A complex of complementary pulsed neutron sources, neutron and radiographic nano-diagnostic instruments at the Institute for Nuclear Research RAS

E.A. Koptelov1, Yu.V. Ryabov1, A.A. Alekseev1, S.F. Sidorkin1, M.I. Grachev1, V.A. Fedchenko3, R.A. Sadykov1,2, Yu.B. Lebed1, V.S. Litvin1, S.P. Kuznetsov3, E.S. Clementyev1,4, P.A. Alekseev4, V.A. Trunov5, A.P. Bulkin5, V.A. Ulianov5 and S.N. Axenov4

1 Institute for Nuclear Research RAS, pr. 60-letiya Oktyabrya 7a, 117312 Moscow, Russia
2 Institute for High Pressure Physics RAS, 142190 Troitsk, Moscow Region, Russia
3 Lebedev Physical Institute RAS, 119991 GSP-1 Moscow, Russia
4 RRC “Kurchatov Institute”, 123182 Moscow, Russia
5 Petersburg Nuclear Physics Institute, 188300 Gatchina, Russia

E-mail: koptelov@inr.ru

Abstract. A new large-scale research center for nano diagnostics and neutron and X-Ray studies of nanomaterials is briefly described. This center at the Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS) is based on three specially designed spallation neutron sources driven by primary proton beams. Similar research centers on the basis of the high flux spallation neutron sources are created in the USA, Japan, Great Britain, Switzerland and will be build in China and the EU (Sweden). We discuss neutron and X-Ray instrumentation at the INR RAS and the corresponding domains of research of various materials including nano-systems.

1. Introduction

Neutron scattering is an indispensable tool for the structural and dynamical investigations of new materials, including nanomaterials [1]. As a consequence, a lot of new research centers for nano-diagnostics and for the detailed studies of nanomaterials are created on the basis of the spallation neutron facilities in the USA, Japan, Great Britain, Switzerland and a few will be build in China and Sweden (the European Spallation Neutron Source) [2]. The intense pulsed neutron beams at such neutron research centers are generated by the primary proton beams, which are provided by large accelerating facilities. A similar research center is in operation in the Russian Federation at the experimental area of the large-scale neutron complex of the tree accelerator-driven spallation neutron sources at the Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS). The pulsed 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
presented at INR RAS and the corresponding neutron instruments are either already in operation or under construction.

X-Ray experimental technique (both synchrotron and laboratory X-Ray sources) is a valuable complementary tool for neutron scattering, that is why new synchrotrons are built very close to the neutron scattering research facilities in France, Great Britain, Germany, etc. A few state-of-the art laboratory X-ray instruments are available at the INR RAS for nano-diagnostics.

The research center under discussion is located in Troitsk (a home for many academic and non-academic research institutes) close to 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 and X-ray instruments to a vast scientific community specialized in condensed matter physics, Earth physics, chemistry, biology, nuclear energy, materials science and nano-technology.

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.

2. Spallation neutron sources at the INR RAS

The Neutron Complex of the INR RAS includes three spallation neutron sources: the pulsed thermal neutron source IN-06, the high luminosity 100-ton spectrometer for neutron slowing down in lead LSDS-100 and the neutron source RADEX with a time-of-flight neutron spectrometer based on a beam-stop irradiation facility (RADEX-n-TOF spectrometer). 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 Complex is located in Troitsk, a multi-purpose scientific center of the RAS in the vicinity of Moscow.

The Linac consists of a 400-keV proton injector under operation and a H\(^+\) injector under commissioning, 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° 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 proton driver parameters.

| Parameter          | Designed | Achieved | November 2010 | Nearest future |
|--------------------|----------|----------|---------------|---------------|
| Energy, MeV        | 600 H\(^+\), H\(^-\) | 502 H\(^+\) | 209 H\(^+\) (160 H\(^-\)) | 502 H\(^+\), H\(^-\) |
| Pulse current, mA  | 50       | 22       | 12            | 16            |
| Repetition rate, Hz| 1÷100    | 1÷50     | 1÷50          | 1÷100         |
| Pulse length, µs   | 100      | 0.5÷200  | 0.25÷170      | 0.25÷200      |
| Average current, µA| 500      | 150      | 120 (160 MeV) | 300           |
|                    |          |          | 40 (209 MeV, n-TOF) |               |

The former name of the whole facility was the 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 and nuclear physics 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 and a few instruments are designed for these domains in neutron science.

