Project of the new multifunctional reflectometer GRAINS with horizontal sample plane at the IBR-2M pulsed reactor in Dubna

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Abstract. The new multifunctional reflectometer GRAINS is under construction at the modernized high flux IBR-2 pulsed reactor (IBR-2M) of the FLNP JINR (Dubna, Russia). The principal feature of this reflectometer, the horizontal sample plane (or vertical scattering plane), enables the study of liquid-containing interfaces. The reflectometer will operate in the time-of-flight regime with constant sample illumination during measurements. The important advantage is the constant angular resolution with unvaried background. The additional modes of the GRAINS reflectometer comprise (1) off-specular scattering and GISANS, which are measured simultaneously in the TOF regime at a 2D position-sensitive detector; (2) angular encoding in the horizontal plane, which is provided by a Larmor precession region limited by current sheets in front of the sample; (3) 3D polarimetry in reflection, which is provided by a Larmor precession region around the sample position. The design of the reflectometer is optimised to take better advantage of an exceptionally broad wavelength band of the new cold moderator at the IBR-2M. The set-up will open up principally new possibilities for investigations in the field of interface nano-science at the IBR-2M reactor.

1. Introduction
A present-day tendency in the neutron reflectometry instrumentation is the development of set-ups with horizontal sample plane. The combination of such geometry with the possibility of neutron polarization covers the whole range of research problems connected with the structure of non-magnetic and magnetic nanosystems on interfaces. The scientific program at the modern reflectometer with horizontal sample plane includes the topics such as biological complexes and membranes [1,2]; magnetic colloidal systems [3,4]; polymers and surfactants [6]; layered nanostructures [6-8]. Also, one...
can mention the activity in the development of new research methods based on the Larmor precession of neutron spin [9-11].

In 2007 at the Frank Laboratory of Neutron Physics, JINR (Dubna, Russia) the project on the new multifunctional reflectometer GRAINS (GRAzing Insi dence Neutron Scattering) was started. The ideology of this set-up is based on the realization of last achievements in neutron reflectometry with the use of the pulsed regime at the neutron source—the IBR-2M reactor (modernized version of the previously successful pulsed reactor IBR-2). The main features of the new reflectometer are (1) the horizontal sample plane, which makes it possible to study liquid-containing interfaces; (2) polarization of the neutron beam; (3) full 3D reflectometry including analysis of specular, off-specular and grazing incidence small-angle scattering components; (4) new methods based on Larmor spin precession.

The IBR-2M reactor is a high flux long-pulse neutron source with 5 Hz repetition rate. Such a source provides ideal conditions for the reflectometry. The start-up of IBR-2M for experiments is scheduled for 2011.

2. The principle scheme and parameters of the reflectometer

The principle scheme of the GRAINS reflectometer is presented in Figure 1. The very important new element (in particular, for reflectometry) is the cold mesitylene moderators on the IBR-2M reactor [12]. The new sources will produce a broad wavelength band combined with the gain for cold neutrons. So, a unique momentum transfer band with a dynamic range of about 25 will be available at the GRAINS reflectometer. The immense advantage is that the experiments can be performed in time-of-flight (TOF) regime in one shot without changing the incoming scattering angle. This removes difficulties in fitting the reflected and off-specular scattered intensity measured in several steps in Q-space with different resolution in the overlap regions. The GRAINS set-up is constructed at beam 10 of the IBR-2M reactor, which has an advantage in the wide area of the cold moderator surface (20 x 20 cm²) faced to the beamline. The available flight-pass of more than 20 m allows to optimize the intensity yield for the various focusing possibilities. All elements of the set-up have been optimized for the horizontal geometry.

The head part of the reflectometer containing the vacuum system starts after the cold moderator (2.5 m) and extends towards the collimation system (collimators). The aim of the background chopper after the head part is to cut out the subsidiary power peaks of the reactor. It opens only during the neutron pulse. After the chopper the vacuum collimating system continues up to the sample position and pass through the first resonant spin flipper. Flexible slit-collimators serve to tailor the beam shape for different applications. The deflector and the polarizing mirror are exchangeable units composed of a stack of adjustable mirrors. With deflector or polarizing mirror the direct view from the sample position to the cold moderator is prohibited. The reflection angle on the sample is changed by the regulation of the mirror inclination.

