Conf-911132--7

DEPOSITION OF DEUTERIUM AND METALS ON DIVERTOR TILES IN THE DIII-D TOKAMAK

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SAND--91-1163C

DE92 003648

ABSTRACT

Hydrogen recycling and impurity influx are important issues in obtaining high confinement discharges in the DIII-D tokamak. To reduce metallic impurities in DIII-D, 40% of the wall area, including the highest heat flux zones, have been covered with graphite tiles. However erosion, redeposition and hydrogen retention in the tiles, as well as metal transport from the remaining Inconel walls can lead to enhanced recycling and impurity influx. Hydrogen and metal retention in divertor floor tiles have been measured using external ion beam analysis techniques following four campaigns where tiles were exposed to several thousand tokamak discharges. The areal density of deuterium retained following exposure to tokamak plasmas was measured with external nuclear reaction analysis. External proton-induced x-ray emission analysis was used to measure the areal densities of metallic impurities deposited upon the divertor tiles either by sputtering of metallic components during discharges or as contamination during tile fabrication. Measurements for both deuterium and metallic impurities were taken on both the tile surfaces which face the operating plasma and the surfaces on the sides of the tiles which form the small gaps separating each of the tiles in the divertor. The highest areal densities of both deuterium (from 2 to 8×10^{18} atoms/cm^2) and metals (from 0.2 to 1×10^{18} atoms/cm^2) were found on the plasma-facing surface near the inner strike point region of each set of divertor tiles. Significant deposits, extending as far as 1 cm from the plasma-facing and containing up to forty percent of the total divertor deposition, were also observed on the gap-forming surfaces of the tiles.

I. INTRODUCTION

Increased understanding and control of plasma-surface interactions will be a vital issue in the success of the next generation of tokamak fusion devices such as NET or ITER. First wall surfaces of a nuclear fusion devices impact operation primarily in two main areas. The balance of incident hydrogen isotope flux onto and release from the first wall of tokamak devices, denoted as hydrogen recycling, strongly affects particle control and plasma density of a tokamak discharge. The retention of tritium in such components of future thermonuclear reactors is also undesirable. The influx of higher atomic number (high Z) impurity atoms from the first wall into the plasma causes plasma dilution and raises the effective atomic number (Z_{eff}) of the plasma, resulting in increased radiative power losses.

The relatively low average energy (~100 eV) and high flux (10^{16} cm^2/s to several A/cm^2) of the hydrogen isotopes and high Z impurities on the first wall surfaces of fusion devices create surfaces with fairly high concentration, short range, impurity profiles. This is an ideal situation for the application of ion beam analysis (IBA) techniques to the measurement of impurities (both hydrogen isotopes and high Z atoms). Doyle and Chu present an excellent review of ion beam analysis of plasma-exposed surfaces[7]. IBA methods have been used extensively in the last decade for the post-mortem examination of various components from many of the world's major tokamaks[1-6], however very few ion beam analyses of divertor components have been reported.

In this paper we report the results of analyses, for both deuterium content and higher Z (i.e. metallic) contamination, of 5 sets of lower divertor tiles removed from DIII-D following 4 different operational campaigns covering the period from February 1986 to December 1989.

II. DESCRIPTION OF DIVERTOR AND TILES

The DIII-D tokamak is a versatile device capable of inside or outside limiter, and single or double-null divertor discharges. The lower divertor is composed of 6 concentric rows of tiles encircling the bottom of the tokamak center post. The innermost row of tiles are slanted at a 45° angle between the center post and the next outermost tile row of the divertor floor.

The divertor tiles extend from the centerpost to a radius of 1.8 m with a total surface area of ~7.9 m^2; accounting for approximately 0.11 of the inner surface area in DIII-D. Tiles in the lower divertor floor of DIII-D are separated by gaps approximately 5 mm wide.

A. Description of the 1987 tile set

The 1987 tile set was removed from DIII-D in November, 1987 after 21 months of service in the machine and 5500 plasma discharges. Twenty tiles were examined with IBA techniques, including two subsets of six tiles each of which were contiguously situated along a radial line in the divertor; one subset at the 160° toroidal position, the other at the 297° position in the divertor. Both subsets include the 45° angle tile and 5 tiles from the divertor floor. The plasma-facing surfaces of the tiles in the two inboard and two outboard divertor rows are composed of 1.4 cm thick POCO graphite tiles brazed onto Inconel armor tiles. Tiles in the two central divertor rows have Inconel plasma-facing surfaces. During the 1987 set's tenure inside DIII-D approximately 15% of the inner surface area of the device was covered with graphite.

