Activity Report on the theme "Development of Experimental Facilities for Condensed Matter Investigations with Beams of the IBR-2 Facility" (04-4-1122-2015/2020) for 2018-2020

In 2018-2020, all activities specified in the annual JINR Topical Plans were successfully carried out. The results of the work are reflected in the FLNP Annual Reports (http://flnph.jinr.ru/en/flnp/annual-reports), reports of the FLNP Director at the sessions of PAC for Condensed Matter Physics and JINR Scientific Council, as well as in reports of the SC Department employees at international and national conferences, and in numerous journal publications.

At the 46th meeting of the PAC for Condensed Matter Physics (June 19-20, 2017), a full activity report on the theme for 2015/2017 was presented and approved. It was noted that the planned objectives were successfully accomplished and in all areas of research and developments (cold moderators; calculations and simulation of spectrometers; cryogenic studies; detectors and electronics; control systems of actuators, sample environment equipment and neutron beam choppers; local area network and software) important results that are of key importance for the successful implementation of the program for the development of the complex of IBR-2 spectrometers and condensed matter research were obtained. All these areas are included in the JINR Seven-Year Development Plan for 2017-2023, therefore, it was recommended to extend the theme and project for 2018-2020. This recommendation was then approved by the 122nd session of the JINR Scientific Council (September 18-19, 2017).

Below are brief reports on the main research areas of the theme:

1. New pulsed neutron source at JINR

In 2019, the analysis of conceptual designs for the ***future pulsed neutron source at JINR*** was continued. The main work was conducted at the N.A.Dollezhal Scientific Research and Design Institute of Energy Technologies "NIKIET" (Moscow), and the research and development activities on the dynamics of the pulsed reactor NEPTUN and on the substantiation of the weak positive reactivity effect during the burnup of neptunium (in contrast to the strong negative effect in a plutonium core) were carried out in FLNP SC Department. As a result, the assumption about the positive reactivity effect during the burnup of neptunium was convincingly confirmed.

In 2018, it was shown that a pulsed reactor is preferable to a pulsed booster – it is more stable in operation and much cheaper to develop and maintain. It is from this standpoint that the concept of a neutron source with a thermal neutron flux of at least 10^{14} n/cm^{2}s was considered in NIKIET. In October, 2019, these studies (performed under a contract with JINR) were completed, and the concept of a pulsed reactor with nuclear fuel based on ***neptunium nitride*** was recognized as the basis for further work on the project. Figure 1 shows a schematic sketch of the NEPTUN reactor.

At present, three leading specialized institutes of the Russian Federation are involved in the project of a future advanced pulsed neutron source with neptunium fuel at JINR: NIKIET, A.A.Bochvar High-technology Research Institute of Inorganic Materials (VNIINM, Moscow), and A.I.Leypunsky Institute of Physics and Power Engineering (IPPE, Obninsk).

It should be emphasized that the peak thermal neutron flux of up to $5 \cdot 10^{16}$ n/cm^{2}s, which is expected for the NEPTUN reactor, is an order of magnitude higher than the same value for the most intense European Spallation Source (ESS) with a proton beam power of 5 MW, which will be put into operation in the coming years.

During 2019, a scientific and methodological justification was prepared for the opening of a new theme within the Topical Plan for JINR Research and International Cooperation, related to the development and construction of a new neutron source at JINR.

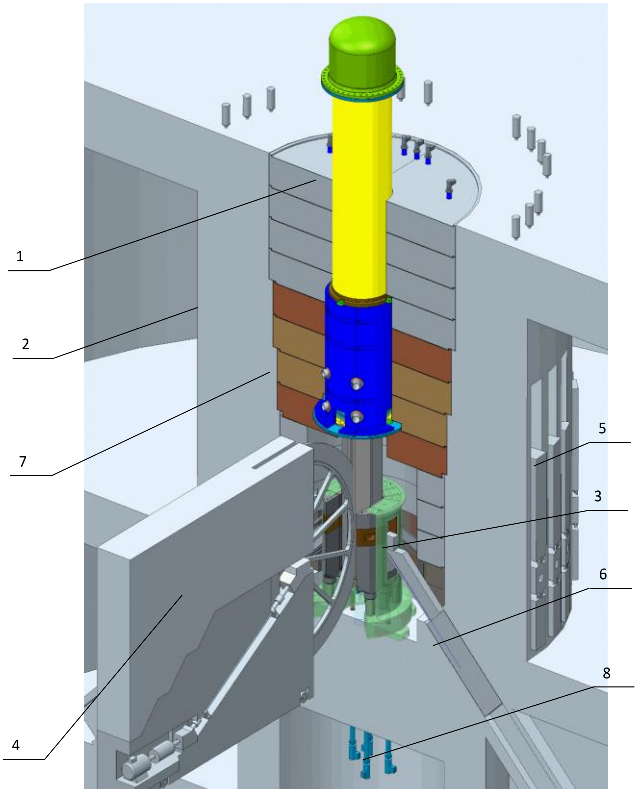

Fig. 1. The NEPTUN reactor in mass concrete: 1 – reactor vessel; 2 – mass concrete; 3 – stationary reflector; 4 – reactivity modulator; 5 – neutron beam shutters; 6 – technological part of the moderator; 7 – thermal shield; 8 – drives of control and protection system units.

2. Complex of CM-201 and CM-202 cryogenic neutron moderators

During the reporting period, the main elements of the control system of the CM-201 pelletized cold moderator (including software) were developed, installed and successfully tested on a specially constructed test stand on IBR-2 beamline 3. **Figure 2** shows the control program for the CM-201 pelletized cold moderator with a new cryogenic system.

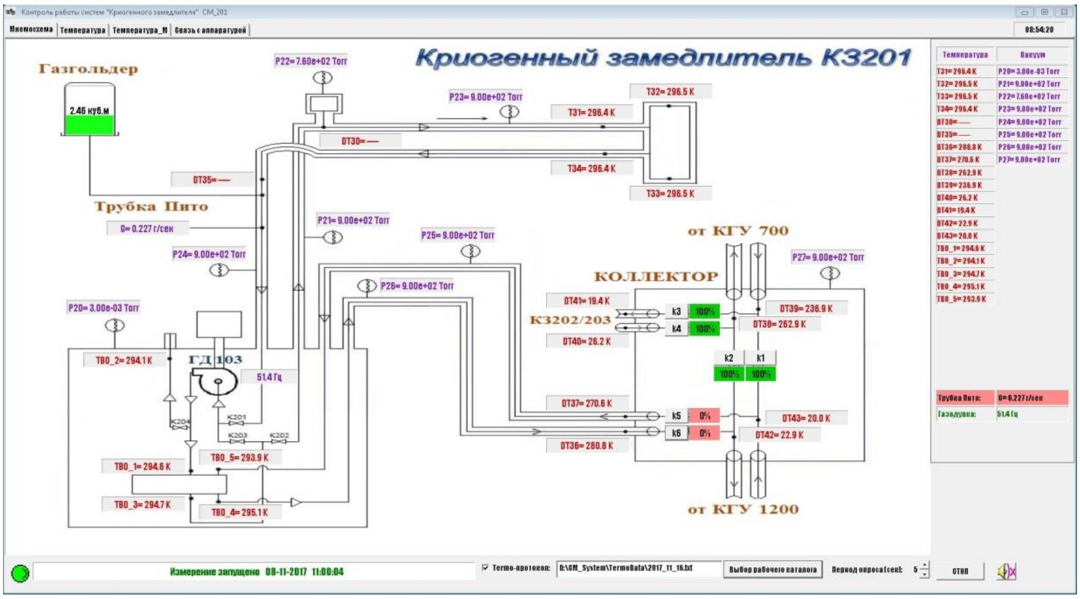

Fig. 2. Control program for the CM-201 pelletized cold moderator.

In 2018-2020, in the framework of the ongoing modernization of the complex of cryogenic moderators, at the test stand of CM-201 we carried out experiments with a new diaphragm flowmeter (DF), which was mounted on the gas outlet pipe using quick-release vacuum couplings on the same line with the Pitot-tube flowmeter used up to the present time to determine the flow rate of helium in the pipeline. During the tests, the diaphragm flowmeter showed stable operation for five temperature modes: 293 K, 100 K, 80 K, 60 K and 25 K. The DR readings were calibrated using a Pitot tube. Readings were recorded using differential pressure sensors of four types: for 25, 100, 250 and 400 Pa. During the experiments it was found that a differential pressure sensor for 250 Pa is most suitable for standard operating conditions of the cryogenic moderator. Basing on the results of the work, for two cryogenic moderators CM-201 and CM-202, it was decided to use a diaphragm flowmeter as a device for measuring helium flow rate.

