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Weight Change Measurements of Erosion/Deposition at Beryllium Limiter Tiles in ISX-B

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Abstract

The weight changes of Be tiles which functioned as a rail limiter in ISX-B for more than 3500 beam-heated discharges have been determined. The net weight loss for the limiter was 2.0 g, with the central tiles losing a total of 3.2 g and the inboard tiles gaining 1.2 g. The weight loss is attributed primarily to the release of Be droplets as a result of limiter surface melting. The weight gains resulted from an inward flow of molten material along the limiter surface. The results indicate high erosion (melt loss) with incomplete and nonuniform redeposition (melt flow) of limiter material during periods of limiter melting.

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1. Introduction

The erosion of limiters and other components exposed to high particle and heat fluxes in the plasma edge of fusion devices is a major concern in component lifetime and plasma contamination. Erosion rates have been measured in a variety of fusion devices at test limiters and divertor plates using surface probes (1-5), laser-induced fluorescence (6-9), thin-layer activation (10), and isotopic markers (11). These measurements have provided localized information on erosion rates and mechanisms, but have not addressed the macroscopic, long-term erosion/redeposition behavior of limiter and divertor structures. In this paper, we report the use of weight change measurements to monitor the erosion and redistribution of limiter material at a rail limiter during three months of beam-heated operation in the ISX-B tokamak.

The weight change measurements were part of the ISX-B beryllium limiter experiment which is described in detail elsewhere (12-14). The intent of this experiment was to evaluate the performance of beryllium as a limiter material under conditions of hydrogen fluence, thermal cycling, and heat fluxes expected in breakeven machines. In particular, this experiment served as a precursor to the possible use of beryllium limiters in the European JET device. The weight change results provide quantitative information on the erosion/deposition behavior of the beryllium limiter.

2. Experimental

The limiter consisted of 12 individual beryllium tiles arranged in a rail assembly and mounted at the top of ISX-B. Each tile was approximately $10 \times 10 \times 2.5$ cm^3 and 260 g with the front surface curved to maintain a constant power loading for a power 1/e decay length of 2 cm. Half of the tiles were tessellated with a square array of 1 cm deep slots to limit surface stresses. The tessellations did not appear to influence the weight change results. Photographs of the installed limiter are shown in Figure 1 and the position of the limiter in relation to the plasma is indicated in the inset of Figure 2.

The beryllium limiter functioned as the main limiter of ISX-B for more than 3500 beam-heated discharges with typical plasma parameters I_p=116kA, B_T=11kG, $n_e=4 \times 10^{13}/cm^3$, P_B=0.8MW (0.2s), and t=0.3s. Under these conditions, the maximum power flux to the limiter was 2 KW/cm^2. Early in this sequence, the plasma current was raised to 155 kA for 300 discharges to test the limiter at higher power loads. The 155 kA discharges resulted in surface melting of the limiter (Figure 1) which had not been observed at 116 kA. The general topographic features developed on the surface during this limited 155 kA high power operation persisted throughout the experiment. The total deuterium fluence to the central 20 cm^2 of the limiter was approximately 2×10^{22} D/cm^2.

Prior to installation in ISX-B, the limiter tiles were cleaned ultrasonically in methyl alcohol and acetone, dried in a rough vacuum, and weighed to an accuracy of <1 mg using a large mechanical balance. Following completion of the experiment, the limiter was carefully disassembled and the individual tiles were placed in plastic bags which had been previously weighed. The tiles were then reweighed in the bags to insure that there was no additional loss of material due to abrasion or handling.

3. Results

The weight change results are summarized in Figure 2 and Table 1. Overall, the limiter showed a net weight loss of 2.0 g with the central tiles losing 3.2 g and inside tiles gaining 1.2 g. Surface probe measurements (15, 16) indicate that approximately 0.2 g of beryllium was uniformly distributed around the torus. The remainder of the weight loss is presumed to be in the form of small droplets of molten material which were observed on the inside wall and at the bottom of the vacuum vessel in the vicinity of the limiter. One of the central tiles (Tile 7) had been gamma activated prior to installation of the limiter (17). Activity representing approximately 0.7 g of beryllium was found on the inboard side of the limiter following the experiment. The measured weight loss of Tile 7 was 1.1 g implying that more than half of the lost material was redistributed inward along the limiter. This is consistent with the observed weight gain of the inner tiles. Examination of the photographs of Figure 1 suggests an inward directionality to the flow of molten material on the limiter surface which could account for the weight gain. Since the limiter was mounted horizontally, this flow was probably driven by electromagnetic forces.

