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Exposure of CFC-materials to high transient heat loads in the TEXTOR tokamak

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Abstract

Transient high heat flux events like ELMs, vertical displacement events and disruptions can cause the thermal ablation of plasma facing material. Until now experimental work in this field had been carried out by exposing material specimens to heat loads by electron or laser beam or by tests in pulsed plasma accelerators. In the present work carbon specimens were directly exposed to intense plasma fluxes in the TEXTOR tokamak. The exposure was performed with a fast probe allowing the insertion of the material over a distance of 9 cm into the edge plasma for a duration of 80 ms. The results of in-situ diagnostic measurements and of the post-experiment examination of the specimens are compared with a reference experiment by electron beam and with numerical analyses. Results indicated that the heat flux to the probe surfaces and the probe erosion is much lower than expected.

Keywords: TEXTOR; Disruptions; Material probe; Carbon fibre composites

1. Introduction

In next generation tokamak fusion devices the plasma facing components will be frequently subjected to transient high heat flux events like ELMs, vertical displacement events and disruptions [1]. During the incidence of high heat fluxes the plasma facing materials are subjected to thermal excursions which cause the ablation of material.

Until now the behaviour of plasma facing materials under pulsed heat fluxes was investigated in simulation experiments with laser and electron beam irradiation, or with plasma pulses from plasma accelerators [2–5]. These experiments showed strongly varying ablation results which depend on the incident species (photons, electrons, plasma), their fluxes and energies.

In a tokamak environment the ablated material will interact with the incident plasma, which results in collisional processes with the surrounding plasma particles, including ionization, excitation and the subsequent loss of plasma energy by radiation. These processes in turn change the parameters of the incident plasma and thus a modulation of the incident heat flux can take place.

The work in this paper covers the study of the material behavior and the interaction of the ablated material with the incident plasma under transient high heat fluxes in the TEXTOR tokamak. A carbon fiber composite material (CFC) was exposed to the edge plasma of TEXTOR using the Fast Probe of UCSD (University of California at San Diego).

Parallel to these experiments, reference tests on the same material were carried out by electron beam heating in the JUDITH electron beam facility. The results of the experiments were compared to numerical calculations performed with the A * THERMAL computer code.

2. Experimental

2.1. Probe experiments in TEXTOR

The probe experiments were carried out using the pneumatically driven fast probe of the UCSD-Team at

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TEXTOR. The use of this probe allowed exposure of material specimens of 120 mm length with a quadratic cross section of 16×16 mm to the edge plasma. With regard to the plasma the probe tip was at floating potential and electrically isolated against other components.

The material tested was CF 260 from Schunk, a woven plain fabric PAN-fibre carbon–carbon composite with layered 2D structure. The density was very low with $\rho = 1.4$ g/cm^3 and the thermal conductivity was $\lambda = 1$ W/mK across the fibre reinforcement and $\lambda = 10$ W/mK in the plane of the fibre weave at room temperature. This material was selected because of the low thermal conductivity values on the purpose of maximizing carbon erosion already under relatively low incident heat fluxes.

The insertion depth of the probe was 9 cm in front of the main limiter radius of TEXTOR, which was positioned at $r = 46$ cm. The travel time of the probe tip from the limiter radius up to the end position was 25 ms each for the in and out movement. The dwell time at the end position was 80 ms. The probe tip was inserted into Ohmic and NBI-heated hydrogen discharges which usually had a discharge duration of 6 s. Taking the local values of plasma temperature and density 9 cm in front of the main limiter in the NBI-heated discharges $T_e = 600$ eV and 1.2×10^{13} cm^{-3}, the calculated incident heat flux to the outermost tip of the probe would be $q'' = 88$ kW/cm^2 assuming an energy transmission factor through the plasma sheath of $f = 6.5$ [6]. The CF260 specimen was subjected to eight repeated exposures with similar plasma parameters.

Plasma diagnostics used were among others HCN-interferometry for electron density and temperature measurements, He-beam diagnostics, optical emission spectroscopy (OES) and bolometry. Specifically for the probe experiments local OES was prepared to measure the emission of excited carbon species directly in front of the probe tip. In addition, thermocouples were mounted within the specimens at a distance of 2 mm from the heated surfaces.

After the experiments, the morphology of the exposed surfaces was investigated by SEM and profilometry.