Work continued on the development of a new method of counting frozen pellets and monitoring their movement during pneumatic transportation through the feed pipeline to the cryogenic moderator chamber. The method is based on the use of an optical sensor, in which two light-guiding fibers are in optical contact. When a pellet passes between the light-guiding fibers, the signal is interrupted, and the motion control program records this event. In the course of laboratory experiments on the test stand, it was found that the maximum error of the optical sensor in counting glass beads is 7.5%, which makes it possible to determine with sufficient accuracy the number of beads that passed through the pipeline section and then got into the moderator chamber. The data obtained in laboratory conditions were used in preparation for testing the optical sensor on the test stand of the CM-201 cryogenic moderator. In the framework of these experiments, it is planned to perform two procedures of loading frozen pellets (~ 20,000 pcs) from the dosing device into the moderator chamber of the test stand. It is expected that during the loading process, the optical sensor will successfully count the number of pellets moving towards the chamber with a detection error of no more than 8%.

During the scheduled preventive maintenance of the IBR-2 reactor, it is planned to install the CM-201 cryogenic moderator at its regular place in the direction of IBR-2 beamlines 1, 4-6, 9. After the installation of the moderator, the following starting-up and adjustment activities are planned: to cool helium charge/discharge pipelines and the moderator chamber to the lowest possible temperature (22 K); gas flow measurement in a pneumatic conveying pipeline using a diaphragm flow meter at various temperatures; to control cryogenic valves of the distribution collector of the cryogenic system using the CM-201 control software package, to test the operability of the whole complex. After the successful completion of commissioning, two test procedures of loading frozen pellets (in the amount of 1 l per loading) into the moderator chamber at the reactor core will be carried out with counting pellets using the optical sensor.

In one of the cycles of operation of the IBR-2 reactor in 2020, the CM-201 moderator chamber will be loaded in the operating mode at a rated reactor power of 1.6 MW.

A large amount of work has been performed on modeling a screw-type discharging device for the CM-201 moderator. The simulation results have shown that the creation of this device at the IBR-2 reactor with the current parameters of the head part of the cryogenic moderator (arrangement of radiation shielding, diameters of pipelines, severe restrictions on geometric dimensions of accessory equipment, etc.) is a hard-to-fulfill task. Therefore, it was decided to postpone this project for its possible implementation at the new neutron source of FLNP JINR, where, with a high probability, it will be possible to create favorable conditions for the use of such a device.

In the reporting period of 2018-2020, the regular operation of the CM-202 cryogenic moderator continued, during which the moderator operated faultlessly for seven IBR-2 reactor operation cycles. In total, by the end of 2020, the CM-202 cryogenic neutron moderator has operated for physics experiments for more than 4,000 hours, of which for more than 1,000 hours with a new cryogenic system, which includes two cryogenic facilities with a total cooling capacity of 1,900 W. The new cryogenic system made it possible to reduce the temperature of the working substance in the moderator chamber to 22K and thereby increase the cold neutron flux density by 15-20%. The experimental dependences of the neutron spectrum and the gain factor in the cold neutron flux density obtained during the operation of the cold moderator for physics experiments for IBR-2 beamline 7c (NERA spectrometer) and beamline 8 (REMUR reflectometer) at different temperatures are shown in **Fig. 3**.

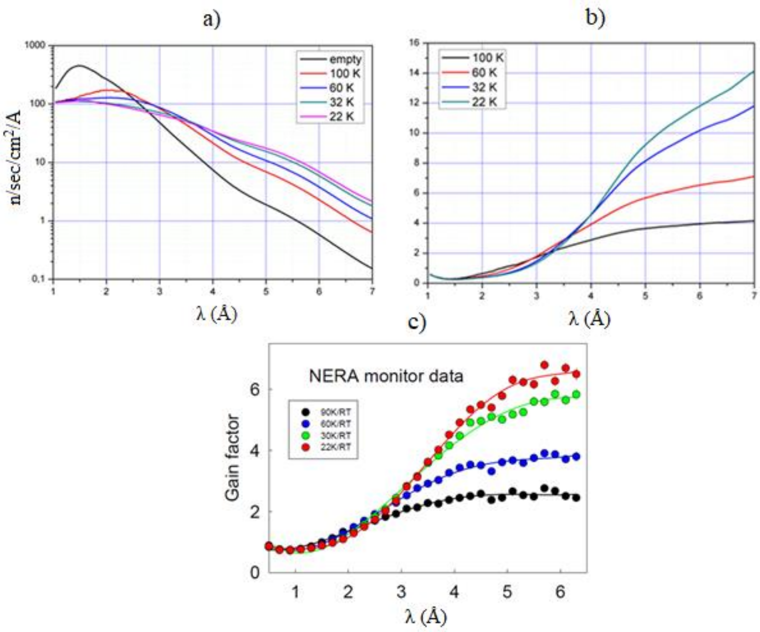

Fig. 3. Neutron spectra (a) and gain factor (b, c) in the cold neutron flux density from the surface of the cold moderator at different temperatures as compared to the cold neutron flux density from the surface of the thermal room-temperature water moderator. The graphs in figures *a* and *b* were obtained with the REMUR reflectometer, and in figure *c* – with the NERA spectrometer.

The analysis of the obtained results has shown that as compared to a thermal room-temperature water moderator, the cold moderator at a temperature of 22 K provides almost 6 times more cold neutrons for the NERA spectrometer and 14 times more for REMUR, which makes it possible to significantly shorten the exposure time for samples under study and reduce errors in results.

In the course of studying the possibility to extend the operation time of the cold moderator for physics experiments, it was found that at a reactor power of 1.8 MW and standard duration of the IBR-2 cycle of 11 days or ~ 520 MW·h (~ 160 MGy), the dynamic viscosity of the mixture of mesitylene and methaxylene, which is in an inert atmosphere of helium, increases to ~ 23 mPa·s (viscosity of pure mixture – 1.15 mPa·s). At this viscosity value, the irradiated molten mixture can be rather quickly and completely removed from the moderator chamber via a special drainage system, which means that there is no need to use dopants to reduce the viscosity of the mixture during irradiation. Nevertheless, any changes in reactor power, cycle duration, and other important parameters should be given due consideration.

Using gas chromatography, the content of gaseous radiolytic hydrogen produced in the moderator chamber was determined in two reactor operation modes: in the water moderator mode and in the cryogenic moderator mode. The measurements showed that the maximum concentration of radiolytic hydrogen in helium inside the chamber, as well as inside the helium inlet and outlet pipelines, reaches 6.5%. This concentration of hydrogen is safe and cannot result in the generation of excessive pressure, formation of an explosive mixture and the occurrence of other potentially dangerous factors that can destroy the moderator chamber and lead to an emergency during the IBR-2 operation at rated power.

3. Investigation of radiation resistance of materials with radiation research facility

In 2018-2020, the following major activities were performed with the radiation research facility at IBR-2:

- The temporary storage facility for solid radioactive waste on beamline №3 was modernized, which made it possible to improve the current radiation situation.
- The transport system of the radiation facility for handling samples directly under irradiation was upgraded, which allows shorter exposure times and lower neutron fluence. The application of this system is most important when irradiating various types of scintillators.
- The robotic arm was integrated into the video surveillance and distance measuring equipment for handling highly active samples in high ionizing radiation fields (**Fig. 4 *a***). A local dosimetry system was installed on the robotic arm for automatic measuring of doses during irradiation sessions (**Fig. 4 *b***). One of the main advantages of this system is a significant reduction in the radiation exposure of the personnel, as well as the acceleration of the process of transportation of highly active samples to the storage after irradiation. In addition, for the convenience of users, the facility was equipped with a flexible cable duct for the safe movement of cables and electronic components of printed circuit boards during online measurements under irradiation.

a

b

Fig. 4. Photos of the robotic arm taken using one of the cameras of the video surveillance and distance measuring system: **a** – pneumatic clump of the robotic arm at the moment of removing the container with a highly radioactive sample; **b** – dose measurement using the local dosimetry system at the moment before the robotic arm removes the container with the sample (radiation dose rate on the surface of the container ~ 78 mSv/h).

- In cooperation with VBLHEP JINR, Academy of Sciences of the Republic of Uzbekistan and Ural Federal University (Yekaterinburg), investigations of the nature of radiation-induced defects in samples of topazes and some other minerals after irradiation are in progress (**Fig. 5 *a***).
- In cooperation with the Laboratory of Magnetic Sensors of the Lviv Polytechnic National University, investigations of radiation resistance of graphene-based magnetic sensors (3D Hall sensors) were carried out within the framework of international projects for the development of ITER and DEMO fusion reactors.
- In cooperation with the State Corporation Rosatom and JSC “SSC RF TRINITI”, the study of neutron-physical characteristics of divertor neutron flux monitors based on uranium fission ionization chambers was conducted. According to special work programs, both chambers were irradiated at the IBR-2 reactor. Using newly developed programs and test methods, experiments were carried out on irradiation of new prototypes of a six-channel detection system together with detector units under conditions of intense neutron fluxes.
- In cooperation with the Belarusian State Technological University (BSTU), Minsk, Republic of Belarus, investigations of radiation resistance and changes in physical properties after irradiation of new promising materials for neutron guides were performed.
- In cooperation with MEPhI, the investigation of radiation degradation of nanoheterostructures based on AlGaAs/GaAs was carried out.
- In cooperation with the Institute of Nuclear Physics of the Academy of Sciences of the Republic of Uzbekistan, the effect of neutron radiation on the structure and some properties of aluminum alloys AMG-2 and SAV-1, which are used to manufacture the cladding of fuel rods for nuclear reactors was studied.
- In cooperation with the European Spallation Source research centre, work is underway on the irradiation of detector materials (Kapton printed circuit boards (**Fig. 5 *b***)) and boron carbide neutron choppers.
- In cooperation with DLNP and VBLHEP JINR, experiments on irradiation of samples of silicon scintillators and electronic components of printed circuit boards were conducted to study their electrical and physical properties under irradiation (**Fig. 5 *c***).

