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SIMULATION OF HOT-SPOT FORMATION AT ITER VESSEL SURFACE DURING MULTIPLE TRANSIENT EVENTS

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1. Introduction.

Operation of ITER is assumed to be the H-mode. A characteristic feature of this regime is the transient release of energy from the confined plasma onto plasma facing components (PFCs) by multiple ELMs (about 10^4 ELMs per ITER discharge), which play a determining role in the erosion rate and production of the essential armour roughness at the vessel surface. Similarly, the transient power fluxes during disruptions can affect significantly their lifetime and lead to a significant growth of the armour roughness. . The expected fluxes on the ITER divertor during the transients are: Type I ELM energy fluxes of 0.5 – 4 MJ/m^2 in timescales of 0.3-0.6 ms [1].

Tungsten and beryllium macrobrush armour are foreseen as PFC for the ITER vessel. During intense transient events (TE) in ITER evaporation, surface melting, melt motion, and melt splashing are seen as the main mechanisms of PFC erosion [2]. A noticeable surface roughness of the W-brush targets (with a magnitude exceeding 100 μm) after repetitive ELM-like loads was obtained in the experiments at plasma gun facilities [3]. Existence of such surface roughness can lead to essential perturbation of the electric field strength above the surface, formation of the hot spots at the armour surface during transient loads and as a consequence significant increase of surface damage and influx of eroded material into the SOL.

Numerical simulations of the code MEMOS was applied for the damage simulations of single transient events with further extrapolations to repetitive TE [2,4] demonstrated significant surface roughness caused by multiple TE. For the repetitive TE loads only a few simplified studies were carried out [3] based on the assumption that the total erosion is the linear composition of the erosion after single transient loads applied to the undisturbed surface. Unfortunately such simplified approach can not adequately simulate consequence of repetitive TE loads (nonlinear accumulative effects). For the adequate numerical simulations of the macrobrush armour damage the code MEMOS was significantly upgraded. To investigate the non-linear accumulative effect of multiple TE loads on the PFCs the model was generalized in order to take into account the change of surface profile after each transient event. Now each next TE load changes the target surface.

The numerical simulations were carried out for the multiple ELM-like heat loads with the reference energy density Q=1.6 MJ/m^2 and the timescale τ=0.5 ms, The numerical simulations for the ITER ELM-like repetitive heat loads with the plasma pressure below 0.01 MPa were done for W-brush armour to obtained expected surface roughness which can further used for estimation of the electric field disturbance near the armour surface.

The model of the hot spot formation was developed and implemented into the code MEMOS. Calculation of the electric field above real surface profile obtained after repetitive ELM-like heat loads at the W macrobrosh armour was done. Probability of the hot spot formation at the brush edges damaged by repetitive ELM-like heat loads was estimated.

2.W-brush target erosion under repetitive ELM-like plasma heat loads.

The numerical simulations of repetitive ELM-like heat load consequence on the brush shapes were carried out for the W targets preheated up to 500^{o}C. Heat load with the reference energy density Q = 1.6 MJ/m^2, τ =0.5 ms having Gaussian profile with half-width of 8 cm was applied. Two sets of the plasma pressure at the target were used, p=0.1, 0.2 MPa (QSPA-T conditions [3]) and p= 0.005, 0.01 MPa (ITER-like). The brush target is similar to experimental one: brush size D=1 cm, distance between brushes 0.05 cm, radius of the brush edge rounding was varied R_e=0.1, 0.15, 0.2 cm. Inclination of the plasma stream is 30^o for QSPA-T conditions and about 5^o for the ITER.

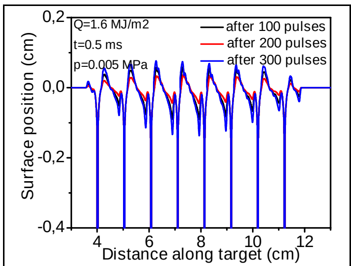

Fig.1. View of target

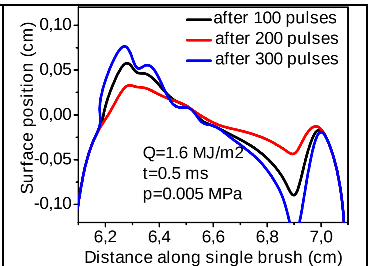

Fig.2. View of single brush

For given heat loads calculated depth of melt pool below 36 μm (per pulse) and the negligible evaporation depth were obtained. Tangential friction force generates melt motion along the brush surface with melt velocities up to 1.3 m/s for QSPA-T and up to 0.3 cm/s for ITER-like. Numerical simulations demonstrated evidently non linear accumulative effect of repetitive TE heat loads, namely fast formation of the bridges between brushes for QSPA as it was observed in the experiments. In ITER-like case rather moderate melt motion along brush surface leads to the appearance of the mountains at the brush edges with rather sharp shape (Fig. 1). The shape of the mountain is shown in Fig. 2 in more detail. Such periodic structure can lead to the disturbance of the electric field and appearance of the electric current sources at the target surface.

