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MATHEMATICAL MODELING OF URANIUM NEUTRON-PRODUCING TARGET OF SUBCRITICAL ASSEMBLY NSC KIPT

V.V. Gann*, G.V. Gann, B.V. Borts, I.M. Karnaukhov, O.O. Parkhomenko
NSC "Kharkov Institute of Physics and Technology", Kharkov, Ukraine
**Corresponding Author e-mail: gann@kipt.kharkov.ua*
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This work is devoted to calculating the rate of radiation damage production in a uranium target irradiated with high-energy electrons with an energy of 100 MeV. The Monte Carlo program MCNPX was used to perform a complete mathematical modeling of a complex of processes occurring in a uranium target when irradiated with high-energy electrons: the development of an electromagnetic shower, the production of photoneutrons, the transport of particles in the target and the creation of radiation damage in it. The analysis showed that fragments of U-238 photo-fission give the main input into the rate of damage production in a uranium target which reaches the value of 100 dpa/year. The expected service life of a uranium target under irradiation is 3 years of operation at full accelerator power.
Keywords: *Uranium; Electron; Subcritical assembly; Radiation damage*
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INTRODUCTION

The neutron source of the NSC KIPT with a power of 100 kW consists of a linear accelerator of electrons with energy of 100 MeV, which irradiate a thick neutron-producing target; the photoneutrons generated in it enter the subcritical assembly (SCA), where they are multiplied and the neutron flux is increased tens of times. The highest neutron flux can be obtained using a uranium neutron-producing target. The service life of a uranium target under irradiation is largely determined by the dose of radiation damage accumulated in it (in displacements per atom).

Previously, the authors have already estimated the radiation damage production in uranium target irradiated by high-energy electrons with energy of 100 MeV [1]. In this work, a complete mathematical modeling of all nuclear-physical processes in a uranium target was performed using the Monte Carlo program MCNPX. It has been shown that the main contribution to the rate of damage formation in a uranium target when irradiated with electrons with an energy of 100 MeV (1 mA) is made by photofission fragments of U-238, and the expected service life of a uranium target in the subcritical assembly of a neutron source at NSC KIPT has been assessed.

URANIUM TARGET MODEL

The target consists of a set of uranium plates with sizes 66x66 mm and various thicknesses (see Table 1), coated on the both sides with Al layers 0.7 mm thick. The 1.75 mm gap between the plates is filled with water. The target is separated from the vacuum chamber of the electron accelerator by an input window made of aluminum 2 mm thick. Behind the target is a chamber filled with helium (marked in yellow in Fig. 1).

Table 1. Plate thicknesses U (in cm), numbered in Fig. 1 from top to bottom:

№	1	2	3	4	5	6	7	8	9	10	11	12
Thickness	0.3	0.25	0.25	0.25	0.3	0.3	0.4	0.5	0.7	1	1.4	2.25

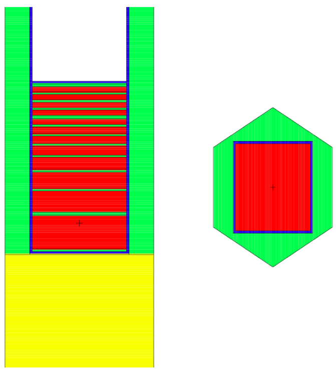

Figure 1. Uranium target of the neutron source NSC KIPT

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A plane-parallel beam of electrons with a square cross-section of 64x64 mm with 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 react with atomic nuclei, and as a result of the (γ, n) reaction, neutrons are produced, which enter the subcritical assembly, where they multiply, and radiation damage is created in the target.

RESULTS OF MATHEMATICAL MODELING

The MCNPX program was used [2], which allows to perform the Monte Carlo modeling of all nuclear-physical processes involving electrons, neutrons and gamma quanta, taking into account the specific geometry of the target. Figure 2 shows the profile of the energy release in the target under flow of incident electrons Φ = 1.7 1014 el/(cm^2 s). Energy is mainly released in uranium, with only a small fraction of energy released in aluminum and 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 doubling of the electron flow, and then the electron beam is decelerated due to the processes of ionization and emission of bremsstrahlung gamma quanta.

