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Journal of Nuclear Materials 313–316 (2003) 223–229

journal of nuclear materials

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B_4C-limiter experiments at TEXTOR

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Abstract

In the TEXTOR tokamak the five top and five bottom poloidal carbon limiter blocks have been replaced by inertially cooled copper blocks coated with a 170 μm VPS-B_4C layer. Similar limiter blocks have been inserted through lock systems, extensively diagnosed in situ as well as ex situ. During the thermal load by the plasma, the surface temperature rose and decayed extremely fast which can be explained by a different thermal conductivity and heat capacity of the coating. For heat loads below 8 $\mathrm{MW\,m^{-2}}$ no severe cracking or delamination of the B_4C-coating were observed. Due to the insulating behaviour of the layer, distinct craters developed on both limiter types, which reached down to the copper surface and are assumed to be caused by electrical arcs. An oscillation of the evolution of the surface temperature has been observed under certain conditions, which is clearly correlated to the use of the coated test limiter. Particle fluxes as well as hydrogen inventory turned out to be very similar to those from a low-*Z* surface in a carbon surrounding. No significant impact of the plasma on the coating and vice versa was observed.

PACS: 52.40.Hf; 52.25.V; 52.70; 66.70; 07.60.R; 73.30
Keywords: B_4C; Limiter; Heat loads; Arcing; Optical spectroscopy

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1. Introduction

For the Wendelstein W7-X stellarator, presently under construction at Greifswald, Germany, protective B_4C-coatings for the plasma facing first wall panels are being developed. The aim of these low-*Z* coatings is to inhibit interaction of the metal surfaces with the plasma, which, otherwise, would lead to a high-*Z* impurity influx. B_4C is a clearly favoured material, due to its lower *Z* number, the good oxygen gettering of B, which might even lead to a simultaneous boronisation during the long (max 30 min) plasma discharges, a procedure which is already an approved technique for wall conditioning of fusion devices [1]. Moreover it shows a favourable behaviour under microwave radiation with electron cyclotron resonance frequency. The plasma spray technique offers the possibility to coat three-dimensionally curved surfaces with materials of very high melting temperatures at reasonable costs and is capable of producing layers with thicknesses of about 1 mm. The characterisation of such coatings concerning purity, surface roughness, adhesion and cohesion strength, sputtering behaviour, thermal conductivity, and thermomechanical properties has already been published elsewhere [2,3]. In this paper we focus on the behaviour of the coatings under plasma exposure with high heat

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PII: S0022-3115(02)01577-5

loads. In particular, the particle release, electrical and thermomechanical properties and resulting surface modifications have been investigated.

2. Experiment

The 10 blocks of the upper and lower poloidal TEXTOR limiter have been replaced from pure graphite to vacuum vapor sprayed (VPS)-B_4C on Cu ones. The surfaces to be coated of the poloidal limiters had a semi-cylindrical shape, those of the test limiters had the shape of a spherical segment (Fig. 1). Typical dimensions were $130 \times 80 \times 60$ mm^3. The limiters, manufactured of oxygen-free copper (OF-Cu) are inertially cooled in order to achieve similar temperatures within the coatings during the discharges of up to 10 s pulse length as are expected for the actively cooled first wall steel panels during normal operation of W7-X. The average thickness of the coating was 170 μm, the porosity 3%, and the average surface roughness $R_a = 3.4$ μm. No intermediate layer was applied. The individual blocks were equipped with thermocouples and heaters. The particle emission from the limiter surface was detected by means of a CCD-spectrometer and video cameras in combination with interference filters [4]. The test limiters were additionally observed with a pyrometer and a fast diode. All limiters were grounded to the liner via a 10 Ω resistor, which allowed the determination of the currents flowing to the limiter. Core plasma parameters were monitored with the standard TEXTOR diagnostics. TEXTOR was normally operated under the following discharge conditions: $I_p = 350$ kA, $B_t = 1.75$–2.25 T, NBI-heating power of 2.7 MW and ICRH power up to 1 MW.

