Comparison of Polarizers for Neutron Radiography

M. Schulz¹,², P. Böni¹, C. Franz¹, A. Neubauer¹, E. Calzada², M. Mühlbauer¹,², B. Schillinger¹,², C. Pfeiderer¹, A. Hilger³, N. Kardjilov³
¹Technische Universität München, Physik Department, E21, Garching, Germany
²Technische Universität München, Forschungsneutronenquelle Heinz Maier Leibnitz (FRM II), Garching, Germany
³Helmholtz Zentrum Berlin, Berlin, Germany
E-mail: michael.schulz@frm2.tum.de

Abstract. Imaging with polarized neutrons is a new method to measure the spatially resolved magnetisation. It is based on the interaction of a polarized neutron beam with magnetic fields. In this paper we present an overview of different polarizing techniques and their application for neutron imaging. The performance of various setups is discussed. It is demonstrated that radiography with polarized neutrons may evolve into an important technique for determining the homogeneity of ferromagnetic samples.

1. Introduction
In conventional neutron radiography the attenuation of the intensity of a neutron beam transmitted through a sample is measured. By means of longitudinal polarization analysis the contrast obtained in neutron imaging for ferromagnetic samples may be varied by making use of the interaction between the nuclear magnetic moment \(\mu\) of the neutron and a magnetic field inside and/or around the sample. In particular, the depolarization of the neutron beam may be used to map out variations of the ferromagnetic properties and their dependence on external parameters such as stress, pressure, magnetic field or temperature as well as internal characteristics such as chemical composition, defects and stress. In fact, for sufficient resolution it may even become possible to determine the domain distribution inside samples [1].

Imaging with polarized neutrons is a new field of great current interest. Various techniques have been developed such as phase contrast imaging as well as the depolarization of a neutron beam on transmission through ferromagnetic samples [2–4]. In a series of exploratory first studies, conventional polarizing equipment for neutron scattering was used. In the following we compare various concepts for imaging with polarized neutrons paying special attention to the two major technical requirements: (i) how to maintain high spatial resolution, and (ii) to how to illuminate the sample homogeneously while maintaining a high beam polarization.

2. Experimental Technique
Neutron radiography is traditionally performed with a pinhole setup, where the resolution is determined by a beam collimation given as the ratio \(L/D\) of the distance \(L\) between pinhole and sample and the diameter \(D\) of a circular pinhole [5]. Typical \(L/D\)-ratios range from 300 to 1000 [6–8], where the collimation improves as the ratio increases. Together with the distance
Figure 1. Various setups for neutron imaging with polarized neutrons. The setups (a) and (b) involving $^3$He filters and setup (c) using solid state benders have been used at the ANTARES (FRM II) and CONRAD (HZB) beam lines, respectively.

$d_{SD}$ between sample and detector (SDD) the ratio $L/D$ determines the maximum geometrical resolution possible, given as $r = d_{SD}/(L/D)$. Clearly, as a prerequisite for radiography with polarized neutrons the equipment used must not degrade the $L/D$-ratio or $d_{SD}$. We have therefore tested various combinations of conventional polarizers and analyzers as shown in Fig. 1 to determine the ideal conditions, without special efforts to adapt these techniques to the special requirements of the pinhole setup used in radiography. In the following we compare the properties of these setups for neutron imaging as tested on various topical materials.

The basic setup used for all measurements consisted of a neutron polarizer, followed by a spin flipper, a polarization analyzer, and a position sensitive CCD detector that records the image of a neutron sensitive scintillator, which is placed behind the analyzer. The sample was attached to a GF-coldhead with a base temperature of 5 K. The depolarization of the transmitted neutrons was measured for various inhomogeneous, ferromagnetic samples. The measurements using a $^3$He spin filter were carried out at the ANTARES beam line at FRM II, Munich, and those with solid state benders were made at the CONRAD beam line at HZB, Berlin.

