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Net erosion measurements on plasma facing components of Tore Supra

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Abstract

Erosion of the plasma facing components is a crucial point of investigation in long pulse operation of future fusion devices. Therefore erosion measurements have been undertaken in the Tore Supra tokamak. After each experimental campaign, different plasma facing components have been monitored in situ by non-destructive means, in order to evaluate their net erosion following a long plasma exposure. This paper presents the results obtained over three experimental campaigns on the Tore Supra ergodic divertor B_4C-coated neutralisers and CFC Langmuir probes. The erosion on the Langmuir probes after one year of plasma exposure can reach 100 μm, leading to an effective erosion coefficient of around 5×10^{-3} to 10^{-2}, in reasonable agreement with values found on other tokamaks. The erosion of the ergodic divertor neutraliser plates is lower (10 μm). This is coherent with the attenuated particle flux due to a lower incidence angle, and might also be due to some surface temperature effect, since the neutralisers are actively cooled while the Langmuir probes are not. Moreover, the profile along the neutraliser shows net erosion in zones wetted by the plasma and net redeposition in shadowed zones. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Erosion; Redeposition; Tore Supra; Carbon

1. Introduction

Erosion and redeposition, related to key issues such as lifetime of the plasma facing components, tritium inventory and core plasma contamination, are a crucial point of investigation in long pulse operation of future fusion devices. Dedicated measurements have already been performed in several tokamaks, such as DIIID [1], JET [2] or Asdex Upgrade [3]. In Tore Supra, different plasma facing components have been monitored in situ by non-destructive means, in order to evaluate their net erosion after an extended plasma exposure. This paper presents the results obtained by this procedure, which has been repeated four times, covering three experimental campaigns.

2. Experimental set up

2.1. Description of the ergodic divertor

The erosion measurements have been performed on the Tore Supra ergodic divertor (ED). This device creates a magnetic perturbation in the plasma edge, which leads to a stochastic boundary layer where the field lines are open, allowing efficient screening of the central plasma from the edge [4]. The ED is formed by six modules regularly spaced on the low-field side of the torus. In 1996, an improved version was implemented, with a vented neutraliser structure permitting an increased heat and particle exhaust capability [5]. This vented structure is made of seven poloidally distributed neutralisers, numbered from A to G from the top to the bottom of the machine (see Fig. 1). Each neutraliser is formed of 2–4 elements called fingers. These 30-cm long fingers are actively cooled, and made of a copper heat sink covered by a 250 μm coating of B_4C (boron carbide). The ED is equipped with 14 Langmuir probes distributed around the torus, and classified by the

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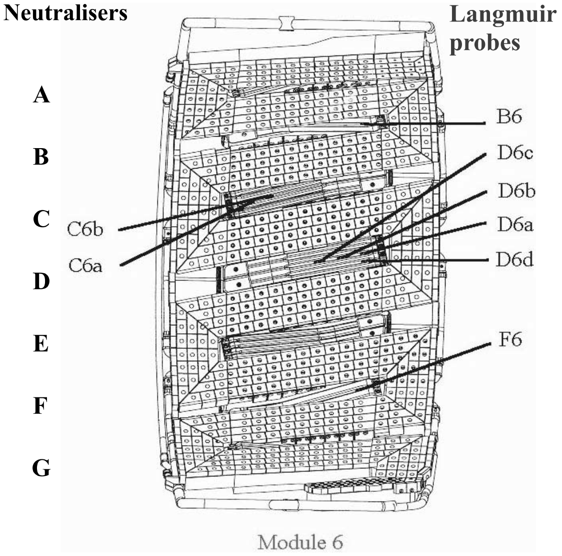

Fig. 1. View of the module 6 of the ergodic divertor equipped with Langmuir probes.

neutraliser and the module number. Moreover, a few neutralisers are equipped with several Langmuir probes, referred to as *a*, *b*, *c* and *d* (no indication means type a configuration). This is illustrated in Fig. 1, showing the ED module 6, where a large number of probes are concentrated.

Two types of erosion measurements have been performed following each experimental campaign, starting in 1997 after the first year of exploitation of the improved ED: the length of the Langmuir probe tips and the thickness of the neutraliser B_4C coating.

