DE LA RECHERCHE À L'INDUSTRIE

Damages on tungsten plasma facing components after experimental campaigns in WEST

Third IAEA Technical Meeting on Divertor Concept – 4th November 2019

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OUTLINE

- **Background**
  - WEST mission
  - Lower divertor
  - Summary of C3 campaign
- **PFU #12 – damages due to transient event**
  - Damages overview on a trailing edge
  - Focus with optical microscopy
  - Crack network development
- **PFU #12 – damages along edges**
- **Damages on chamfered PFUs**
- **Optical hot spots**
  - Optical hot spot (OHS) definition
  - Evidences of OHS after operations

WEST missions : pave the way towards ITER actively cooled tungsten divertor procurement and operation

First tokamak with actively cooled W monoblocks in full metallic environment

- Optimization of industrial scale production / qualification processes ahead of ITER divertor procurement
- Assessment of power handling capabilities / lifetime of ITER high heat flux tungsten components in tokamak environment (high heat flux / high fluence)
- Validated scheme for protection of actively cooled metallic plasma facing components

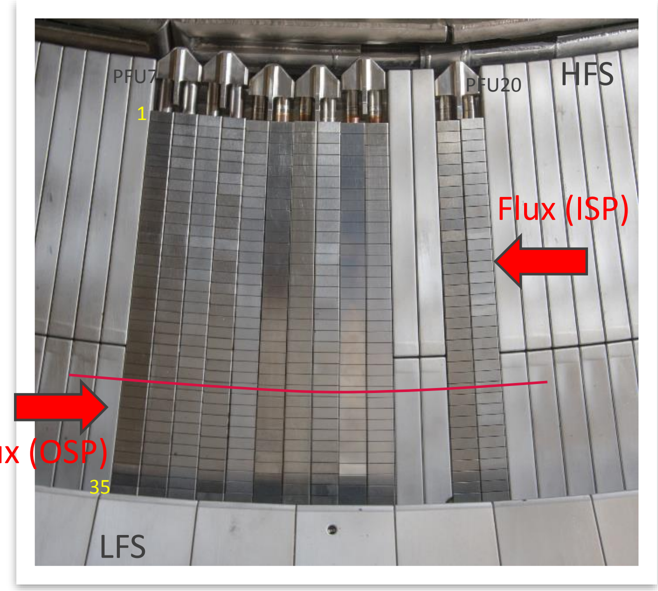
W monoblocks ITER-like PFUs (Plasma Facing Unit)

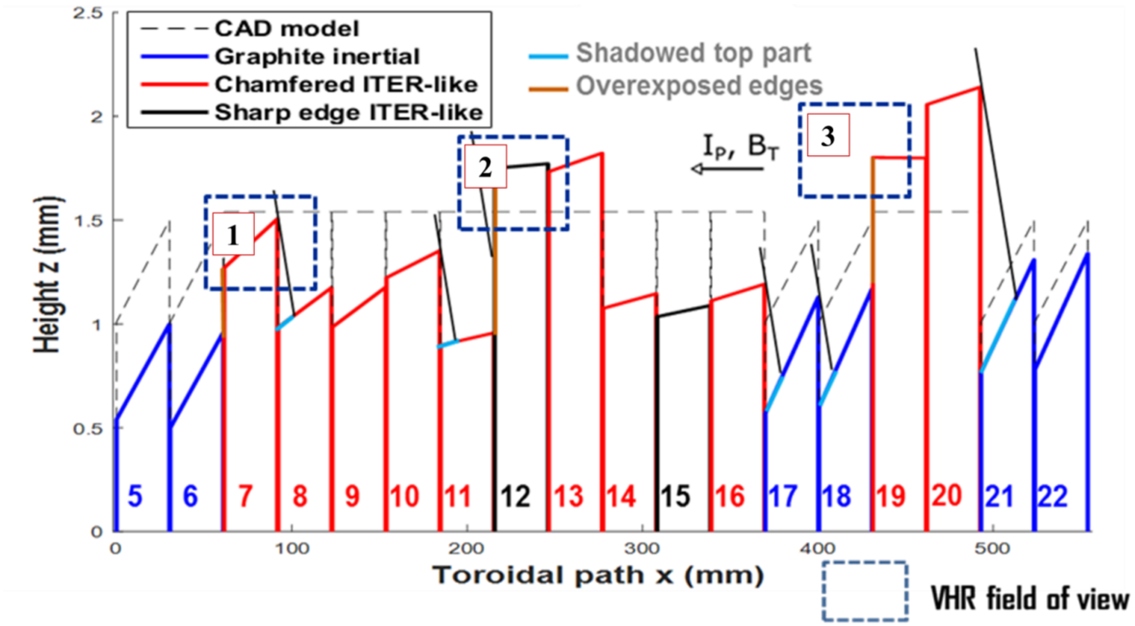
Inside view of WEST – C3 campaign start

Past C3 campaign (05/2018 – 01/2019)

Focus on lower divertor and ITER-like PFC

- 12 W monoblocks PFC on a specific location, from 6 suppliers (F4E, JADA and ASIPP)
- No shaping on W monoblocks, but sharp & chamfered edges
- First significant exposure of ITER-like PFC during this campaign (up to 2.5 MW/m²)
- Dedicated diagnostics in particular :
  - Very High Resolution infrared camera – 0.1mm per pixel
  - Accurate misalignment measurements (~50µm)





Three PFU misalignment > ITER specification (0.3mm) at OSP:

- PFU 7 : 0.31 mm
- **PFU 12 : 0.79 mm**
- PFU 19 : 0.63 mm

PFU 12 at risk

Significant exposure time and large number of transients

- 2.5 hours of plasma exposure, with 5GJ of injected energy
- L-mode operation, 700 disruptions in C3, more than 1000 disruptions in total
- Up to 5MW heating, with important radiated fraction (0.5 to 0.8)
- Moderate parallel heat flux at the OSP: 20 to 50MW/m² i.e. 1 to 2.5 MW/m² on the divertor target

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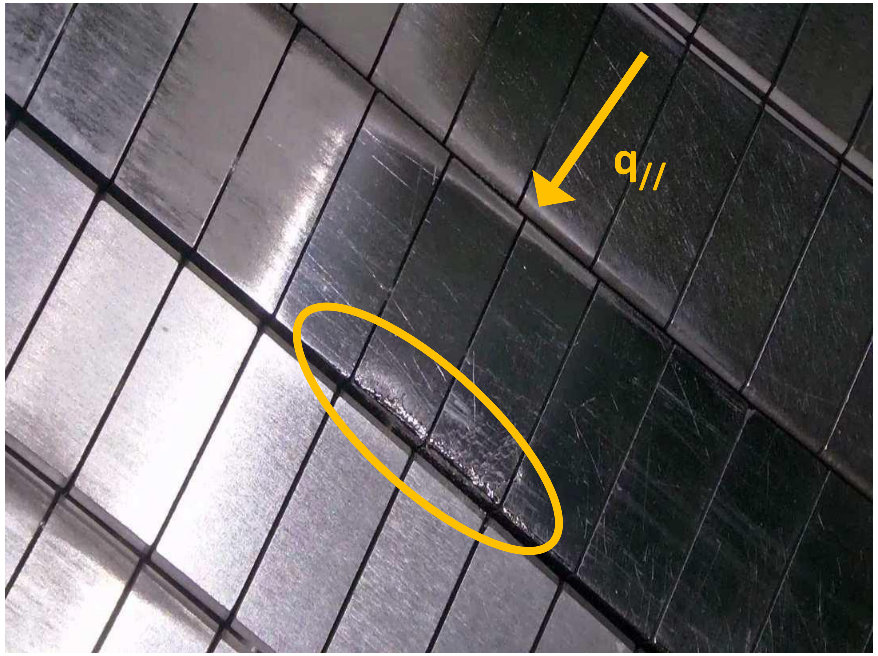
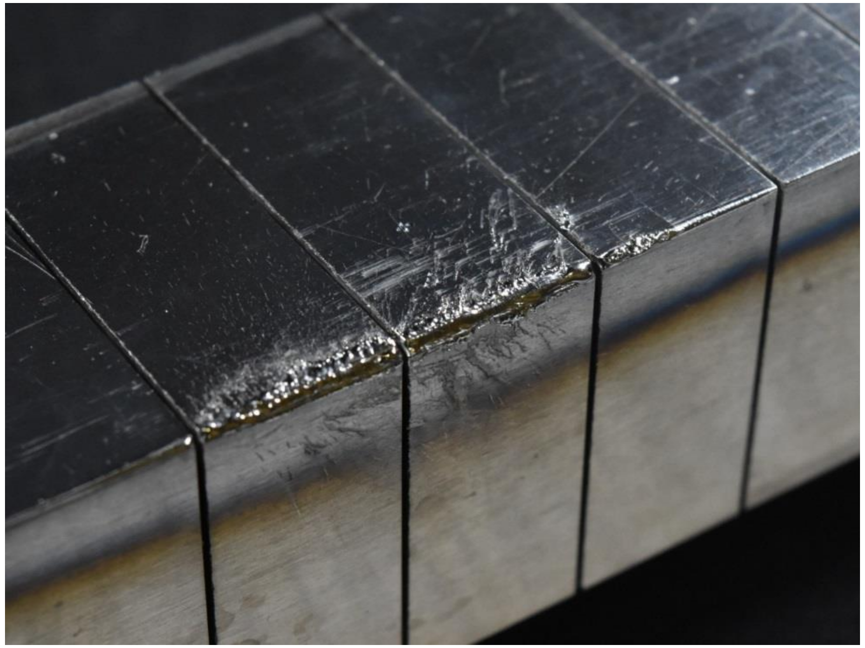
Damages overview on a trailing edge

- Damaged area identified after C3a using the robotic Articulated Inspection Arm during experimental campaign
- Localization on the trailing sharp edge
- Combination of single / few powerful events (>200MW/m² parallel during 10ms) with 0.8 mm misalignment
- No evolution during following operation C3b

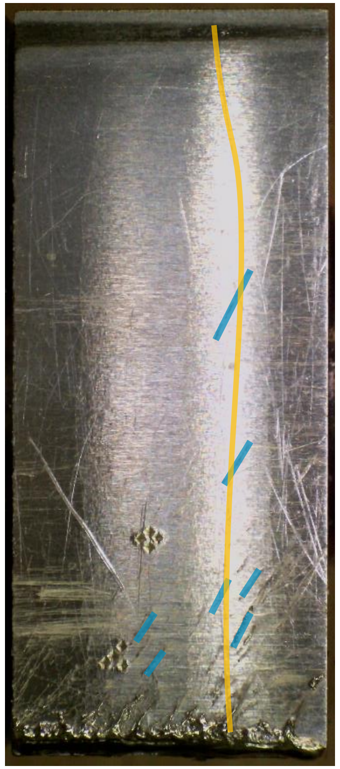
Articulated Inspection Arm inspection – in-situ view



Ex-situ inspection between C3 and C4



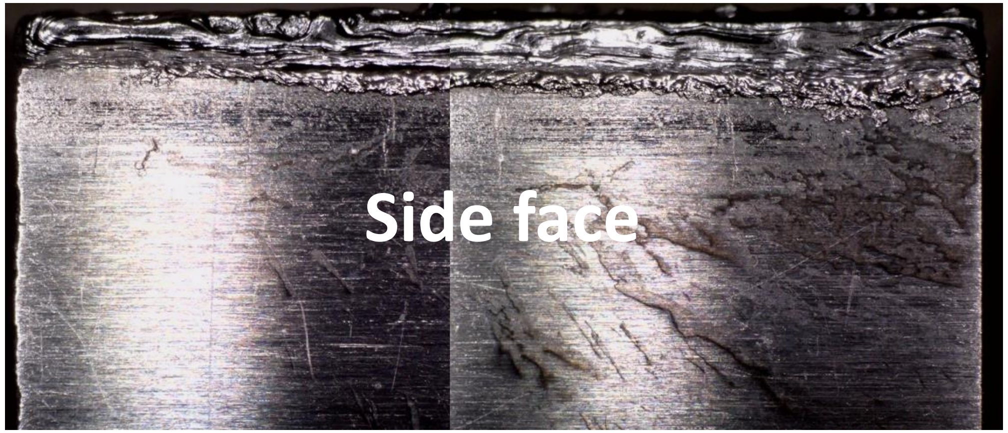
Melted W across monoblock and long crack



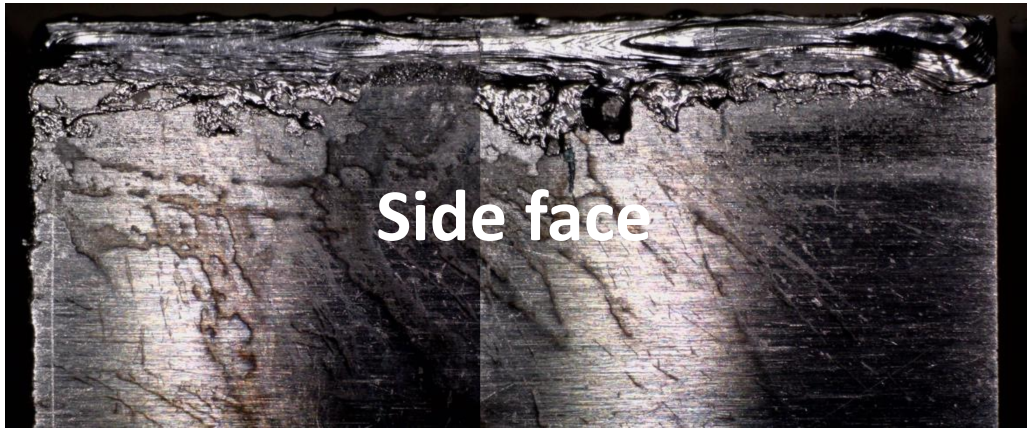
Focus with optical microscope

- PFU #12 dismounted at the end of C3 -> large melted area (0.5mmx0.5mm) on 2 monoblocks and a half