2.2. Experiments in the electron beam facility JUDITH

The JUDITH electron beam facility [7] was used to apply surface heat loads on a CF260 specimen of identical dimensions. The heat flux was deposited by 120 kV electrons for pulse durations of 100 ms onto a surface area of 16×16 mm. The specimen was exposed to $q'' = 30$ kW/cm^2 which was a value selected to approximate the theoretically calculated heat flux of the TEXTOR tests. After the experiments the surfaces of the specimen were investigated by SEM and profilometry.

The results of the experiments in TEXTOR and JUDITH were compared with numerical calculations using the A*THERMAL code [8] which was developed for the analysis of transient processes during the exposure of plasma facing materials to high heat fluxes.

3. Results

3.1. Probe experiments in TEXTOR

Upon introduction of the CFC-probe into the edge the overall plasma was strongly affected, but it recovered quickly after the probe was withdrawn from the plasma. A few discharges were terminated by disruptions possibly caused by the carbon impurity influx from the probe. The further description concentrates on one typical discharge with a probe insertion to 9 cm (#62803), since the other discharges of this experimental series showed quantitatively similar results.

The emission of C-atoms from the probe tip into the plasma resulted in a strong instantaneous increase of the total number of electrons in the discharge, shown in Fig. 1. From the decay of the number of electrons the average confinement time of the carbon impurities was derived by fitting a set of exponential decay functions $\langle \exp -(t - t_n/\tau) \rangle$ with $\tau_p = 50$ ms. Fig. 2 shows the numerical approximation of the electron generation from the ionization of inflowing C-atoms and the subsequent loss of these electrons from the discharge. Assuming that all inflowing carbon was ionized to C^{6+}, the total number of carbon atoms eroded from the hot probe surface per pulse was 1.5×10^{19} at.C per plasma exposure.

During the insertion of the probe, as seen in Fig. 3, the density profile is disturbed and a shoulder develops in the electron density distribution. Like in pellet injection discharges the particles are subsequently swept towards the centre and increase the central density.

The intensity of the CV-line radiation increases spontaneously upon the insertion of the probe, Fig. 5. This increase corresponds to the increase of the total number of electrons, Figs. 1 and 3. It is likely therefore, that the electron density increase reflects the C-atom influx from the probe tip.

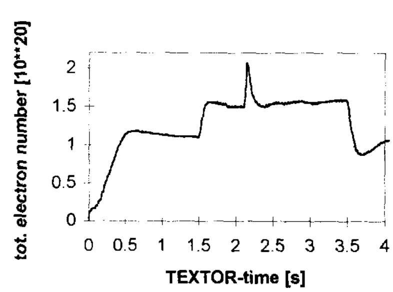

Fig. 1. Total number of electrons during discharge #62803; NBI was from 1.5 to 3.5 s, probe was inserted at 2.10 s.

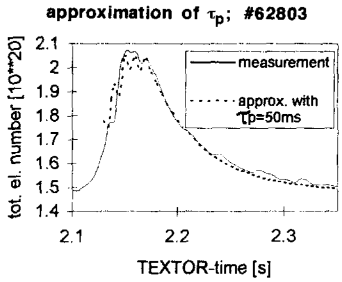

Fig. 2. Numerical fit to evolution of the number of electrons during the insertion period of the CFC-probe, discharge #62803.

At the position of the probe tip ($r = 37$ cm) the ECE-measurements show a decrease of the electron temperature from $T_e = 600$ eV to $T_e = 360$ eV, Fig. 4. Other T_e measurements by He-beam at a radial position of $r = 43$ cm experienced an even more drastic drop at positions radially outside of the probe tip.

The total radiation from the plasma was measured by bolometer, Figs. 5 and 6. The additional power radiated from the plasma due to the emission of C-impurities from the probe reached $\Delta P_{rad} = 1.5$ MW at the peak, Fig. 5. By integration, the energy radiated during this period was calculated to be about $Q_{rad} = 5 \times 10^4$ J. Dividing this value by the estimated number of emitted C atoms, Fig. 2, gives a radiated energy of $E_{rad} = 19.5$ keV/C at. The space and time resolved radiation profile in Fig. 6 indicates that the impurity radiation was emitted from the edge plasma, where subsequently also the decrease of the electron temperature was observed. In the plasma centre the fully ionized C no longer radiates.

