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SCIENTIFIC AND TECHNICAL JUSTIFICATION FOR OPENING A NEW THEME
JINR TOPICAL PLAN for 2020-2022

Theme code		**Laboratory**	FLNP
		Departments	NICM, CM, NP, IBR-2, IREN, MTD, ETD, DB, RPW, NS group

Field of research: «Condensed Matter Physics (04)»

Theme title: «Development of the Conceptual Design of a New Neutron Source at JINR»

Theme leaders:
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Brief annotation

Introduction

Condensed matter investigations using nuclear physics methods is one of the main research areas at the Joint Institute for Nuclear Research, which is stated in the JINR Charter [1], recent “road maps” and the JINR seven-year plans including the Seven-Year Plan for the Development of JINR for 2017-2023 approved at the session of the Committee of Plenipotentiaries of the Governments of the JINR Member States held on November 21-22, 2016.

The widespread use of neutron scattering techniques for studying the atomic and magnetic structure of solids began after the end of the World War II with the use of research nuclear reactors. The very first studies revealed the main differences between neutron methods and X-ray scattering techniques, namely, the sensitivity of neutrons to the isotopic composition and magnetic properties of objects under study [2,3]. The construction of specialized reactors with extracted neutron beams dates back to the 1960s. Thus, for example, in the USA the construction of a high-flux beam reactor at BNL began in 1961 and in 1965 the reactor went critical. It was the first reactor with a heavy water moderator in which the maximum thermal neutron flux density was reached at a certain distance from the core, which made it possible to place the head parts of neutron guides in this area [4]. A total of 818 research reactors have been built in the world so far and 23 are in the planning or development stage at the moment. At present, however, there are only 227 operating reactors [5], with only 51 of them being intended for research on extracted neutron beams. Thus, together with neutron sources driven by proton accelerators [6], there are about 60 facilities in the world with extracted neutron beams for condensed matter research. Interestingly, the number of currently operating synchrotron radiation sources is about the same [7].

Development of neutron sources in FLNP JINR

The IBR reactor constructed at JINR on the initiative of the first JINR Director D.I.Blokhintsev, was, in fact, the world's first specialized source of neutrons for research on extracted beams. With an average power of only 1 kW, in its possibilities it corresponded to a stationary reactor with a power of several MW due to the pulsed operation mode with a pulse duration of 36 μs and repetition rate from 8 to 80 Hz [8].

The modernization of the cooling system allowed the reactor to operate at an average power of up to 6 kW [9]. Later on, an operating mode with an average power of 3 kW and pulse repetition rate of 5 Hz was used, with the pulse duration increasing to 50 μs, and the peak power being about 15 MW [10].

The pulse duration is the key parameter that determines the energy resolution for a fixed flight path: $\frac{\Delta E_n}{E_n} = \sqrt{\left(\frac{2 \cdot \Delta t^2}{t}\right) + \left(\frac{2 \cdot \Delta L}{L}\right)}$, where E_n is the neutron energy, t – time of flight, L – flight path, Δt – neutron pulse duration, ΔL – uncertainty of the flight path related to the finite dimensions of the source and moderator, as well as the neutron detector. If the contribution of the flight path uncertainty is neglected, then with a decrease in the pulse duration, it becomes possible to approach the source, maintaining the energy resolution at the same level, which will result in a quadratic increase in the neutron flux density at a research instrument.

The fast neutron pulse duration obtained at the first IBR reactor ensured a sufficiently good energy resolution at flight paths of up to 1000 m, however, the source did not provide a record-breaking neutron flux density at a given energy resolution. By the end of the 1950s, there appeared neutron sources on the basis of electron accelerators with a short pulse ($\Delta t < 1$ μs) and high neutron yield, which ensured their leadership. Thus, in Harwell (Great Britain), starting from 1952, investigations of nuclear reactions induced by neutrons with an energy of 15-120 MeV were conducted on beams of the source based on a 150-MeV proton synchrocyclotron [11]. In 1959, also in Harwell, a neutron source driven by an electron accelerator with an energy of 28 MeV and a ^{235}U target in a subcritical state was put into operation. The pulse duration of fast neutrons of this source varied in the range from 5 ns to 5 μs, which, in combination with specialized moderators and flight paths from 5 to 300 m, provided the broadest opportunities for research [12]. A sufficiently comprehensive review of pulsed neutron sources at the end of the 1970s is presented in [13]. In 1964, following the global trends towards higher resolution, the first IBR reactor of the Joint Institute for Nuclear Research was equipped with a 30-MeV electron accelerator and began to operate in a booster mode with a pulse duration of about 5 μs [14]. In the summer of 1968, the IBR reactor with a microtron began to be used in a rare pulse mode (1 pulse per several seconds), with the result that the average power was 6 kW and the instantaneous power reached 1 GW! By the middle of 1968, a more advanced pulse reactor IBR-30 with an average power of 25 kW was constructed, which in a very short time (from August 1968 to June 1969) replaced the first IBR. In March 1970, a new reactor was put into operation in combination with a linear electron accelerator LUE-40 with an energy of 40 MeV and beam power of 2 kW, providing a pulsed thermal neutron flux density on the moderator surface of up to 10^{14} n/cm^2/s [15]. The IBR-30 + LUE-40 complex using extracted neutron beams in seven directions, with flight paths from 10 to 1000 m, made it possible to conduct research in the energy range from meV to tens of keV with a good energy resolution and high intensity [10].

