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J. P. Gunn, J. Bucalossi, Y. Corre, M. Diez, E. Delmas, N. Fedorczak, A. Grosjean, M. Firdaouss, J. Gaspar, T. Loarer, et al.

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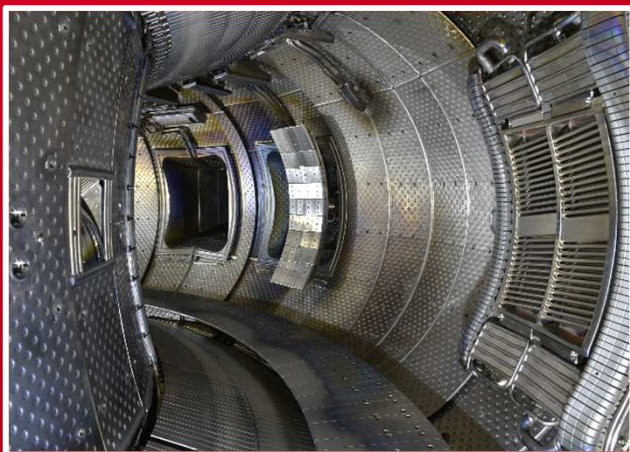
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Thermal loads in gaps between ITER divertor monoblocks: first lessons learnt from WEST

J. P. Gunn, J. Bucalossi, Y. Corre, M. Diez, E. Delmas, N. Fedorczak, A. Grosjean, M. Firdaouss, J. Gaspar,^a T. Loarer, M. Missirlian, P. Moreau, E. Nardon, C. Reux, M. Richou, E. Tsitrone, and the WEST team^b

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The 24th International Conference on Plasma Surface Interactions in Controlled Fusion

24-29 January, 2021, Jeju, South Korea

The need for tungsten monoblock shaping in the ITER divertor

Justification for final decision on shaping solution

Observations of damage at optical hot spots in WEST

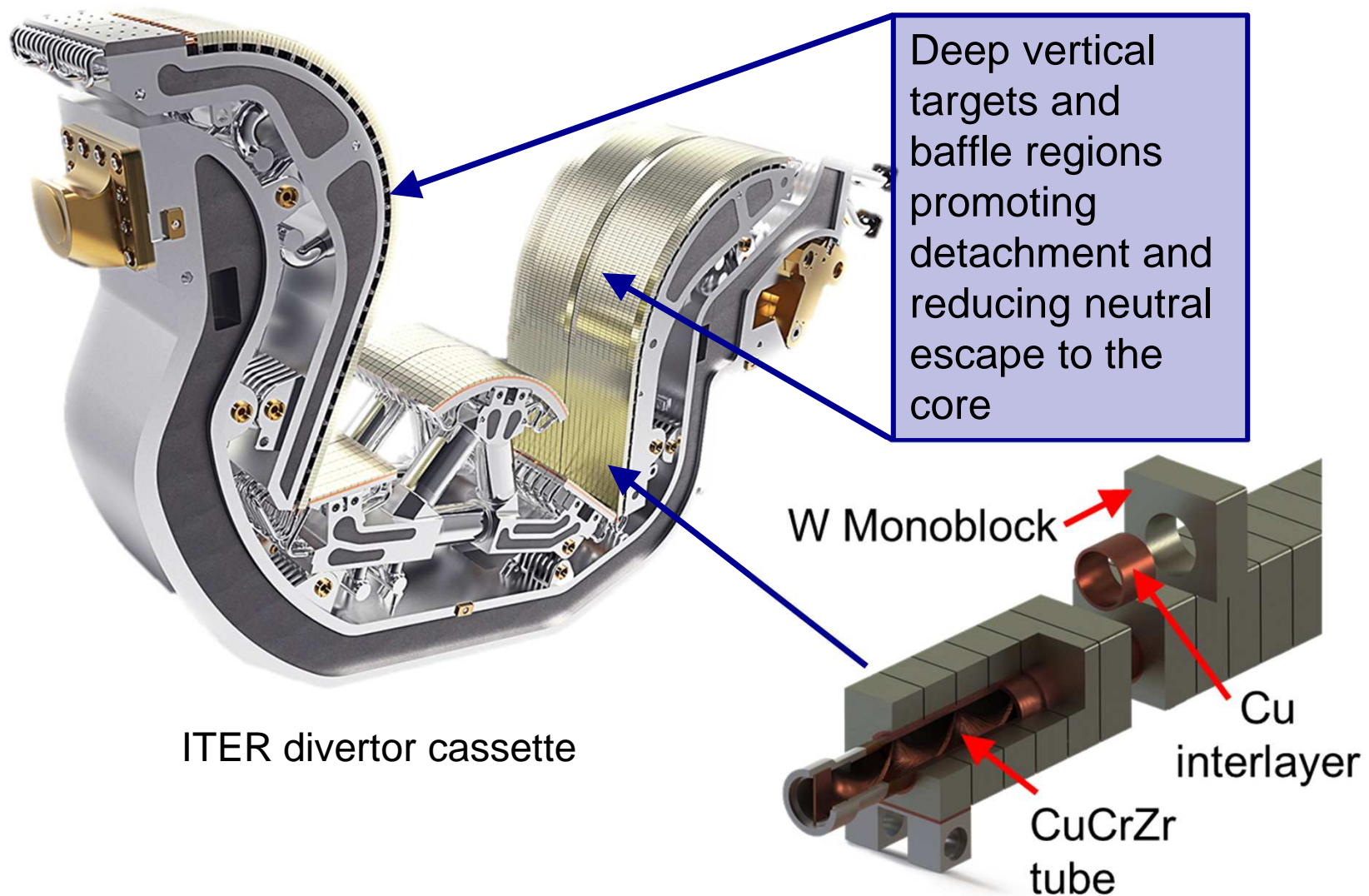
First attempts to try to understand how the damage is caused

