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GAMMA AND FAST NEUTRONS FLUX RADIATION MINIMIZATION DURING THE CONCENTRATED FLUX FORMATION OF DELAYED NEUTRONS

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The concept of a concentrated neutron flux shaper for neutron-capture therapy of cancer has been developed. A technique for two-stage minimization of the accompanying fast neutron flux and gamma radiation background during the formation of a delayed therapeutic neutron flux is discussed. A variant of the shaper design of epithermal neutrons based on the use of collimators directed from a part of the spherical surface along the radius to the center to concentrate the flux density of these neutrons on the irradiated object is proposed.

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INTRODUCTION

The creation of new technologies, and the search, and development of the most effective methods for treating cancer today is an urgent task for the world community of physicists, engineers, and physicians in the fight against cancer. The achievements of modern physics are widely used in medical technology. The total number of high-tech medical equipment is more than 110 thousand nuclear physics devices, not including electron microscopes and X-ray machines [1, 2].

Through the joint efforts of physicists, engineers and physicians, many centers have introduced combined models of PET + CT, MRI + CT and other tomographs. This branch of the world industry is developing very rapidly.

Accelerators in the high-tech chain of medical equipment make up a significant share of 15%, being also the most expensive equipment. Despite this, their count is rapidly increasing.

World's trends in development technology and acceleration technology currently look something like this:

– increase in the count of linear accelerators with energy range up to 25 MeV for radiation therapy;

– increase in the count of proton-beam for nuclear medicine;

– development of accelerator technology for stereotaxic surgery (dimension reduction, weight with increasing the irradiation beam power);

– development and large-scale implementation in clinic therapeutic practice of compact small-sized neutron sources for neutron and neutron capture therapy based on high-precision electron accelerators with a power of up to 35 MeV [9] with the possibility of generating reactive and delayed fission neutron fluxes and subsequent formation of therapeutic beams from them for the treatment of oncological diseases.

The rapid development of nuclear energy, the development, and creation of modern high-tech particle accelerators, and the development of physical experiment technology also stimulated applied nuclear research. They caused a new direction in "nuclear medicine", including methods for creating neutron radiation therapy.

At present, almost all specialized oncological centers in the world have installed aileron linear accelerators to generate gamma quanta and use them in radiation therapy with both electrons and gamma quanta, which are formed during the interaction of electrons with various nuclear targets that generate braking power. gamma radiation. Unique «Gamma Knife» and «CyberKnife» installations have been developed and are already in use. They are the most modern methods in stereotactic radiosurgery [1, 2]. Schematic diagram of the operation of the gamma knife is presented in Fig. 1.

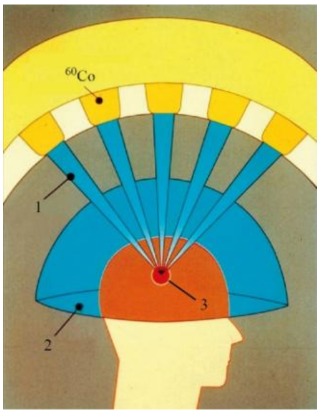

Fig. 1. Schematic diagram of well-known Gamma Knife operation principle: 1 – gamma rays; 2 – helmet; 3 – concentrated irradiation zone

No less important, but also more effective, is the method of neutron capture therapy, since neutrons are radiation with a high linear energy transfer and tumor destruction is mainly due to nuclear reactions inside the cancer cell. Neutron beams are much more powerful. They release energy through nuclear interactions in the target tissue, which is made up of cancer cells, 20 to 100 times more than conventional radiation therapy. Therefore, a very important procedure is the delivery of certain stable nuclei, such as boron and gadolinium, to cancer cells, which have a unique ability to capture thermal neutrons with a high probability, under the influence of which nuclear reactions induced.

In general the procedure this method consists of the fact that before the start of the radiation therapy session, the patient is injected with a drug, for example, nonradioactive ^{10}B, which with a higher probability, approximately four to seven times, accumulates in cancerous tumor cells compared to healthy ones.

