Project Activity Report

Development of a wide-aperture backscattering detector (BSD) for the HRFD diffractometer

THEME: Development of Experimental Facilities for Condensed Matter Investigations with Beams of the IBR-2 Facility

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Introduction

The High-Resolution Fourier Diffractometer (HRFD) developed in the framework of collaboration between FLNP JINR (Dubna), PNPI (Gatchina) and VTT (Espoo, Finland) has been operating at the IBR-2 reactor since 1995. Its initial design, the principle of operation and nominal parameters are described in detail in [**1**]. The examples of numerous studies carried out with HRFD and the ideas on the possible development of the diffractometer are presented in [**2**, **3**]. In the past few years, some of the key units that became morally obsolete or worn out, have been replaced. Particularly, in 2016 a new mirror neutron guide and fast Fourier chopper were put into operation and previously there had been a complete replacement in the data acquisition and experiment control electronics. The current status of HRFD is described in [**4**]. At present, the most important element of the program for further modernization of HRFD is the replacement of existing backscattering detectors with a new version.

Any modern high-resolution neutron diffractometer is a complex and expensive instrument, therefore precision neutron diffraction experiments with a very high resolution (at a level of $\Delta d/d \approx 0.002$ or higher) are currently carried out only in a few most advanced neutron laboratories in the world. At present, in Russia it is possible only at FLNP JINR (Dubna). Moreover, the HRFD diffractometer at the IBR-2 reactor is one of three or four neutron diffraction instruments in the world where it is possible to conduct experiments requiring the resolution of $\Delta d/d \approx 0.001$ or higher. HRFD is mainly intended for the **precision structural analysis of polycrystalline substances** with an average unit cell volume of up to ~500 Å^3. Typical examples are the studies of mercury-based high-temperature superconductors with different amounts of oxygen or fluorine in the basal plane [**5**, **6**], and the doped manganites with colossal magnetoresistance [**7**, **8**], modern functional alloys and electrode materials [**9**, **10**]. HRFD is also used to perform an **analysis of single crystals** when its unique d_{hkl} resolution is needed, e.g., to study phase separation in $La_2CuO_{4+\delta}$ crystals due to low-temperature diffusion of hyperstoichiometric oxygen [**11**].

The layout of HRFD at the IBR-2 reactor is presented in **Fig. 1**.

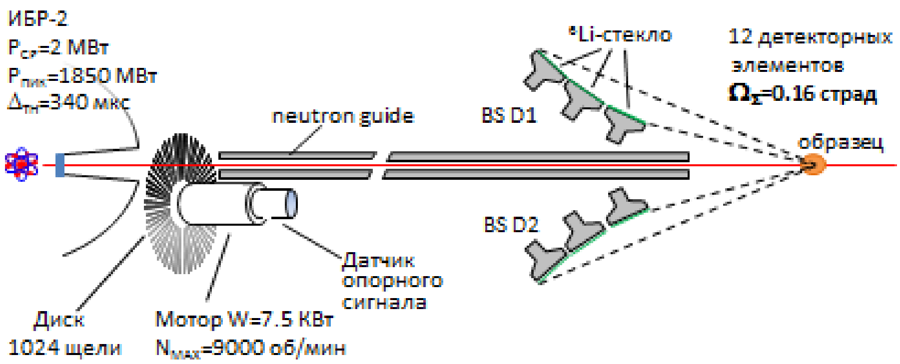

Fig. 1. Layout of HRFD at the IBR-2 reactor.

At present the HRFD detector system consists of three detectors, two of which are located at scattering angles of ±152°, and the third one is at 90°. The first two detectors are mainly used for studying the structure of polycrystals and the third one is employed for measuring internal stresses. The detecting element is Li-glass-based scintillators. From the present-day viewpoint, the HRFD detectors have two disadvantages: high sensitivity to the γ- background and an insufficiently large solid angle (~0.16 sr). Due to this, the resulting diffraction spectra have a rather high background and low (by modern criteria) data set rate, despite the fact that the neutron flux at the sample position is sufficiently high (10^7n/cm^2/s). Thus, the diffraction spectrum obtained with the TOF diffractometer POWGEN3 (SNS/ORNL, $\Delta d/d \approx 0.001$) due to a large-area ZnS(Ag)-based detector (the solid angle covered by the detector is 1.5 sr) will have a low background and ~10 times better statistics than the spectrum from the same sample measured using HRFD. The current project is aimed at eliminating these drawbacks. Its implementation will permit us to radically improve the parameters of the HRFD diffractometer and bring it to the leading positions in the world. The estimates show that the solution of these problems will allow an approximately two- to three-fold increase in the number of conducted experiments, and in this respect will make it possible to substantially improve the accuracy of the obtained structural information, as well as to significantly enhance the capabilities of the diffractometer in performing experiments under various external conditions on the sample.