2.2. Measurements of Langmuir probes tips

The Tore Supra Langmuir probes are made of 5 mm spherical carbon fibre composite (CFC) tips, inserted into a CFC cylindrical shield. The distance between the top of the probe and the shield (a few mm) has been measured using a Palmer micrometer. The precision obtained is around 10 μm. In addition to the 14 ED probes, four probes of the inner first wall (IFW), located on the high field side of the machine, have also been analysed. They are located in the same poloidal section and numbered from 1 to 4, from 5° above to 15°, 25°, and 45° below the equatorial plane.

2.3. Measurements of the B_4C coating thickness

The thickness of the B_4C coating on different fingers of the ergodic divertor has been estimated using an ultrasonic probe. The standard deviation of measurement is around 5 μm. The study was focused on the ED module 6, where the two medium fingers of neutralisers C, D and E have been analysed. A measurement of the B_4C thickness has been performed every 2 cm along each of the six analysed fingers. The 0 cm position corresponds to the finger edge, alternating left and right side to take into account the magnetic configuration.

3. Experimental results

3.1. Erosion of the Langmuir probes

Fig. 2 represents the net erosion (positive values) or redeposition (negative values) deduced from the distance measured between the probe tip and the shield. Both the IFW and the ED probes exhibit the same behaviour: after a first strong net erosion following the 97 campaign (50–150 μm), most probes have experienced net redeposition during the 98 campaign (up to 100 μm), and moderate net erosion/redeposition during the 99 campaign (lower than 50 μm). This can be related to the different orientations of the experimental programme: while the 97 campaign was aimed at obtaining high-power discharges, the 98 and 99 campaigns were more oriented towards highly radiating regimes. Moreover, the 99 campaign was shortened for technical problems A reduction in the effective erosion coefficient has already been reported in other tokamaks during detached plasma operation [1]. The eroded thickness measured on Tore Supra probes is also comparable with measurements performed on JET divertor target probes under a similar fluence [2].

3.2. Erosion of the B_4C coating

Fig. 3 presents the B_4C thickness profiles measured on one finger of neutraliser E. The error bars represent

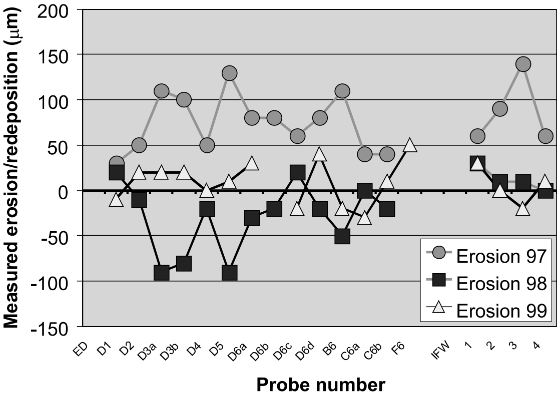

Fig. 2. Measured net erosion (positive values)/redeposition (negative values) on the Langmuir probes of the ergodic divertor (ED) and the inner first wall (IFW).

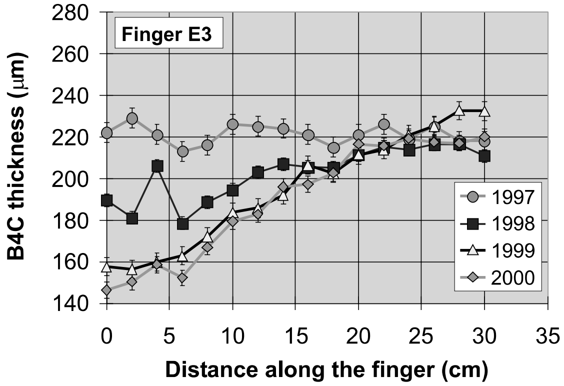

Fig. 3. Thickness of the B_4C coating measured on finger 3 of neutralisers E of the ergodic divertor module 6 after experimental campaigns 1996–1999.

the standard deviation of the measurement. Although the erosion pattern is not that clear on the other neutralisers of module 6 (not shown here), the measured thickness tends to decrease on the first part of the finger (net erosion), and to increase on the remaining part (net redeposition). This trend is more pronounced after several experimental campaigns. It can be correlated with shadowing effects on the neutralisers, which restrict the zone of fingers wetted by the plasma, due to magnetic configuration of the ED. This effect has already been described by theoretical considerations [6,7] and also observed experimentally [8]. The eroded part of the neutralisers corresponds to the region in direct contact with the plasma (roughly the first 15 cm of the finger) while the part where redeposition occurs corresponds to the shadowed region. This feature (redeposition dominating in shadowed zones) has already been observed at other tokamaks [1]. The erosion profile along the finger is also coherent with visible spectroscopy measurements [9]: the D_α and CII emissions are concentrated in the zone exposed to the plasma and decrease along the finger as the erosion profile, while the CIII emission remains broader.

