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Neutron beam shaping assembly optimization for the neutron generator at the Institute of Applied Physics of RAS

© *S.S. Vybin, S.V. Golubev, I.V. Izotov, V.A. Skalyga*

Federal Research Center A.V. Gaponov-Grekhov Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia
E-mail: vybinss@ipfran.ru

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The results of the neutron beam shaping assembly (BSA) numerical modeling are shown in this work. The neutron generator is based on the ion source GISMO (Gasdynamic Ion Source for Multipurpose Operation) which was developed at IAP RAS. It is able to produce ion beams with total current of several hundreds of mA and at the energy of up to 100 keV. It is suitable for neutrons production from the D-D reaction. The optimization of the BSA geometric parameters was carried out. The neutron source is supposed to use for cellular cultures irradiation, which is made in the interest of the boron-neutron capture therapy development.

Keywords: Neutron generator, High-current gasdynamic ion source, neutrons, numerical modeling.

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At the present time, the development of boron-neutron-capture cancer therapy technology is hampered by the insufficient number of neutron sources available with sufficient intensity [1]. At the Institute of Applied Physics of the Russian Academy of Sciences, development of a continuous intense (expected neutron yield of the order of $10^{11}\,\mathrm{s}^{-1}$) neutron generator based on the D–D-reaction [2] is underway. The facility includes a gas-dynamic ion source that generates a beam of deuterium ions (with a total current of several hundred milliamperes) directed at a neutron-generating target. Neutron generation with an average energy of about 2.5 MeV occurs as a result of the D–D-reaction during bombardment of a solid (copper) target operating in the autosaturation mode by a deuterium ion beam. The design value of the total beam current is 500 mA with its energy equal to 100 keV. It is planned to realize the total neutron yield at the level of $10^{11}\,\mathrm{s}^{-1}$ with the possibility of its further increase by increasing the beam energy up to 200–300 keV.

It is intended to use this neutron generator for experiments on neutron irradiation of cell cultures as well as laboratory animals. Depending on the problem statement, the biological sample should be exposed to a neutron flux of thermal (less than 0.5 eV) or epithermal (from 0.5 to 30 keV) energy ranges. To reduce the energy of the generated fast neutrons, a neutron moderator is used, which is placed between the source and the sample.

To prepare for the experiment, it is necessary to optimize the parameters of the decelerating system. This will reduce the negative effects of fast neutron radiation, as well as reduce the required irradiation time of the samples to achieve a biological effect.

This paper presents the results of numerical calculations of a neutron flux generation system that includes a moderator, reflector, and neutron shielding. The latter is necessary to reduce the radiation background in the vicinity of the plant to an acceptable level during experiments. The work describes the design of a system for conducting a cell culture irradiation experiment. The aim of the optimisation was to increase the flux of thermal neutrons through the sample while reducing the flux of higher energy neutrons. The geometrical dimensions of the neutron flux shaping system were optimized.

The basis of this type of neutron generator is an ion source. It is a gas-dynamic electron cyclotron resonance ion source [3] in which the plasma is supported by radiation from a technological gyrotron [4] with a frequency of 28 GHz and power up to 10 kW. Transverse plasma confinement is provided by the presence of an open magnetic trap of the mirror machine type, created by a set of permanent magnets made of alloy Nd–Fe–B. The facility also includes an ion beam extraction system, a target assembly, and a neutron flux generation system (Fig. 1). To ensure continuous operation of the unit, forced water cooling of the elements on which the ion beam may settle is provided.

The neutron flux generation system is a multilayer structure consisting of a moderator surrounding the target, a neutron reflector, and biological shielding that reduces the background radiation level in the room (Fig. 2). Water was used as the moderator material. Lead was chosen as the neutron reflector material. The neutron shielding includes layers of borated polyethylene with a boron content of 30% by weight (PB-30), as well as layers of lead necessary to attenuate the secondary γ radiation flux.