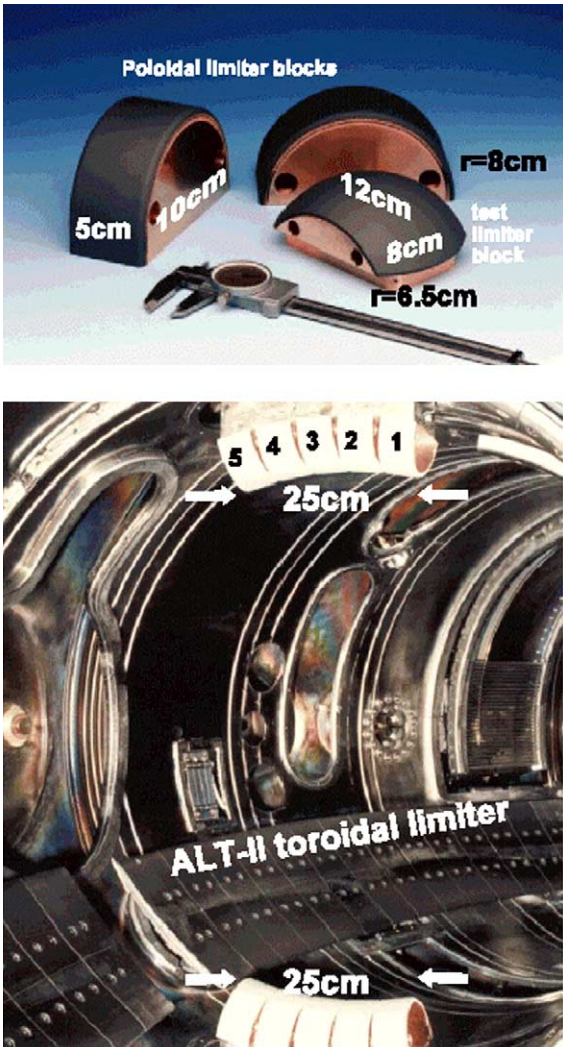

Fig. 1. The toroidal and poloidal limiter components and the poloidal view into TEXTOR. The numbers on the poloidal blocks refer to those in Fig. 3(b).

3. Results and discussion

3.1. Poloidal limiters

The poloidal limiters can be moved into or retracted from the plasma, the radius of which is normally defined by the toroidal belt limiter ALT-II at $r_{\mathrm{Lim}} = 46$ cm. Generally the 'active' surface of a single limiter block amounted to about 20 cm^2. Boronisation 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. However, for first exposure experiments TEXTOR was started with pure glow discharge conditioning in deuterium in order to study the behaviour of the B_4C-layers ab initio. At full heating power the thermal load on the active surface of these limiters at the last closed flux surface (LCFS with $r_{\mathrm{Lim}} = 46$ cm) amounts to about 7.5 MW m^{-2} for a TEXTOR discharge with a radiated fraction of 50%. The calculated temperature rise using [5]

$$\Delta T_{\mathrm{surface}} = 1.44\sqrt{\frac{1}{c\rho\lambda}}q\sqrt{\tau} \tag{1}$$

with a thermal conductivity $\lambda = 4.0/0.015$ W cm^{-1} K^{-1}, a density $\rho = 8.92/2.27$ g cm^{-3}, a specific heat capacity $c = 0.385$–$0.53/1.75$ J g^{-1} K^{-1} for copper/boron respectively and heat flux q in W cm^{-2} would, for an exposure time τ of 4 s, amount to about 675 K neglecting for an estimate the presence of the layer (which is actually an upper limit for the copper (see Section 3.2)). In the worst case this could nearly lead to a melting of the copper ($T_{\mathrm{melt}} = 1356$ K) taking into account a common starting temperature of 525 K, but would not affect the B_4C-layer ($T_{\mathrm{melt}} = 2360$ K). In order to avoid this unfavourable condition and provide a more general representative exposure, a permanent position of the poloidal limiters 1 cm behind the LCFS was chosen, where the heat flux and the corresponding temperature dropped by 66%.

