The Impact of Nonambipolar Energy Flow on Plasma Facing Materials Erosion and Forecast for ITER.

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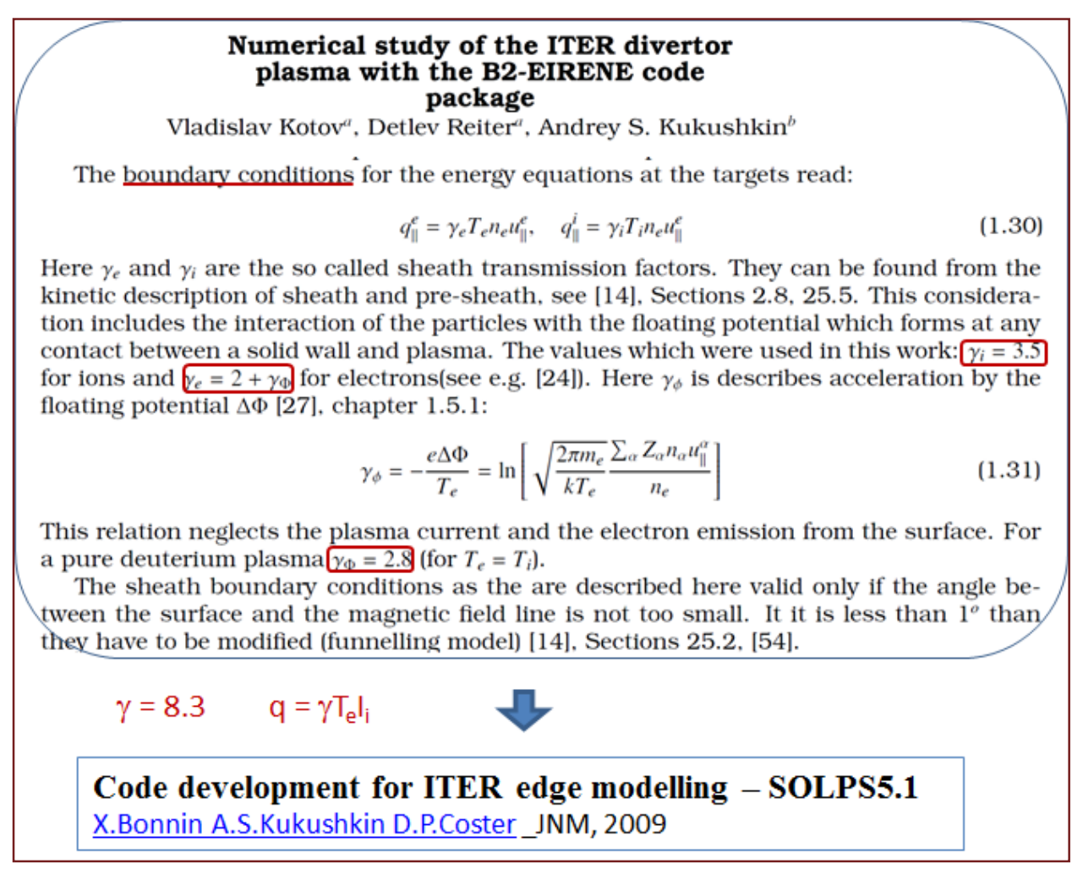
Introduction

Carbon bloom

Hot spot ⇨ Recrystallization
⇨ Melt splashing
(JET safety CCTV system ~ 900 ^{0}C)



Numerical study of the ITER divertor plasma with the B2-EIRENE code package
Vladislav Kotov[a], Detlev Reiter[a], Andrey S. Kukushkin[b]

The boundary conditions for the energy equations at the targets read:

$$q_{\|}^{e} = \gamma_e T_e n_e u_{\|}^{e}, \quad q_{\|}^{i} = \gamma_i T_i n_e u_{\|}^{e} \qquad (1.30)$$

Here γ_e and γ_i are the so called sheath transmission factors. They can be found from the kinetic description of sheath and pre-sheath, see [14], Sections 2.8, 25.5. This consideration includes the interaction of the particles with the floating potential which forms at any contact between a solid wall and plasma. The values which were used in this work: $\gamma_i = 3.5$ for ions and $\gamma_e = 2 + \gamma_\Phi$ for electrons(see e.g. [24]). Here γ_ϕ is describes acceleration by the floating potential $\Delta\Phi$ [27], chapter 1.5.1:

$$\gamma_\phi = -\frac{e\Delta\Phi}{T_e} = \ln\left[\sqrt{\frac{2\pi m_e}{kT_e}}\frac{\sum_\alpha Z_\alpha n_\alpha u_{\|}^{\alpha}}{n_e}\right] \qquad (1.31)$$

This relation neglects the plasma current and the electron emission from the surface. For a pure deuterium plasma $\gamma_\Phi = 2.8$ (for $T_e = T_i$).
The sheath boundary conditions as the are described here valid only if the angle between the surface and the magnetic field line is not too small. It it is less than 1° than they have to be modified (funnelling model) [14], Sections 25.2, [54].

$\gamma = 8.3$ $q = \gamma T_e I_i$

Code development for ITER edge modelling – SOLPS5.1
X.Bonnin A.S.Kukushkin D.P.Coster _JNM, 2009

