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Operation of TEXTOR-94 with tungsten poloidal main limiters

A. Pospieszczyk [a,*], T. Tanabe [f], V. Philipps [a], G. Sergienko [e], T. Ohgo [b], K. Kondo [c], M. Wada [d], M. Rubel [h], W. Biel [a], A. Huber [a], A. Kirschner [a], J. Rapp [a], N. Noda [g]

[a] *Institut für Plasmaphysik, Forschungszentrum Jülich GmbH, TEC, Association Euratom-kfa, Jülich, Germany*
[b] *Department of Physics, Fukuoka University of Education, Munakata, Fukuoka, Japan*
[c] *Graduate School of Energy Science, Kyoto University, Uji, Kyoto, Japan*
[d] *Department of Electronics, Doshisha University, Kyotanabe, Japan*
[e] *Institute for High Temperatures of the RAS, Association IVTAN, Russia*
[f] *Center for Integrated Research in Science & Engineering, Nagoya University, Nagoya, Japan*
[g] *National Institute for Fusion Science, Toki, Gifu, Japan*
[h] *Alfven Laboratory, Royal Institute of Technology, SE-10044 Stockholm, Sweden*

Abstract

In TEXTOR-94, experiments have been performed with the upper and lower poloidal limiter blocks made of vapour 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 found no restriction for operation at any density with auxiliary heating. For Ohmic conditions the same density with testlimiters could be reached. Under siliconized conditions no severe accumulation of tungsten in the plasma centre could be detected. The blocks could in general stand surface temperatures below 1700 K. Most of them survived also temperatures above 3000 K without exfoliation. However, some blocks showed severe damage by melting or exfoliation probably due to insufficient contact of the tungsten layer with the graphite.

Keywords: Coating; High-Z material; Limiter materials; TEXTOR 94; Tokamak; Poloidal limiter; Tungsten; Heat load

1. Introduction

Tungsten is one of the high-Z materials, which is favoured as wall or divertor material in future fusion devices. The reasons for this are both much lower erosion and higher redeposition than for carbon based materials. This can be a considerable advantage for long pulse or steady-state fusion devices where erosion and redeposition may determine the lifetime of plasma facing materials. In TEXTOR-94, several experiments have already been carried out using full or twin (one half made of graphite and the other half of tungsten) tungsten test limiters [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 the lower poloidal TEXTOR-94 limiter have been replaced from pure graphite to vacuum vapour sprayed (VSP) tungsten (about 0.5 mm) deposited on graphite with a rhenium interlayer. This kind of limiters also allows the study of the behaviour of these coatings under strong thermal loads (i.e., more than

* Corresponding author. Tel.: +49-2461 5536; fax: +49-2461 3331.

E-mail address: a.pospieszczyk@fz-juelich.de (A. Pospieszczyk).

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10 MW/m^2), which might be typical for excessive power loads on divertor tiles. In addition the long term behaviour of tungsten components, which have been exposed to a boundary plasma for several hundred of discharges, and their influence on the discharge behaviour can be determined.

The major subjects, which have been studied, are the power and temperature which such limiters can bear during plasma operation and their influence on the general plasma performance. Important questions are also the uptake of the W-layers concerning hydrogen and their particle release rates and central concentrations of tungsten, oxygen, carbon and hydrocarbons. Parts of the latter subjects will be presented in [2].

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 100 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 simultaneously also of the poloidal limiter blocks as they could not be protected by valves.

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 viewing along a radial coordinate (see Fig. 4) and video cameras in combination with interference filters for a 2-d observation [3]. 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 W XXVI∼XXX around 5 nm from the plasma center.

