Time-Dependent Measurements of Metal Impurity Densities in a Tokamak Discharge by Use of Laser-Induced Fluorescence

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(Received 2 May 1980; revised manuscript received 16 January 1981)

Measured Fe I densities in the edge region of the impurity study experiment (ISX-*B*) tokamak in Ohmic and neutral-beam–heated discharges are consistent with calculated densities, if one assumes that sputtering of the stainless-steel walls by charge-exchange neutrals is the dominant production mechanism. Fe I and Ti I densities observed during plasma shift experiments indicate that the limiters play only a minor role in impurity production in D_2 discharges. This also suggests that most metals are sputtered from the walls.

PACS numbers: 52.70.Kz, 52.25.Ps

Heavy metal impurities can play an important role in the power balance of large tokamaks. They can alter the energy confinement time, current profile, and local power balance because of their intense line radiation. It has been predicted that fractional concentrations of metals (e.g., tungsten) as low as 0.01% will prevent ignition of a tokamak reactor.[1] Accordingly, understanding and controlling impurities is of crucial importance for the development of a tokamak fusion reactor.

Using the technique of laser fluorescence spectroscopy we have recently reported the first direct measurements[2-4] of Fe I, Fe II, Ti I, and Ni I in a tokamak. In this Letter we show that sputtering of the stainless-steel walls by charge-exchange neutrals appears to be the dominant metal-impurity production mechanism in the impurity study experiment tokamak (ISX-*B*). This represents the first clear-cut evidence of significant impurity generation by this mechanism in a tokamak.

As is illustrated in Fig. 1, the experimental arrangement consists of a pulsed-laser system,[5] coaxial fluorescence-detection optics,[6] and computer-controlled data acquisition and timing electronics. The optogalvanic effect[7] is used to adjust the laser wavelength to the resonance transition to be excited. Variations in the laser output power are monitored with a photocell. The laser beam travels horizontally about 5 m to the ISX-*B* vacuum vessel. Once inside the vessel, it is deflected onto a vertical path which passes through the 27-cm–minor-radius plasma on a line which is 1 cm inside the nominal plasma edge at the machine midplane.

The laser and optical system were calibrated absolutely for Fe I prior to the ISX-*B* measurements by use of an Ohmically heated effusive oven.[8] Rayleigh scattering from N_2 was used as a transfer standard to check the detection sensitivity before and after the optics were installed on ISX-*B*. Consequently, considering uncertainties in the calibration procedure and in Rayleigh scattering, we estimate that measured iron densities in ISX-*B* are in error by less than 50%. Titanium densities are deduced from the observation geometry, detector efficiency, and transition probabilities, and may be in error by a factor of 2.

The relative importance of the limiters and stainless-steel (SS) vacuum walls as sources of Fe (the dominant metal impurity in ISX-*B*) has been determined by comparing edge-region Fe I and Ti I densities and behaviors in several series of Ohmically heated discharges with either a titanium carbide (TiC) or a SS outer limiter and a SS inner limiter. Comparisons are made dur-

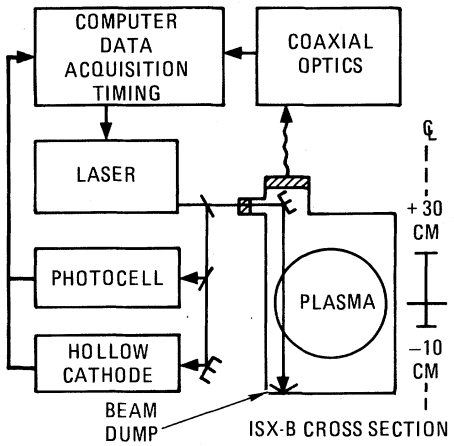

FIG. 1. Schematic diagram of the ISX-*B* laser-induced fluorescence experiment. The detected volume element is about 3 cm long and 3 mm in diameter. Different vertical sections of the discharge (−10 to +30 cm relative to the machine midplane) can be viewed by translating the optics.

