Appendix 1

Form № 24

PROJECT

Construction of a Complex of Cryogenic Moderators at the IBR-2 Facility

Theme: «Development of the IBR-2 Facility with a Complex of Cryogenic Neutron Moderators»

Theme code: 04-4-1105-2020/2022

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DATE OF SUBMISSION OF PROJECT PROPOSAL TO SOD _________

DATE OF LABORATORY STC _________ DOCUMENT NUMBER _________

DATE OF FIRST APPROVAL OF THE PROJECT ______________

Appendix 2

Form № 25

PROJECT ENDORSEMENT LIST

Construction of a Complex of Cryogenic Moderators at the IBR-2 Facility

Theme: «Development of the IBR-2 Facility with a Complex of Cryogenic Neutron Moderators»

Theme code: 04-4-1105-2020/2022

APPROVED BY JINR DIRECTOR	___________________	«____»________2019
ENDORSED BY		
JINR VICE-DIRECTOR	___________________	«____»________2019
CHIEF SCIENTIFIC SECRETARY	___________________	«____»________2019
CHIEF ENGINEER	___________________	«____»________2019
HEAD OF SCIENCE ORGANIZATION DEPARTMENT	___________________	«____»________2019
FLNP DIRECTOR	___________________	«____»________2019
FLNP CHIEF ENGINEER	___________________	«____»________2019
PROJECT LEADER	___________________	«____»________2019
ENDORSED		
PAC for CMP	___________________	«____»________2019

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Introduction

Most modern experiments are conducted in the wavelength range from 0.4 Å and above [1]. This is the region of "thermal" (0.4-4 Å) and "cold" (4-28 Å) or long-wavelength neutrons. A decrease in the energy of the neutron flux down to the energy of "cold" neutrons ($5 \cdot 10^{-3}$ eV) and lower enhances the wave functions of the neutron, and it begins to "see" not only individual atoms, but also their conglomerations, large molecules and molecular structures. Long-wavelength neutrons make it possible to study biological objects, nanomaterials, magnetic structures, etc. with high accuracy. They are most preferable for studying complex and magnetic structures, phase transitions, processes of synthesis of substances in real time, etc. [2].

In the framework of theme 1105, a complex of cryogenic neutron moderators is being constructed at the IBR-2 nuclear research facility, the successful implementation of which will allow obtaining the optimal neutron spectrum on each of 16 research instruments. For accomplishing this purpose, and taking into account the technological features and geometrical shape of the reactor, three cryogenic neutron moderators are planned to be placed around the core (Fig. 1):

- CM-201 for beamlines 1, 4, 5, 6, 9
- CM-202 for beamlines 7, 8, 10, 11
- CM-203 for beamlines 2, 3.

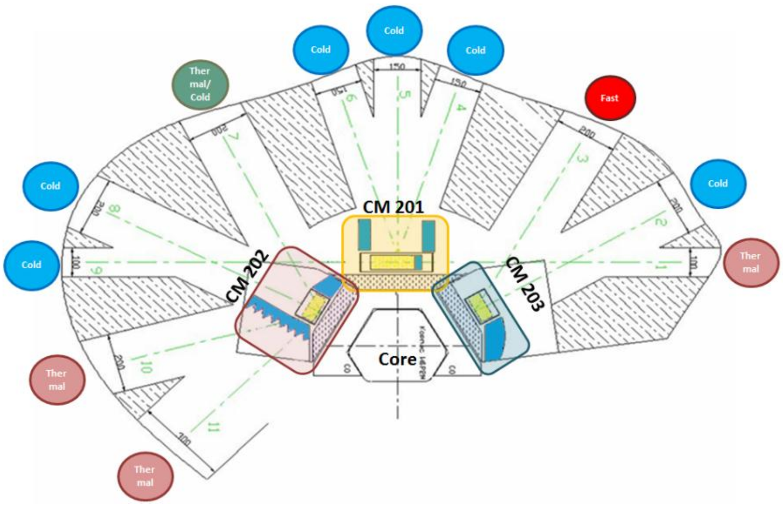

Fig. 1. Arrangement of cryogenic moderators around the core of the IBR-2 reactor to ensure optimum spectrum for each research instrument. Here, CM stands for a cold moderator, “thermal”, ”cold”, “fast” – for thermal, cold, fast neutrons, respectively.