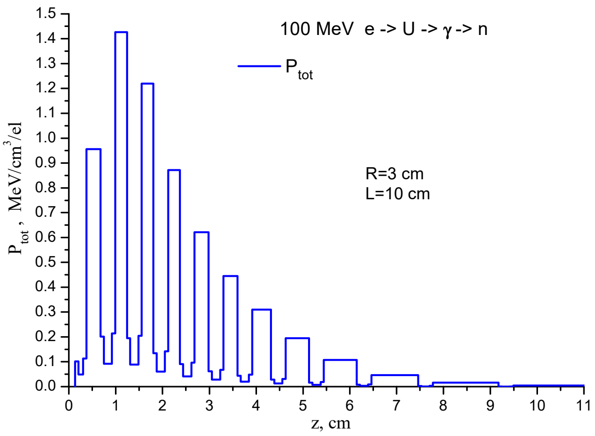

Figure 2. Distribution of energy release in the target

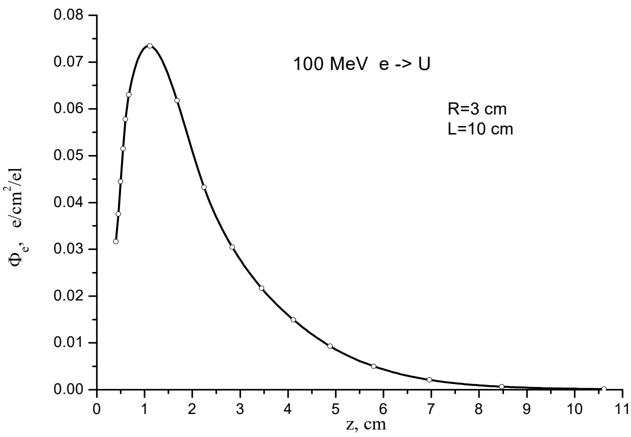

Figure 3. Electron flux distribution along the length of the target

Figure 4 shows the distribution of gamma ray flux density along the length of the target calculated by the MCNPX program (per one incident electron). Such a profile is formed as a result of bremsstrahlung gamma quanta emission, as well as the processes of positron annihilation with the emission of photons. The attenuation of the photon flux occurs due to the creation of electron-positron pairs by photons near the nucleus, as well as the absorption of photons by nuclei and atomic systems. The maximum of photon flux in the target occurs at a depth of 1.6 cm (the depth is measured from the target entrance window).

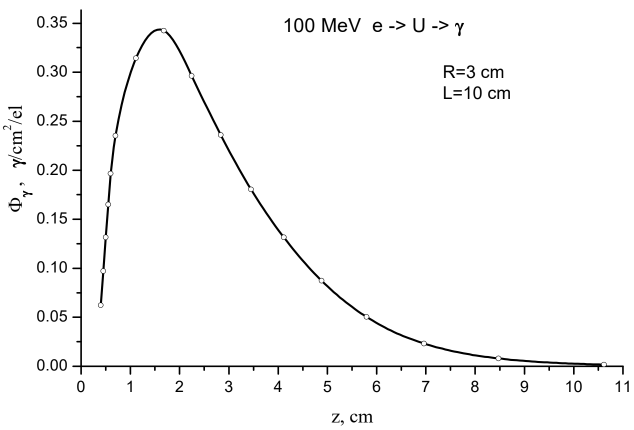

Figure 4. Distribution of the gamma ray flux along the length of the target

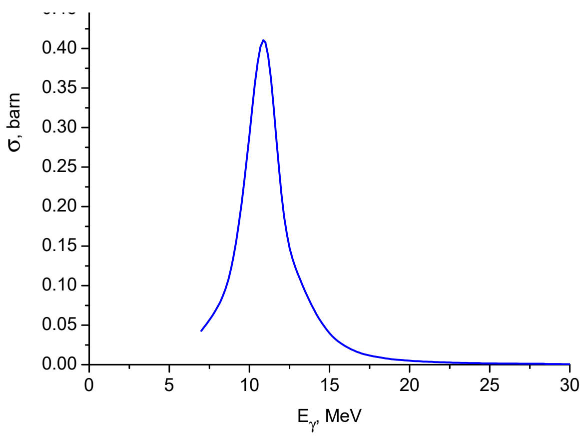

Figure 5. Dependence of the reaction cross section (γ, n) on photon energy for U-238

Photo-neutrons are released from the nuclei under the gamma ray irradiation. The reaction cross section (γ, n) on the U-238 nucleus, taken from the nuclear database [3], is presented in Figure 5. The MCNPX program allows determining the photo-neutron yield at various target depths. The distribution of the resulting photo-neutron flux along the length of the target is shown in Figure 6 (per one incident electron).

The photo-fission reaction of U-238 nuclei can also occur under photon irradiation, the dependence of its cross section on energy [3] is shown in Figure 7.

