Primary and secondary damage of limiter tiles in FTU induced by runaway electrons

ISTITUTO PER LA SCIENZA E TECNOLOGIA DEI PLASMI
Consiglio Nazionale delle Ricerche

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WIP, Frascati 15/09/2025

ENEA ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT
ICMATE Istituto di Chimica della Materia Condensata e di Tecnologie per l'Energia
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Outline of the presentation

- Background.
- *Primary local* damage induced by RE beams.
- *Secondary non-local* damage induced by RE beams.
- Summary, conclusions and outcomes.

Background

- RE control and mitigation have been largely investigated in the past years, not the same for the induced damage on plasma-facing components (PFCs);
- RE interaction with PFCs leads deep volumetric melting and thermal shock driving material explosions [1,2,3];
- The topic of RE-PFC interactions became prominent after the recent ITER re-baselining, which foresees that the "*Start of Research Operation*" campaign will use an inertially cooled W first wall to avoid early damage to water-cooled panels due to unmitigated disruptions and RE [4];
- Water leaks following RE-PFC interaction are a main concern in current and future devices, such as ITER and DEMO where active cooling of PFCs is planned.

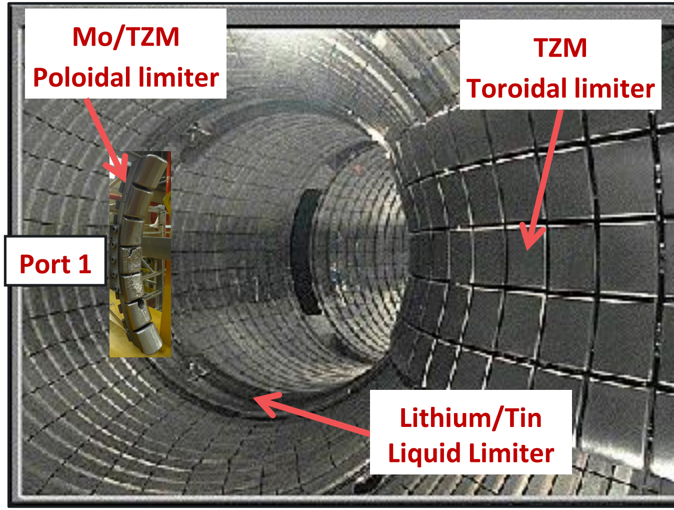
[1] M. De Angeli et al., NF Letter, 63 (2023) 014001. [2] E. M. Hollmann et al., PPCF, 67 (2025) 035020.
[3] S. Ratynskaia et al, «*Runaway electron-induced plasma facing component damage in tokamaks*", ref. to arXiv:2506.10411.
[4] R. A. Pitts et al., NME, 42 (2025) 101854.

Background

- FTU wall was kept at cryogenic temperatures with the toroidal limiter at ~ -100°C (between pulses) and ~ -70÷0°C (during discharges);

- Typical values of the RE energies and currents: 15÷35 MeV and 150÷230 kA [1], → such energies lead to deep RE penetration in the bulk of hit material;

- Typical RE termination points were: i- the midplane of the poloidal limiter [2] for outward RE beams; ii- anywhere along the toroidal limiter for inward RE beams [3,4]; iii- the liquid limiter in the bottom (when in use).



Poloidal cross-section view of the vacuum vessel.

[1] Esposito B. et al 2017 PPCF 59, 014044. [2] M. Ciotti, et al 1995 JNM 220–222, 567.

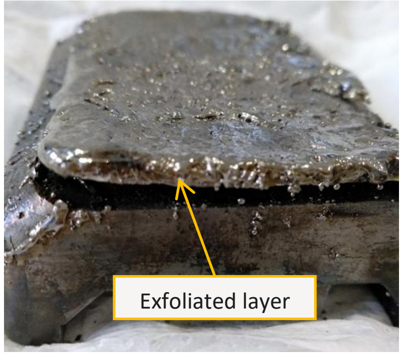
[3] G. Maddaluno, B. Basilio, 1999 JNM 266-269, 593. [4] G. Maddaluno, et al 1997 JNM 241-243, 908.

Primary localized damage induced by RE beams

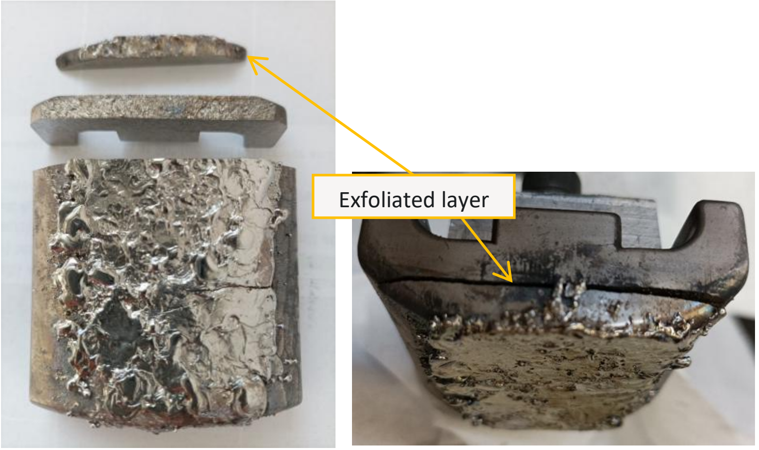
Primary localized damage by RE beams on poloidal limiter tiles

- The poloidal limiter tiles at the mid-plane were the preferred termination location of REs due to the outward shift of the RE orbit, *typically during start-up and ramp-up phases*;
- Such tiles were the primary *localized* PFCs damaged by REs;
- Observed damages: *(i) surface or deep melting; (ii) surface layer exfoliation; (iii) cracks.*

Poloidal Limiter

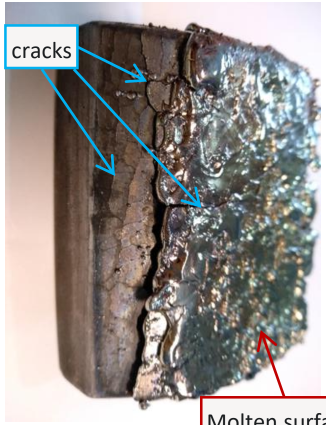


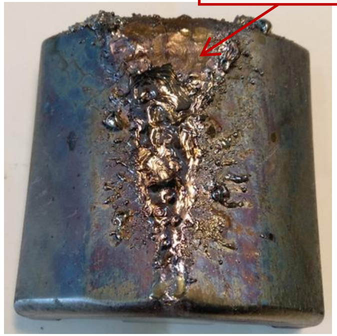
Poloidal tile, Feb-Dec 2019



Poloidal tile, Apr 2017-Feb 2019

Poloidal tile, Oct 2018-Feb 2019





Poloidal tile, Oct 2018-Feb 2019

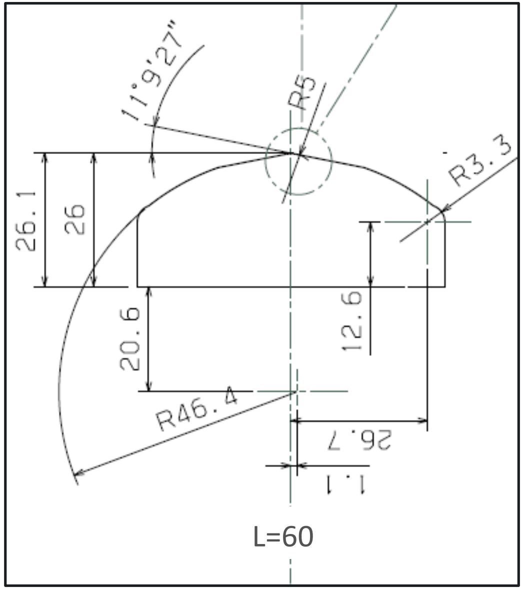
Primary localized damage by RE beams on poloidal limiter tiles

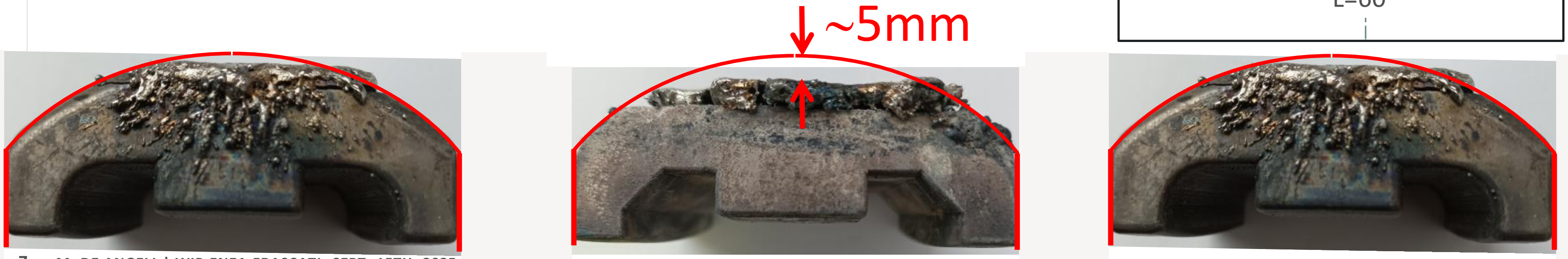
Material loss:

The side view of the equatorial poloidal tiles reveal several material loss, up to ~5÷6 mm deep, and bulk melting compared to the original mechanical drawing.

This is the *integral* results over many experimental weeks or several experimental campaigns.