3. Results

Fig. 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

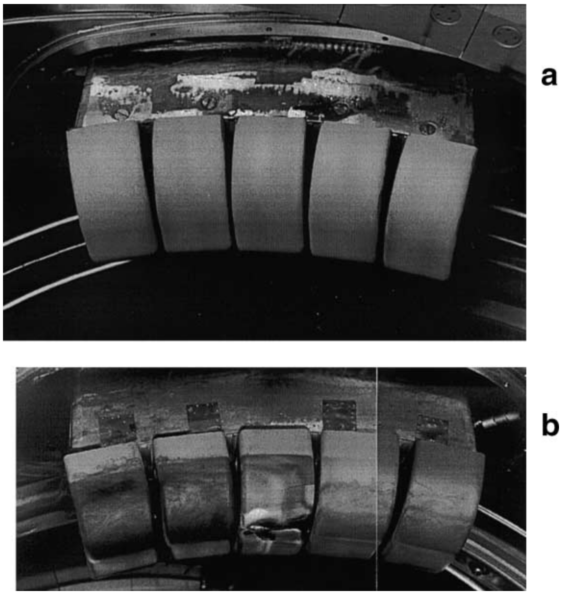

Fig. 1. Tungsten poloidal limiter tiles: virgin (a) and after about 150 discharges (b). The damage of the central block is a result of exfoliation.

high heat loads at the beginning of the campaign, they have been very carefully exposed to the plasma for a restriced time during the flat top phase of the discharge. During other programmes they were retracted into a rest position 3 cm behind the last closed flux surface in order to prevent unintentional overload and destruction but were still subject to coating from the plasma.

3.1. Behaviour after boronization

The ratio of convective power to total input power $(1-\gamma)$ [γ = radiated 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. Fig. 2 shows the behaviour of a plasma just after a fresh boronization, which resulted in discharges with $\gamma \leqslant 0.4$ i.e., high convective loads. From the temperature rise of $\Delta T \approx 35$ K in the bulk of the limiter 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 $\Gamma_D^{LIM} = 1.2 \times 10^{19}/(cm^2\ s)$, 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 the hydrogen flux Γ_D^{ALT} to the ALT-II limiter drops by about 10%. Assuming a linear correlation between D_α-intensities, fluxes and the energies they carry this would mean a reduction of the total plasma energy by 60 kJ

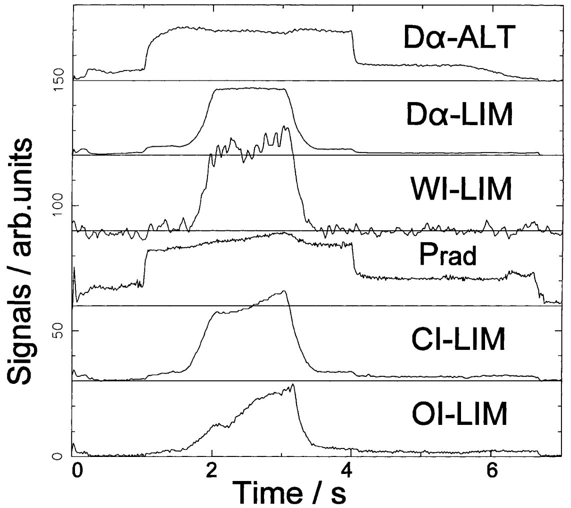

Fig. 2. Limiter at 45 cm: 2–3 s; NBI (1.3 MW) 1–4 s; at 2.5 s: $\Gamma_{\mathrm{D}}^{\mathrm{ALT}} = 2 \times 10^{18}/(\mathrm{cm\ s})$, $\Gamma_{\mathrm{D}}^{\mathrm{LIM}} = 2.8 \times 10^{19}/(\mathrm{cm\ s})$, $P_{\mathrm{rad}} = 0.6$ MW, $\Gamma_{\mathrm{WI}}^{\mathrm{LIM}}/\Gamma_{\mathrm{D}}^{\mathrm{LIM}}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

