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PLASMA INSTALLATION FOR RESEARCH OF PLASMA-SURFACE INTERACTION

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This work describes some of the features of the developed plasma setup for studying surface-plasma interactions. Results of the study of the interaction of tungsten and beryllium with plasma are presented. This facility is intended for testing materials and equipment of the Kazakhstan Materials Science Tokomak and for conducting a study of plasma-surface interactions. The main elements of a plasma installation are an electron beam gun, a plasma-beam discharge chamber, a vacuum interaction chamber, a cooled target device, an electromagnetic system consisting of electromagnetic coils, a lock device for quick changing and moving diagnostic tools or irradiated samples without depressurization of the installation. Experiments to study changes in the structure of tungsten and beryllium during plasma exposure have shown that after irradiation, the surface is subjected to erosion and pores form on the surface.

Keywords: plasma, plasma installation, tungsten, beryllium, irradiation.

Introduction

Recently in our country work is underway in to create the Kazakhstan Material-science of Tokomak (KMT) in the National Nuclear Center of the Republic of Kazakhstan, which will be used for research to substantiate the design and safety of a thermonuclear energy reactor [1]. As is known, the solution to the problem of creating reactors of controlled thermonuclear fusion is largely determined by the choice of structural materials for the most critical reactor assemblies (the first wall, its protection and the diverter). They experience a powerful impact of irradiation with neutrons, alpha particles and protons, as well as thermal loads from the side of thermonuclear plasma. The choice of structural materials is based on the results of studying the processes occurring during the interaction of the plasma of a thermonuclear reactor (TNR) with structural elements facing it [2]. However, the complexity and multifactorial nature of the interaction of the KMT plasma with structural materials, as well as the high cost of full-scale tests on full-scale installations, determine the need for its experimental modeling using small specialized simulation installations. Among such facilities, linear simulators with electron-controlled plasma generation [3–7] have several advantages as devices that allow combining the effect of plasma with electron beams when tested with high heat flux. In this regard, a plasma unit was developed for testing materials and equipment of the KMT and for conducting a study of plasma-surface interactions.

The purpose of this work is to study and describe in detail some of the features of the developed plasma setup for studying surface-plasma interactions and experimental study of the interaction of tungsten and beryllium with plasma.

1. Parameters of plasma installation

The developed plasma beam installation (PBM) is universal and allows testing materials under the conditions of complex exposure to them of both the plasma flow and the powerful heat load created by the electron beam. The use of a plasma setup makes it possible to quickly obtainpreliminary experimental data on the behavior of materials under conditions of their interaction with plasma under high thermal load, which will make it possible to make corrections to the methodology of experimental studies on KMT [8, 9].

The main elements of a plasma installation are an electron-beam gun (EBG), a plasma-beam discharge chamber, a vacuum interaction chamber, a cooled target device, an electromagnetic system consisting of electromagnetic coils, a lock device for quick change and movement of diagnostic tools or irradiated samples without depressurization installation [10]. A general view of a simulation stand with a plasma-beam installation is shown in Figure 1.

