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Operation of TEXTOR-94 with a Tungsten Poloidal Main Limiter System

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Abstract

In TEXTOR-94 experiments have been performed with the upper and lower poloidal limiter tiles made of vapor sprayed (VSP) tungsten (about 0.5 mm) deposited on graphite with a Rhenium interlayer. A series of discharge conditions have been performed (density scan, scan of the auxiliary heating power, radius scan). There has been no restriction for operation at any density with auxiliary heating. For Ohmic conditions the same density with testlimiters - and even higher - could be reached. At high discharge power losses by radiation no severe accumulation of tungsten in the plasma centre could be detected. The blocks could in general stand surface temperatures below 1700 K. However, most of them survived also temperatures above 3000 K without exfoliation. However, some blocks showed severe damage by melting or exfoliation probably due to not sufficient contact of the tungsten layer with the graphite.

Keywords:

tokamak, poloidal limiter, tungsten, heat loads

1. Introduction

Tungsten is one of the high -Z materials, which is favored as wall or divertor material in the future. The reason for this is that both its erosion is much lower and its redeposition higher than for carbon based materials. This can be a considerable advantage for long pulse or steady state fusion devices where erosion and redeposition may significantly limit the lifetime of plasma facing materials. In TEXTOR-94 several experiments have already been carried out using full or twin tungsten test limiters (one half made of graphite and the other half of tungsten) [1], which can be inserted into the main plasma or withdrawn on a shot-to-shot basis. However, the active area of these limiters is comparatively small and their influence on the main plasma may not be typical. Therefore, in order to increase the interactive tungsten surface area up to a relevant number, the ten blocks of the upper and lower poloidal TEXTOR-94 limiter have been replaced from

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pure graphite to vacuum vapor sprayed (VSP) tungsten (about 0.5 mm) deposited on graphite with a Rhenium interlayer. These kind of limiters also allow the study of the behaviour of these coatings under strong thermal loads (i.e. more than 10 MW/m^2), which might be typical for excessive power loads on divertor tiles.

2. Experiment

TEXTOR was normally operated under the following discharge conditions: I_p = 350 kA, B_t = 1.75–2.25 T, NBI-heating power of 1.3 MW and ICRH power up to 1 MW. The 10 poloidal limiter blocks have each a length of 130 mm, a height of 80 mm (bottom) 65 mm (top) and a curvature of 50 mm on both sides in toroidal direction. Within about 100 ms they can be moved into or retracted from the plasma, the radius of which is normally defined by the toroidal belt limiter ALT-II at r_{Lim} = 46 cm. In general the "active" surface of the poloidal limiter amounted to about 200 cm^2. Boronization (in the first part of the campaign) and siliconization (in the second half) was routinely applied for surface conditioning of the inner wall and non removable limiter components.

The individual blocks were equipped with thermocouples and heaters. The particle emission from the limiter surface was observed spectroscopically by means of a CCD-spectrometer and video cameras in combination with interference filters [2]. The surface temperatures were measured via a CCD-camera with a cut-off filter at 850 nm, which could be cross calibrated by a pyrometer aiming at the same spot on one of the blocks.

Core plasma parameters are monitored with the standard TEXTOR diagnostics. In addition an XUV spectrometer has been installed for the observation of the spectral emission of the quasicontinuum radiation of WXXVIII around 5 nm from the plasma center.

3. Results and Discussion

The two main subjects, which have been studied, are the following: How much is the power / temperature which such limiters can bear during plasma operation - and - is there any harming influence on the general performance. Other subjects of importance are e.g. the uptake of these W-layers concerning hydrogen and their particle release rates for tungsten, oxygen, carbon and hydrocarbons. Parts of the latter subjects will be presented in [3].

Figure 1 shows the arrangement of the upper limiter blocks and their appearance before and after about 150 discharges. In order to prevent these blocks from too high heat loads at the beginning of the campaign, they have been very carefully exposed to the

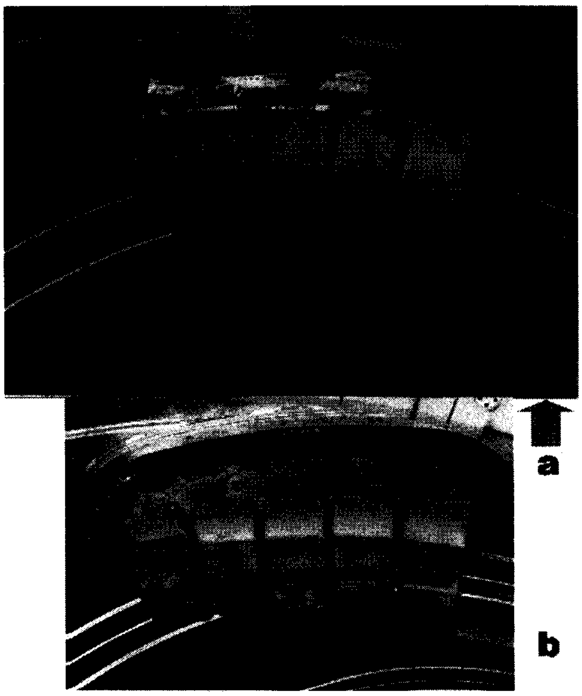

Fig. 1 Tungsten poloidal limiter blocks: virgin (a) and after about 150 discharges (b).