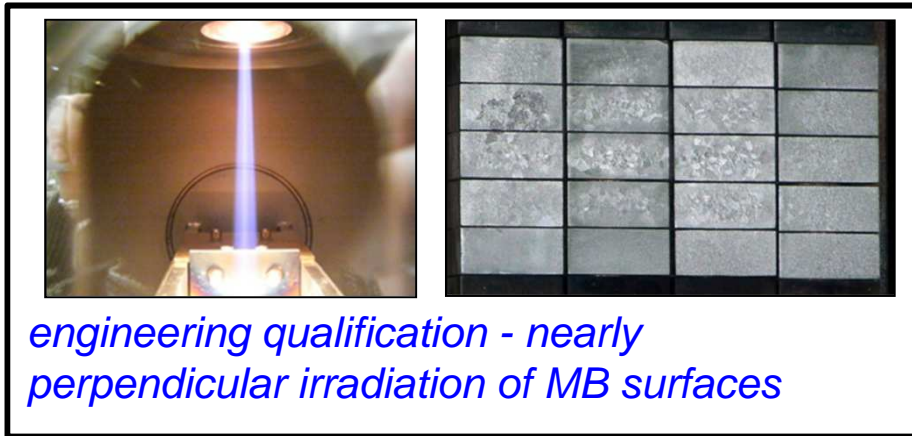
Consequences for ITER?

The ITER tungsten divertor



- The most sophisticated tokamak divertor ever built
 - 54 individual cassettes, fully water cooled, designed to handle up to ~100 MW in steady state
 - Now entering the procurement phase → design complete

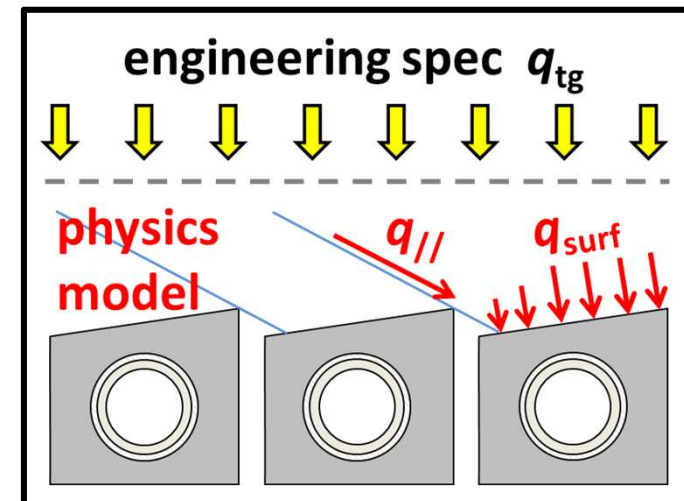




Real loading conditions in a tokamak are quite different than under an electron beam

