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Research Reactor PIK: The First Experiments

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Abstract—The parameters and current status of development of the highest-power neutron source of the PIK research reactor (Petersburg Nuclear Physics Institute named by B.P. Konstantinov of National Research Centre "Kurchatov Institute" (NRC "Kurchatov Institute"–PNPI), Gatchina) are described. The results of the first experiments on the obtained neutron beams are reported, which were performed at bringing the PIK reactor to the power mode of operation. The PIK research reactor complex, running at its full design capacities, will determine the strategy of development of neutron studies in the Russian Federation for several decades and will become the basis for the International Center for Neutron Studies.

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INTRODUCTION

The PIK (Russian abbreviation for the Shell-type Research Beam) reactor (Fig. 1) was intended and designed at the beginning of the 1970s as a source of most high-power neutron beams. A successful layout reactor scheme, which was proposed for the PIK reactor in 1966 [1], was later used in almost all beam reactors with heavy-water reflectors. The dramatic history of the reactor development, which was described in [2], lasted for more than 40 years.

The situation started changing in 2010, when at the initiative of M.V. Kovalchuk, the Research Center

Fig. 1. Neutron research complex with the PIK reactor in Gatchina (Russian Federation).

NRC “Kurchatov Institute”–PNPI was included in the Program of joint activity of the organizations, belonging to the NRC “Kurchatov Institute.” As a result, the physical launch of the reactor in 2011 at a power of 100 W confirmed the neutron-physical reactor parameters, obtained during calculations and experimentally at the “Physical Model of the PIK Reactor” critical bench.

Since July of 2013, the NRC “Kurchatov Institute”–PNPI has been developing the concept of a complex of experimental stations and its engineering infrastructure. The accepted strategy was putting the PIK reactor into operation via successive stages of increasing the reactor power and the number of its technological and research systems.

In 2018, within the first stage of the Energy Launch Program, the reactor systems were tested at a power of up to 100 kW.

The experimental channels for novel systems are being developed within the “Development of the Device Base of the PIK Reactor Complex” project, which will make it possible to mount them before the design elements reach large activity.

All stages of increasing the power and launching new systems and scientific equipment are being performed under constant State supervision by the regional branch of Rostekhnadzor within the operating licence issued by its central office.

In the end of 2020, five experimental stations of the first stage were put into operation for conducting experiments on the ejected beams.

In 2021, the reactor was transferred to the power mode of operation of the stage of mastering the reactor power of up to 10 MW. In March 2022, the reactor power of 7 MW was achieved, which confirmed the high qualification of the personnel and demonstrated stable and reliable operation of the reactor and technological systems.

Preparations are under way for the transition from launching core to an operational set of fuel assemblies providing a satisfactory reactor cycle of about 25 days between fuel reloads. The concept of the new fuel for the PIK reactor is based on the use of commercial fuel elements (TVELs) of the CM reactor with increased loading of ^{235}U, the use of a burnable absorber and modernization of the fuel cartridge design. Currently, preparations are under way to make a contract with the “TVEL” enterprises of the State Corporation “Rosatom” for the supply of the first batch of new fuel in 2023.

Simultaneously with an increase in the reactor power, a complex of experimental equipment for carrying out scientific experiments is being developed.

The use of a neutron radiation source is most efficient if the highly efficient neutron beams, ejected from the high-flux reactor, are delivered without loss to ultra-modern experimental setups, which make it possible to carry out most advanced research in all above fields. Therefore, both components (i.e. high performance of the neutron source itself and the current level of the instrumental base) are of equal importance for successful implementation of the scientific programs of the International Centre for Neutron Research at the PIK reactor. Thus, one of the basic principles of the overall concept of developing the experimental-station—improvement of the instrumental base—should “go hand in hand” with the source improvement.

The provision of the PIK reactor with a complex of modern equipment is carried out within two projects: “Reconstruction of the Laboratory Complex of the PIK Research Reactor Complex” (2017–2020) and “Creation of the Instrumental Base of the PIK Reactor Complex” (2019–2024). As a result of these projects, a research complex, equipped with 25 neutron stations, a cold-neutron source, a hot-neutron source, and an ultra-cold-neutron source will be created, which will satisfy the demands for neutron research both from the scientific and technical complex of Russia and from a large part of the European partners for many years. Ten neutron-guide systems make it possible to transport neutrons to 17 experimental facilities, located in the neutron-guide room under low-background conditions. In total, it is planned to organize up to 50 positions on beams in three experimental halls of the complex, at which different research groups can simultaneously carry out experiments. The instrumental program of the PIK reactor complex was described in detail in [3].

