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Studies of plasma interactions with tungsten targets in PF-1000U facility

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Abstract. This paper presents results of experimental studies of tungsten samples of 99.95% purity, which were irradiated by intense plasma-ion streams. The behaviour of tungsten, and particularly its structural change induced by high plasma loads, is of great importance for fusion technology. The reported measurements were performed within a modified PF-1000U plasma-focus facility operated at the IFPiLM in Warsaw, Poland. The working gas was pure deuterium. In order to determine the main plasma parameters and to study the behaviour of impurities at different instants of the plasma discharge, the optical emission spectroscopy was used. The dependence of plasma parameters on the initial charging voltage (16, 19 and 21 kV) was studied. Detailed optical measurements were performed during interactions of a plasma stream with the tungsten samples placed at the *z*-axis of the facility, at a distance of 6 cm from the electrode outlets. The recorded spectra showed distinct WI and WII spectral lines. Investigation of a target surface morphology, after its irradiation by intense plasma streams, was performed by means of an optical microscope. The observations revealed that some amounts of the electrodes material (mainly copper) were deposited upon the irradiated sample surface. In all the cases, melted zones were observed upon the irradiated target surface, and in experiments performed at the highest charging voltage there were formed some cracks.

Key words: plasma-surface interaction • plasma streams • tungsten • plasma focus • PF-1000U

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Introduction

Studies of plasma-surface interactions and associated processes are of high importance for the development of plasma physics and technology [1, 2]. In spite of extensive research, many important questions remain still unsolved, for example, there is a lack of information about dynamics of the materials erosion during the plasma-surface interactions.

It is well known that tungsten is foreseen as a plasma-facing material in a future fusion reactor, which will provide an intense neutron radiation. Discharges of the plasma-focuses (PF) type, which generate intense plasma streams and high neutron yields, can help to enhance our knowledge about the effects of neutron irradiation upon tungsten and tungsten alloys, and in particular about changes of their microstructure and surface erosion. It should be noted that tungsten-based materials are also used in many other systems used for studying physics of gas discharges and near-electrode processes as well as different technical applications.

Taking into account the facts mentioned above, detailed studies of plasma-tungsten interactions, using intense pulsed plasma-ion streams generated by high current discharges of the PF type, have been undertaken [3]. The main aim of our recent studies was to determine plasma parameters during a free propagation of the plasma-ion streams and their interactions with tungsten targets, as well as to investigate the surface erosion of the irradiated samples. Such data are of particular importance for fusion technology.

Experimental set-up

The reported experiments have been performed within the PF-1000U facility equipped with coaxial copper electrodes identical as in earlier experiments [2–4], but inside the inner electrode (anode), an additional gas-puffing valve was placed, which could be used for the axial injection of a chosen gas. During the reported studies, the initial filling gas in the experimental chamber was pure deuterium under pressure of 1.2 hPa for discharges performed at the charging voltage of 16 kV, and 1.6 hPa for shots performed at the charging voltage 19 and 23 kV. The same value of the gas pressure was not possible to apply due to the safety and quality reasons of the discharge. These discharges were supplied from a 1.32 mF condenser bank at the charging voltage varied from 16 to 23 kV. It could store energy ranging from 130 to 350 kJ. The maximum intensity of the discharge current amounted to 1.3–1.6 MA, respectively.

The investigated targets were made of 99.95% purity tungsten produced by the WOLFTEN Co. The dimensions of samples W1-W5 were (3 × 3 × 0.1) cm^3 and those of W6-W7 samples were (3 × 3 × 0.03) cm^3, but the size of the sample surface, which was irradiated by the plasma streams, was the same in all cases (3 × 3) cm^2. The exposed samples were located at the electrode symmetry axis, at a distance of 6 cm from the electrodes ends.

In order to determine the main plasma parameters, that is, the electron density and temperature, and to study the behaviour of impurities at different instants of the plasma discharge, spectra in UV and visible range were recorded. The optical measurements were performed by means of a Mechelle®900 optical spectrometer, which provides the optimal spectral and temporal resolution for our experimental conditions. The observation window was situated side-on the main experimental chamber and was equipped with a collimator coupled with the spectrometer through a quartz fibre cable, as shown in Fig. 1.

The Mechelle®900 spectrometer equipped with a CCD camera could operated in the wavelength range from about 300 to 1100 nm, with different acquisition (ranging from 100 to 50 ms) and delay times. In the described spectroscopic measurements, the exposition time equal to 100 ns or 1 μs was used most often.