The development of fluxes from the limiters immediately after the implementation is shown in Fig. 2(a) and (b) for a series of 30 discharges with constant plasma parameters ($\bar{n}_e(0\ \text{cm}) = 9 \times 10^{18}\ \text{m}^{-3}$, $n_e(47\ \text{cm}) = 1 \times 10^{18}\ \text{m}^{-3}$, $T_e(47\ \text{cm}) = 80\ \text{eV}$). It is remarkable that for about 15 discharges the relative boron fluxes decrease by 30% to a value, which is also reached (after an even steeper drop) after a conventional boronisation. A similar behaviour is also noted for the chemical erosion of carbon as deduced from the CD-band and boron from the BD-band emission (which shows a practically negligible contribution), where a reduction of even 60% is found. This result is an already well known behaviour of medium and low-Z materials in a carbon surrounding [6] and results from the fact that carbon material from the entire wall is deposited onto the B_4C and re-eroded afterwards. Eventually, this results in material mixing at the erosion dominated zones, and in carbon film formation in deposition areas.

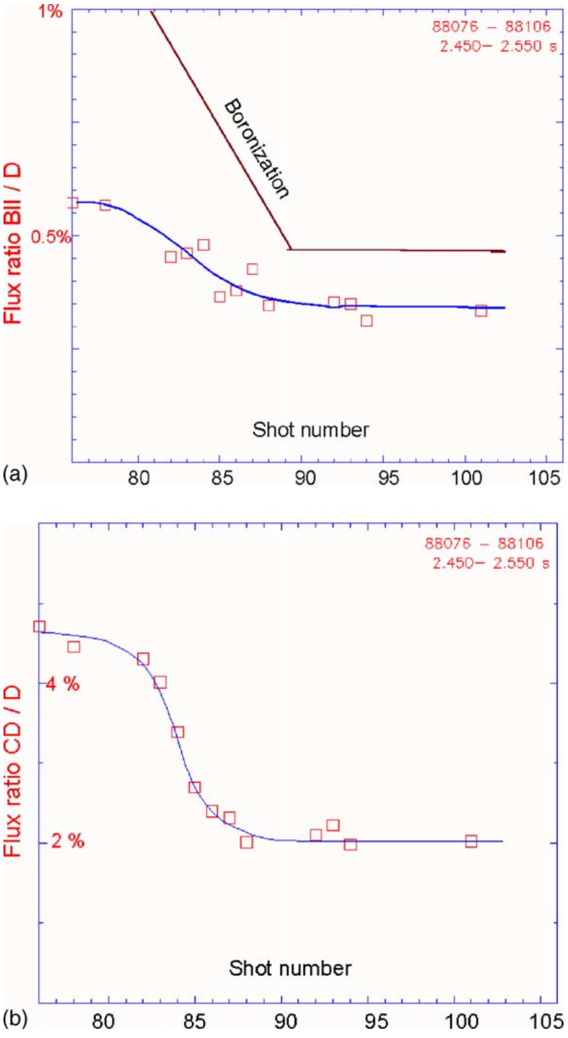

Fig. 2. Behaviour of flux ratios during several consecutive discharges just after the implementation of the poloidal B_4C-limiter blocks: (a) boron and (b) CD.