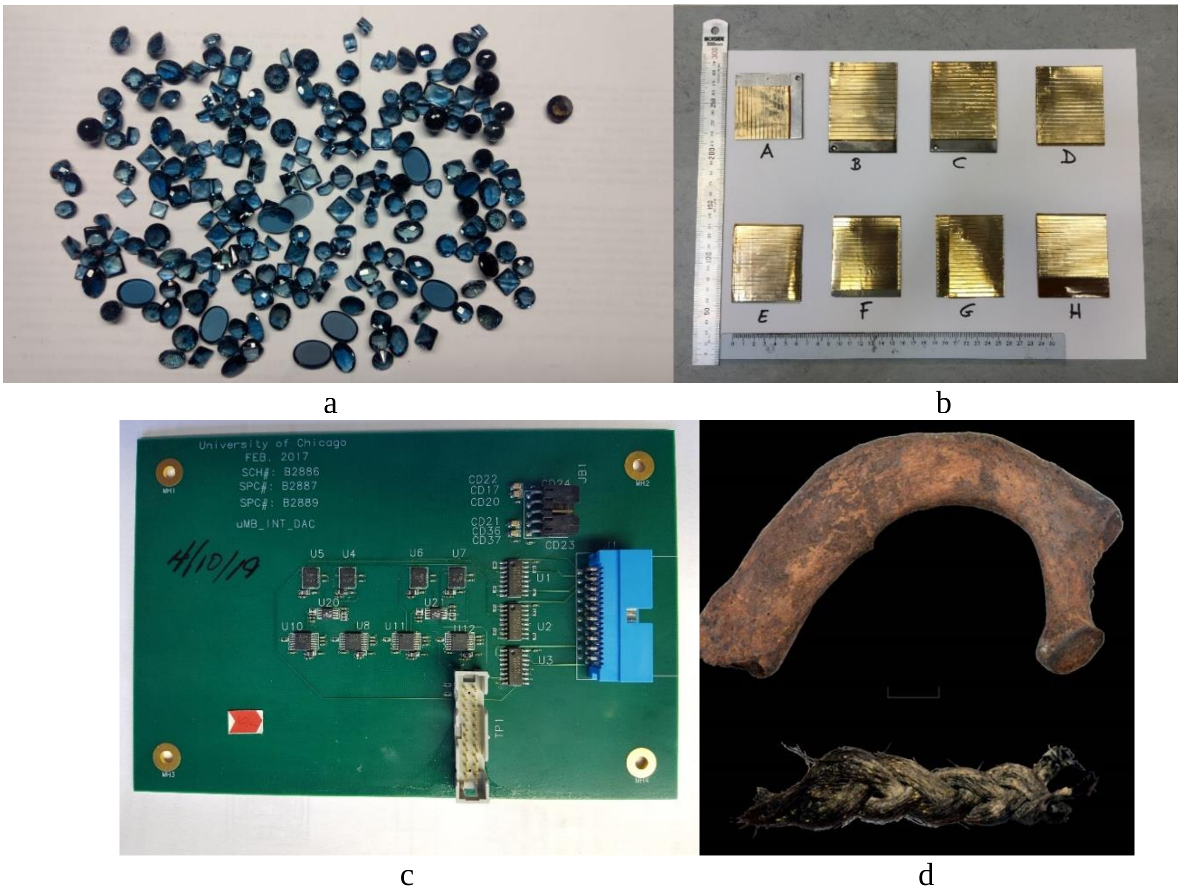

Fig. 5. Samples after irradiation on beamline 3 of the IBR-2 reactor: ***a*** – samples of topazes; ***b*** – detector materials; ***c*** – electronic components of printed circuit boards; ***d*** – fragments of the remains of members of Tsar Ivan the Terrible's family.

- In cooperation with the Moscow Kremlin State Historical and Cultural Museum and Heritage Site, work is underway to study the isotopic composition of the remains of the members of Tsar Ivan the Terrible's family using neutron activation analysis (NAA) to identify or confirm the causes of their death (**Fig. 5 *d***).
- In cooperation with the Institute of Archeology of the Russian Academy of Sciences, experiments were started to study the elemental composition of ancient ceramics found during excavations in the Volga Bulgaria region using the NAA method, which makes it possible not only to date cultural layers and hence the artifacts from other materials contained in them (remains of buildings and structures) but also to receive a lot of other important information about the production technology, population movements, etc.

4. Simulation of neutron instruments

During the reporting period, the development and support of the modules of the program for simulating neutron spectrometers and experiments for VITESS (Virtual Instrument Tool for European Spallation Source) were continued. Almost half of all VITESS modules have been developed in FLNP; in particular, the tasks of simulating polarized neutron instruments have been almost completely realized. It can be said that simulation, calculations and optimization of parameters of various units using VITESS programs were carried out for almost all IBR-2 spectrometers; the results of this work can be found in FLNP Annual Reports and publications.

The most recent results were obtained in the study in which, using the VITESS software package, the influence of the background at the IBR-2 reactor on data of reflectometry measurements was evaluated. For this purpose, the operation of a pulsed source with characteristics close to those of the IBR-2 reactor was simulated. The simulation of reflectometry measurements showed that for the same neutron spectrum in the beam and the background, the delayed neutrons begin to smooth the specular reflection curves only at sufficiently high momentum transfer. This effect is insignificant in the working q-ranges of reflectometers at IBR-2 (**Fig. 6**). Methodological studies of background conditions at other spectrometers will be continued in the framework of the new theme.

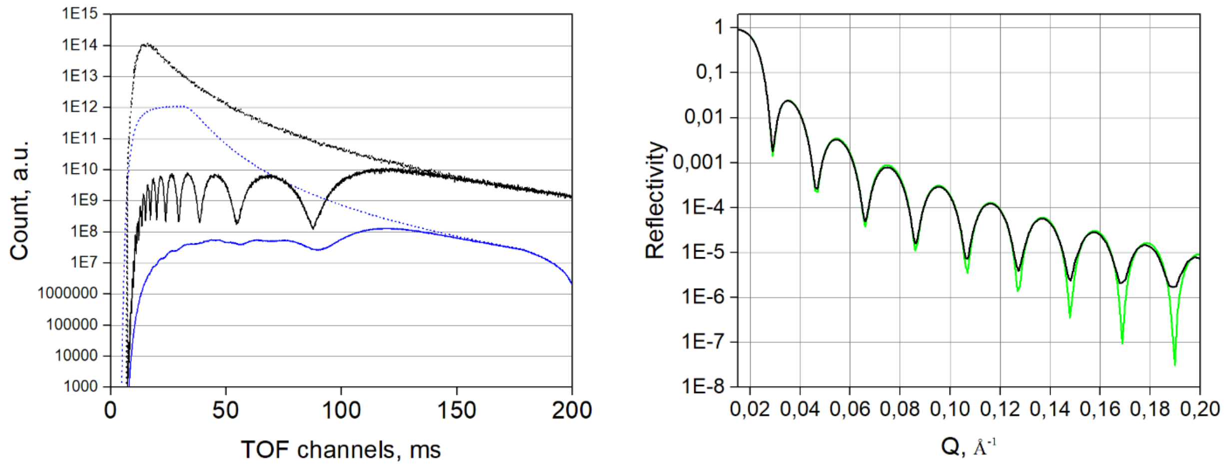

Fig. 6. Left: TOF spectra of direct and reflected beams for two sources separately. Blue – delayed neutrons, black – neutrons from a pulsed source. The dotted line corresponds to direct beams, the solid line – reflected beams. Right: reflectivity curves with (black) and without (green) background source.

