The INR RAS Neutron Complex – present status and new prospects

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Abstract. The status and future plans of the Neutron Complex at the Institute for Nuclear Research, the Russian Academy of Sciences (INR RAS), are reviewed. The Complex includes three spallation sources drived by the high flux proton Linac: the pulsed source of thermal neutrons IN-06, the pulsed source of epithermal neutrons RADEX and the 100-ton Lead Slowing Down Neutron Spectrometer. Over the past two years, major improvements have been made to the sources and neutron instruments. In particular, in 2010 the IN-06 source was put into operation and a set of instruments for condensed matter was tested. The spectra of the direct beams and the TOF spectra of standard samples were measured. The available experimental techniques include neutron diffraction, reflectometry and inelastic neutron scattering. Plans were made to raise the number of instruments and to improve the efficiency of the system.

1. Introduction

INR RAS is the only research center in Russia capable of generating intensive neutron beams by the spallation reaction. The range of applications of the neutron beams at this institute is very wide, ranging from condensed matter physics and materials science to fundamental nuclear physics and nuclear technologies. The Neutron complex of the INR RAS is based on a large accelerating facility, similar to many neutron centers in the world, including existing spallation neutron facilities in the USA (SNS and LANSCE), Japan (JSNS), Great Britain (ISIS), Switzerland (SINQ) and a few facilities under construction, in particular in China (CSNS) and Sweden (ESS). Neutron scattering is an indispensable tool for the structural and dynamical investigations of materials, for nuclear physics [1]. Spallation neutron sources are very efficient compared to the reactor-based neutron facilities [2].

The intense neutron beams at such neutron research centers are generated by the primary proton beam, which is provided by a linear accelerator. Spallation neutron sources provide different neutron energy distributions so one can choose an appropriate one depending on the scientific task and the required energy (or neutron wavelength) range. Due to a variety of tasks and objects to study the neutron instruments are designed for various branches of the neutron experimental technique: neutron diffraction, inelastic neutron scattering, neutron reflectometry, small-angle neutron scattering, neutron radiography [3]. All these branches are existing at INR RAS and the corresponding neutron instruments are either already in operation or under construction. We have a set of instruments primarily designed for condensed matter research and also a few instruments for the experiments in the nuclear physics domain.

The research center under discussion is located in Troitsk some 20 km from Moscow. Taking into account the unprecedented concentration of scientific institutes and universities in Moscow and its region, the research center at INR RAS provides an access to neutron instruments to a vast scientific community specialized in condensed matter physics, Earth physics, chemistry, biology, nuclear energy, materials science and nano-technology.

Due to proximity of the INR RAS Neutron complex in Troitsk to one of the largest cities a very important aspect is an ecologically-friendly regime of the neutron generation at the INR RAS since no fissile materials are involved and no radioactive waste is produced at the neutron facility. This complex is the only ecologically-friendly neutron research center in Russia since all other intense neutron sources in the country (stationary or pulsed reactors) rely on the nuclear fission process and on fissile materials (subjects of the non-proliferation issue).

2. Spallation neutron sources at the INR RAS

The Neutron Complex of the INR RAS is a multipurpose large-scale facility. It includes three spallation neutron sources: the pulsed thermal neutron source IN-06 (thermal neutrons), the high luminosity 100-ton spectrometer for neutron slowing down in lead LSDS-100 (high-energy neutron source) and the neutron source RADEX (thermal and epithermal neurons).

The operation of the INR RAS Neutron complex is governed by the high-current proton Linac. The total length of the Complex including the Linac exceeds 800 m. The Linac consists of a 400-keV proton injector under operation and a H^- injector, lowenergy beam transport lines, a 750-keV RFQ booster cavity, five Drift Tube Tanks of the DTL initial Linac part with the energy 100 MeV, and 27 modules (four sections each) of the Disk and Washer accelerating structure of the Coupled Cavity Linac (CCL) with energy 600 MeV. A DTL RF system consists of six 5-MW pulsed-power 198.2-MHz RF stations. The CCL system has 31 RF stations based on 3.75-MW 991-MHz klystrons. A low-level RF system allows keeping the RF setting of the accelerating field with stability at the level 0.1% for amplitude and 0.1^o for phase. The details on the proton driver, the neutron sources and experimental areas are provided in [4]. The general layout of the neutron sources and the proton driver is depicted in figure 1. See Table 1 for the main proton driver parameters.

