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Developing Rapid and Advanced Visualisation of Magnetic Structures Using 2-D Pixelated STEM Detectors

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In Transmission Electron Microscopy (TEM) electron diffraction patterns, imaged from the back focal plane of the objective lens, reveal rich information about the structure of materials. The sharpest patterns are obtained using a parallel (semi-convergence angle < 1 mrad) electron beam which typically illuminate an area with a diameter of 100 nm. In Scanning Transmission Electron Microscopy (STEM) the electron beam is focused to form a fine probe, potentially with sub-Ångström diameter, where image signals are collected by detectors which integrate single intensity values for each scan position from two-dimensional scattering in the back focal plane. A key aspect to obtaining high resolution information is that the performance of scanning and detection should be performed rapidly in order to provide live imaging for the user but to also to mitigate for instabilities and specimen drifts.

Recently, advances in fast direct electron counting systems have enabled the development of 2-D pixelated detectors that can operate at fast acquisition speeds. Applying these to the STEM technique enables imaging of the contents of the back focal plane at high frame rates, i.e. the full diffraction pattern can be acquired for every scan position in a STEM dataset. This yields a 4 dimensional dataset: two spatial probe position dimensions, and two reciprocal detector positions. While this opens up many new and exciting research avenues, there are still many challenges in how to use the 4-D datasets optimally. In this work we focus on solutions for performing live or near-live magnetic imaging using a fast pixelated STEM detector.

The experimental work was performed on a probe corrected Jeol ARM200cF equipped with a Medipix3 fast pixelated detector capable of acquiring at 1100 frames per second. To image magnetic induction in the materials the STEM was operated in Lorentz mode[1], which involves turning off the objective lenses so that the sample resides in a near field free environment. A custom aberration corrector mode was utilised to enable probe semi-convergence angles from 0.4-3.0 mrad with corresponding probe diameters from < 1 nm to 6 nm[1]. For magnetic samples, the Lorentz interaction with the beam results in electron wave phase changes and beam deflections proportional to the magnetic induced phase gradients across the sample. Using a pixelated detector the direction and strength of the integrated magnetic induction for the sample can be quantitatively measured by tracking the angular deflection of the bright field disc.

This presentation will focus on solutions for live imaging of magnetic structures in FeAl thin films patterned with Ne^+ ions, shown in Fig. 1. An example of magnetic contrast is shown in (c-h), where the areas within the circle (seen in Fig 1a) are ferromagnetic, while the area outside is paramagnetic. The light and dark magnetic contrast is due to deflection of the electron beam, and the figures show two different methods for extracting this deflection. In (c-f), only a single pixel at the edge of the STEM disk is used from each diffraction pattern, with the different figures having the pixel at different places on the disk (marked by the points in (b)). For (g-h), a more advanced edge detection is performed. Here, cross correlation is used to determine the position of the disk. As seen in Fig. 1(g-h), the edge detection techniques clearly produce increased level of magnetic contrast and better signal to noise, but is much more computationally demanding. Thus for live imaging, the more simple method is more suited.

We will also show how offloading the data processing to central and graphical processing units allows for rapid processing with different methods. This includes the single pixel and edge detection methods explained above, as well as centre of mass methods. Lastly, the output data is transferred into Digital Micrograph using open and standard network components, which enables both control of the detector system and live imaging to be performed on a single machine. The presentation will also touch on file formats chosen for data storage and ways of visualising the 4-D datasets.

[1] S. McVitie, *et al*, "Aberration corrected Lorentz scanning transmission electron microscopy", Ultramicroscopy, Volume 152, May 2015, Pages 57-62

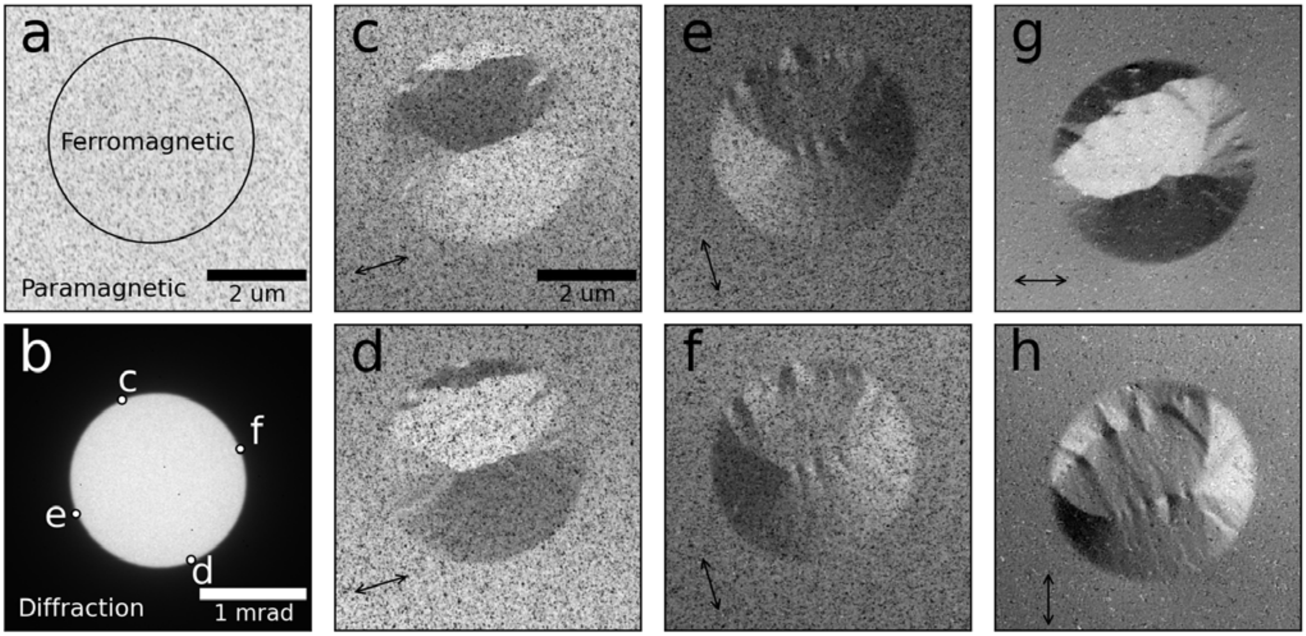

Figure 1. STEM imaging of Ne^+ ion patterned FeAl, all from one 4-D dataset. (a) Bright Field image, showing which areas has been patterned. (b) Sum over all the probe positions, giving an average STEM diffraction disk. Points showing the location of the single pixel synthetic aperture used in (c-f). (c-f) Magnetic contrast from shifts in the STEM disk, using a single pixel in the diffraction pattern in (b). (g-h) Magnetic contrast using edge detection on the STEM disk. (g) Horizontal magnetic induction, the double headed arrow indicate the component of integrated magnetic induction mapped. (h) Same as (g), for vertical magnetic induction.