MA 6: Magnetic Imaging Techniques I

Time: Monday 9:30–12:45 Location: POT/0361

MA 6.1 Mon 9:30 POT/0361

Nanoscale Dipolar Fields in Artificial Spin Ice Probed by Scanning NV Magnetometry — •Ephraim Spindler[1], Vinayak Shantaram Bhat[2], Elke Neu[1], Mathias Weiler[1], and M. Benjamin Jungfleisch[2] — [1]Fachbereich Physik and Landesforschungszentrum OPTIMAS, RPTU in Kaiserslautern, Germany — [2]Department of Physics & Astronomy, University of Delaware, Newark, USA

Artificial spin ices (ASI) offer a versatile platform to study frustration and collective spin dynamics in engineered magnetic lattices. We employ scanning probe microscopy based on a single nitrogen-vacancy (NV) center in diamond - a non-invasive, nanoscale quantum sensing technique - to study two square-lattice ASI systems with varied inter-element coupling strengths.

We use NV fluorescence quenching for rapid state determination and continuous-wave optically detected magnetic resonance to quantitatively map magnetic stray fields and extract vectorial dipolar field information. We fit the experimentally determined field components to micromagnetic simulations to infer local magnetic configurations in an iterative procedure.

These micromagnetic modeling results demonstrate that our method successfully quantifies the deviation between the expected and detected dipolar coupling field strengths, which we describe using an effective saturation magnetization. We show that the subtle magnetization tilt induced by small external fields is detectable and quantifiable through its impact on the local dipolar stray fields in the ASI.

MA 6.2 Mon 9:45 POT/0361

Probing nanoscale magnetic phenomena with cryogenic scanning NV magnetometry — •Mirko Bacani[1], Clemens Schäfermeier[1], Ankit Sharma[1], Christopher Kelvin von Grundherr[1], Dieter Andres[1], Khaled Karrai[1], Gabriel Puebla-Hellmann[2], Jan Rhensius[2], Andrea Morales[2], and Florian Otto[1] — [1]attocube systems GmbH , Haar, Germany — [2]QZabre AG, Zurich, Switzerland

Emerging technologies increasingly rely on precise control and understanding of magnetic phenomena at the nanoscale and cryogenic temperatures. NV magnetometry offers a unique approach, combining quantum sensing with scanning probe precision to achieve magnetic field mapping at resolutions and sensitivities beyond conventional limits. We present cw-ODMR imaging of materials hosting emergent quantum and topological magnetic phenomena, including Abrikosov vortices in BSCCO and YBCO, interlayer domain textures in twisted bilayer CrSBr, magnetic domains in skyrmions-hosting Ir/Fe/Co/Pt multilayers, and meronic spin textures in synthetic antiferromagnets.

The imaging was performed by the cryogenic scanning NV magnetometer integrated into a closed-cycle cryostat with turnkey operation from 2-300 K. The system reaches the sensitivity of 3 uT/sqrt(Hz) with automated ODMR for quantitative stray-field mapping. These results exemplify the versatility of cryogenic NV magnetometry as a tool for probing superconductivity, correlated magnetism, and emergent spin textures in quantum materials.

MA 6.3 Mon 10:00 POT/0361

Switchable magnetic nanowire probes for differential magnetic force microscopy — Florian Sandbaumhüter[1,2], •Aniruddha Sathyadharma Prasad[1,2], Rachappa Ravishankar[1,2], Volker Neu[1], Bernd Büchner[1,2], and Thomas Mühl[1] — [1]IFW Dresden — [2]TU Dresden

Recent work on magnetic force microscopy (MFM) has highlighted the need to implement a differential MFM technique to better eliminate interfering electrostatic and topographical crosstalk from MFM images. In addition, the use of specialized MFM probes containing iron-filled carbon nanotubes (FeCNTs) as the sensing element has enabled easy quantitative imaging of magnetic fields and field gradients [1]. In this talk, we demonstrate in-situ differential MFM in a reversed tip-sample arrangement. This is based on our switchable magnetic probes which consist of FeCNTs attached to micron-sized electromagnets, i.e. planar microcoils [2]. The large field gradients of these microcoils make sure that there is only a minimal effect on the sample being measured. Furthermore, the highly inhomogeneous fields produced by our microcoils also provide a new playground for studies of domain wall motion in ferromagnetic nanowires.

