Condensed Matter Physics

Current trends in the development of scientific research dictate the necessity of an interdisciplinary approach to addressing scientific problems with the use of complementary nuclear physics methods. JINR possesses a unique experimental base (the pulsed research reactor IBR-2, the FLNR accelerator complex, and the Nuclotron) and a wealth of experience in theoretical studies accumulated at BLTP. This allows the Institute to conduct advanced fundamental and applied research in condensed matter physics and related fields — biology, medicine, materials science, geophysics, engineering diagnostics — aimed at probing the structure and properties of nanosystems, new materials, and biological objects, and at developing new electronic, bio- and information nanotechnologies.

1. Research fields

Nanosystems and nanotechnology

Study of nanosystems by neutron scattering methods. Neutron methods of investigation of matter make it possible to obtain detailed information about the atomic and magnetic structure and dynamics of materials at the atomic (micro-) and supra-atomic (nano-) levels. The main research directions are the following: magnetism of layered nanostructures; nanodiagnostics of magnetic colloid systems in volume and interface, of carbon nanomaterials, and of polymer nanodispersion materials aimed at the definition of their structure characteristics at the nanolevel and their role in the formation of physical properties; formulation of recommendations for the development and production of nanostructures and their application in nanotechnology; studies of the nanostructure and properties of lipid membranes and lipid complexes, of the supramolecular structure and functional characteristics of protein biological macromolecules, DNA, RNA, and of the structure of lipid-protein complexes. In view of the commissioning of the CARS microscope, studies of DNA and vibrational spectra of proteins are envisioned.

Experimental and theoretical studies in the field of radiation-ion technology. Accelerated heavy ions are a unique instrument for research in the radiation physics of solid matter. A significant advantage of accelerated heavy ions is their high defect-forming capability allowing, within a short time, the creation of radiation defect density in materials which is comparable with the density obtained at neutron irradiation during several years. An important feature of the use of heavy ions is an opportunity both to modify macroscopic properties of materials and to develop nanosize structures in them. The main areas of research are the studies of the effect produced by multicharged ions with energies from ~ 1 keV/n to ~ 10 MeV/n on materials aimed at modification of their nanostructure, tests of radiation resistance, and targeted modification of properties; synthesis of nanoobjects with unique properties to be applied in electronics, optics, telecommunications, measurement technology, etc; studies of the properties of micro- and nanopores produced by the ion track method in various materials to develop elements of nanofluid technology, to create molecular sensors, and to model biological membranes; development of new promising materials based on secondary structures produced on track membranes by metallization, plasma processing, plasmochemical grafting, impregnations (controlled semipermeable membranes — gates, light-emitting diode matrices, anisotropic optical filters, X-ray radiation filters, etc.).

Detectors for investigation of nanostructures and new materials. Development of the GaAs-based gamma detectors for nanostructure investigations, micro-pixel avalanche photodiodes and their application in nanoindustry, investigation of nanomaterials by positron-annihilation spectroscopy methods and synthesis of photon crystals on the basis of dioxide silicon nanoparticles.

Theoretical studies of nanostructures. The main directions of research are the studies of electronic, thermal and transport characteristics of various modern nanomaterials and nanostructures.

Radiobiological research

Cancer treatment with proton beams. The project has three stages. The first is the development of the method of conformal cancer treatment at the DLNP Phasotron, education of personnel and certification of proton therapy for the use in Russia and other countries. The second stage is oriented towards the construction (in collaboration with IBA, Belgium) of a special medical cyclotron for cancer treatment. The last stage is the proton therapy technology and equipment transfer to the Russian Proton Therapy Centre (at Dubna or elsewhere) with a capacity of 1000 patients per year.

Investigation of mechanisms of the genetic action induced by accelerated multicharged ions. Studies of regularities and mechanisms of formation and repair of DNA damages in human cells. Studies of heavy-ion action on the chromosomal mechanism in human cells. Mutagenic effect of LET radiation on cells of various organisms.

Studies of the action of heavy particles on the ocular structure: the lens and retina. The main purpose of the proposed research will be simulation *in vivo* and *in vitro* conditions of the molecular mechanisms of the origin of the lens-form opacity (cataract) in humans exposed to heavy-ion irradiation.

Studies of regularities of biological effects of accelerated heavy ions on the central nervous system. The main purpose of the planned research on this subject will be studies of morphological, cytological, molecular, and physiological damage in the central nervous system structures, and of the modification of behavioral functions in irradiated animals.

Mathematical simulation of biophysical systems. Elaboration of mathematical models is planned of the induced mutation process in pro- and eukaryote cells at the action of radiation with different physical characteristics. It is planned to use the molecular dynamics methods in the simulation of the 11-cys retinal rhodopsin chromatophore and the surrounding amino acid residue in the chromatophore area at the physiological regeneration of the visual pigment.