A time delay of the exposition in relation to the current peculiarity (so-called current dip) was changed from discharge to discharge in order to collect information about dynamics of the investigated discharges. The electron density of a freely propagating plasma stream was estimated from a full width at the half maximum (FWHM) value of the D_β spectral line, taking into account the linear Stark broadening effect. It should be mentioned that in the recorded optical spectra, the D_α line showed often a strong reabsorption, and the D_γ line was not identified in many cases.

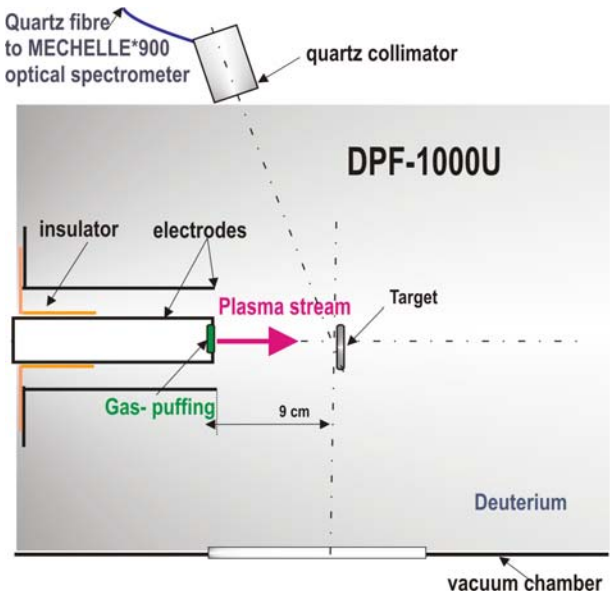

Fig. 1. Scheme of the experimental set-up used for studies of plasma-target interactions.

Experimental results

Preliminary experiments within the PF-1000U facility were performed without any target to investigate characteristics of freely propagating plasma and ion streams. An example of the optical spectrum recorded for a free plasma-ion stream is presented in Fig. 2.

During successive experiments, different charging voltages (from 16 to 23 kV) were applied and corresponding optical spectra were recorded in order to determine variations in plasma electron density values [5, 6]. Temporal changes of the electron density, as calculated on the basis of the measured Stark broadening of the D_β spectral line, are shown in Fig. 3.

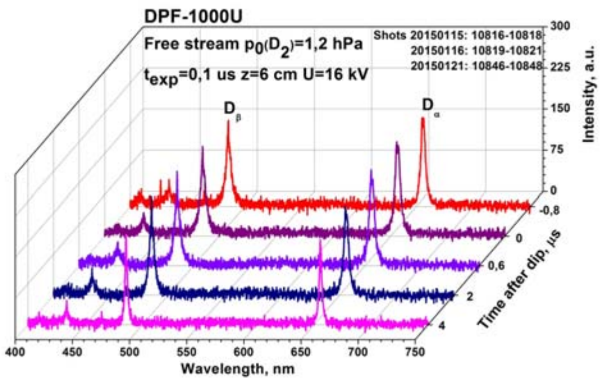

Fig. 2. Optical spectrum recorded for a freely propagating plasma stream emitted from the PF-1000U facility during a discharge performed at the charging voltage equal to 16 kV.

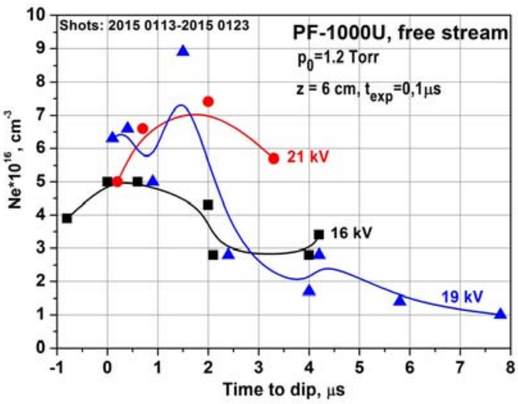

Fig. 3. Temporal changes of the electron density during PF-1000U discharges performed at the initial charging voltages U = 16, 19 and 21 kV.