The two-coordinate position-sensitive detector (PSD) for the GRAINS reflectometer is constructed at FLNP JINR. Its design is based on a multiwire proportional chamber with delay line readout. Signals from both delay lines and an anode signal come through preamplifiers to a constant fraction timing five-channel discriminator and are registered in data acquisition and accumulation block (DAAB), which contains of signal level converter NIM-TTL, field programmable gate array (FPGA) and high-speed interface with optical communication link to a personal computer. The data acquisition and accumulation system can operate in two modes: in the mode of histogram accumulation in internal memory of the DAAB block and in the list mode, when “raw” data are accumulated directly on a PC hard disk. All functions of the block are programmable. Logic and time simulation of operation of the block was carried out using Quartus II package from ALTERA.

The expected parameters of the GRAINS reflectometer are presented in Table 1.
Figure 1. Principle scheme of the GRAINS horizontal reflectometer in top view (upper scheme) and side view (lower scheme). The upper length limit (moderator-detector) is 30 m. The Larmor-precession device is not shown for simplicity; it will have two positions, before and around the sample, respectively. “Polarizing mirror” stands for a stack of adjustable mirrors for polarizing and non-polarizing modes.

Table 1. Main expected parameters of reflectometer GRAINS

| Parameter                  | Value                                      |
|----------------------------|--------------------------------------------|
| Beam size                  | $100 \times 10$ mm$^2$                     |
| Wavelength range           | $0.5 - 15$ Å                               |
| Incident angle range       | $3 - 25$ mrad                              |
| Q-range                    | $0.001 - 0.6$ Å$^{-1}$                     |
| Angular resolution         | $3 - 10 \%$                                |
| Sample size                | $50 \times 50$ mm$^2$                      |
| Neutron flux on the sample | $3.0 \times 10^6$ cm$^{-2}$ s$^{-1}$       |
| Deflecting mirrors         | Supermirror, $m = 2$                       |
| Analyzer                   | Fan type, $m = 2$                          |
| Detector                   | PSD, $^3$He, $200 \times 200$ mm$^2$, resolution $2 \times 2$ mm$^2$, count rate $10^6$ s$^{-1}$ |

3. Main options of the reflectometer
At present, the majority of published data in reflectometry concerns specular reflection, from which the structural information perpendicular to the surface of a sample is obtained. For this purpose, the $Q_\perp$ vector perpendicular to the surface is scanned as a function of the incoming scattering angle in the monochromatic mode or the wavelength in time-of-flight. A further step in the sample characterisation is to obtain information about the lateral structure of surfaces and interfaces from off-specular scattering and GISANS. A combined measurement of specular reflection, off-specular and GISANS, called complete reflectometry [13], probes lateral correlations in a depth sensitive way providing a 3-dimensional structural analysis. In complete reflectometry the detailed neutron wave field along the surface normal created by dynamical scattering is taken into account. These recent developments are taken into account in the lay-out of the new horizontal reflectometer. A flexible collimation system allows to install a slit-shaped incoming beam for the set-up of specular reflection with off-specular scattering and a pencil-shaped incoming beam for the set-up of complete reflectometry. In particular a good resolution along $Q_\perp$, which is the necessary base for the depth sensitivity of off-specular scattering and GISANS, is guarantied.
Magnetic GISANS measurements including the polarisation analysis of specular together with off-specular scattering following [13] is taken into account in the lay-out of the new horizontal reflectometer.