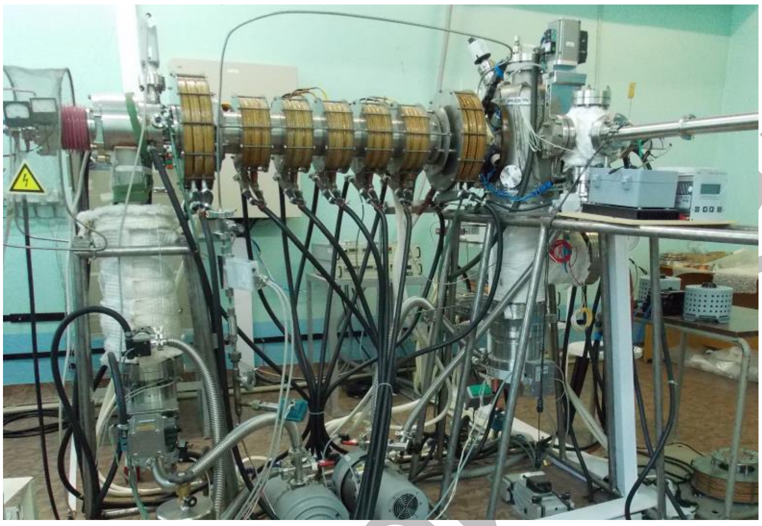
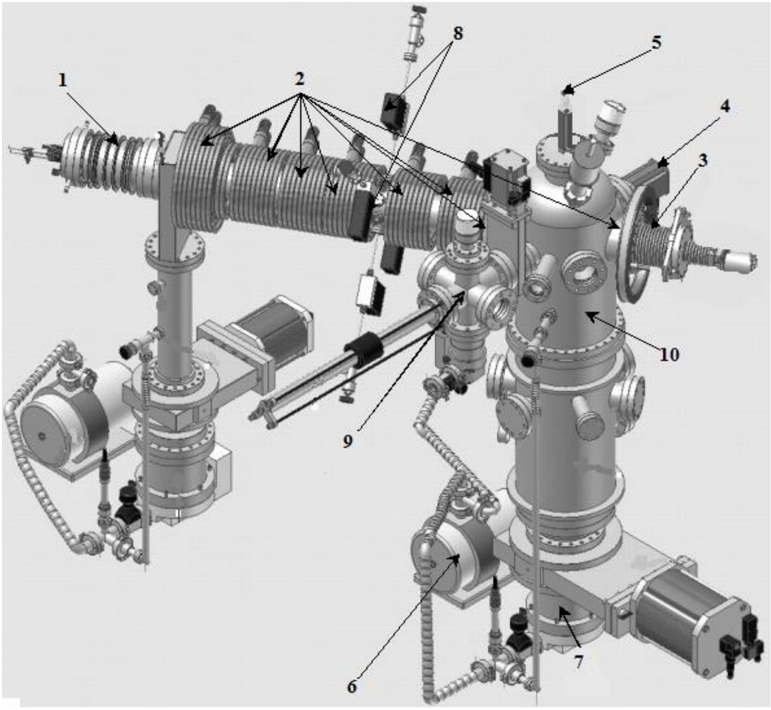


Fig.1. General view of the plasma installation.

A schematic representation of the installation is shown in Figure 2. The vacuum chamber includes a discharge chamber and an interaction chamber. In this case, the discharge chamber is made in the form of a narrow cylinder with a length of 0.9 m and a diameter of 0.2 m, and the interaction chamber is made in the form of a cylinder with a length of 0.5 m and a diameter of 0.4 m, located perpendicular to the discharge chamber. The cooled target device is a hollow cylinder with inlet and outlet tubes for cooling it with water. In this case, the plasma receiver is made so that it is possible to install the irradiated sample. The electron gun consists of a heated thermionic tungsten cylindrical cathode and a hollow anode. All gun assemblies are water-cooled, which ensures its operability, both in high-voltage vacuum mode and in low-pressure arc mode. The vacuum pumping system includes two fore vacuum and two turbo molecular pumps capable of providing a pressure of residual gases in the chamber at a level of $5 \cdot 10^{-8}$ Pa.

The performance of the pumping means may vary widely, depending on the gas-dynamic conditions of the experiments. The gas injection system consists of vacuum leaks, designed to ensure the gas inlet into the vacuum chamber with a stream size in a strictly specified small range, with the possibility of smooth adjustment. The leakage control is carried out by a personal computer, which ensures a stable flow of the working gas. The gateway device with a rod allows for translational-rotational movement for rapid change and movement of diagnostic tools or irradiated samples without depressurization of the installation. The plasma diagnostics system includes a quadruple mass spectrometry Langmuir probe. Warming up, control of parameters, diagnostic tools, as well as a complex of electric power sources of the electron gun, consisting of a direct heat block a voltage-regulated high-voltage unit for generating a primary beam of beam-plasma discharge, high-voltage unit for the controlled thermal testing without the beam-plasma discharge.

The installation management system includes computer programs for remote control of installation nodes. The recording of the current information and the display on the screen is generated by means of the information and measurement system (power supply system, vacuum pumping, gas supply systems, gas, air, air and gas, air flow systems, vacuuming systems, gas flow systems, gas and air conditioning systems, vacuuming systems, gas flow systems and other applications.



1- electron gun; 2 - electromagnetic coils; 3 – cooled plasma receiver; 4 - mass spectrometer; 5 - Langmuir probe; 6 - foreline pumps; 7 - turbo molecular pumps; 8 - gas pump system; 9 - sluice device for quick change and movement of diagnostic tools or irradiated samples; 10- vacuum chamber.

Fig.2. Schematic representation of a plasma installation.

The plasma installation provides the following plasma flow parameters: plasma flow diameter up to 30 mm; magnetic field strength generated on the axis of the installation of 0.1 T; magnetic field strength in the electron gun area of 0.2 T; the current in the plasma is 1 A; The plasma density in the beam is up to 10^{13} cm^{-3}, the electron plasma temperature is up to 30 eV.

