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Tungsten limiter tests in ASDEX Upgrade

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Abstract

In order to prepare for tungsten coating to be applied to the low field side poloidal guard limiters, 1 μm W-coated CFC limiter tests have been performed in ASDEX Upgrade. The test limiters were exposed to H-mode deuterium plasmas with the neutral beam heating at maximum 5 MW for approximately 1 s. The power flux deposited on the test limiter was calculated by solving the 3-D heat conduction equation by using the measured time dependent surface temperatures as boundary conditions. The experimental results show that the heating with more radial NI beams leads to a higher local deposited power with a longer radial decay length related to banana particle loss. Strong localized W erosion was found at the tip of the test limiter due to arcing, which obviously depends on the neutral beam injection (NBI) geometry.

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Keywords: Poloidal limiter; Tungsten coated carbon; Power flux; Erosion; ASDEX Upgrade

1. Introduction

High-Z materials such as tungsten (W) have been considered as a plasma facing material for a steady state burning plasma device like ITER [1]. To examine the feasibility of tungsten as a plasma facing material in future fusion research and reactor devices, the area of W-coated graphite tiles has been increased from campaign to campaign in ASDEX Upgrade. For this purpose a tungsten coated first wall and high heat flux components have been developed for application in ASDEX Upgrade [2]. Most of the experimental results in ASDEX Upgrade operated with large area W-coated fine grain graphite tiles indicate that there is no negative influence on the plasma performance [3,4]. For the goal of a full W machine, 12 poloidal guard limiters (CFC) on the low field side in ASDEX Upgrade will be also replaced by W coated limiters in the future. However, fast particle loss may lead to localized damage of the limiters on the low field side [5,6]. In ASDEX Upgrade the limiter glows on the low field side, as frequently observed in discharges with NBI, and/or ICRH-minority heating, and are attributed to fast ion loss resulting in high local power loads, which may become a problem with tungsten coated limiters. In order to understand better these effects, tungsten limiter tests have been performed with a W-coated CFC probe on a movable manipulator in the midplane of ASDEX Upgrade.

This paper describes experimental results on measurements of the power flux to the test limiter and the behavior of the W erosion in discharges with different

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NI beams. It is reported that power flux in the far SOL region and the strong local W erosion due to arcing obviously depend on using NI beams related to banana particles loss.

2. Experimental methods

Test limiters were made from 3-D CFC(SEP N11) with 1 μm tungsten layer deposited by PVD. The size and the geometry of the test limiter are shown in Fig. 1. The front part of 15 mm length can be positioned in front of the ICRH protection limiter. It is shaped to have an angle of 45° to the toroidal direction for smoother deposition. The thickness of 15 mm in the vertical direction is about the size of the larmor radius of deuterons of 10 keV in a magnetic field of 2 T. To estimate the integral energy flow to the test limiter, it was designed as a calorimeter with two thermocouples mounted inside at 5 mm and 25 mm from the front surface, as shown by the dotted lines in Fig. 1(b). The test limiter was mounted on a movable midplane manipulator in ASDEX Upgrade, and positioned 15 mm in front of the ICRH protection limiter. The surface temperature distribution of the test limiter (only one side) was measured with a 2-D infrared camera. Details of the infrared camera diagnostic in ASDEX Upgrade are described in [7]. The power flux deposited on the test limiter was calculated by solving the 3-D heat conduction equation (ANSYS finite element code) by using the measured time dependent surface temperatures as boundary conditions. The test limiter is assumed to be thermally isolated during the discharge. Temperature dependent conductivity and heat capacity of the material are used, and the W thin layer was omitted in the calculation. In ASDEX Upgrade there are two neutral beam injectors (NBI-1 and NBI-2) displaced toroidally 180° to one another. Both injectors consist of two radial and two tangential beams. A more detailed description of NBI system is given in [8,9]. In order to investigate the influence of fast ion losses the same discharge parameters were repeated with neutral beam heating using NBI-1 and NBI-2, respectively.

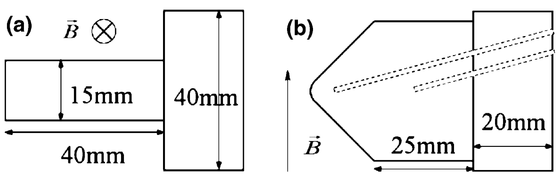

Fig. 1. The size and the geometry of the test limiter. (a) toroidal view, and (b) top view.

