NOVEL DEVELOPMENT AND CONSTRUCTION OF EQUIPMENT FOR THE SPECTROMETER COMPLEX OF THE IBR-2 FACILITY

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Cryogenic moderators

In 2015, work and research continued on a special stand of a cryogenic pelletized moderator with an inclined section at an angle of elevation of 40° in the direction of experimental beamlines № 4,5,6. Hardware and software of the stand have demonstrated stable and trouble-free operation during all experiments and in the future will be used in a real moderator CM201.

The trial operation of the CM202 moderator was conducted in February and March 2015. The moderator operated during two reactor cycles for 9.5 days in each round; in 2014 its continuous operation was 10.5 days. During its operation there were no accidents or emergency situations.

In the framework of the development of the CM202 moderator a device was proposed for nitrogen-free charging of frozen pellets into a dosing machine; its computer model is shown in **Fig. 1**.

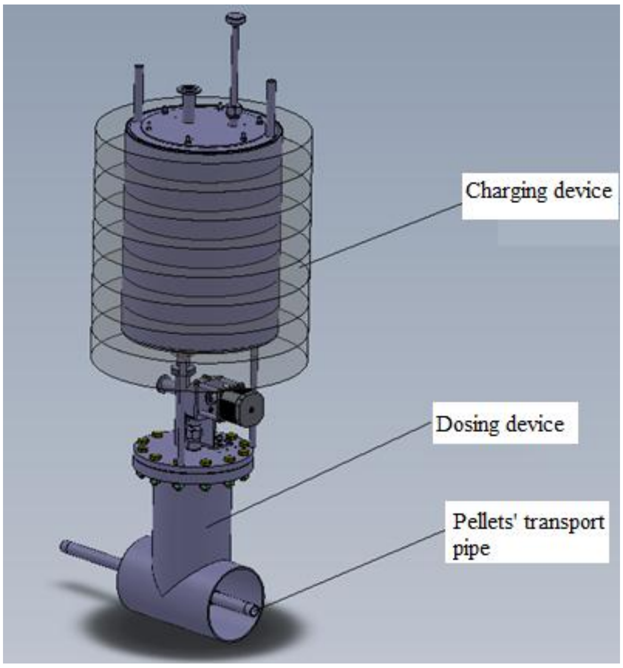


***Fig. 1**. A device for nitrogen-free charging of frozen pellets into a dosing machine of the pelletized moderator of IBR-2.*

The main advantage of this device is that in the process of loading of frozen pellets into the dosing machine, liquid nitrogen will not leak into the pneumatic pipeline. This will make it possible to avoid problems related with the freezing of liquid nitrogen in the pipeline, namely, in the heat exchanger of the cold moderator.

The modernization of the system of sensors for monitoring the passage of mesitylene pellets in moderators CM202 and CM201 has been carried out.

During the two cycles of operation of the cold moderator, experiments have been performed to obtain a neutron microbeam using a waveguide and beam spatial splitting from a non-collinear magnetic system (reflectometer REMUR) as well as texture analysis of olivine (rock) has been done (spectrometer SKAT). The results have shown a gain in the neutron flux by a factor of 3-10 when using the cold moderator for these experiments.

The main problem with using a pelletized cold moderator on metaxylene and mesitylene is a limited time of its continuous operation for physics experiments. At present, it amounts to 10.5 days, which is actually equal to the duration of a standard reactor cycle with a warm-water moderator (11 days). At the same time, after irradiation for 10.5 days the viscosity of a metaxylene and mesitylene mixture is observed to increase (more than 20 times higher, see **Fig. 2**), which may become an obstacle for safe and reliable operation of the moderator. This requires further study. In the near future the development and improvement of the pelletized moderator will be focused, first of all, on looking for opportunities to prolong its continuous operation.

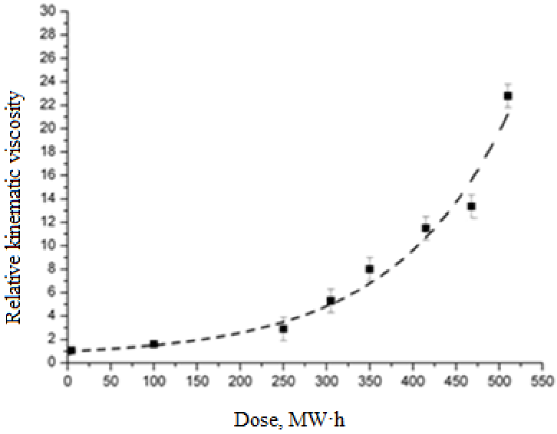


Fig. 2. Relative kinematic viscosity for different doses of irradiation of a mixture of mesitylene and metaxylene (points - experimental viscosity values, dashed line - approximation).