The installation provides the following plasma flow parameters: the plasma flow diameter in front of the target is from 5 to 100 mm; the magnetic field strength generated on the EBG axis is 0.1 T; magnetic field strength in the electron gun area of 0.2 T; the current in the plasma is 1 A; The plasma density in the beam is up to $10^{13}cm^{-3}$, the electron plasma temperature is up to 100 eV.

Plasma installation works as follows. The electronic pad is formed by an axially symmetric electronic pad. The cathode of the gun is heated by electron bombardment from the heater thread. The power of the gun is regulated by the cathode heating power. The electronic probe is fed with the working gas supplied to the discharge zone, forming a plasma-beam discharge. Plasma shots are assembled using an electromagnetic system, which creates a longitudinal magnetic field in the discharge chamber. With a fall of the world the plasma discharge enters the sample of the test material installed in the plasma receiver, which is located in the interaction chamber. Figure 3a-b shows the process of irradiation with a tungsten plasma beam.

The plasma beam in the installation chamber is formed when the working gas is supplied to the chamber when the electron beam is tuned. Hydrogen, deuterium, helium, etc. are used as the working gas. To simulate the effect of plasma on materials in the plasma-beam discharge mode, it is sufficient to use from 2% to 30% of the maximum power of the electron gun. To obtain maximum power on the target without the development of breaks in the transport channel, the accelerating voltage should be increased and the beam current should be reduced.

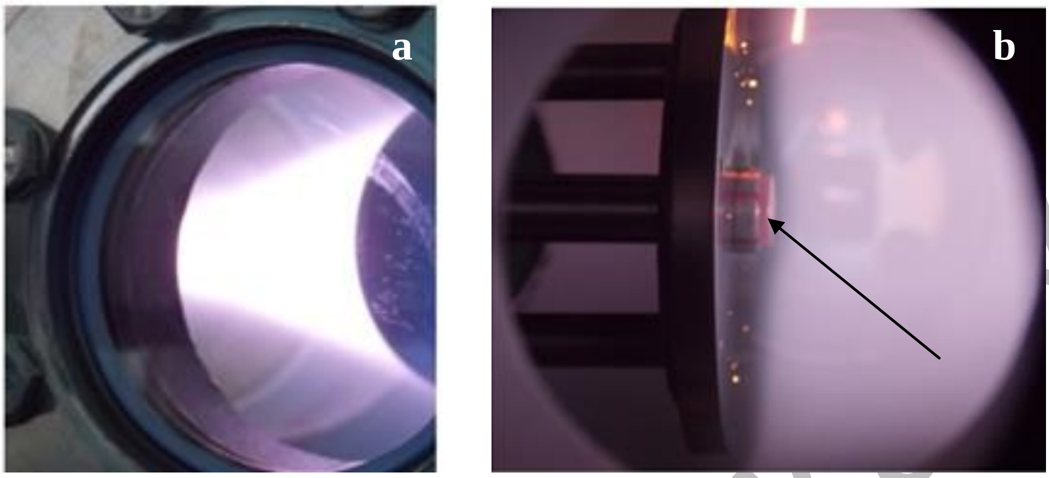


Fig.3. The process of irradiation with a tungsten plasma beam: a) - plasma beam ignition, b) - the arrow indicates the sample under the influence of plasma.

Recording of current information and display it on the display screen is generated by the information-measuring system. PBM is equipped with a system of remote control of PBM nodes with an information screen. To determine the parameters of the plasma flux in the PBM, a Langmuir probe is used. The method of probe diagnostics is based on measuring the current density of charged particles when an electrical conductor is placed in plasma, depending on its potential [11]. When testing materials for PBM, the control of the environment in the cavity of the interaction chamber was carried out using a CIS-100 quadruple mass spectrometer manufactured by Stanford Research Systems. Figure 1-2 shows the CIS-100 mass spectrometer externally. The analyzer of residual gases with a closed ion source (mass spectrometer) CIS100 was attached directly to the working chamber through valves. Unlike open gas source (RGA) residual gas analyzers, CIS devices are simultaneously connected to a high-vacuum turbo molecular pump, which ensures that the ionizer is at a pressure of 10^{-9} mm. hg art. [12].Performing the proposed installation [13] to study the interaction of plasma with the material allows obtaining the following benefits:

- high performance by reducing the time to replace the irradiated samples, as well as by remote control of the power supply system, vacuum pumping system, gas installation system;
- the presence in the design of the vacuum chamber of two turbo-molecular pumps, two flow heaters and two differential pumping diaphragms located in the vacuum chamber, which makes it possible to break the vacuum chamber into sections with different pressures, and also allows to obtain a working gas with the lowest residual gas from water vapor.