B. Description of the 1988 and 1989 tile sets

The 1988 tile set was in service during 1000 plasma discharges in DIII-D between January to June 1988. The 1989 tile set saw use over the course of 3500 discharges during the period from July 1988 to March 1989. Both sets are composed of UCAR-1792 graphite tiles (~5 cm thick) from the 67° toroidal position in the lower divertor. The 1989 set includes the 45° angle tile and all 5 outer divertor tiles. The 1988 set lacks the radially outermost tile but includes the two lowest centerpost tiles from the same toroidal position. Following the insertion of other graphite tiles into the device in January 1988 40% of the inner surface of DIII-D was covered with graphite.

C. Description of the 1990 tile sets

Two separate sets of 5 cm thick UCAR-1792 graphite tiles placed in DIII-D in March 1989 were removed in December 1989 following exposure to ~2000 discharges. Both sets include 6 tiles (the 45° tile and 5 divertor floor tiles) positioned contiguously at two different toroidal angles in the divertor. One set is from the 97.5° position, the other from the 105° line. Throughout the tenure of both 1990 tiles sets 40% of the interior of DIII-D was covered with graphite tiles. During the last month of the campaign DIII-D underwent a carbonization process which deposited a thin amorphous layer of carbon over the entire interior of DIII-D[8].

III. ANALYSES

All of the tiles were analyzed using the external microbeam facility developed at Sandia National Laboratory[9]. A new sample stage provides the capability of handling a variety of sample shapes and sizes with a positioning accuracy of better than ±5 μm. The principal advantages of the external beam technique are rapid sample setup and change-over, and the ability to handle even very large samples non-destructively. The last point has been important to the DIII-D experiment in the past since there are a limited number of replacement tiles available.

Analysis spot sizes on the order of 1 mm at a distance of 1 cm from the exit window foil are achievable. Line scans consisting of analysis points at 0.5 or 1 cm intervals along the toroidal centers of each tile set were performed upon the plasma-facing surfaces of each tile. Other line scans starting near the plasma-facing surface and extending toward the divertor floor using 0.5 or 0.2 cm intervals between analysis points were performed on the edges of some of the tiles. Point, and occasionally line scan analyses were also performed upon the bottom of the tile feet, i.e. upon the mounting surfaces which were not exposed to the plasma but instead were in contact with the tokamak floor. Figure 1 displays a set of the typical sort of analyses scans on a tile from the third divertor row.

A. External Nuclear Reaction Analysis (X-NRA) for deuterium

The $D(^3He,p)^4He$ reaction was used to measure the deuterium (D) content. Incident ion energy was controlled by varying the distance between the sample and the beam exit window as discussed elsewhere[10]. The areal density of deuterium in the sample was determined using a technique developed at Sandia[5,11] which averages two "apparent" areal density measurements obtained with 750 and 1800 keV ^3He ions. The measurements were calibrated using standards composed of thin, stoichiometric layers of ScD. This technique has an accuracy of better than 20% for D profiles which decay exponentially in depth (which has been shown to be the case for our earlier DIII-D data[10] and is assumed to be the case here) as long as the e-folding length of the depth profile does not exceed 5 μm.

B. External Particle Induced X-ray (X-PIXE) Analysis for metals

PIXE provides a sensitive measure of the elemental areal densities of metals present in up to the first hundred microns of a sample. 4.5 MeV protons extracted through a thin stainless steel exit window were used to analyze the tiles for impurities such as Ti, Cr, Fe, Ni, Cu, and Mo. The impurities were assumed to be in the relatively thin layer of material deposited on the tiles during tokamak operation. The depth probed is greater than the thickness of the deposited layer and therefore thin target standards were used to calibrate the PIXE analyses.

IV. RESULTS AND DISCUSSION

The results of line scans for deuterium on the plasma facing surfaces of the divertor tiles from all sets examined are presented in figure 2 as plots of measured deuterium areal density versus major radial position along the divertor. All the tile sets except one experienced a similar pattern of deuterium deposition; a high amount of D deposition on the inboard portion of the divertor between 110 and 130 cm major radius, decreasing deposition on the central tile rows of the divertor, and again a slightly increasing D retention on the outboard divertor tile row. This pattern is consistent with particle flux measurements made in the divertor region of

DIII-D which show that for single null diverted discharges in DIII-D, the highest particle fluxes are in the region of the inner strike point of the plasma. Note that the amount of D measured on the inner strike point area of the 1990 tile sets (~$8x10^{18}$ D/cm^2) is 2 to 3 times higher than was measured on the 1989 and 1988 tile sets. Near the end of the 1990 campaign the DIII-D tokamak was carbonized; the entire inner surface of the torus was covered with a thin amorphous carbon film. DIII-D performance was noticeably improved by carbonization for up to 40 discharges and it is possible that the higher amounts of retained D are a result of higher power discharges and sweeping of the strike point across the divertor[8].

