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Research on interactions of plasma streams with CFC targets in the Rod Plasma Injector facility

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Abstract. This paper present results of optical spectroscopy studies of interactions of intense plasma streams with a solid target made of carbon fibre composite (CFC). The experiments were carried out within the Rod Plasma Injector (RPI) IBIS facility. The optical measurements were performed first for a freely propagating plasma stream in order to determine the optimal operational parameters of this facility. Optical emission spectra (OES) were recorded for different operational modes of the RPI IBIS device, and spectral lines were identified originating from the working gas (deuterium) as well as some lines from the electrode material (molybdenum). Subsequently, optical measurements of plasma interacting with the CFC target were performed. In the optical spectra recorded with the irradiated CFC samples, in addition to deuterium and molybdenum lines, many carbon lines, which enabled to estimate erosion of the investigated targets, were recorded. In order to study changes in the irradiated CFC samples, their surfaces were analysed (before and after several plasma discharges) by means of scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS) techniques. The analysis of the obtained SEM images showed that the plasma irradiation induces noticeable changes in the surface morphology, for example vaporisation of some carbon fibres and formation of microcracks. The obtained EDS images showed that upon the irradiated target surface, some impurity ions are also deposited, particularly molybdenum ions from the applied electrodes.

Key words: CFC target • optical spectroscopy • plasma streams • plasma-target interaction

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Introduction

Research on the interactions of intense plasma streams with various materials is of primary importance for the development of fusion technology [1]. Therefore, different constructional materials have been irradiated within various plasma machines in many laboratories [2–6]. Among different materials, applied in various plasma experimental facilities, samples made of carbon fibre composite (CFC), which was often used in older plasma magnetic-confinement devices, were also investigated. Studies of the behaviour of this material were performed, e.g., using pulsed plasma streams generated within plasma-focus (PF) facilities [2], but such streams contained many impurities from metal electrodes. Therefore, it was reasonable to use plasma streams emitted from a so-called Rod Plasma Injector (RPI), which (due to self-screening of the rod electrodes by their own magnetic fields) can produce plasma containing smaller amounts of impurities [7, 8].

In order to obtain new information about behaviour of CFC samples irradiated by relatively clean deuterium plasma, it was decided to use the RPI-IBIS facility [7, 8] operated at the NCBJ in Otwock-Swierk, Poland. The main aim of the reported study was to investigate optical emission spectra – first from plasma propagating freely in the RPI-IBIS vacuum chamber (in order to determine the optimal operational mode of this machine), and next to investigate spectra from plasma interacting with a CFC target.

Experimental set-up

The RPI-IBIS facility was equipped with two coaxial electrodes of 9 and 13 cm in diameter, respectively. Both electrodes were about 20 cm in length, and each of them consisted of 32 thin molybdenum (Mo) rods distributed symmetrically around the electrode peripheries [7, 8]. The facility was equipped with a fast-acting gas valve used to inject some amount of the working gas, and the main discharge could be powered from a condenser bank charged to 30–35 kV. Depending on a time delay (τ) of the initiation of the main discharge in relation to the injection of the working gas, the facility could be operated in different modes [9, 10]. At small delays τ (and small amounts of the injected gas), the facility operated in a so-called deposition by plasma erosion (DPE) mode, when fast electrons bombarding rod electrodes caused their erosion and emission of ions from the electrode material. At longer delays τ (and larger amounts of the injected gas), the device operated in a so-called plasma ion deposition (PID) mode, when the emitted plasma stream contained mainly ions of the applied working gas, as shown in Fig. 1.

It should be noted that in contrast to systems with solid coaxial electrodes in the RPI IBIS facility, some ions can penetrate the multi-rod electrodes and move towards the z-axis to form an axial plasma jet. A general view of such penetrable multi-rod electrodes is presented in Fig. 2.