In the process of irradiation with thermal neutrons of the ^{10}B nucleus, a thermal neutron is captured, resulting in the formation of an unstable radioactive ^{11}B nucleus, which will quickly decay into an alpha particle with an energy of 1.48 MeV and a ^{7}Li nucleus with an energy of 0.84 MeV, as well as a gamma quantum with an energy of 0.48 MeV, which leads to a total energy release within the cancer cell of 2.79 MeV due to the high rate of deceleration (with an average value of 162 keV/µm and 169 keV/µm, respectively) and the low range of these particles in water or body tissue – 5.2 and 7.5 µm, with a characteristic cell size for the human body. The deceleration rate of the gamma-quantum is significantly lower – 0.3 keV/µm. Therefore, 86% of the energy from the reaction is released within the cell. Thus, the selective accumulation of ^{10}B nuclei inside tumor cells and their subsequent irradiation with neutrons should lead to the destruction of tumor cells with relatively limited damage to surrounding healthy cells. However, the problem remains to development a drug capable of providing an even higher difference in ^{10}B concentrations in cancerous and healthy cells.

Radiation therapy is one of the most effective and popular methods of treatment in oncology. It is necessary for at least 60% of patients at different stages of cancer [3, 4].

The purpose of this work is to develop a concept for creating a concentrated slow neutron flux shaper with a minimum accompanying background of fast neutrons and gamma radiation.

The shaper plays a very important role in creating therapeutic slow neutron fluxes. The degree of warming depends on the presence in its composition of various functional elements that determine the final parameters of the neutron flux. For example, to form the geometric dimensions of neutron fluxes, special slow neutron collimators are required, and to form the spectral composition of the neutron flux, moderators are used: (water, polyethylene, paraffin) and absorbers containing boron and cadmium. This makes it possible to change the average neutron energy by removing the low-energy component for neutron impact therapy (NST) or leaving epithermal neutrons for neutron capture therapy (NCT). The use of the appropriate geometry (radial or tangential) of the location of the collimator with the moderator relative to the direction of the main neutron flux will minimize the accompanying background of gamma quanta and fast neutrons, which in this case are harmful.

To achieve the stated goal this work is supposed to use delayed fission neutrons [5, 6]. They are produced by a high-current electron beam with energies up to 35 MeV in a combined target. The combination target consists of refractory tungsten and fissile material. It is supposed to use standard pellets for fuel rods made of uranium dioxide with a density of 10.6 g/cm^3 enriched with ^{235}U up to 5%. In this case, the power in the beam of accelerated electrons should be sufficient for the formation of the required amount of delayed fission neutrons for the formation of a therapeutic flow of slow neutrons. It is assumed that the carriers of delayed neutrons will be precisely activated ^{235}U dioxide pellets delivered to a special moderator of delayed neutrons. Along the trajectory of their movement, the impossibility of direct visibility by the core shaper is ensured. Due to this, the ingress of the accompanying background of fast neutrons and gamma radiation coming from the active zone of the electron accelerator into the shaper is excluded.

The general scheme of activated target transportation is shown in Fig. 2. Activated targets are delivered to the shaper using a conveyor. They make a circular motion around shaper center, while emitting delayed neutrons. As a result concentrated flux of therapeutic neutrons is formed on the irradiated object. After the completion of the circular motion around the center of the shaper and the emission of delayed neutrons in the shaper, the uranium dioxide targets are returned to the core of the electron accelerator for reactivation. Thus, targets are transported cyclically as many times as necessary to reach a therapeutic dose when the object is irradiated.

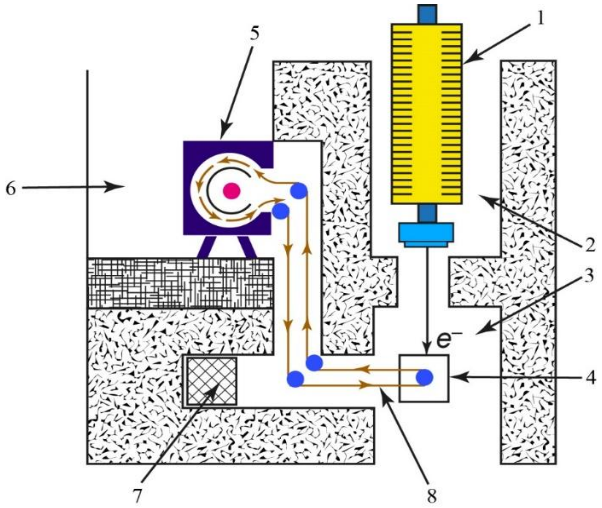

Fig. 2. General view of system for transporting activated targets from the active zone to the shaper: 1 – Electron accelerator; 2, 3 – accelerator bunker; 4 – active zone; 5 – shaper; 6 – radiation therapy room; 7 – radioactive waste repository; 8 – conveyor