The erosions measured on the neutralisers, in the order of 10 µm on average, are roughly a factor of 10 lower than the erosions measured on the probes. This can be explained by a decrease in the incident flux due to the field line incidence, quasi-perpendicular in the case of the Langmuir probe, while nearly tangential in the case of the neutralisers. The field line angle of incidence, close to 8° on the neutralisers, gives a flux reduction factor of 7 with respect to the normal incidence, in agreement with the observed lower erosion.

Another explanation could be the influence of surface temperature, since the neutralisers are actively cooled while the Langmuir probes are not. The temperature of the B_4C coating lies in the range 200–250°C in ohmic discharges and stays below 500°C with additional power. The temperature of the Langmuir probe increases constantly during the shot and can reach very high values above 1000°C. In the case of erosion of B_4C by D^+ ions, the sputtering coefficient exhibits a weak dependence upon the surface temperature below 500°C [10] and is comparable with physical sputtering for carbon (around 2×10^{-2}). In the case of carbon however, the chemical sputtering is shown to be important between 300 and 800°C, with a peak at around 500°C, while RES starts above 1000°C. There are therefore cases where the sputtering coefficient is expected to be higher on the CFC probes than on the B_4C coating.

Another effect which should be taken into account is the covering of the B_4C coating by a redeposited carbon layer, as Tore Supra is a carbon-dominated machine. However, below 500°C, the sputtering coefficient for carbon and B_4C is not significantly different.

4. Analysis: determination of an effective erosion yield

Using the flux determination and the erosion measurements of the Langmuir probes, an effective erosion coefficient Y_{eff} can be determined:

$$Y_{\mathrm{eff}} = \frac{eN_{\mathrm{C}}}{\int \Phi(t)\,\mathrm{d}t}, \tag{1}$$

where e is the eroded thickness, N_{C} the carbon density in the material [1], and $\int \Phi(t)\,\mathrm{d}t$ is the incident particle flux given by the Langmuir probes, integrated over the whole experimental campaign.

A database has been established by selecting shots where the ED Langmuir probes were activated: 1006 shots for the 97 campaign, 924 for the 98 campaign and 517 for the 99 campaign [2]. However, the number of selected shots can differ quite significantly from one probe to another, as they were not all activated at the same time. The D2 and B6 probes have been operated only during the 99 campaign.

The electron temperature T_{e} measured by the ED probes ranges from 15 to 50 eV, yielding an impact energy of around 75–250 eV for the D^+ ions impinging on the neutralisers, if one assumes $T_{\mathrm{i}} = T_{\mathrm{e}}$ and takes into account the sheath acceleration [3]. The electron density n_{e} lies between 10^{18} and 1.5×10^{19} m^{-3}. This corresponds to particle fluxes between a few 10^{22} up to 10^{24} m^{-2} s^{-1}.

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[1] Atomic data for carbon have been chosen for the calculation: $N_{\mathrm{C}} = 1.25 \times 10^{29}$ m^{-2}.

[2] The analysis has not been carried out for the IFW probes, as these are not systematically activated. A significant contribution could therefore be missing, yielding misleading results.

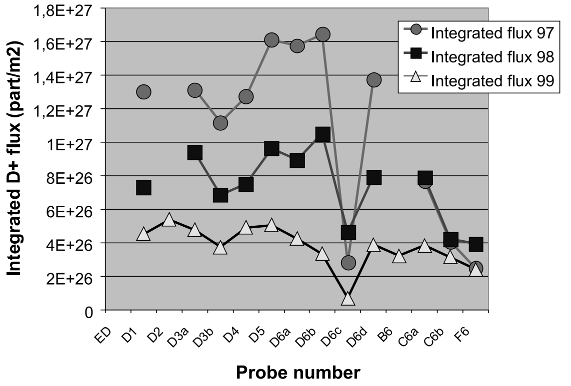

Fig. 4. D^+ ion flux on the Langmuir probes of the ergodic divertor integrated over the 97, 98 and 99 experimental campaigns.