At the time when IBR-30 was constructed, the possibilities of increasing the power of reactors of the first IBR type were almost exhausted because gas cooling of movable reactivity modulators with fissile material inserts could not be used at power levels of more than 100 kW. Therefore, when designing the next-generation pulsed reactor IBR-2 with an average power of 4 MW, its constructors proposed to mechanically modulate the reactor reactivity by means of special movable reflectors—two rotors rotating near the reactor core [16, 17]. The construction of IBR-2 took longer than the first pulsed reactor of JINR. The physical startup of the reactor was carried out in the period from the end of 1977 to the beginning of 1978 (more than 10 years after the start of design work) and the power startup and the beginning of investigations took place four years later [18, 19]. By the beginning of the 1980s, the experimental reactor hall had already been equipped with a number of neutron spectrometers [20]. Since 1984 to the present, the IBR-2 reactor has been operating for 2500 h a year, providing research opportunities for scientists from different countries within the framework of the user program started in the 1990s [21]. In the period from the end of the 1990s to 2011, the IBR-2 reactor was modernized with a temporary shutdown of the reactor in 2007-2010. During this time, the main and auxiliary reactivity modulators, reactor vessel, control system, part of sodium cooling pipelines and other reactor equipment were replaced. In 2010-2011, the physical (December 2010) and power (July-October 2011) startups of the upgraded reactor were carried out [22, 23]. In 2012, the user program was resumed and research activities were continued on 15 neutron spectrometers [24, 25, 26].

Research in the field of condensed matter physics in Dubna

In scattering experiments with slow neutrons, it is necessary to measure the scattering angle of monochromatic neutrons in the case of elastic scattering or the change in their energy in the case of inelastic scattering. At steady-state neutron sources, this is accomplished by choosing a specific wavelength by means of a monochromator and varying the scattering angle. On a pulsed neutron source, owing to the time-of-flight technique, it is possible to determine the characteristics of neutrons scattered at a certain angle in a wide range of wavelengths using point neutron detectors. If a large-area position-sensitive detector is used, it becomes possible to detect scattered neutrons in a wide range of wavelengths and scattering angles simultaneously.

Condensed matter investigations using time-of-flight neutron spectroscopy began on the first reactor of the Joint Institute for Nuclear Research almost simultaneously with the development of neutron resonance spectroscopy. In as early as two years after the start of operation of the first IBR reactor, on the initiative of physicists from the Institute of Nuclear Physics in Krakow, an indirect-geometry inelastic neutron scattering spectrometer was constructed and studies of quasi-elastic scattering of cold neutrons by water and energy of local vibrations of impurity atoms in copper and lead were carried out [27, 28, 29]. Later on, this facility evolved into the Krakow-Dubna indirect-geometry spectrometer KDSOG at IBR-30, and then into KDSOG-M and NERA-PR at IBR-2. Another type of inelastic scattering spectrometer was constructed by physicists from IPPE (Obninsk) [30].Studies of the structure of solids using neutron diffraction methods on a pulsed source began in Dubna and Sverke (Poland) in the group of B.Buras in 1962. Right in the first studies carried out in FLNP, many of the predicted advantages of time-of-flight diffractometers were confirmed, first of all, high speed of data collection and possibility to obtain three-dimensional diffraction spectra [31].

Having been tested at the first pulsed reactor IBR of JINR, time-of-flight neutron scattering techniques were successfully developed at IBR-30, and later on at IBR-2. During the design and construction of IBR-2, unique research instruments for small-angle and inelastic scattering, Fourier diffractometry, and reflectometry of polarized neutrons were developed and constructed, and for the first time, effects of pulsed magnetic fields on a sample synchronized with neutron pulses were tested. Pioneering investigations of high-temperature superconductors, studies of chemical reactions in real time, ribosome structure, mechanical stresses and engineering analysis, structural phase transitions at high pressures — all this was done within the first 20 years of operation of the IBR-2 reactor and continued after its modernization [32, 33, 34, 25].

