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Pulsed Spallation Neutron Source Based on the Proton Synchrotron U-1.5

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Abstract—The project of a pulsed spallation neutron source driven by a 1.32-GeV proton beam accelerated in the existing rapid cycling proton synchrotron U-1.5 at the National Research Centre "Kurchatov Institute" (NRC KI)—Institute for High Energy Physics (IHEP) is presented. This option would constitute a short-term cost-effective diversification of applied research capabilities of the U-1.5 machine (orbit length 99 m), the facility otherwise employed as a ring injector (booster) into the subsequent larger proton synchrotron U-70 (1.487 km). The source will be used primarily for neutron time-of-flight research techniques.

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INTRODUCTION

The modern trends in the development of science, engineering, and technologies are largely related to the progress in studying natural and artificial crystalline and amorphous materials. Success depends crucially on the availability of methods for investigating the structure and properties of substances, materials, and products on various spatial and temporal scales. The use of neutron beams is one of the main methods for these studies, complementary to synchrotron radiation (SR) techniques. High-intensity neutron fluxes can be obtained using:

(i) fission reaction (research and, more rarely, commercial nuclear reactors),

(ii) nuclear reactions, initiated by accelerated charged-particle beams.

The majority of these studies are performed worldwide based on nuclear reactors that were mainly constructed in the 1960s–1970s. The regulatory lifetime of these facilities (reactors) has expired or is due to expire in the nearest decade. The commissioning of new research facilities, based on the reactor technology for obtaining neutron fluxes, is a rare event and is unlikely in the future because of the environmental movement.

Further neutron studies are related to a great extent to the systems based on proton accelerators. Note that the neutron fluence of these sources at megawatt beam power and proton energy in the range of 1–1.5 GeV often exceeds the corresponding values of research nuclear reactors. It should also be noted that commissioning and decommissioning of neutron systems, based on accelerator technologies, is much simpler than for the systems based on nuclear reactors.

PURPOSE OF THE PROJECT

The purpose of this project is the development of a pulsed neutron source (PNS) based on spallation reactions, driven by a proton beam with an average power of up to 3 kW as a result of its interaction with extended (full absorption) dense targets. The setup is based on the existing accelerator complex U-70 of NRC KI–IHEP (Protvino, Moscow Region) and will be used to analyze the properties of materials and products in the nano- and subnanometer ranges and carry out research in nuclear physics. The facility will be mainly used for neutron time-of-flight experiments.

Successful realization of the project will make it possible to decrease the existing deficit in research neutron sources in Russia and the world. A scientific and technical basis will be established for the practical training of scientific and engineering personnel in the field of neutron research.

One can state that the system under development is a prototype of a pulsed neutron source (proposed in

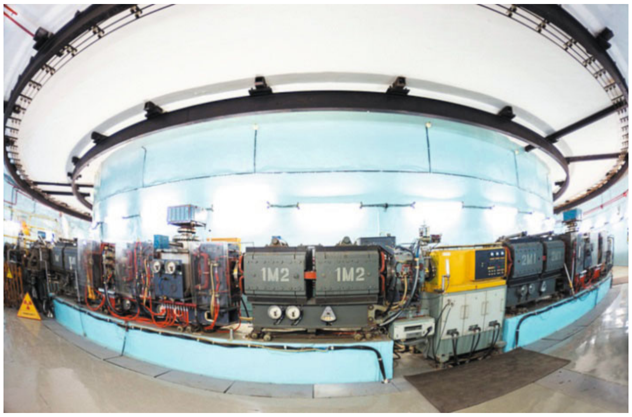

Fig. 1. Proton synchrotron U-1.5.

2010, NRC KI–IHEP, OMEGA project), based on megawatt proton beams [1]. Specifically for this reason, the names *PNS OMEGA* or *prototype PNS OMEGA* are used for the proposed facility.

TECHNICAL PREREQUISITES

The project relies on successful Russian and world experience in the construction amd operation of spallation neutron sources, also based on ring resonant proton accelerators. The GNEIS neutron source (1-GeV synchrocyclotron; PNPI, Russia) is one of them [2]. The foreign counterparts with a much larger driver-beam power are the SINQ (590-MeV isochronous cyclotron; PSI, Switzerland) [3], ISIS (0.8-GeV synchrotron; RAL, United Kingdom) [4], and J-PARC (3-GeV synchrotron, JAEA/KEK, Japan) [5] sources.

Within the project, the research PNS OMEGA, based on the spallation reactions driven by (1.3–1.5)-GeV proton beams with a power of up to 3 kW, will be designed. A high “result/cost” factor and short implementation time with reduced technical risks are expected. There are two prerequisites for this.