There are several ways to prolong the non-stop operation of the cold moderator:

1) Creation of a system of continuous loading/unloading of pellets. This system makes it possible to unload the frozen pellets with high radiation load, and to load new unexposed ones, thereby providing an optimum viscosity of the mixture. The creation of this system at the IBR-2 reactor is a challenging engineering task. At the present time the development of a full-scale prototype of a device for loading/unloading pellets has started for conducting tests on the stand of the pelletized moderator.

2) Introduction of different additives to the initial working mixture. When using additives, two mechanisms of viscosity reduction of a mixture under irradiation are possible. The first one is based on the replacement of some of mesitylene molecules with more radiation-resistant aromatic hydrocarbons. These may be naphthalene and anthracene molecules consisting of benzene rings. By using these additives, radiation resistance of the mixture may increase up to 1.5 times with a slight decrease in the cold neutron flux. The second mechanism is based on the addition of substances with heavy nuclei by which a certain part of recoil protons occurring as a result of neutron moderation will be slowed down. Thus, a small spatial replacement of mesitylene molecules with homogeneously distributed microparticles will be inessential for neutron moderation. These additives may be neutron nonabsorbing materials: nanopowders of diamond, zirconium, lead.

3) Prolongation of operation time of the pelletized moderator by replacing the working mixture of mesitylene and metaxylene with another substance with better radiation resistance and equivalent neutron-physical properties (yield of cold neutrons, etc.). This substance may be triphenylmethane.

Using triphenylmethane as a potential pelletized cold moderator for IBR-2, an important point is the possibility of manufacturing pellets of the right shape, required size, with good hardness and strength, which is essential for ensuring their transportation to the cold moderator chamber. In 2015, we carried out research work that proved the possibility of producing solid pellets of triphenylmethane with the desired properties (photo of pellets is shown in **Fig. 3**).

Fig. 3. *Pellets of triphenylmethane.*

Radiation Research Facility

In 2015, the following research activities were performed on the facility:

- measurement of low neutron fluences (10^{11} - 10^{15} n/cm^2) using various neutron detectors in a curved tube of the irradiation facility located on beamline 3 of the IBR-2 reactor;
- test irradiation of specimens of silicon photomultipliers from Hamamatsu (in cooperation with ITEP, MEPhI, VBLHEP and CERN);
- studies of radiation resistance of promising detector materials (single crystals of diamond) for CERN (ATLAS project) and Nanjing University (China);
- investigation of radiation resistance of magnetic sensors (3D-Hall sensors) in the framework of the international project ITER (**Fig. 4**);
- irradiation of Iridium-193 isotope for obtaining isotopes of promising materials for medicine (in cooperation with FLNR).

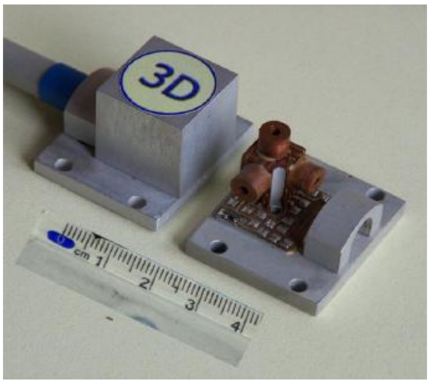


Fig. 4*. Magnetic sensors (3D-Hall sensors).*

Technical specifications for modernization of the radiation research facility (installation of biological shielding, modernization of facility motion control unit) have been prepared. The implementation of these tasks is scheduled for 2016.

Calculations and simulation of spectrometers

The development of new modules and improvement of old ones of the VITESS software package for simulation of neutron instruments continued. Particular emphasis was placed on VITESS modules that simulate spectrometers with polarized neutrons. In the first half of 2015 studies on the simulation of a spin-echo small-angle spectrometer (SESANS) were carried out in cooperation with the NICM Department. The simulation was performed with a set of model spheres with a fixed radius, thus bringing the simulation closer to a real experiment. For this purpose we had to make laborious adjustment of the VITESS modules responsible for simulation of spectrometer components including the module of a pulsed magnetic field (t_dependent_magnetic_field) and the module for simulating a small-angle sample (sample_sans). A general scheme of the spectrometer is shown in **Fig. 5**.