TABLE I. Plasma conditions.

Case	Toroidal field (T)	Plasma current (kA)	$\bar{n}_e$ (10^{13} cm^{-3})	One-turn voltage (V)	Z_{eff}	Working gas	Discharge length (ms)	Outer limiter
A	1.31	140	3.3	1.3	3.1	D_2	130	SS
B	1.35	106	3.8	1.4	3.7	D_2	150	TiC
C	1.31	120	3.0	1.5	4.0	H_2	160	SS
D,*E*	1.31	150	3.2	1.3	2.8	D_2	130	TiC
F	1.15	150	4.0	0.5	2.4	D_2	180	SS

ing the stable, reproducible portion of the discharges, 25 ms $\lesssim t \lesssim$ 125 ms. The main limiters are separated toroidally by 120° from the fluorescence observation volume. Plasma conditions[9] are summarized in Table I.

Since Ti gettering had never been used in ISX-*B*, the only source of Ti was the outer TiC limiter. Thus, the behavior observed for Ti should also be observed for other metals which come only from the limiters. Experimentally, we see substantial increases in [Ti I] when the plasma is shifted horizontally at 60 ms, from its nominal center position to a position just 1.5 cm closer to the TiC limiter [see Fig. 2(b), cases *D* and *E*].

An entirely different behavior is observed for [Fe I] in a similar shift experiment as shown in Fig. 2(a). Iron densities are symmetric about the plasma horizontal center position and, relative to [Ti I], they are weakly dependent on the amount of plasma shift. Note in Fig. 2(a) that the inner and outer limiters are different and the total plasma shift is 9.5 cm. In addition, for unshifted discharges iron densities remained approximately unchanged when the TiC outer limiter was replaced by a SS limiter [see Fig. 2(b), cases *A* and *B*]. Because the iron densities we measure do not depend significantly on the degree of interaction between the plasma and the limiters or on the limiter material, we conclude that the limiters are not responsible for our signals in standard unshifted D_2 discharges. Thus, most of the edge-region impurities we measure are due to interactions with the wall.

Spectroscopic measurements of Fe XVI and Ti XI in the bulk plasma[10] for similar shift experiments are consistent with our edge-region results. This indicates that impurity behavior in the bulk plasma closely follows the edge-region impurity behavior that we observe. Consequently, iron impurities in the bulk plasma are also quite probably due to interactions with the walls.

Thermal evaporation of wall material and arcing at the walls are unlikely mechanisms for impurity generation during most ISX-*B* discharges. Wall temperatures[9] are low and arcing has been observed[11] only at the initial or end phases of well-behaved discharges. Thus, ion- and neutral-particle sputtering at the walls are more likely production mechanisms.[12]

If sputtering of the SS walls by charge-exchange hydrogen or deuterium neutrals dominates ion sputtering, then the resulting edge-region neutral iron[13] density is given approximately by

