Multi Dimensional Characterization of Magnetic Materials

CD Phatak

Materials Science Division,

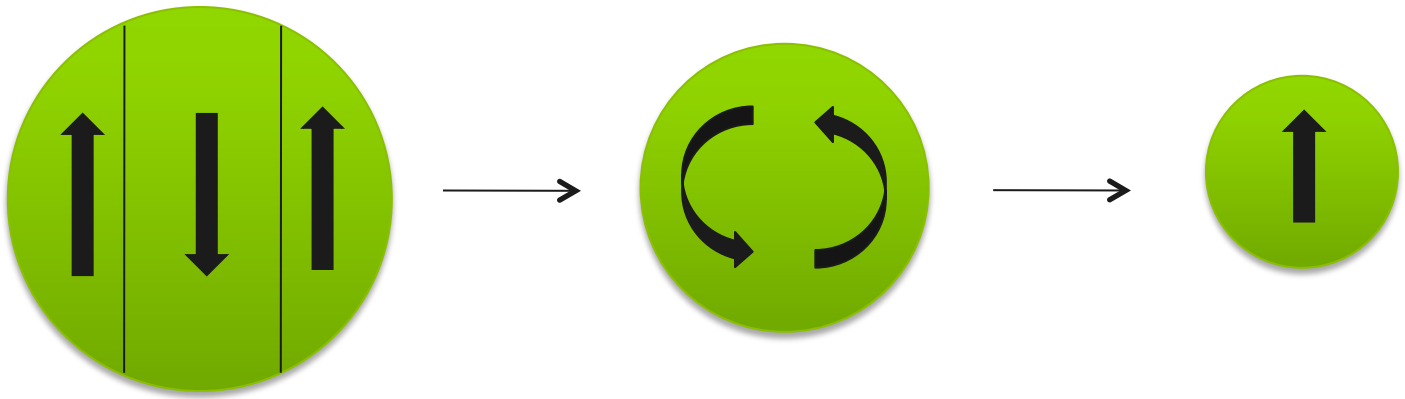
Argonne National Laboratory

CScADS Workshop

July 26, 2010

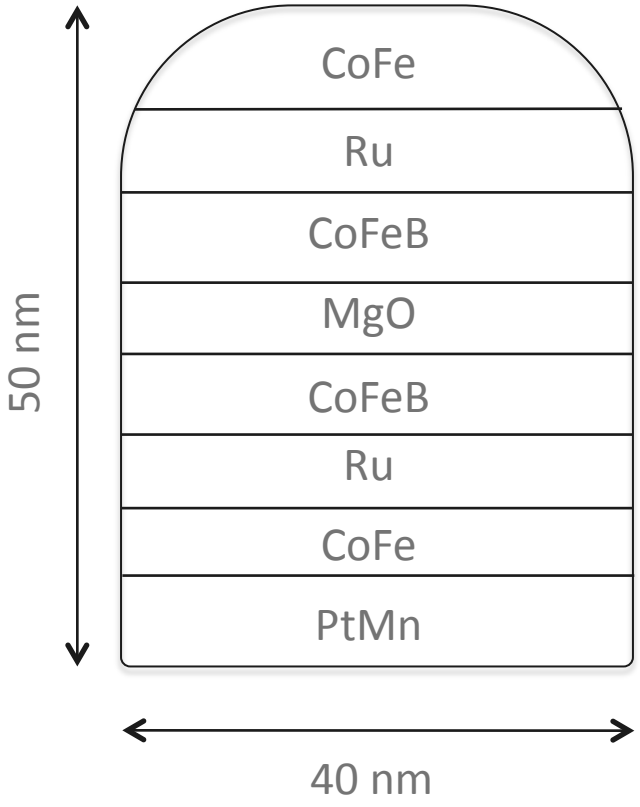
Objective

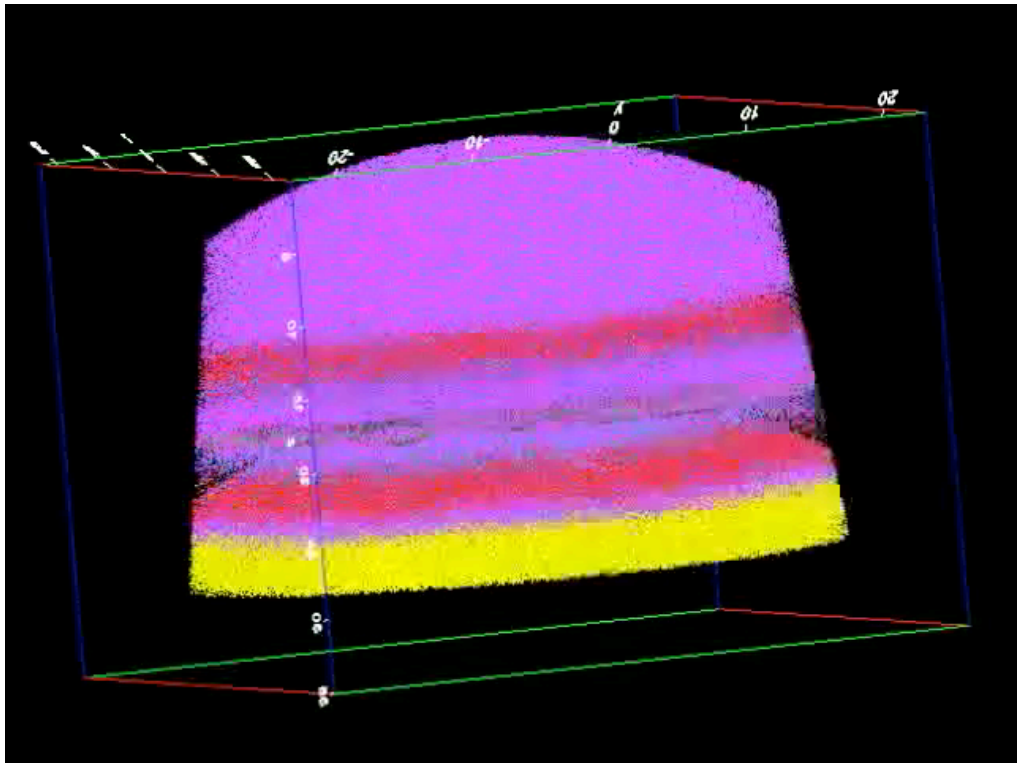
- Structure-Property relationship forms the central paradigm of Materials Science.
- Device characteristics depend on microstructure, interfaces and chemical composition.
- Behavior of devices studied as a function of external stimuli such as magnetic field, electric field, temperature. This consists of static as well as dynamic experiments.
- In nanoscale magnetic materials, the shape of the sample has big influence on the magnetic field.



