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ACCELERATOR-BASED PLASMA-WALL INTERACTION STUDIES ON THE TEXTOR TOKAMAK

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ABSTRACT

Deposition probes are commonly used to determine plasma edge characteristics in tokamaks. Such probes are frequently analyzed using accelerator-based techniques and can yield information on impurity fluxes, hydrogen fluxes and energies, and surface erosion rates in the plasma edge. Several types of deposition probes have been employed to investigate the plasma edge region of the TEXTOR tokamak in Jülich, FRG. TEXTOR is a moderate size tokamak (major radius = 1.75 m) that is capable of 2-3 s discharges and contains a liner that can be heated to 600°C. These capabilities make TEXTOR particularly attractive for the study of plasma-wall interactions. Several countries, including the United States, Sweden and the host nation, are carrying on active research programs in the area of plasma-edge studies. This research has included measurements of plasma, impurity, and power fluxes at various radii in the scrapeoff layer. The results achieved in characterizing the plasma edge in these recent probe studies on TEXTOR will be reviewed.

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I. INTRODUCTION

During the last several years the use of collection probe techniques to characterize the scrapeoff layer of magnetic confinement fusion experiments has become widespread.[1] The plasma edge region of a confinement device is a difficult environment in which to make measurements, containing, as it does, both ions and neutrals of a variety of species at energies ranging from tenths of electron volts to tens of kilovolts. Complex physical and chemical processes are taking place on the walls and limiters.[2] Large magnetic fields are always present and destructivley high power levels can be encountered during disruptive behavior. Optical methods which can be used under these conditions are often limited to observation of a single state of a single element or are dependent upon detailed modeling of local conditions to obtain quantitative results. Deposition probes, on the other hand, are sensitive to all states of all elements and can be easily used to determine the types and quantities of impurities present in the edge. With interpretation, probe measurements are also capable of determining fluxes and energies of hydrogen isotopes. Time resolution during a discharge can be achieved by using rotating or moving collectors. Electrical biasing can be used to incorporate the features of a Langmuir probe into the system and thermocouple temperature measurements can be used to measure heat fluxes. This versatility, along with its ability to detect many elements simultaneously and its basic simplicity, have made the deposition probe a principal diagnostic for the plasma edge region.

After a deposition probe has been exposed in the scrapeoff layer the amounts of impurities and hydrogen isotopes retained on the samples must be determined. It is here that accelerator based analysis techniques make a significant contribution.[1,3] The absolute quantities of impurity elements on the surface can be measured easily by Rutherford backscattering (RBS), normally with MeV ^4He ions, and the hydrogen isotopes present can be determined using nuclear reaction analysis (NRA) or elastic recoil detection (ERD).[4] All of these methods have been applied on TEXTOR exposed samples.

TEXTOR is a moderate size tokamak (Major radius = 1.75 m, minor radius = 0.5 m) at the Kernforschungsanlage (KFA) Julich, FRG, that was designed for the testing of fusion related technologies. It incorporates two features that make it particularly interesting for the study of plasma-material interactions. First it is capable of comparatively long (2-3 s) discharges that can be used to study impurity accumulation, and second, it contains a liner inside the vacuum vessel that can be heated to 600°C during operation. Plasma-wall interaction studies on TEXTOR are the subject of an international collaboration and to date six different collection probes, including the present one, have been employed on the tokamak.

II. EXPERIMENTAL PROCEDURE

Both single crystal silicon and carbon (Papyex) collection probes were exposed in the TEXTOR plasma edge using an automated insertion system that permitted remote positioning of the samples and automatic rotation during a discharge for time-resolved measurements. A schematic diagram of the probe and its relation to the plasma are shown in Fig. 1. The probe was kept at the floating potential for all measurements and the samples were masked by a titanium window. No titanium was detected on any of the samples. All measurements were made in standard ohmic discharges having the following parameters: toroidal field = 2T, plasma current = 340 kA, line average electron density = 2-3 x 10^{13} cm^{-3}, central electron temperature >1 keV, and discharge length = 2.5 s. The temperature of the inconel liner was 130°C and the stainless steel main limiters were at a minor radius of 45 cm. The probe was located on the horizontal midplane of the tokamak on the outside wall between toroidal field coils seven and eight, only one sector in the ion drift direction from the main limiters. Measurements were made as a function of time for various radial positions in both hydrogen and deuterium plasmas.

After exposure the samples were removed and transported in air to a 2.5 MeV Van de Graaff accelerator facility for analysis. Retained impurities were measured by RBS on both carbon and silicon samples. The (100) single crystal silicon samples were oriented with the incident 2.0 MeV ^4He beam channeled along the <110> axis at 45° to the surface normal. The solid state detector was placed at a scattering angle of 135°. This geometry, with the incident beam in an axial channeling direction,[5] reduces the backscattering from the silicon substrate and improves the signal to background ratio by a factor of ~50, permitting more rapid processing of the samples. Oxygen, although lighter than the substrate, can also be observed using this technique. The polycrystalline carbon substrates were analyzed with the beam at normal incidence and the detector at an angle of 166°.