4. Discussion

It is evident from Figures 1 and 2 that the limiter experienced substantial erosion and redistribution of material during its operation in ISX-B. Extrapolated to steady-state, the material loss at the central tiles would require daily tile replacement. Of course, this extrapolation would be unreliable if the weight loss occurred primarily during the high current discharges which resulted in limiter melting. The existence of molten flow patterns on the limiter surface and beryllium droplets on the vacuum vessel walls strongly suggests that limiter melting was responsible for much of the weight change. The observation (15, 16) that only 10% of the beryllium loss was deposited uniformly on the torus walls suggests that sputtering and evaporation were less important erosion mechanisms.

Sputtering estimates based on available beryllium sputtering data (18) suggest that a combination of deuterium sputtering and self-sputtering of the limiter could account for approximately 10% of the observed weight loss. Beryllium evaporation would contribute less than 1% of the weight loss for a plane limiter surface, but could be significantly enhanced at local hot spots created by protrusions in the melted region with reduced thermal contact to the bulk. There is evidence from spectroscopy (12) that the beryllium content in the plasma was much higher after the initial surface melting than before the melting for similar discharges. The beryllium density in the plasma steadily increased as the base limiter temperature increased, further indicating the importance of thermal processes (12) in impurity introduction.

Implantation of deuterium and impurities (19) is insufficient to account for the observed weight gain of the inner tiles, but could contribute to the small weight gain of the outer tiles. It is apparent from the directionality and volume of the inward flow of molten material on the limiter surface that limiter melting during the period of high current operation was responsible for most of the beryllium redistribution. This horizontal flow suggests a position instability for the melt layer due to electromagnetic forces which could contribute significantly to local erosion during fault conditions (such as disruptions) which result in surface melting.

5. Conclusions

This paper summarizes the results of weight change measurements which were performed on the individual segments of a beryllium rail limiter during extensive beam-heated operation in ISX-B. Substantial erosion and redistribution of limiter material was observed, with the central tiles losing a total of 3.2 g and the inner tiles gaining 1.2 g. The weight loss is attributed primarily to the release of beryllium droplets following surface melting during high current operation. An inward flow of molten material along the limiter surface accounted for most of the weight gain. This suggests a position instability for the melt layer. Overall, the results indicate high erosion (primarily melt loss) and incomplete and non-uniform redeposition (primarily melt flow) of limiter material for conditions which involve periods of limiter surface melting. The results also establish the usefulness of weight change measurements for monitoring long-term erosion/deposition behavior of limiters and other plasma edge components.

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Table 1. Summary of Weight Change Results

Tile Number	Installed Weight (g)	Weight Change (g)
1 (inside)	260.8242	+0.0957
2	266.2631	+0.0400
3	260.5752	+0.8826
4	267.1097	+0.1462
5	261.0954	-0.8961
6	266.5720	-0.7425
7	260.6792	-1.1108
8	260.4349	-0.3235
9	260.5964	-0.0895
10	266.3416	-0.0092
11	259.5123	+0.0026
12 (outside)	266.9151	+0.0011

Figure Captions

Figure 1 Photographs of the beryllium limiter before operation in ISX-B (top), following a period of high current operation which resulted in surface melting (center), and at the end of the experiment (bottom). Note that topographic features developed during the high current operation continue to be recognizable after more than 3500 beam-heated discharges.

Figure 2 Weight change of the individual beryllium tiles as a function of their radial position. The location of the limiter with respect to the plasma is indicated in the inset.