[1] Freitag, Norbert H., et al. Communications Physics 6, 11 (2023).
[2] Sathyadharma Prasad, Aniruddha, et al. Communications Materials 6, 164 (2025).

MA 6.4 Mon 10:15 POT/0361

Magnetic Vector Tomography of Thick Chiral Magnets — •Polly Mitchell[1], Claire Donnelly[1,3], Luke Turnbull[2], Jeffrey Neethirajan[1], Rikako Yamamoto[1,3], Marina Raboni Ferreira[1], Burkhard Kaulich[2], and Luke Higgins[2] — [1]MPI CPfS, Dresden, Germany — [2]Diamond Light Source, Harwell Campus, Didcot, UK — [3]SKCM[2] Hiroshima University, Hiroshima, Japan

Complex three-dimensional (3D) textures such as Bloch points, chiral bobbers and hopfions form in chiral magnets through the interplay between Dzyaloshinskii-Moriya and exchange interactions. The 3D nature of such structures provides advantages such as higher degrees of freedom, and the potential for volume-based information encoding. However, the investigation of thick samples presents a number of challenges: first, whether the cancellation of opposing magnetic vectors through the sample will hinder the 3D reconstruction, and second, the high absorption of soft x-ray and electron microscopies. Here we address both challenges, obtaining experimental insight into the 3D configuration of thick chiral magnets. By performing numerical simulations of magnetic vector tomography, we find that increased angular sampling mitigates vector cancellation, allowing accurate high-resolution 3D mapping of samples up to 3μm thick. Following this insight, we harness pre-edge phase soft X-ray ptychography to perform magnetic tomography of a 700nm thick $Co_8Zn_9Mn_3$ sample. In this way, we are able to recover the 3D magnetisation vector field of a thick chiral sample, demonstrating magnetic tomography as a robust technique to recover complex configurations in thick magnetic systems.

MA 6.5 Mon 10:30 POT/0361

Self-Consistent Magnetic Force Microscopy Simulator Framework — •Dominik Schramm[1], Claas Abert[2], Jakub Jurczyk[1], and Amalio Fernández-Pacheco[1] — [1]Tu Wien — [2]Universität Wien

With the advancement in 3D nanofabrication techniques such as Focused Electron Beam Induced Deposition (FEBID), manufacturing of complex magnetic nanostructures emanating more complex stray fields becomes feasible. [1] To quantify these fields, the development of a modified Vector- Magnetic Force Microscope (MFM), resolving all three spatial components of the stray field while still maintaining industrial feasibility, is targeted.

To design an optimized MFM tip, the micromagnetic simulation framework Neuralmag is leveraged to simulate an MFM signal. The simulator allows us to self-consistently study the impact of tip geometry, inclination angle, magnetic state as well as additional oscillatory modes not only on the output, but also on the magnetic states of tip and sample themselves. Furthermore, the simulator is employed to simulate MFM along a topographically non-trivial sample surface.

[1] A. Fernández-Pacheco, et al. Nat Commun 8, (2017) 15756.

MA 6.6 Mon 10:45 POT/0361

Toward 3D magnetic force microscopy: Simultaneous torsional cantilever excitation to access a second, orthogonal stray field component — •Jori F. Schmidt[1], Lukas M. Eng[1,2], and Samuel D. Seddon[1] — [1]TU Dresden, Institute of Applied Physics, Nöthnitzer Strasse 61, 01187 Dresden, Germany — [2]ct.qmat: Dresden-Würzburg Cluster of Excellence EXC 2147, TU Dresden, 01062 Dresden, Germany

Magnetic Force Microscopy (MFM) is a technique for recording maps of the magnetic stray field above a sample, as is for instance well documented for skyrmions. The magnetized tip usually couples to the out-of-plane magnetic sample stray field through cantilever oscillations perpendicular to the sample surface. Nevertheless, the stray field has a 3-dimensional distribution, the reconstruction of which has not been widely performed so far due to the uniaxial sensitivity of standard MFM.

