Polarized Neutron Radiography with a Periscope

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Abstract. The interaction of the magnetic moment of the neutron with magnetic fields provides a powerful probe for spatially resolved magnetisation measurements in magnetic materials. We have tested a periscope as a new type of polarizer providing neutron beams with a high polarization and a low divergence. The observed inhomogeneity of the beam caused by the waviness of the glass substrates was quantified by means of Monte-Carlo simulations using the software package McStas. The results show that beams of high homogeneity can be produced if the waviness is reduced to below $1 \cdot 10^{-5}$ rad. Finally, it is shown that radiography with polarized neutrons is a powerful method for measuring the spatially resolved magnetisation in optically float-zoned samples of the weak itinerant ferromagnet Ni$_3$Al, thereby aiding the identification of the appropriate growth parameters.

1. Introduction
Radiography and tomography with polarized neutrons is increasingly being recognized as a powerful method in the investigation of magnetic field distributions. For instance, in a technical context it may be used to map out the field distribution across complex solenoids [1]. Further, in real materials it may be used to probe directly internal magnetic fields arising from, e.g., superconducting vortices [1], variations in thin magnetic films [2] and inhomogeneous ferromagnets [3]. In particular, the depolarization of the neutron beam may be used to map out variations of ferromagnetic properties as a function of external parameters such as stress, pressure, applied magnetic and electric field or temperature as well as internal characteristics such as chemical composition, defects and stress. In fact, for sufficiently high resolution it may even become possible to determine the properties of magnetic domains inside bulk samples [4].

Depolarization radiography is based on the measurement of the beam polarization transmitted through a sample as determined with a longitudinal polarization analysis setup. Here, the contrast obtained in neutron imaging of magnetic field distributions may result from their interaction with the nuclear magnetic moment $\mu$ of the neutron. An important prerequisite for neutron imaging are polarizers providing high polarization while not affecting the beam collimation and a giving high spatial homogeneity.

In this paper we propose a new type of polarizer for neutron imaging based on the principle of an optical periscope (cf. Ref. [5]). The neutron periscope is composed of two parallel polarizing neutron supermirrors giving rise to a zig-zag reflection of the neutron beam (see Fig. 1), yielding a theoretical beam polarization of 99% and ideally conserving the beam collimation, thus allowing for high spatial resolution [6]. Furthermore most of the gamma and fast neutron contamination
of the neutron beam emerging from the moderator is stopped by interrupting the direct line of sight with shielding material. This helps to improve greatly the S/N ratio by reducing the background. As a disadvantage strong stripe artifacts with variations in intensity are observed in the images acquired with the periscope. In this paper, the origin of these artifacts is discussed and quantified. It is shown that glass substrates with a waviness $\eta < 1.0 \cdot 10^{-5}$ rad will provide homogeneous beams suitable for polarized neutron radiography. As a test case we have measured a sample of Ni$_3$Al after optical float-zoning to demonstrate, that concentration fluctuations in this compound originate in the peritectic properties of this compound.

2. Experiments
The measurements described in this paper have been performed at the ANTARES beam line at FRM II, Munich. The setup consists of a periscope polarizer, followed by a spin flipper, a $^3$He polarization analyzer, and a position sensitive CCD detector that records the image of a neutron sensitive scintillator, which is placed behind the analyzer as shown in Fig. 1. Due to geometrical constraints the periscope could only be installed close to the sample position, which restricted the beam to an area of approximately 17.5 × 40 mm. The polarization was determined by measuring the intensity of the transmitted neutron beam for neutrons with spin up and spin down. The periscope was assembled from four polarizing FeSi, $m = 3.88$ supermirrors of the size 500 × 40 × 2 mm each. Two mirrors were concatenated on each side of the setup with an inclination angle of 1° with respect to the incoming beam.

Images without a sample in the beam (open beam images) were acquired for $\lambda = 3.2$ Å with the detector approximately 1 m behind the exit of the periscope. These images show a pronounced stripe structure with strong variations in intensity (see Fig. 2a). Of course these stripes cancel, when the polarization is evaluated from the raw images as shown in Fig. 2c for a Ni$_3$Al sample. However, a large statistical error in the calculated polarization is observed in areas of low counting statistics.

For further measurements polycrystalline rods of Ni$_3$Al, a weakly ferromagnetic itinerant-electron compound with a nominal Curie temperature $T_C \approx 40$ K [7], were prepared in a bespoke rod casting facility using a water-cooled Cu crucible. The polycrystalline rods were subsequently optically float zoned to attempt growth of a large single crystal. While several large single crystal grains formed none of them dominated the resulting rod. The Ni$_3$Al sample was attached to a GF-coldhead with a base temperature of 5 K. In several depolarization radiography measurements we established that the polycrystalline rods displayed highly homogenous ferromagnetic properties, while the float-zoned rod exhibited substantial variations.