Description of the wide-aperture backscattering detector (BSD)

The general view of BSD is schematically shown in **Fig. 2.**

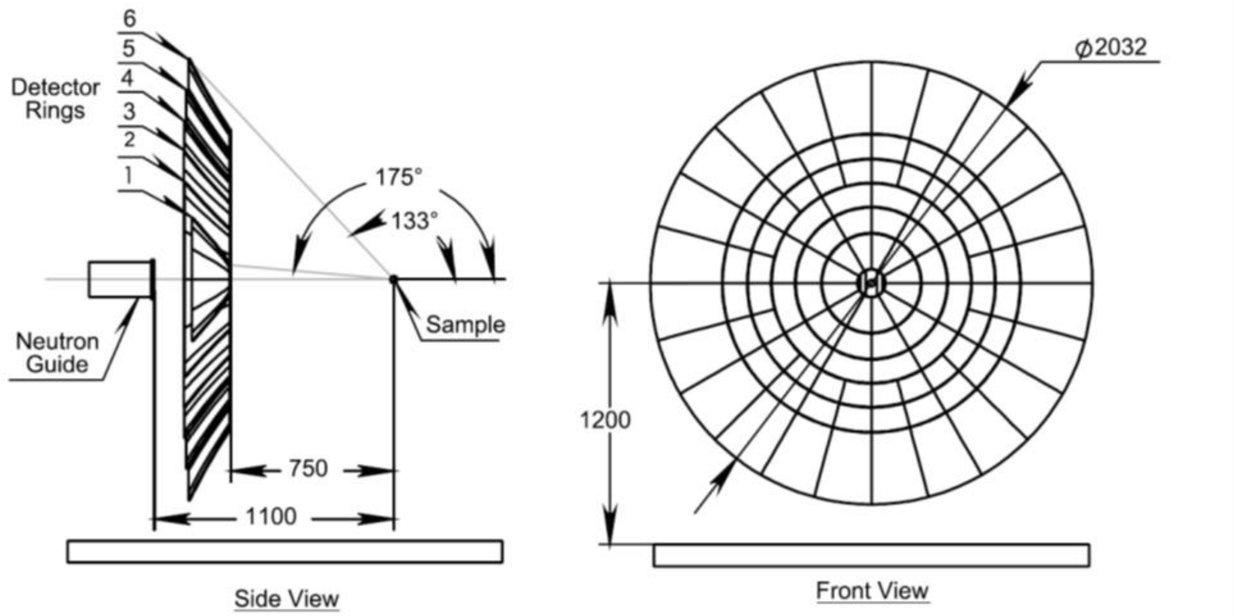

Fig. 2. Schematic of the large-aperture backscattering detector.

The detector has a ring structure reflecting the axial symmetry of the neutron scattering by the sample. The detector comprises 6 rings of scintillation screens. The three outer rings are divided into sectors of 15°, and the three internal ones – into sectors of 30°. Six rings completely cover the scattering angle interval $2\Theta=(133\text{-}175)°$. The total solid angle of the detector is $\Omega_D \approx 2.0$ sr.

Each sector in the schematic is an independent detector element consisting of a scintillation screen, WLS fibers for light collection and a photomultiplier. A scintillation screen in each sector is not solid, but consists of smaller, tightly fitted to each other fragments which follow the surface shape of space-time focusing with the required accuracy.

The output of each photomultiplier is connected to the Data Acquisition and Accumulation (DAQ) System developed at the Laboratory. The System components are described in detail in [**12**]. The system allows one to receive and process information from 240 independent detectors, suppressing events caused by background gamma-rays. The system is designed in the NIM standard. In its full configuration, it consists of 8 units of amplifiers-discriminators with 32 inputs each and one data accumulation unit.

