

OVERVIEW OF FUEL RETENTION IN TUNGSTEN, GRAPHITE AND COMPOSITE TEST LIMITERS

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1. Introduction

Selection and testing of materials for plasma facing components (PFC) in next-step fusion devices is an important and strongly addressed point in the research programme carried out at the TEXTOR tokamak [1-3]. The aims of testing candidate materials are: (a) to evaluate their impact on the plasma performance, (b) to recognise the material erosion and damage, (c) to determine the fuel retention. In recent years experiments with some tens of various materials have been performed. The intention of this work is to give an overview of fuel retention and material mixing processes occurring on three types of limiters: graphite, tungsten and a composite consisting of a B₄C layer (*tetraboron carbide*) sprayed on a thick copper substrate. The composite was tested as a candidate for high heat flux components of the Wendelstein-7X stellarator [4,5].

Fuel retention in PFC predominantly derives from the local and global ion transport in the plasma edge [6,7]. The quantitative effects are strongly material and temperature dependent [7]. In graphite and carbon fibre composites (CFC) the retention is determined by a co-deposition process leading to the formation of layers containing fuel species and carbon mixed with other plasma impurity atoms [6,7]. In case of sole tungsten, the inventory is mostly connected with a direct implantation of ions and neutrals [8].

2. Experimental

The limiters are inserted into the torus in the form of so-called test limiters of mushroom shape installed on special manipulators which allow the change of the radial position, the rotation and heating (indispensable for W) of the limiter heads [3, 8-10]. Following the exposure to a series of discharges (total exposure time to the plasma of up to 600 s) the limiters are retracted from the machine, transferred to a surface analysis station and then examined with a number of ion beam analysis methods in order to determine their

surface morphology. The amount and distribution of deuterium and boron are determined by means of nuclear reaction analysis (NRA), whereas the content other elements (e.g. C, W, Si, Cu) is examined with Rutherford backscattering spectroscopy (RBS). Figure 1 exemplifies the shape of the test limiters used at TEXTOR.



Fig. 1 B₄C coated limiter after the exposure to the plasma. Dimensions of test limiters: projected length 120 mm (toroidal direction), projected width 60 mm (poloidal direction), radius of curvature 140 mm, height 45 mm, area of the plasma facing surface 100 cm². The lines of analyses were crossing the damaged areas.

3. Results and discussion

Following the exposure to the plasma the distribution of retained deuterium is non-uniform over the limiter surface. In general, the deposition zones (approx. 20 mm wide), related to carbon transport and its co-deposition, are observed on far ends of the limiter. The D content in these zones amounts to $5 - 10 \times 10^{17}$ D atoms cm⁻² and it is rather dependent on the exposure time than on the initial target composition. Distinctly lower and material-dependent contents of fuel species are found in the top part exposed to high heat loads: $1 - 3 \times 10^{16}$ cm⁻² and below 1×10^{15} cm⁻² in sole graphite and in sole tungsten, respectively. The results regarding the fuel retention and distribution in those test limiters have previously been presented in detail [3,8]. In the following section these results will be compared with those recently obtained for a B₄C coated one.

The test limiter shown in Fig.1 was exposed to seventeen NBI heated discharges (total plasma operation time around 100 s) until its surface became damaged by overheating. This is in contrast to the sole C and W specimens whose surfaces were not damaged when exposed under similar conditions. In the areas of the highest heat loads, the B₄C coating is damaged (exfoliated and/or molten) but no layer detachment has occurred and no bare copper substrate is exposed. Over the whole surface there are pits caused by arcing. The analyses were done along eight lines (Fig. 2): three in the toroidal and five in the poloidal direction. They were chosen in order to recognise the D content in damaged and non-damaged zones, i.e. in areas of possibly different chemical composition. Plots in Fig. 3a and b show the deuterium distribution along the poloidal and toroidal direction, respectively.

Two scans in each direction are presented: one crossing the exfoliated area (open symbols) and the other one outside this area (filled symbols). There are significant differences, by a factor of 8 - 10, in the amount of trapped fuel in those two areas: $5 \times 10^{16} \text{ cm}^{-2}$ and $4.5 \times 10^{17} \text{ cm}^{-2}$ outside and inside the damaged area, respectively. Transition in fuel content between the zones is very sharp and, moreover, the distribution of deuterium in the exfoliated zone is deeper (over $3 \mu\text{m}$) than in the adjacent region ($<0.5 \mu\text{m}$). It gives a clear indication that the chemical composition of the zones differs distinctly. Besides of B, C and D the presence of copper and silicon is detected over the whole surface. While the Si presence is related to the machine siliconization, the Cu overlayer originates most probably from the local transport of copper eroded of the sides of the specimen. The contribution of the arcing on the test specimen and the erosion of main poloidal limiters (also of Cu coated with B_4C) to the spread of copper can not be excluded. The latter effect, however, is not considered as the major source because the plasma contamination by Cu was negligible.