On the one hand, the expertise and engineering infrastructure of NRC KI–IHEP in the construction and operation of proton accelerators and beam transfer lines for extracted beams of charged particles, in experimental physical installations with fixed external targets, and accompanying sections of radiation physics and technology will be involved.

On the other hand, the most complex and expensive PNS component—intense accelerator of charged particles (protons)—is already available. The proton synchrotron U-1.5 (Fig. 1), which is a ring injector (booster) for the large proton synchrotron U-70, has been successfully used for a long time in the operational accelerator complex U-70. The PNS IMEGA will be located near U-1.5 on the ground floor in subbuilding no. 3N of the Booster campus (Fig. 2). The technical parameters of synchrotron U-1.5 in its current state, which are topical for the PNS development, are listed in Table 1. Based on Table 1, one can conclude the following.

First, the proton-beam energy of U-1.5 (1.32 GeV) is near the flat maximum of the specific “neutron/proton/GeV” yield for an extended dense target (~25) [6]. Specifically for this reason, the energy of driver beams of the PNSs based on proton synchrotrons are in the range from 0.8 GeV (ISIS, United Kingdom) to 3.0 GeV (J-PARC, Japan).

Second, the temporal (packet–pulsed) structure of the U-1.5 beam, imposed by the conditions of injecting from 1 to 29 bunches into the U-70 ring, also meets the requirements of the PNSs with a short-pulsed driver proton beam. Indeed, the width of one pulse (bunch) in the U-1.5 beam does not exceed 0.1 μs, which is much shorter than the characteristic time of neutron retardation in a light moderator (no more than 5–10 μs, in dependence of target size and

Fig. 2. Booster campus.

design). Therefore, the shape of neutron pulses depends only slightly on the shape of the bunches of the driver proton beam. At the same time, the periodicity of proton bunches from the U-1.5 (60 ms, repetition rate of 50/3 Hz) is favorable for the use of neutron time-of-flight techniques. The above-mentioned operational PNSs are characterized by comparable pulse repetition rates: 50 Hz (ISIS) and 25 Hz (J-PARC).

Third, for technical reasons, it is unlikely that the attainable beam intensity in the U-1.5 (taking into account its upgrade) will exceed 1 × 10^{12} protons/bunch. Therefore, the average beam power on a neutron-generating target will not exceed 1–2 kW. On the one hand, this circumstance simplifies radically its design, which is attractive from the point of view of using the existing buildings of the Booster campus (Fig. 2). At the same time, OMEGA PNS will not be able to generate large neutron fluxes, which limits inevitably the region of its application to analytical neutron-physical studies of not very dense objects and nuclear physics. Investigations on extreme radiation materials science remain inaccessible.

THE MAIN CHARACTERISTICS OF THE PROJECT

The project provides modernization and technical re-equipment of the main technological systems of the operational proton synchrotron U-1.5 and its injector—proton linear accelerator Ural-30 (Fig. 3)—in order to increase the proton-beam intensity. The list of the developed and upgraded objects is as follows:

(i) the source of negative hydrogen ions (H^-) for transition to the scheme of charge exchange injection into U-1.5, which makes possible a few-fold increase in its intensity;

(ii) the key technological systems of the linear accelerator Ural-30: the modulator of the RF supply system, the RF-power control system to compensate the effect of loading of accelerating cavities by the beam current, and the system for diagnostics of the beam of protons and H^- ions;

(iii) the key technological systems of the proton synchrotron U-1.5: straight section with a charge-exchange target for injection of the H^- beam, equipment of the accelerating RF-stations, the system for the magnetic-field correction and diagnostics of the beam parameters, and the pulsed and kicker magnets;

(iv) a new transfer line for transporting the proton beam ejected from U-1.5 to the neutron-generating target;

(v) a neutron-generating target station and the neutron beamlines with the experimental equipment.

The parameters of the proton beam of U-1.5 as a driver beam for the OMEGA PNS after carrying out the above activities are listed in Table 2.

Table 1. Parameters of the proton synchrotron U-1.5

Parameter	Value
Injection energy, MeV	30
Accelerated-beam energy, GeV	1.32
Orbit length, m	99.16
Beam intensity, proton/bunch	(1–4) × 10^{11}
Packet-pulsed mode	
– number of beam pulses (bunches) in a packet	1–29
– pulse repetition period in a packet, ms	60
– pulse repetition rate in a packet, Hz	$50/3 = 16_{2/3}$
– repetition period of bunch packets, s	8–10
Pulse (bunch) width, ns	80–100

A new power supply system of the ring electromagnet of U-1.5, which was put into operation in 2021, is expected to make it possible to increase the beam energy from 1.32 to 1.50 GeV and decrease the repetition rate of packets from 8–10 to 6.5 s (compare Tables 1 and 2).

