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### **Research Highlight**

### X-ray's as a Magnetic Nano-Probe

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X-ray scattering is, in many ways, an ideal probe of magnetic nanomaterials since it allows in-situ, non-invasive investigation of both structural and dynamical properties of materials with nanoscale or even atomic resolution. Deeply penetrating ability of x rays make it a useful probe of truly bulk properties of materials, an advantage over electron scattering and microscopy, or scanning tunneling techniques. The ability to "see" deep inside non-transparent samples and to couple to "invisible" order parameters makes it possible to study samples that cannot be investigated with visible or infrared spectroscopy techniques. And unlike visible light microscopy which has practical resolution limit  $\approx 200$  nm due to Rayleigh criterion, the fundamental diffraction-limited resolution of x-ray scattering based techniques is well below 1 Ångström.

High degree of x-ray energy tunability at synchrotron facilities further makes it possible to perform measurements that are element-specific to specific chemical constituents, or use corelevel sensitivity at the resonant edges to study magnetism with resonant magnetic scattering. We have recently demonstrated the high degree of spatial coherence available at high-brilliance synchrotron facilities enables a novel approaches to image nanoscale magnetic structure.

### <u>Coherent X-ray Diffractive Imaging.</u>

**Phase-retrieval lens-less imaging.** While the temporal evolution of the x-ray speckle pattern can provide valuable information about fluctuation of the specific order parameter (orbital, charge or spin ordering), reconstruction of reciprocal space speckle "snapshot" pattern back into real space image based on phase-retrieval algorithms, known as Lensless X-ray Imaging, can provide detailed real-space information of both real and imaginary parts of the domain complex order parameters.

**Imaging Extended Objects with Ptychography Approach.** A novel approach to iterative phase retrieval called the Ptychographic Iterative Engine (PIE) [1-10] PIE is based on the idea of



collecting coherent diffraction patterns from overlapping regions on the sample and using this information for unambiguous and fast phase retrieval, and imaging of extended objects on lengthscales greater than the size of the illuminated beam (see **Figure 2**) This approach can also be applied to extended objects of, in principle, unlimited size.

**Figure 1:** Schematic of the experimental setup for lens-less principle, unlimited size. ptychographical imaging (left) and the cyclic iterative algorithm of phase recovery. Adapted from Refs. [2,4]

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We have performed PIE reconstructions of simulated data and so far the outcomes are quite favorable. There are several advantages to using the coherent diffractive imaging techniques,



Figure 2: (a) Example of reconstructed magnetic domain structure obtained by 4x4 scanning of overlapping exposures. The extreme dark and light colors represent two anti-parallel fully saturated magnetization values  $(M_s)$  normal to the plane of the magnetic film (b) Reconstructed complex illumination function (amplitude shown as brightness and phase as hue) of the incident xray beam. From Tripathi et al, [11]

### <u>Coherent X-ray Diffractive</u><sup>a</sup> <u>Imaging of Extended Magnetic</u> <u>Nanostructures.</u>

We have successfully performed to our first ever knowledge Coherent X-rav Diffractive Imaging (CDI) of magnetic d nanostructures. The approach of CDI is a lens -less alternative to lens-based techniques, such as magnetic microscopy – whereby the diffraction pattern formed by scattering a coherent x-ray beam from a sample is inverted numerically to form an image of the object. By removing the need for optics, the spatial resolution achievable is no longer limited by the quality of the optical elements, but by the highest spatial frequencies measured in the x-ray diffraction pattern.

such as ptychography, over other imaging approaches, such as, for example, scanning X -ray Nanodiffraction:

1) The spatial resolution can exceed the dimensions of the x-ray beamspot.

2) The resolution is not limited by the quality of the focusing optics, but only by the coherent x-ray flux

3) Both phase and amplitude of the appropriate order parameter is retrieved, making the CXDI highly sensitive to "phase defects", such as phase strain, compression, dilatation or shear, presence of edge dislocations, as well as more complex topological phase defects, such as anti-phase domains, phase slips, screw dislocations etc.



**Figure 3: (a)** domain evolution as the magnetic field is decreased from saturation towards zero magnetic field. (a) Hysteresis loop of sample magnetization as a function of applied magnetic field; (b-f) magnetic domain reconstructions from series of diffraction patterns taken at various points of magnetic hysteresis curve shown in (a). From Tripathi et al, [11]

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We demonstrated the basic principle of magnetic CDI where by subtracting coherent diffraction patterns collected on- and off- magnetic resonance (in this case at  $M_5$  Gd adsorption edge) one can couple directly to magnetic structure induced by Gd – therefore achieving elemental sensitivity to magnetic moment and eliminating charge scattering contribution.

We have performed the CDI measurements on labyrinthine stripe domains in magnetic multilayers of GdFe, and have successfully demonstrated that both the real-space magnetic structure of the sample and the complex illumination function of the x-ray beam incident on the sample can be recovered in ptychographical approach (see Fig. 3).

The project demonstrates our ability not only to develop in-house algorithms that work on simulated or man-made objects, but can also be transferred to real-life systems. The measurements were performed at sector 2 of Advanced Photon Source at Argonne in collaboration with Ian McNulty of APS and Eric Fullerton and his group at UCSD.

#### **References:**

- O. Bunk, M. Dierolf, S. Kynde, I. Johnson, O. Marti, and F. Pfeiffer, "Influence of the overlap parameter on the convergence of the ptychographical iterative engine," *Ultramicroscopy* 108, 481 (2008).
- [2] J. M. Rodenburg, "Ptychography and related diffractive imaging methods", in Advances in Imaging and Electron Physics (2008), Vol. 150, pp. 87.
- [3] P. Thibault, M. Dierolf, A. Menzel, O. Bunk, C. David, and F. Pfeiffer, "High-Resolution Scanning X-ray Diffraction Microscopy," *Science* **321**, 379 (2008).
- [4] M. Dierolf, O. Bunk, S. R. Kynde, P. Thibault, I. Johnson, A. Menzel, K. Jefimovs, C. David, O. Marti, and F. Pfeiffer, "Ptychography & lensless X-ray imaging," *Europhysics News* 39, 22 (2008).
- [5] H. M. L. Faulkner and J. M. Rodenburg, "Error tolerance of an iterative phase retrieval algorithm for moveable illumination microscopy," *Ultramicroscopy* **103**, 153 (2005).
- [6] J. M. Rodenburg, "A simple model of holography and some enhanced resolution methods in electron microscopy," *Ultramicroscopy* **87**, 105 (2001).