1. DEVICE FOR FORMING A CONCENTRED FLOW OF SLOW NEUTRONS

The geometrical construction of proposed device based on a spherical body with a diameter of 60 cm, inside which there is an empty cavity with a diameter of 40 cm. The irradiated object is located in the center of the empty cavity (see Fig. 2). The space between the surface of the empty cavity and the outer surface of the spherical body is filled with special material for absorbing gamma radiation and neutrons. This material is radiation protecttion against ionizing radiation emitted from the activated target. The activated targets before transportation to the shaper were irradiated in the activation zone (4). They emit both delayed neutrons with an average energy of 0.5 MeV and gamma quanta, which can penetrate through a layer of radiation protection material (shielding) and affect the irradiated object inside the device.

First of all, the shielding materials should include heavy elements, such as lead or bismuth for better absorption of gamma radiation, and cadmium and borated polyethylene neutrons for partially cooling and absorbing delayed neutrons.

In detail proposed construction of the shaper is presented in Fig. 3. The main characteristic is providing concentrated epithermal delayed neutron flux on the irradiation object with low intensity of gamma-irradiation. Increasing the concentration of neutron flux in the central part of the shaper is supplied by a multi-channel collimation system (4). For our case, we propose to use nearly 400 cone collimators that provide irradiation of a 0.3 cm diameter zone in the system center.

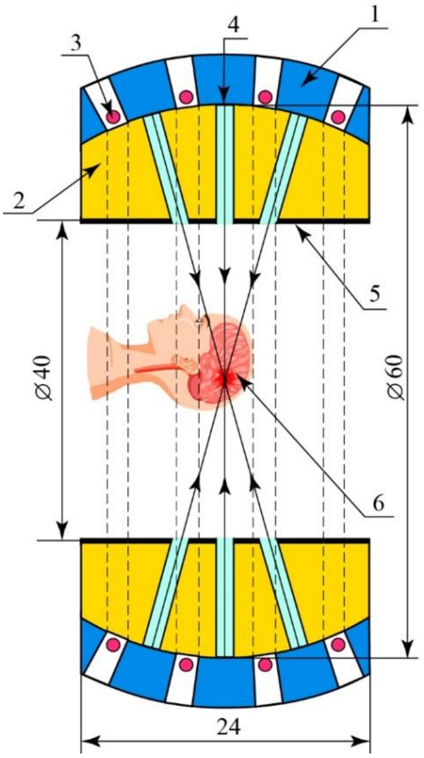

Fig. 3. The design of the shaper of the concentrated therapeutic neutron flux (without a graphite reflector): 1 – Moderator; 2 – radiation protection; 3 – activated target; 4 – channel of collimator; 5 – cadmium layer; 6 – irradiated object. All dimensions are in cm

The activated ^{235}U dioxide targets (3) connected in the 4 independent chains. They have circular movement around the spherical shaper and are located in the 4 channels of the moderator (1).

Delayed neutrons passing through the moderator (1) change their energy close to epithermal range value (from 0.5 eV to 10 keV). They are directed to a therapeutic beam formed and focused by multi collimator system to the irradiated object located in the center of the shaper.

Activated target in the form of «micro» heating generating element (fuel element) could has 3 cm length and be in the shape of a chain link. Such shapes assembled into a closed loop connecting the shaper and the active zone located at the irradiation facility of the electron accelerator.

Every meter of the chain included no less than of 30 shapes. For all single chain length equaled to 20 m the total quantity activated targets could be equal to 600 and 4 channels conveyor consists of 2400. For proposed shaper construction four closed loop the same length (20 m) after neutron and gamma-activation in the activation zone (irradiation facility) will have transported to the shaper by special trajectory of movement. The general idea of special trajectory application is minimization of fast neutron and gamma background radiation.

