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CHANGES OF THE RADIATION CHARACTERISTICS OF SURFACE OF TUNGSTEN AS A RESULT OF INFLUENCE OF HELIUM ION BEAMS

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The change in the radiation characteristics of the surface of tungsten was studied. Helium ions beams with energies of 0.12 and 4 MeV were used. Curves of ionization and damage are got on length of free run of ions of helium. The change the radiation characteristics of the surface of tungsten was studied. In the case of treatment with a beam of helium ions with energies of 0.12 MeV an increase in the hardness of the tungsten surface was found. Bubbles development has been studied. The appearance of tungsten tendrils around the bubbles, the formation of hills and valleys was considered.

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INTRODUCTION

One of the problems of implementing nuclear installations, based on the reactions of nuclear fusion, is the resistance of the materials of the first wall, the diverter. The materials of the first wall are exposed to various factors. Among them, the most important are the following: a) thermal effect in the mode of thermal generation; b) exposure to plasma in the event of a current failure; c) radioactive effects of nuclear fusion products that are not contained by the electromagnetic field (neutrons, ions, and so on).

For example, in magnetic fusion reactors (MFE) similar to ITER, the plasma parameters that have been established will have the following characteristics: ~ 5…20 $MW\cdot m^{-2}$ heat. The next output ~ $10^{24}H^{+}m^{-2}\cdot s^{-1}$ (1…10 eV) protons и ~ $10^{22}…10^{24}H^{2+}m^{-2}\cdot s^{-1}$ (<500 eV) helium ions [1].

For the reactors of IFE with the laser pumping (HAPL), the reactor wall will be exposed to helium and deuterium ions with energies from 1 keV to 10 MeV. As well as helium flows with low energies ~ 10^{15} m^{-2} (in the range of 100…200 keV). And helium flows with high energy~ 10^{15} m^{-2} (in the range of 200 keV to 10 MeV) [2].

Based on this, when choosing promising materials for the manufacture of the first wall, they are guided, first of all, by a high melting point. At the same time, due to the criticality of the impact of the above factors, materials scientists pay attention to such features as the orientation of the texture in relation to the source, etc.

Therefore, it is necessary to determine what material will be used in thermonuclear reactors. It should be taken into account that in a thermonuclear reactor the first wall is at a high temperature (>1200 K). In this case, the development of several processes is possible.

Significant heating of the material of the first wall can lead to tempering of the material and softening of the surface layer, which can lead to equipment failure and failure.

When the material of the first wall is heated to high temperatures, separate melting regions may appear (lake melting). In this case, the material is sprayed into the region where the plasma is located. As a result of splashes of molten metal entering the plasma, it is contaminated and the characteristics of the plasma composition change. We assume that the main mechanism that causes sputtering is bubble boiling. Bubble boiling leads to strong evaporation. Splashes from the surface of the melt are due to the action of the Kelvin-Helmholtz instability. This instability is based on the circulation motion of liquid metal in the melt pools, the influence of the plasma flow and metal recoil during evaporation.

During operation of a thermonuclear reactor, the surface of the first wall is irradiated with fast neutrons (14.2 MeV, ~2 dpa) and nuclear fusion products. Irradiation significantly changes the lattice structure of the material due to the appearance and accumulation of lattice defects. The operation of the reactor is accompanied by the appearance of flows of helium ions, which also worsens the lattice structure of the material.

Damage to the microstructure of the material of the first wall of a thermonuclear reactor can significantly change the thermal characteristics of the material, mechanical properties (hardness, plasticity, etc.), swelling characteristics, spraying. At consideration of perspective materials for creation of the first wall of thermonuclear reactor tungsten is a promising candidate. It has several specific properties that allow its use in thermonuclear reactors [3-9].

These are such characteristics: high temperature of melting, strength at high temperatures, residual strength after cooling, significant thermal conductivity, and significant resistance to erosive spraying. Tungsten does not almost retain tritium.

Also, these properties of tungsten are necessary when it is used in the construction of storage RAW [10], the creation of radiation-protective materials [11].

It is necessary to mark that all these characteristics are important at the use of tungsten as a diverter or material of the first wall in a thermonuclear reactor [4, 6, 7, 9].

PURPOSE OF WORK

A study of changes of structure is surfaces of tungsten, which happened as a result of irradiation the beams of ions of helium. Determination of the main macroscopic characteristics of the tungsten surface.

