CONRAD-2 - The neutron imaging instrument at HZB

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Introduction

The imaging facility at the BER II reactor was designed in 2004 and constructed in 2005 as an instrument supporting the materials research activities at the former HMI (department SF3). At that time, V7 (CONRAD-1) was situated at the neutron guide NL-1B (^{58}Ni-coated) with a characteristic wavelength of 2.2 Å. The space behind the neutron guide did not allow for a long collimation path since only 5 m of unoccupied space was available. Therefore, the beam size at the sample position was limited to 10 cm x 10 cm. This size is too small for many conventional imaging purposes and was a competitive disadvantage to other existing facilities worldwide. This was one of the reasons to concentrate on the development of novel methods which benefit from the cold neutron beam and the low background at the instrument. Significant development was performed to expand the radiographic and tomographic capabilities of the beamline [1]. New techniques were implemented, including imaging with polarized neutrons [2], Bragg-edge mapping, grating interferometry [3, 4] and high-resolution neutron imaging [5, 6]. These methods were provided to the user community as tools to help addressing scientific problems over a broad range of topics such as superconductivity, materials research, life sciences, cultural heritage and paleontology. Industrial applications including fuel cell research have also been fostered by these new developments that also helped to increase and improve the scientific output of the facility and to attract new users [7].

Upgrade

The upgrade program of CONRAD-1 (V7) from October 2010 to October 2012 included: i) an exchange of the ^{58}Ni-coated neutron guides (M=1.2) by new superrmiror guides (M=3 in the curved section and M=2 in the following straight section, see Fig. 1), ii) an increase of the collimation path from 5 m to 10 m and iii) provision of a more spacious experimental environment and user work places. The expected effects were to improve the efficiency of neutron transport and to increase the beam size due to the larger beam divergence and longer collimation path. Additionally, the curvature of the guide was increased in order to enlarge the distance from the shielding of the neighboring instrument.

Following a commissioning period with neutron supply from August 2012, V7 (after the upgrade named CONRAD-2) has been back to full user operation since October 2012 and the first user experiments have been successfully completed.

The expected intensity gain has been confirmed to be a factor of 10 at the end of the guide (at the pinhole position) and a factor of 2.4 at the sample position (at a distance 10 m from the pinhole at a defined L/D ratio). The obtained beam size now allows for investigating samples up to 30 cm x 30 cm directly (without scanning the sample, which allows for going up to 50 cm x 50 cm). This corresponds to a gain of 4 in comparison to the previous configuration. The new methods such as energy-selective imaging and grating interferometry will benefit from the increased neutron flux and better beam collimation as well.

