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Spectroscopy of the tungsten plasma produced by pulsed plasma-ion streams or laser beams

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ABSTRACT

The paper reports on experiments, which concerned studies of plasma produced from a tungsten (W) target bombarded by powerful (ca. 5 μs, 1–5 MW/cm^2) plasma-ion streams in RPI-IBIS plasma accelerator, and a similar target irradiated with intense Nd:YAG laser pulses (0.5 J, 3 ns, ca. 5.3×10^9 W/cm^2) in another vacuum chamber. In both experiments optical measurements were performed with a Mechelle®900 spectrometer, which enabled the spectrum from 300 nm to 1100 nm to be recorded, and different WI- and WII-lines to be identified. From space- and time-resolved measurements of those lines, basic W-plasma parameters were estimated. During W-plasma expansion the electron temperature was found to be 0.8–1 eV and electron concentration $(2–8) \times 10^{16}$ cm^{-3}. The emission of higher-ionized W-ions (up to W^{+6}) was confirmed by measurements with an ion-energy analyzer. Structural changes in the irradiated targets were investigated with an optical microscope and SEM.

1. Introduction

Tungsten (W) and W-alloys constitute important constructional materials, which are often used in high-temperature plasma research facilities, and are to be used in future fusion reactors, e.g., ITER. Therefore, information about behaviour of W- samples under intense electromagnetic- and corpuscular-fluxes are of primary interest for plasma physicists and engineers. Valuable information about the erosion of such samples can be gained from spectroscopic observations. In fact, the spectral emission from plasma facing W-components has been investigated in different laboratories [1–3]. Unfortunately, the available data have been rather scarce and further studies have appeared to be needed. The main aim of the reported studies was to perform a more detailed spectroscopic study of pure W-targets irradiated with intense plasma-ion streams or laser beams. The second aim of our research was to collect of some information about structural changes in the irradiated W-targets.

2. Investigation of W-targets irradiated with pulsed plasma-ion streams

The described experiments were performed within the RPI-IBIS (Multi-Rod Plasma Injector IBIS at IPJ in Swierk) [4] equipped with two coaxial electrodes of about 20 cm in length. The electrodes were of 9 cm and 13 cm in diameter, and each of them consisted of 32 thin molybdenum rods oriented parallel to the *z*-axis. The working gas (hydrogen or deuterium) was injected into the inter-electrode region with a fast acting valve, as shown in Fig. 1. After the pulsed injection of the chosen working gas the RPI-IBIS facility was powered from a 30 kJ, 30 kV, condenser bank. The most important operational parameter was a time-delay (τ) between the triggering of a fast gas-valve and the application of a high-voltage pulse, because it determined the spatial distribution of the working gas cloud. The described experiments were performed at delays τ = 170 μs (a slow mode) and τ = 130 μs (a fast mode). The emission of pulsed plasma-ion streams was recorded by means of a filtered CCD camera, placed behind a lateral optical window, and a spatial structure of the plasma-ion streams was investigated with a pinhole camera equipped with nuclear track detectors. In all cases the ring-shaped structure of the ion emission was observed and explained as a result of ion deflections by local magnetic fields. From an analysis of the recorded tracks, as performed with an optical microscope, it was estimated that in deuterium-shots an