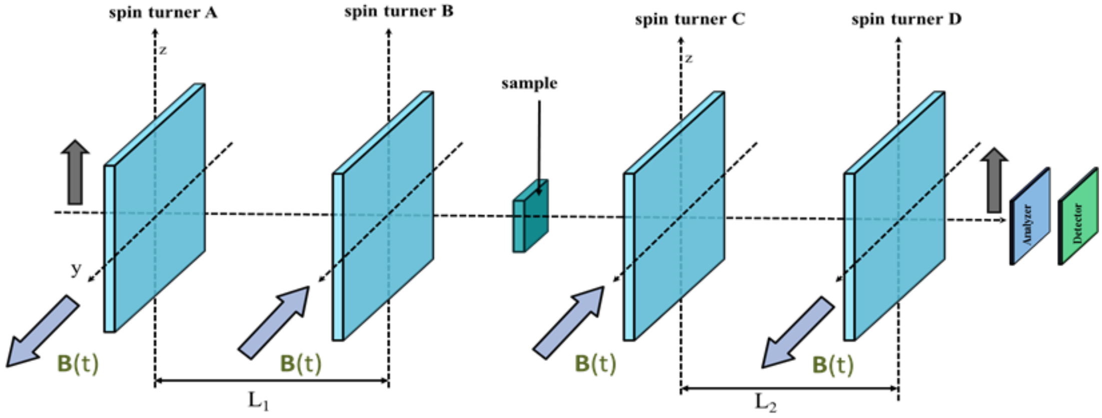


Fig. 5*. General scheme of a spin-echo spectrometer with 4 flippers with pulsed gradient magnetic fields B(t).*

To verify the correctness of the obtained results of the Monte Carlo simulation of a spin-echo spectrometer, an analytical evaluation has been performed as well. It should be noted that an analytical evaluation is possible only for a simple ideal spectrometer. As a rule, for a real instrument even with a model sample the Monte Carlo simulation is the only tool to evaluate the parameters of a spectrometer. For the simulation the following parameters were chosen: field frequency – 100 kHz, amplitude ─ 5200 Gs, radius of the sphere in the sample ─ 10 nm. **Figure 6** shows the results of the Monte Carlo simulation in comparison with the analytical evaluation. The obtained simulation results testify the adequacy and correctness of the used Monte Carlo mathematical model.

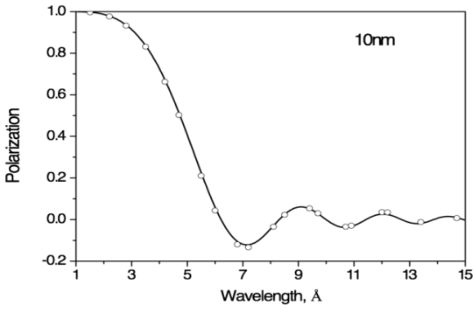


Fig. 6*. The results of the Monte Carlo simulation (points) and analytical evaluation (solid line).*

The development of special mathematical models and corresponding programs for the simulation of neutron scattering (including magnetic scattering) from samples (including rough multilayer samples) was continued. The studies were carried out with reflectometric multilayer samples with a regular surface structure using the Parratt's method and kinematic approximation. Using the developed programs we performed virtual GISANS experiments in the kinematic approximation with thin-film samples and a regular surface structure to obtain diffraction. A provision was made for simulation of surface roughness and interfaces. The developed programs have an input and output data format which is compatible with DWBA BornAgain. Below (**Fig. 7,8**) are the results of GISANS simulation of two virtual experiments in the kinematic approximation:

1. Diffraction from columns of ^{58}Ni isotope on a silicon substrate (column height – 200 Å, column width – 50x50 Å, periods – 100x100 Å in the horizontal plane).
2. Diffraction from columns on a rough surface of ^{58}Ni isotope (column height – 200 Å, column width – 50x50 Å, periods – 100x100 Å in the horizontal plane). The parameters describing the roughness were chosen as follows: σ = 23 Å, ξ = 200 Å, which to a greater extent corresponds to a real sample.

The simulation results show that the diffraction is detectable and this will allow us to determine lattice parameters from a diffraction pattern in a real experiment.

