RESEARCH ON INTERACTIONS OF INTENSE DEUTERIUM PLASMA STREAMS WITH SiC TARGETS IN PLASMA-FOCUS EXPERIMENTS

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The paper presents results of experimental research on emission of the visible radiation (VR) from intense deuterium plasma streams propagating freely within a vacuum chamber or interacting with silicon-carbide (SiC) targets. The investigated pulsed plasma streams were generated by high-current discharges realized within two facilities of the Plasma-Focus (PF) type, i.e. within the PF-1000U facility operated at the IFPiLM and the PF-360U device operated at the NCBJ. Detailed measurements have been carried out using optical emission spectroscopy (OES) technique. Parameters of plasma were estimated from the D_α line only. Structural changes of the irradiated SiC targets were analyzed by means of a scanning electron microscope (SEM) and energy dispersive X-ray spectrometer (EDS).

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INTRODUCTION

Investigation of plasma-surface interactions and associated processes is of primary importance for further development of plasma physics and technology. Experimental studies are carried out in this direction at many laboratories with the use of various plasma sources, including plasma-focus (PF) facilities [1-3]. Among different materials of interest for fusion technology there is also a silicon-carbide (SiC). Hence, it is of interest to study a SiC target behavior under irradiation by powerful plasma-ion streams, and in particular investigate carbon- and silicon-lines emitted from plasma created near the target surface. Preliminary studies of SiC targets have already performed earlier within the modified PF-1000U facility in Warsaw [4]. Some new studies have recently been carried out within the modified PF-360U facility in Otwock-Swierk. The main aim of this paper has been to compare results of research on SIC targets in the PF-1000U and PF-360U experiments.

1. EXPERIMENTS WITHIN PF-1000U

To investigate interactions of powerful plasma streams, with SiC samples, the use was first of the modified PF-1000U facility. It generated intense plasma streams (jets) of an averaged density equal to about 10^{17} cm^{-3} and velocity of about 10^7 cm/s, as measured at a distance of 9 cm from the electrodes outlets. Those streams contained also fast deuteron beams of energies from about 80 keV to several hundreds keV, and sometimes even to several megaelectron volt [5,6]. Energy spectra of deuteron beams had the maximum in the range of 100-200 keV. The flux density of deuterons > 380 keV amounted to about 2.4 x 10^9 cm^{-2}, while > 700 keV it was about 10^9 cm^{-2}. The facility was equipped with a 230 mm-i.d. inner electrode made of copper, with a central 50 mm-i.d. tungsten insert.

In order to investigate the interaction of such streams with SiC targets, the use was made of the optical emission spectroscopy (OES) technique. The optical measurements were carried out side-on by means of a quartz collimator and an optical-fibre cable coupled with a Mechelle®900 spectrometer, as shown in Fig. 1.

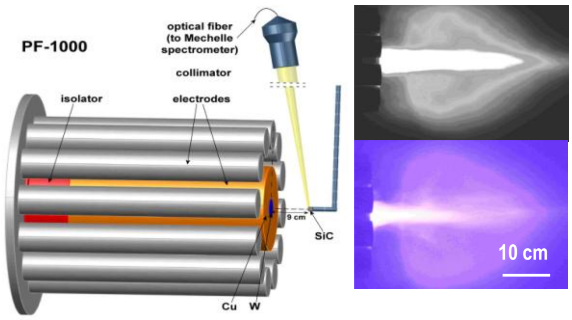

Fig. 1. Electrodes of the PF-1000U facility with the experimental set-up for OES and time-integrated visible-radiation (VR) pictures of a discharge

The Mechelle®900 spectrometer was equipped with a PCO SensiCam camera and software needed for an analysis of recorded optical spectra. The OES studies were started with the measurements of a free-propagating plasma stream, i.e. without any target. During 380 kJ discharges the main plasma-ion pulse lasted about 0.2 µs, and its intensity decayed in several tens µs. The optical spectra of the free-propagating plasma stream showed that it emitted intense Balmer lines of the working gas (D_α and D_β) and many spectral lines from the electrode materials (mainly Cu), as shown in Fig. 2 (top).