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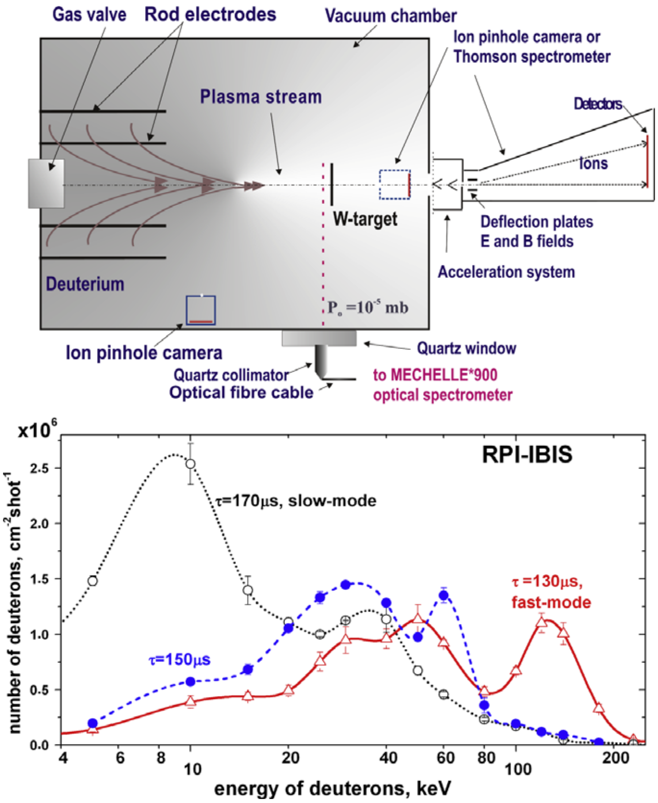

Fig. 1. Scheme of RPI-IBIS facility with a side-on quartz window for spectroscopy and diagnostic tools for corpuscular measurements of pulsed plasma-ion streams; below – energy distributions of deuterons, as measured for the slow, medium and fast mode.

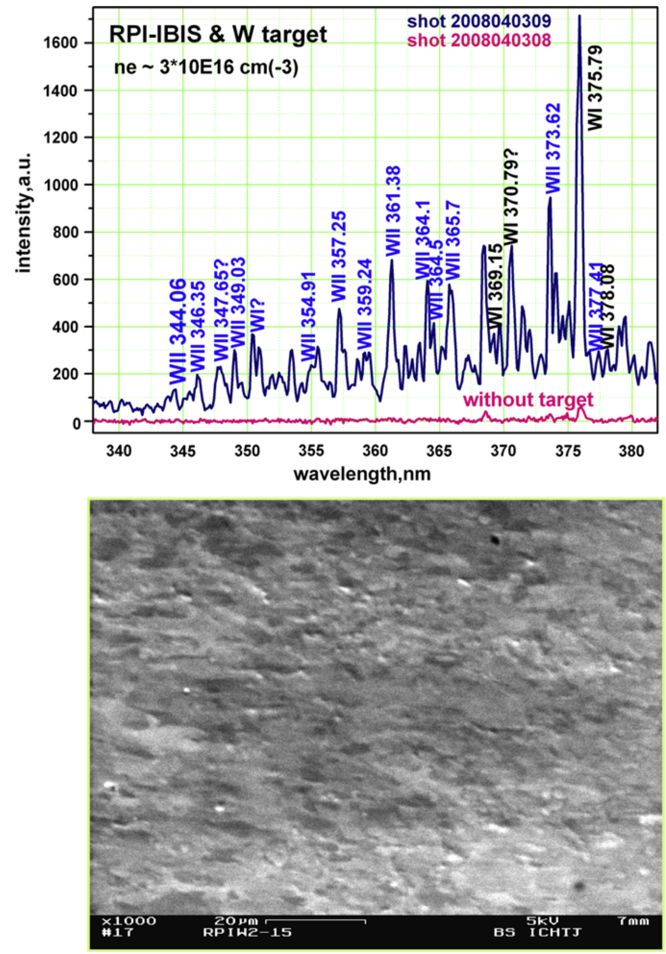

Fig. 2. Part of the optical spectrum (from 340 nm to 380 nm) recorded at the exposition equal to 10 µs, which shows distinct tungsten WI- and WII-lines, as well as some impurities. Below – a SEM image of the W-target surface, which was partially destroyed by the pulsed plasma-deuteron streams within the RPI-IBIS facility.

