ITER ELM's SIMULATION WITH PLASMA ACCELERATORS

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Motivation

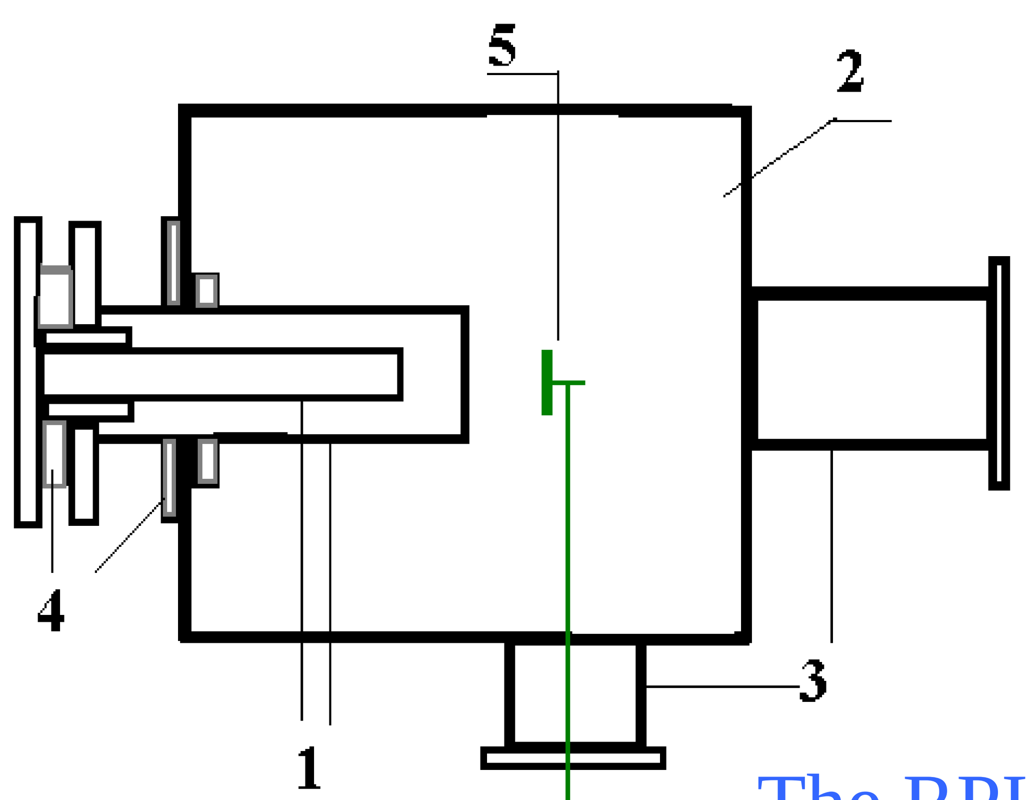
Important issue for ITER divertor targets is determination of surface erosion under Edge Localized Modes (ELM) of Q = (1-3) MJm^{-2} during t = (0.1-0.5) ms for each event. The simulations with large numbers of plasma impacts at different energy densities on tungsten targets are required for estimation of tolerable size of ELMs and identification of main erosion mechanisms of materials relevant to ITER . Other important issue that need to be studied experimentally in the ITER simulation conditions is behavior of divertor materials under the helium ions bombardment during multi-pulsed repetitive ELM-like plasma loads, which are below/close to the melting threshold. The effects of helium ions impact (blistering, flaking), helium dynamics in surface layers, its influence on cracking development in tungsten (helium retention in microcracks volume) are still actual topics.

Material response to multiple exposures: QSPA, pulsed plasma guns, E-beams are used

Investigations of residual stresses in the surface layers of exposed tungsten targets. Its correlation with cracking and influence on tungsten damage in dependence on the exposition doses and heat loads.

Results of QSPA and PPA plasma exposures are compared also with short-pulse PSI experiments (τ~ 0.1-5 µs) with a pulsed plasma gun and dense plasma-focus facilities in Poland, aiming at studies of a surface damage and tungsten impurities behaviour in near-surface plasma formed in front of the target.

