm}^3$	ref. 4
Ion temperature	20 eV, Maxwellian	ref. 4
Circulating ion flux	$2 \times 10^{18}/\text{cm}^2\text{-s}$	ref. 4
Circulating impurity fluxes:		
Oxygen	$2\text{-}5 \times 10^{16}/\text{cm}^2\text{-s}$	ref. 1,2
Iron	$2\text{-}5 \times 10^{15}/\text{cm}^2\text{-s}$	ref. 1,2
Carbon	$2 \times 10^{15}/\text{cm}^2\text{-s}$	ref. 1
Titanium (with TiC limiter)	$4 \times 10^{14}/\text{cm}^2\text{-s}$	ref. 2
Flux scrapeoff length:		
Hydrogen and Iron	2 cm	ref. 1
Iron impurity density:		
Neutral	$10^7\text{-}10^8/\text{cm}^3$	ref. 9,10
Total (for E = 25 eV)	$5 \times 10^9/\text{cm}^3$	ref. 1
Surface erosion rate	$2 \times 10^{15}/\text{cm}^2\text{-s}$	ref. 3

At outer wall position (away from limiter)

Neutral hydrogen impact	$2 \times 10^{16}/\text{cm}^2\text{-s}$	ref. 4
Mean neutral energy	30 eV (with high E tail)	ref. 4
Iron impurity deposition	$<10^{12}/\text{cm}^2\text{-s}$	ref. 4
Surface erosion rate	$<10^{14}/\text{cm}^2\text{-s}$	ref. 3

Table II. Typical EBT-S edge parameters as inferred from surface probe and laser-induced fluorescence measurements. The data are for plasma operation at $\sim 5 \times 10^{-6}$ Torr and 100 kW.

5 cm from outer cavity wall (center midplane)

Electron density	$1 \times 10^{11}/\text{cm}^3$	ref. 12
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Neutral aluminum:

Sputtered flux (from wall)	$3 \times 10^{13}/\text{cm}^2\text{-s}$	ref. 12
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Mean inward velocity	$3 \times 10^5 \text{ cm/s}$	ref. 12
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Ionization length	14 cm	ref. 12
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1.5 cm from outer cavity wall (center midplane)

Ion density	$10^{11}/\text{cm}^3$	ref. 6
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Ion temperature	20 eV, Maxwellian	ref. 6
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Circulating ion flux	$10^{17}/\text{cm}^2\text{-s}$	ref. 6
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At outer cavity wall (center midplane)

Aluminum deposition	$3 \times 10^{13}/\text{cm}^2\text{-s}$	ref. 8
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Aluminum erosion	$4 \times 10^{13}/\text{cm}^2\text{-s}$	ref. 8,12
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Figure Captions

- Fig. 1. Time-resolved impurity deposition along field lines 2 cm outside the limiter radius in ISX-B. These data are for non-gettered discharges with a TiC outer limiter and 1.1 MW of neutral injection at 80-180 ms.
- Fig. 2. Deuterium retained on silicon samples located in front of (x) and behind (o, □) a 6.7 mm aperture facing field lines 1.5 cm from an outer cavity wall of EBT-S.
- Fig. 3. Velocity distribution of neutral aluminum 5 cm from an outer cavity wall in EBT-S. Negative velocities correspond to transport away from the wall.

TIME-RESOLVED IMPURITY DEPOSITION - ISX-B
1.1 MW NBI

FIG. 1

FIG. 3