Materials challenges with fusion plasmas

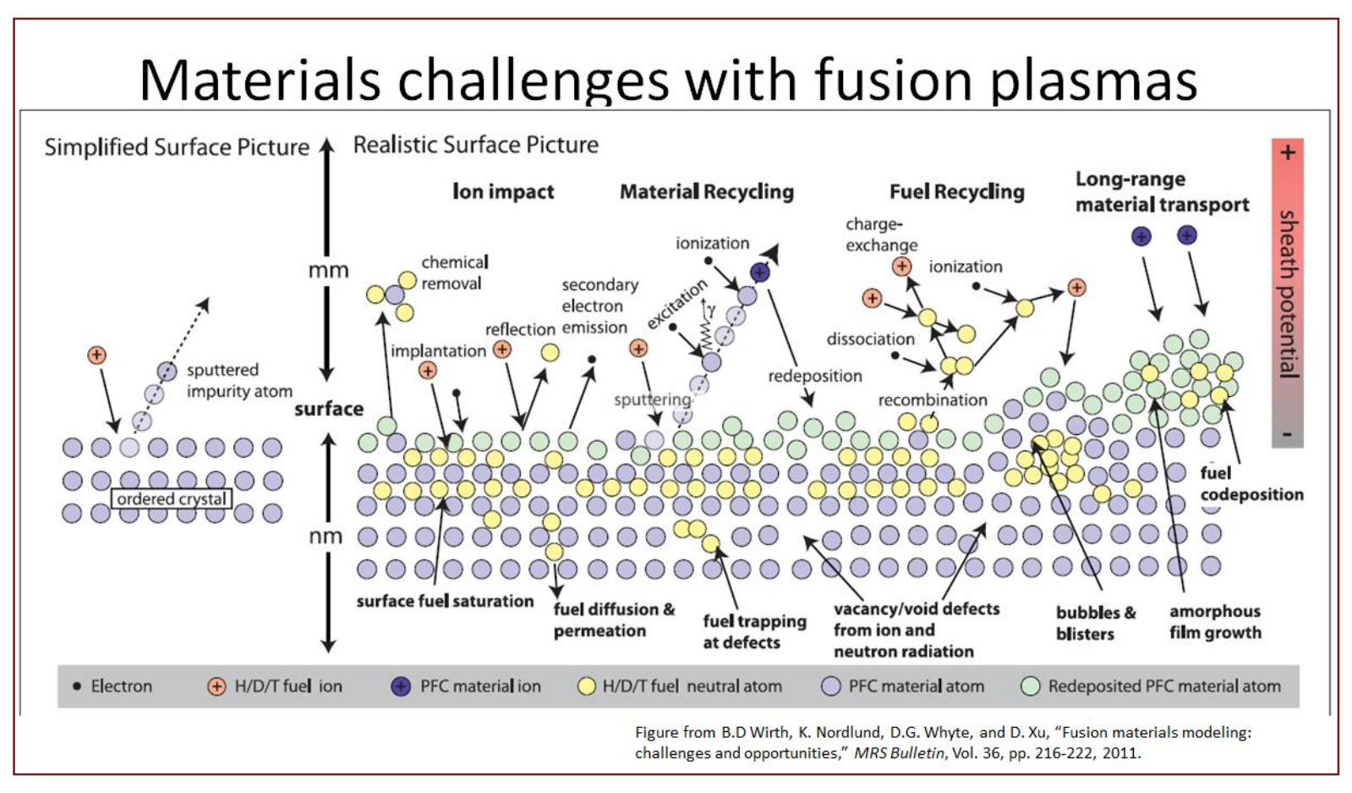
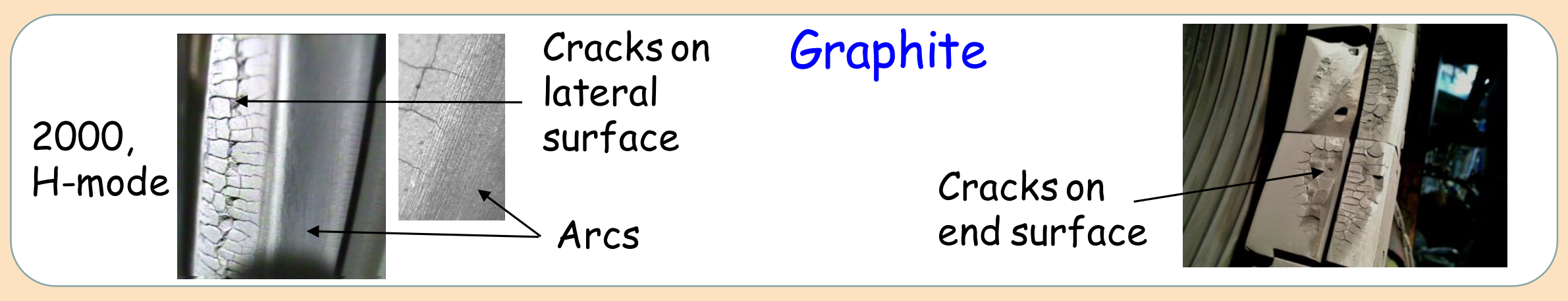


Figure from B.D Wirth, K. Nordlund, D.G. Whyte, and D. Xu, "Fusion materials modeling: challenges and opportunities," *MRS Bulletin*, Vol. 36, pp. 216-222, 2011.

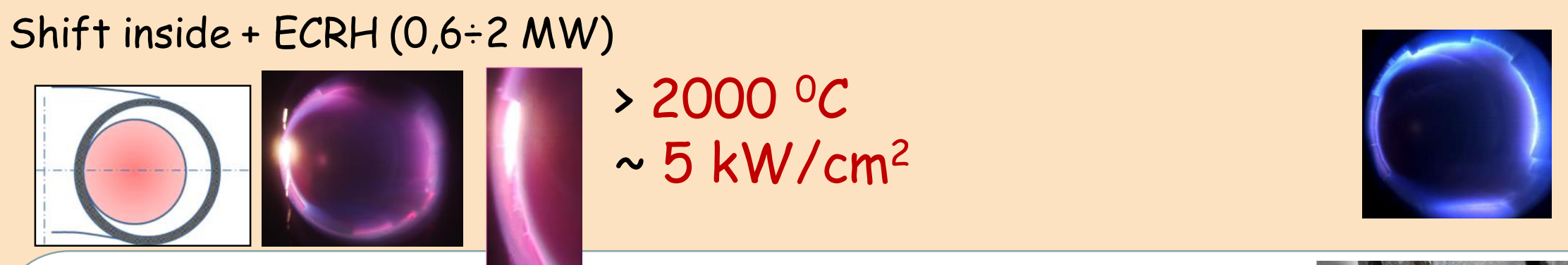
Tokamak T-10, comparison of internall and external C / W tiles

T-10, R=1,5m, a=0,35m, Ip<250kA, ∆t<1 sec, Poloidal (circular) limiter

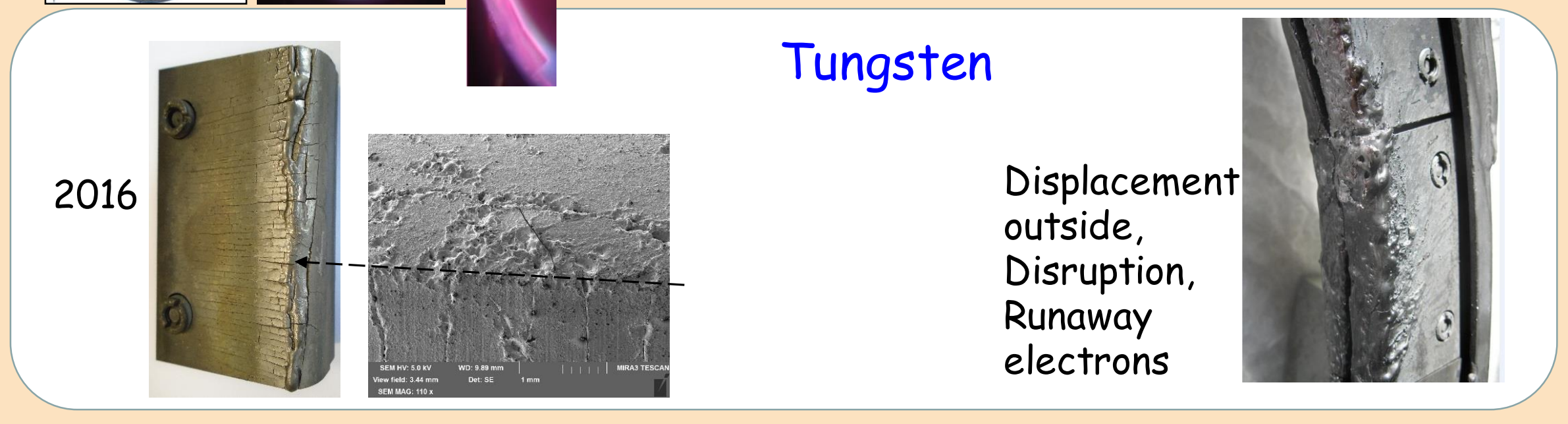
Incide Outside



Shift inside + ECRH (0,6÷2 MW)

