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POSTMORTEM NEAR SURFACE ANALYSIS OF BERYLLIUM LIMITER TILES FROM ISX-B

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ABSTRACT

Beryllium is a promising material for plasma-side components in magnetic confinement fusion devices and is being considered for possible use in the Joint European Torus (JET). In order to test beryllium as a limiter material, a collaborative JET/ISX-B experiment was carried out in which the ISX-B tokamak was operated for more than 4000 discharges with a beryllium limiter. At the end of the test period the limiter was removed and the composition of the near-surface region of selected tiles was analyzed as a function of position by Rutherford backscattering. The amount of deuterium retained near the surface was measured by nuclear reaction analysis. Chromium, iron, and nickel were the dominant metallic impurities in the surface with a combined concentration on the order of 10^{16} cm^{-2}. Oxygen surface coverages were generally in the mid-10^{16} cm^{-2} range. A consistent trend in the impurity data was that heavily damaged or melted areas generally incorporated more impurities. The amounts of deuterium trapped in the tiles ranged from 1 to 5×10^{17} cm^{-2} over all of the surfaces exposed to the plasma. No deuterium was detectable on surfaces (the protected sides) not directly exposed to the plasma.

I. INTRODUCTION

Beryllium is being considered as a material for the fabrication of plasma-side components in magnetic confinement fusion devices.[1] It has

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the advantages of low z, high thermal conductivity, good thermal shock resistance, and low self-sputtering rates. On the negative side, there are health hazards associated with the handling and fabrication of beryllium, and its melting point is relatively low (1283°C). In order to study the application of beryllium to a tokamak environment, a joint JET/ISX experiment was carried out in which the ISX-B tokamak was operated for an extended period with a beryllium limiter. A complete description of the experiment and its results has been published elsewhere.[2] At the completion of the experiment, the limiter was removed and its surface composition was analyzed using accelerator-based techniques. The results of these analyses are presented in this paper.

II. EXPERIMENTAL PROCEDURE

The beryllium limiter was made up of twelve individual beryllium tiles attached to a single movable support. The tiles were shaped as indicated in Figure 1 and had dimensions of $10.0 \times 10.0 \times 2.5$ cm^3. The surfaces facing the plasma on six of the tiles were originally smooth, while the surfaces of the other six were tessellated to minimize thermal stresses. The locations of each of the tiles relative to the plasma are shown in the figure. While installed in ISX-B the limiter tiles were exposed to more than 4000 neutral beam injected deuterium discharges. Parameters for most of these discharges were set to provide a maximum heat flux to the limiter of 2.5 kW/cm^{2}s for ~0.2s. This was within the design limits of the tiles. For 500 of the discharges, however, the heat flux was raised to 4–5 kW/cm^{2}s, which was sufficient to cause surface melting of the beryllium. This melting produced protrusions that acted as localized hot spots even at the lower power levels. Total deuterium fluence to the limiter during the test period was greater than $10^{22}/cm^2$. Upon completion of tokamak operations, the limiter was removed from the machine and three of the tiles (#2, 7, 11) were analyzed at the positions indicated in Figure 1 for near surface elemental composition using Rutherford backscattering (RBS) with 2.0 MeV ^4He and for retained deuterium using nuclear reaction analysis ($D(^3He,p)^4He$).

III. RESULTS AND DISCUSSION

The impurities found in the surfaces of the tiles were primarily the transition metals (Cr, Fe, Ni) and oxygen. Chromium was the dominant metal, probably as a result of extensive chromium gettering carried out prior to the beryllium limiter experiment. Titanium was also observed at a concentration equal to approximately 15% of the transition metal concentration, and was due to a history of titanium gettering in ISX. The amounts of the principal impurities found at each of the analyzed spots in Figure 1 are shown in Table I. Values are given for both the surface concentration (0 to 200 nm deep) and the bulk concentration (>200 nm deep). Values for the bulk concentrations are not precise because of the possible contribution that can be made to ion scattering depth profiles by surface roughness.

At almost all locations examined on the tiles there was a peak in the amount of impurities at the surface with a small but measurable concentration extending to depths beyond the limit of observation (~ 1μm). The depths at which impurity atoms are observed in the beryllium are greater than the range of such atoms at reasonable edge energies. Thus the deeper impurities could not have been directly implanted and must have been thermally driven.

The total amount of metallic impurities near the surface ranged from 0.3 to 6.0 × 10^{16} cm^{-2} except for one arc track that showed 9 × 10^{16}. Erosion appears to dominate deposition for the metals near the center of tile #7 since the largest amounts are seen near the edges. Subsurface metal impurity concentrations at depths up to 1 μm were substantially increased during beryllium limiter operation. Observed concentrations varied from a few hundreths to a few tenths of an atomic percent, which is close to the solubility limit for these metals in beryllium.

Oxygen surface coverages were generally in the mid 10^{16} cm^{-2} range. Higher values were observed for the visually damaged locations noted in the data. As was the case for the metals, oxygen concentrations below the surface increased during the test period, resulting in concentrations of 1–2 atomic percent at a depth of 500 nm, with higher values again being observed in damaged areas.