2. Experimental procedure

In this work, we studied the interaction of plasma with tungsten and beryllium using the developed plasma setup. Tungsten samples of 99.97% purity in the form of a cylinder 10 mm in diameter and 5 mm high, as well as TGP-56 beryllium samples of $10\times10\times5$ mm^3 in size, were cut on an EDM machine. Before irradiation, the samples were ground and polished. The samples were irradiated with a plasma beam in the helium, hydrogen and deuterium medium. During irradiation, the pressure in the chamber was 2×10^{-3} Torr. Table 1 shows the modes of irradiation of samples of tungsten and beryllium.

The research of the microstructure of the samples before and after irradiation was performed using a JSM-6390 scanning electron microscope.

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Table 1. Modes of irradiation of samples.

Sample	Power of primary beam $W_{el.p.}$, W	Workinggas	Bias potential on target, B	Ion concentration, 10^{17} $м^{-3}$	Irradiationtime, c
W	2500	hydrogen	-1200	$2{,}69\cdot10^{17}$	3600
W	2500	hydrogen	-1600	$2{,}86\cdot10^{17}$	3600
W	500	helium	-1000	$2{,}06\cdot10^{17}$	21600
Be	1500	hydrogen	-1200	5,84	1800
Be	1500	deuterium	-1200	3,04	1800
Be	1500	helium	-1200	5,16	1800

3. Experimental results and discussion

3.1. The change in surface W when irradiated by a plasma beam

Figure 4 shows the SEM images of tungsten samples irradiated with hydrogen plasma at an accelerating potential of –1200 V and –1600 V. Images were taken at high magnifications. The topography of the irradiated surface indicates its strong erosion. It can be seen that as a result of irradiating tungsten with stationary plasma, etching pits in the size from 100 nm to 500 nm are formed in the grain body, as a result of sputtering of the surface caused by ion bombardment. In addition, microcracks and small pores are created in the volume of tungsten.

In particular, when irradiated with an accelerating potential of –1600 V, a large number of small pores with a size of 0.2 μm to 1.0 μm are created. The system of cracks and pores creates a transport path between the surface and the volume of the material, so you can expect deep penetration of ions into the volume of the metal. The reason for the occurrence of these structural disorders, apparently, are mechanical stresses in the tungsten lattice caused by implanted hydrogen.

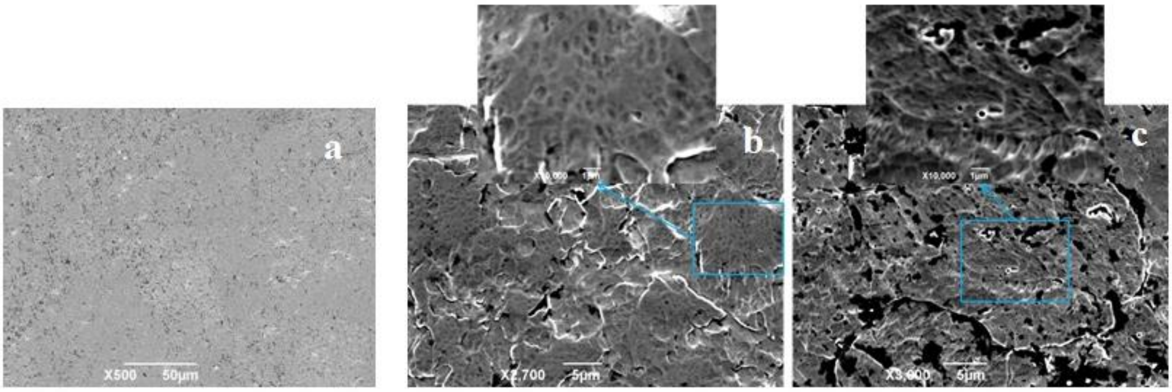

Fig.4. SEM-images of the surface of a tungsten sample before (a) and after irradiation with a plasma beam in a hydrogen medium at an accelerating potential of -1200 V (b) and -1600 V (c)

Figure 5 a-b show the SEM-image of a sample of tungsten irradiated with helium plasma, resulting in a large number of small pores ranging in size from 0.5 μm to 1.5 μm. As a result of irradiation of tungsten with stationary plasma along the grain boundaries, etching pits appear in the grain body. In addition, a large number of micro cracks are created in the volume of tungsten. It is assumed that they are directed from the surface into the depth of the metal, as well as the cause of the occurrence of these structural disorders are mechanical stresses in the tungsten lattice caused by implanted helium [14].