CHARACTERISTICS OF THE PIK REACTOR

The PIK reactor is a compact neutron source with a ~50-L core, surrounded with a heavy-water reflector. The maximum unperturbed fluence of thermal neutrons reaches 5×10^{15} n/(cm^2 s) at the central water cavity and 1.2×10^{15} n/(cm^2 s) in the reflector at a thermal reactor power of 100 MW (Fig. 2). The core is located in a reactor tank and is cooled with light water under a pressure of 5 MPa. The reactor tank, in turn, is located in the reflector tank, filled with heavy water. The reactor parameters and its characteristic were described in detail in [2].

THE MAIN PARAMETERS OF THE PIK REACTOR

The thermal power is 100 MW; the heat-flux density, averaged over the perimeter of fuel elements, reaches 10 MW/m^2, which corresponds to about 6 MW per 1 L of the core volume at the hot point; and the load, averaged throughout the core, is 2 MW/L. Well-developed fuel elements of the SM type with a fuel height increased to 500 mm are used.

To emit neutron radiation from the PIK-reactor reflector and irradiate samples, the PIK reactor is equipped with a significant number of experimental channels (Fig. 3). The central experimental channel

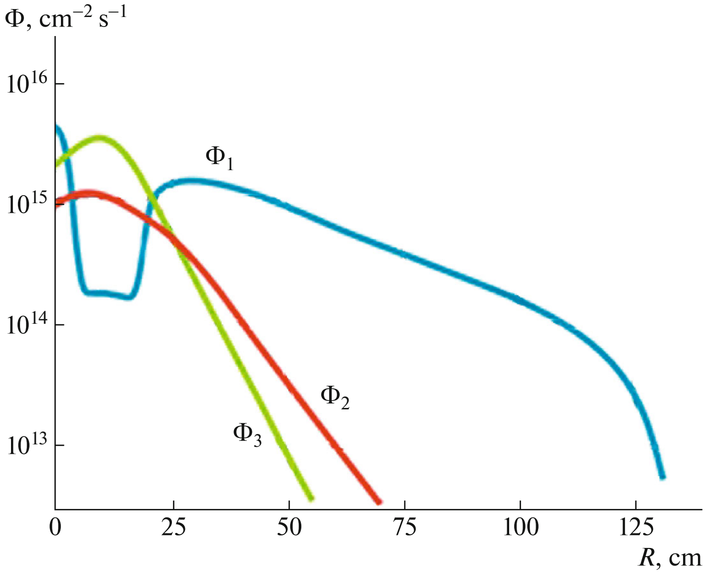

Fig. 2. Distribution of neutron fluences: Φ_1 is the thermal-neutron fluence ($E < 0.6$ eV), Φ_2 is the epithermal-neutron fluence (0.6 eV $< E < 5$ keV), and Φ_3 is the fast-neutron fluence ($E > 5$ keV).

