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RADIATION DAMAGE IN TUNGSTEN TARGET OF THE "KIPT NEUTRON SOURCE"

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In this work, mathematical modeling of a complex of processes occurring in a tungsten target under irradiation with high-energy electrons with an energy of 100 MeV: an electromagnetic shower, the production of photo-neutrons, and particle transport along the target, damage from neutrons of the subcritical assembly. It was found that the greatest contribution to the rate of damage formation in a tungsten target give the elastic scattering of high-energy electrons on nuclei.

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INTRODUCTION

At the National Scientific Center "Kharkov Institute of Physics and Technology" (NSC KIPT, Kharkov, Ukraine) together with the Argonne National Laboratory (ANL, USA) has successfully carried out the physical start-up of a neutron source (NS) based on a subcritical assembly controlled by a linear electron accelerator (as a driver).

Two options are considered as the target material: - tungsten and uranium-molybdenum alloy. Previously, the authors have already analyzed the radiation damageability of a uranium target under irradiation with high-energy electrons with an energy of 100 MeV [1], and therefore, this work is devoted to a tungsten target.

Today, tungsten is the main material for solid-state targets, both in operation and under construction, megawatt accelerator-controlled nuclear systems (ADS) [2 - 4]. Despite a number of disadvantages, the reason for its use is rather high neutron yield and thermal conductivity.

The tungsten target NS NSC KIPT has already worked under a beam of high-energy electrons with an energy of 100 MeV in the process of tuning the accelerator and the physical start-up of the installation for more than a year in total. Therefore, evaluation the radiation resistance of a tungsten target is very important problem.

The lifetime of the NS depends on the limit of radiation dose for the target material (in displacements per atom). To determine the radiation dose in a thick target under the action of high-energy electrons, it is necessary to evaluate the contribution of elastic and inelastic processes to defect formation: scattering and nuclear reactions involving high-energy electrons, neutrons, and gamma quanta.

The aim of this work was computer modeling using the MCNPX code of complex processes occurring in a tungsten target under irradiation by high-energy electrons: an electromagnetic shower, photo-neutron production, particle transport along the target, and damage in the target by neutrons from the subcritical assembly.

1. TUNGSTEN TARGET MODEL

The target consists of seven 66×66 mm tungsten plates of various thicknesses (see Table) with a tantalum coating 0.26…0.27 mm thick. The gap between the plates is 1.75 mm filled with water. The target is separated from the vacuum chamber of the electronic conductor by an aluminum entrance window of 2 mm thick. Behind the target is a helium-filled chamber (marked in yellow in Fig. 1.

Thickness of plates W (in cm)

1	2	3	4	5	6	7
0.25	0.25	0.247	0.353	0.358	0.555	0.95

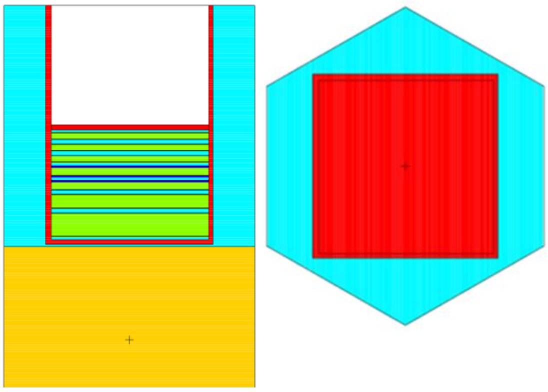

Fig. 1. Geometry of the tungsten target model

A plane-parallel electron beam with a square cross section of 64×64 mm with an energy of 100 MeV and a power of 100 kW is incident on the target. An electromagnetic shower develops in the target, bremsstrahlung gamma quanta enter into reactions with atomic nuclei and photo-neutrons appear, which enter the subcritical assembly, where they multiply.

2. RESULTS OF COMPUTER MODELING USING THE MCNPX CODE

The process of electron interaction with the target material was simulated using the MCNPX code [5]. The profile of energy release in the target is shown in Fig. 2. Energy is mainly released in metal plates, and only a small fraction of energy is released in water.