Techniques & Data

- Atom Probe Tomography
  - Each atomic position in 3D is recorded



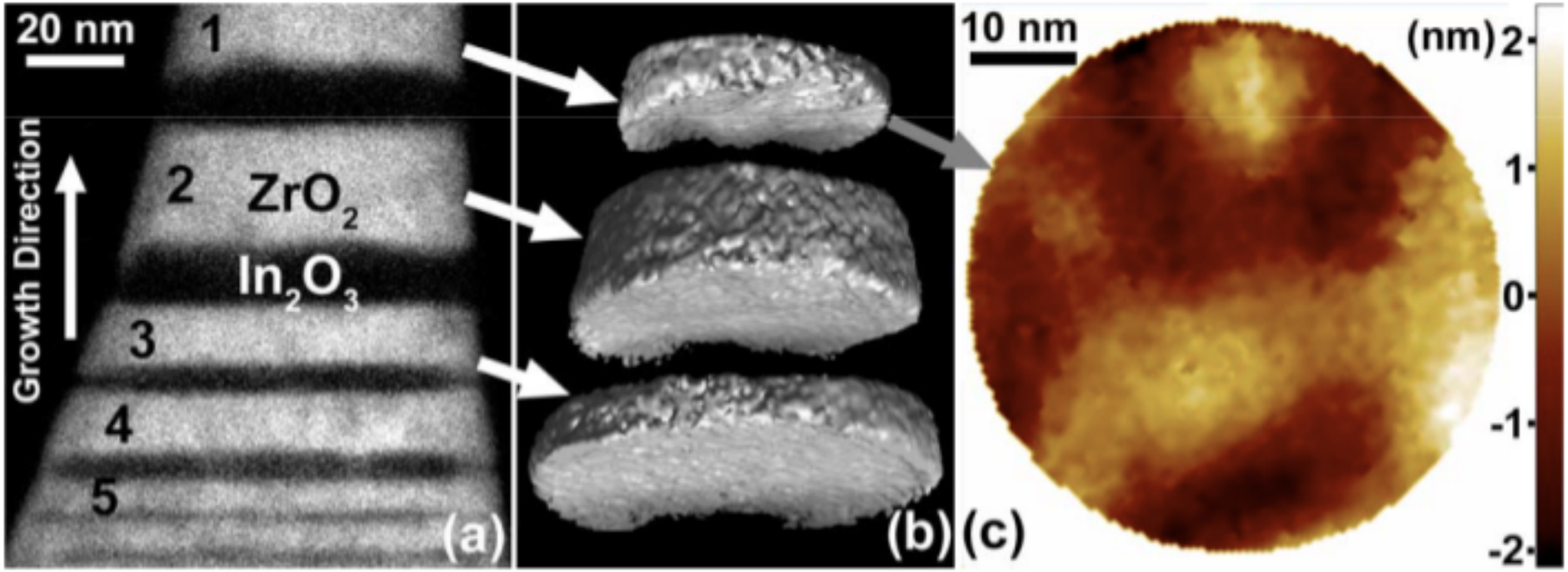


Data visualization created using IVAS software

Data courtesy Dan Schreiber, Northwestern University, IL.

Techniques & Data

- Transmission Electron Microscopy – Energy Filtered Tomography
  - Chemical information recorded by resolving the energy peaks for individual elements



* X. Zhong et. al. *Microscopy and Microanalysis*, **15**(Supp 2), 2009.

Images collected using upto 4K by 4K CCD, within a tilt range of -80^o to +80^o at 2^o intervals. Alignment of images and 3D reconstruction of the data set followed by analysis using commercial available software.