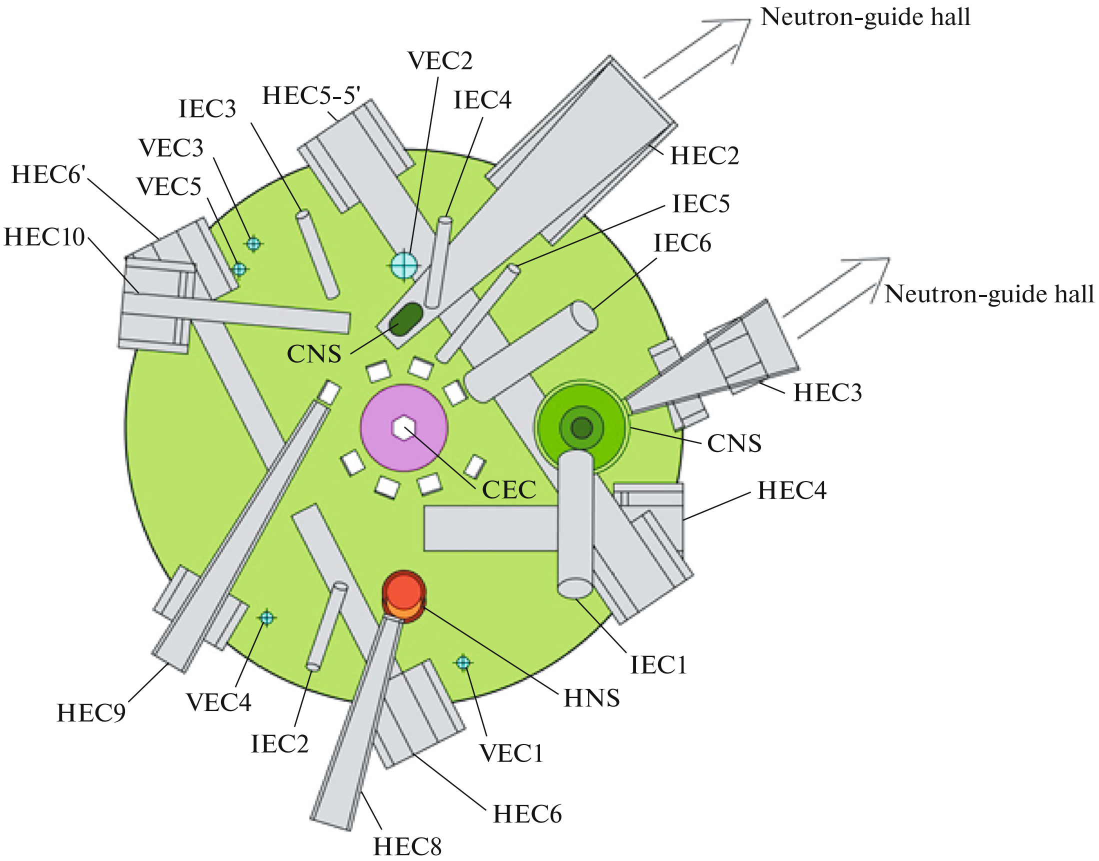

Fig. 3. Schematic diagram of the experimental channels of the PIK reactor.

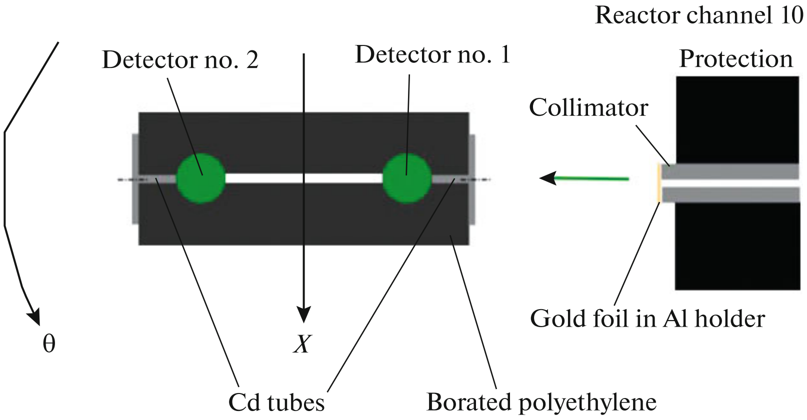

Fig. 4. Experimental scheme for measuring the absolute flux in the HEC-10 channel.

(CEC) is located in the water core cavity. The unperturbed fluence of thermal neutrons in the cavity is 5×10^{15} n/(cm^2 s). There are also nine horizontal experimental channels (HECs) (100–250 mm in diameter, fluences of thermal neutrons at the output are in the range of $(0.2–3) \times 10^{11}$ n/(cm^2 s)), six inclined experimental channels (IECs) (90–140 mm in diameter, fluences of thermal neutrons at the output are in the range of $(0.4–2) \times 10^{10}$ n/(cm^2 s)), and seven vertical experimental channels (VECs) (41–155 mm in diameter, fluences of thermal neutrons at the bottom are in the range of $(1–3) \times 10^{14}$ n/(cm^2 s)).

While thermal neutrons ($T \sim 300$ K) are formed directly at the reactor reflector, the formation of neutrons with higher or lower energies requires the use of special moderators, kept at some specific temperatures. There are two sources of cold neutrons in the HEC-2 and HEC-3 channels in the PIK reactor. Liquid deuterium at a temperature $T = 20$ K is used as a moderator, and the hot-neutron source is located in the HEC-8 channel. Graphite at temperature $T =$ 1200–2000 K is used as a moderator. Neutrons are transported to the experimental stations in the neutron-guide hall through ten special neutron guides. The number of beam positions can be increased using branching (the total length is ~1200 m). The neutron fluence at the output of neutron guides is $(0.1–1.3) \times 10^{10}$ n/(cm^2 s).

