Optical emission spectroscopy of plasma produced from tungsten target irradiated within RPI-IBIS facility

Elzbieta Skladnik-Sadowska, Krzysztof Czaus, Karol Malinowski, Marek J. Sadowski, Katarzyna Nowakowska-Langier, Maryna S. Ladygina, Igor E. Garkusha

Abstract. The paper presents recent research on characteristics of deuterium plasma streams generated within an RPI-IBIS (multi-rod plasma injector) facility, and optical spectra of plasma produced during the interaction of these streams with a tungsten target placed at a distance of 20 cm from the electrode outlets. Distinct WI- and WII-lines were recorded and the noticeable erosion of the W-target was observed for shots delivering > 4 J/cm^2 on the target surface.

Key words: optical spectroscopy • free plasma stream • RPI-IBIS facility • plasma interaction with tungsten

E. Skladnik-Sadowska✉, K. Czaus, K. Malinowski, K. Nowakowska-Langier
National Centre for Nuclear Research,
7 Andrzeja Sołtana Str., 05-400 Otwock/Świerk, Poland,
Tel.: +48 22 718 0610, Fax: +48 22 779 3481,
E-mail: e.skladnik@ncbj.gov.pl

M. J. Sadowski
National Centre for Nuclear Research,
7 Andrzeja Sołtana Str., 05-400 Otwock/Świerk, Poland
and Institute of Plasma Physics and Laser Microfusion (IPPLM),
23 Hery Str., 01-497 Warsaw, Poland

M. S. Ladygina, I. E. Garkusha
Institute of Plasma Physics,
National Science Center, "Kharkov Institute of Physics and Technology" (NSC KIPT),
1 Akademicheskaya Str., 61108 Kharkov, Ukraine

Received: 19 September 2011
Accepted: 21 November 2011

Introduction

Research on interaction of intense plasma streams with different constructional materials, and in particularly with tungsten (W), are of primary importance for the construction of various fusion facilities, including the ITER (international tokamak experimental reactor). Studies of the behavior of tungsten targets have been undertaken in various plasma laboratories. Some preliminary studies of the interaction of pulsed plasma streams with a W-target have also been performed within an RPI-IBIS facility at the Andrzej Sołtan Institute for Nuclear Studies (IPJ, Otwock/Świerk, Poland) [6]. The obtained results have demonstrated applicability of this facility for material studies. The main aim of this work has been the continuation of the preliminary studies and investigations of the dependence of optical-emission spectra on the RPI-IBIS operational conditions during the free propagation of plasma streams as well as during their interactions with a W-target.

Experimental results

During the experiments to be reported, the RPI-IBIS facility was equipped with coaxial electrodes made of 32 thin molybdenum (Mo) rods distributed symmetrically on cylindrical surfaces of 9 and 13 cm in diameter, and about 20 cm in length. To inject a working gas (pure D_2) the use was made of a fast-acting gas valve situated at the z-axis, near the nest of electrodes. Discharges were initiated at a delay (τ) after the gas injection, and powered from a condenser bank charged to the maximum of 30 kJ, at 30 kV. The facility generated pulsed

