MATERIALS UNDER EXTREME ENERGY AND PARTICLE LOADS: FROM SURFACE DAMAGE TO SURFACE MODIFICATION

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Outline

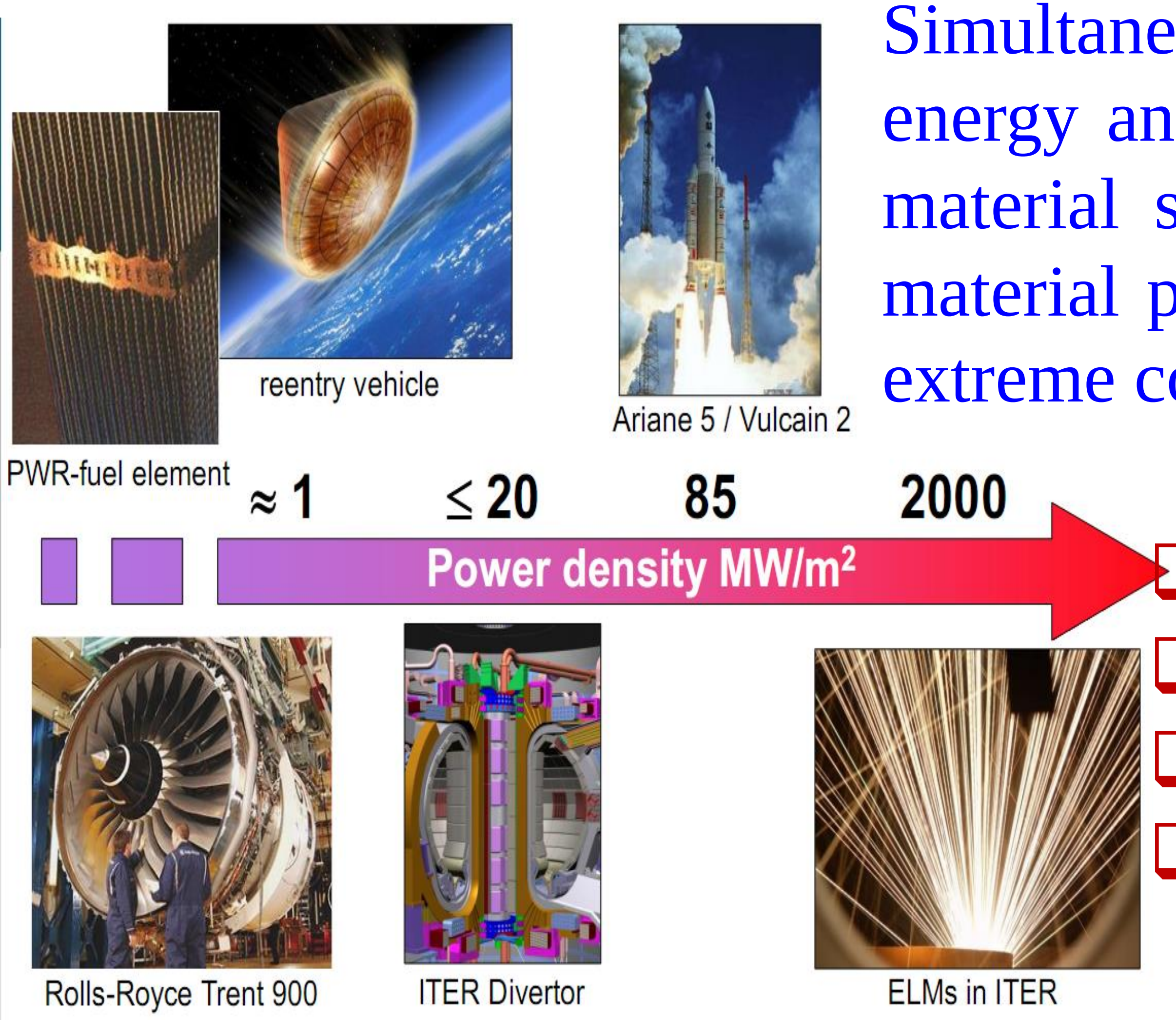
- **Introduction**

  Objectives of simulation experiments
- **Experimental facility and diagnostics**

  QSPA Kh – 50 device
- **Surface damages**
  - ❑ Creation of shielding layers
  - ❑ Macro and intergranular cracks development
  - ❑ Melt motion
  - ❑ Droplets/dust ejection
- **Surface modification**
  - Re-solidified/modified layer
  - Coatings modification
- **Conclusions**

Introduction

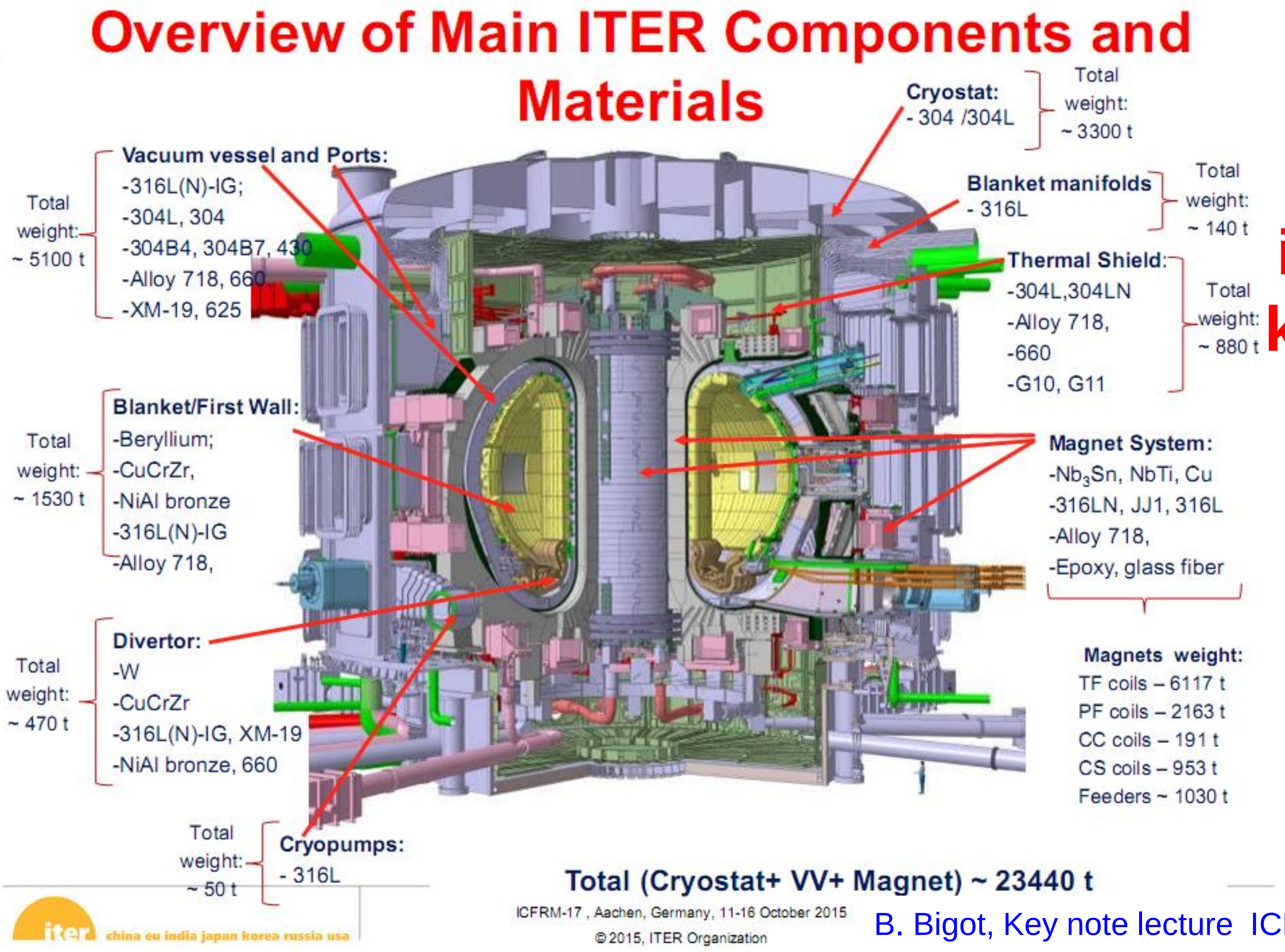
Simultaneous impacts of high energy and particle loads to the material surface are typical for material performance in various extreme conditions:



