Testing tungsten plasma facing components in WEST and AUG Tokamaks: Lessons for ITER

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* E. Joffrin et al 2024 Nucl. Fusion 64 112019 https://doi.org/10.1088/1741-4326/ad2be4
** http://west.cea.fr/WESTteam
*** H. Zohm et al 2024 Nucl. Fusion 64 112001 https://doi.org/10.1088/1741-4326/ad249dAix Marseille

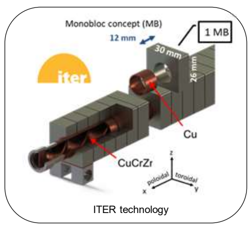
Need for tungsten PFC testing in tokamak condition

Next step fusion devices will face unprecedented heat loads and particle fluence: reliable PFC operation required [R. Pitts et al., NME 2019]

→ ITER divertor has to survive > 10 years, 2000 hours of plasma time

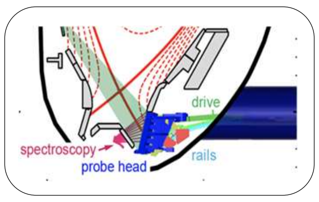
Tungsten (W) Environment Steady-state Tokamak:

- Superconducting toroidal field coils, actively cooled
- Long pulse record with LHCD: 22 min.
- Actively cooled ITER-grade lower divertor
- Steady-state heat flux q_n up to 12 MW/m²



ASDEX Up-Grade:

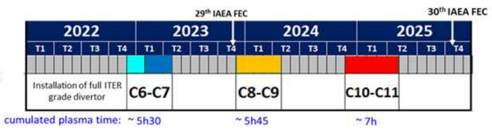
- Full W device (upper and lower W-divertor)
- Divertor (DIM) and midplane manipulators (MEM)
- Transient ELM heat flux $q_\perp$ up to 100 MW/m²



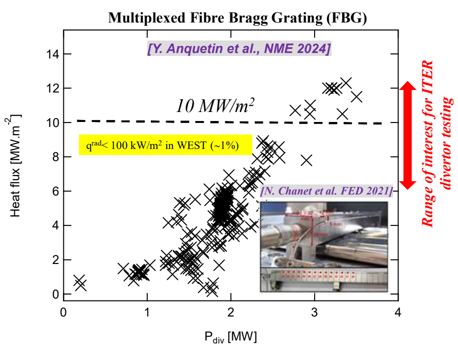
Heat Load on castellated and shaped components (WEST)

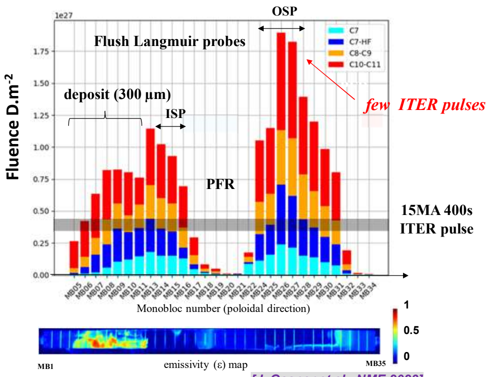
WEST phase 2 operation

- > 4000 plasma discharges (2400 disruptions)
- > 18 hours total plasma cumulated time
- Total cumulated deuterium fluence: 1.8x10²⁷ D.m⁻²
- Net erosion ~20 µm on the OSP



Steady-state heat flux computed with FBG sensing probes and cumulated deuterium fluence during C6-C11 experimental campaigns

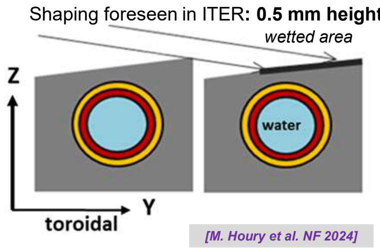




ITER relevant ion-fluence and heat flux achieved in WEST

Toroidal bevel at monoblock scale

Shaping foreseen in ITER: **0.5 mm height toroidal bevel**



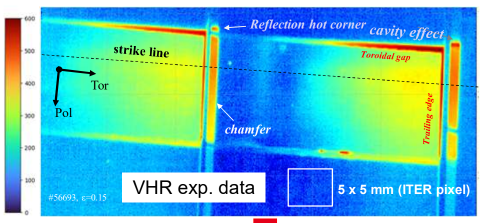
[M. Houry et al. NF 2024]

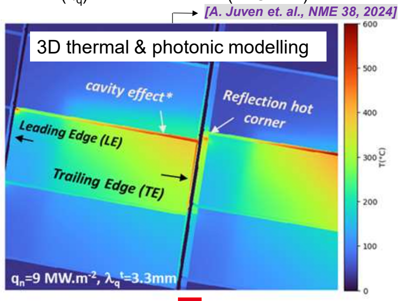
- Protection of the leading edges (LEs)
- Reduction of the wetted area → +20% higher load flat top geometry
- **PFC assembling** is critical:
  - vertical misalignment (ITER tolerance = ±0.3mm)
  - PFC tilt ±1° measured in WEST (ITER?)

