NUKLEONIKA 2015;60(2):293–296
doi: 10.1515/nuka-2015-0048

ORIGINAL PAPER

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OPEN

Study of tungsten surface interaction with plasma streams at DPF-1000U

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Abstract. In this note experimental studies of tungsten (W) samples irradiated by intense plasma-ion streams are reported. Measurements were performed using the modified plasma focus device DPF-1000U equipped with an axial gas-puffing system. The main diagnostic tool was a Mechelle®900 optical spectrometer. The electron density of a freely propagating plasma stream (i.e., the plasma stream observed without any target inside the vacuum chamber) was estimated on the basis of the half-width of the D_β spectral line, taking into account the linear Stark effect. For a freely propagating plasma stream the maximum electron density amounted to about 1.3×10^{17} cm^{-3} and was reached during the maximum plasma compression. The plasma electron density depends on the initial conditions of the experiments. It was thus important to determine first the plasma flow characteristics before attempting any target irradiation. These data were needed for comparison with plasma characteristics after an irradiation of the investigated target. In fact, spectroscopic measurements performed during interactions of plasma streams with the investigated W samples showed many WI and WII spectral lines. The surface erosion was determined from mass losses of the irradiated samples. Changes on the surfaces of the irradiated samples were also investigated with an optical microscope and some sputtering and melting zones were observed.

Key words: DPF-1000U • electron density • gas-puffing • plasma stream • tungsten

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Received: 12 June 2014
Accepted: 5 January 2015

Introduction

Plasma-focus (PF) devices are sources of hot and dense plasma streams which can be used for erosion tests of different materials [1, 2]. In recent year there is a growing interest in tungsten, because it is often used in different fusion devices, including various tokamaks; for example in the large ITER facility a divertor is made of tungsten [3]. It is also assumed that tungsten will be the main material of the first wall of plasma vessel in future thermonuclear power plants. Hence, an investigation of the behavior of tungsten under high thermal and corpuscular loads becomes of primary importance.

In this paper we describe how the pulsed plasma streams generated by the DPF-1000U facility [4] interact with some selected tungsten targets. The DPF-1000U facility is located at the Institute of Plasma Physics and Laser Microfusion in Warsaw, Poland, and it allows to perform heat load tests of various materials [5]. The main aim of this study was to investigate free plasma streams and their interactions with the selected tungsten samples by means of an optical emission spectroscopy, and to investigate tungsten surface after its irradiation.

Experimental setup

The measurements described in the following were performed with the use of the modified DPF-1000U device equipped with an axial gas-puffing system [4]. The main experimental chamber was filled up with the pure deuterium under the pressure of 1.2 Torr. The gas-puff system was triggered about 2 ms before the discharge was initiated. The gas valve injected about 1 cm³ of the pure deuterium (grade 99.7%, containing <5000 ppm of the deuterium hydride, <200 ppm of the hydrogen, and <2 ppm in total of hydrocarbons). Since the mechanical valve was open for at least several milliseconds, a gas inflow occurred practically during the whole plasma discharge. The plasma discharges were supplied from a large 1.32 mF condenser bank charged up to the initial voltage of 19 kV, which corresponded to the energy of 240 kJ. The maximum discharge current amounted to 1.5 MA.

The target for the material tests was a pure (99.95%) tungsten (W) sample of dimensions 3 cm × 3 cm, mounted on the z-axis perpendicularly to the plasma flow in the DPF-1000U, at a distance of 9 cm from the outlets of the electrodes, as shown in Fig. 1. That distance was chosen for the reason that the current sheath collapses usually at the z-axis at a distance of 7–8 cm from the electrode outlets, as one can see from interferometric images. Therefore, the presence of the target located at this distance does not affect the formation of the pinch column. The neutron yield from the shots without the target was on average about $Y_n = 6 \times 10^{10}$, while that from the shots with the W target was $Y_n = 7 \times 10^9$. It should be noted that there were no attempts to optimize the neutron yield as it was not the main aim of this experiment.