It was estimated that, for a driver beam with the parameters from Table 2, the time-of-flight neutron studies can be performed over path lengths of about 20 m, which are available in the Booster campus (Fig. 2), in a wide range of neutron energies: from thermal (≥0.01 eV) to intermediate (≤1 keV).

The plan of the OMEGA PNS is shown in Fig. 4. The letter designations of the main components are given in Table 3.

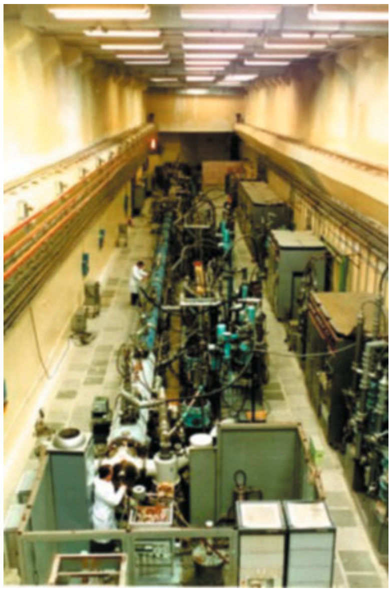

Fig. 3. Linear accelerator Ural-30.

Table 2. Main characteristics of the driver proton beam

Parameter	Value
Energy of accelerated protons, GeV	1.32–1.50
Number of protons per pulse (bunch)	10^{12}
Pulse repetition period in a packet, Hz	$50/3 = 16_{2/3}$
Number of pulses in a packet	29
Repetition rate of packets, s	6.5
FWHM of a pulse (bunch), ns	50
Beam power (average), kW	1.2
Neutron yield, neutron/proton	33
Neutron intensity at a lead (tungsten) target, neutron/s	1.5×10^{14}

BEAM TRANSFER LINE

The beam transfer line for the proton beam extracted from the synchrotron U-1.5, located in sub-building no. 3N of the Booster campus, includes the initial part of the existing beamline from U-1.5 to U-70 and a newly established branch of the of the beam transfer line.

The latter includes five dipole magnets (*D*) and six quadrupole lenses (*Q*). The total beam-deflection angle is 55.5°. The angle between the proton-axis direction before the target and the longitudinal axis of building no. 3N is 15°. The new beamline is 33 m long.

Preliminary calculations showed that the total size of the proton beam transported along the beamline, with geometric emittances of 25π and 14π mm mrad in the horizontal and vertical planes, respectively, does not exceed half aperture of the magneto-optical elements in both transverse planes. The linear and angular dispersions are completely suppressed. The round beam, formed at the input end face of the target, is 22 mm in diameter.

THE TARGET STATION AND RESEARCH BEAMLINES

The plan view of the target station with the proton-beam transport line in building no. 3N is shown in Fig. 5. The target unit is shielded by concrete and steel radiation protection blocks. Six neutron beamlines, spaced by 15° and enumerated counter clockwise *1*–*6*

