The detector systems of the IBR-2M spectrometers.

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Abstract. The variety of research being conducted at the instruments on the external beams of the IBR-2M pulsed fast reactor in Frank Laboratory of Neutron Physics Joint Institute for Nuclear Research (FLNP JINR) is the reason of the differences in the requirements of the detectors for these instruments. This leads to the necessity of developing a variety of detectors in the Laboratory that are used in experiments. This report reviews the neutron detection systems developed and used at the instruments on the external beams of the IBR-2M pulsed research reactor, the current status and operating features of which have been considered.

1. Introduction

The pulsed high-intensity neutron reactor IBR-2 [1] is the main facility of the Frank Laboratory of Neutron Physics (FLNP) at the Joint Institute for Nuclear Research (JINR). It was put into operation in 1984 and was modernized in 2007-2011. The unique complex of neutron instruments of the reactor allows a wide range of cross-disciplinary research to be carried out in the fields of condensed matter physics, material science, chemistry, biology, geophysics, pharmacology, medicine, nuclear physics, ecology, etc. The essential parts of the experimental equipment are the detectors of neutrons and the detector systems on which they are based.

2. Data Acquisition and software

Electronic and software systems used on the reactor [2] are unified as much as possible. For multi-counter detector systems consisting of helium or scintillation counters, as well as for annular (“ring”) detectors DAQ systems based on MPD16 and MPD32 [3] units are used. The maximum number of connected counters is 16 for MPD 16 and 240 for MPD32. For 1D and 2D position-sensitive detectors PCI the system DeLiDAQ [4] or a new DeLiDAQ2 [5] NIM unit is used. All the electronic systems can operate in the Time-Of-Flight (TOF) mode. The electronics are standardized and the specific features of each spectrometer are taken into account when programming the internal FPGA. All the electronic components have been developed in FLNP, JINR (DeLiDAQ developed in collaboration with HZB, Berlin).

Software includes SONIX+ [6] [7] software complex and DeLiDAQ [8] software system. SONIX+ is a software for the automatization of experiments. It is extensible, based on the Python script language and allows fully automated experiments to be carried out. Software system DeLiDAQ has been designed for real-time data observation and detector testing. It is based on the ROOT library. The parts of DeLiDAQ can be embedded in other systems.
3. Detector systems of the IBR-2 spectrometers

The list of scientific instruments at IBR-2 includes 3 reflectometers, 2 inelastic spectrometers, 1 small-angle spectrometer, 7 diffractometers, 1 spectrometer for neutron radiography and tomography, 2 installations for nuclear physics and installations for radiation materials science and neutron activation analysis. Here is some information about the neutron detector systems on these installations.

3.1. Reflectometers

The REMUR reflectometer (beam №8) is intended for the study of properties of thin films, limits of the section in multilayered structures, various types of streamlining, self-organization in biological systems, etc. by the method of specular and not specular reflection of neutrons from the surface of films. The reflectometer with polarized neutrons REFLEX (beam №9) is designed for the study of structural properties of thin films and layered nanostructures. Reconstruction has added a chance to operate this instrument as a spin echo small-angle neutron scattering spectrometer. The GRAINS instrument at beam №10 is a multifunctional neutron reflectometer with a horizontal sample plane, intended for the determination of the reflectivity of thermal neutrons in various dimensions from surfaces and interfaces. It has the possibility to measure both the solid-solid and the liquid-solid interfaces, liquid surfaces. Each of these three instruments is equipped with a 2D PSD and a 3He proportional counter on the moving platform.

The position-sensitive detector (figure 1) is a general purpose detector developed in FLNP JINR. It is designed for neutron diffraction and neutron reflectometry. The sensitive area of 2D PSD is 200x200 mm², the spatial resolution is 2x2,3 mm², efficiency for the thermal neutrons (2A) is 65%. The detector is made on the principle of the multiwire proportional chamber. An anode, a cathode and drift planes are located in the hermetically sealed internal volume of the detector. The time of neutron detection is determined by the anode signal, coordinate information received using delay lines. Detectors of this type are rather universal, and at the same time cheap tools for the neutron measurements what the experience of use on the installations at FLNP JINR testifies to. The same 2D PSD is operated at some other research centers in Russia, as well as at the research reactor LVR-15 of Nuclear Physics Institute (NPI ASCR) in Rez near Prague, the Czech Republic.