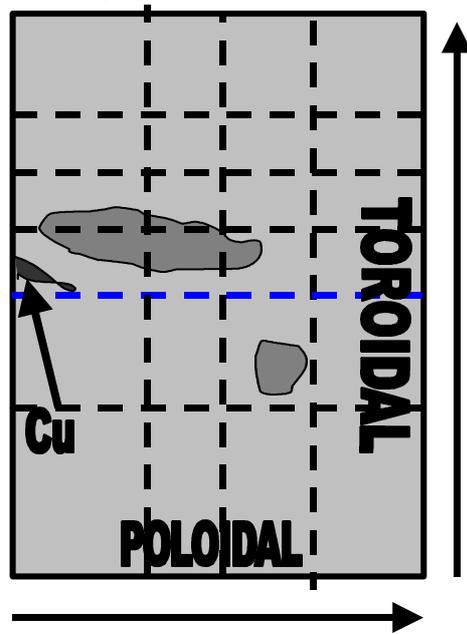
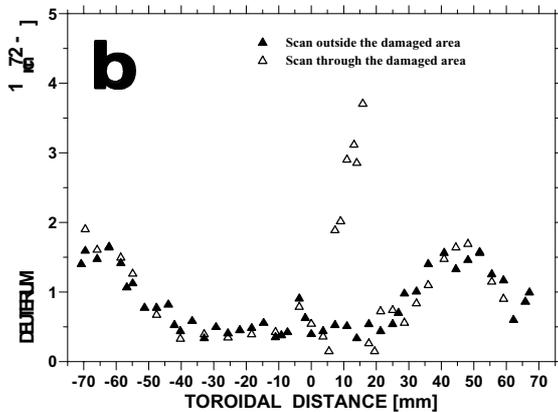
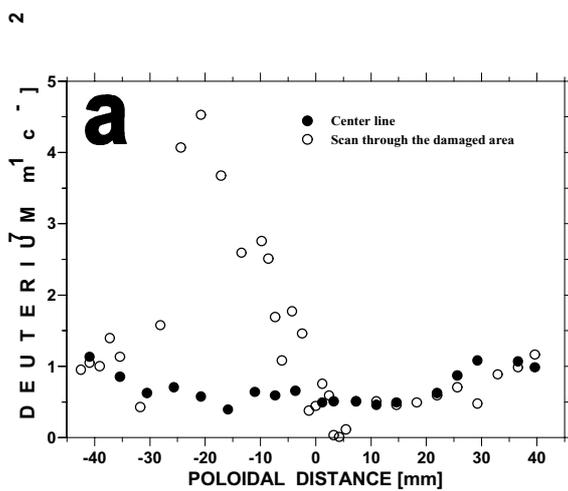


Fig. 2 (above) Lines of ion beam analysis.

Fig. 3 Deuterium distribution and concentration on the test limiter: (a) along the poloidal direction; (b) along the toroidal direction.

The damage to the coating occurred at the surface temperature exceeding 1800 °C, as inferred from thermography ($T_m(B_4C) = 2300$ °C). The melted region contains bigger amount of Cu than observed on the rest of the surface but, nevertheless, Cu remains the minority species in comparison to B and C. One may suggest that the event stimulated chemical reactions and phase transition in the overheated topmost layer. Detailed analysis of the literature data [11,12] for Cu – B, Cu – C (and Cu – Si) systems show that simple binary compounds, acetylenides or low-copper eutectic alloys can be excluded. Exact composition of compound(s) [Cu-B-C-Si] resulting from high temperature reaction and material mixing on PFC can not then conclusively be inferred. However, the mixture formed has high affinity towards the retention of deuterium. This feature should be taken into account when considering B₄C coated copper as a potential candidate material for PFC. It is also worthwhile to stress that the retention of fuel in the B₄C layer is twice bigger than that observed in sole graphite exposed under similar conditions. It is nearly two orders of magnitude bigger than that measured in tungsten ($< 1 \times 10^{15}$ cm⁻²).

The results clearly show significant differences in fuel inventories between tungsten and carbon-containing materials. They also might indicate that no co-deposition of fuel (tritium inventory) should be expected in a device with PFC made of tungsten.

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