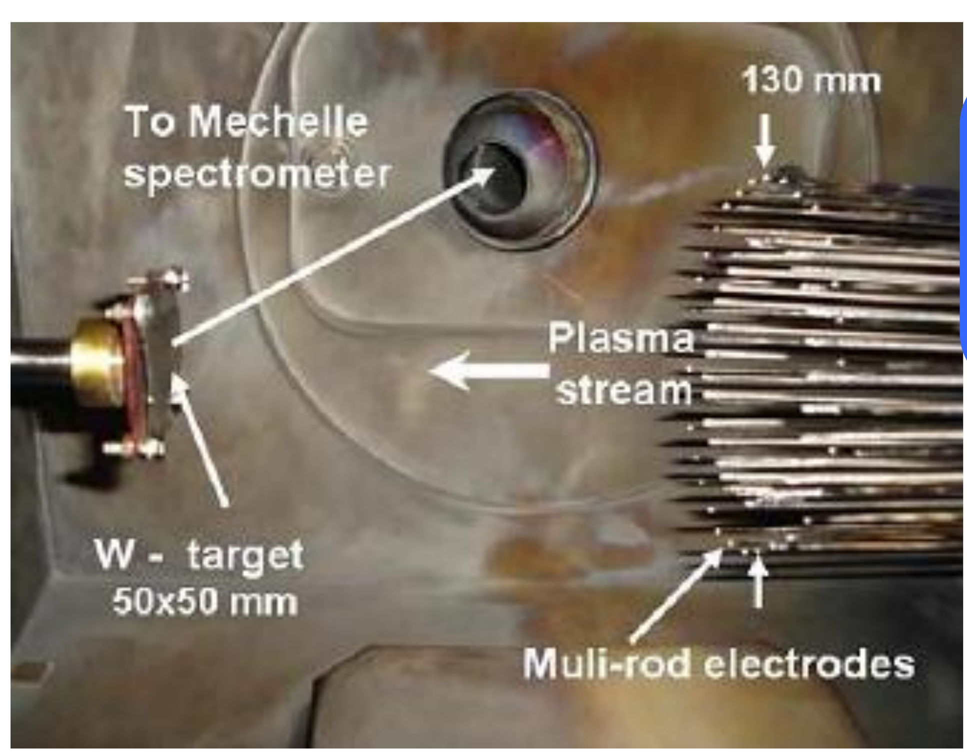
PPA



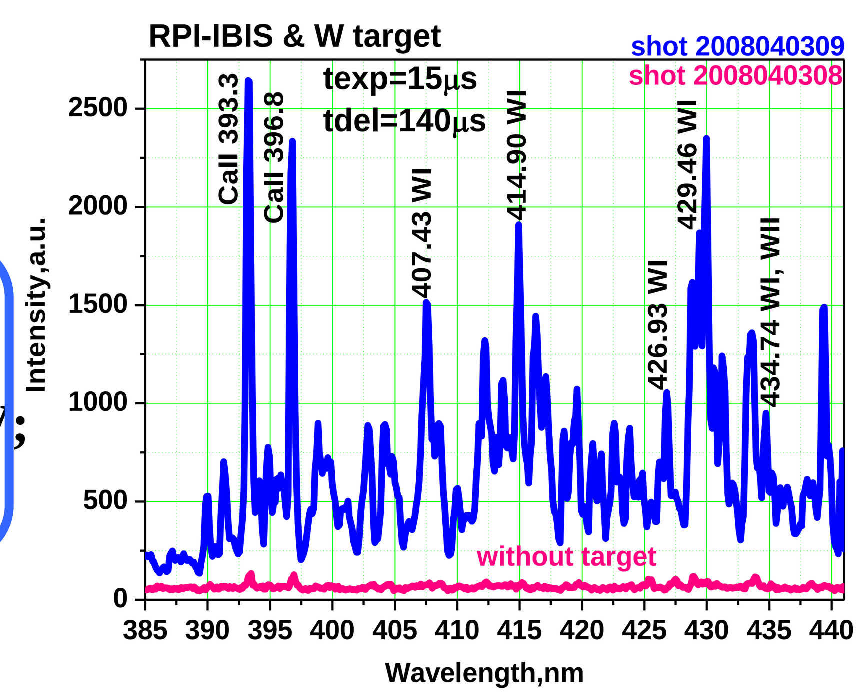
The pulsed plasma accelerator PPA generates plasma streams with ion energy up to 2 keV, plasma density (2-20) × 10^{15} cm^{-3}, a maximum specific power of about 10 MWcm^{-2} and plasma energy density varied in the range of (5-40) Jcm^{-2}. The plasma stream duration was 3-6 µs. Both, helium and hydrogen were used as working gases.

1-palsed plasma accelerator, 2- vacuum chamber, 3- vacuum ports, 4-isolators, 5 -target

The RPI-IBIS facility

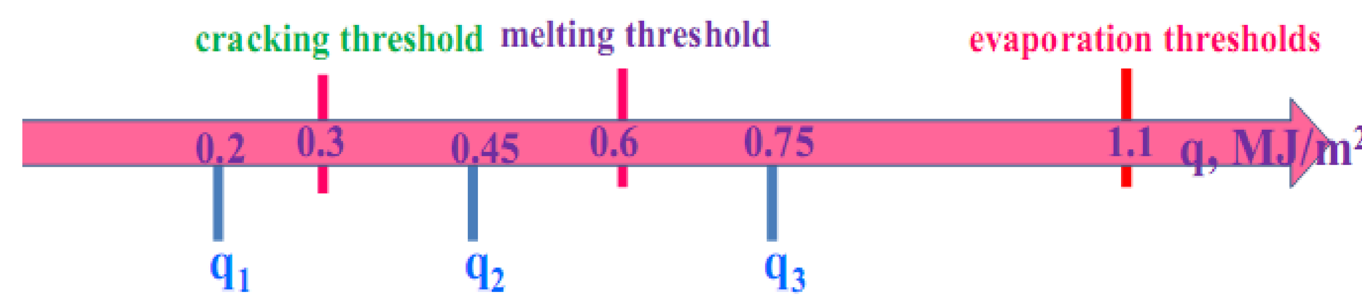


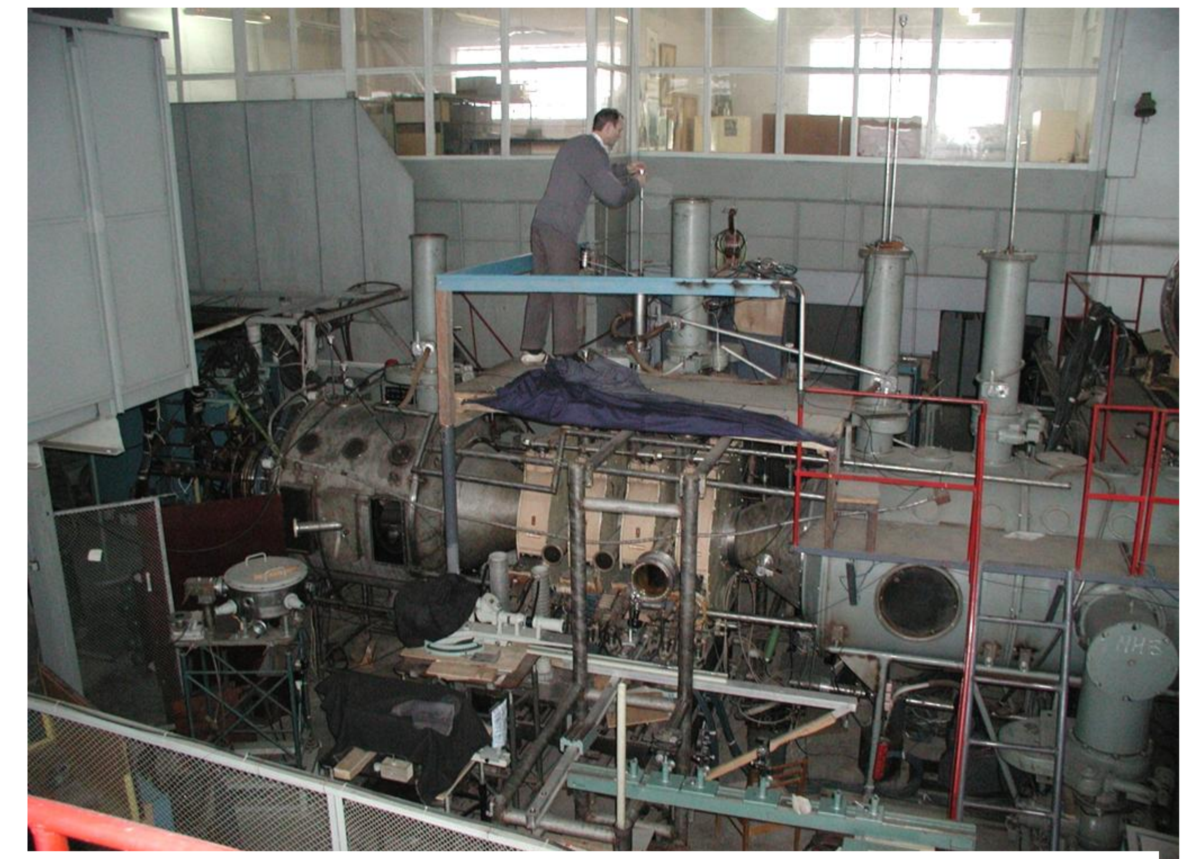
Pulse duration τ,=1-3 µs ;
Plasma density N_e , 3*10^{16}cm^{-3} ;
Plasma temperature T, 3-5 eV;
Energy density ρ_w, 14 mJ/m^2