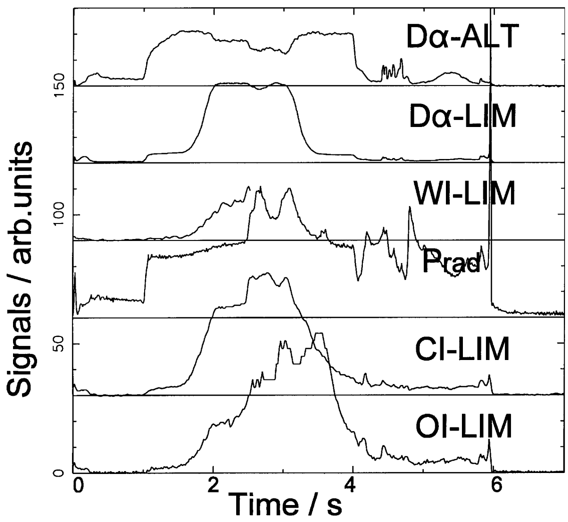

Fig. 3. Limiter at 44.5 cm: 2–3 s; NBI (1.3 MW) 1–4 s; at 2.4 (2.7) s: $\Gamma_{\mathrm{D}}^{\mathrm{ALT}} = 1.6\,(1.3) \times 10^{18}/(\mathrm{cm\ s})$, $\Gamma_{\mathrm{D}}^{\mathrm{LIM}} = 3.1\,(3.0) \times 10^{19}/(\mathrm{cm\ s})$, $P_{\mathrm{rad}} = 0.6\,(1.2)$ MW, $\Gamma_{\mathrm{WI}}^{\mathrm{LIM}}/\Gamma_{\mathrm{D}}^{\mathrm{LIM}} = 0.0004$, $\Gamma_{\mathrm{CII}}^{\mathrm{LIM}}/\Gamma_{\mathrm{D}}^{\mathrm{LIM}} = 0.01\,(0.014)$, $\Gamma_{\mathrm{OII}}^{\mathrm{LIM}}/\Gamma_{\mathrm{D}}^{\mathrm{LIM}} = 0.0034\,(0.005)$.

(from $P_{\mathrm{tot}} = 1.5$ MW and $\gamma = 0.6$), which is 1.5 times more than expected. Obviously the energies of the scraped particles are actually less in the outer parts of the boundary layer [8].

The calculated energy decay length amounts to 0.8 cm, which would lead to a doubling of the power load onto the blocks during an additional insertion of 0.5 cm of the limiter into the plasma. The resulting effects can be seen in Fig. 3, where the scraped particle flux amounts to more than 20% with an additional increase at 2.5 s, when the plasma puts an additional load onto the upper limiters. Although for 1 s the heat load exceeds 20 $\mathrm{MW/m^2}$ with surface temperatures of the blocks in the order of 3000 K, no obvious damage has been detected during the exposure phase. Most of the signals do not show major discontinuities – oxygen is thermally expelled out of the surface and the W-flux signal cannot be traced anymore as it disappears in a strong Planck radiation background. However, an exfoliation of the central block of the upper poloidal limiter occurred at around 4.5 s, which did not harm the ongoing of the discharge (see Fig. 1). This block did not even show the highest energy uptake according to the thermocouple signal – obviously an indication for an imperfect adhesion of the W-layer on the C-substrate, something which was frequently observed in the course of the campaign when exfoliation effects occurred. There are also unexpected findings in comparison with tungsten test limiter experiments performed earlier. The tungsten flux ratio $\Gamma_{\mathrm{WI}}^{\mathrm{LIM}}/\Gamma_{\mathrm{D}}^{\mathrm{LIM}}$ is about an order smaller and the flux ratio $\Gamma_{\mathrm{CD}}^{\mathrm{LIM}}/\Gamma_{\mathrm{D}}^{\mathrm{LIM}}$ 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 – when they were placed for several hundred discharges in a rest position 3 cm outside the last closed flux surface – and behaved then in many respects as normal carbon limiters except at surfaces where the carbon layer had been sputtered away during intensive impinging particle fluxes as main limiter systems. 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. The 1-d observation geometry for the spectral observation of the upper limiter supports this differential coating impressively (Fig. 4): the carbon layer (characterized by a high CD-production) appears deep in the last closed flux surface whereas it is sputtered away at the zones of the highest loads. These carbon coatings could be removed efficiently only after short exposure times of a freshly built-in block but very inefficiently after long exposure times [3].

Under no plasma conditions led NBI- and/or ICRH-power heated discharges to remarkable W-concentrations. Fig. 5 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 from diffusing into the plasma center. During these experiments both the tungsten fluxes and concentration continuously rose during the discharge time when the poloidal limiter was being inserted; there seemed to be mechanisms, which gradually change either the sputtering rate, -surface, or responsible

