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High temperature erosion of tungsten exposed to the TEXTOR edge plasma

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Introduction

Tungsten is foreseen for the upper divertor regions in ITER, the full divertor for JET and is the most promising candidate to replace CFC carbon also at the high heat flux lower divertor areas. The main advantage is its low sputtering coefficient and low tritium retention capability. An open question presently discussed is the possibility of enhanced erosion of tungsten at high temperatures, as reported for tungsten exposed to a high current argon plasma arc [1] and observed for beryllium [2]. The previous high heat flux experiments fulfilled on TEXTOR [3] had demonstrated that a tungsten test limiter can be heated by the plasma up to temperatures in excess of 3000°C when the limiter is inserted deeper into the plasma (2-3 cm inside the LCFS (last closed flux surface). Previous experiments showed that, at high temperatures, oxygen impurities can be released from the bulk which complicates the analysis of the high temperature erosion due to the possible physical and chemical sputtering of oxidized tungsten. The investigation of high temperature erosion of tungsten in the edge plasma of tokamaks is important to qualify the operational limits for this material.

Experimental setup

In the present experiment, a solid tungsten plate (75 x 63 mm^2) with a thickness of 2 mm is facing the ion drift side of a graphite roof limiter having an angle of 20° to the magnetic field lines. The side of the plate faced to the plasma was mechanically polished. The thermal contact of the plate with graphite substrate was especially worsened to increase the surface temperature. The surface temperature of the tungsten plate was measured by two single colour pyrometers (wavelength 1.69 μm and 1.58 μm) at the position of maximum heat flux in the middle of the plate. The temperature distribution over the surface was measured by a video camera equipped with an infrared edge filter with a cut-off at 0.85 μm. Two thermocouples inserted into graphite limiter through holes at ion drift and electron drift sides were used to measure the limiter base temperature and total deposited energy. The released flux of tungsten atoms from the plate was measured spectroscopically in the near UV spectral region (280 nm – 308 nm) to reduce the influence of the thermal radiation continuum from the hot surface. For this purpose a 0.5 m focal length spectrometer (ARC Spectra Pro500) equipped with an intensified CCD camera (Proxitronic HL4) was used. The test limiter was preheated up to 350°C and inserted through a limiter lock into the plasma from the top of the TEXTOR vessel [4]. The limiter was aligned in such a manner that its vertical edges were parallel to the magnetic field lines (12.75° angle with respect to the toroidal magnetic field). The viewing chord of the spectrometer was tangentially to the tungsten plate surface but some part of the surface of the tungsten was also in the spectrometer view with this limiter alignment. The main plasma parameters of the TEXTOR during this experiment were: I_p = 355 kA, B_T = 2.25 T, $\bar{n}_e = 4 \cdot 10^{13}$ cm^{-3}, a = 47.2 cm, Z_{eff} ~ 1.4, P_{NBI}= 1.2 MW for 5s, P_{tot}= 1.4 MW, radiation level $\gamma \approx 0.45$.

Experimental results

The position of the test limiter was changed shot by shot with steps of about 0.2 cm from one discharge to the other resulting in maximum surface temperatures increasing from 600°C for r = 47.9 cm to 3400°C for r = 46 cm. The heat flux density from the plasma evaluated from thermocouples by a calorimetric method increases exponentially with the limiter position as shown in fig.1 and reaches about 5.5 MW/m^2 at the position r = 46 cm where the measurement discussed here were done. The heat flux derived from the pyrometer data is higher, as seen on fig.2, which is due to the assumption of equal heat fluxes on ion and electron sides of the limiter and poloidally homogeneous distribution. The spectroscopic measurements showed no measurable oxygen release from the hot tungsten plate up to 2000°C, in contrast to earlier measurements on solid tungsten limiters[3], which is probably due to a reduced impurity content of the tungsten plate used in the present experiment. Many spectral tungsten lines could be identified in the measured spectrum

