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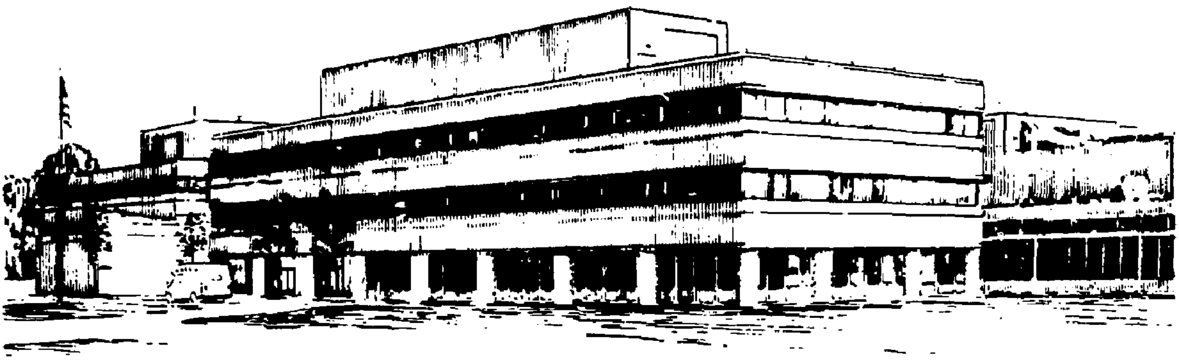

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Charge-Exchange Neutral Hydrogen Measurements in TFTR Using Pd-MOS Microsensors

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Abstract

An array of Pd-metal-oxide-semiconductor (Pd-MOS) diodes has been used to monitor the fluence and energy of charge-exchange neutral hydrogen isotopes striking the wall of the Tokamak Fusion Test Reactor (TFTR). The array was positioned 4 cm behind the graphite-tiled wall at the toroidal midplane and exposed to several hundred plasma discharges. Hydrogen isotopes striking the Pd-MOS diodes were detected by measuring the leakage current, which is affected by the presence of these species at the Pd/SiO_2 interface. It was found that the midplane flux strongly increased for neutral-beam heated plasmas and correlated with co-injected neutral beam power. The majority of the neutral flux was <50 eV in energy but its energy distribution extended to above 500 eV.

I. Introduction

There is ample evidence that plasma-wall interactions strongly affect the performance of tokamaks [1,2]. To understand these interactions, it is useful to monitor the flux and energy of particles that escape from the plasma and strike the wall. Such measurements are complicated by the difficulty of placing appropriate diagnostics inside the vacuum vessel at the first wall. Collector probes have been frequently used to measure particle fluxes over long exposure periods [3,4] or for selected individual plasma shots [5], but the necessity of inserting, exposing, removing, and subsequently analyzing the samples makes acquiring data tedious. Time-of-flight spectrometers [6] or electrostatic analyzers equipped with stripping cells [7] can supply immediate, time-resolved information about neutral particle fluxes and energies, but their large size and complexity limit widespread use. The development of small, remotely-operated particle diagnostics is therefore desirable.

For high-energy particles, Si surface barrier detectors or scintillators perform adequately [8,9]. At lower energies, other techniques are required. Carbon-film resistor probes have been developed to measure the resistance increase caused by particle damage [10]. Good time-resolved sensitivity to particles with energies above the damage threshold in carbon can be obtained, but the damage is largely irreversible and the probes must be replaced after a number of shots.

Another approach is to use Pd-gated metal-oxide-semiconductor (Pd-MOS) diodes as particle detectors [11]. Their main limitation is that they do not provide time-resolved information during a discharge. However, Pd-MOS sensors can produce a shot-by-shot record of the hydrogenic particle fluence and energy. They respond to small fluences of energetic hydrogen isotopes selectively and reversibly, are small in size, and can provide an electrical readout of hydrogen particle fluence. Energetic hydrogen that is implanted into the Pd layer rapidly diffuses to the Pd/SiO_2 interface, where it accumulates and causes a change in the barrier height of the device. Hydrogen is detected by monitoring the leakage current, which is exponentially related to the barrier height. The behavior of these devices has been previously described in detail [11–13].