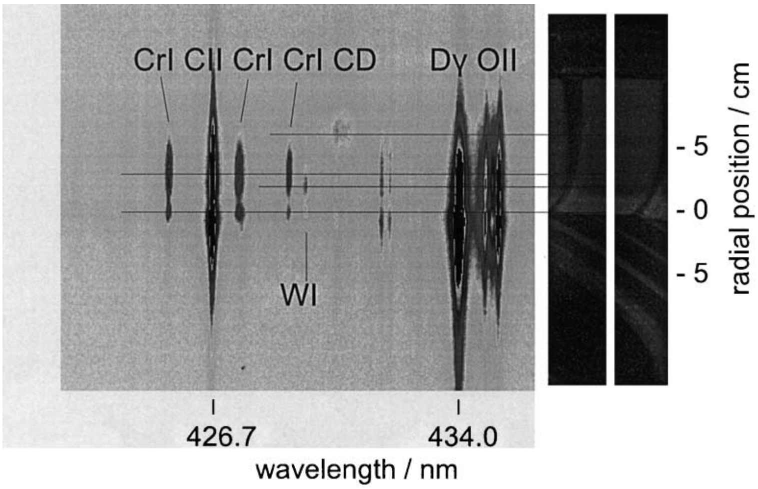

Fig. 4. Spatially resolved spectra along the central upper poloidal limiter block, which displays the origin of the different sources. The plasma radius coordinate (with zero at the limiter surface and the viewing volume as a white vertical line) is indicated on the right, the horizontal lines mark the place of origin on the limiter block.

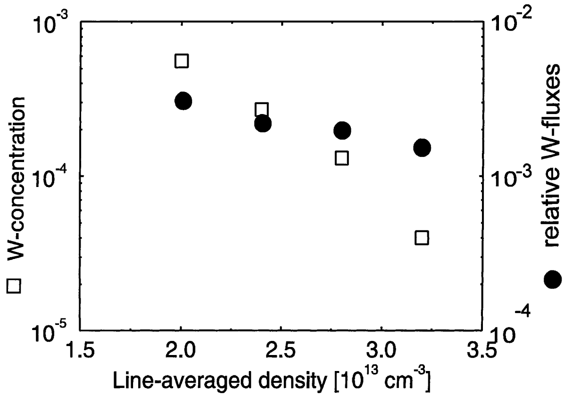

Fig. 5. W-concentration and relative fluxes during a density scan with ICRH-power of 1 MW ($r_{LIM} = 46$ cm). If one assumes a linear correlation between central proton density and hydrogen influx, the scales can also be treated as central W-density and W-influx with a respective scale factor.

particles during longer power loads onto the limiters. Because of the restricted discharge duration this effect could not have been studied further in detail during the boronization campaign.

After the end of the first campaign all five blocks of the upper and one of the bottom limiter have been replaced by fresh ones. The 0.5 mm W-coating of the inner bottom block was completely exfoliated, although it had never experienced extreme heat loads. This layer could further be analysed with surface analytical methods. It was found that a strong intermixing between C, B, and W had occurred in the surface region – an indication for a deep diffusion or compound formation (e.g., W_2C). Deuterium was detected over the whole surface (in the order of percent of C & B) – even in areas which had been very hot. On the rear side, which normally should have been in contact with the substrate, D, B, and C were existing only in very small quantities.

3.2. Behaviour after siliconization

The general performance of the plasma discharges with poloidal tungsten limiters proved in some respects 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, which led to formation of a strongly adhesive carbon coating when the limiter was in the SOL for more than 1000 discharges (see above). Therefore, even ohmic discharges could display density limits at least equal to similar ones with tungsten test limiters. This is shown in Fig. 6 with the poloidal W-limiter even 4 cm further more in than the main limiter ALT-II. In this case, however, the radiated power was very close to the total input power – a common result of a siliconization 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 $\bar{n}_e(0) = 4.5 \times 10^{13}$ cm^{-3} at 3.1 s, both the tungsten fluxes and the tungsten concentration in the center (represented by the W-quasicontinuum radiation around $\lambda = 5$ 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 – i.e., after a boronization – ohmic discharges of only 75%