On the basis of the presented results, one can easily see that for discharges at the charging voltage of 16 kV, an average electron density was about 4×10^{16} cm^{-3}, while at 19 kV, the observed electron density peak reached about 9×10^{16} cm^{-3}. In the case of a charging voltage of 21 kV, the maximum density value was only 7.5×10^{16} cm^{-3}, but an average electron density was slightly higher than for 19 kV. It can be suspected that instabilities in plasma focus are developed more often when the charging voltage is increased and the initial filling gas pressure in vacuum chamber is higher. In all the investigated operational regimes, the maximum values of the plasma electron density were observed in the first microseconds after the current peculiarity (dip), which corresponded to the maximum plasma compression. After about 2 μs, the electron density dropped to an average level observed for freely propagating plasma-ion streams. It should be also noted that in the case of discharges for 16 kV, the deuterium-filling pressure in the PF-1000U experimental chamber was 1.2 hPa, while in other cases, it was higher (1.6 hPa). This was induced by safety requirements for discharges performed at higher charging voltages.

The successive experiments and spectroscopic measurements were carried out with exchangeable tungsten targets located at a distance of 6 cm from the electrode outlets, as described above. The recorded optical spectra from plasma near the investigated targets showed distinct WI and WII spectral lines, as presented in Fig. 4.

These spectral lines were evidently emitted by the exited W-atoms and single-ionised W ions, which were generated during the plasma interaction with the target. One can easily notice that the optical spectra recorded at the exposition time of 0.1 and 1 μs show similar features with some differences in their intensities. The identified W lines enabled the process of tungsten ablation to be analysed at different experimental conditions. Another part of the optical spectra, which were recorded during interactions of plasma-ion streams with the investigated W-targets, is shown in Fig. 5.

It should be mentioned that the considered spectral lines appeared on average about 2–4 μs after the current dip, but to record distinct tungsten lines, it

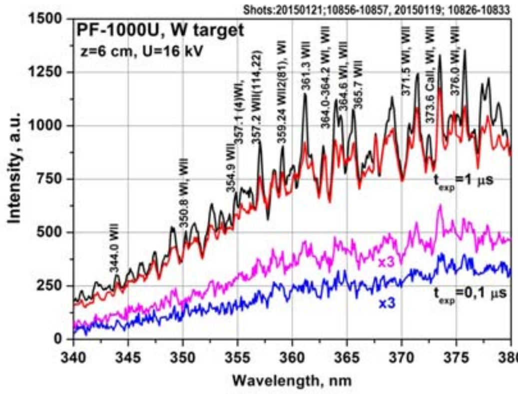

Fig. 4. Optical spectra in the wavelength range from 340 to 380 nm recorded during interactions of high-temperature plasma streams with the W-target for four different shots, at the spectrometer exposition time equal to 0.1 and 1 μs.

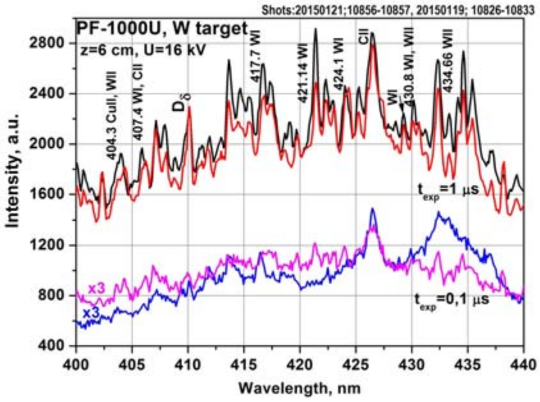

Fig. 5. Optical spectra in the wavelength range from 440 to 480 nm obtained during interactions of plasma streams with the W-target, which were recorded with exposition time 0.1 and 1 μs.

was necessary to apply longer exposition time, for example, 1 μs. The spectra presented in Figs. 4 and 5 show that the observed WI and WII lines were relatively intense even for discharges performed at a lower charging voltage (16 kV). It should also be mentioned that intensity of tungsten spectral lines has been enhanced when the applied working voltage was increased. It means that plasma streams produced by such discharges could induce a considerable erosion of the W-target. Moreover, it also suggests that the energy density of the plasma streams is high enough to ablate the investigated material [2].

In order to investigate changes in the target surface morphology, which were induced by interactions of intense plasma streams, an additional analysis was performed by means of an optical microscope. The microscopic observations revealed that at the determined experimental conditions in addition to the target erosion some amounts of the electrodes material (mainly copper, because the red/gold colour of the deposited material is clearly seen) were deposited upon the sample surface. This effect is visible on the microscopic pictures presented in Fig. 6.