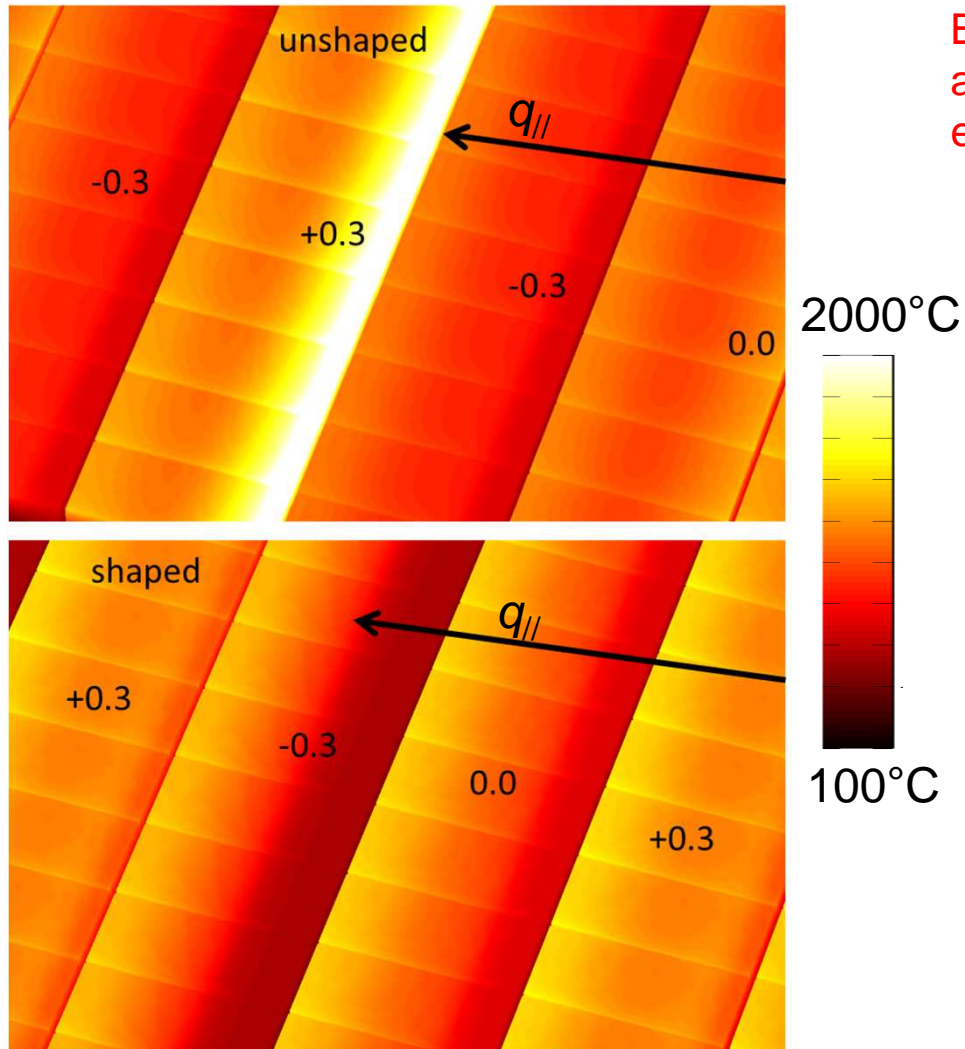
- near glancing B-field incidence angle $\sim 3^\circ$
- Larmor gyration around field lines