3.2. Inelastic scattering

There are two inelastic instruments on IBR-2, the spectrometer DIN-2PI on beam №2 and NERA-PR on beam 7b. Both spectrometers are equipped with multi-counter systems based on 3He counters, covering large area. The DIN-2PI inelastic neutron scattering spectrometer is a "direct geometry", double time-of-flight, multi-counter system with a set of curved-slit and background choppers, and a cadmium periodic shutter for background measurements. The spectrometer offers a wide range of resolutions, energy transfers, momentum transfers, scattering angles and sample environments. The NERA-PR spectrometer is an inverse geometry time-of-flight multi-purpose instrument. It was designed to study inelastic and quasielastic neutron scattering with simultaneous monitoring of the phase of the sample by neutron diffraction. The detector system of the spectrometer NERA-PR [10] consists of two symmetrical sections. Each section includes nine chambers, with multi-counter arrays. One chamber intended for diffraction measurements includes blocks of counters with collimators and eight chambers for inelastic measurements are equipped with counters, beryllium filters and analyzers.
(crystals or pyrolytic graphite). Filters and analyzers are used for switching between working regimes with various luminosity and energy resolution.

3.3. Small-angle scattering

The YuMO small angle scattering (SANS) spectrometer operates on the beam №4 of the IBR-2M reactor. It can obtain information about sizes, spatial correlations and shapes of objects in a range of 1 nm to several hundred nanometers. It is suitable for the study of polymers, biological objects, colloidal solutions and surfactants. The YuMO detector system consists of two ring detectors [11] placed one after another and a monitor of the direct beam. The appearance of the ring detector is shown in the figure 2a. All detectors work in the vacuum casing of the spectrometer. Each ring detector is divided into 8 rings, which allows the angular distribution of the neutron flux to be measured. All the rings of a detector are located in a single gas volume. The ring detectors have a central hole for the passage of the direct beam through the detector to the direct beam monitor. The direct beam monitor is a low-efficiency multiwire proportional chamber with a \(^{10}\)B neutron converter. It is designed to calibrate the intensity of the incident beam.

3.4. Diffractometers

The biggest classes of instruments on the IBR-2 reactor are the diffractometers. The DN-12 neutron diffractometer is intended for the investigations of micro-samples at high pressure. It is located at beam №12. The sapphire/diamond anvils in combination with low-background neutron diffractometry have allowed the pressure range of the experiments to be extended to several GPa. The detector system of the DN-12 diffractometer consists of a multi-counter detector system, covering 0.125 sr.

The DN-6 spectrometer for microsample investigations is the direct development of the existing spectrometer DN-12. The detector system includes a set of proportional counters and a 16-section ring detector [12]. The ring sectioned detector (figure 2b) covers an angle of 360 degrees in the circular plane. The detector is divided into 16 sectors, 22.5 degrees each, located in the same hermetical volume. Each of the radial sectors is additionally divided into 6 sections along the cylindrical surface, thus the total number of measuring channels is 96. Sections and sectors are mechanically limited with laminated fiberglass plates with a thickness of 1 mm. The width of the entrance window of the detector is 7 mm, the thickness of the sensitive volume is 40 mm. The radius of the internal part of the detector is 320 mm. The efficiency to thermal neutrons (4A) reaches \(\sim 70\%\).