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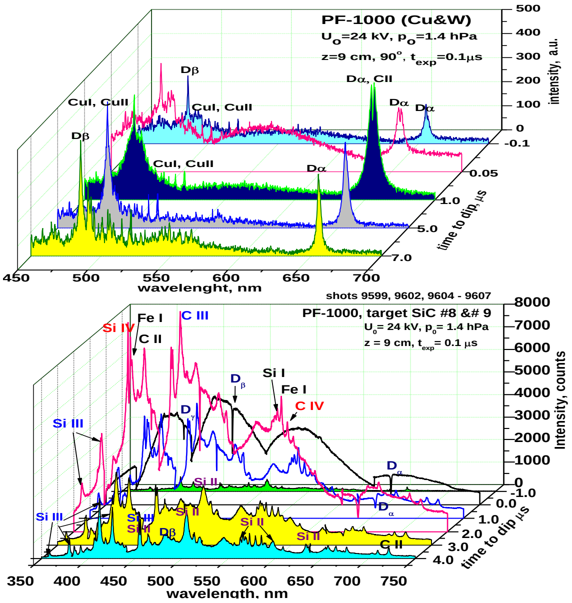


Fig. 2. Comparison of VR spectra recorded at different instants of PF-1000U discharges without any target (top) and with a SiC-target (bottom)

In the next step, a SiC target (1 cm^3 cube) was placed at a distance of 9 cm from the electrode ends, and a series of discharges was performed. Each plasma-ion stream induced some erosion of the irradiated SiC sample and produced a plasma layer in front of the target. A power- flux density upon the target surface from each plasma stream reached 10^9...10^{10} W/cm^2, and that from fast ions beams amounted to 10^{12} W/cm^2 [4]. Optical spectra, as recorded at different time delays after so-called "current dip", were analyzed to identify Si- and C-lines. The Balmer lines from the working gas, i.e., D_α, D_β and D_γ could not be used for a quantitative analysis because of strong re-absorption effects. The recorded spectra contained intense Si-ion lines, e.g. Si I 579.5...615.5 nm, Si II 412.8...678.4 nm, Si III 380.6...456.7 nm and Si IV 314.9 nm. There were also identified intense C-lines, ranging from C II 426.7...723.1 nm to C IV 580.1 nm. During the first phase of the plasma-target interaction (in about 2 µs) the emission of Si III, Si IV, C III and C IV lines was observed, while at larger delays the spectra showed Si II and C II lines only. The optical emission of plasma produced from the irradiated SiC target decayed in about 10 µs.

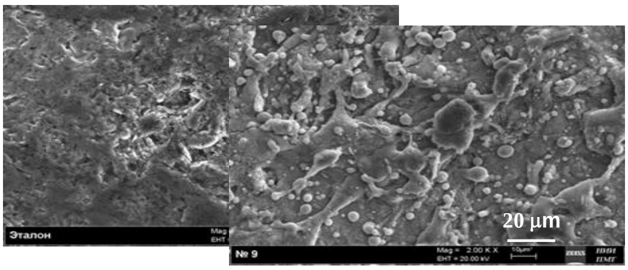
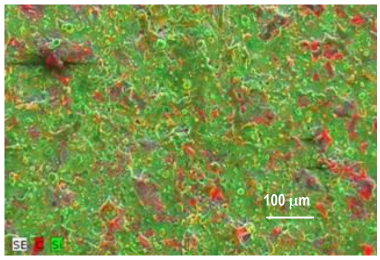


Fig. 3. Images of the surfaces of the virgin SiC sample (left) and irradiated sample № 9 (right), as obtained by means of SEM technique

The irradiated SiC samples were later subject to a detailed surface-analysis by means of SEM and EDS techniques. SEM images of the virgin SiC sample and irradiated sample are shown in Fig. 3. From a comparison of the presented images one could see that the irradiation of the SiC samples resulted in fritting of the surface layers of the carbide phase and in the production of droplets of sizes from several to tens µm. Thermal stresses resulted in the formation of relatively long cracks in the sample surface layer. The observed macro-particles resulted from the evaporation and sputtering of the SiC target surface and as well as some erosion of the PF-1000U electrodes and the sample holder, that led to deposition of the eroded materials.

The SEM pictures of the virgin and irradiated samples were also compared with images obtained by means of EDS. It enabled a distribution of different elements to be determined, as shown in Fig. 4.



