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Perturbation of tokamak edge plasma by laser blow-off impurity injection[a)]

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We describe measurements of tokamak edge plasma perturbations caused by rapid injection of impurities such as Sc, Fe, and Mo into Ohmically heated PLT discharges. The temporal evolution of the radiated power, convected power, charge-exchange neutral flux, electron temperature, density, and floating potentials were monitored using recently developed fast bolometers, directional calorimeters, and other diagnostics. The central radiated power can be doubled without plasma disruptions. Radiation from the edge then increases tenfold for ~2 ms. Neutral efflux at the limiter decreases up to two orders of magnitude for approximately 20 ms after injection. The electrical potential of the limiters increases, approaching the potential of the vacuum vessel. MHD activity in the $m = 1$ (sawtooth) mode tends to increase while that in the $m = 2$ and $m = 3$ modes decreases. The power flowing along field lines in the limiter shadow region sometimes increases or sometimes decreases by more than a factor of 4. The density and electron temperature in the limiter shadow region, generally, does not change more than 50%.

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I. INTRODUCTION

One technique for injecting impurities into tokamak plasmas is to use a laser to ablate material from a surface near the plasma.[1] This technique, called laser blow-off (LBO) impurity injection, has the feature of injecting controlled amounts of impurities from a localized source in very brief pulses. It has been used as a diagnostic for transport studies,[1,2] for ion temperature determination,[3] for plasma rotation measurement,[4] for spectral line identification,[5] and for detecting impurities residing on walls.[6]

The LBO technique probably will lend itself to additional applications in controlled fusion research. One possibility is in plasma control. LBO injection can change the MHD activity of the plasma. For instance, it may be possible to alter dangerous MHD activity (such as activity which will evolve to a major disruption), to a more benign activity using LBO injection. Also, LBO injection can increase radiative cooling from the bulk plasma and reduce charge-exchange flux near limiters. Thus LBO injection may be useful for reducing loading and erosion of the first walls and limiters during disruptions.

This paper concentrates on changes in the plasma edge caused by LBO injection. In Sec. II we discuss diagnostics used to study effects of LBO injection. In Sec. III we present observations for a PLT shot. In Sec. IV we give generalizations, and in Sec. V we give interpretations and conclusions.

II. DIAGNOSTICS USED FOR LBO STUDIES

LBO injection is performed almost routinely in PLT and PDX. To date, there is a data base of approximately 6000 PLT and 1000 PDX shots where LBO injection occurred. This paper concentrates on several runs in PLT, with Ohmic heating only, where a wide variety of edge diagnostics were manned. The diagnostics used included the standard ones providing global information such as the loop voltage, plasma current, and line-integrated electron density, as well as various local diagnostics described below.

The LBO injector is located at the midplane. Photographs and movies of the impurities entering the plasma were made from a port at a toroidal angle of $-60°$ (counter-clockwise) from the injector. Results are reported in these conference proceedings.[7]

The primary limiters were top and bottom mushroom limiters at $+60°$ (clockwise) from the impurity injector. They were positioned at a minor radius of 40 cm, and were electrically connected to the vacuum vessel through 10 Ω resistors. Their potentials were monitored. A low energy neutral spectrometer with a rapid time resolution (~0.25 ms) was used to detect neutral deuterium efflux from the plasma near these limiters.[8,9]

A calorimeter with a slow response time (20 ms) located at $-120°$ measured energy flux in the edge flowing through a narrow aperture.[10] A Langmuir probe at $+120°$ measured n_e and T_e in the edge.[11] A fast pyroelectric power detector with a $LiTaO_3$ element and a 0.1 ms response time, and a slower bolometer array with a 20 ms response time were located close to the Langmuir probe. These bolometers viewed chords in a vertical plane. A survey spectrometer, located at $+160°$, scanned wavelengths between approximately 100 and 1100 Å at 20 ms intervals.