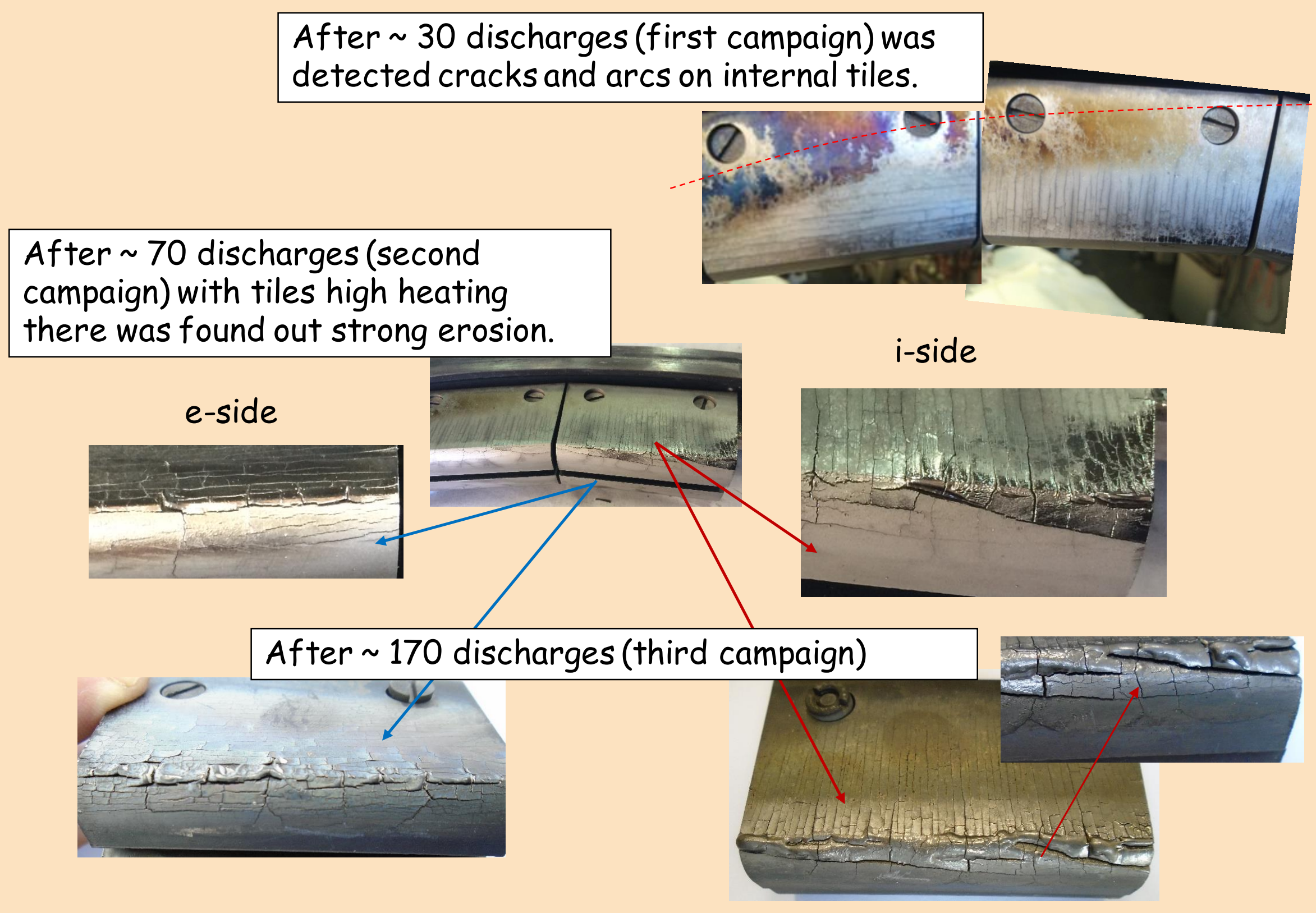


> 2000 ^{0}C
~ 5 kW/cm^2



Erosion of internal and external tiles differ fundamentally. On internal tiles the area of erosion more wider, than λ_q. In opposite to external tiles, all lateral surface of internal tiles cover by strong cracks.

T-10, W tiles / post-mortem analysis / History



After ~ 30 discharges (first campaign) was detected cracks and arcs on internal tiles.

After ~ 70 discharges (second campaign) with tiles high heating there was found out strong erosion.

After ~ 170 discharges (third campaign)

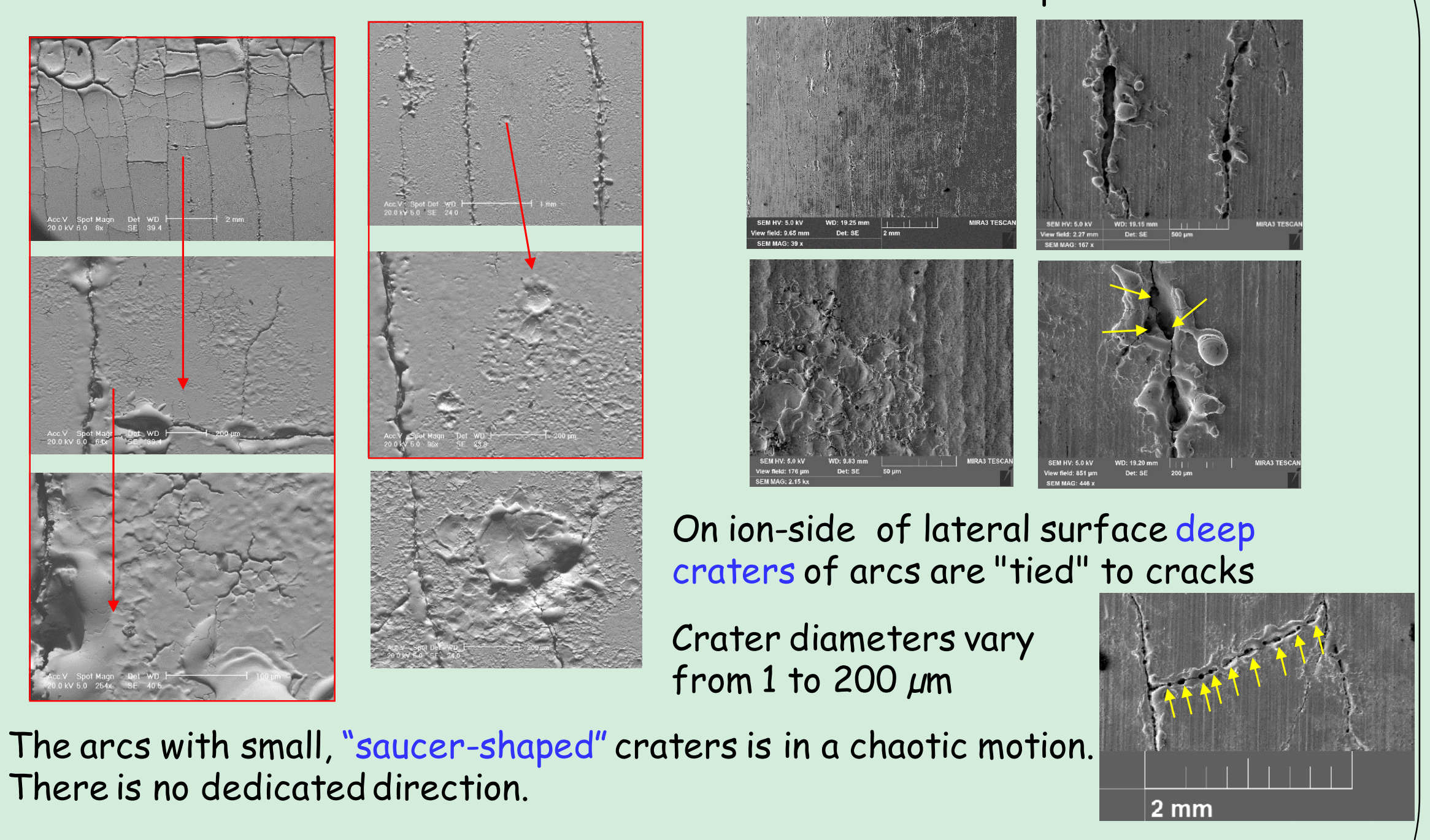
After extreme heating of internal tiles it was detected typical metallic luster of melted metal and many deep, long cracks on both sides of tiles surfaces.