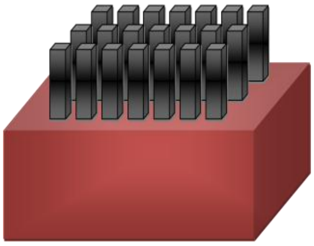
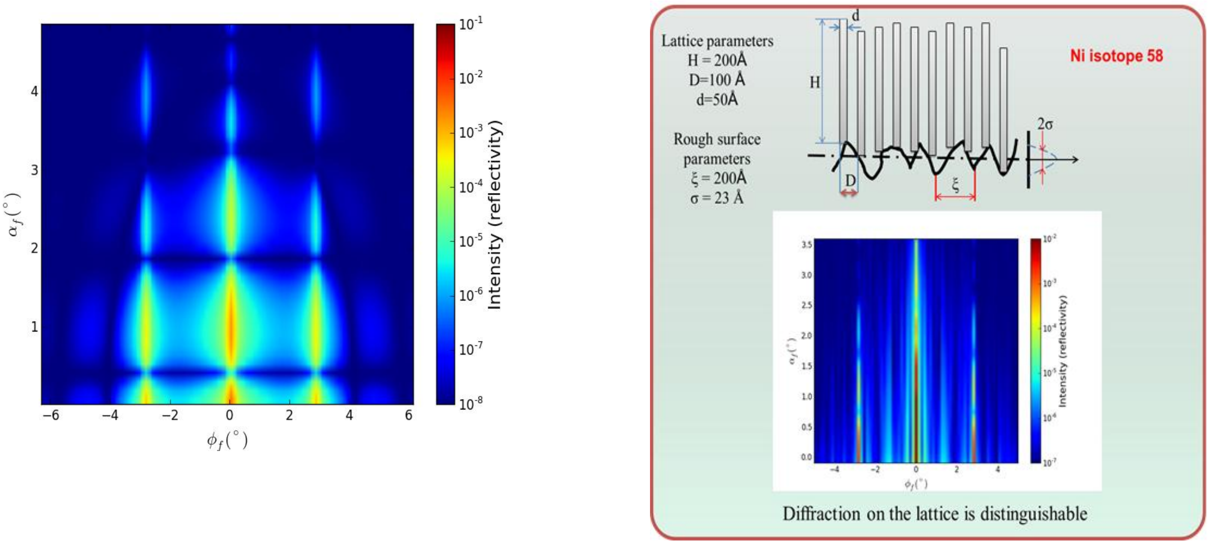


***Fig. 7**. An example of a sample for a GISANS experiment.*



a) b)

***Fig. 8**. Simulation of a GISANS experiment: diffraction from ^{58}Ni isotope columns: a) on a smooth silicon substrate, b) on a rough surface.*

FSS spectrometer

Work was continued on the construction of a new high-resolution Fourier diffractometer on IBR-2 beamline 13 on the basis of the units of the FSS spectrometer from the GKSS research center (Geesthacht, Germany). In cooperation with PNPI (Gatchina) and the NICM Department neutron guide sections were assembled (**Fig. 9**), alignment of optical sections was done, vacuum equipment was installed and vacuum sealing of the neutron guide was conducted.

***Fig. 9**. The exit section of the neutron guide on IBR-2 beamline 13.*

At present, activities are carried out to measure beam characteristics at the exit of the neutron guide and to improve the background conditions at the diffractometer. **Figure 10** shows the distribution of beam intensity along the x-axis at the exit of the neutron guide. The distribution width corresponds to the geometric aperture of the neutron guide, which is 15 mm.

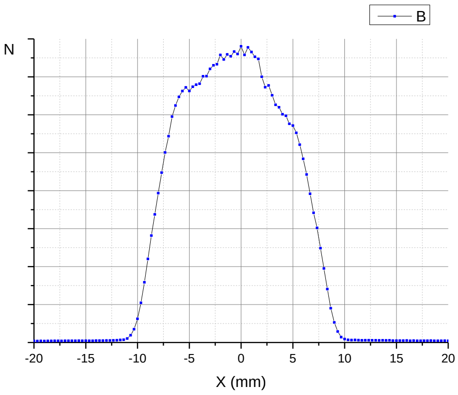


***Fig. 10**. Distribution of beam intensity along the x-axis at the exit of the neutron guide.*

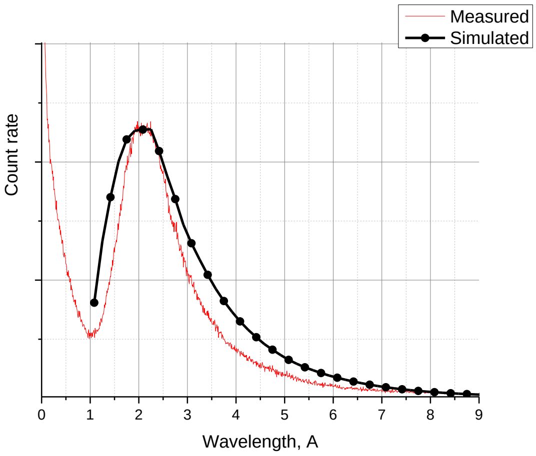


***Fig. 11**. Calculated and measured distributions of the neutron beam intensity at the exit of the mirror neutron guide.*

Figure 11 illustrates a comparison between the output beam intensity distribution calculated by the Monte Carlo method (reflection coefficient used in the calculations was R = 0.99) and the spectrum obtained for a vanadium sample placed at the exit of the mirror neutron guide used in GKSS. Positions of the maxima of the measured and calculated spectra coincide. The narrowing of the measured spectrum can be explained by the low quality of the coating of the mirror neutron guide. The measured maximum flux density across the beam is about 1.3 x 10^6 n/(s·cm^2).