"shaped" means 0.5 mm toroidal bevel to avoid exposed poloidal leading edges



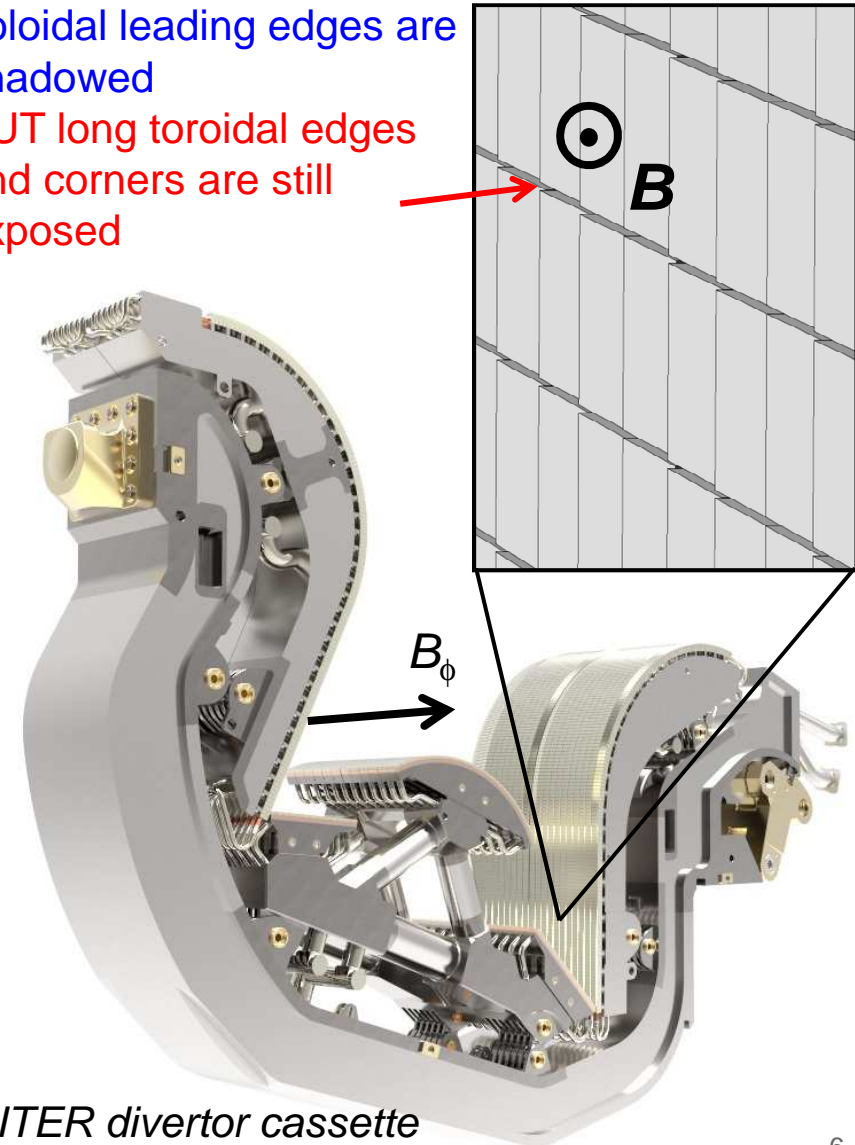
J. P. Gunn, S. Carpentier-Chouchana, F. Escourbiac, T. Hirai, S. Panayotis, R. A. Pitts, Y. Corre, R. Dejarnac, M. Firdaouss, M. Kočan, M. Komm, A. Kukushkin, P. Languille, M. Missirlian, W. Zhao, G. Zhong, "Surface heat loads on the ITER divertor vertical targets", Nucl. Fusion **57**, 046025 (2017).

steady state thermal response of misaligned PFUs at outer vertical target



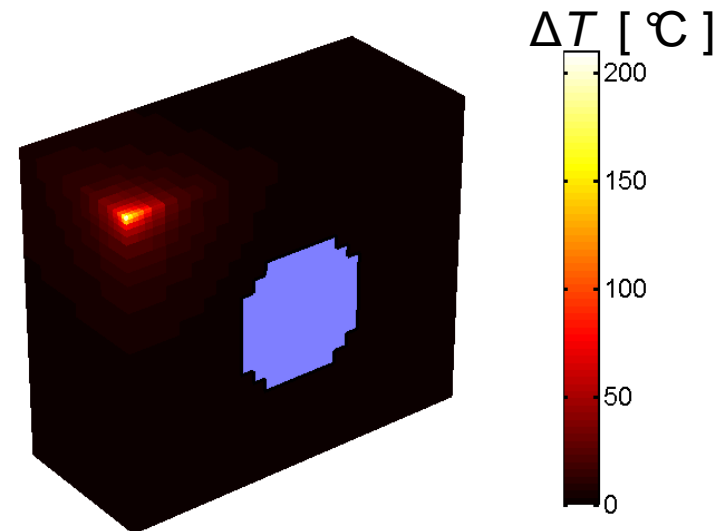
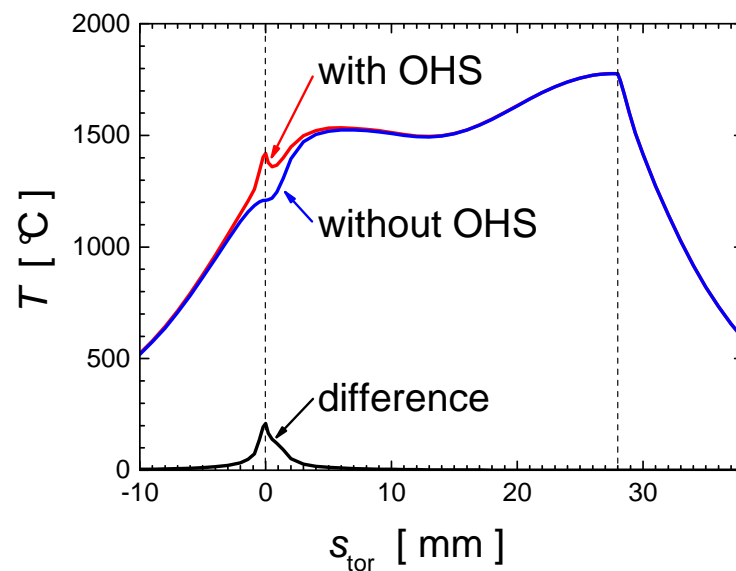
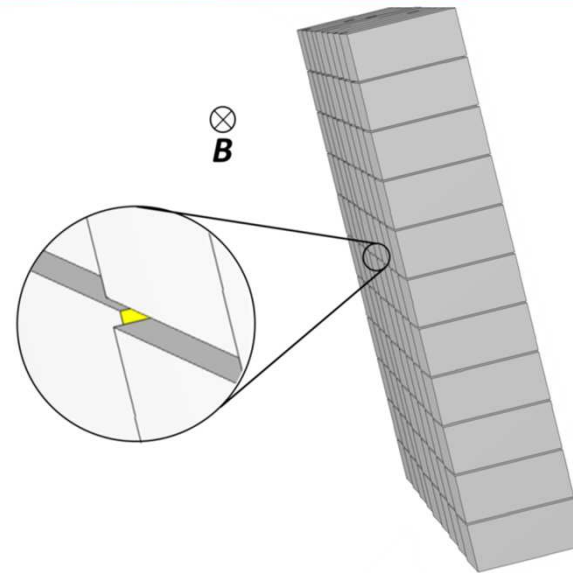
poloidal leading edges are shadowed