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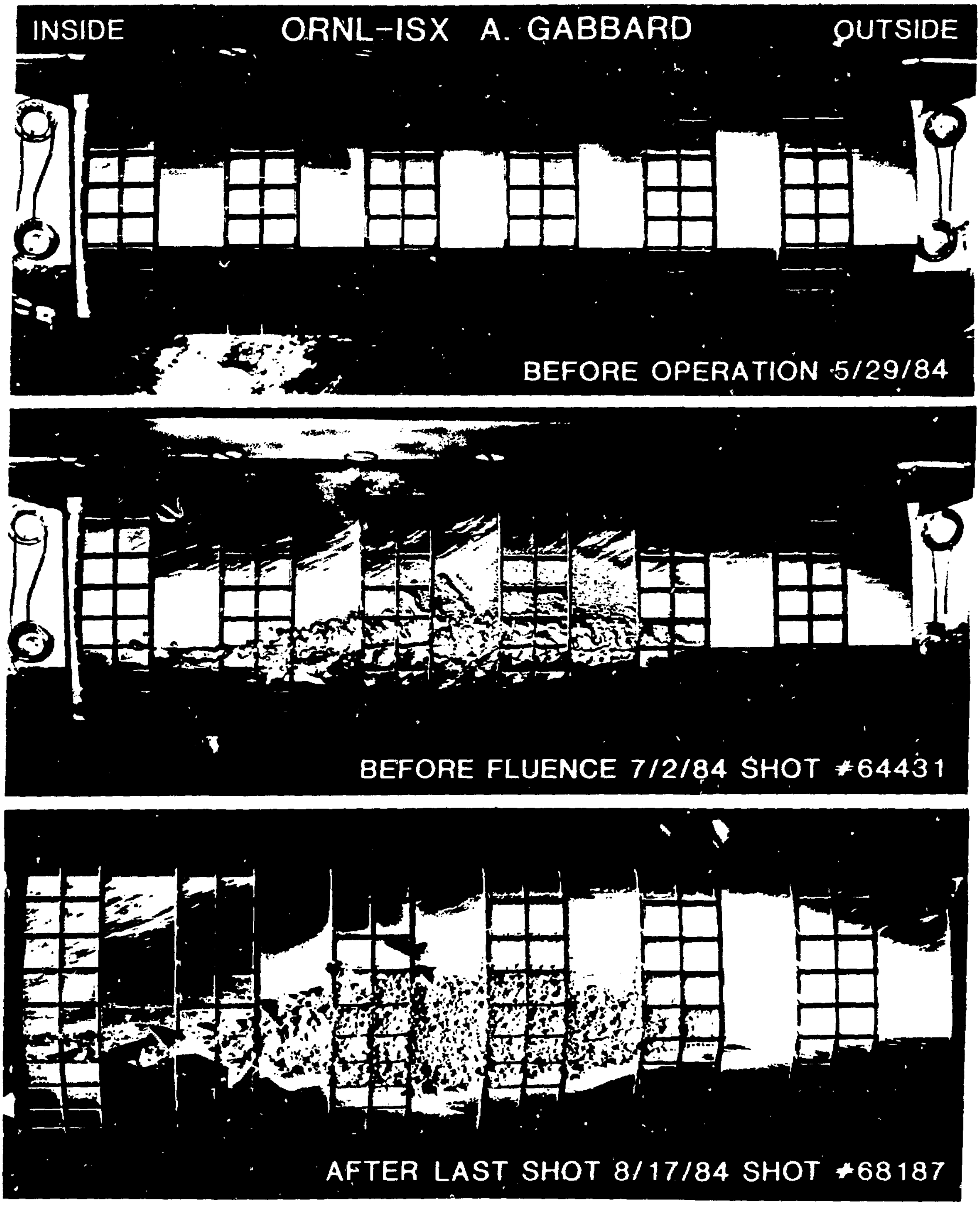