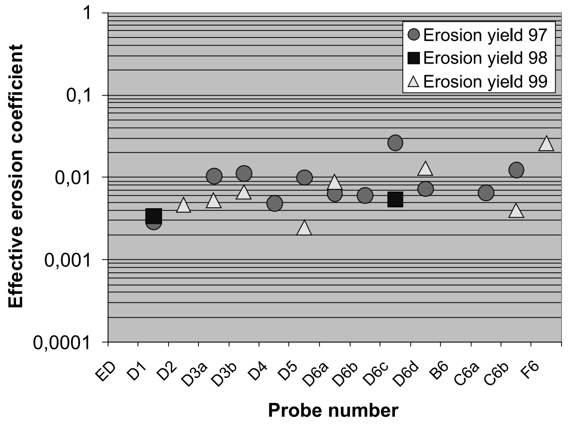

Fig. 5. Effective erosion coefficient calculated for the Langmuir probes of the ergodic divertor.

The result from the integration of the Langmuir probe data is shown in Fig. 4. The fluence obtained is in the order of a few 10^{26} m^{-2} per experimental year. As already mentioned, the integrated flux is significantly lower for the 98 and 99 campaign than for the 97 campaign.

As shown in Fig. 4, toroidal distribution of the particle flux in the equatorial plane of the ED, measured by the probes in the type Da configuration (probes D1–D6a), is rather uniform. The discrepancy from one module to another might be attributed to some misalignment. The D6c probe, located 20 cm away from the finger edge, is located in the low flux shadowed region, as predicted.

The effective erosion coefficient deduced from Eq. (1) is shown in Fig. 5 [3]. It presents values between 5×10^{-3} and 10^{-2}, in agreement with similar experiments in JET [2]. However, the net erosion coefficient reflects the competition between erosion and redeposition processes, therefore the gross sputtering coefficient could be much higher, as expected for sputtering of carbon by deuterium ions [11]. For instance, preliminary simulations have been undertaken to model the carbon emission around the ED neutraliser as measured by visible spectroscopy [9], leading to an estimated redeposited fraction of sputtered carbon from 15% to 30%, depending on plasma conditions. Moreover, the carbon self-sputtering could also play an important role. Taking into account a small fraction of carbon in the incident ion flux measured by the Langmuir probes (considered here as pure deuterium) can lead to a significant build-up of the redeposited layer. Nevertheless, it is not possible to distinguish between physical or chemical sputtering from these global measurements. Simulations performed in [9] including physical sputtering only have shown a reasonable agreement with the measured carbon emission. However, evidence of chemical sputtering has been found experimentally by visible spectroscopy. CD band has been observed for discharges with additional power while it was not in ohmic discharges, probably due to a lower surface temperature. This might not be contradictory, as it has been shown in simulations performed for JET [2] including chemical sputtering. Indeed, due to the short mean free path of the hydrocarbon molecules and their prompt redeposition, this process increases the gross erosion rate, but does not affect the net erosion rate much.

5. Summary

Net erosion measurements have been performed over the last three experimental campaigns on the B_4C-coated neutralisers and CFC Langmuir probes of the ergodic divertor. Erosion of the ED Langmuir probes after one year of plasma exposure can reach 100 μm, leading to an effective erosion yield of around 5×10^{-3} to 10^{-2}, which is in reasonable agreement with values found on other tokamaks. Erosion of the ED neutraliser plates is lower (10 μm), which is coherent with the attenuated particle flux due to a lower angle of incidence, and might also be due to some influence of the surface temperature, since the neutralisers are actively cooled while the Langmuir probes are not. Moreover, profile along the neutraliser shows a net erosion in zones wetted by the plasma and net redeposition in shadowed zones. The ED neutralisers have now been dismantled and will be submitted to thorough surface analysis to characterise the redeposited layers in more detail.

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[3] Negative values of Fig. 2, corresponding to redeposition, are not processed here.

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