New materials

Studies of new materials by neutron scattering methods. The main areas of research include studies of crystalline and magnetic structures of new functional materials, nano- and macrostructures of magnetic semiconductors, atomic dynamics of materials by neutron scattering methods, analysis of the interrelation between the peculiarities of their structure and physical properties.

Theoretical research of new materials. The planned programme of theoretical research will be mainly focused on the analysis of new materials with strong electron correlation that assumes studies of new cooperative phenomena, new types of ordering, magnetism in low-dimension systems and quantum critical phenomena. Theoretical research in this field will be directed to the support of experimental studies of these materials by neutron scattering.

Engineering diagnostics. Earth sciences

The main areas of research are determination of internal stresses in bulk materials and products, studies of the texture and properties of minerals and rocks.

2. Expected results

Nanosystems and nanotechnology

Determination of the depth distribution of magnetization in layered nanostructures, analysis of the influence of proximity effects on magnetic properties. Formulation of recommendations for the design and creation of nanostructures for the use in elements of nanoelectronics.

Definition of structural parameters and mechanisms of stabilization of magnetic colloidal systems, carbon nanomaterials, and identification of the relationship between the structure of the investigated systems and their physical and chemical properties.

Investigation of interparticle interactions and clusterization of magnetic colloidal systems in various types of liquid and solid media. Determination of quantitative and functional characteristics of new polymers.

Analysis of nanostructural modification, targeted modification of the change of properties and radiation resistance of materials under the influence of multicharged ions, synthesis of solids with unique properties for applications in electronics, optics, communications equipment, measuring equipment, etc.

Development of theoretical models to describe electronic and thermal transport characteristics of nanosystems, in particular carbon nanotubes.

Obtaining of information about transport properties of asymmetric electrically charged track nanopores; obtaining of data on the properties of composite track membranes with controlled selectivity.

Development of new types of track nanomembranes (including under innovative projects).

Characterization of the nanostructure of a model lipid matrix of the upper layer of human skin, definition of the role of individual ceramides in the formation of its diffusion properties.

Characterization of the diffusion process of pharmaceutical solutions through model lipid matrices. Definition of structural and functional characteristics of biological macromolecules.

Radiobiological research

Detection of molecular disorders in DNA of human cells under the action of heavy charged particles and structural damage to the chromosome apparatus; analysis of genetic control of induced mutation in cells with different levels of genome organization.

Formulation of recommendations on the threshold doses of charged particles that can cause damage to the lens, retina, and of methods of prevention of eye diseases.

Development of mathematical models of mutation process in cells of pro- and eukaryotes induced by radiation of different quality, modeling of structures of biologically important macromolecules.

Synthesis of new radioisotopes for medical applications.

New materials

Determination of the crystal and magnetic structures and physical properties at the nanolevel in complex oxides of transition metals, multiferroics.

Determination of peculiarities of the molecular dynamics and parameters of the crystalline structure of bioactive materials.

Identification of structural characteristics of materials for the future use in hydrogen power and solid-state fuel elements; analysis of the phonon mode behaviour in reactor materials.

Construction of theoretical models of mutual influence of the electronic structure, magnetic and transport properties of complex systems.

Obtaining of data on peculiarities of the synthesis in metals of multicomponent monodisperse nanophases in the process of low-dose heavy-ion irradiation.

Engineering diagnostics. Earth sciences

Definition of internal stresses in geological materials (texture, deformation), bulk materials, and products for nuclear science and technology.

Definition of internal stresses in industrial materials and products. Identification of rock instability patterns to develop awareness of processes in earthquake foci.

3. Experimental and methodological base

Neutron scattering research

The reconstruction of the IBR-2 reactor— the main basic facility at JINR for neutron research in the field of condensed matter physics, with world-level parameters and the only one of this kind in the JINR Member States, — will be completed during 2010. Research with spectrometers at the reactor involves a user programme based on requests from scientists of Member States to conduct experiments. The work on the physical and power start-up of the reactor with a complex of thermal and cold moderators will be carried out in stages:

1. Physical start-up and beginning of the power start-up, first physics experiments (with water moderators) — in 2010.

2. Completion of the power start-up — in 2011.

3. Implementation of the complex of cryogenic moderators: moderator for channels 7–11 — in 2010, moderators for channels 2–3 and 4–6 — in 2011.