In experiments with RPI-IBIS device was recorded and identified in spectra some distinct WI and WII lines. It was possible due to the use of a short pulse length (1-5 µs) and a successful choice of a time delay (τ) and the time of exposure during the spectra recording

QSPA Kh-50

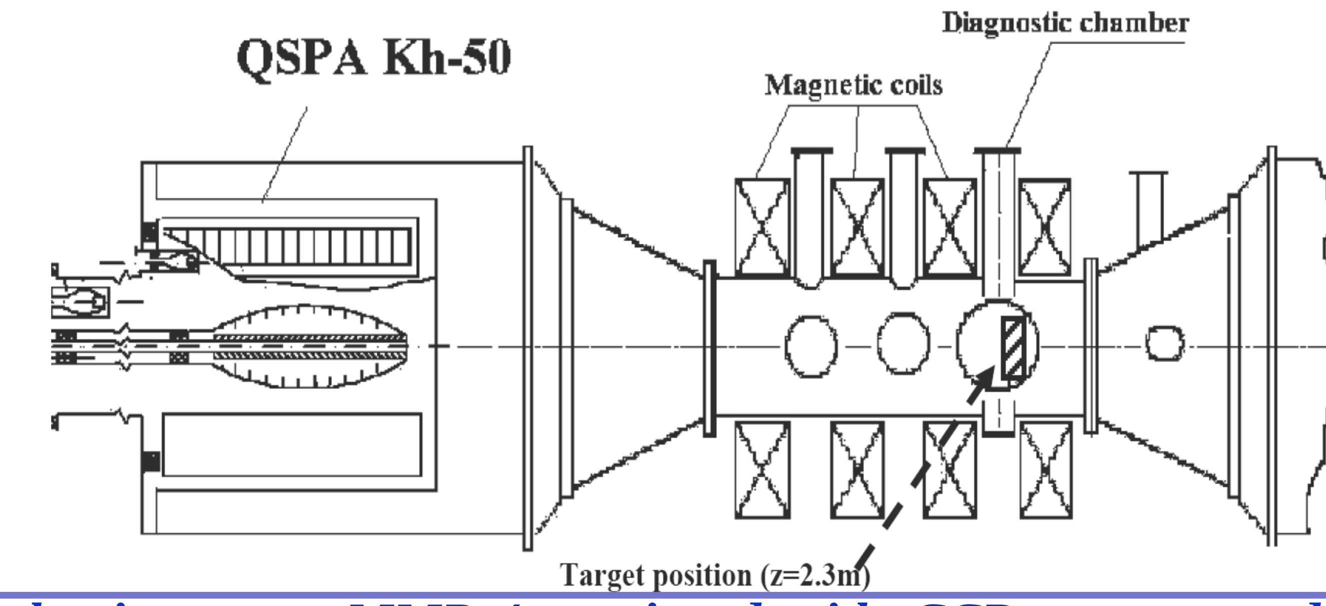




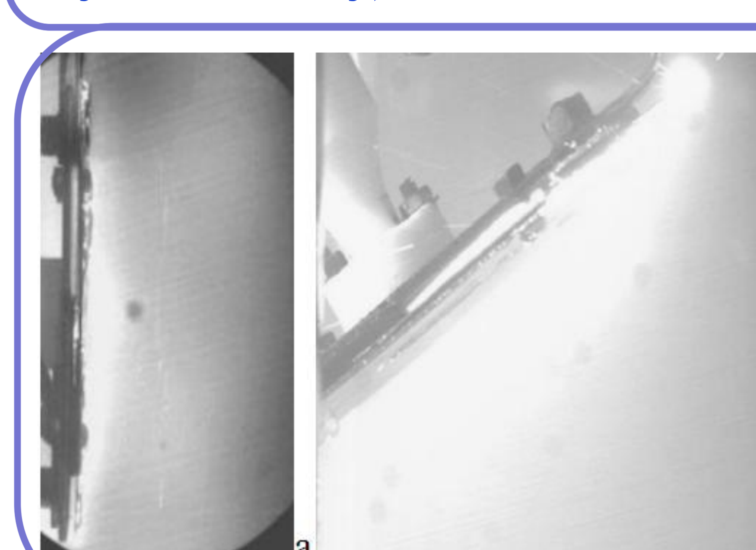
Energy density ρ_w = (0.5…30) MJ/m^2,
Plasma pulse duration τ ≈ 0.25 ms;
P_{max} = (3-18) bar, n = (0.2-5) 10^{16} cm^{-3};
B_0 =0.54 T (β ≈ 0.3…0.4);
Diameter of plasma stream- 15 cm