Retained deuterium was measured by means of the $D(^3He,p)\alpha$ nuclear reaction with an incident beam energy of 700 keV. The detector was covered with 2 mil stainless steel to keep backscattered ^3He and alpha particles from interfering with the proton spectrum. Although hydrogen can be detected directly by NRA [$^1H(^{19}F,\alpha\gamma)^{16}O$ or $^1H(^{15}N,\gamma)^{16}O$], elastic recoil detection was used for this purpose in the present work. The incident beam was 2.3 MeV ^4He at 15° from the sample surface and the scattered hydrogen was detected at an angle of 30° from the incident direction. Both hydrogen and deuterium can be detected in this manner, and a typical spectrum is shown in Fig. 2. Because of the relatively short ranges associated with the low energy hydrogen and deuterium implanted in the tokamak exposed samples, depth distributions of these isotopes were not useful.

If absolute quantities of hydrogen or deuterium present in exposed samples can be measured as a function of exposure, then the incident fluence and energy can be determined by comparison with appropriate trapping curves that show the quantity retained as a function of incident fluence and energy.[6] The results achieved with this method were confirmed by measurements of damage to the single crystal silicon samples as shown in Fig. 3. Such damage has been shown to be representative of the energy and fluence of the incident particles.[7] In the figure the lattice damage, as represented by the surface peak during axial channeling, is compared with curves of damage vs. incident fluence and energy for monoenergetic deuterium. The results for a position 4 cm outside the limiter radius indicate a flux of ~5 x 10^{15}/cm^2 shot at an energy of 150 eV.

III. RESULTS AND DISCUSSION

A. Impurities

The principal impurities found in the plasma edge region of TEXTOR have been previously reported[8] and were oxygen, iron, chromium, nickel, molybdenum, and traces of tungsten or tantalum. Carbon, which cannot be detected on Papyex substrates and can be only poorly resolved by RBS on silicon, may also be present in significant quantities, but was not included in these measurements. At 2 cm outside the limiter radius average deposited fluxes were ($cm^{-2}s^{-1}$): oxygen = 6 x 10^{15}, iron = 3 x 10^{15}, chromium = 8 x 10^{14}, nickel = 3 x 10^{14}, and molybdenum = 2 x 10^{13}. The radial distributions of these impurities flowing along the field lines in the electron drift direction are shown in Fig. 4. These results are for silicon samples exposed to time-integrated discharges with the main limiters at 45 cm. The metallic impurities show a monotonic decrease with radius that is less than exponential. The e-folding distance observed for the metals is ~2.5 cm. The relatively sharper decrease at r = 48-49 cm is due to the effects of the inner limiter and the secondary limiters on the ICRH antenna which are located at this radius. The behavior of the deposited oxygen flux is different from that of the metals. The oxygen flux decays more slowly with radius, indicating that the source or mechanism of introduction into the plasma for oxygen is different than for the metals.

Possible saturation effects in the deposition of impurities were investigated by exposing samples to various numbers of discharges. The results are shown in Fig. 5. Here the quantities of stainless steel, molybdenum, and oxygen retained on the probe at three different radii are plotted against the number of discharges to which the silicon samples were exposed. It is apparent that saturation effects for oxygen occur after the first discharge, while for the metals the deposition rate is essentially constant for six discharges. A comparison of this data with time-resolved data for fluences of less than one discharge demonstrates that the deposition rate for oxygen is approximately constant up to the one discharge level (1.5×10^{16} cm^{-2}). This linearity is important in relating measurements of accumulated impurities to the incident flux. Thus the measured results for metals are valid for exposures of up to six discharges, but results for oxygen may be suspect beyond one discharge.

The time dependence of the impurity fluxes was measured for 2.5 s TEXTOR discharges using rotating probe techniques. The results at a radius of 49.7 cm are given in Fig. 6. The time resolution of the data is ±0.14 s. The initial peak near time zero has been generally observed on other machines[1] and is ascribed to positional instability during the startup phase. Such instability also appears to be the explanation for the peaking in these TEXTOR discharges, since the measured horizontal position of the plasma was very unsteady at that time. The peak that is especially prominent in the transition metal flux and is centered at one second into the discharge, however, cannot be readily explained. Plasma position, density and temperature are all nearly constant during this part of the discharge and no other perturbations to the plasma at this time have been observed.

B. Hydrogen Isotopes

Nuclear reaction analysis was used to determine the amount of deuterium trapped in samples exposed to different numbers of discharges.[9] The data were then compared with trapping curves (see Sect. II) to estimate incident flux and energy. A flux of 1-1.5 x $10^{16}/cm^2$ discharge with a Maxwellian energy distribution of ~100 eV was found at 5 cm outside the limiter radius.

The use of ERD to determine both hydrogen and deuterium fluxes is illustrated in Fig. 7. In this case deuterium gas was puffed into a hydrogen plasma as indicated in the figure. Both hydrogen and deuterium were monitored using the time-resolved rotating collection probe at 3.6 cm behind the limiter. The puffed deuterium is detected immediately on the collection probe, but the amount decays gradually when the gas inlet is closed. The amount of deuterium then rises sharply as the discharge ends. In this case the discharge ended in less than two seconds with a minor disruption. The final increase in both H and D fluxes is presumably due to the increased contact with the wall and limiters during this disruption.

C. Other Probe Measurements

A number of different surface probe systems have been used on TEXTOR for plasma edge studies. Each of them emphasized a different aspect of the plasma-wall problem, and each of them employed a different investigative technique. Two of them operated during the time frame of the present measurements and one of them relied on accelerator based analysis techniques. In this section the characteristics of these systems will be briefly described and results pertinent to the present work will be discussed.