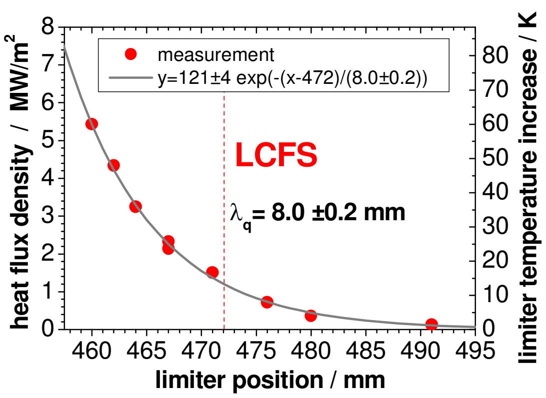

Fig.1 Peak heat flux density on the tungsten plate surface measured by thermocouples

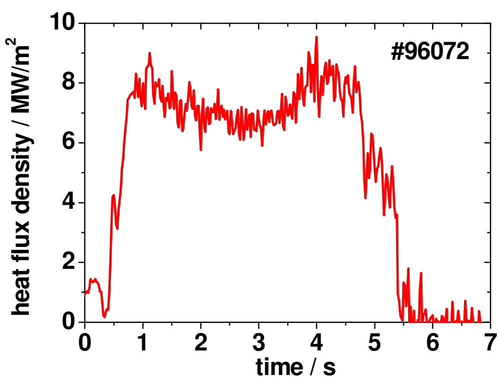

Fig.2 Heat flux density derived from pyrometer at r=46 cm

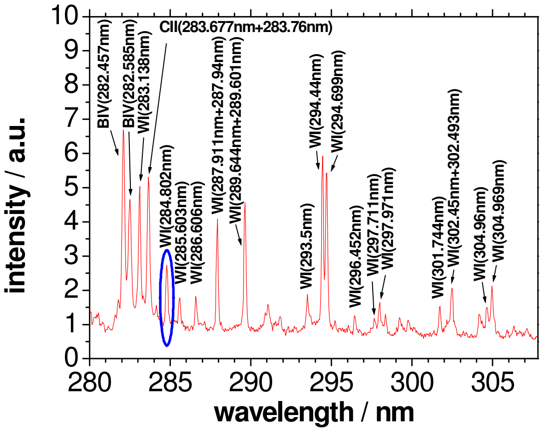

Fig.3 Spectrum measured in front of W plate

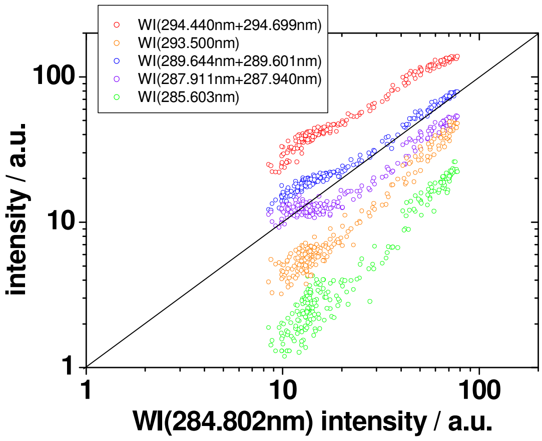

Fig.4 Spectral line intensities dependences.

shown in fig.3. However, the line intensity ratios were not constant as shown in fig.4. The strongest lines WI(289.644nm+289.60nm) and WI(294.440nm+294.699nm) saturated at maximum intensities and the weakest line WI(285.603nm) had a bad signal to noise ratio. Thus, the WI(284.802nm) spectral line marked on fig.3 was used for the tungsten flux measurements which had best intensity within the dynamical range of the ICCD camera of the spectrometer. To evaluate the surface temperature from pyrometer signals, the pyrometer signals were compared with the thermocouples prior to each discharge and were corrected by a temperature dependent spectral emissivity of tungsten [5]. With this correction the absolute accuracy of the surface temperature measurement was about of 50°C. The measured evolution of the H_β(486.1nm), CII(283.677nm+283.76nm) and WI(284.802nm) spectral line intensities in front of the test limiter together with surface temperature of the tungsten plate are shown in fig.5. The atomic tungsten flux from the plate was nearly constant up to a temperature of about 3200 K. With a further temperature rise, the flux grows exponentially by a factor of 7 at 3600K (close to melting point of tungsten). The measured tungsten flux can be very well fitted by a sum of two fluxes