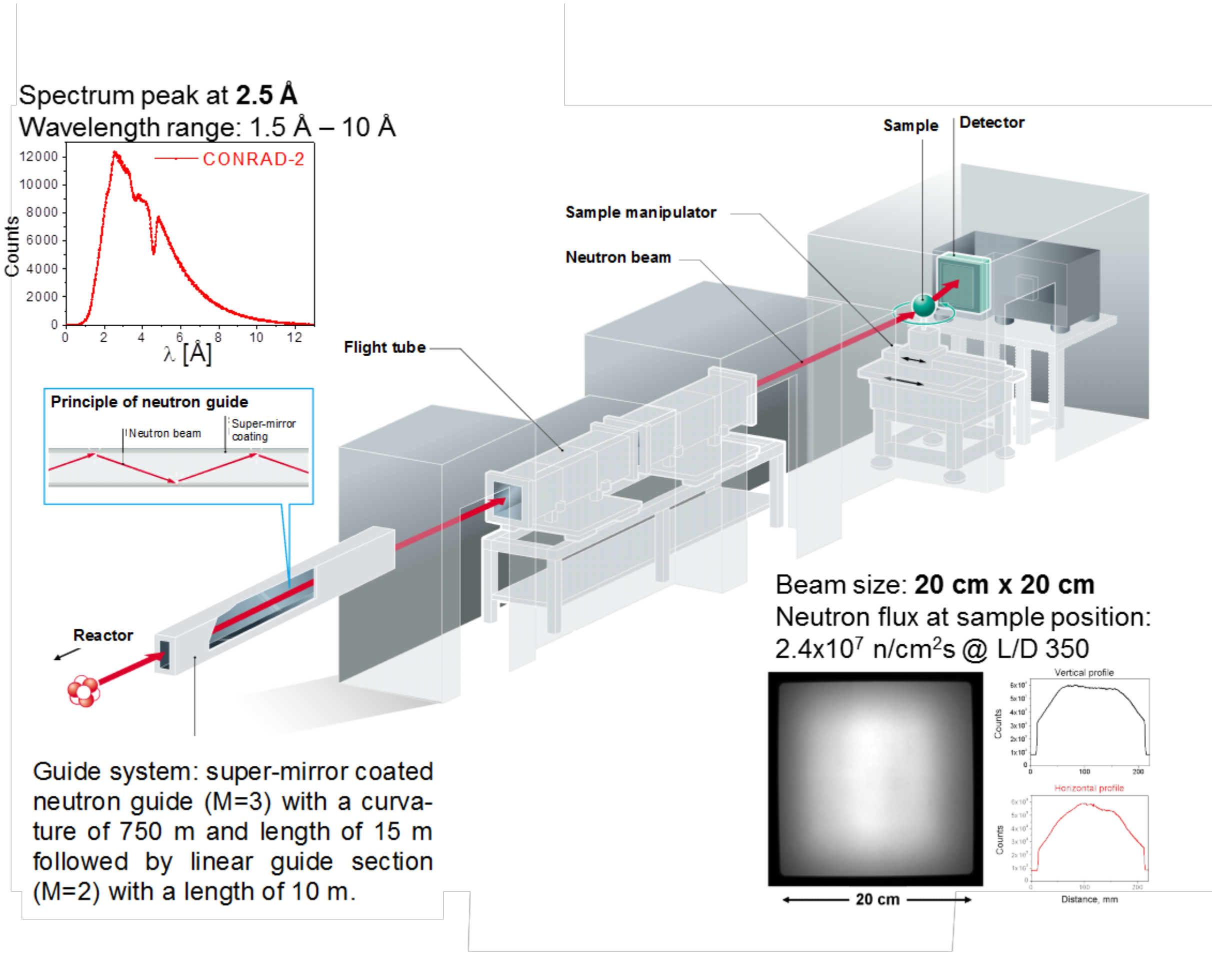

Fig.1 CONRAD-2 instrument layout

Scientific Case

V7 (CONRAD-1) has widely been recognized as a versatile and flexible instrument for innovative neutron imaging and has made decisive contributions to the development of new methods by exploiting different contrast mechanisms for imaging. The reason for the success in method development is the flexibility of the facility which permits very fast change of the instrument's configuration and allows for performing non-standard experiments.

CONRAD-2 is well suited for absorption contrast radiography and tomography used frequently in industrial applications but also for energy-selective measurements due to the double-crystal monochromator and velocity selector installed. Solid-state polarizers are used for imaging with polarized neutrons. Phase grating setups can be used for grating interferometry experiments where phase contrast and dark-field imaging is used to obtain spatially resolved information about the microstructure of the materials in question or about their magnetic properties. The instrument is equipped with a prototype of a high-resolution detector, which can provide images of samples with a pixel size down to 6.4 µm (1 µm will be feasible in the future) at reasonable exposure times.

A. Absorption contrast imaging: There is a broad spectrum of applications based on the most direct imaging mode.

   Fuel cell research: Investigations, especially in-situ, of the water distribution in operating low-temperature fuel cells are amongst the most important applications of neutron imaging due to the numerous scientific questions that can be addressed. The ability of the neutron beam to easily transmit thick layers of metal on the one hand while, on the other, neutron absorption is very sensitive to hydrogenous substances, e.g. water, helps to visualize very small amounts (min. 10 µm thickness) of water. In image sequences with repetition rates of 6 to 30 frames per minute, the dynamics of water transfer has been visualized in single and multiple fuel cell stacks. Tomographic investigations of such stacks have been performed in which the water distribution was resolved three-dimensionally [7], Fig. 2a.

   Plants: Water transport in plants is one of the most important factors for life, since it is a fundamental necessity for photosynthesis. Neutron radiography using D_2O as a tracer is an outstanding method to visualize water movement in small plants from the root system, through the stem and out to leaves and blossoms. In this way, parameters such as the rate of water uptake and the reaction to toxic atmosphere or soil conditions has been investigated.

   Archeology, paleontology and geology: Neutron imaging has found use in the investigations of fossils, and for the study of archeological artifacts. The ability of neutron radiation to penetrate thick layers of metal and stone makes neutron tomography a unique tool for investigations of a broad range of samples, ranging from metal such as historical weapons or jewelry to fossils and geological samples.

   Energy-selective imaging: The double crystal setup can be used to measure residual stresses in metallic samples. The device allows one to tune the neutron wavelength between 1.5 Å and 6.0 Å continuously with a wavelength resolution of approximately 3%. Areas of applications are residual stress accumulation and annealing, analysis of fatigue, optimization of welding techniques (e.g. friction stir welding) and various industrial inspection procedures. The energy-selective method can be applied successfully to material phase separation by choosing the neutron wavelength to be between the Bragg edges of the two material phases (e.g. γ– and α–ferrite). A combination of this technique with tomography allows for a volumetric phase separation in heterogeneous materials. For experiments which require coarse wavelength resolution (e.g. between 10 % and 30 %) a velocity selector with a wavelength band from 3 Å to 6 Å is available.

B. Beyond absorption contrast, various scientifically promising fields have emerged:

   Imaging with polarized neutrons: Magnetic imaging has some tantalizing prospects for future studies of magnetic phenomena throughout science and technology: the establishment and trapping of magnetic flux in superconductors below the critical temperature, the skin effect in conductors or magnetic domain distributions in bulk ferromagnets [2]. In some cases, the method can also be extended to three dimensions in analogy to standard tomography. To achieve this, the development of advanced algorithms for tomographic reconstruction of complex vector magnetic fields is under development.