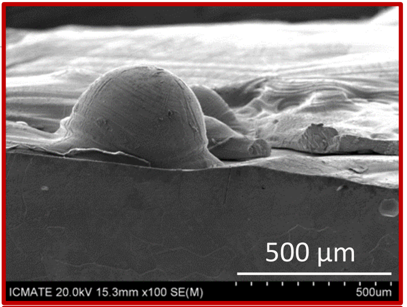
Mechanical drawing of the equatorial tile of the poloidal limiter. Measures in mm.



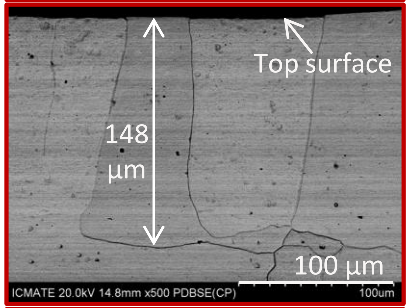


Depth profile of a damaged **poloidal limiter tile**, exfoliated flake

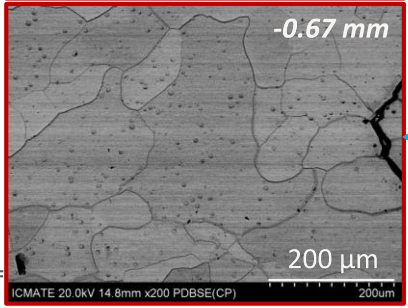
Top surface view:
molten layers



Cross-section view just below the top surface:
vertically columnar grains → *experienced melting and temperature gradient.*



Cross-section view 0.67mm below the top surface:
equiaxial grains → likely underwent recrystallization.



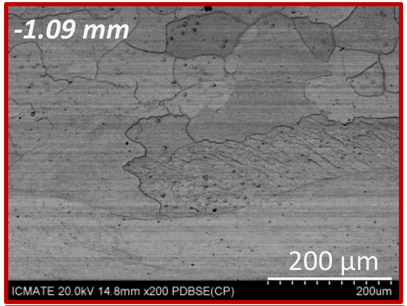
Upper piece

Thickness: 6 - 7 mm

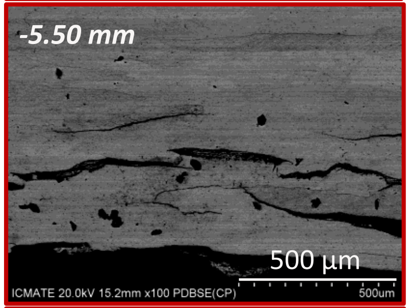
Poloidal tile, Apr 2017-Feb 2019

Apparent total damaged depth from grains size analysis: ~1200 µm.

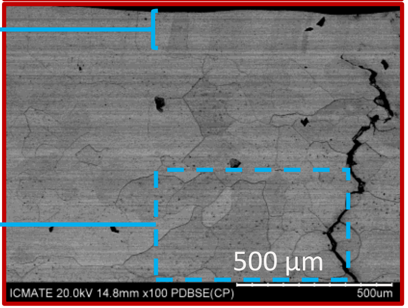
Similar results were found in EAST (C. Xuan, NME 34, 2023, 101377) and JET (I. Jepu, NF 64, 2024, 106047)



Cross-section view 1.09mm below the top surface:
horizontally elongated grains → *likely result of the manufacturing route.*



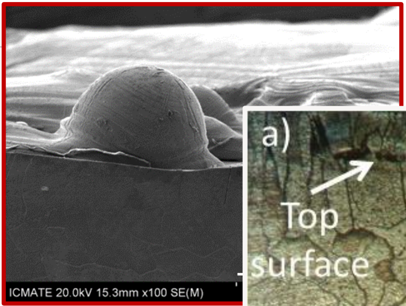
Cross-section view, bottom surface:
horizontally elongated grains and cracks → *no recrystallization but thermal fatigue.*



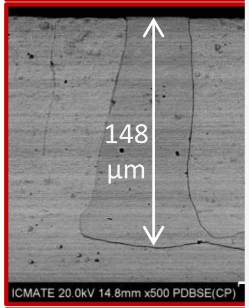
Cross-section view just below the top surface:
Example of inter-granular crack in bulk.

Depth profile of a damaged **poloidal limiter tile**, exfoliated flake

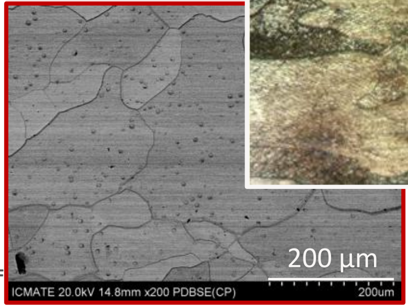
Top surface view:
molten layers



Cross-section view just below the top surface:
vertically columnar grains
→
experienced melting and temperature gradient.

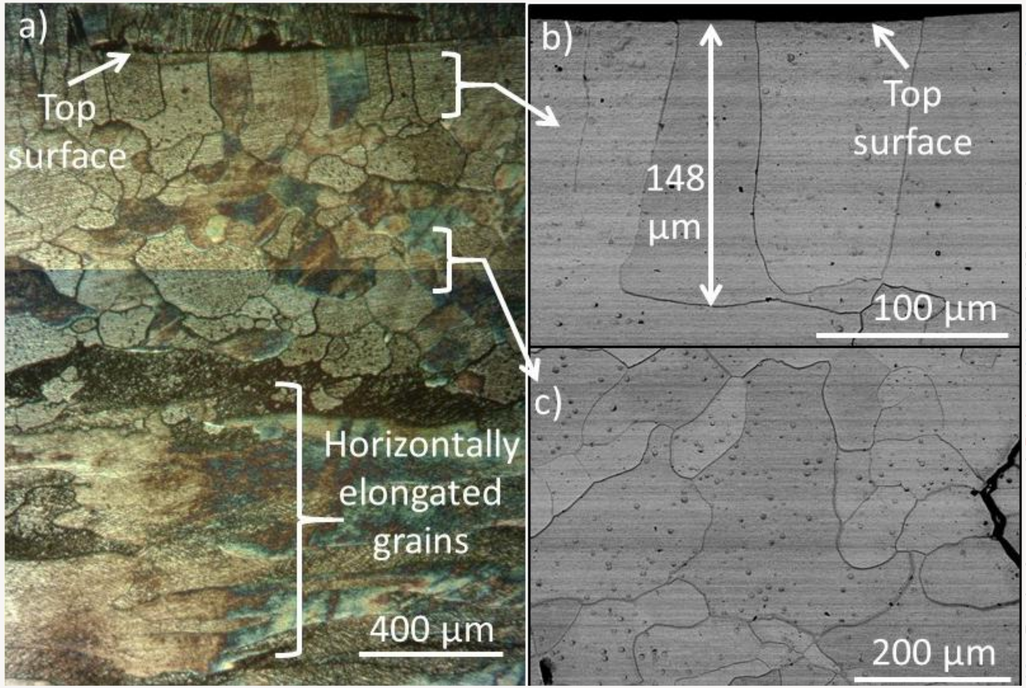


Cross-section view 0.67mm below the top surface:
equiaxial grains
→ likely underwent recrystallization.

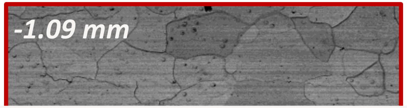


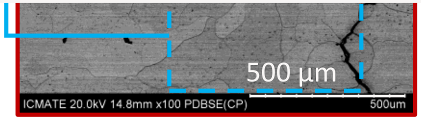
Upper piece

Thickness:



Similiar results were found in EAST (C. Xuan, NME 34, 2023, 101377) *and JET* (I. Jepu, NF 64, 2024, 106047)





Cross-section view 1.09mm below the top surface:
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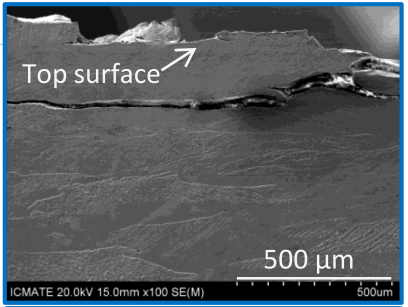
ss-section view, ottom surface:
ontally elongated and cracks → no ystallization but ermal fatigue.

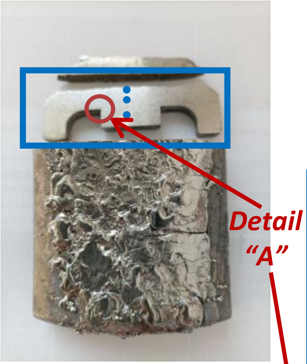
-section view just the top surface:
ample of inter-granular crack in bulk.

Depth profile of a damaged **poloidal limiter tile**, bulk flake

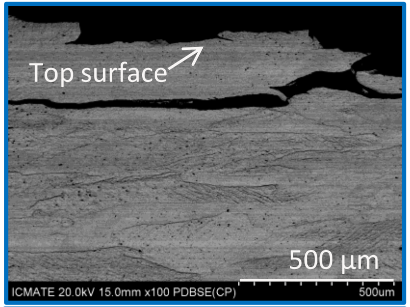
Cross-section view just below the top surface: *horizontally elongated grains (→manufacturing route) and inter-granular crack.*



Lower piece



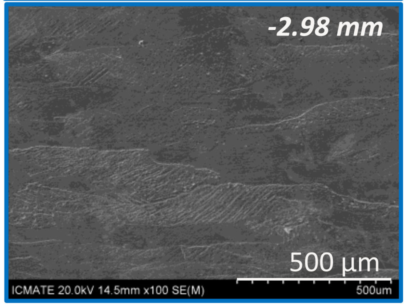
Poloidal tile, Apr 2017-Feb 2019

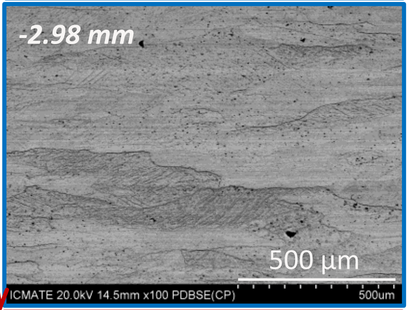


Corresponding BSE images.

