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Inhomogeneous heat loading to high-*Z* test limiters depending upon the limiter materials

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Abstract

The change in the temperature distribution was investigated for different target materials by inserting a Ta/W twin limiter into TEXTOR edge plasmas. Depending upon the limiter material and the limiter location, the position of the maximum temperature on the limiter surface changed. A three-dimensional heat transfer calculation taking the radiation loss from the surface into account was conducted to find out the factors governing the heat flux onto the test limiter. The result for the Ta test limiter shows that the experimentally observed temperature asymmetry in the toroidal direction can be explained if the plasma heat flux decreases exponentially from the last closed flux surface with the e-folding length of the ion drift side about 50% longer than that of the electron drift side. The intensity of D_β light around the ion drift side of the limiter was larger than that at the electron drift side by about 30%, corresponding with a larger particle flux to the ion drift side.

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Keywords: Plasma-wall interaction; Heat flux; High-Z; TEXTOR; Tungsten; Tantalum

1. Introduction

Overheating due to high heat load can cause a severe damage of plasma facing components (PFC) in a fusion reactor. Several factors affect the heat deposition and the resulting temperature distribution on the PFC surface, and modification of the plasma sheath is known to play an important role in determining the heat flux [1]. Nonlinear interactions between solid material wall and surrounding plasma have been studied in TEXTOR-94 by inserting test limiters into the edge plasmas. In high heat flux exposure experiments using the TEXTOR tokamak, a hot spot arising from the thermal electron emission was observed on carbon limiters above a critical temperature of 2400 °C [2]. Inhomogeneous heat load to W test limiters was also observed at a very high heat flux, elevating the surface temperature of the limiter as high as thermal electron emission should affect the plasma sheath [3].

Recently, a Ta test limiter was inserted to investigate the difference in hydrogen recycling from W. As their volumetric densities and atomic numbers are similar, close values of particle and energy reflection coefficients

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are expected for Ta and W. Meanwhile, a substantially smaller thermal conductivity of Ta as compared to that of W should make it easy to find the inhomogeneous heat load by observing the temperature distribution on the surface. Therefore, the temperature distribution on the Ta test limiter was measured by taking an infrared thermograph, and the measured distribution was compared with a three-dimensional (3-D) heat transfer calculation to estimate the heat load onto the limiter surface.

2. Experimental method

TEXTOR-94 was operated under standard discharge conditions with a toroidal magnetic field of $B_t = 2.2$ T, and a plasma current of $I_p = 360$ kA. To realize a high heat flux the plasma was heated by neutral beam injection (NBI) for 2 s with 1.8 MW beam power from 1 s after the start of a discharge. The plasma density at the center was constant at 3×10^{13} cm^{-3}, while the electron temperature increased from 700 eV to 1 keV during NBI was injected. The flat top of the discharge lasted from 1 to 3 s with NBI, and 3 to 5 s without NBI. Minor radius of the plasma was determined by the ALT-II toroidal belt limiter to be 46 cm.

The test limiter was inserted into the plasma at a specified minor radius from the top of the TEXTOR torus by a limiter-lock system [4]. One half of the test limiter was made of W, and the other half was made of Ta, as shown in Fig. 1. The limiter can be rotated to any angle with respect to the confinement magnetic field. Usually, the limiter was fixed in the orientation that it extended 12 cm length in the toroidal direction, and 8 cm width in the poloidal direction. To avoid localized high heat flux at edges, the top surface of the limiter facing the plasma had a spherical surface with 7 cm radius. The surface of the limiter was observed with a CCD camera through an infrared transmission filter with a cut-off wavelength of 850 nm. An optical pyrometer measured the surface temperature of the limiter at the point 2 cm from the center toward the ion drift

