Electromagnetic Field Mapping at the Nanoscale in the Transmission Electron Microscope

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Off-axis electron holography is a powerful technique for recording the phase shift of a high-energy electron wave that passes through an electron-transparent specimen in the transmission electron microscope. The phase shift is, in turn, sensitive to the electrostatic potential and magnetic induction in the specimen. Recent developments in the technique have included the use of advanced specimen holders with multiple electrical contacts to study nanoscale working devices and the use of ultra-stable transmission electron microscopes to achieve sub-$2\pi/1000$-radian phase sensitivity.

We are currently working on the application of off-axis electron holography to the measurement of electrostatic potentials and electric fields around electrically-biased atom probe tomography needles. Each experiment involves applying a voltage between a needle and a counter-electrode. The recorded phase shift can be analyzed either by fitting the phase distribution to a simulation or by using a model-independent approach that involves contour integration of the phase gradient to determine the charge enclosed within the integration contour. Both approaches require evaluation of the difference between phase images acquired for two applied voltages, in order to subtract the mean inner potential (and sometimes also the magnetic) contribution to the phase. On the assumption of cylindrical symmetry, the three-dimensional potential and field around such a needle can be determined from the results.

We are also working on a model-based approach that can be used to reconstruct the three-dimensional magnetization distribution in a specimen from a series of phase images recorded using electron holography. We generate simulated magnetic induction maps by projecting a best guess for the three-dimensional magnetization distribution onto a two-dimensional Cartesian grid. We simulate phase images of arbitrary three-dimensional objects from any projection direction by making use of known analytical solutions for the phase shifts of simple geometrical objects, with numerical discretization performed in real space to avoid artifacts generated by discretization in Fourier space, without a significant increase in computation time (Figs. 1 and 2). This forward simulation approach is then used in an iterative model-based algorithm to solve the inverse problem of reconstructing the three-dimensional magnetization distribution in the specimen from a tomographic tilt series of two-dimensional phase images. This approach avoids many of the artifacts that result from using classical tomographic techniques such as filtered backprojection, as well as allowing additional constraints and known physical laws to be incorporated.

When recording weak phase shifts, it is important to remember that the sample must remain clean and undamaged for the time required to acquire images with a sufficient signal to noise ratio, that electron-beam-induced charging can affect the measured phase shift and that for crystalline specimens careful comparisons with dynamical simulations may be required even for a thickness of only a few atoms.