Post-Mortem analysis

T-10, SEM, i-side, Zoo

Wide erosion area

Arcs – the main phenomenon



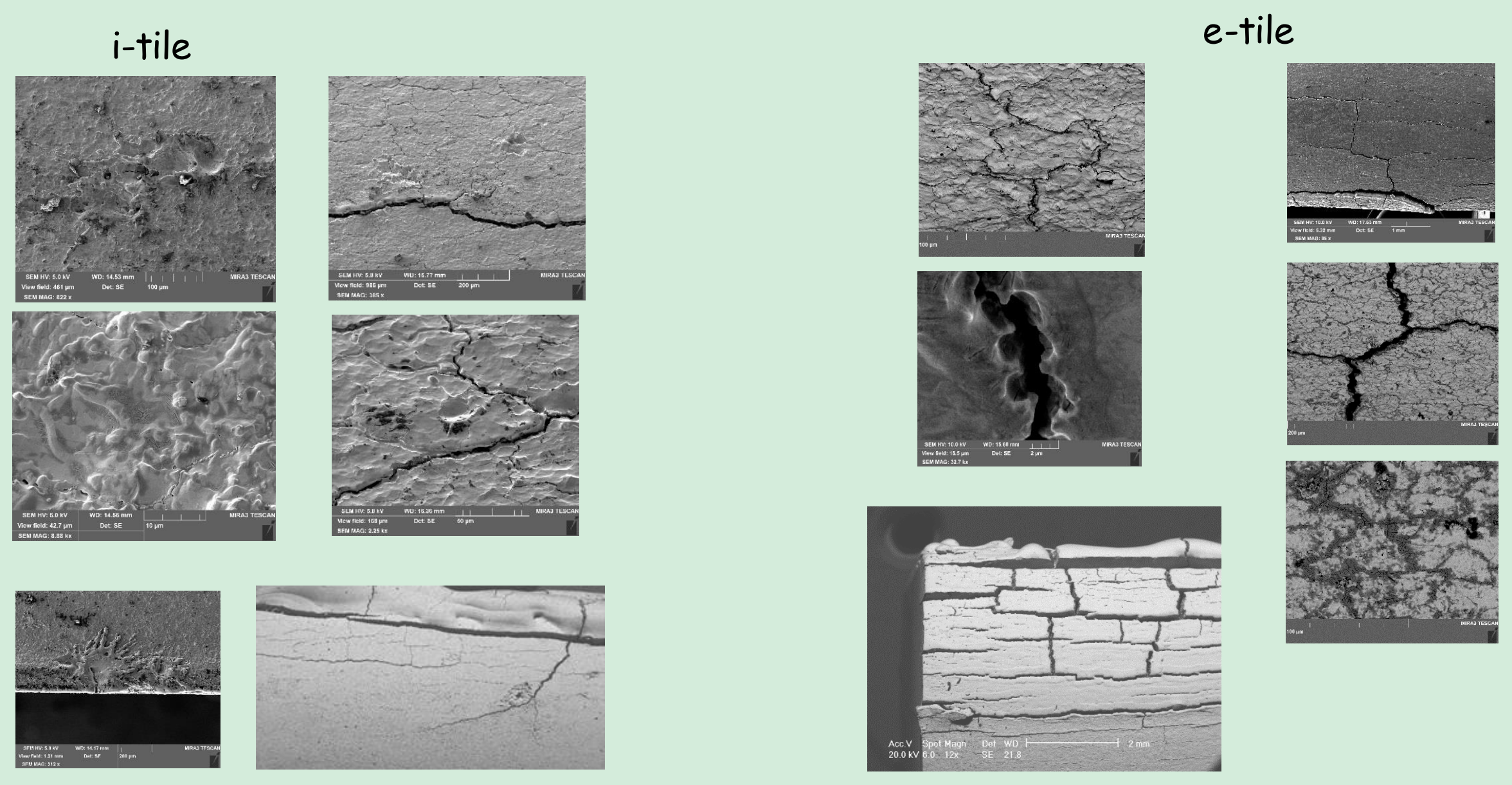
On ion-side of lateral surface deep craters of arcs are "tied" to cracks

Crater diameters vary from 1 to 200 μm

The arcs with small, "saucer-shaped" craters is in a chaotic motion. There is no dedicated direction.

When moving, small arcs merge into large ones, that is transition of cathode cells of the first type to the second type.

T-10, SEM, tile end, Zoo

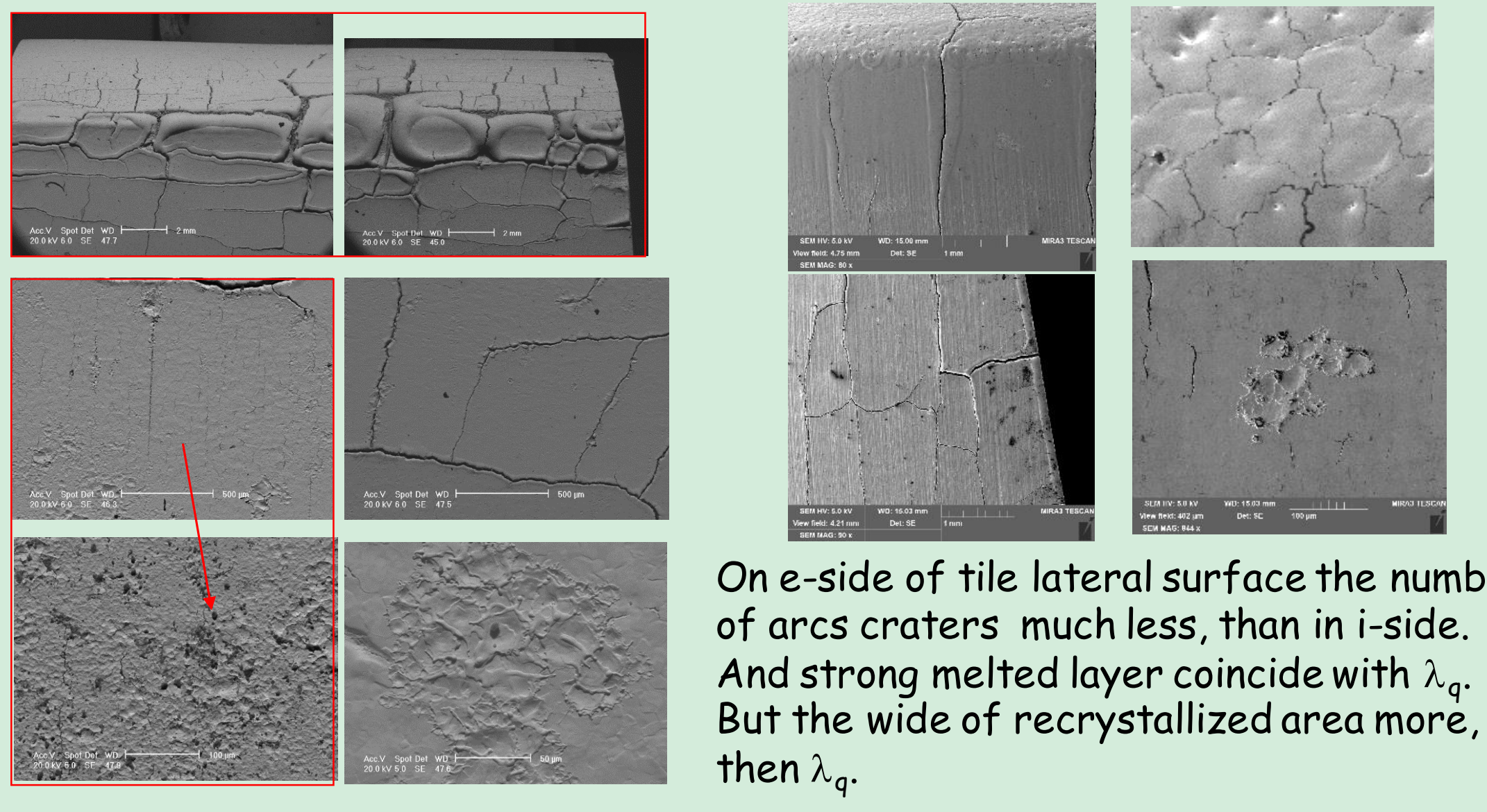


Melting, further recrystallisation and cracks formation – is the main phenomenons on the end surfaces.