- ❑ turbines
- ❑ space apparatus,
- ❑ nuclear engineering
- ❑ fusion

J. Linke , PFMC-16, Neuss, 15-19, May 2017

Introduction



Overview of Main ITER Components and Materials

Cryostat:
- 304 /304L
Total weight: ~ 3300 t

Vacuum vessel and Ports:
-316L(N)-IG;
-304L, 304
-304B4, 304B7, 430
-Alloy 718, 660
-XM-19, 625
Total weight: ~ 5100 t

Blanket manifolds
- 316L
Total weight: ~ 140 t

Thermal Shield:
-304L,304LN
-Alloy 718,
-660
-G10, G11
Total weight: ~ 880 t

Blanket/First Wall:
-Beryllium;
-CuCrZr,
-NiAl bronze
-316L(N)-IG
-Alloy 718,
Total weight: ~ 1530 t

Magnet System:
-Nb_3Sn, NbTi, Cu
-316LN, JJ1, 316L
-Alloy 718,
-Epoxy, glass fiber

Divertor:
-W
-CuCrZr
-316L(N)-IG, XM-19
-NiAl bronze, 660
Total weight: ~ 470 t

Magnets weight:
TF coils – 6117 t
PF coils – 2163 t
CC coils – 191 t
CS coils – 953 t
Feeders ~ 1030 t

Cryopumps:
- 316L
Total weight: ~ 50 t

Total (Cryostat+ VV+ Magnet) ~ 23440 t

ICFRM-17 , Aachen, Germany, 11-16 October 2015

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iter china eu india japan korea russia usa

Materials issues are key factors for ITER And DEMO success

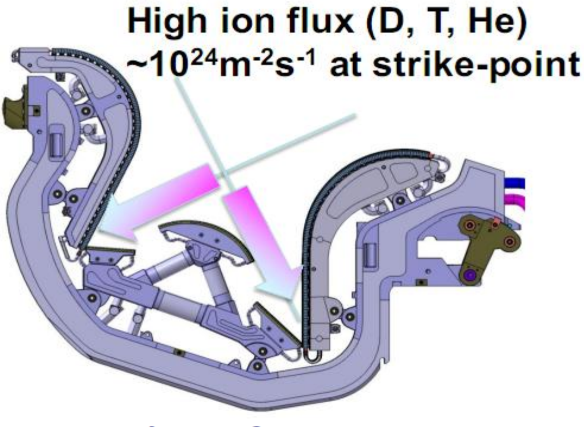
B. Bigot, Key note lecture ICRFM-17, October 2015

Introduction

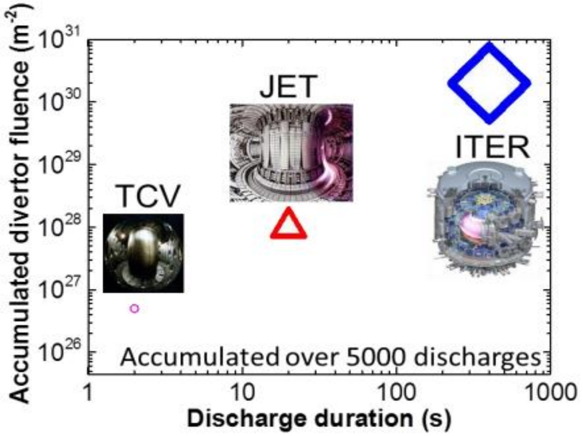
Heat load relevant to ITER : Steady-state heat loads 10 (20) MW/m^2

Transient events : **DISRUPTION** (Q = (10-100) MJ/m^2 ; pulse duration (1-10) ms)

Type I ELM: (Q =(1-3) MJ/m^2 (up to 10 GW/m^2); t = (0.1-1) ms; up to 10^6 events)



High ion flux (D, T, He)
~10^{24}m^{-2}s^{-1} at strike-point



ITER will reach unprecedented fluences

- **700 m2 beryllium**
  - First wall
  - Low Z: good plasma compatibility
  - Good oxygen getter
  - Good thermal conductivity

- **~150 m2 tungsten**
  - Divertor
  - Low sputtering yield
  - Highest melting point (3422°C)

B. Bigot, Key note lecture ICRFM-17, October 2015

The detailed experimental studies of threshold values for the damaging processes under fusion reactor relevant loading scenarios are required for evaluation of the materials performance under transient events.

QSPA Kh-50 Device

✓The energy range of ITER disruptions and ELMs will be clearly higher than in the existing tokamaks

✓Material response to multiple exposures are studied with ions and electrons beams, liner facilities, pulsed plasma guns and QSPA,

✓Quasi-stationary plasma accelerators (QSPA) are attractive facilities for :

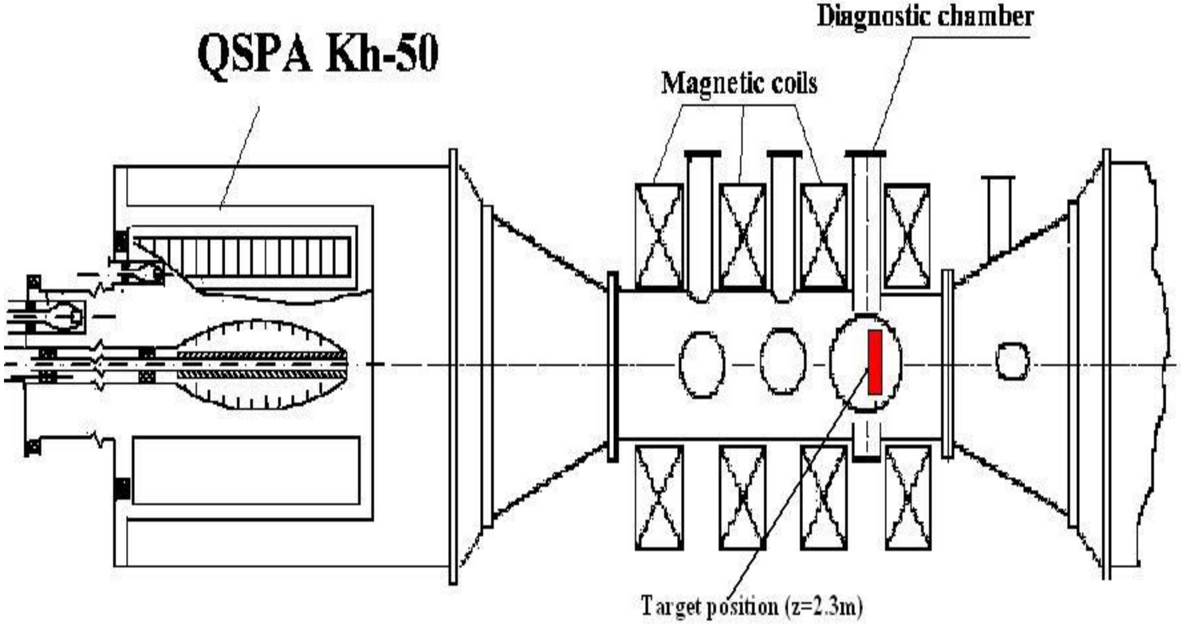
- Simulation of heat loads typical for disruptions and ELMs

- Study of plasma/surface interaction (shielding, melting, evaporation, erosion mechanisms)

- Measurements of data for validation of numerical models

The QSPA Kh-50 is the largest and most powerful device of QSPAs

QSPA Kh-50 Device and diagnostics



Energy density ρ_w = (0.5…30) MJ/m^{2},
Plasma pulse duration τ ≈ 0.25 ms;
P_{max} = (3-18) bar, n = (0.2-5) 10^{16} cm^{-3};
B_0 =0.54 T (β ≈ 0.3…0.4);
Diameter of plasma stream- 15 cm

The plasma accelerator inserted in vacuum chamber of 1.5 m in diameter.
Diameter of vacuum chamber inserted in the magnetic solenoid is 0.4 m.
Total length of vacuum chamber is 10 m.