Cross-section view (-2.98 mm): *horizontally elongated grains*

→ manufacturing route.

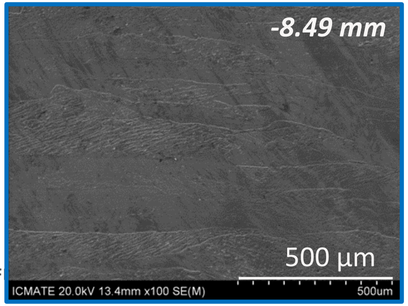




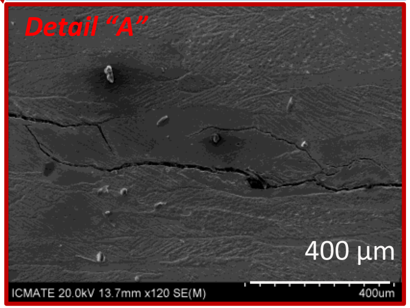
Corresponding BSE images.

Cross-section view (-8.49 mm): *horizontally elongated grains*

→ manufacturing route.



The grains structure, along the whole cross section, is almost constant → *manufacturing route.*

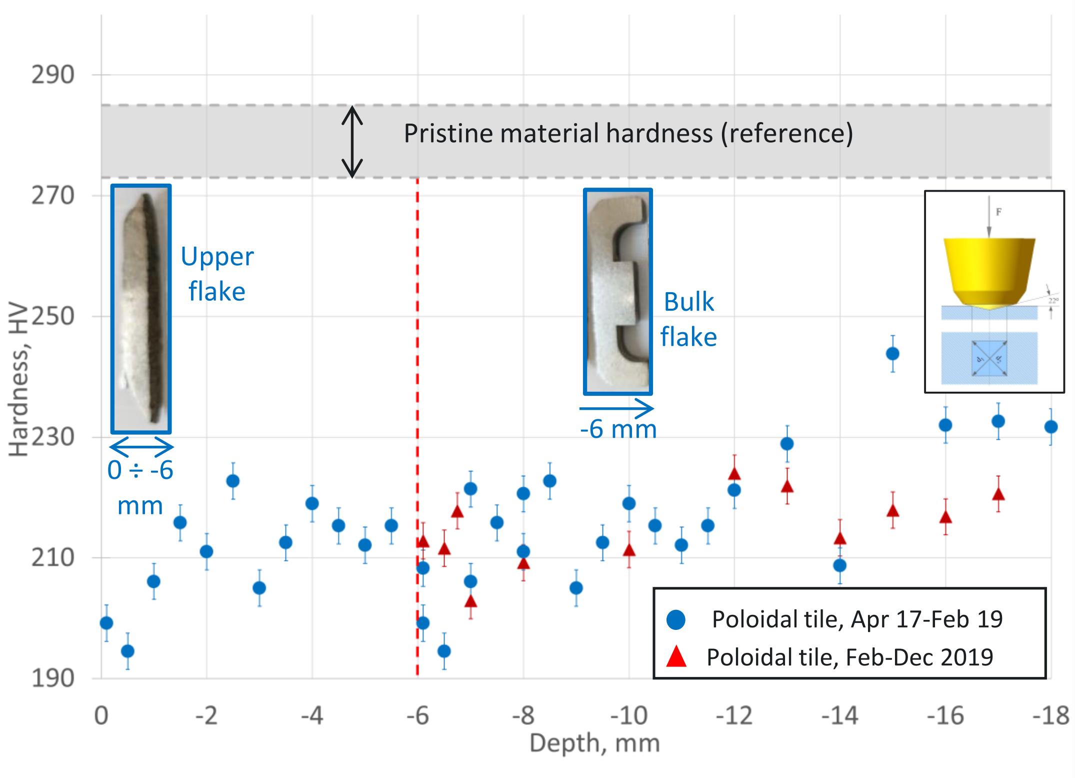


Detail "A": *few mm long inter-granular crack*

→ thermal cycles stress.

Hardness of poloidal tiles exposed to plasma & RE beams

- Carried out microhardness tests in Hardness Vickers scale ($HV_{0,2}$=200, accuracy: ±3) along cross-section profiles of poloidal tiles.
- No appreciable differences along the cross-section between upper and lower pieces.
- Degradation of ~65 HV compared to a pristine material (279±6 HV, i.e. never exposed to plasma/REs).

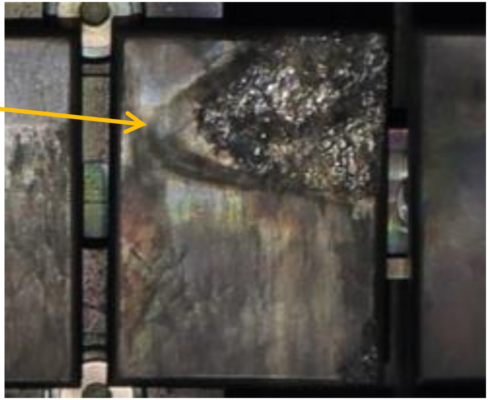


Graphic of cross-section hardness in Vickers scale for two different poloidal tiles.

Primary localized damage by RE beams on toroidal limiter tiles

- The toroidal limiter was hit by RE beams randomly along the toroidal direction, do not having any preferred termination point, by inward RE beams following some plasma disruptions [1];
- Observed damages: *(i) surface or deep melting; (ii) cracks; (iii) structural degradation of a few mm in depth.*

Toroidal tile, P8



Toroidal tile, P7-12dx

Toroidal tile, P12-n6-sx

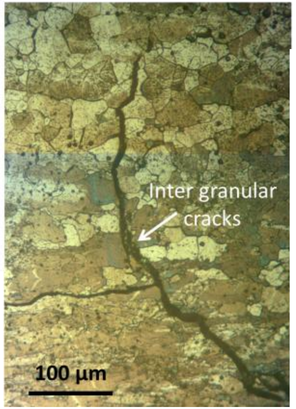
Toroidal tile, P1-09-01

This tile have been cut and SEM mapped along the depth profile, in the red line location, in the molten region.

[1] G. Maddaluno, et al 1997 JNM 241-243, 908.

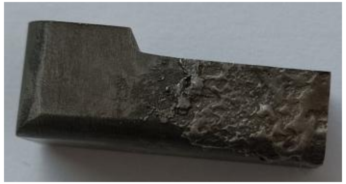
Primary localized damage by RE beam on toroidal limiter tiles

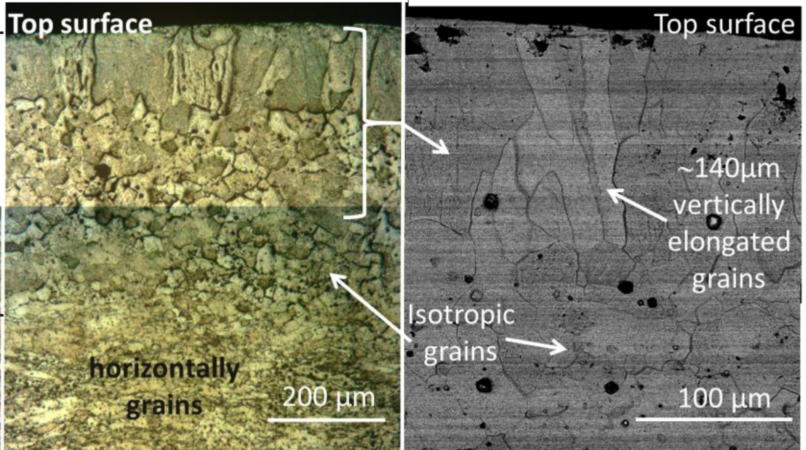
- A toroidal limiter, hit by RE beam, was cut in the molten area surface and the resulting cross-section was analysed by mean of Electron and optical microscope, and hardness test device;
- Found less pronounced structures than for poloidal tiles (i.e. vertically elongated, equiaxial, and horizontally elongated grains);
- Millimeter long intergranular cracks.



Cross section analyses of the molten area of tile P12-n6-sx.

