Destruction of tungsten limiters in the T-10 tokamak under high plasma heat loads

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Abstract. Tungsten limiters were tested in the T-10 tokamak. The limiters were made from the ITER-grade WMP “POLEMA” tungsten. The influence of the edge tokamak plasma on tungsten limiters leads to significant cracking of tungsten. The heat load of up to 2 MW·m⁻² leads to the micro-crack development at the grain boundaries accompanied by the loss of grains. The heat loads that exceed 5 MW·m⁻² lead to the macro crack development. Under the present T-10 tokamak conditions, the heat and particle fluxes in the edge plasma lead to the significant destruction of tungsten limiters during the experimental campaign. During the disruption and runaway electron formation, extreme heat loads of more than 1 GW·m⁻² cause strong melting of tungsten on the inner and outer part of the ring limiter.

1. Introduction

Tungsten is viewed as the plasma facing material for ITER [1, 2], as well as for the next generation fusion machines (such as DEMO). Thus, tungsten testing under high heat flux (HHF) loads during transient events (ELMs and disruptions) is very important for the ITER operation prediction. The investigation of tungsten melting and erosion under HHF was fulfilled on JET, AUG, Т-10, LHD and a number of other fusion devices [1, 3, 4].

Under the real tokamak conditions, the combination of heat and particle fluxes can enhance tungsten damage and erosion. Different mechanisms in the edge plasma can concentrate energy on small zones of the divertor, limiters or wall. The heat loads, although less than the transient one (from ELMs, disruptions or runaway electrons), can be sufficiently high to cause damage or melting of tungsten. These effects should be examined under the real plasma condition to obtain valuable information for the ITER operation with tungsten. This paper presents the results of analysis of tungsten limiters of the T-10 tokamak after the 2015–2016 experimental campaign.
2. Experiments on the T-10 tokamak

During the T-10 operation with graphite limiters, significant cracking and erosion of graphite tiles was observed in the regions with the heat loads up to 1–2 MW \cdot m^{-2}. The destruction of graphite tiles by the runaway electrons was local, but very intensive, which caused frequent (every 4–5 years) replacement of the tiles. In 2015, carbon limiters were replaced with tungsten limiters on the T-10 tokamak (Fig. 1). T-10 tokamak has a major radius \( R = 1.5 \) m, rail limiter with a radius of 0.30 m and a circular limiter of radius 0.33 m. The limiter was made at the “Efremov Institute” from the ITER-grade WMP “POLEMA” tungsten, which is used for the ITER divertor plates manufacturing. The impurities content does not exceed 0.05%, according to the certificate of the “Polema” company. Tungsten has high thermal conductivity and heat capacity. The thermal conductivity of VMP tungsten is 170–175 W/m K, which is 2.5 times higher than that of MPG-8 graphite. The heat capacity of the T-10 tungsten limiters is 2.5 times higher than of the limiters that are made from graphite.

Tungsten has a polycrystalline structure with a typical grain size of 30 µm and a porous surface. Cracks with a width of 1–2 µm were observed at the grains boundaries, as well as deeper in the material (Fig. 2). Cracks around the perimeter of grains can lead to chipping of the surface under high mechanical and thermal loads. Tungsten limiters of the T-10 tokamak do not have active cooling. The surface of the limiters was cooled via radiation and thermal conductivity.

Heat flux from the plasma to the limiters was evaluated from the experimental data of Langmuir probes, which are located on the limiters and in the SOL of T-10. The temperature of the limiters was measured via thermocouples at a depth of 8–10 mm from the surface. The surface temperature of the limiters was evaluated from the visible radiation, which was recorded by fast optical camera.

3. Results

During the experimental campaign (November 2015 – December 2016), the T-10 tungsten limiters were exposed to ~2500 experimental shots. The normal T-10 operating shot duration was 1 s. Approximately 300–400 shots were terminated by disruptions and formation of the runaway electron beam. The ohmic heating power did not exceed 0.5 MW, and the ECR heating reached 2.5 MW during stable discharges, as well as during the discharges when disruption plasma interacts most intensely with the outer and inner part of the ring limiter (near the equatorial plane) and the top of the rail limiter (Fig. 3). Those zones suffered the strong destruction.

