Shielding of the tungsten target exposed to the high-energy hydrogen plasma flow by gas injection

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1. Introduction

The aim of this work was the study of the impact of nitrogen/neon injection on the shielding of tungsten under heat loads by high-energy hydrogen plasma flows. This investigation is one of the stages in understanding the mechanisms of the shielding effect that underlie divertor lifetime. The data obtained can be of interest for solving such a problem as the development of a dissipative divertor for ITER [1]. Also, this work is closely related to research on the design of powerful soft X-ray radiation sources based on pulsed plasma accelerators [2].

2. Experimental scheme

The plasma flows were produced by the pulse electrodynamic plasma accelerator at the MKT facility and transported along the longitudinal magnetic field of up to 2 T to the tungsten target. The experimental scheme is shown in Figure 1.

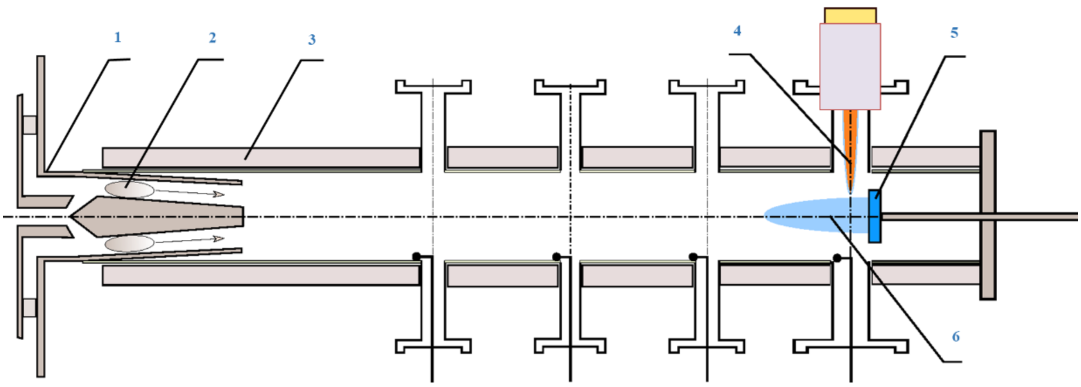


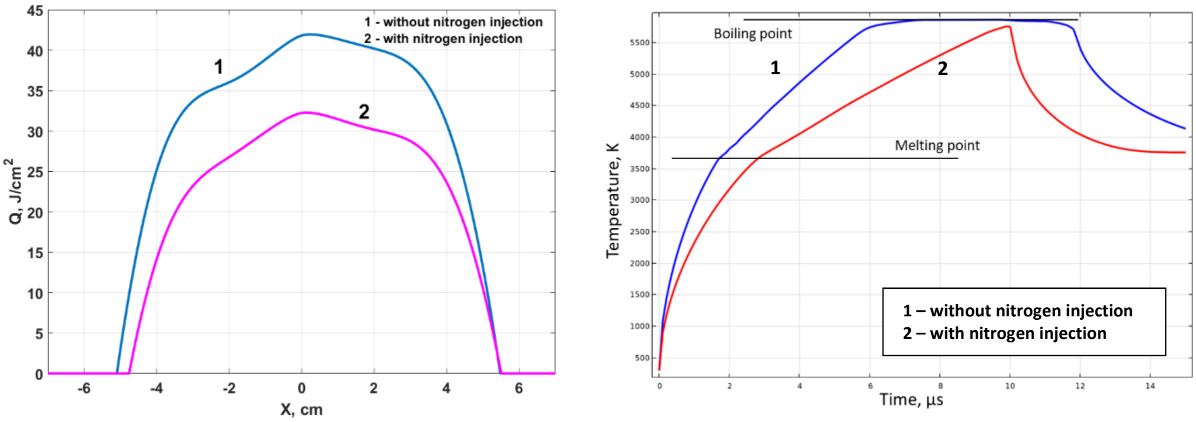
Fig.1. The MKT facility scheme for the gas and solid-state targets. 1 - pulse plasma accelerator; 2 - accelerated plasma; 3 - solenoids; 4 – gas jet; 5 – solid target; 6 - target plasma.

