Ernst Ruska-Centrum für Mikroskopie und Spektroskopie mit Elektronen ER-C

JÜLICH FORSCHUNGSZENTRUM

Towards electron holographic tomography of three-dimensional magnetization distributions in ferromagnetic nanotubes

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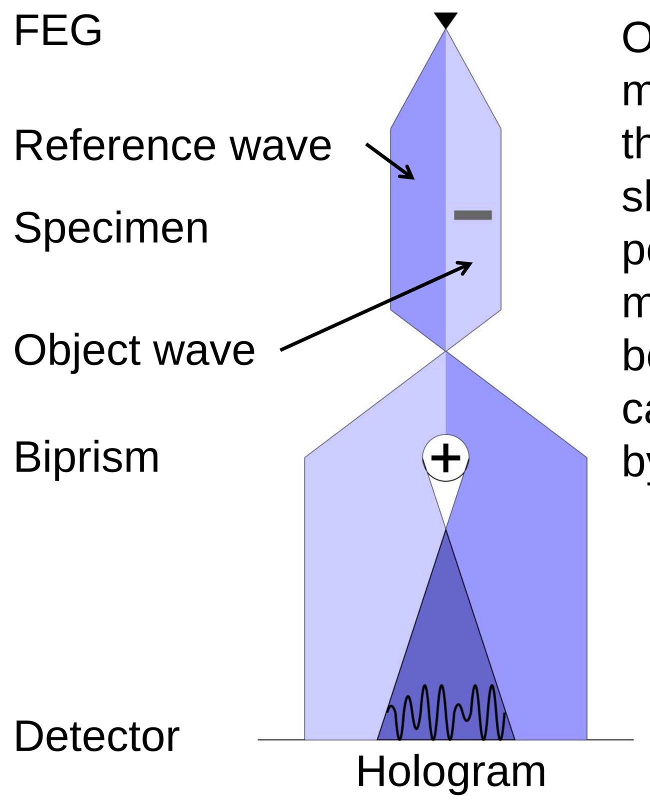
Introduction

The development of an experimental technique that allows the three-dimensional (3D) magnetisation distribution inside a nanoscale object to be measured quantitatively is of great importance for fundamental and applied research in nanomagnetism. Off-axis electron holography is a powerful technique for the study of magnetic fields in materials in the transmission electron microscope (TEM) [1, 2]. Here, we demonstrate the acquisition of tilt series of electron holographic magnetic induction maps of a CoFeB nanotube, as input for a model-based algorithm that can be used to reconstruct its 3D magnetisation distribution with nm spatial resolution.

Off-axis electron holography

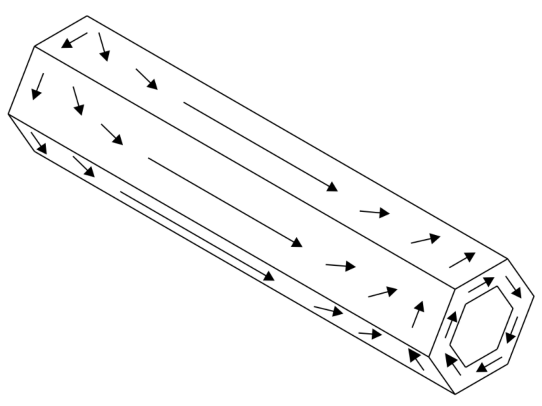


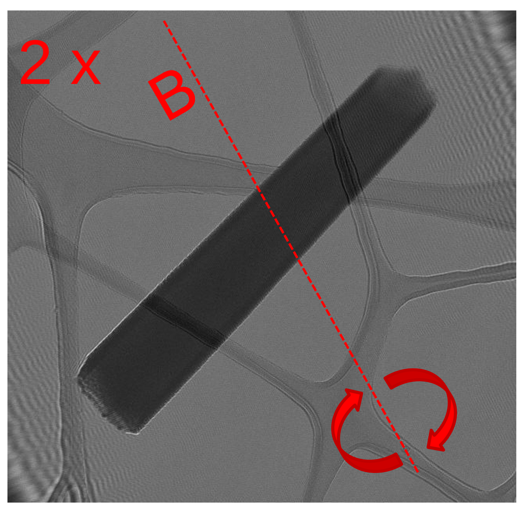
Off-axis electron holography can be used to measure the phase shift of the electron wave that has passed through a specimen. The phase shift is, in turn, sensitive to the electrostatic potential and the in-plane components of the magnetic flux density, projected in the electron beam direction. The electrostatic contribution can be removed by turning the sample over or by reversing its magnetisation.