Heat load

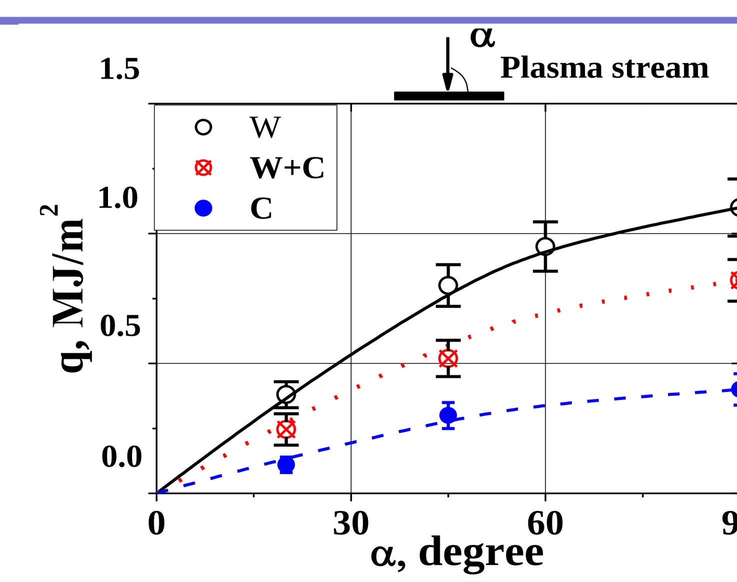
- **q_1=0.2 MJ/m^2; below the tungsten cracking threshold**
- **q_{cth}= 0.3 MJ/m^2 tungsten cracking threshold**
- **q_2=0.45 MJ/m^2; between the cracking – and melting thresholds**
- **q_3=0.75 MJ/m^2 between the melting- and evaporation thresholds**



Surface analysis was carried out with an optical microscope MMR-4, equipped with CCD camera and with Scanning Electron Microscopy (SEM). Measurements of weight losses and microhardness of the surface were performed. XRD method was applied for structure analysis and measurements of stresses in thin surface layer (X-ray tensometry)

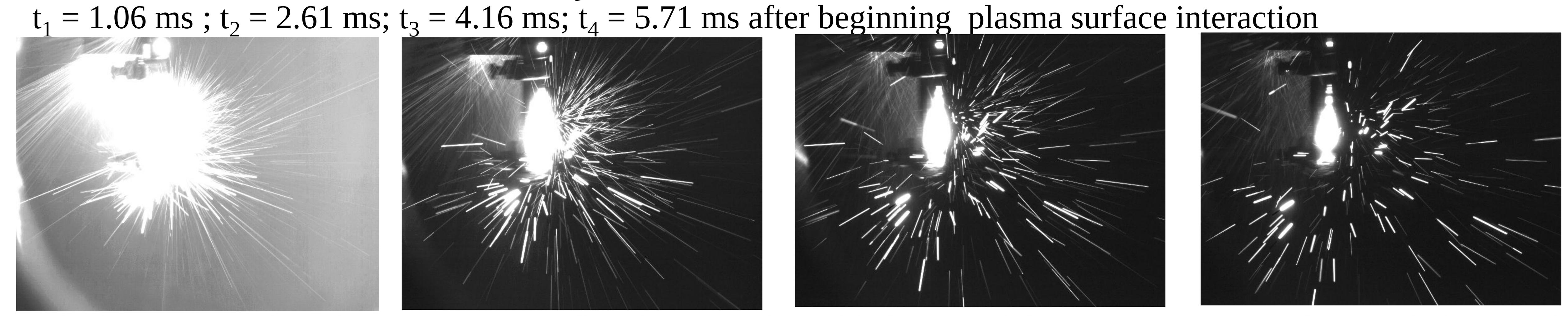


Images of plasma stream interaction with the target for t= 30 µs after beginning of plasma-surface interaction: a- normal impact, b- inclined; t_{exp}= 1.2 ms