THE MAIN PART

To determine the suitability for work in thermonuclear reactors of a material, simulation techniques are used. An effective method is the use of contaminated particle beams.

In our case the beams of ions of helium with different energies are applied. We will mark that helium has low solubility in a tungsten. Also it results in the strong defects of grate, that reduces hardness of tungsten substantially.

The samples that were in the reactor are radioactive. Therefore, simulation makes it possible to study the changes of defects of grate of surface of tungsten.

To understand the mechanisms of radiation damage, it is necessary to conduct an experiment in cold conditions. This will make it possible to separate the contributions of the radiation and thermal factors.

As a working machine, a helium ion accelerator was used [12-15]. It is possible to use the IR radiometric method for monitoring beam parameters for beam diagnostics [16].

The accelerator has such working characteristics: pulse current 700 μA, pulse length 500 μs, average current 0.7 μA, repetition frequency 2…5 imp./s, current density $(0.15…0.44)\cdot10^{13}$ part./cm^2.

The samples are irradiated in the mode when the temperature does not exceed 1000ºC. The beam energy is 0.12 MeV (in the injection mode) and 4 MeV (in the acceleration mode).

It should be especially noted that it is possible to carry out studies with helium ions of low and high energies. This allows you to significantly expand the spectrum of research.

It is known [17] that helium beams with low energy produce defects in the form of pores. These defects change the physical characteristics of the tungsten surface. Among these characteristics there is hardness, density, strength. It is necessary to define how the again got defects cooperate, with an already existent structure. It is also necessary to find out the dynamics of development of these defects. The decision of these questions allows to find out the degree of change of structure of tungsten, as material of the first wall. Study of dynamics of development of defects, enables to execute the prognosis of terms of exploitation of the first wall. Tungsten was the target. The tungsten was of high purity. Tungsten had the following composition (Table 1).

Samples in the form as pucks 2 mm thick and 10 mm in diameter were used for research. The use of samples of this configuration makes it possible to obtain the display of all the effects of irradiation on the surface of the sample, from the side of irradiation.

Experimental work on the effect of a beam of accelerated helium ions on tungsten samples was supplemented by numerical calculations. We used the SRIM program code [18]. Additional calculations were conducted by the package of softwares of Geant4 v 4.9.6p02 [19].

Table 1

Chemical composition of the W

Additives	(%)	Additives	(%)
(W)	99.5	(Mn)	0.01
(Fe)	0.03	(Pb)	0.01
(Mo)	0.05	(Ca)	0.01
(Cr)	0.05	(Si)	0.02
(Co)	0.02	(Mg)	0.001
(Al)	0.02	(S)	<0.005
(Ni)	0.02	(P)	<0.005
–	–	($O+H_2O$)	<0.25

The SRIM and Geant4 v 4.9.6p02 software packages make it possible to determine a damage profile, which makes it possible to estimate the change in target density along the path of helium ions. Using the SRIM package, ionization profiles are found and the number of phonons produced is determined. These characteristics are necessary for a detailed study of the mechanisms of changes in the properties of the tungsten surface, which occur as a result of irradiation with helium ion fluxes.

When tungsten samples were irradiated with helium ions with an energy of 4 MeV, the studies were carried out in two temperature regimes, irradiation of samples at temperatures of 330…340 K and irradiation of samples at temperatures of 670…720 K.

The irradiation dose was $1.62\cdot10^{18}$ ion/cm^2. In this case, the dose of radiation damage was 8.19 dpa. This dose of radiation damage in real conditions will be accumulated in a long time.

Similar temperature ranges were observed when tungsten samples were irradiated with helium ions with an energy of 0.12 MeV (120 keV). In this case, the radiation dose was $1.7\cdot10^{18}$ ions/cm^2, and the radiation damage dose was 93.78 dpa.

Changes in the structure of the sample material occur along the path of the helium ions. Density, number of dislocations, loops change. As a result of irradiation with a flow of helium ions, tungsten is ionized and phonons are formed. The calculated data on ionization, damage, and phonon production are presented in Table 2.