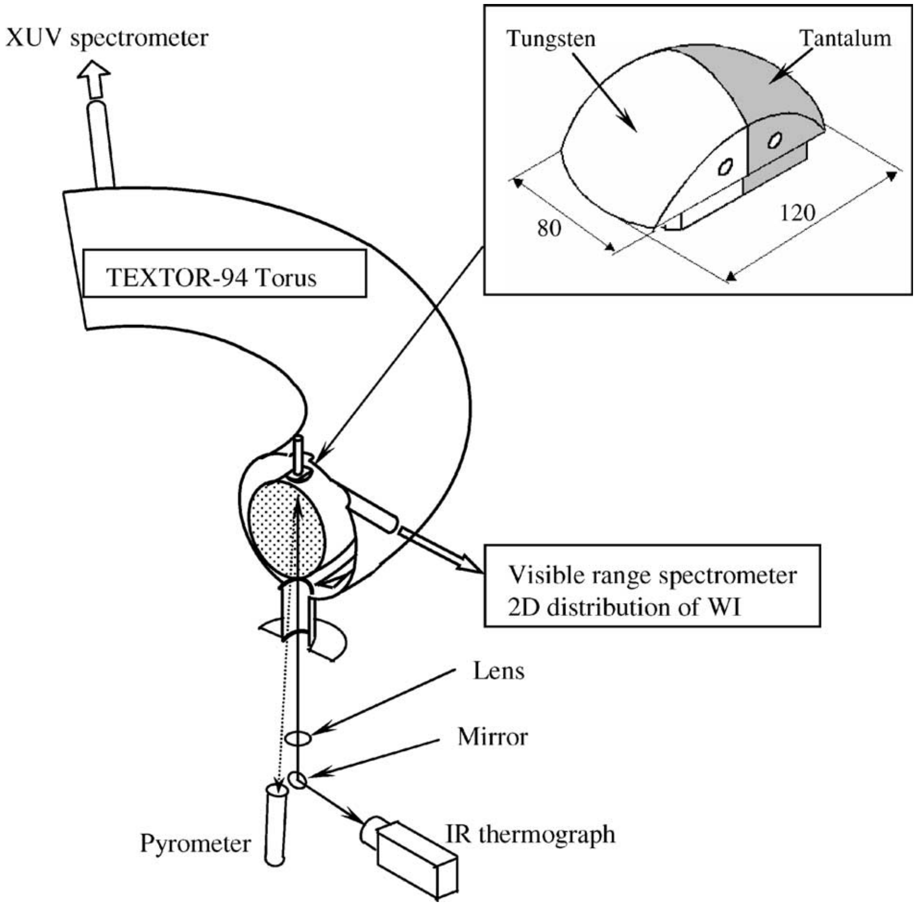

Fig. 1. The experimental setup used to investigate the heat load onto a Ta–W test limiter.

side in the toroidal direction. The optical spectrum of the plasma near the limiter was measured with a spectrometer in the wavelength range from 410 to 435 nm. Intensity distributions of CII, D_β and WI line spectra were obtained as 2-D images by CCD cameras equipped with narrow band interference filters. A pair of thermocouples was inserted into the body of the limiter from the backside. The measuring tip of each thermocouple was located 2 cm away from the center of the limiter in the toroidal direction, and about 7 mm from the limiter surface.

3. Results and discussion

3.1. Temperature distribution

A typical result of the temperature distribution obtained from the infrared thermograph is shown in Fig. 2. The top of the test limiter was located at the minor radius of 47.5 cm, which was 1.5 cm behind the ALT-II limiter. At this limiter location, the XUV spectrometer signal showed the presence of high-Z quasi-continuum spectrum indicating the penetration of W and Ta in the plasma core. Namely, the particle flux of the plasma 1.5 cm farther from the last closed flux surface had enough energy to cause high-Z emission from the test limiter. The position of the maximum temperature on the Ta limiter was about 2 cm from the center of the limiter toward the ion drift side in the toroidal direction. On the W limiter, the position of maximum temperature was located at about 1 cm from the center to the electron drift side in the toroidal direction. The part adjacent to the groove joining the Ta and W limiters was heated due to a slight misalignment between the two limiters.

By using the reported values of emissivity, thermal conductivity, and heat capacity for Ta and W [5,6], a temperature distribution nearly identical to Fig. 2 could be simulated by a 3-D FEM calculation. A heat flux in the poloidal direction about 25% of that in the toroidal direction was necessary to match the observed temperature distribution by the calculation, similar to the case of the carbon limiter [2]. The angle between the toroidal direction and the magnetic field line of force was 5°, while the angle between the assumed direction of the heat flux and the magnetic field line was about 15°.