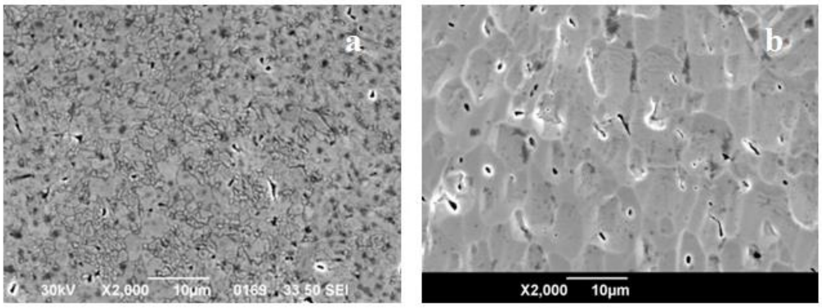

Fig.5. SEM image of a sample of tungsten irradiated with a helium plasma at an accelerating potential of -1200 V (a) and -1600 V (b)

3.2. Changes of Be surface variation upon plasma beam irradiation

Figure 6 shows SEM-images of the surface of beryllium samples before (Fig.6, a) and after irradiation in helium (Fig.6, b), hydrogen (Fig.6, c) and deuterium (Fig.6, d). Studies of the beryllium microstructure on a raster electron microscope showed that after irradiation a porous structure is formed. Pores of different bulk density are formed (Fig.6, a-d).

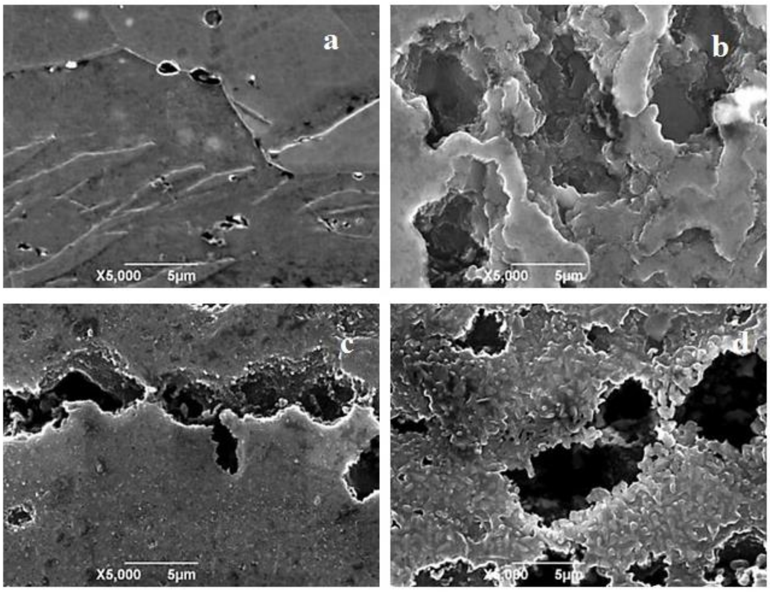

Fig.6. Surface modification of beryllium samples after irradiation.

A strong destruction of the structure is observed in the samples irradiated with hydrogen and helium plasma. At the same time, after irradiation with helium plasma, the surface of beryllium acquired a spongy structure, the reason for which is the appearance of large gas bubbles along which the main crack passes in the process of sample destruction. Spreading drops are visible on the surface. It can be assumed that these are products of erosion that have returned to the plasma sample during irradiation.

Conclusion

Thus, simulation facilities are very efficient, since they allow for the on-line testing of candidate materials from the NFR, replenishing the database on various aspects of plasma-surface interaction, testing the computational models and working out diagnostic methods in fairly well programmed conditions. The study of plasma-surface interactions with the help of simulation plasma systems allows us to substantiate the choice of materials for a thermonuclear energy reactor. At the same time, the installation developed by the author has a high productivity by reducing the time for changing the irradiated samples, as well as by remote control of the power supply system, the vacuum pumping system, and the gas supply system of the installation.

Experiments conducted to study changes in the structure of tungsten and berylliums during plasma irradiation have shown that pores are formed on the surface after irradiation. Moreover, after irradiation with helium plasma, etching pits are formed on the surface of tungsten. And on the surface of beryllium, droplet-like particles are formed, which are products of erosion. They were formed by sputtering the surface with helium ions.

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