3. Simulations
To prove that the stripe structure observed in our measurements arises from the waviness of the supermirrors used in the periscope, a model of the polarizer was simulated with the Monte Carlo simulation software McStas [8]. The instrument was simulated as follows: The neutrons with a wavelength of $\lambda = 3.2 \pm 0.05$ Å emerge from a pinhole with a diameter of 2 cm at a distance 4.3 m away from the source and follow a flight path of 13.8 m from the pinhole to the entrance of the periscope. For the periscope, non-polarizing supermirrors with $m = 3.88$ were considered, since the polarization is not of importance for the stripe structure. The waviness of the mirrors on one side of the periscope was approximated by a profile composed of two triangles with a base angle of $2 \cdot 10^{-4}$ rad. This angle corresponds to the typical waviness of standard supermirrors on glass substrates. In a second simulation, a waviness $\eta = 2 \cdot 10^{-5}$ rad was used to assess the effect of using glass of higher surface quality (i.e., polished borkron glass, which has optical quality). The intensity observed at the position sensitive detector at the exit of the periscope for both simulations is shown in Fig 2b.
Figure 1. The setup used for the measurements described in this paper consists of a periscope polarizer and a $^3$He analyzer. By placing shielding material behind the upper reflecting mirror, the direct line of sight to the moderator can be interrupted.

Figure 2. a) Open beam image acquired with the periscope. A pronounced stripe structure is observed, b) Results of the simulations for a waviness $\eta = 2 \cdot 10^{-4} \text{rad} \ (\text{left})$ and $2 \cdot 10^{-5} \text{rad} \ (\text{right})$. c) Polarization of the beam transmitted through inhomogeneous Ni$_3$Al as evaluated from the raw images. The stripe structure vanishes, however strong statistical variations are observed. All images show the entire height of the beam of $\approx 40 \text{mm}$.

4. Results and Discussion

The simulations shown in Fig. 2b yield a stripe structure that is in good qualitative agreement with the data shown in Fig. 2a. Intensity variations of a factor of $\approx 4$ are observed for a waviness $\eta = 2 \cdot 10^{-4} \text{rad}$. Each of the triangles that was used for approximating the profile reproduces a sequence of regions with high and low intensity. If the frequency of the ondulations of the profile is increased, the number of stripes increases as well. Actually, the wavelength $\Lambda$ of the ondulations of the profile is determined by the length $L$ of the substrates. Typically, it turns out that $L/\Lambda = 0.5$ or 1. By pushing the mirrors against a flat support structure, it should be possible to reduce $\eta$ to $2 \cdot 10^{-5} \text{rad}$ leading to intensity variations of $\approx 25\%$, which is tolerable for neutron radiography. Using polished borkron glass, $\eta$ can be reduced even to below $1 \cdot 10^{-5} \text{rad}$, providing very homogeneous beams.

We tested the feasibility of a periscope for depolarization radiography in a study of the itinerant-electron ferromagnet Ni$_3$Al. This compound has recently attracted great interest as a possible candidate exhibiting a ferromagnetic quantum critical point, i.e., a second order ferromagnetic to paramagnetic transition at zero temperature driven by quantum fluctuations [9]. However, for an unambiguous identification of a QCP high quality (homogenous)
single crystals are essential. In our attempts to use optical float-zoning for the growth of large single crystals we observed the emergence of layers of depolarization normal to the growth direction. This suggests oscillations of the composition along the growth direction as expected of crystallization close to a peritectic point (interestingly the data do not suffer from the vertical waviness introduced by the supermirrors). However, there is conflicting information on the precise location of a peritectic point in the metallurgical phase diagram of Ni$_3$Al (some reports place it at the Ni-rich and others at the Ni-poor side of the stoichiometric composition [10]). To resolve this issue and determine the ideal growth conditions a comprehensive series of optical float zoning tests with starting rods of varying composition are needed. Clearly depolarization radiography thereby will prove instrumental as a tool to eventually obtain large single crystals.

5. Conclusion and Outlook
We have shown that a periscope assembled from optically flat borkron glass and coated with polarizing supermirror $m \approx 4$ provides a homogeneous beam with high polarization of the order of 99%. Ideally, the periscope is placed directly before or after the pinhole which – together with the length of the flight path – defines the resolution of the primary beam line via the $L/D$ ratio [3]. The proposed setup yields a large illuminated area at the sample position. Moreover, the background for radiography is markedly reduced. If a short solid state polarizer between sample and detector is introduced, radiography can be performed with high spatial resolution. The experiment on Ni$_3$Al demonstrates, that polarized neutron radiography yields important information on the magnetisation density in inhomogeneous samples, which is of utmost importance for a proper understanding of samples that show a strong dependence of i) the Curie temperature on the composition or ii) phase separation. One may consider a radiography setup with polarized neutrons as a spatially resolved magnetometer that provides magnetic parameters very efficiently. In turn, the results from radiography will help to improve the growth techniques for crystals.

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 SwissNeutronics for providing the polarizing supermirrors.

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