# Structural analysis of the eroded CFC tiles of Tore Supra: Insights on ion transport and erosion parameters


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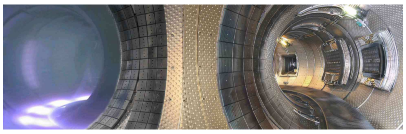
## Deuterium Inventory in Tore Supra



Load the PFCs in D

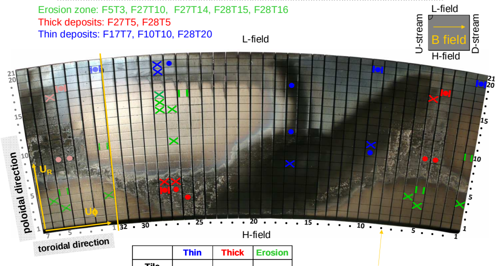
Do in situ particle balance

Dismantle the Toroidal Pump Limiter

Do ex-situ post mortem analyses

## Toroidal Pump Limiter

Positions of the analysed tiles with respect of the deposition pattern

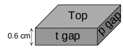



| | Thin | Thick | Erosion |
|---|---|---|---|
| Tile | × | × | × |
| Top | ● | ● | ● |
| Gaps | ❙❙ | ❙❙ | ❙❙ |

## This Study

Post mortem SEM, TEM, AFM, Raman analyses of the top surface of eroded TS tiles

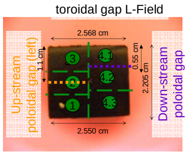
- Experimental estimation of the erosion rate of CFC
- Differential fibre/matrix erosion rate
- Ripple patterning characterization on tile surface




All the TPL tiles were provided by the SEP Company and the CFC is a C/C composite, N11®Sepcarb type, composed of a 3D texture of bundles of ex-PAN fibers embedded in a pyrolytic carbon matrix. Fibers and matrix are both graphitic.

## Cutting of the tile F27T10

toroidal gap L-Field




toroidal gap H-Field

## Plasma parameters on the F27T10 tile

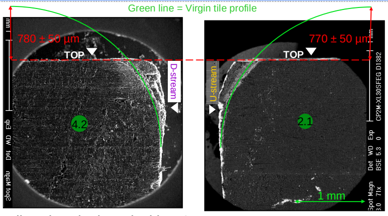
DITS

- Ion flux ~ 11.6 $10^{21}$ $D^+$ / $m^2$ s
- duration = 1.8 $10^4$ s
- $N_e$ = 2 $10^{12}$ $cm^{-3}$, $T_e$ = 20 eV, $T_i$ = 100 eV
- $P_{cond}$ = 1.2 MW

Cumulated operations up to DITS

- Ion flux ~ 14.4 $10^{21}$ $D^+$ / $m^2$ s
- duration = 1.4 $10^5$ s
- $P_{cond}$ = 1.5 MW

## SEM analysis of poloidal gap profile after cutting : F27T10




Virgin tile edge designed with a 2 mm curvature

Net erosion thickness measured on toroidal cross-section of tiles

D-stream gap deposit is curved / U-stream gap deposit is sharp

D-stream is loaded / U-stream gap is shadowed

Erosion rate = 5.5 ± 0.4 nm $s^{-1}$

C sputtered flux = 5 $10^{20}$ $m^{-2}$ $s^{-1}$

Sputtering yield ~ 9%

## Eroded C flux and sputtering yield from SEM measurement

Scaling of gross carbon erosion in TS [Hogan,Marandet]

$\Phi$ (C/s) = 5.$10^{20}$ x $P_{cond}$(MW)

Gross erosion x 0.4 = net erosion

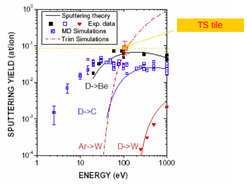


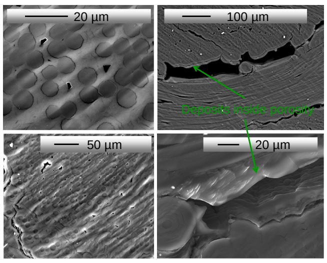

Fig. 1. Sputtering yields for C, Be and W bombarded with D ions [23]. For C, chemical erosion enhances the yield at low energies and yields are extrapolated to the threshold by MD calculations [87]. For W, impurity sputtering, such as Ar ions, dominates. [J. Roth, JNM, 390-391 2009]