Two surface analysis stations using Auger electron spectroscopy (AES) for sample analysis were installed on TEXTOR for the evaluation of wall conditioning procedures.[10,11] Samples of the first wall material (Inconel 625) were exposed at the wall position to radio frequency supported glow discharge (RG) and electron cyclotron resonance (ECR) cleaning and then analyzed by AES. In this way the effects of the cleaning on the walls could be determined. Wall condition was then correlated with plasma performance. These probes were not used to characterize the scrapeoff layer during tokamak discharges.

A material manipulator has been installed on TEXTOR by a collaborative effort from Switzerland.[12] This manipulator can install and remove samples from a large number of different locations in the liner. The device is meant for long term exposure of samples, such as the testing of first wall materials and coatings, and is not used for plasma edge characterization.

An interesting probe has been installed by members of the Institut fur Chemie 1 at KFA, Julich.[13] This probe was designed primarily for measuring hydrogen isotope fluxes in the edge during tokamak discharges. It uses conventional deposition probe collection of particles on graphite strips and can operate in the time-resolved mode. Analysis of the retained fluence, however, is done in situ by thermal desorption and mass spectrometric detection. Hydrogen fluxes were measured for standard discharges similar to those reported here. Fluxes of 10^{16}/cm^2 shot with a Maxwellian energy of 100 eV were found at 4 cm behind the limiter radius in the electron drift direction. These are comparable to the results reported in the present work. An attempt to use this thermal desorption probe to measure heavier impurities has so far been unsuccessful.

The work most comparable to that reported here was carried out on the "Stockholm probe" which was located 140° toroidally in the ion drift direction from our probe. This probe used rotating Papyex collectors in cylindrical geometry and RBS analysis to determine impurity fluxes in the edge. For exposures in the ion drift direction comparable fluxes of the transition metals (5.5 x 10^{15} cm^{-2} s^{-1}) and somewhat higher fluxes of oxygen (x2 to 3) were observed at comparable radii.[14] A substantial difference in e-folding lengths was observed with a value of 1.0 cm being measured at their toroidal location. Since different flux tubes are being sampled by the two probes, it is difficult to determine whether these differences are the direct result of proximity to the limiter.

IV. CONCLUSION

Accelerator based analysis techniques and passive deposition probe exposures were used to characterize the plasma edge region of TEXTOR. Using RBS, the species and quantities of impurities in the scrapeoff layer were determined as functions of radial position and time for standard ohmic discharges. Retained quantities of hydrogen isotopes were measured by NRA and ERD. Trapping curves were then used to determine incident fluxes and energies from these values.

Comparisons with other probe measurements show modest agreement with regard to impurity fluxes and hydrogen fluxes and energies in the edge, but indicate that toroidal variations of 2 to 3 may be expected in some cases. In summary, the international collaborations on TEXTOR in the area of plasma-materials interactions have fostered this and a number of other investigations that together have led to an improved understanding of conditions in the plasma edge.

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FIGURE CAPTIONS

Fig. 1 Exposure geometry for the time-resolved deposition probe showing silicon collection samples mounted on the rotating drum.

Fig. 2 Elastic recoil detection spectrum illustrating the separation of H and D for the indicated geometry.

Fig. 3 Damage (surface peak yield) for single crystal silicon (100) as a function of dose and energy for monoenergetic incident deuterium. The ●s are measured damage for samples exposed 4 cm outside the limiter radius in TEXTOR.

Fig. 4 Radial distribution of FeCrNi (○), O (□), and Mo (△) fluxes along the field lines in the electron drift direction during ohmic hydrogen discharges.

Fig. 5 Saturation effects observed in plots of retained impurities versus number of hydrogen discharges at radii of 47.6 (○), 49.5 (□) and 51.4 (△) cm.

Fig. 6 Time-resolved fluxes of FeCrNi (○), O (□) and Mo (△) for ohmic hydrogen discharges. Time resolution is ±0.14 s.

Fig. 7 Retained hydrogen (□) and deuterium (○) fluxes versus time for deuterium puffing into hydrogen discharges at 3.6 cm outside the limiter radius.

