HIGH-FLUX PULSED NEUTRON SOURCE DRIVEN BY A PROTON ACCELERATOR FOR BEAM RESEARCH

A.V.Vinogradov, Yu.N. Pepelyshev, A.D.Rogov, S.F.Sidorkin

INTRODUCTION

The high-flux neutron source on the basis of the IBR-2M pulsed reactor operating at the Frank Laboratory of Neutron Physics and providing neutron flux density on the order of ~ 10^{13} cm^{-2} s^{-1} will be reaching the end of its lifetime by the beginning of 2040-ies and shut down. As an alternative to IBR-2M, it is proposed to consider a source based on a subcritical pulsed assembly driven by a proton accelerator. Other types of neutron sources at present and in the long term do not allow obtaining high neutron-physical parameters necessary for advanced scientific research [1]. On the other hand, there are quite a number of potential variants of neutron sources driven by proton accelerators. In [2] all variants of neutron sources driven by a proton beam are classified into a certain number of categories, for each of which an optimal variant is found. The optimization of the source consisted in obtaining the maximum thermal neutron flux density with achieving acceptable values for other parameters relevant to the source operation. Basing on the results of the above-mentioned work, we propose a pulsed neutron source which is optimal in respect of its neutron-physical and technical parameters, and, most importantly, demonstrate the possibility of its practical implementation. The paper provides a brief description of the source with a sufficiently detailed calculation-based rationale.

1. CONCEPTUAL REQUIREMENTS FOR A PULSED NEUTRON SOURCE

The basic requirements for a new neutron source are as follows:

- Thermal neutron flux density on the surface of a flat water moderator of the source should be no less than ~ 10^{14} cm^{-2} s^{-1}.
- Proton beam power on the target should be no more than 0.1 MW.
- It is necessary to ensure a high level of nuclear and radiation safety and use only a deeply subcritical regime. According to the current nuclear safety rules at K_{eff} = 0.98 there is no need for a protection system, as is required for a critical reactor. These rules apply to subcritical systems of low (so-called zero) power (kW). In the future, nuclear safety rules for high-power (MW) subcritical systems may be changed to meet more stringent requirements, because it is necessary to take account of various kinds of power and other reactivity effects arising from disturbances in the source core and malfunctions of the accelerator. In this case, nuclear safety can be ensured by a deep subcriticality of the core.
- Feasibility.

2. BRIEF DESCRIPTION OF THE SOURCE

This section provides a brief description of the source. The individual elements of the source will be described in more detail in other sections below. The model of the proposed source is presented in Fig. 1. The source consists of a core with plutonium dioxide (PuO_2) fuel. The core is divided into two parts. A rotating disk, which is placed between the two separate parts of the core, performs several functions: first, it serves as a target for a proton beam, second, as a reactivity modulator to reduce the background between pulses and, third, facilitates heat removal. The axis of rotation of the target disk is directed vertically. According to the classification given in [2], the source under consideration belongs to the category of pulsed one-core boosters. Core loading is performed in a horizontal plane with densely packed fuel elements in a cassette-free variant. The core is cooled by water. Thus, the booster belongs to the sources with a mixed spectrum of neutrons: 98% of neutrons in the core are fast and resonance neutrons. Pulse repetition rate is 30 s^{-1}.

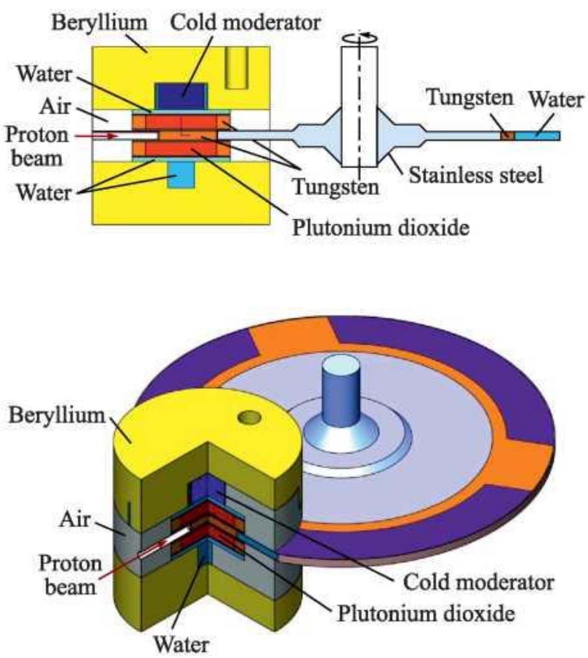


Fig. 1. Model of a pulsed neutron source with a rotating tungsten target and plutonium dioxide core.

The core is surrounded by a beryllium reflector. Thermal neutrons are emitted from the surface of water and cold moderators installed in two planes — above and below the core. Moderators of optimal sizes adjoin the surface of the corresponding premoderators placed directly above the core. The premoderators are separated from the core by a layer of gadolinium or a tungsten-rhenium alloy — a material with a high cross-section in the resonance neutron energy region. In the upper part of the moderators, a cold moderator (CM) is installed; the design of CM is similar to that of para-hydrogen moderators of the ESS [3]. Neutron beamlines are placed tangentially to the core, which reduces the direct radiation background from the core. Water moderators in the lower plane are divided into two groups, in one of which there is a "poisoned" moderator to reduce the thermal neutron pulse duration. Thus, researchers working with extracted neutron beams will have the opportunity to use a wide spectrum of neutrons ranging from thermal to cold neutrons.

3. TARGET

The external pulsed neutron source for a subcritical assembly is provided by the generation of neutrons during the deceleration of the proton beam in the target. In the course of the spallation reaction in the final stages of the cascade process, so-called spallation neutrons are emitted with a spectrum close to the spectrum of fission neutrons. Then, primary neutrons are multiplied in the core surrounding the target.

3.1. General description of the target. Neutron-physical characteristics of the targets from [2] are used as initial data to choose optimal targets for the given design of the core. By way of example, Fig. 2 shows the variation of the average neutron flux density per one proton with an energy of 1 GeV on the surface of isolated targets of tungsten, lead, thorium, uranium-238 and natural uranium, as a function of the radius of the targets.

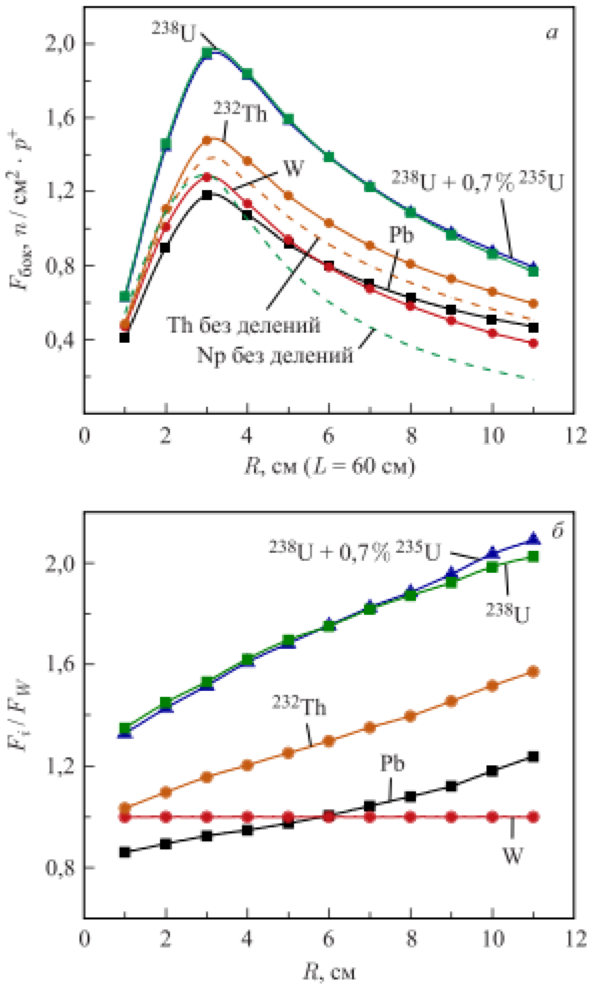


Fig. 2. Variation of the average neutron flux density per one proton with an energy of 1 GeV from the lateral surface of 60-cm long cylindrical targets of tungsten, lead, thorium, uranium-238 and natural uranium as a function of the radius of the targets (a) and the same for a tungsten target (b).