Thus, in comparison with the existing research reactors, PIK should provide unique possibilities for both carrying out more through neutron studies and novel experiments, which are currently inaccessible on the Russian research reactors. Despite quite a long launching time of the PIK reactor, it remains highly urgent. The number of scientific problems that can be solved using neutron beams, increases each year. Instruments are being improved, and the intensity of neutron beams is being increased.

The PIK reactor will overcome all active research reactors in terms of the neutron-beam parameters and experimental capabilities.

FIRST EXPERIMENS ON NEUTRON BEAMS

In December 2020, five research stations of the PIK reactor complex were put into operation. These are as follows:

(i) test neutron reflectometer (TNR), designed for testing neutron polarizing and non-polarizing mirrors of neutron guides and other neutron-optical devices, including those intended for the reactor complex;

(ii) TEX-3 texture diffractometer for the texture X-ray diffraction applications, including the study of the texture of construction and technical materials;

(iii) polarized-neutron diffractometer (PND) for analysis of the specific features of magnetic ordering in crystal structures;

(iv) NERO-2 polarized-neutron reflectometer for the analysis of the surface structures, interfaces, thin films, and multilayer structures of both magnetic and nonmagnetic materials;

(v) T-Spektr test neutron time-of-flight spectrometer for recording the neutron spectrum at the output of the experimental channels and neutron guides of the reactor.

The experiments on the stations were performed at the stage of reactor transition to the power operation mode, at which the thermal power of 10 MW must be reached. The following methodical experiments were carried out: measurement of the absolute neutron flux on horizontal experimental channel no. 10, study of the characteristics of the four-mode neutron-beam former (polarizer) on the TNR reflectometer, analysis of the characteristics of the neutron-optical former (polarizer) on the NERO-2 reflectometer, etc.

The absolute neutron flux was measured using two independent methods, including measurement of the neutron-beam density using the gold-foil activation method and proportional counters. A schematic diagram of the experimental setup is shown in Fig. 4.

The setup was located in the protection system of the monochromator of the TEX-3 system [4]; it comprised two detectors in the form of proportional

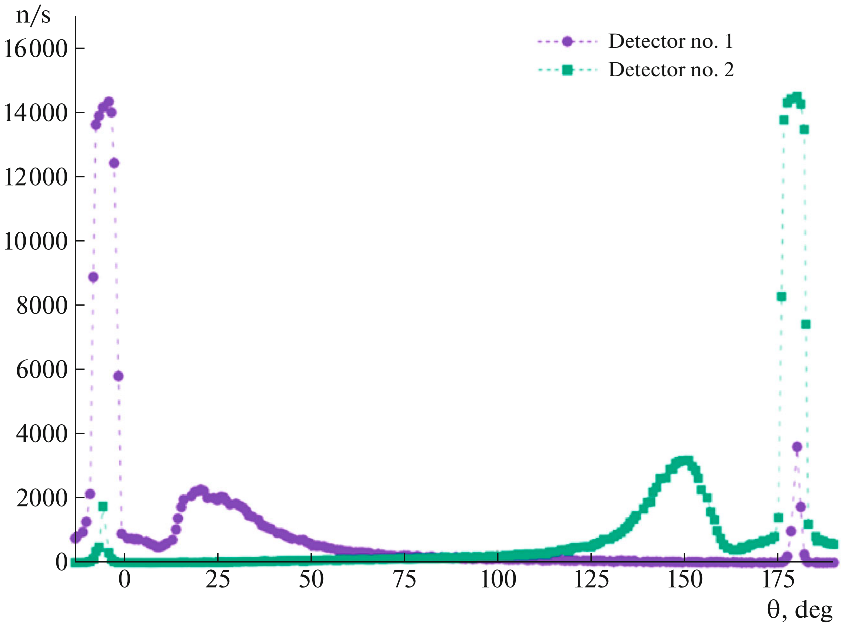

Fig. 5. Azimuthal scanning over angle θ.

counters, placed in borated polyethylene. A channel 5 mm in diameter was formed between the detectors in polyethylene to provide beam passage to the second detector. The neutron beam was formed by a collimator located in demountable reactor protection system. The whole setup was located on the movement table with the possibility of azimuthal rotation (angle θ).

Figure 5 shows the results of azimuthal scanning over angle θ around the axis orthogonal to the drawing plane in Fig. 4. Two intensity peaks, recorded by detectors 1 and 2, correspond to two working sites in which the main measurements were performed (sites 1 and 2).

Thus, as a result of the experiments performed using two independent methods, the fluence of thermal neutrons at the output of the HEC-10 PIK reactor was measured for the first time. The fluence was ~10^6 (n/(s cm^2) at a reactor power of 100 kW, which coincided with the theoretical estimate. The measurement results are listed in Table 1.