During the reported experimental studies, the condenser bank of the RPI IBIS facility was charged initially to U_0 = 30 kV, and the stored energy amounted to W_0 = 33 kJ. At these operational parameters, the obtained plasma jet had energy flux

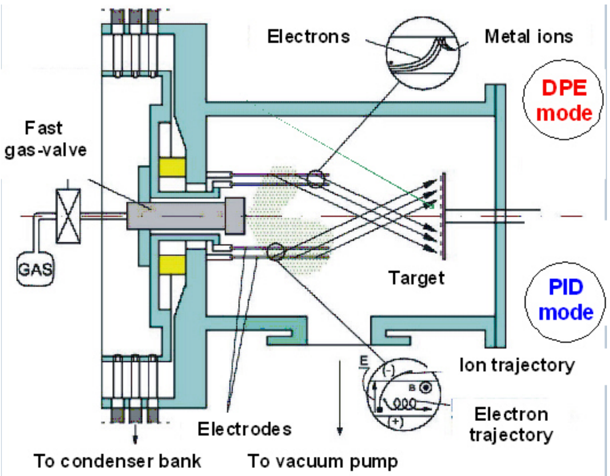

Fig. 1. Scheme of the RPI-IBIS facility with inserts, which show trajectories of electrons and ions in different operational modes of this device [9].

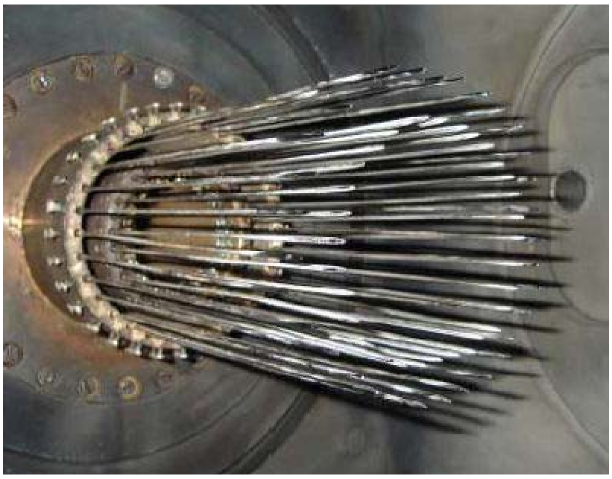

Fig. 2. Picture of the coaxial electrodes of the RPI-IBIS facility, which were composed of many thin molybdenum (Mo) rods distributed symmetrically upon cylindrical surfaces of 9 and 12 cm in diameter, respectively.

density equal to about 8 J/cm^2. The duration of the main plasma-jet generation was about 200–300 ns, but the whole discharge lasted several microseconds and the plasma visible radiation (VR) could be observed even to 100 μs.

In order to investigate the generated plasma--ion streams, the optical emission spectroscopy (OES) measurements were performed by means of a Mechelle®900 spectrometer coupled through a fibre cable with an optical collimator, which was situated behind a quartz window placed side-on the main experimental chamber. This collimator was oriented in such a way that it was able to observe a small (1 cm in diameter) region at the discharge axis, at the distance of 20 cm from the electrodes ends. At the same distance (z = 20 cm), there were subsequently placed exchangeable CFC targets of (10 mm × 10 mm) surface and 6 mm in thickness. These CFC samples were investigated with routine SEM and EDS techniques before the irradiation and after several plasma discharges.

Experimental results

As mentioned above, the first series of OES measurements was performed for freely propagating plasma streams, i.e. without any target. Optical spectra were recorded at the exposition time equal to 100 μs, for several discharges, which were performed at different time delays τ between the gas-valve triggering and the application of a HV pulse. The τ value was changed from 170 to 210 μs in order to determine the best experimental conditions. The optical spectra from the RPI IBIS facility, as recorded at different time delays, are presented in Fig. 3.

One can easily notice that at τ = 170 μs (in the so-called DPE mode) in addition to the characteristic deuterium Balmer lines the recorded spectra contained many impurity (mainly molybdenum) lines. For discharges performed at τ = 210 μs (in the so-called PID mode), the optical spectra contained distinct D_α, D_β and D_γ lines and a small amount of

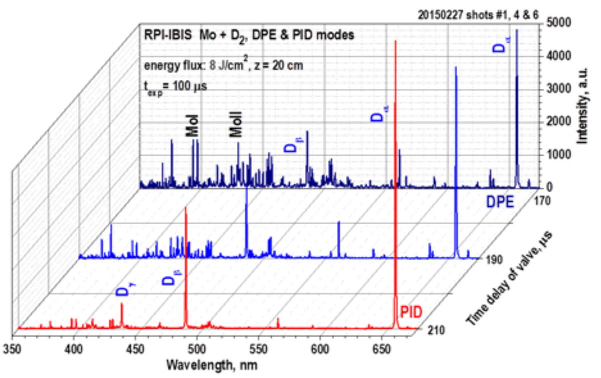

Fig. 3. Optical emission spectra recorded in the visible wavelength range within the RPI-IBIS facility without any target, but at different time delays τ determining various operational modes.