Magnetic and non magnetic GISANS implies, as already mentioned, a pencil-shaped collimation of the incident beam. A considerable decrease of the flux on the sample is the consequence. This decrease of flux will be counterbalanced by the application of angular encoding with Larmor precession. If the incoming scattering angle is encoded its angular divergence can be enlarged and thus flux on the sample is increased. A pilot experiment on the TOF-reflectometer REMUR (IBR-2) has been performed [14]. A second important application of Larmor precession is 3-dimensional analysis of magnetisation distribution in layered magnetic samples. In standard experiments the external magnetic field and the neutron magnetic moment are oriented parallel to the sample surface. From such experiment one gets information about the depth distribution of the mean value of in-plane magnetic moments. The off-specular magnetic scattering probes the magnetic fluctuations along the surface plane and gives information about their magnetisation state through spin-flip or non-spin flip scattering. However, a full 3-dimensional analysis is only obtained if the polarisation of incoming neutron can be adjusted with respect to the magnetisation directions in the sample. In reflectometry this effect can be obtained if the neutron performs Larmor precession with the plane of its magnetisation rotation perpendicular to the external field [15]. Like this missing matrix elements in the magnetic interactions are measured in an elegant way in TOF. For this purpose a weak magnetic Larmor-precession field around the sample position is contained in the lay-out of the new horizontal reflectometer.

References

[1] Heinrich, T., Ng, D. J., Vanderah, P., Shekhar, M., Mihailescu, H., Nanda, M., Loesche, Langmuir 25 (2009) 4219
[2] T. Gutberlet, B. Kloesgen, R. Krastev, R. Steits, Adv. Eng. Mater. 6 (2004) 832
[3] V. Lauter-Pasyuk, H. Lauter, G. Gordeev, P. Müller-Buschbaum, B. P. Toperverg, W. Petry, M. Jernenkov, A. Petrenko, V. Aksenov, Physica B 350 (2004) E939
[4] A. Vorobiev, J. Major, H. Dosch, G. Gordeev, D. Orlova, Phys. Rev. Lett. 93 (2004) 267203
[5] T. L. Kuhl, J. Majewski, J. Y. Wong, S. Steinberg, D. E. Leckband, J. N. Israelachvili, G. S. Smith, Biophys. J. 75 (1998) 2352
[6] V. L. Aksenov, K. N. Jernenkov, Yu. N. Khaidukov, Yu. V. Nikitenko, A. V. Petrenko, V. V. Proglyado, G. Andersson, R. Waeppling, Physica B 356 (2005) 9
[7] V. L. Aksenov, Yu. V. Nikitenko, A. V. Petrenko, V. M. Uzdin, Yu. N. Khaidukov, H. Zabel, Cryst. Rep. 52 (2007) 403
[8] V. F. Kozhevnikov, C. V. Giuraniuc, M. J. Van Bael, K. Temst, C. Van Haesendonck, T. M. Mishonov, T. Charlton, R. M. Dalgliesh, Yu. N. Khaidukov, Yu. V. Nikitenko, V. L. Aksenov, V. N. Gladilin, V. M. Fomin, J. T. Devreese, J. O. Indekeu, Phys. Rev. B 78 (2008) 012502
[9] R. Andersson, L. F. van Heijkamp, I. M. de Schepper, W. G. Bouwman, J. Appl. Cryst. 41 (2008) 868
[10] W. G. Bouwman, J. Plomp, V. O. de Haan, W. H. Kraan, Ad A. van Well, K. Habicht, T. Keller, M. T. Rekveldt, Nucl. Instrum. Methods 586 (2008) 9
[11] M. Jernenkov, S. Klimko, V. Lauter-Pasyuk, B. P. Toperverg, M. Milyaev, L. Romashev, V. Ustinov, H. Lauter, V. Aksenov, Nucl. Instrum. Methods 586 (2008) 116
[12] S. Kulikov, E. Shabalina, In Proc. of the 17th Meeting of the International Collaboration of Advanced Neutron Sources, Santa Fe, NM, USA, Apr. 24-29, 2005, Eds. G. J. Russel, J. J. Rhyne, B. V. Maes, Los-Alamos: LANL, 2006, Vol. 2, p. 341.
[13] Lauter-Pasyuk V., Lauter H., Jernenkov M., Toperverg B., In ILL Annual Report 2004, ILL, Grenoble, 2005.
[14] Lauter H., Toperverg B., Lauter-Pasyuk V., Petrenko A., Aksenov V., Physica B, 350 (2004) E759
[15] Lauter H., Lauter-Pasyuk V., Toperverg B., Romashev L., Milyaev M., Krinitsina T., Kravtsov E., Ustinov V., Petrenko A., Aksenov V., Journ. Mag. Mag. Mat., 258-259, 338-341, (2003)