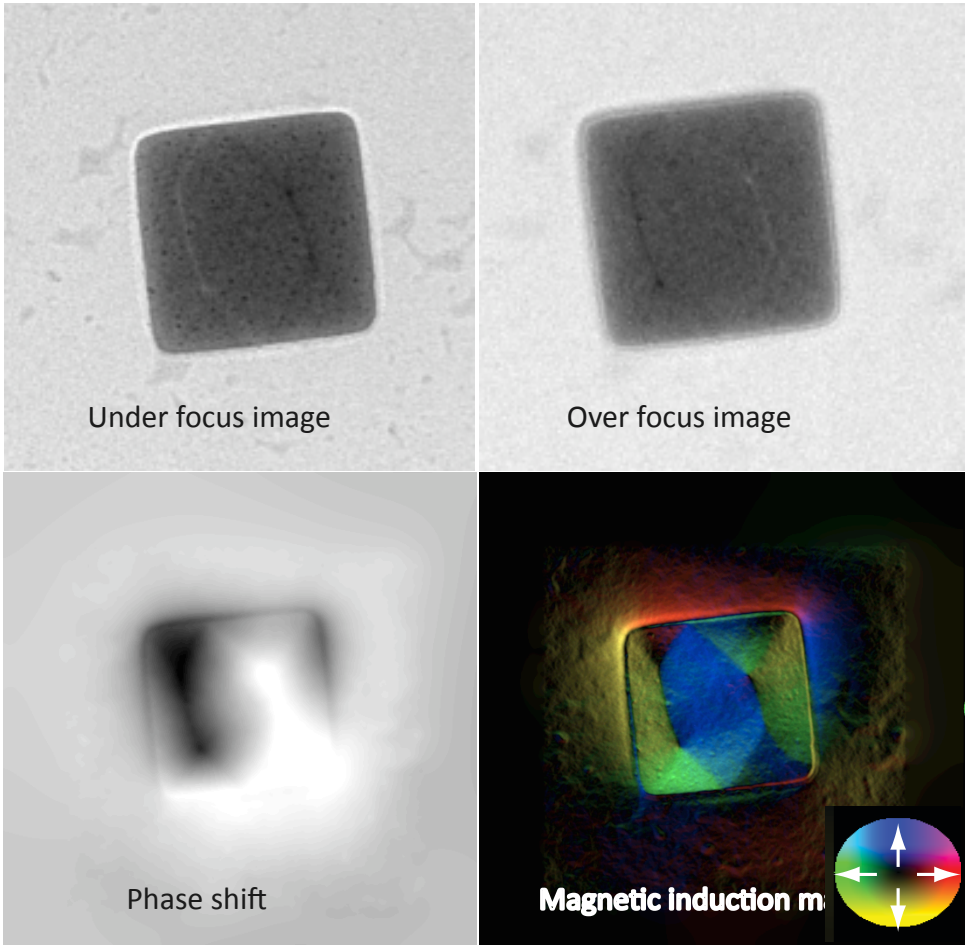
Techniques & Data

- Lorentz Transmission Electron Microscopy

• Magnetic Domain structure in square Permalloy island

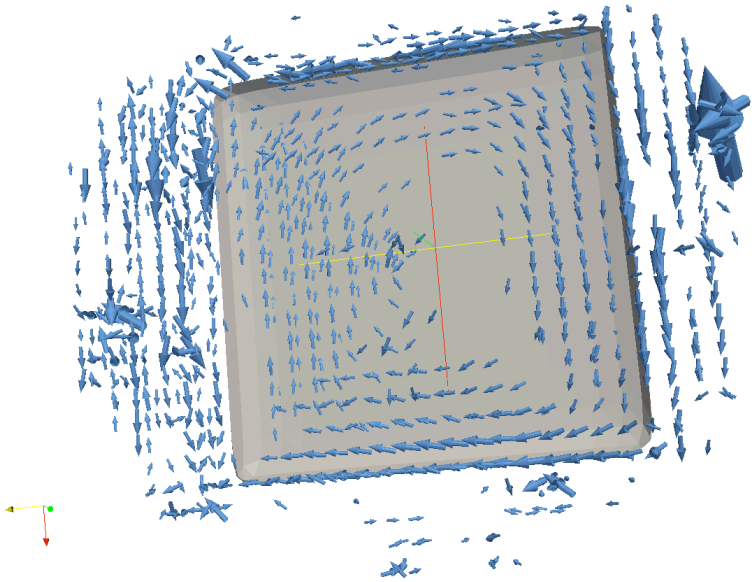
• Phase shift of electrons relates to the two dimensional projection of the magnetic induction