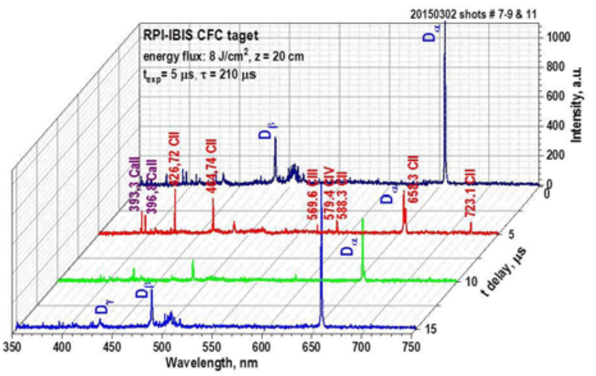

Fig. 5. Comparison of optical emission spectra recorded within the RPI-IBIS facility during interactions of pulsed plasma streams with the investigated CFC targets, as obtained with the short exposition time t_{exp} = 5 µs, at different instants after the maximal current.

impurity lines. Therefore, for further studies, it was decided to apply a time delay τ = 210 µs, which enabled streams of almost pure deuterium plasma without many impurities to be generated.

After choosing the optimal operational mode in the RPI-IBIS facility, the first CFC target, as described above, was installed. The optical spectra emitted from plasma formed at the irradiated target surface were recorded at the exposition time equal to 15 µs and 100 µs. A comparison of the optical

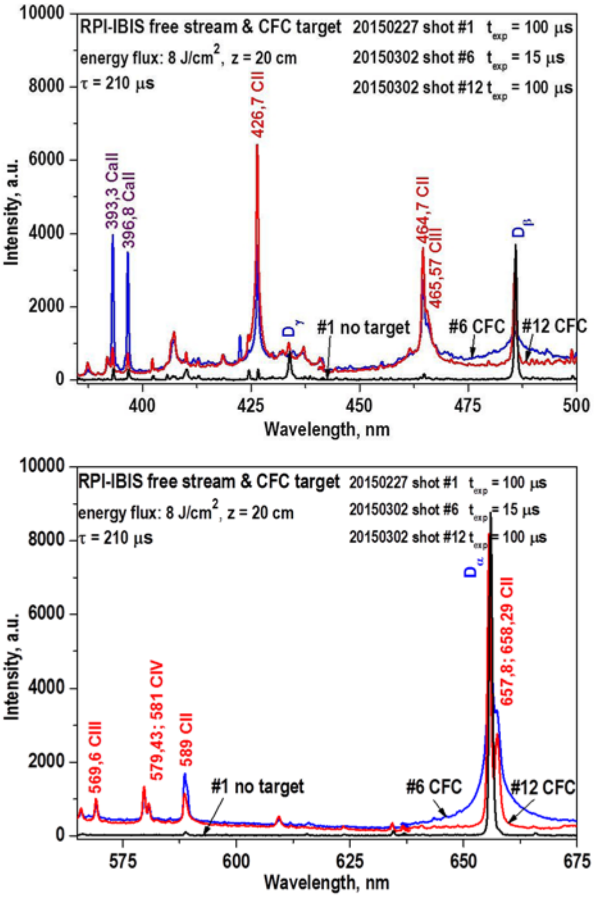

Fig. 4. Comparison of different parts of the optical emission spectra, which were recorded in the RPI-IBIS facility during a discharge without any target (shot #1 at t_{exp} = 100 µs) and two discharges performed with the CFC targets (shot #12 at t_{exp} = 100 µs and shot #6 at t_{exp} = 15 µs).

spectra, as obtained without and with the CFC target, is presented in Fig. 4.

One can easily see that for discharges with the CFC target the recorded spectra contained D_α, D_β and D_γ lines and different CII, CIII and CIV lines originating from the target material as well as some CaII lines, which probably originated from the material of the electrode insulator [10].

Taking into consideration that parameters of plasma during the discharge change very quickly in time, the next series of the spectroscopic measurements was carried out with the exposition time equal to 5 µs. It enabled more accurate time-resolved information to be obtained. Some examples of the optical spectra, as recorded with the exposition of 5 µs at different instants of the discharge, are shown in Fig. 5.

These results show that CII 426.72 and CII 464.74 lines from the CFC target appeared in the period of 5–10 µs after the discharge beginning. Hence, one can deduce that the CIII and CIV lines (visible in the spectra shown in Fig. 3) were evidently emitted in other instants of the plasma-target interaction.