The local OES measurement of the CII emission from C^+ ions near the probe tip which acted as C-impurity

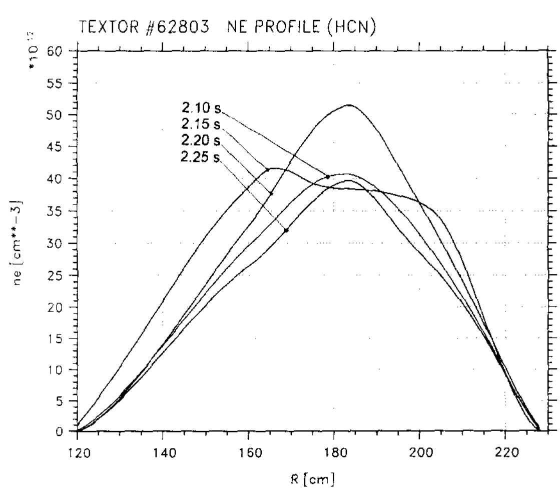

Fig. 3. Space resolved electron density profiles at different time steps of discharge #62803: before and during probe insertion; after retraction of the probe.

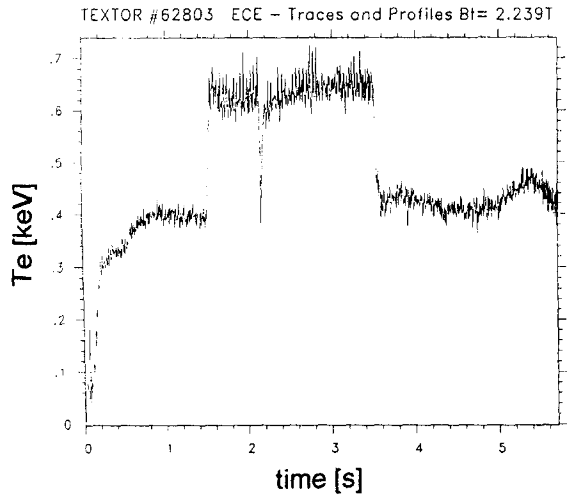

Fig. 4. Electron temperature at $r = 36$ cm, corresponding to the maximum insertion depth of the probe, discharge #62803.

source displays a sharp peak after the insertion of the probe, Fig. 7. From measurements of the Doppler broadening and of the Doppler shift the velocity and temperature of the C^+ ions was deduced to $v_{C^+} = 1640$ m/s and $T = 25$ eV.

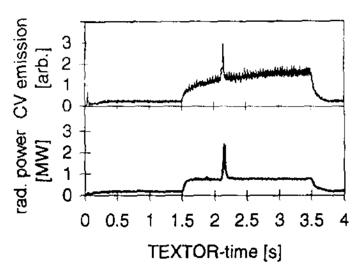

Fig. 5. CV-emission during discharge and time evolution of radiated power from plasma; #62803.

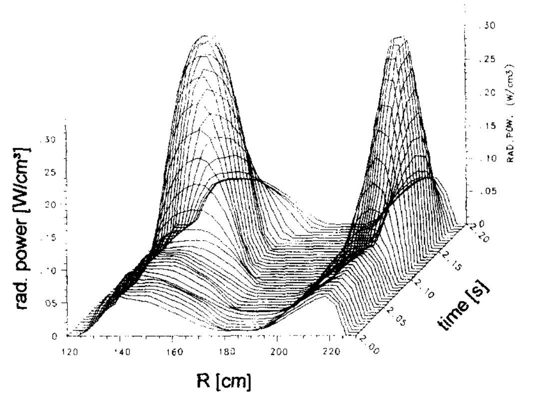

Fig. 6. Space resolved radiation profile; bolometric measurement during discharge #62803.

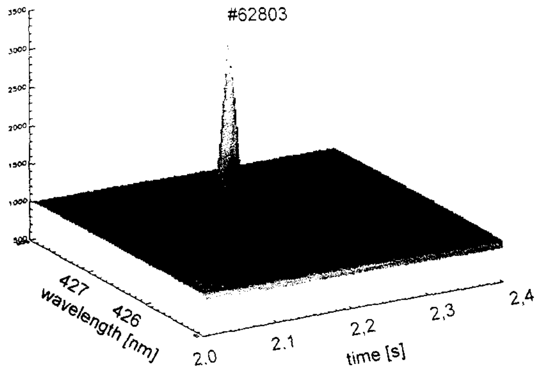

Fig. 7. CII-emission in the direct vicinity of the probe, discharge #62803.