BUT long toroidal edges and corners are still exposed



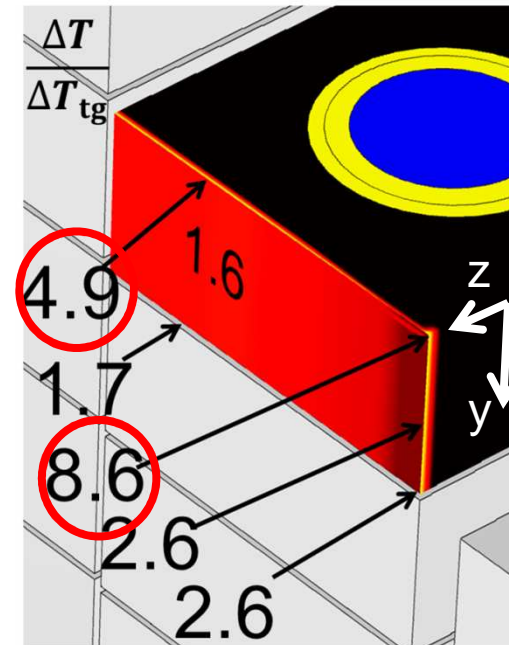
"optical hot spot" = monoblock corners visible at gap crossings when looking along magnetic field lines

Full parallel heat flux but tiny wetted area
~0.2 mm²
-negligible temperature increase for steady state heat loads (inter-ELM)



5 keV ELM ions
Larmor radius ~2 mm
Intense heat flux focused onto upper edge of toroidal gap

Direct irradiation of optical hot spot by parallel heat flux



Transient temperature increase due to ELM (normalized to ideal axisymmetric surface response)

**the number 1.0 corresponds to temperature rise at perfect axisymmetric target for a given transient (ELM) energy fluence*

" [...] It has been decided to implement only a toroidal bevel on the top surfaces of MBs in the high heat flux areas (straight portions) of the vertical targets.

