# Post-mortem analyses of the Tore Supra toroidal limiter: experimental evidence of ion transport in a magnetized sheath

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**Abstract**

The topography of tiles dismantled from the main plasma-facing component of Tore Supra has been analyzed by scanning electron microscopy. Erosion zones show striation corresponding to a surface ripple. Deposition zones show well-oriented deposits with tip shapes. We show that these features are footprints of ion flow at the component surface. They are in good agreement with what is expected by modeling of ion trajectories in the case of grazing incidence in a strongly magnetized sheath.

## Introduction

D and T retention in the plasma facing components (PFCs) of magnetic fusion devices should remain limited for safety reasons. In the case of carbon PFCs, retention mainly originates from the deposition of hydrogenated carbon layers due to the erosion induced by ion bombardment and to the ability of carbon to bond with H isotopes [1]. The main PFC of the Tore Supra tokamak is the toroidal pump limiter (TPL) situated at the bottom of the chamber. Due the magnetic field ripple, ion flux onto the TPL is non uniform and competition between erosion and deposition leads to either erosion- or deposition-dominated zones.

We analyse in this paper how the TPL surface features, for erosion as well as for deposition zones, bring experimental evidence of the ion transport in a magnetized sheath.

## Samples and methods

The TPL is composed of ~600 fingers of 21 graphitic tiles made of Sepcarb®N11 carbon fibre composite: a 3D texture of bundles of ex-PAN fibres embedded in a pyrolytic carbon matrix. Each tile is approximately 2 x 2 $cm^2$. During the Deuterium Inventory in Tore Supra campaign, a sector of the TPL was dismantled and tiles were extracted for analysis [2]. Three typical zones can be distinguished: the erosion dominated zone, where the ion flux is the highest and where no deposition exists, the thin deposition zone where deposits are well-attached, and the thick deposition zone where deposits easily flake.

Scanning electron microscopy (SEM) measurements were performed at the CP2M (Université d'Aix-Marseille, France) using a Philips XL 30 microscope to analyse the topography of the different zones. Fig. 1 is a photograph of the dismantled sector where the different zones are shown and where the tiles analyzed using SEM are indicated. Note that the magnetic field is almost purely toroidal, with deflections less than 3.5° in both the vertical or poloidal directions. Tiles are named according to their location (FxTy meaning Tile y from Finger x). Due to the limited number of toroidal coils (18), the magnetic field configuration is periodic and the sector contains a full period of the TPL (32 fingers), so that the tile F3T5 at the bottom right of the figure can also represent the corresponding tile at the bottom left.