Monoblock 14 – Top and side views



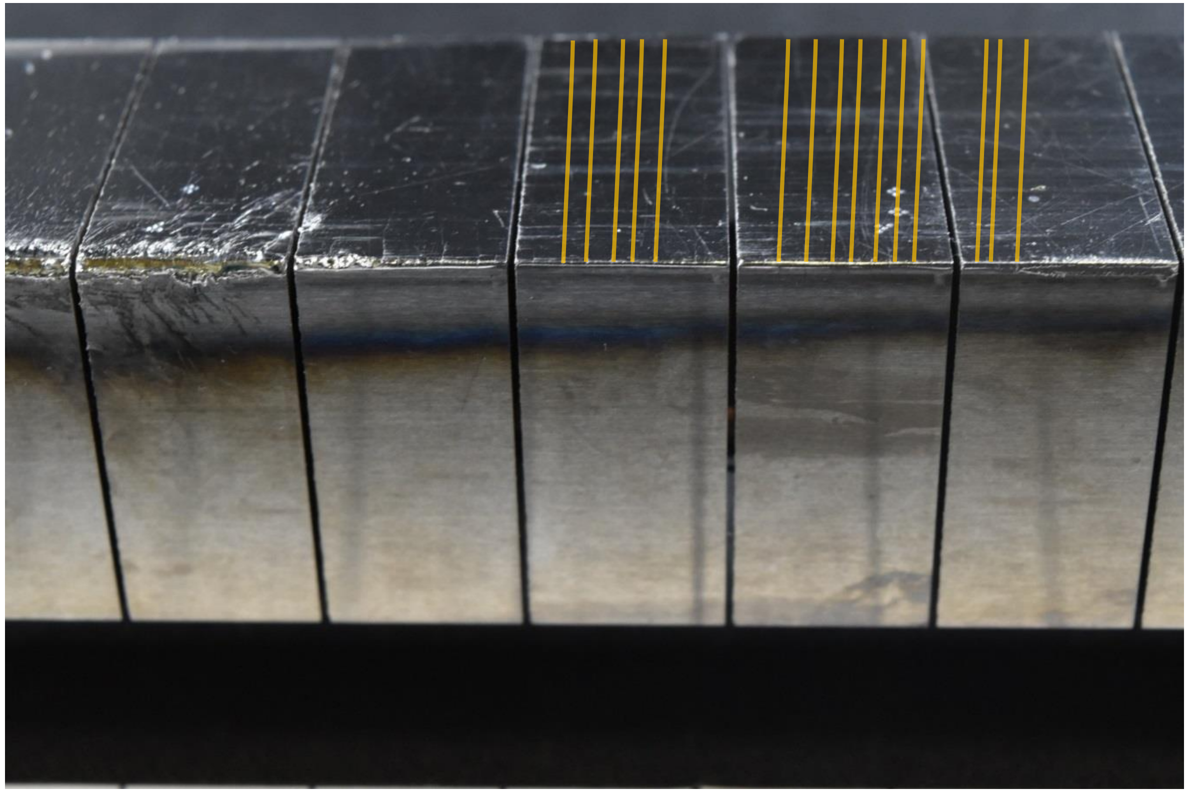
Monoblock 15 – Top and side views



PFU #12 – damages due to transient event

Crack network development

- Long cracks in yellow on monoblocks far from the melted area (and melted material in blue)
- Specific to this area, meaning that it is caused by a localized single / few transient event



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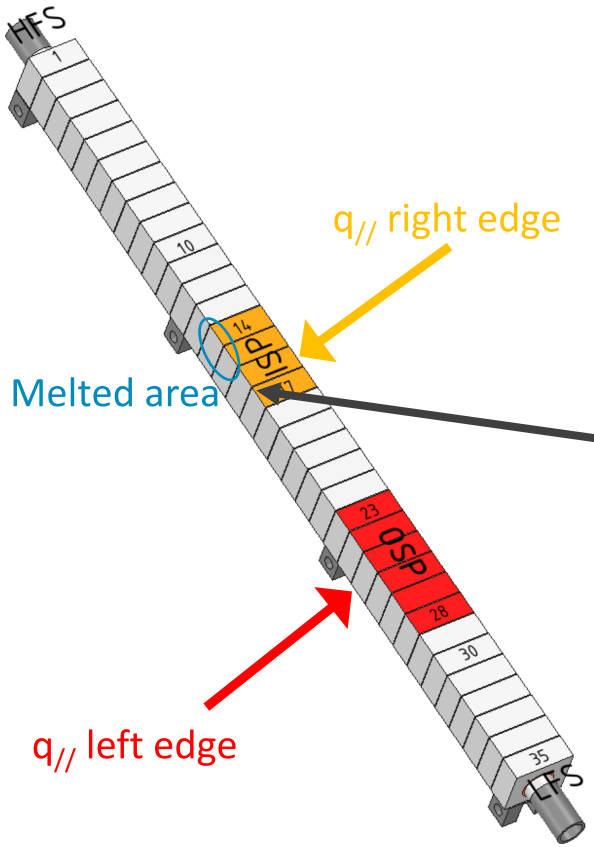
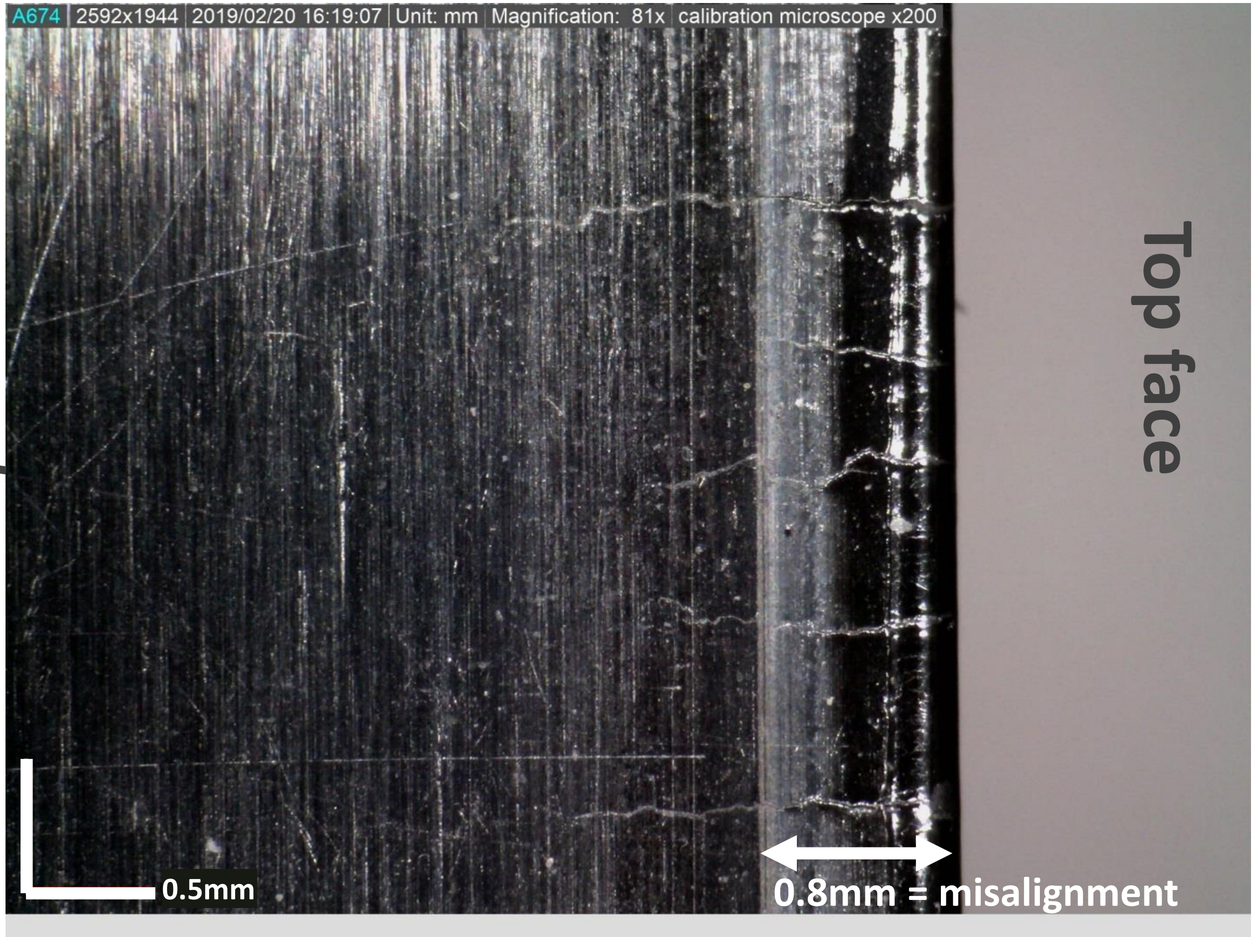
mb 17 – left edge - non exposed side close to the melted area