- The plasma energy density and surface heat loads were measured by **movable calorimeters**.
- The plasma pressure was measured by means of **piezoelectric detectors**.
- Optical emission spectroscopy (OES) methods were used for the determination of the electron density and temperature.
- Observations of plasma –surface interactions were performed with a **high-speed digital camera** (10 bit CMOS pco.1200 s) PCO AG.
- Surface analysis was carried out with an optical microscope MMR-4 and Scanning Electron Microscope

Examples of Plasma Parameters in Different Regimes QSPA Kh-50

Parameters	ELM 0 simulation	ELM 1 simulation	ELM 2 simulation	ELM 3 simulation	Disruption
Plasma stream energy density [MJ/m^2]	0.4	0.9-1.0	1.2-1.5	2.4-2.5	24-30
Target Heat Load [MJ/m^2]	0.22	0.45	0.7-0.75	1-1.1	0.65-0.7 (strong vapor shielding)
Plasma load duration [ms]	0.25	0.25	0.25	0.25	0.2-0.25
Maximal dynamical pressure of plasma stream [MPa]		0.48	0.32	0.45	2
Average plasma density [10^{16} cm^{-3}]		1.5-2.5	0.5-0.7	0.2-0.3	4-8
Plasma stream diameter [cm]	12-14	12-14	16	16	14
Surface effects	below crack threshold	no melting	melting	Evaporation start	Strong vapor shield

Heat load to the target surfaces vs. the energy density of impacting plasma stream

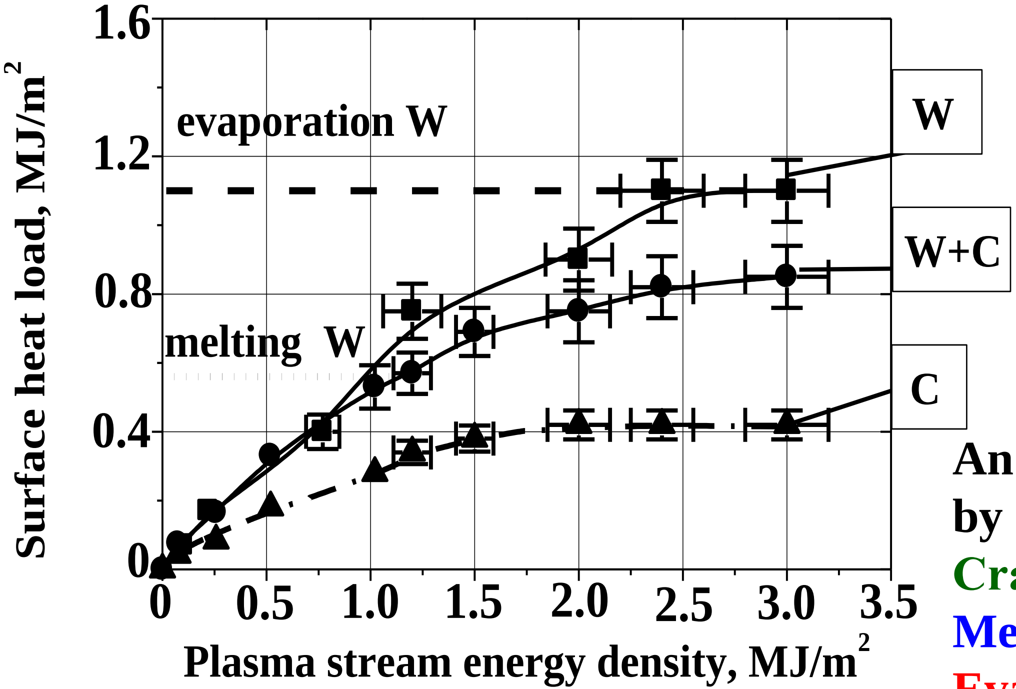


Image of plasma stream interaction with the target for t= 30 μs after beginning of plasma-surface interaction.

An energy thresholds for Tungsten exposed by QSPA Kh-50 pulses of 0.25 ms

Cracking ~ 0.3 MJ/m^2

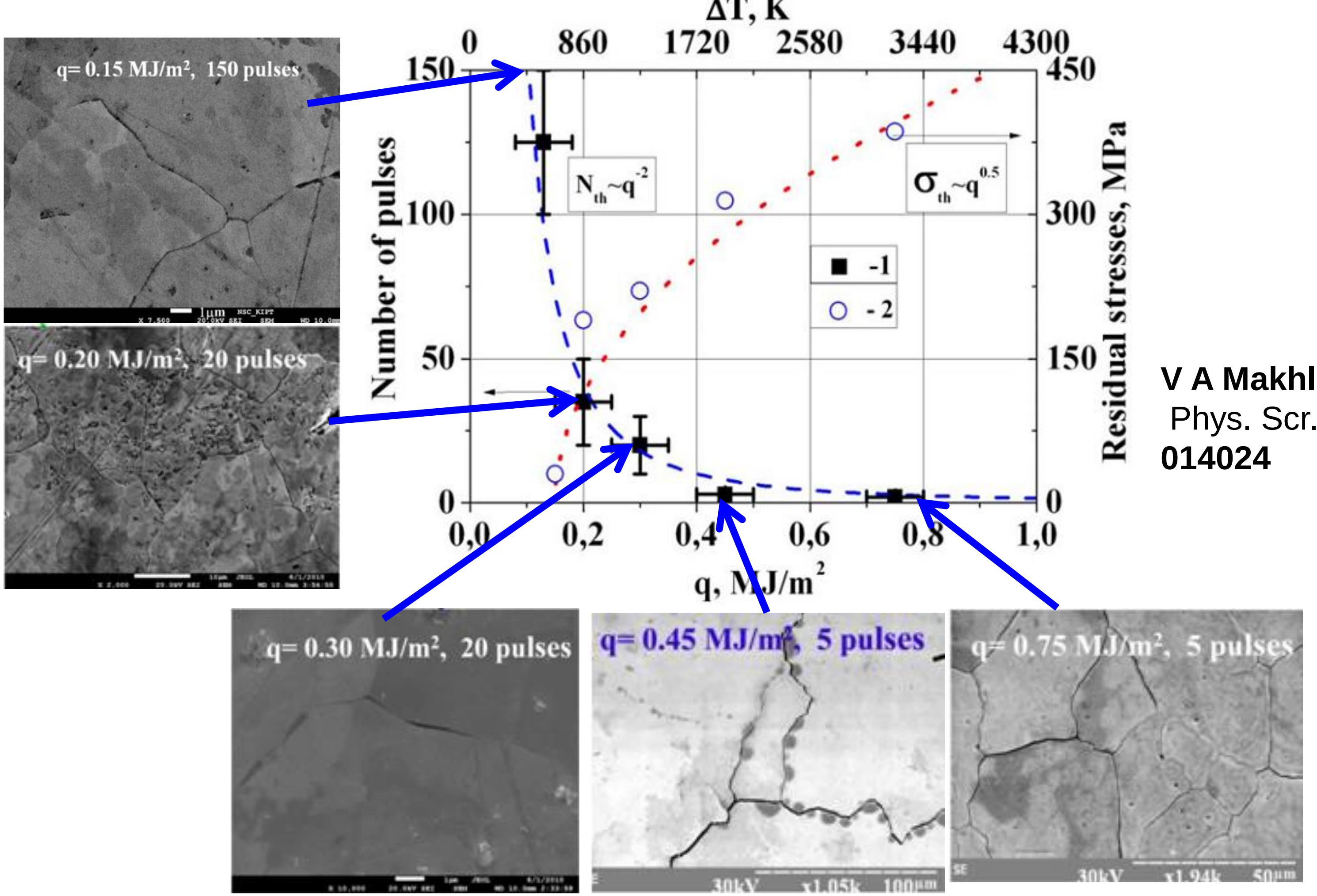
Melting is ~0.6 MJ/m^2

Evaporation ~ 1.1 MJ/m^2

I.E. Garkusha et. al. **J. Nuc. Mat. 390–391 (2009) 814**; I.E. Garkusha et al. **J. Nucl. Mater. 415 (2011)** S65;
V A Makhlaj et. al. **Phys. Scr. T145 (2011) 014061**; V A Makhlaj et. al. **Phys. Scr. T159 (2014) 014024**

- Due to a vapor shield formation the exposed armour target will be protected from the high heat load and erosion by evaporation will be reduced in hundred times