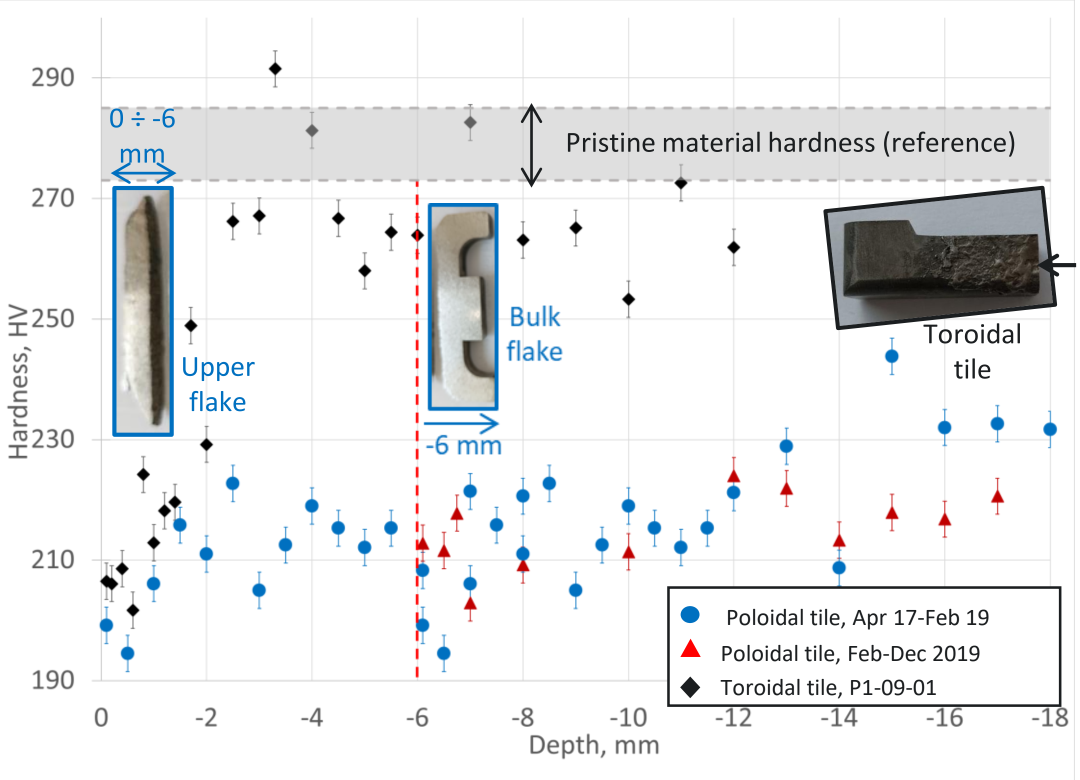
~ 600 µm





Hardness of toroidal tiles exposed to plasma & RE beams

- Carried out microhardness tests in Hardness Vickers scale ($HV_{0,2}$=200, accuracy: ±3) along cross-section profiles of poloidal and toroidal tiles.
- On the contrary of the poloidal tiles, a hardness degradation of ~65 HV was observed only in the first ~2 mm below the upper surface of the toroidal tile (maybe also due to the shallow RE beam incident angle).

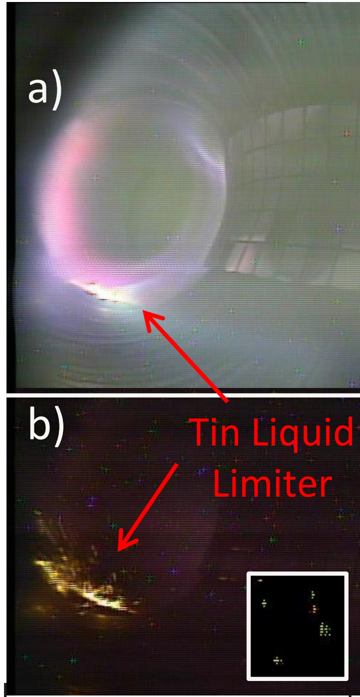


Graphic of cross-section hardness, in Vickers scale, for two poloidal and one toroidal tiles.

Primary localized damage by RE beams on tin liquid limiter

- The tin liquid limiter (TLL) where exposed in FTU Port 1 (bottom) from Sept 2016 to Dic 2019;
- in some cases of VDE followed by disruptions, during elongated plasma configurations, RE beams hit the TLL;
- the TLL was consisting of a capillary, actively cooled, porous system (CPS): a W wire network, diameter ~50μm, pores ~30μm filled with a 10-100μm layer of liquid tin [1];

⇒ Visual inspection led to the conclusion that the W TLL mesh was not macroscopically damaged after exposure to plasma and RE.



Vis camera of shot #42706 (disruption). Frame just before (a) and after (b) explosion like-event due to RE beam striking on TLL. Note the insert in fig. (b) showing camera pixels saturation by γ or hard X-rays bursts.

TLL image before (left) and after (right) exposure in FTU experimental campaigns.

[1] A. Vertkov et al., FED 117 (2017) 130.

Secondary nonlocal damage induced by RE beams

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Explosion-like event upon RE beam termination on the poloidal limiter

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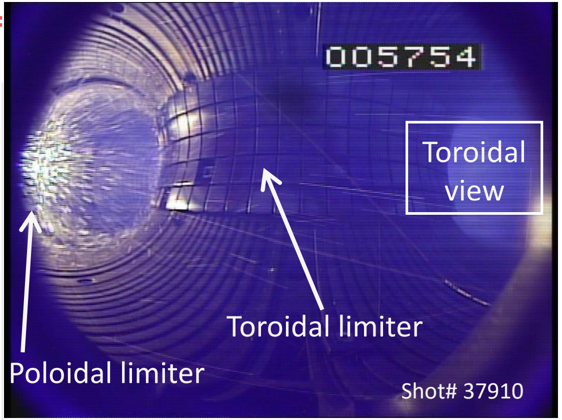
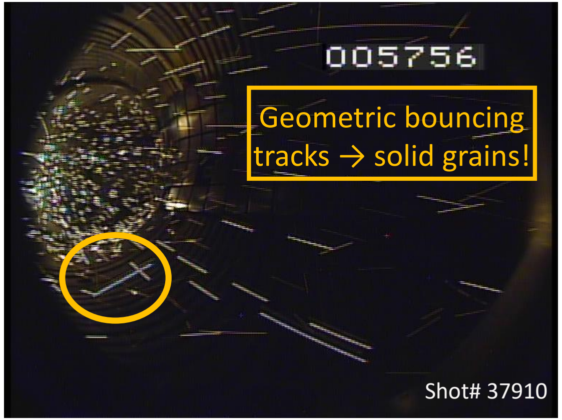
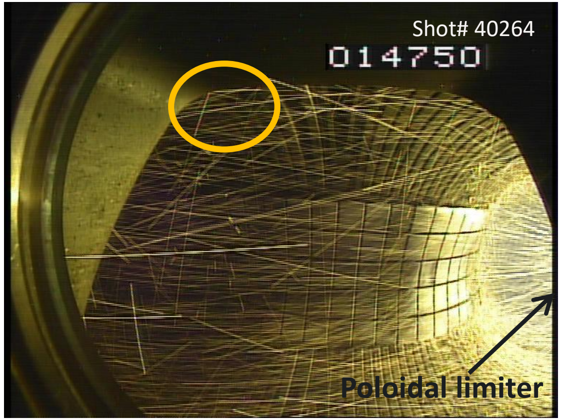
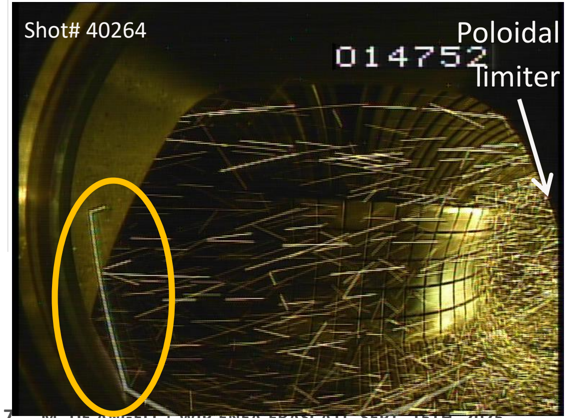
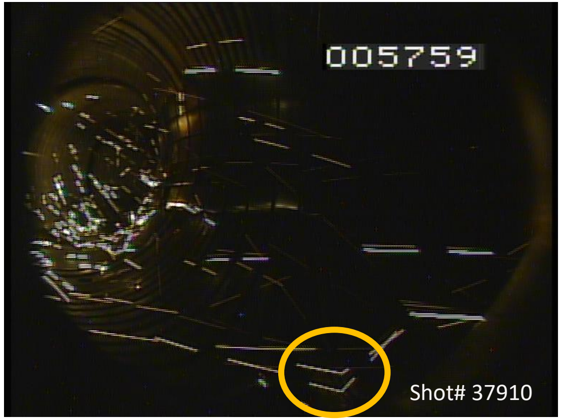


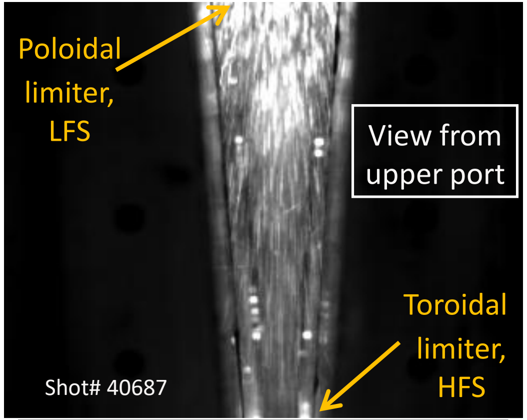








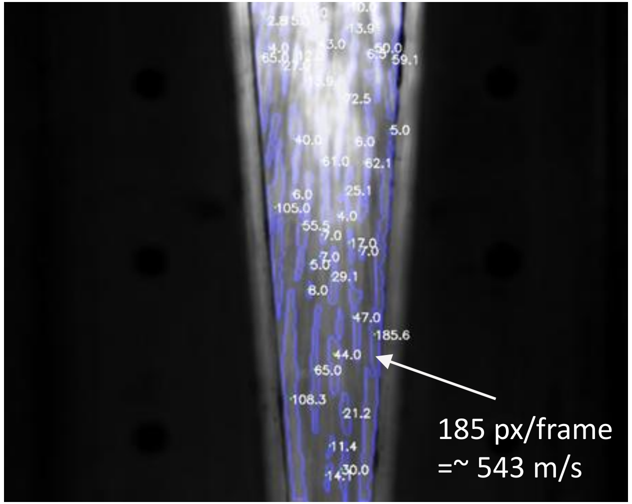
Frame rate: 25Hz; Integration time: 40ms