Figure 1

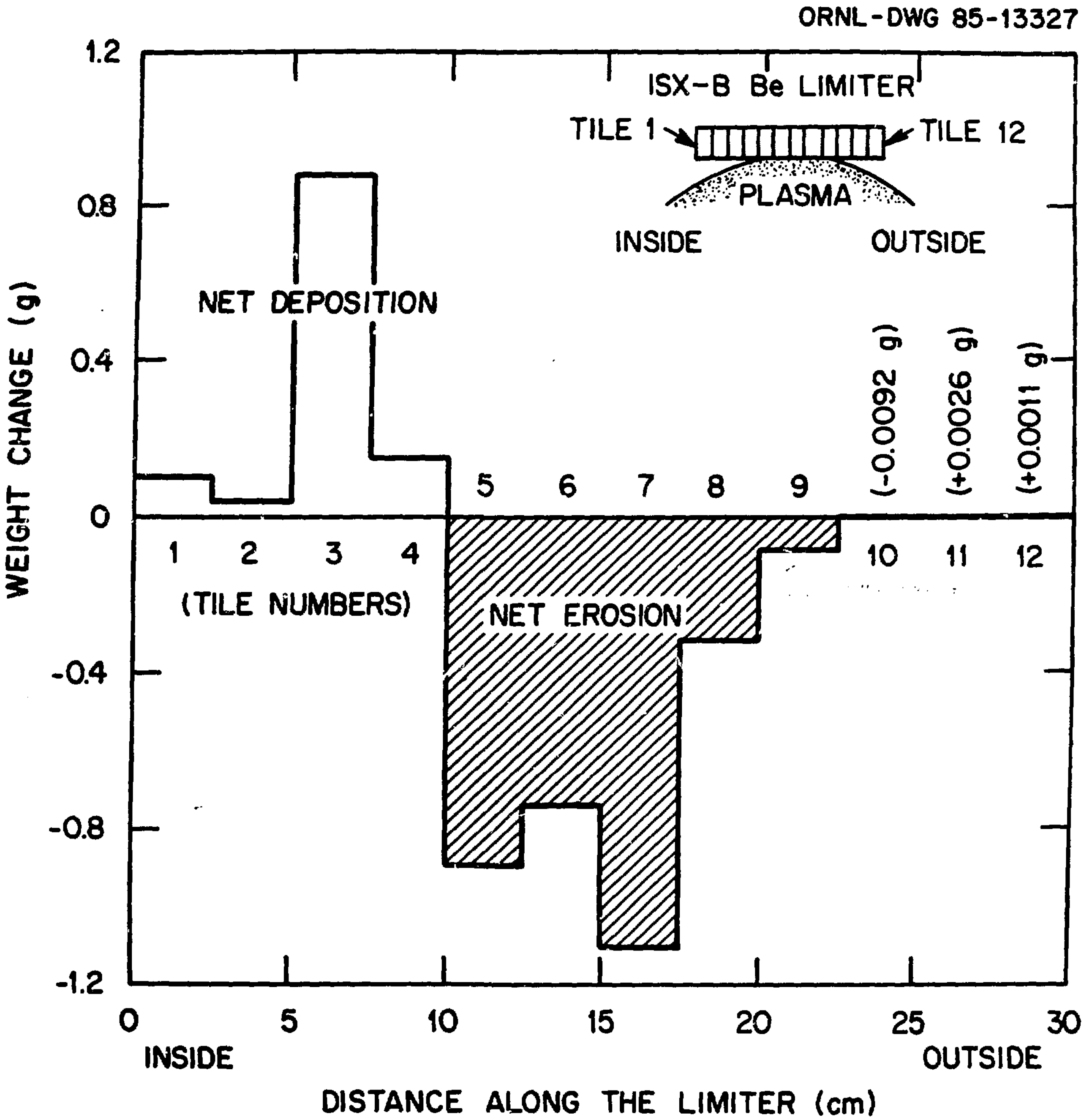
ORNL-DWG 85-13327
ISX-B Be LIMITER
TILE 1
TILE 12
PLASMA
INSIDE
OUTSIDE
NET DEPOSITION
NET EROSION
(TILE NUMBERS)
1
2
3
4
5
6
7
8
9
10
11
12
(-0.0092 g)
(+0.0026 g)
(+0.0011 g)
WEIGHT CHANGE (g)
1.2
0.8
0.4
0
-0.4
-0.8
-1.2
0
5
10
15
20
25
30
INSIDE
OUTSIDE
DISTANCE ALONG THE LIMITER (cm)

Figure 2