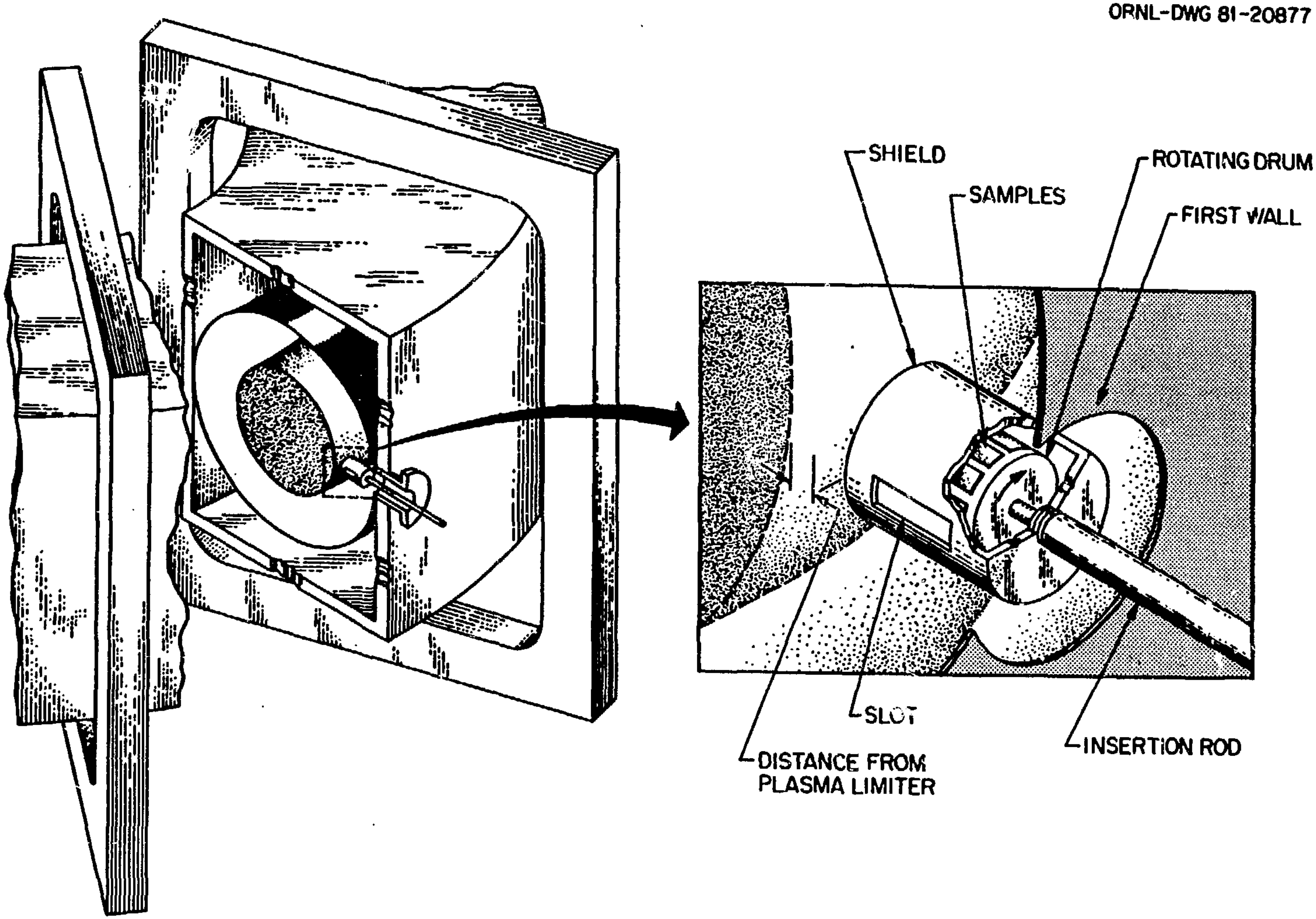

ORNL-DWG 81-20877
SHIELD
ROTATING DRUM
SAMPLES
FIRST WALL
SLOT
INSERTION ROD
DISTANCE FROM
PLASMA LIMITER