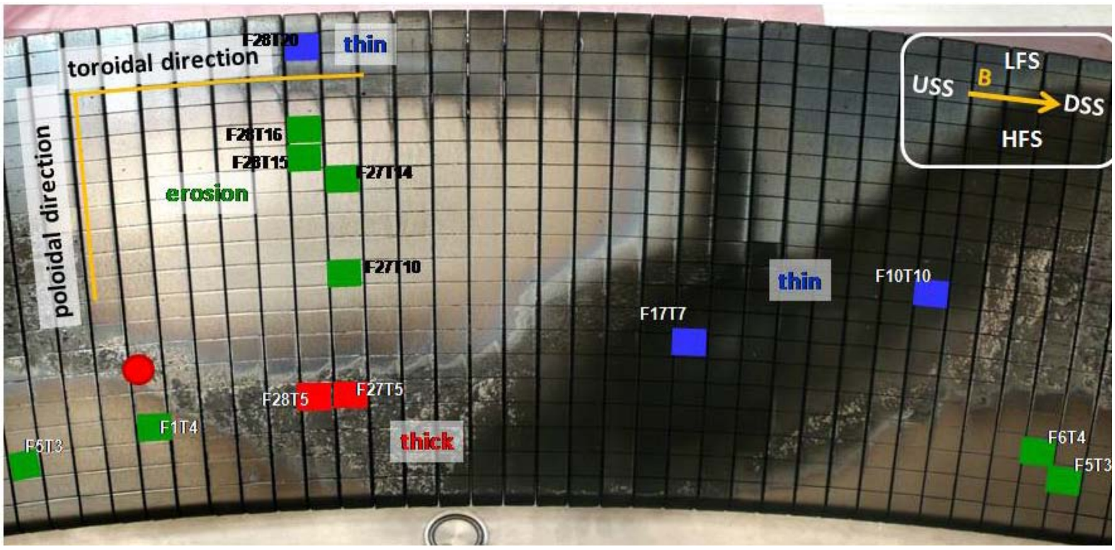


Fig.1: Photograph of a sector of the Tore Supra Toroidal Pump Limiter (TPL). The tiles analyzed by SEM are indicated. The shiny zones are erosion zones (green tiles), the blueish/black zones are thin deposition zone (blue tiles) and the grey/looking coarse zones are thick deposition zones (red tiles). The toroidal direction and its perpendicular (poloidal) direction are indicated. The insert at the top right displays the labels used for orientation, i.e. in the toroidal direction, USS (DSS) refers to the Up-Stream Side (Down-Stream Side) and in the poloidal direction, LFS (HFS) refers to the Low-Field Side (High-Field Side). Tile labels refer to the toroidal (finger number) and poloidal (tile number) positions. The red point is where the magnetic field is purely tangential.

## Results

Fig. 2a-b-c-d show SEM images of the top surfaces of tiles F27T10, F5T3, F27T5 and F28T20, respectively. In cases a and b, erosion is dominant; the cross-section of the original composite fibres as well as open porosities are clearly visible. There are additional marks of erosion such as the striation due the rippling of the surface, in oblique direction. This striation, which is approximately symmetrical for these two tiles, has been proven to be along the ion speed direction [3]. Such striation is visible all over the surface of the eroded tiles analyzed. The striation angle with respect to the toroidal direction varies in the range 30 - 50°. No systematic behaviour with neither the toroidal nor the poloidal positions has been evidenced and a 15° variation can be observed for example through the passage of a large porosity. Conversely, the LFS-DSS → HFS-USS orientation is observed for all over the erosion zone corresponding to tiles F27T10, F28T14, F28T15, F28T16 while the LFS-USS → HFS-DSS orientation is observed for all over the erosion zone corresponding to tiles F5T3 and F6T4. At the frontier of the two zones, there is a thick deposition zone (tile F27T4, F28T5). In this case (case c) thick, flaky and tip-shaped deposits are observed. Tips are oriented perpendicularly to the toroidal direction, pointing towards LFS [4]. Case d is intermediate and corresponds to a zone of thin deposition weakly plasma loaded. The image shows both striation and tips in the same direction. This indicates that the tip direction together with the striation orientation give the local ion speed projection on the TPL surface.