Shift of cracking threshold with decreasing of heat load

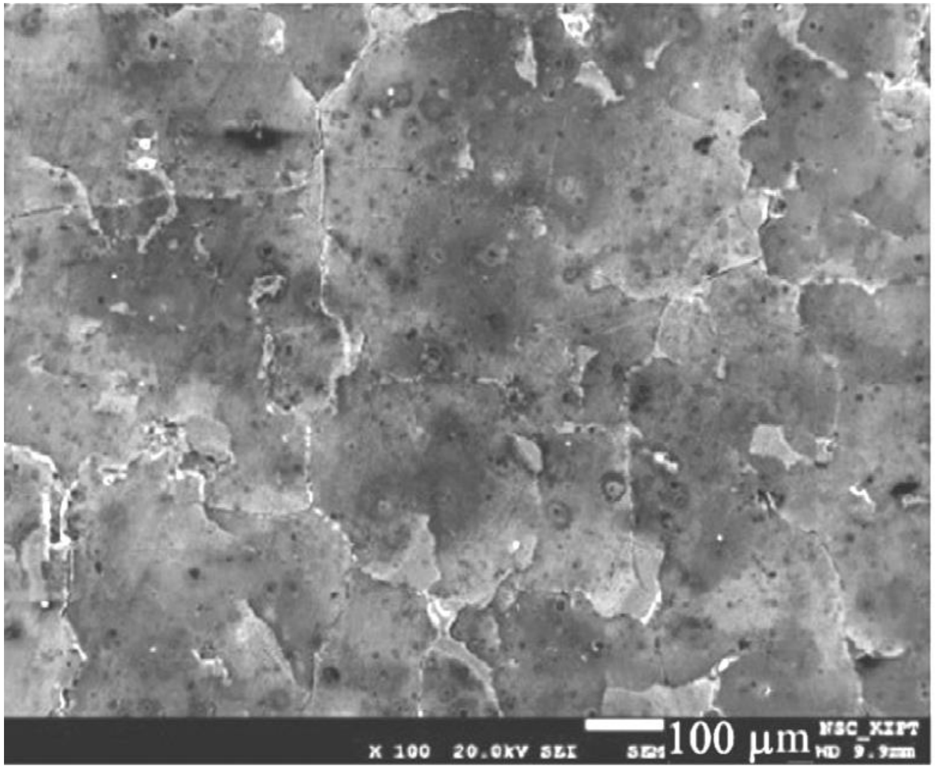


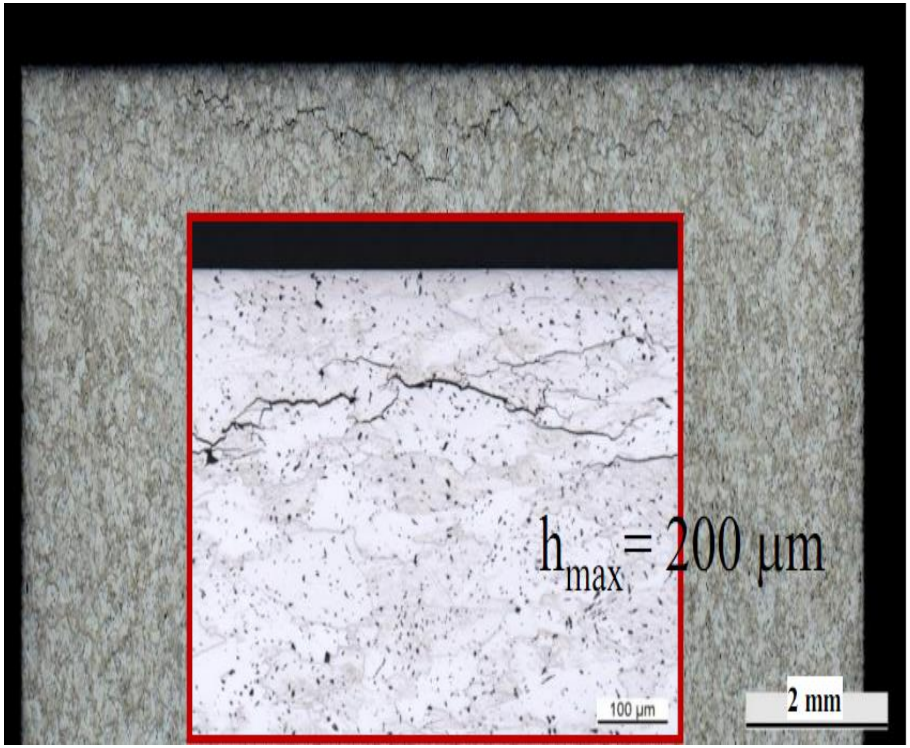
V A Makhlaj et. al.
Phys. Scr. **T159 (2014) 014024**

Dependence of the number of pulses (rectangles) and residual stresses (circles) that led to the appearance of cracks versus the heat load (q).
Corresponding changes of the target surface temperature (ΔT) are also shown.

Heat load above cracking and below melting thresholds

Macro cracks development





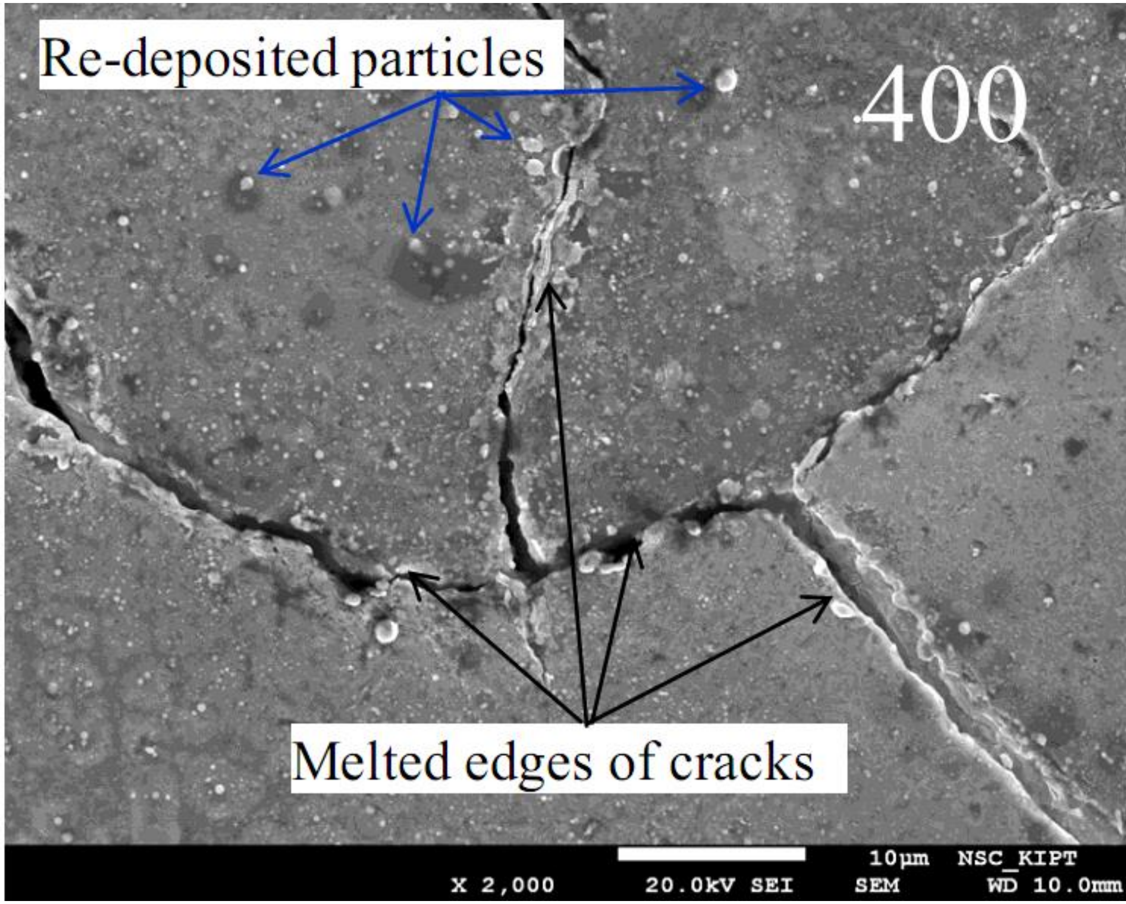
- ❖Cracks appear on exposed surfaces and inside of samples.
- ❖Development of cracks led to increases of roughness of exposed surfaces.
- ❖Solid particles may split from the crack edges during its rupture.