$$\varphi(x) = \underbrace{C_E \int V(x,z)dz}_{\text{electrostatic contribution}} - \underbrace{\left(\frac{e}{\hbar}\right)\int\int B_\perp(x,z)dxdz}_{\text{magnetic contribution}}$$

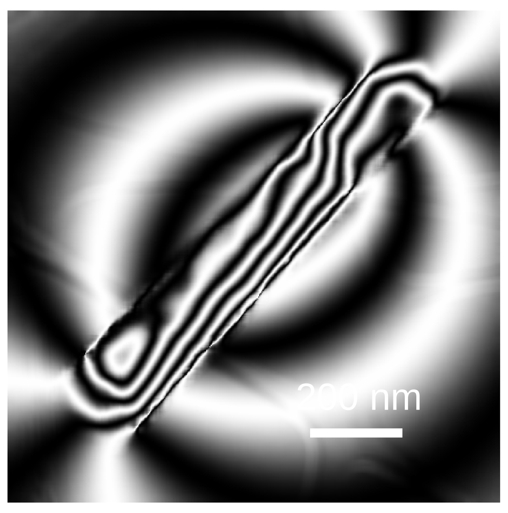
Magnetic nanotube

We studied a ferromagnetic nanotube of CoFeB deposited around a GaAs nanowire, in which theoretical predictions suggest that magnetic vortices with opposite chirality may form close to its ends [3].