In view of the fact that up to 5 instruments "view" the surface of each of the moderators, the most logical solution is to construct moderators that have a cryogenic chamber to form a cold neutron beam and thermal chambers to produce a thermal neutron beam in the specified directions. Distilled water is used as a moderating material in thermal chambers, and in the cryogenic chamber the moderating medium is a mixture of mesitylene and metaxylene in the ratio of 1/3 in a solid phase in the form of beads with a diameter of 3.5-4 mm.

1. Physical and methodological justification

1.1. Expected results and new developments

In 2012, the first stage of the project has been completed—the CM-202 moderator was put into trial operation. Using this moderator, a number of experiments were carried out at the REMUR (beamline 8), SKAT (beamline 7b) and NERA (beamline 7c) spectrometers to evaluate the advantages gained from the use of cold neutrons. The experiments on the REMUR reflectometer have demonstrated the possibility of splitting a microbeam without the use of polarization analysis, which reduces the measurement time by a factor of 2 as compared to that using a water moderator. In addition, owing to a 10-fold increase in intensity in the region of cold neutrons, it became possible to expand the working range of the setup up to 16 Å. The beam axis of the SKAT diffractometer passes through a part of the cryogenic chamber and a part of the grooved water moderator, with the result that a mixed neutron spectrum is formed at the sample position, which is optimal for a physics research instrument. This leads to a 4-fold increase in the neutron flux in the wavelength region of 4.31 Å, thus reducing the measurement time by a factor of 4, and the increase in intensity made it possible to identify a single peak of calcite (104) in complex-textured olivine, which was overlapped by peaks from other minerals in case of thermal moderator operation [2-4]. To produce an intense flux of cold neutrons in the direction of beamlines 1, 4, 5, 6, 9, it is necessary to construct a combined moderator (CM-201) that would form the optimal spectrum of the neutron flux at research instruments on extracted beams.

During the period from 1999 to 2000, a series of studies were performed on the high-resolution Fourier diffractometer HRFD (beamline 5) and multipurpose diffractometer DN-2 (beamline 6) at the IBR-2 reactor. The experiments have shown new possibilities that arise due to the use of cold neutrons. A range of research tasks has been identified, and a comparative analysis of the cold moderator with a standard grooved water moderator has been performed [5].

The main results were quantitative and qualitative improvements in the operation of the HRFD and DN-2 diffractometers. By quantitative improvements, one should understand the total neutron flux incident on the sample, which increases almost twice with the use of the cold moderator (methane at 60 K) as compared to the case of using a grooved water moderator operating at 300 K (Fig. 2). Such an increase is due to the specific transmission band of the curved neutron guides (characteristic wavelength 1.5 Å) on beamlines 5 and 6.

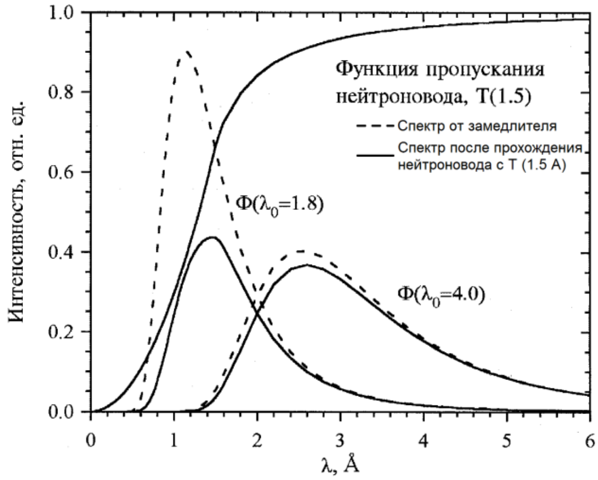

Fig. 2. Maxwell distribution of the neutron flux from the moderator at 300 K (λ_0 = 1.8 Å) and 60 K (λ_0 = 4 Å). The dashed line shows the total flux and the solid line – the flux at the sample position after passing a curved neutron guide with transmission T(λ) (characteristic wavelength 1.5 Å).