Table 1. The main parameters of the linear accelerator at INR RAS

	Designed	Achieved	February 2012	Nearest future
Energy, MeV	600 H^+, H^-	502 H^+	209 H^+, H^-	502 H^+, H^-
Pulse current, mA	50	22	15	16
Repetition rate, Hz	1 to 100	1 to 50	1 to 50	1 to 100
Pulse duration, μs	1 to 200	0.25 to 200	0.25 to 200	0.25 to 200
Average current, μA	100	200	120	300

The former name of the whole facility was Moscow Meson Factory. Nowadays it is converted into the Neutron Complex of the INR RAS due to the shift of the focus of the main interest from the physics of mesons to the studies of condensed matter (including nano-systems). However the branches of nuclear energy investigations and fundamental physics of neutron interactions are still active at the INR RAS and a few instruments are designed for these domains in neutron science.

The pulsed neutron source IN-06 is the major “working horse” of the Neutron Complex. It was designed primarily for the neutron studies of structure and dynamics of condensed matter by thermal neutron scattering method on different instruments and a variety of experimental techniques. Measurements at the IN-06 may cover different fields of solid matter and soft matter investigations in science and technology.

Two other spallation neutron sources (LSDS-100 and RADEX) are used mainly for neutron data collection for nuclear energy technologies and nuclear physics. However the RADEX source has a capability in the field of the neutron studies of condensed matter by epithermal and thermal neutrons.

The integrated neutron flux depends on the Linac proton-beam pulse duration (0.25 - 200 μs) and it could be up to 1.2×10^{15} n/s in the full solid angle (4π Sr). In the current time the Linac provides the primary beam with the proton energy 209 MeV and the current up to 120 μA. The project parameters are the following: the proton energy 600 MeV and the current up to 500 μA, which will be achieved in the near future. The intensity of the secondary neutrons and the neutron pulse length are controlled by the accelerator output and its parameters (power and pulse length).