Figure 6 shows a photo of the NERO-2 polarized-neutron reflectometer. The results of neutron-physical tests on the NERO-2 station included tuning of the formed neutron-optical former. The results of the first measurements, performed on the NERO-2, were reported at the RNIKS-2021 conference [4]. The neutron-optical former was previously tuned using a laser source. Then, the former position across the neutron-beam axis was scanned in order to determine the channel coordinates (Fig. 7).

Based on the scanning results, shown in Fig. 7, the limits of the channels were determined as follows:

(i) technological (adjusting) channel without optics: $x = 52$ mm, the width is 1 mm;

(ii) polarizing channel (FeCo/TiZr supermirror, $m = 2$): $x = 29$–39 mm, the width is 10 mm;

(iii) unpolarizing channel (Ni/Ti supermirror, $m = 2$): $x = 8$–18 mm, the width is 10 mm.

The working position of the unpolarizing-channel supermirror was determined by scanning the former position across the neutron-beam axis and rocking around the vertical axis. Figure 8 shows the profile of the angular intensity distribution for the neutrons reflected from the Ni/Ti supermirror (m = 2) of the unpolarizing channel of the reflectometer former.

Table 1. Measured values

Position	Detector 1, n/s	Detector 2, n/s	Detector 1, n/(s cm^2)	Detector 2, n/(s cm^2)	On foil, n/(s cm^2)
1	12447.27	887.76	8.29×10^5	0.59×10^5	1.3×10^6
2	871.01	12735.79	0.58×10^5	8.48×10^5	

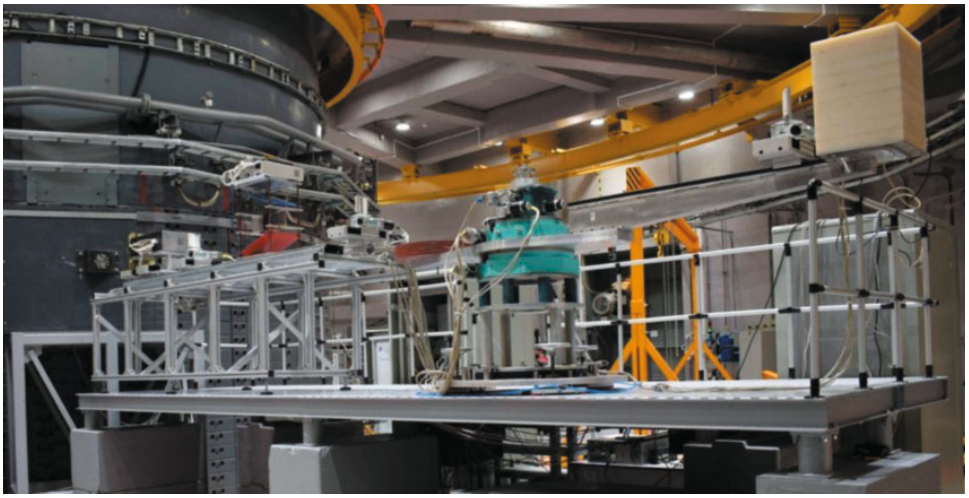

Fig. 6. NERO-2 polarized-neutron reflectometer.

Figure 9 shows the TEX-3 texture diffractometer. The general description of the TEX-3 was presented in [5].

The TEX-3 diffractometer was upgraded, and a system of encoders was installed on the drive of the mechanisms of detector rotation with respect to the sample, which made it possible to control the displacement and operating capacity of the air supply system of the pneumatic supports. A series of experiments was performed, including analysis of the dependences of neutron-beam intensity on the angular position of the monochromator with respect to the vertical axis (at a power of 400 kW) and on the transverse detector shift from the maximum (at powers of 400 and 800 kW) (Fig. 10).

