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Tungsten melting and erosion under plasma heat load in tokamak discharges with disruptions

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ABSTRACT

Full tungsten poloidal and mushroom limiters were tested in series of experiments with disruptions in the T-10 tokamak. Significant melting, formation of small craters and erosion of the tungsten limiter have been observed after ~400 discharges with disruption. A theoretical description of the tungsten erosion at disruption in tokamak plasma is presented. The proposed model was verified by comparison with experimental observations in the T-10. The results are used for the erosion prediction of the ITER tungsten divertor.

Introduction

Tungsten is foreseen as plasma facing material for ITER, DEMO and fusion neutron source because of its high melting point, low sputtering yield and high thermal conductivity. The problem of melting and erosion of tungsten under high heat flux (HHF) loads during transient events (ELMs and disruptions) is the key issue for the ITER [1,2]. Recent progress in research on tungsten plasma facing components (PFCs) for the ITER and nuclear fusion applications have been reviewed in [1–6]. Combined heat and particle loadings effects are important because they could enhance surface damage and erosion. There still remain uncertainties of erosion, surface morphology and microstructure changes by these combined loadings in real edge tokamak plasma conditions. Although transient heat loads should be reduced in the ITER to some acceptable level, effects of occasional modest transients on surface damage should be examined. ELMs load on the divertor plates in the ITER will reach a value of ~0.6–3.5 GW m^{-2} (see [7]), which exceeds the power required for tungsten melting. An incident high heat flux on a tungsten surface can produce ablated vapor. Vapor shielding layer (cloud) reduces the energy transported to the surface and limits the energy absorbed by the surface. The dynamics of melting layer and vapor shielding layer over the surface depends on many factors including plasma pressure onto the surface, heat pulse duration, complex interaction of eroded debris and incident plasma, plasma and particles incident power (see [8–10]). These factors should be taken into account for the estimation of transients effects (ELMs and disruptions) in the ITER. The plasma particles energy absorbed by the material surface is reduced by the vapor shielding layer. For tungsten surface such energy limit is ~0.5 MJ m^{-2} at plasma pulse duration ~0.5 ms.

HHF loading on tungsten test plates have been recently modeled in plasma accelerators QSPA [11,3]. However, the pressure of plasma flows in the QSPA differs from the conditions in the ITER. In the ITER plasma pressure over the material surface is expected up to 10^2–10^3 Pa during ELMs and 10^2–$4 \cdot 10^3$ Pa at disruption events. In the QSPA plasma flow pressure is of several atmospheres. Thus, tungsten erosion under HHF load should be examined in real edge tokamak plasma too. In modern tokamaks the HHF load on the PFCs is observed at disruption events when combined impact of plasma and high-energy electrons (with energies of ~0.1–5 MeV

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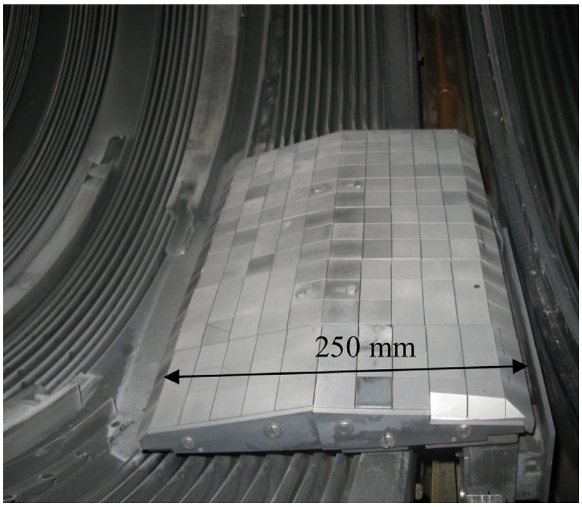

Fig. 1. Tungsten mushroom shaped limiter at bottom inside the T-10 tokamak chamber.

within a few milliseconds) leads to overheating and local damage of the PFCs. Such experiments can adequately model the HHF loading in the ITER.