Table 2

Energy loss and damage of tungsten samples (W(99.5)) when irradiated with helium ion beams with energies of 0.12 or 4 MeV

Energy loss, E_{He} = 0.12 MeV. Damageability – 146 displacements/ion			
Parameters	Ionization, (%)	Displacements, (%)	Phonons (%)
Ions He+	93.88	0.08	0.70
Cascade of Displacement	1.35	0.27	3.57
Energy loss, E_{He} = 4 MeV. Damageability – 338,7 displacements/ion			
Parameters	Ionization, (%)	Displacements, (%)	Phonons (%)
Ions He+	99.40	0.02	0.04
Cascade of Displacement	0.10	0.02	0.20

From a Table 2 it is evidently, that the main effect on the sample material is ionization. An insignificant part of the energy of the helium ion beam is spent on the formation of phonons. It is also necessary to note the weak influence of the displacement cascade on the change in the radiation characteristics of the process.

For samples that were irradiated with a 4 MeV helium ion beam, the calculated sample ionization curve and the effect of the displacement cascade on ionization are shown in Fig. 1.

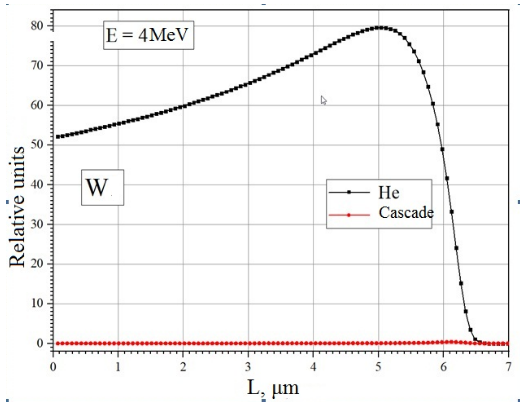


Fig. 1. Graph of ionization of the surface of sample of tungsten (helium ions with an energy of 4 MeV)

On a horizontal axis we have a run of ions of helium in micrometers. The values along the vertical axis are given in relative units.

A curve similar in structure was also obtained for samples that were irradiated with a helium ion beam with an energy of 0.12 MeV. The ionization graph is shown in Fig. 2.

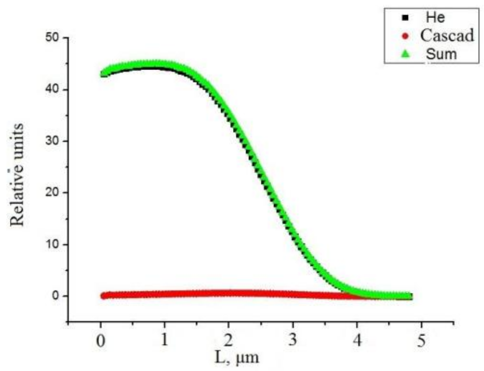


Fig. 2. Graph of ionization of surface of sample of tungsten of W (ions of helium with energy 0.12 MeV)

The ionization maximum is at a depth of 5…6 µm for tungsten, which was irradiated with helium ion beams with an energy of 4 MeV. The ionization maximum is observed at a depth of 1.5 µm for tungsten, which was irradiated with helium ion beams with an energy of 0.12 MeV.

Damage graphs are shown in Fig. 3,a,b. This is for the case of an ion beam with an energy of 4 MeV.

Graphs (a) and (b) in Fig. 3 differ in the values along the vertical axis. On Fig. 3,a the values are a thousand times greater than in Fig. 3,b. From the analysis of the graphs, we can conclude that tungsten makes the main contribution to damage. All other inclusions give only minor violations. These violations are located in the district of 6 µm.