The main applied diagnostics was the optical emission spectroscopy, performed by means of a Mechelle®900 spectrometer. It was coupled with an optical collimator situated behind an optical window side-on relative to the investigated target. The spectrometer was equipped with a CCD-camera and it was used for recording spectra of plasma emission within a wavelength range of 300–1100 nm, with the acquisition time equal to 0.1 μs. A time delay of the exposition was changed from shot to shot in order to collect information about discharge dynamics. The plasma electron density of a freely propagating stream was estimated on the basis of the half-width of the D_β spectral line, taking into account the linear Stark effect, as described in [6].

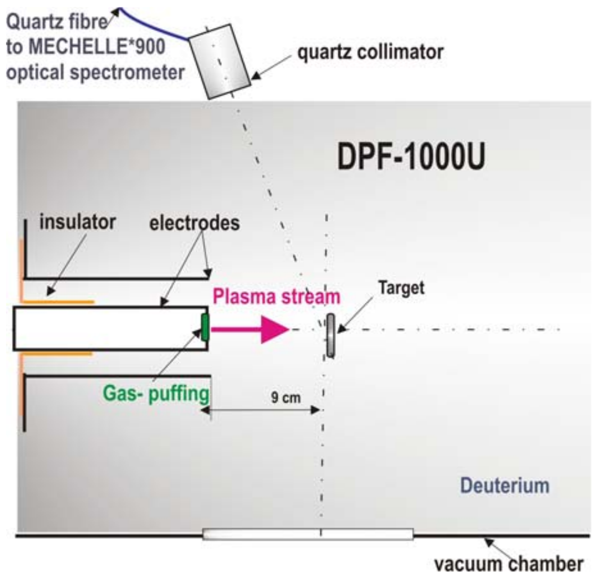

Fig. 1. A schematic view of the experimental setup which shows positioning of a the target and of the optical collimator within the modified DPF-1000U facility.

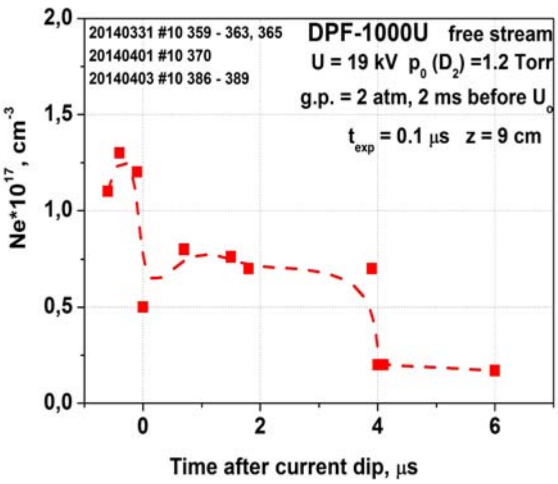

Fig. 2. The temporal changes of the electron density during the DPF-1000U discharge performed at the initial pressure p_0 = 1.2 Torr of D_2, with the use of gas-puffing (1 cm³, at 2 atm) started about 2 ms before the discharge was initiated.

Experimental results

Temporal changes of the electron density, as calculated from the measured Stark broadening of the D_β line, are presented in Fig. 2. It was found that the maximum electron density was approximately 1.3×10^{17} cm^{-3} and it was reached close to the moment when the maximum plasma compression occurred, which was accompanied by a peculiar behavior of the discharge current (the so-called current dip). After this phase the electron density decayed in about 6 μs.

The optical emission spectra of the freely propagating plasma streams were recorded at different instants before and after the current dip, as shown in Fig. 3. From the presented optical spectra it can be easily seen that distinct impurities appeared at z = 9 cm approximately 4 μs after the discharge current dip, and that their population increased strongly during the subsequent 4–5 μs. Some spectral lines of Cu ions, which originated from the erosion of electrodes, were recorded during the whole discharge, but the intense spectral lines of C ions were only observed about 4 μs after the current dip.