The 1987 tile set from the 159° toroidal position exhibits a totally different pattern of deuterium retention. The inner region of the divertor exhibits a two peaked structure of D retention. No explanation for this pattern has been discovered, although it has been suggested that a misaligned junction between two tiles in the inner divertor region could cause such a pattern by creating a relatively high point (low deposition/high erosion area) surrounded by low areas (high deposition/low erosion).

Figure 3 shows the results of similar scans made across the plasma facing surfaces for metals. In the 1989 and 1990 tile sets, while the total amounts are much less (~$1x10^{18}$ D/cm^2), the deposition patterns for metals are similar to those of deuterium for the same tiles, although the radial variation is not as great. This is not the case for the 1988 tile set which exhibits virtually no radial variation in metal deposition, nor the 1987 tile set which has a metal deposition pattern completely different from that for deuterium. In the 1987 tile set on measurements of metal deposition could be made on the two central tile rows due to their metallic (Inconel) surface. The 1989 and 1990 data suggests that codeposition of deuterium and metals (and probably carbon) as has been observed on limiters from other tokamaks[1] may be occurring on the divertor of DIII-D as well, but the overall data from the four campaigns is not definitive.

The high level of metallic deposition seen on the 1987 tiles is due to the large amount of metal surface area (~85%) exposed in the tokamak during that campaign and the large number of discharges (~5500). Relatively low levels of metals were deposited on the 1988 tile set, and in fact, most of the metal detected on the 1988 set is believed to be due to manufacturing contamination of the UCAR-1792 tiles. Visual examination of the 1988 tiles discovered a large number of embedded metallic particles distributed over all the surfaces of the tiles, including surfaces not exposed to deposition during operation of the machine (e.g. mounting surfaces, tile bottoms). X-PIXE analysis revealed the particles to be iron based; they were not visible on any of the other tile sets.

The data from two different toroidal positions in both the 1987 and 1990 campaigns does not indicate large toroidal differences in metal deposition on the lower divertor of DIII-D. This agrees with the previously reported results of in-situ beta-backscattering examinations of the divertor performed by Mills[12]. Neither does there appear to have been a large amount of toroidal variation in deuterium deposition during the 1990 campaign. Toroidal variation in deuterium deposition is seen for the the 1987 campaign, again with no known explanation for the difference from the other years.

Fairly extensive analyses for deuterium (and to a lesser extent for metals) were performed upon the non-plasma facing surfaces (edges) of the tiles from the 1990 and 1989 tile sets. In general, both D and metal deposits on the edges of the tiles decay exponentially with distance from the plasma-facing surface of the tile. This pattern is well illustrated in figure 4 by semi-log plots of D areal density versus depth below the plasma-facing surface for five different tile edges from the 1990 tile sets. The slopes of the deposit profiles are similar in most cases, yielding e-folding lengths on the order of half a centimeter for deposition on the edges.

On the inner three divertor tile rows the two toroidal edges of each tile experienced nearly identical amounts of deuterium deposition, while on the outer three rows the relative deposition on the two edges varied with no discernible pattern. Also, the deposited areal density of D on the toroidal edges of a tile was roughly proportional to, and greater than, that on the same tile's plasma surface. This is not the case for the radial tile edges where deuterium deposition on the outer radial edge of each tile was two to three times greater than that on the inner radial tile edge. The pattern of deposition on the outer poloidal tile edges was nearly opposite that of plasma surface deposition, with the greatest amounts deposited on the outermost divertor tile rows. Deposition on the inner radial tile edges was fairly constant with radial tile position.

One notable aspect of the edge analyses for metals deposition on the 1990 tile sets was the increase of Fe deposition, relative to the total deposition of other metals, with distance from the plasma surface as illustrated in figure 5. No Fe particles were visible on the 1990 tiles (as were on the 1988 tiles), but since an actual increase in Fe deposition with distance from the plasma is highly unlikely, these results suggest that Fe is present in the matrix of the graphite tiles in amounts around $5x10^{16}$ atoms/cm^2. Since the tiles were not examined for metals prior to use in DIII-D exposure to the tokamak operation can not be ruled out as the source of the Fe, but contamination in the manufacturing process seems a more likely possibility. This suggests a possible use for X-PIXE as a quality control check for graphite manufacture (indeed following the analyses of these DIII-D tiles X-PIXE was used to identify high levels of Cr contamination on newly produced carbon-fiber composite tiles for the inner bumper limiter of the Tokamak Fusion Test Reactor (TFTR)).

The elemental composition of the metals deposited on or near the plasma-facing surfaces of tiles in DIII-D is nearly constant. 58% Ni, 18% Cr, and 12% Fe, with the remaining 12% a combination of Ti, Mo, and Cu. This composition indicates that Ni-rich Inconel is the main source for metallic contamination of the divertor in DIII-D. This is as expected since those portions of the interior of DIII-D not covered with graphite are of Inconel construction.