This is due to the fact that there is no direct visibility of the active zone by the shaper. After the end of activation in the activation zone, the targets become sources of delayed neutrons with an average high activity period of about 10 s. During this period of time, it is necessary to realize the activated targets transportation to a sufficiently remote distance from the active zone to the shaper.

Experimental data of activity dependence versus time measurement are presented in Fig. 4. And it has an exponential low. During the time of movement around the shaper, the activated targets emit the delay neutrons with an average energy of 0.5 MeV. Gamma activity of the radioactive decay of the samples is absorbed by complex radiation protection (2) system, which includes to itself cadmium layers (5). Cadmium layers application is necessary for the ignition of thermal neutron background which is produced by a radiation protection system with tangential geometry.

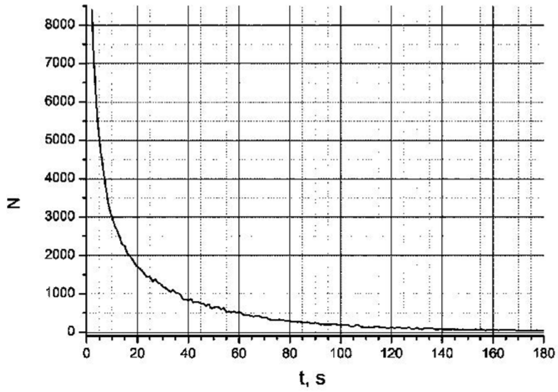

Fig. 4. Decay activity of activated ^{235}U dioxide targets slow down neutron measurement, energy range from 0.5 eV to 10 keV [4]

2. SOME CALCULATIONS ABOUT THE POSSIBILITY OF THERAPEUTIC NEUTRON FLUX DENSITY PRODUCTION

To generate delayed therapeutic neutrons for neutron capture therapy application, the developed concept proposes to use delayed fission neutrons. They can be formed under high-power electron beam interaction on the order of tens of kW with a combined target. The combined target could consist of a refractory tungsten primary target for generating photoneutrons and a secondary – uranium dioxide target. Under the photoneutron interaction with uranium dioxide, a fission reaction is taken place; as a result, both prompt and delayed fission neutrons are emitted. In this case, 2–3 neutrons are produced for each fission event. The number of delayed neutrons is about 1% of the total number of produced ones.

As for our opinion, this is the most convenient method, in comparison with the traditional ones [3, 4], for obtaining the necessary flux densities of therapeutic neutron beams used in neutron capture therapy of cancer, since this method gives rise to the possibility for an average lifetime equal to about 10 s to move the activated target from the active zone to the shaper at a sufficiently remote distance, on the order of several tens of meters. In this case, the activated target is a source of delayed neutrons, located at a minimum distance from the irradiated object. In this version of the geometry, a more favorable ratio for the production of therapeutic neutrons is obtained than in the traditional method. This is because the flux density of therapeutic neutrons is inversely proportional to the square of the distance from the source to the irradiated object. In the traditional method, the delayed neutron moderator is located at a long distance from the irradiated object.

The process of photoneutron interaction with fissile material in the activation zone is accompanied not only by the formation of prompt and delayed fission neutrons, but also and by background gamma radiation from electrons interacting with the primary target. Prompt neutrons and the accompanying background of gamma radiation from the primary target are harmful and must be minimized in accordance with the requirements for therapeutic neutron beams.

When the activated target is transported, the accompanying background is gradually suppressed. In the first stage, as soon as the target leaves the activation zone prompt neutrons to disappear due to their short lifetime on the order of 10…14 s. The accompanying gamma background on the shaper also disappears, since the trajectory of the activated target from the active zone to the shaper excludes the possibility of direct vision of the active zone by the shaper.

At the second stage, the accompanying background from the activated target is suppressed in the shaper due to the tangential geometry of the location of the activated target and the moderator relative to the collimator, as shown in Fig. 4. For such a geometrical composition, the target does not fall into the field of view of the collimator directed at the irradiated object. The space between the collimators is filled with a material representing a combination of radiation protection materials, which limits the passage of the accompanying fast neutrons and gamma background radiation from the activated target to the irradiated object. Those neutrons that have passed through the shield and become thermal are absorbed by cadmium layers installed after the collimators. This is necessary to ensure that there is no background on the irradiated object and that the size of the concentrated spot of slow neutrons set by the collimators is maintained.