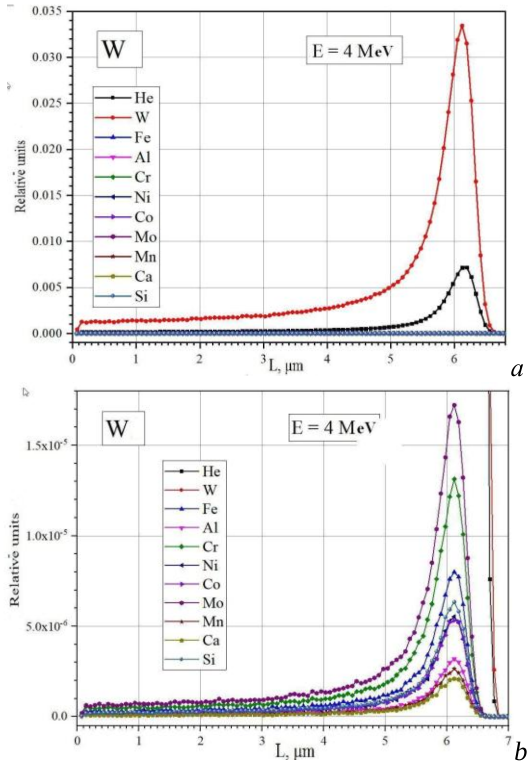


Fig. 3. Graph of distribution in a tungsten sample that was irradiated with a helium ion beam with energies of 4 MeV: on the vertical axis, the maximum value is 0.035 relative units (a); on the vertical axis, the maximum value is 1.5·10^{-5} relative units (b)

Similar curves were also obtained for a beam of helium ions with an energy of 0.12 MeV.

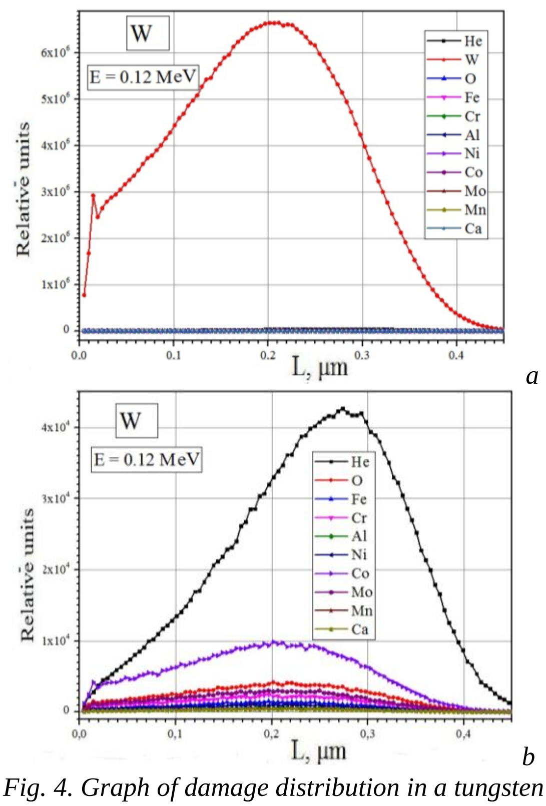


Fig. 4. Graph of damage distribution in a tungsten sample that was irradiated with a helium ion beam with energies of 0.12 MeV: on the vertical axis, the maximum value of 6·10^6 relative units (a); on the vertical axis, the maximum value of 4·10^4 relative units (b)

The values on the vertical axis of the graph (Fig. 4,a) are one thousand times greater than the values on the vertical axis of the graph (Fig. 4,b). Therefore, when irradiated with a beam of helium ions with an energy of 0.12 MeV, the main contribution to the violation of the sample surface structure is made by tungsten.

Except for the above enumerated effects, for the term of service of material of the first wall, other also mechanisms of violations influence. One of the effects that disturb the surface structure is the effect of material sputtering from the surface of the samples. This changes the mechanical properties of the material of the first wall of the reactor. Plasma contamination is also possible.

For each of the elements that are in the alloy, the values of the average sputtering energy were calculated and the number of sputtered atoms was found. The calculations were carried out both for a helium ion beam with energies of 0.12 MeV and for a helium ion beam with energies of 4 MeV. The results of the numerical calculation are shown in Table 3.

Table 3

Numerical values of the number of sputtered atoms (sputtered atoms quantity) and the average sputtering energy (sputtered average energy)

	Beam energy, 0.12 MeV	Beam energy, 0.12 MeV	Beam energy, 4 MeV	Beam energy, 4 MeV
Additives	Sputtered atoms Quantity ($N \cdot 10^{-5}$ atom/ion)	Sputtered average energy (eV/atom)	Sputtered atoms Quantity ($N \cdot 10^{-5}$ atom/ion)	Sputtered average energy (eV/atom)
(W)	2390	91.5	94.0	531.0
(Fe)	0.8	34.1	5.7	7562
(Al)	0.7	27.0	2.9	25.5
(Cr)	2.2	53.2	8.5	117
(Ni)	0.7	86.7	<0.1	<0.1
(Co)	1.3	170.3	<0.1	<0.1
(Mo)	1.1	24.5	0.1	21.1
(Mn)	0.5	5.4	<0.1	<0.1
(Ca)	1.2	7.0	<0.1	<0.1
(Si)	0.4	11.2	<0.1	<0.1
(Pb)	2.0	12.0	<0.1	<0.1
(O)	9.0	11.2	0.6	7.39
(Mg)	<0.1	<0.1	0.1	13.0
(S)	0.4	28.2	<0.1	<0.1
(P)	0.1	37.1	<0.1	<0.1