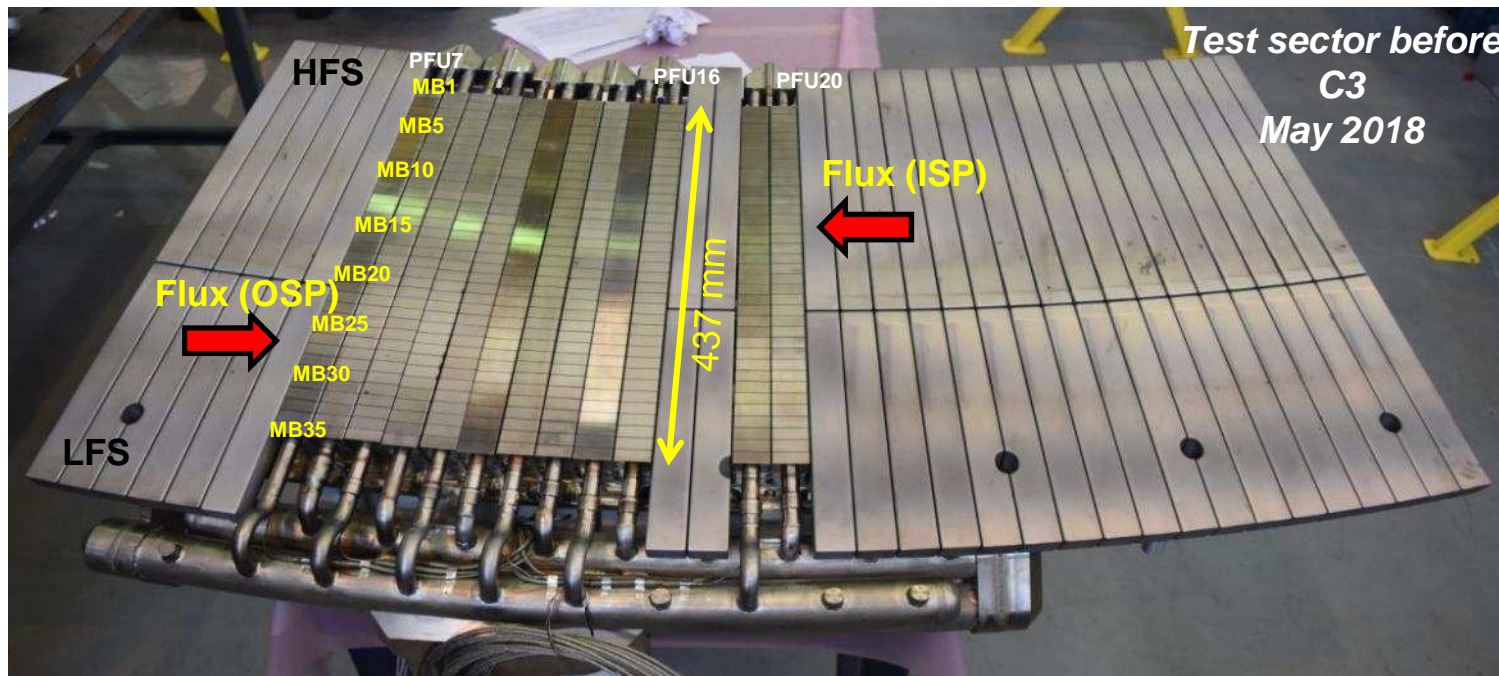
This decision consciously acknowledges that melting of TG edges and at optical hotspots may have to be accepted at both targets.

Further experimental work and modelling is required to evaluate the consequences for the MB lifetime."

R. A. Pitts, X. Bonnin, F. Escourbiac, H. Frerichs, J. P. Gunn, T. Hirai, A. S. Kukushkin, E. Kaveeva, M. A. Miller, D. Moulton, V. Rozhansky, I. Senichenkov, E. Sytova, O. Schmitz, P. C. Stangeby, G. De Temmerman, I. Veselova, S. Wiesen, "**Physics basis for the first ITER tungsten divertor**", Nuclear Materials and Energy **20**, 100696 (2019).

The WEST lower divertor is mostly composed of uncooled, W-coated graphite PFUs.

For the C3 campaign in 2018, one sector was equipped with 12 actively cooled, ITER-like W PFUs (unshaped, no toroidal bevelling → **exposed leading edges**)



