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THE EFFECT OF A SMALL HELIUM ADDITION ON THE PLASMA-SURFACE INTERACTION IN QSPA

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The synergistic effects of tungsten exposure to combined hydrogen and helium particle fluxes as well as transient thermal loads need to be extensively studied for implementation of fusion reactor project. The mixture of hydrogen and helium was used as the working gas for plasma stream generation within the QSPA-M accelerator. The parameters of the mixed hydrogen and helium plasma were similar to those of pure hydrogen plasma generated in QSPA-M. It was shown that the small addition of helium (5 %) to hydrogen does not strongly influence plasma surface interaction. The influence of the external magnetic field on plasma surface interaction is also discussed.

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INTRODUCTION

The behavior of plasma-facing materials (PFMs) under plasma ion bombardment and heat fluxes is a critical issue for the realization of future fusion devices such as ITER and DEMO. PFMs will be exposed to steady state and transient thermal loads, namely edge localized modes (ELMs), vertical displacement events (VDEs) and plasma disruptions, as well as high hydrogen, helium and neutron fluxes. Helium will be present in a fusion plasma as an intrinsic impurity. Therefore, it is very important to study the interaction of helium and hydrogen-helium plasmas with PFMs. It is well-known that He has a damaging impact on the surface morphology during plasma exposure, for example, inducing tungsten (W) fuzz, blisters, helium bubbles and other [1-5]. Nevertheless, the synergistic effects of tungsten exposure to combined particle fluxes of different kinds (hydrogen, helium, etc.) and transient thermal loads need to be extensively studied.

Quasi-stationary plasma accelerators (QSPA) are capable of reproducing ELM impacts in terms of both heat load and particle flux to the surface and can provide plasma transportation in an external magnetic field, which mimics the divertor conditions [6-9]. The energy transfer from pure hydrogen plasma to material surfaces during plasma–surface interactions (PSIs) in a magnetic field has been investigated in the recently developed quasi-stationary plasma accelerator, the QSPA-M [7, 8]. The study analyzed the features of plasma visible radiation and performed investigations of energy transfer to the material surface for varied plasma heat loads and external magnetic field values. Calorimetry, optical emission spectroscopy and high-speed imaging were applied for PSI characterization. For perpendicular plasma incidence, it has been shown that the transient plasma layer is formed in front of the surface due to the stopped head of the plasma stream, even for rather small plasma heat loads which do not result in surface melting. The plasma density in this near-surface layer is much higher than in the impacting stream, resulting in a screening effect for energy transfer to the surface. The shielding effect due to the formation of a dense plasma layer in front of the exposed surface should be favorable for material performance. This effect is particularly important for decreasing the overall erosion of plasma-facing components during a large number of repetitive ELMs.

The experimental studies of vapour shielding of liquid-metal tin capillary porous structures (CPS) under plasma loads relevant to fusion reactor transient events have been also performed in complementary simulation experiments using QSPA-M and QSPA Kh-50 experimental facilities [8]. It has been shown that a pronounced vapour shield effect is dominating for exposed surfaces under the disruption heat loads. However, some moderate dynamical screening of the surface from the impacting plasma stream could appear also in the case of much smaller loads attributed to ELMs. This screening arose even during exposures below the target evaporation threshold.

This article presents the investigations conducted within QSPA-M of plasma shield formation in front of a surface and the transfer of energy from the plasma stream consisting of a hydrogen and helium mixture to the material surface.

1. EXPERIMENTAL FACILITY AND DIAGNOSTICS

The experiments were carried out using the QSPA-M device which can reproduce conditions of ITER ELM [6]. The discharge voltage in the QSPA-M accelerating channel achieved 10 kV and the discharge current was 400 kA. The plasma pulse duration slightly exceeded 100 μs. The maximum value of the hydrogen plasma pressure measured with a piezo detector amounted to 0.3 MPa. The plasma stream was around 5 cm in the presence of a B-field and increased to 15 cm when the external magnetic field was switched off. The value of energy density in the axis region of the plasma stream varied in a range of 0.1 to 1 MJ/m^2 [6-9].

The average value of plasma density estimated using H_β hydrogen spectral line in free pure hydrogen plasma stream was Ne = (2...3)·10^{21} m^{-3} without an external B-field and reached Ne = (2...3)·10^{22} m^{-3} when the magnetic field was applied [7].

The gas mixture of 95 % of hydrogen and 5 % helium was used as a plasma-forming substance in the accelerating channel of QSPA-M in the experiments. Optical spectroscopy was used for the determination of plasma parameters (electron density and temperature) in front of exposed surfaces and the studies of the target impurity behavior in the plasma shield during a plasma surface interaction. It should be noted that the hydrogen spectral line H_β (4861 Å), as well as the line of He II with a wavelength of 4685 Å were used to evaluate plasma density [9, 10]. Exposition time was 10 μs.