Complementary to neutron techniques, the possibilities of synchrotron X-ray sources in the National Research Centre "Kurchatov Institute" (Moscow, Russia), ESRF (Grenoble, France), Spring 8 (RIKEN, Japan), SOLARIS (Krakow, Poland) and other research centers are successfully used today and will continue to be used in the future [35].

At present, the suite of spectrometers at the modernized IBR-2 reactor comprises 15 specialized research instruments including 8 diffractometers, one small-angle scattering spectrometer, three reflectometers (two of them provide the possibility of using polarized neutrons), two inelastic neutron scattering setups, neutron radiography and tomography facility. Two extracted beams of the IBR-2 are used for experiments in nuclear physics, and one more experimental beamline is intended for studying the radiation resistance of materials and electronic circuit components. Since 2005, FLNP has been producing position-sensitive neutron detectors based on multiwire proportional chambers with delay line readout, as well as scintillation detectors. All detector equipment, including electronics and software, is designed and constructed in FLNP [36].

The results of investigations conducted in leading research neutron laboratories, many of which operate under user policy program, are published annually in thousands of articles and form the basis for patents in various fields of science and industry. An example is the situation in Europe, a region that nowadays is a leader in the field of neutron research. About 160 instruments operate on European neutron sources in the framework of user programs. The total experimental time amounts to 30,000 instrument-days per year resulting in about 1,900 scientific articles annually, i.e. one publication for every 16 days of operation of one instrument [37]. The scientific efficiency of IBR-2 at FLNP JINR is comparable with that of other neutron centers operating under the user policy program. Fifteen spectrometers available for research at the reactor operating for 2500 hours per year produce approximately 90 articles per year, i.e. one publication for every 17 days of operation of one spectrometer at IBR-2.

IBR-2 Pulsed Reactor, Status and Prospects

A major modernization of the IBR-2 reactor was undertaken in connection with the expiration of the design service life of its main components: reactor vessel, cooling system pipelines and other equipment. This work was started in the mid-1990s with the support of the Ministry for Atomic Energy of the Russian Federation (now the State Corporation ROSATOM). On the basis of the studies of a new type of fuel pellets irradiated in the IBR-2 reactor before its shutdown for the final stage of modernization, it was decided to use this type of fuel (with a central hole in fuel pellets). It was also decided to design a more compact reactor core by abandoning the central irradiation channels that existed in the original design. For more than 10 years, work was carried out on the design of a new reactor and movable reflector, preparation of scientific and technical justification of a new type of fuel, organization of specialized area in JINR for assembling fuel bundles for the upgraded reactor from fuel rods manufactured at Mayak. A long-term shutdown of the reactor to replace the basic equipment took only 4 years (2007-2010). At present, the reactor operates for more than 2500 hours per year, providing the opportunity for research to more than 100 scientists from the JINR Member States and other countries of the world, who annually perform more than 200 experiments in the framework of the user program. A comparable number of experiments are carried out by the employees of the Division of Condensed Matter Research and Development of the Frank Laboratory of Neutron Physics. The service lifetime of the reactor vessel, pipelines of the sodium cooling system, as well as reserve of fuel assemblies stocked up at the modernization stage, determines the service-life limit of the upgraded IBR-2 reactor set by its Chief Designer, N.A.Dollezhal Research and Development Institute of Power Engineering (NIKIET) to be reached in 2035-2042 depending on the operating conditions. The main task of the Laboratory for this period is to ensure reliable and stable operation of the reactor with a consistent planned continuation of work on its modernization, namely, the replacement of auxiliary equipment that had not been replaced during a long-term shutdown in view of the fact that its service life had not expired at that time. Also, the top priority for these years will be the completion of construction and further development of the complex of cryogenic moderators as well as equipping of IBR-2 spectrometers with modern neutron-guide and detector systems, which will allow JINR to maintain its leading position in the field of neutron scattering research in condensed matter physics until the end of IBR-2 operation.