Technical design of the backscattering detector (BSD) at HRFD

Within the framework of development of the technical project, the necessary calculations have been performed, which allowed to choose optimal parameters of the detector and its configuration, both from the viewpoint of technological feasibility of its manufacturing, and its positioning at the HRFD diffractometer. Some of the most significant results of these calculations will be given below.

The general view of the developed BSD in full configuration is presented in **Fig. 3**. The detector consists of 12 identical independent from each other 30°-sectors. The design of an individual sector is shown in **Fig. 4**.

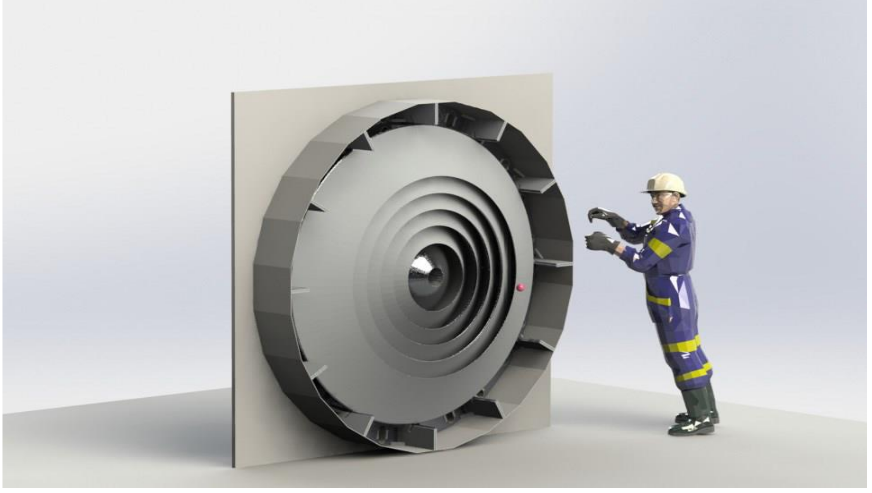

Fig. 3. General view of BSD.

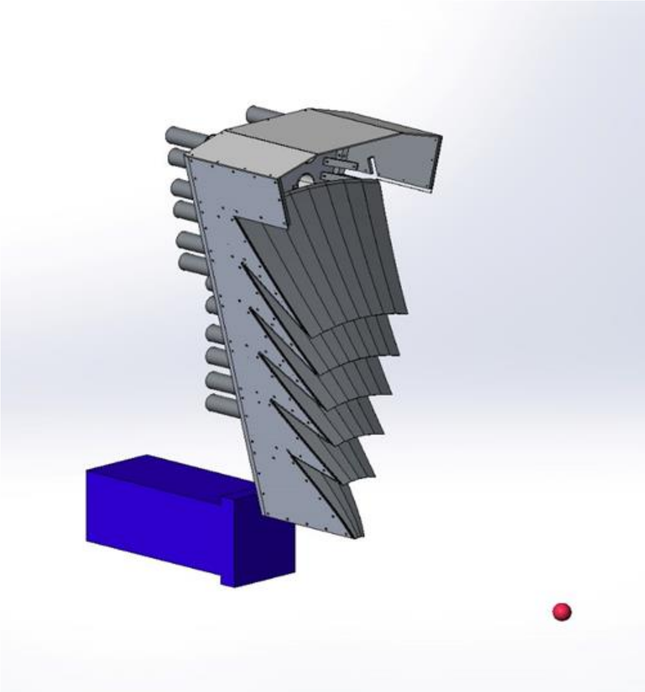

Fig. 4. General view of the 30°-sector of BSD.

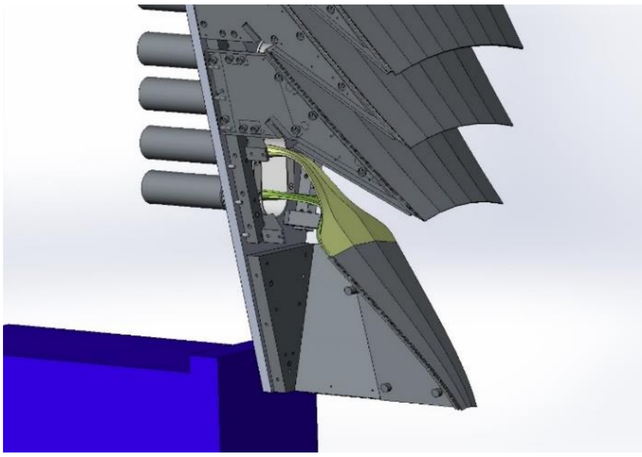

Fig. 5. Fragment of the 30°-sector of BSD.