Fig. 3(a) shows a single poloidal limiter block after about 1000 discharges, which included also a boronisation and several different experimental scenarios. This block and also the other top and bottom tiles show remarkable 'dots' on their surface, which could already be noticed by visual inspection through a window after the first day of exposure. From simultaneous investigations with B_4C-coated test limiters, which were removed from the machine after one experimental day, it was found that these 'dots' were actually holes with a diameter of about 0.1 mm reaching in most cases down to the copper substrate. A profound description of these phenomenae is presented in a different paper [7]. However, the distribution of these craters is not uniform over the circumference of the limiter. As it is shown in Fig. 3(b) – with slight modifications for the different blocks – a larger number of craters can be found in places which correspond to positions about 4 cm behind the LCFS. This supports the hypothesis that the formation of the craters is triggered by bipolar arcs between the limiter and some near-by liner elements (e.g. inner bumper limiter, RF-antenna). It should be particularly noted here that the number of craters did not grow ad infinitum but remained more or less constant after some time. This is probably due to the carbon deposition process, which both prevents the formation of new craters due to a growing conductivity and fills partly the old ones.

3.2. Test limiters

As already mentioned, the limiter lock systems on TEXTOR allow flexible plasma exposures and investigations with numerous diagnostic tools and a fast removal of the objects for an ex situ diagnostic. Therefore, specific experiments were carried out with B_4C-coated mushroom limiters e.g. increasing the heat flux to find the maximum load. Such a series can be seen in Fig. 4, where the behaviour of the surface and the increase of the bulk temperature is shown as a function of the test limiter position (LCFS is at 46 cm). Several things are remarkable: The increase during the start of the NBI-heating phase and even more the drop of the temperature after its end cannot solely be explained by a simple heating of the copper substrate. The respective times for the latter would be in the order of seconds. There is a strong fluctuation on the temperature signals during the NBI-phase, which suddenly disappears at larger radii