The measured D areal densities on the divertor tiles can be used to estimate the total number of deuterium atoms on the DIII-D lower divertor. Toroidal symmetry for D deposition on the plasma-facing surface of the divertor is assumed. The average of areal densities measured along the two line scans performed at two different toroidal tile sets from 1990, multiplied by the area of the lower divertor surface (~7.9 m^2) yields an estimate of $1.73x10^{23}$ D atoms on the plasma-facing surface of the lower divertor. D areal densities from the edge scans of the 1990 tile sets, multiplied by the size of each edge and the total number of edges in each divertor row were used to predict the total number of D atoms on the edges of tiles in the lower divertor: $1.16x10^{23}$ D atoms. Thus the total amount of D retained on the lower divertor of DIII-D after the 1990 campaign is estimated to be nearly $2.9x10^{23}$ D atoms with an uncertainty on the order of ±50%. This is equivalent to a divertor inventory of nearly 0.73 grams of tritium assuming 1990 to be a DT plasma campaign.

The total number of metal atoms on the plasma-facing surface of the lower divertor can also be estimated by similar means. Again using the data from the 1990 tile sets it estimated that $2.95(\pm 1.4)\times 10^{22}$ metal atoms have been deposited on the divertor surface in 1990. This is equivalent to ~2.74 g of Fe.

V. CONCLUSIONS

X-IBA techniques have been used to obtain numerous measurements of areal densities of metals and D deposited on lower divertor tiles removed from the DIII-D tokamak over the last three years show a fairly consistent pattern of deposition. Deposition is high on the inboard tile rows, lower in the central portion of the divertor, and increases again near the outermost tile row. The presence of this pattern in the data from three tile sets in 1989 and 1990 suggest that erosion and codeposition of carbon, D and metals as has been seen on the limiters of other tokamaks is also occurring in DIII-D. However conflicting data obtained from two earlier run campaigns precludes a definitive conclusion at this time. The deposited metals were composed of 58% Ni, 18% Cr, and 12% Fe. The remainder of the metal deposition was a mixture of Ti, Mo and Cu. This composition indicates that Inconel is the main source of metals in DIII-D. High levels of Fe (5×10^{16} atoms/cm^2) found on areas of the tiles which should not have been affected by operation of the tokamak indicate that Fe contamination on the tiles has possibility occurred during manufacture. Analyses of the nonplasma-facing edges of the tiles indicate that deposition on these edges decreases exponentially with distance from the plasma, and that nearly as much D is deposited in the gaps between tiles (1.16×10^{23} D atoms) as on the plasma-facing surfaces (1.73×10^{23} D atoms) of the divertor. This result could have serious implications for the design of divertors for future devices such as ITER. Obviously the larger the number of gaps or crevices in the design, the more deuterium (or tritium) will be retained in the divertor.

ACKNOWLEDGEMENTS

D.S. Walsh is under contract to Sandia National Laboratories and is supported by the U.S. Department of Energy, Office of Fusion Energy, under contract no. DE-AC04-76DP00789.

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FIGURE CAPTIONS

1. Typical analysis scans performed on the divertor tiles. The tile pictured is from the third divertor row. The arrows indicate the scans.

2. The results of X-NRA scans for deuterium across the plasma-facing surface of five tile sets from four different DIII-D campaigns plotted versus radial position in the tokamak. Tiles were aligned such that the scans were along a straight line at the indicated toroidal positions.

3. The results of X-PIXE scans for metals across the plasma-facing surface of five tile sets from four different DIII-D campaigns plotted versus radial position in the tokamak. Tiles were aligned such that the scans were along a straight line at the indicated toroidal positions.

4. Semi-log plots of measured deuterium areal density versus distance from the plasma-facing surface on the edges of five different divertor tiles from the 1990 tile sets. The straight line slopes indicate an exponential deposition profile.

5. Plot of the relative composition of metal deposition on a toroidal edge of a row 5 tile from the 1990 105° toroidal position set. Note the relative increase of Fe in the deposit as a function of distance from the plasma. This suggests Fe contamination in the graphite matrix.