T-10, SEM, e-side, Zoo

Wide erosion area

Recrystallisation – is the main phenomenon



On e-side of tile lateral surface the number of arcs craters much less, than in i-side. And strong melted layer coincide with λ_q. But the wide of recrystallized area more, then λ_q.

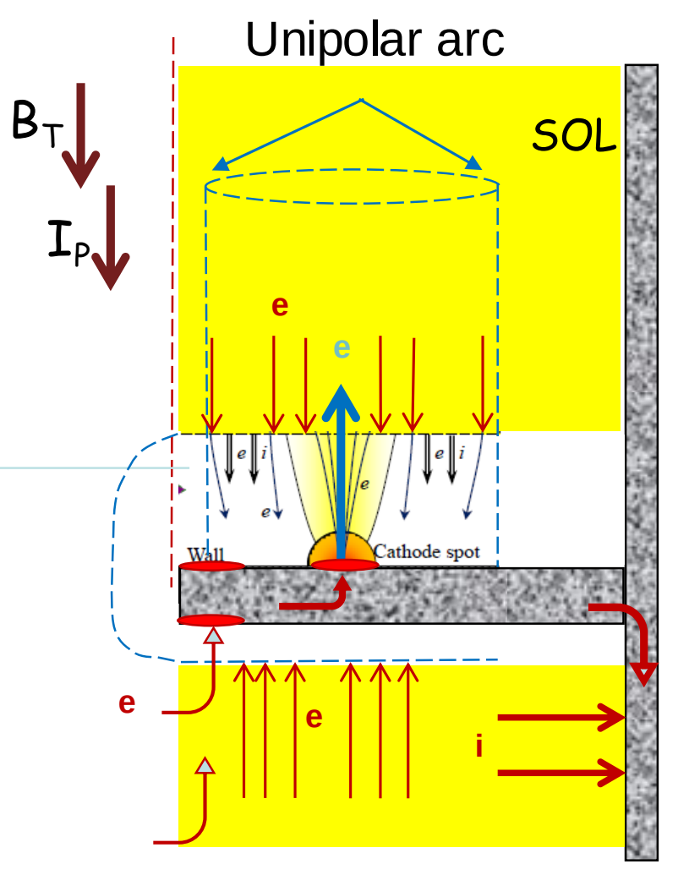
Craters have no connection with cracks.

The e-side leading edge heat up stronger, than on i-side. Very likely, sub-energetic electrons to contribute in such heating.

Non-ambipolar model of SOL plasma flow to the limiter

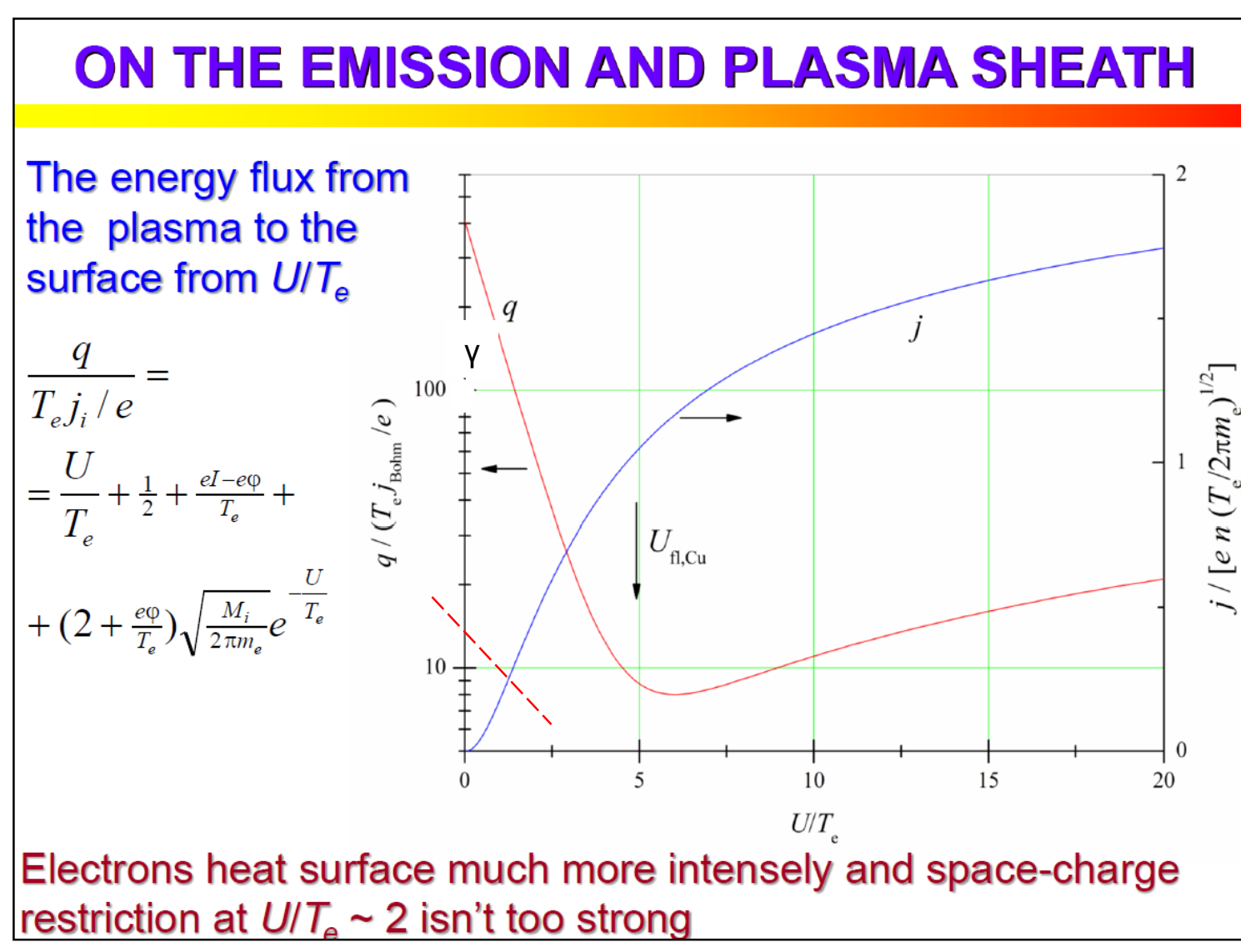
The energy source for arcs – part of bulk energy flow through LCFS (Last Close Flux Surface), which reach limiter surface by electron thermal conduction mechanism.

Arcs originate after preliminary heating of limiter and exist in quasi-neutrality conditions on limiter – $I_{Total} = 0$



Nonambipolar flow

Nedospasov A.V., Nuclear Fusion, 1986, v.26, No 11, 1529-1536. "Effect of anomalous transport of plasma convection in the poloidal limiter shadow of a tokamak".