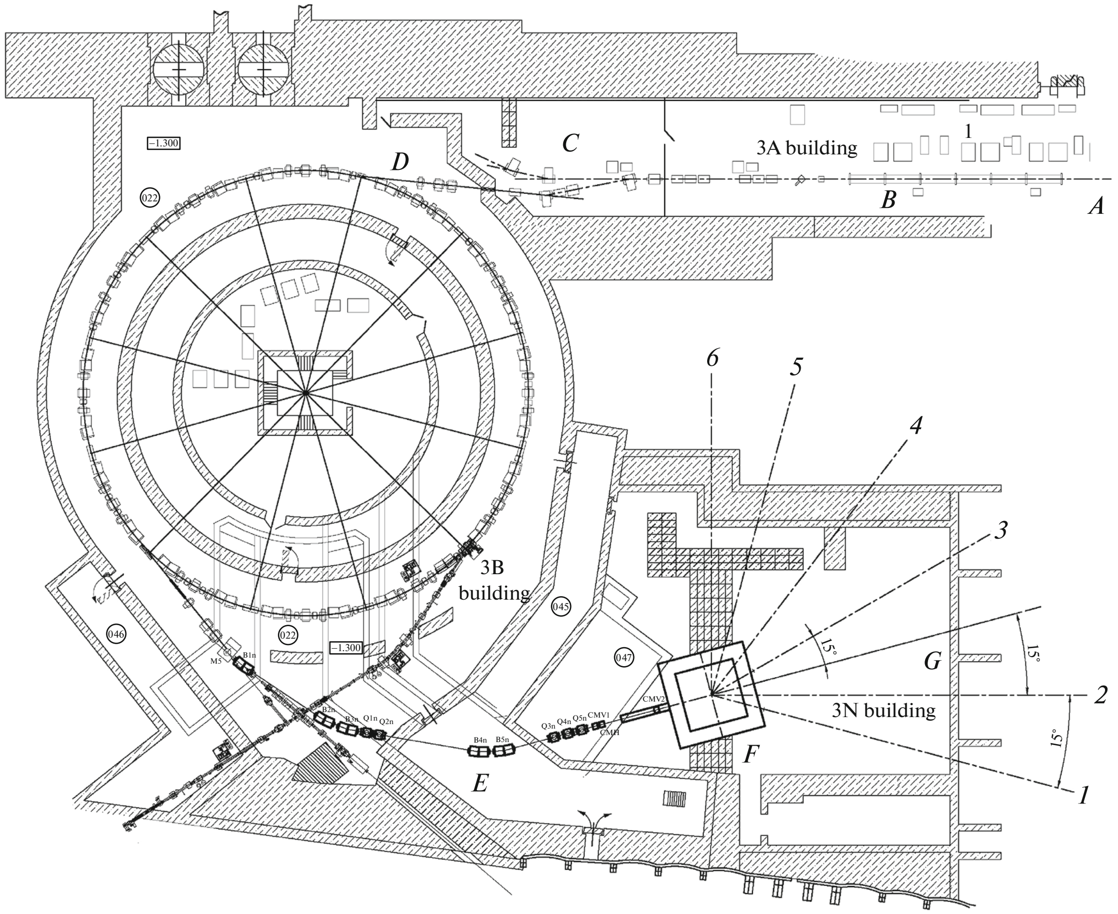

Fig. 4. Plan view of the OMEGA PNS.

in Fig. 4, emerge from the target unit. Beamline *2* is parallel to the axis of building no. 3N.

The central part of the target unit without radiation protection is shown in Fig. 6, in which numbers indicate (*1*) water-cooled hermetic container with a 0.25-m-long tungsten target, (*2*) closed circuit of demineralized cooling water, (*3*) six reflector layers $0.1 \times 0.6 \times 0.6$ m^3 in size, (*4*) water moderator, and (*5*) external housing of the removable target unit.

In the first phase of the project, it is planned to develop three pilot stations out of six. Tentatively, those are:

(i) neutron time-of-flight general-purpose reflectometer;

(ii) general-purpose diffractometer;

(iii) bench for neutron-activation analysis.

The detailed composition and purpose of the experimental facilities will be determined at the next design stages after discussions with scientific organizations of the Russian Federation that are interested in the studies at the OMEGA PNS in framework of a Shared Research Center.

The facility also provides for the possibility of creating in the future an irradiation bench, designed for studying the radiation sustainability of the electronic element base or production cross sections of target radionuclides in both neutron and proton radiation fields (forward direction along the incident driver proton beam, Fig. 4).

EVALUATION OF THE EFFECTS DUE TO THE PROJECT IMPLEMENTATION

The project suggests construction of a pulsed neutron source based on an accelerator of charged particles (protons) as an alternative to neutron sources based on research nuclear reactors of low and medium power. Many of them are close to the end of their scheduled service life. In the post-Chernobyl period, construction of new research reactor facilities is associated with noticeable opposition from the environmentally concerned public.

Table 3. Main PNS components

Designation	System
A	Source of negative hydrogen ions H$^-$
B	Linear accelerator Ural-30
C	Beam transfer line for injected beam to synchrotron U-1.5
D	Proton synchrotron (booster) U-1.5
E	Beamline to transfer the driver proton beam to the target
F	Neutron-generating target station
G	Neutron transport beamlines and experimental stations

The project intends to alleviate the current shortage of research neutron sources in Russia and abroad; it takes into account the demand for neutron-physical research methods in various fields of modern science, equipment, and technology, including defense industry.

The facility will be an essential constituent of the national scientific and technical base: a network of neutron sources for the consolidation of the research community in practical work with neutron instruments (in particular, for the development of relevant neutron physics techniques and education and training of research and engineering personnel for other (flagship) facilities).