Based on the given data, the mid-coefficient sputtering (Sputtered Ratio) of the surface of the tungsten sample was obtained. In the case of irradiation with a beam of helium ions with energies of 0.12 MeV, it is equal to $2.41 \cdot 10^{-2}$ atom/ion. When irradiated with a beam with an energy of 4 MeV, the average sputtering coefficient (Sputtered Ratio) of the tungsten surface is $0.11 \cdot 10^{-2}$ atom/ion.

The application of these results makes it possible to find the change in the mass of tungsten during operation. Tungsten is used as the material of the first wall. We can determine the change in the density of tungsten on the way of run of ions of helium.

In the process of irradiation of tungsten with beams of helium ions with energy of 0.12 MeV, helium ions are implanted into tungsten. As a result of implantation of helium ions, defects are formed in tungsten. It is necessary to study the processes of appearance of micro defects in the area of implantation and their development. The degree of interaction of these micro defects with the tungsten base should be determined.

When studying the effects of implantation, hardness measurement using nanoindentation was used [20]. An increase in hardness of up to 30% was obtained. A decrease in thermal conductivity of 50% was found.

When a sample was examined that was irradiated with 0.12 MeV helium ions, an increase in hardness of 20% was found. Graphs of hardness change are shown in Fig. 5.

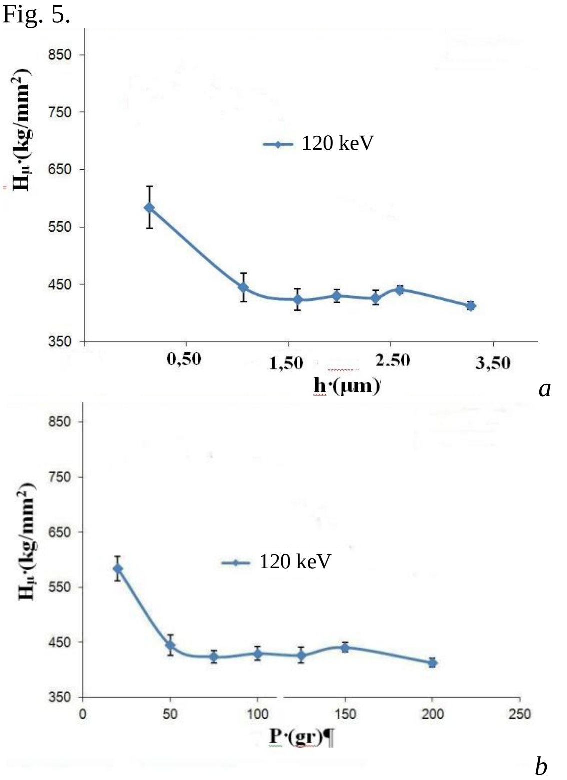
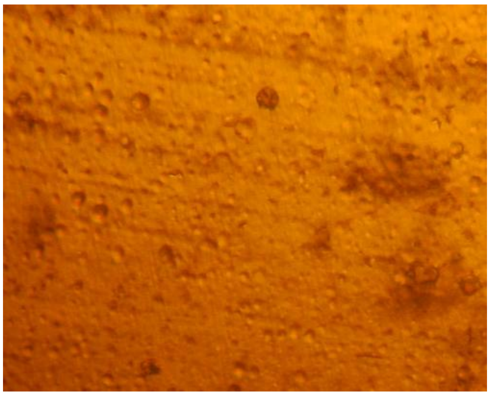


Fig. 5. Change to hardness of surface of samples of tungsten; in depending from a depth (a); depending on the attached loading (b)

As follows from the graphs of changes in hardness, even at a depth of 1 µm, the hardness becomes the same as the hardness of the entire sample. Thus, in the case of irradiation with an ion beam with energies of 0.12 MeV, the change in hardness occurs in a thin layer with a depth of up to 1 µm.