Fig. 1

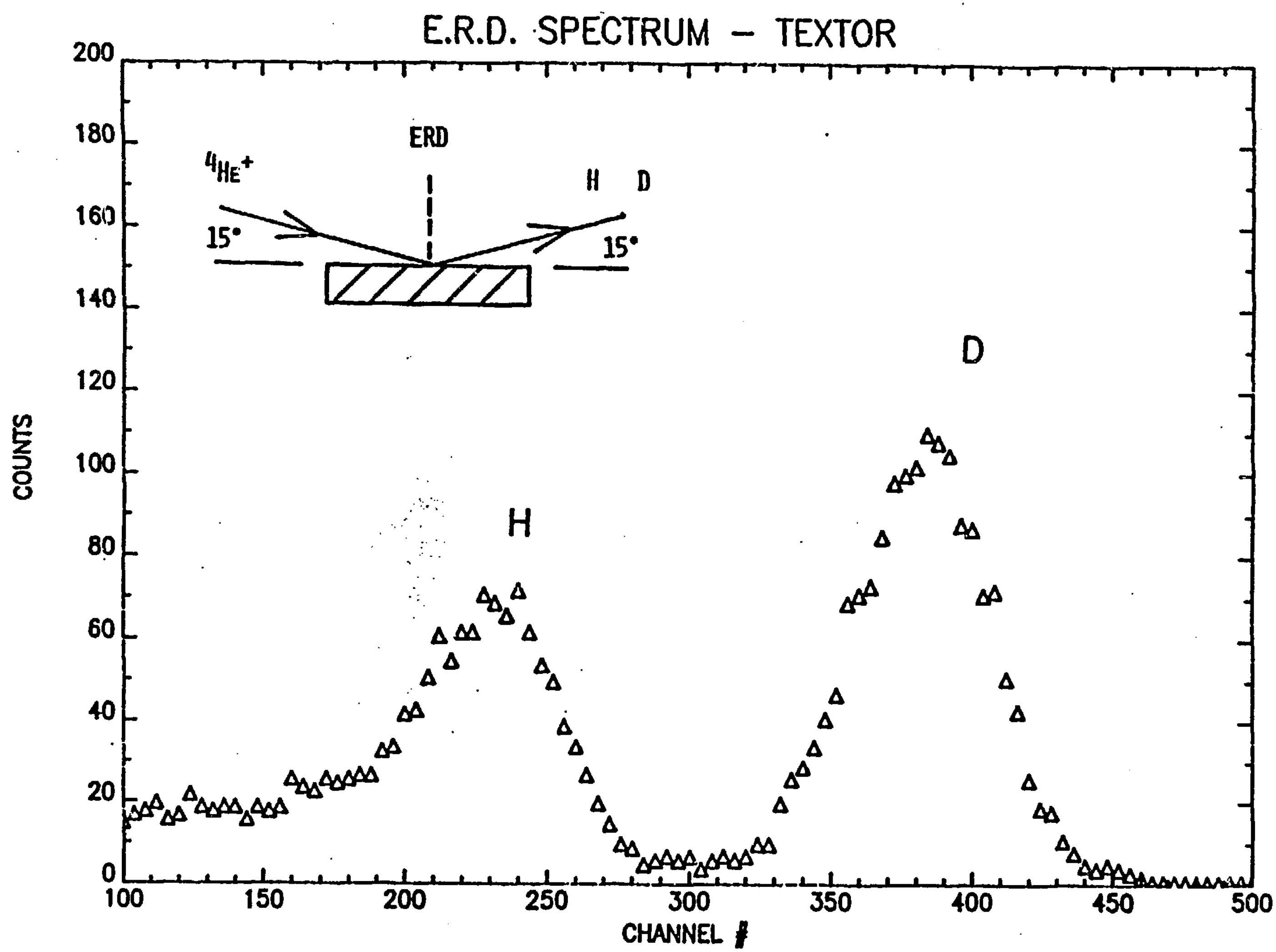

E.R.D. SPECTRUM – TEXTOR
ERD
4HE+
15°
H D
15°
H
D
COUNTS
CHANNEL #
0
20
40
60
80
100
120