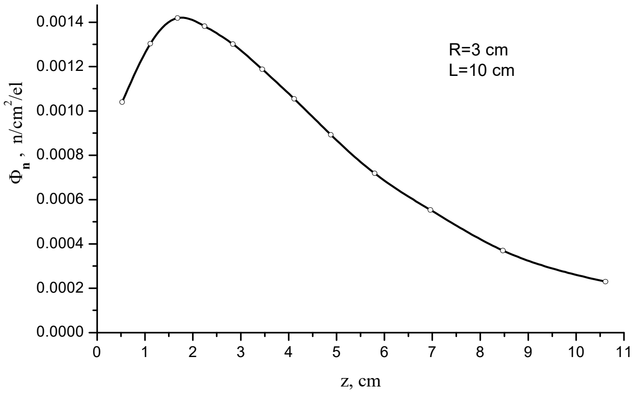

Figure 6. Distribution of neutron flux along the length of the target

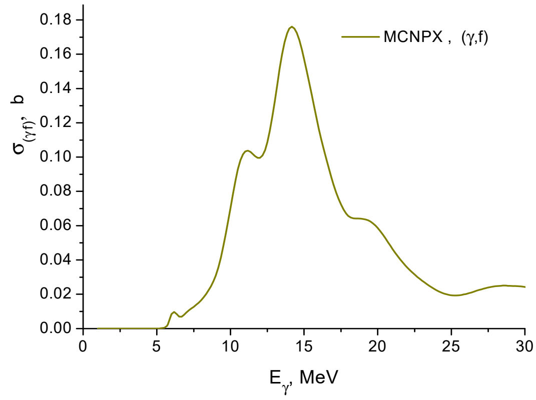

Figure 7. Dependence of the photo-fission cross section for the U-238 nucleus on photon energy

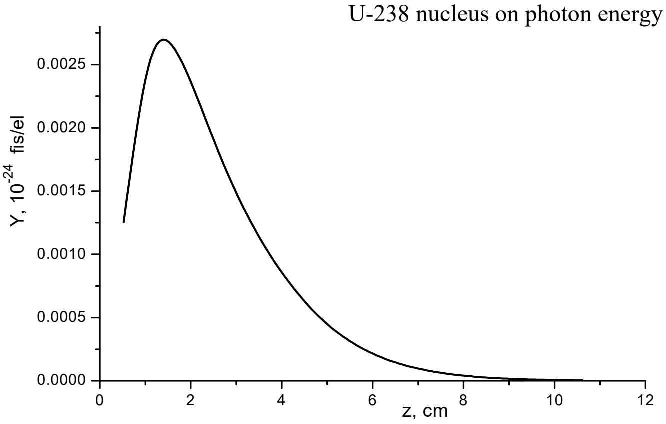

Figure 8. Dependence of the fission probability for the U-238 nucleus on the depth along the length of the target

The MCNPX program allows to calculate the probability distribution of U-238 nuclei fission along the length of the target (see Figure 8).

As one can see in Figure 8, the maximum probability of fission for U-238 is achieved at a depth of ~1.4cm, and the maximum burnup rate of U-238 is 0.055% per year.

CALCULATION OF RADIATION DEFECTS FORMATION RATE IN THE URANIUM TARGET

The rate of radiation damage production in a uranium SCA target was estimated in [1], and it was found that the photo-fission fragments give the main input into the rate of damage formation, and the contribution of all other reactions is only a few percent. In this work, we calculated the damage to a uranium target by photofission fragments using two methods: by calculating cascades of atomic collisions in uranium using the SRIM program [4] and by the NRT standard method [5].

Figure 9 shows the scattering of uranium photo-fission fragments: La-139 with energy of 70 MeV and Mo-96 with energy of 100 MeV, calculated using the SRIM program. Both fragments create cascades of atomic displacements in uranium, in which 190 000 displaced atoms are formed per uranium fission.