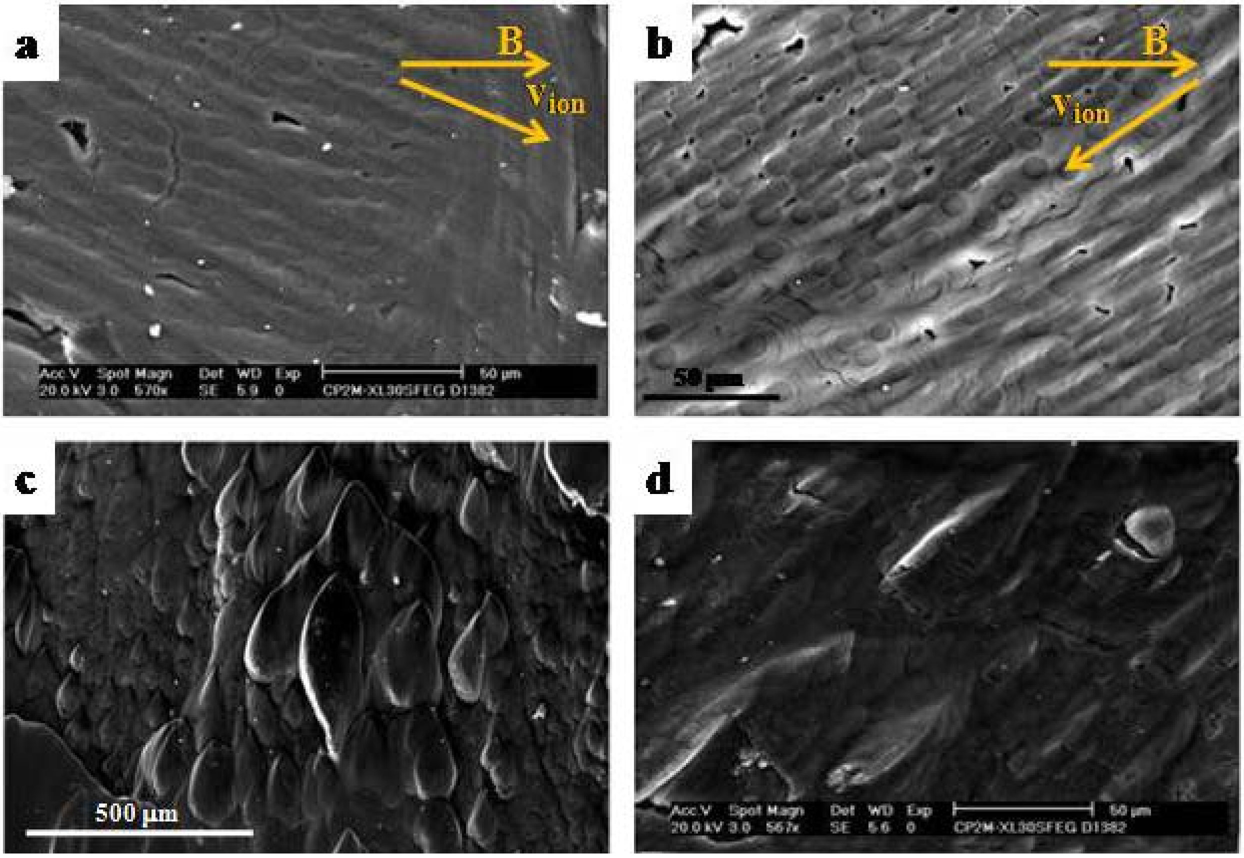


Fig.2: SEM images of the top surfaces of (a) tile F5T3 (eroded) ; (b) tile F27T10 (eroded) ; (c) tile F27T5 (thick deposits) and (d) tile F28T20 (thin deposits).

**Discussion**

Magnetic field lines are helicoidally winded around the secondary axis of the torus, with a small poloidal component ($B_\theta$ / $B_\phi$ ~ 0.06). In the scrape-off-layer (SOL), magnetic field lines are open and impact the TPL with a grazing incidence. The footprint of the plasma on the TLP surface displays the same periodicity as that of the magnetic configuration. Each pattern is constituted of two loaded zones where erosion is dominant, separated by the contact point where the magnetic field is purely tangential (schematically indicated by the red point in Fig.1). In the SOL, ions are accelerated along the magnetic field lines, i.e. mainly toroidally, and enter the sheath at the sonic velocity. Due to the symmetry of the two erosion zones wrt the contact point, the direction of this velocity changes from one side to the other. Then ions are further accelerated in the sheath, whose degree of magnetization is defined by the ratio of the Larmor radius by the Debye length (parameter $\zeta$, estimated here between 5 and 10). For such values of $\zeta$ and for an incidence of ~ 3°, the twist of the velocity (i.e. the deviation from the parallel direction in the TPL plane) is in the range 40 - 45° (Fig. 8b of ref.[5]). The observation of the striations shown in Fig. 2a and 2b is consistent with this description of ion trajectories, i.e. (i) a toroidal component at the sonic speed along the magnetic field (2) a poloidal component resulting from the acceleration in the magnetized sheath.

Thick deposits observed in Fig. 2c are close to the contact point where the toroidal component of the ion speed is null. Ion trajectories are then dominated by the poloidal component, in agreement with the orientation of the deposit tips.

## Conclusion

Through post-mortem analyses of tiles dismantled from the Tore Supra toroidal pump limiter, we have shown that the erosion marks such as striation as well as the deposition features such as the tip-shape of the deposits are footprints of ion trajectories. These results bring a straightforward verification of modelling of a magnetized sheath.

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