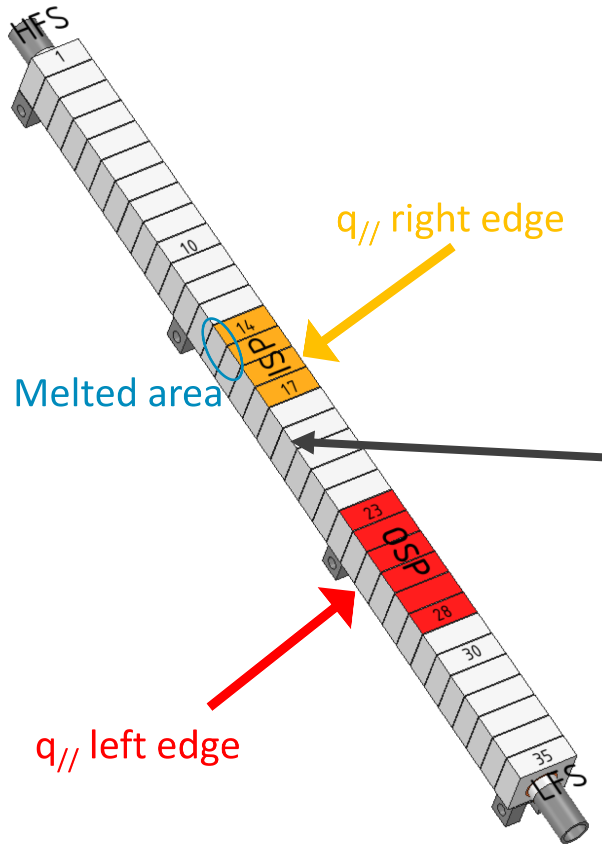


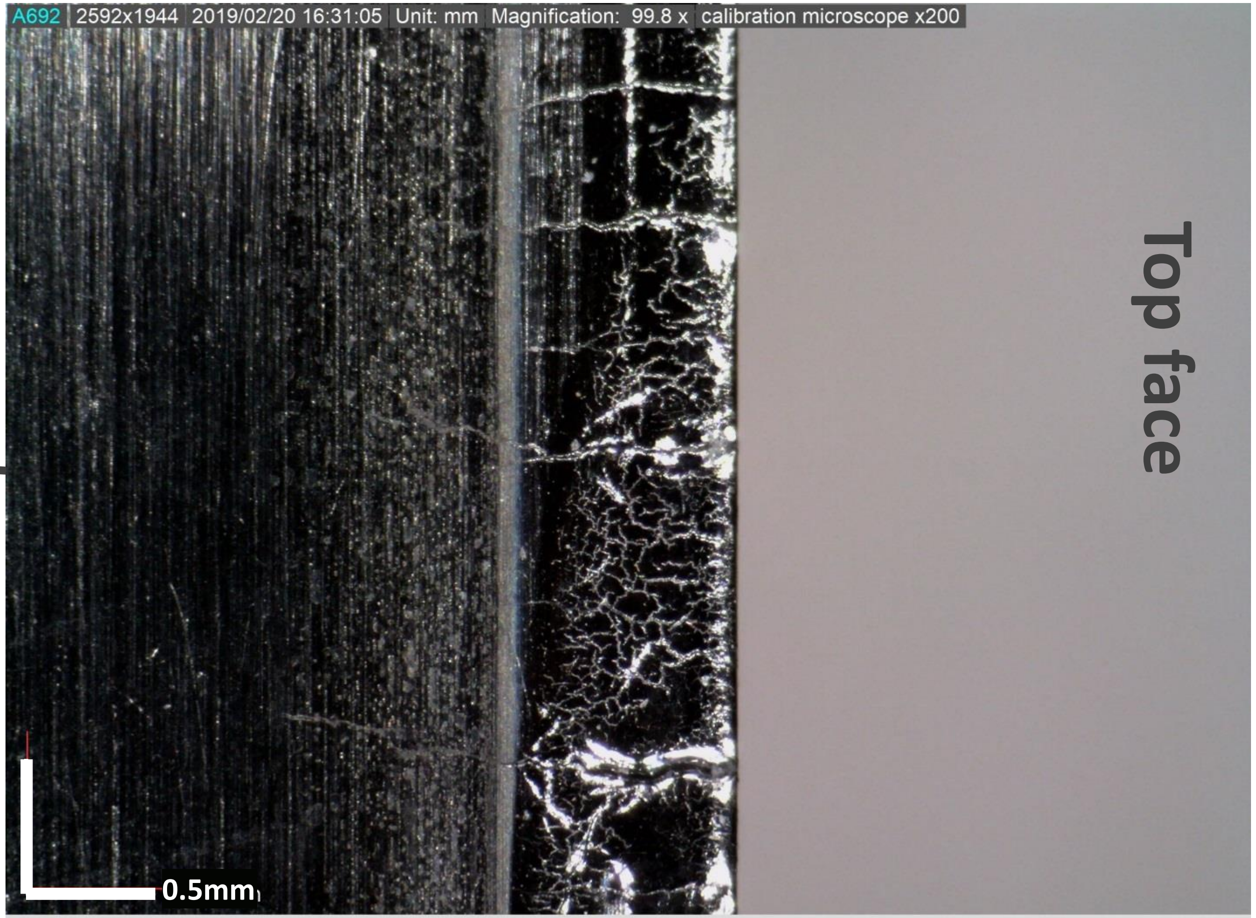


- 2mm deep vertical cracks – horizontal cracks
- Regular and numerous cracks

PFU #12 – damages along the edges

mb 19 – left edge - non exposed side

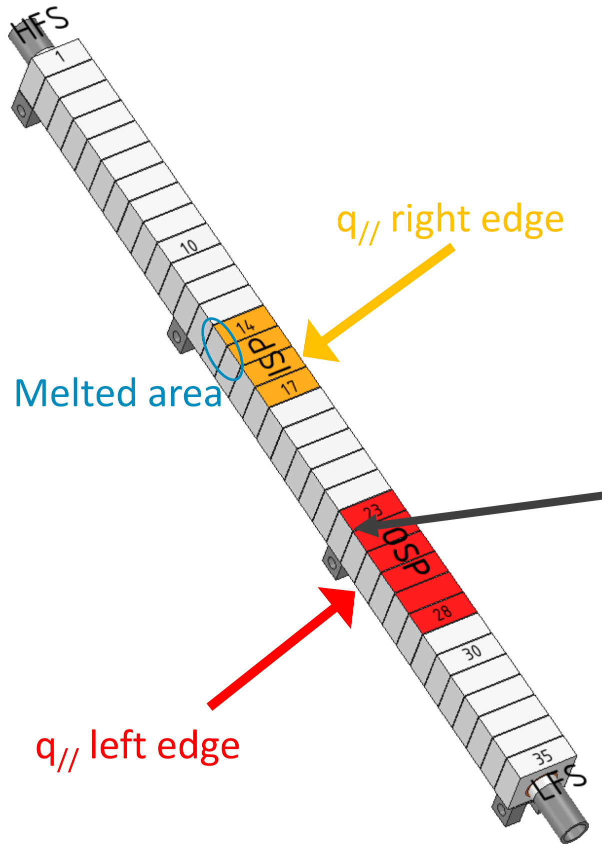


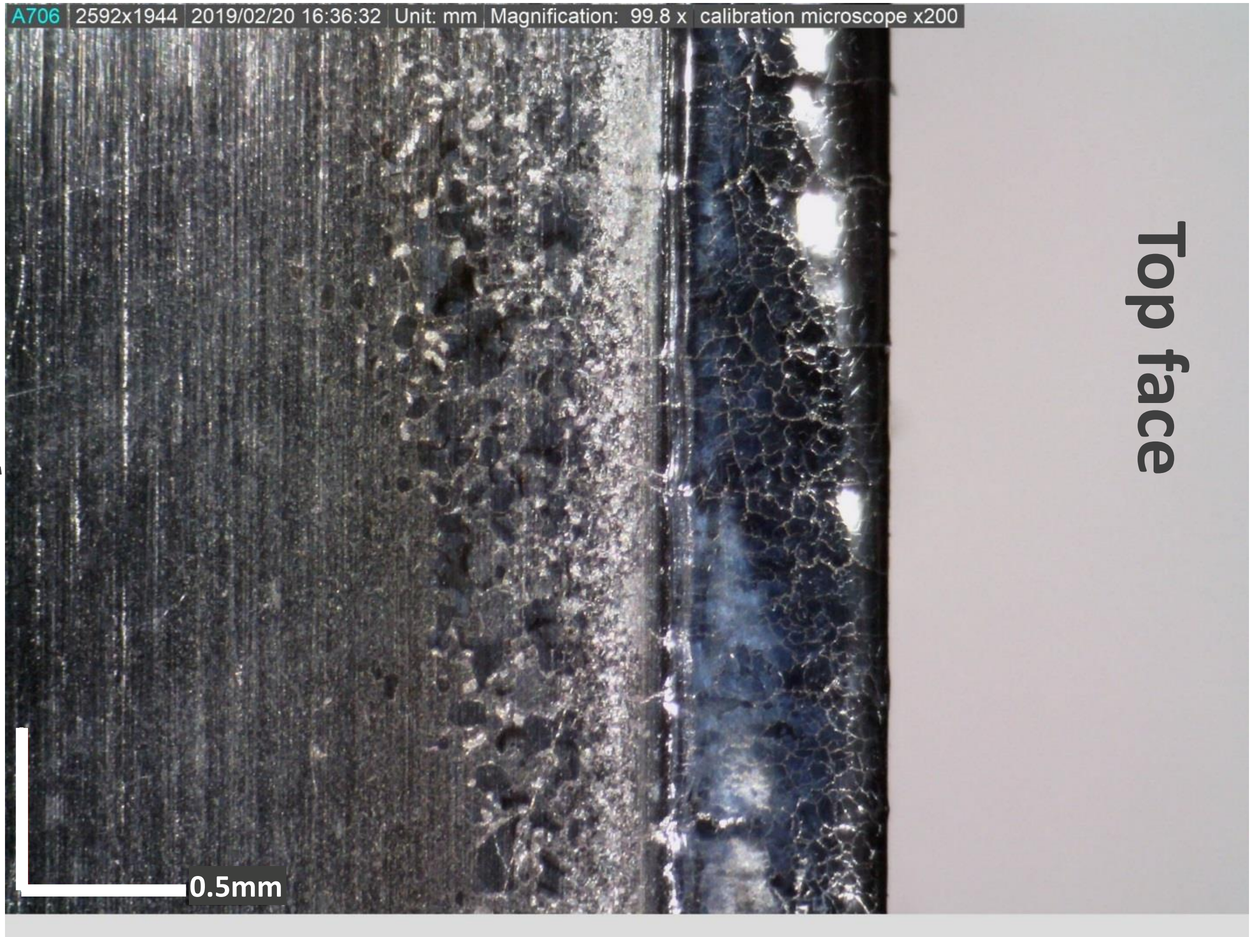


- Crack network well developed near the top surface
- Melting along the cracks

PFU #12 – damages along the edges

mb 23 – left edge - exposed side at the outer strike point

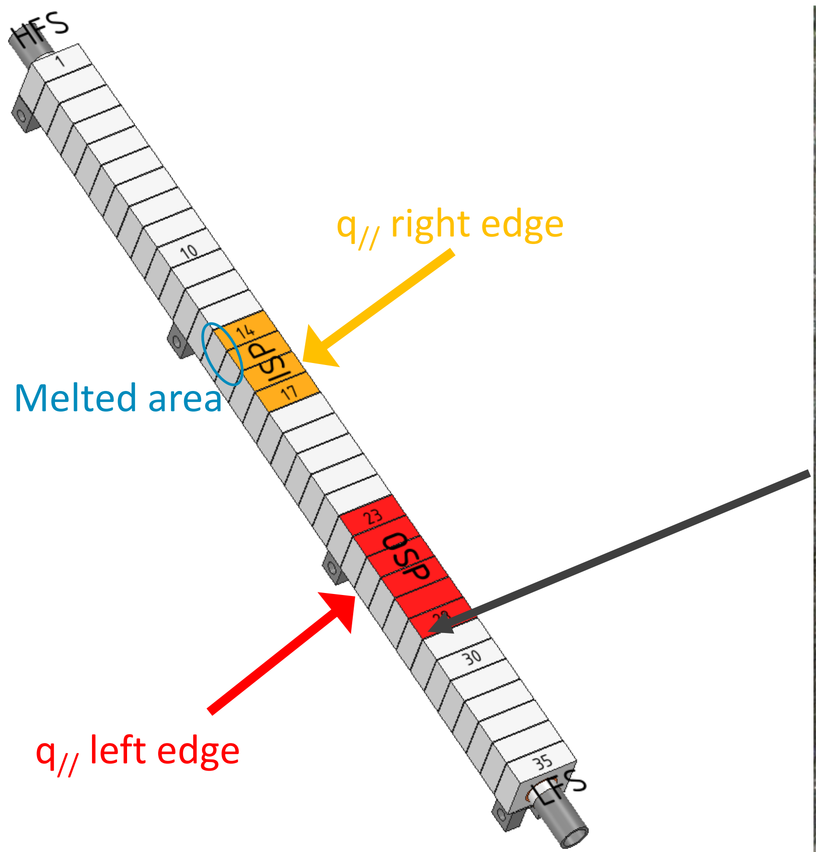


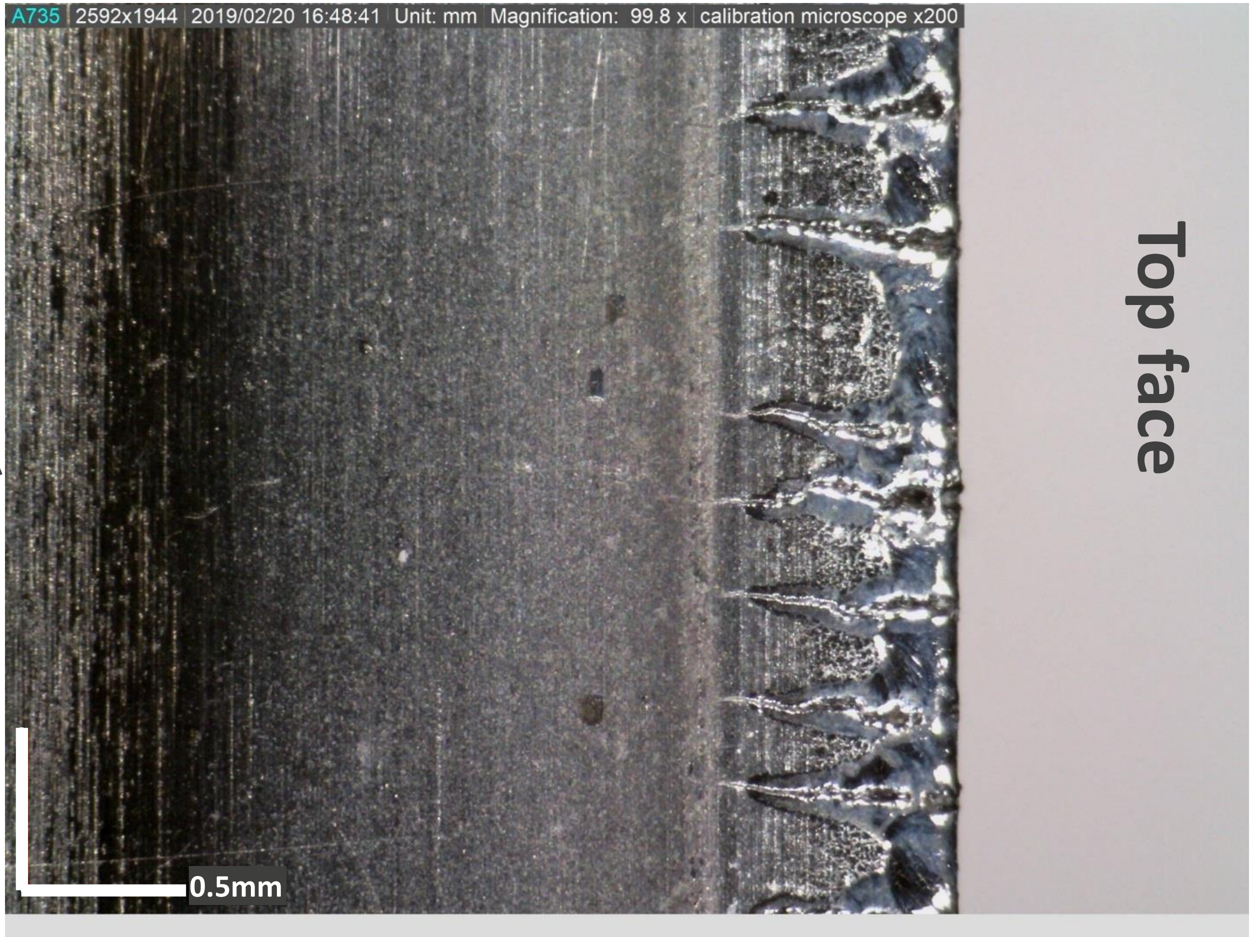


- Crack network well developed in the thickness
- Structural modification deeper than 2mm

PFU #12 – damages along the edges

mb 28 – left edge - exposed side at the outer strike point

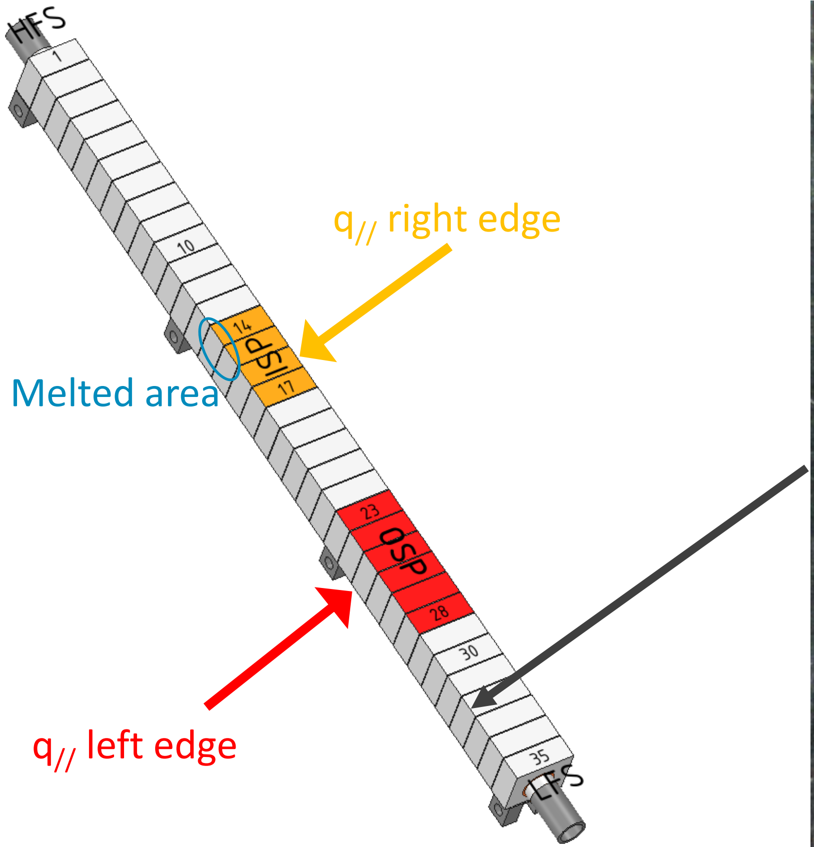




- Crack network well developed in the thickness
- Melting along large cracks

PFU #12 – damages along the edges

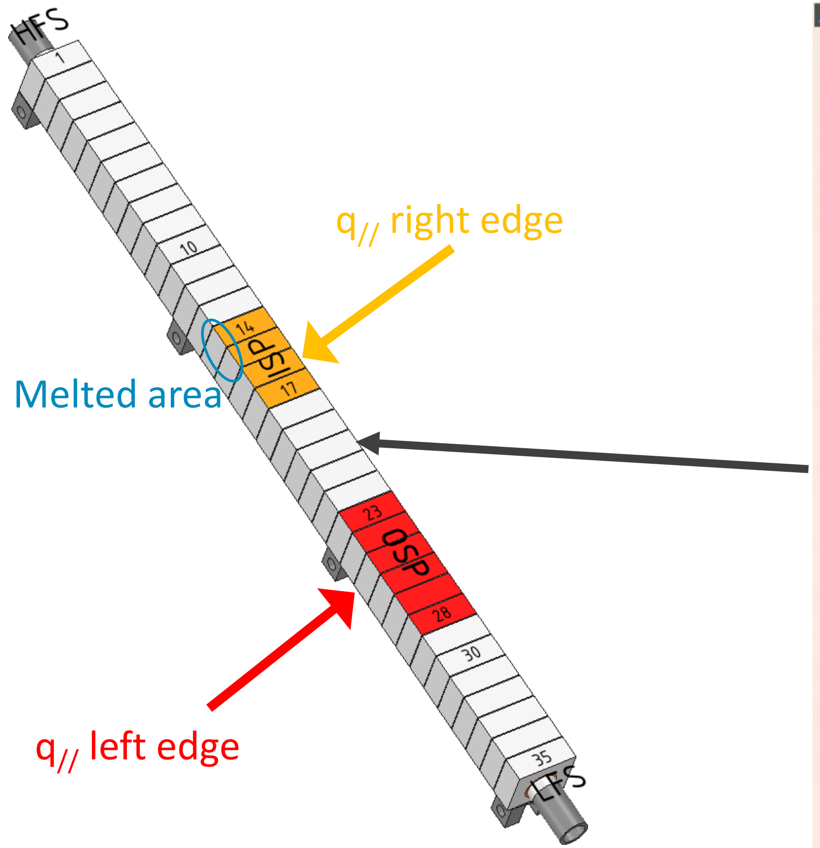
mb 32 – left edge - exposed side far from the outer strike point