The advantage of the proposed method lies in the fact that the shaper design provides for the possibility of using a large number of collimators to concentrate the neutron flux density on the irradiated object, which will be equal to the sum of the fluxes from all collimators. The number of collimators can be varied depending on their need.

For example, accelerated electron beams with energy of 35 MeV and total power of 36 kW, are often applied for photoneutron [9] production under refractory tungsten target irradiation. Well known, at the maximum energy of accelerated electrons equal to 35 MeV, the region of the giant dipole resonance (GDR) of correspondent the photonuclear reactions cross sections are under active operation. Such a condition provides the maximum yield of photoneutrons for the proposed energy range of accelerated electrons. Besides slowing down the flux of photoneutrons during interaction with ^{235}U dioxide, a fission reaction is excited too, as a result, the additional prompt and delayed neutrons are produced.

Thus, the presence of calculated estimates of the number of delayed neutrons necessary for the formation of slow neutrons at energy of accelerated electrons equal in our case to 35 MeV takes place.

We will proceed from the fact that the intensity of photoneutron production by the cooled W-target under 1 kW electron beam irradiation is 10^{12} n/s. Then the photoneutron intensity at 36 kW electron beam will be $3.6\cdot10^{13}$ n/s. Let them be emitted from the center of a sphere with a radius of 10, 5 cm of which is occupied by the primary target, the other 5 cm by a water moderator layer. And activated fissile material target is located on the surface of a sphere surrounding the primary target with water cooling it, and applied as a photoneutron moderator. The breeding target is a microfuel element containing uranium dioxide pellets with a density of 10.6 g/cm^3 enriched by ^{235}U up to 5%.

After fast neutron passing through the moderator, the flux density of slow neutrons interacting with the breeding target is approximately 30% of the primary flux – $1.2\cdot10^{13}$ n/s.

Let us determine the number of ^{235}U nuclear fission events in the activated target under the action of this neutron flux. The tablet volume is 1 cm^3. We use the above parameters of the activated target and determine the nuclear density of ^{235}U in uranium dioxide with enrichment of 5%.

The UO_2 molecule consists of one uranium atom and two oxygen atoms, the molecular weight is 238 + 32 = = 270. The number of molecules per 1 cm^3 is $10.66\cdot10^{23}/270 = 2.4\cdot10^{22}$. Then one cubic centimeter of uranium dioxide contains $2.4\cdot10^{22}$ uranium atoms and $4.8\cdot10^{22}$ oxygen atoms.

From here we determine the nuclear density of ^{235}U in uranium dioxide with enrichment of 5%. It is $N_n =$ $= 0.05\cdot2.4\cdot10^{22} = 1.2\cdot10^{21}$ 1/cm^3.

The number of fission events N_f could be determined from well known relation (1):

$$N_f = Q_n\cdot N_{\text{n.}}\sigma_{\text{T}}, \tag{1}$$

where Q_n is the thermal neutron flux density, σ_{T} is the cross section for nuclear fission by thermal neutrons.

Above, we noted that the movement of targets from the activation zone of the accelerator to the shaper and vice versa is carried out using a four-row conveyor along a closed loop about 20 m long. The entire conveyor loop can accommodate $2.4\cdot10^3$ ^{235}U dioxide targets containing $1.2\cdot10^{21}$ 1/cm^3 nuclei. Assume that the conveyor is moving at the linear speed of 20 m/s. Then the number of ^{235}U nuclei per one second, which are in the active zone under irradiation by thermal photoneutrons, will be $N_n = 1.2 \cdot 10^{21} \cdot 1/\text{cm}^3 \cdot 2.4 \cdot 10^3 = 2.88 \cdot 10^{24}$ 1/cm³.

We substitute the numerical values of the parameters into relation (1) and determine the number of fission events $N_f = 1.2 \cdot 10^{13} \cdot 2.88 \cdot 10^{24} \cdot 5.8 \cdot 10^{-22} = 20.044 \cdot 10^{15}$ N_f/s.