In the ITER, the maximal thermal load of the plasma flow on the divertor plate occurs in a narrow layer near the strike points. It is expected narrow heat flux widths in the ITER divertor. In the ITER it is supposed that a vapor shielding layer will not be formed over the divertor plates in the narrow heat flux widths because of the rapid removal of the erosion product from this zone due to strong cross-field E × B drift. Lack of vapor shielding layer over the surface is also supposing during disruptions accompanied by beams of nonthermal electrons impacted on the limiters of the T-10 tokamak. In this paper the experimental observation of the tungsten melting and erosion in the T-10 tokamak discharges with disruption and model of the molten layer motion under the impact of nonthermal electrons beam in tokamaks at disruption event are presented.

Experiments with the tungsten PFC in the t-10 tokamak

In this section the experiments with tungsten limiters and accidental melt of its surface in the T-10 tokamak discharges with disruption are described. The T-10 tokamak is a circular cross-section limiter tokamak with major radius $R = 1.5$ m, vessel radius $a = 0.4$ m. In the 2015 campaign graphite limiters (used in previous campaigns, see [12] and references therein) were replaced by full tungsten limiters in order to study the impact of tungsten on plasma operation and tungsten erosion and migration. The tungsten tiles were installed as PFCs of a poloidal and a mushroom limiters of the T-10 tokamak (Fig. 1). These limiter tiles were made of the ITER grade (IG) MP tungsten (the same grade as used for manufacturing the ITER divertor plates) at Efremov Institute. Typical surface structure of the tungsten plate is shown in Fig. 2. The poloidal limiter constructed of paired tungsten plates (of $\sim 67 \times 38$ mm^2 size and 10 mm thick) mounted on a stainless steel ring at the top, outer board and inner board in the same poloidal section of the tokamak vacuum chamber. The mushroom limiter is mounted from castellated tungsten blocks of the structure similar to the ITER monoblocks. All the tungsten plates are not cooled and electrically connected with the tokamak chamber.

The bottom mushroom shaped limiter was installed bottom at minor radius $a = 30$ cm producing the SOL with typical parameters described in [12]. The poloidal limiter radius was of 34 cm.

Fig. 2. SEM micrograph of virgin microstructure of the tungsten surface.

In the 2015 campaign with tungsten limiters the typical plasma parameters in ohmic discharges were: plasma current $I_P = 0.15$–0.27 MA, toroidal magnetic field $B_T = 2$–2.4 T, plasma pulse duration was 0.4–1 s, central line-averaged density up to $\sim 3 \times 10^{19}$/m^3, central electron temperature up to ~1 keV allowing for incident heat flux of ~1–5 MW/m^2 onto the edge of tungsten mushroom limiter at the steady state. At the steady state the heat load onto the outer board poloidal limiter plates is much less because it operates in the SOL.

In the 2015 campaign the series of ~400 experiments with disruptions has been made. Registration of visible light (Fig. 3) shows the increasing of surface temperature of the edge of poloidal and mushroom limiters at the disruption stage (Fig. 3b). At the disruption the plasma discharge column is shifted toward outer board leading to the increasing of heat load onto poloidal limiter plates. In the end of discharge runaway electron beam is formed in the outer board of plasma. At the end of discharge the ejection of droplets from the poloidal limiter has been detected on the outer board side of the tokamak. This phenomenon is supposing due to post-disruption runaway electron beams interacted with the poloidal limiter. Plasma and nonthermal electron beam parameters at the plasma disruption stage are described in detail in [13,14].

During the shutdown after the 2015 run campaign tungsten tiles of the limiters were inspected. No erosion and melting has been observed on the plates of mushroom installed at the bottom of the chamber. At the same time multiple melt occurrences (Fig. 4) were observed on the outer board plates of poloidal limiter as a result of high-power runaway electron beam. Significant melting, formation of small craters and erosion has been observed on the damaged tungsten plates. The craters with a diameter of 1–5 mm and of 1–3 mm of the depth were observed (Fig. 4a,b). In these experiments the melt material motion perpendicular to the magnetic field was not registered as expected when the $\mathbf{j} \times \mathbf{B}$ forces are caused by thermo-electric emission.

The tungsten molten droplets (Fig. 4c) ejected from the erosion zone of poloidal tungsten plates were observed on plasma facing surfaces. The largest scale fraction of tungsten droplets with a diameter from about 1 mm to about 3 mm (Fig. 4c) are mainly observed on the bottom surface of vacuum chamber and mushroom

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