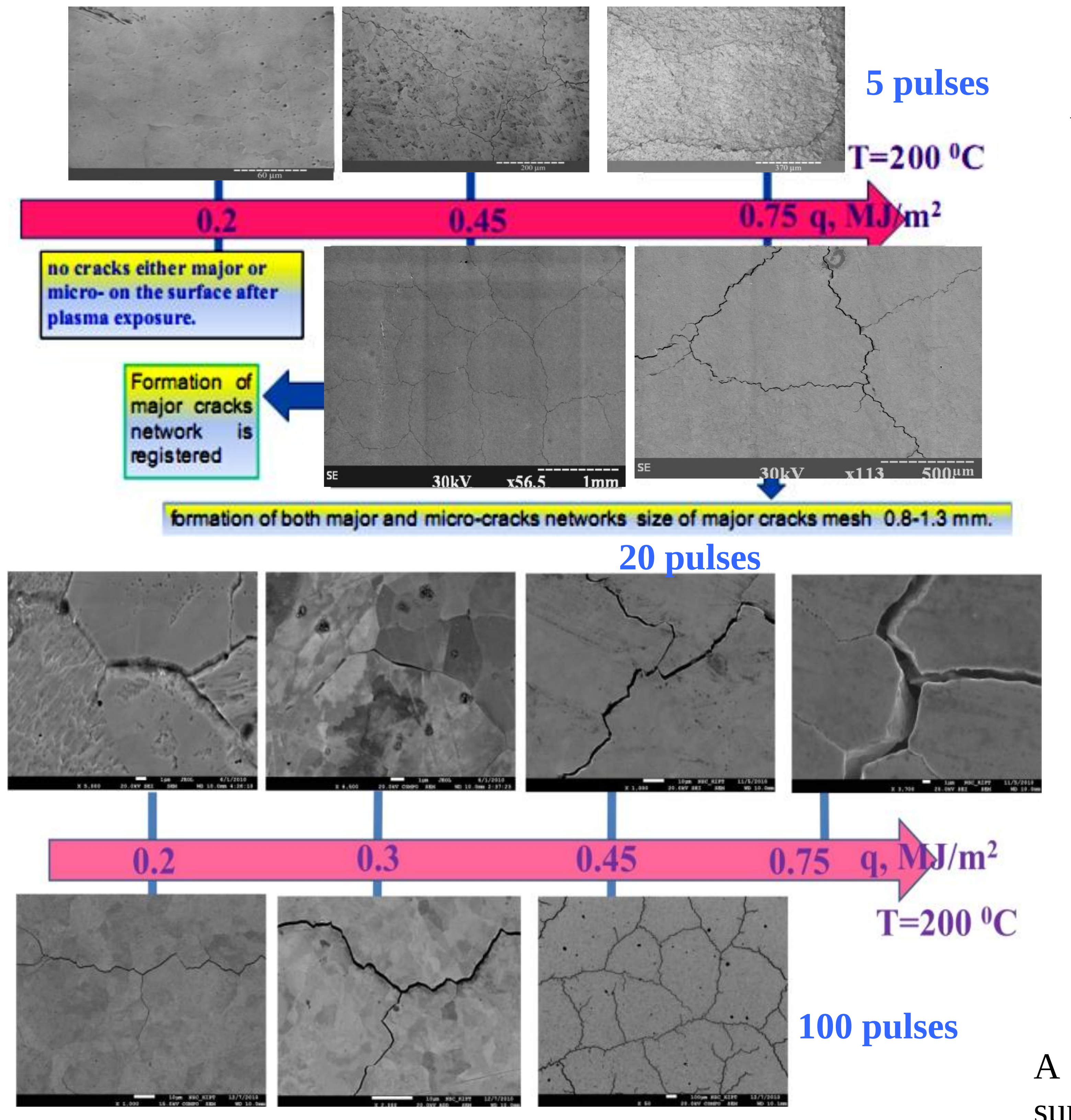
Heat load to target surfaces vs. incidence angle of impacting plasma stream. Plasma energy density is 2.4 MJ/m^2

Droplets splashing from tungsten melt t_{exp}= 1.55 ms,
t_1 = 1.06 ms ; t_2 = 2.61 ms; t_3 = 4.16 ms; t_4 = 5.71 ms after beginning plasma surface interaction



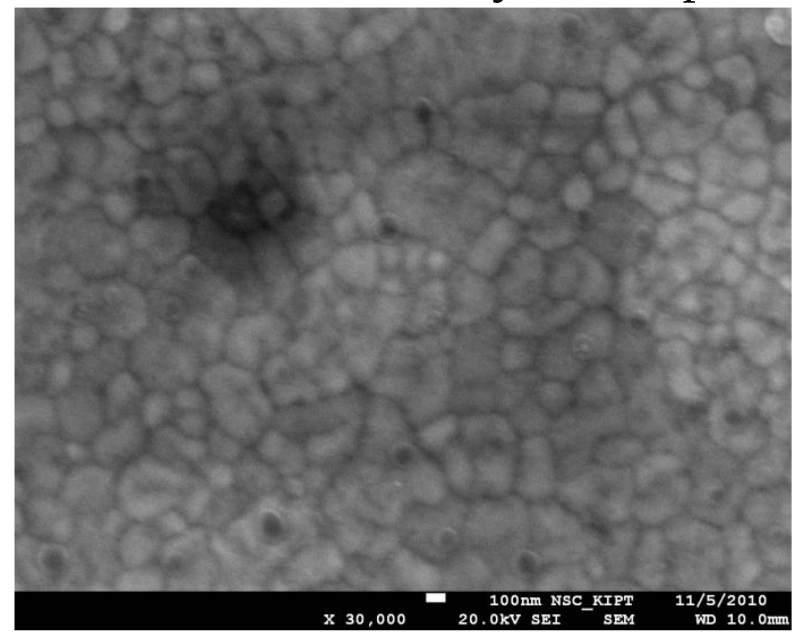
Fast droplets are generated at earlier time moments. Smaller velocities are observed for late stage of observation. During intermediate stage both groups of droplets with fast and lower velocities are observed

SEM images of tungsten surface after 5, 20 and 100 QSPA pulses of different heat load T_0 =200 ^{0}C

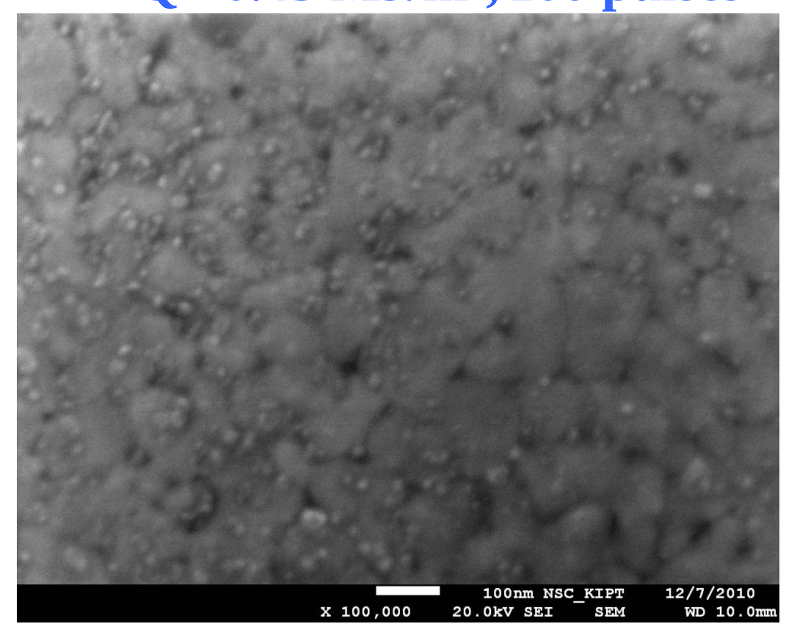


Q= 0.75 MJ/m², 20 pulses

submicron- and nano-sized cellular structures in the modified surface layer of exposed W targets