Tungsten, as can be seen in Fig. 2, ranks below thorium and uranium in neutron yield, but is valued for the absence of phase transitions and its ability to withstand high temperatures, which is important for reliable operation of the target. Moreover, calculations show that the actual location of the target in the center of the core compared to its isolated position, somewhat reduces the advantage of uranium over tungsten in neutron yield. Therefore, the above-mentioned circumstances do not allow us to use high neutron-physical characteristics of a uranium target to the full extent. At the same time, targets made of uranium or thorium can serve as a backup for increasing the neutron yield.

The target is a rotating disk with tungsten inserts. As calculations show, two variants of the target can be realized: a target without reactivity modulation and a target with this function. The surface of both sides of the target disk with the function of reactivity modulation is covered with 3-mm-thick layers of hafnium (gadolinium) with water in between. Three inserts of tungsten are radially embedded in the disk 120° apart. Each insert is a target on which the proton beam impinges synchronously with the rotation of the disk. Thus, three neutron pulses are generated per one revolution of the disk. A schematic representation of the target disk is shown in Fig. 3.

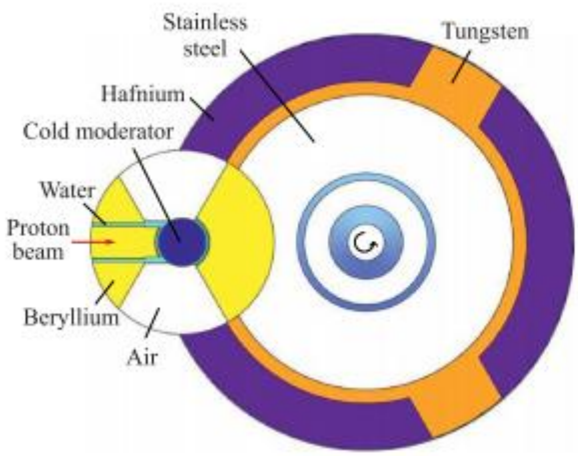


Fig. 3. Schematic representation of the target disk.

The strength characteristics of the target should ensure its rotation at $10\ s^{-1}$. To provide the desired rate of change of modulated reactivity, the linear speed of the rim in the core should be no less than 100 m/s. This requirement imposes a limit on the radius of the target disk: it should be no less than 1.0-1.5 m.

3.2. Target as a reactivity modulator. As mentioned above, the disk target is used to reduce the background between pulses as a reactivity modulator. Protons are injected at the moments of maximum reactivity, when the tungsten insert is between the two parts of the core. In the intervals between the pulses the tungsten insert goes beyond the core boundaries, which results in an increase in the core subcriticality and a decrease in the power. For a subcritical assembly with a reactivity modulator, the reactivity on prompt neutrons $\varepsilon = \rho - \beta$ is represented as a sum $\varepsilon = \varepsilon_m + \varepsilon_{\mathrm{rm}}$, where ε_m, is the maximum value of reactivity, $\varepsilon_{\mathrm{rm}}$ is the normalized reactivity of the modulator. If there is no modulator, $\varepsilon_{rm} = 0$. The reactivity ε is always negative.

The moment of injection is taken to be the moment when the reactivity of the subcritical assembly ε_m reaches its maximum value. The corresponding multiplication regarding prompt neutrons is $Y = 1/-\varepsilon_m$, where $\varepsilon_m < 0$. For calculations to evaluate background between pulses the following values were used as initial characteristics of the reactivity modulator: modulator efficiency $\Delta K_{rm} = 0.02 - 0.04$, parabola coefficient near the maximum reactivity $\alpha = 1.14 \cdot 10^5$ s^{-2}. Figure 4, by way of example, shows a change in the normalized reactivity of the modulator as a function of the time of rotation of the target, that is, the reactivity whose maximum value is assumed to be zero.

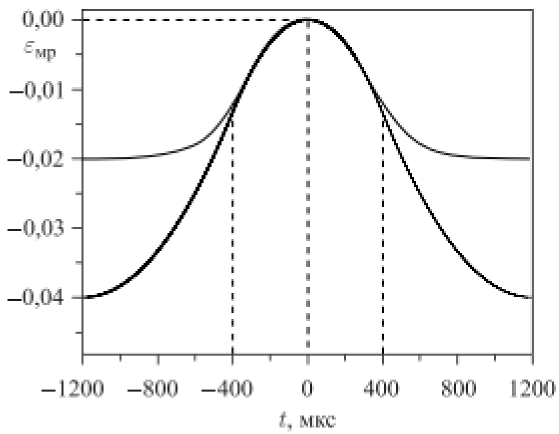
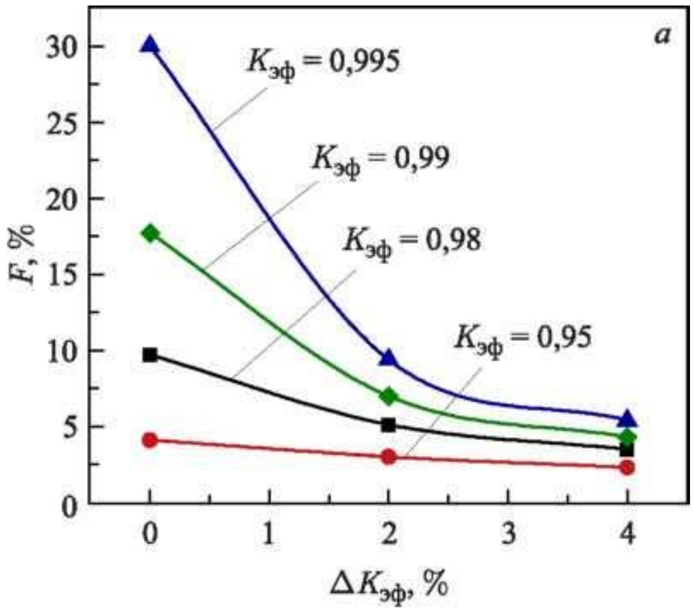


Fig. 4. Normalized reactivity pulse of the source determined by a reactivity modulator.

Figure 5 shows a change in the fraction of the background between pulses as a function of the reactivity modulation depth at some values of the multiplication factor (multiplication) and as a function of the multiplication factor at some values of the modulation depth. Calculations were performed at a core power of 8 MW and prompt-neutron lifetime of 0.5 μs.



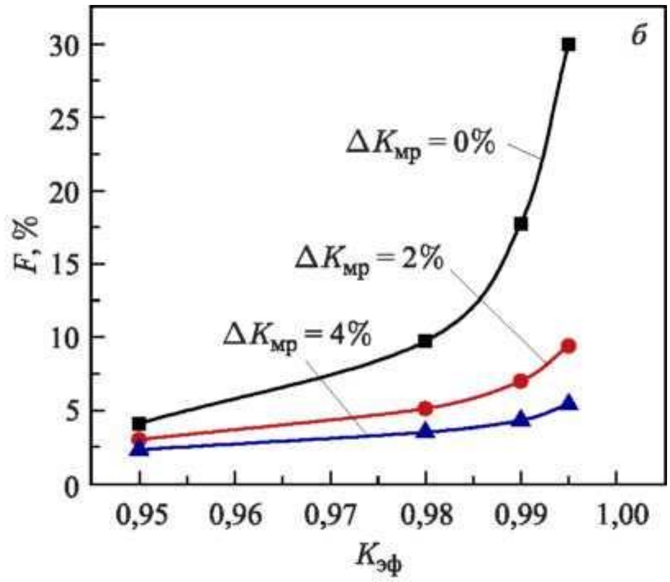


Fig. 5. Neutron background between pulses, *F*, in percentage of total power, as a function of reactivity modulation depth ΔK_{rm} at a multiplication of 20 (K_{eff} = 0.95), 50 (K_{eff} = 0.98), 100 (K_{eff} = 0.99) and 200 (K_{eff} = 0.995) (a) and as a function of K_{eff} at ΔK_{rm} = 0, 2 and 4% (b). Prompt neutron lifetime is τ = 0.5 µs.

