Neutrino Physics and Rare Phenomena, Astrophysics

In 2016 the **Baikal** collaboration made one more step to reach its goal of constructing a cubic-kilometer scale neutrino detector (NT-1000 project). The first full-scale cluster of the standard design (8 strings of 3 sections each, radius 60 m, 288 optical modules in total) was deployed during the winter expedition from February to March 2016. It was proved that extended sections of 525m length were constructible and operable. Data acquisition is are proceeding now.

Since the plan for the next-year expedition is to deploy the second full-scale cluster of the standard design, it is important to produce 288 new optical modules. That is why we made the production line at JINR in 2016 year which is capable of making 300-600 optical modules per year. That should be enough to meet the needs of the experiment even when we deploy two clusters per year. At present 233 optical modules are assembled and 144 of them have passed the test procedures. Assembling and testing the other optical modules are in progress. Moreover, the procedure of testing 12 optical modules as single section, which is a minimal unit of the data-acquisition system of the detector, began at specially designed test benches.

One of the most important achievements of the last year is the construction of a new control station on the shore of Lake Baikal, which includes new power-supply detector control system, data-processing, and data storage systems. Preliminary data processing consists of aggregating event data from different sections, making the time and amplitude calibrations of the detector, and obtaining the coordinates of the optical modules via the acoustic-positioning system data corresponding to the event time. All these tasks were accomplished in 2016.

In 2016 within the **Daya Bay** project the doubling of the acquired statistics (1230 days of DAQ) and the improvement the uncorrelated detection efficiency uncertainty from 0.2% to 0.13% allowed refining the neutrino oscillation parameters: $\sin^2 2\theta_{13} = 0.0841 \pm 0.0033$, $\Delta m^2_{ee}=(2.45\pm0.08)\cdot10^{-3}$ eV^2 [1]. It is the most precise measurement of both oscillation parameters.

A theory of neutrino oscillations based on wave packets was developed. It predicts the loss of coherence of wave packets and suppression of neutrino oscillations. The first limits on the coherence parameters are obtained. The upper limit on the relative neutrino energy spread is $\sigma_{rel}<0.20$ (95% CL) [2], which is equivalent to the lower limit on the spatial size $\sigma_x<10^{-11}$ cm (95% CL). The measurement is based on the Daya Bay data acquired during period of 621 days.

Within the **JUNO** project a scanning station for large 50’’ photomultiplier tubes (PMTs) was designed and manufactured. Its purpose is to measure differential (zonal) characteristics: photodetection efficiency, amplification, etc. Scanning station software is developed and is at the debugging stage. Several new scanning stations are being manufactured and prepared to be shipped to China. A prototype of the Top Tracker support was designed and produced. An algorithm to control the performance of the plastic scintillator by using the signal of cosmogenic muons is developed. We have developed a method and software for optimal veto volume determination in order to cut off long-lived isotopes of $^{8}He/^{9}Li$ produced in the interactions of cosmogenic muons. This optimization is needed to maximize the fiducial volume of the detector.

In 2016 limits on the neutrino fluxes associated with the gamma- ray bursts are obtained by the **Borexino** collaboration [3]. The analysis of the seasonal signal variations in Borexino is completed confirming the solar origin of the observed neutrino signal.

Limits on the spin-independent WIMP-nucleon cross section have been obtained using 1422±67 kg·d of data acquired with the prototype of the Dark Side detector, the. These cross sections for the WIMP particles with a mass of 100 GeV (100 GeV, 10 TeV) are $2\cdot10^{-44}$ ($8.6\cdot10^{-44}$, $8.0\cdot10^{-43}$) cm^2 at the 90% C.L. respectively [4].

During 2016 within the **NOvA** experiment analysis based on exposure of $6.05\cdot10^{20}$ POT (Protons On Target) was performed and new results were obtained [5-7] for the muon neutrino oscillation parameters. In particular, an interesting hint for the nonmaximal θ_{23} mixing was obtained for the first time at the $>2.5\sigma$ significance level.