III. IMPURITY INJECTION EFFECTS

A number of impurity injection effects have been reported and correlated with the quantity injected.[12] These include an increase in $\bar{n}_e, V_L$, and radiated power, and a decrease in plasma current. Figure 1(a) shows the variation of the radiated power and the intensity of a Sc line caused by ablating a varying amount of Sc. The T_e profile determined by Thomson scattering has been observed to become more peaked

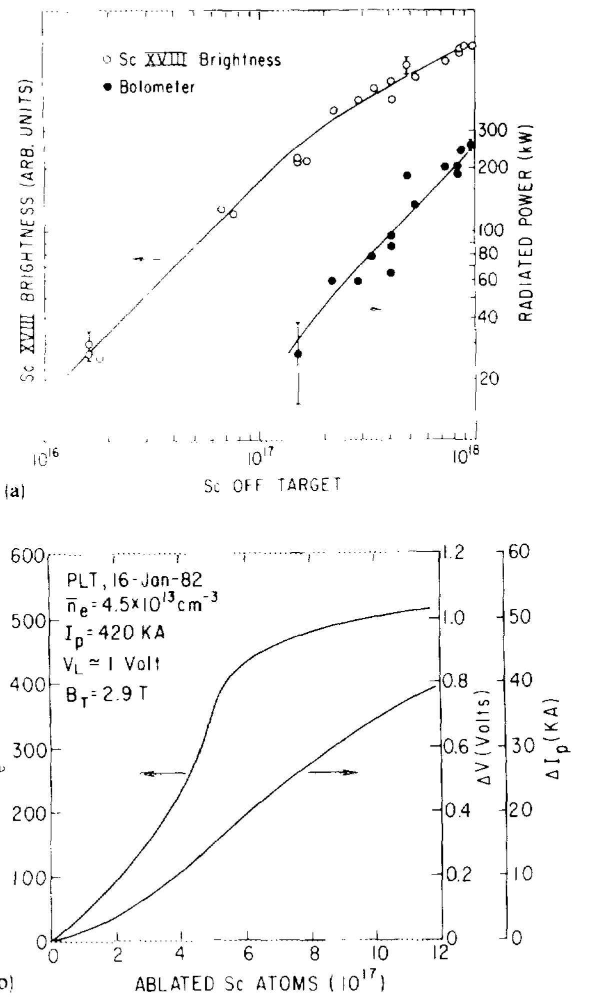

FIG. 1. Variations of plasma parameters caused by ablating varying amounts of Sc with LBO: (a) changes in the radiated power and the brightness of Sc XVIII; (b) changes in the central electron temperature, loop voltage, and plasma current.

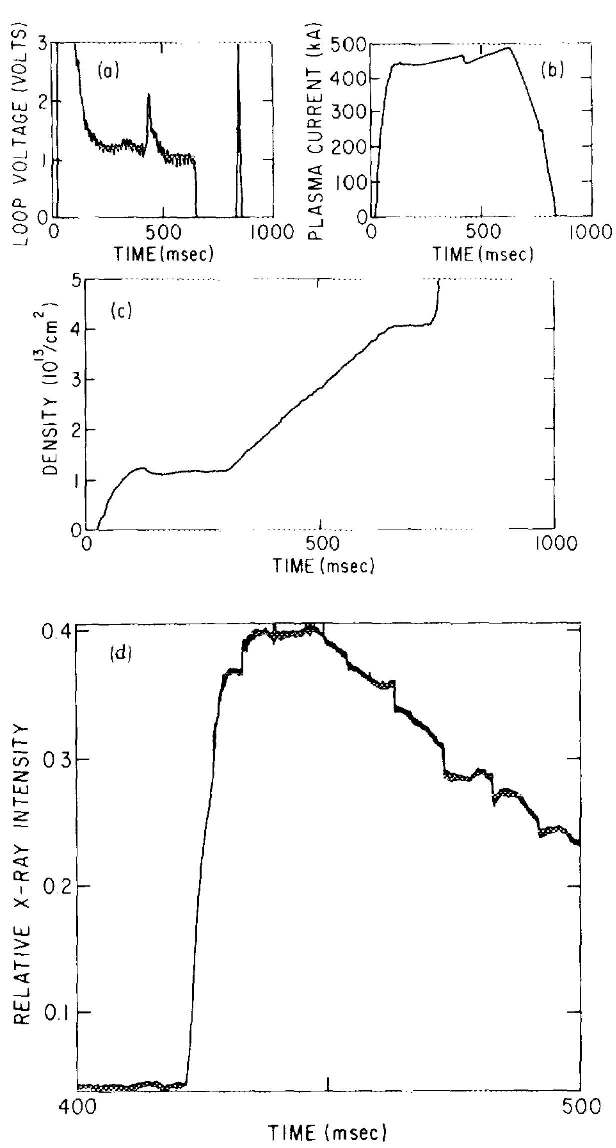

FIG. 2. Global plasma conditions for a PLT discharge with Fe injection: (a) toroidal loop voltage; (b) plasma current; (c) line average electron density; (d) central soft x-ray signal.

initially, though the central temperature later falls several hundred eV due to the increased radiation losses. Figure 1(b) shows the variation of the central electron temperature, loop voltage, and plasma current.