As can be seen from Fig. 5, the reactivity modulation is required at a sufficiently high multiplication of more than 50 ($K_{eff} > 0.98$). In this case, the neutron background decreases significantly. In this case, the reactivity modulation depth should be sufficiently large — $\Delta K_{rm} > 0.02$. Under conditions of deep subcriticality ($K_{eff} < 0.95$, multiplication of 20) reactivity modulation has little effect on the reduction of the background. Therefore, at a multiplication factor $K_{eff} < 0.95$ and less, the modulation function during the rotation of the target can be excluded. In this case, the design of the target becomes simpler and more similar to that of the target at the ESS.

To provide deep reactivity modulation at a multiplication of 50, the target is designed basing on the idea of a neutron trap. The neutron trap "breaks" the neutron bond between the two parts of the core in the period between power pulses when the tungsten inserts of the target disk are out of the core.

4. CORE

The core with plutonium dioxide (PuO_2) fuel consists of two halves separated by a gap to accommodate the target disk (Fig. 6). Both halves of the core are filled with densely packed fuel elements identical to those of the IBR-2 pulsed reactor, but in a cassette-free variant. To reduce the prompt neutron lifetime and decrease the pulse duration, the core is separated from moderators by a 2-mm thick layer of gadolinium. The core loading is performed in a horizontal plane. Water is used as a coolant. Here, it may be desirable to get away from high-temperature technologies for core cooling, which are typical for fast reactors with plutonium-based fuel, such as, for example, the IBR-2 reactor. But the main purpose of using water for core cooling is as follows. First, to obtain high neutron fluxes on the core surface, we need a sufficiently compact core. Water softens the neutron spectrum, which increases the efficiency of fuel elements and, correspondingly, reduces the core loading. In addition, water cooling is more efficient than sodium cooling. This fact makes it possible to increase the fuel rating and maintain the required small volume of the core. The parameters of the water cooling system of the source and reactivity-related effects are discussed in the sections below. Here, it will only be noted that to avoid the water effect upon fuel exchange, calculations of the core loading were performed for the fuel-element cladding made of an alloy with hafnium as a thermal neutron absorber. The addition of 2% of hafnium to the stainless fuel-element cladding removes almost 1.4% of reactivity at a nearly constant neutron lifetime. The reactivity effects are discussed in more detail in Section 10.

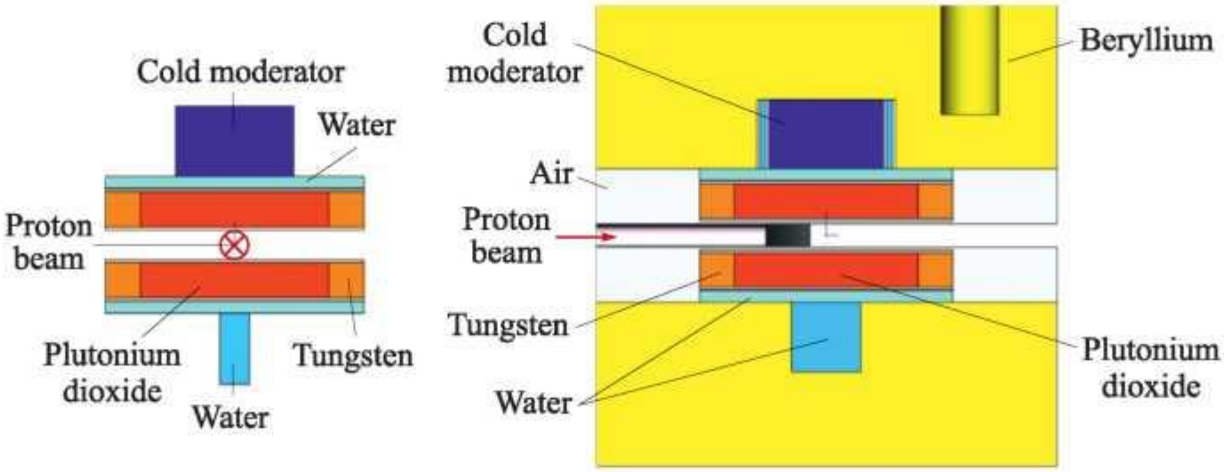


Fig. 6. Scheme of the model of the core surrounded by moderators.

The fuel is plutonium-dioxide (PuO_2) sleeve-type pellets with a diameter of 7.4 mm inserted as a column in a fuel element with an external diameter of 8.62 mm. A full loading of the core at a multiplication of 50 (K_{eff} = 0.98) is 580 fuel elements. The spacing of the spacer grid for fuel elements is 9.11 mm. The maximum burnup of plutonium heavy elements in the core is 10%. The basic parameters of the core are provided in the summary table listing parameters of the source (Table 5, Section 11).

5. ACCELERATOR

The basic parameters of the proton accelerator for the proposed neutron source are listed in Table 1.

In the case of high-current proton accelerators, efforts are made to reduce the pulse current, but for pulsed neutron sources it should be increased in order to provide a high average flux at a lower pulse repetition rate. To maintain high pulse parameters of the accelerator, a storage-buncher can be used, which makes it possible to reduce a long pulse of 100-200 μs to a shorter one with a corresponding increase in the pulse current. Therefore, additional consultations with the accelerator developers are required regarding the parameters marked by asterisks in the table. The length of the linear part of the accelerator with superconducting resonators may be 300 m or more.

Many of the parameters given in Table 1 are implemented on existing accelerators and used in different countries for generation of cascade-spallation neutrons [3,4].

Table 1. Basic parameters of the proton accelerator.

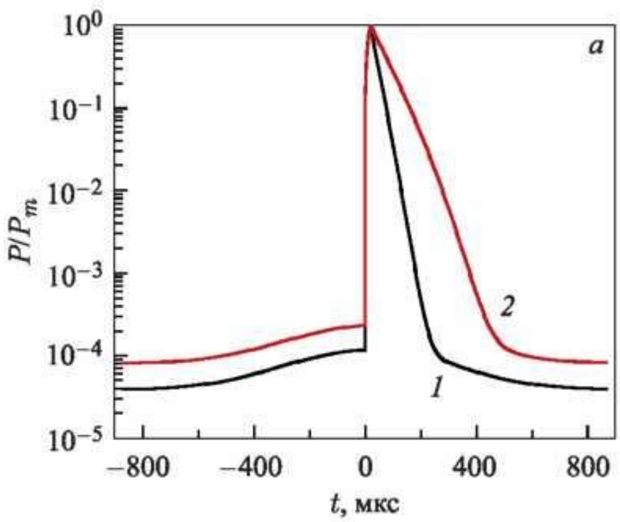
Parameter	Value
Kinetic energy of protons, GeV	1.2
Pulse repetition rate, s^{-1}	10-30
Average proton current, mA	0.028-0.083
Proton beam power on target, MW	0.03-0.1
Proton pulse duration, μs	20-200*
Peak current, mA	up to 50*

Note. Proton pulse duration and peak current parameters marked by * require further consultations.

6. PULSE CHARACTERISTICS OF THE SOURCE

The following pulse characteristics of the source are of importance: power pulse in the core and thermal neutron pulse on the surface of the water moderator.