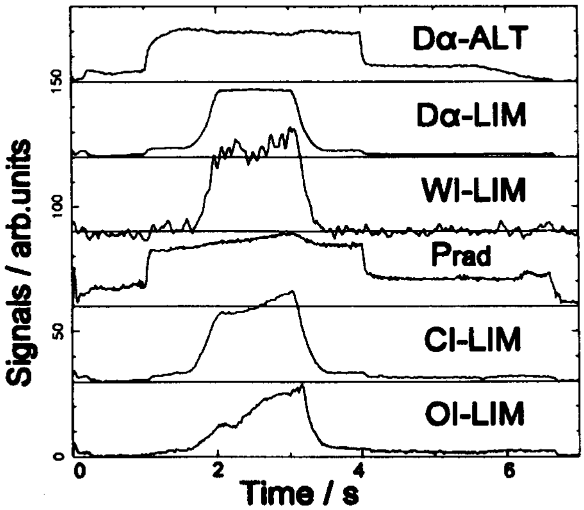

Fig. 2 limiter at 45 cm: 2–3 s; NBI (1.3 MW) 1-4 s; at 2.5 s: $\Gamma^{ALT}_D = 2 \times 10^{18}$/(cm s), $\Gamma^{LIM}_D = 2.8 \times 10^{19}$ /(cm s), P_{rad} = 0.6 MW, $\Gamma^{LIM}_{WI}/\Gamma^{LIM}_D$ = 0.0002, $\Gamma^{LIM}_{CII}/\Gamma^{LIM}_D$ = 0.01, $\Gamma^{LIM}_{OII}/\Gamma^{LIM}_D$ = 0.003.

plasma for a restriced time during the flat top phase of the discharge. During other programmes they were retracted nearly to liner position to prevent unintentional overload and destruction.

The ratio of convective power $(1 - \gamma)$ [γ= radiated power] to total input power proved to be quite different for boronized and siliconized conditions - for the latter it was about a factor of 3 smaller - which led to incomparable discharge scenarios.

Figure 2 shows the behaviour of a plasma just after a fresh boronization, which resulted in discharges with $\gamma \leq 0.3$ i.e. high convective loads. From the temperature rise in the bulk of $\Delta T \approx 35$ K one can derive an energy load of about 40 kJ in 1 s (i.e. a heat flux of 12 MW/m^2 for the "active" limiter surface), from which a maximum surface temperature of about 1700 K can be calculated [4]. The resulting D-flux at T_e = 80 eV is $\Gamma^{LIM}{}_D = 1.2 \times 10^{19}/(cm^2s)$, which is in good agreement with the measured one under the assumption of an "active" limiter surface of 100 cm^2. During the insertion of the limiter $\Gamma^{ALT}{}_D$ drops by about 10%, reducing the total plasma energy by 90 kJ, which is 2 times more than expected; however, the energies of the scraped particles are less in the outer parts of the boundary layer (see Fig. 3).

There are also unexpected findings in comparison with the test limiter experiments. The tungsten flux ratio $\Gamma^{LIM}{}_{WI}/\Gamma^{LIM}{}_D$ is about an order smaller and the flux ratio $\Gamma^{LIM}{}_{CD}/\Gamma^{LIM}{}_D$ for hydrocarbons one order larger. It may well be possible that these two ratios depend on each other: the poloidal limiters could not be protected against intensive carbon deposition during "normal" plasma operation and behaved in many respects as normal carbon limiters except at surfaces, where the carbon layer had been sputtered away during intensive impinging impurity fluxes. However, these - sometimes intentional - "cleaning" procedures proved to be very sensitive to the power loads on the individual blocks; either the cleaning effect was small or there was a danger that the W-layer suffered by exfoliation. This relative independence of relative W-fluxes could be seen during scans of the auxiliary power (both for ICRH and NBI). As main reason for the release of tungsten sputtering by impurities could again be found. This is shown in fig. 4 when an unintentional drop of the upper limiter occurred by interference of ICRH into the limiter control system. However, it demonstrates that not so much the energy of the impinging particles is the cause of tungsten sputtering but the kind of impurities. From comparison of the D, CI and OI signals one can conclude that oxygen is the constituent, which causes a major contribution to the tungsten sputtering.