Cryogenics

Major activities in the area were carried out in accordance with the project on the development of a cryostat for temperature and magnetic investigations of condensed matter at the DN-12 spectrometer. The project is being implemented in cooperation with the National Institute of Research and Development in Electrical Engineering ICPE-CA, Bucharest, Romania. In 2015, a detailed design was developed and 3D-simulation was performed for a horizontal cryostat with a superconducting magnet producing a magnetic field of 4 T, and a cryostat with a high-pressure cell for the magnet, which are cooled by closed-cycle cryocoolers. The design documentation for the cryostats was prepared. The drawings were forwarded to SPA "Atom" to manufacture all mechanical components of the cryostats. Tests of the cryocoolers were conducted. It has been established that their characteristics meet the specifications. **Figures 12** and **13** present the computer models of the cryostat and magnet.

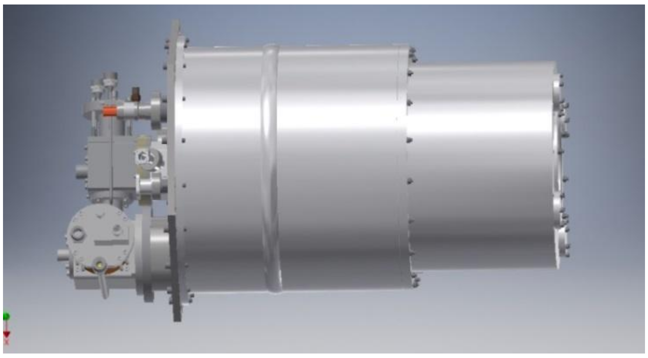


Fig. 12*. A horizontal cryostat for the DN-12 spectrometer. A general view (left).*

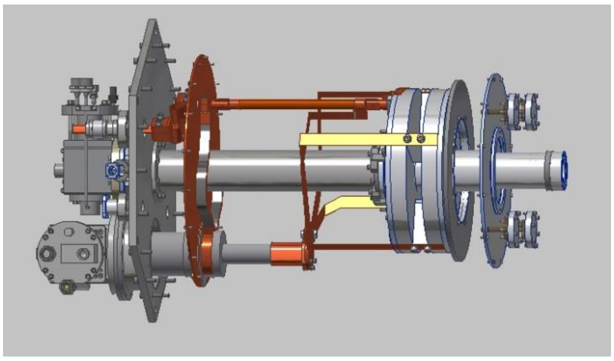
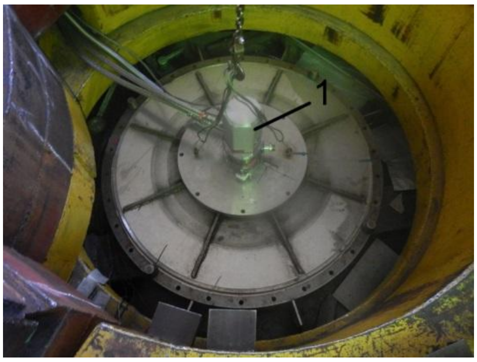


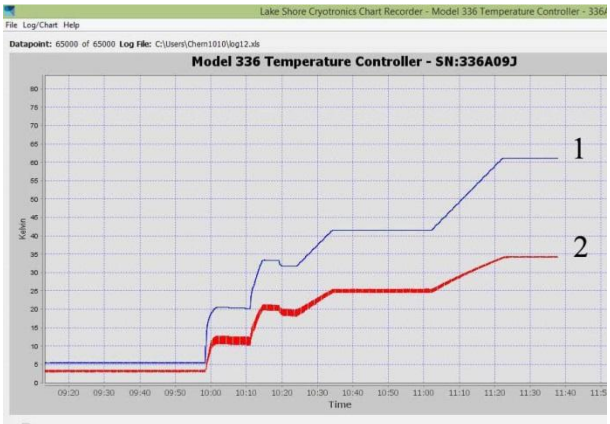
Fig. 13. *The magnet of the cryostat and its horizontal shaft for loading the cryostat with a high-pressure cell (right).*

The magnet is a Helmholtz pair of magnets made of a high-temperature superconducting tape of the second generation YBCuO (manufactured by "SuperOx", Russia). The magnet is cooled by a closed-cycle cryocooler to a temperature of (10 - 20) K. The cryostat with a high pressure cell, which in its turn is cooled by another closed-cycle cryocooler, is inserted into the center of the magnet through a horizontal shaft. The temperature of the cell is regulated by a controller in the range of (4 - 300) K.

The cryostat with a closed-cycle cryocooler was tested and prepared for installation on the DIN-2PI spectrometer. **Figures 14, 15** present a photo showing a cold head of the cryocooler in the shaft of the spectrometer and time dependences of the temperature of the sample chamber and the cryocooler second stage in the process of temperature regulation.

