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Application of tungsten for plasma limiters in TEXTOR

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Abstract

Three different types of W limiters were exposed in the TEXTOR plasma and the response of the plasma and materials performance of the limiters were investigated.

1. A W bulk limiter operated with preheating above 800 K withstood a plasma heat load of about ~20 MW/m^2 for a few seconds with some slight surface melting during the highest heat load shot. However, it was severely damaged when operated at around 500 K.
2. A C/W twin test limiter, half made of bulk W and the other half of graphite (EK-98) gave very useful information on how low- and high-Z materials behave under conditions of simultaneous utilization as PFM such as cross-contamination and the influence of a large mass difference on hydrogen reflection and deposition.
3. Two sets of main poloidal W limiters made of vacuum vapor sprayed (VPS)-W deposited on graphite (IG-430U) with a Re interlayer could absorb about 60% of the total convection heat and the ohmic plasma with a density as high as 5×10^{13} cm^{-3} was sustained. Most of the VPS-W coated limiters tolerated a heat load of ~20 MW/m^2.

This series of W limiters experiments in TEXTOR has shown that W is applicable as a PFM, if its central accumulation is avoided by NBI and/or ICRH heating. Nevertheless, some concerns still remain, including difficulty of plasma start-up, W behavior in higher temperature plasmas, and materials' selection. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

Recent extensive studies on high-Z materials in TEXTOR [1–9], ASDEX-U [10] and Alcator C-mod [11] have shown that the plasma does not collapse due to high-Z accumulation so long as the sputtered high-Z atoms do not penetrate deep into the plasma. Because of its brittleness, however, a question still remains on what types of W materials are suitable as PFM. In this study, three different types of W limiters have been exposed in TEXTOR plasmas and the response of the plasma and the material performance of the limiters were investigated. They are (1) a bulk W-test limiter, (2) a C/W twin test limiter, half made of bulk W and the other half of graphite (EK-98), and (3) main poloidal W limiters. After the plasma exposure, the limiter surface was analyzed by various techniques including RBS, NRA, SIMS, AES, XPS and so on. Since the behavior of W impurity and its accumulation in the plasma center have been reported elsewhere [12,13], the present paper focuses on the material properties of W exposed to the plasma.

2. Experimental setup

The experimental setup is schematically shown in Fig. 1 for both the test limiter and main poloidal limiters.

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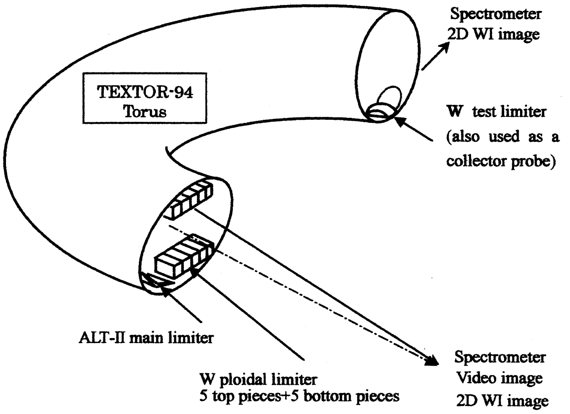

Fig. 1. Schematic of the experimental setup.

Two different kinds of test limiters were tested; one a bare (pure) W limiter cut from W block manufactured by powder metallurgy and the other was a C/W twin limiter in which one half of the limiter was made of W the same material used as the pure tungsten limiter and the other half, graphite (EK-98). The whole test limiter was 120 mm × 80 mm in toroidal and poloidal directions, respectively, with mushroomed or spherical surface. It was inserted from the bottom or top into the TEXTOR-94 edge plasma through a limiter-lock manifold. In the case of the C/W twin limiter, the entire limiter could be rotated to change the tungsten and graphite faces to either the ion-drift-side or the electron-drift-side.

Two W main poloidal limiters were made of five pieces of vacuum plasma sprayed (VPS)-W coated graphite (IG-430U) with rhenium (Re) interlayers (supplied by Plansee). They were $180 \times 3.5 \times 80$ mm^3 (length × width × height) and had curved surfaces. They were inserted from both the bottom and the top of the plasma (See Fig. 1). The coating technique applied was the same as that used in the W coated divertor tiles of ASDEX-Upgrade [14].