The project is focused on creating a multidisciplinary Shared Research Center for third-party orga-

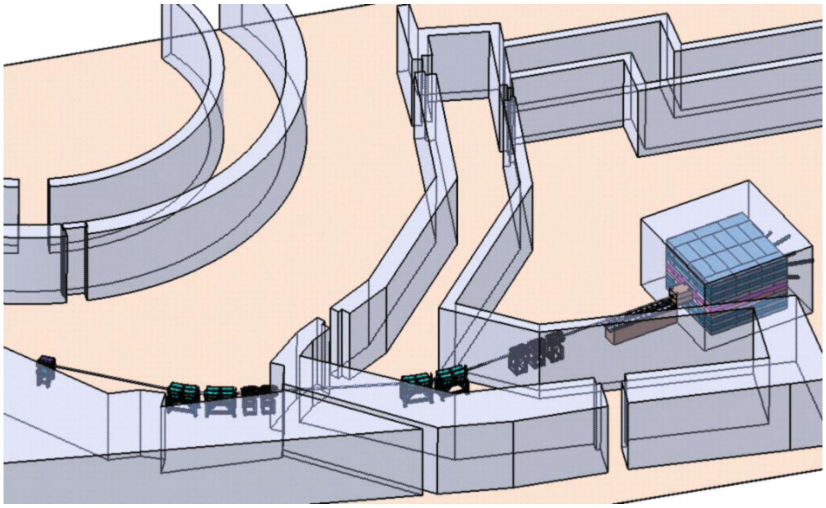

Fig. 5. Plan view of the target station.

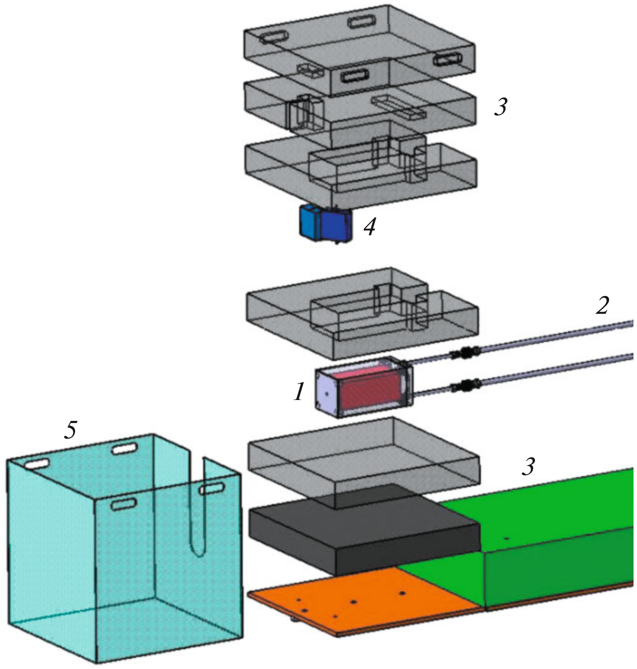

Fig. 6. Central part of the target unit.

nizations to carry out their experimental research using pulsed neutron fluxes.

Due to the size and topology of the experimental hall and the arrangement of stations, the project will make it possible (in contrast to the mega-science neutron sources, which contain from 20 to 50 stations inflexibly specified to specific research method) to reconfigure quickly beamlines towards the interest of individual research groups. This possibility is achieved by assemblying a neutron-generating target station, in which moderators and reflectors can be optimized to a specific experimental station in order to increase the neutron flux intensity on the sample. In addition, the parameters of the charged particle accelerator make it possible to vary quickly the characteristics of the primary (driver) proton beam (energy, intensity, frequency of extraction spill cycles, etc.).

CONCLUSIONS

Realization of the OMEGA PNS project will create (with minimum technical risks and resource and time expenditures) a unique scientific facility for studies on pulsed fluxes of non-reactor (spallation) neutrons.

The characteristics of the OMEGA PNS neutron beams are optimal for generation of short neutron pulses for neutron time-of-flight research techniques.

Realization of the OMEGA PNS project will extend the possibilities of using the accelerator complex U-70 (the largest in Russia operational charged-particle accelerator) for other topical fundamental and applied studies with intense beams of primary and secondary high-energy particles.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. http://www.ihep.ru/files/IHEP-2-10.pdf
2. O. A. Shcherbakov, A. S. Vorob'ev, and E. M. Ivanov, Phys. Part. Nucl. **49** (1), 81 (2018).
3. W. Wagner, Y. Dai, H. Glasbrenner, et al., NIM A **562**, 541 (2006).
4. D. J. S. Findlay, D. J. Adams, T. A. Broome, et al., *Proc. 10th EPAC, Edinburgh, Scotland. June 26–30, 2006,* p. 935.
5. H. Kobayashi, *Proc. 10th EPAC, Edinburgh, Scotland. June 26–30, 2006,* p. 930.
6. Yu. A. Stavisskii, Usp. Fiz. Nauk **176** (12), 1283 (2006).

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