3. Results and discussion

3.1. Power deposition on the test limiter

Two test limiters were exposed in two similar H-mode deuterium discharges (#17428 and #17505) operated at $I_p = 1$ MA and $B_t = -2$ T with neutral beam heating by NBI-1 and NBI-2, respectively. The temporal behavior of the line averaged density, NBI heating power and $R_{sep} - R_{lim}$ of the midplane separatrix distance is shown in Fig. 2 for both discharges. In each discharge, two tangential beams were used for heating, one was operated from 1.0 s to 4.0 s at 2.5 MW, and another was added from 2.4 s to 3.3 s at 2.5 MW, therefore, there was a maximum power of 5 MW for the duration of 0.9 s. However, tangential beams used in #17428 have more central and radial injection than the one used in #17505 [8]. At the beginning of the discharge, the separatrix was moved towards the test limiter, and then quickly away from the test limiter, and finally kept at a distance of about 2.8–3.0 cm from 1.0 s to 2.9 s. The separatrix was moved radially away from the test limiter with a velocity of 0.01 cm/ms from 2.9 s to 3.3 s for measurements of the power flux decay length in the SOL.

Interesting experimental results were obtained by varying the neutral beam injection geometry with fixed heating power and duration of heating using the same plasma parameters. Shown in Fig. 3 is the temperature distribution on the surface of the test limiter at the time of 2.9 s of the maximum temperature for both discharges. The results show the presence of a maximum on the front upper part of the test limiter, around 2330 K for the case of the radial beams and 1980 K for the tangential beams. In fact, it is clearly found that there is a local erosion area on the front upper edge of the test limiter in the case of radial beams (see Fig. 6). Moreover, similar local damage was observed in the W-uncoated CFC test limiter with the same geometry. Therefore, although the local inhomogeneous heat

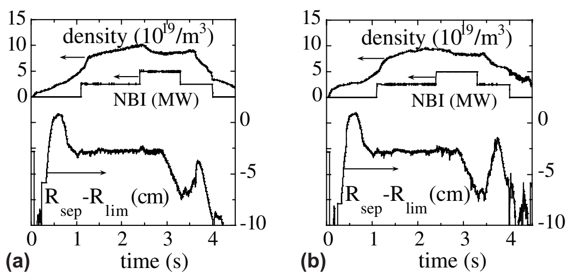

Fig. 2. The temporal behavior of the line averaged density, NBI heating power and $R_{sep} - R_{lim}$. $R_{sep} - R_{lim}$ means the midplane distance between the separatrix and the test limiter. (a) for #17428. (b) for #17505.

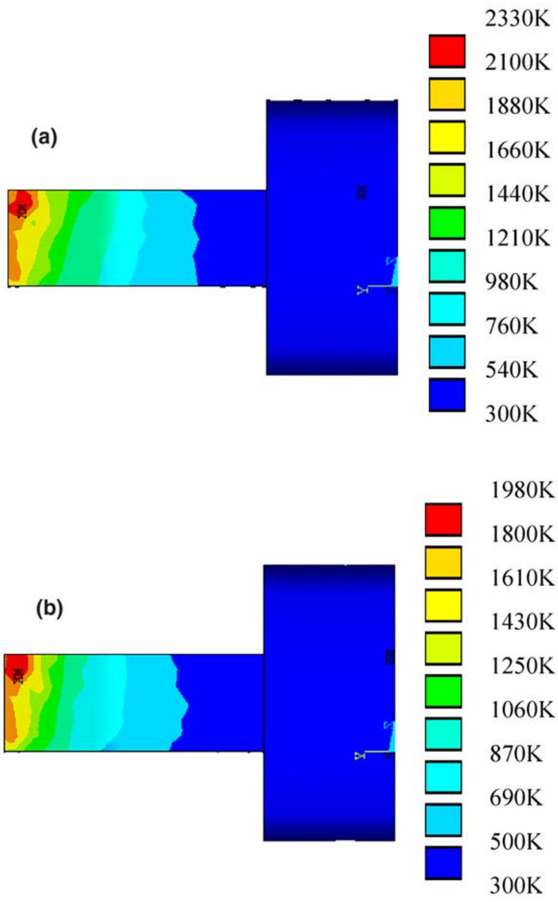

Fig. 3. The temperature distribution on the surface of the test limiter at the time of 2.9 s. (a) for #17428 and (b) for #17505.