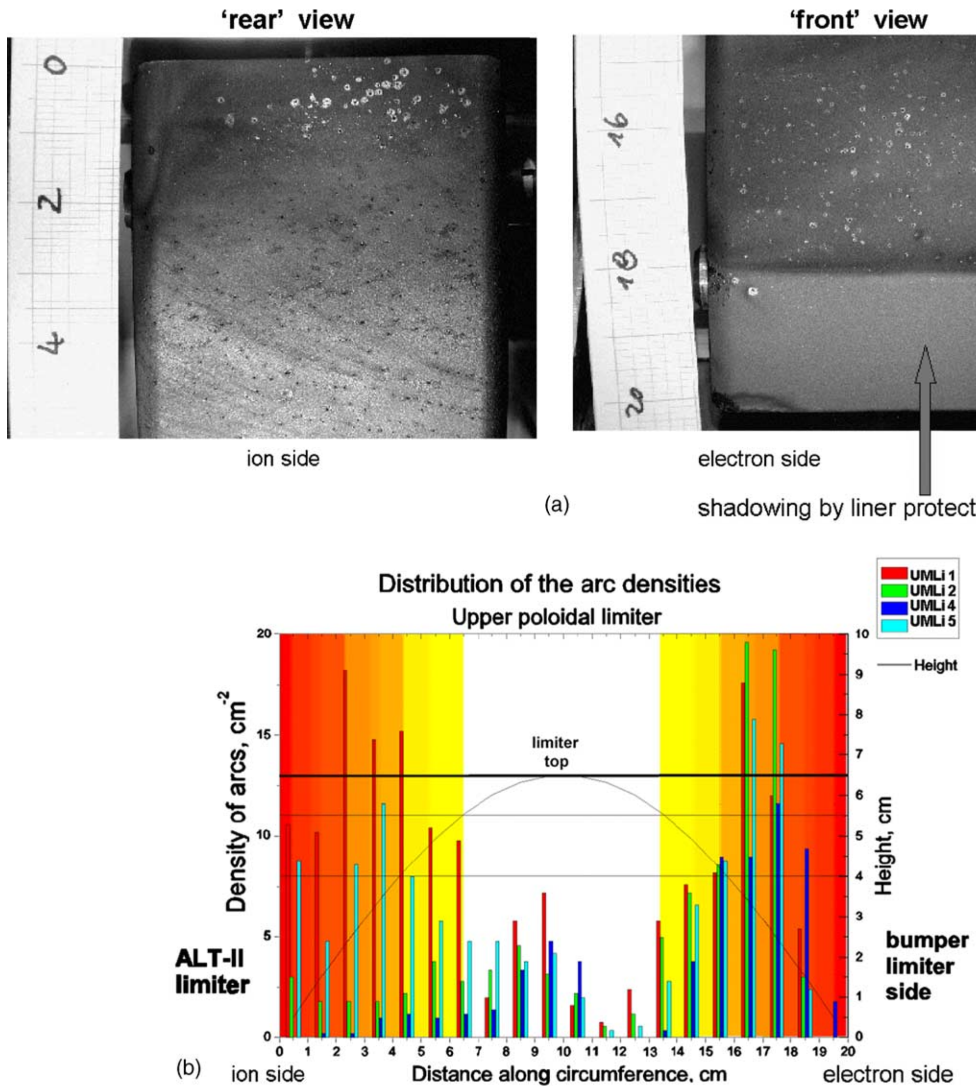

Fig. 3. (a) Arc traces on the inner poloidal top limiter block. The view is in both cases onto the short side (plasma interaction zone) of the limiter (see Fig. 1) and the scale in cm as indicated. (b) Distribution of the arc traces along the circumference of the upper poloidal limiter. The blocks can be identified in Fig. 1. The shadowed areas represent zones, where a short connection length exists between the limiter and other boundary hardware components. The horizontal lines below the limiter top indicate the position of the ICRH-antenna and the inner bumper limiter respectively. The conversion from the circumference scale into a limiter height above its base plate is represented by the cosine curve.

after the melting of the layer (at $r = 46.1$ cm for #88883).

In the following the presence of a B_4C-layer on the copper will be treated in detail. For the calculation of the heat flux q from the measured surface temperature the code THEODOR was employed [8]. For constant conditions q is related to the surface temperature by

$$q = (\lambda/d)\Delta T_{\text{surface}} \tag{2}$$

with $d = 170$ μm for the layer thickness and λ the respective value for B_4C (see Section 3.1). The reproduction of the incoming heat flux could only be verified if a perfect coupling to the copper was assumed! Another way of determining the heat flux is to derive it from the heat content measured by the rise of the copper bulk temperature:

$$q = cm\Delta T_{\text{bulk}}/(\tau A), \tag{3}$$

where m is the mass of the limiter block (2.5 kg), τ the duration of exposure (2 s) and A the exposed area (40 cm^2). As can be seen in Fig. 5(a) these two heat fluxes agree very well with each other, which justifies the

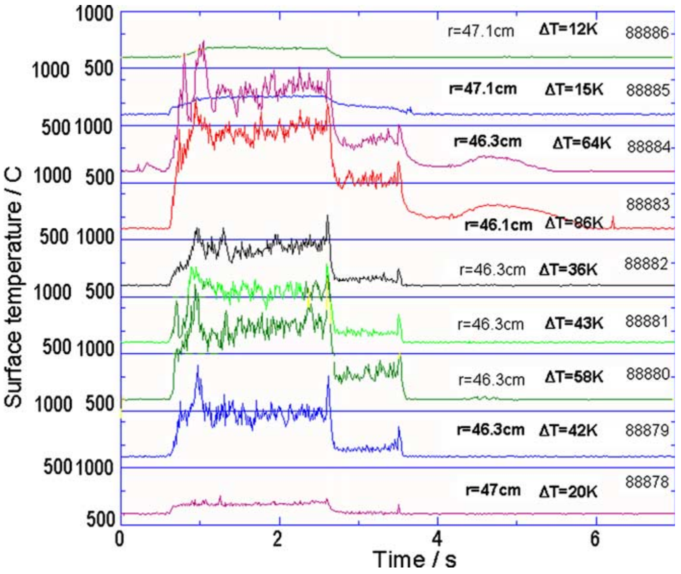

Fig. 4. Behaviour of the surface temperature of a B_4C test limiter and the resulting temperature rise within the copper block as function of radial limiter position. NBI-heating of the plasma with co-injection (1.4 MW) is from 0.5 to 3.5 s and with counter injection (1.3 MW) from 0.6 to 2.6 s. #88886 is with counter injection only. The base line of the temperature scale amounts to 500 °C for each trace. The next upper horizontal line indicates a value of 1000 °C for each respective surface temperature signal. For a better visibility with a high magnification a stacked display was chosen.

