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ORIGINAL STUDY

Conceptual Design of the ARMAN Neutron Reflectometer at the WWR-K Reactor (INP, Almaty, Kazakhstan)

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Abstract

The concept of the new experimental setup — neutron reflectometer ARMAN (Almaty Reflectometer of MonochromAtic Neutrons) is presented. The instrument is to be placed at beamline 4 with thermal neutrons at the WWR-K reactor of the Institute of Nuclear Physics, Almaty, Kazakhstan. The instrument features a horizontal scattering geometry with a vertically oriented sample with the size of beam 2 × 50 mm^2. The reflectometer will operate with a monochromatic neutron beam in two modes: with and without polarization of the incident beam. The monochromatization will be provided by a double-crystal monochromator of pyrolytic graphite plates with the working wavelength range of 1.8−2.8 Å and expected resolution Δλ/λ in the range of 1−3 %. The schematics and main elements together with the numerical estimates of the expected neutron flux in different places of the beamline are discussed.

Keywords: Research reactor WWR-K, Experimental facility, Neutron reflectometry, Simulation, Technical parameters, Detector system

1. Introduction

At present, there is a growing interest in multilayered structures for nanotechnologies [1], which stimulates the development of the methods for measuring characteristics of thin-film structures at interfaces [2]. Neutron reflectometry is a technique allowing the analysis of depth profiles of various interfaces including thin coatings, biological membranes, adsorption layers, etc. [3,4]. A unique opportunity to study magnetic heterostructures is provided by reflectometry of polarized neutrons, which, together with the nuclear density distribution, makes it possible to characterize the layer-by-layer distributions of the magnetization vector including complicated noncollinear magnetic structures. In this regard, world neutron centers are actively developing neutron reflectometry instrumentation [5]. Typically, the development of such instrumentation begins with the realization of specular reflectometry, in which one measures the dependence of the reflectivity R (ratio between intensities of the reflected and incident beams) on the momentum transfer projection, Q_z, on the normal (conventionally z-axis) to the interface under study. Q_z is determined by the neutron wavelength, λ, and the scattering angle, θ, as

$$Q_z = \frac{4}{\pi} sin \frac{\theta}{2}$$

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Thermal neutrons ($\lambda > 1$ Å) are reflected at very small angles in the vicinity of the critical value Q_{zc} (for $Q_z < Q_{zc}$, reflectivity $R = 1$), so $Q_z \sim \theta/\lambda$. It means that the working range, $\otimes Q_z$, which is the difference between the achievable minimal and maximal values Q_{zmax} and Q_{zmin}, is wider for larger scattering angles with a fixed value of the wavelength. It might happen that for available ranges of the scattering angles and wavelengths and for the certain structures the condition $Q_{zmin} > Q_{zc}$ is valid. To have an access to the range between Q_{zc} and achievable Q_{zmin} in this case one needs to increase the available wavelength at the instrument. For the realization of instruments with $\lambda > 4$ Å, a so-called source of cold neutrons ($\lambda \sim 10$ Å) is required. In this case, to transport neutrons to the instrument, long (~10 m) neutron guides can be efficiently used, which additionally allows one to place the instrument far from the reactor core and increase the signal-to-background ratio at the maximum achievable values of the momentum transfer [6,7]. A backside is that a specialized guide hall is required, which is a problem for average-power research reactors (power < 10 MW) usually limited in space for the installation of extended neutron instruments, such as the reactor WWR-K (power 6 MW) at the Institute of Nuclear Physics (Almaty, Kazakhstan) [11,12]. The maximization of signal-to-background ratio is a challenge in this case.

Here, we propose the concept of a compact neutron reflectometer with thermal neutrons at an average-power research reactor trying to solve the problem mentioned above. To reduce the background effect, a double-crystal monochromator is considered, which provides a high rate of monochromatization together with shifting the neutron beam from the direct view of the source. The fine tuning of the neutron wavelength is achieved by mutual rotation of the crystals, while the parallel shift is determined by the rotation angle of the first crystal and distance between the crystals [8–10]. A reflectometer of such kind is under development at the horizontal beamline 4 of the WWR-K reactor in INP. The instrument is named as ARMAN – Almaty Reflectometer of MonochromAtic Neutrons (translated as 'dream' from Kazakh). This paper presents the conceptual design of the instrument including the description of its main elements and technical characteristics expected.