Moreover, the new results establish oscillation in the electron neutrino appearance mode, $\nu_\mu\rightarrow\nu_e$, with the $>8\sigma$ level. This signal slightly prefers Normal Hierarchy (NH) of the neutrino mass, while Inverted Hierarchy (IH) with the lepton CP violation value $\delta_{CP}=\pi/2$ is ruled out at the level of $>3\sigma$.

The present NOvA statistics corresponds to about 1 project year (from 6 years expected in total). The new data (especially with antineutrino beam planned also for 2017) will help to resolve degeneracies in the effects of mass hierarchy, $\delta_{CP,}$ and θ_{23} octant.

Physicists from JINR DLNP take an active part in the **NA61/SHINE** experiment at CERN. In 2016 the analysis of the experimental data was completed and new important results were published about the precision measurements of hadron production in interactions of 31 GeV/c protons with a thin carbon target and with a T2K replica target [8, 9]. These results are crucial for predictions of neutrino and antineutrino fluxes at the J-PARC accelerator complex, and thus will allow further reduction of systematic uncertainties in determination of neutrino oscillation parameters by the T2K experiment.

The **NEMO-3** detector, which had been operating in the Modane Underground Laboratory from 2003 to 2010, was designed to search for neutrinoless double-β ($0\nu\beta\beta$) decay. Seven isotopes (^{100}Mo, ^{82}Se, ^{130}Te, ^{116}Cd, ^{150}Nd, ^{96}Zr, ^{48}Ca) were studied by the simultaneous recording of the energy and track of the event, ^{100}Mo and ^{82}Se with standing out since they were the most massive ones [10, 11]. No evidence for neutrinoless double beta decay was observed, which led to obtaining limits on the effective neutrino mass that are among the best to date, especially for the ^{100}Mo and ^{82}Se isotopes.

As evolution of NEMO-3, the **SuperNEMO** experiment (new generation experiment to search for neutrinoless double beta decay) is being performed. As the first phase, its first module called Demonstrator is under construction. It will contain 7 kg of ^{82}Se and will be able to reach the NEMO-3 sensitivity for the 0νββ decay in only 5 months. If no background events in the 0νββ region are detected after 2.5 years of data taking, which implies an exposure of 17.5 kg·y, the half-life sensitivity will be increased to $T(0\nu) > 6.5\cdot10^{24}$ y (90% C.L.), leading to a mass sensitivity of $<m_{\beta\beta}> <$200-400 meV. The SuperNEMO Demonstrator module is currently under assembly at the LSM, the last part will be assembled at the beginning of 2017. Data taking will start in the second half of the year to measure the level of background achieved.

The **EDELWEISS** program searches for evidence of direct WIMPs from the Milky Way galaxy scattering off Ge nuclei within cryogenic Ge crystals. The EDELWEISS detectors are cryogenic (working temperature ~20 mK) Ge bolometers allowing simultaneous measurement of phonon and ionization signals. A comparison of the two signals provides highly efficient event-by-event discrimination between nuclear recoils and electrons. In 2016 the main objective of the EDELWEISS collaboration was to accumulate WIMP data from 800 g FID detectors with active rejection of the surface background. EDELWEISS continues testing new approaches to extending the investigated WIMP masses to the low-mass region.

In 2016 the results of the search for low-mass WIMPs at EDELWEISS-III were published. The 90 % C.L. exclusion limit set for the WIMPs with $m_\chi = 4$ GeV/c^2 is $1.6\cdot10^{-39}$ cm^2 [12, 13]. Positive results reported by some other experiments were directly verified. It is important that the achieved EDELWEISS-III sensitivity completely covers the region of positive CoGeNT results obtained with the same nucleus (Ge).

The **νGeN** is experiment is intended for detection of coherent neutrino - Ge nucleus elastic scattering using special HPGe detectors developed by DLNP (JINR, Dubna) in collaboration with BSI (Riga). To be sensitive to the coherent scattering signal, the νGeN experiment is placed under reactor of power #3 at the Kalinin Nuclear Power Plant (KNPP) at the point where the neutrino flux is greater than $5.4\cdot10^{13}$ per cm^2 per sec (minimal distance 10 m). In the scope of the project we work on creation and investigation of new low-threshold semiconductor detectors made from different materials (HPGe, CZT, SiC). The aim of this R&D is to build detectors with an energy threshold of 200 eV and below for further delated study of the coherent scattering process.