In this paper we describe a diagnostic probe based on Pd-MOS diodes that is designed to monitor charge-exchange (CX) neutral hydrogenic atoms striking the wall of TFTR. The probe was used to monitor the CX particle fluence and energy during various operating modes of TFTR and provided information about plasma conditions that either enhance or suppress plasma-wall interactions.

II. Experiment

The detector consisted of an array of six Pd-MOS diode microsensors, each having an active area about 400 μm in diameter, arranged in a 2 by 3 pattern on a 5 mm square Si substrate [13]. The Pd contact on each diode in the array was 50 nm thick, and the oxide barrier was about 2 nm. On selected diodes in the array, Au layers of up to 50 nm were deposited to provide a means for energy discrimination.

A small heater and thermocouple attached to the base of the detector provided temperature control. This assembly was placed in a protective housing and centered 3 cm behind an 8 mm aperture. The housing was mounted on a movable probe [14], which enabled the detector to be stationed a few cm behind the graphite-tiled first-wall of TFTR, at a position 111 cm from the vacuum vessel centerline. The probe location was at the midplane of the torus in Bay E and was oriented to look radially inward, almost perpendicular to the toroidal field lines. This position and the presence of a collimating aperture ensured that only CX neutral particles struck the surface of the diode array.

After installation, the detector was heated to approximately 110 °C for 5 minutes to purge it of hydrogen and restore its sensitivity. The heat treatment was repeated whenever the detector response saturated due to accumulation of hydrogen isotopes in the diodes.

For operation, a 0.5-2.0 V reverse bias voltage was applied to the diode array elements and the leakage current, I_r, through the diodes was measured at fixed time points before and after each plasma discharge. The change in leakage current, ΔI_r, was taken as the diode's response to the plasma shot. During the discharge, the bias voltage to the diode array was shut off in order to avoid generating large spurious signals from photocurrents.

The diode response is calibrated from the saturation behavior of the diode. It is known from laboratory measurements that saturation occurs when approximately one monolayer of hydrogen (2×10^{15} cm^{-2}) is trapped at the Pd/SiO_2 interface [12]. So I_r at saturation provides a calibration point for the total amount of retained hydrogenic species in the diode. The zero point is established by measuring I_r after a heat treatment, which purges the Pd layer of trapped hydrogen species by thermal diffusion and desorption at exposed surface sites [15].

In order to relate ΔI_r to incident hydrogen isotope fluence, the implant fraction (1-R, where R is the reflection coefficient) and the relative degree of saturation of the diode must be known. The implant fraction can be estimated given the energy distribution of the incident particle flux. Below 50 eV R exceeds 0.8 for H at normal incidence on amorphous Au and Pd surfaces, while above 800 eV, R drops below 0.5. The degree of saturation can be obtained by reference to the zero point.

III. Results

Several hundred deuterium plasma discharges were monitored during the 1988 summer run period. The data collected were used both to check sensor performance and to identify correlations between the CX flux and the operating conditions of TFTR.

A typical diode response curve obtained for one plasma discharge is shown in Fig. 1. The diode current during the before-shot reading interval is stable and constant. The bias voltage is turned off 2 s prior to the plasma shot causing a large shift in the leakage current. During the shot, induced photocurrents are seen at the beginning of the discharge and especially during the start-up of neutral beam injection. Photocurrents cease at the end of a discharge, but the hydrogenic-induced change in diode current resulting from the accumulation of hydrogen isotopes at the Pd/SiO_2 interface persists. Thus, the hydrogen-induced current can be measured after the discharge without interference. When the bias voltage is re-established, the after-shot reading of the diode current is recorded. The arrows in Fig. 1 define the ΔI_r resulting from the plasma shot.