World trends in the development of neutron sources

A rapid growth in the number of research reactors in the early 1960s gave way to stabilization in the second half of the 1980s and then was followed by a decrease in their number. The main reason for this phenomenon is the same that led to certain stagnation in the development of nuclear power industry—a severe accident at the Chernobyl nuclear power plant, which resulted in serious radioactive pollution of vast territories of Ukraine, Belarus, Russia, and some European countries. At that very time, Carlo Rubbia, the Nobel Prize winner in Physics in 1984, for electric-power production proposed to use installations with subcritical assemblies of fissile materials, driven by protons or deuterons, in which a beam of charged particles accelerated to 0.5-2 GeV is directed to a target of heavy material (tungsten, mercury, lead). The scientific and experimental development of such systems allowed the creation of neutron sources driven by heavy charged particle accelerators with metal targets and a beam power of up to several megawatts, which is 1-2 orders of magnitude higher than the power of the first specialized accelerator-based neutron sources.

At present, the technological constraints related to heat removal from a research reactor core or neutron-producing target of an accelerator-based neutron source limit the average neutron flux density on the moderator surface to about 10^{15} n/cm^2/s for steady-state research reactors and 10^{14} n/cm^2/s for pulsed neutron sources of any type. The peak neutron flux density at existing and upcoming pulsed sources of any type cannot exceed 10^{16} n/cm^2/s, which is apparently the technological limit [38]. The Frank Laboratory of Neutron Physics proposes to construct at JINR a neutron source with record-breaking parameters, and one of the variants is the combination of two existing approaches – accelerator-driven and reactor-based research neutron source.

So, at present, all leading economically developed countries of the world are actively developing and supporting research neutron sources with extracted beams for neutron scattering studies. The leader is the European Union, where 160 research instruments operate on 13 neutron sources. In the near future, the flagship of the future European neutron infrastructure—European Spallation Source—will be commissioned with an initial suite of research instruments, however, all 22 neutron spectrometers will be put into operation only 13 years later [39, 37]. It is very important to note that the need for new neutron sources is recognized in all circles of the scientific community involved in neutron beam research. Thus, for example, the ESS project leaders Ken Andersen and Colin Carlile, even before the first neutrons are produced at the ESS, have started a discussion of a new next-generation European neutron source, which is to replace the ESS in about 50 years [40]. At the same time, in Europe and in other countries, work is underway on projects of medium- and low-intensity sources, which are to ensure the reproduction of qualified researchers capable of using advanced technologies on sources with record high intensities [41, 42].

In the USA, neutron sources driven by proton accelerators are successfully operating and developing. At the same time, there are no research reactors comparable in capabilities to heavy-water high-flux research reactor at the Institute of Laue-Langevin (Grenoble, France) [43, 44, 45]. The American scientific community recognizes that the United States has lost its leadership in the field of neutron research and calls for the creation of new neutron sources of both accelerator-driven and reactor-based types [46].

In Russia, at the moment, the construction of a high-flux heavy-water research reactor PIK [47, 48] at the NRC "Kurchatov Institute" - PNPI is nearing completion. But as in the case of the ESS, the full suite of research instruments will become available for scientific investigations only quite a long time after the power startup of the reactor, which is currently underway.

Thus, the IBR-2 reactor provides a unique opportunity for researchers from the JINR Member States for conducting world-class condensed matter investigations by neutron scattering methods and preserves the leading position of JINR in this area. In order to ensure the steady development of this research area in the future and secure the leadership, it will be necessary to create a neutron source with extracted beams and a suite of state-of-the-art instruments by the time the service life of the IBR-2 reactor is expired. The most optimal variant is considered to be the one when the new source starts its operation before a complete shutdown of IBR-2, and in the meanwhile the laboratory team is participating in the implementation of the experimental program at IBR-2 and developing experimental instruments at the new source. This approach was successfully realized during the construction of IBR-2, when investigations in the field of condensed matter physics were conducted at the IBR-30 reactor.

Current status of the development of conceptual design of a new neutron source at JINR

The need for a new neutron source at JINR to replace the IBR-2 was realized at the Laboratory almost immediately after the completion of the final stage of its modernization. In the preparation of the 7-year plan for the development of JINR for 2017-2023 this task was included in the final version of the document as one of the priorities. At the 42nd meeting of the Program Advisory Committee for Condensed Matter Physics of JINR on June 22, 2015 in the report of V.N.Shvetsov, containing FLNP proposals to the JINR seven-year development plan for 2017-2023, the issue of creating a new source was raised for the first time. At the 45th meeting of the Program Advisory Committee for Condensed Matter Physics of JINR on January 19, 2017, V.L.Aksenov presented two design concepts of the new source that had been drawn up in the Laboratory and gave an overview of the situation with neutron sources in Europe for the coming decades. By now, at several meetings of the PAC for Condensed Matter Physics, the FLNP specialists have presented the technical details of the two proposed concepts and provided a preliminary rationale for the scientific program for the new neutron source. In the framework of the preparation of the JINR Strategic Development Programme until 2030, an international Working Group of the Commission for JINR Strategic Long-Range Planning was established to coordinate and elaborate the scientific and technical justification of the project on the construction of the fourth-generation Dubna neutron source. Two meetings of this Working Group were held in 2018 and 2019. In 2018, an international Workshop was convened to consider advanced ideas and potential experiments for the new source.