ON THE EMISSION AND PLASMA SHEATH

The energy flux from the plasma to the surface from U/T_e

$$\frac{q}{T_e j_i / e} = \frac{U}{T_e} + \frac{1}{2} + \frac{eI - e\varphi}{T_e} + \left(2 + \frac{e\varphi}{T_e}\right)\sqrt{\frac{M_i}{2\pi m_e}}\, e^{-\frac{U}{T_e}}$$

Electrons heat surface much more intensely and space-charge restriction at U/T_e ~ 2 isn't too strong

Mikhail M Tsventoukh, Lebedev PI RAS

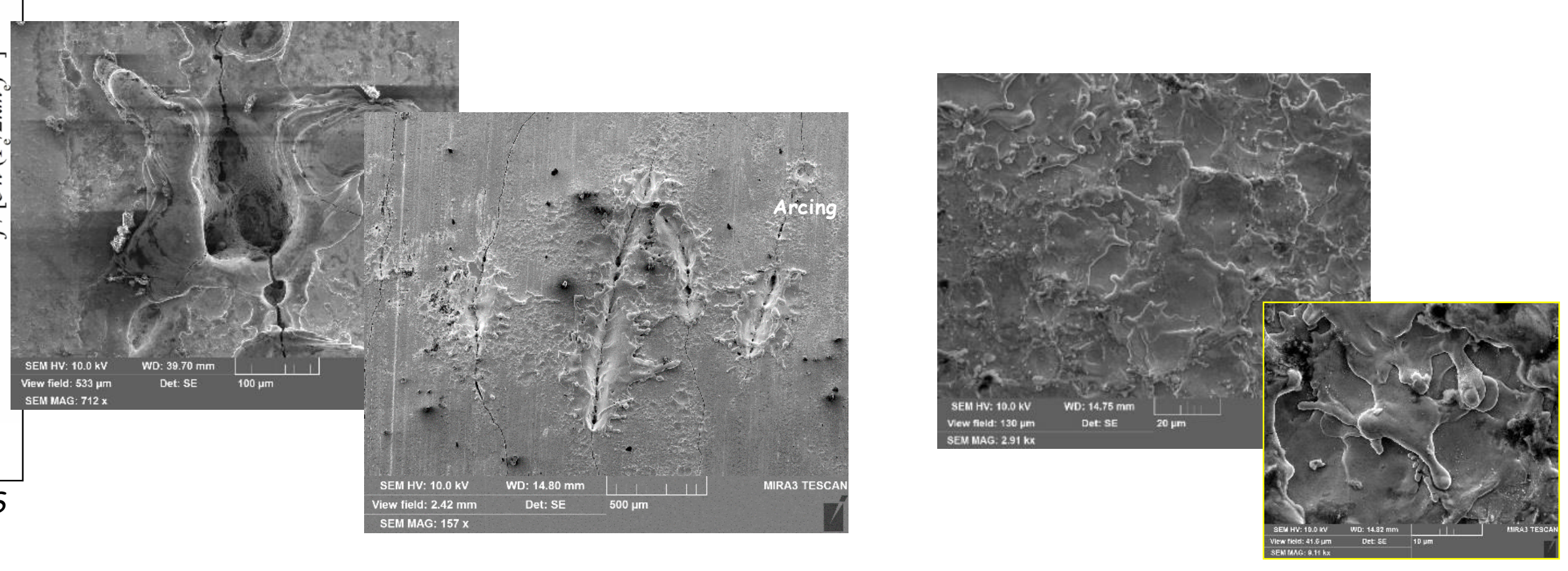
Surface overheating (selfheating)

The main parameter of energy and particle flow on limiter is the Debye potential U

$q = \gamma j_i T_e$

$\gamma = 6.8$ (ambipolar flow)
$\gamma \sim 10$ (weak nonambipolar flow)
$\gamma < 23$ (thermionic emission)
$\gamma > 25$ (arcing or runaway)

When arcing appears, there can be a "self-heating" of the limiter surface, since in SOL, the power is collected from full surface of the plasma column and leads to the limiter by a small area through the electron thermal conduction mechanism.

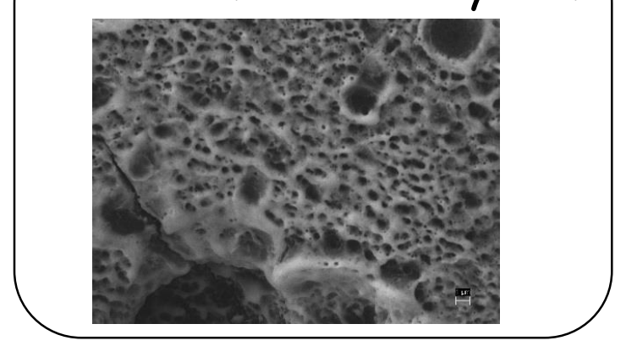


Arcs, sparcs and nonambipolarity origin leads to additional extra heating of the limiter.

Ecton model - spark, as main mechanism of surface erosion

All three stages of the vacuum discharge, - breakdown, sparks and arcs, are based on **microexplosions** of the "cathode" surface, explosive electron emission and **ectons**.

Arcs on melted beryllium



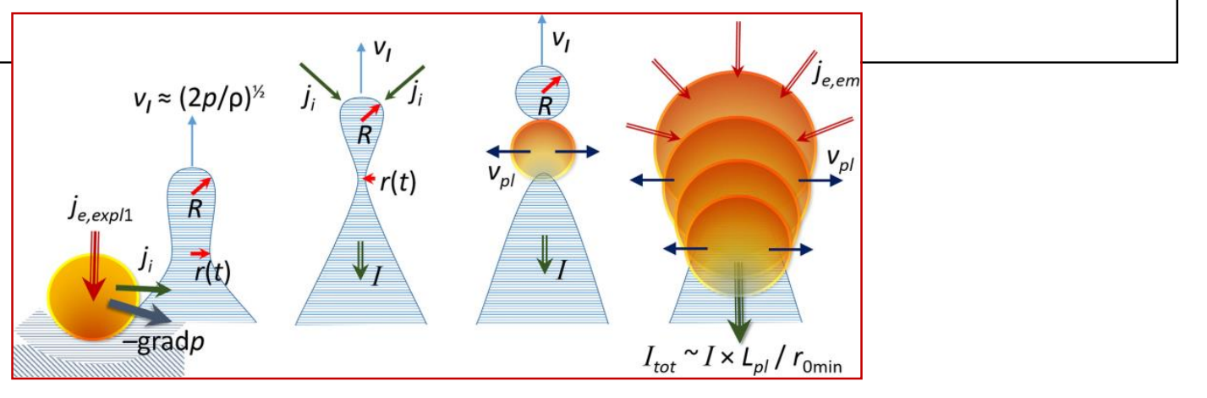
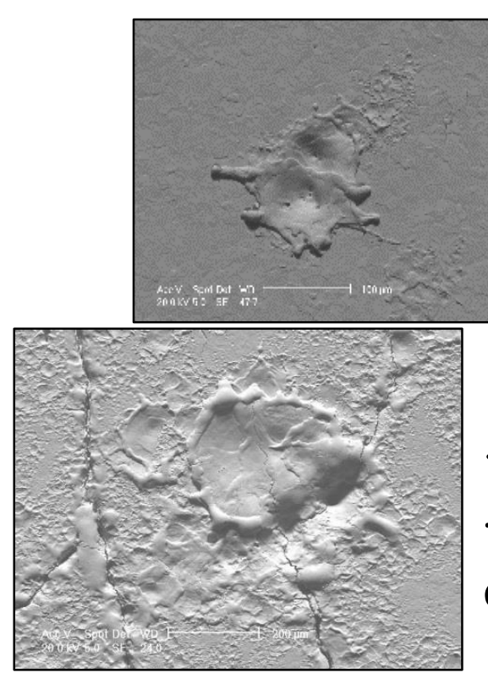


FIG. Sketch of the model of tearing and electrically exploding liquid-metal jet as the mechanism of the self-sustaining explosive-electron-emission cells of the plasma discharge cathode spot:



The spark stage is accompanied by a continuous renewal of microexplosions, which are initiated by the plasma and jets of liquid metal from previous microexplosions. Drops of liquid metal are formed as a result of their detachment from liquid metal jets.