The power pulse shape was estimated by solving a point kinetics equation. The accelerator parameters corresponded to the data presented in Table 1, and a change in modulator reactivity as a function of time — to the data in Fig. 4. The power pulse shape was calculated for a subcritical state of the source with a basic multiplication factor of 0.98 (multiplication with delayed neutrons being taken into account — 50). The prompt neutron lifetime was 0.5 and 1.3 μs. These values were determined by the design features of the core and obtained independently using Monte-Carlo calculations. A primary source of spallation neutrons was generated for a tungsten target at a proton energy of 1.2 GeV. Data were obtained on the shape of the power pulse in the core, as well as on the effect of the prompt neutron lifetime on the background between pulses under the action of modulated reactivity. Some results of calculations of the power pulse shape are presented in Fig. 7 and Table 2 at a primary proton pulse duration of 20 μs. This duration is chosen as the minimum possible for the generation of thermal neutrons in a water moderator with a short thermalization time. Usually, time constants of the neutron flux decay in water moderators are at a level of ~ 60 μs.



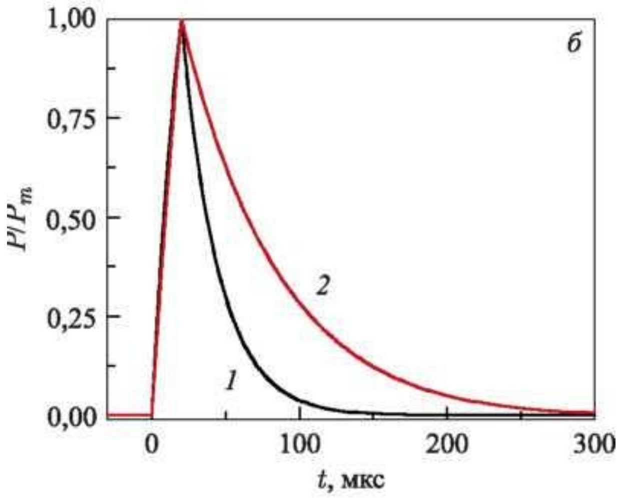


Fig. 7. Calculated power pulse shape of the neutron source as a fraction of the maximum value at K_{eff} = 0.98 for two prompt neutron lifetime values of 0.5 μs (1) and 1.3 μs (2); frequency and duration of proton pulses are 30 Hz and 20 μs, respectively: a) logarithmic scale, b) linear scale.

It can be seen from Fig. 7 and Table 2 that the neutron lifetime significantly affects the pulse duration and has little effect on the background. The background, as shown in 3.2, decreases markedly with the insertion of the reactivity modulator at a multiplication closer to that of the reactor mode – 50 or greater. To decrease the pulse duration at a fixed multiplication, as can be seen from Fig. 7, it is important to have a short lifetime of prompt neutrons. The pulse duration in a subcritical system is determined by the proton pulse duration and the character of the decay of the main component of the neutron flux with the time constant $\tau = \tau_n/\Delta\varepsilon$, where τ_n and $\Delta\varepsilon$ are the prompt neutron lifetime and prompt subcriticality of the system, respectively.

Table 2. Parameters of power pulse in calculations using a point model.

Parameter	Value	
Multiplication factor, K_{eff}	0.98	
Average thermal power of the source, MW	8	
Target	W	
Pulse repetition rate, s^{-1}	30	
Average proton current, mA	0.083	
Proton beam power on target, MW	0.1	
Proton energy, GeV	1.2	
Proton pulse duration, μs	20	
Efficiency of reactivity modulator, abs. units	0.04	
Pulse energy, MJ	0.45	
Neutron lifetime, s	$0.5 \cdot 10^{-6}$	$1.3 \cdot 10^{-6}$
Pulse duration, μs	27	45
Background during pulse period, % of total energy	3.5	3.6
Peak power, MW	9500	5700

The pulse shape of thermal neutrons in a steady-state mode of the source (without a reactivity modulator) emitted from the surface of a flat water moderator was calculated using the Monte-Carlo method (Fig. 8). This figure shows the response of the neutron source to irradiation with a δ-function proton pulse (infinitely short pulse) for two values of the multiplication factor — 0.98 and 0.95. The thermal neutron pulse parameters are given in Table 3. In this calculation, there is no modulating reactivity, the neutron lifetime is sufficiently long (1.3 μs), and therefore the calculations show the maximum possible (as regards the duration) thermal neutron dynamics when exposed to an extremely short proton pulse. Figure 8, *b* displays the thermal neutron pulse shape for a rectangular pulse of protons with a duration of 20 μs. In accordance with the design of the moderators (water of moderators surrounded by beryllium, see Fig. 6), in the thermal neutron pulse there are two exponents of the neutron flux decay with periods of 66 and 235 μs. The first component characterizes the time of thermalization of fast neutrons in a water moderator, the second — in beryllium. It should be noted that the thermal neutron pulse duration of 100 and 70 μs at a multiplication of 50 and 20 significantly depends on the screening of moderators and weakly on the proton pulse duration (Θ_p). For example, at a multiplication of 20 (K_{eff} = 0.95), the thermal pulse duration at Θ_p = 20 μs is 85, and at Θ_p = 30 μs — 90 μs.

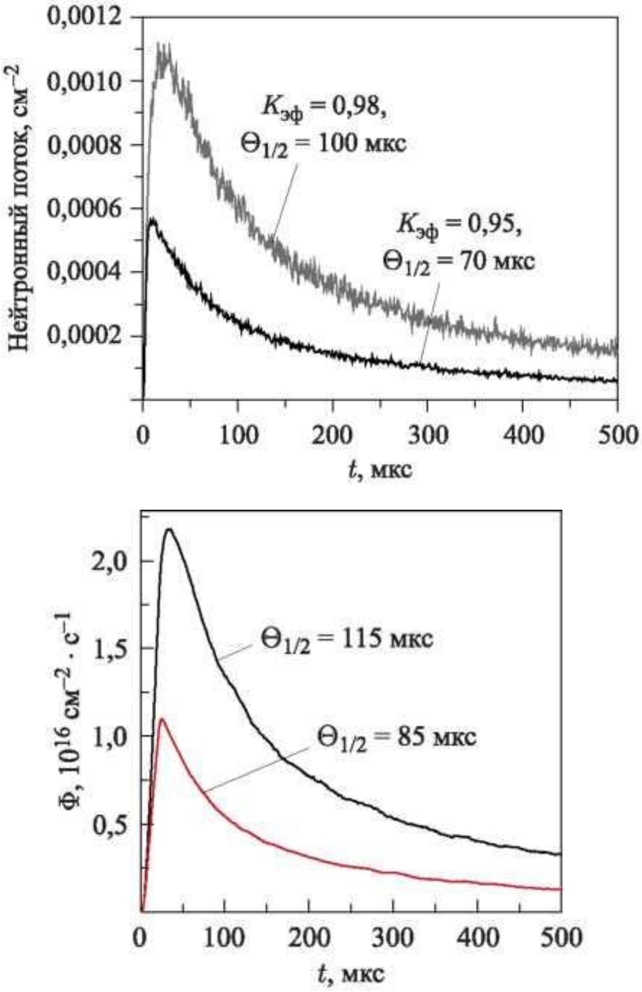


Fig. 8. Thermal neutron pulse shape on the surface of a flat water moderator at a multiplication factor K_{eff} = 0.98 and 0.95 without reactivity modulation: a) δ-function proton pulse irradiation; b) proton pulse with a duration of 20 μs.

Table 3. Parameters of thermal neutron pulse on the surface of a flat water moderator under δ-function proton pulse irradiation of a tungsten target without reactivity modulation.

Parameter	Value	
Pulse repetition rate, s^{-1}	30	
Average proton current, mA	0.083	
Proton beam power on target, MW	0.1	
Proton energy, GeV	1.2	
Proton pulse duration	δ-function pulse	
Neutron lifetime, s	$1.0 \cdot 10^{-6}$	
Multiplication factor, K_{eff}	0.98	0.95
Full width at half maximum, μs	100	70
Average thermal neutron flux density on flat moderator surface, 10^{14} $cm^{-2} \cdot s^{-1}$	2.0	1.0
Peak thermal neutron flux density, 10^{16} $cm^{-2} \cdot s^{-1}$	6.4	4.5

7. HEAT REMOVAL

Data on the heat removal of the neutron source core are given in Table 4. From the analysis of the data from Table 4 it follows that the parameters of the coolant and temperature variation in the core at a specified design source power meet the safety requirements for core cooling.