5. Cryogenics and vacuum systems

Major activities in this research area of the theme were carried out in the framework of the project “***Development of a PTM sample environment system for the DN-12 diffractometer at the IBR-2 facility***” aimed at developing a horizontal-vertical cryostat for temperature and magnetic condensed matter investigations at the DN-12 spectrometer. The project is implemented in cooperation with the National Institute of Research and Development in Electrical Engineering ICPE-CA, Bucharest, Romania. At present, work on the project is successfully nearing completion (late 2020). At this session of PAC, a project activity report will be presented as a separate report. The magnet is currently being tested. Here we show only the general view of the magnet (**Fig. 7**) and the dependence of the magnetic field strength on the magnitude of electric current supplied to the magnet coils (**Fig. 8**).

Fig. 7. HTSC magnet and current leads.

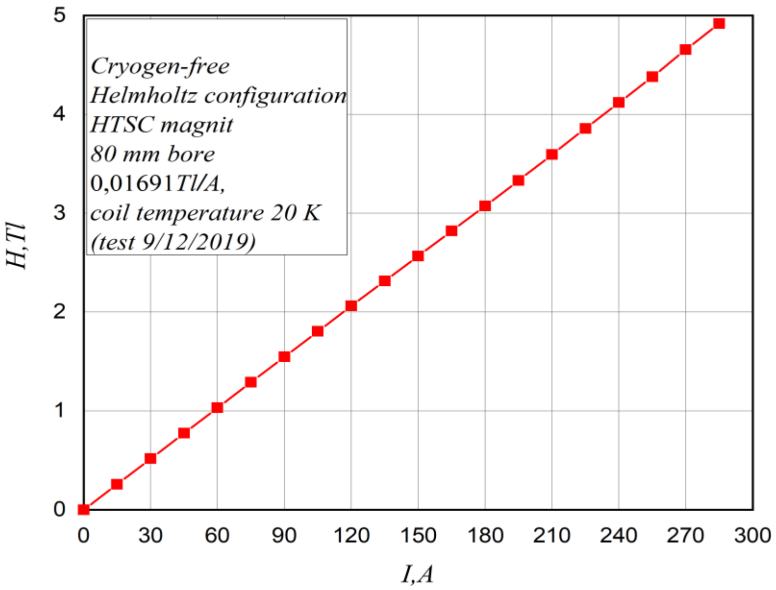

Fig. 8. Dependence of the magnetic field strength on the magnitude of electric current supplied to the magnet coils (this characteristic turned out to be strictly linear, which indicates that there are no signs of degradation of the HTSC tape).

The cryostat is a system that depends only on an electric power source. The cooling system of the compressors of cryocoolers and the power source of the superconducting magnet is autonomous, based on closed water circulation. In the summer (during the reactor shutdown for preventive maintenance) and autumn of 2020, it is planned to install the cryostat of the magnet on the DN-12 diffractometer.

The development of continuous-flow cryostats based on closed-cycle cryocoolers was completed. In particular, we developed a $^{3}He/^{4}He$ refrigerator on the basis of a closed-cycle cryocooler with a continuous flow system of heat exchangers (**Fig. 9**). By design, the refrigerator is a column of heat exchangers located on the cold head of a cryocooler. This column is inserted into a vertical sealed shaft with a diameter of 150 mm made of thin-walled stainless steel. There is an evaporator for liquid ^{3}He or ^{4}He at the lower end of the shaft. In the ^{4}He liquefaction mode, a cooling capacity of 1.6 W at 4.2 K was achieved, and in the ^{4}He refrigerator mode the final temperature was 1.4 K. In the ^{3}He refrigerator mode with continuous pumping and condensation, the final temperature was 0.78 K. In a single mode, with a zero condensation rate, the final temperature reached by the ^{3}He refrigerator was 0.52 K. **Figure 10** shows a graph of the temperature of the evaporator of the refrigerator versus the operating time in the continuous and single modes, as well as the temperature of the second stage of the cold head of the cryocooler.

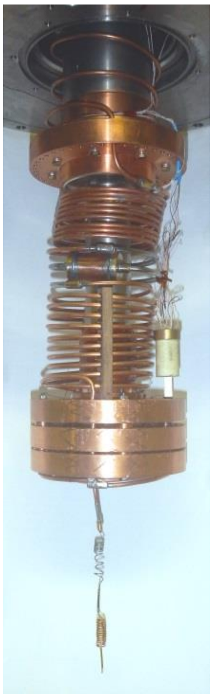

Fig. 9. Refrigerator with a continuous flow system of heat exchangers.

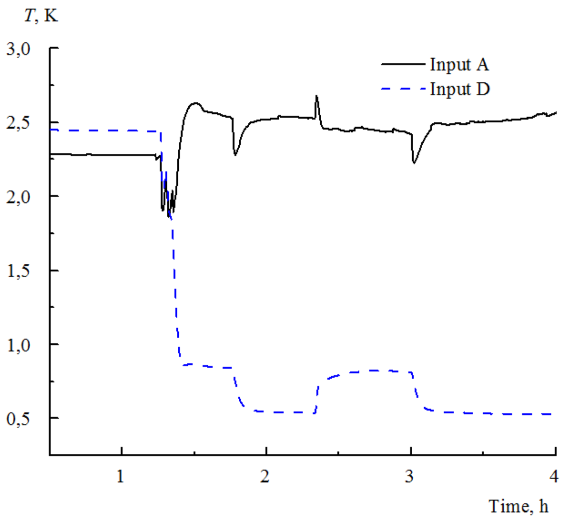

Fig. 10. Switching from the continuous mode to the single mode and back (temperature of the evaporator varies from 0.78 K to 0.52 K). Input A - temperature of the second stage of the cryocooler. Input D is the evaporator temperature.

A mode with a zero external pumping rate of ^{3}He was realized, in which the time of maintaining temperature with a positive constant drift of 1.5*10^{-3} K/h in the temperature range of 1.05-1.5 K is 11 days (**Fig. 11**).

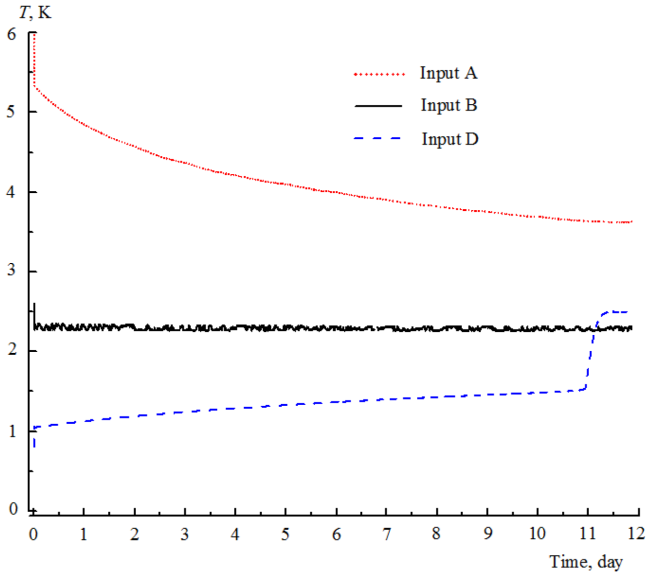

Fig. 11. Mode with a zero external-pumping rate: the temperature of the evaporator rises slowly from 1.05 K to 1.5 K in the period of 0-11 days, then increases sharply to 2.7 K and stabilizes at this level (Input A – temperature of heat exchangers; Input B – temperature of the second stage of the cryocooler; Input D – temperature of the evaporator).

In connection with the development of a cryostat with a magnet with a horizontal sample loading shaft, it was necessary to study the heat inflow due to the heat exchange of gas in the cryostat with a horizontal sample loading configuration. For this purpose, a cryostat with a GM-cryocooler was manufactured. This cryostat has a vertical stainless steel tube, which is connected to the second stage of the cryocooler by means of a copper thermal bridge. The tube was filled with helium gas, and the cryostat was installed in several positions by rotating in the range of 0-180 degrees relative to the vertical axis. During the experiment, the temperature of the ends of the thermal bridge was measured. It was experimentally shown that the heat inflow due to the heat exchange gas is insignificant in any position of the cryostat. In this study, we obtained experimental data necessary for designing spectrometers, in which shaft cryostats can be installed in any spatial orientation.

The shaft cryostat with a shaft diameter of 80 mm at the NERA spectrometer was upgraded. The cryostat used a pulse-tube cryocooler, which was due to its operation only in vertical orientation according to the configuration of the NERA spectrometer. The cold head of the cryocooler with the expired service life period was replaced with a GM type cold head. Experiments were conducted to check the operability of the cryostat, which showed the possibility of its operation in both vertical and horizontal positions, with almost the same final temperature of 4.5 K.

New nitrogen equipment was installed and put into operation in experimental hall №1 and building 117/2, and the vacuum systems of neutron guides on beamlines 7, 9 and 10 were upgraded.