ARROWS INDICATE SCAN DIRECTION

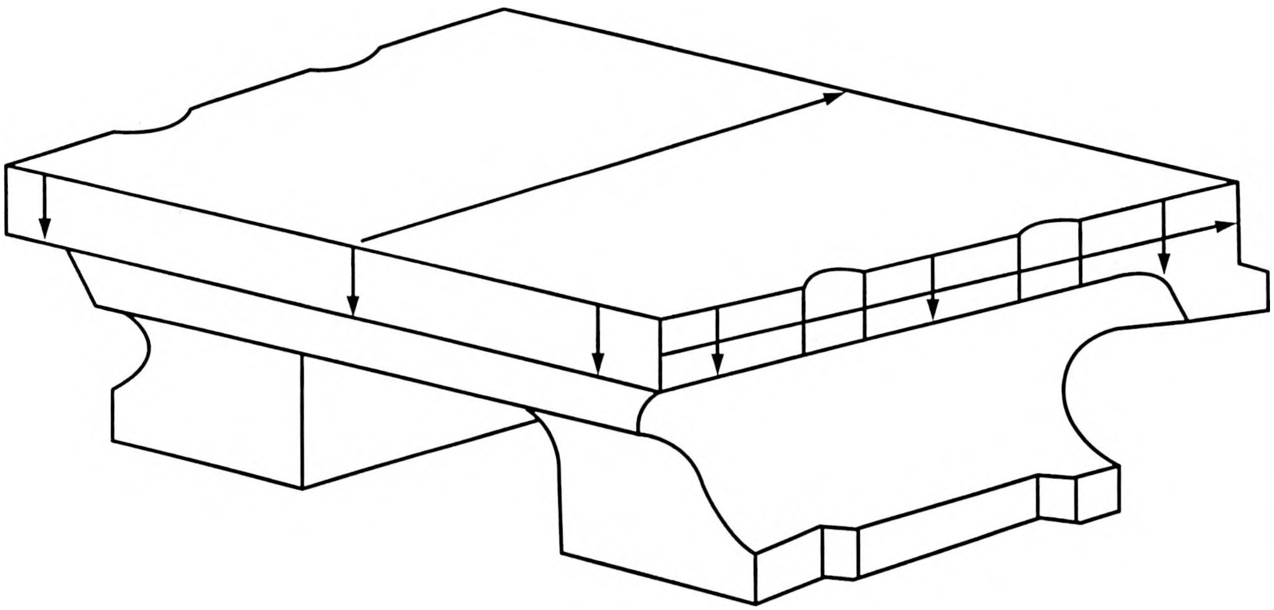

figure 1

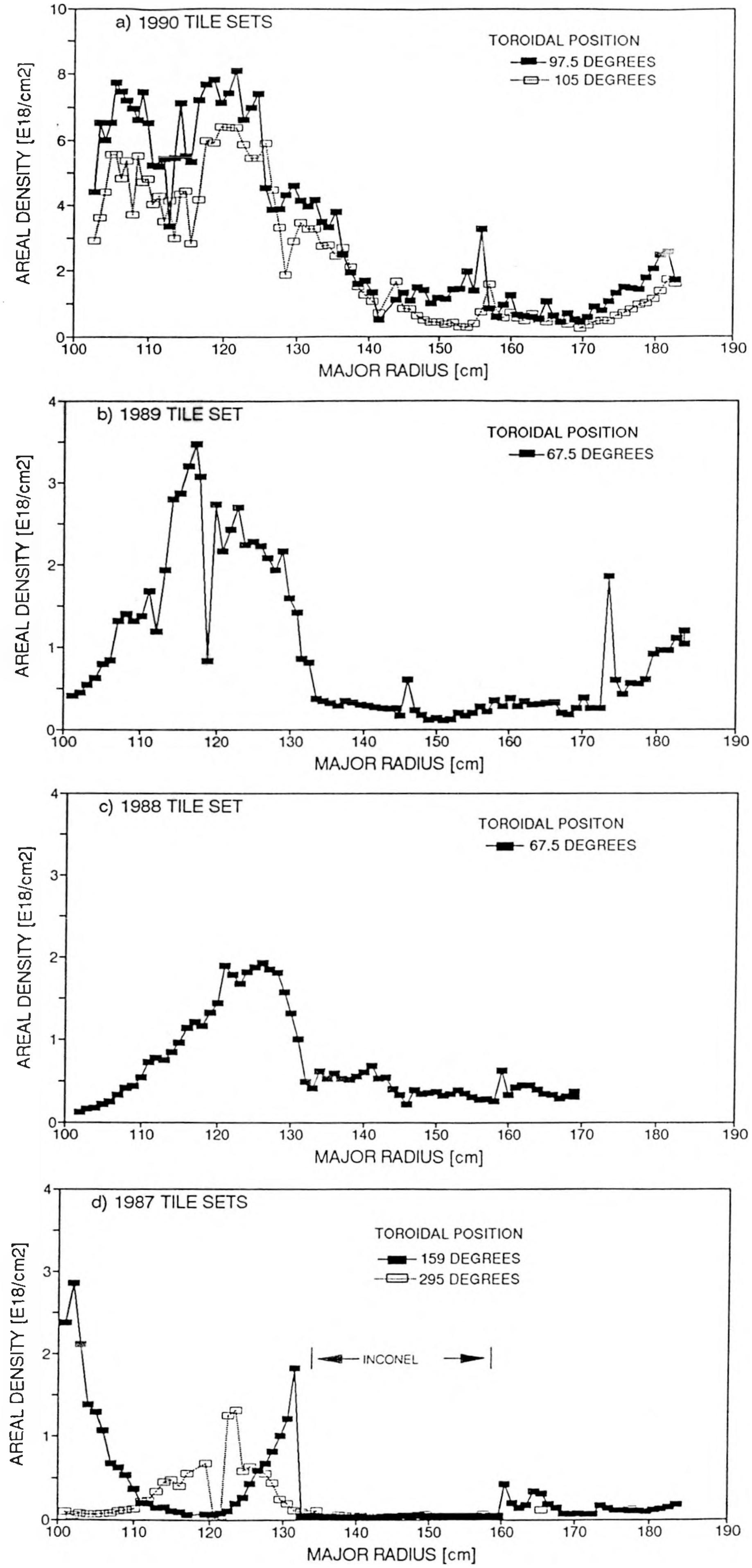
a) 1990 TILE SETS
TOROIDAL POSITION
97.5 DEGREES
105 DEGREES
AREAL DENSITY [E18/cm2]
MAJOR RADIUS [cm]
b) 1989 TILE SET
TOROIDAL POSITION
67.5 DEGREES
AREAL DENSITY [E18/cm2]
MAJOR RADIUS [cm]
c) 1988 TILE SET
TOROIDAL POSITON
67.5 DEGREES
AREAL DENSITY [E18/cm2]
MAJOR RADIUS [cm]
d) 1987 TILE SETS
TOROIDAL POSITION
159 DEGREES
295 DEGREES
INCONEL
AREAL DENSITY [E18/cm2]
MAJOR RADIUS [cm]