The principal improvement consists in a significant increase in the resolution of the HRFD and DN-2 diffractometers, which depends on the moderator mode, or, neutron spectrum. Thus, the resolution of the diffractometer, R, is improved for larger interplanar spacings d_{hkl}, since R ~ 1/d. So, the cold moderator makes it possible to measure diffraction peaks in the region of large d_{hkl} at large scattering angles, i.e. with a fairly good resolution, which is extremely important for studying magnetic structures and multiphase samples, as well as for detecting small distortions in the crystallographic symmetry. An example of such an improvement on HRFD is the detection of clear ferromagnetic peaks in $La_{0.83}Sr_{0.17}MnO_3$ manganites observed in a high-resolution measurement mode only in case of using the cold moderator (Fig. 3).

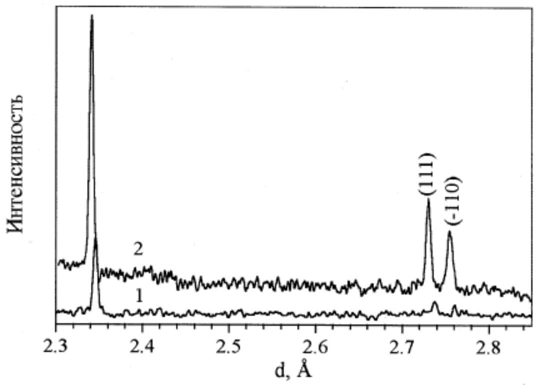

Fig. 3. Diffraction spectra of $La_{0.83}Sr_{0.17}MnO_3$ (sample temperature 8 K) in the region of large d_{hkl} measured during the same time period with the grooved moderator (curve 1) and cold moderator at T = 60 K (curve 2). The diffraction peaks (111) and (-110) are associated with the ferromagnetic ordering of Mn magnetic moments.

Figure 4 illustrates a real-time study of structural processes in the synthesis of $YBa_2Cu_3O_{6.5}$ (Y-123) superconductor from the initial components Y_2O_3, $BaCO_3$ and CuO performed on the DN-2 diffractometer. The study has shown that the formation of the final compound goes through intermediate phases: $BaCuO_2$, $Y_2Cu_2O_5$, Y_2BaCuO_5. Phase identification was carried out in the d_{hkl} range of 2-4 Å. A significant increase in the statistics in this range was achieved due to the increase in the cold neutron flux, thus improving the accuracy in the determination of oxygen index by a factor of 2 [6].

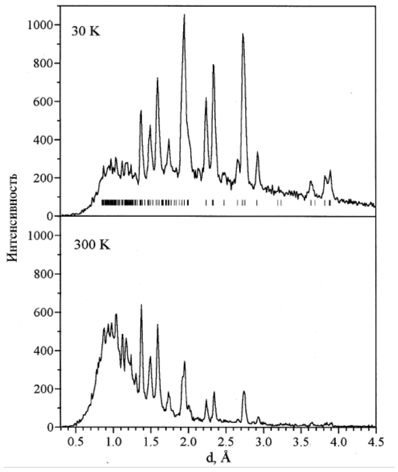

Fig. 4. Comparison of diffraction spectra of $YBa_2Cu_3O_{6.5}$ measured during 1 min at temperatures of 300 K (bottom) and 30 K (top). Diffraction peaks (indicating the presence of super-stoichiometric oxygen) in the range of 3.5-4 Å are practically invisible in the case of the thermal moderator.

Taking into account the demonstrated improvements at the IBR-2 instruments, as well as the global interest to the research using long-wavelength neutrons, it is necessary to complete the project of construction of a complex of cryogenic neutron moderators at the IBR-2 reactor on the basis of dispersed mesitylene, create infrastructure, upgrade equipment for reliable operation of systems and develop software.

In 2020-2022, in the framework of theme 1105 within the project "Construction of a complex of cryogenic moderators at the IBR-2 facility" it is planned:

- to continue CM-202 operation in a trial operation mode and carry on studies on the viscosity of the working substance depending on the ionizing radiation dose;
- to start trial operation of CM-201 and determine its neutron-physical parameters in various modes of operation and at different temperatures on IBR-2 research instruments;
- to continue modernization of the cryogenic system of the moderators' complex in view of the purchase of a new refrigerator with a cooling capacity of 1800 W at 10 K;
- to optimize the operation of the equipment of the cryogenic system with regard to newly installed equipment;
- to develop and carry out laboratory tests of a device for batch discharging pellets in a solid phase from the moderator chamber;
- to test on a full-scale stand of CM-201 and implement a device for optical counting of pellets;
- to organize a special place for designing, manufacturing and testing for strength and tightness of cryogenic pipelines, bellows joints, sealed vacuum feedthroughs.