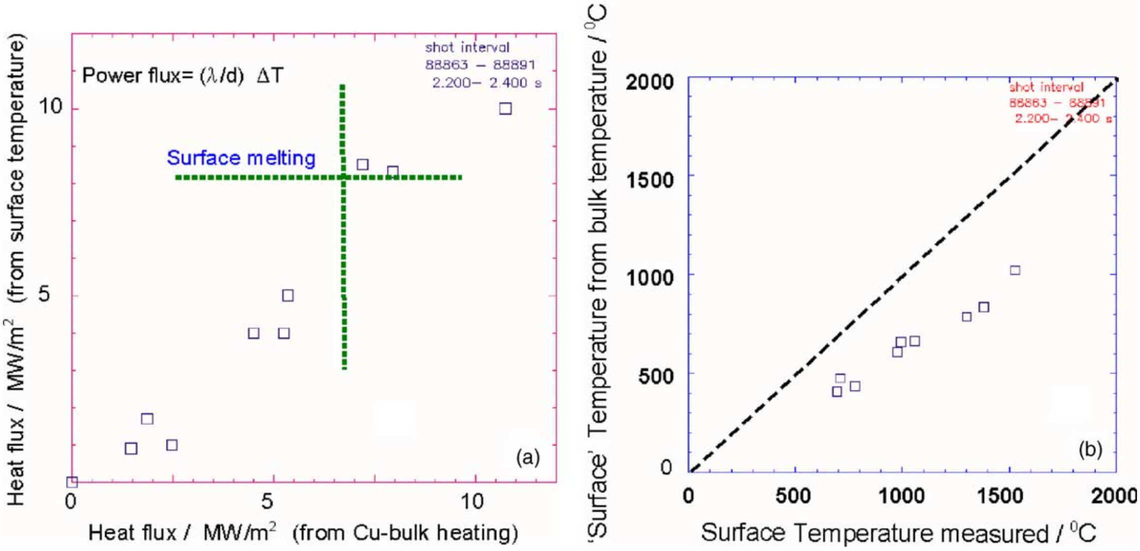

Fig. 5. (a) Comparison of modelled heat flux according to [8] to measured heat flux. Indicated is the limit from where noticeable damage to the B_4C-surface occurred. (b) Calculated temperature of the copper 'surface' from the temperature rise within the copper block versus measured B_4C-surface temperature.

assumptions made. By inserting this flux in Eq. (1) one is also able to calculate the temperature rise at the copper surface.

$$\Delta T_{\text{Cu-surface}} = 1.44\sqrt{\frac{c}{\rho\lambda\tau}\frac{m}{A}}\,\Delta T_{\text{Cu-bulk}} + T_0. \qquad (4)$$

The result is shown in Fig. 5(b). As it should be the measured surface temperature of B_4C is always larger than the temperature of the copper at the interphase. The difference between the dotted line and the data points represents the temperature gradient within the B_4C-layer, which amounts to only about 30%.