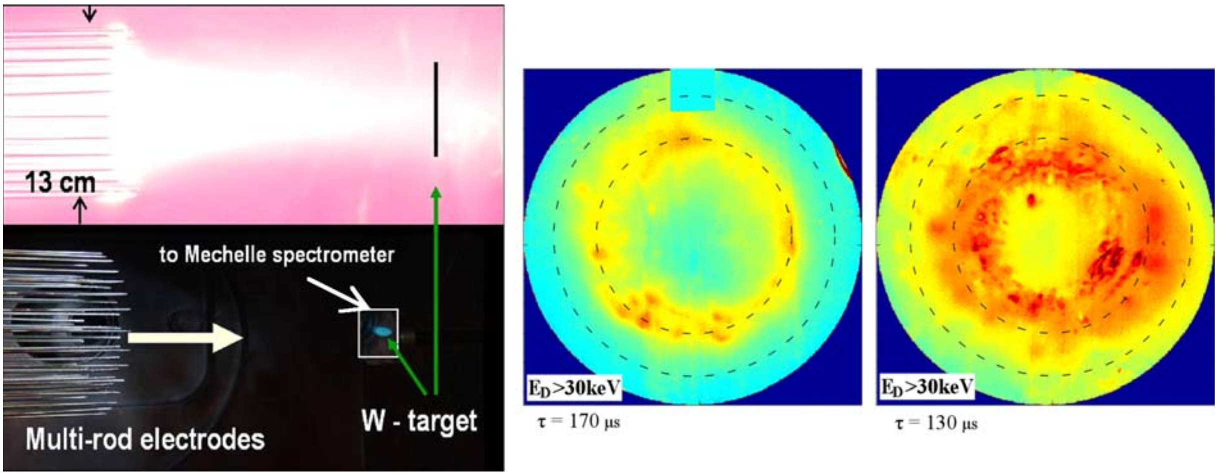

Fig. 1. Time-integrated picture of a plasma stream (left top), the experimental set-up (left bottom), and pinhole images of ion beams (right) recorded at a distance of 20 cm for two different operation modes.

plasma streams containing intense ion beams. Some experimental results are shown in Fig. 1.

The operational mode of the RPI-IBIS facility was changed by changing time delay τ from 130 to 200 μs, and to determine detailed characteristics of the emitted plasma streams use was made of a Thomson analyzer [3, 5], ion pinhole cameras [3] and a Mechelle®900 optical spectrometer [6]. To enable time-resolved measurements of the emitted ions the Thomson analyzer was equipped with a set of miniature scintillation detectors coupled (through optical cables) with separate photomultipliers, as shown in Fig. 2.

The measurements performed with the Thomson analyzer proved that the amount of impurity ions (e.g. Mo^+ from the electrodes) is very low and the deuteron

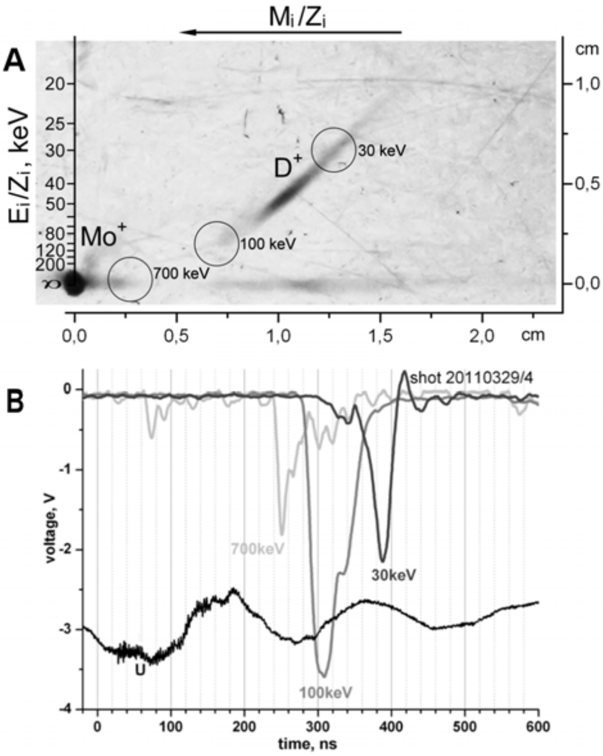

Fig. 2. Thomson parabolas with positions of detectors used for time-resolved measurements (A) and deuteron signals from different energy channels in a comparison with a voltage waveform (B).

energy spectrum extends from a few keV to about 700 keV with the maximum at about 40 keV. The period of the plasma stream emission was about 0.5 μs, while the ion (deuteron) pulses lasted 0.1–0.2 μs.

Measurements of optical emission spectra were carried out by means of a Mechelle®900 optical spectrometer, which could operate in the wavelength range from about 300 nm to 1100 nm, at the expositions (t_{exp}) varying from 100 ns to 50 ms, while the quarter-period of the discharge was about 3 μs, and the whole emission of pulsed plasma stream lasted about 0.5–1 μs. The measurements were performed for discharges carried out at τ = 170–200 μs (medium modes) without and with a W-target (4 × 4 cm^2, 1 mm in thickness) placed at a distance of 20 cm from the electrode ends. Some exemplary results are shown in Fig. 3.