Sample № 9
carbon (red)
silicon (green)

Fig. 4. EDS mapping of the sample № 9, which shows a distribution of silicon and carbon

To identify various elements on the irradiated samples the use was also made of the EDS technique. For a virgin sample there were recorded characteristic lines of primary materials, i.e., C and Si only. For the irradiated samples, in addition to those lines one could also identify lines corresponding to other elements (such as Cu, Fe, Al and O), as shown in Fig. 5.

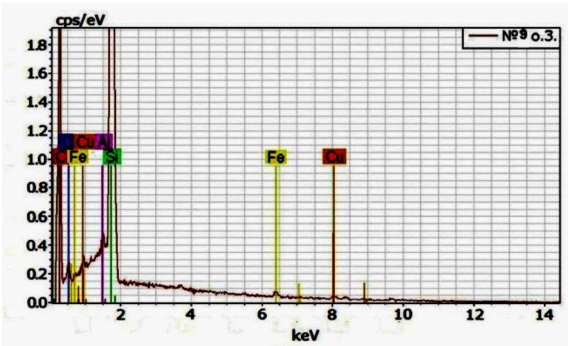


Fig. 5. Characteristic lines of elements, as obtained with EDS for the sample irradiated in PF-1000U

The admixtures of the other elements originated from the electrodes and constructional parts of the PF-1000U chamber, but their concentration within the irradiated surface layer was low.

2. EXPERIMENTS WITHIN PF-360U

The second part of the described studies was performed within the modified PF-360U facility equipped with Mather-type coaxial electrodes made of copper-tubes [7]. A background pressure was equal to 6 mbar D_2, the charging voltage of a condenser bank was 30 kV, and energy supplied to PF discharges amounted to about 125 kJ. The maximum discharge current reached about 1.5 MA, and the pulsed plasma streams were emitted mainly during the current peculiarity (dip), which occurred about 5 µs after the discharge initiation. The investigate a SiC sample (1 cm^3 cube) was placed on the symmetry axis of the PF-360U electrodes in a stainless-steel holder, which was designed to prevent a deposition of its material upon the irradiated sample surface.

The OES measurements were carried out mostly at a distance of 9 cm from electrode outlets. The use was made of a side-on quartz window and an optical collimator, which was coupled through a fibre-cable with a Mechelle®900 spectrometer, as in the case of the previous studies [4]. The SiC target was oriented perpendicularly to direction of the plasma-ion stream motion, as shown in Fig. 6.

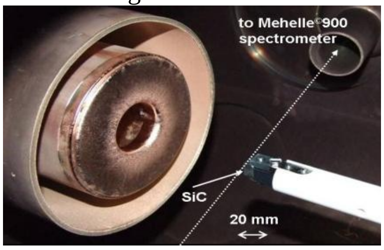


Fig. 6. Picture of PF-360U electrodes and the target

Temporal changes of the optical spectrum emitted from a free propagating plasma stream, which were recorded during the PF-360U discharge without any target, are presented in Fig. 7 (top). Those spectra show that the free plasma-ion stream was relatively clean and it contained a low quantity of impurities.

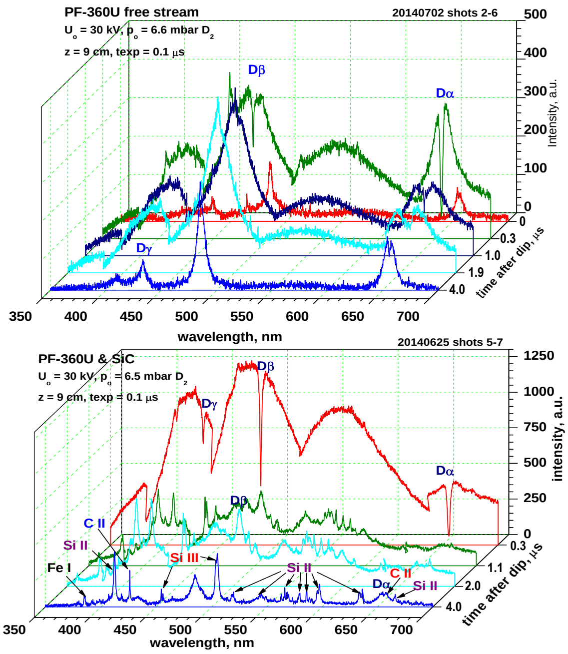


Fig. 7. Comparison of the visible radiation (VR) spectra recorded at different instants of the PF-360U discharge without any target (top) and with the SiC -target (bottom)