2. Principal design of reflectometer

The WWR-K reactor has five radial horizontal channels available for implementation of neutron scattering methods. Three of them are already occupied by the following instruments: channel 1 - TITAN neutron tomography [13–15], channel 2 - AGAVA irradiated materials radiography, channel 3 - INAA instrumental neutron activation analysis [16,17]. Channel 5 is allocated for a powder diffractometer, which is under development.

The schematic of the proposed ARMAN reflectometer is shown in Fig. 1. It consists of the following main elements: neutron source, in-pile and out-pile collimation system, double-crystal monochromator, neutron beam deflector-polarizer, two slit apertures, sample position and detector system.

Channel 4 for the neutron reflectometer has a constant cross-section with a diameter of 100 mm at the channel's bottom (i.e. the plane on which neutrons penetrate into the channel) and at the channel outlet from the reactor. The horizontal channel provides direct and intensive extraction of the neutron beam with minimal losses. The use of the existing channel infrastructure increases the reliability and cost-effectiveness of the project.

The distance from the channel bottom to the exit is 3350 mm. It means that the monochromator can be installed at a distance of ~3.5 m to the bottom. The channel geometry determines the divergence of the neutron beam of about ~ 30 mrad. The thermal neutron flux, Φ, at the channel exit was measured by

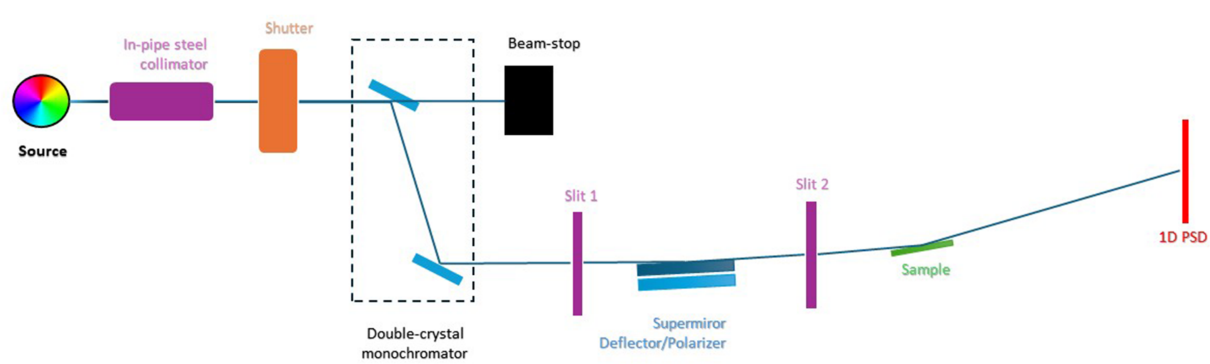

Fig. 1. Schematic of the neutron reflectometer under consideration. Top view.

gold foil activation, $\Phi = 10^9$ n/cm^2/s. To limit the beam divergency an in-pile steel collimator (thickness 600 mm, rectangular aperture with cross-section of 10×70 mm^2) was installed in the channel before the beam shutter. The collimator decreases the beam divergence in the horizontal plane down to 6 mrad with the effective decrease in the thermal neutron flux by three times. The design allows for effective suppression of neutrons deflected from the axial direction, improving spatial collimation and reducing parasitic scattering from the channel walls. The steel walls of the pipe provide additional protection against scattered and background radiation, and also prevent the activation of surrounding structures, maintaining radiation safety during operation of the installation. An additional boron out-pile collimator (thickness 500 mm, rectangular aperture with cross-section of 10×70 mm^2) was installed in the channel after the beam shutter between the monochromators in the double-crystal monochromatic system described below.

In accordance with the design of the instrument (Fig. 1), the double-crystal monochromator provides a parallel shift of the beam to a distance of 250–300 mm. Such design has a number of advantages in comparison with a single monochromator: lower background level of fast neutrons and γ-radiation, the possibility to vary the energy or wavelength of neutrons. Pyrolytic graphite PG plates ($40 \times 30 \times 5$ mm in size, with a mosaicity of 7 mrad) will be used as monochromatizing elements. The considered double monochromator allows variation of the neutron wavelength in the range of 1–3.5 Å and at the same time conserves the geometry of the instrument. Pyrolytic graphite has high reflectivity over a wide angular range. This ensures an intense neutron beam output with minimal losses in the selected wavelength range. Due to its mosaic structure, it reflects neutrons with a small spread of directions, which is especially useful for experiments where high beam brightness is important. Such a crystal is compact, stable and works well at high fluxes, making it an excellent choice for a neutron monochromator [18,19].