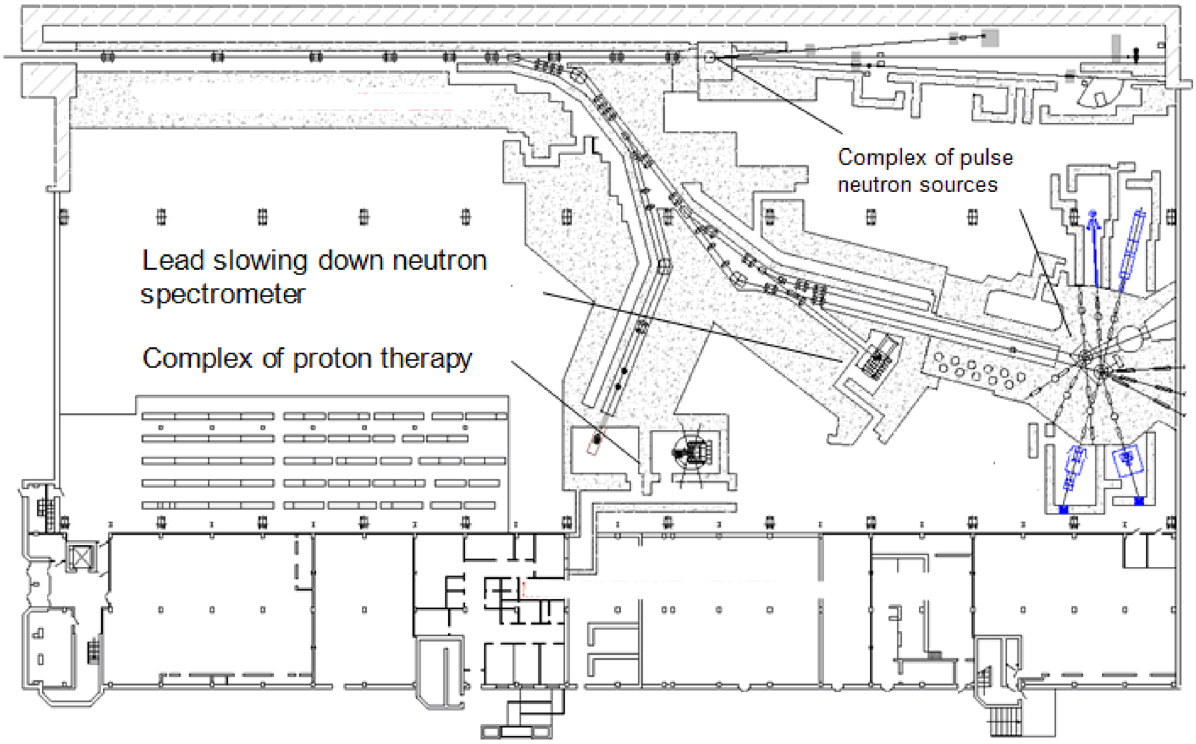

Figure 1. The layout of the main experimental hall of the Neutron Complex.

3. Neutron instrumentation at the INR RAS

The first stage of the Neutron Complex includes a number of neutron beamlines and instruments at IN-06 (see [5] for details on the instruments). The plan of the experimental hall with the neutron instruments of the 1st stage at this source is shown in figure 2.

Another three instruments (the 2nd stage) will be located in the second experimental hall (design project is under way) on the neutron beamlines in the forward direction with respect to the incoming proton beam.