In the step the OES measurements were performed during expositions of the investigated SiC target. Some optical spectra, as measured perpendicularly to the z-axis, are shown in Fig. 7 (bottom). In this case the recorded spectra show that plasma, generated by interactions of the primary plasma-ion stream with the target, was cumulated at the target surface for about 0.3 μs. That plasma emitted intense deuterium lines (D_α , D_β and Dγ), which showed strong re-absorption effects. The identification of other spectral lines was impossible. In later phases one could however identify C II, Si II, Si III and Fe I lines. During the first period the strong re-absorption of the D-lines made it impossible a quantitative assessment of deuterium plasma density.

Important information might be gained from a direct analysis of the irradiated SiC target surface. It was investigated by means of SEM, as shown in Fig. 8.

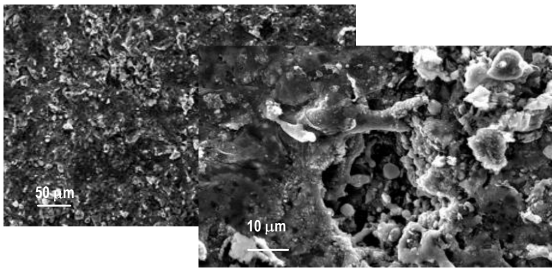


Fig. 8. SEM images of the surface of the SiC sample № 6 irradiated within PF-360U

In some cases a very strong erosion effects upon the irradiated target surface, and even micro-droplets of the melted target material were observed. In order to investigate an elemental composition of the irradiated target surface the use was made of the energy-dispersive X-ray spectroscopy (EDS) technique, as shown in Fig. 9.

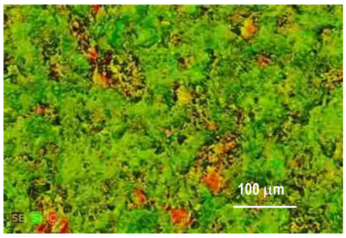


Fig. 9. EDS mapping showing a distribution of silicon and carbon upon sample No. 6, which was irradiated in the PF-360U facility

In general, the EDS mapping images obtained from the irradiated SiC samples differed considerably from those recorded for the virgin samples. There were observed many regions of high concentration of silicon, and a smaller amount of micro-zones of high concentration of carbon, probably as graphite inclusions. After the sample irradiation the total quantity of the carbon upon the sample surface was decreased, and the silicon distribution became almost uniform. More accurate information could be gained from the EDS diagrams, a shown in Fig. 10.

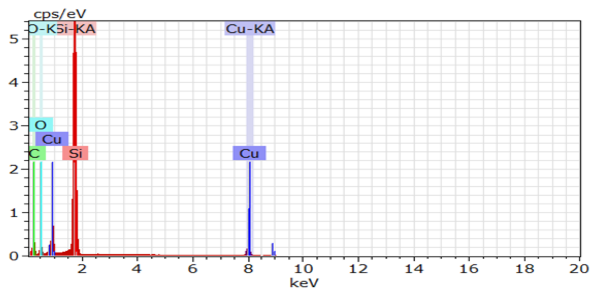


Fig. 10. Characteristic lines of various elements that were recorded with EDS of the irradiated sample surface

In the total spectrum of elements observed upon the surface of the samples irradiated within the PF-360U facility, besides basic components of the material under investigation (i.e. Si and C) one may identify traces of of other elements, as copper (Cu) and oxygen (O). Those elements were possibly evaporated from surfaces of the PF-360U insulator and electrodes, as well as from some construction parts of the vacuum chamber. They were subsequently precipitated by the target surface from a vapor phase.