Frame rate: 383Hz; Integration time: 618µs

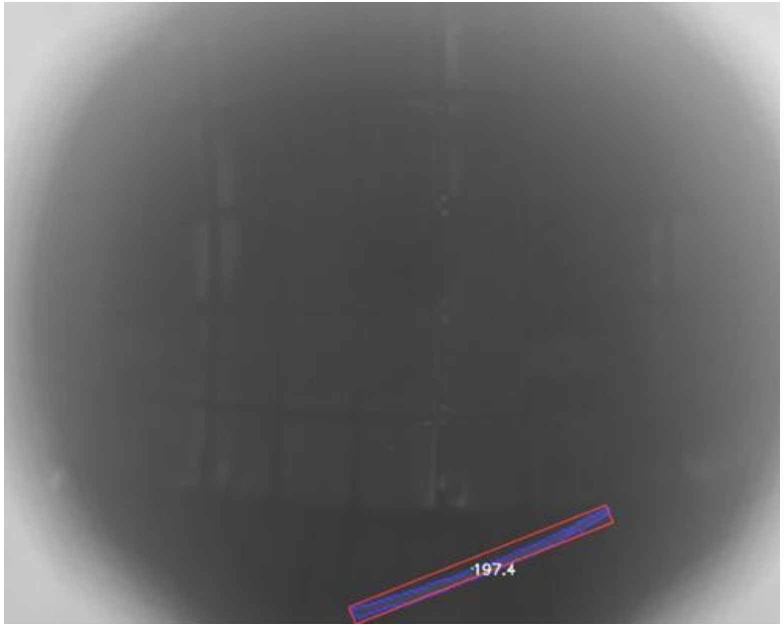
Dust speed estimation by IR and Vis fast cameras

Shot 40713. Runaway during rump up phase. Upper view of poloidal limiter by IR camera.



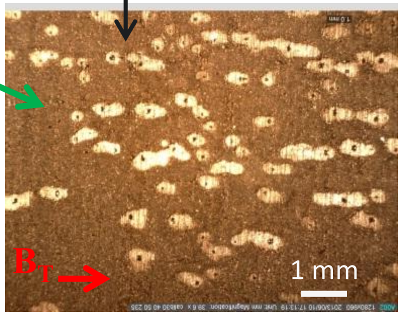
IR camera: 383 fps, integration time 618 μs

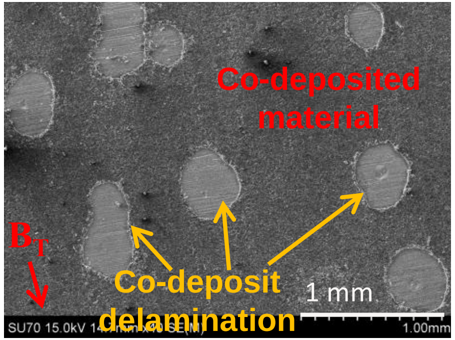
Shot 40307. Dust 2D velocity of 799m/s. Equatorial view of toroidal limiter Vis camera.



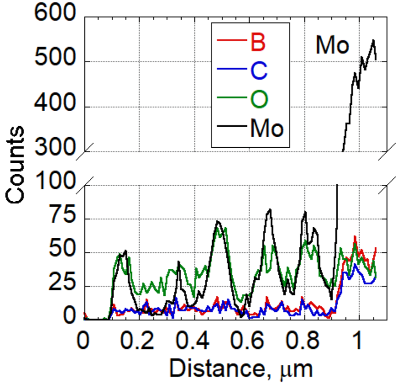
Unexpected secondary nonlocalized induced damage on nearby tiles

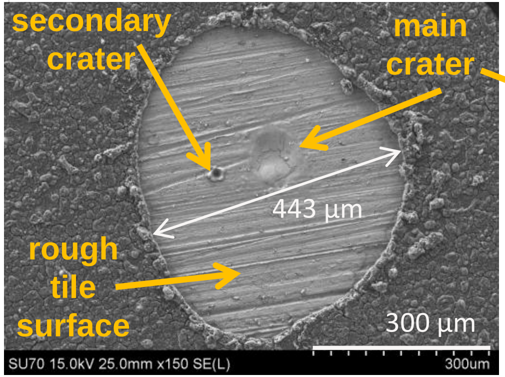
Toroidal limiter tile P12-n6-sx along with optical & electron microscope images of craters at different magnification.

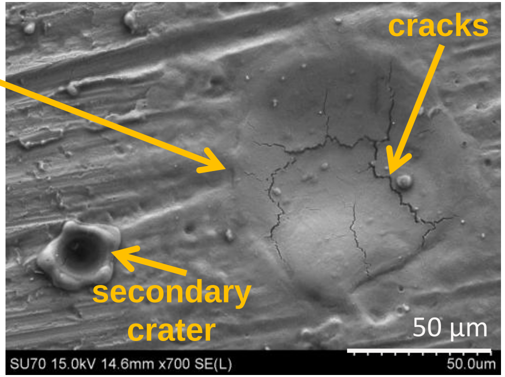




TEM/EDX depth profile from [1].







- Dust ejected, upon RE beam interaction with the poloidal tiles, induces craters & co-deposit delamination on nearby PFCs [1].
- Co-deposit on toroidal tiles in FTU was, mainly composed by Mo oxide.

[1] M. De Angeli, et al 2023 NF Letter 63, 014001.

Crater reconstruction & morphology

Parameter:	Diameter	Depth
Co-deposit halos	250÷400µm	5÷8µm
Main craters diameter	50÷100µm	3÷12µm

Dimensions of actual craters found on FTU tiles [3].

Mo projectile, diam/speed	*Craters diameter*	*Craters depth:*
63-71µm at 700÷800 m/s	77÷100µm	7÷15µm

Craters characteristics of reconstructed craters by a light gas dust gun system [3].

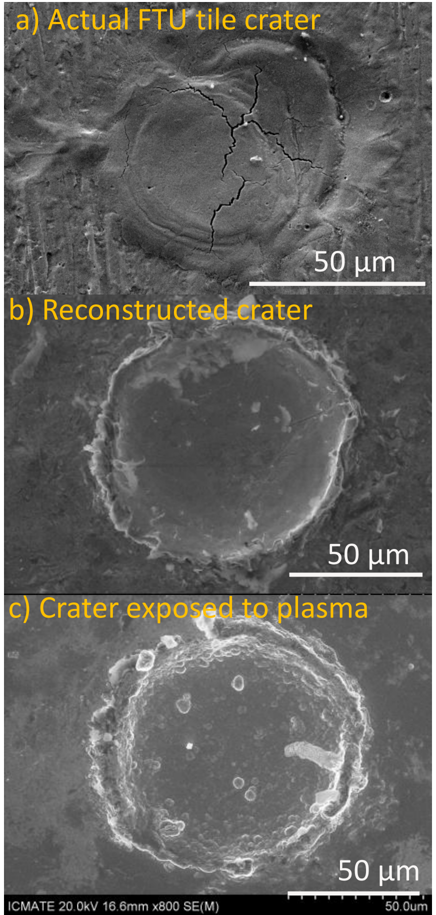
- In-lab crater reconstruction by light gas gun (b) and linear plasma exposure (c) (Ar, T_e= 5.6eV, N_e=6.35x10^{16} m^{-3}, Γ=1.0x10^{24} ion/m^2, V=-70V, t=135min) → rim smoothing.
- Estimated dust impinging velocity ~700÷800 m/s [1].

→ Morphology well reconstructed;

X Cracks not reproduced: thermal stress, or increase of ductile-brittle transition temperature due to irradiation.

Lab conditions vs *FTU actual conditions*:

- Mo dust is solid and at RT *vs* Mo dust is solid but still very hot;
- Target @ RT and -100°C *vs* FTU tile @ -100÷0°C.



SEM images of a) actual FTU crater, b) crater by gun system, c) crater after plasma exposure.

[1] M. De Angeli, et al 2003 NF Letter 63, 014001.

Empirical crater damage law

On the basis of a craters database, developed by means of a light gas dust gun in the dust velocity (v_{imp} ⩾1 km/s) and size (D_d =50÷150 μm) regimes of interest, empirical damage laws has been established [1,2] allowing *infer dust size and speed from crater diameter and depth*:

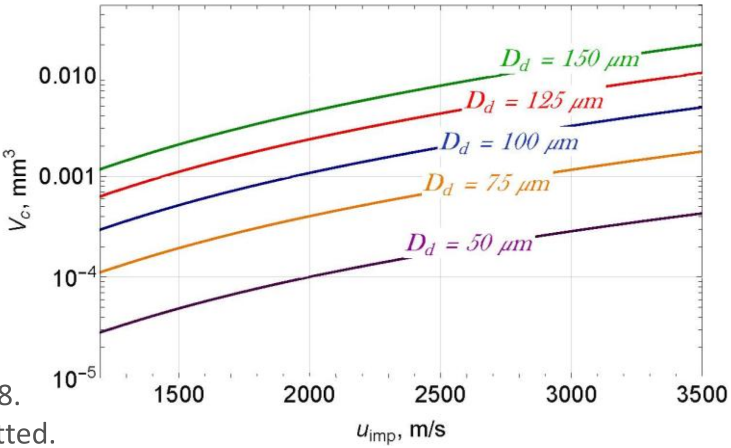
$$D_c = 0.0257(D_d)^{1.02}(v_{imp})^{0.550} [\mu m] \quad \text{and} \quad H_c = 0.0000107(D_d)^{1.31}(v_{imp})^{1.268} [\mu m]$$

where D_c is the crater diameter and H_c is the crater depth [1].