Varying the flow velocity of (4-6)×10^7 cm·s^{-1}, the plasma ion density of (2-4)×10^{15} cm $^{-3}$, and the magnetic field in front of the target, it was possible to reach the heat load on the tungsten of 40÷400 J·cm^{-2}. Full energy of plasma flow was ≈ 30 kJ with pulse duration of 10÷15 µs. A supersonic plane gas jet was directed along with the target front surface using a flat Laval nozzle. The gas density reached up to **n** ~ 10^{17} cm^{-3} with a jet cross-section of **L×w** ≈ 2×10 cm^2.

In the presented work, the following diagnostics methods were used: a transmission grating spectrometer with the 500 nm grating period and an MCP camera recording emission in the 1÷70 nm spectral range with spatial and temporal resolution. The exposure time of the MCP camera in the experiment was 2 µs. In addition, a set of thermocouples mounted on the backside of the target measured the energy absorbed by tungsten during the plasma load.

3. Experimental results

Figure 2(a) illustrates the distribution of the absorbed energy density over the surface of a tungsten target for different experimental conditions. In the first case, the gas jet was not used and the plasma flow directly interacted with the target surface. The absorbed energy density distribution has a domed shape with maximum located around the geometric center of the target surface, its value was about 41 J/cm^2. In the second case, the results were obtained using nitrogen injection, which led to a noticeable decrease in the absorbed energy density by tungsten. Its maximum value was about 32 J/cm^2.

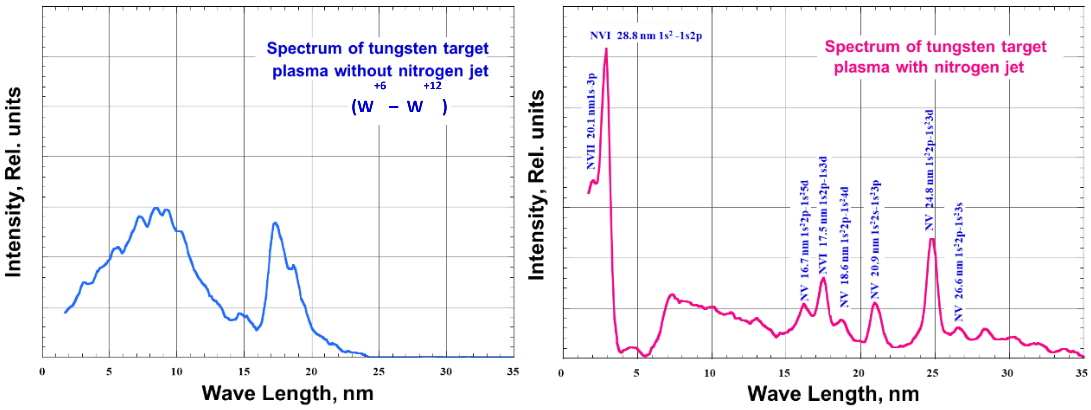


(a) (b)

Fig.2. Absorbed energy distribution over the target surface (a) and calculated max temperature of the tungsten target surface (b). The heat load on the target was modeled by a rectangular pulse with a duration of 10 µs.

Numerical simulation of heating the tungsten target by a thermal pulse shows that, in the experiments with nitrogen injection, the target surface was not reach the boiling point. In the case without nitrogen injection, intense evaporation of tungsten from the surface occurred. The calculated max temperature on the surface of the tungsten target is shown in Figure 2(b).