2. Electric field and hot spots formation.

Intensive erosion leads to a formation of corrugate wedge-type shape of W-brush target (Fig.1). Analysis of the surface roughness shows that topography of the material surface after exposition is not a trivial stochastic variation of heights. The surfaces layers have hierarchy of granularity with the pronounced wedge-type shape of 1-3mm in height and width. The sharpening of surface roughness changes the electric field pattern in adjacent plasma by increasing the electric field at the vicinity of the wedge tips. It can be shown here that the enhanced electric field could trigger arcs and initiate hot spots. We consider an electric sheath region bounded by a corrugated surface of electrically grounded conductor and an imaginary flat boundary somewhere upstream to the SOL region held fixed at a floating potential$\sim T$. We evaluate the electric potential φ / T in the region by solving the Poisson equation at the plate:

$$\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y} = \frac{4\pi j_i \sin\phi}{V_{th} T}(1 - \sqrt{m_i / 2\pi m_e} e^{-e\varphi/T}) \approx \varphi / \lambda_d^2 , \qquad (1)$$

where λ_d is the Debye length, V_{th} is the ion thermal velocity, ϕ is the angle between magnetic field and the plate, j_i. is the ion saturation current. Here x is the coordinate along the plate and y is along the magnetic field line. The boundary values at the conductor $(\varphi = 0)$ and in the opposite boundary $(\varphi = 1)$ was assumed. The standard variation formulation of a finite element method can be used to solve the problem [5]. The potential at the lateral magnetic field lines bounded the SOL domain, was specified as a linear function of y. After integration of Eq.1 one can obtain a set of equipotential lines by the numerical spline interpolation (see Fig.3). The roughness of the equipotential lines is gradually changed toward the top region, where $\varphi \sim 1$ is assumed.

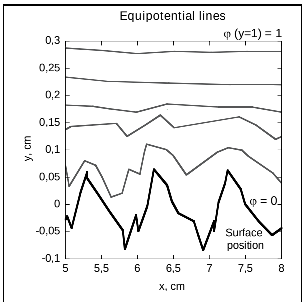

Fig. 3 Calculated equipotential lines over the rough surface.

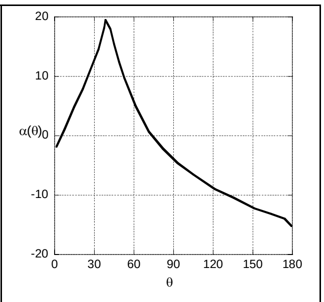

Fig. 4 α values vs wedge cone angle θ. $E_r \sim 1/r^{\alpha}$ [6].

One can see that at the wedge tips the electric field can be so strong, that can easily facilitate the generation of arcs and hot spots. Electric field on perfect metallic wedges behaves like $E_r \sim r^{\alpha}$, presenting a singularity when $\alpha < 0$ [6]. Abnormal electric field appears usually for very sharp wedges, $\alpha \approx -\frac{1}{4}\theta^2 + O(\theta)$. This can be found analytically by solving Laplace's equation in spherical coordinate system for 2D wedge shape. A quasi-analytic procedure based on the theory of Legendre and Lame's functions was used to determine α. Fig 2. shows the α parameter vs the sharpness of the cone wedges, θ.

Formation of the hot spots requires the current density on the surface in excess to some threshold value ~ 0.1-1A/cm^2 (for W). This can be expected first from the wedge tips at some cone angle value (see Fig.4), when a strong increase of the field emission of electrons takes place. The current density of field electrons emission is described by the Fawler-Nordheim tunnelling law and strongly depends on the electric field. At the electric field value $E \sim 3 \cdot 10^7\, V/cm$ the field emission current reaches the threshold value $\sim 1 A/cm^2$ and triggers the hot spots. The electric field at the wedge tip can be estimated as $E_0/E \sim (r/a)^{\alpha(\theta)}$, where $E_0 \sim 1 keV$ is the energy of incident particles, $a \sim 1 cm$ is the typical width of the wedge (see Fig. 1) and $\alpha(\theta)$ is the wedge cone angle (see Fig. 4). This allows one to estimate the critical value of the wedge curvature (radius) at the tip position. Estimation gives, $r \sim 0.5 cm$, which is in the range of expected values (see Fig. 1). This evaluation indicates the high probability of the hot spot formation and arcs initiation on the diverter plates caused by surface distraction during the multiple transient events. This additional erosion mechanism could lead to substantial contamination of plasma and the material distraction and requires a further investigation.

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