Numerical modelling using the code PHITS [5] was carried out by Monte Carlo method in three-dimensional space. The model includes a neutron source, a neutron flux generation system, and a sample. The neutron source is a circle, at each point of which neutrons are emitted isotropically with energy 2.5 MeV. Such a model approximates the real situation in which neutrons are generated

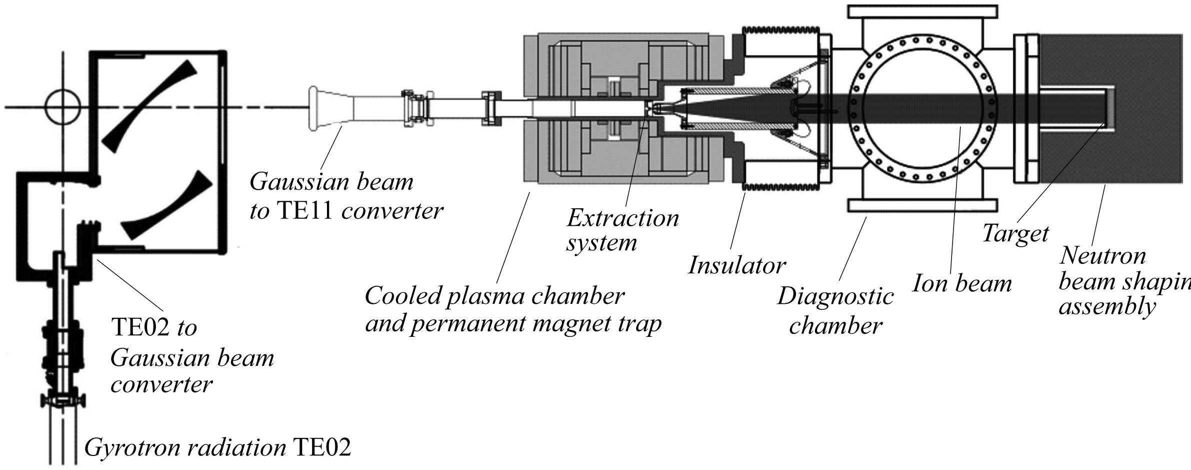

Figure 1. Schematic of a neutron generator including a gyrotron, a cooled plasma chamber and permanent magnet trap, an ion beam extraction system, a target, and a neutron flux generation system. The designations TE11 and TE02 correspond to the modes of an electromagnetic wave propagating in a circular waveguide.

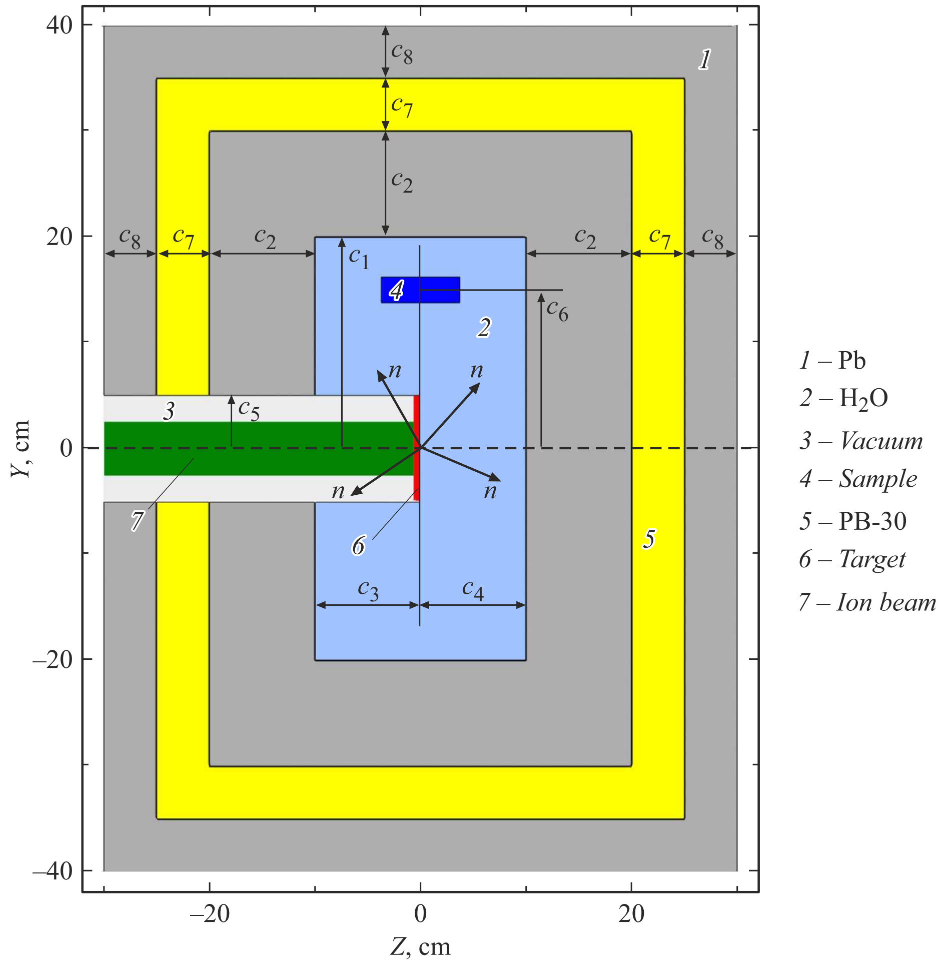

Figure 2. Scheme of the neutron deceleration system with indication of its geometrical parameters. The vertical cross section at $X = 0$ cm is presented. Arrows show possible directions of propagation of the generated neutrons.