In 2016 after some additional tests in Dubna the setup was delivered to the KNPP and assembled in the room located just under the reactor of power unit #3. Now the spectrometer is under commissioning. Integration of all parts of the setup (passive and active veto systems, data acquisition, moving platform that will change the distance between the detectors and the neutrino source) is in progress. The neutrino data acquisition begins in 2017.

In June 2016 the **GERDA** Collaboration meeting released the first set of data accumulated during 6 months. The expected background of 0.001 counts/(keV·kg·yr) was reached. The first Phase II and previous Phase I data were analyzed together (total exposure 34.4 kg·yr). A new half-life limit for neutrinoless double beta decay was set to be $T_{1/2}(0\nu) > 5.3\cdot10^{25}$ years (90% C.L.). The sensitivity was $4.0 \cdot 10^{25}$ years [14]. Due to the unprecedented background level no background count in the region of interest is expected until we reach the design exposure of 100 kg·yr in 2018. Thus, GERDA Phase II is the first background free experiment aimed at searching for $0\nu\beta\beta$. Consequently, our sensitivity will increase linearly, unlike the case in other projects where it is proportional to the square root of exposure. At the end of the data taking the GERDA Phase II sensitivity of 10^{26} years will be achieved.

At the end of 2016 a new international collaboration (preliminary name is NG-Ge76, Next Generation Ge-76) was formed. The goal of this new effort is to build a next generation ton-scale experiment to search for the neutrinoless double beta decay of ^{76}Ge. The first phase of this project with 200 kg of germanium detectors will be performed at the modified GERDA setup.

The IACT telescopes with ~10 m^2 mirror and ±5o FoV are added to the **TAIGA** experiment to improve the detector sensitivity and decrease the energy threshold down to ~1.5 TeV for energy spectrum measurements of the known gamma sources and more efficient discrimination between gamma and hadron EAS. The JINR responsibility is to design, produce and test the IACT telescope mechanics. After the combined mechanical tests the IACT was delivered to the Tunka area [15].

The **NUCLEON** device is placed as an additional payload on board of the RESURS-P N◦2 satellite that was launched on 26 December 2014. Preliminary results are obtained from the charge distribution measurements of cosmic ray nuclei from lithium to iron and from the spectrum measurements of CR protons and He nuclei. They are in the reasonable agreement with other experimental data, in particular with the ATIC, SOCOL, CREAM, TRACER and AMS-2 results [16].

The **TUS** mission was launched at the end of April 2016 aboard the dedicated ”Lomonosov” satellite, and is expected to operate for 3-5 years. Now the TUS detector is working in the flight test regime. Unexpectedly, new background events were discovered which were not found before in the TATIANA and TATIANA-2 space flights. Short and powerful UV pulses arise in the UV filter due to interactions of CR hadrons that generate a trigger signal. The program of the TUS event visualization was developed at JINR. It allows the conclusion that at the ~200th time step the CR particle interacted inside the UV-filter and produced secondary charged particles that generated light pulses. These light pulses along the path of secondary particles were registered by photodetector and produced a trigger [17].

Physics of Elementary Particles

In the **ATLAS** experiment a search is conducted for resonant high-mass new phenomena in dielectron and dimuon final states. The search uses 13.3 fb^{-1} of proton-proton collision data, collected at $\sqrt{s} = 13$ TeV by the ATLAS experiment at the LHC in 2015 and 2016. The dilepton invariant mass is used as the discriminating variable. No significant deviation from the Standard Model prediction is observed. Upper limits at 95% credibility level are set on the cross-section times branching ratio for resonances decaying to dileptons, which are converted into lower limits on the resonance mass, ranging between 3.36 TeV and 4.05 TeV, depending on the model.