***Fig. 14**. Photo of a cryocooler cold head (1) in the shaft of the DIN-2PI spectrometer (right).*




Lake Shore Cryotronics Chart Recorder - Model 336 Temperature Controller - 336

Datapoint: 65000 of 65000 **Log File:** C:\Users\Chem1010\log12.xls

***Fig. 15**. Time dependence of the temperature of the sample chamber in the process of temperature regulation: 1 - temperature of the sample chamber, 2 - temperature of the cryocooler second stage (left).*

Detectors and electronics

A 2D gas position-sensitive detector (PSD) for the REMUR spectrometer has been manufactured and tested with a neutron source. It has been designed to replace the available outdated PSD of the spectrometer. Also, all scintillation counters and electronic components of the fourth section of the ASTRA detector for the FSD diffractometer have been manufactured, adjusted and tested. Both detector systems are ready to be put into operation in the coming IBR-2 cycles. In the process of manufacturing of scintillation counters we have developed a new design and layout of the counters in the ASTRA detector, making it possible to provide as high accuracy of positioning of scintillation surfaces as need be, which is important for detectors using a space-time focusing principle. In addition, the new design allows us to significantly reduce the material resources required for manufacturing of the detector. A 3D-model (**Fig. 16**) and a technical design of the new detector system, which is planned to be manufactured in 2016-2017 and installed in place of the existing sections of the detector ASTRA at FSD, have been developed.

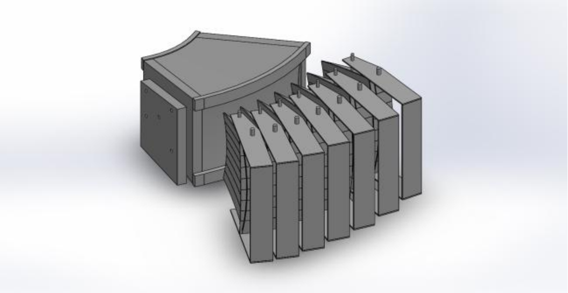


***Fig. 16**. New layout of the modules of the detector ASTRA.*

A prototype of a ring small-angle detector has been developed for the DN-2 diffractometer (**Fig. 17**). The prototype consists of one ring with the cathode divided into 16 independent sectors. Signals can be picked up by both the anode wire and each individual sector of the cathodes, thereby determining the angles φ and θ. We have tested the prototype and obtained amplitude spectra from the anode and individual cathodes.

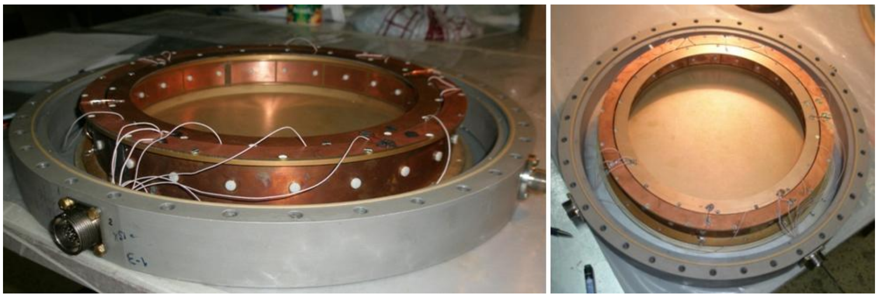


Fig. 17*. Prototype of a ring small-angle detector for the DN-2 diffractometer.*

On the DN-6 diffractometer a new ring neutron detector for obtaining neutron spectra at a scattering angle of 90° has been put into operation. The detector consists of 16 sections with 6 independent detector elements each (helium proportional counters) with background shielding and collimation. Charge-sensitive preamplifiers (96 channels), three modules of 32-channel amplitude discriminators and a 192-channel digital data acquisition and accumulation module (MPD) were developed and manufactured specially for this detector. The electronics was adjusted and all the equipment with the software of the diffractometer was tested. The available multi-section ring detector relocated to the scattering angle of 45° and the new one was integrated into a single measurement system (**Fig. 18**).