At present, a contract "Development of a conceptual design of a high-flux pulsed neutron source of periodic operation based on a proton accelerator and multiplying target" has been concluded between JINR and N.A.Dollezhal Research and Development Institute of Power Engineering (NIKIET) under which the design study of two variants of the neutron source proposed by FLNP will be carried out. The final report on the contract is expected by the end of 2019.

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Stages:

- Scientific rationale for a new source, "white book";
- Development and justification of the choice of the conceptual design of a high-flux pulsed neutron source of periodic operation;
- Preparatory work for the development of production technology for fuel/target for the new source;
- Development of the concept of arrangement of neutron moderators, extracted neutron beams and instruments;
- Preparation of initial data for the development of a technical design of the source with research instruments on extracted neutron beams.

Expected scientific results

- Feasibility study for construction of a new neutron source;
- Scientific rationale:
    - Scientific program;
    - Suite of instruments for condensed matter research;
    - Proposals for experiments in nuclear physics and studies of neutron properties;
- Initial data for technical specifications for the design of the new source with a suite of research instruments on extracted beams.

List of Participants from JINR

Laboratory	№	Name	№	Name
FLNP	1.	Aksenov V.L.	14.	Rogov A.D.
	2.	Belyakov A.A.	15.	Trepalin V.A.
	3.	Bulavin M.V.	16.	Chudoba D.
	4.	Vinogradov A.V.	17.	Shabalin E.P.
	5.	Dolgikh A.V.	18.	Shvetsov V.N.
	6.	Kozlenko D.P.		
	7.	Culicov O.		
	8.	Kulikov S.A.		
	9.	Kucerka N.		
	10.	Lychagin E.V.		
	11.	Mukhin K.A.		
	12.	Pepelyshev Yu.N.		
	13.	Rzyanin M.V.		

Participating Countries, Institutes and International organizations:

Country or International Organization	City	Institute or Laboratory
Russia	Moscow	NIKIET
	Moscow	VNIINM
	Moscow	NRC KI
	Moscow, Troitsk	INR RAS
	Gatchina	PNPI

Belarus	Minsk	BSTU
Romania	Bucharest	INCDIE ICPE-CA
Argentina	Bariloche	CAB
Czech	Rez	NPI ASCR
Hungary	Budapest	Wigner RCP
Germany	Berlin	HZB
	Julich	FZJ
Sweden	Lund	ESS ERIC
France	Grenoble	ILL
Uzbekistan	Tashkent	INP UAS
South Africa	Pretoria	UP

Realization period: 2020 - 2022

Total estimated cost of the theme

№	Description of activities	Total cost	Expenses per year (k$)		
			2020	**2021**	**2022**
1.	Development and justification of the choice of conceptual design of the new source	1354k$	437 k$	451 k$	466 k$
2.	Preparatory work for the development of production technology for fuel/target for the new source	1354 k$	437 k$	451 k$	466 k$
3.	Preparation of scientific rationale for the project of the new source with a suite of research instruments on extracted beams	451 k$	146 k$	150 k$	155 k$
4.	Organization and preparation of workplaces for new employees	272 k$	88 k$	91 k$	93 k$
TOTAL		**3431 k$**	**1108 k$**	**1143 k$**	**1180 k$**

Cost estimates for the theme

№	Description of budget items	TOTAL 2020-2022	incl. 2020
1	Salaries	841 k$	254 k$
2	Insurance payments	255 k$	77 k$
3	Social fund	55 k$	17 k$
4	International scientific and technical cooperation	300 k$	100 k$
6	Equipment	180 k$	60 k$
10	Research and technological development	1800 k$	600 k$
TOTAL		**3431 k$**	**1108 k$**

AGREED:

JINR Chief Scientific Secretary

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«____» _____________________2019

Head of Planning Department

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«____» _____________________2019

Head of Scientific-Organization Department

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«____» _____________________2019

FLNP Director

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«____» _____________________2019

FLNP Scientific Secretary

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«____» _____________________2019

FLNP Economist

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«____» _____________________2019

Theme Leader

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«____» _____________________2019

Theme Leader

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«____» _____________________2019