Search for gluinos in final states with an isolated electron or muon, multiple jets and large missing transverse momentum are performed using proton–proton collision data at a centre-of-mass energy of $\sqrt{s}$=13 TeV. The dataset used was recorded in 2015 by the ATLAS experiment at the Large Hadron Collider and corresponds to an integrated luminosity of 3.2 fb^{-1}. Six signal selections are defined that best exploit the signal characteristics. The data agree with the Standard Model background expectation in all six signal selections, and the largest deviation is 2.1 standard deviation excess [18].

Search for new resonances with mass larger than 250 GeV decaying to a Z boson and a photon was performed. The Z bosons are identified through their decays either to charged, light, lepton pairs ($e^+ e^-$, $\mu^+ \mu^-$) or to hadrons. The data are found to be consistent with the expected background in the whole mass range investigated and upper limits are set on the production cross section times decay branching ratio to $Z\gamma$ of a narrow scalar boson with mass between 250 GeV and 2.75 TeV [19].

Within the **Mu2e** project the calorimetry R&D was performed: a matrix of CsI crystals was tested in electron beams at YERPHI and Frascati, and an energy resolution of 6.4% was obtained from the tests within at 35 MeV electron beam of LUE-75 at YERPHI. The photodetectors R&D for BaF2 crystals is also under way, and development of a photodetector sensitive to the fast component of the spectrum of the crystal in the range up to 260 nm and insensitive to the slow component peaking at 310 nm is in progress. Photocathodes with upper p-emitter layer of AlGaN:Mg are used as photodetectors suitable for discrimination of only the fast emission components of BaF2 crystals. applied. An AlGaN photocathode with the Al mass fraction x=0.3 was combined with a microchannel plate within one device. The Co-60 tests showed FWHM~10% [20-22].

The Cosmic Ray Veto system, light collection from extruded scintillation plates with holes around the fibers filled with various fillers was investigated. An original solution to fill the holes with optical resin or rubber was found. The light collection from the strips filled with CKTN-MED(E) with 1.2 mm fibers is 1.8 times higher than in to the dry case [23].

The analysis of the $D^+\to K^-\pi^+e^+\nu_e$ decay channel based on the data collected in the **BES-III** experiment in 2010 and 2011 at the $\psi(3770)$ resonance is completed. Using a nearly background-free sample of 18262 decays we measured the branching fraction $B(D^+\to K^-\pi^+e^+\nu_e)$ = (3.71±0.03±0.08)%. For $0.8 < m_{K\pi} < 1.0$ GeV/c^2 the branching fraction is $B(D^+\to K^-\pi^+e^+\nu_e)$ = (3.33±0.03±0.07)%. A partial wave analysis showed that in addition to the dominant $\bar{K}^*(892)0$ process, there is the S-wave contribution of (6.05±0.22±0.18)%, and all other components are negligible. The parameters of the $K^*(892)^0$ resonance and the form factors based on the spectroscopic pole were also measured. $K^*(892)^0$ helicity basis form factors were measured in a model-independent way [24].

In 2016 within **COMPASS** experiment the DLNP JINR group observed photoproduction of the exotic charmonium X(3872) in the reaction $\gamma^*N \to X(3873)\ N'\ \pi^\pm$. The result is important for the understanding of the nature of exotic XYZ states studied before at electron-positron and hadron colliders. The group actively participated in the quality analysis of physics data collected in 2016. The possibility of their use for the study of the exotic charmonium was investigated.

Within the **PANDA** project, in addition to the approval of the Technical Design Report for the PANDA Muon System, the DLNP group constructed a big prototype of the system. This prototype comprises a laminated steel absorber (range system) with the total weight of around 10 t, which represents all substructures of the Muon System, and 272 eight-wire Mini Drift Tubes (MDT detector) 1 m long. Strip boards with 1-cm-wide strips are positioned on top of MDT layers. The strips run perpendicularly to the wires. The total number of the readout channels is about 4000 (2000 for wires and 2000 for strips). The DAQ and trigger system of the COMPASS/CERN experiment is adapted for the purpose of the beam test. The prototype passes tests with the T9/PS/CERN test beam. Three tuning/debugging runs were conducted at CERN to the moment. In 2017 the DLNP JINR group plans to perform runs for direct calibration of different prototype structures for muons, pions and protons.