The test neutron reflectometer is located in the HEC-9 channel. The neutron spectrum of the output beam, filtered off from fast neutrons by a supermirror, was previously measured according to the time-of-flight technique [6]. Then, the main optical devices were successively aligned at the TNR. The results were reported at the RNIKS-2021 conference [7]. In particular, an alignment over the neutron beam of one of the main units (specifically, four-mode former (polarizer)) was performed to check its characteristics. To provide exact alignment of the channels, a 0.5-mm-

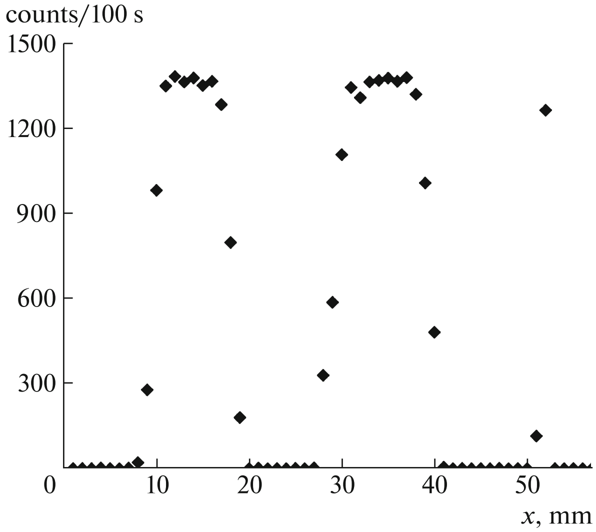

Fig. 7. Dependence of the neutron-radiation intensity, recorded by the detector, on the position of the neutron-optical former.

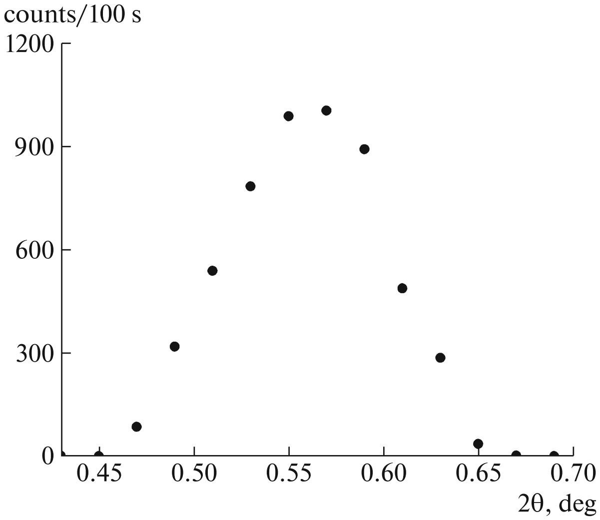

Fig. 8. Angular profile of the neutron beam, reflected from the Ni/Ti supermirror ($m = 2$), of the unpolarizing channel of the former.

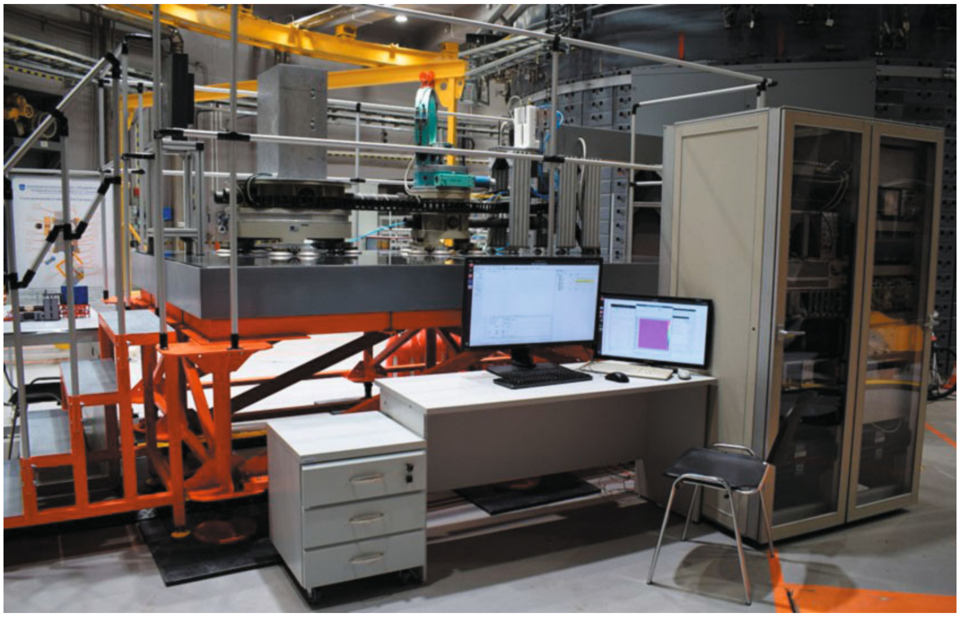

Fig. 9. TEX-3 texture diffractometer.