Bubbles are born on the surface of tungsten samples when helium ions act. These bubbles gradually grow and increase in size. Photos of the tungsten surface are shown in Fig. 6.

a



b

Fig. 6. Surface of sample of tungsten (is the non-irradiated sample (a); a sample is radiation-exposed by the beam of ions of helium with energies 0.12 MeV (b))

The surface of the non-irradiated tungsten sample (see Fig. 6,a) had a smooth shape. Various craters are observed after irradiation (see Fig. 6,b). An enlarged image of the surface area is shown in Fig. 7.

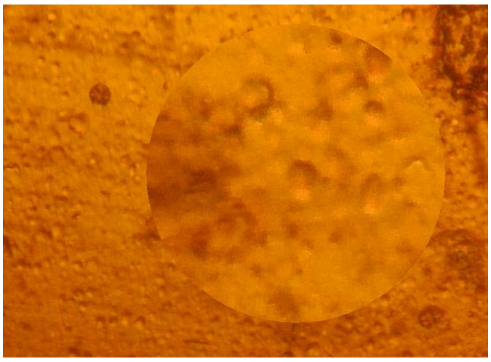


Fig. 7. An enlarged fragment of the surface of a tungsten sample after irradiation

On Fig. 6, it is clearly seen that the craters that remained after the formation of bubbles have different sizes. This indicates their constant growth. In tungsten, in which helium ions were implanted, large growths were found around the craters. Also found out the large steps of sliding off. For non-implanted tungsten, outgrowths and steps are much smaller [22, 23].

Irradiation of tungsten with beams of helium ions leads to the appearance of the so-called tungsten “fuzz” at the edges of craters (on growths) [21]. The formation of “fuzz” and its growth leads to elongation of the crater edges and an increase in tungsten evaporation under the action of a helium ion beam [21-23].

CONCLUSIONS

1. The changes of radiation descriptions of tungsten, which are initiated by treatment of sample of tungsten by the beams of ions of helium, are considered.

2. Ionization and damage curves along the track of ion penetration into tungsten were found by numerical methods.

3. For each element, from the composition of tungsten, the number of sputtered atoms and the average sputtering energy were obtained. The average sputtering coefficient was determined.

4. Using the average spraying coefficient and medium spray energy made it possible to determine the loss of mass, depending on the characteristics of the beam of ions (the beam energy, its fluuens, etc.)

5. An increase in hardness was found by 20%, in the surface layer of a tungsten sample, which came as a result of irradiation with a beam of helium ions with an energy of 0.12 MeV.

6. It has been suggested that the growth of the tungsten “fuzz” depends on the pressure of the bubbles on their walls and the degree of extrusion of the tendrils on the surface.

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ЗМІНА РАДІАЦІЙНИХ ХАРАКТЕРИСТИК ПОВЕРХНІ ВОЛЬФРАМУ В РЕЗУЛЬТАТІ ДІЇ ІОНІВ ГЕЛІЮ

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Досліджувалася зміна радіаційних характеристик поверхні вольфраму. Застосовувалися пучки іонів гелію з енергіями 0,12 і 4 МеВ. Отримані криві іонізації і пошкоджень по довжині вільного пробігу іонів гелію. Знайдено збільшення твердості поверхні вольфрамової мішені в разі обробки пучком іонів гелію з енергією 0,12 МеВ. Вивчався розвиток бульбашок. Розглядалися поява вольфрамових вусиків, утворення горбів і долин.

ИЗМЕНЕНИЕ РАДИАЦИОННЫХ ХАРАКТЕРИСТИК ПОВЕРХНОСТИ ВОЛЬФРАМА В РЕЗУЛЬТАТЕ ВОЗДЕЙСТВИЯ ИОНОВ ГЕЛИЯ

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Исследовалось изменение радиационных характеристик поверхности вольфрама. Применялись пучки ионов гелия с энергиями 0,12 и 4 МэВ. Получены кривые ионизации и повреждений по длине свободного пробега ионов гелия. Найдено увеличение твердости поверхности вольфрамовой мишени в случае обработки пучком ионов гелия с энергией 0,12 МэВ. Изучалось развитие пузырьков. Рассматривались появление вольфрамовых усиков, образование холмов и долин.