Figure 2

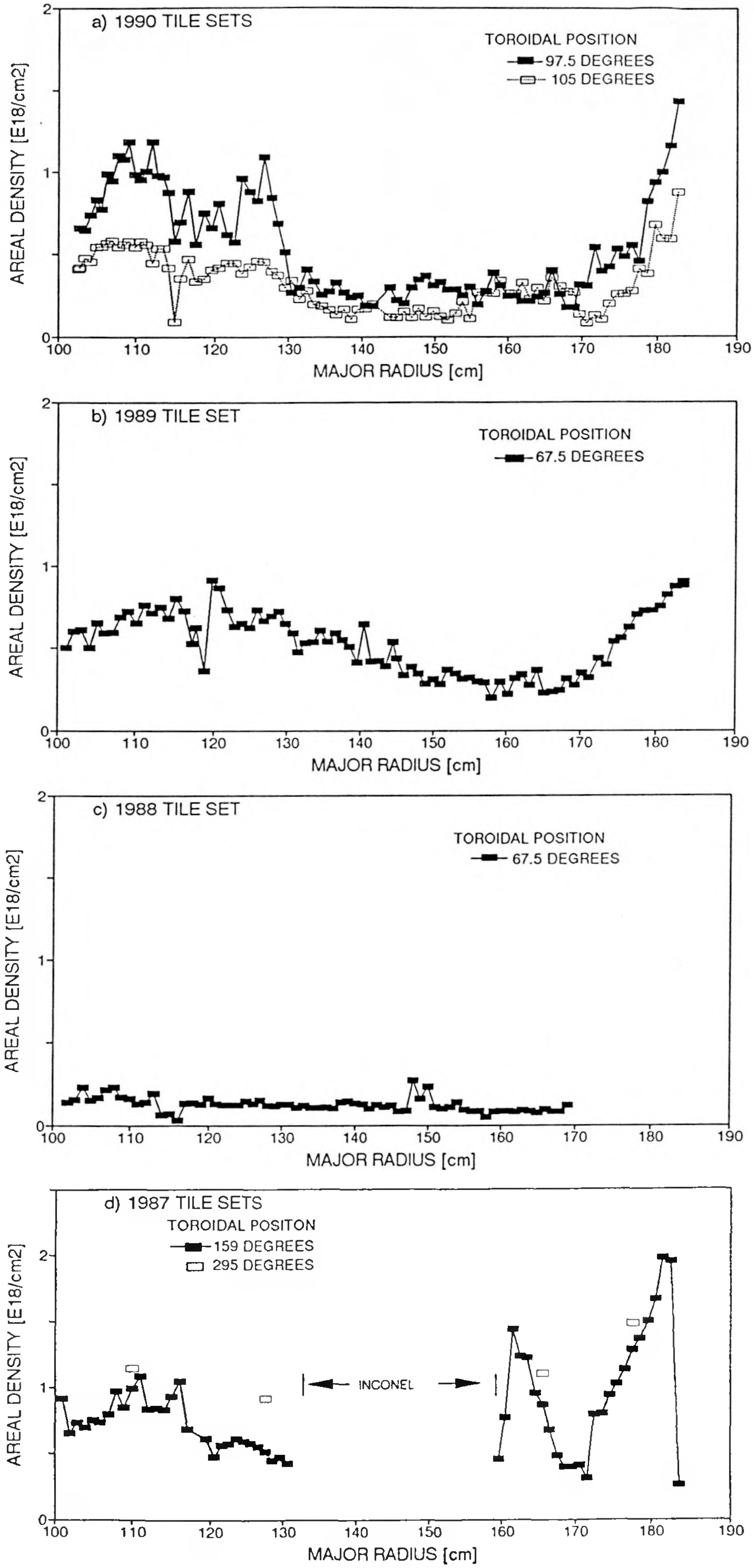
a) 1990 TILE SETS
TOROIDAL POSITION
97.5 DEGREES
105 DEGREES
AREAL DENSITY [E18/cm2]
MAJOR RADIUS [cm]
b) 1989 TILE SET
TOROIDAL POSITION
67.5 DEGREES
AREAL DENSITY [E18/cm2]
MAJOR RADIUS [cm]
c) 1988 TILE SET
TOROIDAL POSITION
67.5 DEGREES
AREAL DENSITY [E18/cm2]
MAJOR RADIUS [cm]
d) 1987 TILE SETS
TOROIDAL POSITON
159 DEGREES
295 DEGREES
INCONEL
AREAL DENSITY [E18/cm2]
MAJOR RADIUS [cm]
0
1
2
100
110
120
130
140
150
160
170
180
190