The occurrence of plasma disruptions had a noticeable effect on the diodes. In some cases, after a disruption I_r was found to have diminished, suggesting that a net release of hydrogenic species from the Pd layer occurred. It is possible that heating of the diode structure during a disruption caused thermal release of the accumulated hydrogen. The thermocouple at the base of the detector indicated no significant temperature variation (always $<5\ ^\circ C$), but transient heating of the diode surface cannot be ruled out. Consequently, measurements made during disruptions were not considered reliable.

The measured CX fluences for a series of neutral-beam heated and ohmically heated plasmas are shown in Fig. 2. The flux to the outer midplane wall can vary by an order of magnitude depending on the operating conditions of TFTR. With neutral-beam injection, there is a noticeable variation in the shot-to-shot fluence and this effect was studied in more detail. The CX flux during ohmic plasmas is typically smaller than during neutral-beam heated plasmas. In some cases where no plasma formed the diode array gives a negative response, which results from measurement error as well as the gradual release of trapped hydrogen that occurs when diodes are kept in vacuum [12].

Examination of the shot-to-shot variation in the wall flux for neutral-beam heated plasmas indicates that co-injected neutral beams produce larger CX fluxes to the midplane wall than counter-injected sources. This behavior is shown in Fig. 3, which plots the measured CX fluence per shot for a series of plasmas each having about 14 MW of neutral beam heating. A correlation between the neutral beam balance parameter and the CX flux to the wall is evident.

The energy distribution of the CX flux was measured by comparing the response of the Au covered diodes. TRIM code [16] calculations indicate Au layers of 5, 10, 20, 30 and 50 nm stop D with energies less than approximately 20, 50, 100, 200, and 500 eV, respectively. Since hydrogen isotopes have a low permeability in Au [17], those stopped in the Au layer do not migrate into the Pd layer and do not contribute to the measured signal.

Fig. 4 shows the response of diodes with 0, 5, 20, and 50 nm Au overlayers to a series of 1.6 MA plasmas with balanced neutral beam injection at powers from 14 to 25 MW. In general terms, the CX flux appeared to increase during each shot series and slightly with neutral beam power. The CX flux was attenuated by the Au layers, although some CX particles penetrated even the thickest Au layer, implying that the CX flux had a component above 500 eV.

IV. Discussion

The practical issues for utilizing Pd-MOS diodes as plasma-edge diagnostics have been previously discussed [11]. Here we will focus on judging the performance of the diodes and commenting about the CX flux observations.

In its present configuration, the Pd-MOS diode array proved useful as a qualitative shot-to-shot CX fluence monitor. The most satisfactory results were obtained when monitoring the relative differences in a series of plasma shots rather than measuring absolute fluences. The assignment of an absolute fluence scale depends upon knowing the details of the energy spectrum of the incident particles. It is clear from the measurements that particle energies in the CX flux range from below 50 eV to above 500 eV. However, the energy resolution of a six element array is not sufficient to map out this energy distribution in detail and there is some uncertainty in estimating R, which is needed to establish the fluence scale. In the present measurements, a value of 0.7 was used for R, based on TRIM code calculations for an averaged energy of 50 eV. The resulting fluence scale is considered accurate to no more than a factor of two. In principle, uncertainties in the fluence scale can be reduced by using a larger array of diodes to improve the energy resolution.

It is interesting to compare the CX flux seen in neutral-beam heated and ohmic plasmas. Both previous measurements on TFTR and ASDEX using a carbon resistance probe [10,18] and the current results indicate that the CX flux is higher from neutral-beam heated plasmas. Changes in the plasma-edge temperature and density that accompany neutral-beam heating may be primarily responsible, since these parameters determine CX production rates and re-ionization lengths. The core plasma density appears to be less important. For the plasmas referred to in Fig. 2, the line-integrated plasma density is lower in the neutral-beam heated discharges ($\approx 1\times10^{19}$ m^{-3}) than in the ohmic discharges ($>2\times10^{19}$ m^{-3}). Higher plasma densities lead to shorter re-ionization lengths for CX particles, so CX emission from the core is more efficiently attenuated.