Table 4. Basic core-cooling parameters.

Parameter	Value
Rated power, MW	10-15
Specific power density of the core, kW/l	350-550
Volume, l	20-26
Height, cm	46
Cross-section area of the core, cm^2	570 ($46 \times 6.2 \times 2 = 570.4$)
Coolant flow area, cm^2	90 (570 $cm^2 \cdot 0.153 = 87.2$)
PuO_2 fuel loading, kg	172 (26 l – 0.691 · 9.6 g/cm^3)
Volume fractions of materials of the core: PuO_2 fuel steel water	 0.691 0.157 0.153
Flow rate, m^3/h	94-157
Water velocity, m/s	3-5
Water temperature at core inlet, °C	45-50
Water heating in the core at 120 m^3/h, K	35-50 (~ 4 atm)

8. MODERATORS AND THERMAL NEUTRONS

Since the task is to generate neutrons from the surface of the source, let us evaluate the overall neutron balance. For the booster at K_{eff} = 0.98 and the accelerator parameters given in Table 5 (see Section 11), the neutron balance is as follows: the total number of neutrons produced in fission per one proton is 1900, of which 620 go to sustain the chain reaction and only 520 leave the boundaries of the core. Thus, the total leakage of neutrons of all energies from the core surface is 27% and the efficiency of the source as a neutron generator is no more than 30%. The efficiency of the source in generating thermal neutrons is even less.

Figure 9 shows the layout of thermal and cold neutron moderators relative to the core, which are placed in two planes with a wide angular access of 60° for neutron beamlines to the surfaces of all moderators on each side. The lower moderator consists of two parts — water moderator of gun-type geometry and water moderator poisoned with boric acid to reduce the pulse duration.

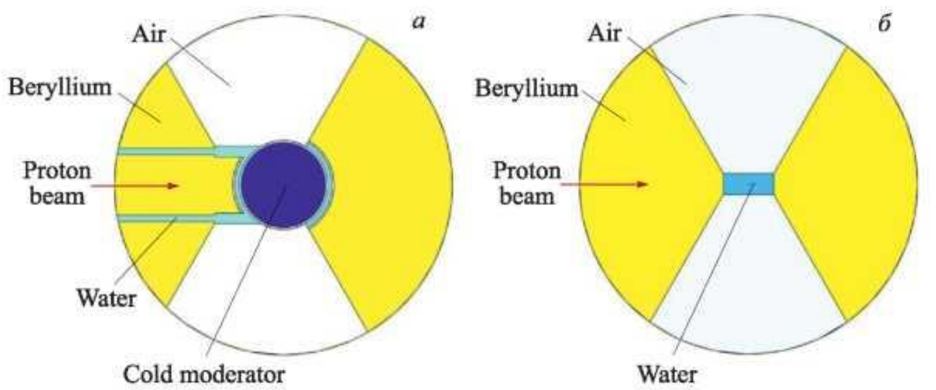


Fig. 9. Layout of neutron moderators: a) top view, b) bottom view.

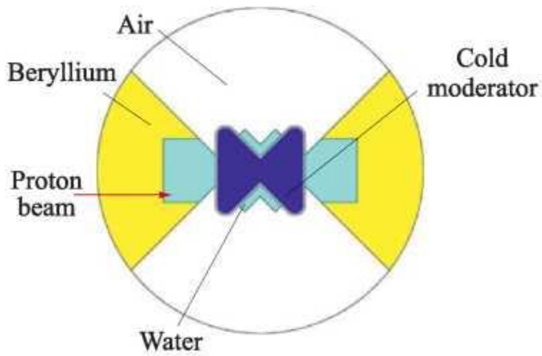


Fig. 10. Layout of a "butterfly"-type neutron moderator.

The upper moderator also consists of two parts — water flat moderator and cylindrical cold moderator based on para-hydrogen [5]. The diameter of the cold moderator is 16 cm, the thickness of pre-moderators is 1 and 2.5 cm. All moderators are viewable from both sides from neutron beamlines. For all moderators, the possibility of direct incidence of fast neutrons into thermal neutron beamlines is eliminated. Depending on the direction of the neutron beam, the "viewable" part of the upper moderator can generate either only cold neutrons, or both cold and thermal neutrons, i.e. in the second case, some neutron beamlines “see” the so-called bispectral moderator.

Additionally, a "butterfly"-type moderator is considered as one of the promising variants of a cold moderator with high luminosity in some directions at a small solid angle [5]. This moderator can be used as a replacement for the main one. In the “butterfly”-type moderator, as in the case of the main cold moderator, para-hydrogen is used. A schematic view of the moderator is presented in Fig. 10. According to [5], cold neutron luminosity in some directions of neutron beamlines from the side of the “butterfly” moderator can be increased twice or more.

Figures 11 and 12 show the calculated energy distributions of thermal and cold neutrons on the surface of flat water, bispectral and cold moderators for two values: K_{eff} = 0.98 and 0.95. Due to the fact that thermal neutron beamlines do not directly view the surface of the core, the fraction of thermal neutrons in the full spectrum of neutrons is quite large.

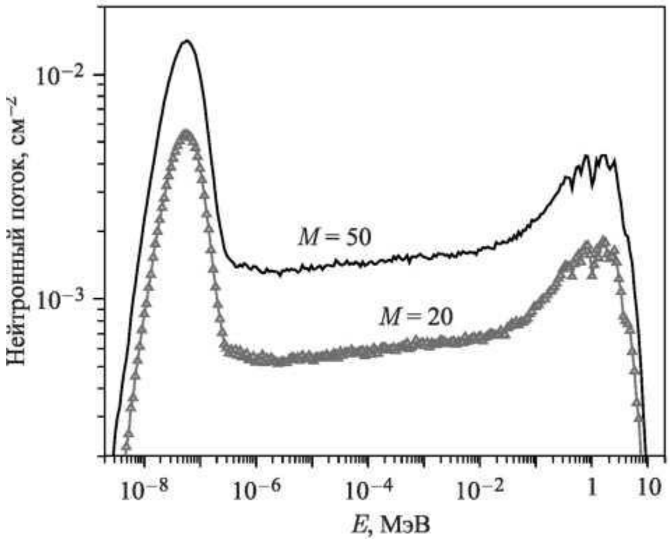
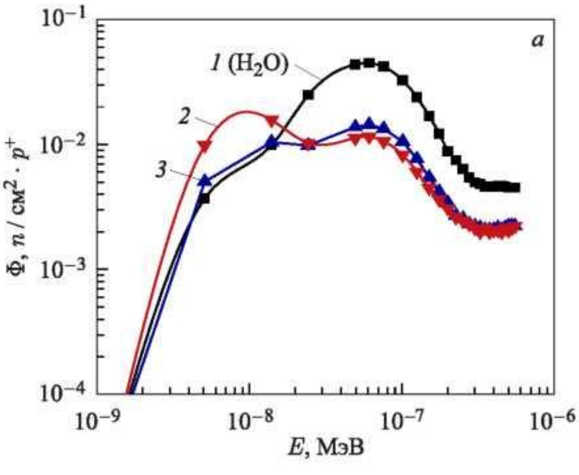


Fig. 11. Energy distribution of thermal neutron flux on the surface of a flat water moderator for two values of multiplication — 50 and 20.



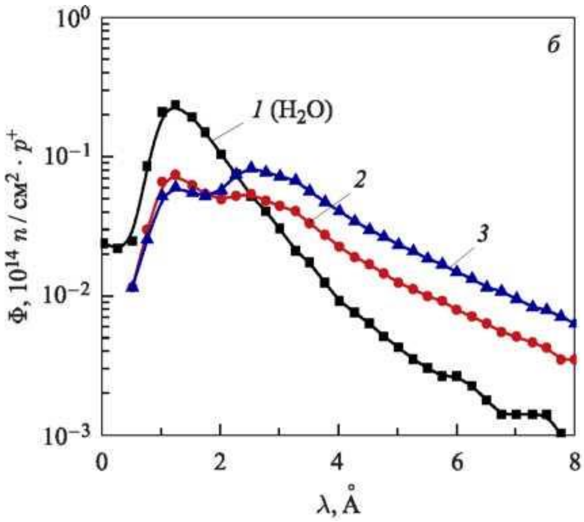


Fig. 12. Dependence of the neutron flux density on energy (a) and wavelength (b) on the surface of moderators: 1 – lower water moderator; 2 – upper bispectral moderator; 3 – only cold moderator.