Figure 3

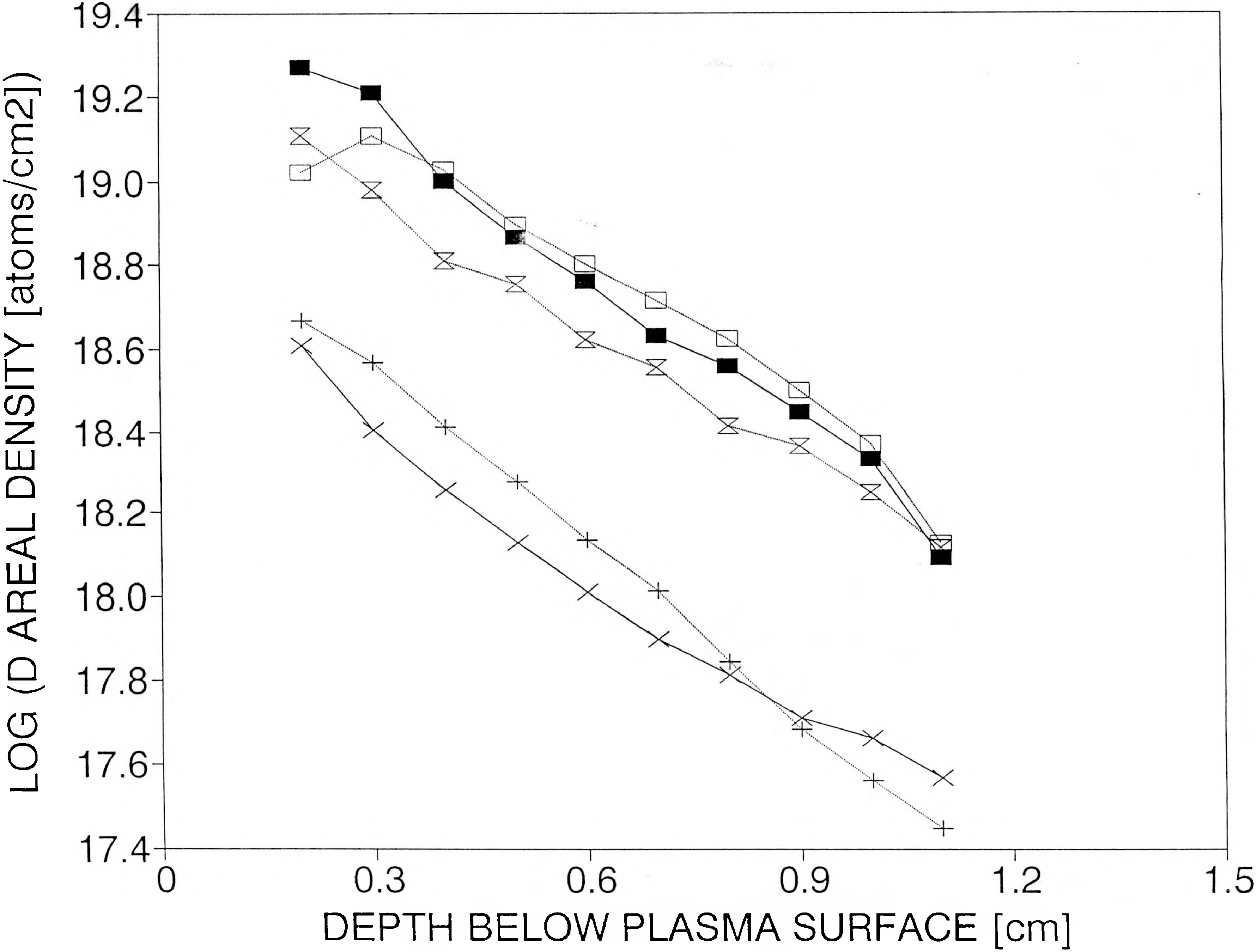
19.4
19.2
19.0
18.8
18.6
18.4
18.2
18.0
17.8
17.6
17.4
LOG (D AREAL DENSITY [atoms/cm2])
0
0.3
0.6
0.9
1.2
1.5
DEPTH BELOW PLASMA SURFACE [cm]