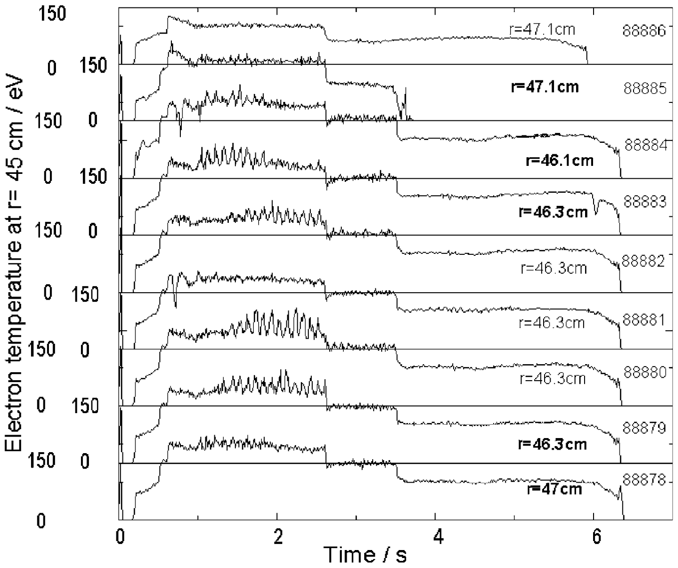

Fig. 6. Behaviour of the electron temperature at a plasma radius of 45 cm for the same discharges as shown in Fig. 4.

Above an average power flux of 8 MW m^{-2} the surface layer began to melt at positions of maximum heat loads (#88883 in Fig. 4). This process immediately changed the electrical properties of the layer. This can be seen in Fig. 4 when comparing the surface temperatures of #88878 and #88885, one notes a reduction of the 'spiking noise'. This 'noise', which continues over the whole exposure time and was also simultaneously seen as light emission by a fast diode, could be in many cases identified as the appearance of arcs on the B_4C [7]. The melting of some parts of the layer obviously reduced the probability of their appearance.

The influence of the insulating properties is also reflected by the behaviour of the boundary plasma (Fig. 6). The insertion of the limiter induces oscillations in the electron temperature, but they become smaller or disappear after the melting accident. Similar oscillations of the electron density are much weaker. Although the oscillations are connected with the use of the limiter, no cross correlations between them and the spikes on the surface temperature could be detected.

A surface analysis of this test limiter has been carried out and has been in detail presented elsewhere [9]. The minimum deuterium content is not less than 3×10^{16} cm^{-2}, i.e. not less (or even higher) than that detected on graphite test limiters exposed under similar conditions at TEXTOR. The greatest D content is found in eroded (exfoliated) regions (3×10^{17} cm^{-2}), indicating that the composition of those areas is chemically different from the composition of B_4C. A deep depth distribution of deuterium (~4 μm) is observed in some areas. Copper is distributed over nearly the whole limiter surface ($C_{Cu} \sim 1$–50×10^{15} cm^{-2}), which is probably the result that the limiters still present some non-coated copper surfaces to the plasma (see Fig. 1).

4. Conclusions

Tests of B_4C-coated limiters on a copper base have shown that this material is appropriate for a use as wall material for W7-X with loads of 200 kW m^{-2}. Surface modifications by arcs, however, should be carefully studied further, but, according to the experiments carried out so far, are not assumed to become a major problem. In detail the following results have been obtained.

Erosion and hydrogen inventory: The limiter behaves as every low-Z object in a carbon surrounding and shows similar particle release properties as a pure carbon surface – the hydrogen inventory, however, may be significantly higher in destroyed areas.

Crater formation: These are probably caused by electrical arcs and are strongly favoured by the insulating properties of the B_4C-layer. As by continuous carbon deposition the conductivity increases and the old craters are filled, the arc formation is reduced and changes, which might also lead to a different behaviour of the plasma boundary temperature.

Thermomechanical properties: No severe cracking or exfoliation of the coating below heat loads of 8 MW m^{-2} happened. The heat transfer between the B_4C-layer and the copper is high because of a nearly perfect adhesion. Thermomechanical stresses could partially be compensated by plastic deformation of the copper.

It was found in addition, but could not be shown here in detail, that stainless steel substrates displayed a very similar arc formation, which appear also at certain radii. However, copper appears as a better heat sink.

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