6. Detectors and electronics

In FLNP, within the framework of the theme under discussion, several types of neutron detectors based on multiwire proportional chambers filled with a gas mixture of $^{3}He+CF_4$, which were designed both to equip the newly developed and constructed IBR-2 spectrometers (for example, GRAINS, DN-6, RTD), and to upgrade detector systems for the available instruments (HRFD, REMUR, REFLEX, DN-12, etc.). These include:

• **Two-dimensional monitor position-sensitive detector** (PSD) with low attenuation of the incident neutron beam (active area – 100×100 mm^2, coordinate resolution ~ 4×4 mm^2). The detector is used to measure neutron beam profiles on IBR-2 beamlines.

• **One-dimensional PSD** (active area – 200×80 mm^2, coordinate resolution ~ 2 mm, detection efficiency for thermal neutrons (2Å) ─ more than 60%). These detectors are installed on the HRFD and REFLEX spectrometers, as well as provided to M.N.Mikheev Institute of Metal Physics of the Ural Branch of RAS (Ekaterinburg), NRC "Kurchatov Institute" (Moscow) and Obninsk branch of the L.Ya.Karpov Scientific Research Institute of Physics and Chemistry (Obninsk).

• **Two-dimensional PSD** (active area – 200×200 mm^2, coordinate resolution ~ 2×2.3 mm^2, detection efficiency ~ 65%). These detectors are installed on the IBR-2 spectrometers (REFLEX, GRAINS and RTD), and are also used for the cryogenic moderator to control the filling of the moderator chamber with mesitylene pellets (monitoring is conducted by taking neutron images of the moderator chamber by a 2D PSD using the "camera obscura" technique). Detectors of this type were provided to the Institute for Nuclear Research of RAS (Troitsk), NRC "Kurchatov Institute" and four detectors – to the Nuclear Physics Institute of ASCR (Řež, Czech Republic). A general view of the 1D and 2D detectors is shown in **Fig. 12 *a, b***.


a)

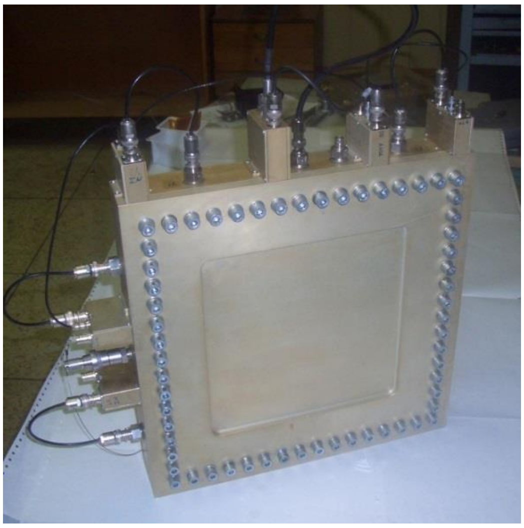
b)

Fig. 12. 1D (a) and 2D (b) PSD.

In these PSD, a signal from the anode is used as a start pulse, and coordinate data are read out of the cathodes via delay lines. In FLNP, for acquisition and accumulation of data from PSD, two types of unified programmable modules were developed: De-Li-DAQ 1 (designed in cooperation with HZB, Berlin) and De-Li-DAQ 2D.

• **Multi-section ring-shaped thermal neutron detector** for diffraction studies on microsamples in axial geometry on the DN-6 diffractometer [3]. The detector consists of 16 sections, which share the same gas volume. Each section, in its turn, is divided into 6 cells along the generatrix of cylindrical surface. The total number of detecting elements is 96. Signals from individual cells are read from independent anode wires, which are placed in the geometric centers of the cells. Charge-sensitive preamplifiers are located near the anode wires inside the gas volume. Individual data readout from each cell provides the necessary flexibility for tuning and positioning the detector. The detector has no analogues in the world and provides the same detection efficiency for all detector elements.

• In 2018, a new **ring-shaped multi-section detector** (**Fig. 13**) designed for small-angle neutron scattering studies was put into operation at the RTD real-time diffractometer. The difference between this detector and previous ring detectors is the possibility of simultaneous determination of angular and radial coordinates of detected neutrons. Due to its original design, the detector is a useful tool for any research where angular and/or axial anisotropy of thermal neutron scattering is observed. The authors of the proposed design filed an application for invention (RU 2018108597) “Gas-filled detector for small-angle thermal neutron scattering measurements”.

Fig. 13. Photo of the ring-shaped multi-section detector on a test stand.

The detector is divided into 9 independent equidistant coaxial rings. The cathodes of each ring are divided into 16 independent sectors forming 144 independent detector elements. Signals are read from anode wires (shared by all rings) and from each of 16 cathodes. To eliminate the effect of impulse noise and reduce electronic noise, the preamplifiers of detector elements are placed inside the gas volume.

Digital electronics for data acquisition and accumulation are based on unified MPD modules, and comprise 5 modules of 32-channel discriminators and an MPD32 controller.

In terms of their characteristics all the detectors described above are comparable to the world’s best analogues and in some cases even surpass them in a number of parameters. All the detectors are widely applied both in FLNP and in other scientific centers of the JINR Member States. Until recently, there were some problems in the manufacture and assembly of detectors, related to the small size and insufficiently high air purity class of a clean room (CR), but at the end of 2018, the activities on the creation and commissioning of CR (**Fig. 14**) were completed. The CR is located in FLNP bldg 119 and comprises two clean zones: an anteroom and a working area. The anteroom is used for assembling and cleaning the component parts of detectors, as well as a dressing room for entering the working area. The working area serves for mounting and washing detector electrodes, as well as for assembling detectors. The total area of the clean room is 44.7 m^2, and the area of the working zone is 29.8 m^2. The clean room maintains an excess pressure, constant temperature and humidity, and the air is filtered to remove aerosol and suspended particles. The air purity in the anteroom corresponds to ISO 7 class, in the working area ― to ISO 6 class in accordance with GOST ISO 14644-1-2002. The major activities on creating a clean room were performed under a contract with LLC "ITT".

Fig. 14. Working in a clean room.

The creation of CR allows us to significantly reduce the time required for assembling neutron detectors, and, most importantly, improve the quality of performed work. New equipment is being put into operation: an ultrasonic bath for cleaning PSD frames, a new winding machine for stretching wires over the frames of multi-wire gas detectors. The winding machine will significantly speed up the production of frames and reduce the time of creating gas detectors.

Studies were carried out on the possibility to use additive technologies in the development of neutron detectors. A 3D printer RAISE3D Plus based on fused deposition modeling technology and stereolithographic photopolymer 3D printer Flashforge Hunter were purchased and put into service. Using these printers, the positioning elements of the detector modules for the NERA-PR spectrometer and a number of auxiliary devices were manufactured.

In 2019, in the framework of the development of ***gas detectors***, a large amount of work was carried out to upgrade the detector system of the NERA spectrometer. Various variants of detector modules, which differ in the number of counters in the assembly, were designed and manufactured. The modules consist of proportional helium counters Helium-18/200-8.0 from KONSENSUS (Zaprudnya, Moscow Region), which are similar to SNM-18 counters. Variants of the modules consisting of 3, 4, and 5 counters were developed (**Fig. 15**). The efficiency of the modules was simulated using the GEANT 4 software package (CERN). Using the simulation results, we selected the variants that are best suited for use on the NERA spectrometer. Several versions of the modules were manufactured. Their counting characteristics and efficiency were measured with a laboratory neutron source and the NERA spectrometer. On the basis of the results of the tests, a variant consisting of 5 counters was selected as a working one. New modules of counters were manufactured, assembled and tested along with the electronics for both arms of the NERA detector system. Fasteners for fixing counters in the new modules were made on a 3D printer. At present, the new detector system has been put into operation.

Fig. 15. Variants of the detector modules for the NERA spectrometer, ready-assembled with a preamplifier and interference shielding.

A 2D PSD for the HRFD diffractometer was manufactured, tested and put into operation.

A test refillable counter was developed to test gas mixtures of neutron detectors. Two such counters, designed to measure amplitude spectra at various pressures and compositions of gas mixtures, were produced by LLC KONSENSUS.

In cooperation with Dubna State University, work is underway to develop and construct neutron converters based on boron carbide enriched in ^{10}B isotope. A unique technology has been developed for deposition of a thin layer of boron carbide on a large-area aluminum substrate by magnetron sputtering. The first specimens of sputtered films were produced (**Fig. 16**). The results of the work are planned to be used in the development of neutron detectors (primarily neutron monitors). The main results of the work were reported at scientific conferences and seminars, and publications are being prepared.