Here, we introduce a novel way towards experimentally mapping the full 3D sample stray field, by simultaneously oscillating the MFM cantilever at its vertical (out-of-plane) and lateral (in-plane) fundamental resonance frequencies, thus making it possible to directly compare and quantify the vertical MFM (V-MFM) and the lateral MFM (L-MFM) signals. We have tested this novel setup for its overall performance and signal-to-noise ratio, using a hard disk with known magnetization, where a good agreement was found between experimental results.[1]

[1] J. Schmidt et al., J. Appl. Phys. 136, 113904 (2024): https://doi.org/10.1063/5.0226570

15 min break

MA 6.7 Mon 11:15 POT/0361

Hamiltonian reverse engineering from magnetic skyrmion images via deep learning surrogates — •Moritz Winterott[1,2] and Samir Lounis[3] — [1]Peter Grünberg Institut, Forschungszentrum Jülich & JARA, Germany — [2]Faculty of Physics, University of Duisburg-Essen, Germany — [3]Institut für Physik and Halle-Berlin-Regensburg Cluster of Excellence CCE, Martin-Luther Universität Halle-Wittenberg, Germany

The extraction of physical parameters from experimental observations is a central inverse problem in condensed matter physics. Complex magnetic textures such as skyrmions are imaged via Scanning Tunneling Microscopy (STM), which probes the local density of states (LDOS). Inferring the underlying interactions by matching theoretical models to experimental LDOS is often computationally expensive. In this work, we introduce a deep-learning framework that serves as a fast and accurate surrogate for this modeling process. Our approach employs a novel neural network architecture that integrates modern Transformers[1,2] with Convolutional Neural Networks (CNNs) to extract spatial features from energy-resolved LDOS images and to learn the highly nonlinear mapping to the parameters of an effective tight-binding Hamiltonian. These parameters encode the skyrmion texture, hopping amplitudes, and spin-orbit coupling strengths. Also, on-the-fly noise augmentation during training enhances robustness, enabling the model to maintain high accuracy even for noisy experimental data.

[1] Vaswani et al. NeurIPS '17; [2] Devlin et al. Proc. NAACL-HLT '19.

MA 6.8 Mon 11:30 POT/0361

Can a Quantum Computer Simulate Nuclear Magnetic Resonance Spectra Better than a Classical One? — •Keith R. Fratus, Nicklas Enenkel, Sebastian Zanker, Jan-Michael Reiner, Michael Marthaler, and Peter Schmitteckert — HQS Quantum Simulations GmbH, Karlsruhe, Germany

The simulation of the spectra measured in nuclear magnetic resonance (NMR) spectroscopy experiments is a computationally non-trivial problem, and as such, it represents a problem for which a quantum computer may provide some practical advantage over traditional computing methods. In order to understand the extent to which such problems may provide examples of useful quantum advantage, it is important to understand the limitations of existing classical simulation methods. In this talk, we present our classical solver designed to solve such problems, and benchmark its performance. We find that it performs well, even outside of the more typical experimental regimes, and discuss what implications this may have for future efforts to demonstrate quantum advantage in the context of NMR.

MA 6.9 Mon 11:45 POT/0361

From imaging static magnetic fields to characterization of GHz magnetic noise - multi-method magnetometer comprising NV, MFM and MOKE — •Nele Harnack, Björn Josteinsson, Andrea Morales, Simon Josephy, and Gabriel Puebla-Hellmann — QZabre Ltd., Zürich (Switzerland)

Nanoscale imaging of static and GHz magnetic fields allows the in-depth study of phenomena like skyrmions, spin-waves and antiferromagnets. Experimental techniques include nitrogen-vacancy (NV) magnetometry, magnetic force microscopy (MFM) and magneto-optic Kerr effect (MOKE) [1,2]. In NV magnetometry, a spin defect in diamond serves as an atomic-scale sensor, delivering quantitative results and high resolution [3]. Here, we show how NV centers yield information complementary to MFM and MOKE - stray field and reconstructed magnetization - in a comparative study of BiYIG using the three techniques. The study is performed on a commercial microscope (QSM), enabling fast localization of the sample region when switching between modes. NV imaging provides insight beyond static field imaging [4]. Here we use scanning relaxometry (T1) to image the GHz magnetic noise present in the sample. The combination of methods enables an in-depth study of magnetic textures in BiYIG, with NV extending the capabilities of well-established techniques by measuring the coupling of the NV spin state to spin fluctuations in the material.

[1] Kazakova et al; J. Appl. Phys., 2019, 125, 060901. [2] Kimel et al; J. Phys. D: Appl. Phys., 2022, 55, 463003. [3] Degen; Appl. Phys. Lett, 2008, 92, 243111. [4] Finco et al.; Nat. Comm., 2021, 12, 767.