1.2. Competitiveness

At present, the complex of cryogenic moderators being constructed in the framework of the given project is the only operating cold neutron source in the Russian Federation. By comparison, in the world there are more than 15 such sources operating on reactors and accelerators of medium and high power. The completion of the project of construction of cryogenic moderators at the IBR-2 reactor will provide an opportunity to expand the range of experiments, as well as improve the resolution of research instruments and will allow the IBR-2 facility to maintain its attractiveness and leading position among high-flux research facilities in the world.

2. Main characteristics of equipment and units in the project

2.1. Cryogenic helium cooling system of the complex of moderators

The main sources of cold in the system of cryogenic moderators are two cryocoolers: KGU 700/15 with a cooling capacity of 700 W at 20 K from SPA Geliymash and KGU 1200/10 with a cooling power of 1200 W at 10 K. The KGU 700/15 cryocooler has two main modes of operation at a temperature of 20 K and 80 K. After upgrading the system in 2017-2019, it became possible to change the temperature in the moderator chambers in the range from 20 K to 150 K. By changing the temperature of the moderating material, the peak of the neutron flux can be shifted to the region of longer or shorter wavelengths, making the moderator more “flexible” and easily adaptable to specific experiments. The modernization of the system made it possible to reduce the temperature of the moderating material by 10 K, which gave a gain factor in the cold neutron flux of up to 22% in the wavelength region of 7 Å. Figure 5 presents data on the gain factor in the cold neutron flux at different temperatures of the moderating material, which were obtained at the REMUR (beamline 8) and NERA (beamline 7b) spectrometers.

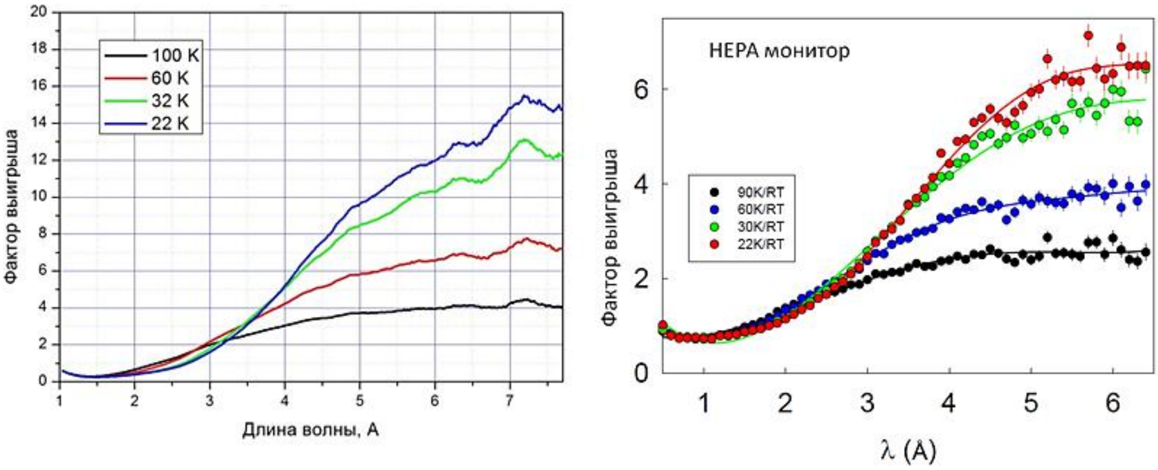

Fig. 5. Gain factor in the cold neutron flux at different temperatures of the moderating material for the REMUR spectrometer (left) and NERA spectrometer (right).

To improve performance reliability and get an opportunity to work at temperatures below 20 K, within the framework of the project in 2020-2022, it is planned to purchase a new refrigerator with a cooling capacity of 1800 W at 10 K. The general layout of the equipment of the new refrigerator at the cryogenic site of the IBR-2 reactor is shown in Fig. 6. The reconstruction of the premises will be carried out according to JINR project №AC-5792-18.