V. Makhlai et.al. Nuclear Materials and Energy 9 (2016) 116–122

Heat load above cracking and below melting thresholds
Surface modification

- **High number of plasma pulses result in surface modification**
- **The melting onset of edge of cracks is observed whereas other surface remains non-melted**
- **Melted edges of cracks eject small particles.**
- **Such particles are deposited back to the target surface by plasma pressure.**
- Particles melted even for rather small heat loads below the surface melting threshold

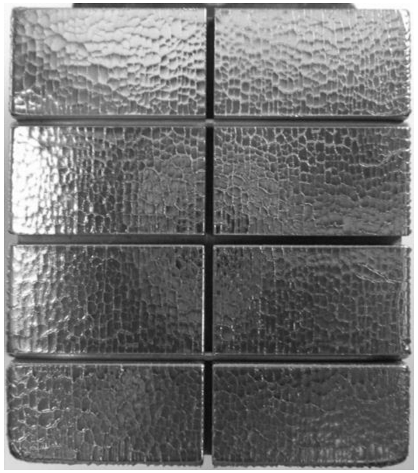
$Q= 0.45\ MJ/m^2$, 400 pulses



V. Makhlai et.al. PSI-22, Rome 2016

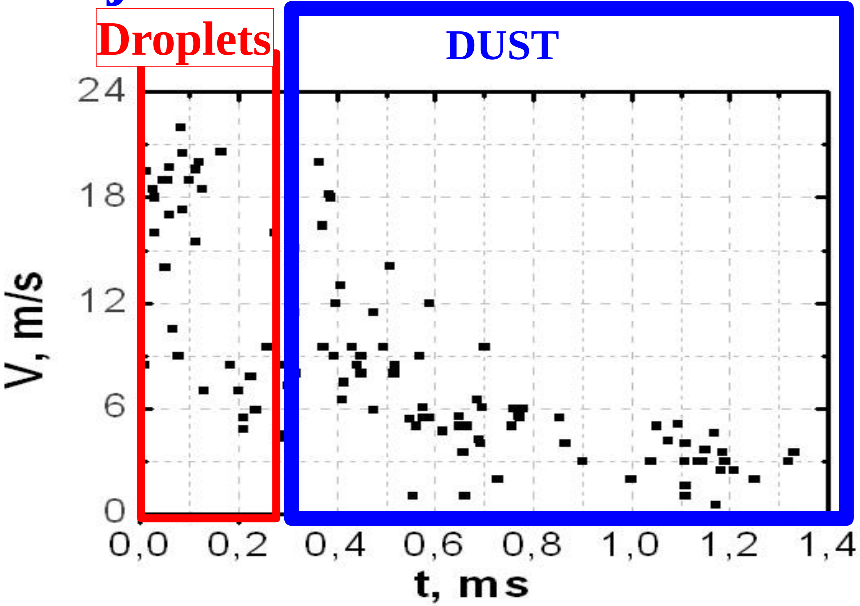
Heat load above melting threshold

Droplets/dust ejection



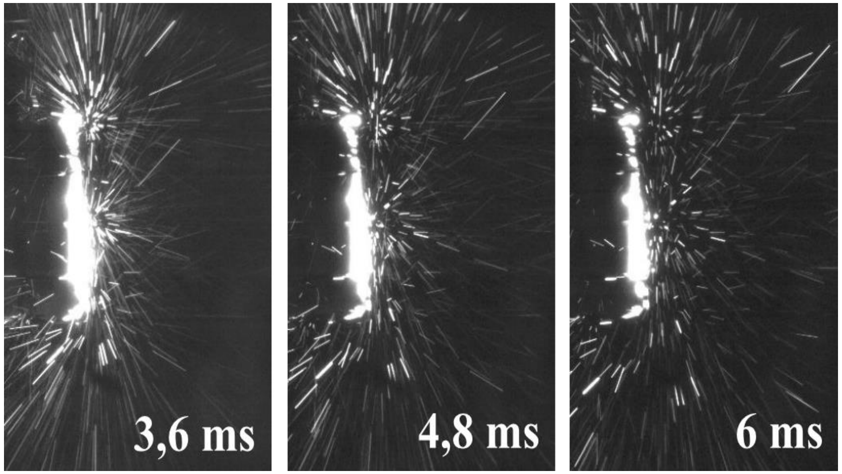
Castellated tungsten target is sample of 5x5x1 cm^3 with slots. The size of each target unit is 2.2x1.2 cm^2 which is close to ITER divertor reference design

t_{exp}= 1.2 ms



Velocity distribution of ejected particles v.s. particle start-up time from the exposed surface;

- **The melted/dust particles splash from the tungsten surface**
- **Maximum velocity of ejected particles is 24 m/s**
- **Estimated tungsten melting time of 90-100 μs**
- **Solid particles start from the surface after the pulse end t>250 μs**

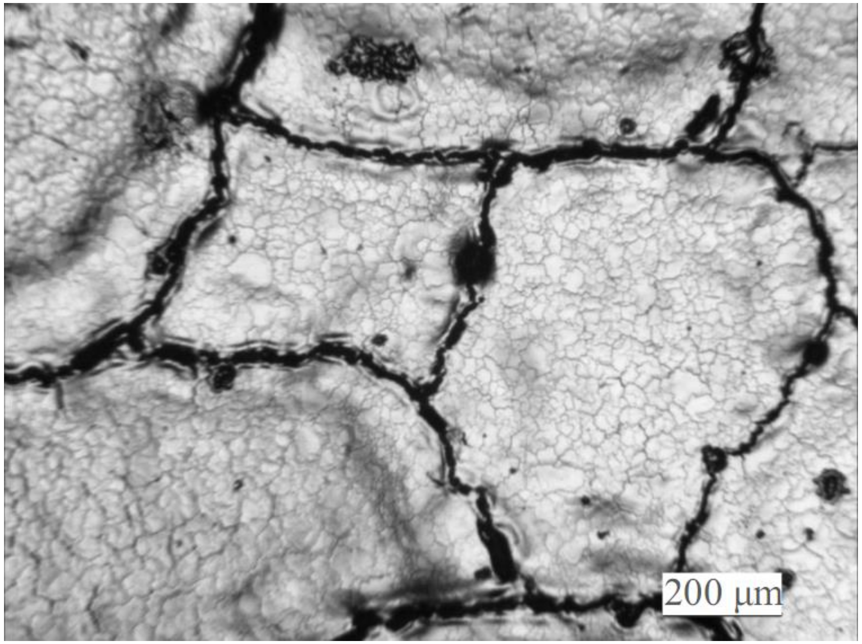


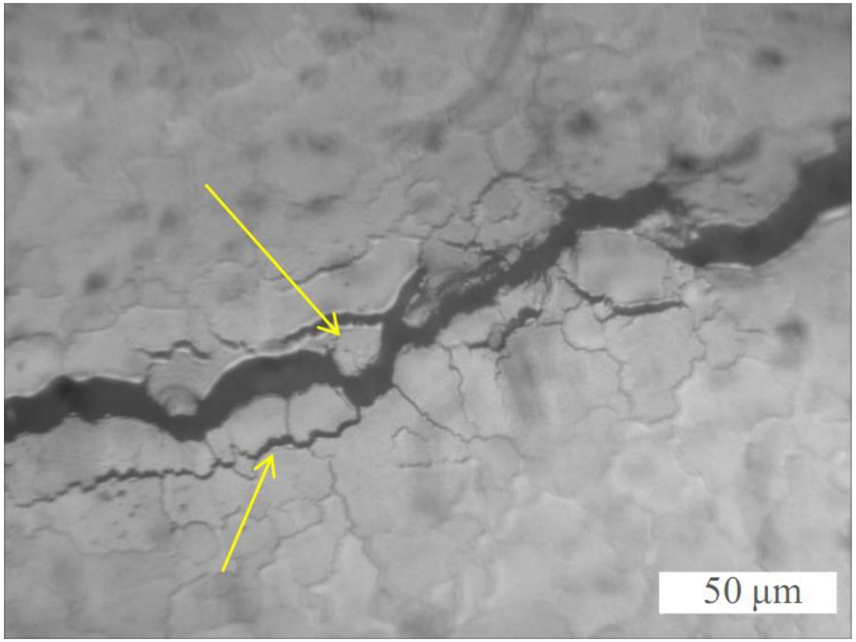
High-speed imaging of plasma interaction with tungsten target

S.S. Herashchenko, et. al. Prob. At,. Sci and Tech 2017, №1(107), p. 119)

Heat load above melting threshold

Macro and intergranular cracks development





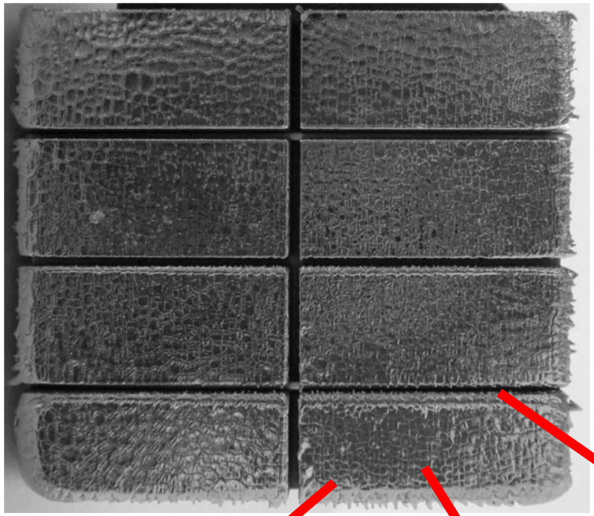
- ❖**Networks both macro and intergranular cracks appeared on exposed surfaces after a lot of plasma pulses**
- ❖**Particles ejected from the surface due to the cracking development and major cracks bifurcation.**
- ❖**The droplet generation mechanism is due to Kelvin-Helmholtz instabilities**