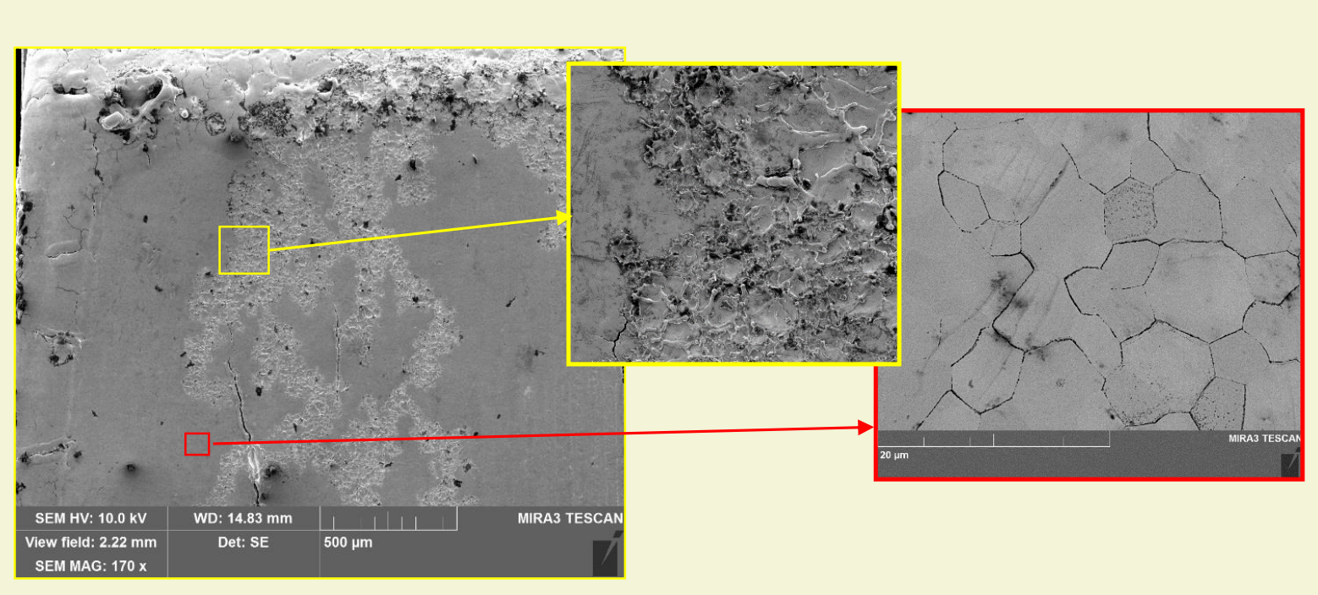
The appearance of electrons is caused by the rapid overheating of the micro-regions of the "cathode" (up to **10^4 °C**) and is essentially a type of thermionic emission.

One of the main reasons for the occurrence of microexplosions is the Joule heating of the microcavities of the "cathode" surface by a high density current.

See M Tsventoukh, PHYSICS OF PLASMAS 25, 053504 (2018)

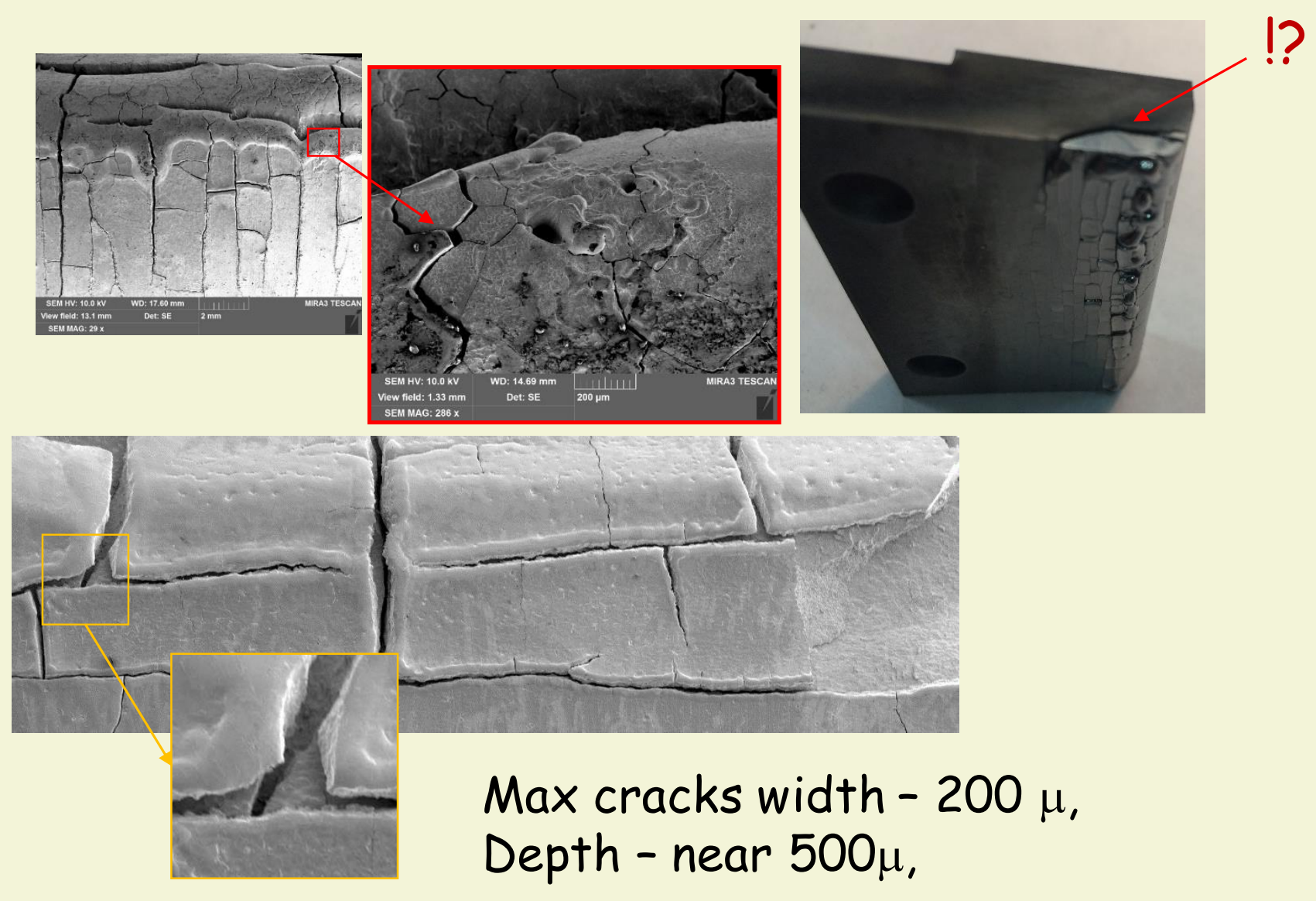
Side effects, as a result of surface overheating

Resolidificated W



The thickness of recrystallized W layer – 50 ÷ 300 мкм
Estimation gives the max value of heat flux near 50 MW/m^2.