The spectra, which were recorded in the whole VR range, contained lines of the deuterium Balmer series and some impurity lines. Clean deuterium plasma was obtained at τ = 200 μs. For experiments with a W-target there appeared many WI- and WII-lines, which were identified by means of the NIST database [4]. Spectral lines of higher ionized W-ions have not been identified due to the observed wavelength range and a lack of appropriate spectroscopic data in the available data bases [2, 4]. Other examples of the optical spectra, as recorded in experiments with the W-targets for plasma streams of 7 J/cm^2, are presented in Fig. 4.

On the basis of the observed Stark effect for the D_α line, it was estimated that the electron plasma density [1] in front of the target changed from about 10^{17} cm^{-3} to 7×10^{16} cm^{-3} at about 15 μs after the current peculiarity (corresponding to the instant of the intense ion beams emission). The electron density values did not change noticeably when the discharge energy was changed by reduction of the number of active condenser sections (from 5 to 3 sections).

The operation of the RPI-IBIS facility under the conditions, which ensured the emission of deuterium-plasma streams with a small amount of impurities, a satisfactory energy flux (varied from 3 to 7 J/cm^2), and a relatively high power density (of the order of 1–5 MW/cm^2), enabled studies of a behavior of a W-target irradiated by the chosen plasma-ion loads to be performed. Examples

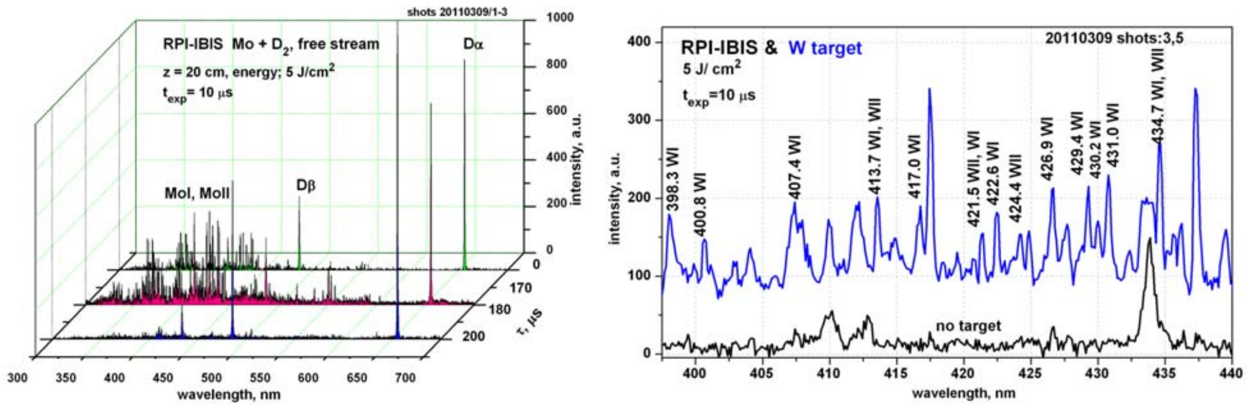

Fig. 3. Optical spectra of a free-propagating plasma stream measured at z = 20 cm with exposition t_{exp} = 10 µs for shots with different τ values (left) and a part of the spectrum (right), as recorded in the same plane for shots without and with the W-target (plasma flux of 5 J/cm^2).