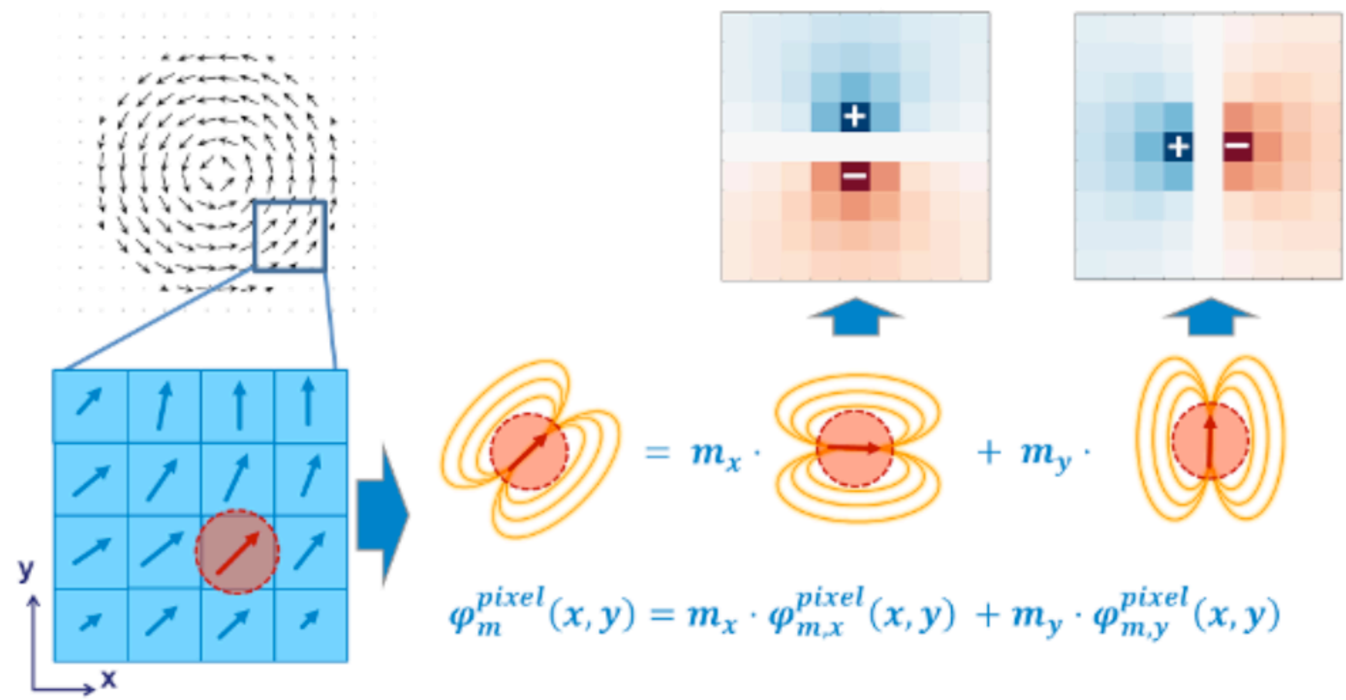

Figure 1. Illustration of the simulation process: The projected two-dimensional magnetization distribution is sub-divided into pixels which are represented by simple geometries (e.g., a disc). The contribution to the phase shift from every pixel is calculated in the form of two pre-computed components, which are oriented along the axes of the grid.

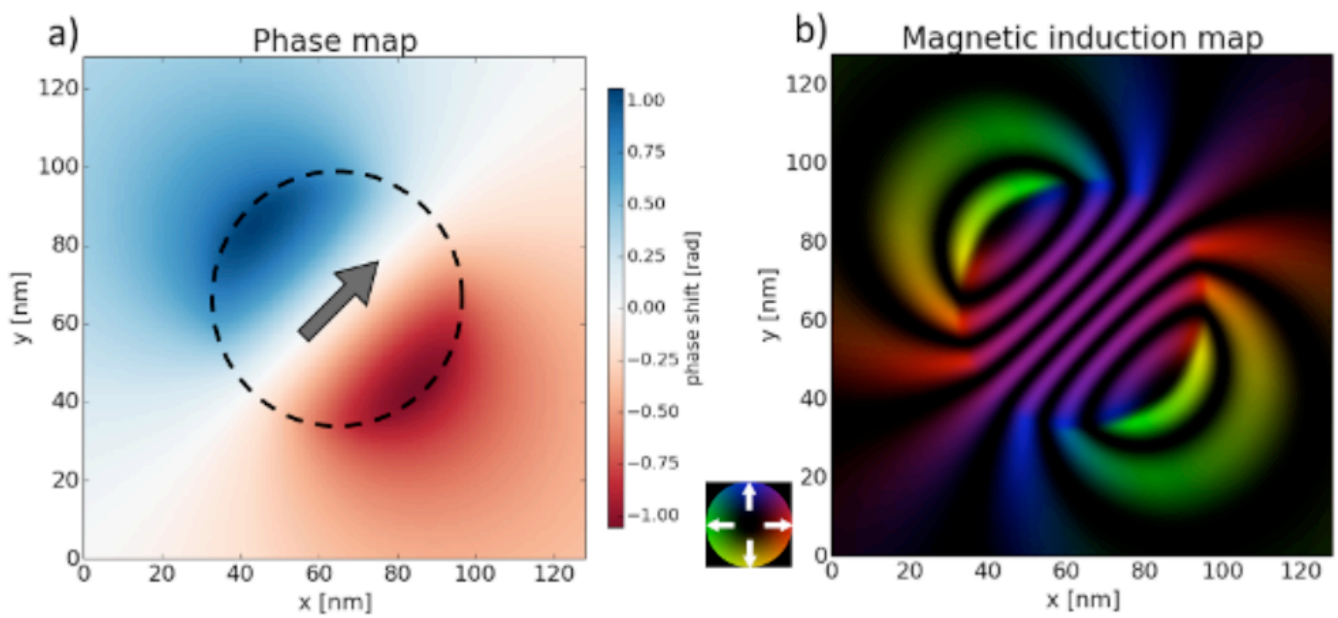

Figure 2. a) Simulated magnetic phase shift of a uniformly magnetized sphere with a radius of 64 nm in a 128×128×128 nm^3 volume. The magnetization direction is indicated by the arrow. b) Corresponding magnetic induction map (20× phase amplified). The colors represent the direction and magnitude of the phase gradient, according to the color wheel shown.