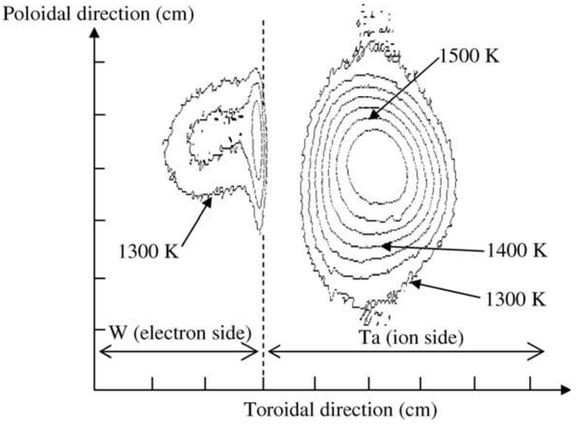

Fig. 2. A typical thermograph output data.

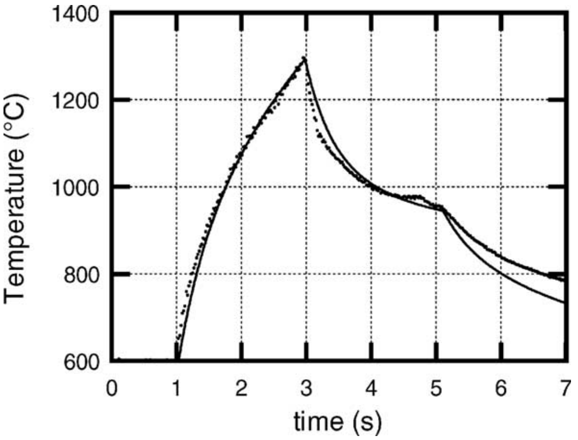

Fig. 3. A comparison between the surface temperature measured with an optical pyrometer (dashed line), and that calculated from the 3-D FEM (solid line).

The agreement between the measurement and the calculation can be also checked with the time dependence of surface temperature. In Fig. 3, the surface temperature on the Ta limiter measured by the optical pyrometer is compared with the calculation result at the corresponding surface position. On the other hand, the calculated bulk limiter temperature did not agree with thermocouple data. The temperature measured by the thermocouple decayed much faster than the calculated temperature [3]. Poor contact of the thermocouple to the limiter and/or the heat transfer along the thermocouple lead could cause this discrepancy.

The point of the maximum heat load can be calculated with a simple analytic form, assuming the heat flux decays exponentially against the minor radius. The solid line in Fig. 4 indicates the toroidal distance from the position of the maximum heat load to the limiter center as a function of the e-folding length for the heat load, r_L. Also plotted in Fig. 4 are the results for position of the maximum temperature obtained by the 3-D FEM calculation for different e-folding length. Due to heat transfer and distributed heat load, the distance from the position of the maximum temperature to the limiter center, x_m, becomes smaller than that from the position of the maximum heat load. From the figure, the measured value of about 2–2.5 cm for x_m corresponds to about 0.6–0.7 cm e-folding length for the heat flux. The distance x_m is also affected by the thermal conductivity of the limiter material. As W has substantially larger

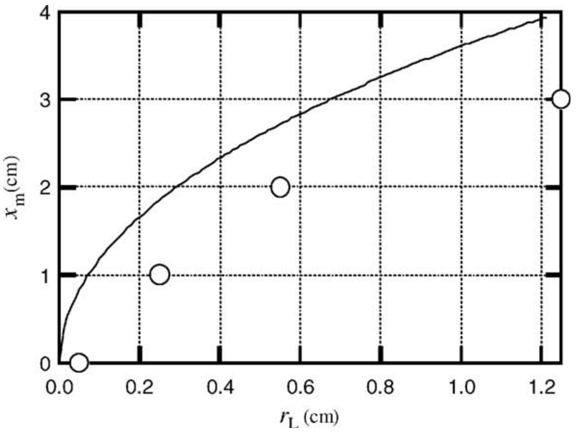

Fig. 4. A plot of the spacing between the maximum temperature position on the Ta test limiter and the limiter center, x_m as a function of e-folding length of the heat load, r_L. The solid line shows the distance of the maximum heat load from the limiter center.

thermal conductivity, x_m becomes smaller than in the case of Ta. This was confirmed experimentally by rotating the limiter. When Ta faced the ion drift side, x_m was 2.5 cm on Ta limiter, and 1.2 cm for W limiter. When Ta faced the electron drift side, x_m on Ta was 1.6 cm with x_m of 1.9 cm on W.