![Figure 2](image_url)

**Figure 2.** 8-section SANS ring detector. (a) 16-section ring detector (b).

The EPSILON (beam № 7a-1) strain/stress diffractometer allows bulk samples to be investigated and strain in space and time to be resolved, separately for each phase [13]. Its 9 banks of \(^{3}\)He counters mounted on a ring at 2\(\theta=90\)°. The SKAT [14] (beam № 7a-2) detector system is a multi-counter diffractometer consisting of three independent detector rings. Each detector system is characterized by
a unique scattering geometry of the detectors, allowing texture experiments to be carried out with high and very high resolution. The RTD (former DN-2) spectrometer is a general purpose time-of-flight diffractometer with medium interplanar spacing resolution. RTD is designed for research processes in real time mode. The detector system of RTD consists of ring detectors (eight rings like the YUMO detector) in reverse and small angles of dispersion in axial geometry, blocks of 8 proportional counters on intermediate corners (15-135 degrees) and 2D PSD 200x200 on a rotary platform on the angles of dispersion from 2 to 140 degrees.

Specifics for the operation of Fourier diffractometers is the method of time-focusing. This method has very strict requirements for determining the time of registration of neutrons and that is why these diffractometers use mostly scintillation-based detector systems. At IBR-2 there are three Fourier diffractometers: HRFD at beam №5, FSD at beam №11 and FSS at beam №13 (under construction).

The HRFD [15] is a neutron reverse time-of-flight High Resolution Fourier Diffractometer designed for precision analysis of polycrystalline structures. HRFD combines high neutron flux at the sample position with high resolution over a wide range of d-spacing. On the HRFD spectrometer three scintillation detector systems with $^6$Li glasses are supplemented by a $^3$He 1D PSD. The aperture of the scintillation detectors is 0,2 sr, the active area of 1D PSD - 200x80 mm$^2$.

The high resolution Fourier Stress Diffractometer FSD [16] is a neutron reverse time-of-flight diffractometer intended for precise residual stress investigations in bulk samples and advanced materials. The main specific feature of FSD is the capability of analysis of triple correlations of the signals from the neutron source, the Fourier-chopper and the detector. This leads to a substantial decrease of the correlation background, better quality of diffraction patterns, and permits the useful wavelength interval to be extended. The spectrometer FSD has a scintillation system ASTRA [17] with combined electronic and geometric focusing, and a backscattering detector with 16 $^6$Li-glass scintillator elements (figure 3). ASTRA consists of two multielement sections with $^6$LiF+ZnS neutron converter and wavelength shifting fibers-type readout.

![Figure 3. The FSD detector system. Part of ASTRA scintillator detector system (a), backscattering detector (b).](image)

FSS is a time-of-flight Fourier spectrometer for non-destructive characterization of residual stresses in various polycrystalline materials. The equipment for this spectrometer was received from the research center GKSS (Geesthacht, Germany). The detector system of the FSS spectrometer will include 2 banks of scintillator detectors with $^6$Li-glass.

3.5. Neutron radiography and nuclear physics

Neutron radiography is a powerful non-destructive testing method. The experimental station of neutron radiography and tomography, the NRT is located on beam №14. A collimated beam with a size of 200x200 mm$^2$ goes through the sample. A scintillator detector with $^6$LiF/ZnS scintillator...
screen and CCD-matrix is used for neutron detection. The overall spatial resolution of the system is about 230 µm.

Various types of detectors are used at nuclear physic experiments. The experimental complex KOLKHIDA [18] operates on IBR-2 beam №1a. It is designed for the investigation of nuclear neutron precession and nuclear magnetic structure. It consists of a polarized neutron spectrometer and a polarized nuclear target installation. A 3He counter is used as a neutron detector and a 235U fission chamber is used to monitor the primary neutron beam.

For experimental studies with fast neutrons a new device, “neutron telescope”, was developed [19]. It operates on the principle of recoil protons from a hydrogen-containing gas target. This device makes it possible to measure the kinetic energies of neutrons with a good resolution (~2%) in the range from 100 keV to 14 MeV. It can be used to determine the spectra of fast and resonant neutrons of all the neutron-producing targets of IBR-2, IREN and EG-5 FLNP, as well as other installations.

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