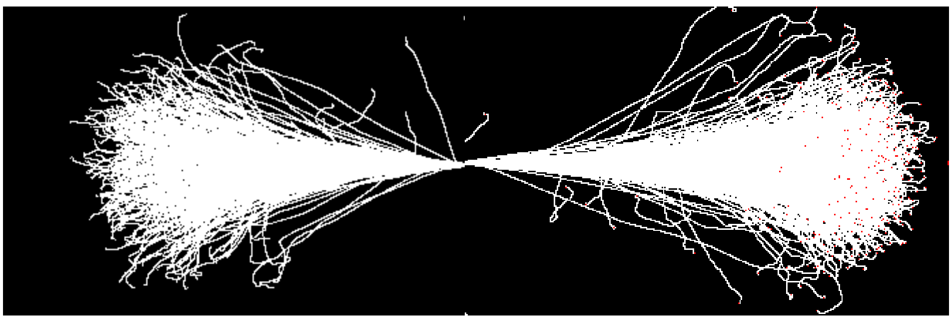

Figure 9. Picture of the scattering of U-238 fission fragments: on the left - the trajectories of La-139, on the right - Mo-96

Figure 10 shows the distribution of radiation defects production rate by fission fragments along the uranium target, calculated using the SRIM program. This rate is 103 dpa per year at the maximum of damage production.

Calculation according to the NRT standard gives 104 000 displaced U atoms per one photo-fission and, accordingly, the value of 50 dpa/year for the maximum rate of damage production.

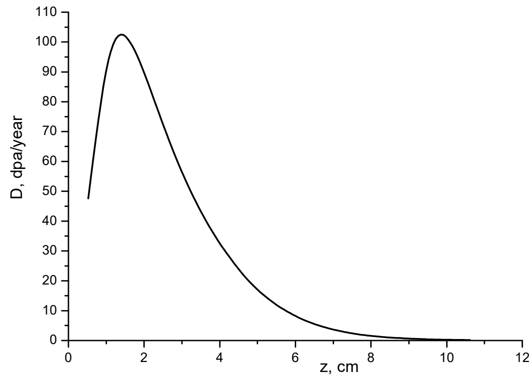

Figure 10. Rate of radiation defects accumulation in U along the length of the target

CONCLUSIONS

The U-238 photo-fission fragments give the main input into the rate of damage formation in the uranium target irradiated by electrons with energy of 100 MeV (1 mA). The contribution of other processes (electrons, photoneutrons, target neutrons, neutrons from the PCS) is only a few percent. The contributions of various defect creation mechanisms to the rate of damage dose accumulation in the uranium target are presented in Table 2.

Table 2. Contributions of radiation damage mechanisms to the rate of NRT dose accumulation

	Electrons 100 MeV	Photoneutrons	Photofission	Target neutrons	Assembly neutrons
Damage rate (dpa/year)	1	0.05	50	2	0.3

The maximum burn-up rate of U-238 is Ymax = 0.055% per year, and the maximum rate of accumulation of the NRT dose of radiation damage in a uranium target is Dmax = 50 dpa/year and is achieved at a depth of ~ 1.4 cm.

An analysis of the dependence of radiation embrittlement on the burn-up of the target material carried out in [6] showed that at burn-up values less than 0.2%, the target material still has a sufficient margin of plasticity. Therefore, the expected service life of the uranium target is 3 years of operation at full accelerator power.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

ORCID

V.V. Gann, https://orcid.org/0000-0002-3451-1840; **G.V. Gann,** https://orcid.org/0009-0004-6916-027X
B.W. Borts, https://orcid.org/0000-0003-0387-3491; **O.O. Parkhomenko,** https://orcid.org/0000-0001-9671-8874

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МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ УРАНОВОЇ НЕЙТРОНО-УТВОРЮЮЧОЇ МІШЕНІ ПІДКРИТИЧНОЇ ЗБІРКИ ННЦ ХФТІ

В.В. Ганн, Г.В. Ганн, Б.В. Борц, І.М. Карнаухов, О.О. Пархоменко
ННЦ "Харківський фізико-технічний інститут", Харків, Україна

Ця робота присвячена розрахунку швидкості набору дози радіаційних ушкоджень в уранової мішені при опроміненні високоенергетичними електронами з енергією 100 МеВ. З використанням програми MCNPX методом Монте-Карло виконано повне математичне моделювання комплексу процесів, що відбуваються в урановій мішені при опроміненні високоенергетичними електронами: розвиток електромагнітної зливи, народження фотонейтронів, транспорт частинок у мішені та створення в ній радіаційних пошкоджень. Аналіз показав, що найбільший внесок у швидкість утворення пошкоджень в мішені вносять уламки фотоподілу U-238, а максимальна швидкість створення дефектів досягає 100 зна/рік. Очікуваний ресурс роботи уранової мішені під опроміненням становить 3 роки на повній потужності прискорювача.
Ключові слова: *уран; опромінювання; електрони; підкритична збірка; радіаційні ушкодження*