Additionally, plasma electron density for discharges with and without CFC sample for instants of 0–5 µs were calculated. In this calculation, the known relation was made use of [11]:

$$N_e = A\,(\Delta\lambda)^B$$

where $A = 1.02 \times 10^{16}$ and $B = 1.45$.

The calculated electron density for freely propagating plasma streams was equal to about 1.25×10^{15} cm^{-3}. When plasma stream was interacting with a CFC sample, the computed density (at a distance of 20 cm from electrodes) was 5.67×10^{15} cm^{-3}, and in the period 5–10 µs (when carbon lines were most distinct), this parameter amounted to 7.9×10^{15} cm^{-1}. It means that during the interaction of plasma streams with the CFC target, the estimated density was at least four times higher.

In order to study changes upon the surface of the irradiated CFC sample, SEM pictures of a virgin (not-irradiated) sample were taken, which was exposed to 10 successive plasma discharges. A comparison of these SEM pictures, as obtained at different magnifications, is presented in Fig. 6.

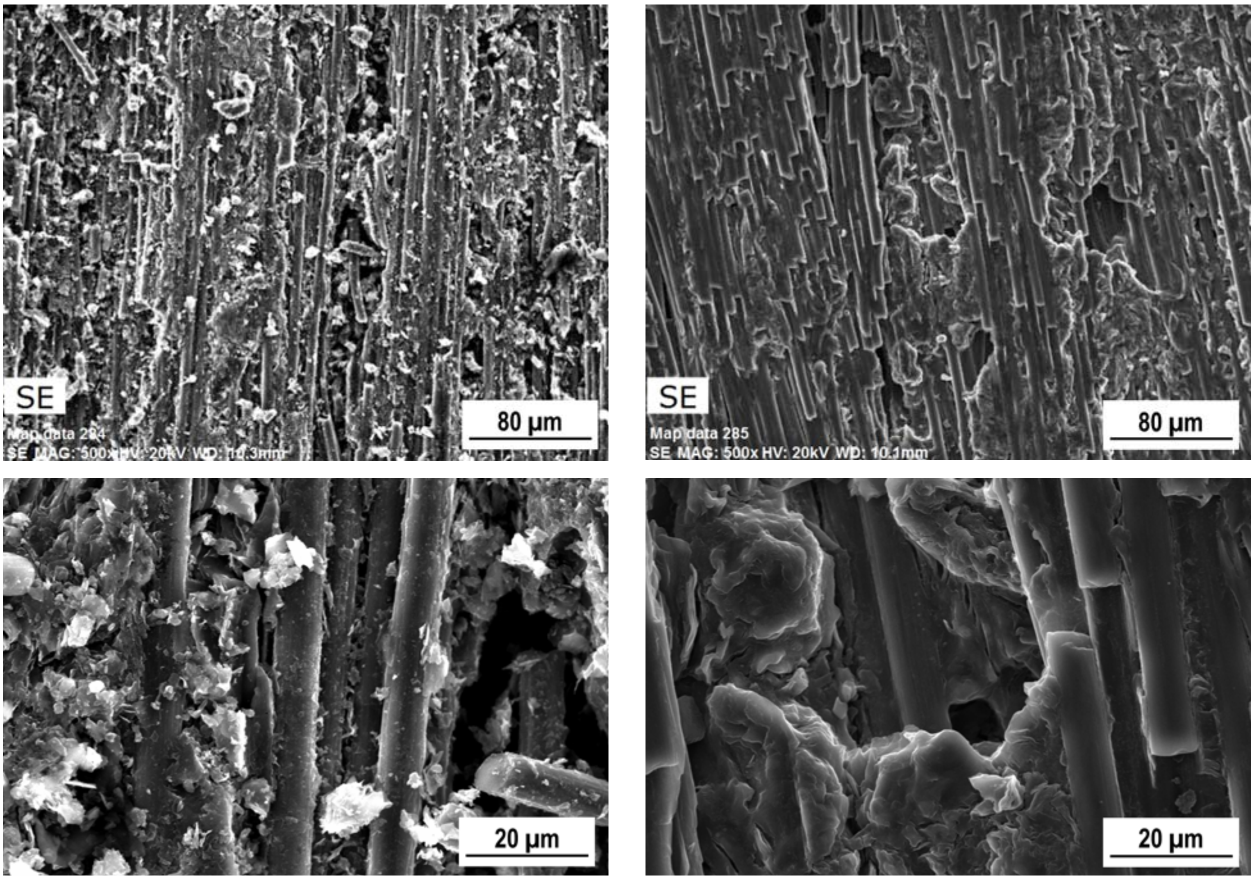

Fig. 6. Comparison of SEM images of a virgin CFC sample (left) and that irradiated by 10 plasma discharges (right). These images were obtained at different magnifications: 500× (top pictures) and 3000× (bottom pictures).