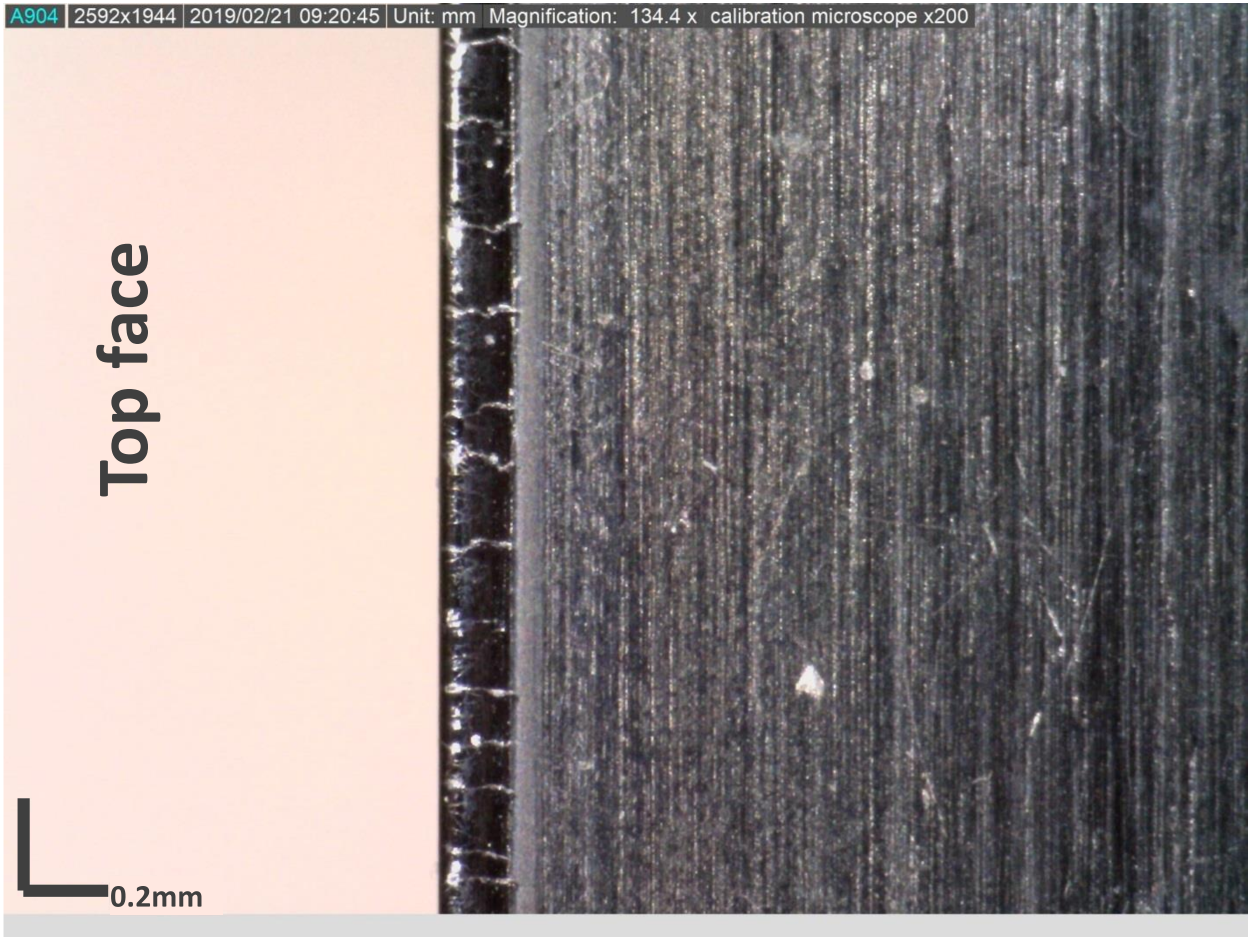


- Regular thin cracks visible

PFU #12 – damages along the edges

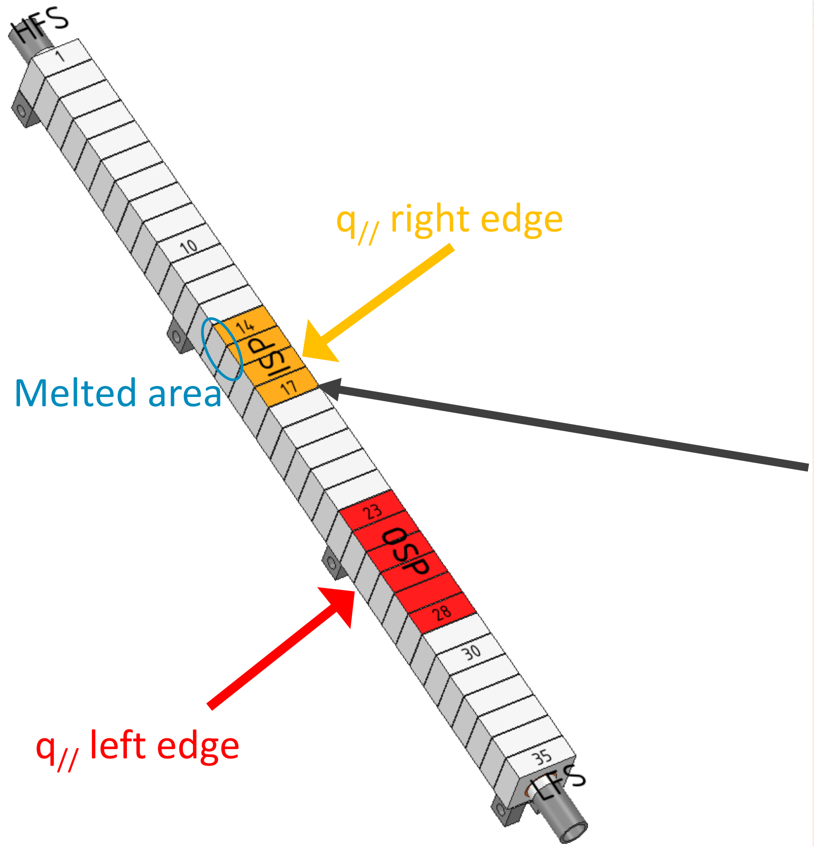
mb 20 – right edge – non exposed side

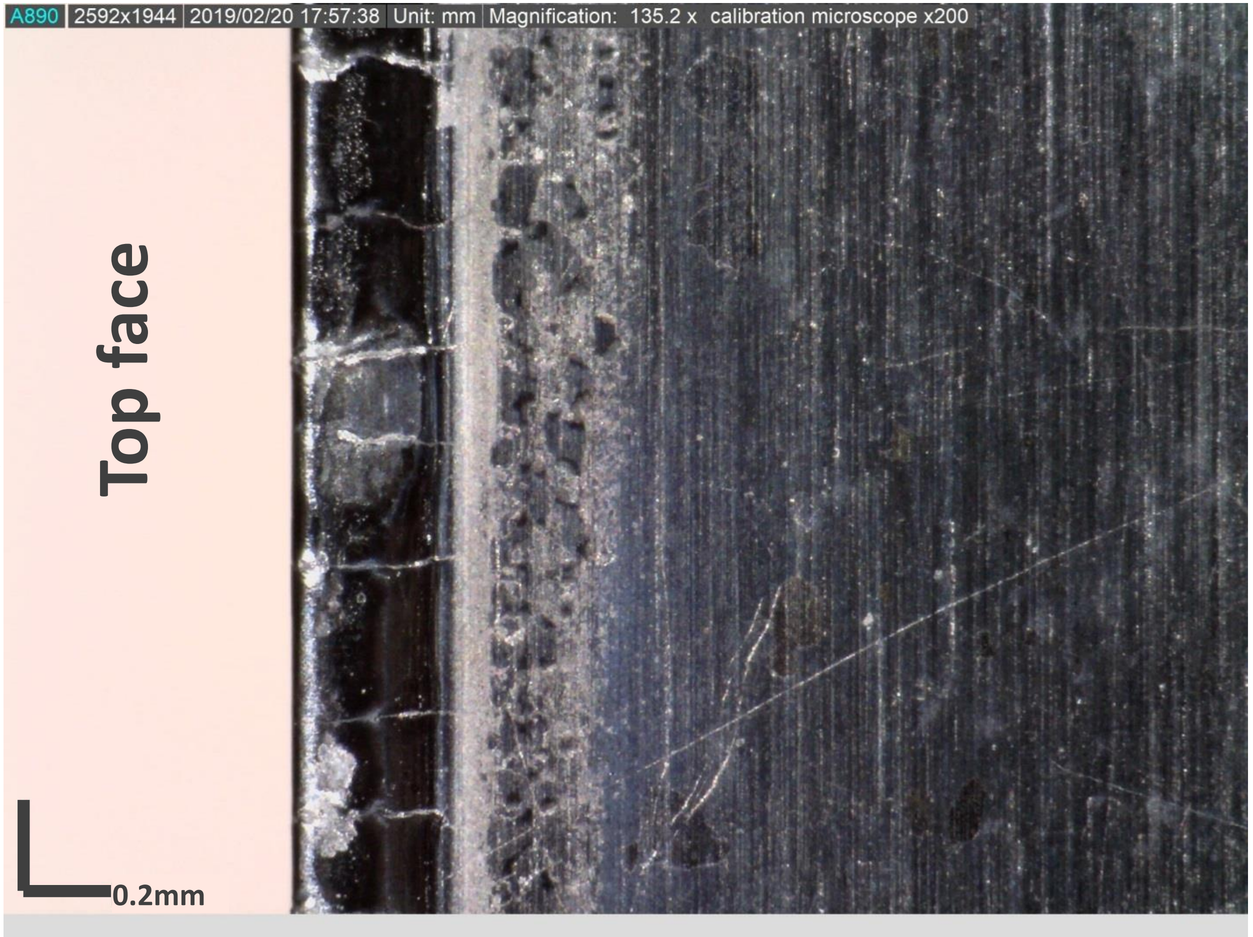




- Regular thin cracks visible with melting

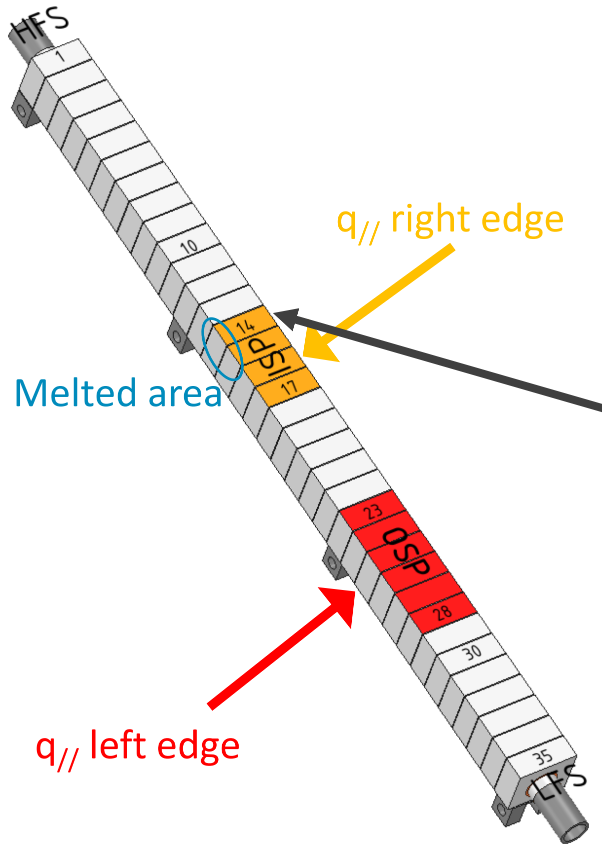
mb 17 – right edge – exposed side at the inner strike point near the melted area