$$[\mathrm{Fe\,I}] = 0.7(1/V)\textstyle\sum_E \Gamma(E)S(E), \qquad (1)$$

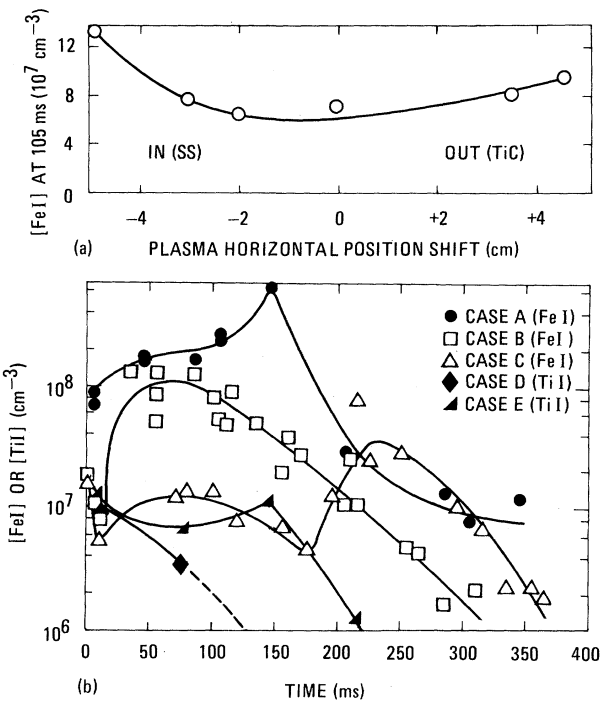

FIG. 2. (a) Measured [Fe I] at 105 ms vs the plasma horizontal position shift in a D_2 Ohmically heated discharge. The plasma nominal center position is at 0 cm. (b) Measured [Fe I] (plasma centered) and [Ti I] (plasma centered for case *D* and plasma out 1.5 cm for case *E*) vs time. Densities in the afterglow ($t \gtrsim 150$ ms) depend on when (or if) plasma position control is lost.

where the factor 0.7 accounts for the fractional iron concentration in stainless steel type 304, V is the most probable velocity[14] of sputtered iron, E is the incident neutral energy, $S(E)$ is the sputtering yield[15] of nonoxidized SS, and $\Gamma(E)$ is the charge-exchange neutral flux to the walls. The differential charge-exchange neutral flux, $d\Gamma/dE\,d\Omega$, was measured[16] 20° toroidally from the fluorescence excitation volume and is assumed to be toroidally symmetric over this small angle. Furthermore, the angular dependences which are inherent in Eq. (1) have been approximated by assuming a $\cos\theta$ distribution, where θ is the angle from the plasma surface normal, for the differential charge-exchange neutral outflux, and by equating $S(E)$ with twice the normal incident sputtering yield of SS to account for the increased sputtering efficiency[14] with angle of incidence.

We have evaluated Eq. (1) by summing[17] E from 0.2 to 2 keV for Ohmically heated hydrogen and deuterium discharges (Fig. 2) and for a neutral-beam–heated deuterium discharge (Fig. 3). In Table II we show the remarkably good agreement between measured and calculated iron densities for these three series of discharges which have widely varying plasma parameters. These results strongly suggest that sputtering by charge-exchange neutrals is the dominant metal-impurity production mechanism in ISX-B in D_2 discharges. If we assume poloidal and toroidal symmetry, the flux of iron produced by this mechanism is more than enough to account for all the iron in the discharge.[10]

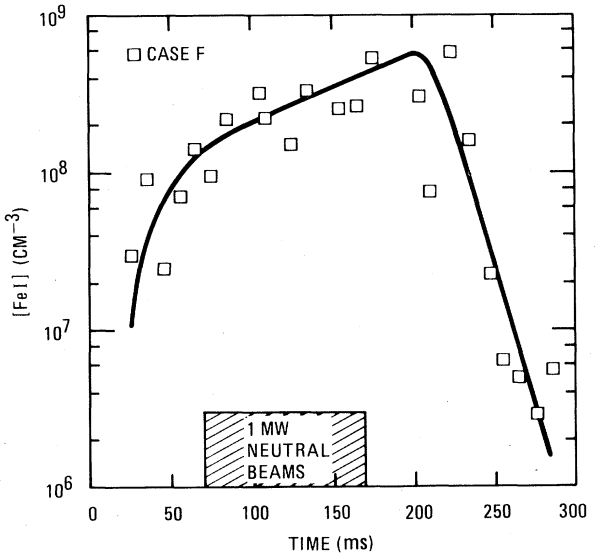

FIG. 3. Measured [Fe I] vs time for a series of neutral-beam–heated discharges with the plasma positioned at nominal center.

