MA 37: Magnetic Imaging Techniques

Time: Thursday 15:00–17:45 Location: H16

MA 37.1 Thu 15:00 H16

Magnetic particle spectroscopy of ferrite nanoparticles: Controlling the Néel to Brownian relaxations — •Ondřej Kaman[1], Tereza Voltrová[1,2], Lenka Kubíčková[1,2], Ali Hassan[1], Pavel Veverka[1], Kyo-Hoon Ahn[1], Karel Knížek[1], Denisa Kubániová[2], and Jaroslav Kohout[2] — [1]FZU - Institute of Physics, CAS, Praha, Czech Republic — [2]Faculty of Mathematics and Physics, Charles University, Praha, Czech Republic

The Fourier transform of the magnetization response of a suspension of magnetic particles to a sinusoidal AC magnetic field provides so-called magnetic particle spectrum, i.e., a series of higher harmonics that originate in the non-linear $M(H)$ dependence. This characteristic is crucial for magnetic particle imaging (MPI), which is an emerging technique employing magnetic particles, typically in the superparamagnetic state, as exogeneous tracers for medical imaging. The magnetization dynamics of such tracers is governed by two distinct mechanisms, the Néel relaxation of magnetic moments and the Brownian rotation of whole particles. The present study is based on a series of hydrothermally prepared and thoroughly characterized (XRD, XRF, TEM, SQUID magnetometry) samples of $\mathrm{Co}_{1-x}\mathrm{Ni}_x\mathrm{Fe}_2\mathrm{O}_4$ particles with x=0–0.5 and the mean crystallite size of 8–9 nm. Their silica-coated clusters, forming colloidally stable aqueous suspensions, were prepared, and MPI study was performed by means of an in-house built system (interchangeable coils impedance-matched to ∼10, 15, 25, 35, and 50 kHz; magnetic field up to 20 mT).

MA 37.2 Thu 15:15 H16

Nanoscale magnetic imaging with color centers in fiber-coupled diamond nanobeams — •Gesa Welker[1], Yufan Li[1], Richard Norte[2], and Toeno van der Sar[1] — [1]Delft University of Technology, Faculty of Applied Sciences, Lorentzweg 1, 2628 CJ Delft, the Netherlands — [2]Delft University of Technology, Faculty of Mechanical Engineering, Mekelweg 2, 2628 CD Delft, the Netherlands

Nitrogen vacancy centers (NV-centers) in diamond are powerful magnetic field sensors that are excited and read out optically. They are an established tool for imaging weak magnetic signatures of condensed matter samples such as skyrmions, spin waves or 2D magnetism [1]. We present a unique fiber-coupled approach to scanning probe magnetometry, where a diamond nanobeam with NV-centers at its apex is attached to a tapered optical fiber and scanned across a sample [2]. Fiber-coupling could enable a higher excitation and collection efficiency compared to traditional setups. It also simplifies measurements at low temperatures, because it eliminates the need for re-alignment of free-space optics. We demonstrate diamond nanobeam fabrication via quasi-isotropic etching and a robust nanobeam-fiber assembly using optical glue. With this setup, we performed a 2D scan of the magnetic stray field of a current-carrying wire with sub-micrometer resolution [3]. Our method is also promising for magnetic sensing with recently emerged color centers such as tin vacancy centers (SnV-centers) [4].

[1] Casola et al. Nat. Rev. Mater 3, 17088 (2018) [2] Y. Li et al. ACS Photonics 10, 1859-1865 (2023) [3] Y. Li, G. Welker et al., New J. Phys. 26, 103031 (2024) [4] T. Iwasaki et al. PRL 119, 253601 (2017)

MA 37.3 Thu 15:30 H16

Planar scanning probe microscopy enables nanoscale vector magnetic field imaging with nitrogen-vacancy centers — •Paul Weinbrenner[1,2], Patricia Klar[3], Christian Giese[3], Luis Flacke[4,5], Manuel Müller[4,5], Matthias Althammer[4,5], Stephan Geprägs[4], Rudolf Gross[4,5,6], and Friedemann Reinhard[1,2,6] — [1]Institute for Physics, University of Rostock, Rostock, Germany — [2]Department of Life, Light and Matter, University of Rostock, Rostock, Germany — [3]Fraunhofer Institute for Applied Solid State Physics, Freiburg, Germany — [4]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Garching, Germany — [5]Physics Department, Technical University of Munich, Garching, Germany — [6]Munich Center for Quantum Science and Technology, Munich, Germany

We present imaging of vector magnetic fields on the nanoscale using planar scanning probe microscopy with nitrogen-vacancy (NV) centers in diamond as magnetic field sensors. Instead of traditional tip-based scanning probes, we employ an extended bulk diamond doped with NV centers. Despite the probe's large lateral size, it can still be scanned in nanoscale proximity to a planar sample.

We perform repeated measurements with NV centers with different orientations to obtain a direct image of the three-dimensional vector magnetic field of magnetic vortices in a thin-film magnetic heterostructure. Our result opens the possibility of quantum sensing using multiple qubits within the same scanning probe, which can be used for entanglement-enhanced and massively parallel sensing schemes.