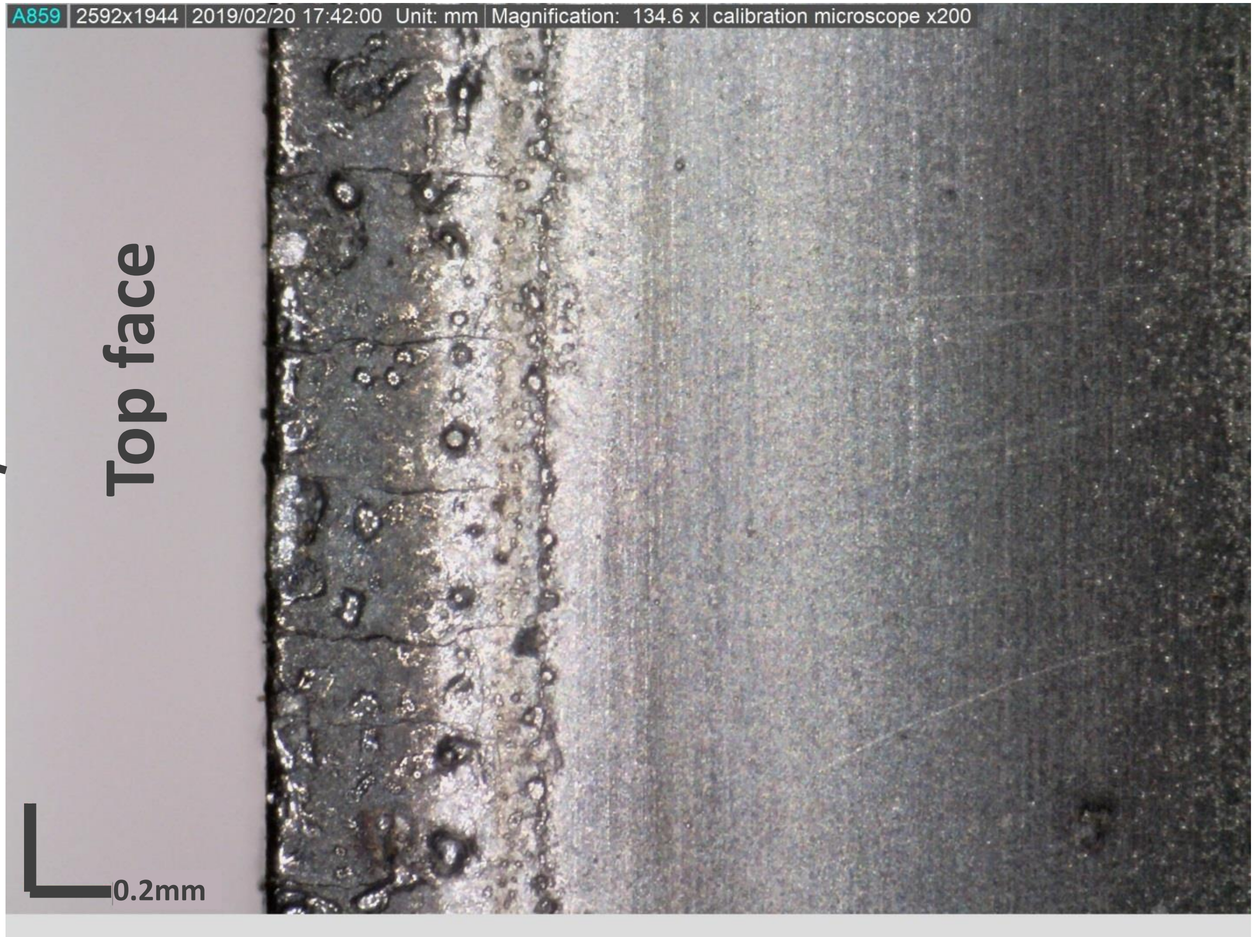




- Regular thin cracks visible with melting
- Missing material

mb 14 – right edge – exposed side at the inner strike point near the melted area

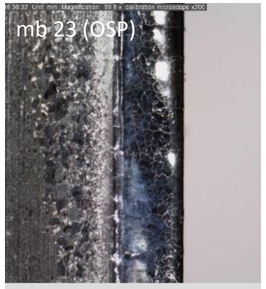


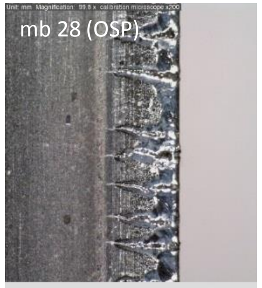


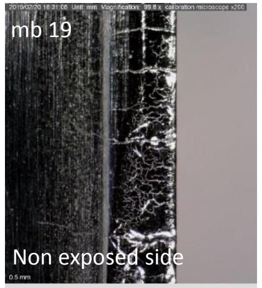
- Regular thin cracks
- Many droplets

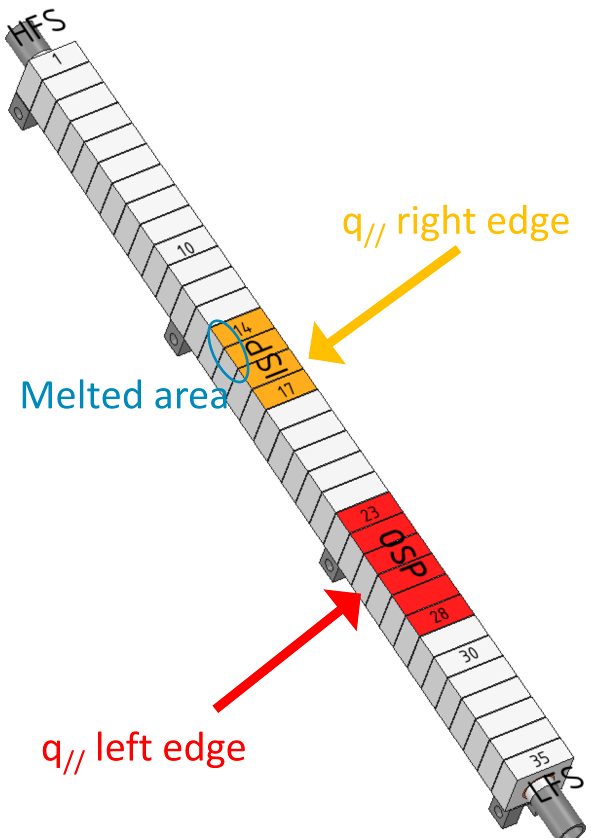
PFU #12 – damages along the edges

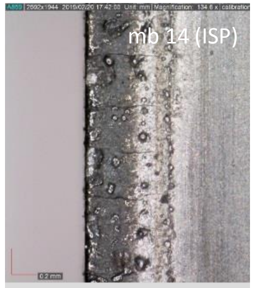
Misalignment responsible for cracks, melting and droplets

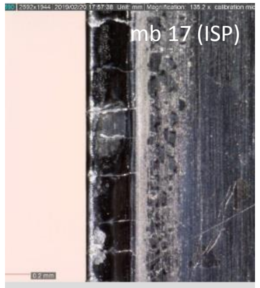


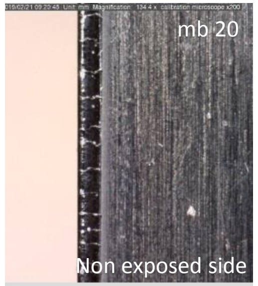












- Cracks and small melting visible on 2/3 of the PFU (mb 11 to 32)
- Important damages at the non exposed side (heat flux higher at the OSP than ISP)

- Cracks and small melting visible on 1/3 of the PFU (mb 7 to 20)
- Few damages at the non exposed side (heat flux lower at the ISP than OSP)

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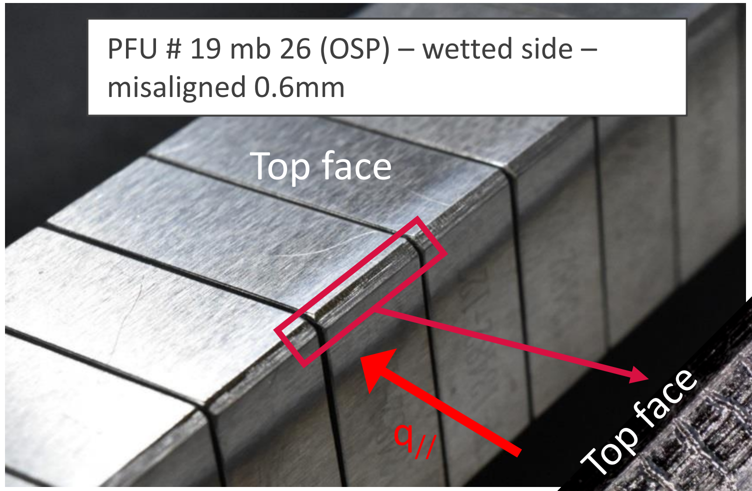
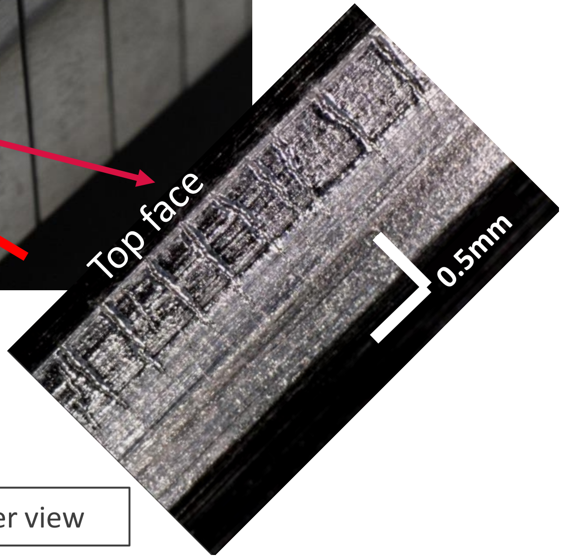
Damages on misaligned chamfered PFU

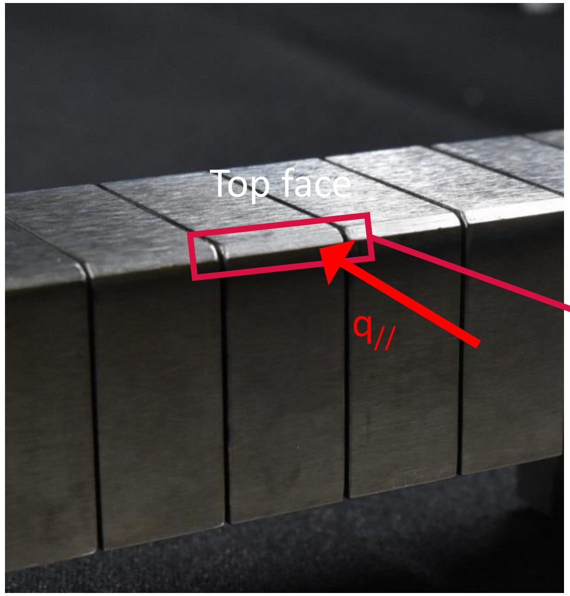
Cracks and melting are also observed on chamfered PFUs

PFU # 19 mb 26 (OSP) – wetted side – misaligned 0.6mm

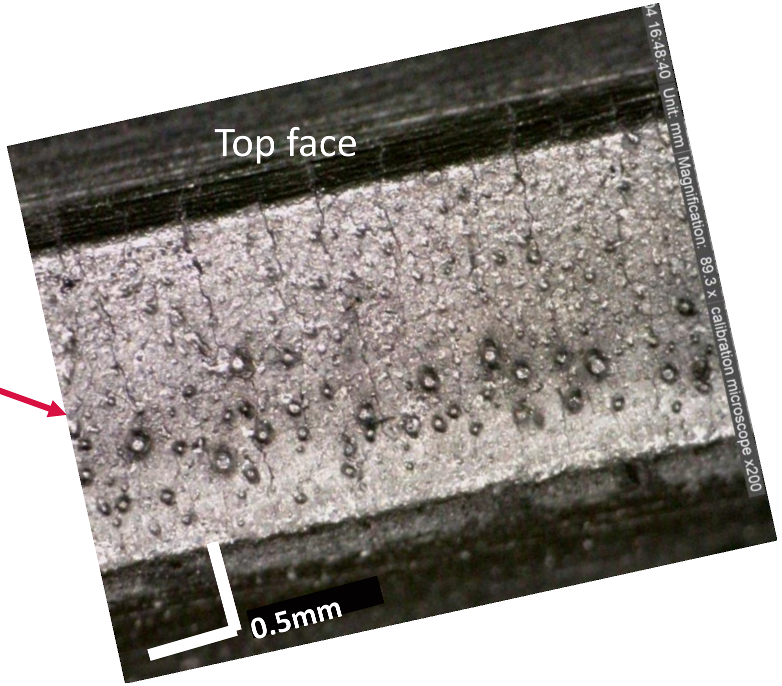




PFU # 19- mb 26 (OSP) Chamfer view



PFU # 20 mb 15 (ISP) – wetted side – misaligned ~1.0mm



PFU # 20 mb 15 (ISP) Chamfer view

- Same type of damages on different locations, on chamfered PFU
- Chamfer not sufficient to prevent damages for significant misalignment

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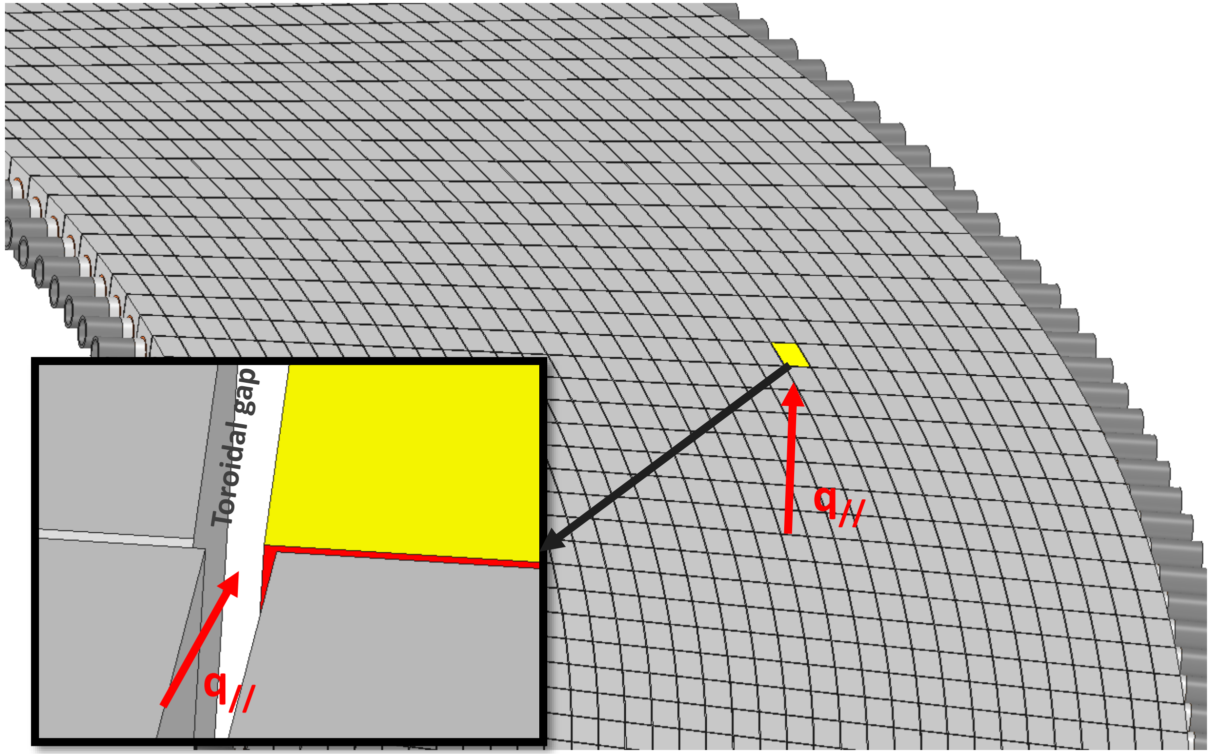
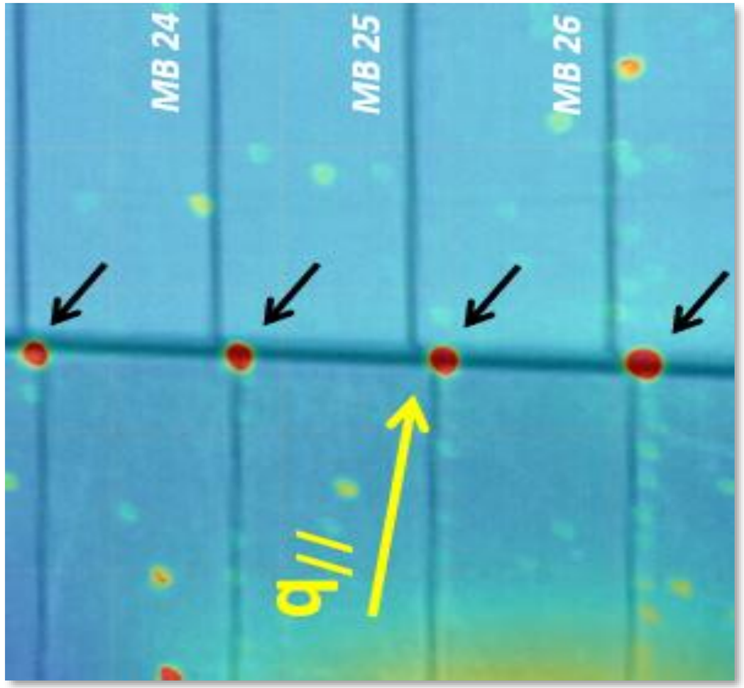
Heat flux on a toroidal face due the particles flowing in a toroidal gap