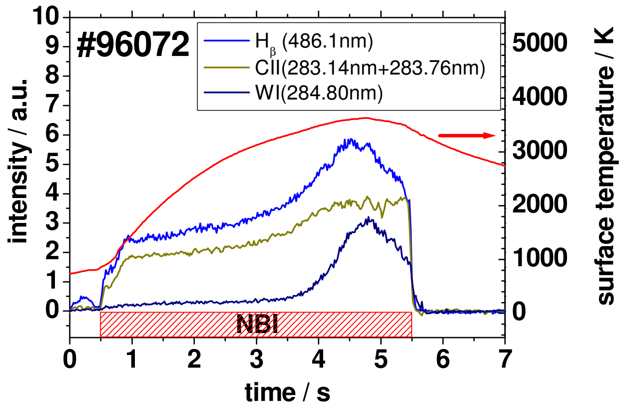

Fig.5 Evolution of spectral line intensities and surface temperature

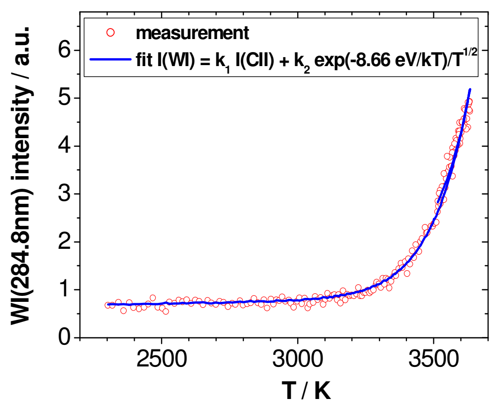

Fig.6 Tungsten flux versus temperature

i.e. sputtering by carbon ions and usual evaporation of tungsten. The result of such fitting is shown on fig.6.

Discussion and conclusion

The behaviour of line intensities shown on fig.4 indicates that sputtered and sublimated atoms have a different population of electronic states. The reason for this can be that the sublimated atoms have about a 6 times shorter penetration depth due to their different kinetic energy with sputtered tungsten atoms of about 10 eV (penetration depth about of 2 mm [8]). The sublimated atoms are released with thermal energy, which is less then 0.3 eV and its penetration depth should be about of 0.3 mm. The electron energy distribution strongly changes close to the surface due to the presence of thermoelectrons from the hot surface, which can affect the excitation rates. The population of the ground state (especially its fine structure) of the sputtered tungsten atoms is different from the population of evaporated atoms and this can change the excitation rate too. The viewing line of the spectrometer crosses tangentially a part of the plate surface including the IR measuring point, therefore, the resulting flux is an average value across the plate. However, the surface temperature changes less than 200 K within the viewing line and such an inhomogeneity does not essentially disturb the temperature dependence of the evaporation rate. Using the vapour pressure of tungsten from [6], the tungsten flux is estimated to be about $4 \cdot 10^{17}$ atoms/cm$^2 \cdot$s at temperatures below 3000K. This flux of sputtered tungsten atoms corresponds to about 4% of the plasma flux to the surface estimated from the heat flux density shown on fig.2. This value is in good agreement with previous measurements with tungsten limiters in TEXTOR [7, 8]. Finally, one must conclude that there is no enhancement of atomic tungsten release exceeding physical sputtering and normal thermal sublimation for temperatures below 3700K under present conditions at TEXTOR.

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