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LANGMUIR PROBE MEASUREMENTS OF THE
SCRAPE-OFF PLASMA IN ISX-A

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ABSTRACT

A fixed double Langmuir probe was used to investigate the temporal behavior of the scrape-off plasma in the ISX-A tokamak. During gas puffing, the ion saturation current dropped rapidly to a very low level while the line average density showed a steady increase. This sudden transition was due mainly to a density change of more than a factor of five while the electron temperature remained relatively constant at ~ 10 eV. This behavior was easily observed at points away from the limiter with mild and moderate gas puffing rates, and near the inner edge of the limiter with strong gas puffing. In order to explain the phenomenon, it is suggested that there may be two distinct layers in the scrape-off plasma and that the boundary between the layers moves inward toward the limiter. The existence of the boundary has been confirmed indirectly by sudden shifts of the plasma during feedback control experiments.

The scrape-off plasma formed by the limiter in tokamaks is very important in connection with impurity production and transport, power balance, pellet fueling, and possible influence on stability. Gas puffing [1] has been used widely to obtain improved plasma parameters in tokamaks. We report observations, in the ISX-A tokamak using a double Langmuir probe, showing that two steady states exist at positions behind the limiter during the tokamak discharge with gas puffing. These states are characterized by a density difference of more than a factor of five; in addition, the transition is from the higher to the lower density state in time, opposite to the trend of the line average density of the plasma column. Furthermore, the transition is often observed in advance of the major disruptions by 10-20 ms. The density change, confirmed by a sudden shift of the plasma column during the feedback control experiments, suggests that the transition in time may be caused by a boundary layer moving inward toward the limiter during gas puffing.

The ISX-A tokamak has the following machine parameters: major radius $R = 92$ cm, minor radius $a = 26$ cm, maximum toroidal magnetic field $B_T = 18$ kG. The double Langmuir probe is located $\sim 80^\circ$ away from the stainless steel limiter toroidally and 0.64 cm from the inner edge of the top limiter at the major radius in the shadow of the limiter. It is oriented perpendicular to the toroidal magnetic field and constructed with identical nickel tips which are separated by 1.1 cm. Each tip has a surface area of 0.08 cm^2 . Probe currents are determined by the voltage across a 1-k Ω resistor shunted by a 1- μ F capacitor. Various bias potentials are applied between the probes by dc sources. In order to obtain a characteristic curve, a sequence of reproducible tokamak

discharges is required. Normally a stainless steel limiter fixes the plasma radius at 26 cm; however, in the measurements reported here, a carbon limiter was also used to fix the plasma radius at 25.6 cm and at 23.8 cm.

Figures 1(a) and (b) show the typical behavior of the line average electron density $\bar{n}_e$, the envelope of the poloidal magnetic field fluctuations $\tilde{B}_\phi$ (MHD), the total plasma current I , and the loop voltage V around the torus. We have noted that MHD fluctuations are large in the initial period of gas puffing but that they are always at a very low level for the period of steady increase in $\bar{n}_e$. In this shot, the toroidal magnetic field was fixed at $B_T = 12.7$ kG; gas puffing starts at 20 ms and has a duration of 130 ms at the rate of 17.5 torr-liter/s. Since the carbon limiter was placed 2.54 cm inside the stainless steel limiter, the Langmuir probes were located 3.2 cm behind the edge of the carbon limiter. Figure 1(c) shows typical probe current and bias potential. These traces were triggered 4 ms before the discharge. The variation of the upper trace, the bias potential between the terminals of the dc source, is due to its internal resistance. The ion saturation current, shown in the lower trace, starts to increase at 40 ms in a manner similar to $\bar{n}_e$ in Fig. 1(a), maintains the same level from 45-80 ms, and then drops to a low level, which is maintained from 100-170 ms. Between 50 and 170 ms of the discharge, the line average density is the only parameter changing considerably in time, and the movement of the plasma column is no larger than 0.5 cm.

A set of data has been obtained during the sequence of the discharges in which macroscopic plasma parameters were highly reproducible. The

I-V characteristic curve of the double Langmuir probe [2] was obtained and the results are shown in Fig. 1(d). In this analysis, it has been assumed that the electron density is equal to the ion density. At 40 ms into the discharge, the density and temperature are $n_e \cong 3 \times 10^{11} \text{ cm}^{-3}$, $T_e \cong 30 \text{ eV}$; then gas puffing effects start to appear as the edge cools and density increases. The temperature and density rise to and maintain steady-state values of $n_e \cong 1.5 \times 10^{12} \text{ cm}^{-3}$, $T_e \cong 9 \text{ eV}$, respectively, for 45-80 ms; then the density decreases to $n_e \cong 2.5 \times 10^{11} \text{ cm}^{-3}$ while the temperature remains at the same level. The same density behavior has been observed when the probes are positioned at 1.4 cm behind the carbon limiter with constant gas feed and additional gas puffing of 4.3 torr-liter/s.