• Color wheel representation of 2D vector field very easy to interpret

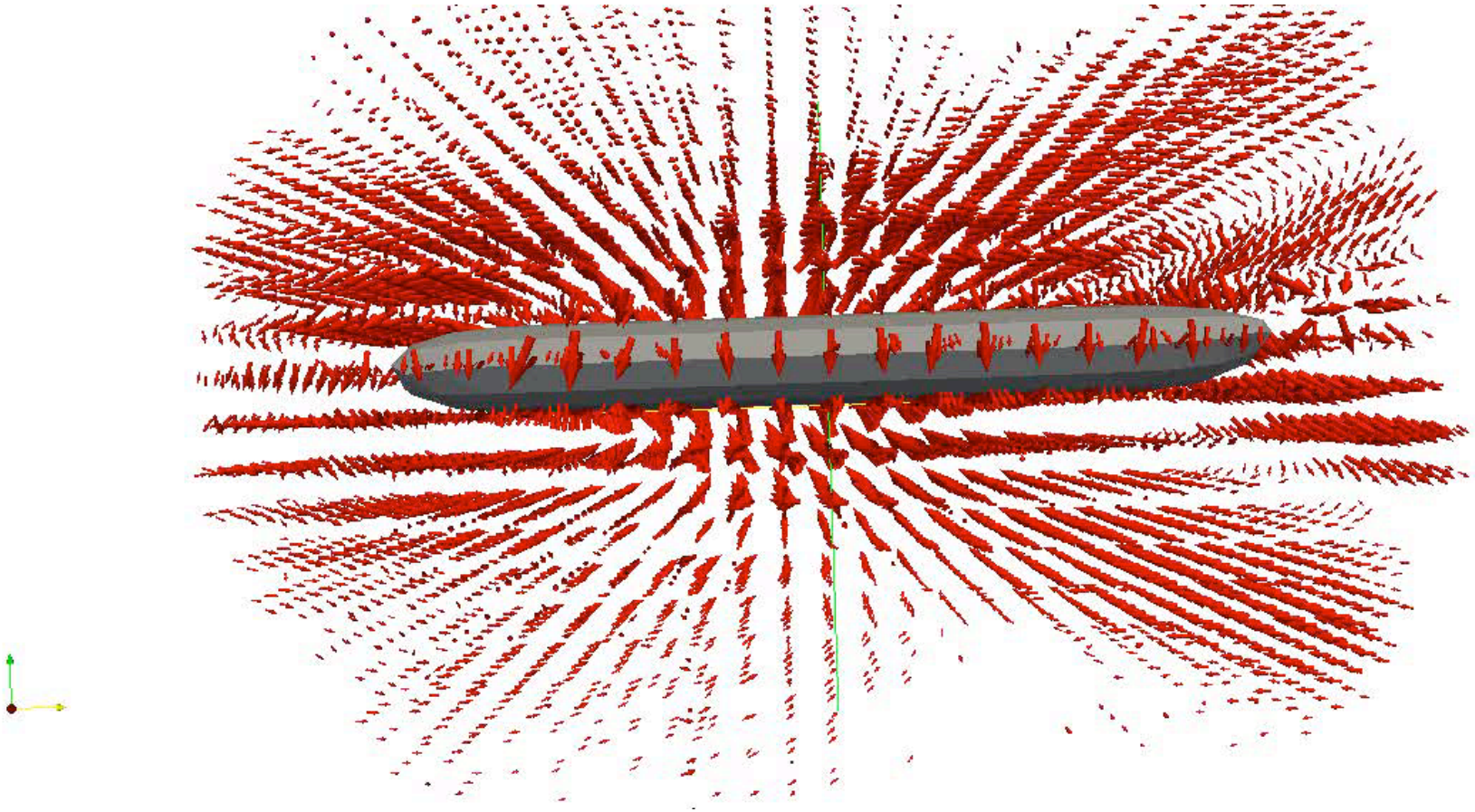


Vector Field Electron Tomography

- Combining tomography technique with Lorentz Microscopy, it is possible to determine 3D magnetic induction and the vector potential of the sample
- Images typically acquired using 2K by 2K CCD
- Tilt range from -75 deg. to + 75 deg with 2 deg. tilt steps
- At each tilt angle, 3 images acquired to reconstruct the electron phase shift
- Repeat 4 tilt series of the same structure
- Total number of images – 348 (for single experiment)