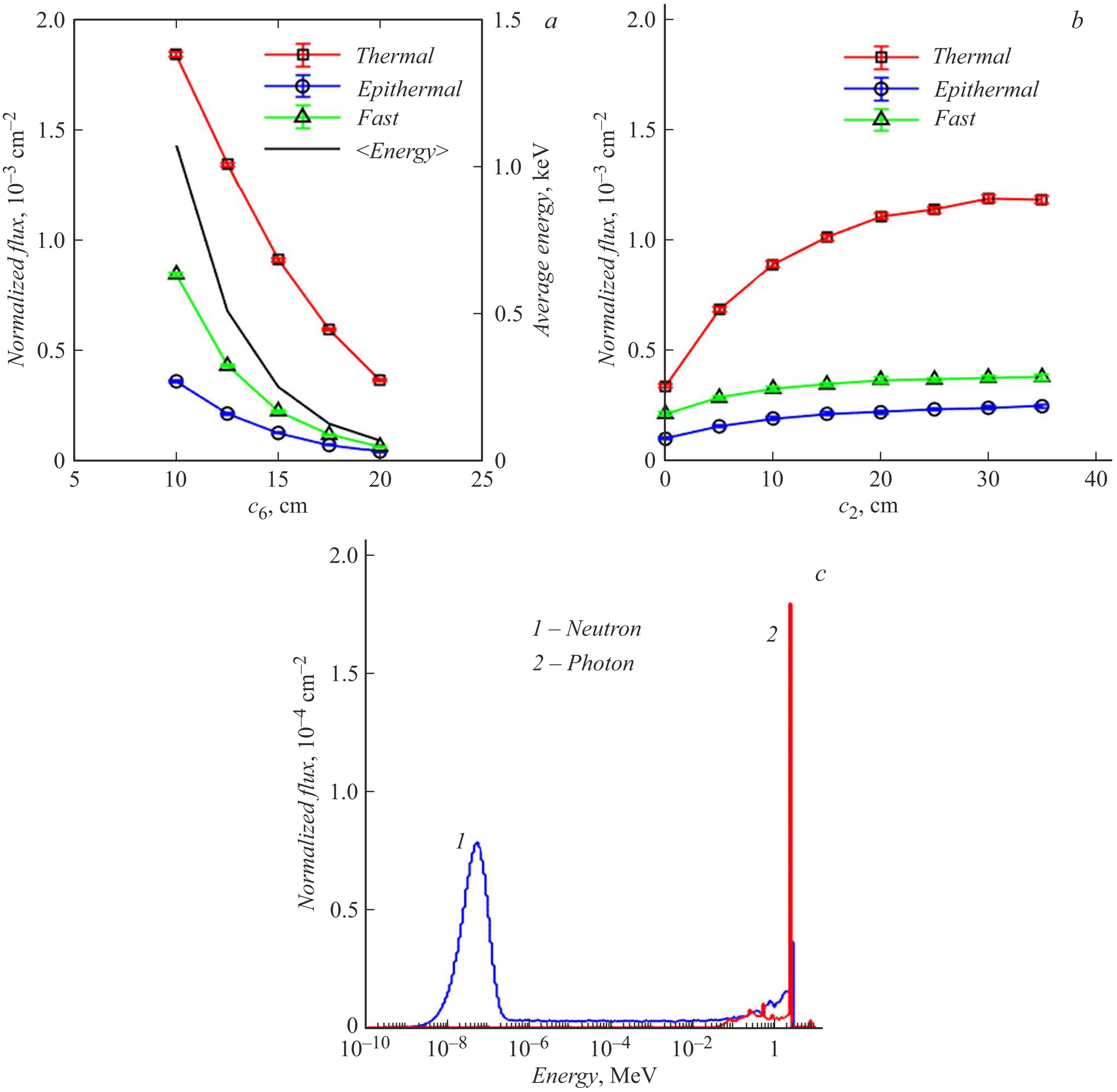

Figure 3. *a* — dependence of neutron flux of different energy ranges (thermal, epithermal, fast) (left scale) and average neutron energy (right scale) on the distance to the sample.*b* — dependence of neutron flux of different energy ranges on reflector thickness. *c* — energy spectrum of neutron flux through the sample calculated with the following parameters: $c_1 = 25$ cm, $c_2 = 30$ cm, $c_3 = 5$ cm, $c_4 = 5$ cm.