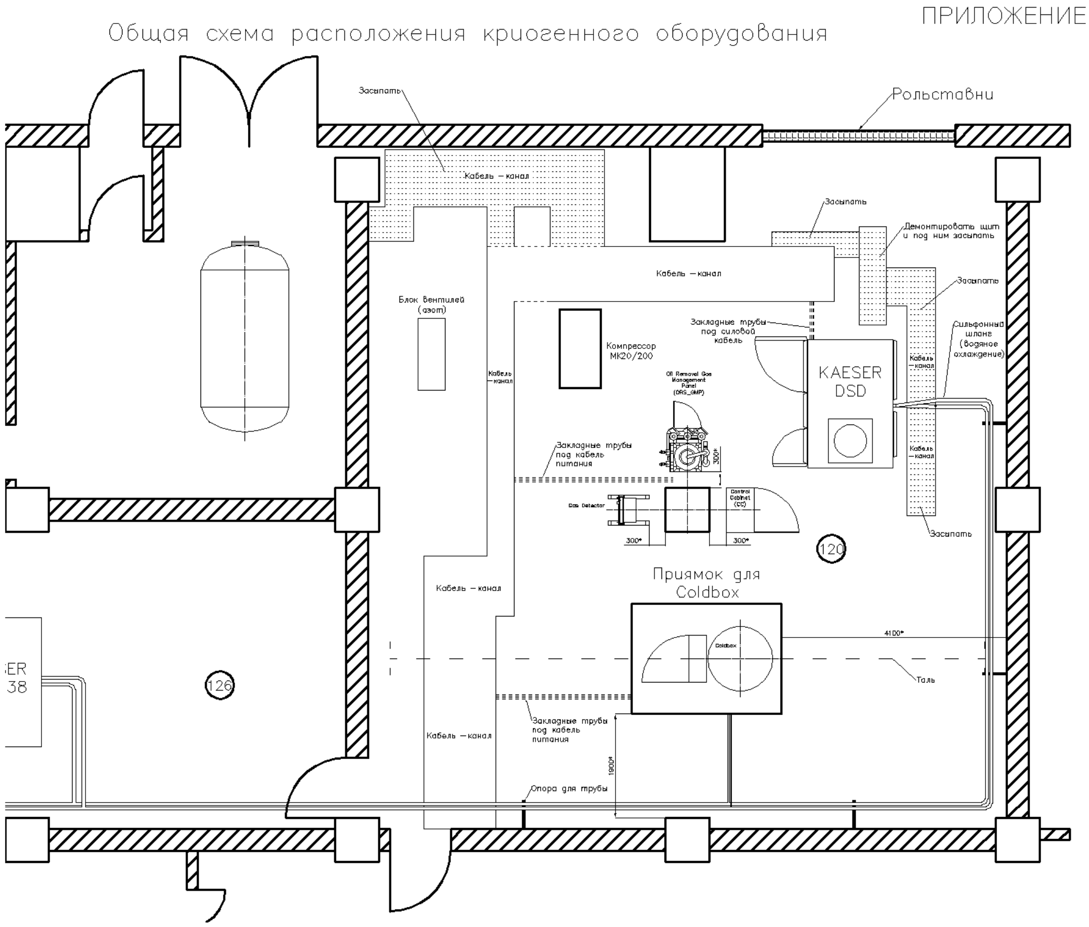

Fig. 6. General layout of the cryogenic equipment of the cryocooler KGU 1800/10.

2.2. Heat exchangers and cryogenic collector

The cryogenic system includes two heat exchangers produced by SPA Geliymash with one and two gas blowers. These heat exchangers provide separation of helium flows and cooling of the cryostat-moderator loop from the KGU-cryostat loop. Within the framework of the project, a cryostat with one gas blower that provides cooling of the loop of the central direction of CM-201 will be installed at the cryogenic site.

To integrate the cryogenic system of refrigerators into a single interchangeable system, a special cryogenic collector for helium flow distribution in the system of the complex has been developed in FLNP. The collector will allow us to separate helium flows from the machines and provide independent temperature regimes in various directions (CM-201, CM-202, CM-203). A general schematic of cryogenic and vacuum equipment of the moderators' complex is shown in Fig. 7.