For each fission event, there is a yield of 2.5 neutrons, then the total yield of fission neutrons is $Yn = 20.044 \cdot 10^{15} \cdot 2.5 = 5 \cdot 10^{16}$ n/s. The number of delayed neutrons in this case is 1% of all fission neutrons and, accordingly, is equal to $5 \cdot 10^{14}$ n/s. Then the slowing neutron flux density in the shaper at the moderator outlet in front of the collimator will be $1.25 \cdot 10^{12}$ n/(s·cm²). On the irradiated object, the flux density passing through one collimator will decrease by a factor of 900 due to the distance to it equal to 30 cm and will be equal to $1.38 \cdot 10^9$ n/(cm²·s).

Note that the design of the shaper has about 300 collimators, which are located after the moderator on a spherical surface and directed towards the center of the irradiated object. Due to this, the slowing neutron flux density on the irradiated object can increase by about 300 times. The total increase in the density of neutrons so far on the irradiated object will be $1.38 \cdot 10^9 \cdot 3 \cdot 10^2$ n/(cm²·s) = $4.14 \cdot 10^{11}$ n/(cm²·s), respectively.

The flux density of slowing neutrons on the irradiated object, formed with the help of the shaper proposed in the concept for application for neutron capture therapy, is at the level of the best world standards. We also note that in this configuration of the shaper design, some of the slowed down neutrons leave the shaper, going outside. Using a graphite reflector in which it is necessary to place the shaper, this drawback can be significantly eliminated and, due to this, the flux density of therapeutic neutrons on the irradiated object can be significantly increased.

As shown in [6], the minimum flux density of slow neutrons during radiation therapy should not be less value than 10^9 n/(cm²·s), and fast neutrons should not exceed 10%. The degree of damage to tumor cells during neutron therapy can be assessed using a simple relation [8]

$$NT \sim \rho^{10}\text{B} \cdot \varphi \cdot t \cdot \sigma_T, \quad (2)$$

where ρ^{10}B is the concentration of ^{10}B, for 1 μg/1 ml of the tumor; t is the duration of tumor irradiation, min; φ – thermal neutron flux density at the location of the tumor; σ_T is the cross section of thermal neutron capture by the ^{10}B nucleus. For a concentration of ^{10}B equals 30 μg/ml for 60 min of irradiation in each milliliter of tumor volume $\sim 2 \cdot 10^{10}$ α-particles and ^{7}Li nuclei are born as a result of neutron capture process. In experiments [6], a preparation containing 99% ^{10}B was used, which selectively accumulated in cancer cells. There are about 10^9 cells in 1 ml of a tumor, so there are about 20 α-particles and ^{7}Li nuclei per each tumor cell [8].

Only a few α-particles are sufficient to destroy one cancer cell [7]. Based on this calculation results, for a shaper without a graphite reflector, the exposure time for an irradiated object at a flux density of $4.14 \cdot 10^{11}$ n/(cm²·s) will be about 8.7 s instead of one hour.

This is a very important factor in carrying out neutron-capture therapy of a cancerous tumor, since it significantly reduces the duration of a radiation therapy session. The developed concept of development a shaper capable of providing a concentrated flux of therapeutic neutrons on an irradiated object opens up prospects for installation such facilities directly in clinics, provided that they are provided with the required flux density of delayed fission neutrons. This problem can be solved by using small-sized, high-current electron accelerators [9]. The design of the shaper, which uses the principle scheme of a gamma knife, characterized in that instead of cobalt gamma sources, polyethylene moderators are used as sources of therapeutic neutrons after passing through them delayed fission neutrons emitted from activated targets of uranium dioxide enriched up to 5% ^{235}U. Schematically, the shaper may look as shown in Fig. 5 and is located in a special room. The shaper in its design must be equipped with a graphite reflector and biological protection that provides the necessary radiation standards when operating personnel work with it. In addition, it must be equipped with all automated peripherals in the same way as in the Gamma Knife device.