The variation in CX flux observed for nominally identical plasmas may indicate changes in recycling. The increase in the CX flux seen in Fig. 4 for successive shots at constant NBI power is consistent with a gradual increase in the recycling rate. Such behavior results as hydrogen levels build up in plasma-facing graphite components [2].

The correlation observed between the CX flux and the neutral-beam balance may also be related to variations in edge-plasma conditions. Langmuir probe measurements of the TFTR edge-plasma during neutral beam heating show that the neutral beam balance affects edge densities by up to a factor of ten [19]. Also, a vertically viewing high-energy CX analyzer on TFTR similarly shows enhanced CX emission with increasingly unbalanced co-injection. Unbalanced injection leads to high toroidal rotation speeds, which has a direct influence on plasma behavior, such as broadening the ion-temperature profile [20]. Increased CX emission appears to be another consequence.

V. Conclusions

Based on the operating experience gained in TFTR, Pd-MOS sensors appear to be of use for studying plasma-wall interactions. The diodes, which collect data integrated over the duration of each plasma discharge, also sense photocurrents induced by plasma radiation and may be influenced by transient heating during disruptions. In TFTR, the CX flux to the outer midplane wall is influenced by various operating parameters, such as fueling mode and neutral-beam balance. We find that the CX flux from neutral-beam heated plasmas is typically larger than from ohmic plasmas and that co-injection produces a relatively greater CX flux than does counter-injection. Most CX particles appear to have energies below 50 eV, but particle energies were observed to extend above 500 eV.

Acknowledgments

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Figure Captions

Fig. 1. Smoothed response of an uncoated Pd-MOS diode to one TFTR discharge. The measured leakage current, I_r, with applied bias becomes more negative after exposure to energetic hydrogen isotopes. The plasma was initiated at $t=0$ s and neutral beam injection began at $t=4$ s.

Fig. 2. Comparison of charge-exchange fluence per shot for neutral-beam heated (17 MW) and ohmic plasmas in TFTR.

Fig. 3. Effect of neutral beam balance on CX fluence per shot in a series of TFTR plasmas. Total neutral-beam power, P_{tot}, is 14 ± 1 MW in each case. The balance parameter is $(P_{co}-P_{ctr})/P_{tot}$ where P_{co} and P_{ctr} are the co- and counter-injected neutral-beam powers.

Fig. 4. Measured CX fluence per shot for a series of TFTR plasmas having 14 to 25 MW neutral-beam power. The response of four Pd-MOS diodes having 0 (○), 5 (□), 20 (◇), and 50 (△) nm Au overlayers is shown.

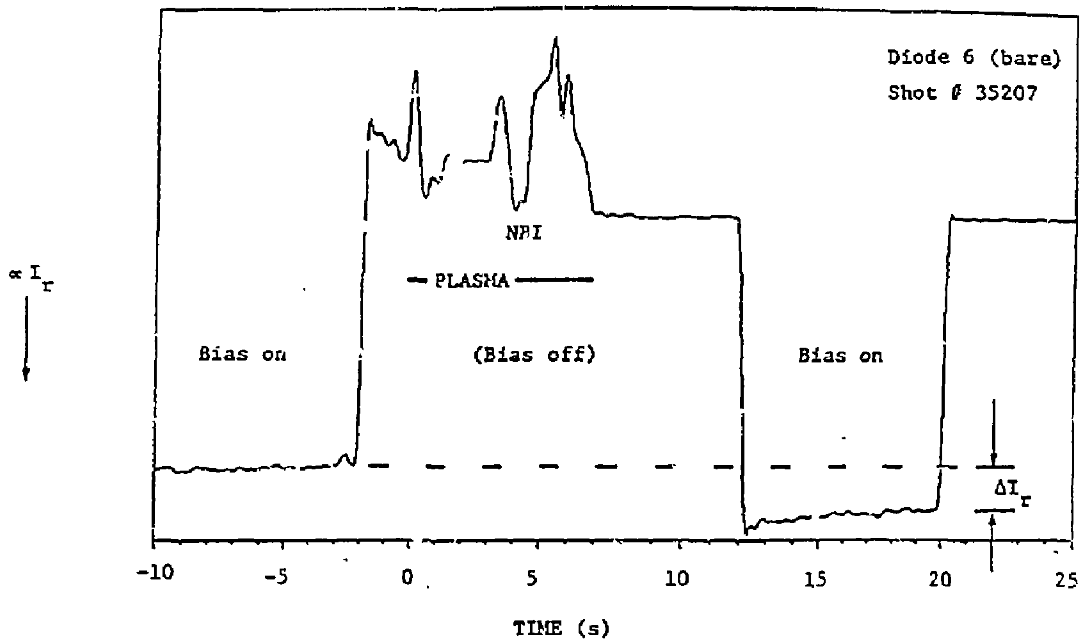
Diode 6 (bare)
Shot # 35207
NBI
PLASMA
Bias on
(Bias off)
Bias on
ΔI_r
$\propto I_r$
-10
-5
0
5
10
15
20
25
TIME (s)