➢ Surface metrology mandatory in strike point region (in case of deviation)

Very High spatial Resolution (VHR) IR thermography [0.1mm/pixel] to assess the temperature response under ITER relevant heat load condition: # power level, strike line position, heat flux expansion (λ_q) and wetted areas (PFC mis.)

[A. Juven et al., NME 38, 2024]





➢ T° gradient on MB scale (# loading from HHF tests)

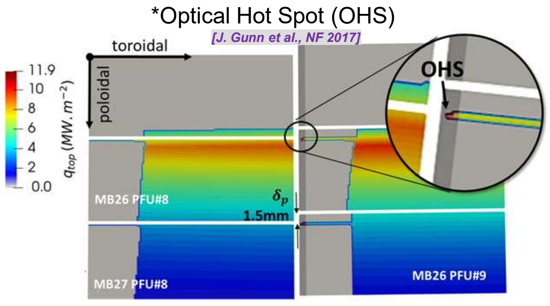
- 0.5 mm toroidal bevel offers **good protection on poloidal LEs**
- MFL can still penetrate and strike the LE with high incidence angle*

[Q. Tichit et al., NME 2024]

Strong effect of the specular reflection in toroidal gaps (TG) and trailing edge (TE)

*Optical Hot Spot (OHS)

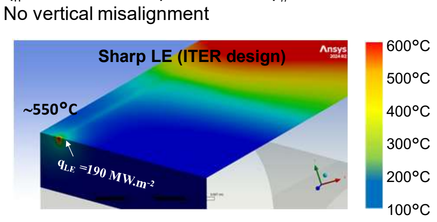
[J. Gunn et al., NF 2017]



Heat loading on poloidal gaps: PFC flux simulation

Thermal response estimation WEST L-mode plasma:

- q_n = 10 MW.m⁻² top surface → $q_{//}$ = 190 MW.m⁻²
- No vertical misalignment



Very high heat flux expected on the OHS (tiny surface):

➢ In cold area → acceptable temperature in L-mode nominal 10 MW.m⁻² with no vertical misalignments
➢ high thermo-mechanical stresses & erosion locally, 20 MW.m⁻² slow transient ?
➢ Numerical tools (PIC code) predict potential issue for ITER during transients

[J. Gunn et al., NF 2017]

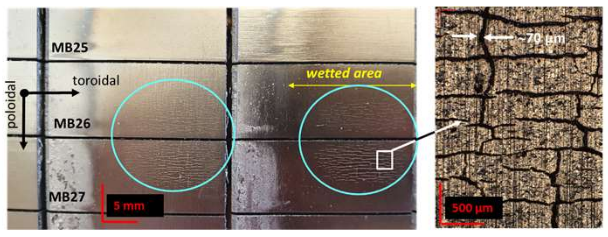
Tungsten cracking

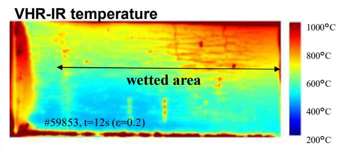
Spontaneous cracks forming

No more crack on the LE thanks to the toroidal bevel

Spontaneous cracks appear on the top surface of MB, in wetted area @ the outer strike point

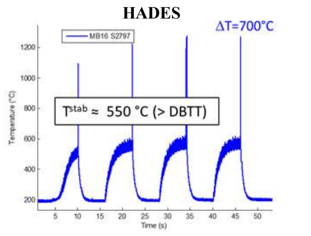
- Failure not expected from standard HHF at those levels of steady-state
- Visible "in-operando" in C9, heat flux ~10 MW/m² [M. Diez et al., PFMC 2025]
- *Brittle cracks also detected in EAST [Y. Wang et al. 2025 Nucl. Fusion]*