For convenient alignment, the monochromators are placed on rotary stages with aluminum holders. The second monochromator is additionally equipped with a linear translation stage, allowing for the selection of the desired neutron wavelength by varying the combination of reflection angles and the position of the second crystal (see Fig. 2).

The setup includes two supermirrors mounted on a common platform: one serves as a filter, and the other as a polarizer. Depending on the selected measurement mode, the appropriate mirror can be quickly positioned in the beam path by linearly moving the platform. This design enables fast switching between polarized and unpolarized modes, as well as the use of beam filtering without disassembling or reconfiguring the beamline.

The advantages of this approach include compactness, flexibility in experimental conditions, and reduced preparation time. In addition, the filter-deflector improves the spectral composition of the beam by eliminating higher-order reflection from the neutron beam, and the polarizer provides a highly polarized neutron beam, thereby expanding the experimental capabilities of the instrument.

A neutron supermirror Fe/Si will be used as a beam polarizer, providing reflection of neutrons with a certain spin projection. The choice is due to the compactness of the design, high degree of polarization (up to 95 % and higher) and the ability to work in a wide range of wavelengths.

The collimation system will consist of two slit diaphragms made of cadmium plates and with the ability to change the width in the range from 0 to 15 mm and

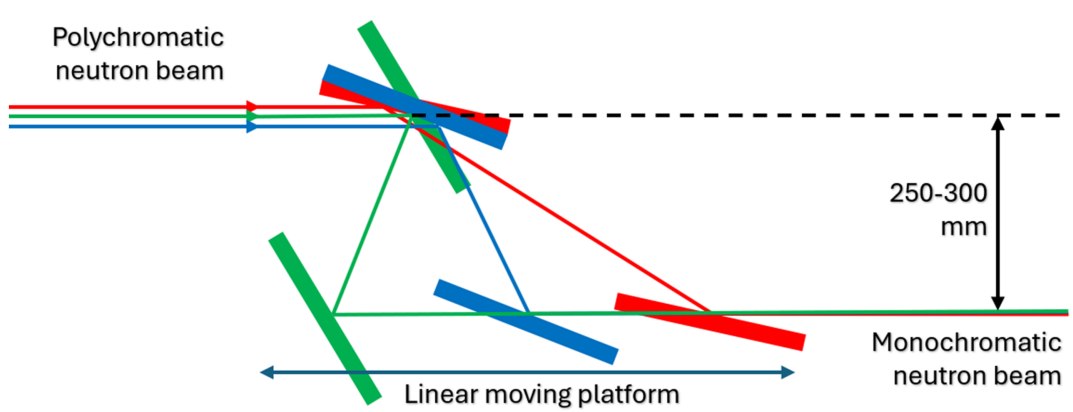

Fig. 2. Schematic of the double-crystal monochromator.

the height from 0 to 80 mm. The maximum achievable distance between these collimating slits of the reflectometer will be 1.5 m.

The sample table will provide the ability to move and adjust the position of the sample relative to the incident beam. To adjust the sample in the neutron beam, the holder is mounted on an optomechanical platform (with a linear translation perpendicular to the beam at the distance of 200 mm, with a rotation on 360° and a goniometric platform for tilt control of ±15°). All motors of these devices will be controlled by the reflectometer experiment control system.

The reflectometer detection system will consist of a monitor, a detector and counting electronics. A neutron monitor will be a single counter filled with He3 that records the incident neutron flux near slit 2. The detectors will be a tandem of a single counter based on ^{3}He and a one-dimensional linear position-sensitive detector (LPSD), a multi wire ^{3}He-filled proportional chamber [20] with a working area of 80*200 mm^2. The efficiency of thermal neutron registration by a single counter is 80 % at wavelength $\lambda = 1.8$ Å, and for the 1D PSD detector it is at a level of 50 % with a resolution of ~ 2 mm. Using a point detector together with a 1D SPD allows combining high measurement accuracy with the ability to record the intensity distribution over angles. The point detector provides reliable data for specular reflection, and the 1D PSD provides fast collection of information on diffuse scattering and side signals. This speeds up the experiment and allows for a comprehensive analysis of the beam behavior.