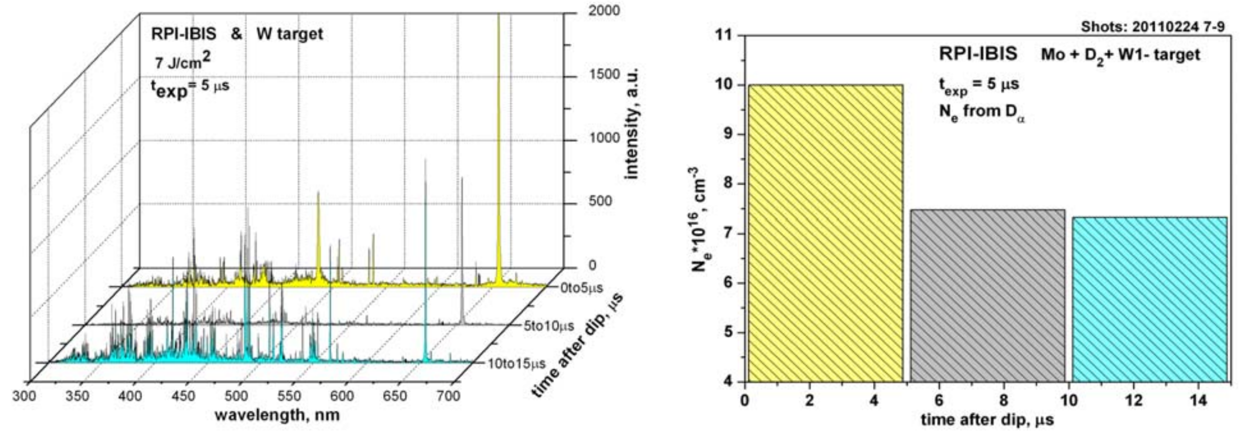

Fig. 4. Optical spectra from plasma in the front of the W-target irradiated by a plasma flux of 7 J/cm^2, as recorded with t_{exp} = 5 µs at different instants after the current dip (left) and temporal changes of a plasma density, as calculated from the D_α line profile (right).

of the optical spectra, which were obtained at different energy fluxes, are shown in Fig. 5.

The erosion of the irradiated W-target (amplitudes of the WI- and WII-lines) depended evidently on the irradiation power, and it occurred when the energy flux was above 3 J/cm^2. The erosion of the W-target surface was investigated in a similar way as in the previous target experiments performed with a large PF-1000 facility [7]. In particular, the use was made of the scattering electron microscope (SEM) technique. The SEM pictures, which were taken from the virgin W-target and that irradiated by several shots, showed noticeable changes in the target surface structure (and some microcraters), as presented in Fig. 6.

The changes in target surfaces included partial melting and blistering, while almost circular microcraters

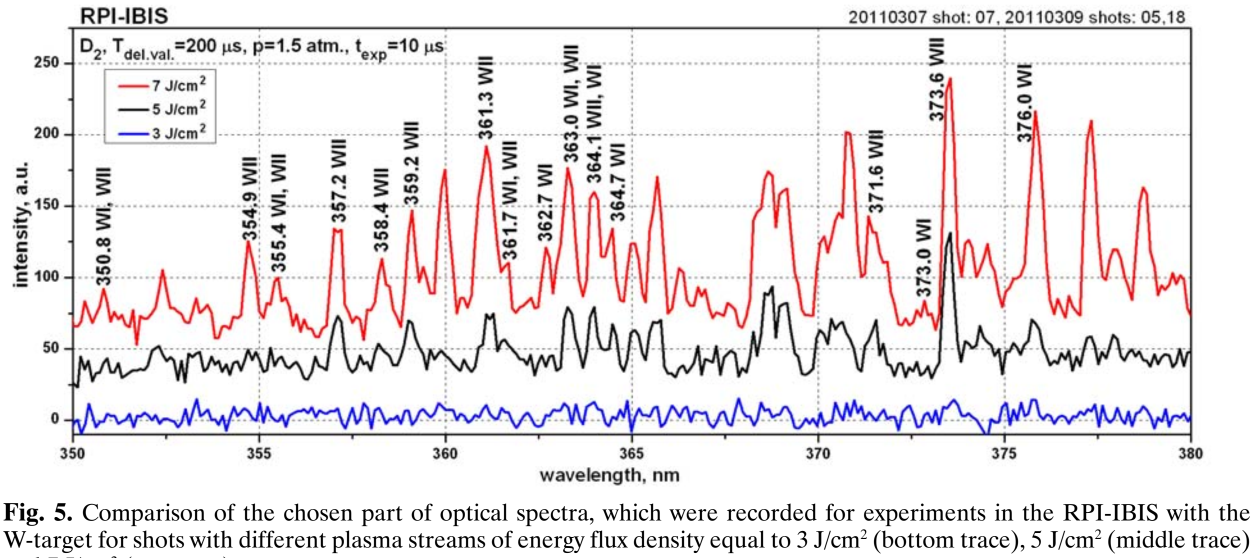

Fig. 5. Comparison of the chosen part of optical spectra, which were recorded for experiments in the RPI-IBIS with the W-target for shots with different plasma streams of energy flux density equal to 3 J/cm^2 (bottom trace), 5 J/cm^2 (middle trace) and 7 J/cm^2 (top trace).