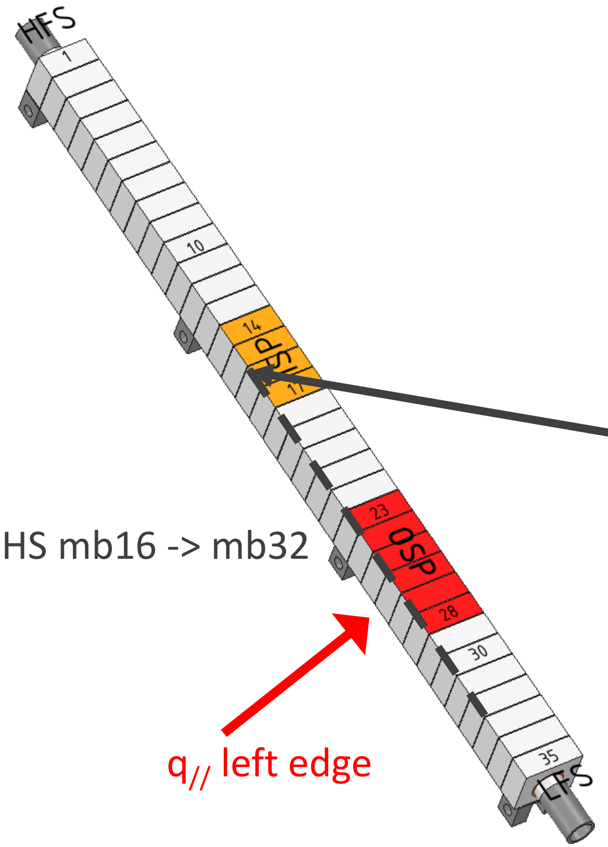




VHR Infrared image of OHS during a disruption (digital level) on PFU13 (aligned with PFU12)

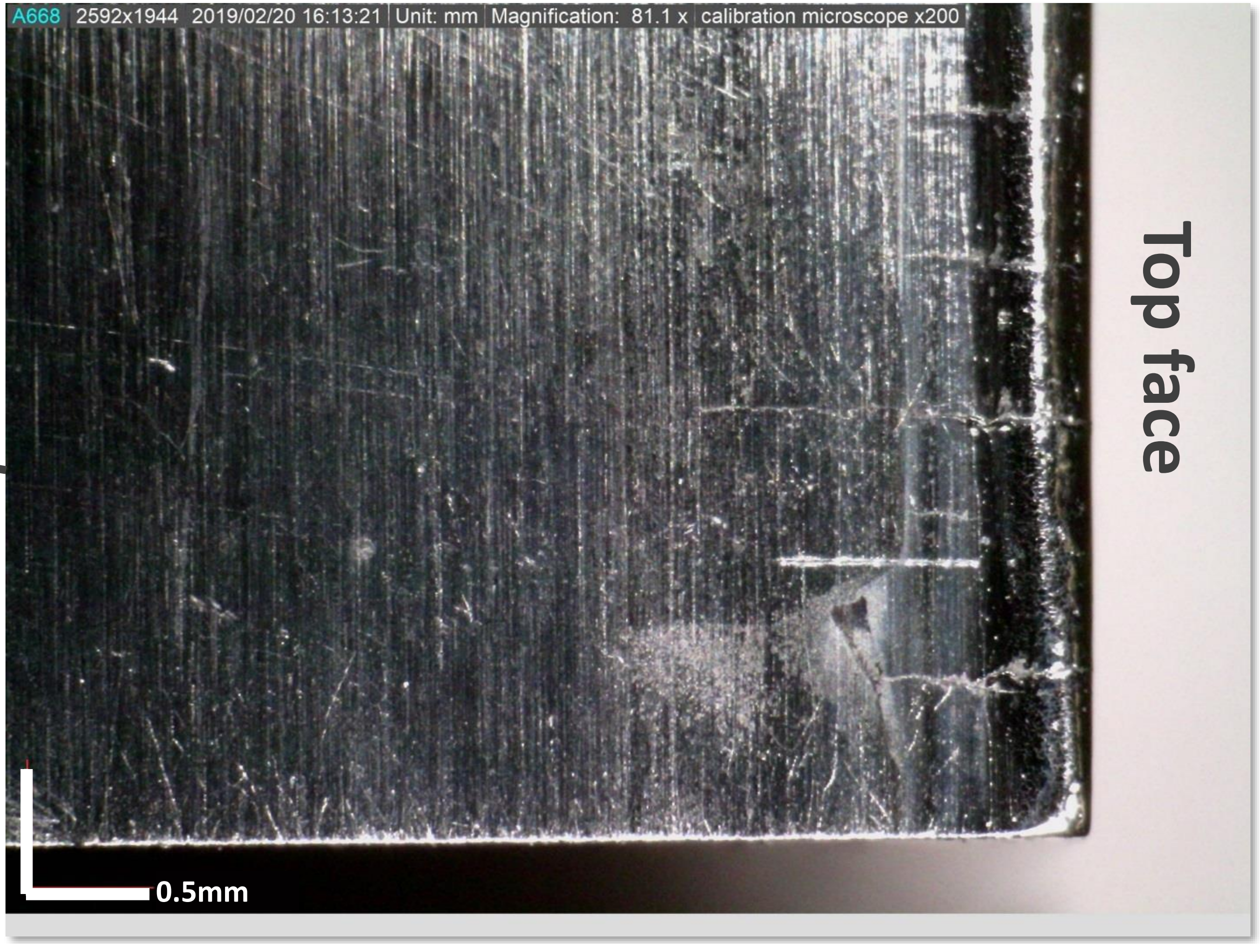
- OHS has a deep triangular shape, depending of geometry and plasma equilibrium
- OHS observed for perfectly aligned PFU on the corner or on the face
- Simulations have shown that the thermal response of W monoblock to OHS can be an issue for ITER, during ELMs and transient (*Surface heat loads on the ITER divertor vertical targets*, **J. P. Gunn et al.**, 2017, Nucl. Fusion**)**

mb 16 – non exposed edge



OHS mb16 -> mb32

$q_{//}$ left edge



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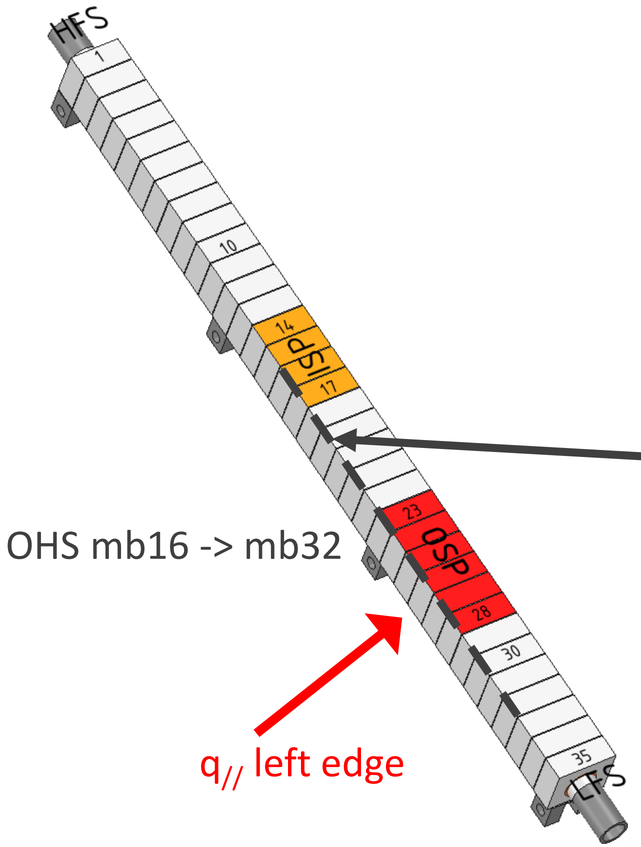
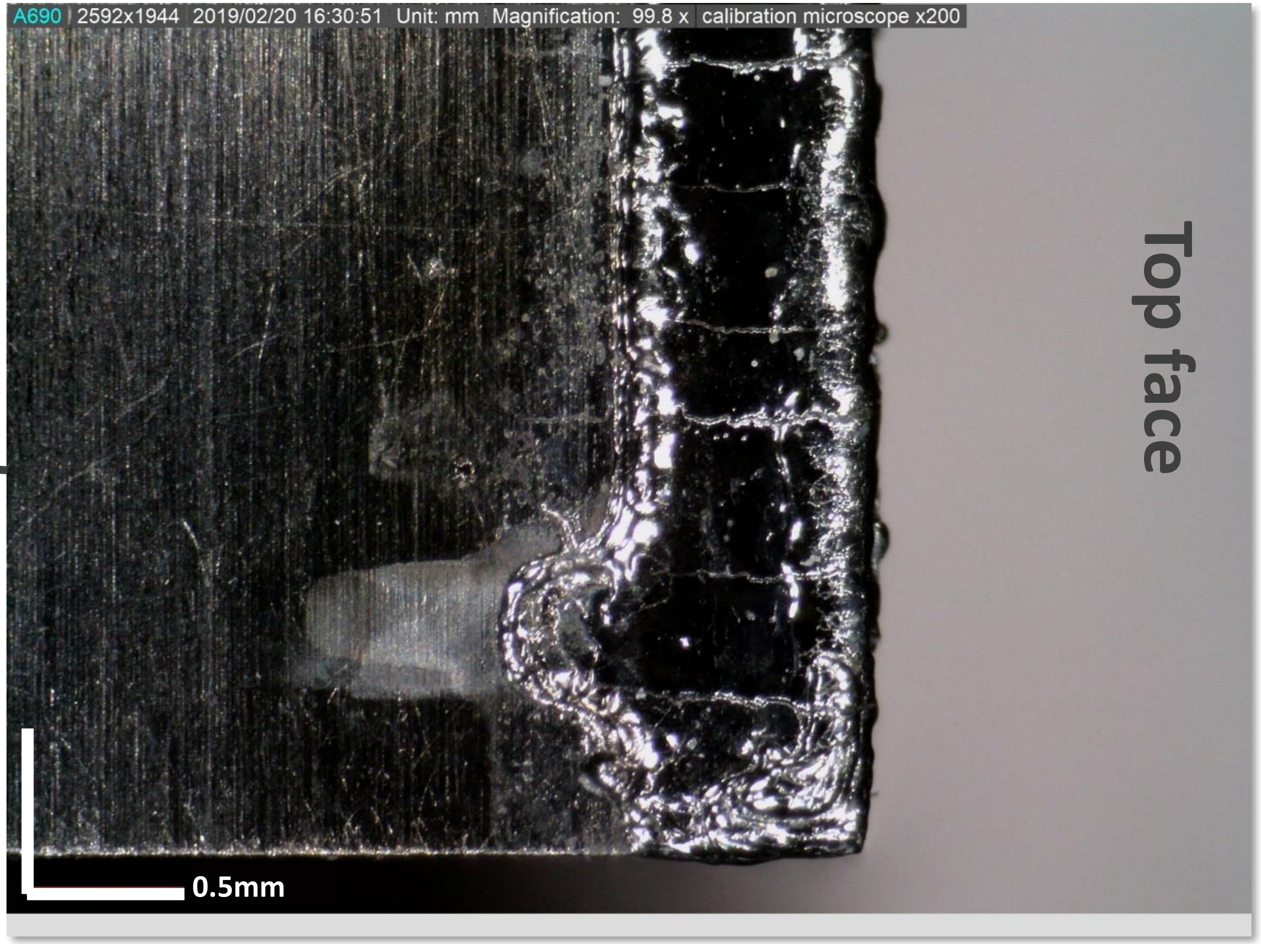
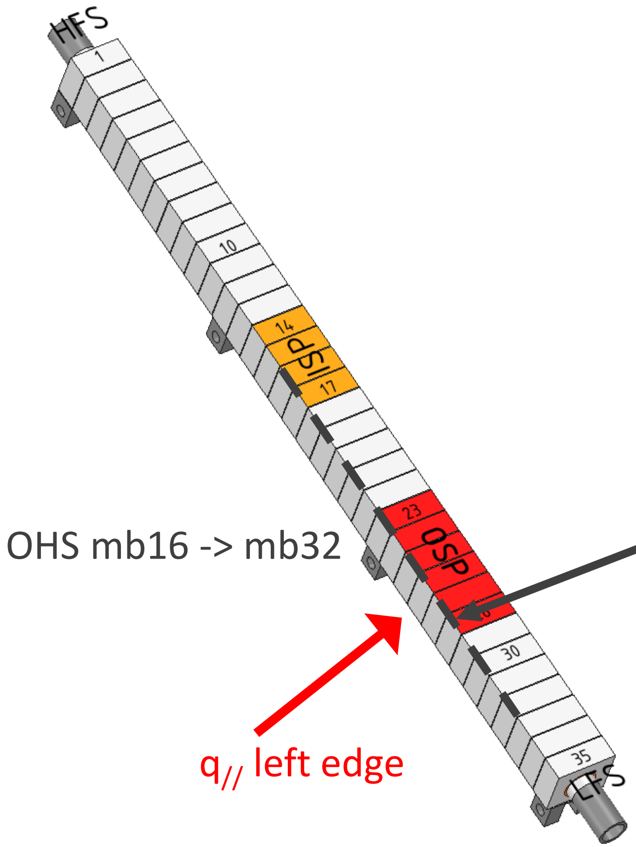
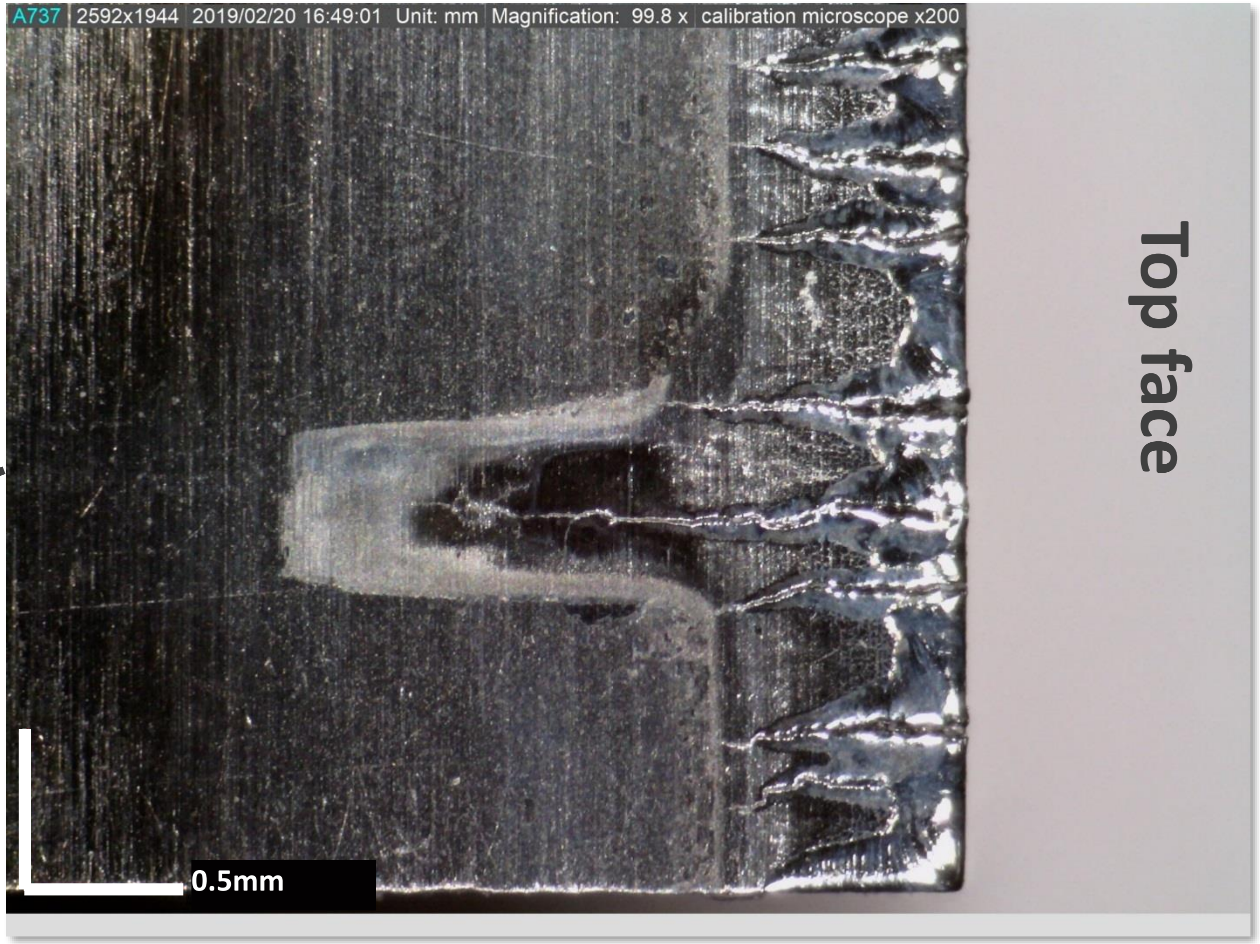