The observed smaller x_m at the electron drift side can be explained by a smaller e-folding length of the heat flux at the electron drift side. The observed spacing of 1.2–1.6 cm for the electron drift side corresponds to 0.3–0.5 cm e-folding length, which is about half of that for the ion drift side. The lengths of the magnetic field line to the main ALT-II limiter were 13.7 m for the ion drift side and 9.2 m for the electron drift side, respectively. However, the larger e-folding length of the heat flux layer on the ion drift side cannot be attributed to the longer field line on the ion drift side. Similar asymmetry in the e-folding length of the heat flux was also observed on another test limiter location, where the field line length to the ALT-II from the ion drift side was shorter than that from the electron drift side.

As the limiter was inserted deeper into the discharge, the distance of the maximum temperature from the limiter center decreased. This can be understood as the steeper heat flux gradient in the deeper part of the plasma causing smaller e-folding lengths, which was deduced from the local electron temperature and density distributions measured by the He atomic beam method [7]. The result was 1.4 cm for the discharge condition that corresponded to the surface temperature distribution fitted with the FEM calculation assuming the e-folding length for the heat flux of 0.7 cm. Thus the local e-folding length of the heat flux near the limiter seems decreased by the presence of the limiter.

The total heat flux to each side of the limiter is not simply determined by the e-folding length of the heat flux. If we assume the same heat flux at the plasma boundary and let the heat flux exponentially decrease with the observed e-folding length, the maximum surface temperature of the electron drift side should be much smaller than the experimentally observed value. To recover the measured temperature distribution, the total heat flux to the electron side must be about 80% of that to the ion drift side. The boundary plasma layer conveying the heat flux to the limiter seems compressed at the electron drift side.

3.2. Particle flux

The intensity of D_β emission around the limiter was integrated in space by separating the region into electron drift side and ion drift side. The integrated intensity around Ta limiter in the ion drift side and that in the electron drift side measured by rotating the test limiter were normalized to the deuteron fluxes measured at the top poloidal limiter. In Fig. 5, the ratio of the normalized integrated intensity of D_β at the ion drift side to that at the electron drift side is shown as a function of time for the Ta limiter. As shown in the figure, the ratio changes from 1 to 1.5 in the steady state NBI heating condition indicating larger D_β signal on the ion drift side. The effect of hydrogen adsorption by Ta may appear at low temperature [8], but was not clearly observed for the temperature range of the Ta limiter surface of the present experiment. Electron densities and temperatures of the edge plasmas measured by the atomic beam method were similar between two discharges of the opposite limiter orientations. Assuming that the plasma conditions near the limiter were the same, the normalized integrated ratio of D_β signal can give a crude estimation of the ratio of deuteron particle flux. The 30%

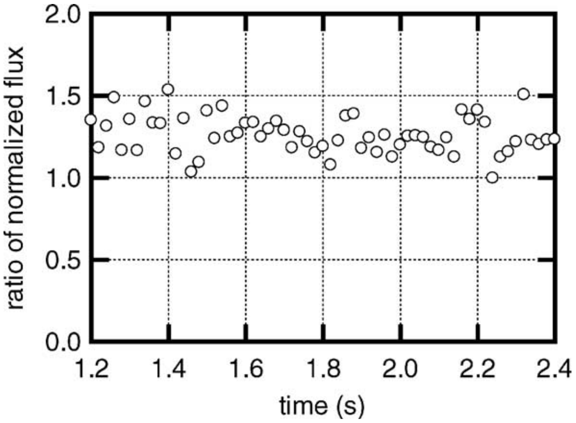

Fig. 5. The normalized ratio of D_β signals integrated for the ion drift side to that for the electron drift side of Ta limiter.

higher signal of D_β at the ion drift side coincide with the 30% higher heat flux on the ion drift side.

4. Conclusion

By comparing the measured temperature distributions on the test limiter surface with that calculated by 3-D FEM, a heat load asymmetry from 20% to 30% higher to the ion drift side was found to exist. The e-folding length of the heat flux was smaller on the electron drift side by a factor of 2, which yielded the heat flux value too small to explain the observed temperature distribution. As the particle flux on the ion drift side also seems about 30% higher than that on the electron drift side, some mechanism that compresses the thickness of the heat flux layer on the electron drift side should exist.

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