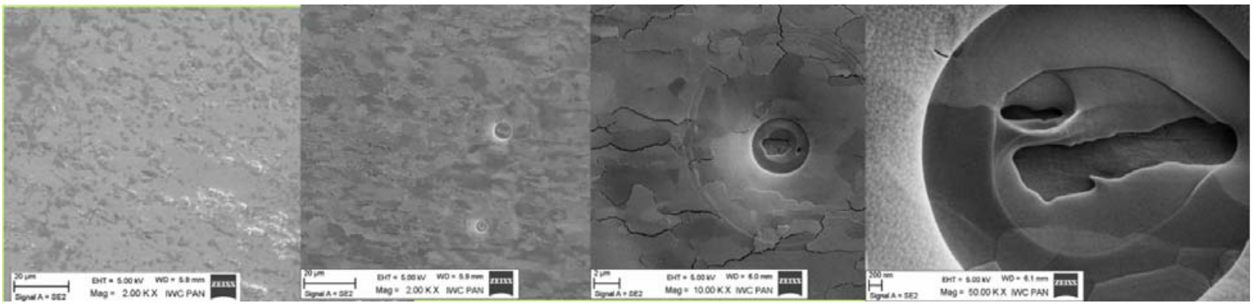

Fig. 6. SEM picture of the virgin W-target (left) and that of the W-target irradiated by 6 shots producing deuteron-plasma streams (each lasting about 2 μs). The first two pictures were taken at magnification 2000×, while the next at 10 000× and 50 000×, respectively.

(of 2–12 μm in diameter) showed strong vaporization of the target material and relatively deep changes in its structure. Those microcraters were probably produced by intense microbeams of very energetic ions (mostly deuterons), which were detected earlier by means of the pinhole cameras and NTD, as described above. The observed erosion effects in the irradiated W-targets will be studied in more details under different experimental conditions in the near future.

Summary and conclusions

The most important results of this study can be summarized as follows. The experimental results obtained with the RPI-IBIS facility, i.e. characteristics of the emitted plasma-ion streams and the recorded optical spectra, confirmed that this device is useful for research on interactions of plasma streams with W-targets at power fluxes amounting to about 5 MW/cm^2. The evident advantages of this facility were relatively high kinetic energies of the ions, e.g. protons and deuterons, ranging up to several hundreds keV, as well as very high power loads in spots of the ion microbeams. The maximum electron density at the irradiated W-target surface was estimated to be about 10^{17} cm^{-3}. The erosion effects in the irradiated W-targets were observed for shots producing pulsed plasma streams of energy density > 3 J/cm^2 upon the target surface, and it was found that the erosion of the target was about 10 times stronger at 5 J/cm^2 and about 20 times – at 7 J/cm^2. More accurate estimates of W-plasma parameters during the interaction of plasma-ion streams with W-targets would require measurements by means of a spectrometer with higher spectral resolution, possibly in a wider spectral range. Spectroscopic data on higher ionized W-ions are also needed. As regards the erosion effects, they should be studied in more details under various conditions and with different techniques.

Acknowledgment. This work was partially performed in the frame of an agreement about scientific collaboration between Poland and Ukraine, which was supported by a grant from the Ministry of Science and Higher Education, Poland.

References

1. Griem HR (1968) Plasma spectroscopy. Pergamon Press, New York
2. Kurucz-database; http://www.pmp.uni-hannower.de/cgi-bin/ssi/test/kurucz/sekur.html
3. Malinowski K, Skladnik-Sadowska E, Sadowski MJ, Czaus K (2006) Corpuscular diagnostics of deuterium-plasma streams from RPI-IBIS discharges. Czech J Phys 56B:309–314
4. NIST basis; http://physics.nist.gov
5. Sadowski MJ, Czaus K, Malinowski K, Skladnik-Sadowska E, Zebrowski J (2009) Mass- and energy-analyses of ions from plasma by means of a miniature Thomson spectrometer. Rev Sci Instrum 80:053504
6. Skladnik-Sadowska E, Malinowski K, Sadowski MJ *et al*. (2008) Study of deuterium plasma interaction with a tungsten target within RPI-IBIS facility. Probl Atom Sci Tech 6, Series: Plasma Phys 14:95–97
7. Skladnik-Sadowska E, Malinowski K, Sadowski MJ *et al*. (2011) Optical spectroscopy of free-propagating plasma and its interaction with tungsten targets in PF-1000 facility. Contrib Plasma Phys 51:288–292