The distribution of the electron flux along the length of the target is shown in Fig. 3 (per one incident electron). The development of an electromagnetic shower leads to a twofold increase in the electron flux density, and then deceleration of the electron beam occurs due to the processes of ionization and emission of bremsstrahlung gamma quanta.

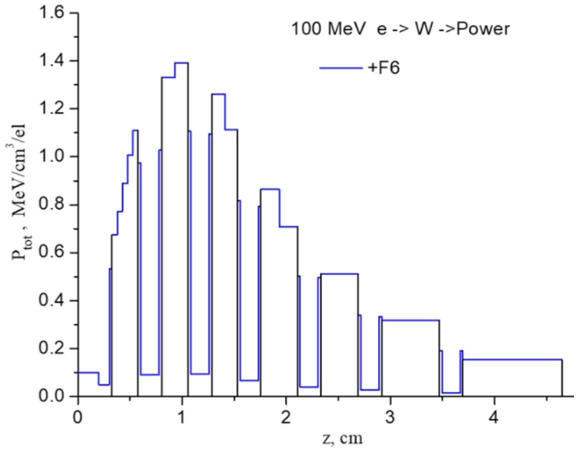

Fig. 2. The distribution of the volumetric power along the length of the target

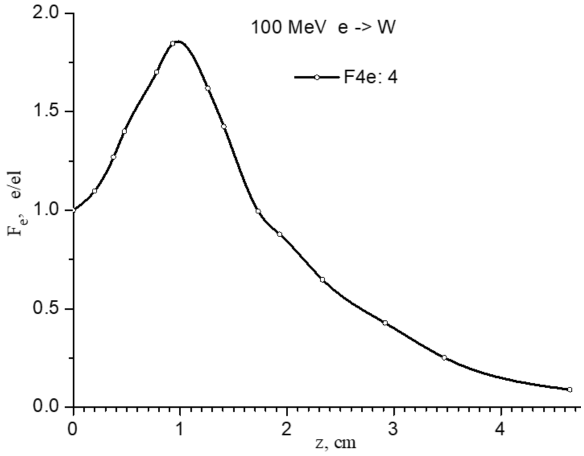

Fig. 3. Distribution of the electron flux along the length of the target

Fig. 4 shows the distribution of the flux density of gamma quanta along the length of the target (per one incident electron).

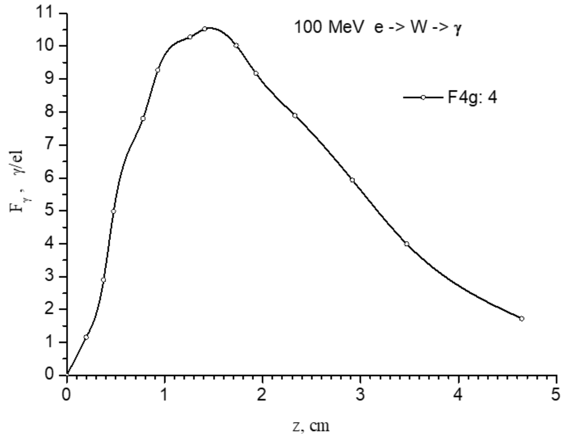

Fig. 4. Distribution of the flux of gamma quanta along the length of the target

Such photon distribution profile is formed as a result of the processes of bremsstrahlung gamma quanta emission during the scattering of electrons by nuclei, the production of electron-positron pairs by photons near the nuclei, and processes of positron annihilation with emission of photons. The damping of the flux is due to absorption of photons by nuclei and atomic systems. The maximum of photon flux in the target is at a depth of 1.3 cm (the depth is measured from the target entrance window).