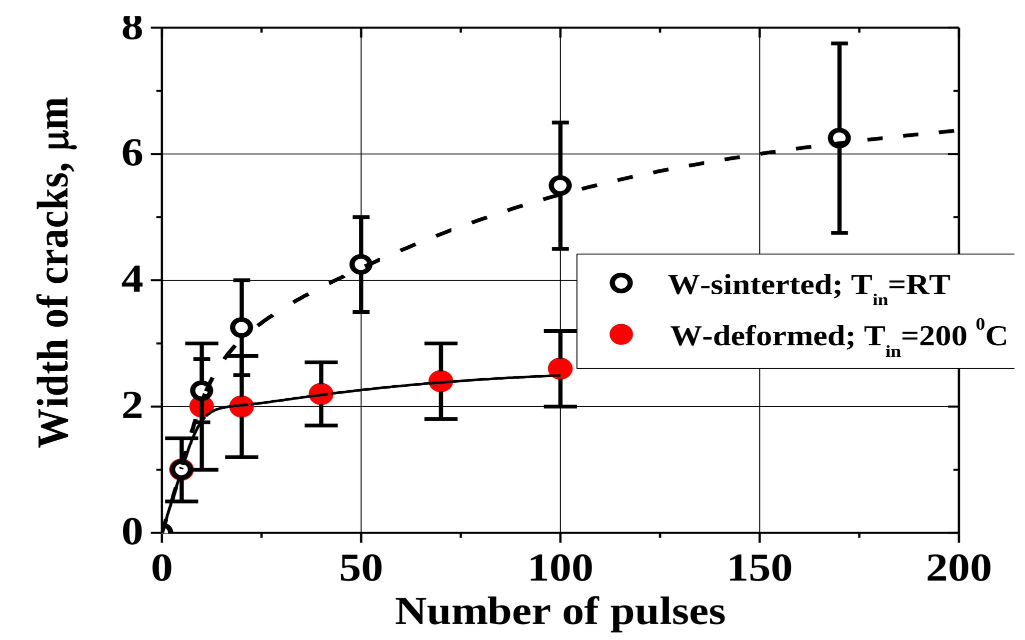


Q= 0.45 MJ/m², 100 pulses

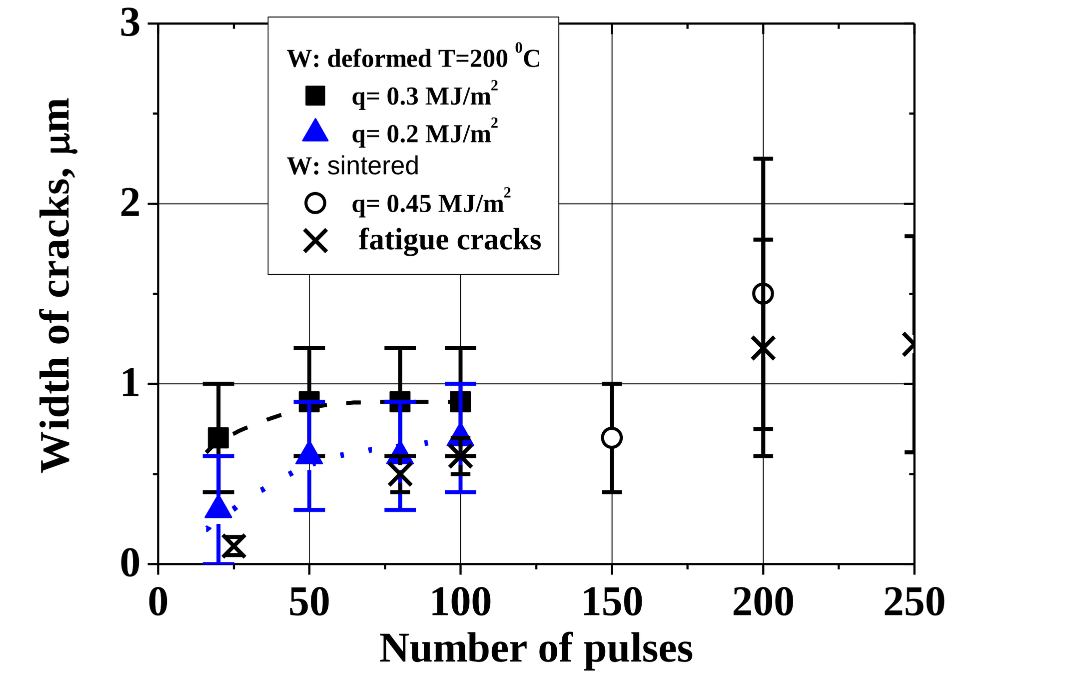


A lot of nano-particles are observed on the surface on the edges of submicron cells.

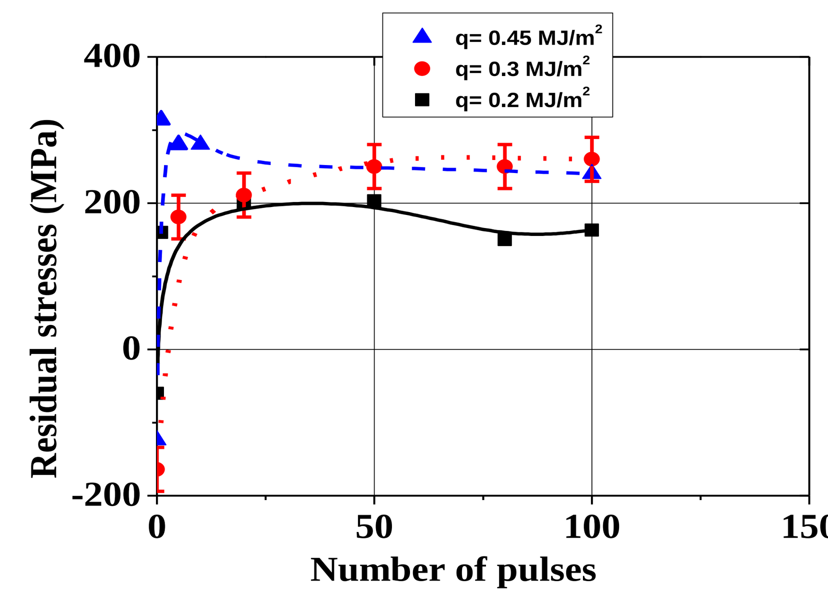
Width of macro cracks on tungsten surfaces' of different grades v.s. number of plasma pulses of 0.45 MJ/m².