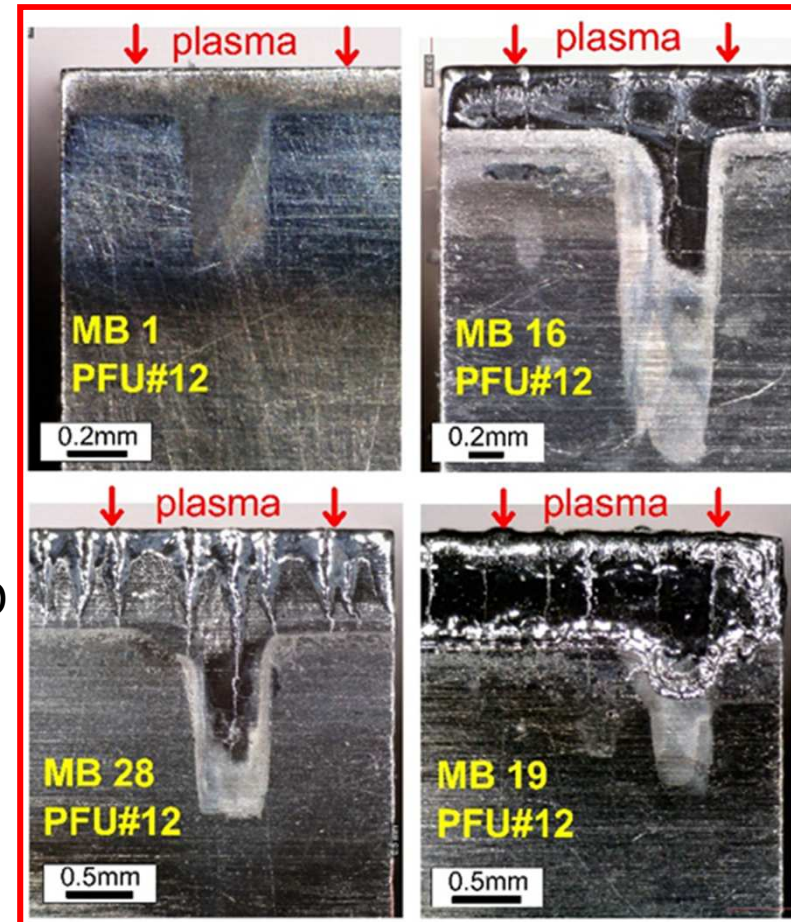
First observations:

Clear evidence of optical hot spots

Cracking and melting of exposed surfaces (poloidal leading edges and optical hot spots) over full poloidal extent of divertor, even on areas that should see no steady state heat flux

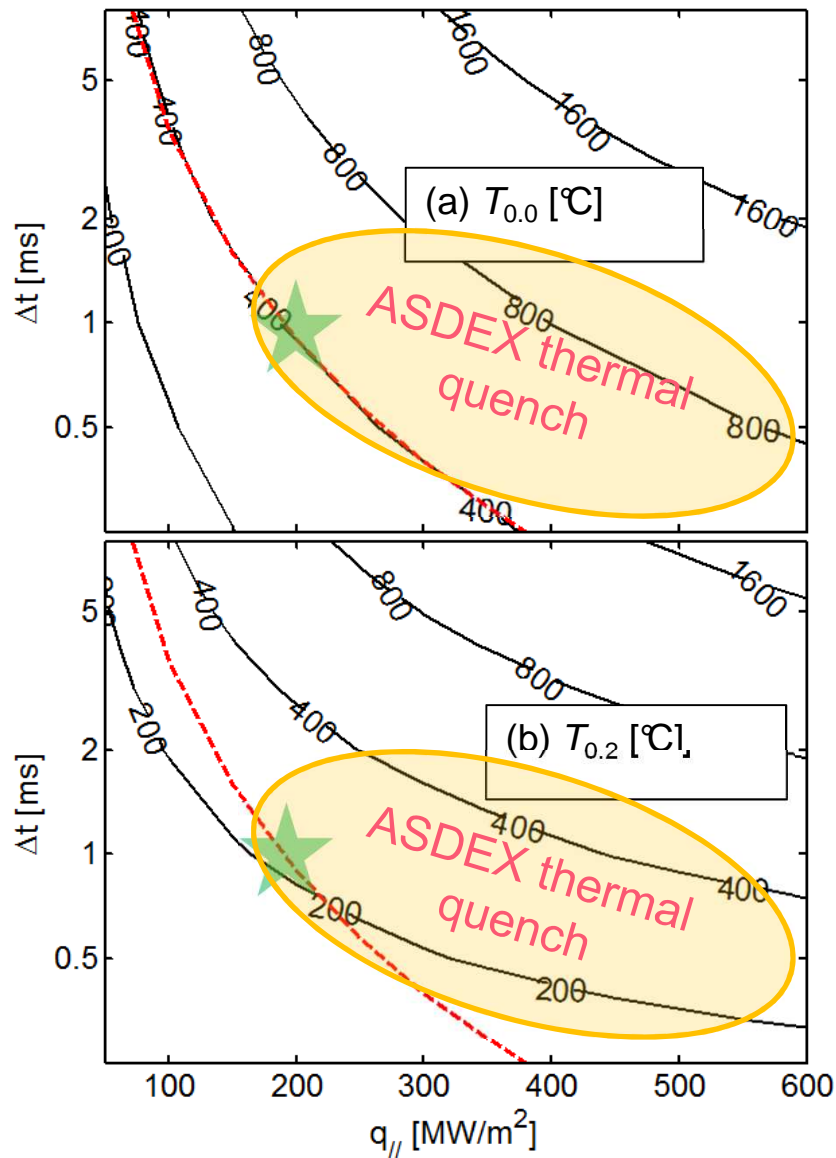
Operational hypothesis: brittle cracking of cold W due to transient events (disruptions and MHD crashes)