The excavated crater volume V_c read as: $V_c = \frac{1}{6}\pi H_c\left(\frac{3}{4}D_c^2 + H_c^2\right)$

→ *allows the use of witness plates in RE experiments in tokamaks rather than challenging cameras!*

In FTU case, the assumption that the *excavated volume* corresponds to *excavated material* could not be true since the impact velocity regime of interest (v_{imp}~1 km/s) is located on the border between deformation and disintegration impact regimes [1].

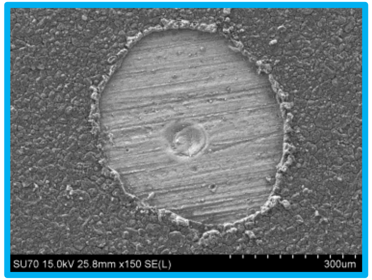


[1] P. Tolias, et al., 2023 FED, 113938.
[2] P. Tolias, et al., 2025 FED, submitted.

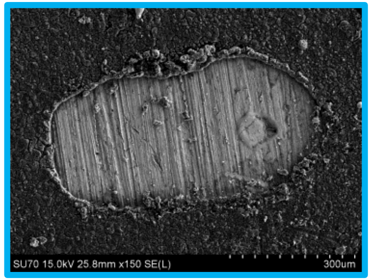
Evaluation of co-deposit delamination surface on dust impacts

Material erosion and migration

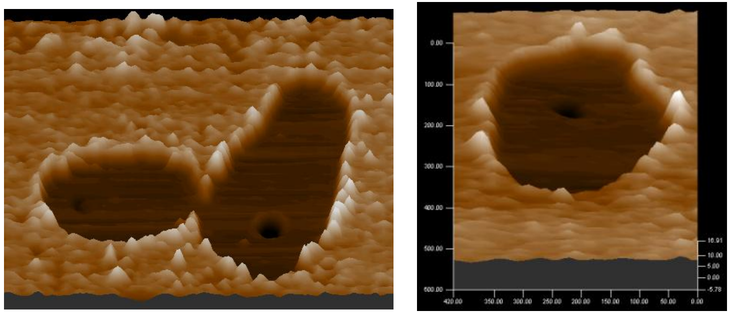
Toroidal tile T2 P12-n6-sx



0.148 ±0.054 mm^2



0.232 ±0.061 mm^2



Profiler images of haloed craters

Tile	Surface of circular halos, mm^2	Surface of elongated halos, mm^2
T1	$8.8\text{x}10^{-2} \pm 3.8\text{x}10^{-2}$	$1.08\text{x}10^{-1} \pm 3.0\text{x}10^{-2}$
T12	$9.6\text{x}10^{-2} \pm 5.0\text{x}10^{-2}$	$1.32\text{x}10^{-1} \pm 7.4\text{x}10^{-2}$

Mean removed co-deposit surface area. The average values have been evaluated on the basis of a total of 13 (T1) and 65 (T2) [1].

- Circular and elongated co-deposit delamination shape were found.
- Different average delaminated areas in different limiter tile locations.
- Craters average density: ~71 crat./cm^2 → delaminate surface that could be removed: ~0.6% ÷ 9% (all circular to all elongated delamination).
- Co-deposit thickness on T2: ~8µm.

[1] M. De Angeli, et al., 2025 NME, submitted.

Summary

- I fasci RE in FTU inducono danni primari localizzati sulle tegole dei limiter poloidale, toroidale e sul limiter di metallo liquido, e di tipo secondario non-localizzato sui PFCs nelle vicinanze (es. sulle tegole del limiter toroidale).
- *I danni primari* includono: i-perdita di materiale fino a ~6mm di profondità e fusione del materiale; ii-delaminazione superficiale di ~7mm di spessore; iii- ricristallizzazione interna del materiale fino a ~1mm di profondità; iv-degradazione meccanica delle proprietà del materiale per decine di mm; v-cracks intergranulari superficiali e interni; vi- espulsione di polveri solide veloci.
- Nessun danno apparente al limiter di metallo liquido, *ulteriori analisi devono essere condotte per escludere danni non evidenti*!
- *I danni secondary* includono: i-formazione di crateri dovuti all'impatto con polveri veloci; ii-cracks nei crateri; iii-rimozione e migrazione di codepositi di materiale pre-esistente.

$\Rightarrow$ *Nonostante i danni severi provocati dall'interazione RE con i PFC, non ci sono state interruzioni delle campagne sperimentali dovute ai danni causati da RE!*

Conclusions and outcomes

- Grande attenzione viene posta ai danni causati dai RE ai PFC nei tokamak all'interno della comunità "plasma-wall interaction", questo fenomeno, infatti, rappresenta una minaccia significativa per la sostenibilità e la longevità dei futuri reattori a fusione come ITER e DEMO. Infatti, le perdite di refrigerante dovute all'interazione RE-PFC sono la principale preoccupazione negli attuali e futuri reattori per la Fusione!

Questo problema sta diventando un «hot topic» all'interno della comunità PWI!

Contributi agli studi RE-PFC basati sui dati ottenuti da FTU:

- M. De Angeli et al., NF Letter 63 (2023) 014001 "*Evidence for high-velocity solid dust generation induced by runaway electron impact in FTU*";
- Oral invited to EPS 2024 Satellite Meeting "*Runaway electron-induced PFC damage*";
- Accepted paper S. Ratynskaia et al, "*Runaway electron-induced plasma facing component damage in tokamaks*", appears at arXiv:2506.10411.
- Submitted paper M. De Angeli et al, "*Primary and secondary metallic PFC damage induced by runaway electron dissipation in FTU*" to Nuclear Material and Energy journal, 2025.

Conclusions and relevance

Grazie per l’attenzione!

Backup slides

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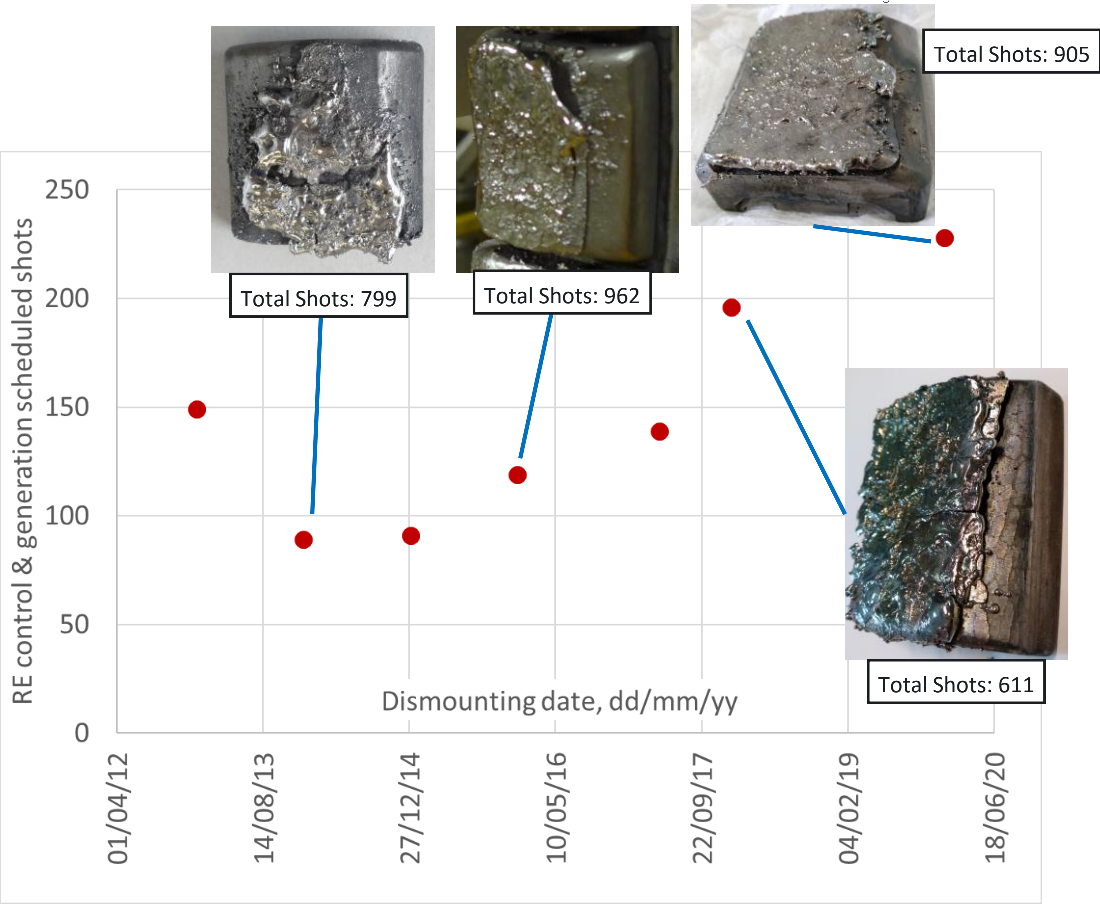
Primary localized damage by RE beams on poloidal limiter tiles