Cracks

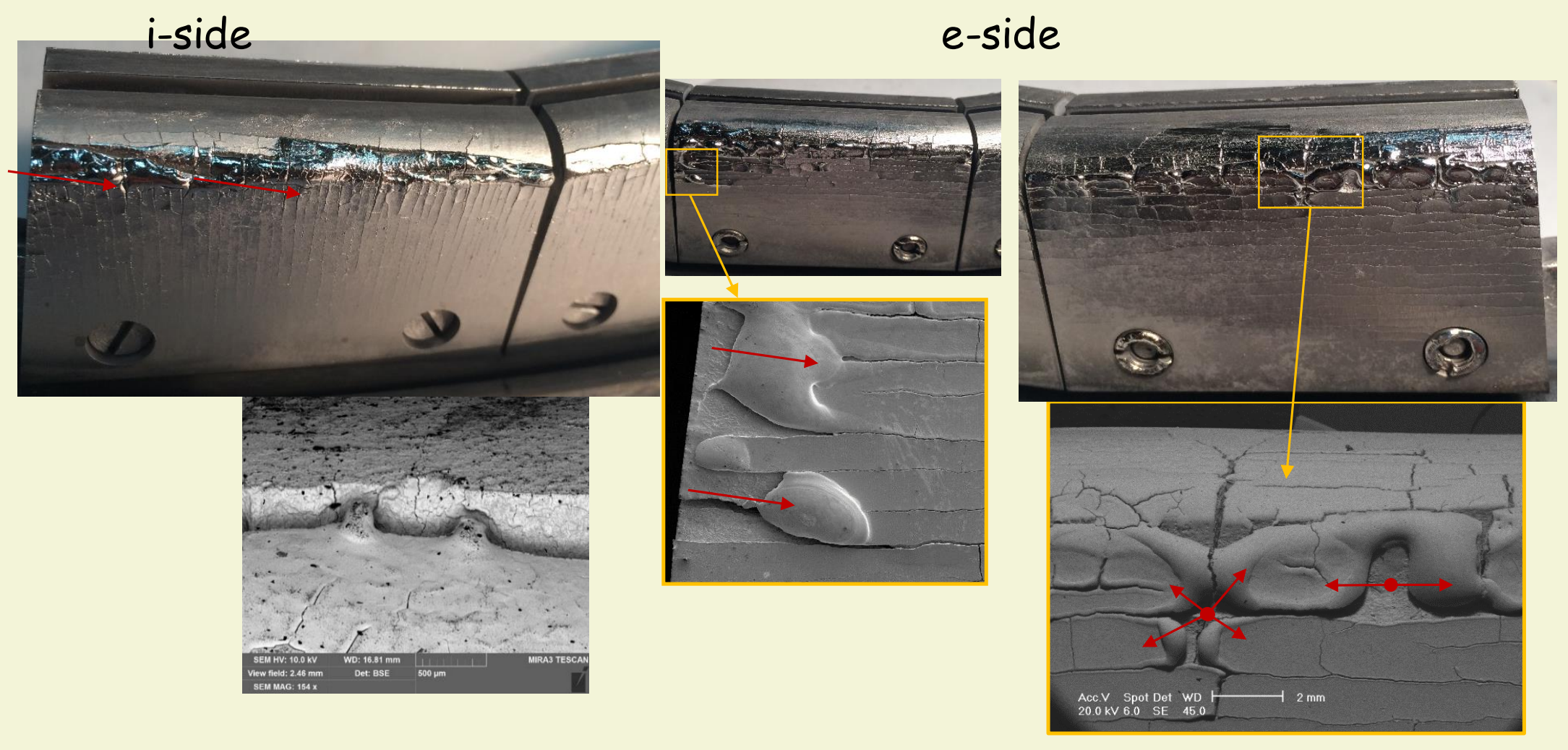


Max cracks width – 200 μ,
Depth – near 500μ,

When molten tungsten cool down it cracks and flakes. The layer cracks can "tear" bulk tungsten.

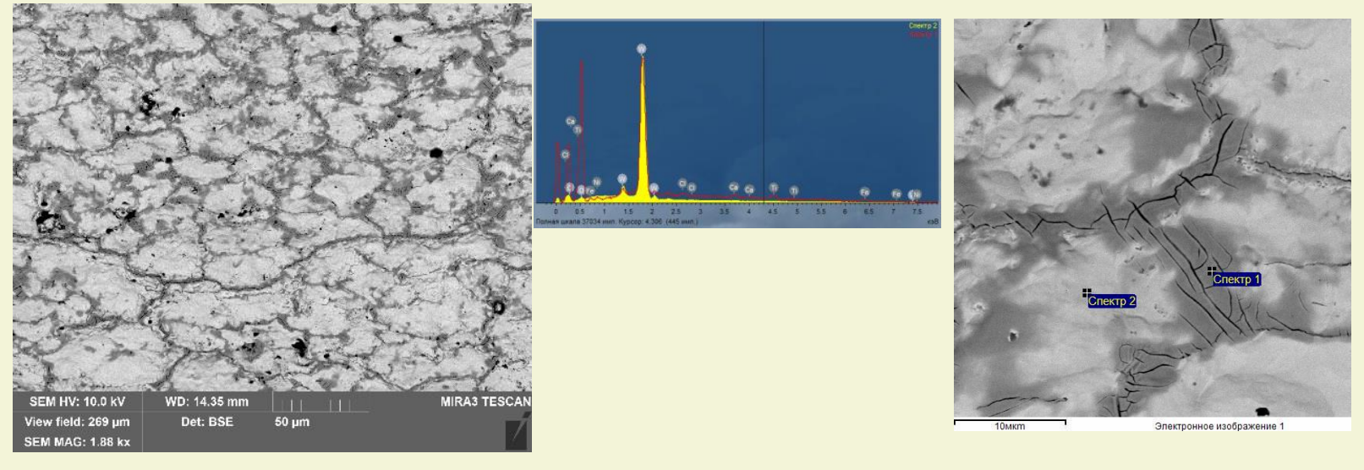
Melt motion

Leading edge melting of W tiles (> 3460 ^{0}C) !!



Melt motion can originate from force of gravity, from surface tension and from J×B forces.

Tungsten oxides originate



Under resolidification of molten W there is separation of pure tungsten from tungsten oxides on the tiles end.
Tungsten oxides can further be **the reason of cracks**.

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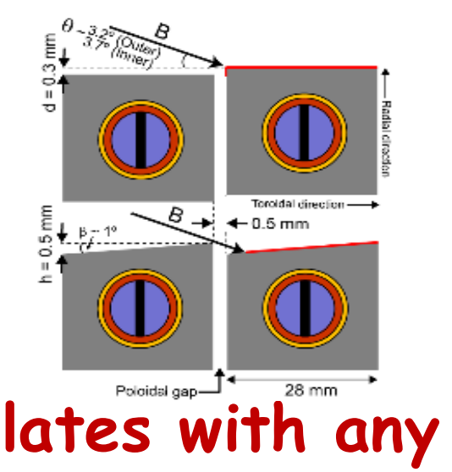
Summary

It was shown in T-10, that initial heating of limiter, and followed thermal emission and explosive electron emission, can lead to **overheating** and melting of the W limiter surface layer.
The main mechanism of heating W tiles is sparking, additionally to arcing and heating by electrons in nonambipolar flow.

One of the possible reasons may be **turbulence in the sheath layer** - i.e. fluctuations of the Debye potential. When a certain potential is exceeded, a spark jumps and an ecton is injected into the plasma.

If so, then:



The idea of "Leading edge" protection of the ITER W divertor targets by tilting can fail to function in ITER divertor plasma.
It is possible that in ITER arcs will melt the edges of the plates with any surface geometry and at a surface temperature below the melting point.

The ecton flux from the surface of the liquid metal can provide **J × B force** sufficient to move the molten drop.

It is necessary **to double-check the simulations of ITER energy and particle balance** (in SOLPS… or any) **and heating of the divertor plates**, introducing the non-ambipolarity of the plasma flow on metallic surfaces. Under these conditions, there can be **"self-heating"** of the surface, by analogy with "self-sputtering".

Resolidification of the melt layer leads to strong cracking and **gas retention** problem.