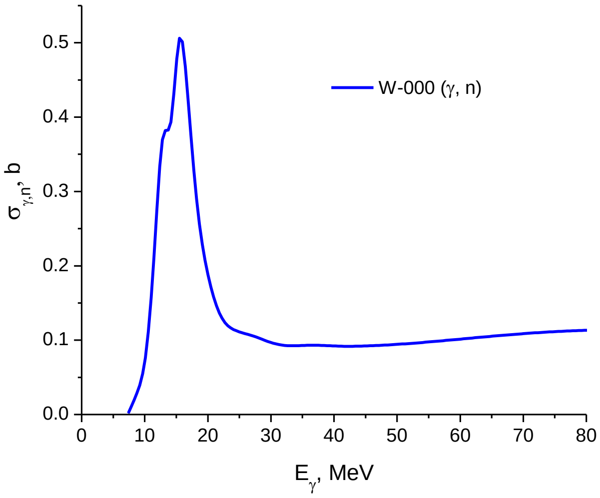

Fig. 5. Cross section of photoneutron production in tungsten [7]

Due to interaction of gamma quanta with the nuclei, neutrons are emitted from nuclei as a result of the (γ, n) reaction, the cross section of which for tungsten is shown in Fig. 5. The cross section has a pronounced maximum due to the giant dipole resonance in the electromagnetic interaction of a gamma quantum with a nucleus [6]. The distribution of the neutron flux resulting from photonuclear reactions along the target is shown in Fig. 6 (calculation using the MCNPX code).

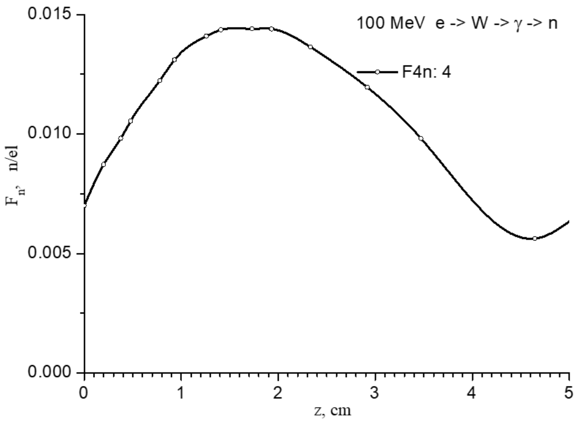

Fig. 6. Distribution of the neutron flux along the length of the target

Using the simulation results obtained above, it is possible to calculate the rate of radiation damage accumulation in the target.

3. RADIATION DEFECTS PRODUCTION RATE IN A TUNGSTEN TARGET

In a tungsten target under electron irradiation with an energy of 100 MeV radiation defects appear. The main sources of the formation of such defects are recoil nuclei arising from electrons and neutrons scattering on nuclei, as well as from photonuclear reactions.

3.1. Calculated by the method described in [7], the cross section for the formation of radiation defects in tungsten irradiated by electrons with energy E_e is shown in Fig. 7.

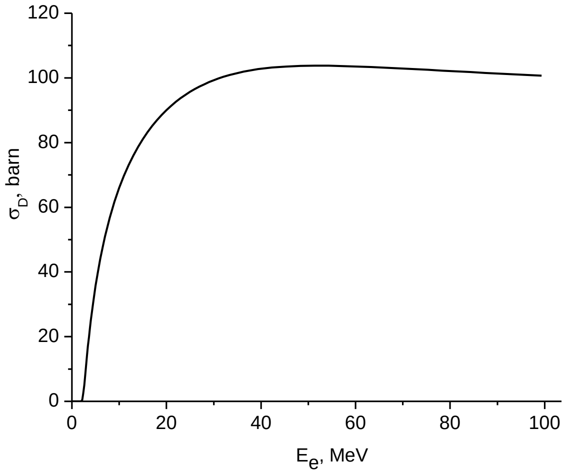

Fig. 7. Dependence of the defect formation cross section in W, irradiated by electrons, on energy

The cross section of defect formation in tungsten under neutron irradiation is shown in Fig. 8 [8].