140
160
180
200
100
150
200
250
300
350
400
450
500

Fig. 2

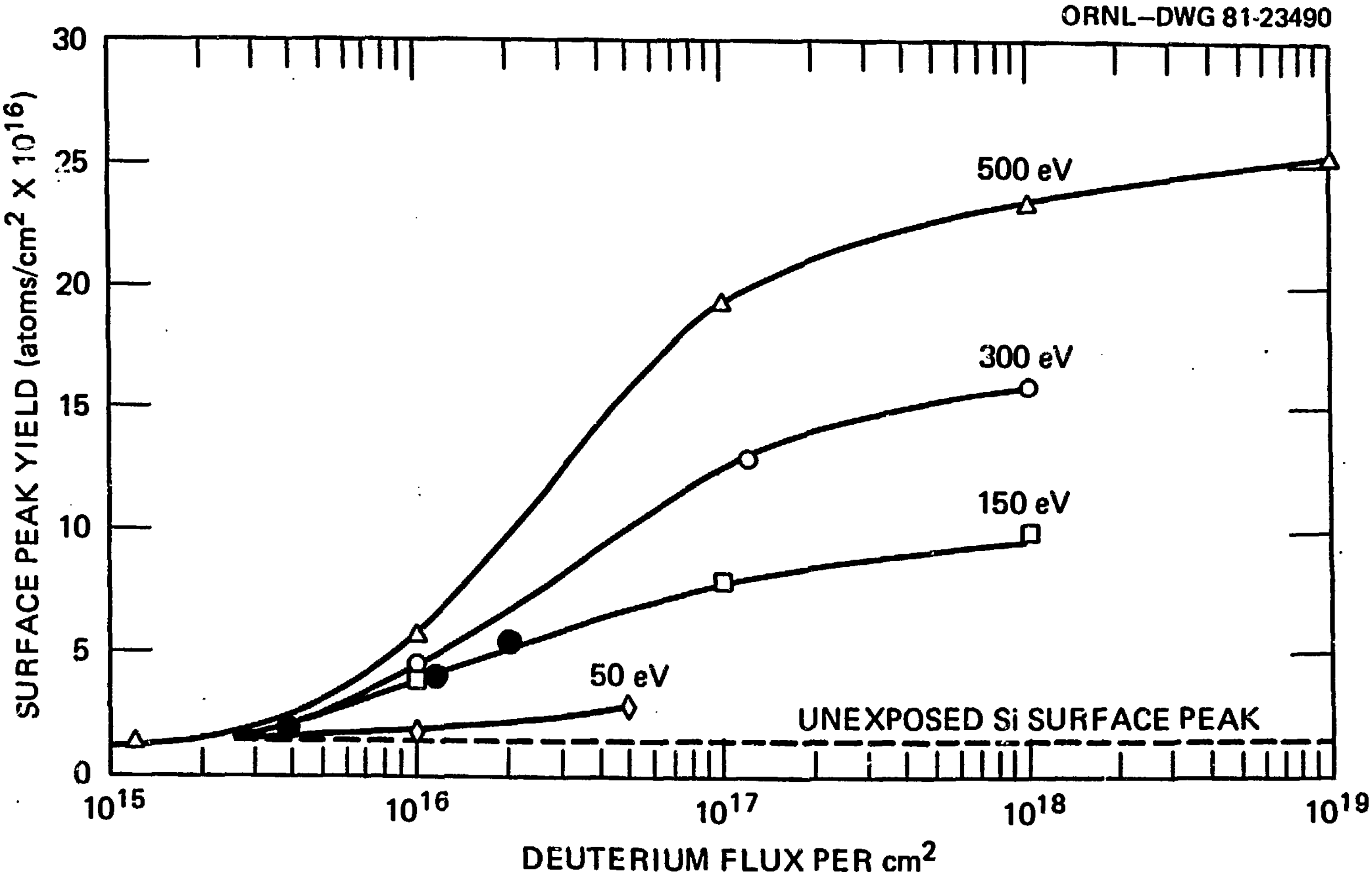
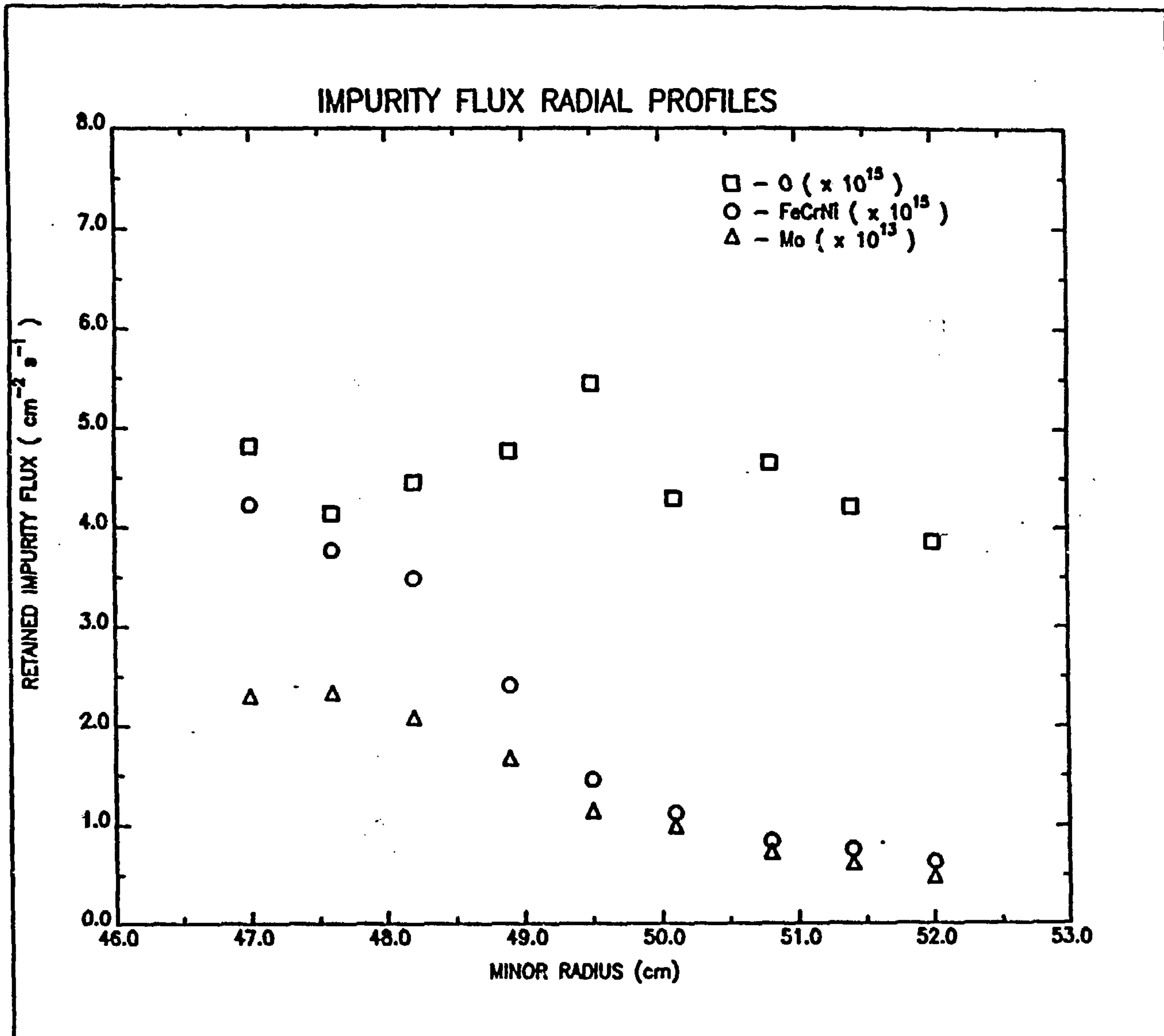