3. Results
Fig. 2 shows typical data of the spatially resolved beam polarization for different samples as measured with the setups depicted in Fig. 1. White areas indicate areas of high polarization, i.e., parts of the sample with unchanged polarization. Black areas designate maximum depolarization. It is immediately evident that the depolarization of the beam for the samples studied is highly inhomogeneous.

Using $^3$He as a polarizer has the advantage of leaving the beam collimation as well as the beam homogeneity unaffected, making it ideally suited for neutron imaging. However, the bulky magnetostatic box needed to create a homogeneous field surrounding the $^3$He cells leads to a large $d_{SD}$. Therefore, the spatial resolution is seriously reduced. To improve the setup, the non-magnetic scintillator can be placed inside the box directly after the $^3$He cell. This decreases...
Figure 2. a) – c) Images of the beam polarization after transmission of ferromagnetic samples taken with the setups (a) through (c) shown in Fig. 1. The differences in image quality for the different methods are clearly visible. The samples are: (a) a Fe alloy, (b) a Ni alloy and (c) a Pd alloy; (d) intensity code for the polarization shown in the images.

d_{SD} in our case to $\approx 30$ cm.

At FRM II, the $^3$He gas is polarized at low pressure using the optical pumping facility HELIOS [9, 10] and filled into pyrex cells. These cells are transported to the beam line and installed in the magnetostatic boxes. Because of inhomogeneities of the magnetic field and collision with the wall the polarization of the $^3$He gas relaxes, leading to a decrease of the polarization of the neutrons. Therefore, a regular exchange of the $^3$He cells is required. Using $^3$He as a polarizer and analyzer (see Fig. 1a) leads to a complicated time dependence of the polarization, which can in principle be corrected. Moreover, the transmission of the cells is also time-dependent. Currently, at the beam line ANTARES at FRM II the gas has to be exchanged every 24 hours. For typical applications one generally maximizes the term $P^2T$, which yields a beam polarization $P$ of up to 80% and a transmission $T$ of $\approx 50\%$ for $3\,\text{He}$.

For most recent experiments, a RF spin flipper was integrated into the magnetostatic box that allowed to select the polarization of the cell thus allowing to use a broad wavelength band of neutrons, yielding a high neutron flux. For the polychromatic measurements, a Be-filter was inserted to remove neutrons with a wavelength $\lambda < 4\,\text{Å}$ [11]. This way, the polarization of the neutrons could be improved, i.e. for a $^3$He polarization of 70%, a flipping ratio of 7 was obtained. The image shown in Fig. 2(a) has been obtained using this setup yielding a resolution of $\approx 0.4\,\text{mm}$. Of course, for a quantitative determination of the field integral as described in [2, 3], a polychromatic beam cannot be used. By reducing the size of the magnetostatic box, the resolution could be improved further.

For the setup using a standard bender[12] as standard polarizer as shown Fig. 1(b) a poor spatial resolution is observed in the reflection plane, because the bender increases the beam divergence. Moreover, the beam becomes inhomogeneous. These effects show up due to the curved channels. Hence, the images are smeared in the horizontal direction. With $d_{SD} \approx 30$ cm, which was required by the $^3$He analyzer, no satisfactory images could be obtained (see Fig. 2(b)), i.e., the sample was completely smeared out in the horizontal direction. Even with a shorter $d_{SD}$, the image would still be severely blurred. A more favorable position for the bender would be to place it closely behind or before the pinhole. Such a setup was not feasible at the ANTARES beam line due to the geometrical constraints mentioned above. The divergence of the beam will still be increased but the bender acts as a pinhole source itself, thereby defining the collimation of the beam.