The pulsed neutron source IN-06 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-n-TOF spectrometer) are used mainly for neutron data collection for nuclear energy technologies and nuclear physics. The RADEX-n-TOF spectrometer 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 - 160 µs) and it could be up to $1.2 \times 10^{15}$ n/s in the full solid angle ($4\pi$ Sr). In the current time the Linac provides the primary beam with the proton energy 209 MeV and the current up to 150 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 Neutron Complex of INR RAS. 1- Linac; 2- Experimental Complex; 3- Proton storage ring (not completed); 4- RADEX neutron source with neutron guides for TOF spectroscopy; 5- spallation neutron source IN-06 with neutron beamlines for the condensed matter studies; 6- target box for accelerator driven systems studies; 7- tungsten target; 8- LSDS-100 neutron source.

3. Neutron and X-Ray instrumentation at the INR RAS

The first stage of the Neutron Complex includes a number of neutron beamlines and instruments at IN-06. 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 nanoscience 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 Russian 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 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 researchers from 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. So the scattering plane must be vertical in such a case. 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) mm² (10 mm size is in the vertical plane, and 70 mm -- in the horizontal one). The characteristic wavelength of this neutron guide is about 1.7Å. The small angle scattering option of “Horizon” provides an opportunity to study samples with the characteristic length scales of nanometers. A closed cycle refrigerator for neutron scattering is available on this instrument. “Horizon” has been successfully tested in November 2010.

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 Russian 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 (D2, 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 cm³, 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 1.2Å. A special neutron concentrator (TiNi supermirror-based technology) was designed, build and placed into the beamline to enhance the neutron flux density at the longer wavelength side of the spectrum. The first experiments on “Hercules” have been performed in November 2010. These measurements demonstrated a good counting rate and a reasonable resolution of this neutron diffractometer.

DIAS (under construction) is a powder diffractometer, a high-resolution diffractometer of reverse geometry with temporal focusing, and an inelastic scattering diffractometer of inversed geometry (fixed final neutron energy). This multi-functional instrument was designed in collaboration with the Russian Research Centre “Kurchatov Institute”. DIAS is intended for studies of both structures and dynamics in samples of different nature and at various conditions including low and high temperatures, high pressure and magnetic field.

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 widen 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.

“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.
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 2nd 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-n-TOF neutron source.

In addition to the neutron facilities, a set of modern X-ray instruments is available for the structural research at ambient and low temperatures, ambient and high pressure. These instruments (German-made by Stoe and Huber) include X-ray instruments for powder samples (Stadi MP diffractometer) and single-crystals (4-circle diffractometer Huber and image plate diffractometer Stoe IPDS II). X-ray measurements are possible using MoKα1 and CuKα1 radiation thanks to monochromators installed on the instruments.

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 outlined above is available now for the studies and diagnostics of different materials including solid and liquid samples, soft matter, functional materials and nanosystems. A set of modern X-ray instruments for the structural studies and nano-diagnostics is available as a complementary experimental tool. These facilities will provide an easy access to various neutron scattering techniques for a vast scientific community from Moscow and its region, numerous research institutes and universities.

References
[1] Neutron Applications in Earth, Energy and Environmental Sciences, Springer Series: Neutron Applications and Techniques, Liang L, Rinaldi R, Schober H (Eds.), Vol. XVIII, 2009.
[2] Carpenter J M and Yelon W.B, Neutron Sources, in Neutron Scattering, Skold K and Price D L (Eds.) Methods of Experimental Physics 23 A, Academic Press, New York 1986.
[3] Schober H, Neutron Scattering Instrumentation, Springer 2008.
[4] Koptelov E A and Kravchuk L V, Proc. Int. Conf. ICANS-XVIII, Dongguang, 2007.