Comparison of cracks' width on tungsten surfaces of different grades v.s. number of plasma pulses.



Future increase of irradiation dose led to fast rise of width of cracks for non-deformed (sintered) targets. Crack width achieved 6 μm for this W-grade exposed by 100 plasma pulses. At the same time width of macro cracks is almost 2 times less for deformed tungsten.



Residual stresses in preheated to 200 ^{0}C tungsten targets versus the number of plasma pulses of 0.20 MJ/m² ; 0.3 MJ/m², 0.45 MJ/m² .

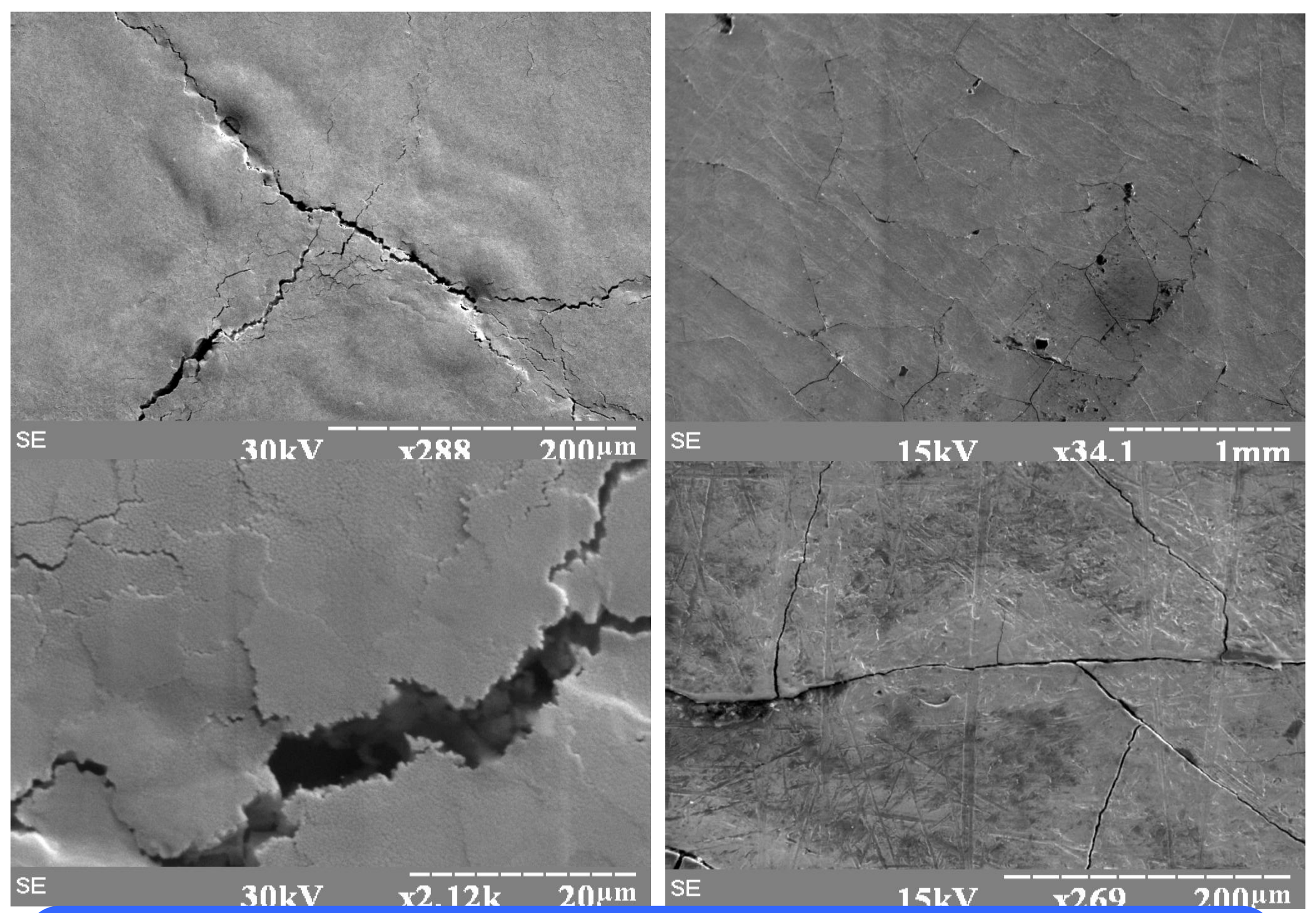
❖The diffraction profiles lightly changes as a result of hydrogen plasma exposures below melting threshold.

❖The large density of defects on tungsten surface causes a broadening of line after helium plasma irradiation.

❖Plasma treatments lead to annealing of material and perfection structure.

❖The value of a_0 initially grows, but then decreases with increasing number of plasma pulses with heat load above melting threshold.