9. NEUTRON BEAMLINES

The design of the neutron source allows highly efficient extraction of thermal and cold neutrons into a large number of horizontal neutron beamlines. The layout of horizontal neutron beams for all moderators located in two planes is shown in Fig. 13. As can be seen from this figure, each moderator is "viewable" from two opposite sides in angular cones of 60°. The angular viewable areas from the side of neutron beamlines for the upper and lower moderators do not overlap. Thus, maximally convenient conditions are created for placing equipment near the beamline exits. This fact contributes to a significant increase in the efficiency of utilizing neutrons from beamlines and neutrons of the source as a whole. The maximum possible number of neutron beamlines in the source under consideration is 48. The proton beam passes through the target at a sufficiently wide solid angle and does not create radiation background interference in the area of neutron beam extraction.

In addition to horizontal beamlines of thermal and cold neutrons, there will be several vertical irradiation beamlines. The spectral composition of cascade-spallation neutrons formed in the tungsten target partially contains high-energy (up to proton energy) neutrons directed along the axis of the proton beam in the direction of biological shielding. Therefore, vertical beamlines allow using near-fission-spectrum neutrons and high-energy component of conversion neutrons for irradiating samples, for example, spacecraft component parts or materials for thermonuclear facilities. Figure 14 shows the simulated spectra of neutrons emitted from the end surface of the tungsten target for some values of the proton energy. These data characterize the spectral composition of neutrons in vertical irradiation beamlines located along the axis of the proton beam and correspond most closely to the neutron spectrum in the vertical beamline passing through the beryllium moderator. For this beamline, the flux density of high-energy neutrons in the energy range of 20-100 MeV with a proton energy of 1.2 GeV is $1.5 \cdot 10^{10}$ cm$^{-2} \cdot$ s^{-1}.

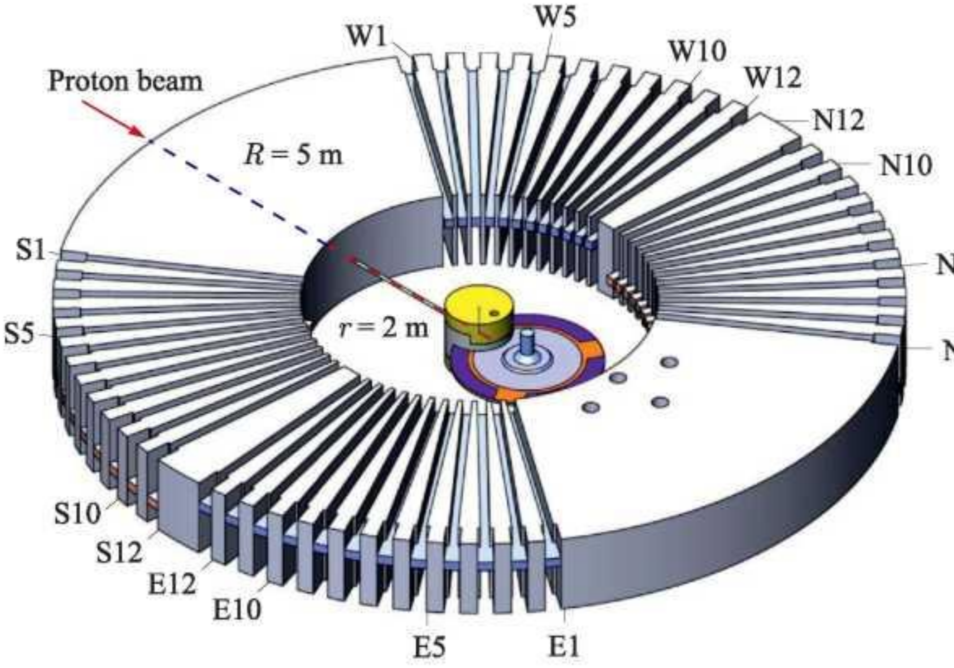


Fig. 13. Layout of the maximum number of horizontal neutron beamlines for two planes of moderators (vertical irradiation beamlines can be seen in the direction of the proton beam).

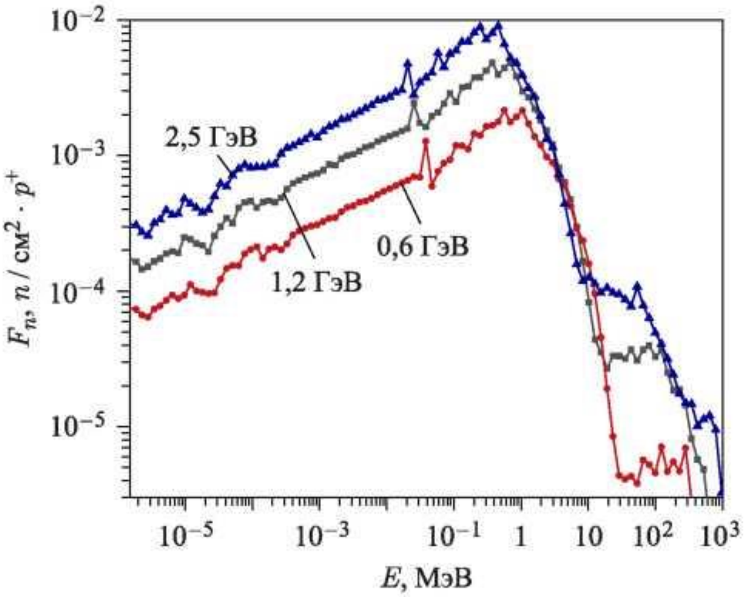


Fig. 14. Neutron flux density per one proton as a function of energy of neutrons coming from the end surface of the tungsten target at proton energies of 0.6, 1.2 and 2.5 GeV.

10. NUCLEAR SAFETY

The neutron source possesses inherent safety features. The main design-basis accident, which consists in a decrease of the volume fraction of water as a result of boiling or loss of coolant, results in the “hardening” of neutron spectrum and a large negative reactivity effect. The calculated effect of total discharge of water (coolant) from the core is negative and does not exceed –5%.

During loading and exchange of fuel elements, a water cavity is formed in their place, which becomes an additional source of thermal and intermediate neutrons. This leads to a positive reactivity effect. To prevent this kind of undesirable effect, fuel-element cladding is made of hafnium-based alloy (thermal neutron absorber) Hf-Nb (2 wt%) – Zr (20 wt%) — GNC20. Then, in the process of removing fuel rods and replacing them with water, the reactivity effect will be negative. For more reliable elimination of the specified positive reactivity component, the core design provides for several bearing partitions made of hafnium. The incorporation of such partitions, first, excludes various kinds of positive effects, and second, improves structural rigidity of the core and, which is very important, reduces the lifetime of prompt neutrons. The latter leads to a corresponding reduction in the power pulse duration.

As an important component of nuclear safety, the reactivity effects arising from various failures and malfunctions in the operation of accelerators should be considered separately. Accelerator failures may result, for example, in an accidental change in the proton energy, current or pulse duration of the proton beam (for example, in case of breakdowns in accelerator sections), etc. These studies are of interest in their own right, and the results will be presented in a separate paper.

11. BASIC CHARACTERISTICS OF THE SOURCE

The basic characteristics of the pulsed neutron source are presented in Table 5. Here, it is necessary to make some comments on the following points. The duration and repetition rate of pulses are determined by the parameters of the accelerator. The values of static parameters of the source, i.e., parameters that can be averaged over time and can be realized at a constant accelerator current, such as the average neutron flux density, average power, etc., depend on the proton beam power on the target. Pulse characteristics (peak values of parameters in pulse) depend on the repetition rate and duration of proton pulses ~ $(f\,\Theta_p)^{-1}$ and are limited by the allowable peak current of the accelerator. In modern accelerators, the maximum allowable peak proton current is ~ 50 mA. Therefore, the parameters of the neutron source in Table 5 are given taking into account the accelerator peak current limit of 50 mA. With technical advances in accelerator design, the peak parameters of the source can be improved.