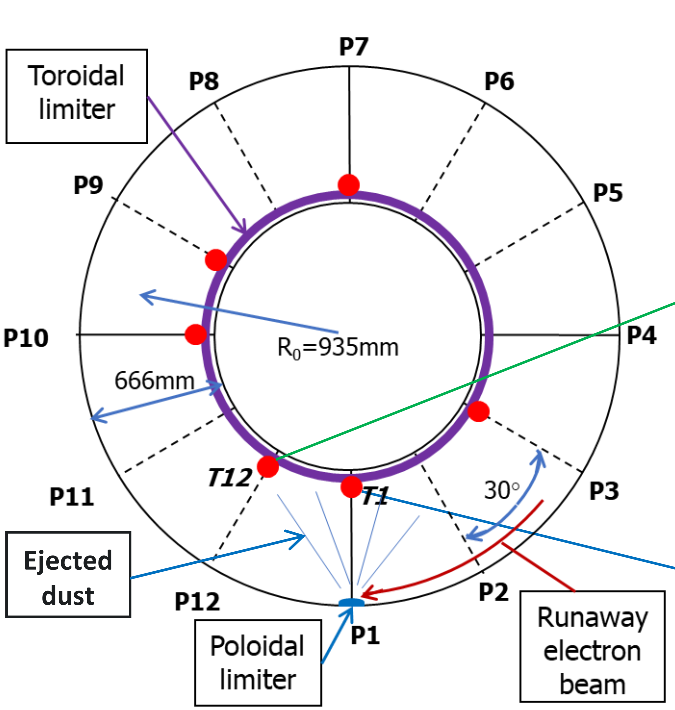
Examples of poloidal limiter, tiles located in the equatorial plane, after yearly technical shut-down.

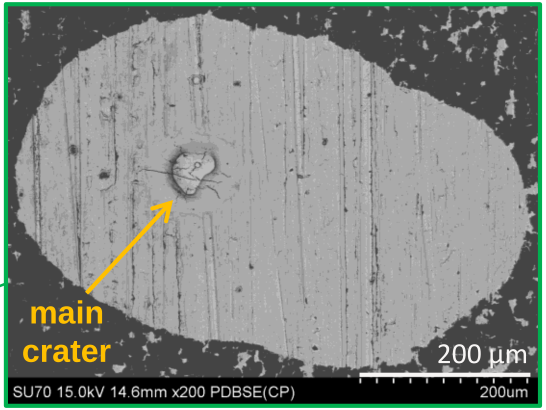
The graphic shows the number of shots carried out during *scheduled RE control* and *RE generation* programs. Below the tile images, the number of total shots during each campaign.

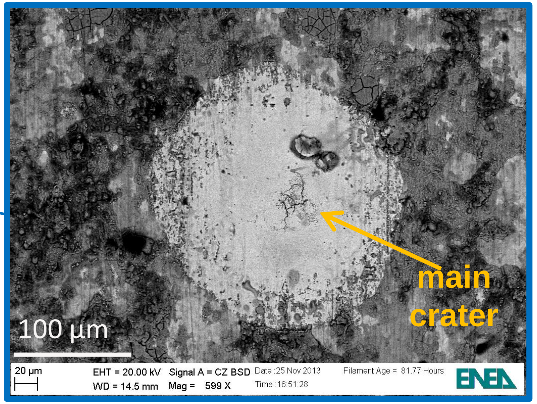
In addition to scheduled RE shots, unexpected RE terminated shots should be accounted.



Layout of FTU REs cascade nonlocalized damages of PFCs







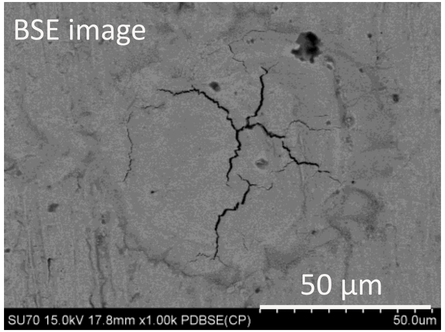
Mainly (~70%) **elongated** craters found on tile T12

Confirm that dust is, usually, ejected from the poloidal limiter!

Mainly **circular** craters found on tile T1

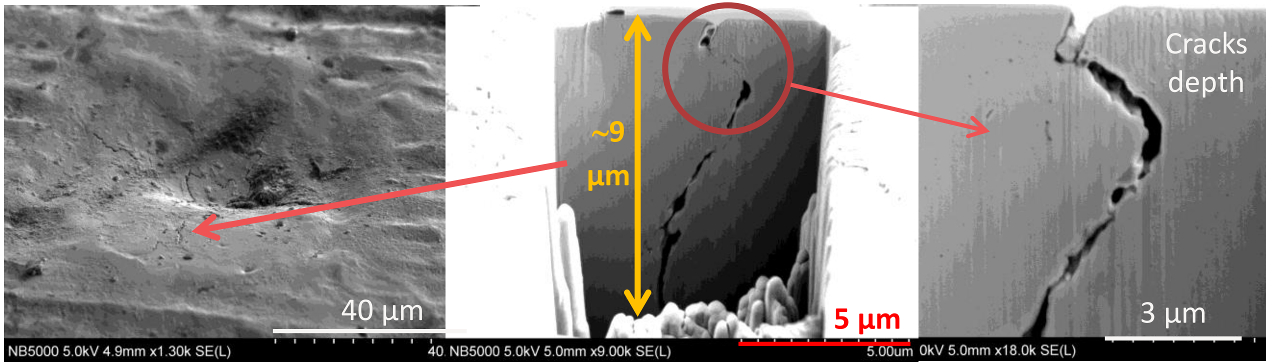
Crack evidence inside craters

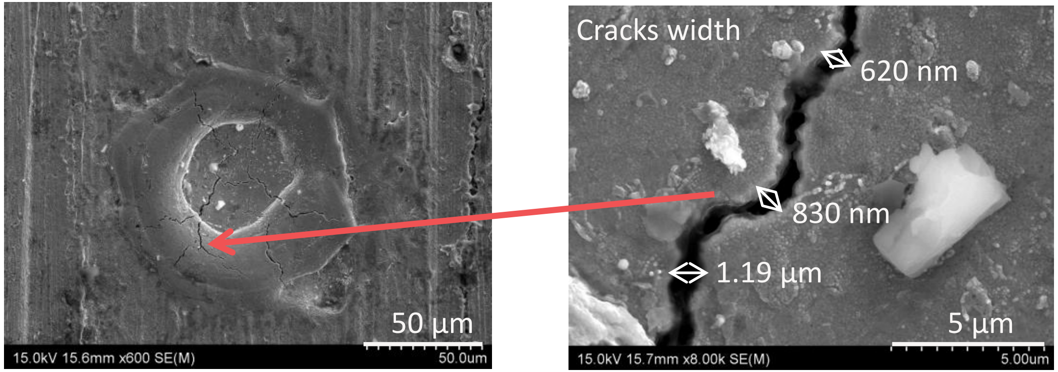
- Cracks are found inside several craters.
- *Cracks width*: 50nm - 1.3µm.
- *Cracks depth*: ? difficult to carry out FIB cross-section inside deep craters!



SEM image of a crater with crack network.

SEM images of the crack cross-section. Crack total depth: 9.3µm.





SEM images of the crack dimension in a crater.

Analyses carried out by E. Fortuna et al., IPPLM.

Additional examples of damaged poloidal limiter tiles

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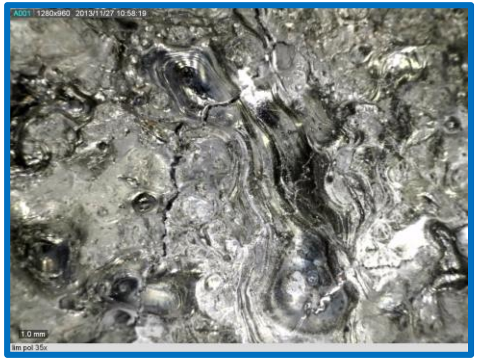
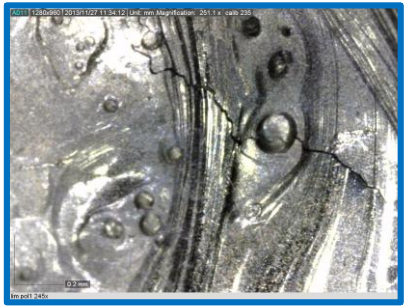
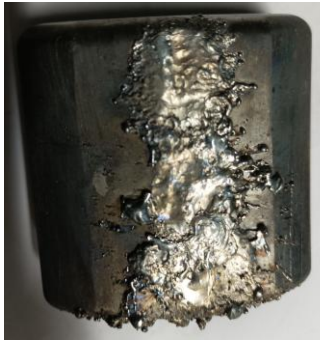