During the 2008-2010 production runs the **PEN** experiment accumulated some 23M $\pi^+\to e^+\nu$ and >150M $\pi\to\mu\to e$ decays as well as significant numbers of pion and muon radiative decays [25]. A comprehensive blind maximum likelihood analysis is under way to extract a new experimental value of $R_{\pi e/\mu}$. The PEN goal is $\Delta R/R \approx 5\cdot10^{-4}$. The first results of the data processing will be available in 2017. Once completed, analysis of the PEN $\pi^+\to e^+\nu\gamma$ data is expected to yield improvements in the SD-structure-dependent amplitude, which constrains F_V-F_A; analysis of the PEN $\mu\to e\nu\nu\gamma$ data is expected to improve the present value of the parameter η.

The international **MEG** collaboration is conducting an experiment to search for the $\mu^+\to e^+\gamma$ decay using the accelerator muon beam at PSI, Switzerland. The final result is based on the full dataset collected by the MEG experiment: $7.5\cdot10^{14}$ stopped muons on the target. No significant excess of events is observed in the dataset with respect to the expected background, and a new upper limit on the branching ratio of this decay $B(\mu^+\to e^+\gamma) < 4.2\cdot10^{13}$ (90% CL) is established, which represents the most stringent limit on the existence of this decay to date [26]. We identified ~13 000 decays $\mu^+\to e^+\nu_\mu\nu_e\gamma$ in a total sample of $1{:}8\cdot10^{14}$ positive muon decays and measured the branching ratio $(6.03\pm0.14(\text{stat.})\pm0.53(\text{sys.}))\cdot10^{-8}$ for $E_e > 45$ MeV and $E_\gamma > 40$ MeV, consistent with the Standard Model prediction [27]. The precise measurement of this decay mode provides a basic tool for the timing calibration, a normalization channel, and a strong quality check of the MEG experiment in the search for the $\mu\to e\gamma$ process.

Within the **GDH&SPASCHARM** project the first ever successful experiment with the active polarized target were realized. High efficiency and a low threshold for the detection of the recoil protons in the target open up new perspectives for the study of the proton spin structure and extraction of the model-independent data. The proton polarization was ≈ 65%, the relaxation time amounted to 100 hours at the temperature of 45 mK in the magnetic field of 0.4 T. The experiment was performed in the beam of circularly polarized tagged photons of the MAMI accelerator (Mainz). Polarization observables for π^0 and π^+ photoproduction were measured, as were the Compton scattering asymmetries allowing extraction of model-independent data on the proton spin polarizabilities.

The $\gamma p \rightarrow p\pi^0$ reaction was studied at laboratory photon energies from 425 to 1445 MeV with a transversely polarized target and a longitudinally polarized beam. The beam-target asymmetry was measured for the first time and new high precision data for the target asymmetry were obtained. The experiment was performed at the photon tagging facility of the Mainz Microtron MAMI using the Crystal Ball and TAPS photon spectrometers. The polarized cross sections were expanded in terms of associated Legendre functions and compared to recent predictions from several partial-wave analyses. The information about the contributions of various baryon resonances was obtained [28].

The double polarization observable and the helicity-dependent cross sections $\sigma_{1/2}$ and $\sigma_{3/2}$ were measured for η photoproduction from quasifree protons and neutrons. The circularly polarized tagged photon beam of the MAMI accelerator was used in combination with a longitudinally polarized deuterated butanol target. The results show that the narrow structure previously observed in η photoproduction from the neutron is only apparent in $\sigma_{1/2}$ and is hence related to a spin-1/2 amplitude corresponding to contributions of nucleon resonances $N1/2^-$ (S11) и $N1/2^+$ (P_{11}). The results are in good agreement with recent reaction model predictions [29].