MA 6.10 Mon 12:00 POT/0361

Nanoscale mapping of magnetic orientations with complex x-ray magnetic linear dichroism — •Marina Raboni-Ferreira[1,2], Benedikt J. Daurer[3], Jeffrey Neethirajan[1], Andreas Apseros[4,5], Sandra Ruiz-Gómez[1,6], Burkhard Kaulich[3], Majid Kazemian[3], and Claire Donnelly[1,7] — [1]MPI CPfS, Dresden, Germany — [2]UNICAMP, Campinas, Brazil — [3]DLS, Didcot, UK — [4]ETH, Zurich, Switzerland — [5]PSI, Villigen, Switzerland — [6]ALBA, Barcelona, Spain — [7]WPI-SKCM2, Hiroshima, Japan

Compensated magnets are of increasing interest for both fundamental research and applications, as their net-zero magnetization enables ultrafast dynamics and robust order. To understand and control this order, nanoscale mapping of local domain structures is essential. Here, we combine X-ray magnetic linear dichroism (XMLD), a spectroscopic technique sensitive to the local Néel-vector orientation, with ptychography, a coherent X-ray imaging technique, to obtain high-resolution images of in-plane magnetic orientations in a model sample exhibiting a Landau pattern. By combining these techniques with an unsupervised machine learning approach, we retrieve the full complex XMLD spectrum of the sample, and map its magnetic domains with sub-100-nm resolution. Our results show that phase contrast is significantly stronger than the corresponding absorption contrast, offering higher spatial resolution imaging. This establishes phase contrast as a high-resolution mechanism for mapping magnetic orientations and paves the way toward higher-dimensional X-ray imaging, including Néel-vector orientation tomography of antiferromagnets.

MA 6.11 Mon 12:15 POT/0361

Development of in-house high-yield in-situ TEM chip production with magnetic thin-films — •Sindre Vie Jørgensen[1], Patrick R. B. Thomassen[1], Trond Hauklien[1], Marthe Linnerud[1], Asle Sudbø[1], David Barriet[1,2], and Magnus Nord[1] — [1]IFY, NTNU, Norway — [2]NYB Partner DA

Transmission Electron Microscopy (TEM) is a powerful tool for studying materials at the nanoscale. For future device materials, being able to apply a biasing voltage during TEM imaging is highly advantageous for observing magnetic domain responses at the nanoscale. We have developed a 'frontside-then-backside' method to create in-situ biasing TEM chips for as-deposited thin-film samples. This creates 100+ chips from a 4" Si wafer per production batch, which is highly customisable, allowing for multiple designs, TEM window dimensions, and circuit layouts simultaneously, with little variation in production time. This method has been tested with 20 nm thick, 5 um wide permalloy thin films with two narrow sections, 2,5 um wide, for a local increase in current density. Bias has been applied during magnetic Lorentz TEM (LTEM) to verify in-situ capabilities by shifting magnetic domain walls within the film via thermal excitation. This greatly expands the utility of the TEM for studying device-relevant magnetic materials, as simultaneous in-situ studies of the magnetics, structure and composition become possible.

MA 6.12 Mon 12:30 POT/0361

Scanning Magnetometry of van der Waals magnets under in-situ controlled strain — •Yuchen Zhao[1], José Claudio Corsaletti Filho[1], Chenhui Zhang[2], Yejin Lee[1], Young-Gwan Choi[1], Elina Zhakina[1], Hyunsoo Yang[2], Elena Gati[1], Claire Donnelly[1], and Uri Vool[1] — [1]Max Planck Institute for Chemical Physics of Solids, Dresden, Germany — [2]National University of Singapore, Singapore, Singapore

In recent years, van der Waals (vdW) magnets have emerged as one of the promising research directions in the field of condensed matter physics. Due to their thin nature, vdW magnets are mechanically more flexible than their bulk counterparts, allowing them to withstand greater strain. Because strain distorts the lattice, it is expected to modify magnetic properties and may even stabilize new magnetic states. While magnetic imaging of vdW materials has so far been limited to small applied strains, achieving and visualizing magnetic textures under large strain remains a significant challenge. Here, we report a technique that enables large in-situ controlled strain engineering of vdW magnets under scanning probe microscopy at room temperature. We use a piezoelectric actuator-based uniaxial strain cell to strain Fe_3GaTe_2 flakes as a proof-of-principle example of our method. By incorporating this setup into the Magnetic Force Microscope (MFM), we can locally probe the influence of strain on magnetic textures, revealing strain modulation of the magnetic configuration. In the future, this setup will open the investigations of strain-induced magnetic effects in a broad class of vdW systems.