The general performance of the plasma discharges with poloidal tungsten limiters proved to be better than expected. One of the major reasons for this behaviour was obviously the all-carbon surrounding of the TEXTOR-94 vessel and built-in components. One of the impressive results was that even Ohmic discharges displayed at least the same or even higher density limits as similar ones with tungsten test limiters. This is shown in fig. 5 with the poloidal W-limiter even 4 cm further

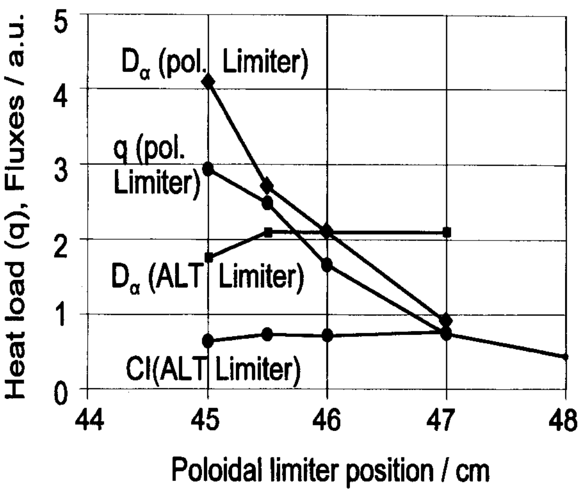

Fig. 3 Fluxes and absorbed heat during a poloidal limiter scan for Ohmic, low density discharges.

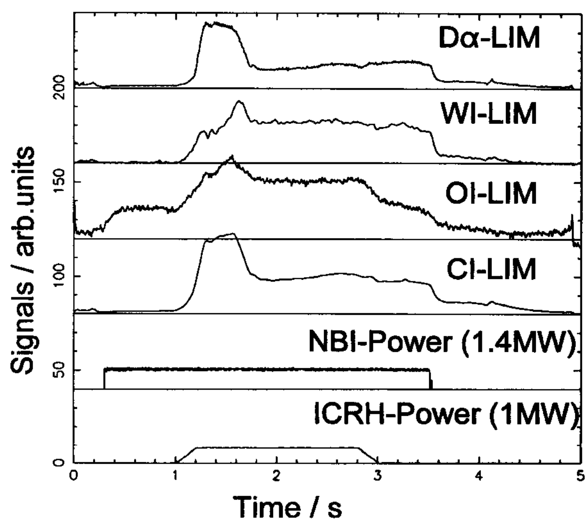

Fig. 4 Poloidal limiter fluxes during a short insertion from 45 cm -> 42 cm between 1.2 s -> 1.6 s.

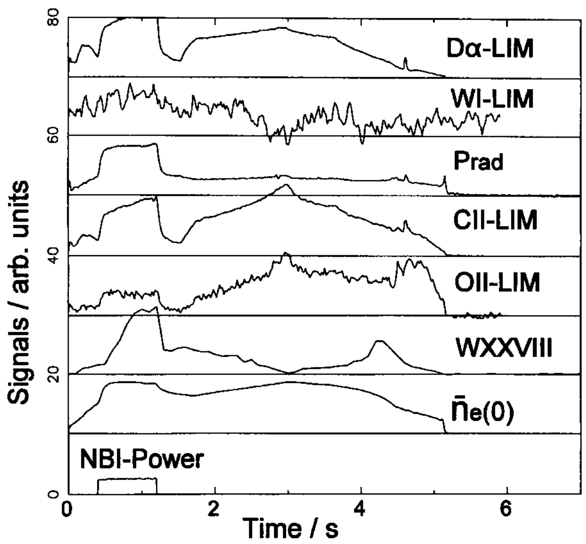

Fig. 5 Ohmic disch. with W-limiter at 42 cm from 1.7 s.

more in than the main limiter ALT-II. However, the radiated power was in this case very near to the total input power - a common result of a siliconisation campaign which had been carried out before these experiments [5]; moreover, the increasing impurity fluxes of carbon and oxygen did not lead to a growing tungsten release. On the contrary, at the maximum level of $\bar{n}_e(0)$ = 4.5 × 10^{13} cm^{-3} at 3.1 s both the tungsten fluxes and the tungsten concentration in the center (represented by the WXXVIII-quasi-continuum radiation around λ = 5 nm) are practically negligible - a very similar behaviour as in ASDEX-U near the density limit [6]. Indeed, during that experimental campaign mentioned the density limit for discharges was equal for carbon and W-limiters. For higher convective powers Ohmic discharges of only 75% of this density could be reached until the strong tungsten accumulation in the center lead to a radiation collapse. Again under no circumstances led NBI- and/or ICRH-power heated discharges to remarkable W-concentrations.