average flux density of deuterons of energy >125 keV (upon the detector) was about 7×10^6 deuterons/cm^2. The average flux density of all deuterons of energy >30 keV, as estimated from images of un-filtered detectors, was higher than 10^7 deuterons/cm^2. It should, however, be noted that the fast deuterons were emitted mostly as micro-beams of diameters of the order of 1 mm. The complex spatial structure of the investigated deuteron beams could be easily observed upon magnified ion images. The corresponding deuteron fluxes amounted to $(0.5–1.5) \times 10^7$ deuterons/cm^2. The background deuteron flux was about 1.3×10^5 deuterons/cm^2 only. Considering geometry of the measuring system, it was estimated that an average deuteron flux density at the pinhole (placed 20 cm from the electrodes ends) was about 1.7×10^{10} deuterons/cm^2. To determine mass- and energy-spectra of the emitted ions the use was made of a Thomson-type spectrometer. An input diaphragm of that spectrometer was placed at a distance of 100 cm from the electrode outlet. From the recorded Thomson parabolae, it was possible to determine the energy distribution of the investigated deuteron beams, as shown also in Fig. 1.

In order to investigate the interaction of the plasma-ion streams with W-samples, there was prepared a W-target of 4-cm × 4-cm area and 2 mm in thickness. That target was fixed upon a special support placed at a distance of about 20 cm from the electrode outlet. Spectroscopic measurements of plasma, which was formed in a front of the W-target after its bombarding by the pulsed plasma-ion stream, were performed by means of the Mechelle®900 spectrometer operated in the range from about 300 nm to 1100 nm, with expositions from 100 ns to 50 ms. The spectrometer was equipped with a software for the fast analysis of the recorded spectral lines. The identification of lines originating from WI- and WII-species was performed, as presented in Fig. 2.

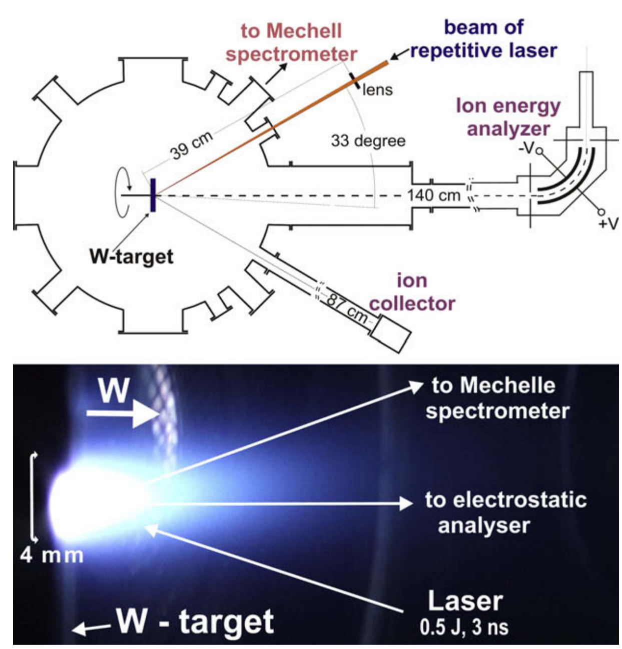

Fig. 3. Experimental set-up for research on behaviour of a W-target irradiated with intense laser pulses, and a time-integrated picture of a W-plasma plume, as taken behind a red filter.

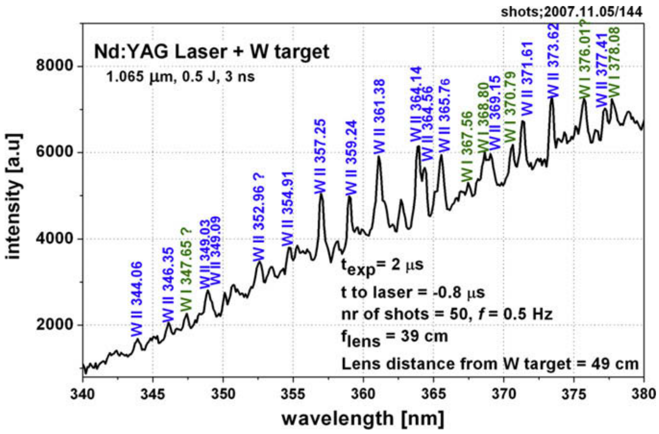

Fig. 4. Spectral lines of W-species, which were produced by Nd:YAG laser pulses (0.5 J, 3 ns) and identified in the wavelength range from 340 nm to 380 nm.