Previous mushroom-shaped poloidal limiter





Examples of cracks inside craters

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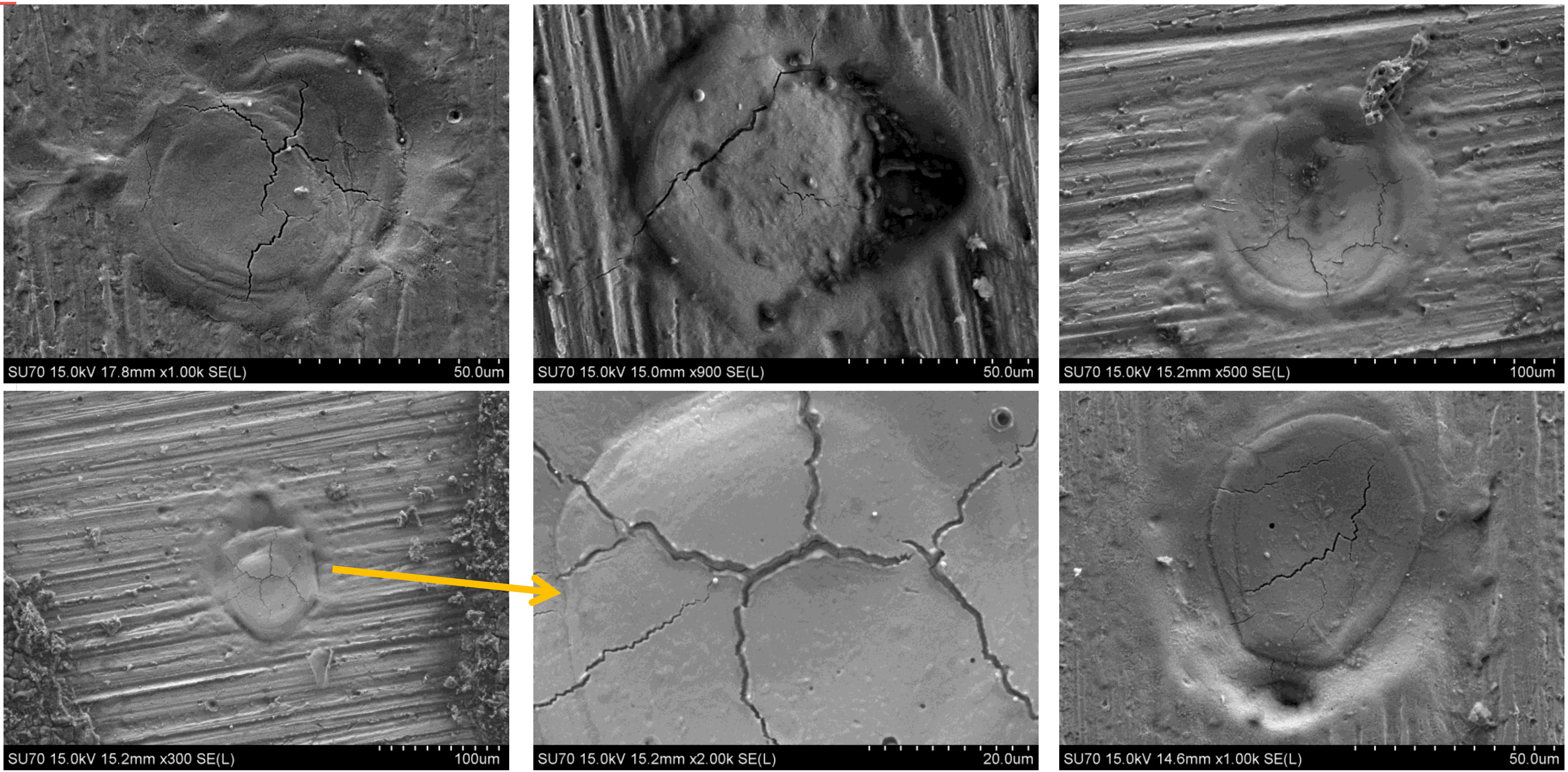
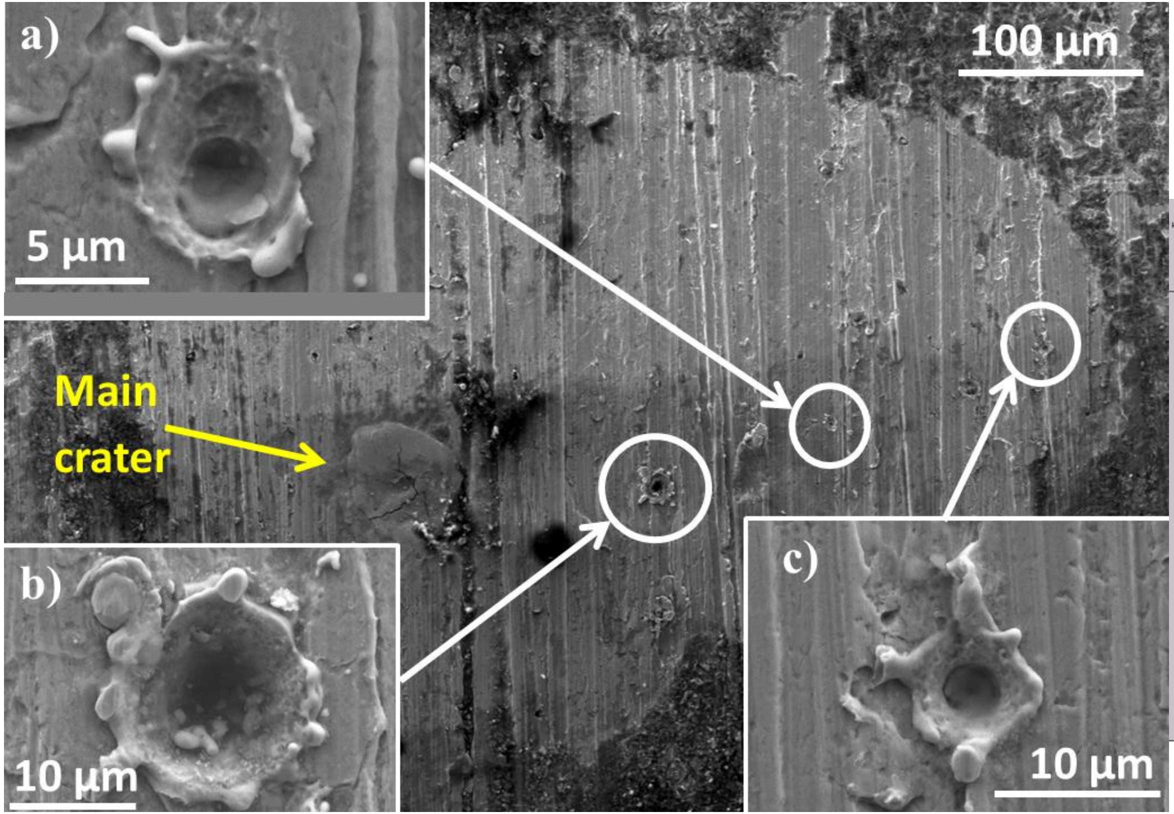
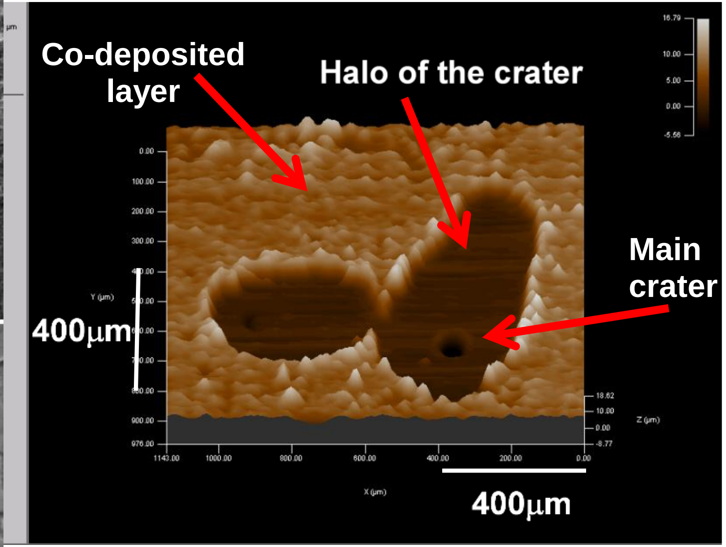


Examples of secondary craters

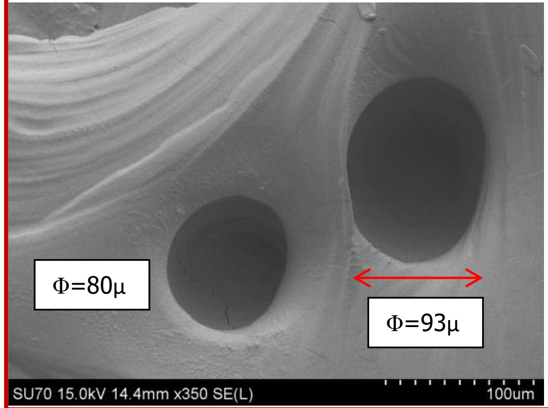


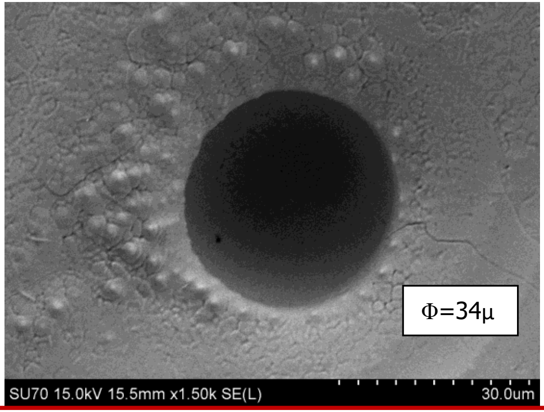
3D image of profiler analyses of two craters



Holes found on toroidal limiter tile and on a probe tip in SOL

Holes found on the molten area on a TZM toroidal limiter tile





Holes found on a Mo tip exposed in SOL area of FTU during few discharges with REs