Surface Topographical Change of Divertor Target Plates Under Conditions Relevant to ITER ELMs

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Abstract. The ITER (International Thermonuclear Experimental Reactor) ELM (Large Amplitude Essential Mode) is an important problem for the terrain change on the surface of the Divertor target plate during the operation of ITER. The main function of the Divertor target plate is to filter out high-energy particles and ions in thermonuclear reactants and maintain the stable operation of subsequent devices. Due to the overload caused by ITER ELM and local extremely high heat emissions, significant terrain changes may occur on the surface of the target plate, leading to operational issues. In this paper, the surface topography of Divertor target under ITER ELM is studied by theoretical simulation and experimental research. Based on experimental measurement results and theoretical simulation predictions, the terrain changes were analyzed and explained. The research shows that ITER ELM operation will cause local high temperature and thermal stress on the surface of the target plate of the Divertor, and the surface will undergo significant deformation and distortion. In addition, the experimental results also indicate that the terrain changes on the surface of the target plate show significant differences not only in the longitudinal and transverse directions, but also in different areas of the target plate surface. Through theoretical simulation and experimental research, this paper obtained the experimental results and theoretical predictions of the terrain changes on the surface of the Divertor target under the operation of ITER ELM, which has important reference value for understanding the lubrication and preventing radiation pollution in the field of thermonuclear fusion.

Keywords: ELMs · tungsten divertor plates · melt motion

1 Introduction

Heat may cause target materials tungsten (W) to undergo melting and evaporation. And the humps induced by melt motion, initiate arc, and shorten the divertor lifetime. In addition, surface roughness will reduce W thermal conductivity, degrade its mechanic strength, result in an increase in tritium retention, affect the physical sputtering yield, and lead to a non-uniform erosion deposition behavior of impurities [1]. Therefore, it is very necessary to study the surface morphological change caused by melt.

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In fact, the existing experimental data of different tokamaks show the actual shape of heat load during type-I ELMs is asymmetric and basically the same even for different the experimental parameters, which decays slower 1.5–5 times than rises, and has an huge influence. Therefore, it is urgent performance under with the real temporal variation rather than rectangular or triangular waveform [2].

In this paper, from under a rectangular waveform to a temporal evolution heat load erosion of the divertor plates, and the ultimately surface morphology is different from those under the rectangular waveform heat load commonly used in other studies.

2 Model Description

The surface of Divertor target plate will be affected by local high temperature and thermal stress, which will lead to deformation and distortion of the surface. This problem needs attention and solution. The splitter, as another key component, undertakes the important task of guiding various high-temperature plasma into the reaction ring collector. In this paper, the diverter is redesigned as a target, and the surface topographic changes of the Divertor target are combined with the diverter target to improve the adhesion and collection of the diverter [3]. The schematic diagram of the diverter target is shown in Fig. 1 below.

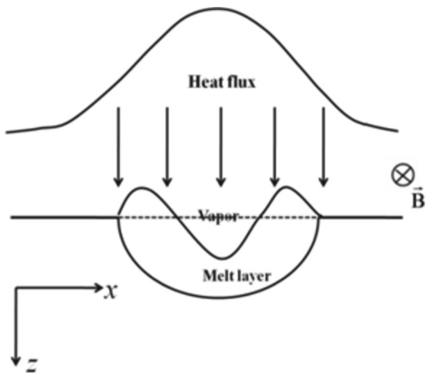

Fig. 1. Sketch of the divertor target.

This design is applied to ITER ELM operation, combining the surface change of Divertor target plate with the diverter target. By redesigning the diverter target, it can cover the terrain changes on the surface of the Divertor target plate, and increase the adhesion and collection. Specifically, the target part of the diverter adopts a replaceable form, changing the original plate structure into an interchangeable multi-layer structure, and adding a needle structure on the surface [4]. The reducing the dispersion of the diverter target. At the same time, the needle like structure enables the diverter target to have higher collection capacity, which can better meet the needs of target collection in various plasma environments. In this paper, the surface topography of the Divertor target plate is combined with the diverter target, which improves the adhesion and collection of the diverter, and establishes a more stable and convenient connection between them. This design method helps to improve the sustainability and stability of Divertor target plate and diverter, and also provides a certain reference value for other ITER related designs [5].