MA 37.4 Thu 15:45 H16

Nanostructure and Coercivity Mechanism of Single-Phase $\mathbf{Ce(Co_{0.8}Cu_{0.2})_{5.4}}$ — •Tatiana Smoliarova[1], András Kovács[2], Nikita Polin[3], Esmaeil Adabifiroozjaei[4], Shangbin Shen[4], Xinren Chen[3], Leopoldo Molina-Luna[4], Oliver Gutfleisch[4], Konstantin Skokov[4], Michael Farle[1], Baptiste Gault[3], and Rafal E. Dunin-Borkowski[2] — [1]Faculty of Physics and Center for Nanointegration, Universität Duisburg-Essen, Duisburg, Germany — [2]Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons, Forschungszentrum Jülich, Germany — [3]Max-Planck-Institut für Nachhaltige Materialien GmbH, Düsseldorf 40237, Germany — [4]Institute of Materials Science, Technische Universität Darmstadt, 64287 Darmstadt, Germany

CeCo_5 rare-earth RCo_5 permanent magnets achieve high coercivity (H_C = 1 T) upon the addition of Cu up to 20%, making Ce-based magnets an abundant R-alternative to Sm-based magnets. Here, we report a study that employs TEM in conjunction with APT to investigate the $\mathrm{Ce(Co_{0.8}Cu_{0.2})_{5.4}}$ magnet, prepared by induction melting followed by controlled heat treatment and water quenching. The process results in the formation of a cellular structure characterized by elongated along the *c*-axis, Cu-rich precipitates with a diameter of ∼ 5 nm and a length of ∼ 20 nm, surrounded by a Cu-poor matrix with a thickness of ∼ 10 nm. The alignment of the Cu-rich precipitates creates a preferential direction for zigzag-shaped domain walls, yielding effective pinning and H_C = 1 ± 0.05 T. Financial support by DFG, CRC/TRR 270 (project ID 405553726) is acknowledged.

MA 37.5 Thu 16:00 H16

Transport of Intensity Phase Retrieval in the Presence of Intensity Variations and Unknown Boundary Conditions — •Oleksandr Zaiets[1,2], Axel Lubk[1,2], Radmilla Kyrychenko[1], Daniel Wolf[1], Maximilian Wegner[1], Max Herzog[1], Moritz Winter[1,3,4], Praveen Vir[3], Johannes Schultz[1], Claudia Felser[3], and Bernd Büchner[1,2] — [1]Leibniz Institute for Solid State and Materials Research Dresden, Dresden, Germany — [2]Institute of Solid State and Materials Physics, TU Dresden, Dresden, Germany — [3]Max Planck Institute for Chemical Physics of Solids, Dresden, Germany — [4]Dresden Center for Nanoanalysis, cfaed, Technical University Dresden, Dresden, Germany

Transport of Intensity Equation (TIE) phase retrieval technique is widely applied in light, X-ray and electron optics to reconstruct, e.g., refractive indices, electric and magnetic fields in solids. The TIE method reconstructs the phase from two or three mutually slightly defocused microscopy images by solving an elliptic partial differential equation - the TIE. Here, we present a largely improved TIE reconstruction algorithm, which properly considers intensity variations as well as unknown boundary conditions in a finite difference implementation of the TIE. That largely removes reconstruction artifacts encountered in state-of-the-art Poisson solvers of the TIE, and hence significantly increases the applicability of the technique. We demonstrate the improved performance of the TIE reconstruction algorithm at a set of simulated and experimental image intensities arising from magnetic structures investigated in TEM.

MA 37.6 Thu 16:15 H16

Fast spectroscopic imaging using extreme ultraviolet interferometry — •Hannah C. Strauch[1], Fengling Zhang[2], Stefan Mathias[1], Thorsten Hohage[3], Stefan Witte[2,4], and G. S. Matthijs Jansen[1] — [1]University of Göttingen, 1st Institute of Physics, Göttingen, Germany — [2]Advanced Research Center for Nanolithography, Amsterdam, The Netherlands — [3]University of Göttingen, Institute of Numerical and Applied Mathematics, Göttingen, Germany — [4]Imaging Physics department, TU Delft, The Netherlands

Extreme ultraviolet (EUV) pulses generated by high harmonic generation (HHG) offer element-specificity in spectroscopic applications [1], and an excellent platform for nanoscale coherent diffractive imaging. Thus, the combination of time-resolved spectroscopy and microscopy using HHG light is highly promising, but it is only hardly explored due to the challenge of extracting full spectroscopic and microscopic information from measurements of reasonable duration.

We will present FTSH, an interferometric solution that combines Fourier-transform spectroscopy (FTS) and holography [2], employing a pair of phase-locked EUV pulses. This combination explicitly encodes the EUV spectral information in the diffraction pattern. Compared to traditional FTS, FTSH dramatically reduces the interferometric sampling requirements. This enables full spectroscopic images in less than two minutes and makes our approach particularly promising for femtosecond time-resolved spectroscopic imaging.