The general representation of the part of the reflectometer after the beam shutter is given in Fig. 3.

3. Expected parameters of the reflectometer

A series of Monte Carlo simulations was conducted with the VITESS program package [21,22], to obtain the spectrum characteristics of the monochromatic beam and the thermal neutron flux after a two-crystal

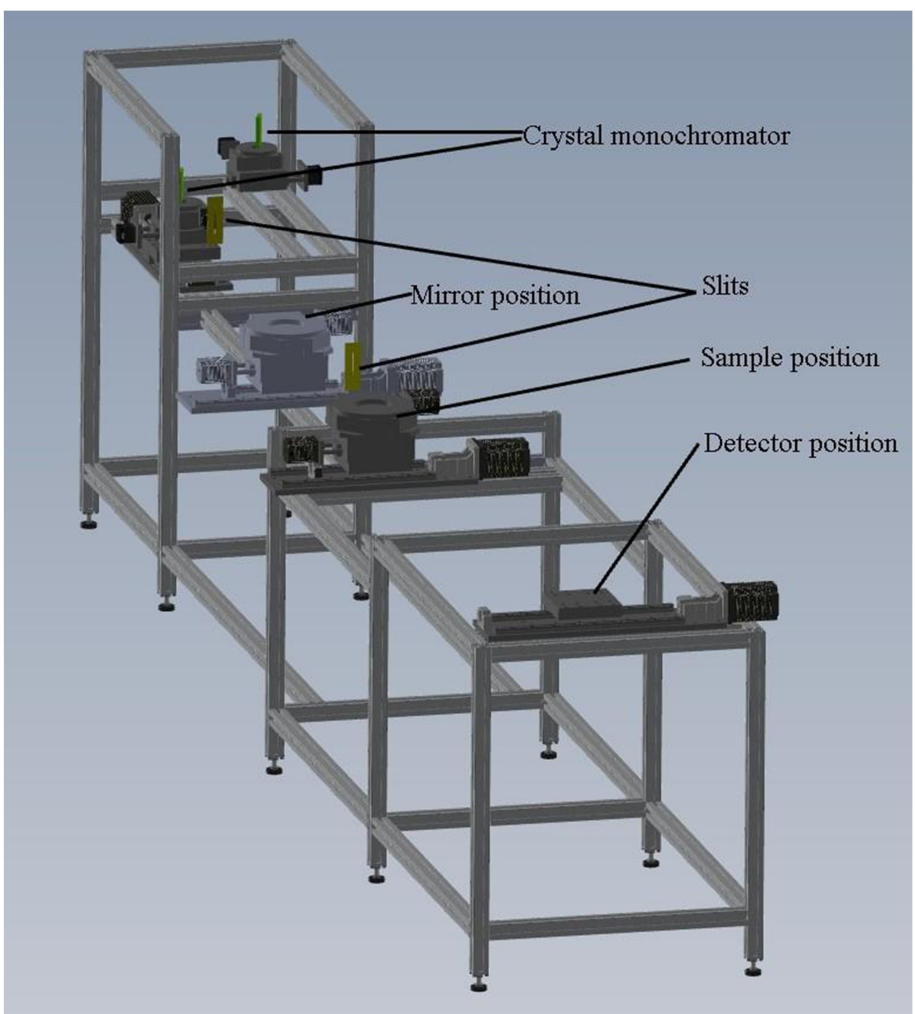

Fig. 3. Schematic 3D representation of the main elements of the neutron reflectometer ARMAN after the beam shutter.

monochromator. The source of HMI reactor has been chosen in our virtual model in VITESS due to close characteristics between WWR-K and HMI reactor. The results of simulation are shown in Fig. 4. The main wavelength as the first order of reflection from PG crystals was chosen to be 2.4 Å. As one can see from Fig. 4-a, the integral intensity in the 2nd order is higher than one in the 1st order. But at the same time, the reflections of the 3rd and 4th orders are lower than the 1st order due to their low intensity in the incident beam from the source.