during the D–D reaction when a circular ion beam hits a solid-state deuterium-containing target. The model takes into account the processes of interaction of neutrons with matter (elastic and inelastic), as well as the processes of neutron capture, which are characterized by the formation of secondary γ-quanta. The values of neutron-nucleus collision cross sections are taken from the JENDL-4.0 [6] database.

The scheme of the neutron flux generation system with indication of its geometrical parameters (c_1–c_8) is presented in Fig. 2. It has cylindrical symmetry with respect to the Z axis (excluding the sample). The sample model is a rectangular parallelepiped with dimensions $5 \times 2.5 \times 10$ cm and is placed inside the moderator. This positioning of the sample relative to the target achieves the best flow uniformity compared to other positions. The transverse size of the ion beam propagation channel is a given ($c_5 = 5$ cm), as it is determined by the width of the ion beam to be formed. The parameters c_7 and c_8 define the thickness of the radiation shielding immediately surrounding the neutron source ($c_7 = c_8 = 5$ cm).

Based on the results of each calculation, the average neutron flux (of different energy ranges) through the irradiated sample is calculated. In this case, the thermal neutron flux is of interest. It is necessary to maximize the absolute flux value and the fraction of thermal neutrons in the beam. These conditions cannot be fulfilled at the same time. It is important to find a balance between the content of the thermal neutron fraction in the beam and the absolute value of the flux. The distance between the neutron source and the sample (parameter c_6) has the greatest influence on the flux. With distance from the source, the fraction of thermal neutrons in the total flux increases (Fig. 3, *a*), while the average neutron energy decreases. We choose the value $c_6 = 15\,\text{cm}$ as the optimal value, since with further increase of the distance the neutron flux decreases significantly and the fraction of thermal neutrons changes weakly.

The parameters $c_1 - c_4$ define the dimensions of the retarder and reflector. They have a smaller effect on the neutron flux compared to the parameter c_6. Note that the neutron flux increases monotonically with increasing reflector thickness (parameter c_2) (Fig. 3, *b*). We choose $c_2 = 30\,\text{cm}$ as the optimum value, since the flux does not change much further. The parameters c_1, c_3 and c_4 define the geometric dimensions of the water retarder. The search for optimal dimensions was carried out by enumerating possible combinations of parameters with a grid spacing equal to 5 cm. The maximum value of thermal neutron flux is achieved at $c_1 = 25\,\text{cm}$, $c_3 = 5\,\text{cm}$, $c_4 = 5\,\text{cm}$. The calculation showed that increasing the parameters c_3, c_4 leads to a decrease in the thermal neutron flux and an increase in the γ-radiation flux on the sample (at a fixed value of c_1). This is because increasing the thickness of the water moderator along the Z axis causes some of the neutrons to be absorbed before hitting the sample.

Fig. 3, *c* shows the energy spectrum of neutron and γ-radiation flux averaged over the sample. The neutron flux peak at high energies corresponds to fast neutrons that have not had time to decelerate before hitting the sample. The γ-radiation peak at energies around 2.2 MeV is due to secondary quanta produced by neutron capture by hydrogen nuclei.

The geometrical parameters of the neutron flux shaping system for the D neutron generator at the IAP RAS were optimized. Based on the results of numerical calculations, the optimum dimensions of the water moderator, lead reflector, and the distance between the neutron generation region and the sample were determined. The results of the calculations will be used in the design and manufacturing phase of the first prototype for this experimental test bed.

The further research plan includes the development of a neutron flux generation system of the epithermal energy range. In it, other materials will be used as neutron moderator (mainly MgF_2).

It is also necessary to refine the computational model taking into account the real geometry and to set the neutron source more correctly (taking into account the scatter in initial neutron energies and anisotropy). This will allow comparison of the results of cell culture irradiation experiments with numerical calculations.

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Conflict of interest

The authors declare that they have no conflict of interest.

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