3 Results and Discussion

3.1 Temporal Evolution of the Energy Flux

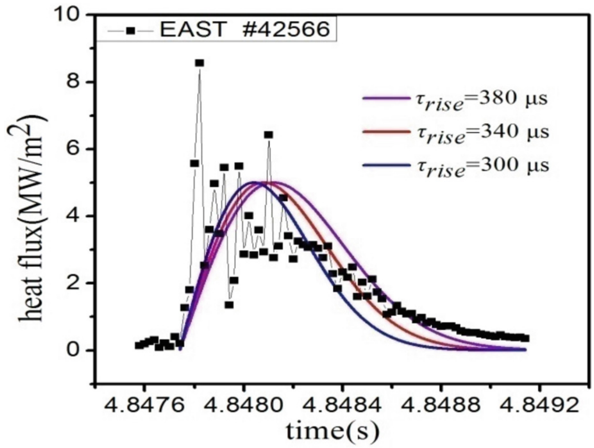

Fig. 2. Experimental temporal evolution of the heat flux on the EAST divertor during a type I ELM and fitted Rayleigh distribution function.

In this paper, the EAST # 42556 shot during the 2012 experimental campaign, which reads,

$$q(t) = q_{\max} e^{1/2} \frac{t}{\tau_{rise}} \exp\left(-\frac{t^2}{2\tau_{rise}^2}\right),$$

The fitted Rayleigh function and the measured experimental data in EAST # 42556 shot are shown in Fig. 2, qmax = 5 MW·m-2, the parameter τrise is taken to three values of 300, 340 and 380 μs, respectively. We can see that the fitted function with the different value of τrise within a certain range is conform well to the experiment date. We integrate the heat flux of EAST shot # 42566 over 1 ms from 4.84774 s to 4.84874 s, the sum is about 2.76 kJ·m-2, which is more agree with the value when τrise is taken to 340 μs. In order to simulate the situation of ITER, we first scale the up to 2900 MW·m-2 and take τrise to be 340 μs in this work, the integral value of which over 1 ms is about 1.6 MJ·m-2 in the range of. Later, in order to estimate the effect of various factors on thermal erosion.

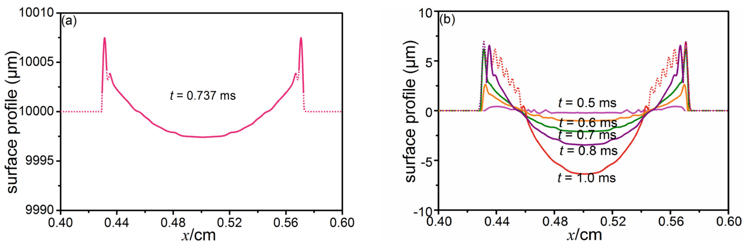

Fig. 3. The surface profile calculated under an ELM with the peak heat flux of 2900 MW·m-2. Note the shot dot line shows the solid surface, and the solid line shows the melt layer surface.

3.2 Surface Profile Evolution

Figure 3 shows the melt surface evolution of W divertor plates under heat, The temperature rises rapidly in the surface region, especially in the vicinity of the separatrix strike point (SSP), melting point is reached at t = 0.292 ms. Then, two humps are gradually formed at the dent edges due to melt motion mainly caused by surface tension. At time 0.736 ms, the melt area reaches the maximum in the range of x = 0.429 to 0.571 cm, the surface profile is relatively smooth, and the outside of the hump is very steep, because the flow velocity of W melt layer is much faster than the melting of marginal region, just as it was observed in the experiment. Two regions near x = 0.433 and x = 0.569 cm have finished solidification another 0.001 ms later, while regions from where to the corresponding edge of the dent, as in Fig. 3(a). This is mainly because the higher the more quicker the flow velocities of the melt layer, which are much larger than those in the regions under the two humps facing to the SSP (near x = 0.433 and x = 0.569 cm), leading to where getting lower and heat flux penetrateing into the bulk easier. Then, the regions near both edges of the dent gradually complete resolidification, the region in the vicinity of the center of the dent still continues to melt, and the melt W mainly driven by surface tension is still flushed to the periphery to form new humps. Melting and solidification occur simultaneously. The surface profiles of humps are waviness formation, as shown in Fig. 3(b). At t = 1.0 ms, the humps regions near both edges (from x = 0.429 to x = 0.457 cm, and from x = 0.541 to x = 0.571 cm) of the dent complete resolidification, while the region from x = 0.457 to x = 0.541 cm is still in melted state. However, the heat load of 1.6 MJ·m-2 lasting 1.0 ms of rectangular power shape cannot cause the target melt.