The plasma stream energy density and heat loads on the surface were measured with a set of movable calorimeters [7, 8]. The plasma pressure was measured with piezoelectric detectors. We used a high-speed (10bit CMOS pco.1200 s) digital camera PCO AG to perform observations of the plasma interactions with exposed targets and studies of the dynamics of material droplets and solid dust particles in front of the irradiated surface. The exposure time ranged from 1 μs to 1 s; the spectral range was from 290 to 1100 nm. The velocities of the emitted particles and the instants of their ejection (from the target surface) are to be calculated using the information from the subsequent camera frames (with visible traces of the particles flying from the target surface after a plasma shot) [7-9].

2. STUDIES OF FREE PLASMA STREAMS

Studies of the parameters of plasma streams on the base of hydrogen and helium mixture were performed for a free propagating plasma and during plasma surface interaction. The effect of magnetic field of up to 0.8 T was also evaluated.

First of all, the use of a gas mixture of 5 % helium (He) and 95 % hydrogen (H) does not significantly change the maximum value (about 400 kA) and waveform of the discharge current in the accelerator channel of the QSPA-M (the duration of the first half-period of 0.1 ms) as compared to the operation with pure hydrogen (Fig. 1). The addition of helium also has a negligible effect on the current-voltage characteristics. Discharge characteristics depend exclusively on the total amount of the working gas (pure hydrogen or mixture H+He).

Fig. 1 also shows the photomultiplier tube measurements of the temporal behavior of the hydrogen and helium spectral lines radiation intensities from the free plasma stream as well as shielding plasma layer in front of the target surface for different values of the magnetic field. The intensity of the irradiation grows significantly in an external magnetic field. It is important to note that in its presence, hydrogen radiation is registered even after the end of the plasma pulse, as the sequence of plasma confinement in the shield is altered by the applied magnetic field. The maximum intensity of helium spectral line radiation was registered at 30...60 μs.

The average value of plasma electron density measured from the hydrogen spectral line is Ne = (5...7)·10^{22} m^{-3} and it weakly depends on the energy density in free plasma stream in magnetic field (Fig. 2,a). The maximum value of plasma electron density is 10^{23} m^{-3} measured from the helium line and is weakly dependent on the magnitude of the magnetic field (see Fig. 2,b).

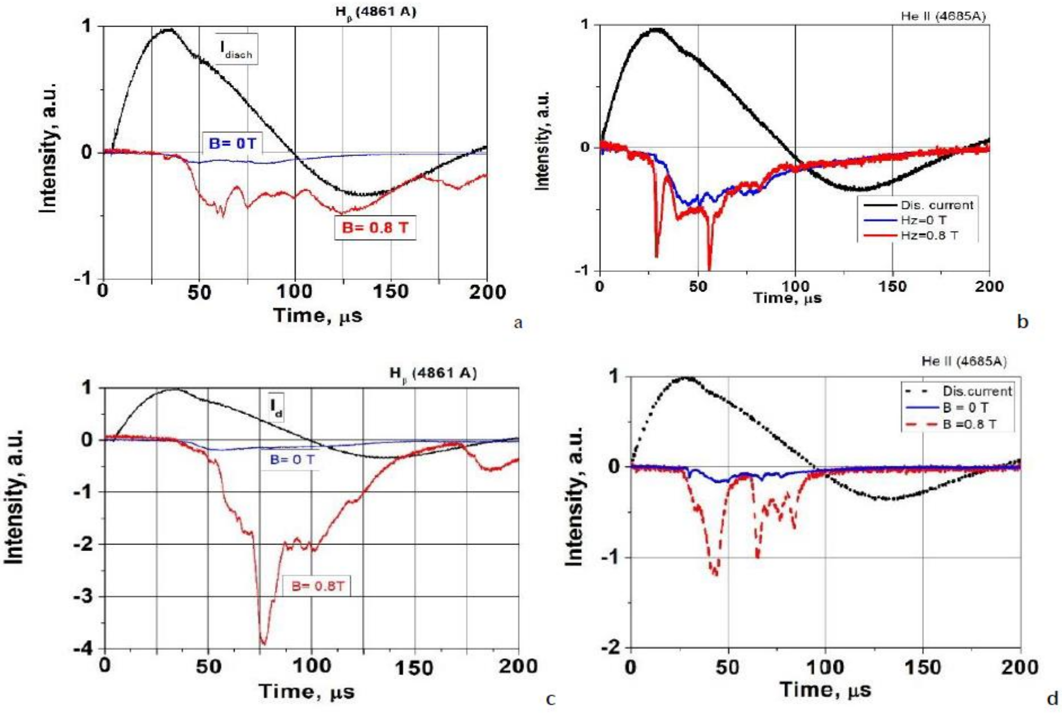

Fig. 1. Intensities of radiation of hydrogen (a, c) and helium (b, d) in a free propagating plasma stream (top line) as well as the shielding plasma layer (bottom line) in front of the target surface (~5 mm) for different values of magnetic field: B = 0 and 0.8 T, and discharge current waveform