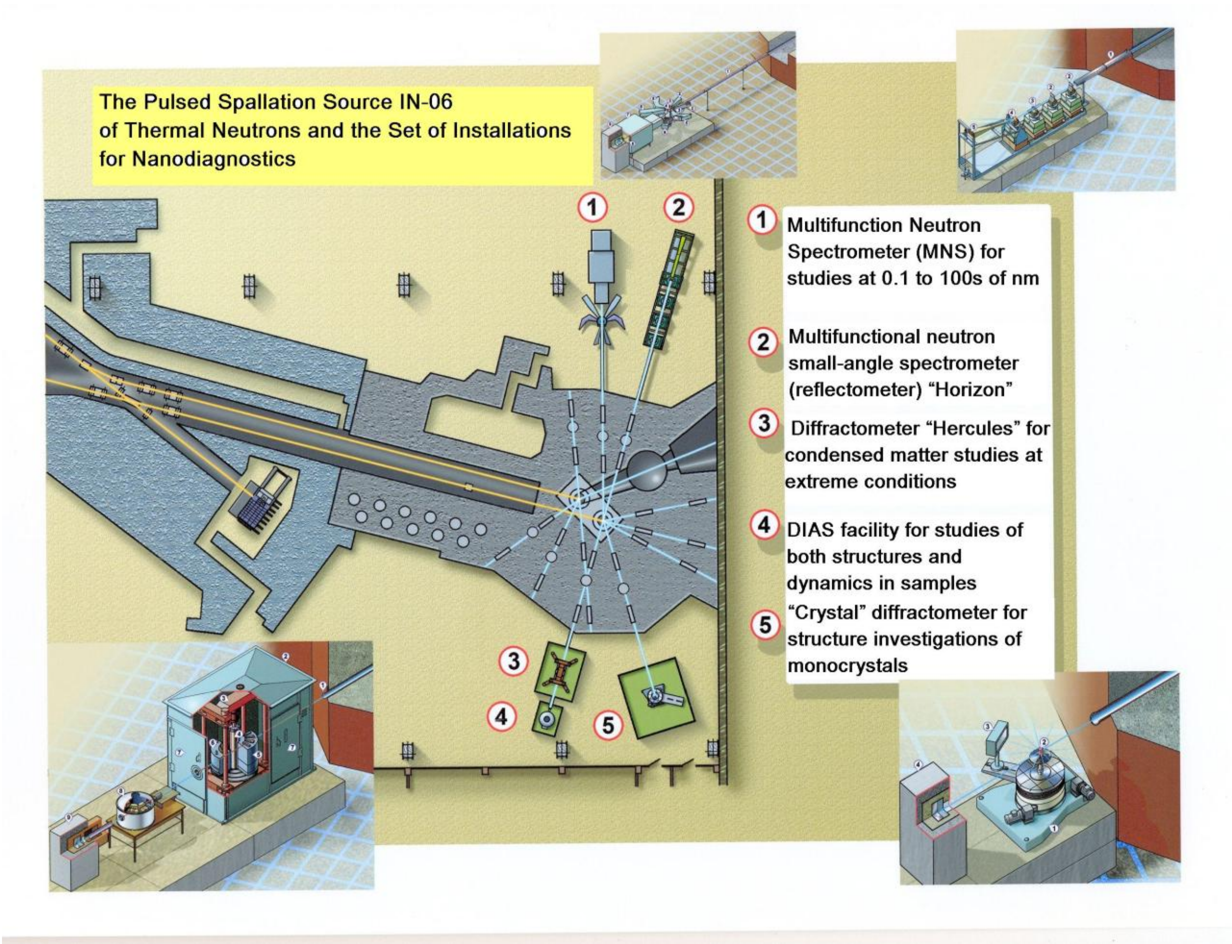

Figure 2. The set of the neutron scattering instrument on the spallation neutron source IN-06 (1st stage). The names of the instruments and the corresponding research branches are indicated on the figure.

The IN-06 instruments for condensed matter studies and nano-science were designed and constructed at the INR RAS in collaboration with several research institutes by research groups involved in the collaboration. Measurements at high pressures and "*in situ"* experiments of hydrogen containing materials are the specific features of the neutron scattering center at the INR RAS.

The following partner research institutes have made substantial contributions to the development of the neutron scattering instruments at the INR RAS: the National Research Centre "Kurchatov Institute", the Institute for High Pressure Physics RAS, the Petersburg Nuclear Physics Institute RAS, the Lebedev Physical Institute of the RAS.

A neutron diffractometer "Hercules" is intended for the condensed matter studies at extreme conditions at the sample position, including high pressure, high and low temperatures. This instrument was designed in collaboration with the National Research Centre "Kurchatov Institute" and the Institute for High Pressure Physics RAS. A special press (force up to 300 ton) and a set of high pressure cells give us a possibility to study the structural properties "*in situ*". The high pressure cells (HPC) has capillaries for filling samples (clatrates, for example) by a gas (D_2, Ar, etc). The HPC operates in a special cryostat. This instrument is well-suited for the studies of hydrogen-containing materials. The sample volume at high pressure can be as large as a few cm^3, which places "Hercules" to the top of the list of the neutron instruments designed to study big samples at high pressure (from a few GPa up to 10 GPa). The maximum of the incoming neutron spectrum on the beamline is about

1.3Å. A special neutron concentrator (TiNi supermirror-based technology) was designed, built and placed into the beamline to enhance the neutron flux density at the longer wavelength side of the spectrum.

A multifunctional neutron small-angle spectrometer (and neutron reflectometer) “Horizon is ready for operation at one of the channels of the pulsed neutron source IN-06. This instrument was designed and assembled by the INR RAS and the Petersburg Nuclear Physics Institute RAS. “Horizon” is intended for studying both liquid and solid samples by the methods of neutron reflectometry and small-angle neutron scattering. Reflectometric studies of liquid samples assume that the surface of these objects is aligned in the horizontal plane by definition. The primary neutron beam of the spectrometer (reflectometer) “Horizon” is formed by the NiMo/Ti supermirror neutron guide, which is seven meter long and bent in the vertical plane. The cross section of the beam just after the neutron guide is equal to (10×70) mm^2 (10 mm size is in the vertical plane, and 70 mm -- in the horizontal one). The characteristic wavelength of this neutron guide is about 1.8Å. The small angle scattering option of “Horizon” provides an opportunity to study samples with the characteristic length scales of nanometers.