Global plasma conditions for a deuterium discharge with iron injection are shown in Fig. 2. A relatively large amount (1.2×10^{18} atoms) of Fe was ablated from the target at 420 ms. The loop voltage increased from 1.2 to 2.1 V, the plasma current decreased by 22 kA, and the diamagnetic loop voltage decreased by 10%. The soft x-ray signal from the central region increased by an order of magnitude and exhibits sawteeth after injection.

Local observations of impurity injection effects for the same shot are shown in Figs. 3–5. The potential of the top limiter, shown in Fig. 3(a), increased (becoming less negative relative to the vacuum vessel) immediately after impurity injection. The potential of the bottom limiter did not change noticeably. The flux and power of neutral deuterium from the plasma near the limiter (mainly due to charge exchange) decreased during injection as shown in Figs. 3(b) and 3(c).

The pyroelectric detector observed a rapid increase followed by a slower decrease in the radiated power shown in Fig. 4(a). The slow bolometer array results in Figs. 4(b) and 4(c) observed the total radiated power to increase from 120 kW prior to a peak of 360 kW after injection, assuming it is toroidally symmetric. Thus the amount of the Ohmic power input which was radiated increased from 22% to 39%. The increased radiation comes mainly from the central plasma, not from the edge. Spectra from the survey spectrometer are shown in Fig. 4(d). It observed a large increase in iron line radiation and background radiation in the 100–400 Å region, 20 ms after injection, but not a large change in the characteristic lines of intrinsic impurities such as oxygen and carbon.

The calorimeter measured energy flow in the direction of the "ion current" at a minor radius of 41.2 cm. Its thermocouple voltage shown in Fig. 5(a) started to decrease 10 ms after injection, indicating the power decreased to approxi-

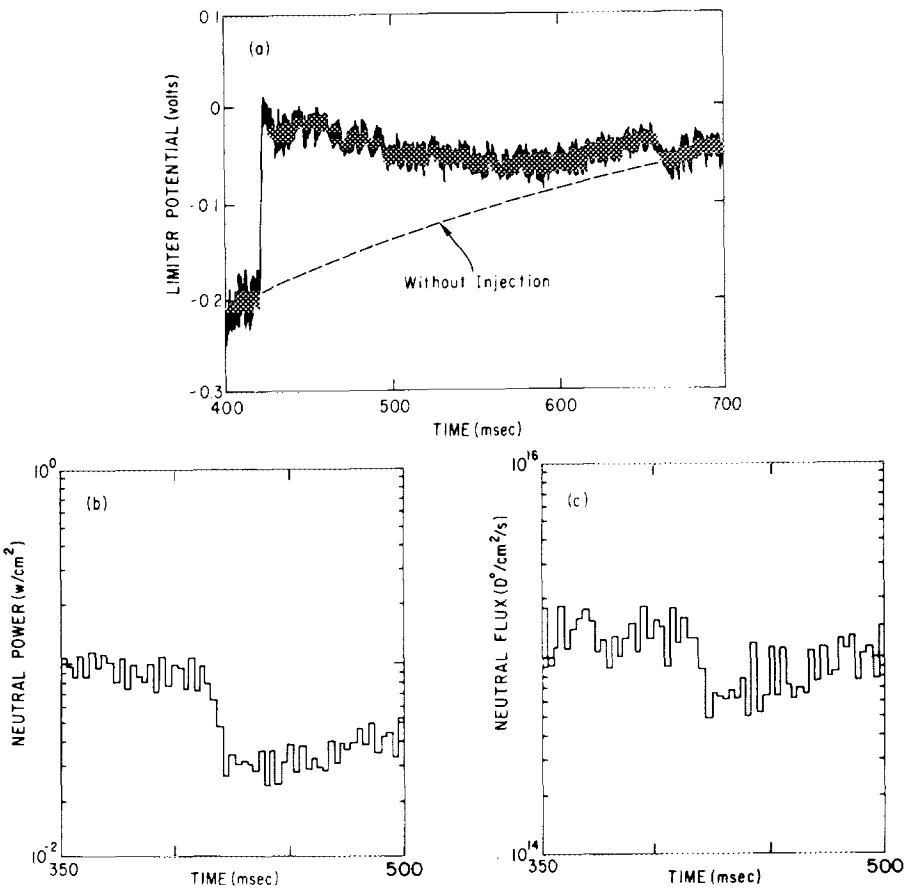

FIG. 3. Plasma conditions near the limiter for the discharge shown in Fig. 2: (a) top limiter potential; (b) low energy neutral deuterium power; (c) low energy neutral deuterium flux.