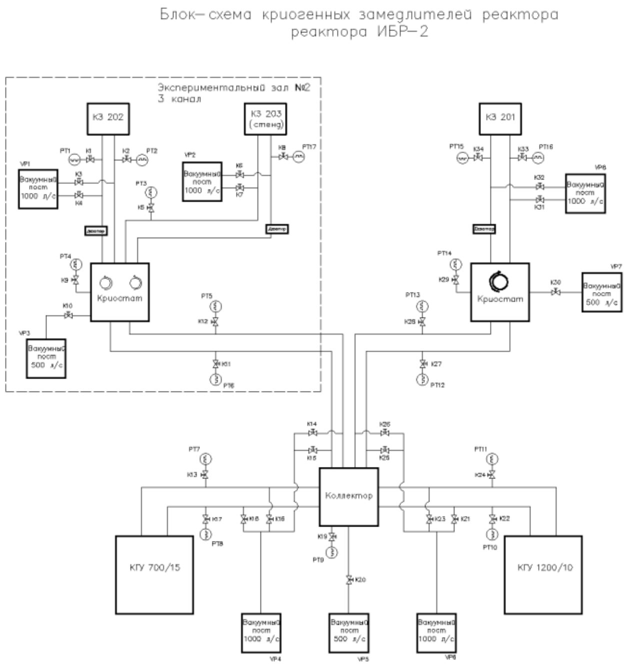

Fig. 7. Block diagram of the cryogenic system of the cold neutron source, where PT 1-PT 16 – manovacuummeters; V1-V33 – manual bellows valves; VP1-VP8 – turbomolecular pumps of different capacities.

2.3. Unique, patented, detachable cryogenic joint for the CM-201 transport pipeline

The joint has a common vacuum jacket, no thermal bridge at the junction, obstacles or steps along the pellet travel path, has a simple design and does not alter the trajectory of pellets.

2.4. Test stand of CM-201 on beamline 3

- development and testing of advanced devices for discharging pellets from the moderator chamber;
- tests of a “dry” dosing device for feeding pellets into the tract;
- research and testing of a new device for optical counting of pellets;
- installation of a new helium flow-measuring device in the pipeline and its testing;
- DXLdp differential pressure transmitters of diaphragm type.

2.5. Vacuum system and equipment

- turbomolecular pumps from Adixen, Simatzu, Leybold based on a turbine with a capacity of 400 to 900 l/s and ACP-40 Roots roughing vacuum pumps; spiral pumps ISP-250 and ISP-500;
- roughing chemical pumps;
- control valves, gate valves, regulating valves, vacuum sensors MKS 925, 901P;
- portable leak detector ASM 310, phoenix 300 dry.

2.6. Cryogenic moderators CM-201, CM-202, water moderator WM-301

- hybrid moderator CM-201 (beamlines 1, 4, 5, 6, 9) with a carriage, shielding block, boron carbide filling to prevent thermal neutrons from the premoderator from getting into the reactor core, working cryogenic chamber to form a cold neutron flux, water premoderator, water chamber to form a thermal neutron flux on beamline 1, water postmoderator, helium direct- and reverse-flow pipelines, water pipelines, pipeline for thermometric equipment, spent mesitylene discharge pipeline.

- hybrid moderator CM-202 (beamlines 7, 8, 10, 11) with a carriage, shielding block, boron carbide filling to prevent thermal neutrons from the premoderator from getting into the reactor core, working cryogenic chamber to form a cold neutron flux, water premoderator, water grooved chambers to form a bispectral neutron flux on beamlines 10 and 11, water postmoderator, helium direct- and reverse-flow pipelines, water pipelines, pipeline for thermometric equipment, spent mesitylene discharge pipeline.
- water moderator WM-301 with a grooved water chamber, boron carbide filling, shielding block and feed and discharge pipelines.

3. Human resource assessment

3.1. Employees involved in the project

Table 1.

Employees involved in the project.

№	Name of Division / Department / Group	Number of persons	Amount of employment
1	FLNP MTD Group № 2	Mukhin K.A. + 10	full-time
2	FLNP MTD	Zaytzev D.V.	full-time
3	FLNP MTD Group № 3	Basyulev E.E. + 3	part-time
4	FLNP DCM Group № 6	Bulavin M.V. + 2	part-time
5	FLNP DCM Group № 3	Petukhova T.B. + 1	part-time (by request)
6	FLNP DCM Group № 4	Sirotin A.P. + 1	part-time (by request)
7	FLNP DB	Kustov A.A. + 1	part-time (by request)
8	FLNP workshops	Kuznetsov A.N.	part-time (by request)

3.2. Publications, conferences and dissertations

In the framework of the project, more than 30 papers were published, including at least 15 in HAC-reviewed journals, 2 Ph.D. theses (1 Ph.D. in physics and math., 1 Ph.D. in engineering science) and 1 Dr.Sc. thesis were defended. The results and plans of the project are regularly reported at Russian and international conferences, including IAEA thematic meetings.