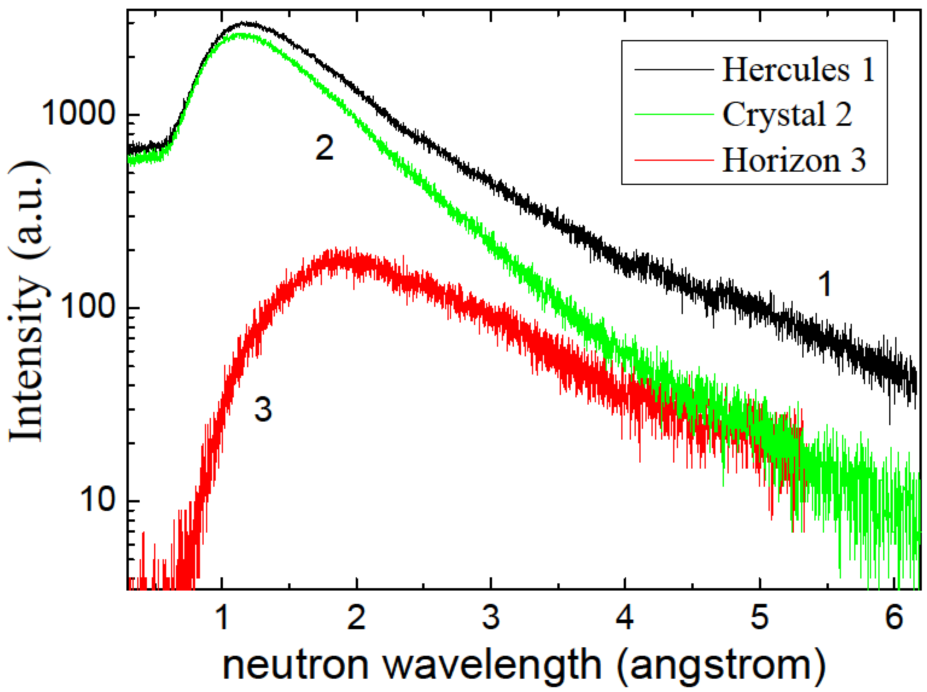

Figure 3. The neutron spectra of the IN-06 source according to the measurements. The names of the beamlines are indicated on the figure.

“Crystal” is a neutron diffractometer for investigations of single crystals at different temperatures and pressures is also ready for measurements. The instrument was designed by the INR RAS. “Crystal” (its first stage) has been successfully tested in November 2010.

A first stage of the Multifunctional Neutron Spectrometer (MNS) has been tested successfully in November 2010. The instrument was designed by the physicist from the Lebedev Physical Institute RAS. The full scale MNS will consist of four modules for the structural studies with different characteristic length scales (up to several hundred nanometers). In order to wider the range of investigated neutron energies and to reduce their losses in air, the supermirror neutron guide is planned. This instrument will be well-suited for the studies of the quasielastic spectral response, lattice dynamics, diffuse scattering.

The neutron spectra of both IN-06 and RADEX neutron sources have been measured recently. Figure 3 depicts the neutron spectra at the sample positions of three IN-06 beamlines corresponding to the instruments “Hercules”, “Crystal” and “Horizon”. The neutron flux on “Hercules” is higher than on other two instruments due to the supermirror neutron concentrator. “Horizon” demonstrates the spectrum with almost absent short-wavelength part since its curved supermirror neutron guide does not allow the high-energy neutrons to get through.

Further development of the neutron studies at the INR RAS will include an upgrade of the IN-06 neutron channels by supermirror neutron guides. This work will be implemented in cooperation with the Petersburg Nuclear Physics Institute. This second stage of development will include also a substantial enhancement of the accelerator performance. A project of a new experimental hall with a few neutron spectrometers is under development now. The instruments of the 2^{nd} stage will provide us a possibility to study quasiparticles in condensed matter, including magnetic excitations and lattice excitations in nanosystems in the energy transfer range up to a few hundred meV or even at the eV range. Such a high energy transfer range is unique in Russia since the INR RAS Neutron Complex is the only spallation neutron facility in the country and the spectrum is very rich in hot and epithermal neutrons compared to the reactor-based neutron sources. Thanks to the relatively high incoming neutron energy, neutron diffraction on highly absorbing systems (samples containing Cd, Gd, Sm, Eu, B) is possible at INR RAS. One small-angle neutron diffractometer for highly absorbing matter is under development now.

A set of complementary installations for material studies by neutrons of thermal and epithermal energies may be arranged at the experimental area of the RADEX neutron source.

Detailed information about the experimental facility at the INR RAS including the linac, the neutron sources and instruments descriptions, schedule of operation, etc., is presented at www.inr.ru.

4. Conclusion

To sum up, the Neutron Complex of the INR RAS provides several beamlines on three neutron sources with different energy distributions ranging from thermal to fast neutrons. A set of neutron instruments is available to the INR RAS scientists and also to a wide user community for the neutron studies in many fields including condensed matter physics, materials science, nanotechnology, fundamental nuclear physics and nuclear technology. Further improvements of the Neutron Complex are planned. In particular both the energy and the current of the proton driver will be increased, new instruments at the neutron sources IN-06 and RADEX will be designed and constructed.

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