We have three reasons for believing that sputtering by hydrogen ions or impurity ions is not the dominant metal-impurity production mechanism. First, if impurity-ion sputtering were dominant, then we would expect the metallic-impurity production rate to correlate with $Z_{\rm eff}$, which is a measure of the total impurity content (mostly oxygen) in the discharge. Thus, we would expect similar edge iron densities for discharges with equal $Z_{\rm eff}$. However, this is not observed for Ohmically heated hydrogen and deuterium discharges (see Tables I and II, cases B and C). Significantly less iron is measured in the hydrogen discharge even though $Z_{\rm eff}$ is slightly greater. Second, the good agreement shown in Table II between neutral-sputtering calculations and experimental results leaves little need to invoke other processes. In particular, sputtering by hydrogen and deuterium neutrals can account for the differences seen in cases B and C in Table II. Third, the sheath potential V_s, inferred from measured[18] edge-region electron temperatures T_e, under the assumption[14] that $V_s = 3T_e$, is too low (< 30 eV) for efficient sputtering[15] by hydrogen or deuterium ions.

Other fluorescence measurements[19] have been made on ISX-B. However, the authors suggest that they were unable to measure densities during the main discharge because of ionization of the neutral iron. Consequently, we cannot directly compare our data with theirs.

In conclusion, we have shown that sputtering of the vacuum walls by charge-exchange neutrals appears to be the dominant metal-impurity production mechanism in D_2 discharges in ISX-B and that the limiters play only a minor role.

We would like to thank S. D. Scott and G. H. Neilson for their charge-exchange neutral flux data and C. E. Bush, R. C. Isler, M. Murakami, J. B. Roberto, R. A. Zuhr, and W. P. West for many helpful discussions. This work depended on the efforts of the entire ISX-B operations

TABLE II. Edge-region [Fe I], cm^{-3}, assuming charge-exchange neutral sputtering.

Case	Discharge	Time (ms)	Measured	Calculated
C	Ohmic H_2	75	1.4×10^7	1.4×10^7
B	Ohmic D_2	75	1.0×10^8	6.0×10^7
F	Beam D_2	150	4.0×10^8	5.6×10^8

crew for its successful conclusion. The work was supported by the U. S. Department of Energy under Contract No. De-AT03-76ET51011.

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Impurity Sources and Accumulation in Ohmically Heated ISX-*B* Discharges

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Spectroscopic observations on the ISX-*B* (impurity study experiment) tokamak indicate that most of the metallic impurities come from the wall in Ohmically heated discharges in which the plasma is kept centered in the vacuum chamber. These impurities appear to accumulate during the quasi-steady-state part of the discharge if the working gas is deuterium but not if it is hydrogen.

PACS numbers: 52.25.Fi, 52.40.Hf

One of the most severe problems in designing a power-producing fusion device is predicting the concentrations of impurities and the influence they may exert on plasma behavior in the absence of a perfect divertor. A first step towards dealing with these problems requires assessments of impurity sources and production mechanisms in presently operating machines. Initial attempts to carry out such a program on the ISX-*B* (impurity study experiment) tokamak ($R = 4$ cm, $a = 27$ cm) have been made by correlating spectral observations of iron and titanium in Ohmically heated discharges with laser fluorescence measurements of these elements in the shadow of the limiter.[1] The main results during the quasi-steady-state part of the discharge (after the breakdown and the current rise) are (1) the wall, rather than the limiters, is the principal source of metallic impurities when the plasma is centered in the vacuum chamber; (2) sputtering by neutral atoms is the most probable production mechanism; (3) the fluxes of the metals in the plasma are consistent with those in the shadow of the limiter if the efficiency of the scrape-off layer is taken into account; and (4) impurities tend to accumulate in the center of deuterium discharges but do not accumulate in the center of hydrogen discharges. In this paper we describe the spectroscopic observations.

It is useful to discuss first the differences between impurity transport in hydrogen and in deuterium in order to establish a background for in-