3.3 τrise Dependence

Figure 4 gives the different τrise of 300 μs, 340 μs and 380 μs, respectively, the heat load duration is 1.0 ms. The region from x = 0.434 to 0.566 cm is still in melted state for τrise of 380 μs at t = 1.0 ms, which is larger than that for τrise of 340 μs, while the melt layer completes resolidification for τrise of 300 μs. This mainly because the bigger the value of τrise is, the more the heat load deposited is, the larger the melt area is, the bigger the melt thickness is—maximum melt thickness is about 58.5μm for τrise of 380 μs, which is bigger 1.6 times than that for τrise of 300 μs, and the slower the resolidification is.

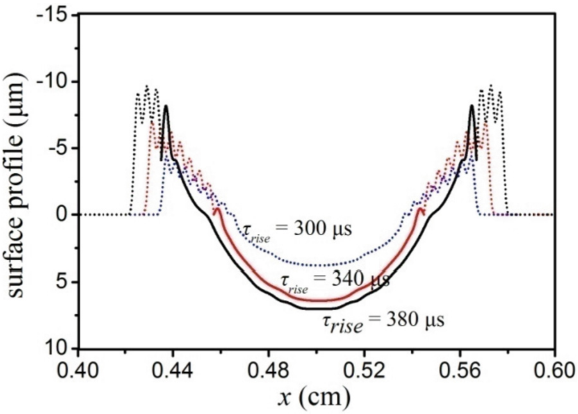

Fig. 4. Note the shot dot line shows the solid surface, and the solid line shows the melt layer surface.

3.4 Surface Roughness

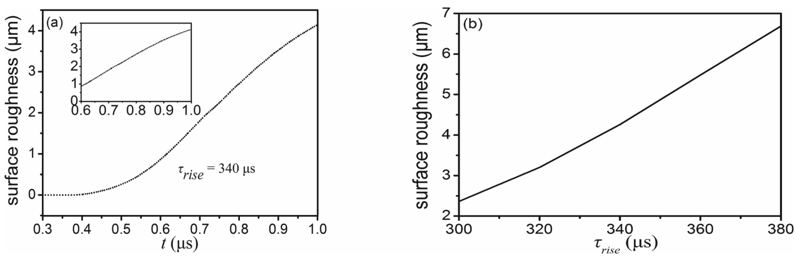

Fig. 5. Surface roughness of W plates versus irradiation duration (a), value of τrise (b).

Figure 5(a) gives irradiation duration. This is mainly because that the bigger the value of τrise, the faster the flow velocity of the melt layer is, the higher the humps are, so the larger the surface roughness is.

4 Conclusion

The temporal evolution load during is fitted by the Rayleigh distribution function according to the EAST # 42556 shot during and is employed, which solves the conductivity equation, including melting, evaporation, and solidification processes. The simulation results show: (i) the surface temperature quickly exceeds the melting point under the type-I ELM heat flux, then, humps are gradually forming at the dent edges due to melt motion mainly caused by surface tension, resolidification occur on the both outsides of the dent, simultaneously, the melt layer located in the vicinity of the center of the dent is still flushed to the periphery to form new humps, resulting in the waviness formation of surface profile; (ii) the value of τrise has a great influence on thermal erosion: the bigger the value of τrise is, the larger the melt area is, the deeper the melt front location is, the slower the resolidification is, the larger the surface roughness is. All the simulation results show the real shape of the a very important to determine the W target erosion and lifetime.

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