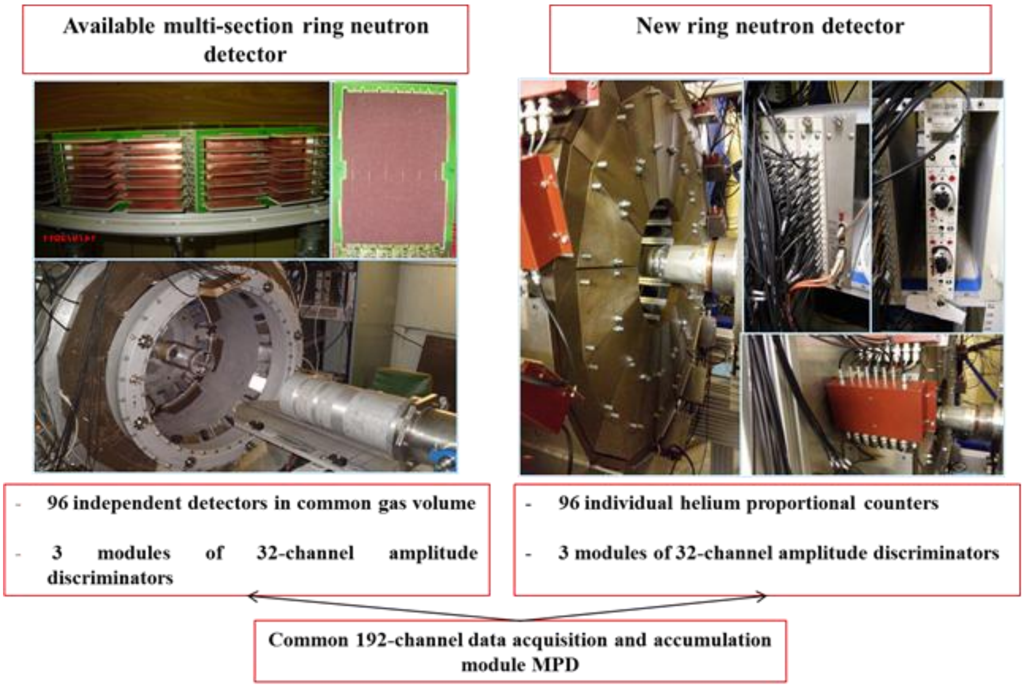
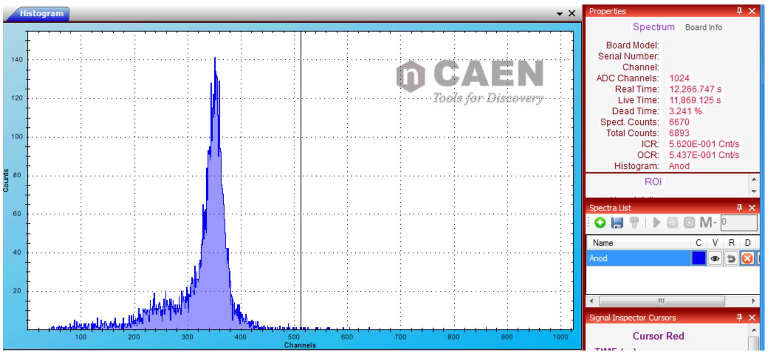


Fig. 18*. New detector system of the DN-6 diffractometer.*

For experimental studies with fast neutrons a new spectrometer based on a proton telescope (PT), in which the measurement of energy distributions of neutron fluxes is performed by measuring the kinetic energy of recoil protons elastically scattered at small angles as a result of (n, p) interaction in a gas hydrogen-containing medium, has been designed, manufactured and tested (detailed description of PT can be found in the Annual Report 2012 and JINR Patent http://www.freepatent.ru/images/patents/13/2445649/patent-2445649.pdf). New versions of PT, electronics and software have been designed in accordance with protocol №4519-4-15/17 of 15.06.2015 between JINR and the National Fusion Research Institute (Daejeon, Republic of Korea), where the spectrometer is planned to be used for the diagnostics of a nuclear fusion reactor (KSTAR). In FLNP it will be used to obtain spectra of fast and resonance neutrons of neutron-producing targets of IREN and EG-5. **Figures 19, 20** show the electrode system of PT and beam spectrum from a neutron generator ING-07.

Fig. 19. *Electrode system of the new proton telescope (left).*



Board Model:
Serial Number:
Channel:
ADC Channels: 1024
Real Time: 12,266.747 s
Live Time: 11,869.125 s
Dead Time: 3.241 %
Spect. Counts: 6670
Total Counts: 6893
ICR: 5.620E-001 Cnt/s
OCR: 5.437E-001 Cnt/s
Histogram: Anod

Anod

Fig. 20. *Beam spectrum from a neutron generator ING-07 obtained using PT (neutron energy 2.5 MeV, gas mixture composition: 500 mbar CH_4 (right)).*

Because of a large amount of unplanned work on electronics and software for the ring detector of DN-6 and proton telescope, only a schematic circuit diagram was designed and hardware components were selected for a USB-3.0 interface unit, and a part of the work (design of a printed circuit board and manufacture of a prototype) had to be postponed until 2016.

Modernization of control systems and actuators of the IBR-2 spectrometers

On the YuMO spectrometer a control system for sample changing (**Fig. 21**) was put into operation. The number of samples in the cassette was increased from 14 to 25 and the time required for automatic sample change was reduced.