The TEXTOR-94 plasma was operated with a plasma current of 360 kA, a 2.25 T toroidal magnetic field, and 6 s discharge duration. Neutral beam injection (NBI) heating with a power of 1.4 MW was applied to the plasma for 2 s. The plasma main radius was limited to be 46 cm by an ALT-II toroidal belt-limiter made of graphite.

Surface processes were observed by spectroscopy, by monitoring line spectra of W and C neutral species. Radial distributions of spectra line intensities emitted from ions and neutrals around the test limiters were measured by an image intensified CCD-camera coupled to a monochromator. The spectra were recorded in the wavelength range from 409 to 435 nm where we observed CII (426.7 nm), WI (429.5 nm), Dγ (434.0 nm) and OII (434.6 nm). The two-dimensional intensity distribution of WI and Dα emissions were observed from the direction tangential to the limiter surface with another CCD-camera through interference filters at 400.8 nm for W, and 656.3 for Dγ with 1.5 nm band width. The third CCD-camera viewed the limiter surface from the bottom through an infrared transmission (850–1100 nm) filter to construct the temperature distribution on the limiter surface. Thermocouples were inserted into drilled holes in both the test limiter and the poloidal limiters to monitor the temperature increase to estimate the heat deposition. After plasma exposure, the contaminated limiter surface was analyzed by various techniques including RBS, NRA, SIMS, AES. Details of the surface analysis are given elsewhere [7,8].

3. Results and discussion

For all three types of limiters, W impurity accumulation at the plasma center in high density ohmic shots was appreciable, and it has been interpreted by neoclassical transport to be caused by a density gradient [12,13]. The present paper focused on the behavior of the limiters themselves during plasma exposure and the results of postmortem analysis.

3.1. Bare W-test limiter

Two different shapes of the bare W limiter were tested and the results have been reported elsewhere [4–6]. Both limiters had the same effect on the plasma.

Effective tungsten sputtering yields extend from about 3% at low plasma densities down to about 0.5% at the highest densities measured. Tungsten is nearly exclusively sputtered by carbon and oxygen and by a significant amount of self-sputtering due to local deposition. Nevertheless W accumulation in ordinary shots was not appreciable, probably owing to the prompt redeposition of W [15,16] near the sputtered area. Model calculations based on measured data show a good agreement with the effective tungsten release rate, but cannot fully explain the observed strong decrease of the W/H sputtering ratio with increasing plasma density [4].

Metallic, shiny erosion zones were clearly separated from carbon deposition zone that appeared at the edge of the limiter. Neither carbon nor deuterium was found by surface analysis in the shiny areas. A very sharp transition from the metallic surface to the carbon deposits occurs within about 2–4 mm. The carbon deposit was about 300 nm thick with a D/C ratio of 0.05–0.1. (See Fig. 6 in Ref. [4].) The sharp increase in the carbon deposition can be understood from the large difference in carbon reflection coefficients between tungsten and carbon.

The W-test limiter was routinely preheated above 700 K and had no damage. However, unintentional operation without preheating (for which temperature was around 450 K, well below DBTT) resulted in the cracking. Fig. 2 shows the damaged W limiter. There was no indication of the cracking during the discharge at all. Probably the crack was nucleated at the machined hole due to residual stress, and it spread over the whole limiter during the cooling phase after the plasma termination. After many high heat load shots, grain growth was appreciable and small cracks run along the grain boundaries; this might serve as the origin of a large crack [3,6]. Although hydrogen retention in the W shiny parts at high temperatures was very small, effects of hydrogen may play a role in the crack formation under plasma-loading conditions.

The maximum heat load to the test limiter was only about 10% of the convective power and most of the remaining power was loaded to the ALT-II poloidal belt limiter. Nevertheless, the highest heat load was estimated to be 20 MW/m^2, and a little melting was found at the front corner as seen in Fig. 2.