Figure 1.

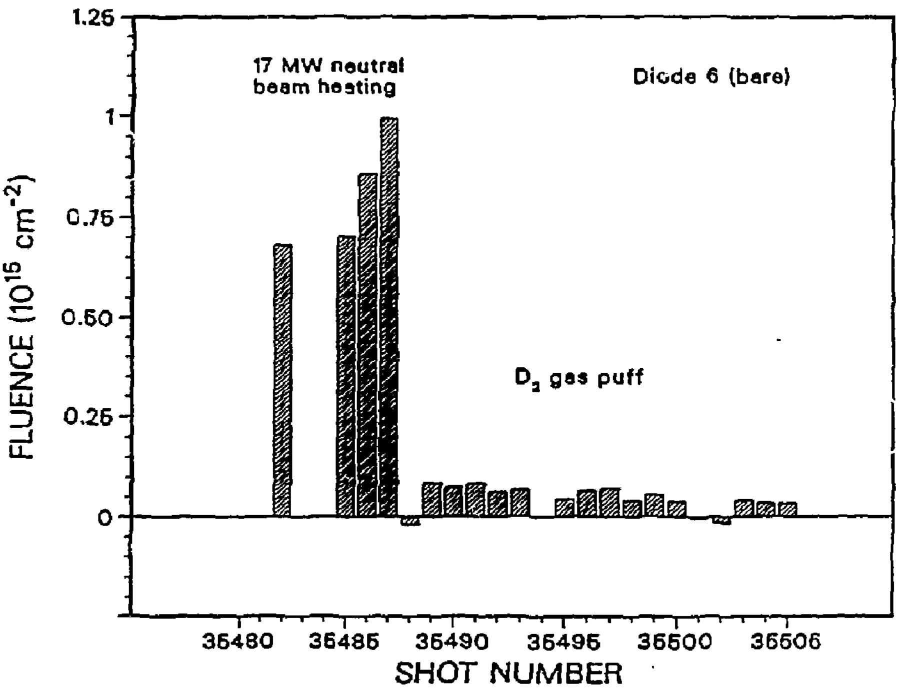
1.25
1
0.75
0.50
0.25
0
FLUENCE (10^{15} cm^{-2})
17 MW neutral
beam heating
Diode 6 (bare)
D_2 gas puff
35480
35485
35490
35495
35500
35505
SHOT NUMBER

Figure 2.