From this comparison, one can see that the virgin surface shows some carbon microfibres and small cracks only. The pictures of the irradiated sample show distinct erosion (evaporation) of some carbon microfibres and larger craters induced by plasma interactions.

To investigate changes in the composition of the sample surface, EDS pictures of a virgin sample were taken, which were irradiated by plasma streams. A comparison of these images is presented in Fig. 7.

In that case, one can see that the EDS picture of the virgin surface shows distribution of carbon atoms, which corresponds roughly to positions of individual carbon fibres. The EDS picture of the irradiated surface shows not only some erosion of that, but also the distribution of molybdenum atoms, which originated from the electrode material.

Summary and conclusion

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

1. The OES measurements performed without any

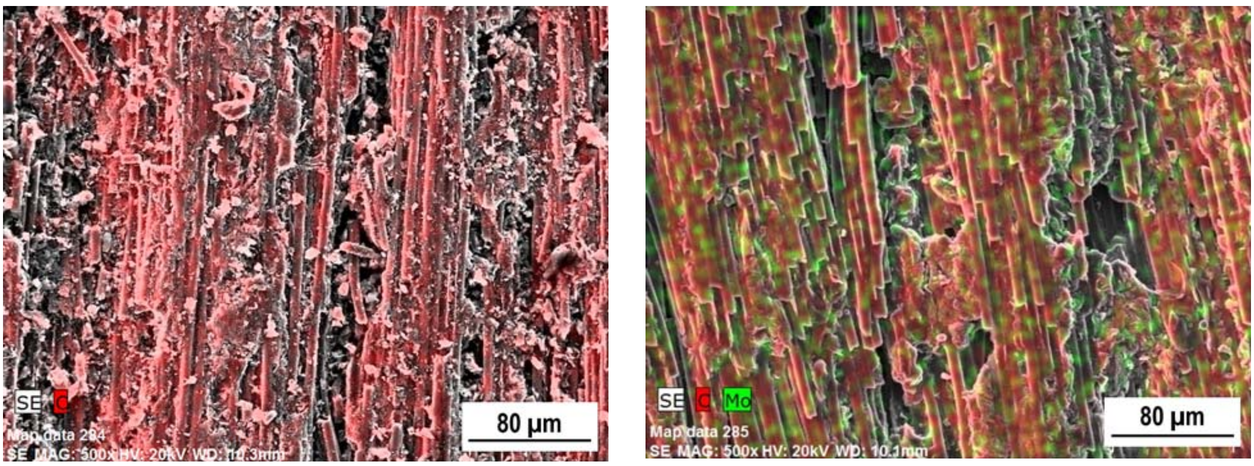

Fig. 7. Comparison of EDS images of the virgin CFC sample (left) and that after a series of plasma discharges (right). The first image shows the distribution of carbon atoms, while the second one shows also some impurity (molybdenum) atoms.

target allowed to record optical spectra characteristic for different modes of the RPI-IBIS operation and to select the optimal operational mode (with a time delay τ = 210 μs), which generates deuterium plasma without many impurities.
2. The optical spectra of plasma interacting with the CFC target showed deuterium Balmer lines and many CII, CIII and CIV lines, which evidently originated from the target material.
3. A comparison of the optical spectra recorded at different exposition times enabled to observe that the carbon spectral lines appear about 5–10 μs after the discharge beginning.
4. When CFC target was irradiated, the electron density (near the target surface) increased at least four times.
5. The SEM pictures of the irradiated CFC target showed distinct erosion of carbon microfibres, and the EDS images confirmed that erosion and showed the deposition of some impurity ions (mainly molybdenum from the RPI IBIS electrode) in spite of the optimal RPI IBIS operational mode.

It can be concluded that to investigate CFC materials irradiated by intense plasma streams, it would be reasonable to compare behaviour of samples delivered by different producers and exposed to higher plasma energy-density fluxes. Accurate weighing of samples before and after their irradiation will be recommended.

This work was performed at the NCBJ in Otwock-Swierk, Poland.

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