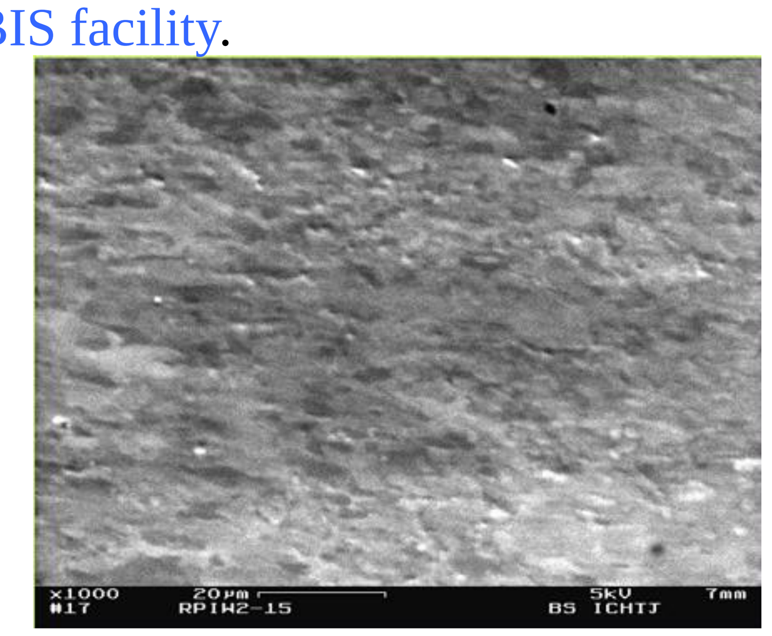
Cellular structure appear in re-solidified tungsten surface. The cell sizes are about 100-300 nm.



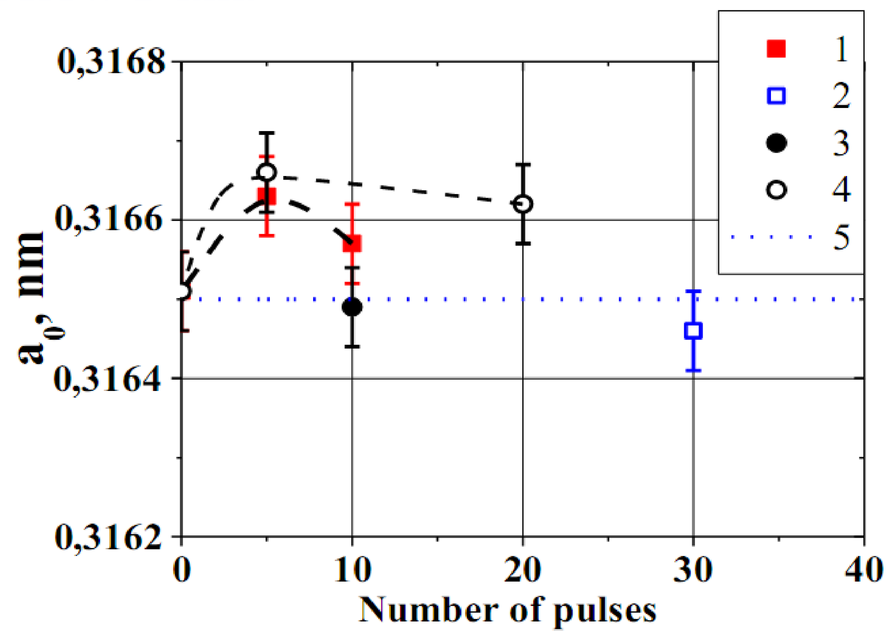
Helium Hydrogen
SEM views of tungsten surface after 10 PPA plasma pulses with heat load above melting threshold

- *Major cracks:*
  - *distance between cracks: 0.35-0.6 mm and 0.25-0.7 mm for PPA helium and hydrogen plasma, accordingly; 0.5–1 mm for QSPA hydrogen plasma streams.*
  - *Width cracks: 4-6 μm for helium and 5-10 μm for hydrogen PPA plasma; 4-6 μm for QSPA plasma streams*
- *Intergranular micro-cracks*
  - *Distance between cracks 15 -20 μm;*
  - *Width cracks about 0.5 μm.*

SEM image of the W-target surface, which was partially destroyed by the pulsed plasma-deuteron streams with in theRPI-IBIS facility.



From this measurements erosion depth was estimated to be below 5 um.



Lattice spacing in the stress-free section of rolled tungsten targets versus the number of pulses of helium (1 - 0.4 MJm^{-2}(PPA); 2 - 0.2 MJm^{-2} (PPA)) and hydrogen (3 0.4 MJm^{-2} (PPA); 4 0.75 MJm^{-2} (QSPA)) plasmas and reference value (5).

Formation of helium-vacancy complexes causes change of lattice spacing and higher level of residual stresses under helium plasma impact.

Conclusions

❖Features of tungsten erosion under repetitive plasma heat loads up to 1.1 MJ/m² lasting 0.25 ms, which are relevant to ITER Type I ELMs, has been investigated. Influence of target inclination and neighborhood W and C as divertor components on the material response to the repetitive plasma heat loads was analyzed.

❖ Cracking thresholds and crack patterns (major- and micro-) in tungsten targets as well as residual stresses after repetitive plasma pulses have been studied for a deformed W material (Plansee AG). Monolithic tungsten which is manufactured according to this technology is considered as ITER-reference grade. The elongated grain orientation was perpendicular to the surface.

❖ Initially, the energy threshold for cracking development is found to be ~0,3 MJ/m² for small number of QSPA K-50 pulses (< 20) of 0.25 ms duration and triangular pulse shape. The clear decrease of energy threshold for cracking development was found for grooving number of repetitive plasma pulses. Even if there are no cracks at all for applied low heat load and small irradiation dose, nevertheless there are appeared cracks on tungsten surface after more than 20 plasma pulses of heat load of 0.2 MJ/m².

❖ The Ductile-to-Brittle Transition occurs in the temperature range of 200 ºC ≤ T_{DBTT} < 300 ºC. For initial target temperature T_0 > 300 C no major cracks are formed on the exposed surface.

❖ Residual stress grows with increase of energy load. Some relaxation of stresses is observed for large number of pulses. Melting of surface layer essentially add to the relaxation of stresses, the residual stress became very small after 20 pulses with melting. For plasma loads below the melting threshold the residual stress is still essential even after 100 pulses in spite of some initial decease with plasma pulses for Q= 0.45 MJ/m². After many pulses stress value is similar for all applied loads (0.2, 0.3 and 0.45 MJ/m²) being on the level of 200-250 MPa.

❖ The described studies of plasma surface interactions have demonstrated that the RPI-IBIS facility can successfully be used for studying of the WI and WII spectral lines emitted from the eroded target material and for research on the plasma interaction with targets made of tungsten, which is of great importance for nuclear fusion technology. .