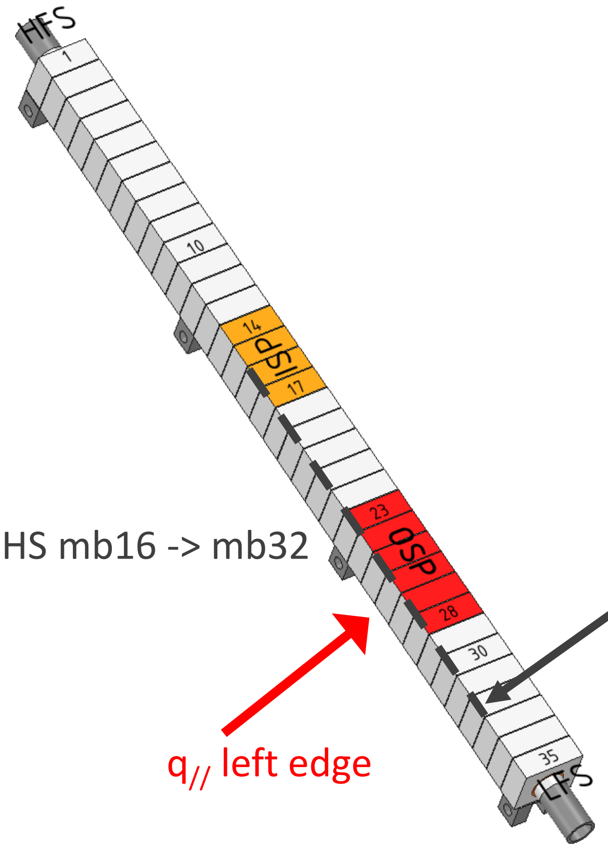


mb 28 - exposed edge at the outer strike point



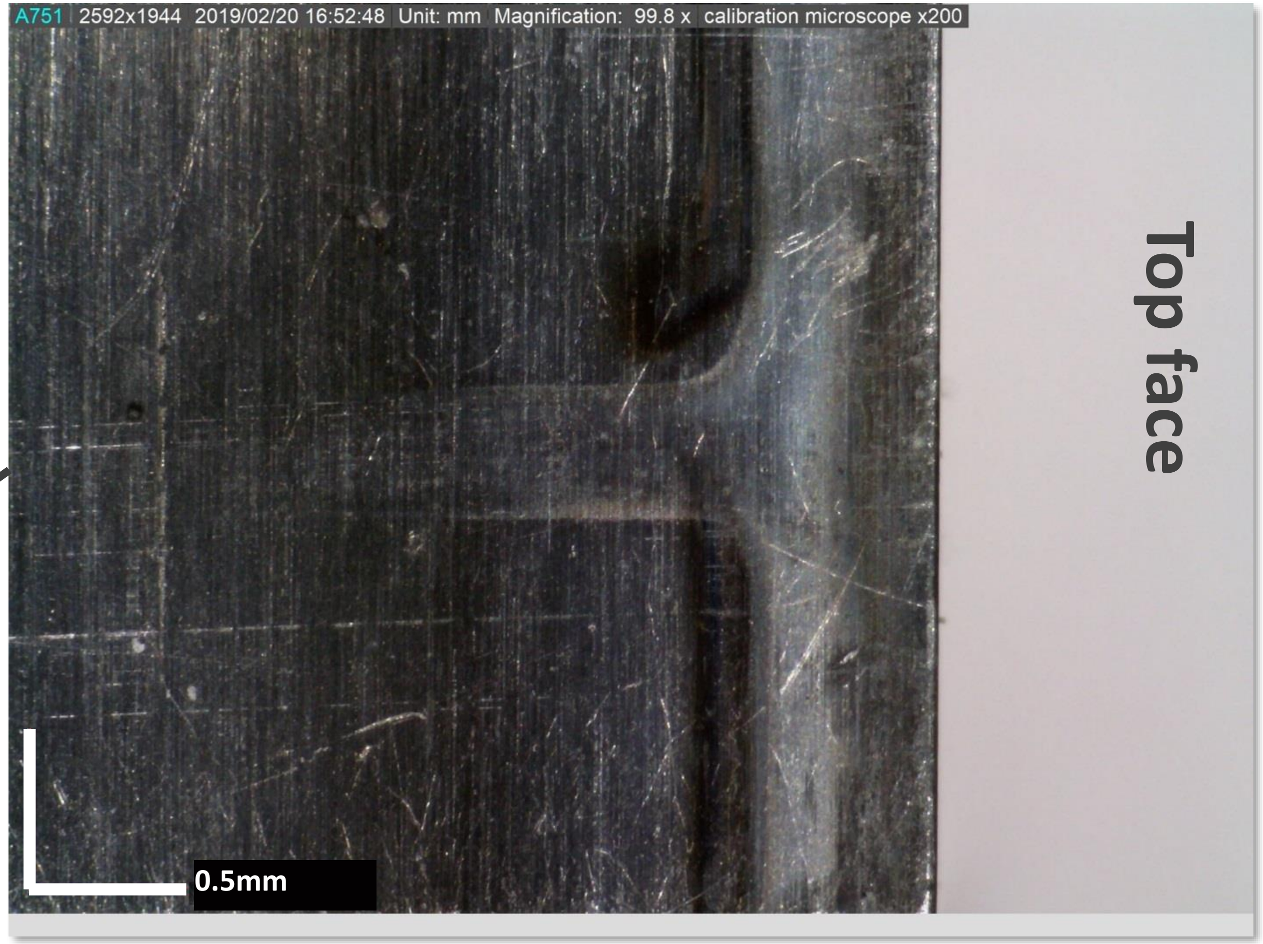


mb 32 - exposed edge far from the outer strike point

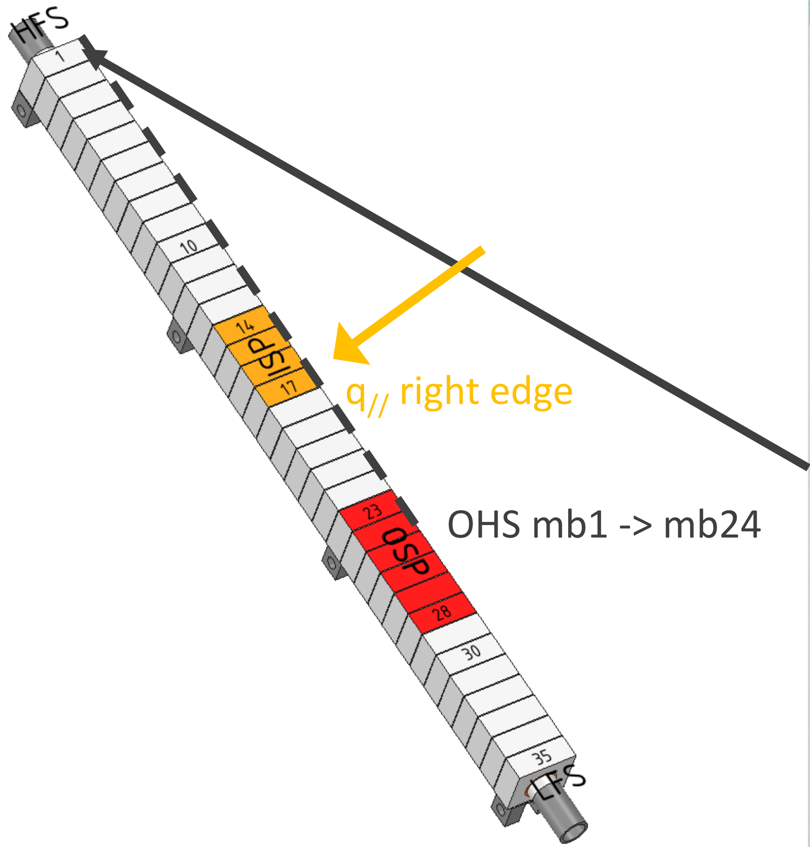


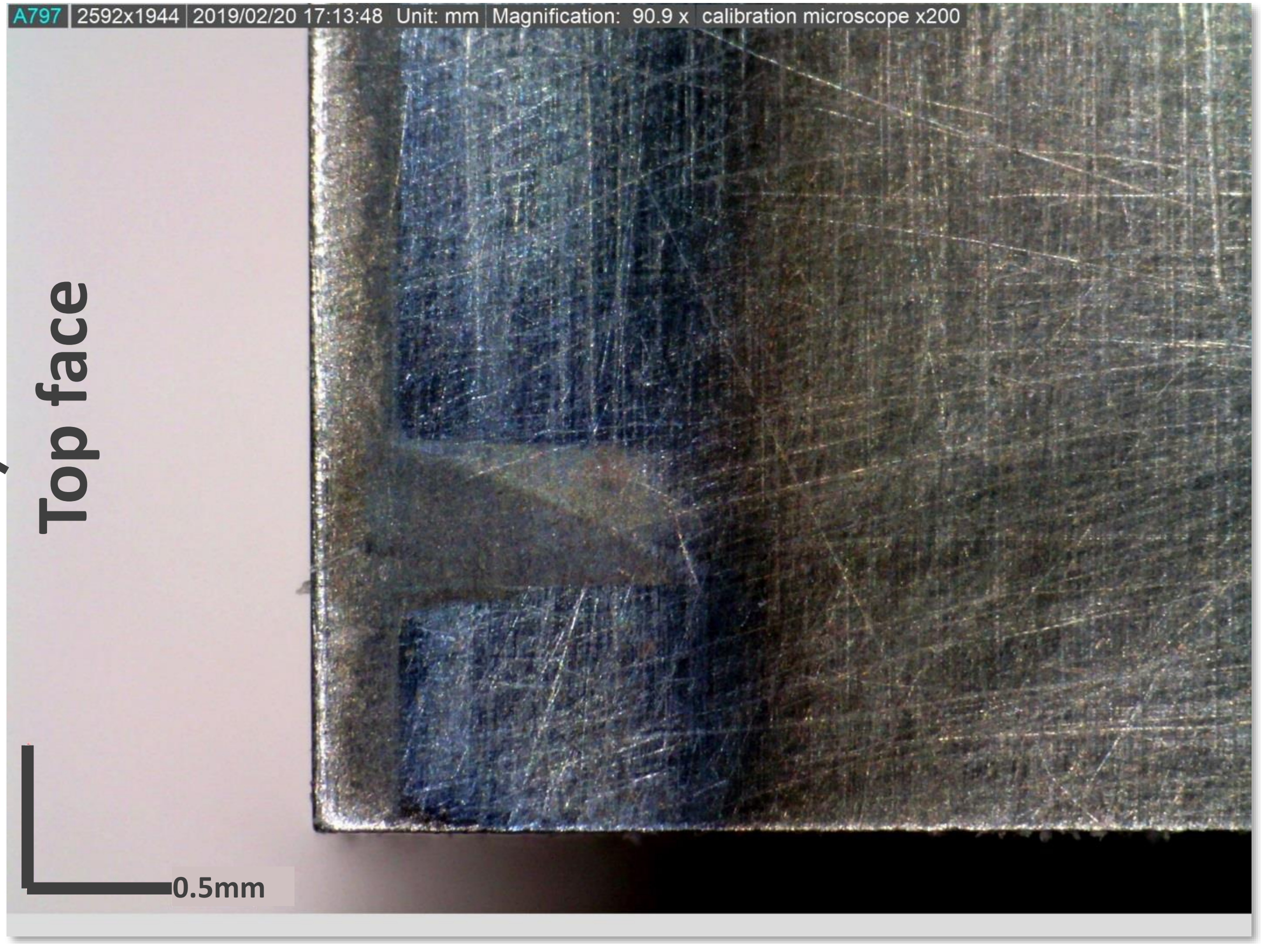
OHS mb16 -> mb32

$q_{//}$ left edge

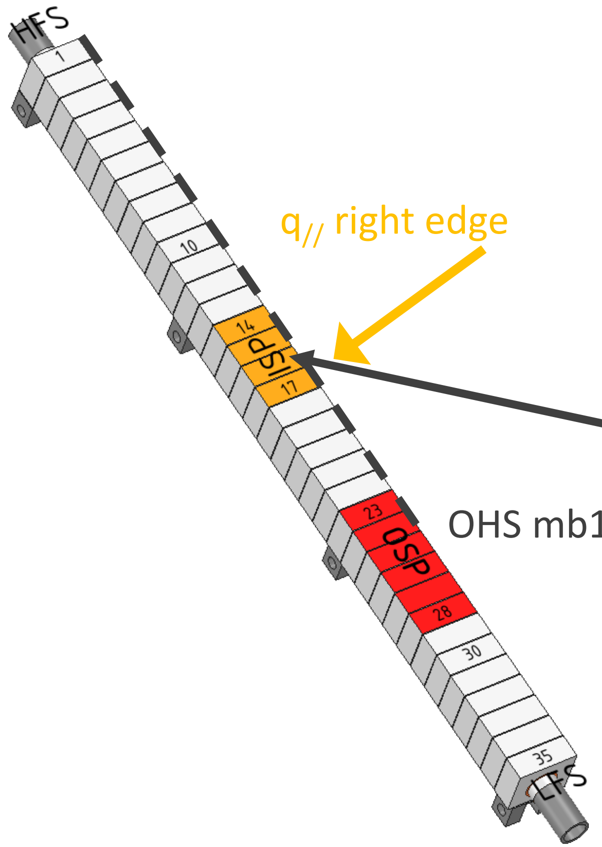


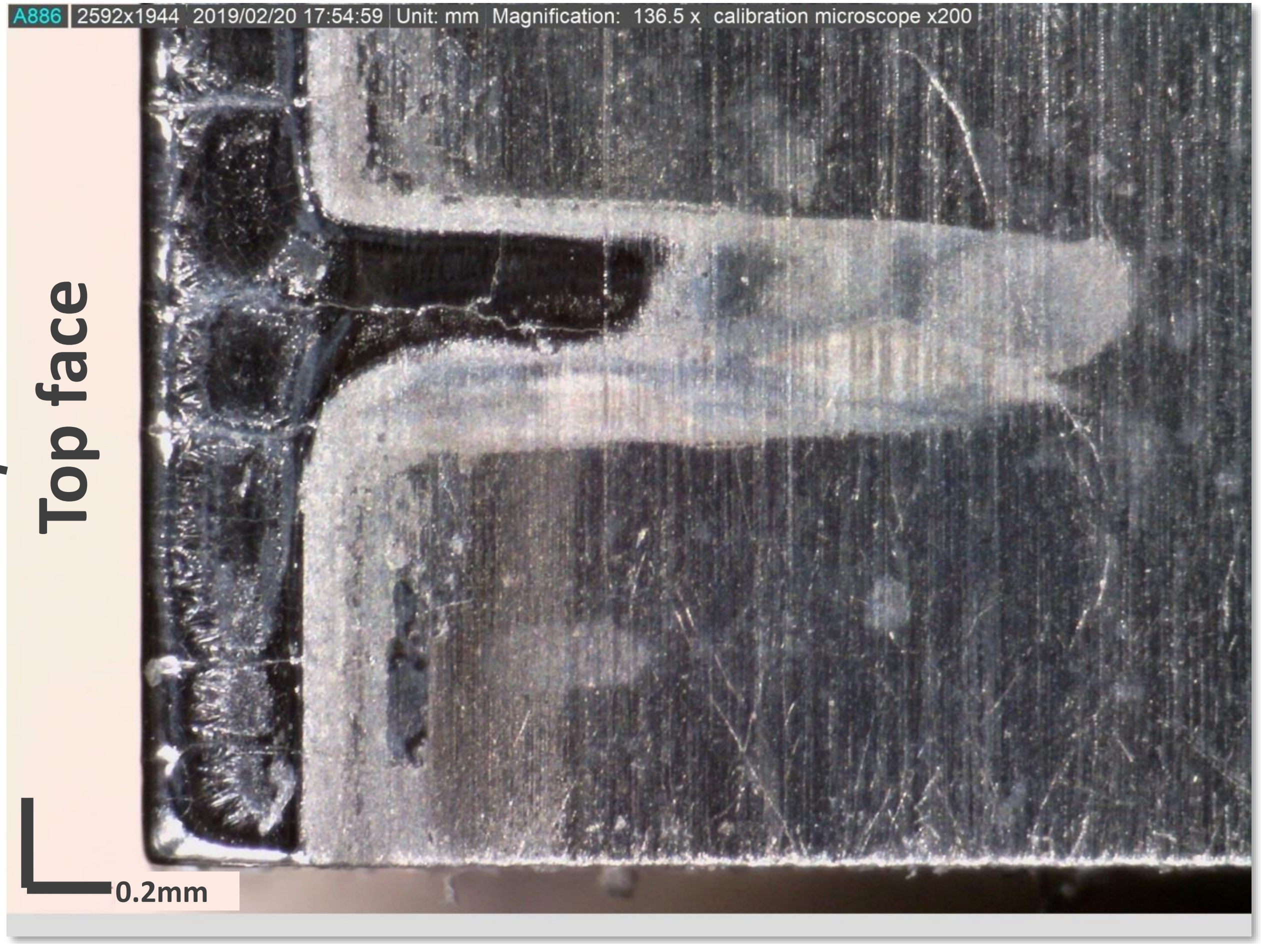
mb 1 - exposed edge far from the inner strike point





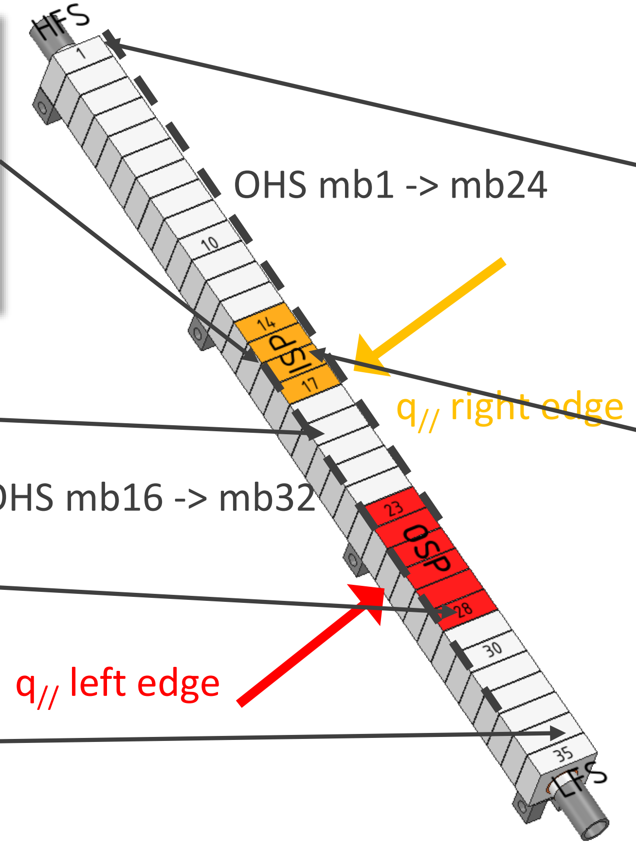
mb 16 - exposed edge at the inner strike point

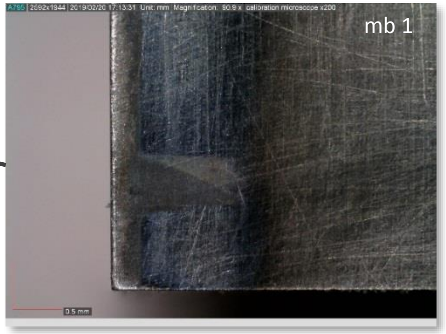


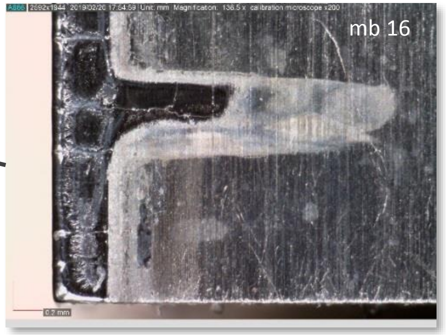


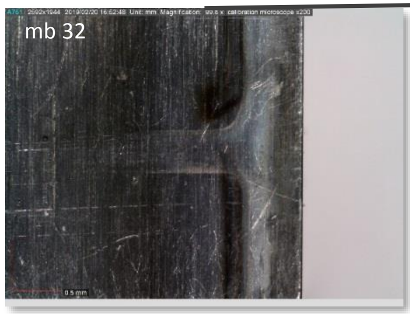
PFU #12 - Evidences of OHS after operations

OHS visible all along the plasma exposed edge, cracks near the strike points







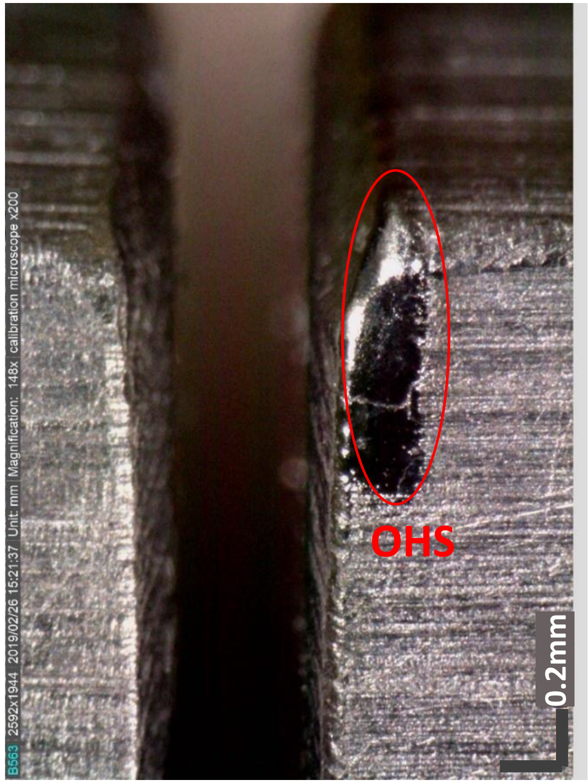


- OHS deeper than misalignment -> exists even with perfect alignment
- Several OHS patterns:
  - Visual mark with no visible damage far from the strike points
  - Additional melting on non exposed edge (mb 19)
  - Melting and cracks up to the tip of the OHS at both strike points

OHS are visible on many locations

- PFU #8 within ITER tolerances and chamfered, but OHS with melting on a corner.

Top face