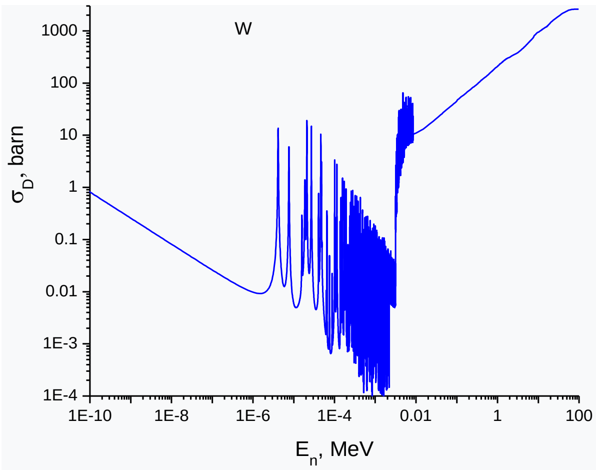

Fig. 8. Dependence of the cross section of defect formation in tungsten on the neutron energy

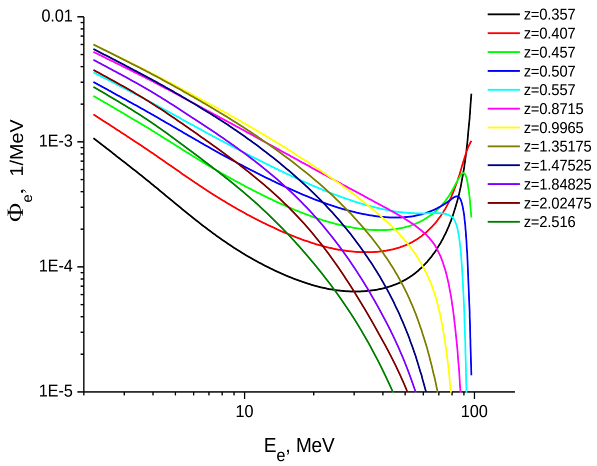

Fig. 9. Electron spectra at different depths along the length of the target

The rate of accumulation of radiation defects upon irradiation with a flux of electrons with a spectrum $\Phi_e(E_e)$ is determined by the expression:

$$\dot{D}_e = \int \sigma_{De}(E_e)\Phi_e(E_e)dE_e. \qquad (1)$$

The electron spectrum $\Phi_e(E_e)$ calculated using the MCNPX program at various depths in a tungsten target is shown in Fig. 9 (per one falling electron). At an accelerator current of 1 ma, we have an electron flux j = 6.15·10^{15} e/s. Using formula (1), we obtain the dependence of the rate of accumulation of defects on the depth $\dot{D}_e(z)$ (Fig. 10).

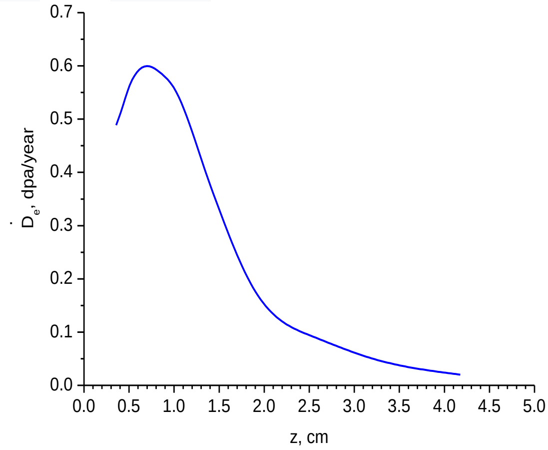

Fig. 10. The rate of defect formation by 100 MeV electrons along the depth W

3.2. The rate of accumulation of radiation defects under irradiation with neutrons with the spectrum $\Phi_n(E_n)$ is calculated similarly:

$$\dot{D}_n = \int \sigma_{Dn}(E_n)\Phi_n(E_n)dE_n. \qquad (2)$$

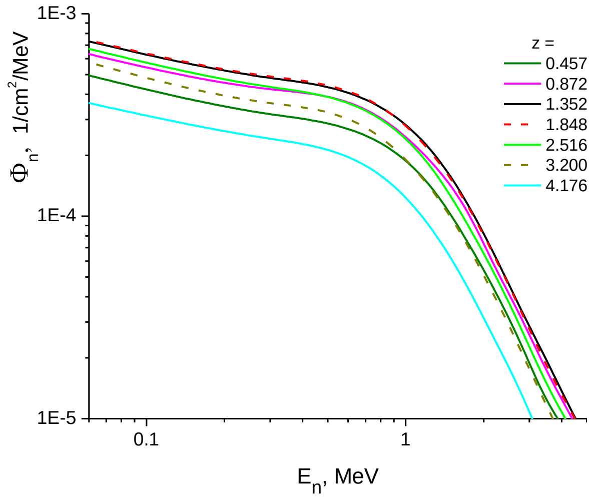

Fig. 11. Photo-neutron spectra at different depths along the length of the tungsten target

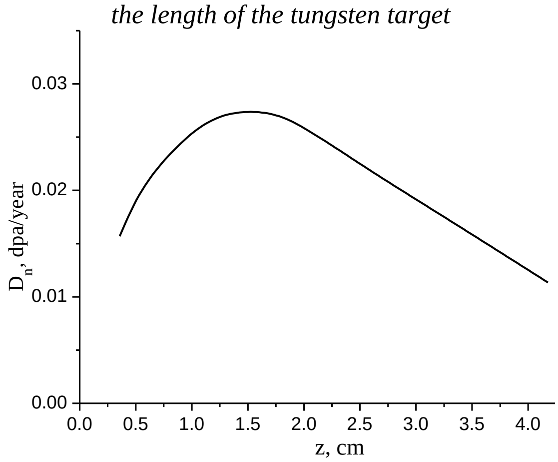

Fig. 12. The rate of defect formation by photo-neutrons in depth in W

The spectrum of photo-neutrons calculated using the MCNPX code at different depths in a tungsten target is shown in Fig. 11. The dependence of the rate of accumulation of defects on the depth z is shown in Fig. 12; it reaches a maximum value of ~ 0.03 dpa/year at a depth of 1.6 cm.

3.3. Let us consider the contribution to radiation damage of recoil nuclei arising in a tungsten target during photonuclear reactions. The maximum cross section for the production of photo-neutrons (see Fig. 5) falls on an energy of 16 MeV. When a photon is absorbed by a nucleus and a neutron is emitted, a recoil nucleus appears. The average energy of photo-neutrons is 1 MeV [4]. Taking into account that the energy of the recoil nucleus T is related to the energy of the emitted neutron E_n by the law of conservation of momentum: $T = E_n\, m/M$ we obtain the value of the average energy of the recoil nuclei T ~ 5400 eV. The threshold displacement energy for tungsten atoms is E_d =70 eV, and according to the formula [9] of the NRT standard $N_D = 0.8T/(2E_d)$ we get that one recoil nucleus creates ~ 31 displaced atoms. The probability of the appearance of a recoil nucleus is determined by the formula:

$$W = \int \sigma_{\gamma n}(E_\gamma)\Phi_\gamma(E_\gamma)dE_\gamma, \qquad (3)$$

where $\Phi_\gamma(E_\gamma)$ is the spectral flux density of photons, which at E_γ = 16 MeV is 0.002/cm^2/MeV (Fig. 13).