The simulation results for the beam reflected from the deflector are shown in Fig. 2-b. The incoming neutron flux from the monochromator with a wavelength of 2.4 Å incidents and scatters from the deflector at the angle of 0.5°, while the higher orders of the beam pass through the filter and are absorbed by neutron-shielding materials. The polarized neutron mode will be implemented using a reflection polarizing supermirror located in the place of the deflector [23,24]. For convenience and simplicity both supermirrors will be placed in one optomechanical platform. The reflectometer mode can be changed remotely by moving one mirror to another.

Also, using the VITESS package, the neutron flux was estimated in various positions along the beam such as: after the monochromators, after the first slit, the sample position (after the filter and the second slit). The results of these calculations are shown in Table 1.

The expected parameters of the ARMAN reflectometer are collected in Table 2.

Optimization of the device parameters and evaluation of the expected characteristics were carried out using Monte Carlo simulation of neutron experiments. The simulations replicate the experimental geometry and conditions, allowing us to evaluate the effects of beam collimation, resolution, and intensity on the reflectivity measurements. This approach provides a basis for selecting optimal settings before conducting physical experiments. Results of this experiment are shown on Fig. 5.

Fig. 5 shows the simulated reflectivity as a function of momentum transfer Q for various collimation slit

Table 2. Main expected parameters of ARMAN reflectometer.

Beam size, mm^2	50 × 2
Wavelength, Å	1.8–2.8
Wavelength resolution, %	1–3
Incident angle range, mrad	3–25
Q_z-range, Å^{-1}	0.001–0.6
Angular resolution, %	5–10
Sample size, mm^2	50 × 50
Neutron flux on the sample, cm^{-2} c^{-1}	1.1 × 105
Deflecting mirrors	Supermirror, m = 2
Detector	1D PSD, ^{3}He, 200 × 200 mm^2, resolution 2 × 2 mm^2 count rate 10^5 s^{-1}

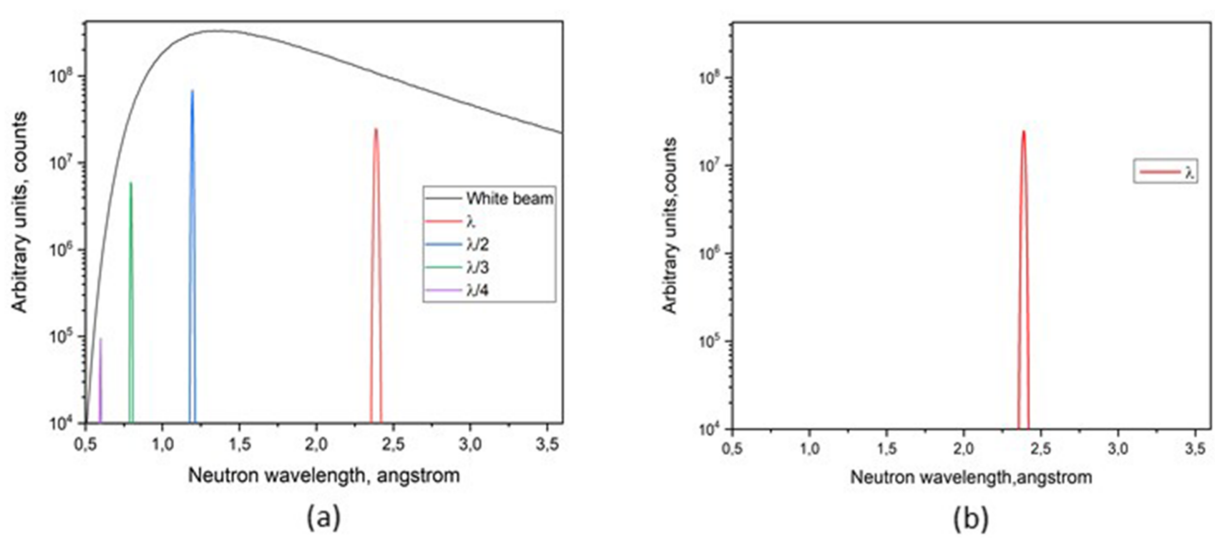

Fig. 4. (a) Spectrum of polychromatic white beam from channel 4 of the WWR-K reactor and neutron beam reflected from the crystal. The main wavelength of neutrons 2.4 Å in red and its higher orders of reflection (λ/2, λ/3, λ/4) are shown. (b) Spectrum of monochromatic neutron beam after scattering from the deflector, and measured at the sample position.