Acquisition of two holograms with reversed magnetisation



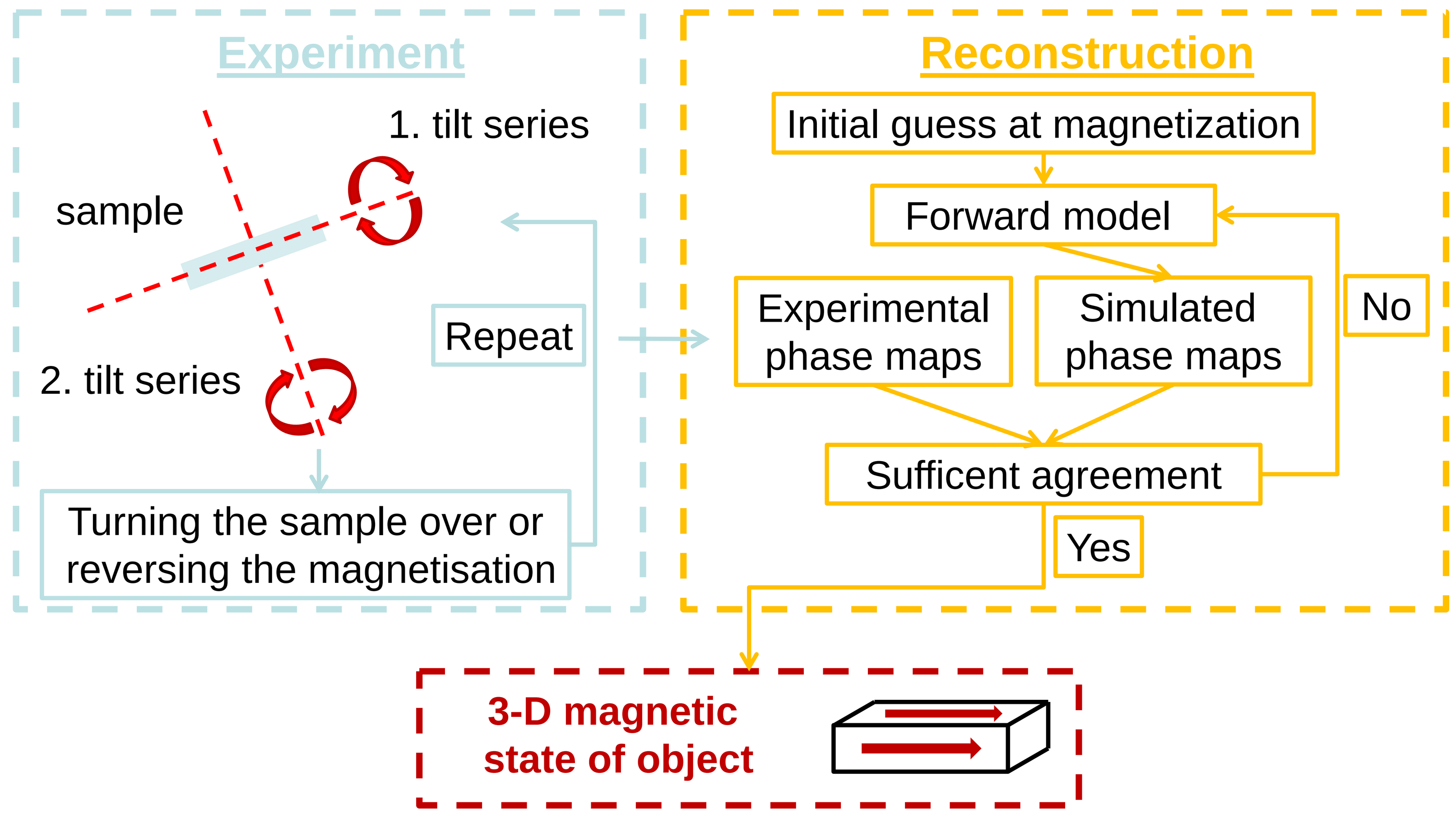
Magnetic induction map

Off-axis electron holograms of an individual ferromagnetic CoFeB nanotube were recorded at 300 kV in magnetic-field-free conditions using a Gatan K2 camera. The electrostatic (mean inner potential) contribution to the phase was removed by reversing the magnetisation direction in the specimen at each specimen tilt angle.

Preliminary analysis of the magnetic phase contours close to the ends of the nanotube suggests that the magnetization does indeed tilt away from its axis, forming vortices of opposite chirality close to its ends.

[1] P. A. Midgley and R.E. Dunin-Borkowski; Nat. Mater. **8** (2009), 271.
[2] M. Lehmann and H. Lichte; Microsc. Microanal. **8** (2002), 447.
[3] P. Landeros, O.J. Suarez, A. Cuchillo and P. Vargas; Phys. Rev. B **79** (2009), 24404.