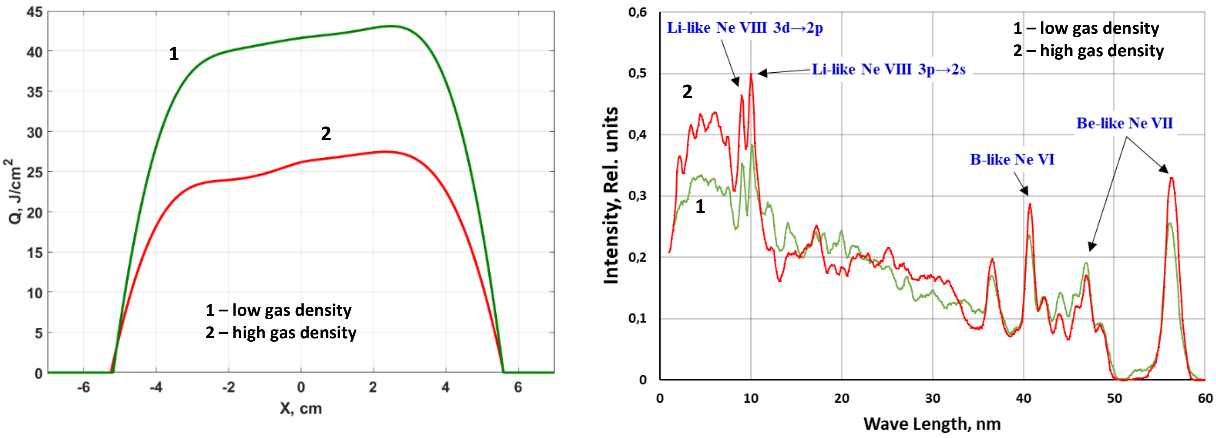
However, radical changes were with the spectrum of the target plasma shown in Figure 3 and, accordingly, with its ion composition. With no gas jet, in the spectral range up to 35 nm, the radiation was characterized only by a broadband spectrum of tungsten. In the presence of a gas jet of nitrogen, only lines of nitrogen ions, from Li-like to H-like, were observed in the same spectral range. Analysis of the spectra shows that the most intense line was the line of the He-like nitrogen ions, which requires ionization energy of at least 100 eV to obtain. So the temperature of the plasma formed near the surface of the target reaches no less than 50 eV, which significantly exceeds the boiling point (≈ 0.5 eV) of tungsten.



(a) (b)

Fig.3. Target plasma spectrum in front of tungsten target without (a) and with (b) nitrogen gas injection.

In the conducted experiments the maximum value of the parameter **n · L** (concentration per unit length) of the gas in the jet was about 4×10^{17} cm^{-2} for nitrogen and 2×10^{17} cm^{-2} for neon. A series of experiments were carried out with a lower value of this parameter for neon. In this case, the maximum absorbed energy density increased from 31 J/cm^2 to 43 J/cm^2. Figure 4(a) illustrates the distribution of the absorbed energy density over the surface of a tungsten target. However, evaporation and ionization of tungsten did not occur. In the target plasma spectra, shown in Figure 4(b), only neon lines from Be-like to Li-like without a broadband spectrum of tungsten were observed.



(a) (b)

Fig.4. Absorbed energy density distribution over the target surface (a) and target plasma spectrum in front of a tungsten target (b) for neon gas jet.

4. Summary

Experiments have shown that the injection of a gas (nitrogen/neon) in front of the target surface significantly reduced the heat load of the plasma flow on the target material. The gas shielding effect prevented heating of the target surface to the boiling point and evaporation of tungsten.

A decrease in the value of the gas jet parameter $\mathbf{n \cdot L}$ down from $(2 \div 4) \times 10^{17}$ cm^{-2} led to an increase in the absorbed energy density by the target. Most likely, the tungsten reached the boiling point. However, no characteristic spectral bands of tungsten were observed in the spectra of the target plasma. Further research is required to determine the minimum value of the gas jet parameter $\mathbf{n \cdot L}$, which would be sufficient for the shielding effect.

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References

1. Pshenov, A. A., Kukushkin, A. S., & Krasheninnikov, S. I. (2020). Influence of Cross-Field Transport in a Divertor on Seeded Impurity Radiation and Divertor Plasma Detachment. Plasma Physics Reports, 46(6), 587–596.
2. V.V. Gavrilov, A.M. Zhitlukhin, D.M. Kochnev, V.A. Kostyushin, I.M. Poznyak, S.A. Pikuz, S.N. Ryazantsev, I.Yu. Skobelev, D.A. Toporkov//Soft X-ray radiation sources based on high-energy plasma flow thermalization with gas and solid-state targets//7th International Congress on Energy Fluxes and Radiation Effects (EFRE-2020 online). Book of Abstracts, p.193.