The behavior of density (see Fig. 2) and plasma radiation (see Fig. 1) are similar to those obtained in pure hydrogen [9]. The mismatch between density values estimated from H$_\beta$ and He II spectral lines is attributed to different regions of line radiation.

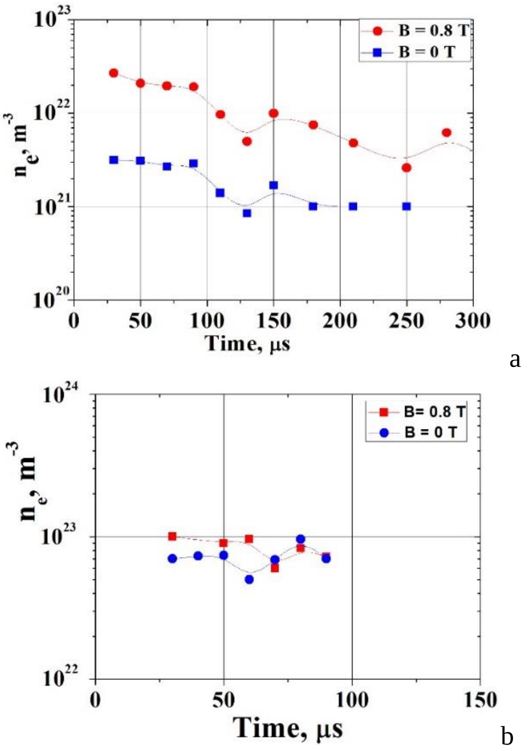

Fig. 2. Electron density in the plasma stream propagating in the magnetic field (B) measured from H$_\beta$ (a) and He II (b)

The maximum energy density of the free plasma stream achieved at U = 10 kV is above Q = 0.75 MJ/m^2. No substantial difference has been observed in the energy density values or their behavior with and without a magnetic field. The evaluation of energy density is similar to the case of using pure hydrogen [7-9].

3. STUDIES OF TRANSIENT PLASMA LAYERS AT PLASMA SURFACE INTERACTION

The electron density of the transient plasma layer was evaluated by the measurement of radiation of the helium spectral line. Maximum electron density was $5\cdot10^{23}$ m^{-3} in the magnetic field. Without the magnetic field, the value of the plasma density of the shielding layer is similar to the one estimated in the free plasma stream within measurement accuracy (see Figs. 2,b; 3).

Radiation intensity near the target surface in the presence of the magnetic field is ten times as high as for B=0 (see Fig. 1). High-speed images of PSI are shown in Fig. 4. Pictures of PSIs were taken under identical conditions. The bright area corresponds to the maximum density of the transient plasma layer that arises near the surface during the plasma stream impact. The width of the bright area increased significantly with the growing value of the magnetic field.

In the presence of an external magnetic field, the energy density saturates at some distance from the surface. Only a part of the plasma energy is transferred to the target surface through the shielding plasma layer (Fig. 5). A different dynamics of energy dissipation in the shielding layer is observed without an external magnetic field. The energy density initially goes up to the maximum value that even slightly exceeds the energy of the incident plasma in the layer of 1...2 cm. After that, the measured specific energy decreases with increasing distance and is comparable to the energy of the incident plasma. Such behavior is similar to the case of the surface irradiation with pure hydrogen [7, 8].