3.2. C/W twin test limiter

The C/W twin limiter experiments gave very useful information on how low-Z and high-Z materials behave under conditions of simultaneous utilization as PFM, where the cross-contamination can occur. The details have been presented elsewhere [9]. The main results are summarized as follows.

Spectroscopic measurements in front of the twin limiter clearly show that WI line emission, which was initially seen only in front of the W side, very rapidly developed on the C side shot-by-shot. This is a clear indication of prompt redeposition after sputtering. On the other hand, C contamination on the W side was not appreciable due to large sputtering. Similar to the bulk W limiter, most of the W part of the C/W twin limiter remained shiny, except at the very edge where C deposition occurred with a very sharp boundary [7]. This is shown in Fig. 3 in the photograph of the C/W twin limiter after plasma exposure and the surface concentration of C, D and W.

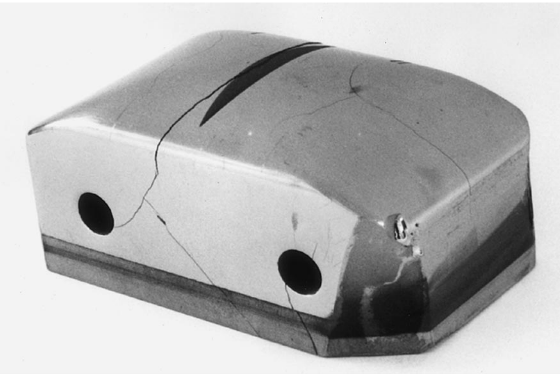

Fig. 2. Photograph of a damaged W-test limiter. Due to unintentional use below 450 K the limiter was cracked. Thick carbon deposits at the front side and a little melting at the front side corner are shown.

Owing to the large mass difference, the absorbed heat was clearly different between the C side and the W side. Because of the much smaller mass of C, the effect of deposited C on W on hydrogen reflection was small, but W on C enhances the reflection [17,18]. As a result, the heat deposition on both sides did not show the expected difference from the difference in the reflection coefficients of pure materials.

On the contrary, sputtering of the deposited C on W is very likely enhanced owing to the efficient momentum transfer from substrate W. Thus the contamination on the smaller mass materials is more serious than that on the larger mass materials. Most of the hydrogen (deuterium) on the limiter was found to be retained on the deposited layers, and it was much higher in the deposited C layer than in the deposited W layer [7]. This is a clear indication of smaller tritium retention in metallic deposits above 500 K (see Fig. 3).

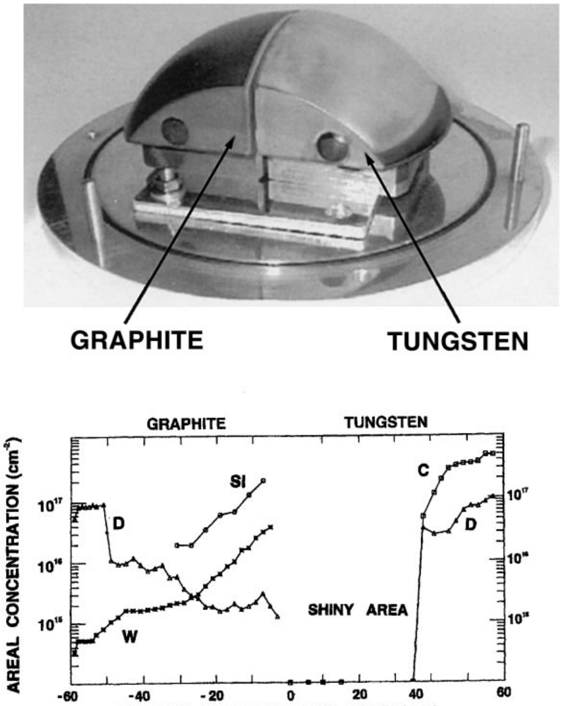

Fig. 3. Photograph of the C/W twin limiter after plasma exposure and its surface concentration of C, D and W.