Fig. 21. *Device for horizontal positioning of samples at the YuMO spectrometer (left).*

Fig. 22. *New control system for monitoring the instrument operation on the basis of interface converters (right).*

On the REMUR spectrometer the number of control channels has been increased from 34 to 36. On two devices absolute linear displacement wire-type (0-2 m) sensors on the basis of absolute angular multiturn sensors have been mounted. On the GRAINS spectrometer the control system of actuators has also been expanded to 28 channels. On IBR-2 beamline 14 a control system of the equipment of the spectrometer for neutron radiography and tomography has been put into operation. The modernization of control systems of the experimental facilities on IBR-2 beamlines 5, 6 and 7a has been carried out. They have become more technologically advanced and easy to operate. Interface converters have been replaced as well. **Figure 22** shows a new control system for monitoring the instrument operation on the basis of interface converters AC4 (USB-RS485) and AC3-M (RS485-RS232).

On the IBR-2 spectrometers the modernization of choppers and their control systems has been continued. In particular, a new drum-type chopper on the basis of 2.2 kW asynchronous motor with a standardized variable frequency drive VFAS1-4022 (**Fig. 23**) has been put into service on the REFLEX spectrometer. A chopper opening sensor on the basis of a magnet and reed switch MKA-10110, which makes it possible to use it in the IBR-2 ring corridor, has been developed and installed. The accuracy of chopper phasing is +/– 150 μs.

***Fig. 23**. New drum-type chopper on the REFLEX spectrometer.*

The control system of the Fourier chopper on HRFD has been upgraded. The frequency drive of the Fourier chopper has been connected to the host PC via a USB fiber optic extender, which has significantly increased the noise immunity of the control system of the chopper.

On a number of spectrometers the modernization of temperature controllers LakeShore has been carried out to connect a larger number of different types of sensors and for communication with a computer via a USB-interface.

Software and computer infrastructure

In 2015, the development of the software package Sonix+ was continued, in which a number of components were added at the request of users or further improved following the operating experience. Among the most important activities were the following:

- development of new components for controlling equipment of a number of spectrometers (RTD HRFD, REMUR, GRAINS);
- supplementation and improvement of programs of graphical user interface (GUI);
- development of a new version of the command library for reflectometers, in which preliminary data processing is conducted simultaneously with the continuation of exposure;

- continuation of development of software tools for testing and debugging of electronics of data acquisition systems.

Eight spectrometers have been connected to the WebSonix service (YuMO, HRFD, FSD, SKAT, NERA-PR, EPSILON, DIN-2PI, REFLEX) making it possible to remotely control the course of an experiment.

In the FLNP local area network the number of WiFi access points in buildings 42 and 117 has been increased. The creation of access points in the IBR-2 reactor premises is technically difficult and has been temporarily postponed. The routers in the reactor control building and experimental hall №1 (building 117) have been upgraded to provide a data rate of 10 Gbit/s.

Due to the change-over to the List-mode in the accumulation of raw data on a number of spectrometers (for example, it is the main mode on Fourier-diffractometers HRFD and FSD) the question arose of providing storage and preliminary processing of large amount of data.

Accumulation and storage of data

Until recently, physicists accumulated and stored experimental data on control computers of spectrometers. Data transmission to the central server of the Laboratory was performed by each user manually when required. At the same time there was always a risk of accidental erasure of data, network failure, losses in case of disk drive failure, etc. To eliminate these problems, in 2014, a centralized network storage was organized on the basis of a file-server Supermicro with two CPU Intel Xeon, 16 GB RAM and 72 TB disk memory (characteristics and description of the software of the server are given in the Annual Report 2014). This storage system provides an automatic transfer of data from the control computer to the file-server during the experiment. The storage capacity is quite sufficient for recording and storing data from all IBR-2 spectrometers.

Preliminary processing of raw data

If the accumulation is conducted in the List-mode, the amount of data can reach several terabytes and their preliminary processing (for example, neutron time focusing, calculation of the cross-correlation function between the intensity of neutrons recorded by a detector and the sequence of delayed functions of modulation of the neutron flux from the pulsed reactor and chopper and reconstruction of high-resolution spectra from initial diffraction data collected on Fourier diffractometers) may take a long time (several hours).

To accelerate the process of data treatment, specialists of the NICM Department have developed a fast algorithm for calculating the cross-correlation function and programs for parallelizing calculations on several processors allowing a several-fold reduction of processing time. Another method to speed up the computation is the application of computing nodes with graphics processors (for example, graphics accelerator GPU NVIDIA can provide a 10-fold acceleration). Such parallel data processing can be organized within individual physics groups or on the central computing servers of FLNP, but we cannot provide their normal load, therefore it is reasonable to use the available computing resources of LIT: heterogeneous cluster "HybriLIT" (http://hybrilit.jinr.ru/) and cloud services (https://cloud.jinr.ru/).

Both of these resources can also be used for calculations and simulation, specifically using the Monte Carlo method. The efficiency of their application will depend on whether it will be possible to parallelize calculations.