Grating interferometry can be used to characterize heterogeneities on the scale of 0.1 µm to 10 µm. Refraction at the magnetic domain walls can be used to visualize magnetic domains [4]. Using tomographic reconstruction [3], the 3D domain network can be analyzed and studied under different external conditions, e.g. varying magnetic fields, Fig. 2b.

High-resolution imaging: Application areas are innovative microcellular materials such as metal and polyester foam structures, porous materials such as 'membrane electrode assemblies' (MEA) or gas diffusion layers, the latter two being crucial components of fuel cells. Borated steels and borated aluminum foams as well as wood are additional candidates for high-resolution neutron imaging [6]. The high penetration depth of a neutron beam in metals combined with high-resolution imaging will enable to trace crack initiation in welded materials or during fatigue testing. Example of high resolution neutron tomography of $LiCoO_2$ battery is presented in Fig. 2c.

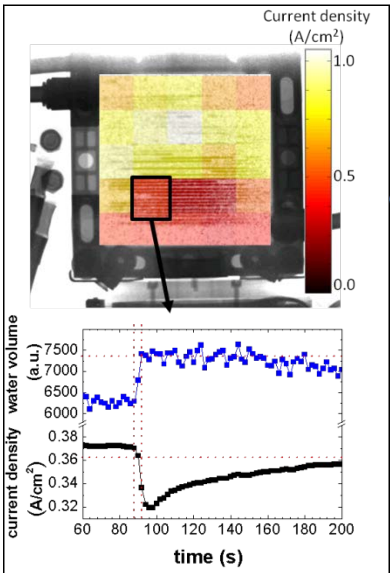

Fig. 2a Correlation between neutron radiography (top) and current density measurement (bottom) in operated PEM fuel cell [7].

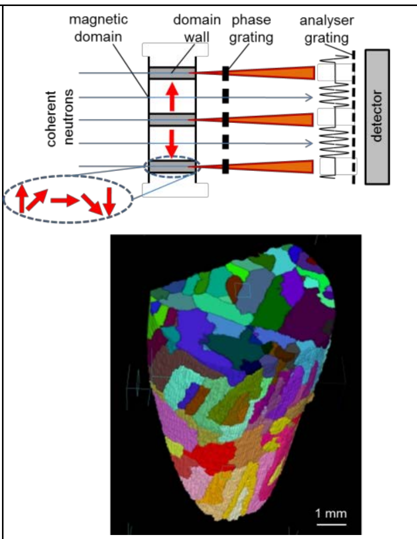

Fig. 2b Multiple refractions at the domain walls are detected by Talbot-Lau type grating interferometry (top). Magnetic domain structure in FeSi single crystal can be visualized in 3D (bottom) [4].

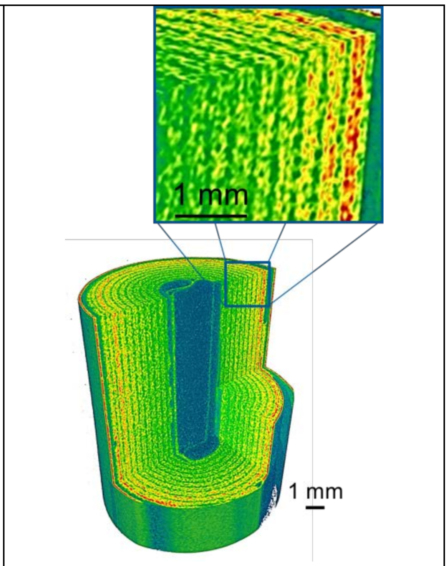

Fig. 2c Virtual cut through 3D data of a $LiCoO_2$ battery. The high-resolution neutron tomography (pixel size 6.4 µm) [6] provides information about the distribution of highly absorbing Li in the battery.

Prospects:

In future, CONRAD-2 (V7) has to face the following facts:

(1) The increase of spatial resolution is a major trend in imaging in general and also in neutron imaging [5, 6]. The beam characteristics of the upgraded CONRAD-2 allow for achieving this goal. The ongoing detector development at the facility already provided promising results [6] and the continuation of this activity is important for the instrument as well as for the neutron imaging community.

(2) The new method developments performed recently, i.e. imaging with polarized neutrons [2], grating interferometry [3, 4], Bragg-edge mapping, have already shown their potential and are already being implemented at other facilities. The next important step is to identify scientific and industrial problems to which these methods can be applied in a sense that they provide unique results not obtainable from other experimental methods.

(3) The trend towards time-of-flight imaging is important in relation to projects for constructing imaging beam lines at the new neutron spallation sources (ESS, SNS, J-PARC and ISIS). In addition to this trend, the strength of energy-selective imaging at continuous sources will be emphasized. The stable beam, the better signal-to-noise ratio and the easier data treatment provide good arguments for further development of this method at continuous neutron sources.

(4) Many imaging facilities from developing countries have been upgraded recently by an installation of digital detector systems. The role of advanced facilities like CONRAD-2 in this situation should be to provide the opportunity for training and education of young researchers. Additionally the facility should play a role also in the establishment of standardization procedures in the neutron imaging community.

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