Figure 5 presents a fragment of a sector on a larger scale. Some of the structural elements are removed, revealing the internal structure of the BSD sector. The detecting elements of each ring have a two-layer structure. In this case, the BSD efficiency increases significantly, which is illustrated by the dependence of the detector efficiency on the scattering angle, shown in **Fig. 6**.

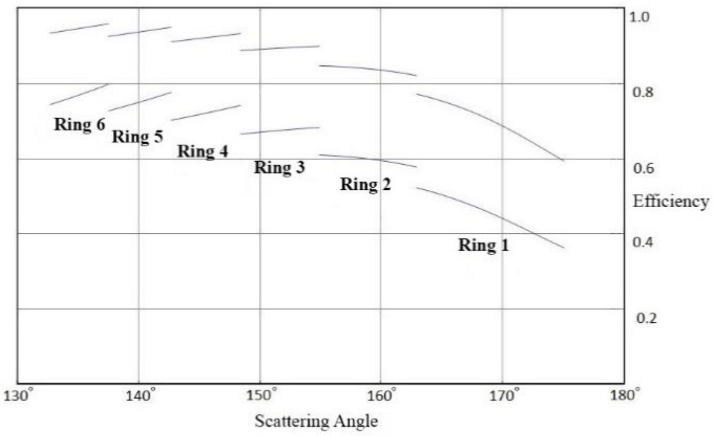

Fig. 6. Dependence of the detector efficiency on the scattering angle.

The lower set of curves presented in the figure corresponds to the standard thickness of 0.42 mm of the scintillation screen. The detector efficiency in this case varies from 36% to 80% and on average it is 65%.

To be limited to such low efficiency, taking into account the rather high complexity of the mechanical design of the backscattering detector, required for ensuring high accuracy and positional stability of scintillation screens, would be highly unreasonable. It was decided to add the second layer of the detecting elements which significantly changed the capabilities of the detector. As it can be seen from the upper set of curves in **Fig. 6**, the efficiency range becomes 59%-96% and on average it increases to 85%. Such increase in efficiency, combined with the aperture increased to 2 sr, brings the backscattering detector to a completely new level. The mechanical design of the detector remains practically unchanged after adding the second layer.

The shape of the detector elements of all the 6 rings satisfies the space-time focusing condition. The perfect surfaces of space-time focusing are the surfaces of revolution, the generatrixes of which are shown in **Fig. 7**.

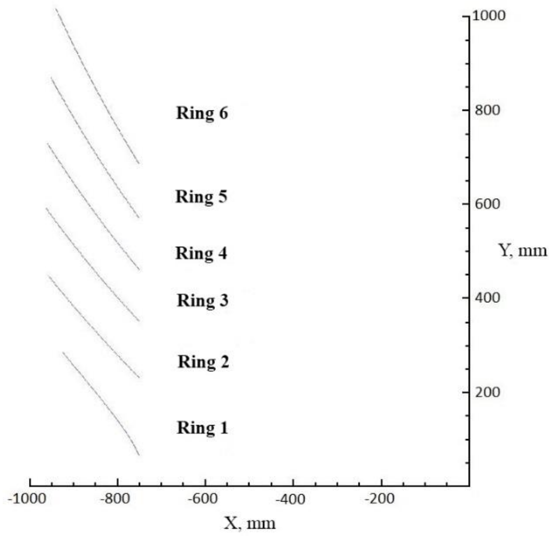

Fig. 7. Shape of the detector elements of the rings.

The contribution of such perfect surfaces to the total resolution of the diffractometer is zero. However, their manufacturing is of great complexity. Therefore, the surfaces of revolution have been approximated by umbrella-type surfaces, which are much easier for manufacturing. As it is shown in Figure 4, the detector rings within one sector are divided: Ring 1 - into 3 segments; Ring 2 - into 4 segments; Ring 3 - into 5 segments; Ring 4 - into 6 segments; Ring 5 - into 8 segments; Ring 6 - into 8 segments. In this case, the spatial deviation of the approximating surfaces from the surfaces of revolution is insignificant, and the contribution to the total resolution of the diffractometer does not exceed 4×10^{-5}.