Particular attention was paid to spectral lines located close to the D_β Balmer-line. More accurate analysis showed that all the recorded tungsten spectral lines were strongly influenced by the instrumental broadening, while for the investigated experimental conditions the Stark effect might be neglected. It was estimated that the upper limit of the plasma electron density ($N_{e\ max}$) was about 10^{17} cm^{-3}, and it was assumed that for some W-lines the Stark constants are about 10^{-3} nm [5]. The spectral analysis was performed using the well known NIST database. Attention was devoted to different spectral lines: 1^0 – the strongest WI- and WII-lines, 2^0 – the separated W-lines with the minimum overlapping, 3^0 – the spectral lines sensitive to variations of electron temperature (T_e), and 4^0 – the spectral lines with profiles deformed by the strong re-absorption. First, T_e values were estimated to give a good agreement of relative intensities of different WI- and WII-lines. The most probable T_e value was found to be about 2–3 eV, which seemed to be realistic for the W-plasma expansion phase. In the second step there were estimated N_e values ensuring the best agreement of the computed and observed WI- and WII-lines. From that analysis it was estimated that the maximum value amounted to about 10^{17} cm^{-3}, while the average electron concentration amounted to 3×10^{16} cm^{-3}. More accurate estimates of W-plasma parameters would require measurements by means of an optical spectrometer with the higher spectral resolution and shorter exposition time.

The erosion of the W-target was investigated by means of an optical microscope and SEM. An example of the SEM image is presented also in Fig. 2. One can observe some roughening of the irradiated surface and local micro-craters of diameters below 1–5 μm.