High-statistics measurements of the photon asymmetry Σ for the $\gamma p \rightarrow \pi^0 p$ reaction were made in the energy range 320−650 MeV. The data were measured with the MAMI A2 real photon beam and the Crystal Ball/TAPS detector systems in Mainz, Germany. The results significantly improve the existing world data and are shown to be in good agreement with previous measurements, and with the MAID, SAID, and Bonn-Gatchina predictions. An indication was found of interference between the very small F-waves and the $N(1520)3/2^-$ and $N(1535)1/2^-$ resonances [30].

In the **COMET** project the preparation of the experiment at the J-PARC accelerator (Japan) on the search for neutrinoless conversion of a muon to an electron is under way. A combine test with the participation of the COMET DLNP group was conducted with the 1.3 GeV electron beam of Tohoku University in 2016. Both the electromagnetic calorimeter (EMC) prototype and the straw-tracker (ST) prototype were used in the test beam. The EMC prototype consisted of 64 LYSO crystals delivered from JINR and divided into 16 modules of 2x2 crystals. Before the beam test all the crystals were studied and certified at JINR and most optimal (giving maximum of light) wrapping material consisted of Teflon+ESR was chosen. Also, the study of 20-μm straw tubes continue at JINR.

Applied Research and Accelerators Physics

In 2016 the **Precision Laser Inclinometer** (PLI) application technique was significantly improved using the previously developed vacuumized prototype. The 2015 measurements showed the necessity of compensating for the inclinometer noise induced by angular motion of the laser beam.

This noise limits the frequency range and does not allow monitoring microseismic oscillations with a frequency below 10^{-3} Hz. In 2016 we proposed an innovative technique of compensation for angular motion of the laser beam using the reference laser beam. Based on this idea, a two-dimensional online compensation system was developed and showed its efficiency: the system compensates for the laser beam noise in a frequency range of $5 \cdot 10^{-6}$ – 0.1 Hz; the PLI sensitivity in the low-frequency range rises by a factor of more than 30 and reaches the spectral density of 10^{-8} rad/$Hz^{1/2}$ at the frequency of $5 \cdot 10^{-5}$ Hz. It allowed us to reach the fundamentally significant result: angular oscillations of the Earth's surface in two orthogonally related directions caused by the gravity influence of the Moon and the Sun were detected.

According to the agreement between the Institute of Plasma Physics of the Chinese Academy of Sciences (ASIPP) in Hefei, Chin, and the Joint Institute for Nuclear Research, Dubna, Russia, the project of a superconducting isochronous cyclotron for proton therapy **SC202** is developed at JINR. The cyclotron will accelerate protons up to 200 MeV with maximum beam current of 1 µA. We plan to manufacture two cyclotrons in China: one will operate at the Hefei cyclotron medical center, and the other will replace the Phasotron at the DLNP Medico-Technical Center and will be used for further research and development of proton therapy for cancer treatment.

Now the physical design of the SC202 cyclotron is developed. Simulations of all systems of the SC202 cyclotron are performed, parameters of the accelerator are chosen, and beam dynamics from the ion source to the exit from the cyclotron is calculated [31-33]. The SC202 project developed at DLNP is approved by the experts commission in Hefei in October 2016. The SC202 systems and elements will be manufactured in 2017, and the cyclotron will be assembled, tuned and tested in 2018. The results of the SC202 tests will be used by ASIPP for commercial production of cyclotrons.

The magnetic system of the specialized monochromatic positron channel (SMPC) for positron annihilation spectroscopy (**PAS**) is constructed at the sector of electron cooling. A new version of the cryogenic source of slow monochromatic positrons with closed-loop cooling based on a helium cryocooler was developed and commissioned. The working temperature of 6 K on the surface of the foil covering the ^{22}Na tablet was achieved. The flux of slow monochromatic positrons is 1.6 10^6 e^+/sec. The source was used to transfer positrons through cryogenic source of slow monochromatic positrons. Six PAS runs with the positron beam were performed in 2016. The investigated materials were Zr, Cu, Ag, and graphite irradiated with heavy ions and also samples of sandblasted stainless steel.

