Exposure of high temperature ceramics to scrape-off layer plasma in the WEST tokamak

B. De Martino[1], J. Gunn[1], B. Guillermin[1], D. Mazon[1], A. Casner[2], A. Cosculluela[3], L. Ciupiński[4], G. Komorowska[4], A. Campos[5], N. Grillet[6], and the WEST team[†]

[1]*CEA, IRFM, F-13108 St-Paul-Lez-Durance, France*

[2]*Université de Bordeaux, CNRS, CEA, CELIA (Centre Lasers Intenses et Applications), UMR 5107, F-33405 Talence, France*

[3]*CEA-CESTA, 33114 Le Barp, France*

[4]*Warsaw University of Technology, Faculty of Materials Science and Engineering, Warsaw, Poland*

[5]*Aix Marseille Université, CNRS, Centrale Med, FSCM, Marseille, France*

[6]*Aix Marseille Univ, Université de Toulon, CNRS, IM2NP, Marseille, France*

[†] *http://west.cea.fr/WESTteam*

1. Context: atmospheric re-entry and Scrape-Off Layer plasma

Space vehicles require robust thermal protection during atmospheric re-entry; ablative heat shields[4], often made from High-Temperature Ceramics (HTCs), are key components of Thermal Protection Systems [1, 2, 3]. However, replicating re-entry conditions on Earth for HTCs testing is extremely challenging due to the extreme particle fluxes (10^{22}-10^{24} part/m^2/s), heat fluxes (10–100 MW/m^2), and exposure times (few seconds). While plasma torches are commonly used, the tokamak Scrape-Off Layer (SOL) offers a promising alternative[6], better reproducing the conditions of re-entry. This project aims at testing: BN, Si_3N_4, SiC, Al_2O_3.

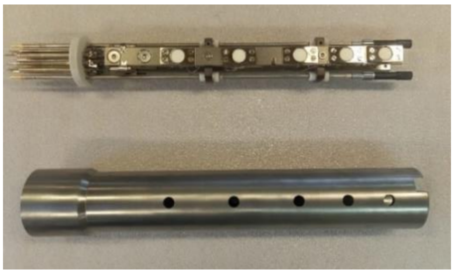
2. Controlled exposure of samples in WEST

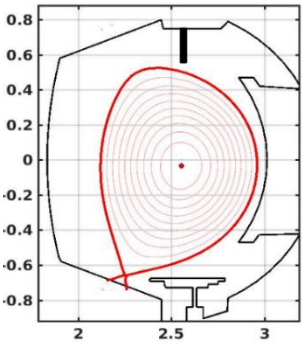
The WEST tokamak is equipped with a series of mobile Langmuir probes, some of which can be fitted with integrated sample holders. These devices offer a unique opportunity for controlled exposure of materials to SOL plasma. The latter can thus be exploited to investigate the ablation dynamics, and survivability of candidate heat shield materials for atmospheric re-entry.

2.1 WEST exposure systems

Reciprocating probe (RCP)[5]: The sample holder, designed by IRFM and shown in Fig. 1 with its TZM sleeve and circular sample-aligned openings, is mounted on the reciprocating probe and allows to expose up to 10 samples of size 9x9x2 mm^3 in the SOL. Two directionally sensitive collector Langmuir probes at the tip record exposure histories. Plunge depth is controlled via a hydraulic system, reaching up to 46 cm below rest position. During each 50-

100 ms plunge, the tip reaches the high-flux layer, sustaining heat fluxes of 10^6-10^7 W/m^2 and particle fluxes of 10^{22} part/m/s.





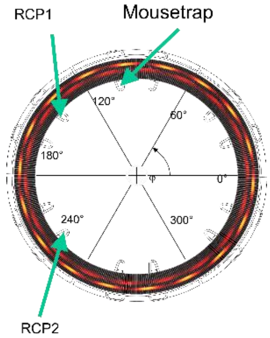


Fig. 1: From left to right: RCP sample holder, poloidal and toroidal section of WEST with probe's position.

Mousetrap[8]: The mousetrap sample holder (stainless steel or TZM), shown in Fig. 2, is installed on the lower divertor between tungsten monoblocks 28 and 29. It consists of an uncooled 36-turn copper coil (0.5 mm wire, 79.2 cm² area) to which a voltage is applied, generating a magnetic moment that interacts with the tokamak field to produce a controlled vertical tilt. A single sample of size 12x10x2 mm^3 mounted at the probe tip, perpendicular to the coil, is exposed over a 3 mm length to the parallel heat flux during each reciprocation, with heat fluxes reaching 10^7-10^8 W/m^2 and particle fluxes of 10^{23}-10^{24} part/m^2/s.

Fig. 2: From left to right: mousetrap device, mousetrap head tip seen from lower divertor PFUs, mousetrap's sample holder.