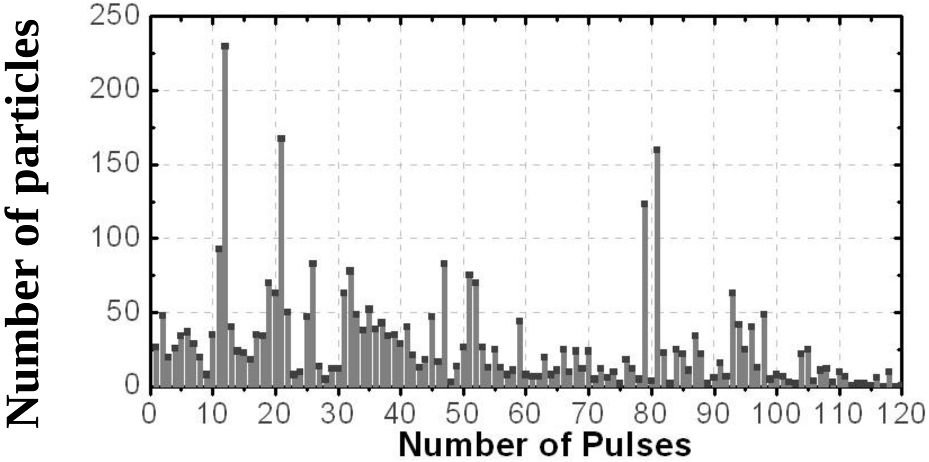
V.A. Makhlaj et al. J. of Nucl. Mat. 438 (2013) S233

Heat load above melting threshold

Melt motion

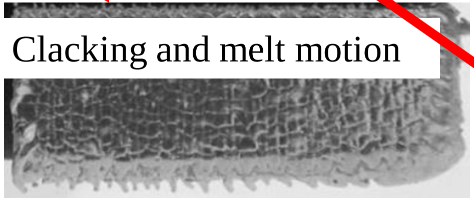
Q= 0.9 MJ/m^2, 120 pulses





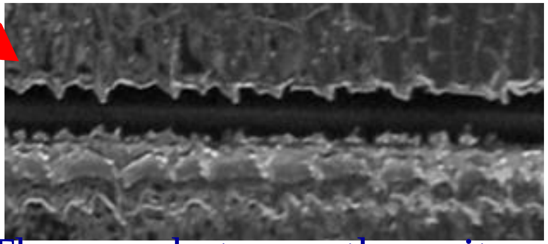
- The particles emission has a threshold character and a cyclic nature.
- The destroyed protuberances and bridges can be additional sources of emitted particles.

Protuberances develop



Clacking and melt motion

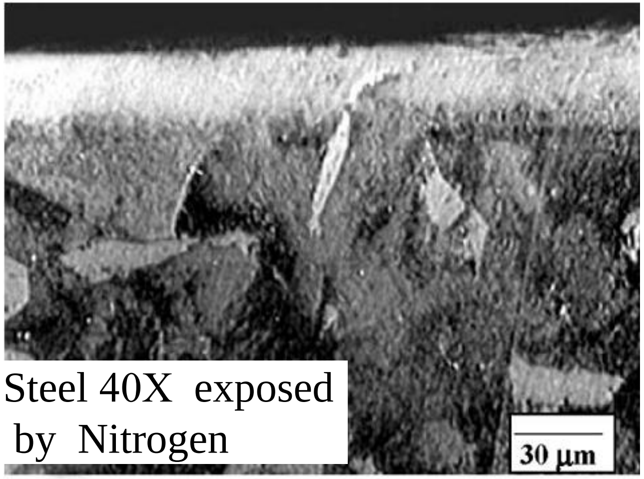
- The protuberances appear on the edges due to the motion of molten layer and develop of Rayleigh–Taylor instability

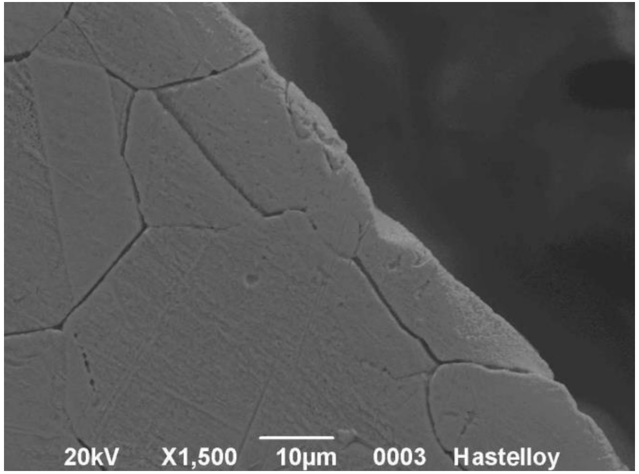


- The gaps between the units are covered by melted material (so-called bridges)

S.S. Herashchenko, et. al. Prob. At,. Sci and Tech 2017, №1(107), p. 119)

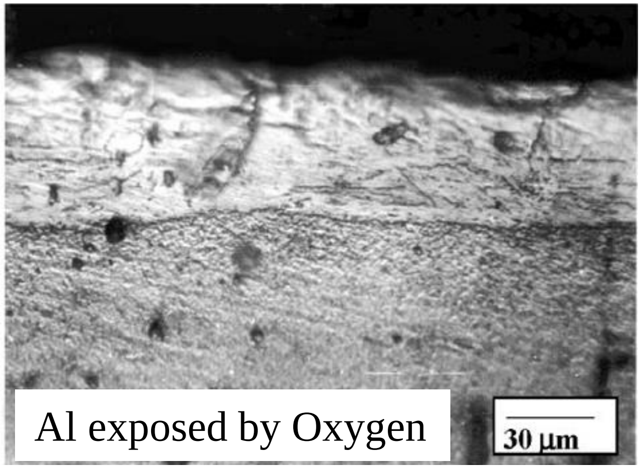
Cross-sections of processed samples

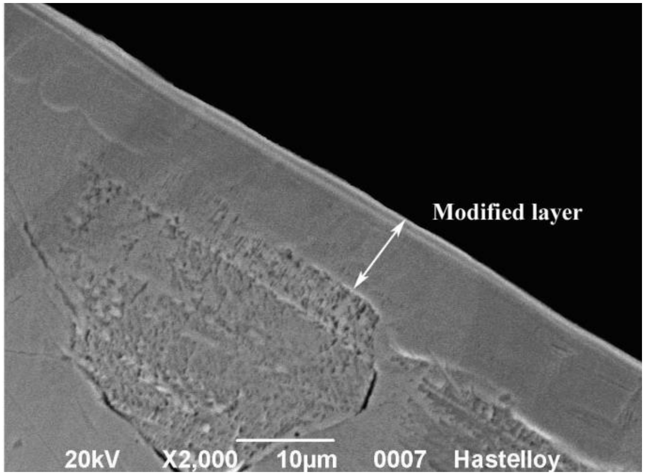

Steel 40X exposed by Nitrogen



Cross-sections Hastelloy

before


Al exposed by Oxygen

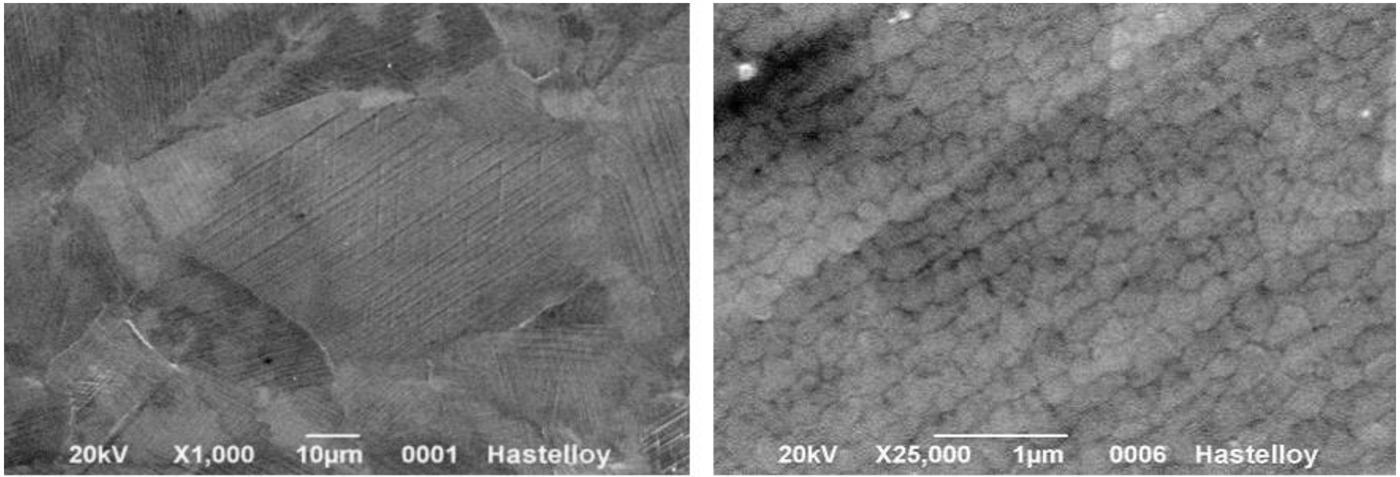


and after plasma treatment

Modified layer is not a coating, it is just modified substrate material (no problem with adhesion)