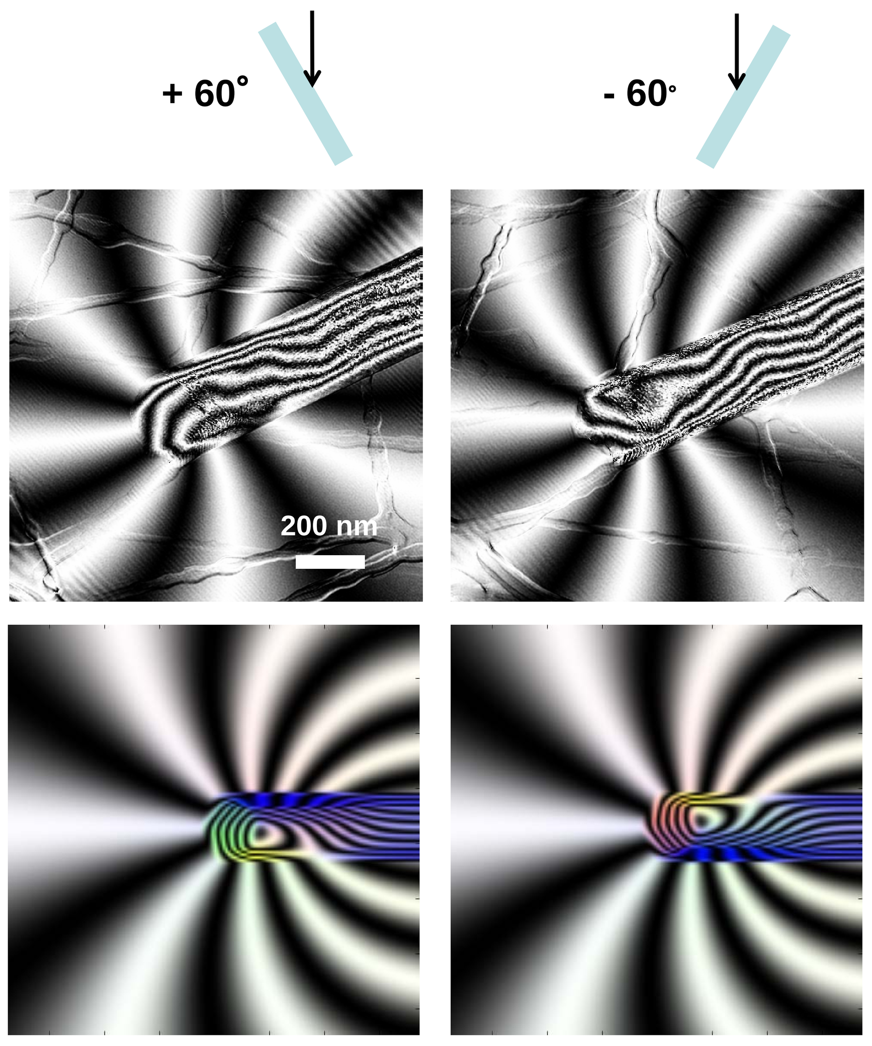
Reconstruction process



Experimental tilt series

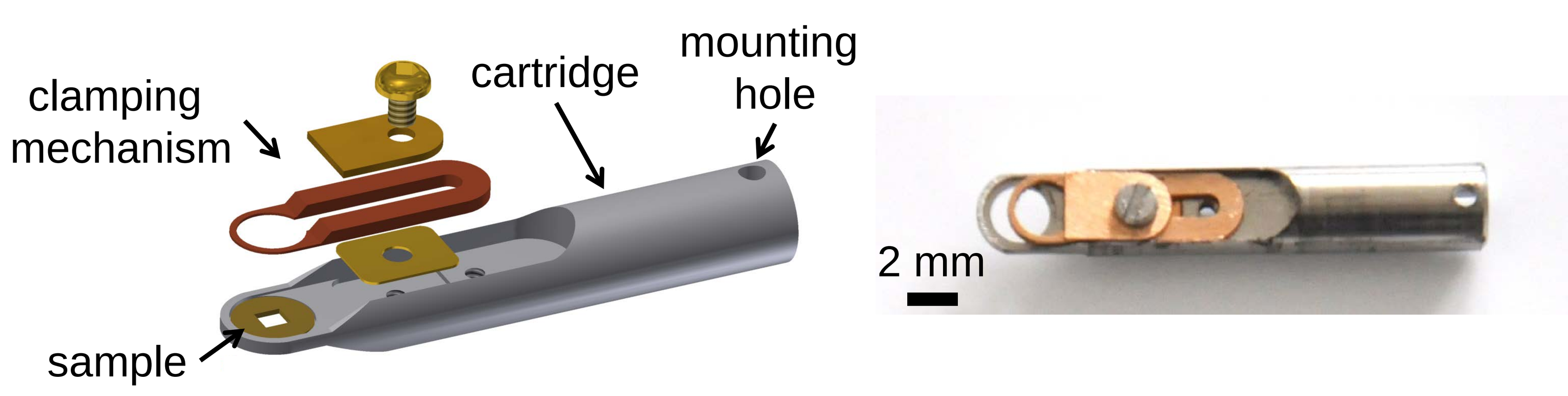
The upper row shows magnetic induction maps of the end of a CoFeB nanotube recorded at specimen tilt angles of +60° and -60°. The phase contour spacing is π radians.

The lower row shows magnetic induction maps calculated for the same specimen tilt angles from a micromagnetic simulation of a CoFeB nanotube that has a magnetic vortex state close to its end.



Instrumentation development

Ongoing work includes the development of a cartridge for a Fischione on-axis tomography holder (Model 2050) to allow conventional 3 mm grids to be turned over in the TEM, in combination with the use of an inclinometer attached to the end of the holder to measure the specimen tilt angle with a precision of 0.1°.



Summary and Acknowledgments

- Experimental tilt series of magnetic induction maps of CoFeB nanotubes that support three-dimensional magnetization distributions have been recorded using off-axis electron holography.
- An on-axis tomography holder that allows the specimen to be turned over in the TEM and the tilt angle to be measured precisely is under development.
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