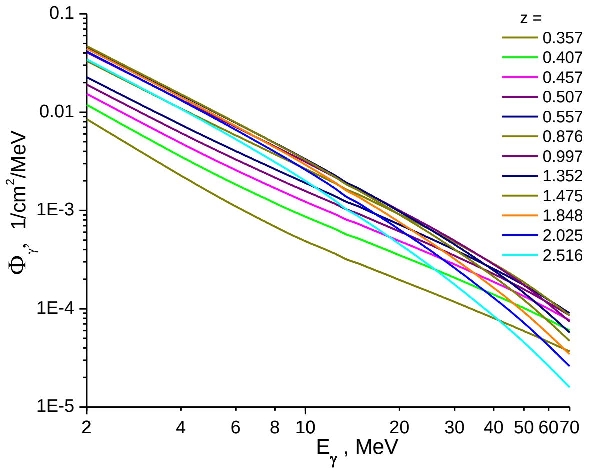

Fig. 13. Spectra of gamma quanta at different depths along the length of the tungsten target

Substituting the photo-neutron production cross-section (see Fig. 5) and the spectral flux density of photons (see Fig. 13) into expression (3), we obtain the probability of the release the photo-neutrons (and the recoil nucleus).

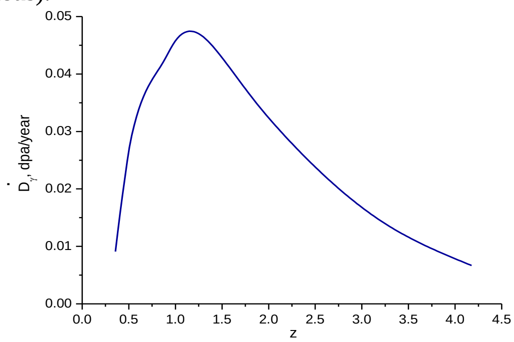

Fig. 14. The rate of defect formation due to the reaction (γ, n) along the depth of the target

Hence, we receive the radiation damage rate along the depth of the target due to the reaction (γ, n): $\dot{D}_\gamma \approx 31 jW$, which reaches a maximum value of 0.05 dpa/year at a depth of 1.2 cm (Fig. 14).

3.4. Let us consider the contribution to defect formation from neutrons coming from the subcritical assembly (SCA) and irradiating the neutron-producing target. Let us estimate the spectrum of neutrons released from the SCA into the tungsten target at k_{eff} = 0.96. In [5], the spectrum of neutrons from SCA with k_{eff} = 0.975 on the surface of a uranium target irradiated with 200 MeV electrons at a current of 0.5 mA was obtained (Fig. 15). A tungsten target irradiated with 100 MeV electrons at a current of 1 ma will give twice as few neutrons as a uranium target at the same electron beam power, and for a SCA with k_{eff} = 0.96, the value of 1/(1-k_{eff}) will be 1.6 times less than for an SCA with k_{eff} = 0.975. Thus, in the case of a tungsten target the data in Fig. 15 should be reduced by a factor of 3.2.

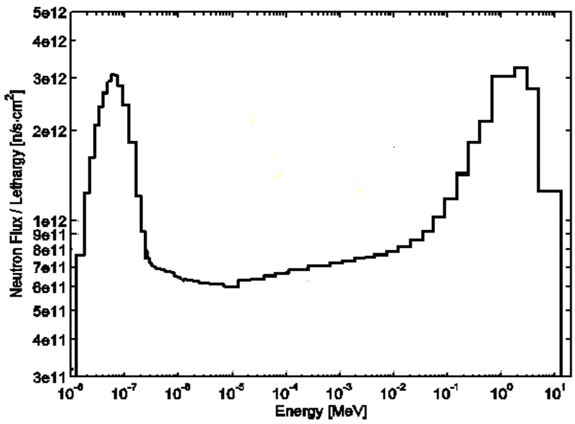

Fig. 15. The spectrum of neutrons from SCA with k_{eff} = 0.975 on the surface of a uranium target irradiated by electrons with an energy of 200 MeV

Using formula (2) we obtain the radiation damage dose rate from SCA neutrons: $\dot{D}_{Ï\,ÊÑ}$ ~ 0.15 dpa/year.