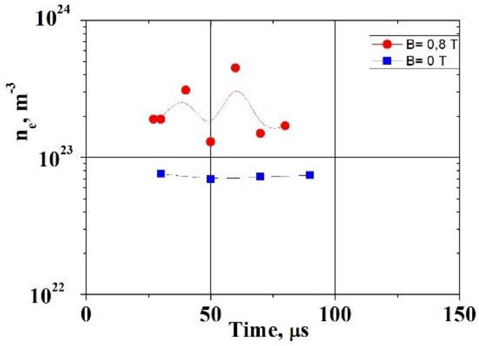

Fig. 3. Electron density in the plasma layer near the tungsten surface exposed to plasma stream at different values of magnetic field (B)

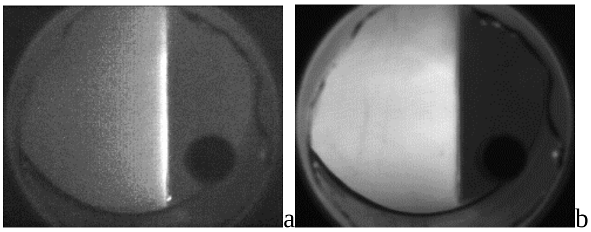

Fig. 4. Images of plasma stream interaction. The energy density of the exposing plasma stream of 0.75 MJ/m^2 at different values of magnetic field (B): B=0 (a), B = 0.8 T (b). Plasma impact is from left to right

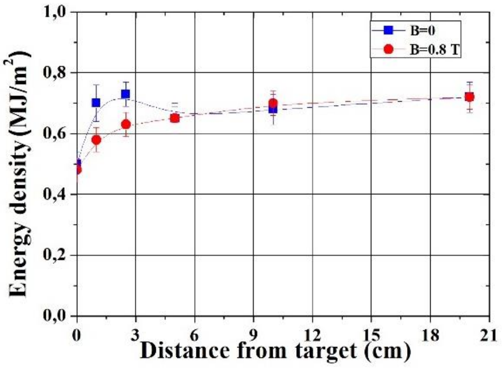

Fig. 5. Distributions of plasma energy density in the shielding layer vs the distance from the tungsten target surface, Q = 0.75 MJ/m^2 at different values of magnetic field (B)

Plasma irradiation (5 plasma pulses) of the tungsten surface resulted in the formation of large crack (width up several µm) networks. The size of the major crack mesh achieved 0.6 mm for hydrogen-helium exposure (Fig. 6). That is similar to the results of pure hydrogen irradiation with the same heat load.

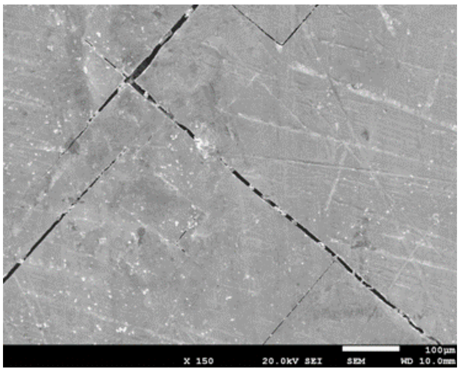

Fig. 6. SEM image of tungsten surface exposed to plasma stream of Q = 0.75 MJ/m²

CONCLUSIONS

The first results of the studies of the parameters of plasma streams generated by the QSPA-M using mixed hydrogen (95 %) and helium (5 %) gases as a plasma-forming substance in the accelerating channel were obtained. The plasma stream was injected into the magnetic field of B=0.8 T.

The parameters of mixed hydrogen and helium plasma were found to be similar to those of pure hydrogen plasma both with and without a magnetic field in QSPA-M. The value of the energy density in the plasma stream achieved 0.75 MJ/m^2. The density of the plasma stream was up to 10^{23} m^{-3} and increased to $4{\cdot}10^{23}$ m^{-3} in the shielding layer near the exposed surface. The radiation intensity near the target surface increased tenfold in the presence of the magnetic field of B=0.8 T. The heat load on the exposed surface was about 0.45 MJ/m^2, resulting in the formation of crack networks on the tungsten surface.

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ВНЕСОК МАЛОЇ ДОБАВКИ ГЕЛІЮ У ВЗАЄМОДІЮ ВОДНЕВОЇ ПЛАЗМИ КСПП З ПОВЕРХНЯМИ

В.О. Махлай, С.С. Геращенко, Ю.В. Петров, М.С. Ладигіна, М.М. Аксьонов, В.В. Чеботарьов, М.В. Кулик, В.В. Стальцов, Д.В. Єлісєєв, Ю.Є. Волкова, Т.М. Меренкова

Для реалізації проекту термоядерного реактора необхідно детально вивчити синергетичні ефекти впливу на вольфрам комбінованих потоків частинок водню і гелію, а також перехідних теплових навантажень. Суміш водню та гелію використовувалася в якості робочого газу для генерації плазмових потоків в установці КСПП-М. Параметри воднево-гелієвої плазми в КСПП-М були подібні до параметрів чисто водневої плазми. Показано, що невелике додавання гелію (5 %) до водню не має сильного впливу на взаємодію плазми з поверхнею. Обговорено також вплив зовнішнього магнітного поля на взаємодію плазми з поверхнями.