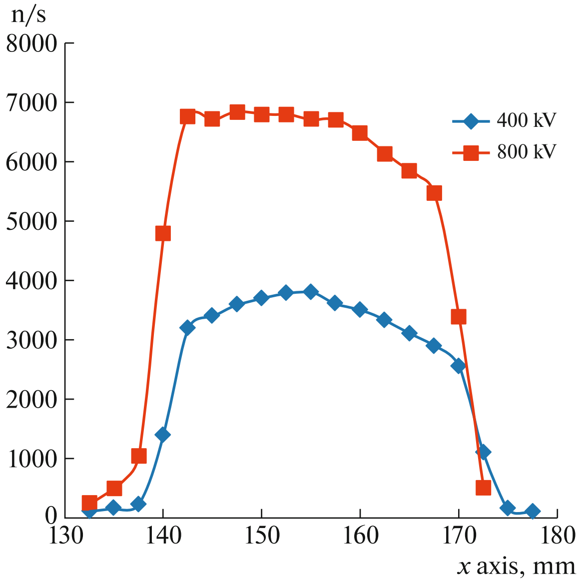

Fig. 10. Dependences of the detector intensity on the transverse shift from the maximum for powers of 400 and 800 kW (30 × 30 mm diaphragm).

wide diaphragm was placed before the former. The photograph of the setup is shown in Fig. 11.

The former was located so as to provide single reflection of the beam in the unpolarizing monochromatic mode from the mirror. After the optimization of the former coordinate at displacement across the beam using a thin diaphragm (0.2 mm), the profile of the beam reflected from the NiMo/Ti mirror monochromator was recorded by the detector at a power of 60 kW (Fig. 12).

The time-of-flight spectra of the forward beam in the third and second former modes were recorded at powers of ~400 and 800 kW, respectively (Fig. 13).

Figure 14 shows the T-Spektr test spectrometer. During the neutron time-of-flight calibration of the spectrometer, the time-of-flight spectra of the HEC-3

Fig. 11. Test neutron reflectometer.

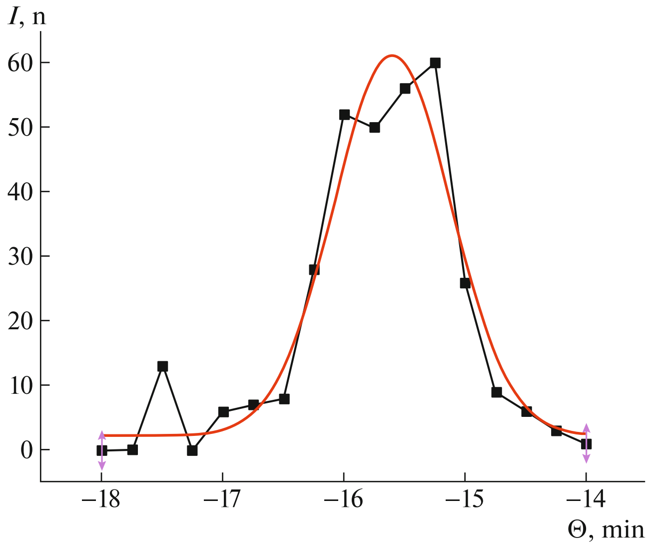

Fig. 12. Profile of the beam reflected from mirror 2 of the four-mode former (monochromatic unpolarizing channel). The beam profile is obtained by scanning the detector with a thin diaphragm (0.2 mm).