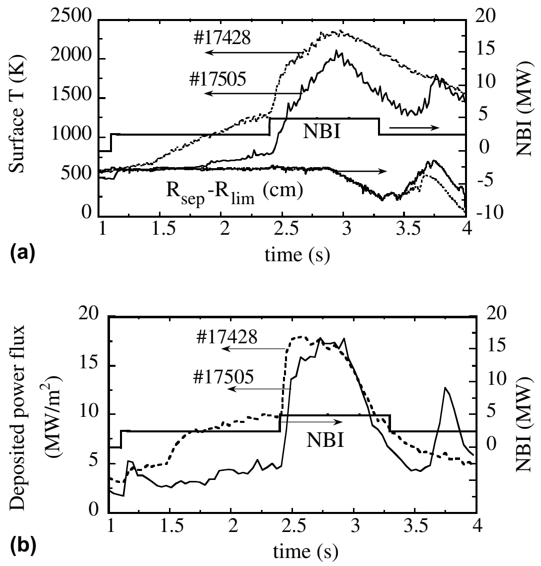

Fig. 4. (a) The temporal evolution of temperature on the front upper part of the test limiter. (b) The temporal evolution of the deposited power flux.

transfer of the W thin layer to CFC substrate could result in local heat-up causing local damage, it is not believed to be a dominant reason for the local damage of the W layer observed in our experiments since the same erosion pattern was also observed on the CFC test limiter without a W layer. This behavior indicates that additional localized power arrived on the front upper part of the test limiter. This additional localized power is believed to be in large part related to fast ion losses. The temporal behavior of the temperature and the calculated time averaged deposited power flux on the front upper part of the test limiter is shown in Fig. 4 for both discharges. Although similar plasma parameters and the same heating power and duration of heating was used in both discharges, the measured results show clearly that the power fluxes to the tip of the test limiter are quite different as shown in Fig. 4(b). In the case of the shot 17428 with neutral beam heating by using the more radial beams, the deposited power flux reaches about 10 MW/m^2 before switching on the second beam, which is higher by a factor of 2 than that for the tangential beam in shot 17505. When the second beam was added at 2.4 s, the deposited power flux increases rapidly to about 18 MW/m^2 at 2.5 s in shot 17428, but to about 14 MW/m^2 at 2.5 s in shot 17505.

As already mentioned, in order to measure the power flux decay length, the separatrix was moved radially away from the test limiter from 2.9 s to 3.3 s, corresponding to the separatrix distance from about 3 cm to 7 cm shown in Fig. 4(a). The decay in the deposited power flux in shot 17428 is slower than that in shot 17505 during scanning, as shown in Fig. 4(b). The deposited power flux on the front upper part of the test limiter during the separatrix position scan is plotted as a function of the midplane distance from the separatrix in Fig. 5. The results show that the deposited power flux in the SOL is decreased from 16 to 8 MW/m^2 resulting in an e-folding length of about 60 mm for the radial beam heating, and about 38 mm for the tangential beam heating.

Concerning this dependence of the power flux in the SOL on NBI geometry, i.e. the more radial NBI leads to a higher power load to the test limiter as well as a longer radial decay length of the power flux, a possible explanation for our experimental results is banana particle losses. The orbits of banana particles in the low field side have a width of several centimeters and can penetrate deep into the SOL and heat the test limiter [10]. In the case of the radial injection, a larger fraction of particles is trapped on banana orbits at the low field side because particles have a smaller ratio of parallel to perpendicular

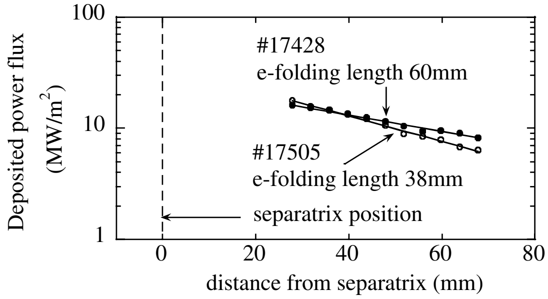

Fig. 5. The deposited power flux from $t = 2.9$ s to 3.3 s in Fig. 4 is plotted as a function of the distance from the separatrix. A distance of zero is the midplane separatrix position.

velocities ($V_{\|}/V_{\perp}$). That is why the power to the tip of the test limiter depends on NBI geometry. The measured long power decay length of 60 mm also supports the conclusion that the test limiter is hit by a large fraction of the banana particles. A detailed discussion is under preparation of these results and a quantitative estimation of power carried by banana particles into the SOL related to kinetic code calculations. For the purpose of this paper, we may conclude that these experimental results indicate clearly that the banana particles can transport a significant fraction of energy into the SOL and could cause a local overheating of the low field side limiters.

It should be noted that the difference between the maximum in the measured temperature by the first thermocouple (inside 5 mm from the front surface) and the maximum in the calculated temperature at this position is about 200 K, and the measured one has a delay of 0.3 s. Poor contact of the thermocouple to the limiter is believed to be the reason for the delay of the maximum temperature. Another reason for the difference in temperature may be the overestimated surface temperature obtained by IR-camera using an emissivity of 0.4 for W. However, tungsten carbide formation was observed on the surface, which may lead to a larger value of emissivity. Therefore, the absolute surface temperature may be overestimated by 20–30%. The relative behavior in the above results should not be significantly affected, however.