The optical spectroscopy measurements performed during the interactions of plasma streams with the investigated W target provided the information about the emission of different WI and WII spectral lines. This shows that the energy density deposited by the applied plasma streams upon the

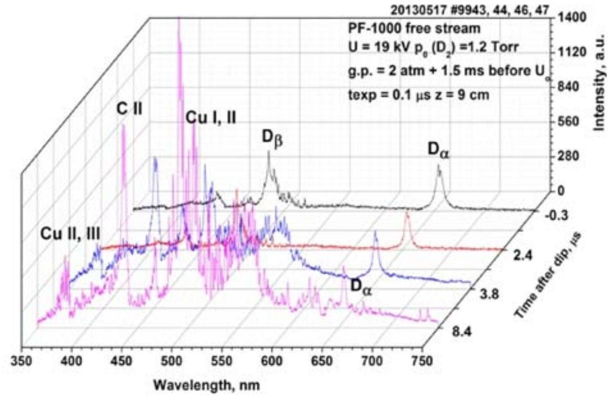

Fig. 3. The temporal changes of the optical spectra, as measured for the freely propagating plasma streams generated in the DPF-1000U at p_0 = 1.2 Torr, with gas-puffing applied 1.5 ms before the initiation of the discharge.

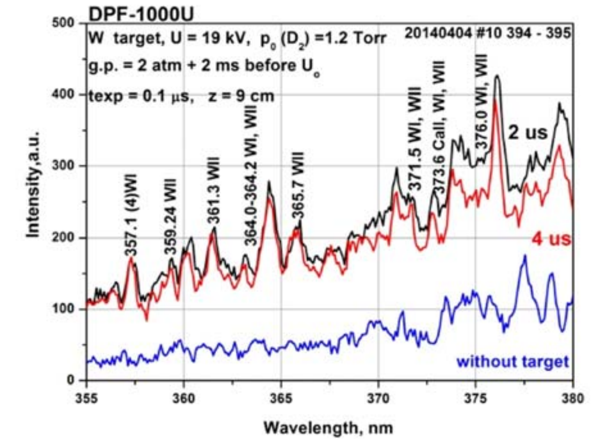

Fig. 4. A selected part of the optical spectrum, as recorded without any target (the bottom trace) and during interactions of plasma streams with the W target, observed at different instants of time: 2 μs after dip (the top trace) and 4 μs after dip (the middle trace).

target surface was sufficiently high to enable the material ablation and to produce doubly ionized atoms. In Fig. 4 we show a comparison of selected optical spectra recorded for shots with the investigated target – showing distinct WI and WII lines – with the spectra observed in the absence of any target.

An additional information about the erosion of the W samples was obtained from the comparison of mass losses of three samples irradiated with different numbers of discharges (see Table 1). It turned out that the W sample lost about 0.5 mg per one discharge, but such an estimate is very rough and a more accurate analysis (e.g. with an EDS method) is needed, because some impurities were deposited upon the investigated targets.

The changes of the targets' surfaces after their irradiation with intense and high-density plasma streams generated by the DPF-1000U facility were studied with the use of an optical microscope. In Fig. 5 we compare microscope images of a pristine