3. Experimental procedure

Sample damage from heat and particle fluxes is assessed by comparing pre- and post-mortem analyses against plasma parameters measured by Langmuir probes and nearby diagnostics. The material characterisation techniques include confocal microscopy (roughness), SEM (surface damage, EDS (impurities), X-ray tomography (erosion).

The collector probes at the base of the RCP sample holder provide time-resolved measurements of probe position, ion saturation current, electron temperature and density, parallel heat flux, and distance from the LFCS during plunges, enabling interpolation of plasma parameters to each sample in the RCP sample holder. An array of flush-mounted Langmuir probes (FMP), Fiber Bragg Gratings near the mousetrap and a wide-angle IR camera allow for continuous discharge monitoring. Data from FMP are used to estimate fluence, deposited energy, and surface temperature via thermal modelling. During the winter campaign of 2024, one sample of each material has been exposed in the RCP sample holder, for a total of 39 pulses and 74 plunges. The cumulated fluences and deposited thermal energy per sample are shown in Fig. 3

as a function of the pulse number. The SEM imaging of the exposed Si_3N_4 after exposure are shown in Fig.4 right, and compared to a corresponding SEM imaging of a virgin Si_3N_4 (left).

Fig 3. Cumulated fluence (left) and thermal energy (right) as a function of pulse number for the 4 materials.

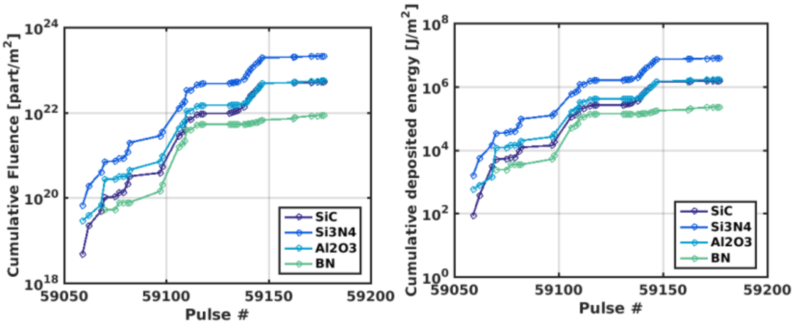
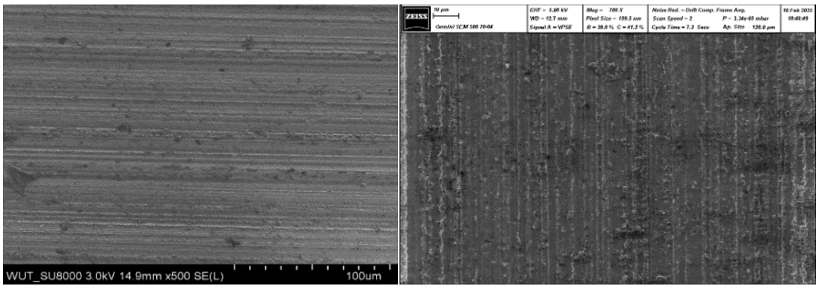


Fig 4. SEM images of a virgin Si_3N_4 (left) and of the Si_3N_4 exposed in 2024 (right), taken under identical conditions. Machining marks are visible on both, but in the exposed sample, they appear melted or widened, indicating surface modification.



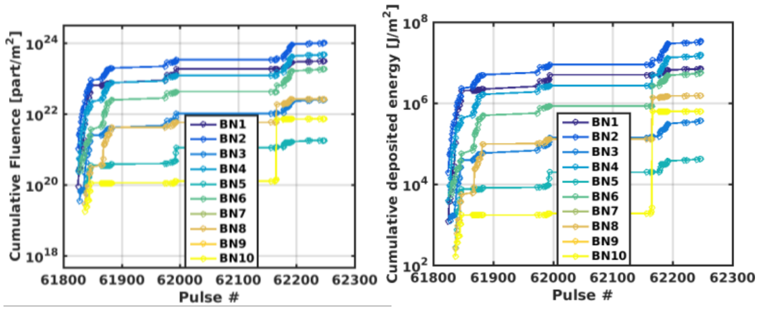
4. Perspectives

4.1 Preliminary results from BN exposure in SOL

Ten BN samples, pre-characterised by SEM and confocal microscopy, were mounted on the RCP and exposed to the SOL plasma during the 2025 winter campaign, over 61 pulses and 281 plunges. Fig. 5 shows the cumulative fluence and deposited energy per sample as a function of pulse number. Up to 15 plunges per pulse (1 plunge/s) were achieved, though plunge frequency is limited to avoid damaging the collector probes. Using BN thermal properties for thermal diffusion computation, and time-resolved ion saturation current data to estimate the parallel heat flux on the sample's surface, it is possible to estimate the sample's temperature during a single discharge. Fig. 5 shows the temperature evolution of the sample, using two assumptions for the ion temperature T_i and electron temperature T_e: $T_i=T_e$, and $T_i=5T_e$, the latter based on measurements in Tore Supra's SOL[9] and recent RFA probe data in similar scenarios on WEST.