These microscopic pictures, as taken with different magnification, show that in addition to the distinct erosion (melting and vaporisation) of the irradiated surface, on the molten layer of the sample

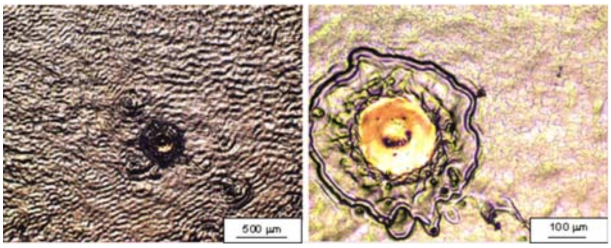

Fig. 6. Pictures of the W-sample surface after its irradiation by three successive PF-1000U discharges at the same conditions: the sample was placed at a distance of 6 cm from the electrodes ends, the deuterium pressure was 1.2 hPa, and the charging voltage was 16 kV. These pictures were taken with different magnification, as shown in the inserted scales.

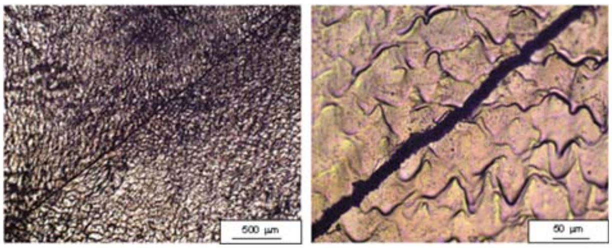

Fig. 7. Pictures of the W-sample surface after its interaction by three successive PF-1000U discharges at the same conditions: the sample was placed at a distance of 6 cm from the electrodes ends, the deuterium pressure was 1.6 hPa and the charging voltage was 21 kV. These pictures were taken with different magnifications, as shown in the inserted scales.

surface one can also observe some craters caused probably by heavy impurity ions, which might originate from the erosion of electrodes. It should be noted that in all the investigated cases, upon the irradiated sample surfaces, the melted zones were observed, but in experiments performed at higher charging voltages, some cracks also appeared, as shown in Fig. 7.

Additional information about the erosion of the irradiated W-targets was gained from a comparison of mass losses, which were determined by the accurate weighting of the virgin and irradiated samples. The results are presented in Table 1.

From the presented data, one can easily see that the average loss of target mass per one discharge was 0.26–1.20 mg, and its highest value was measured for a discharge performed at the highest charging voltage (highest energy) of the condenser bank. The observed jitter of the considered parameter could be explained by irreproducibility of plasma discharges and ion beams occurring inside the generated plasma streams.

Summary and conclusions

The most important results of the reported studies can be summarised as follows:

1. Using the optical emission spectroscopy methods, that is, analysing shapes of the D_β line and taking into account the Stark broadening effects, temporal changes of an electron density in the applied plasma streams were determined.
2. The plasma electron density, as measured at a distance of 6 cm from the PF-1000U electrode outlets, its dependence on the initial charging voltage was analysed and it was found that for discharges performed at U_0 = 19 kV the maximum density appeared about 1–2 µs after the current dip and amounted to about 9×10^{16} cm^3, for shots at U_0 = 21 kV the maximum density was slightly lower (about 7×10^{16} cm^{-3}), but for shots at U_0 = 16 kV, it was considerably lower and amounted to about 4×10^{16} cm^{-3} only.
3. During PF-1000U experiments performed with irradiation of the pure tungsten targets, the recorded optical spectra contained many spectral lines of excited tungsten atoms (WI) and single--ionised tungsten ions (WII).
4. These tungsten spectral lines appeared on average about 2–4 µs after the discharge current dip and they could be easily observed at longer times of the spectrometer exposition, which allowed more intense and distinct tungsten spectral lines to be recorded.
5. The microscopic analyses of the irradiated targets showed the melted zones and microcraters, which contained some amounts of the electrode material, while on the samples irradiated by discharges performed at higher charging voltages, distinct cracks also appeared.

It can be concluded that the modernised PF-1000U facility can be applied for studies of plasma-surface interactions and the optical emission spectroscopy is a useful diagnostic tool, which might be applied together with other techniques, for example surface analysis.

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Table 1. Measurements of mass losses of the irradiated tungsten samples

Sample no.	Deuterium pressure [hPa]	Initial charging voltage [kV]	Number of discharges	Initial mass [g]	Loss of mass [g]	Average loss of mass per one discharge [mg]
W1	1.6	23	1	8.4766	0.0007	0.70
W2	1.6	21	1	8.8445	0.0012	1.20
W3	1.6	21	3	8.9607	0.0015	0.50
W4	1.6	19	1	8.8736	0.0009	0.90
W5	1.6	19	3	9.0435	0.0008	0.26
W6	1.2	16	3	3.5751	0.0029	0.96
W7	1.2	16	10	3.6283	0.0081	0.81

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