The AES analysis showed the deposited W reacted with substrate C to form carbides at higher temperatures. Also the thickness of W and/or penetration of W depended on the temperature and the incident flux. The C deposited at the limiter edge, where the temperature was relatively low, did not form a carbide.

3.3. *VPS-W coated graphite main poloidal limiter*

The main motivation of the main poloidal W limiter experiments was to see the W effect more clearly with increasing W area. The poloidal limiters are movable during the discharges. To avoid the expected difficulty of impurity accumulation in the start-up ohmic phase, the limiters were inserted during the NBI phase or the ohmic phase after terminating NBI. Fig. 4 shows time sequences of plasma parameters for shot No. 79139 in which the limiters were inserted during the NBI phase. In this particular shot, the upper limiter was damaged as described later.

Based on the radiation data and input power, the ratio of the heat absorbed by the poloidal limiters to the total convection heat was estimated to be about 60%, when the limiter was placed deeper than 46 cm. This means that most of the plasma wall interaction has occurred with the W poloidal limiters as expected. The maximum heat load during the NBI shot was around 500 kJ. There is an uncertainty in the time of exposure of the limiters to the plasma, but the heat flux averaged for all blocks of the limiter was estimated to be 13 MW/m^2. However, because of the inhomogeneity of the plasma, the heat load to the individual blocks of the limiter could have been larger than 15 MW/m^2, according to individual thermocouple data.

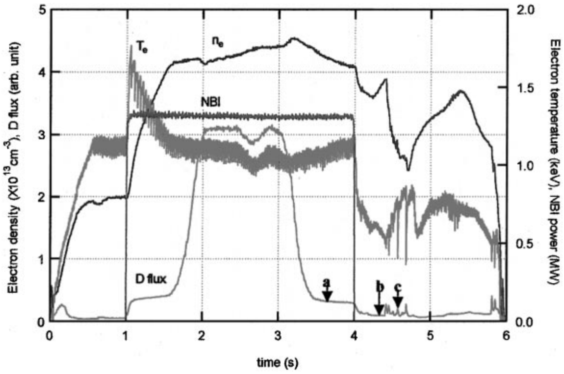

Fig. 4. Time sequences of several plasma parameters of shot No. 79139. The W poloidal limiters were inserted during the NBI phase where the Dγ emission near the poloidal limiter is larger. At the time indicated by the arrow: (a) flake-like objects had fallen from the surface, and at the time indicated by the arrow; (b) a minor disruption had started.

The W accumulation in the plasma center for the poloidal W limiter discharges was nearly the same as that for the W-test limiter discharges. Shot No. 83363 showed a strong W quasi-continuum emission and corresponding radiation from the center. Nevertheless the shot continued in the density ramp-up phase, and attained the highest density (5×10^{13} cm^{-3}) greater than any density attained with the W-test limiter.

Part of the surface layer fell off from the W limiter surface and reached into the plasma on shot No. 79139. The optical image and the image taken through the interference filter of the WI wavelength clearly showed some flake-like-objects falling down from the limiter surface at $t = 3.7$ s (corresponding to arrow (a) in Fig. 4). Although no appreciable degradation of the discharge was observed at this time, some minor disruption in the succeeding phase was triggered, which is marked as the arrow (b) in Fig. 4. During this minor disruption, large central radiation from bolometer arrays and quasi-continuum W band emission around 50 nm in an XUV spectrometer were simultaneously observed. This is the first clear observation that the central radiation was actually due to the radiation from accumulated W in the plasma center in TEXTOR.

Surface inspection after the discharges showed that the VPS-W layer was not damaged in all limiters except three (two in the top and one in the bottom). One at the top was seriously damaged as shown in Fig. 5(b) and the other two (one in the top and another in the bottom)