-Heat loads consistent with cracking threshold determined in JUDITH-1 (Wirtz, PSI 2016)



M. Diez, J. P. Gunn, M. Firdaouss, A. Grosjean, Y. Corre, E. Delmas, L. Gargiulo, E. Tsiatrone and the WEST Team, **First evidence of optical hot spots on ITER-like plasma facing units in the WEST tokamak**, Nuclear Fusion **60**, 054001 (2020).

T [°C] at surface and 0.2 mm below after heat pulse



A notable result of W material testing research is that surface damage is greater when the samples are cold. Brittle cracking was observed on cold W samples ('cold' meaning temperatures below the ductile-to-brittle transition temperature, DBTT) irradiated by moderate heat flux (starting above 200 MW m⁻²) after only a few heat pulses (1 ms duration) in the JUDITH-1 electron beam facility [Wirtz, PSI 2016, NME 2017].

Corresponding heat flux factor is 6 MW s^{1/2} (dashed red curve)

Thermal simulations indicate surface temperature above the DBTT, but bulk temperature (0.2 mm below surface) lower than the DBTT (250-350°C). Plastic deformation in the hot layer followed by cooling leads to cracking.

$$q_{pk} = f_W W_{dia} / 2\pi R f_\lambda \lambda_q \Delta t$$

Heat pulse due to thermal quench in ASDEX, extrapolated to WEST (no fast IR measurements in WEST), is exactly in the right range to produce brittle cracking on WEST monoblock leading edges.

(200 < q_{||} < 600 MW/m² during ~1 ms)

Two reciprocating Langmuir probes equipped with W-La(10%) heat shields are mounted in the outboard limiter

- Different exposure histories, but cracks observed on both
- Same kind of cracks observed on divertor

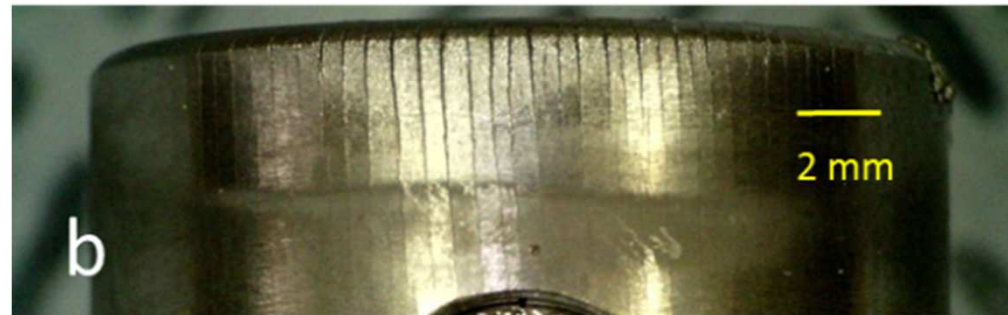
Probe #1 (in operation since beginning of WEST)

>1000 reciprocations

$q_{||} > 10 \text{ MW/m}^2$

many disruptions

Observation: visible wide cracks with local melting



Probe #2 (only operational in C2 campaign)

50 reciprocations

$q_{||} < 1 \text{ MW/m}^2$

4 disruptions

Observation: very fine cracks seen under a microscope



ITER has decided on simple 0.5 mm toroidal beveling of monoblocks

Optical hot spots have been confirmed in WEST and will exist in ITER

Cracking and melting at optical hot spots is already observed in WEST, a newly commissioned tokamak with until now modest heating power

Hypothesis : brittle cracking of cold surfaces due to transient heat pulses.

Expected energy fluence during thermal quench is consistent with brittle cracking threshold observed in JUDITH-1

Observations of Langmur probes with different exposure histories suggest the cracks evolve with time (widening, edge melting)

- exposure to steady heat loads?
- exposure to increasing numbers of disruptions?
- both?

The same phenomenon should be expected even in the first experiments with the ITER divertor

- thermal quenches
- MHD crashes
- small ELMs

Question : does it matter?

Starting in summer 2021, WEST will begin operation with a full W divertor having bevelled monoblocks and optical hot spots. The consequences of brittle cracking of optical hot spots on plasma operation and divertor lifetime will be a high priority area of research.