Table 1. Neutron flux calculated using simulation in VITESS.

Place	After double-crystal monochromators	After the first slit	Sample position
Neutron flux, n/cm^2/s	1.4 × 10^7	5.6 × 10^6	1.1 × 10^5

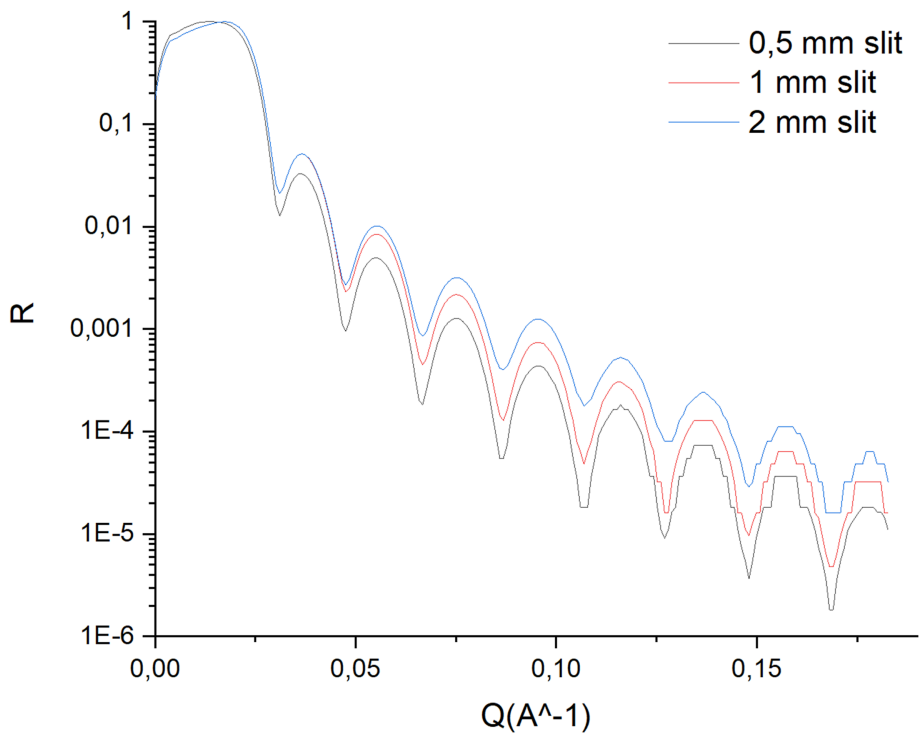

Fig. 5. Reflectivity curves calculated for different collimation slit widths, showing the impact on angular resolution.

widths (0.5 mm, 1 mm, and 2 mm). The model sample used in the simulations consists of a 50 nm Ni thin film on a Si substrate. Increasing the slit width enhances the overall reflected intensity, especially at higher Q, due to the greater neutron flux. At the same time, narrower slits improve angular resolution, making the interference fringes sharper and more distinct. The irregularities and fluctuations observed at high Q are primarily due to the limited neutron statistics in this region, where the reflected intensity becomes very low.

4. Conclusion

The article presents the description and characteristics of a new experimental setup ARMAN for neutron reflectometry, which is currently under development at the WWR-K research reactor in INP, Almaty, Kazakhstan. Numerical results indicate that the considered configuration of the compact reflectometer based on using a double-crystal monochromator is optimal under existing conditions in the experimental hall. The expected technical parameters of the setup will give the opportunity of neutron reflectometry measurements with a horizontal scattering plane (vertical plane of the sample) to determine the reflectivity *R (Q)* from flat surfaces at small grazing angles.

In the next stages of development, it is planned to complete the mechanical construction of the instrument, finalize the data acquisition system, and begin commissioning tests with calibration samples. In parallel, further improvements are planned to extend the capabilities of the instrument.

Among such improvements, it is planned to install a spin-flipper and full polarization analysis, which will allow the study of multilayer magnetic structures using polarized neutron reflectometry. Such improvements will significantly broaden scientific application of the instrument, making it suitable for research in the fields of nanomagnetism, soft matter and biological systems.

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Conflict of interest

There is no conflict of interest.

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