The morphology of the CF 260 surfaces after exposure to eight discharges is shown in Figs. 8 and 9. In the direct vicinity of the edge of the probe tip traces of erosion were found. Macroscopically the edge of the probe was slightly rounded. The SEM micrograph, Fig. 8, shows preferential erosion of the matrix phase and also destruction of the free C-fibre tips. At a distance of about 2–3 mm from the probe tip no thermal damage of the material surface was found. Instead, a redeposited layer of carbon formed at the surface having a pyrolytic structure, Fig. 9. Profilometric measurements and microscopy of the probe surface revealed that this zone of material redeposition extended up to about 30 mm length on the CFC-probe. The volume of the eroded material at the tip zone was roughly estimated from the visible damage after eight plasma exposures and is in agreement with the calculated C-influx into the plasma of 1.5×10^{19} at (0.25 mg) per exposure which was derived from the electron density rise.

3.2. Electron beam heating tests

The exposure of the CF260 material to electron beam pulses of $q'' = 30$ kW/cm^2 for 100 ms resulted in a

30 μm

Fig. 8. CFC-surface after 8 discharges; erosion region close to the edge of the probe tip.

10 μm

Fig. 9. CFC-surface after 8 discharges; redeposition region in about 5 mm distance from the edge of the probe tip.

completely different erosion damage pattern. The material near the surface disintegrated with residues of C-fibres loosely covering the surface. The average erosion per heat flux pulse was 200 μm as measured by profilometry which corresponds to 1.68×10^{22} at/cm^2 per pulse. Numerical calculations with the A*THERMAL code reproduced this result and gave erosion values of 238 μm per heat flux pulse of 30 kW/cm^2 and 100 ms.

4. Discussion

The results of the probe experiments in TEXTOR indicate that the tip of the probe of about 3 mm radial depth was heated very rapidly while the rest of the probe was considerably less heated. Therefore the front tip was a strong source for C-impurities. The standard assumptions of particle (and heat) diffusion into the shadow of a limiter [6] would predict a much more uniform temperature distribution. The reason of the observed shielding of most of the probe is not yet well understood. It is assumed that radiation, cloud shielding of the evaporated carbon, or self-shielding of the probe, in which the probe partially acts as limiter, play an important role. The post-experimental examination of the probe surfaces revealed that detectable erosion took place only on the first 3 mm of the probe tip. Obviously, the other parts of the probe were not exposed to heat fluxes which could have caused thermal ablation of material. Assuming that erosion occurred homogeneously over the length of 3 mm, the total area of the erosion zone was $A_e = 3$ mm $\times$ 16 mm $\times$ 4 = 192 mm^2. The erosion of 1.5×10^{19} at (0.25 mg C) per exposure on this area would result in an ablation depth of about 1 μm per exposure. For this amount of ablation the surface temperature has to reach 3000 K.

Since the evaporation enthalpy of C at elevated temperatures is about 3 eV/at, but the average energy loss per evaporated C atom within the plasma by radiation was

19.5 keV/at, the ablation of only small amounts of carbon (1.5×10^{19} at per exposure) caused strong radiation cooling of the plasma edge. The incident heat flux to the tip of the probe was strongly reduced and on the shaft sides of the probe only redeposited C-atoms and no erosion was observed.

In contrast to this impurity induced cooling effect observed in TEXTOR, the electron beam heated specimen showed very strong thermal ablation (200 μm per exposure), which is also consistent with the results of numerical calculations (238 μm per exposure). As calculated from the plasma parameters in TEXTOR at the probe tip position ($r = 37$ cm), the incident heat flux should have been about $q'' = 88$ kW/cm^2, even higher than the value of the JUDITH experiment ($q'' = 30$ kW/cm^2). Numerical calculations based on the thermocouple response and the ablation from the TEXTOR specimens indicated, however, that the absorbed heat flux at the specimen tip averaged over an exposure time of 80 ms was only $q'' = 2.5$–3 kW/cm^2.

5. Conclusion

Fast probe experiments with CFC-material in TEXTOR showed that a very strong reduction of the heat flux to the probe surface occurs upon the emission of carbon impurities into the plasma and the subsequent emission of radiation in the plasma edge. The time averaged absorbed heat flux to the probe tip was a factor of about 30 lower than the estimated heat flux at a depth of 9 cm within the plasma edge.

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