→ **transients initiate failure?**

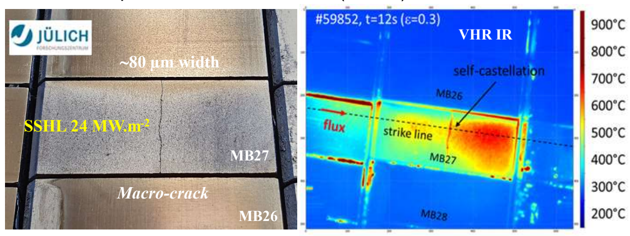
Dedicated HHF testing (e⁻ beam): 5MW.m⁻² steady state heat load (shadowed/loaded areas, no λ_q) 80-160 MW.m⁻² transient (3ms, 6ms, 10ms) 100 cycles



→ *No crack in HHF HADES ("cold" and "hot" MBs)*

Macro-crack failure

- Damages generated in HHF test facility (e-beam) JUDITH 2 → Mimic damage on ITER
- Plasma exposure in tokamak device (WEST)



[A. Durif et al., PFMC 2023] VHR IR data (0.1mm/pixel)

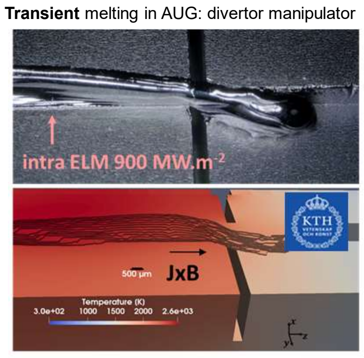
No observable evolution of the crack damaged surface (VHR IR data)

→ **no particular limitation**

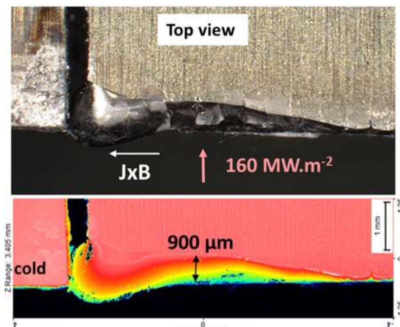
→ **heat exhaust capabilities unchanged (rising and cooling times)**

Tungsten melt transport across PFC gaps

Transient melting in AUG: divertor manipulator



Sustained melting in WEST: actively cooled PFC



[S. Ratynskaia et al., NF 2024]

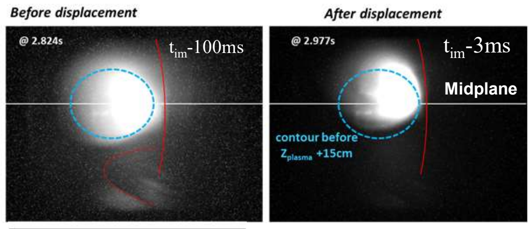
- *MEMENTO (macroscopic melt dynamics) extensively validated through dedicated EUROfusion & ITPA experiments* [S. Ratynskaia et al., NME 2022]
- *Prompt bridge freezing due to slow melt-motion & contact with the surface across the gap (cold) - re-solidification prevents the melt from evolving around the corner*

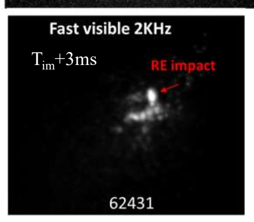
Gap bridging without wetting of the inner gap (no infiltration) in WEST/AUG
→ gaps can be ignored when modelling macroscopic melt motion
→ Consequence subsequent to disruption to be investigated: EM loads

W PFC damage induced by runaway electron incidence

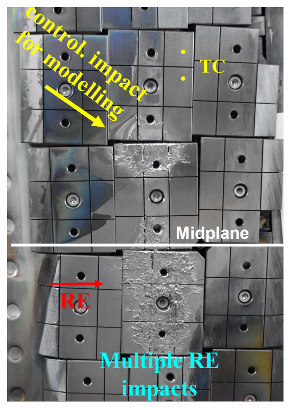
Modelling of ductile (at high T) W with liquid phase not tested yet:

- 1st controlled RE impact experiment on W-material (instrumented tile with TC, fast visible + fast IR cameras)
- Major damage despite high melting point of W





Duration of the RE impact: ~2.5 ms



Bulk W (inner bumper)

[S. Ratynskaia, Plenary talk, 51th EPS Plasma Physics]

Work-flow (GEANT4 - MEMENTO/LS-DYNA) to test predictive capabilities for ITER

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