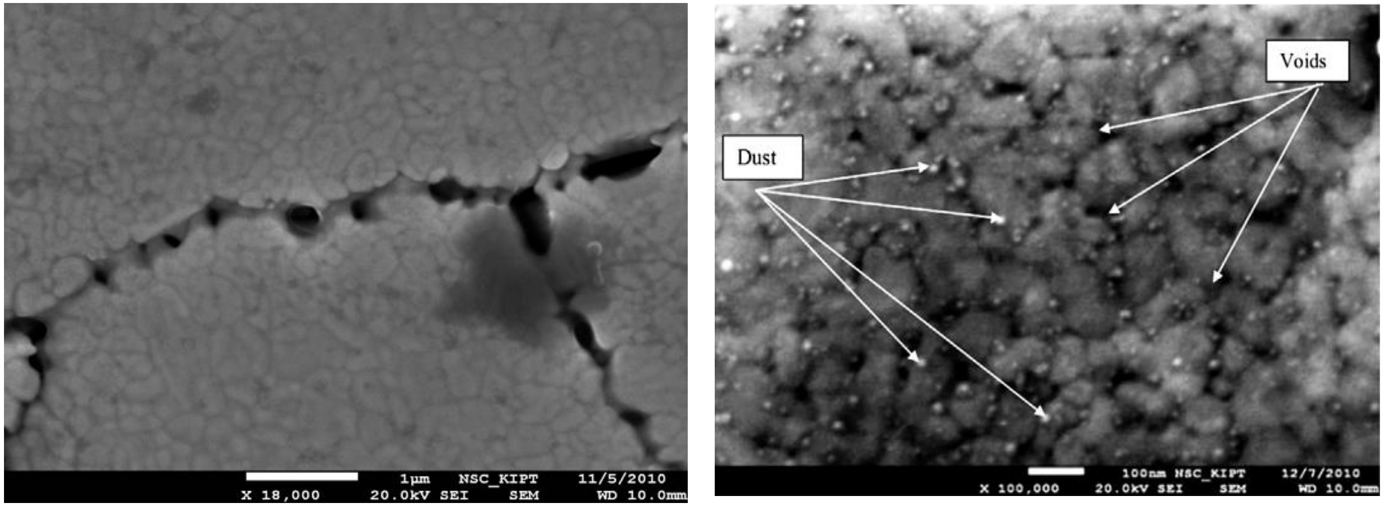
O. Byrka et.al. Acta Technica 56 (2011), T362

Creation of unique surface structures



O. Byrka et.al.
Acta Technica
56 (2011), T362

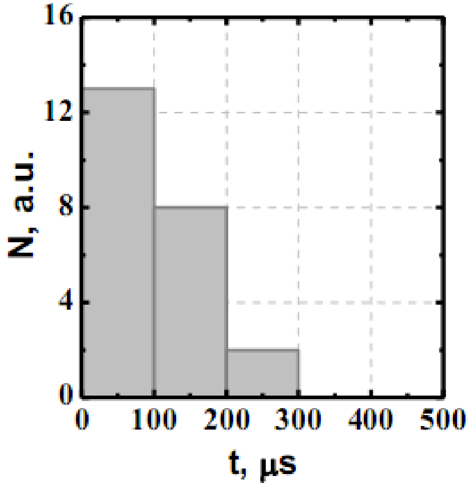
Typical “large-scale" grain of the Hastelloy and structures fine cellular structure inside the grains with submicron- and nano-dimension

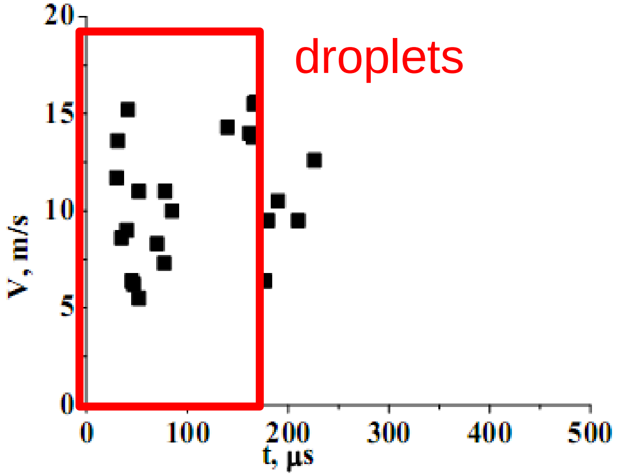


V.A. Makhlaj et al.
J. of Nucl. Mat.
438 (2013) S233

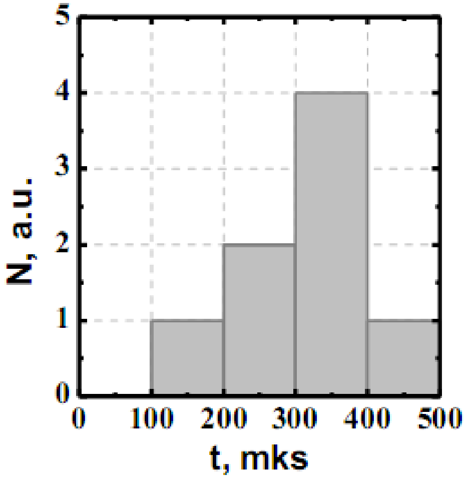
SEM images of the tungsten surface plasma of 0.75 MJ/m^2 and 0.45 MJ/m^2

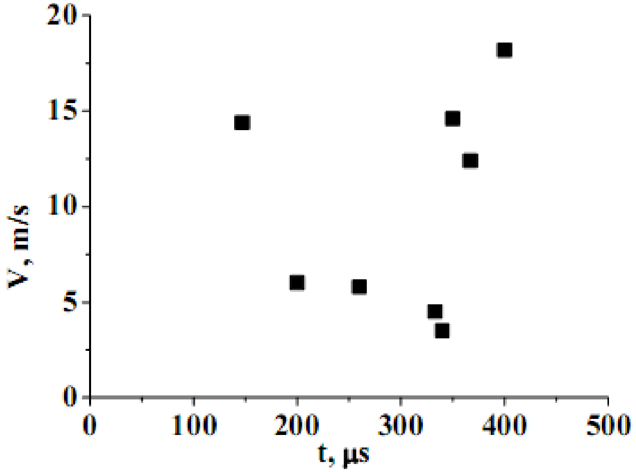
Damaging of castellated targets coated with tungsten