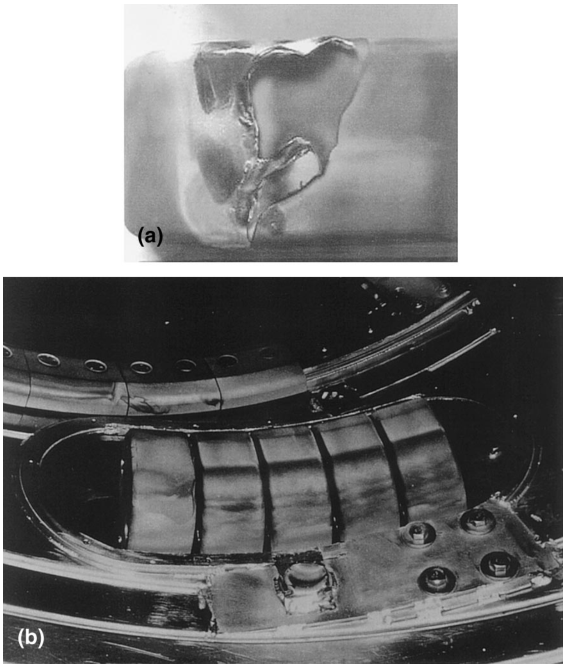

Fig. 5. (a) appearance of the bottom limiters; (b) photograph for the heavily damaged one in the top limiters.

were subjected to cracking and exfoliation of the VPS-W layer. The crack is appreciable in the left end limiter in Fig. 5(a). It should be noted that the cracking in the most heavily damaged one (Fig. 5(b)) very likely started at the ohmic phase after the NBI was forced off, i.e., during the cooling phase in shot No. 79139 given in Fig. 4 and propagated catastrophically like those appearing in brittle materials. Thus the VPS-W layer lost the thermal contact to the substrate and melted in the subsequent shots.

Electron beam tests separately done for flat shaped small pieces of the VPS-W coated graphite made by the same technique showed no damage below 20 MW/m^2 [19]. Therefore, inhomogeneous heat load by the plasma could be one reason for the cracking. The curved surface of the limiter may also have led to additional thermal stress, which initiated the crack at the edge. In ASDEX Upgrade [20], small cracks were observed in the VPS-W coated graphite tiles but did not result in the exfoliation of the W layer. This is mainly because of the smaller heat load in ASDEX Upgrade. But their flat structure could also relax the thermal stress.

As clearly seen in Fig. 5(a), most parts of the poloidal limiter retained a substantial amount of deposited carbon and only the central part remained the original color. The contamination by carbon was clearly seen in spectroscopy as well. In Fig. 6 are compared the emissions from the plasma-surface boundary for the pure W-test limiter to the VPS-W coated poloidal limiters. CII and OII line emissions for the poloidal limiter are appreciable. Consequently, W emission from the surface was substantially smaller than that from a pure W surface of a test limiter. This may be part of the reason why the W poloidal limiters could sustain such a high density ohmic plasma as 5×10^{13} cm^{-3}.

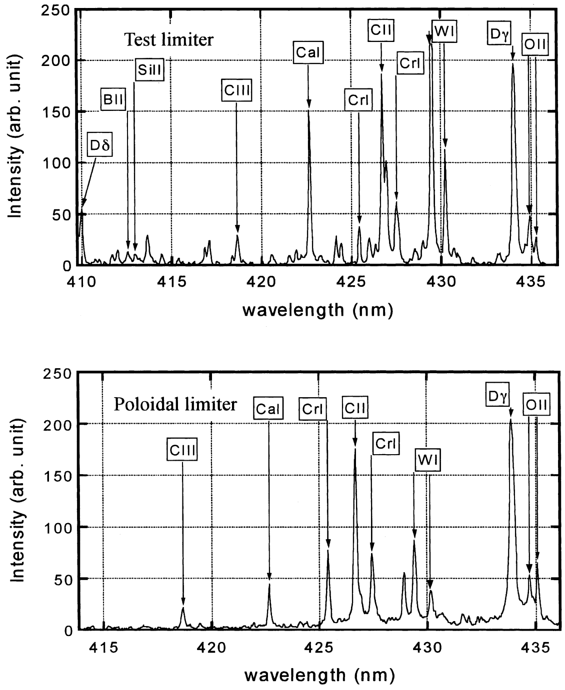

Fig. 6. Comparison of spectral line emissions between the plasma region near the pure W-test limiter and that near the VPS-W coated poloidal main limiter.