In 2016 R&D of **novel semiconductor detectors** in 2016 was mainly concentrated on the research of pixel detectors GaAs:Cr-based and Medipix readout chips and on the research of spectral computed tomography using the MARS CT scanner. Four assemblies of a Timepix readout chip and a GaAs:Cr sensor with very good bump-bond connection (99.8 % active pixels) were produced by the JINR group together with the colleagues from IEAP CTU in Prague, Tomsk State University and

CERN. The detectors were carefully calibrated and installed in the ATLAS detector cavern within framework of the ATLAS-GaAsPix project.

The energy resolution of the GaAs:Cr-based Timepix detector in the Medipix mode of a single pixel using collimated monoenenergetic photons from the synchrotron radiation source VEPP-3M of the Budker Institute of Nuclear Physics in Novosibirsk was measured. The energy resolution reached 1 % at 18 keV. Also, the geometrical mapping of the pixel sensitivity was obtained by scanning the detector with a pencil photon beam along the pixel column. The development of the readout electronics for Timepix detectors was started using the Altera Cyclone 5 SoC FPGA. Now debugging of the data transfer from the detector to PC and the chip DAC setting procedure is in progress.

The software for managing the MARS CT Scanner and preprocessing raw data was upgraded. As a result, errors were eliminated that caused scan interrupting. The gantry stopping procedure was improved, which decreased the gantry oscillation amplitude and time to a complete stop. Scanner management software was developed. The start-stop scanning mode was implemented. Now the program allows receiving images for multiple energy thresholds. To increase the dynamic range of projections, a series of shots can be made in each detector position. This combination allowed spectral tomography scanning. A software for simulating spectral tomography scan was developed using the GEANT4 package and adapted to running on a computer cluster. A method and software for identification of materials in the image domain are under development.

The main goals of the research at the **Medico-technical complex (MTC)** are to carry out medico-biological and clinical investigations into tumour treatment, upgrade equipment and instrumentation, and develop new techniques for treatment of malignant tumours and for associated diagnostics with medical hadron beams of the JINR Phasotron. The following main results were obtained in 2016.

Regular sessions of proton therapy aimed to investigate its efficiency to treat different kinds of ne were performed in collaboration with the Medical Radiological Research Centre (Obninsk) and the Radiological Department of the Dubna hospital. Seven treatment sessions with a total duration of 30 weeks were carried out. Sixty-one new patients were fractionally treated with the medical proton beam. The total number of the single proton irradiations (fields) was more than 4000. Other 33 patients were irradiated using the Co-60 gamma-therapy unit "Rokus-M".

The development of a software-hardware complex for the multileave proton beam collimator prototype with four pairs of leaves was continued. The full-scale collimator will consist of 33 pairs of leaves and will be used in the so-called dynamic proton beam treatment technique. The design of the main components of the 3D treatment planning software for the proton conformal radiotherapy was continued. The elaborated variant of the software was successfully experimentally verified using the heterogeneous “Alderson phantom” and the radiochromic films and is now under clinical tests.

Together with the staff of the Division of Radiation Dosimetry Institute of Nuclear Physics

(Prague, Czech Republic) and Proton Therapy Center in Prague, the comparison studies of the dose distributions outside the target volume using thermoluminescent detectors and radiochromic films in the JINR phasotron radiotherapy proton beam and in the PTC scanning proton beam were continued. These studies are important for estimation of the secondary cancer risk during the proton therapy. The measurements showed that the absorbed doses outside the primary beam in Dubna were slightly higher than the scattering PTC proton beam due scattering of the proton beam on the beam formation elements in the treatment room. Together with the staff of the Institute of Bio-medical Problems and LRB, JINR, influence of protons with different LET on biological objects was studied [34].

A new device for radiation protection of biological objects was developed on the basis of the laser module with a wavelength of 532 nm (green spectrum range). The device was used to test the assumption that primary photoacceptors under the radioprotective action of small doses of 633-nm laser radiation are cytochrome c- oxidases. Experiments conducted on mouse fibroblast cells showed that the radioprotective effect was observed in the laser irradiation dose interval from about 0.4 to 0.85 mJ/cm^2. The maximum radioprotecting effect was observed at the laser radiation energy density of approximately 0.56 mJ/cm^2 [35].

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