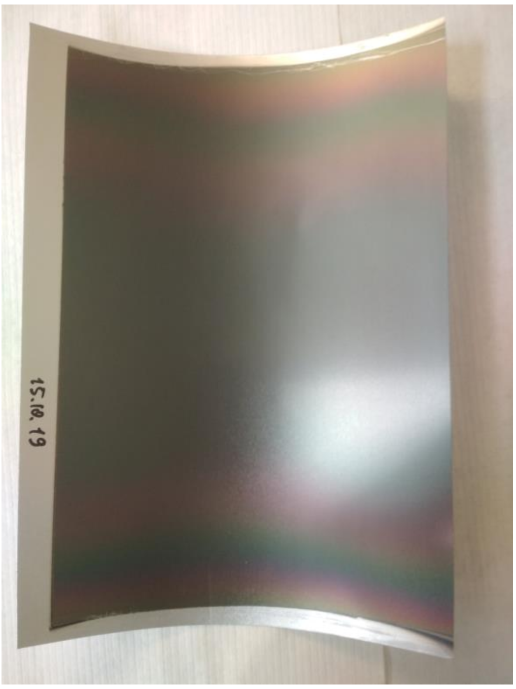

Fig. 16. Specimen of sputtered B_4C film on aluminum substrate (film thickness in the central part – 2 μm).

The tests of the prototype of a PSD based on a multiwire proportional chamber with a ^{10}B-enriched boron carbide converter have been completed (**Fig. 17**). The converter was manufactured in the framework of collaboration with Linköping University and ESS (Lund, Sweden). We obtained a coordinate resolution of 0.9 mm in the coordinate perpendicular to the anode, which is which is two times better than the resolution of existing gas PSD. The layer thickness of the converter prototype is 0.5 μm, thus, in time-of-flight experiments it is possible to achieve the accuracy of determining the neutron detection time at least an order of magnitude higher than that of conventional gas counters. During testing, the prototype with a solid B_4C converter showed good stability in the direct neutron beam, which is important for neutron position-sensitive direct-beam monitors.

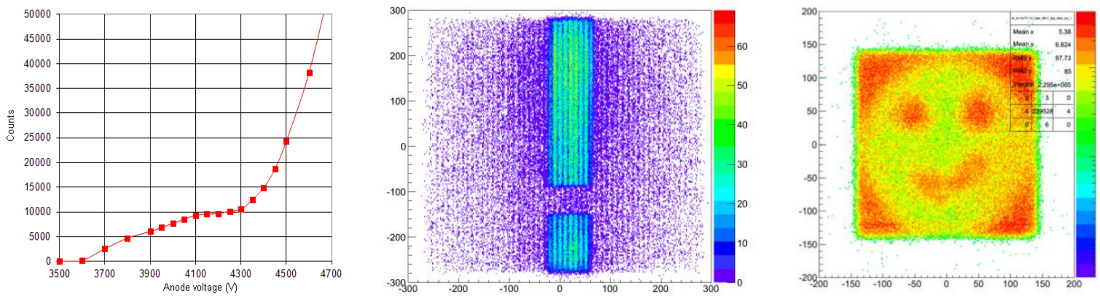

Fig. 17. Left: counting characteristics at 2000 mbar of CF_4. Middle: direct beam of IBR-2 beamline 13 with a 1-cm cadmium plate (channel graduation – 0.194 mm). Right: spectrum from a scattered neutron beam covered by a cadmium mask (channel graduation – 0.388 mm).

A 2D PSD monitor was developed and manufactured for measuring the intensity and spatial distribution of neutron beams at the IBR-2 reactor. A thin layer of B_4C is used as a neutron converter. Measurements of the characteristics of the monitor, including the determination of its absolute detection efficiency for thermal neutrons depending on their energy, are planned to be carried out during the IBR-2 operation cycle in the autumn of 2020.

One of the sixteen modules of the 45° ring detector (**Fig. 18**) for the DN-6 spectrometer, consisting of six Helium-13/90 counters, was assembled. The technique for filling high-voltage terminals of neutron counters with a compound was worked out and improved, which made it possible to reduce leakage currents to 4 nA. The modules for 96 channels of analog electronics were manufactured and tuned. One channel includes a charge-sensitive preamplifier, signal-shaping amplifier, and a high-voltage power filter. Electronics for six channels are housed in one module.

Fig. 18. Module of 45° ring detector for the DN-6 spectrometer.

Preliminary tests were carried out on a test stand with a neutron source. Amplitude spectra and counting characteristics were measured. Using the obtained data, the operating voltage and discriminator thresholds were selected. A data acquisition system consisting of three modules of 32-channel discriminators and a digital module MPD-32 was manufactured and tuned (**Fig. 19**). This made it possible to increase the total number of DAQ channels of the DN-6 spectrometer up to 288.

Fig. 19. 96-channel data acquisition system for the DN-6 spectrometer.

Measurements were conducted with the neutron beam of the DN-6 spectrometer; the obtained TOF spectra are shown in **Fig. 20**.

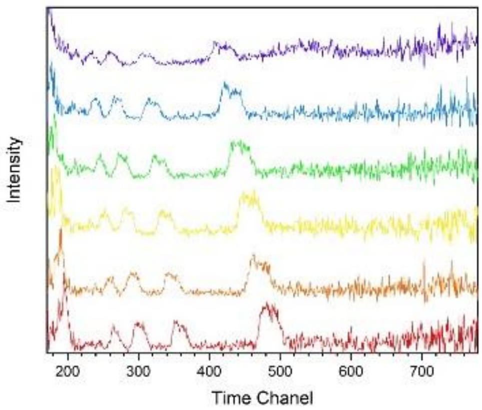

Fig. 20. TOF spectra obtained from one module of 45° ring detector.

In 2019, a series of neutron detection experiments were conducted using new ***semiconductor crystals*** of $LiInSe_2$ that are sensitive to thermal neutrons. The measurements were carried out with crystals measuring $5 \times 5 \times 1.5$ mm^3 (**Fig. 21**) and $10 \times 10 \times 1$ mm^3.

Fig. 21. $LiInSe_2$ crystal ($5 \times 5 \times 1.5$ mm^3).

For the measurements, a laboratory neutron source ^{252}Cf (6.3×10^5 n/s) was used, which was placed at a distance of 5 cm from the detector in a polyethylene moderator. The leakage current was measured and the optimum operating voltage for neutron detection was determined. Spectra were acquired using a multichannel analyzer from Amptek. The measurement results are shown in **Fig. 22**.

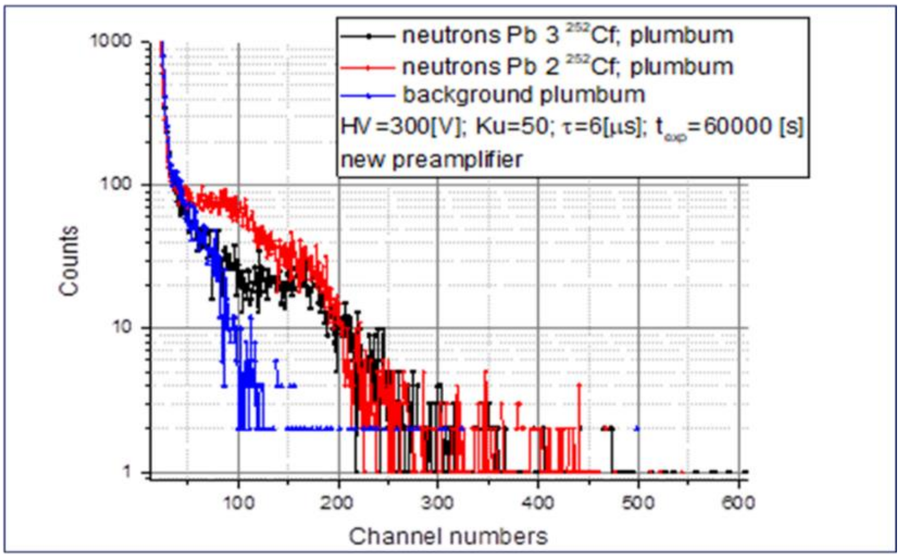

Fig. 22. Amplitude neutron spectra obtained with a ^{252}Cf source (high voltage H_v = 300 V, signal shaping time τ = 6 µs, gain K_U = 50, measurement time t_{exp} = 60,000 s, gamma radiation shielding – lead plate 0.5 cm thick).

The detector was also tested with a real-time diffractometer (beamline 6 of the IBR-2 reactor). In this case, to acquire spectra, we used a standard data acquisition system based on MPD-240 modules. The measurement results are shown in **Fig. 23** and **Fig. 24**.

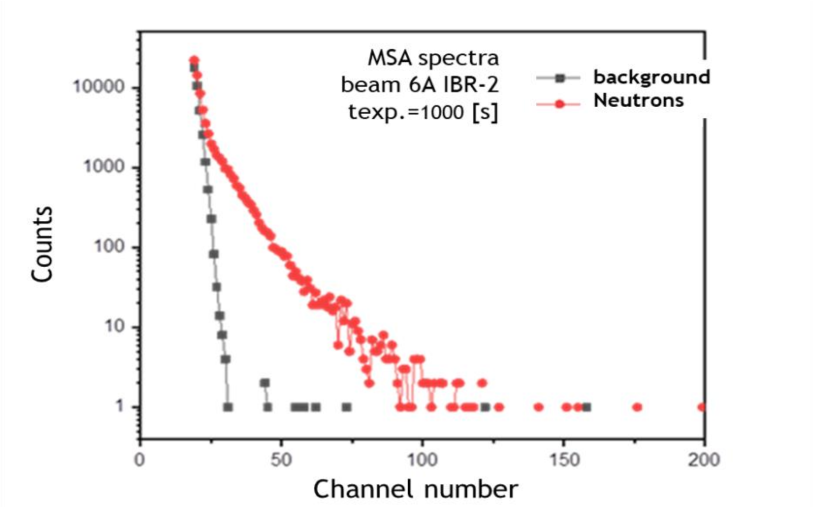

Fig. 23. Amplitude spectra of $LiInSe_2$ measured in a direct beam of IBR-2 beamline 6a (voltage – 300 V, measurement time – 1000 s).