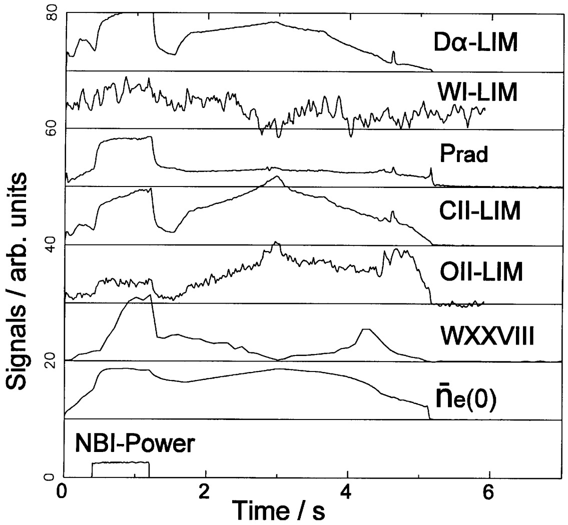

Fig. 6. Ohmic discharge with W-limiter at 42 cm from 1.7 s.

of this density could be reached until the strong tungsten accumulation in the center led to a radiation collapse.

Under siliconized conditions when the limiter could be inserted for a longer time, the latter effects could be better analysed. Fig. 7 shows a strong increase of the oxgen influx during a 4 s exposure of the limiter, which is responsible for a W-flux increase from about 2.5 s. From comparison of the D, C II and O II signals one can conclude that oxygen is the constituent which causes a major contribution to the tungsten sputtering [8]. On the other hand, it demonstrates that not only the kind of impurities is responsible for the strength of the tungsten source but also the energy of the impinging particles – although the oxygen flux is still growing, both tungsten fluxes and concentration decrease with a growing plasma density i.e., falling boundary temperature.

3.3. Behaviour under extreme heat loads

At the end of the campaigns, experiments have been carried out to find the load limits of the tungsten limiter blocks. Fig. 8 shows that, although the total energy uptake is only a half that of the 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 the 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].

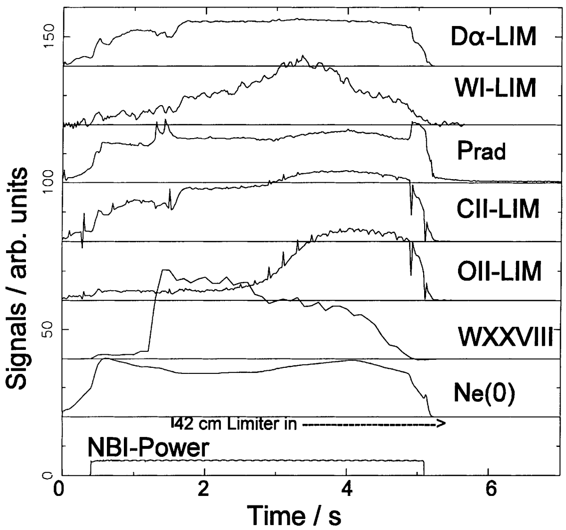

Fig. 7. NBI heated (1.3 MW) discharge with W-limiter at 42 cm from 1.7 s.

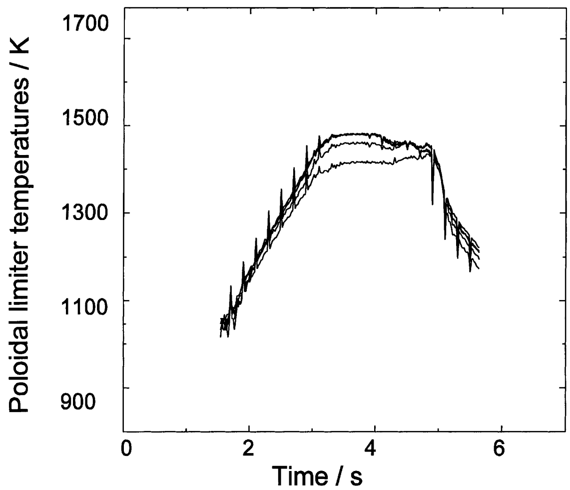

Fig. 8. Surface temperatures of the 5 bottom tiles during NBI-heating (1.3 MW) with W-limiter at 42 cm from 1.7 s.

4. Conclusions

The experiments performed with a poloidal tungsten limiter system on TEXTOR-94 confirmed the previous results with tungsten test limiters. For certain conditions – e.g., a strong carbon coating favoured both by the wall conditioning procedures, the all-carbon surrounding and the limiter rest position – the discharges were practically unaffected by the use of the poloidal limiter system as main limiters. 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 macrocracks 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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