Table 5. Basic characteristics of the neutron source.

Parameter	Value
Source power, MW	8
Fuel	$Pu0_2$
Fuel mass, kg	172
Fuel volume, l	23
Target material	W
Coolant	H_2O
Pulse repetition rate, s^{-1}	30 (10)
Average proton current, mA	0.083 (0.03)
Maximum pulse current, mA	50

Proton beam power on target, MW	0.1 (0.036)
Proton energy, GeV	1.2
Proton pulse duration, μs	55 [40-200] (20)
Prompt neutron lifetime, s	$0.5 \cdot 10^{-6}$
Multiplication factor K_{eff}	0.98 (0.95)
Effective fraction of delayed neutrons β_{eff}, abs. units	$2.165 \cdot 10^{-3}$
Maximum fuel burnup, % Evaluation of burnup in the long term, %	10 20
Average thermal neutron flux density on flat water moderator surface, 10^{14} cm$^{-2} \cdot$ s^{-1}	2.0 (0.8)
Average cold neutron flux density on CM surface, 10^{13} cm$^{-2} \cdot$ s^{-1}: at λ > 2.5 Å at λ > 4.0 Å	 4.2 1.75
Peak thermal neutron flux density, 10^{16} cm$^{-2} \cdot$ s^{-1}	5.3 (6.2)
Full width at half maximum for thermal neutron pulse, μs	< 125 (85)

Note. In parentheses data are given at a pulse repetition rate of 10 s^{-1}.

The proposed variant of the neutron source is only a basic concept, which can also be improved in the process of development.

1. To reduce the pulse duration, the average lifetime of prompt fission neutrons can be reduced to ~ 0.2-0.3 μs, if as a coolant we use a mixture of H_2O-D_2O instead of light water.

2. The fuel element spacing in the core can be increased from 9.1 to 9.5 mm. In this case, the thermal regime of the core will be significantly improved.

3. If in the future we use nitride fuel PuN instead of PuO_2, it will be possible to reduce the volume of the core and significantly improve the basic parameters of the source.

4. Using a rotating target based on natural uranium, it is possible:

– to increase the neutron yield by a factor of ~ 1.4, and correspondingly decrease multiplication down to ~ 36;

– to diminish multiplication down to 20 with some decrease of neutron flux, which will reduce the background between pulses and make it possible to abandon a reactivity modulator at all.

12. COMPARISON OF BASIC PARAMETERS OF NEUTRON SOURCES DRIVEN BY PROTON ACCELERATORS

A brief description of optimal variants of pulsed neutron sources driven by proton accelerators is given in [2]. The source considered in this paper is a generalized optimal solution. There is another approach resulting in a different concept of a promising neutron source instead of IBR-2M. We are referring to the NEPTUN superbooster, a subcritical assembly with the core based on neptunium nitride [6]. For the convenience of further comparison, the model of the source with the core based on plutonium dioxide will be provisionally named PLUTON. A distinctive feature of the NEPTUN superbooster is that the core itself serves as a target generating spallation neutrons. In this case, the proton beam is directed directly to the core body. The NEPTUN superbooster comprises a multiplying target with positive void reactivity feedback, while the PLUTON source is a booster with one core based on plutonium dioxide with an internal target. As follows from the above, the concepts of the sources under consideration are fundamentally different and apart from the proton accelerator have little in common. Naturally, the comparison of the parameters of these sources is of particular interest. The initial data (geometry, structure, composition, etc.) for the calculation of the NEPTUN source were taken from [6]. No other reliable data are available. Principal schematics of PLUTON and NEPTUN used in calculations are presented in Fig. 15. In the case of NEPTUN, the design of the core was drawn in detail, taking account of the heterogeneous structure of fuel loading, volume fractions of constructional materials, and the coolant. The configuration of the equipment surrounding the core (moderators, reflectors, etc.) was also specified in accordance with the description. The neutron-physical characteristics of the source were calculated using the Monte-Carlo method. To evaluate the heat removal, thermal-hydraulics calculations were performed. The power density values used in the calculations of heat removal in PLUTON and NEPTUN are shown in Fig. 16 and 17. The parameters of the accelerator's proton beam were set to be as follows: proton energy – 1.2 GeV, average current – 0.083 mA, power on target – 0.1 MW, pulse repetition rate – 30 s^{-1}, multiplication factor of the core K_{eff} = 0.98 (multiplication 50). Basic information on the comparison of the sources is presented in Table 6.

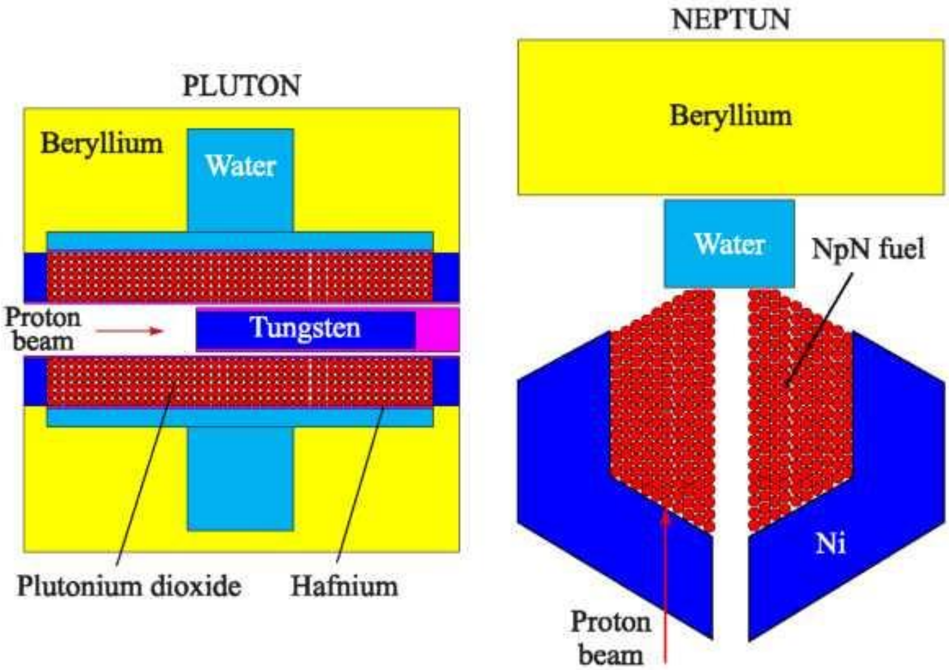


Fig. 15. Principal schematics of PLUTON and NEPTUN used in calculations to compare their parameters.