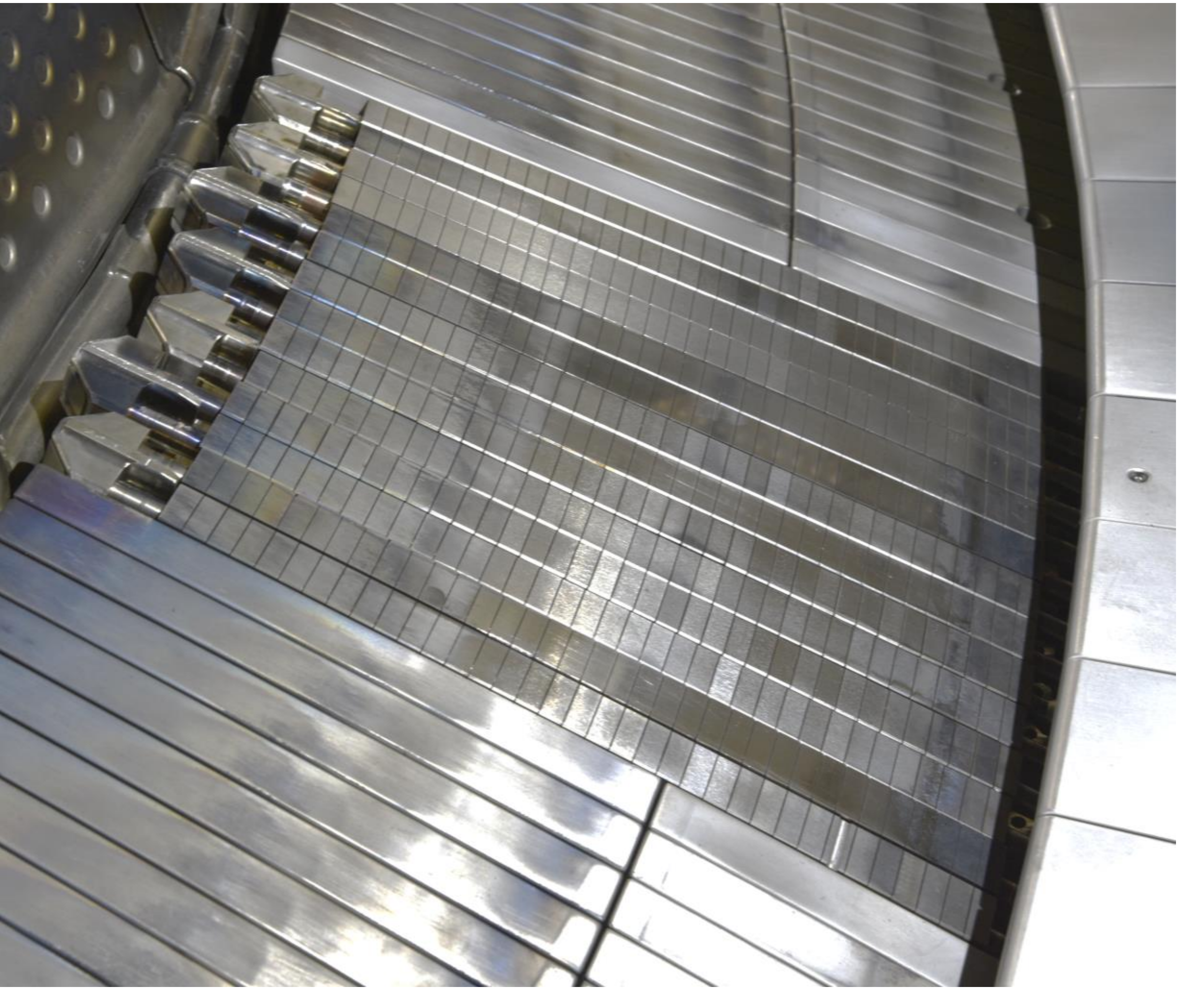
PFU # 8- MB 28 (OSP) - aligned

Summary and conclusion

Damages observed on ITER like PFU already at moderate heat fluxes in WEST

- Cracks and local melting on misaligned PFU side (both for sharp and chamfered) : damages presumably linked to transients outside strike
- Defining PFU misalignment tolerances to constrain the manufacturing and assembly process is required, as specified for the ITER divertor design. This has a consequence on cost and delay.
- Optical hot spots and subsequent damages are observed, even for PFU aligned within specs. They can not be avoided for the current design.

- **Operation not impacted by damages up to now (only 12 ITER like PFU, L-mode operation)**



C4 campaign (July - mid-November) – on-going

- 14 ITER-like PFU installed (from all potential ITER divertor suppliers)
- PFU aligned within ITER tolerances (0.3 mm)
- Damage propagation due to He/D campaign will be monitored
- Increased power up to 100MW/m² (parallel heat flux)

Medium – long term

- **Impact of operating a large number of ITER like PFU on plasma performance : WEST phase 2 in S2 2020**
- **On-going modelling, mandatory to understand the physic of heat loads inside the gaps for next steps fusion devices**

Thank you for your attention