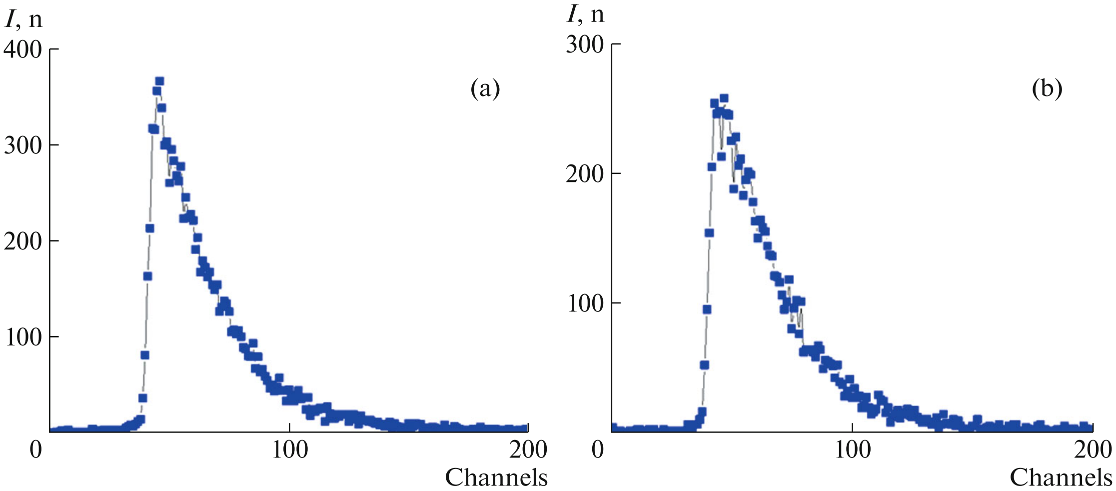

Fig. 13. Spectra of the (a) second (white unpolarizing channel) and (b) third (white polarizing channel) former modes.

Fig. 14. T-Spektr test spectrometer.

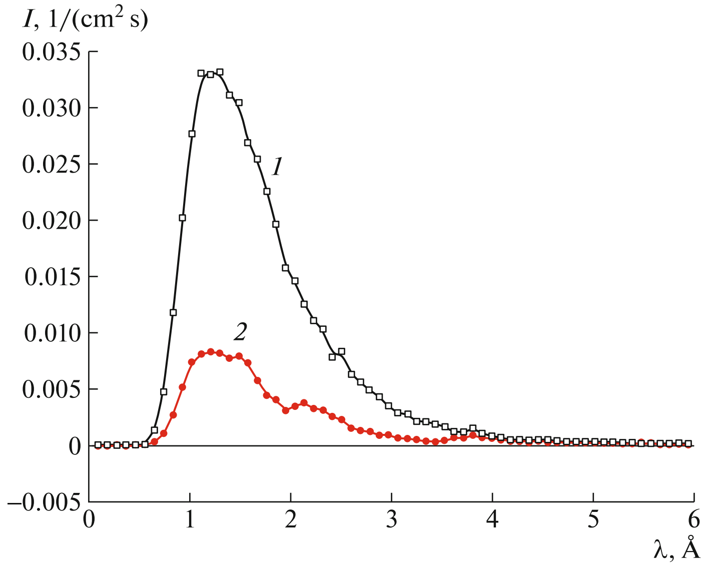

Fig. 15. Spectra (in the linear scale) of (*1*) open beam and (*2*) beam, passed through a polycrystalline Be filter with a thickness of 3.7 g/cm^2.

channel through cadmium (nuclear, mainly absorbing) and beryllium (polycrystalline, mainly scattering) neutron filters were obtained. The measurements were carried out at an uncalibrated reactor power of 85 kW, with one channel used for estimation. As an example, Fig. 15 shows the results of calibration over the beryllium filter. The obtained results indicate complete operating capacity of the instrumentation.

CONCLUSIONS

The planned step-by-step putting of the PIK reactor to the design power of 100 MW is under way, with simultaneous formation of a complex of experimental equipment for carrying out experiments on ejected neutron beams, which should be completed by the end of 2024. The results of the first experiments, which were performed when bringing the reactor to the power mode of operation, coincide with the theoretical expectations and confirm the design parameters of the PIK reactor.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. A. N. Erykalov, D. M. Kaminker, K. A. Konoplev, et al., *Physics of Nuclear Reactors* (Izd-vo FEI, Obninsk, 1966), Vol. III, p. 273 [in Russian].
2. M. V. Koval’chuk, S. L. Smol’skii, and K. A. Konoplev, Crystallogr. Rep. **66** (2), 188 (2021).
3. M. V. Koval’chuk, V. V. Voronin, S. V. Grigor’ev, and A. P. Serebrov, Crystallogr. Rep. **66** (2), 195 (2021).
4. G. P. Didenko, D. A. Ipatov, N. A. Kovalenko, et al., J. Surf. Invest.: X-ray, Synchrotron Neutron Tech. **14**, S144 (2020).
5. V. A. Matveev, N. K. Pleshanov, D. S. Golovastov, and A. V. Sizov, *Proc. Conf. on the Use of Neutron Scattering in Condensed Matter Studies (RNIKS-2021), 2021,* p. 250.
6. V. A. Ulyanov, V. V. Tarnavich, V. G. Syromyatnikov, et al., *Proc. Eur. Conf. on Neutron Scattering, St. Petersburg, Russia, 2019,* p. 321.
7. M. V. D’yachkov, V. A. Ul’yanov, V. G. Syromyatnikov, et al., *Proc. Conf. on the Use of Neutron Scattering in Condensed Matter Studies (RNIKS-2021), 2021,* p. 244.

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