Figures 2(a)-(d) show the cases in which the probes are located 0.64 cm behind the edge of the stainless steel limiter. In this sequence, gas puffing starts at 20 ms and lasts for 150 ms at the rate of 70.3 torr-liter/s. The line average density in Fig. 2(a) starts to rise at 30 ms; $\tilde{B}_\phi$, I, and V have the same behavior in time as the previous sequence. The hydrogen Balmer α line (6563 Å) shown in Fig. 2(b) indicates that the population of neutral hydrogen atoms in the excited state ($n = 3$) decreases in the chamber while $\bar{n}_e$ increases monotonically. The ion saturation current in Fig. 2(c) shows more fluctuations than Fig. 1(c) and an intermediate step appears between 60 and 90 ms in the discharge. About half of the shots in this sequence show clear steps and the rest show a smoothly decreasing pattern in this period. However, all the shots show sharp decreases at ~ 110 ms, and this lower level is maintained with fluctuations. This fluctuation pattern possibly may be explained

by small movements of the plasma column on the order of 0.5 cm. It is observed because the probes are near the limiter edge. Once again, we have observed the same behavior of the density and temperature in time at this position.

On the other hand, with moderate gas puffing, namely 25.2 torr-liter/s, the ion saturation current behavior is not the same as the previous cases at 0.64 cm. The plasma parameters in time shown in Figs. 3(a) and (b) are similar to those in Figs. 1(a) and (b). The ion saturation current in Fig. 3(c) does not show a major drop in the 100-110 ms period. The low level around 180 ms cannot be interpreted as a corresponding phenomenon since the end of the discharge occurs at that time. Therefore, we may conclude that there is no sudden drop of ion saturation current near the edge of the limiter with moderate gas puffing. Figure 3(d) shows the electron density and temperature in the sequence.

Figures 4(a)-(d) show the ion saturation currents in various cases. For all these cases the probes are located 0.64 cm behind the stainless steel limiter. Figure 4(a) shows a shot without gas puffing in which the line average density is in a steady state. In Fig. 4(b), gas is fed constantly and gas puffing starts at 30 ms and lasts for 140 ms at a rate of 15.2 torr-liter/s. The gas puffing rate is programmed to drop gradually to zero at the end of the period. This discharge shows a major disruption at 120 ms. There is a sudden drop in the saturation current before the disruption at 90-110 ms. None of the other diagnostics shows any precursor of this disruption. This may indicate that the major disruption is associated with change in the outer edge profile of the density and temperature and suggests that gas puffing control based on edge density measurements may help to avoid disruptions.

Because the probes are fixed in space, the shift of the plasma column is an alternative way to investigate the profiles of density and temperature. Figures 4(c) and (d) show the ion saturation currents during feedback control experiments. In these cases, there is a constant gas feed and gas puffing starts at 25 ms and lasts for 130 ms at a rate of 11.8 torr-liter/s. In Fig. 4(c), the plasma column has been shifted down about 2.5 cm; thus the plasma sweeps inward past the probes. The decreased ion saturation current indicates low density and/or temperature. In Fig. 4(d), the plasma column is shifted up during 100-140 ms by about 1.7 cm. The increased ion saturation current indicates that hot and/or dense plasma has swept outward past the probes.

Recent observations in the TM-3 [3] and JFT-2 [4] tokamaks have shown that the density profile behind the limiter decreases by two orders of magnitude in a short distance compared to the minor radius. In these experiments, the probes were moved and the data were taken by a voltage sweeping circuit in a steady state without gas puffing. The temperatures were above 20 eV. On the other hand, the density profiles in PLT [5] were similar to those in TM-3 and JFT-2 and the temperature was apparently less than 10 eV with gas puffing. In the PLT experiments, the data were taken during the period in which the ion saturation current was in a steady state with low values while the line average density increased monotonically. Our observations in Figs. 4(c) and (d) are consistent with a narrower density profile even with gas puffing. Thus, sudden drops during gas puffing can be explained by the plasma sweeping inward past the probes. Possible mechanisms for the collective influx of charged particles are, at present, the Ware pinch [6] and the ion

mixing mode [7] theories. Even though our measurements do not directly prove either of these theories, all the phenomena could be well understood by some dynamical pinch effect.

In conclusion, the density and temperature near the limiter are not in steady state during gas puffing, and a sharply decreased density layer with cold temperature moves inward toward the limiter edge. The major disruptions in high density regime operation may be associated with this layer propagating into the main body of the tokamak plasma.

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FIGURE CAPTIONS

FIG. 1. Time behavior of plasma parameters with moderate gas puffing at 20 ms and with the carbon limiter: (a) the line average electron density $\bar{n}_e$ and the envelope of the poloidal magnetic field fluctuations $\tilde{B}_\phi$ (MHD); (b) the total plasma current I and the loop voltage V around the torus; (c) bias potential and current of the probes at 3.2 cm behind the limiter; and (d) the electron density and temperatures in a sequence of reproducible discharges.

FIG. 2. Time behavior of plasma parameters with strong gas puffing at 20 ms and with the stainless steel limiter; (a), (c), and (d) are the same as Fig. 1 and the Balmer α line is shown in (b).

FIG. 3. Time behavior of plasma parameters with moderate gas puffing at 20 ms and with the stainless steel limiter; (a)-(d) same as Fig. 1.

FIG. 4. Time behavior of probe current in various cases: (a) constant gas feed discharge; (b) disruptive discharge; (c) plasma column was shifted down about 2.5 cm at 110 ms; and (d) plasma column was shifted up about 1.7 cm during 100-140 ms.

Fig. 1.

Fig. 2

Fig. 3.

Fig. 4

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