In the poloidal limiter, the boundary between the erosion dominated region and the desorption dominated one was not so clear as those observed in the test limiters as seen in Figs. 2 and 3. The reason is probably as follows. When not in operation, the limiters were withdrawn behind the main ALT-II graphite limiter and their surface was covered by the deposition of C. Afterwards, the plasma was rather dirty and several discharges were required to have clean plasma. After peeling off some parts of the VPS-W layer as shown in Fig. 5(b), the graphite part was directly facing the plasma. This could be the source of the deposited carbon.

As shown in the C/W-test limiter, the reflection of C and W is so different, and the W surface was kept clean. However once some C layer was deposited on W, the reflection was reduced and deposition was enhanced compared to pure W.

Additionally there was a difference in operation temperature. Since the test limiter was usually used above 700 K in order to avoid cracking of bulk W, its surface temperature could easily go over 1000 K from plasma exposure, in which case carbon erosion would be enhanced. On the other hand, the poloidal limiter was operated at nearly the same temperature as the TEXTOR liner, around 500 K. This rather low temperature use of the poloidal W limiter is also likely the reason for the crack propagation and exfoliation of the VPS-W layer, because at this temperature region the W layer must be extremely hard (brittle), and this could be enhanced by either or both of hydrogen and carbon occlusion.

Thus we conclude that the VPS-W coating on graphite could tolerate about 15 MW/m^2. However, the curved shape would result in additional thermal stress and reduce the maximum heat load. The coating is better to use above the DBTT as with pure W, not only to avoid the crack propagation but also to reduce hydrogen retention. Enhanced erosion of deposited carbon by either or both chemical sputtering and RES would also help the W surface to keep the carbon deposition free or less.

4. Conclusions

1. High-Z accumulation in the plasma center in high density ohmic shots was confirmed to be observed for

three different types of W limiters. Such W impurity accumulation is well interpreted by neo-classical transport, and is attributed to a density gradient. Auxiliary heating with NBI and/or ICRH has reduced the accumulation, but the central temperature of TEXTOR is not high enough to extrapolate the present result to a burning plasma. We still need some more experiments of W as a PFM with higher temperature plasmas.

2. The C/W twin limiter experiments were found to give very useful information on the behavior of low- and high-Z elements when they are simultaneously utilized as PFM giving rise to cross-contamination. As a result of the cross-contamination, heat deposition on both sides was rather similar than expected from the difference of the reflection coefficient. Because of the smaller mass of C compared to W, C on W plays a less important role on hydrogen reflection, whereas W on C enhances the reflection substantially. On the other hand, sputter removal of C on W is more frequent than the opposite case. Most of the hydrogen (deuterium) on the limiter was found to be retained in the deposited layer and the retention in deposited carbon was much higher than that in deposited W.

3. With two sets of main poloidal VPS-W coated graphite limiters, we could increase the ratio of the heat absorbed by the poloidal limiter to the total convection heat to about 60%. In other words most of the PMI occurs on the limiter. Under such conditions, ohmic plasma with a density as high as 5×10^{13} cm^{-3} was sustained.

4. Some of the VPS-W coating, which had been confirmed to tolerate an electron heat load of 20 MW/m^2 was exfoliated by a similar heat load from the TEXTOR-94 plasma. The curved surface of the main poloidal limiter probably gave rise to additional thermal stress. Grain growth and hardening of the W layer due to higher temperature operation could be a contributing factor. The usage of the limiter at rather low temperature causes brittleness that could result in cracking. The VPS-W coated surface retains a substantial amount of carbon, and forms a carbon-coated-layer, which produces CH upon hydrogen irradiation. Consequently, the W emission from the surface is substantially smaller than that from the pure W surface of a test limiter.

The series of W limiter experiments in TEXTOR have shown that W is applicable as a PFM, as long as central accumulation of W is avoided by NBI and/or ICRH heating. However, some concerns like difficulty of plasma start-up, W behavior in higher temperature plasma, and the materials' selection remains as future problems to be addressed.

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