Figure 4

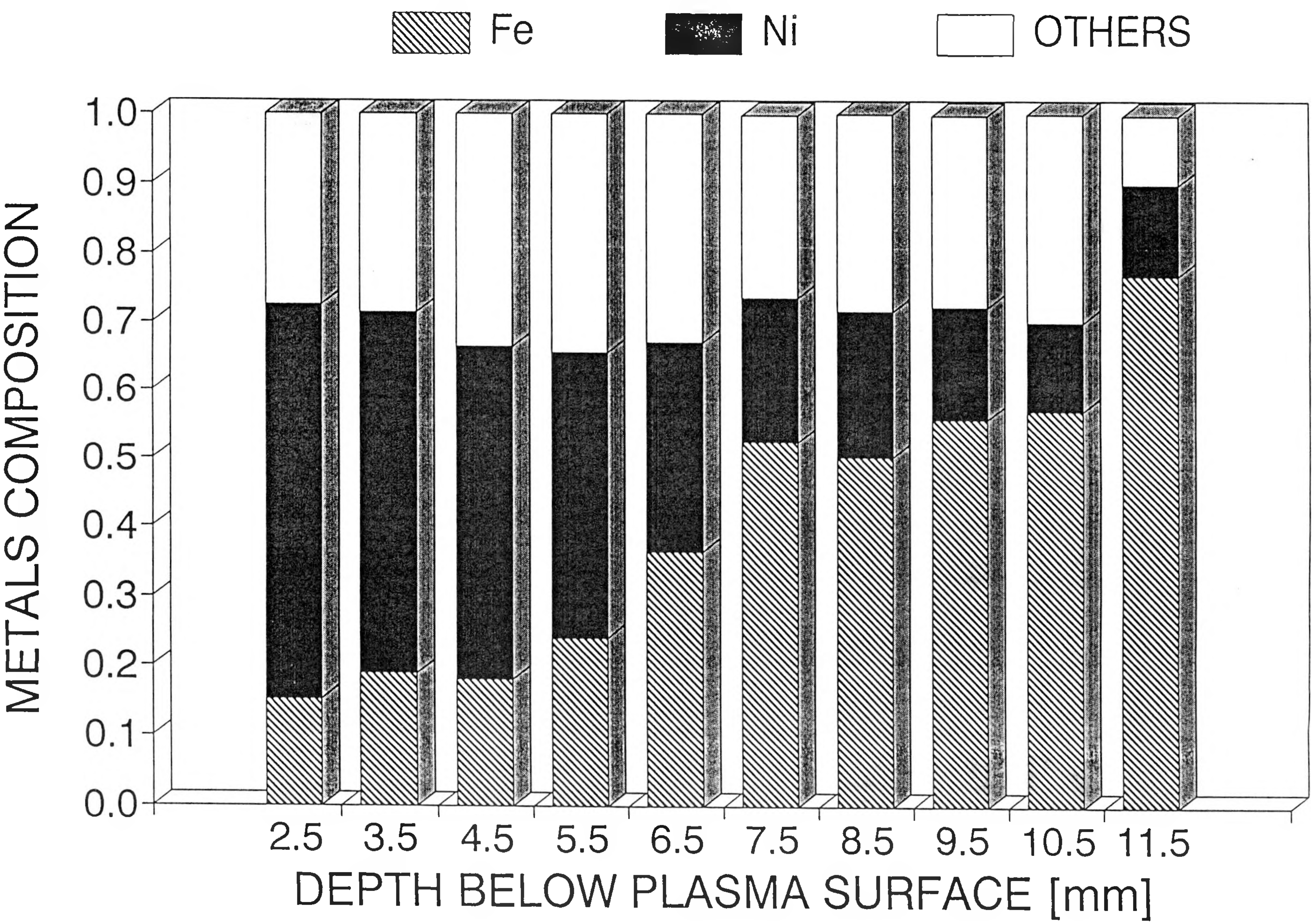
Fe
Ni
OTHERS
METALS COMPOSITION
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
2.5
3.5
4.5
5.5
6.5
7.5
8.5
9.5
10.5
11.5
DEPTH BELOW PLASMA SURFACE [mm]

Figure 5