ORNL–DWG 81-23490
SURFACE PEAK YIELD (atoms/cm² X 10¹⁶)
30
25
20
15
10
5
0
500 eV
300 eV
150 eV
50 eV
UNEXPOSED Si SURFACE PEAK
10¹⁵
10¹⁶
10¹⁷
10¹⁸
10¹⁹
DEUTERIUM FLUX PER cm²

Fig. 3



IMPURITY FLUX RADIAL PROFILES
□ – O (x 10^15)
○ – FeCrNi (x 10^15)
Δ – Mo (x 10^13)
RETAINED IMPURITY FLUX (cm^-2 s^-1)
MINOR RADIUS (cm)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
46.0
47.0
48.0
49.0
50.0
51.0
52.0
53.0

Fig. 4

ORNL–DWG 84-15019

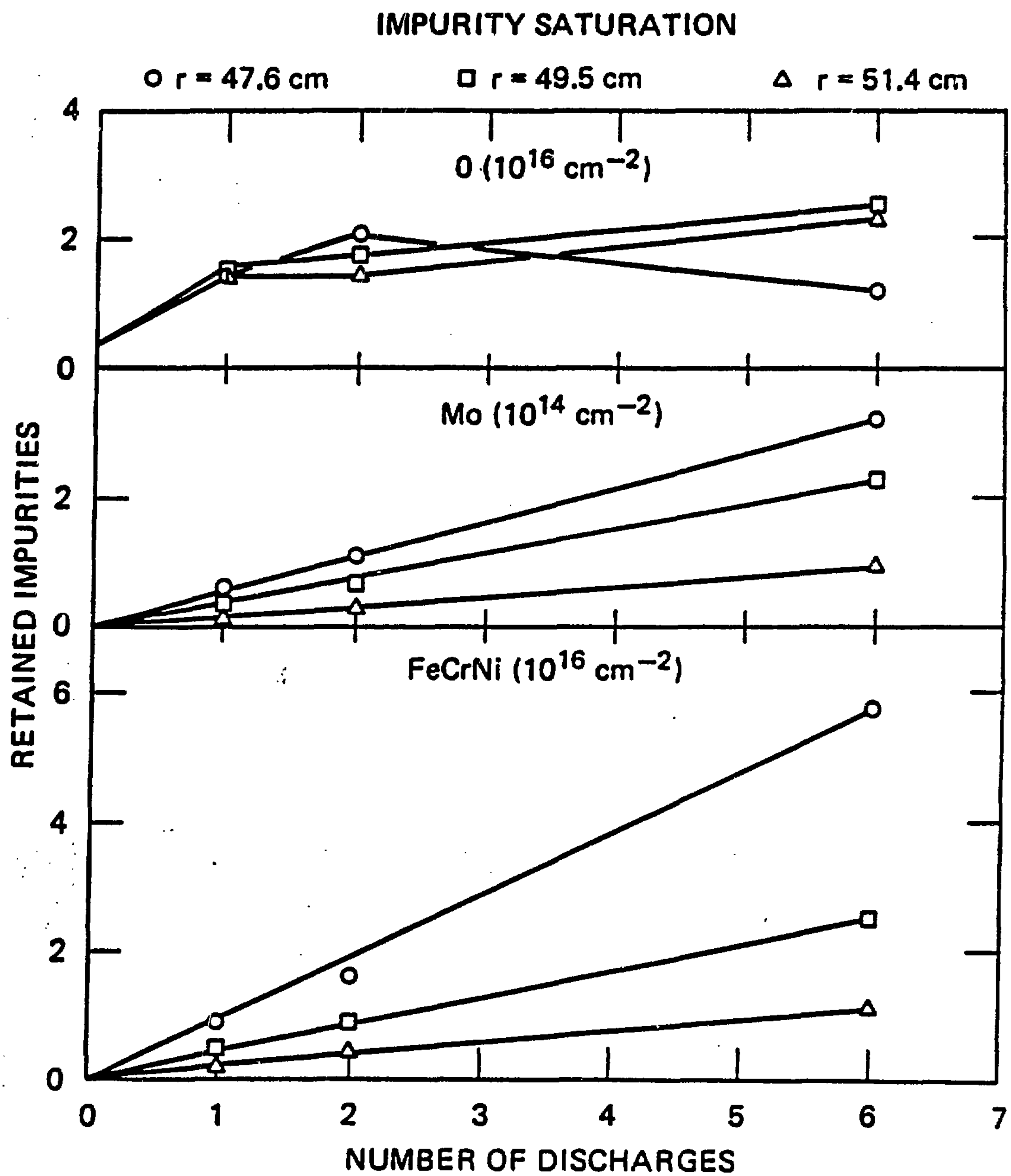


Fig. 5

ORNL–DWG 84-15018

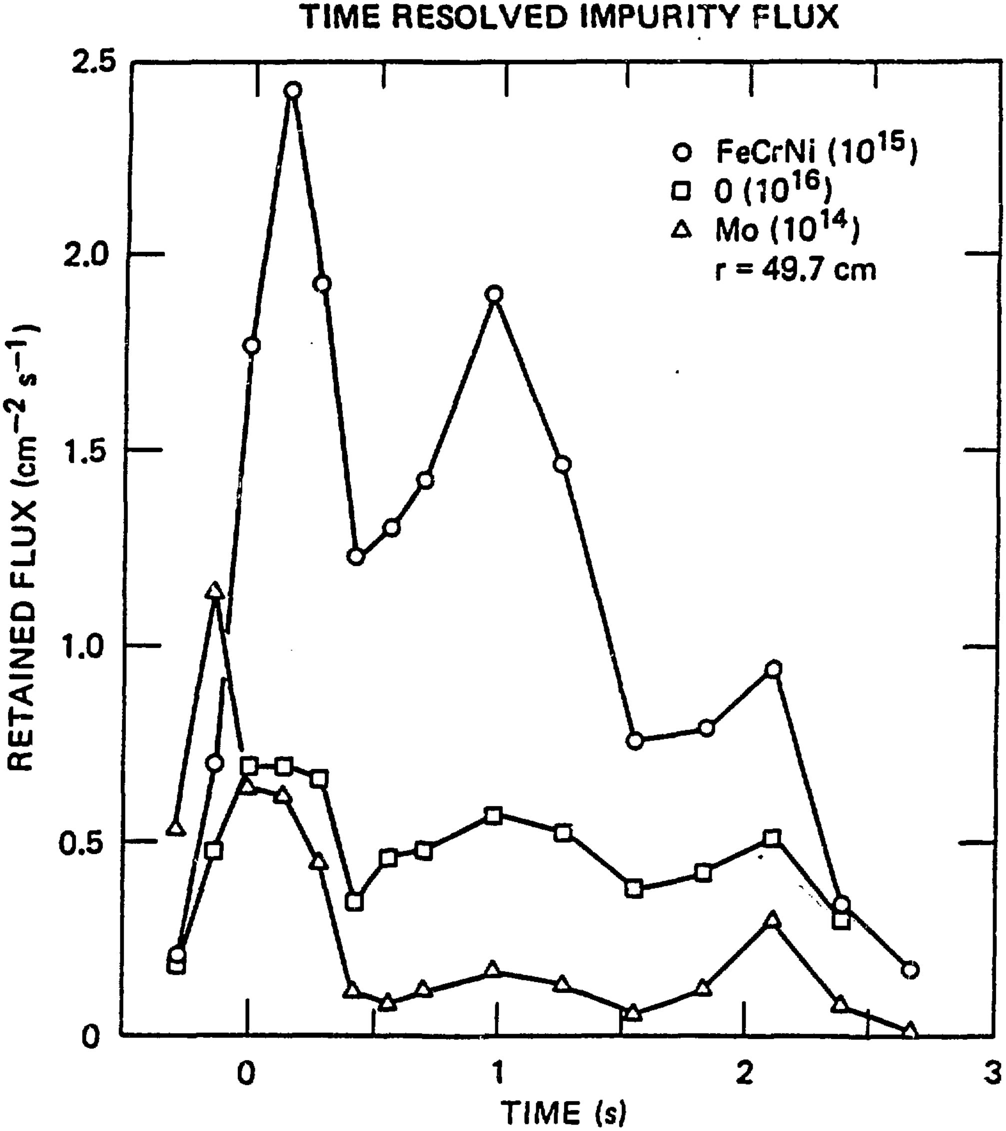


Fig. 6

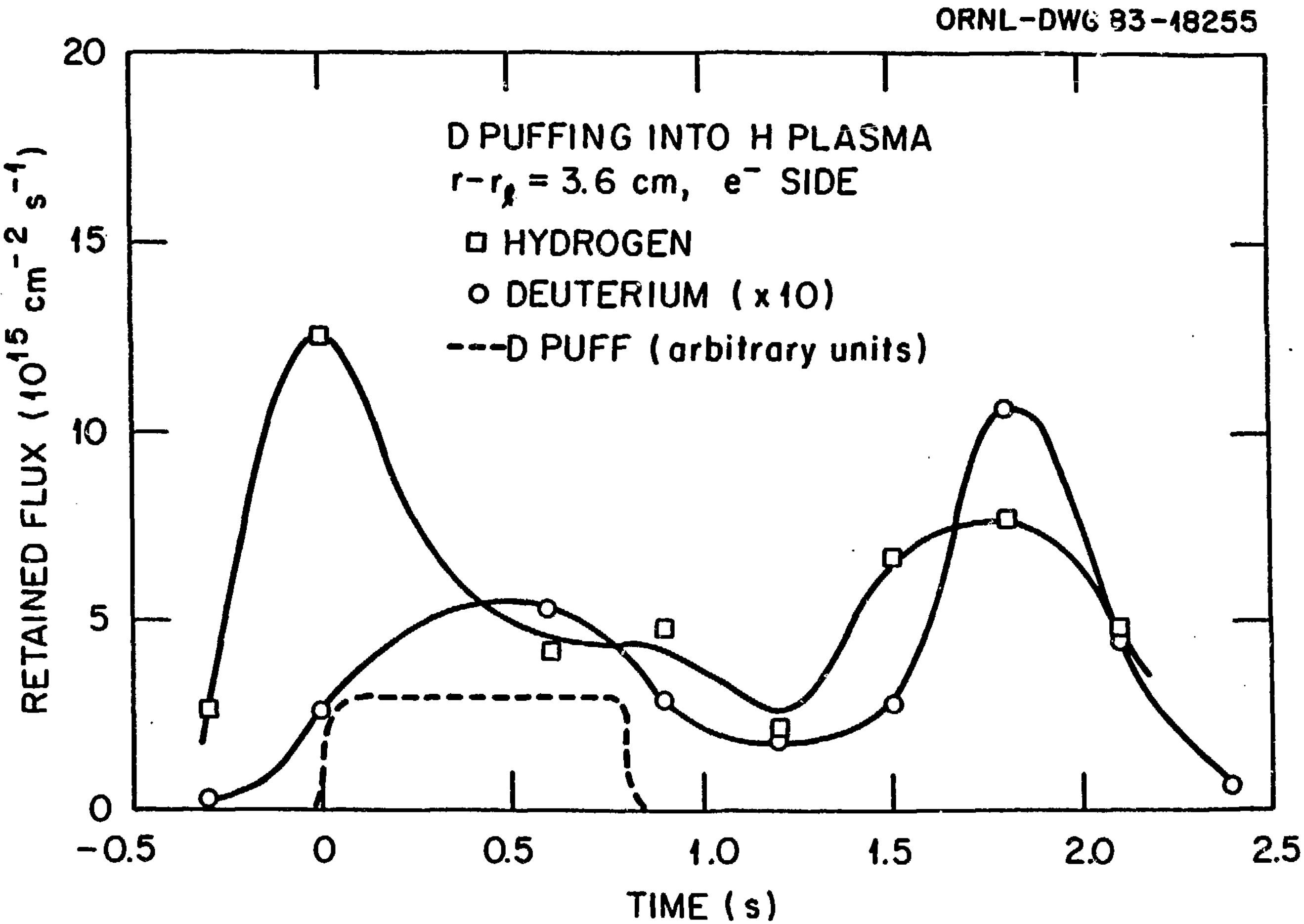

ORNL-DWG 83-18255
D PUFFING INTO H PLASMA
r−r_ℓ = 3.6 cm, e⁻ SIDE
HYDROGEN
DEUTERIUM (x10)
D PUFF (arbitrary units)
RETAINED FLUX (10^15 cm^-2 s^-1)
TIME (s)
20
15
10
5
0
−0.5
0
0.5
1.0
1.5
2.0
2.5

Fig. 7