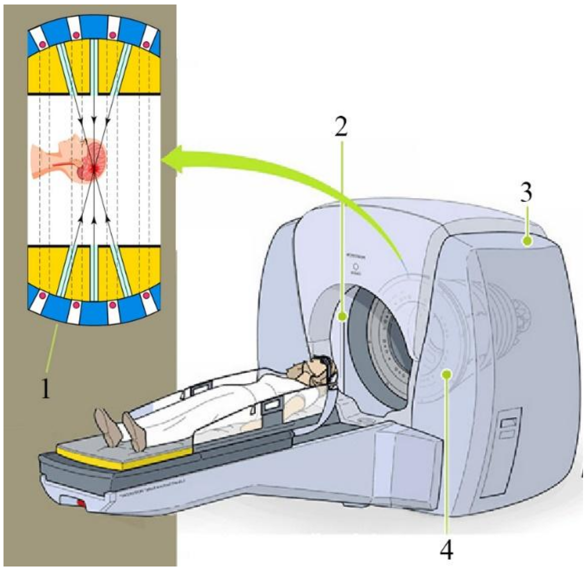

Fig. 5. Proposed scheme for the design of a concentrated therapeutic neutron flux shaper for NCT: 1 – shaper of concentrated therapeutic neutron flux; 2 – video camera and intercom for communication with the patient; 3 – radiation shaper block; 4 – radiation block

Fig. 6. MEVEX accelerator: left – general view; right – view with cover removed

To obtain the indicated flux density, from our point of view, it is necessary to use an electron accelerator with the parameters indicated above (Fig. 6). The most suitable accelerators available on the world market are MEVEX accelerators [9].

Small overall dimensions allow placing it in a small bunker directly in the clinic. Such a proposal and a procedure for obtaining delayed neutrons were first described by us in [5, 6].

3. CONCLUSIONS AND RESULT DISCUSSIONS

A concept has been developed for creating a shaper of therapeutic slow neutron beams for use in neutron-capture therapy of oncological neoplasms. As a source for the formation of slowing neutrons, it is proposed to use delayed fission neutrons with an average energy of about 0.5 MeV and an average activity duration of about 10 s as the most convenient and reliable way to obtain the required therapeutic neutron flux density.

Despite the fact that their number is 1% compared to the total number of neutrons produced in the activation zone, their use proposed in this concept has an advantage over the traditional one, where delayed neutrons are used directly from the activation zone.

In the traditional technique, the moderator can be installed in close proximity to the activation zone and far from the shaper, located at a remote distance of about 10…20 m, while in the present concept, when using delayed fission neutrons emitted by activated targets, they are located in close proximity to of the irradiated object in the shaper itself. The therapeutic neutron flux density depends on the square of the distance from the neutron source to the irradiated object. Therefore, this dependence will be in favor of the option where delayed neutrons are used as a source that irradiates the moderator and generates a flux of therapeutic neutrons in it. At the same time, the suppression of the accompanying background of gamma radiation and fast neutrons, which are harmful, occurs through a two-stage mechanism, at the first stage of which at the moment when the target leaves the activation zone, and at the second stage directly in the shaper due to the tangential geometry of the collimator relative to the source of delayed neutrons irradiating the polyethylene moderator.

The second conceptual proposal is formulated regarding the design of the shaper of the concentrated flux of slow neutrons. It is based on the use of polyethylene moderators of delayed fission neutrons installed in front of the collimators, the number of which can be about 300 pieces. With the help of collimators, slow neutrons are directed along the radius to the center of the irradiated object, where a concentrated flux of therapeutic neutrons is formed, which is used in neutron capture therapy for cancer.

It is shown that on the basis of the developed concept, prerequisites have been created for the development of a full-scale compact source of neutrons directly in specialized clinics for their use in neutron-impact (NST) and neutron-capture (NCT) therapy of oncological neoplasms.

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МІНІМІЗАЦІЯ СУПРОВІДНОГО ФОНУ ГАММА-ВИПРОМІНЮВАННЯ ТА ШВИДКИХ НЕЙТРОНІВ ПРИ ФОРМУВАННІ КОНЦЕНТРОВАНОГО ПОТОКУ УПОВІЛЬНЕНИХ НЕЙТРОНІВ

С.П. Гоков, С.Г. Карпусь, В.Й. Касілов, Г.Д. Коваленко, С.С. Кочетов

Розроблено концепцію формувача концентрованого потоку уповільнених нейтронів для нейтрон-захватної терапії раку. Обговорюється методика двоступінчастої мінімізації супутнього фона швидких нейтронів та гамма-випромінювання при формуванні уповільнених терапевтичних потоків нейтронів. Запропоновано варіант конструкції формувача епітеплових нейтронів на основі використання коліматорів, які спрямовані з частин сферичної поверхні по радіусу до центра для концентрування густини потоку цих нейтронів на об'єкті, що опромінюється.