4. Partner companies and equipment suppliers

- Linde Kryotechnik AG
- Open Joint Stock Company “Cryogenic Technologies”
- BLM Synergie (Adixen, Adixen by Pfeiffer Vacuum)
- Oerlikon Leybold Vacuum
- NIKIET (A.N.Dollezhal Research and Development Institute of Power Engineering)
- FLNP workshops
- Scientific Production Association “ATOM”
- SSDI (State Specialized Design Institute)
- Gertner Group
- Lake Shore Cryotronics, Inc.
- “Industrial expertise”, Ltd.
- Research and development centre “ANKLAV”
- "Leyfikon vacuum service", Ltd.
- Research and Production Enterprise “Covint”
- “Vactron”, Ltd.
- CJSC Special Design Bureau “Chromatek”

5. Time schedule of activities **Form № 26**

Proposed time schedule and required resources for realization of the project «Construction of a complex of cryogenic moderators at the IBR-2 facility»

Description of units and systems, resources, funding sources			Cost of units (k$). Resource requirements	Proposals of the Laboratory for distribution of funds and resources		
				2020	2021	2022
Main units and equipment	1. CM-202		40	15	15	10
	1.1 Commissioning of CM-202		10	–	5	5
	1.2 Automation of vacuum control system (purchase of necessary equipment, software development)		30	15	10	5
	2. Cryogenic system of CM		1180.5	1020.5	95	65
	2.1 Purchase of KGU 1800/10		920.5	920.5	–	–
	2.2 Preparation of rooms for installation of KGU, development of rigging and auxiliary devices, installation		60	40	15	5
	2.3 Expert review of cryogenic system project; commissioning		40	10	10	20
	2.4 Automation of vacuum control system		70	10	30	30
	2.5 Purchase of necessary equipment, modernization and automation of helium supply system		90	40	40	10
	3. CM-201		142	62	55	25
	3.1 Experiments, development and tests of new components, equipment, improvement of operation modes at CM-201 test stand		32	12	10	10
	3.2 Determination of physical and technical parameters of CM-201 and WM-304		60	30	30	–
	3.3 Designing. Manufacturing and installation of biological shield for temporary storage of a backup moderator (room 165, bldg. 117)		25	15	10	–
	3.5 Commissioning and expert reviews		25	5	5	15
	4. New developments		130.5	75	45	10.5
	4.1 Development of concept and experimental model of unit for discharging solid mesitylene from CM chamber (at CM-201 test stand)		60	25	25	10
	4.2 Creation of a site for manufacturing cryogenic pipes and bellows units		70.5	50	20	0.5
Required resources	Norm-hour	FLNP Workshops	6000	2000	2000	2000
		FLNP Design Bureau	3000	2000	500	500
		Reactor	–	–	–	–
Funding source	Budget	Theme 1105	1493	1172.5	210	110.5

The cost estimate was based on a dollar/ruble exchange rate at the Central Bank of the Russian Federation (as of 12.03.2019) and was 66.08 rub per 1 USD.

Project leader K.A.Mukhin

6. Cost estimate

Form № 29

Cost estimate of the project «Construction of a complex of cryogenic moderators at the IBR-2 facility»

№	Description of cost items	Total cost	2020	2021	2022
	Direct expenses				
1	IBR-2 reactor	hour	–	–	–
2	Design Bureau	norm-hour	1000	1000	1000
3	Materials	k$	62	47	30.5
4	Equipment	k$	1065.5	110	25
5	Payment for research performed under contracts	k$	45	53	55
6	Travel expenses a) to nonruble-zone countries b) to ruble-zone countries c) under Protocols	k$ according to ITC plan	 20 8 2	 20 8 2	 20 8 2
	Total direct expenses		1202.5	240	140.5

The cost estimate was based on a dollar/ruble exchange rate at the Central Bank of the Russian Federation (as of 12.03.2019) and was 66.08 rub per 1 USD.

PROJECT LEADER

FLNP DIRECTOR

FLNP LEADING ENGINEER-ECONOMIST

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