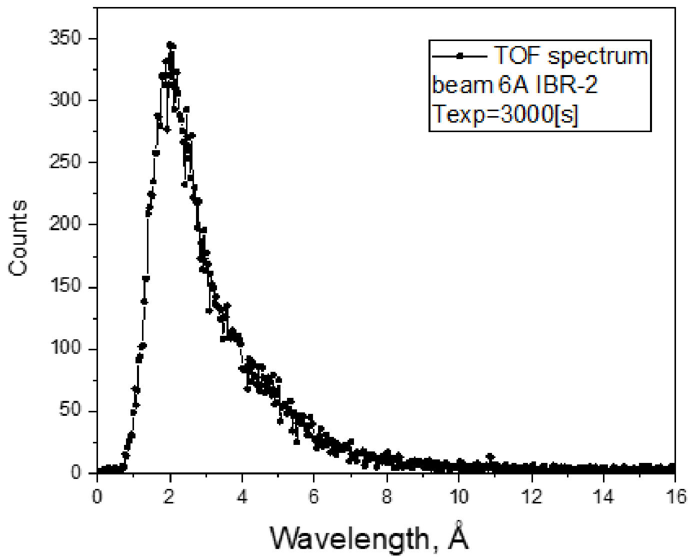

Fig. 24. Time-of-flight spectrum measured for 3000 s (the figure shows the Maxwell distribution of the neutron flux as a function of the wavelength).

The firmware of the DAQ-system DeLiDAQ-2 was upgraded, a number of software components were developed, and comparison tests of three data acquisition systems used at the IBR-2 spectrometers (DeLiDAQ-1, DeLiDAQ-2 and a system based on CAEN N6730 digitizer with DPP-PSD firmware) were carried out. The analysis of the results from the measurements carried out with the REFLEX and GRAINS spectrometers showed that for typical workloads there is good agreement between the results yielded by all three systems, and confirmed that the quality of time-of-flight spectra depends not on the average load, but on the peak load in the input stream. This analysis made it possible to determine the limits and conditions of applicability of the three data acquisition systems and make an adequate choice of electronics for time-of-flight measurements with position-sensitive thermal neutron detectors with delay-line readout. On the basis of the analysis, we can recommend using DeLiDAQ-2 for high-flux measurements, the system based on CAEN N6730 digitizer – for high-precision experiments, and suggest that the outdated DeLiDAQ-1 should be replaced with one of the two systems mentioned above in the near future.

The main activities in the development of ***scintillation detectors*** were conducted within the framework of the project “***Development of a wide-aperture backscattering detector (BSD) for the HRFD diffractometer***” aimed at developing the design, manufacturing mechanical components and constructing one (out of twelve) segments of the detector along with electronics and software, as well as conducting its tests on a test stand. At present, design work has been completed; drawings of the mechanical parts of the detector structural elements were forwarded to SPA “Atom” for production; manufacture of tooling equipment for the creation of detector components is underway; basic equipment and consumables have been purchased. A scale model of BSD is presented in **Fig. 16 A**, and **Figure 16 B** shows the architecture of a data acquisition system for one of the 12 detector segments (the segment is marked in green).

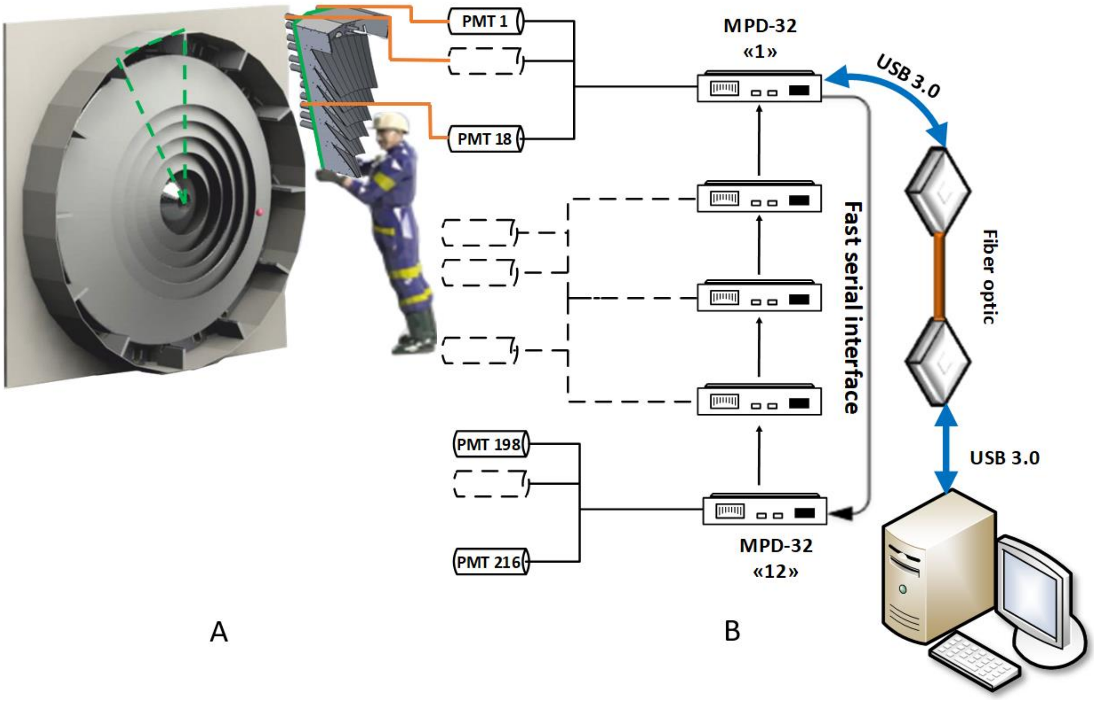

Fig. 25. A scale model of BSD (A) and the architecture of the data acquisition system (B).

In accordance with the project schedule, the development of electronics and software for the data acquisition system for the BSD detector was continued. On the basis of the results obtained in the course of debugging the prototype of the MPD32-based data acquisition module that includes a 32-channel discriminator, time encoder, gigabit transceiver and USB3.0 interface, we developed a working draft of documentation and produced prototypes of printed circuit boards and modules that received the name MPD32-USB3 (**Fig. 26**).

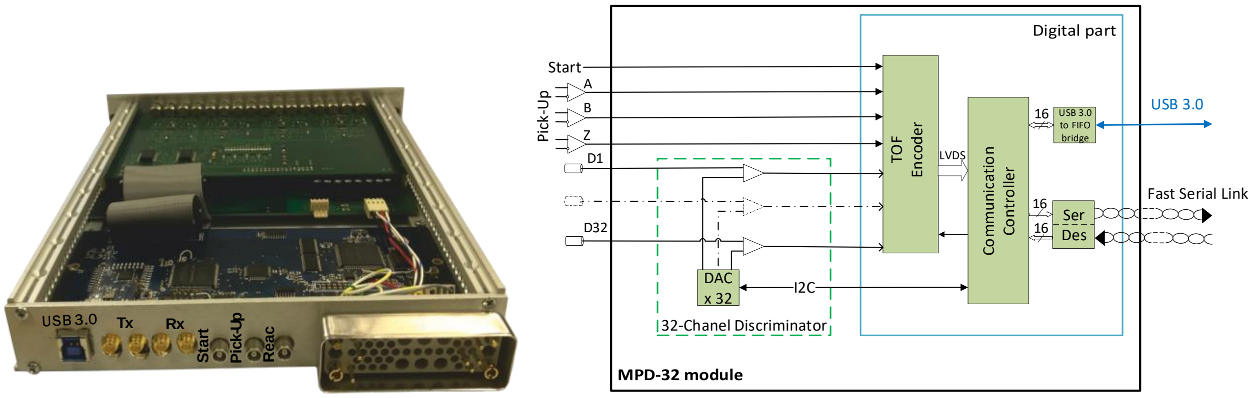

Fig. 26. MPD32-USB3 data acquisition module (left – prototype, right – block diagram).

The architecture and characteristics of the developed data acquisition system meet the project requirements. The manufactured modules are now used for debugging the data transfer protocol and developing software drivers. The communication protocol provides addressed packet transmission of data and commands in a multi-module system with a common USB3 interface. Information on the activities in the framework of the BSD project will be submitted to the PAC as separate report.