The length of a bender can be significantly reduced by using thin Si wafers coated with a
polarizing supermirror. The neutrons are guided through the Si. A setup using two solid state benders was investigated at the radiography facility CONRAD at HZB, Berlin (see Fig. 1c). The performance of the polarizers has been evaluated as described in [13]. A high beam polarization of $\approx 95\%$ was achieved, however, the beam profile was inhomogeneous exhibiting a pronounced stripe structure caused by the wafers of the benders. Because these stripes are fixed for fixed detector and polarizer position, they cancel when the polarization is evaluated from the raw images. For the benders used in this experiment, the wafer thickness was $250 \mu m$ and the length was $\approx 80 \text{mm}$, yielding a resolution of $\approx 0.5 \text{mm}$ [2] (see Fig. 2(c). The resolution can be improved by using thinner Si wafers, which would also allow to build a shorter polarizer, i.e. $d_{SD}$ can be decreased too. Of course, the optimum position of a solid state polarizer would be in front of the pinhole of the beam line.

4. Conclusions and Outlook

The results of our experiments demonstrate that the combination of two $^3\text{He}$ cells, where the scintillator is placed directly behind the analyzer cell inside the magnetostatic box (see Fig. 1a) yields a resolution of $\approx 0.4 \text{mm}$, which is the highest resolution of the setups tested.

Our results indicate that the highest resolution may be obtained if a $^3\text{He}$ spin filter as a polarizer is combined with an optimized solid state bender as an analyzer, if the setup has to be installed close to the sample area of an existing beam line for radiography. In this case the polarizer would not affect the beam collimation and homogeneity at all and also the size of the magnetostatic box would not be crucial for this application. A solid state bender analyzer could be manufactured with a Si wafer thickness of $100 \mu m$ leading to an overall length of the analyzer of only $\approx 5 \text{cm}$. At a collimation of $L/D = 800$ as available at FRM II, Munich this would result in a geometrical blurring of $< 100 \mu m$ in the vertical direction and $100 \mu m$ in the horizontal direction. This would be a great step towards high resolution imaging with polarized neutrons.

If a dedicated beam line for polarized neutron imaging were to be built, the polarizer should be installed before or shortly after the pinhole. This setup would relax the restriction for the polarizer to conserve the beam collimation and thus would largely increase the choice of polarizing devices. Moreover, the background would be reduced significantly.

Acknowledgments

Financial support through DFG Forschergruppe FOR 960 on quantum phase transitions is gratefully acknowledged. We also wish to thank the staff of FRM II and HZB for their support.

References

[1] Badurek G, Hochhold M and Leeb H 1997 Physica B: Physics of Condensed Matter 234 1171–1173
[2] Kardjilov N, Manke I, Strobl M, Hilger A, Treimer W, Meissner M, Krist T and Banhart J 2008 Nature Physics 4 399
[3] Piegsa F, van den Brandt B, Hautle P, Kohlbrecher J and Konter J 2009 Physical Review Letters 102 145501
[4] Schulz M 2009 Nuclear Inst. and Methods in Physics Research, A in press
[5] Schillinger B 1996 Journal of Neutron Research 4 57–63
[6] Grünauer F, Schillinger B and Steichele E 2004 Applied Radiation and Isotopes 61 479–485
[7] Hilger A, Kardjilov N, Strobl M, Treimer W and Banhart J 2006 Physica B: Physics of Condensed Matter 385 1213–1215
[8] Materna T, Baechler S, Jolie J, Masschaele B, Dierick M and Kardjilov N 2004 Nuclear Inst. and Methods in Physics Research, A 525 69–73
[9] Hutanu V, Masalovich S, Meven M, Lykhvar O, Borchert G and Heger G 2007 Neutron News 18 14 – 16
[10] Andersen K, Chung R, Guillard V, Humblot H, Jullien D, Lelièvre-Berna E, Petoukhov A and Tasset F 2005 Physica B: Physics of Condensed Matter 356 103–108
[11] Lorenz K 2007 Proceedings of the 8th World Conference on Neutron Radiography in press
[12] Schaerpf O 1989 Physica B: Condensed Matter 156-157 639 – 646 ISSN 0921-4526
[13] Krist T, Kennedy S, Hicks T and Mezei F 1997 Physica B: Physics of Condensed Matter 241 82–85