For rail limiter, the heat load does not exceed 1.5 MW \cdot m^{-2} with ohmic heating and 2.5 MW \cdot m^{-2} with ECR heating. The runaway electron beam is not deposited on the rail limiter surface. The surface temperature of the limiter estimated from the visible emission did not exceed 1500°C. The temperature
on the bottom surface of tungsten tiles does not exceed 100°C. Strong development of the initial micro cracks was observed on the W-tiles under this conditions. The cracked structure became clear. In addition, loss of grains was observed on the tungsten surface after the experimental campaign (Fig. 4).

![Figure 3](image1.png)

**Figure 3.** Interaction of W limiters with the T-10 tokamak plasma recorded using a fast optical camera: (a) stable ohmic discharge; (b) discharge with ECR heating of 2 MW; (c) disruption and runaway electron beam formation.

![Figure 4](image2.png)

**Figure 4.** Electron microscope images of the rail limiter W surface after the experimental campaign

On the inner and outer board of the torus, thermal loads on the edge of the limiter ring can reach 5 MW m⁻² during ohmic heating, and exceed this value during ECR heating. For the case shown in Fig. 3b, the temperature of the ring limiter surface exceeds 1500°C. Although the mechanism of local energy release on the limiter surface has not been identified yet, it should be noted that such heating cannot be explained by the action of runaway electrons. Cracking in these zones leads to the formation of macro cracks with a width up to 80 microns and lengths from 1 to 50 mm. Cracks on the surface of tungsten plates are directed in longitudinal and transverse directions, forming a net of cracks (Fig. 5). The edges of some cracks are melted. The micro crack structure at the grain boundaries is also observed on the rail limiter W-surface. In the areas with the highest heat loads, tungsten plates are melted and are close to complete destruction.

At the runaway electron beam contact area (at the inner and outer part of the ring limiter near the tokamak equatorial plane), thermal loads of more than 1 GW/m² cause strong melting of the tungsten surface (Fig. 6) [4]. In addition, the melted region suffered significant cracking. Droplets of the melted tungsten with sizes up to 2–3 mm and redeposited tungsten are only observed in the vicinity of the runaway electron strike zone. No melted or redeposited W was observed in other parts of the T-10 vacuum vessel.
Figure 5. Tungsten plates from the inner side of the ring limiter after the experimental campaign (a–c). Melting and cracking of the tungsten surface is observed. Electron microscope micrograph of cracks on the tungsten surface (d).

Figure 6. Melting of tungsten plates on the (a) outer and (b) inner boards of the ring limiter at the runaway electron beam contact area.

4. Conclusions
In 2015, carbon limiters were replaced with tungsten limiters on the T-10 tokamak. The limiters were made from the ITER-grade WMP “POLEMA” tungsten, which is used for the divertor plate manufacturing. WMP tungsten does not contain any impurities and has high thermal conductivity and heat capacity. Tungsten has a polycrystalline structure and a porous surface.

The influence of the edge tokamak plasma on tungsten limiters leads to the significant cracking of tungsten. The heat load up to \(2 \text{ MW} \cdot \text{m}^{-2}\) leads to the micro-crack (1–2 \(\mu\text{m}\) wide) development at the grain boundaries accompanied by the gradual destruction of the surface including loss of grains. Heat loads exceeding \(5 \text{ MW} \cdot \text{m}^{-2}\) lead to the macro crack development up to an 80-\(\mu\text{m}\) width and a length of 5–50 mm. There is no correlation of the development of such cracks with runaway electrons. Under the present T-10 tokamak conditions, the combination of heat and particle fluxes in the edge plasma lead to the strong destruction of tungsten limiters during the experimental campaign. With an expected rise of the ECRH power up to 3.5 MW, the limiter damage should be much stronger.
During the disruption and runaway electron formation, extreme heat loads of more than 1 GW/m² caused strong melting of the tungsten plates on the inner and outer part of the ring limiter near the equatorial plane of the tokamak. Near this zone, the droplets of molten tungsten and redeposited tungsten layers were observed. In other areas of the tokamak chamber, no layers or drops of eroded tungsten were detected.

Acknowledgments
The authors express their gratitude to the T-10 staff for assistance with the experiments. The work is supported by ROSATOM (Contract Н. 4.241.9 В. 17.1011).

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