Figure 6 displays this behaviour for a density scan during auxiliary ICRH-heating. There is obviously a strong screening effect with increasing density, which prevents the tungsten to diffuse into the plasma center. On the other hand one should add that during these experiments both the tungsten fluxes and concentration continuously rose during the discharge time when the poloidal limiter was inserted; there seem to be mechanisms, which gradually change either the sputtering rate, -surface, or responsible particles during longer power loads onto the limiters. Because of the

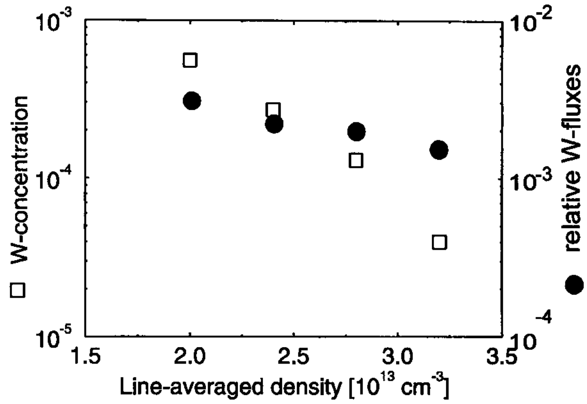

Fig. 6 W-concentration and -fluxes during a density scan with ICRH-power of 1 MW (r_{LIM} = 46 cm).

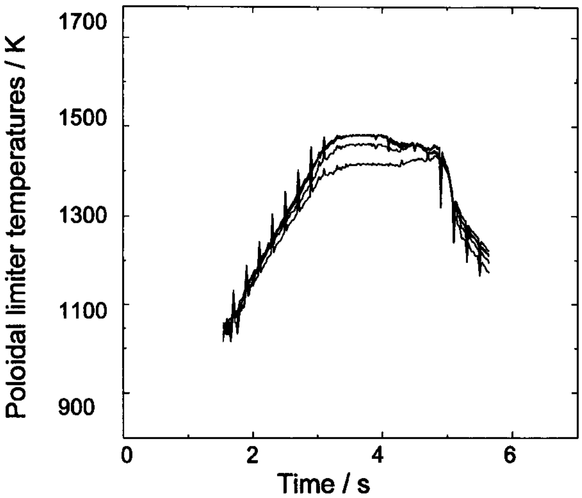

Fig. 7 Surface temperatures of the 5 bottom blocks during NBI-heating (1.3 MW) with W-limiter at 42 cm from 1.7 s.

restricted discharge duration this effect could not have been studied further in detail.

At the end of the campaigns experiments had been carried out to find the load limits of the tungsten limiter blocks.

Figure 7 shows that, although the total energy uptake is only half of that discharge displayed in fig. 2 because of the higher radiation losses, a nearly equal temperature is reached. This measured temperature agrees well on average with calculated one [4]. However, one can already notice that not all blocks have reached the same surface temperature. On the other hand the absorbed energy, represented by the temperature rise measured by the thermocouples, shows a reciprocal behaviour for the individual blocks. A lower surface temperature is obviously a hint for a good contact between W-layer and graphite substrate. When the power load was further increased, those blocks with higher absorbed energy were more resistant to exfoliation than the others, where a bad conduction led to a cracking of the layer with subsequent melting of the tungsten.

However, it was found that most of the blocks could stand energy loads up to about 100 kJ for 1 s, which has led to surface temperatures well above 3000 K. This resulted in the appearance of several major cracks. Microcracks due to grain growth by recrystalisation were not observed. This is in contrast to ASDEX-Upgrade [6], but seems to confirm findings by heat load experiments with identical layers [7].

4. Conclusions

The experiments performed with a poloidal tungsten limiter system on TEXTOR-94 did not only confirm the previous results with tungsten test limiters, but revealed even more promising characteristics. However, one should have in mind that these may be favoured by the wall conditioning procedures and the all-carbon surrounding. In particular

- there has been no restriction for operation at any density with auxiliary heating. For Ohmic conditions the same density with test limiters - and even higher - could be reached.
- At high levels of radiated power no severe accumulation of tungsten in the plasma center could be detected.
- the blocks could in general withstand surface temperatures below 1700 K. However, most of them survived also temperatures above 3000 K without exfoliation. For most of them larger cracks appeared, but microcracks could not be seen. However, 4 blocks (from a total of 16 used) showed severe damage by melting or exfoliation.

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