The fabrication of elements of 14 planes of the ASTRA-M detector is nearing completion. The photo (**Fig. 27**) shows a set of detection elements prepared for installation for one of the detector planes. All manufactured elements were tested on a test stand. We have carried out the investigations and preparatory work that make it possible to conduct comprehensive testing of the ASTRA-M detector on IBR-2 beamline 13 before installing the detector in its regular place on the FSD diffractometer at the end of 2020.

Fig. 27. Set of elements of the Astra-M detector.

A number of methodological studies and developments were carried out, in particular, the basic components were manufactured and the prototype of the scintillation hodoscope was assembled for use as a 2D large-area (up to 1 m^2) neutron detector for small-angle experiments, as well as the study of signals from thermal neutron scintillation counters was conducted and a method for enhancing the counting capacity of these counters was proposed.

A team of employees was formed and trained (laboratory assistants, technicians, engineers – a total of 8 people), which is sufficient to accomplish the tasks of serial production of scintillation neutron detectors, which is especially important for the successful completion of work under the new theme and the new project aimed at constructing a full-scale backscattering detector for the HRFD diffractometer, as well as for a number of other activities.

7. Control systems of actuators, sample environment equipment and choppers for spectrometers

The CC-10 controllers of the chopper control systems at the GRAINS and REFLEX spectrometers were replaced with CC-3U controllers in a 3U chassis, which are connected to a computer via the RS232 interface and provide control over choppers from the experiment control program. The controller is powered by a +5V power adapter, which eliminates the need for using outdated and cumbersome CAMAC crates for the chopper control systems, which were previously used to house CC-10 controllers and their power supply systems. In the future, it is planned to replace CC-10 controllers on other spectrometers as well.

A double-disk chopper with a control system (MIRROTRON Ltd., Budapest, Hungary) for the GRAINS spectrometer was manufactured and delivered to JINR. At present, all equipment is placed in the ring corridor of the reactor. Starting-up and adjustment activities will be carried out in cooperation with the Hungarian specialists.

To simulate the operation of a Fourier chopper and study its characteristics, a special test stand “motor – servo-amplifier” was constructed, which imitates the operation of a real chopper (**Fig. 28**).

Fig. 28. Test stand “motor – servo-amplifier”.

The modernization of ***temperature control systems*** was continued. The installation and commissioning of a regulated power supply 160V*4A on IBR-2 beamline 5 was completed. The DC amplifier EA-PS-160-04 is controlled by LS325 controllers with a voltage of 0÷10 V and supplies a current of 0÷4 A to the heating element, while the voltage can reach 160 V. The range of values of these parameters makes the amplifier suitable for controlling all heating elements used on the IBR-2 spectrometers, both in cryogenic heads and in air “ovens”.

A number of new ***actuators*** were included in the composition of spectrometers, in particular:

− “JJ X-RAY” slit systems (60x120 mm) for collimation of a neutron beam were installed on the HRFD and FSD diffractometers (**Fig. 29**);

− For REMUR, a sample positioning device, controlled by four actuators, was developed.

In both cases, it required a corresponding increase in the number of RS485 control channels.

Fig. 29. “JJ X-RAY” slit system at the FSD diffractometer.

At the radiation research facility, the robotic arm undergoes “training” to expand the range of tasks it performs. The accessory equipment was fine-tuned and adapted taking into account the peculiarities of using the robotic arm.

The capabilities of the interface of the control system of valves of the CM-202 moderator were expanded and the number of remotely controlled valves in the system was increased taking into account its further development. It is planned to design a similar system for CM-201.

The revision and modernization of start signals on the IBR-2 reactor spectrometers was carried out.

Cable ducts were upgraded on IBR-2 beamlines 5, 6a, 6b and 11: in the restricted access areas, cables were placed in wire trays, and in the experimental houses, they were laid in plastic cable ducts. This work will be continued next year for other spectrometers.

8. Software for spectrometers and FLNP network infrastructure

The development of the Sonix+ software package was continued both on users' request and in order to improve the internal structure of the software package on the basis of Python 3 and Qt5 graphic framework. This version of Sonix+ also provides communication with the WebSonix service and automatic saving of measured data in the central repository of FLNP. The new variant of Sonix+ was installed for the REMUR, DIN-2PI, FSD, SKAT, NERA and GRAINS spectrometers.

Modules for connecting new devices (LakeShore temperature controllers, new Fourier chopper, CAEN N6730 digitizer, DeliDAQ2, etc.) were prepared; programs for communication with the repository and a system script library were improved. In the framework of the development of Sonix+ for reflectometers, the instrument tuning program ICE was significantly modified (**Fig. 30**).

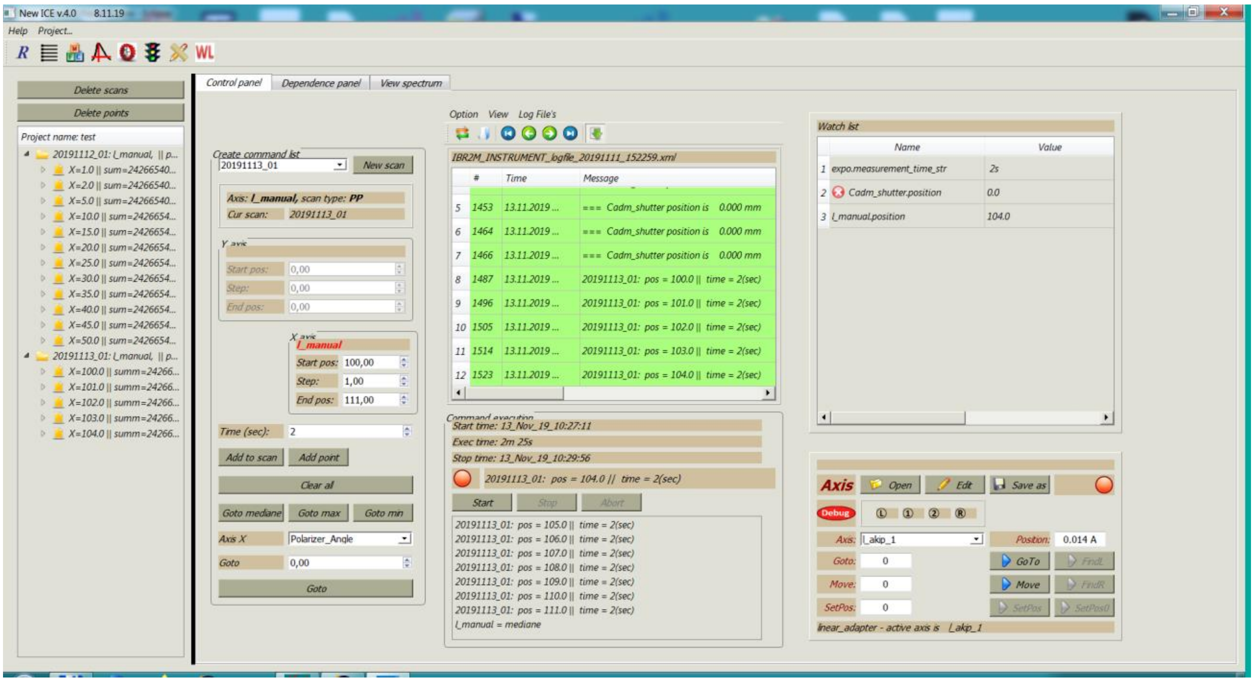

Fig. 30. User interface of the ICE program (version 4.0).

To promptly inform users about the progress of measurements by e-mail and Telegram messenger, a Bot program was developed, which was put into service for the FSD spectrometer.

The debugging of the software interface for DAQ controllers based on the USB-3 interface was continued.

A concept of a central repository of experimental data for the IBR-2 spectrometers was developed and implemented. The user interface of the Journal system was improved for working with data directly in the repository.

A program for controlling the valves of the CM-202 cryogenic moderator was developed and installed.

New FLNP mail servers were put into service. The modernization of the Wi-Fi network in buildings 119 and 42A was completed. To increase the transmission capacity in the FLNP network up to 100 Gb/s, CISCO Catalyst 9500-32C central router was put into operation, to which, in 2020, buildings 42, 42a, 117 and 119 will be connected via transceivers. Further work on upgrading the FLNP local area network will be carried out according to the plans agreed with LIT.

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During the period of implementation of the theme, 75 papers in specialized journals were published and about 60 reports were presented at international and Russian conferences. Three series of studies carried out in the framework of the theme were awarded prizes in the JINR Prize Competitions (two Second Prizes and one Encouraging Prize). One Doctoral (Kulikov S.A.) and one PhD (Bulavin M.V.) dissertations were defended; one PhD dissertation (Chernikov A.N.) was prepared for defense. Among the employees involved in the activities under the theme are two Doctors of Sciences and eight PhD researchers.