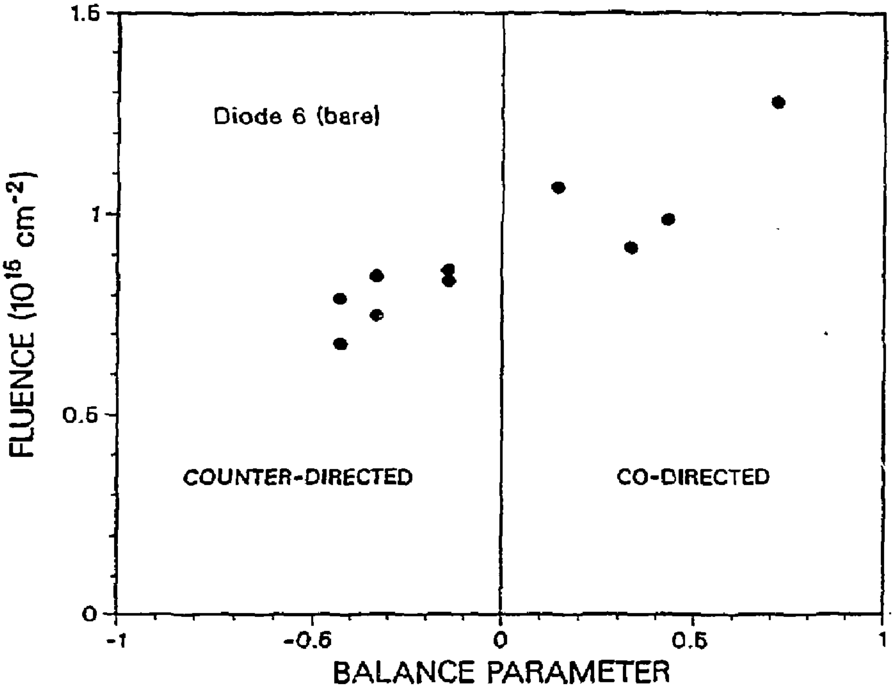
1.5
1
0.5
0
FLUENCE (10^{15} cm^{-2})
Diode 6 (bare)
COUNTER-DIRECTED
CO-DIRECTED
-1
-0.5
0
0.5
1
BALANCE PARAMETER

Figure 3.

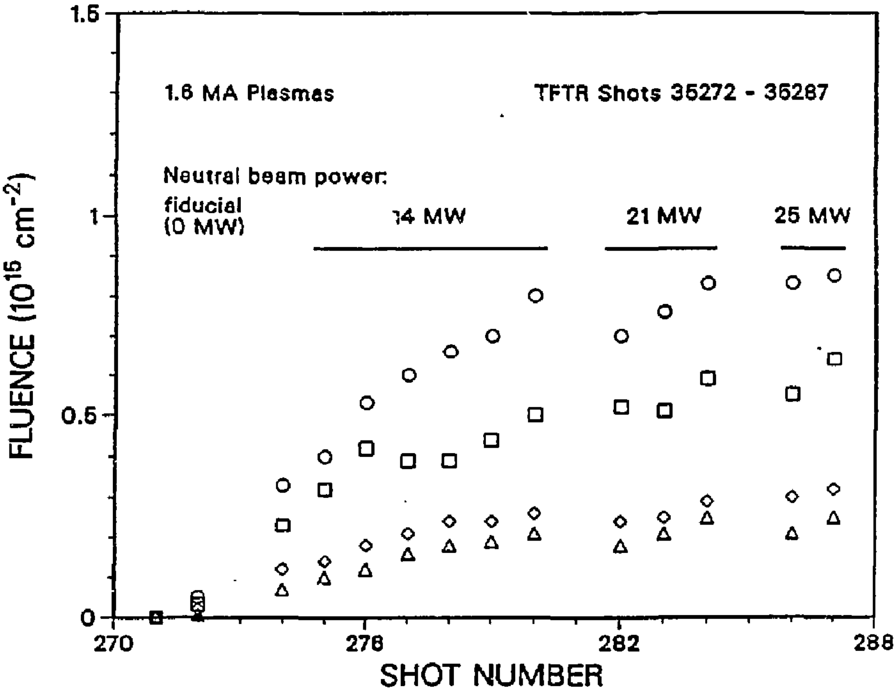
1.6 MA Plasmas
TFTR Shots 35272 - 35287
Neutral beam power:
fiducial
(0 MW)
14 MW
21 MW
25 MW
FLUENCE (10^{15} cm^{-2})
SHOT NUMBER
1.5
1
0.5
0
270
276
282
288

Figure 4.