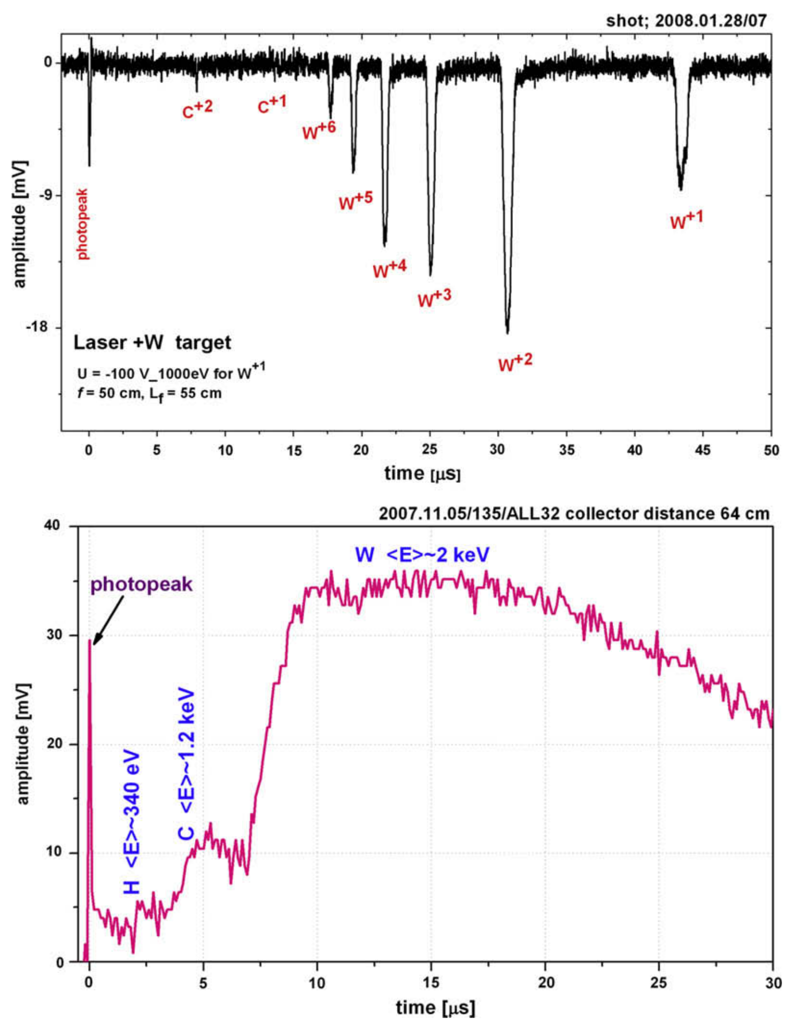

Fig. 5. Peaks of different W-ions with the energy/charge ratio E_i/Z = 1000 eV, which were emitted from the W-target and recorded by means of the IEA and time-of-flight method. Below – typical signals from the ion collector placed at a distance of 64 cm from the W-target centre irradiated with a laser pulse of the power density equal to about 5.3×10^9 W/cm^2.

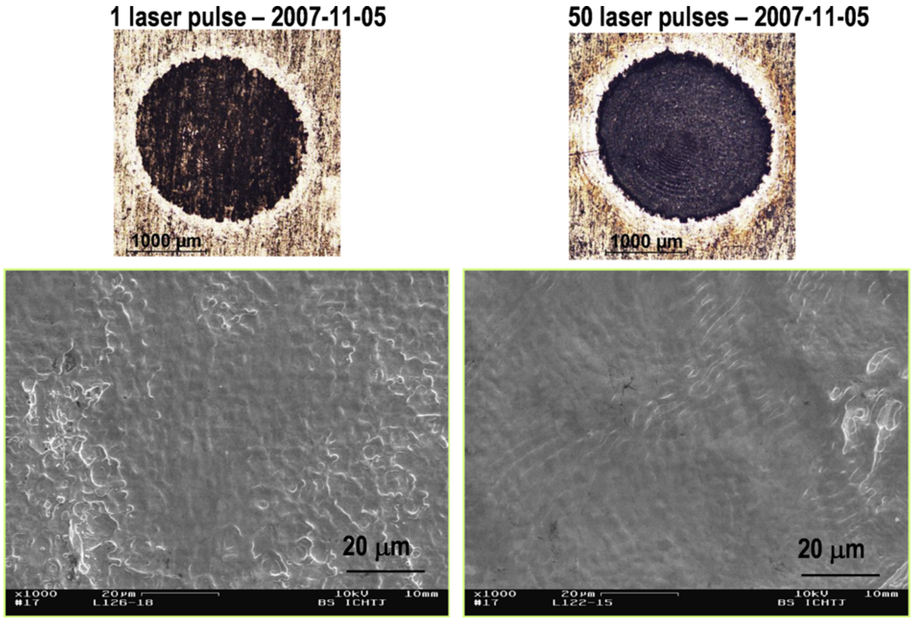

Fig. 6. Macro-pictures and corresponding SEM images of laser craters in the W-target surface, as obtained after different numbers of the Nd:YAG laser pulses (0.5 J, 3 ns), at f = 39 cm, d = 49 cm, $I_L = 5.3 \times 10^9$ W/cm^2.

From other measurements their depth was estimated to be below 5 µm.

It can be concluded that research on behaviour of W-targets during their bombardment by the pulsed plasma-ion streams may be performed in the RPI-IBIS facility at power fluxes below 5 MW/cm^2, but at high kinetic energies of particles (protons or deuterons), ranging to several hundreds keV. In order to reach higher energy loads more powerful plasma accelerators must be applied.

3. Investigation of W-targets irradiated with intense laser pulses

The second series of experiments was carried out at IPPLM in Warsaw, Poland, with the use of intense Nd:YAG laser pulses (0.5 J, 3 ns) focused upon a W-target. In that case the target was made of a pure W-sheet of about 25 mm × 50 mm area and 2 mm in thickness, and it has been placed in the centre of the vacuum chamber equipped with corpuscular- and optical-diagnostic ports, as shown in Fig. 3.