4.2 SiC ablation experiment in Mousetrap

A single SiC sample ($10\times12\times2$ mm³) will be mounted on the Mousetrap device and partially exposed to strike point fluxes in fall 2025. To limit coil ohmic heating, exposure time will be optimized to stay within safe margins. Initially placed in the far SOL, the sample will undergo short reciprocations to compare heating with local Langmuir probe data and validate thermal models. A modified magnetic configuration will then place the strike point directly on the sample, aiming to reach ablation (~1700 °C for sintered SiC[7]). Fig. 6 shows that the ablation threshold can be reached within 3–4 reciprocations of 100 ms, with 1.5 s cooling time.



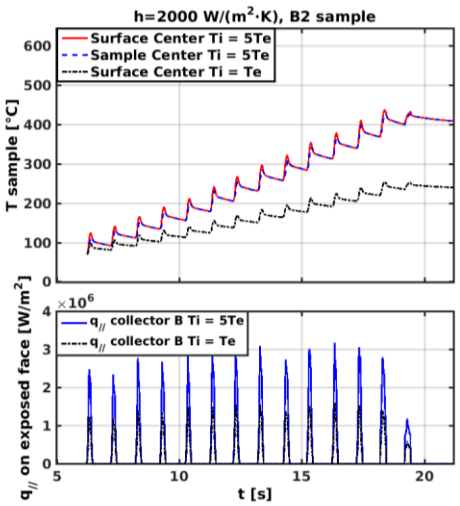


Fig 5. Cumulated fluence (left) and thermal energy (middle) as a function of pulse number for the 10 BN samples. Right bottom: input heat flux as a function of time, measured by collector probe on side B for pulse 62188. Right top: temperature of relevant points of the sample with metallic thermal contact (h = 2000 W/m²K).

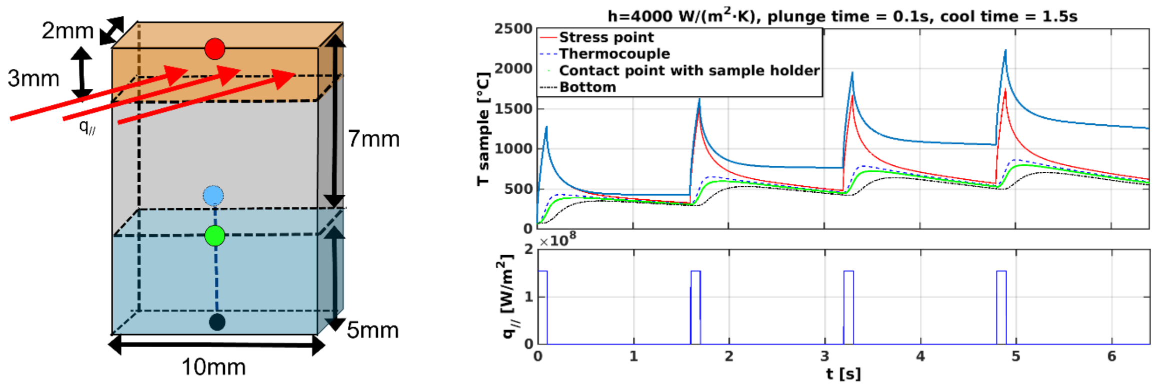


Fig 6 : Left: schematic representation of the sample's geometry. Right bottom: input heat flux as a function of time, representative of the flux measured by flush mounted Langmuir probes on an equivalent scenario, swept on the sample during the probe's tilt. Right top: temperature of relevant points of the sample in presence of a metallic thermal contact (h = 4000 W/m²K) and stress point temperature without thermal contact (blue solid line, upper temperature limit) as a function of time.

5. Conclusions

The WEST tokamak enables controlled exposure of material samples to scrape-off layer plasma. Two complementary exposure systems are currently available, allowing access to different orders of magnitude of heat and particle flux. An experimental procedure was established and successfully validated during the winter 2025 campaign. Post-mortem analyses of exposed BN samples are underway to evaluate surface damage and roughness evolution.

References:

[1] Ifti et al., AIAA Journal. 1-12. 10.2514/1.J061009.

[2] Ni et al., Journal of Advanced Ceramics 2022, 11(1): 1–56

[3] Nisar et al., Ceramics International 48 (2022) 8852–8881

[4] Yamada et al., Trans. JSASS Aerospace Tech. Japan Vol. 8, No. ists27 (2010)

[5] Gunn et al., Journal of Nuclear Materials 337–339 (2005) 644–648

[6] Mazon et al., poster at EPS2023

[7] Yang et al., Aerospace Science and Technology 129 (2022), https://doi.org/10.1016/j.ast.2022.107863.

[8] Gunn et al., 47th EPS Conference on Plasma Physics, Jun 2021, Sitges (E-Conference), cea-03273971

[9] M Kočan et al 2008 Plasma Phys. Control. Fusion 50 125009