Heat load
above
melting
threshold





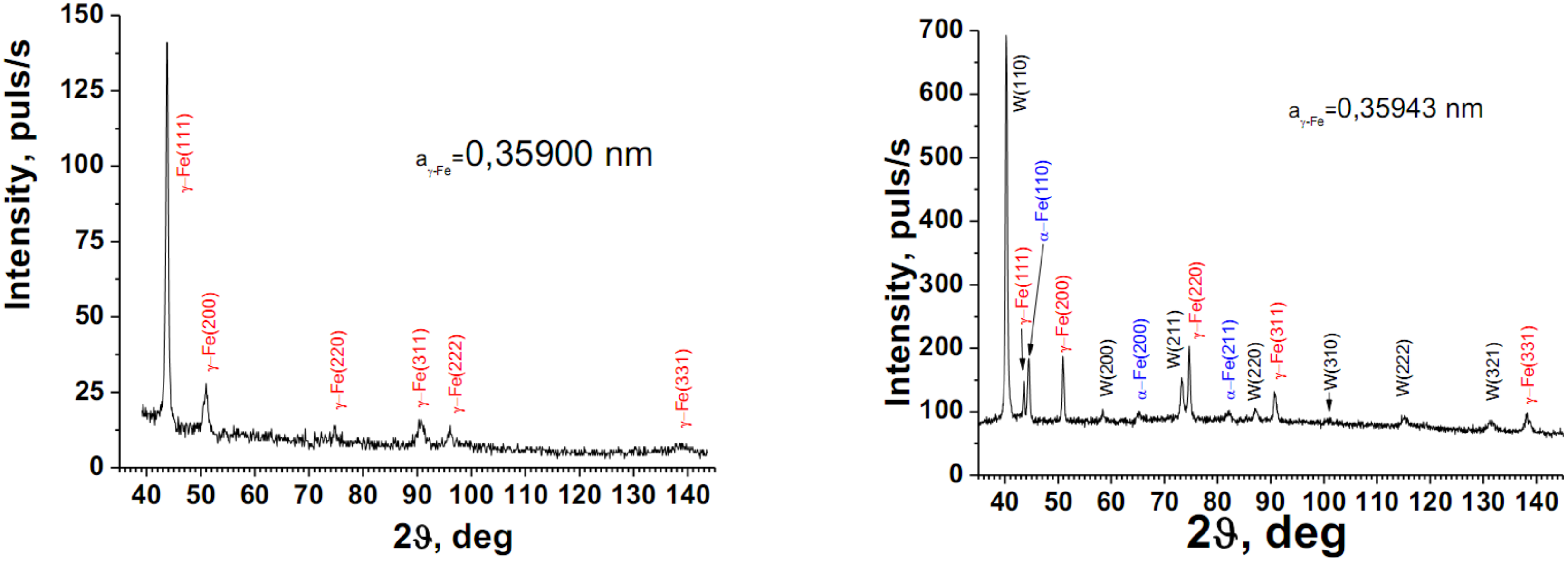
Heat load
below
melting
threshold

The main damage mechanism of the W-coated castellated target was associated with the coating cracking and dust particles emission, while in the case of the surface melting the droplets emission was dominant.

I.E. Garkusha et. al. Phys. Scr. 91 (2016) 094001

Coatings modification under heat load above melting threshold

Diffraction patterns (Cu-Kα irradiation) of Cr18Ni10Ti stainless steel (analog SS321)



Initial

preliminary coated with tungsten (W) and exposed by powerful plasma streams

- α-Fe phase is recognized together with lines of γ-Fe phase and W on exposed surfaces.
- Lattice spacing of γ-Fe in stress free state increased from 0.359 nm up to $a_{\gamma\text{-Fe}}$= 0.35943 nm.
- The concentration of tungsten achieved 2 a.p. in modified layer.
- Tungsten penetrated up to 0.38 μm in depth of modified layer.
- Presence of tungsten leads to decrease of sputtering rate of stainless steel surface.

V. A. Makhlaj , et. al. Prob. At,. Sci and Tech 2016, №6(106), p. 129)

Alloying of surface layers of steel EP-823 under pulsed plasma treatment

element	initial	Modified Mo coatings		Only Plasma irradiation
C	0,167	1,73	2,51	0,44
Si	1,3	1,25	2,5	2,3
Mn	0,82	0,064	0,37	1,4
Cr	12,1	1,15	6,24	18,15
Ni	1,7	0,14	0,6	1,75
Mo	**0,46**	**23,8**	**25,8**	**0,45**
W	0,62	0,58	0,66	0,68
V	0,34	0,024	0,16	0,6
Nb	0,24	0,25	0,22	0,2
N_2	0,026	0,14	0,66	0,054
O	0,155	0,93	2,48	0,62
Ti	0,0046	0,4	0,15	0,005
Co	0,055	0,01	0,002	0,023

Possibility of the modified surface layer creation alloyed with Mo or W for subsequent deposition of thick protective coatings.

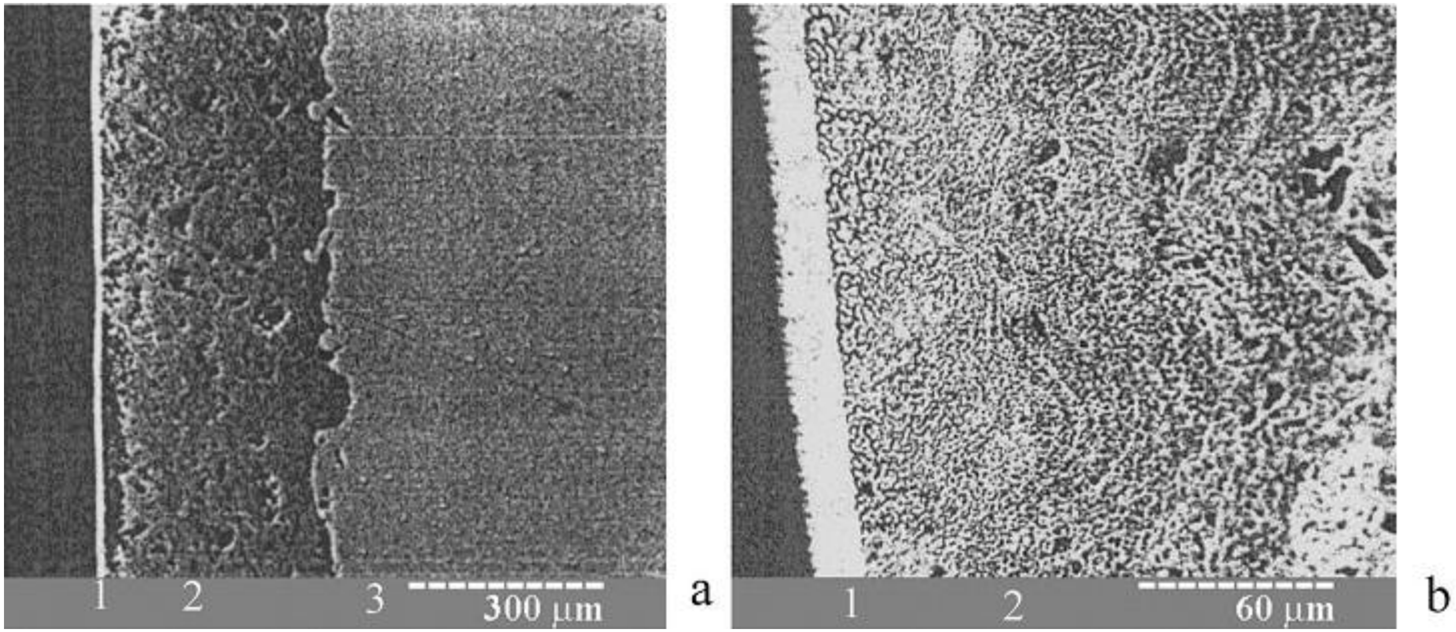
Aim: resistance to corrosion in salts and liquid lead.

Microhardness (Hv [kg/mm^2]) of modification steel EP-823.

	initial	5 pulses- 9×10^{18} ion/cm^2	10 pulses - 1,8×10^{19} ion/cm^2
EP-823 + Mo	**400 kg/mm^2**	**450 kg/mm^2**	**480 kg/mm^2**
EP-823	**400 kg/mm^2**	**400 kg/mm^2**	**385 kg/mm^2**

V. A. Makhlay , et. al. Eur. Phys. J. D **54**, 185–188 (2009)

Modification of thick coatings



Cross sections of modified layers on *Co-32Ni-21Cr-8Al-0.5Y* coatings processed with nitrogen plasma under different magnifications.

1 – modified surface layer; 2 – MCrAlY coating structure; 3 – substrate material.

Inconel 738

1. Size of grains (from tens μm till hundreds nm)
2. Number of porosity in surface layer of coating decreased
3. Roughness of surface decreased

V. A. Makhlay , et. al. Eur. Phys. J. D **54**, 185–188 (2009)

Conclusions

- Highest energy plasma loads are applied for material characterization in extreme conditions.

The detailed experimental studies of threshold values for the damaging processes:

- ❖ roughening, crack formation, evaporation
- ❖ formation of shielding layer
- ❖ melting of the Plasma Facing Components,
- ❖ dust generation

- Moderate short pulsed plasma loads are used for surface modification issues
  - ✓ considerable improvement of physical and mechanical properties of different materials
  - ✓ pre-deposited coating modification and mixing by impacting plasma streams

QSPA –M , December 2015

Visit of EU delegation in NSC KIPT on QSPA-M facility, September 2015

QSPA –team, November 2014

Thank you so much for your attention