Vector Field Electron Tomography



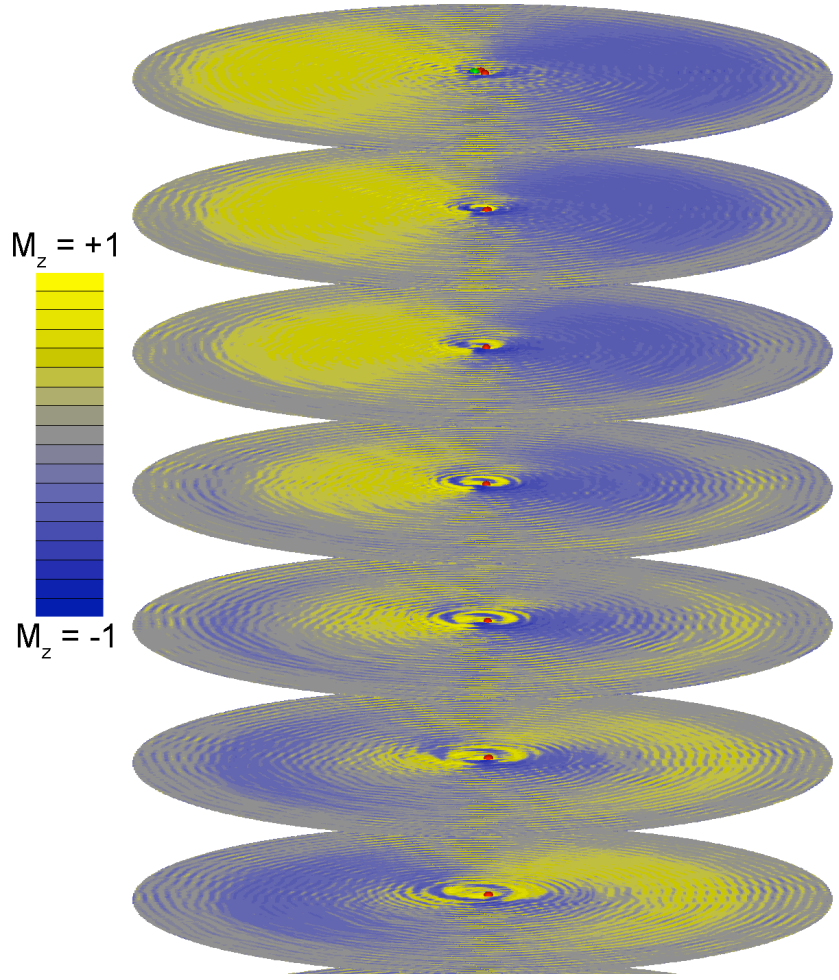
Multi-Dimensional Data Sets

- Micromagnetic simulations

  • Dynamic response of magnetization occurs on a length scale of few picoseconds. The figure shows *z*-component of magnetization with 0.01 ns time step

  • Simulations help in understanding the effect of different excitations due to magnetic field pulse or electric field pulse

  • Data consists of 3-D vector field as well as additional component of time/frequency