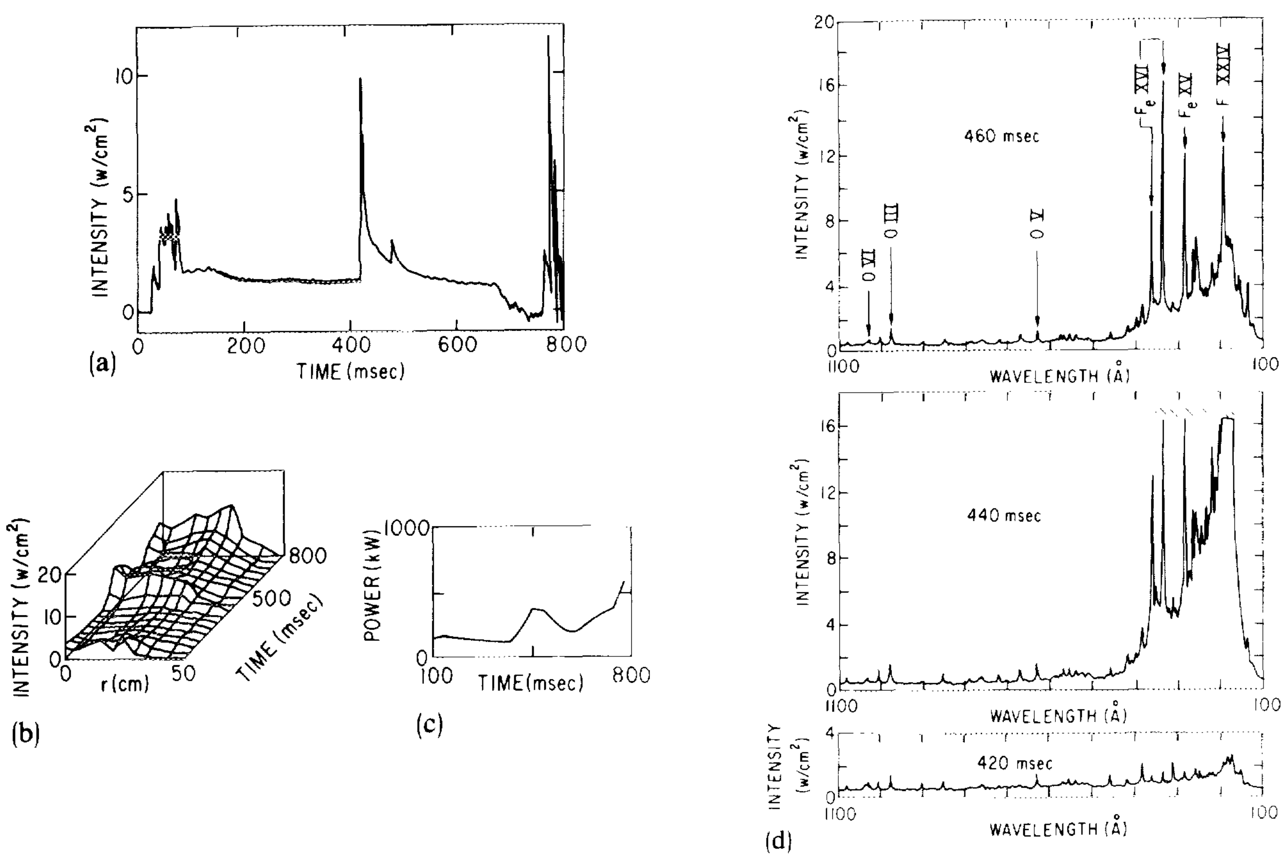

FIG. 4. Radiation from the discharge shown in Fig. 2: (a) power radiated from the region $h = a/2 = 20$ cm below the midplane as measured by the pyroelectric detector; (b) power radiated from the top half of the plasma vs time and minor radius as measured by the bolometer array; (c) total power radiated from the top half of the plasma as measured by the bolometer array; (d) spectral scans at injection and 20 and 40 ms after injection.