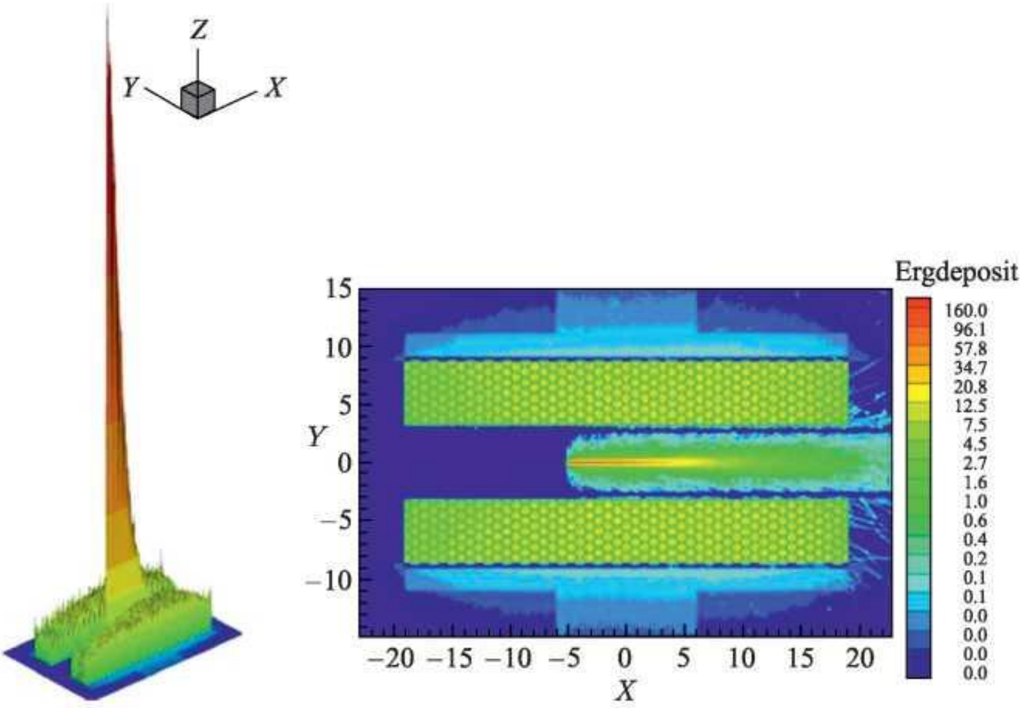


Fig. 16. Power density distribution in the target, core and moderators surrounding the core of PLUTON.

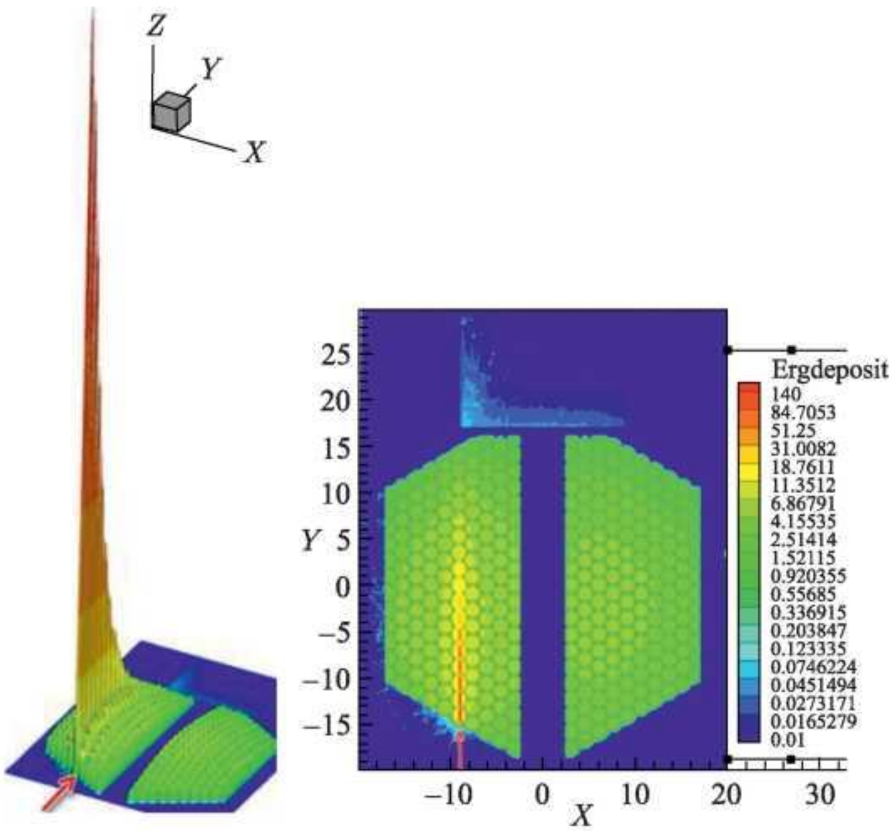


Fig. 17. Power density distribution in the core and moderators surrounding the core of NEPTUN superbooster.

Table 6. Basic parameters of PLUTON and NEPTUN (values in parentheses are the parameters of NEPTUN presented by authors in [6]).

Parameter	Value	
	PLUTON	NEPTUN
Thermal power, MW	8.0	10.0
Fuel	PuO_2	NpN
Fuel mass, kg	172	300
Core volume, l	23	32 (40)
Target material	W	Core material
Target cooling	H_2O	Na
Core cooling		
Maximum heating of the coolant in central fuel rods, °C	75	300
Reactivity effect in the main design-basis accident (loss of coolant), % K_{eff}	-5.3	+ 0.35
Background between pulses, %	3.5	3.2
Average number of conversion neutrons per one proton	24	28
Average thermal neutron flux density on the surface of a flat water moderator, 10^{13} cm^{-2} · s^{-1}	20.0	1.3 (20.0)

As can be seen from Table 6, several NEPTUN superbooster parameters that are considered problematic are marked in red.

• First, the neutron flux density in NEPTUN is 10-15 times lower than that of PLUTON. This difference is due to the design features of the sources.

• Second, temperature conditions of heating the sodium coolant in some spots of the core at a power of 10 MW are at the upper allowable limits.

• Third, the main design-basis accident involving loss of coolant is accompanied by a positive reactivity insertion.

• Fourth, neptunium nitride fuel which is proposed to be used in NEPTUN is unavailable at present. With a different, less dense fuel containing neptunium, the thermal neutron flux will be at a level of ~ 10^{12} cm^{-2} · s^{-1}.

• Fifth, as can be seen from Fig. 17, local hot spots in the maximum power density area under proton beam irradiation may cause sodium coolant boiling with all ensuing consequences.

• To increase the thermal neutron flux density of the NEPTUN superbooster, for example, up to the level of $1.25 \cdot 10^{14}$ cm^{-2} · s^{-1}, it is necessary to increase multiplication up to ~ 500 and, in fact, change to the reactor regime with increasing power of the facility up to 93 MW. Results of the calculation of the variation in the thermal neutron flux density and power of the sources under changes of multiplication are given in Table 7.

Table 7. Comparison of the results of the calculation of thermal power and thermal neutron flux density on the surface of a flat water moderator for PLUTON and NEPTUN for different multiplication values.

Parameter	Value						
	PLUTON Pu + W-target			NEPTUN Np + core-target			
Multiplication factor K_{eff}	0.95	0.98	0.99	0.98	0.99	0.995	0.998
Multiplication $K_{eff} / \Delta K_{eff}$	20	50	100	50	100	200	500
Thermal power, MW	4.5	8.0	16.2	10.0	19.0	37.0	93.0
Average thermal neutron flux density on the surface of a flat water moderator, 10^{13} cm^{-2} · s^{-1}	8.20	20.00	28.00	1.35	2.60	5.20	12.48

13. MATERIAL SWELLING

The problem of material swelling equally applies to both NEPTUN and PLUTON sources. The problem lies in the radiation durability of targets exposed to high-energy protons. In this section the issue is considered only qualitatively, taking into account the experience of the Los Alamos National Laboratory and the ISIS source [7].

Irradiation with protons causes swelling and embrittlement of targets made of tungsten and, to a greater extent, of uranium. Embrittlement occurs within two years even at a relatively low proton current of 30 μA. Nevertheless, in the world practice, preference is given to targets made of tungsten, whose average service life, as experience shows, is two years. To a larger extent, this applies to the PLUTON facility.

The problem of radiation damage in the NEPTUN facility is also of great interest, since the reactor vessel and material of the core exposed to proton irradiation experience high radiation loads. The problem of radiation damage is a separate task and will be considered at the stage of project development.

CONCLUSIONS

The proposed concept of a pulsed neutron source with a thermal neutron flux density of $2.0 \cdot 10^{14}$ cm^{-2} · s^{-1} at a power of 8 MW is feasible and falls into the category of high-flux sources both at present and in the long run. The source is a deeply subcritical system with a high level of nuclear safety. The proton beam power at a proton energy of 1.2 GeV on a tungsten target is 0.1 MW, which is more than an order of magnitude lower than the power of modern accelerators for neutron beam sources.

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