3.2. Local W erosion due to arcing

One test limiter was exposed to three similar shots 17420, 17427 and 17428, using the same beam heating, but the test limiter was positioned at a position of 5 mm in front of the ICRH protection limiter in shots 17420 and 17427, at 15 mm in shot 17428. Another test limiter was exposed in shot 17505. It is clearly seen that there is a local erosion area on the front upper edge of the test limiter. Fig. 6 shows the results of SEM analysis for this erosion area. It is found that extensive arcing occurred in the local erosion area in shot 17428 as shown

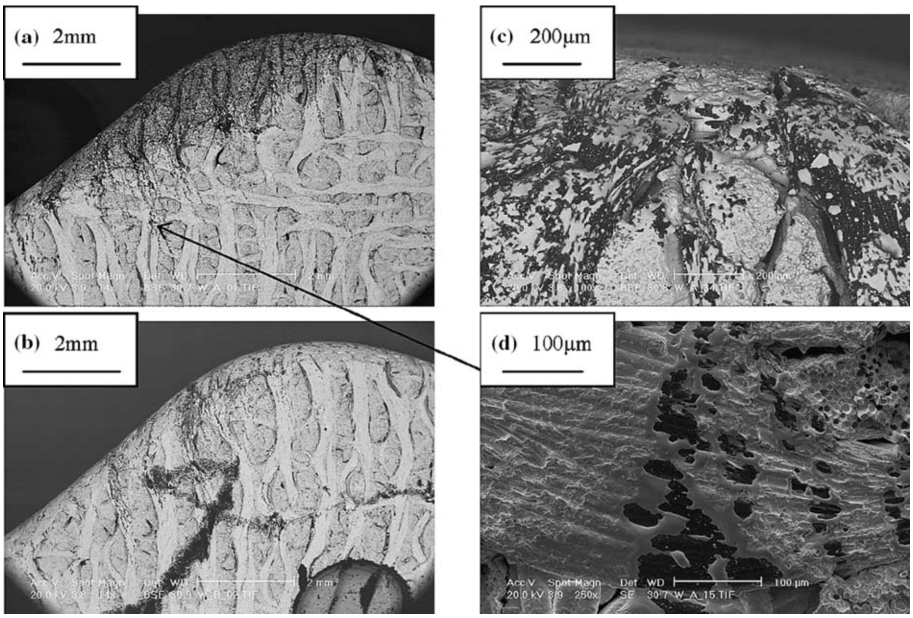

Fig. 6. (a) An overview of SEM image of the erosion area on the test limiter exposed in #17428. (b) An overview of SEM image of the erosion area on the test limiter exposed in #17505. (c) An enlarged SEM image of top area in (a), and (d) an enlarged SEM image of arc spot indicated by an arrow in (a).

in Fig. 6(a), but less arc tracks are found after shot 17505 as shown in Fig. 6(b). These results indicate that in the case of more radial beam injection, more banana particle losses to the limiter result in more arcing. Fig. 6(c) is an enlarged SEM image of the top area in Fig. 6(a), and shows clearly that the tungsten layer is damaged and eroded from the surface. Fig. 6(d) shows an enlargement of an individual arc track. The black regions in Fig. 6(d) indicate the pure carbon surface, where the W coating was removed completely by arcs. The tungsten around the erosion area was melted, which means that the temperature in this localized area is very high. These results may be interpreted as the test limiter being hit by a large fraction of fast ions, which increases the local power deposition. When the local surface temperature is high enough for sufficient thermoelectron emission, a breakdown of the sheath potential occurs and the plasma electron flux to the surface increases strongly, which finally results in arcing. A general nonlinear dynamic relation between high heat flux plasma and electron-emissive hot material surfaces has been studied experimentally and also by a numerical analysis [11].

4. Summary

The power load to the low field side poloidal guard limiters in ASDEX Upgrade was investigated by using W-coated CFC test limiters with different neutral beam heating. The power flux in the SOL depends on NBI geometry. The more radial NBI produces a large fraction of banana particles in the low field side, which leads to a higher local power load to the test limiter with a longer decay length of about 60 mm in the far SOL region.

Strong localized erosion occurred on the front upper part of the test limiter mainly due to arcing occurring in many micrometer-scale areas, which strongly depends on NBI geometry. These results indicate that fast ion losses from auxiliary heating can make a significant contribution to W erosion on the low field side limiters.

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