SUMMARY AND CONCLUSIONS

The most important results of the reported studies can be summarized as follows: 1. Interaction of intense plasma-ion streams with SiC targets were investigated in the PF-1000U and PF-360U facilities by means of the OES technique; 2. The optical emission spectroscopy enabled to determine dynamics of plasma and to identify ion species of free plasma streams and plasma produced at SiC targets surfaces; 3.
Quantitative analyses of the D-lines and estimations of the electron concentration were possible in some cases only, due to re-absorption effects; 4. In high-power PF-1000U facility plasma produced at the SIC target emitted distinct spectral lines ranging from Si I to Si IV and from C II to C IV, while in the smaller PF-360U facility there were recorder lines up to SI III and C III only.5. Surface analyses of the virgin and irradiated SiC samples showed considerable changes in the structure of the surface layers.

Joint experiments performed by the NCBJ, IFPiLM, KIPT and BIMMS teams, by means of different facilities, has already enabled to collect some information about intense plasma streams and erosion of SiC-targets. Such studies should evidently be continued.

REFERENCES

1. M.J. Sadowski, M. Scholz // *Plasma Sources Sci. & Technol.* 2008, v. 17, p. 024001.
2. V.A. Gribkov et al. // *Phys. Scr.* 2011, v. 83, 04560.
3. M.S. Ladygina et al. // *Fusion Sci. Techol.* 2011, v. 60, p. 27.
4. E. Skladnik-Sadowska et al.// *Phys. Scr*. 2014, v. T161014039.
5. M. Scholz et al. // *Nukleonika*. 2001, v. 46, p. 35-39 (in Russian).
6. R. Kwiatkowski et al.// *Nukleonika.* 2011, v. 56, p. 119-123 (in Russian).
7. M.J. Sadowski et al.// *PAST. Ser. „Plasma Phys”*. 2013, № 1, p. 252-257.

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ИССЛЕДОВАНИЯ ВЗАИМОДЕЙСТВИЯ ИНТЕНСИВНЫХ ДЕЙТЕРИЕВЫХ ПЛАЗМЕННЫХ ПОТОКОВ С SiC-МИШЕНЯМИ В ЭКСПЕРИМЕНТАХ НА ПЛАЗМА-ФОКУСЕ

E. Skladnik-Sadowska, R. Kwiatkowski, K. Malinowski, M.J. Sadowski, K. Czaus, D. Zaloga, J. Żebrowski, K. Nowakowska-Langier, M. Kubkowska, M. Paduch, M. Scholz, E. Zielinska, М.С. Ладыгина, И.Е. Гаркуша, В.А. Грибков, Е.В. Демина, С.А.Маслаев, В.Н. Пименов

Представлены результаты экспериментальных исследований по эмиссии видимого излучения из интенсивных дейтериевых плазменных потоков свободно распространяющихся в вакуумной камере или взаимодействующих с SiC-мишенями. Исследуемые импульсные плазменные потоки генерировались высокоточными разрядами на двух установках типа плазменный фокус (ПФ). А именно, установка PF-1000U, работающая в IFPiLM, и PF-360U, работающая в NCBJ. Детальные измерения были проведены с использованием оптической эмиссионной спектроскопии (ОЭС). Параметры плазмы были оценены из D_{α}-линии. Структурные изменения облучаемых SiC-образцов были проанализированы с помощью сканирующего электронного микроскопа (СЭМ) и энергии рентгеновского спектрометра (ЭРС).

ДОСЛІДЖЕННЯ ВЗАЄМОДІЇ ІНТЕНСИВНИХ ДЕЙТЕРІЄВИХ ПЛАЗМОВИХ ПОТОКІВ З SiC-МІШЕНЯМИ В ЕКСПЕРИМЕНТАХ НА ПЛАЗМА-ФОКУСІ

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Представлено результати експериментальних досліджень з емісії видимого випромінювання з інтенсивних дейтерієвих плазмових потоків, що вільно розповсюджуються у вакуумній камері чи взаємодіють з SiC-мішенями. Імпульсні плазмові потоки, що досліджувались, генерувались високоточними розрядами на двох установках типу плазмовий фокус (ПФ). А саме, установка PF-1000U, що функціонує в IFPiLM, та PF-360U – у NCBJ. Детальні вимірювання були проведені за допомогою оптичної емісіонної спектроскопії (ОЕС). Параметри плазми були оцінені з D_{α}-лінії. Структурні зміни опромінених SiC-мішеней проаналізовані за допомогою скануючого електронного мікроскопа (СЕМ) та енергії рентгенівського спектрометра (ЕРС).