4. First physics experiments with cryogenic moderators — in 2011–2012.

Plan of work for the period 2010–2016:

1. Bringing of the IBR-2M reactor to the design parameters. Study of the physical characteristics of IBR-2M.

2. Routine exploitation of the reactor and provision of the programme of physics research at extracted neutron beams.

3. Development and operation of the complex of cryogenic moderators. Acquisition and launching of a new refrigeration unit for channels 4–6.

4. Construction of the reserve movable reflector MR-3R.

5. Upgrade of the reactor's technological equipment with expiring service (air heat exchangers, electromagnetic pumps, etc.).

6. Elaboration of the concept of the use of IBR-2M beyond the year 2030.

Programme for the development of the spectrometer complex for IBR-2M:

1. Implementation of projects for construction of new spectrometers: DN-6, GRAINS, FSD, which will significantly expand the area of research at the IBR-2M reactor at the world level.

2. Upgrade of the existing spectrometers: HRFD, DN-2, DN-12, SKAT/EPSILON, YuMO, REMUR, REFLEX, DIN2-PI, NERA-PR aimed at improvement of their technical parameters (intensity, resolution, effect/background ratio).

3. Development of projects for new spectrometers: a small-angle neutron spectrometer and a reflectometer with atomic resolution.

4. Development and testing of new neutron-optical methods for investigations of the structure and dynamics of nanosystems and condensed matter, including the spin-echo and other methods based on the Larmor precession of neutron spin.

5. Upgrade of spectrometer elements, development of new types of neutron detectors and data acquisition systems, development of the network and computing infrastructure.

6. Cryogenic research.

Funding (k$)
Research programmes

Activities	2010	2011	2012	2013	2014	2015	2016
Neutron scattering research	120	120	130	140	140	140	150
Biomedical research using heavy charged particles	118	139	163	193	232	268	335
Research in the theory of condensed matter	46	50	54	59	63	68	72
Total	**284**	**309**	**347**	**392**	**435**	**476**	**557**

Funding (k$)
Experimental and methodological base

Activities	2010	2011	2012	2013	2014	2015	2016
Modernization of the IBR-2M reactor	960	850	855	375			
IBR-2M operation expenses	500	500	500	500	500	900	1 000
Modernization of the IBR-2M physical security system	1 360	150	150	150			
IBR-2M spectrometer complex: projects of construction and upgrade of first-priority spectrometers (DN-6, SKAT/EPSILON, GRAINS)	533	591	662	650	500	400	100
Projects of upgrade of second-priority spectrometers (FSD, REMUR, YuMO, HRFD, DN-2, NERA, DIN2-PI), development of new methods of research				137	426	674	1045
Development and construction of spectrometer elements, detectors and data acquisition systems; development of the network infrastructure	190	280	390	545	630	665	730
Equipment for cold moderators of IBR-2M, upgrade of moderators	35	50	45	80	100	160	200
Development of the LRB infrastructure	171	145	156	175	207	224	243
Total	**3 749**	**2 566**	**2 758**	**2 612**	**2 363**	**3 023**	**3 318**

Radiation-ion technology, radioisotope and radiobiological investigations

The family of heavy-ion accelerators created at FLNR — IC100, U200, U400, U400M — provides ample opportunities for radiation physics and radioisotope studies with ions from boron up to xenon in the energy range 1–20 MeV/A.

The further development of stand-alone accelerators and creation of accelerator complexes for scientific and applied research, also for the industry, is planned. Particularly:

- improvement of IC100 (vacuum system, increase in beam energy and intensity, acceleration of W-ions, etc.)
- realization of mass irradiation of polymeric films at the DC-60 accelerator (Astana)
- launching of the DC-72 cyclotron in the Cyclotron Centre (Bratislava) for applied and medical applications
- construction of an ECR ion source for radiation processing of materials and multi-elemental implantation
- creation of specialized equipment for testing microelectronic chips at U400 beams.

<u>New innovative projects:</u>

- construction of a specialized accelerator for the BETA project — manufacturing of track membranes for cascade blood plasmapheresis (intensity of $5 \cdot 10^{12}\ s^{-1}$, energy of ions 2.4–2.6 MeV/A)
- development of new types of track membranes for medical purposes within the BETA project
- use of the experimental base (primarily, accelerators) within the framework of the collective-access International Nanotechnology Centre at JINR and in projects developed in the Dubna Special Economic Zone.

Radioecological research, ultrapure isotopes:

- Use of the microtron MT-25 (photonuclear reactions) and cyclotron U200 ((α, xn)-reactions) for producing unique isotopes, e.g. ^{178m}Hf, ^{225}Ac, ^{236}Pu, ^{237}Pu.

Activities	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Development of the experimental base for radiation physics and radioisotope research (IC-100, MT-25, U-200) and new innovative projects (DC-60M, DC-72, TM, etc.)	Performance of work under orders and contracts						