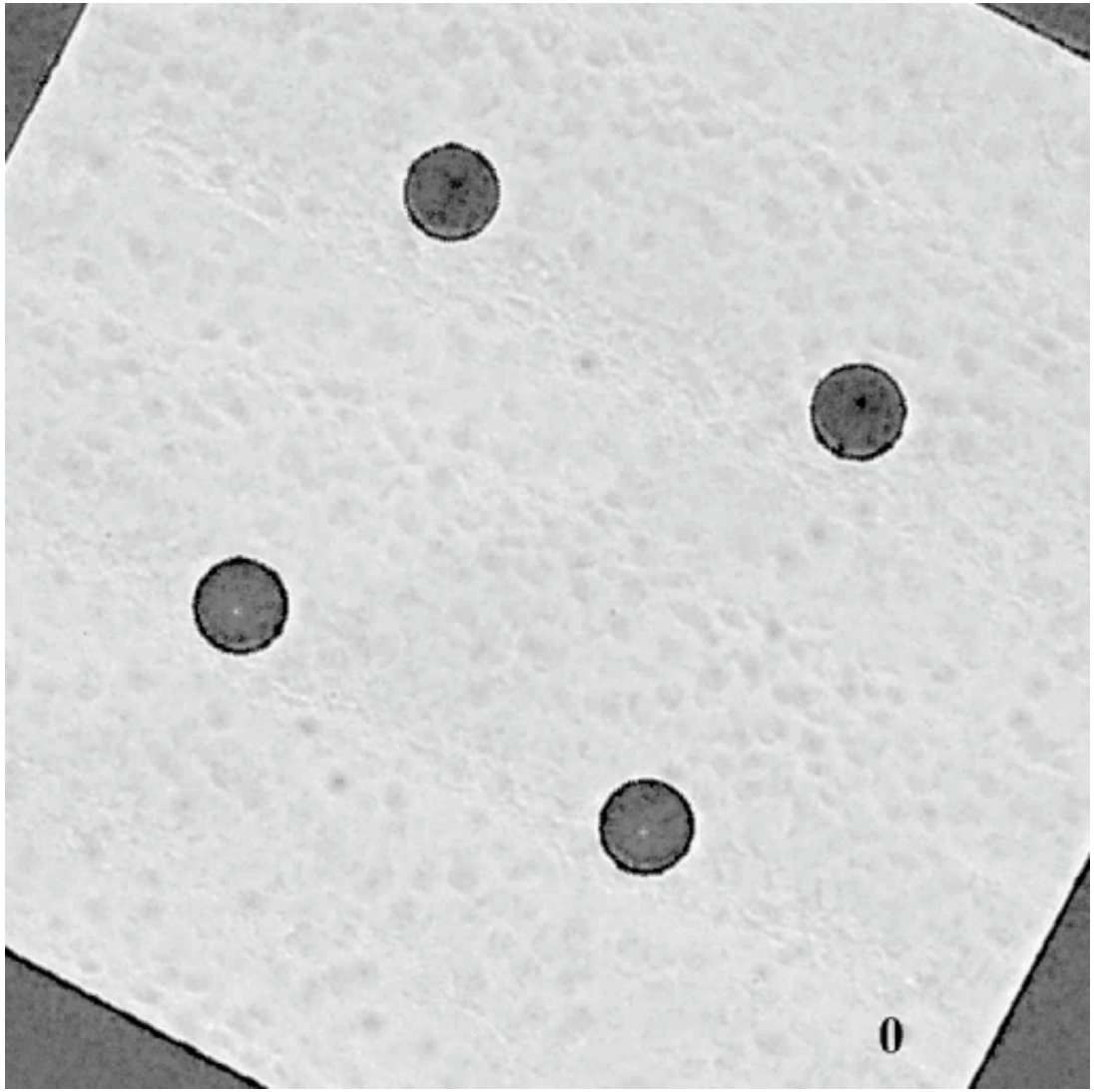


O. Heinonen et. al., *Physical Review B,* 76, 144407 (2007).

Multi Dimensional Data Sets

- In-situ Magnetizing

  • Study the change in magnetization, as a function of the applied magnetic field



Challenges

- Vector Field Data Sets – 3 components of the data at each co-ordinate position (x,y,z). Ability of analyze the data such as curvature of the field, trace of 3D field lines like the classic iron filings test for magnetic field
- Additional variable of time and/or external stimuli such as magnetic/electric field
- Analysis by combining the data sets obtained from multiple experiments
- To maintain the resolution of the instrument, the data processing needs to be done at the highest possible resolution. For e.g, 3D volume or vector field reconstruction on a 2K by 2K by 2K data cube
- Faster processing for alignment of successive tilt series images and iterative reconstruction of the 3D data

Acknowledgements

This work was carried out at Argonne National Laboratory, a U. S. Department of Energy Office of Science Laboratory operated under contract DE-AC02-06CH11357 by University of Chicago Argonne, LLC. We also acknowledge use of the Center for Nanoscale Materials and the Electron Microscopy Center at Argonne National Laboratory (contract DE-AC02-06CH11357)