Work stages and project costs

Project activities are carried out in accordance with the project schedule.
The schedule includes a number of key points:

1. Development of the technical design of the backscattering detector (BSD) for HRFD;
2. Adaptation of the existing technology of manufacturing scintillation detectors for the backscattering detector at HRFD (FLNP JINR);
3. Design and manufacturing of the instrumentation for mass production of sectors of the detector;
4. Design and manufacturing of the mechanical components of the detector;
5. Design and manufacturing of a test stand for testing detector sectors;
6. Manufacturing of one sector of the detector and its testing on the test stand;
7. Manufacturing and adjustment of the MPD modules of the detector electronics and the data acquisition and accumulation electronics; development and debugging of the software.

Up to date, a significant part of the activities scheduled within the framework of the current project has been completed, namely:

- The technical design of the backscattering detector (BSD) for HRFD has been developed, including a set of design drawings;
- The technology of manufacturing of scintillation detectors for BSD at HRFD has been adapted;
- The instrumentation for mass production of sectors of the detector has been designed and mostly manufactured. Merely the manufacturing of the very part of the instrumentation which requires a complete set of manufactured mechanical components of the detector has not been completed yet;
- A complete set of design drawings has been submitted to SPA “ATOM”; here the manufacturing of mechanical components for the first sector of the detector is currently nearing completion;
- A test stand for testing detector sectors has been designed and developed;
- A set of MPD modules of the detector electronics and the data acquisition and accumulation electronics, as well as the related software for testing of the first sector of BSD has been manufactured and adjusted;
- By the end of this year, it is planned to complete the manufacturing of the first sector of the detector and conduct its testing on the test stand.

In accordance with the project schedule, the development of new modules of the electronics, as well as the software of the data acquisition system for BSD is in progress. With reference to the results obtained in the course of debugging the prototype of the new MPD32-based data acquisition module, including a 32-channel discriminator, time encoder, gigabit transceiver and USB3.0 interface, a working draft of the documentation has been developed and the prototypes of printed circuit boards and modules have been produced called MPD32- USB3 [**13, 14**].

In the framework of the project, studies of signals from the scintillation counters of thermal neutrons are carried out aimed at improving their counting capacity.

Along with the activities listed above, a large number of component parts and consumables (PMTs, scintillator and wavelength-shifting optical fibers), as well as electronic modules for the test stand and multi-channel high-voltage modules have been purchased.

The successful implementation of this project is an important step towards the development of a full-scale backscattering detector for the HRFD diffractometer.

In 2018-2019, the expenses within the theme related to the implementation of the project under expenditure items “Materials and Equipment” amounted to 700 kUSD.

Infrastructure and staff

An important stage in the implementation of this project was development of the necessary infrastructure and training of the highly skilled staff.

For this purpose, three workrooms were provided, equipped with the necessary laboratory furniture and equipment.

They include:

1. Workroom for "clean" work with scintillators and optical fibers;
2. Workroom for mounting and assembly of detectors;
3. Workroom for mechanical work.

At present, the team of employees directly involved in the development activities of the detector, consists of 9 specialists including:

- Scientific researchers - 2;
- Design engineer - 1;
- Technician - 1;
- Laboratory assistants - 4;
- Postgraduate student - 1.

All the employees are highly qualified and skilled specialists.

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During the project implementation period, the following papers mentioned in the main list of references have been published by the authors:

1. Balagurov A.M., Balagurov D.A., Bobrikov I.A., Bogdzel A.A. et al., High-resolution neutron Fourier diffractometer at the IBR-2 pulsed reactor: a new concept. Nuclear Inst. and Methods in Physics Research B 436 (2018), pp.263-271.
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3. Bogdzel A., Drozdov V., Kruglov V., Murashkevich S., Prikhodko V. Shvetsov V., «The new data acquisition system MPD-32 for the high-resolution Fourier diffractometer at the IBR-2 pulsed reactor». Proceedings of the 27th International Symposium Nuclear Electronics and Computing (NEC’2019) Budva, Becici, Montenegro, September 30–October 4, 2019, CEUR-WS Vol-2507 (ISSN 1613-0073), pp.142-146 (https://indico.jinr.ru/event/738/contributions/6365/).