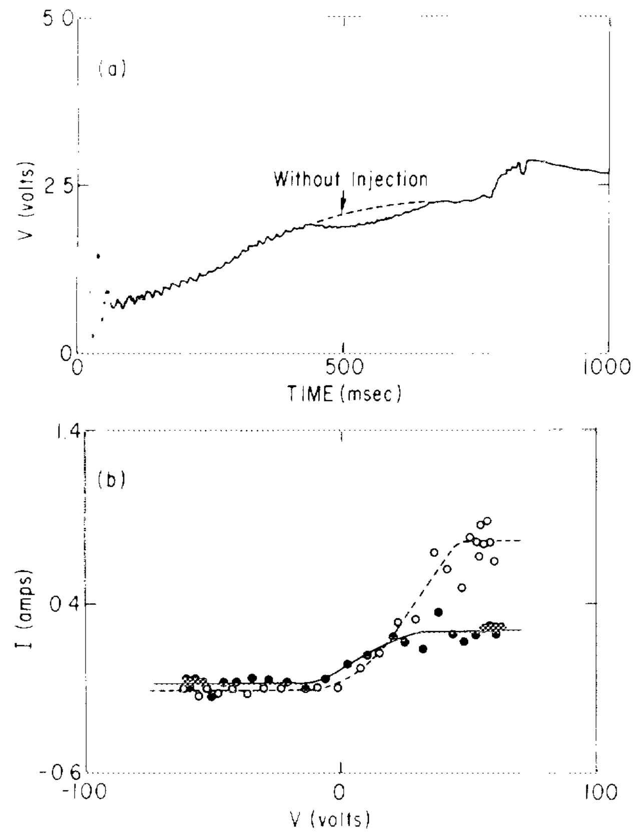

FIG. 5. Plasma conditions in the limiter shadow for the discharge shown in Fig. 2: (a) calorimeter voltage. The power dropped approximately 140 to 0 W/cm^2. (b) Langmuir probe current–voltage characteristics at 320–333 ms (○) and 420–433 ms (●). Between these intervals, N_e dropped 40%, T_e dropped from 7 to 4 eV, and T_i remained around 25 eV.

mately zero at injection, and remained there for more than 50 ms.

The current–voltage characteristics shown in Fig. 5(b), observed by the single-tip Langmuir probe at a minor radius of 43.5 cm, indicate that the electron density decreased and the electron temperature decreased during injection compared to 100 ms before and 100 ms after injection.

IV. GENERAL OBSERVATIONS

The specific observations in the previous section for large amounts of impurity injection generalize as follows: The increase in loop voltage and central soft x-ray emission, and the decrease in plasma current, are always seen.

The MHD activity in the $m = 1$ (sawtooth) mode generally increases, while the $m = 2$ and $m = 3$ modes decrease in intensity. The limiter potentials generally increase towards the vacuum vessel potential. The neutral hydrogen efflux near the limiters decrease, and the average energy decreases. These decreases occur within 1 ms of injection. The fast bolometer observes a very rapid increase as well, typically observing peak radiation of several W/cm^2. The amount of time these signals remain perturbed is comparable for each detector, and varies from 10–150 ms from shot to shot. The fast bolometer scanned across the vertical plane from shot to shot, and observed that the injection-induced emission peaked around $r \sim 20$ cm.

All the changes discussed above tend to be largest for Fe injection, intermediate for Mo injection, and smallest for Sc injection. Sometimes the injection causes disruptions to occur soon after. This is more likely when the amount ablated exceeds 10^{18} atoms.

In the limiter shadow region, the calorimeter sometimes observes transient increases of power (up to 100% increases lasting 50 ms), transient reductions of power (dropping to approximately zero, lasting 200 ms), and sometimes no change. The Langmuir probe observes electron density and temperature changes of up to 50%. The region it effectively probes ($r \gtrsim 43$ cm) does not include the entire radial region scanned by the calorimeter ($r \gtrsim 39$ cm).

V. INTERPRETATIONS AND CONCLUSIONS

The absolute amount of radiation observed by the pyroelectric detector agrees with the predicted value for low charge states within a factor of 2–3. Similarly, that radiated from the plasma core agrees with a factor of 2–3 predicted for the high charge states.

The relaxation of the limiter potential towards the vacuum vessel potential could be caused either by an increase in the space potential (as highly stripped ions accumulate) or by a cooling of the edge, which reduce the sheath potential. Edge cooling could also explain the decrease in the energy of the neutrals observed by the low energy spectrometer. The edge deuterium density, and therefore, flux to the limiters, probably decreases as well, resulting in a reduction of neutral production at the limiter. This would explain the reduction of the neutral flux observed by the low energy spectrometer. Impurity ions in the edge could displace the deuterium without altering the electron density.

We conclude that LBO injection can modify the edge plasma, and can result in temporary reduction of wall and limiter loading due to convection and charge-exchange neutrals.

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