Net erosion measured by post-mortem analysis:

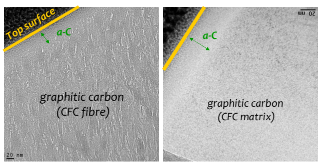
- Consistent with the scaling of gross carbon erosion measured in situ
- Ys higher than excepted
  - Role of chemical sputtering ($T_{surf}$ =500K)
  - Contribution of neutrals and impurities
  - Role of porosity (C/C less dense than graphite)
  - Role of fiber/matrix microstructure

## Thin layer of a-C on top surface

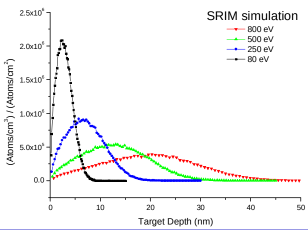
- **SEM analysis**
  - Smooth surface with oblique striation
    - Exposed to high heat and particle fluxes
  - CFC porosity partially filled by deposits (~10 µm)
    - Contribution to retention
  - Contrast shows fiber section



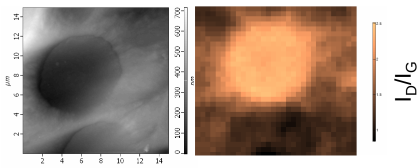

- **TEM analysis of FIB foil**
  - Amorphous carbon layer on top
    - amorphization due to ion bombardment
  - a-C layer thickness 30±10 nm




- **D implentation depth**




## Differential erosion fiber / matrix




AFM image Raman image

- **AFM analysis on F27T10 tile**
  - Fiber lower than matrix (~ 500 nm)
    => Fiber erosion rate higher than matrix
  - Fiber roughness lower than matrix roughness

$$R_q = \sqrt{\frac{1}{l}\sum\left(h(x)-\bar{h}\right)^2}$$

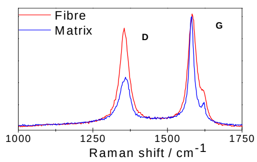
- Surface roughness Rq
  - Fiber ($R_q$ = 6 nm)
  - Matrix ($R_q$=11 nm)

- **Raman analysis on virgin tile**

$I_D/I_G$ ⇔ disorder

- Fiber more disordered than matrix (aromatic domain size smaller)
- Raman estimation of aromatic domain size, $L_a$

$I_D/I_G$ $\propto$ $1/L_a$



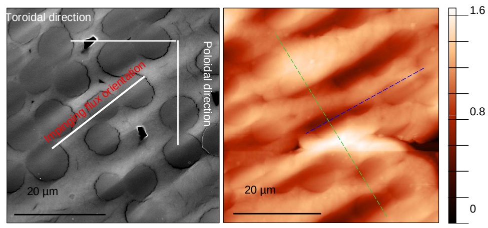

Differential erosion fiber and matrix

Erosion rate ⇔ microstructure

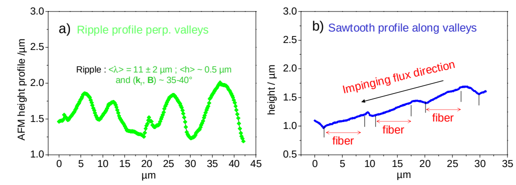
## Conclusions

- **First determination of the erosion rate a few nm/s**
- **First observation of rippling: oblique direction show that the poloidal component of the ion velocity is of the same order of magnitude than the toroidal component, possible origins still to unravel**
- **First observation of a differential erosion of fiber and matrix, importance of the carbon microstructure in the erosion rate**

## Ripple patterning of the tile surface




SEM image AFM image




- **SEM/AFM analysis on eroded tile**

Formation of a ripple pattern

- dynamic balance among
  - fundamental surface processes (erosion of fibre/matrix, ion-induced defect creation) And defect-mediated evolution of the surface morphology
  - ⇔ Impinging flux projection ⊥ to wave vector

⇔ Direction of the sputtering flux on the TPL surface

Formation of a sawtooth profile

- shadowing effect due to 2 different erosion rates
  - ⇔ Impinging flux projection is directive

⇔ Sense of the sputtering flux on the TPL surface