The amount of deuterium retained in the near surface region varied from 1 to 5 × 10^{17} cm^{-2} over all of the surfaces exposed to the plasma. No deuterium was detectable on surfaces (the protected sides) not directly exposed to the plasma. The largest amounts were found in regions that were visually damaged. Deuterium concentrations deeper than ~ 750 nm were not measured because of interfering nuclear reactions with beryllium that occurred at the higher beam energies required.

Clearly defined regions in which erosion or deposition dominated were not consistent over the tested regions of the limiter. This could be a consequence of the extensive thermal damage[3] which produced localized hot spots at protrusions adjacent to "cool" areas of the limiter, each of which would have shown different erosion/redepositon characteristics. The most consistent trend in the data was that heavily damaged and melted spots incorporated more impurities and deuterium.

Limiter surface composition has been studied recently on several other tokamaks. Graphite tiles from JET were analyzed by PIXE, RBS, and NRA and showed nickel (the principal component of the Inconel walls) levels ranging from 1 × 10^{16} to 3 × 10^{17} cm^{-2} and deuterium levels of 10^{16} to 10^{18} cm^{-2}.[4] The highest deuterium levels cannot be explained by implantation and trapping. The graphite rail limiter from PDX was shown to contain 2–3 × 10^{17} cm^{-2} deuterium (comparable to ISX Be tiles) and 1–4 × 10^{17} cm^{-2} iron.[5] Carbon tiles from the movable limiter in ASDEX generally showed iron concentrations of 1–6 × 10^{17} cm^{-2}.[6] In this case a major part of the deposited material was shown to be in the form of droplets with diameters up to a few microns. A SiC coated graphite tile tested in Doublet III showed measurable impurity levels at depths exceeding 5 μm,[7] well beyond the depth at which impurities were measured in the ISX Be tiles. Thus the small amounts of impurities distributed in the bulk of the Be tiles have also been observed in coated graphite tiles. The amount of other metals found on the Be limiter was generally lower than that observed on other machines. This may be explained by the fact that substantial Be was transported around the tokamak and deposited on the walls,[8] covering the stainless steel and minimizing the transport of these elements into the plasma.

IV. SUMMARY

In terms of surface impurity and deuterium content, the Be limiter in ISX-B behaved much like the more conventional materials. As in the case of other tokamaks for which the limiter surface has been analyzed, the operating surfaces of the Be limiter tiles from ISX-B were shown to contain a mixture of the elements present in the vacuum vessel. The amount of foreign metals found on the tiles was somewhat less than has been observed recently on other machines, probably due to Be coating of the walls, while the amounts of retained deuterium were generally comparable, even for different limiter materials.

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FIGURE CAPTIONS

Fig. 1 Diagram of the plasma side of the ISX-B Be limiter showing the analyzed locations and their relationship to the plasma. Also shown is the shape of the individual tiles.

Table I. Concentration of impurities and deuterium on the Be limiter tiles as measured by RBS and NRA at the positions indicated in Fig. 1.

TABLE I

Tile & Position	D	Cr Fe Ni		O	
	Surface ($10^{16}cm^{-2}$)	Surface ($10^{16}cm^{-2}$)	Bulk ($10^{19}cm^{-3}$)	Surface ($10^{16}cm^{-2}$)	Bulk ($10^{20}cm^{-3}$)
Before Installation	-	.12	2.0	3.44	6.20
2 - 1*	44.3	9.35	291.0	8.52	57.7
2	16.6	4.01	28.4	6.93	29.8
3	13.5	2.91	29.4	5.78	24.6
4	12.6	2.61	48.5	5.78	23.8
5**	63.0	4.19	87.5	8.40	76.5
6	7.6	.55	2.39	2.96	7.51
7	8.5	.86	2.83	2.97	7.98
8	10.0	.98	3.88	3.11	9.54
7 - 1	11.4	1.39	26.2	5.77	18.5
2	13.5	1.78	28.9	6.77	17.3
3	39.4	.48	3.50	9.17	46.1
4	44.6	.29	1.93	6.34	20.9
5	41.5	.30	4.86	6.17	15.4
6	31.3	.68	3.63	6.26	17.2
6***	N.A.	1.45	15.8	14.3	62.8
7	7.4	2.83	89.4	4.99	14.3
8	5.6	.57	5.35	4.97	12.8
9	18.4				
10	21.0				
11 - 1	16.5	1.65	6.87	6.57	15.5
2	13.7	.87	6.89	4.98	10.4
3	11.0	.69	5.12	5.92	13.6
4	9.9	.58	4.61	6.13	14.9
5	10.6	1.32	9.74	4.62	14.6
6	11.1	1.43	6.89	3.58	10.0
7	14.3	2.52	18.6	4.64	16.5
8	20.0	6.12	69.3	9.02	43.4

* - Arc Track
** - Damaged Region
*** - Large Droplet