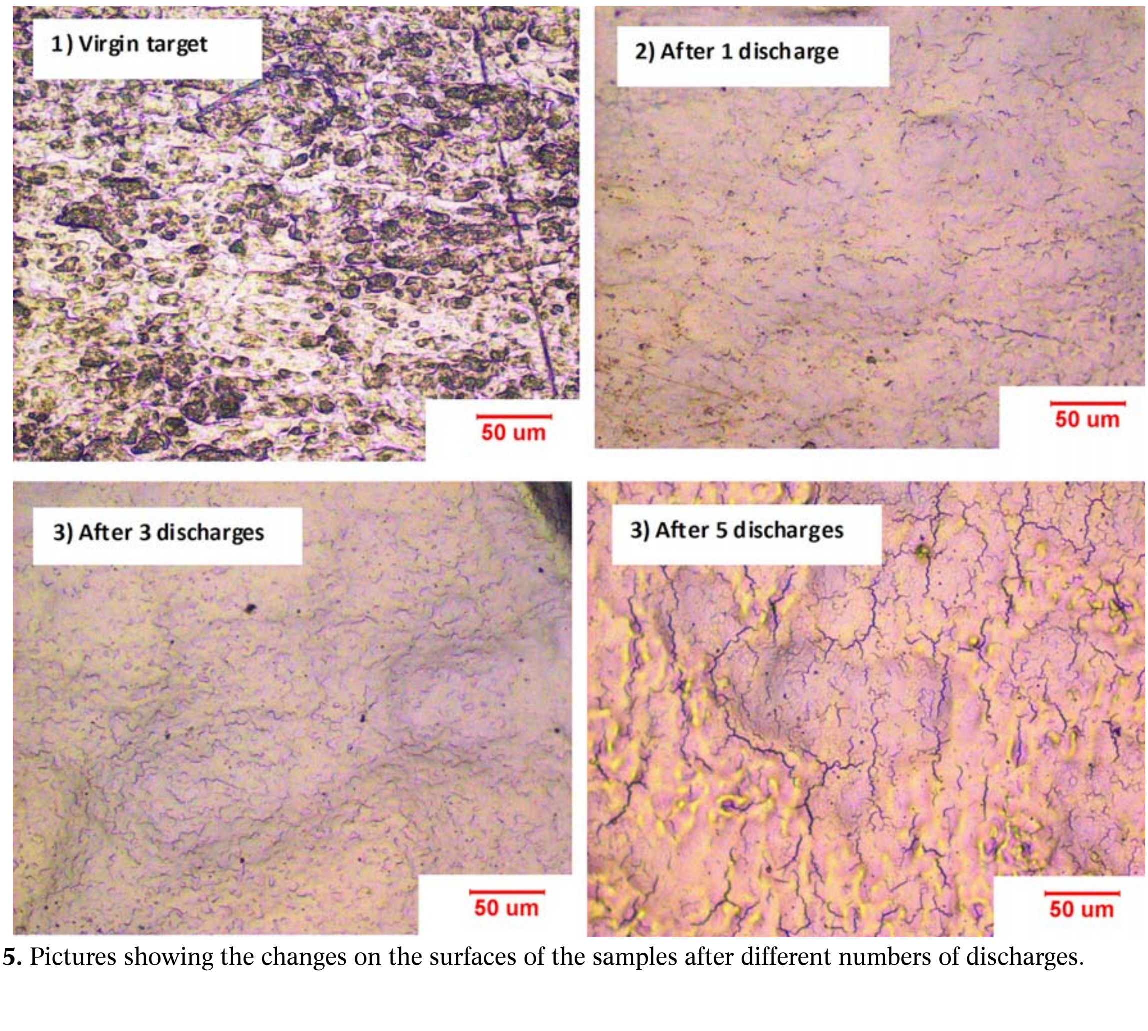

Fig. 5. Pictures showing the changes on the surfaces of the samples after different numbers of discharges.

Table 1. Analysis of mass of the three investigated W samples

	W sample after 1 discharge	W sample after 3 discharges	W sample after 5 discharges
Initial mass [g]	8.2804	8.6732	8.4694
Loss of mass [mg]	0.40	2.50	2.00
Loss of mass per one discharge [mg]	0.40	0.83	0.40

sample (i.e. before irradiation) with images of samples subjected to different number of discharges.

Summary and conclusions

The most important results of the reported studies can be summarized as follows: 1) the temporal variation of the electron density was determined using the optical emission spectroscopy, on the basis of the shape of the D_β line and taking into account the Stark broadening; 2) the estimated maximum electron density amounted to 1.3×10^{17} cm^{-3} and it was observed near the current peculiarity (dip); 3) numerous spectral lines of impurities were observed in the spectra recorded about 4 μs after the current dip, and their population increased in the period from 4 to 8 μs; 4) the spectral lines of Cu I-III (from the central electrode material) and C II-III (probably from the material deposited on the chamber walls) were also identified; 5) the images of targets taken with an optical microscope showed that the irradiated surfaces showed signs not only of sputtering, but also of melting zones.

A more detailed analysis of the targets' surfaces is needed to determine the influence of the impurities which might be deposited upon the irradiated samples.

Acknowledgments. This work was partly supported by the IAEA CRP RC-16954 and RC-16956 grants, as well as the Polish Ministry of Science and Higher Education within the framework of the financial resources in the year 2014 allocated for the realization of the international co-financed projects. This work was performed in Kharkov (Ukraine), in Otwock-Swierk and in Warsaw (Poland).

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