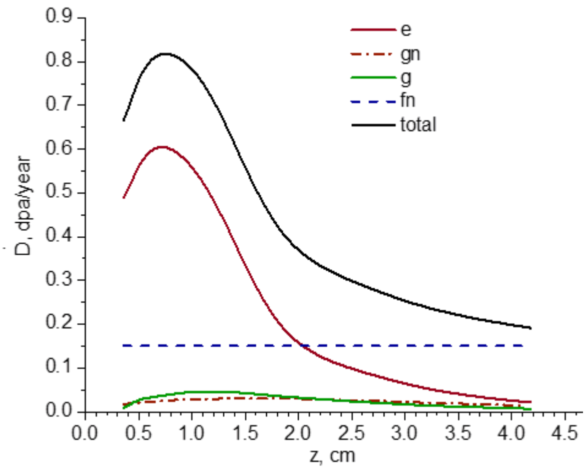

Fig. 16. Total rate of defect formation in tungsten and partial contributions

3.5. In Fig. 16 the total rate of defect formation in tungsten and the partial contributions of various mechanisms of radiation damage are shown: e is the contribution of elastic scattering of electrons, gn – the scattering of photo-neutrons on nuclei, g – formation of recoil nuclei in (γ, n) reactions, fn – scattering of neutrons from the SCA on target nuclei.

According to Fig. 16, the maximum rate of dose $\dot{D}_{max} \approx 0.83$ dpa/year is reached in the second plate of the tungsten target (at a depth of ~ 1 cm). This value is two orders of magnitude less than the rate of dose rise expected in a uranium target with the same irradiation parameters [1].

In works [10 - 12] it was shown that the resource of tungsten targets of the Chinese neutron source CSNS (protons 1.6 GeV, 120 kW) and the European neutron source ESS (protons 2 GeV, 5 MW) is 4-5 years of continuous operation, which corresponds to approximately the same radiation doses of the order of 10 dpa. Hence, it follows that the formation of radiation defects limits the service life of the tungsten target of the NSC KIPT subcritical assembly to ten years.

CONCLUSIONS

The rate of formation of displacements in the tungsten target of the neutron source at the NSC KIPT under the action of irradiation with high-energy electrons with an energy of 100 MeV has been calculated. The contributions of the processes of scattering of high-energy electrons, neutrons and gamma-quanta, the production of photo-neutrons, damage from neutrons of the subcritical assembly are considered. It was found that the greatest contribution to the rate of damage formation in a tungsten target is made by the elastic interaction of high-energy electrons with nuclei.

The maximum dose rate is $\dot{D}_{max} \approx 0.83$ dpa/year and is achieved in the second plate of the tungsten target (at a depth of ~ 1 cm).

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РАДИАЦИОННАЯ ПОВРЕЖДАЕМОСТЬ ВОЛЬФРАМОВОЙ МИШЕНИ НЕЙТРОННОГО ИСТОЧНИКА

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Проведено математическое моделирование комплекса процессов, проходящих в вольфрамовой мишени при облучении высокоэнергетическими электронами с энергией 100 МэВ: электромагнитного ливня, рождения фотонейтронов, транспорта частиц вдоль мишени, повреждений от нейтронов подкритической сборки. Установлено, что наибольший вклад в скорость образования повреждений в вольфрамовой мишени вносит упругое взаимодействие высокоэнергетических электронов с ядрами.

РАДІАЦІЙНА ПОШКОДЖУЄМОСТЬ ВОЛЬФРАМОВОЇ МІШЕНІ ДЖЕРЕЛА НЕЙТРОНІВ

В.В. Ганн, А.В. Ганн, Б.В. Борц, І.М. Карнаухов, П.І. Гладких, О.О. Пархоменко

Проведено математичне моделювання комплексу процесів, що проходять у вольфрамовій мішені при опроміненні високоенергетичними електронами з енергією 100 МеВ: електромагнітного ливню, утворення фотонейтронів, транспорту частинок уздовж мішені, пошкодження від нейтронів підкритичної збірки. Встановлено, що найбільший внесок у швидкість створення пошкоджень у вольфрамовій мішені вносить пружна взаємодія високоенергетичних електронів з ядрами.