The formation of a laser-plasma plume has been observed with a CCD camera operated in the visible radiation (VR) range. An example of a time-integrated picture of the laser-produced W-plasma is presented also in Fig. 3. Using the same optical spectrometer as in the experiments described above, the optical spectra from a W-plasma plume were recorded at different numbers of laser shots. On the basis of those measurements, using GRAMS32-v.6.0 software [6], it was possible to perform identification of WI- and WII-lines described in the NIST database. Particular attention was paid to lines originating from WI- and WII-species, which were emitted in the wavelength range from 340 nm to 380 nm, as shown in Fig. 4.

The recorded WI- and WII-lines were analyzed using the procedure described in the previous section. An input of the continuum radiation (CR) was also taken into consideration. It was found that the most probable parameters of the laser-produced W- plasma plume during the investigated expansion phase were T_e = (0.8–1.0) eV and $N_e = (2–8) \times 10^{16}$ cm^{-3}. It should be noted that those estimates were based on the WI- and WI-lines only. The appearance of higher-ionized ions was confirmed by measurements performed with an electrostatic ion-energy analyzer (IEA). Those measurements showed that the strongest peaks corresponded to WII- and WIII-species, and at the laser power density equal to about 5.3×10^9 W/cm^2 the highest ionization stage corresponded to W^{+6}, as shown in Fig. 5.

It should be added that the ion emission was also measured with an additional ion collector, which was placed at a distance of 64 cm from the W-target. Pulses of different W^{+i} species and impurity ions (H^+, C^+, etc.) were recorded, as shown in Fig. 5.

Structural changes in the target surfaces, after their irradiation with the described laser pulses, were also investigated by means of an optical microscope and SEM technique. Some examples of the corresponding images are presented in Fig. 6. From the optical microscope pictures one can see that laser-produced craters after one shot and after 50 shots were comparable (about 2 mm in diameter). From profile measurements it was estimated that the craters after 50 shots were about 8 µm in depth. From the SEM pictures it can be seen that even one laser-shot induces considerable melting of the crater bottom. Melted domains after 1 shot were from 1 µm to 5 µm, while after 50 shots the crater bottom had more fine structure.

4. Summary and conclusions

The most important results of the described study can be summarized as follows:

The results obtained with the RPI-IBIS plasma accelerator, i.e., data about the emitted plasma-ion streams and the recorded optical spectra, have confirmed that this facility may be applied for research on interactions of plasma streams with W-targets at power fluxes amounting to 5 MW/cm^2. The advantages of this system are relatively high kinetic energies of the ions (protons and deuterons), ranging up to several hundreds keV, and considerably higher power loads in spots of the ion micro-beams.

The data obtained from the described laser-target experiment, i.e., the recorded optical spectra and ion collector signals, have supplied more detailed information about corpuscular- and electromagnetic-emission from a plasma plume produced from the bombarded W-target. The emission of highly-ionized W-ions was not seen in the recorded optical spectra, because of the short wavelength limit of the applied spectrometer and a lack of data for such species in the NIST database, but the appearance of different W-species from W^{+1} up to W^{+6} was confirmed by measurements performed with the ion-energy analyzer.

Investigation of the irradiated W-targets, which was performed with the optical microscope and SEM in the both experimental series, showed considerable structural changes in target surfaces. The applied plasma-ion pulses (ca. 5 μs, 1–5 MW/cm^2) caused an evident roughening of the irradiated surface and local micro-craters of diameters below 5 μm (induced probably by different ion micro-beams). Very intense laser pulses (3 ns, 5.3×10^9 W/cm^2) produced craters of about 2 mm in diameter and up to 8 μm in depth (depending on a number of shots). Bottoms of these craters were strongly melted (see above). The quantitative analysis of the erosion effects requires still more detailed measurements.

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