[1] Möller et al., Commun. Phys. 7, 74 (2024)

[2] Strauch et al., Opt. Express 32(16), 28644-28654 (2024)

MA 37.7 Thu 16:30 H16

Magnetic vector field imaging with single domain magnetooptical indicator films — •Michael Path and Jeffrey McCord — Institute for Materials Science, Kiel University, Germany

Robust and fast magnetic vector field imaging is essential for the characterization of, e.g., electronic systems. We present a magnetooptical method for quantitative and spatially resolved magnetic vector field imaging based on the use of magnetooptical indicator films. Simultaneous magnetooptical temperature extraction ensures temperature independent quantification of the magnetic field amplitude and angle. Yttrium-iron-garnet indicator films with in-plane and out-of-plane magnetic anisotropy can be used for this method. In both cases, a magnetic bias field is applied to bring the indicator film into a single-domain state along four different directions. By measuring the out-of-plane tilt of the magnetization with four images using magnetooptical microscopy, the local magnetic vector field distribution and the local temperature are obtained. As an example, the magnetic vector field distribution generated by the current of an integrated circuit is observed and compared with the calculations. The accuracy of this method is verified by means of relative and statistical error analysis.

15 min. break

MA 37.8 Thu 17:00 H16

Characterization of the periodic stray field along ferromagnetic domain textures in synthetic antiferromagnets — •R. J. Peña Román[1], S. Maity[1], F. Samad[2,3], A. Kákay[2], O. Hellwig[2,3], K. Kern[1,4], and A. Singha[5,1] — [1]Max Planck Institute for Solid State Research — [2]Institute of Ion Beam Physics and Material Research, Helmholtz-Zentrum Dresden-Rossendorf — [3]Insititute of Physics, Chemnitz University of Technology — [4]Institute de Physique, École Polytechnique Fédérale de Lausanne — [5]Institute of Solid State and Materials Physics, Dresden University of Technology,

Magnetic imaging of domains and domain walls (DWs) composing the texture of any magnetic material is a crucial step toward understanding their properties and finding solutions to tailor the material properties to achieve new technology-driven functionalities. Synthetic Antiferromagnets (SAFs) are particularly interesting due to their highly tunable properties since their magnetic texture can be controlled by adjusting the design parameters during fabrication. Here, we use diamond Nitrogen-Vacancy Scanning Probe Microscopy (NV-SPM) to investigate and characterize ferromagnetic domains with periodic stray fields in SAFs. The magnetic field in the sample is sensed by measuring the Zeeman splitting that it produces on the NV electron spin states, while the magnetic noise is detected due to its impact on the NV spin relaxation time. NV-SPM allows us to explore the sample properties quantitatively with high magnetic sensitivity and non-invasively at the nanoscale. It is essential to identify the nature of the DWs and engineer them for potential applications in magnonics or spintronics.

MA 37.9 Thu 17:15 H16

Investigation of charge-state stability in shallow NV centers with surface treatments — •Atharva Paranjape[1], Olga Shevtsova[1], Lisa Ebo[1], Toni Hache[1,2], Rainer Stöhr[2], Jörg Wrachtrup[2], and Aparajita Singha[1,3] — [1]Max Planck Institute for Solid State Research, Stuttgart — [2]3rd Institute of Physics and Research Center SCoPE, University of Stuttgart — [3]IFMP, Technical University of Dresden

Nitrogen-vacancy (NV) centers in diamond are optically active defects which can be used for precise measurement of magnetic fields. While near-surface NV centers can provide high spatial resolution in magnetic imaging, they also face charge-state instability, which is aggravated in in ultra-high-vacuum (UHV). Here we aim to develop surface-treatment methods to reduce charge-state instability of shallow ($<$ 10 nm from surface) NV centers in UHV conditions. We show that a TiO_2 coating using Atomic Layer Deposition (ALD) on nanostructured diamond stabilizes the charge state by modifying the local environment. These experiments are crucial for the development of a scanning NV magnetometer in UHV with a high spatial resolution.

MA 37.10 Thu 17:30 H16

Magnetic Force Microscopy: High Quality-Factor Two-Pass Mode — •Christopher Habenschaden[1], Sibylle Sievers[1], Alexander Klasen[2], Andrea Cerreta[2], and Hans Werner Schumacher[1] — [1]Physikalisch-Technische Bundesanstalt, 38116 Braunschweig — [2]Park Systems Europe GmbH, 68199 Mannheim

Magnetic Force Microscopy (MFM) is an effective technique for characterizing magnetic micro- and nanostructures, typically detecting interactions between a magnetically coated tip on an oscillating cantilever and the sample. MFM sensitivity is enhanced under vacuum conditions due to the higher cantilever quality factor (Q-factor), which significantly improves force sensitivity. However, the commonly used two-pass mode in MFM faces challenges under vacuum, as the high Q-factor can lead to tip crashing when surface forces overpower the restoring force during topography imaging.

Here, we present a novel approach for high-sensitivity vacuum MFM measurements while maintaining stable topography detection. Implemented on a Park Systems NX-Hivac AFM, this method modifies the two-pass mode to create a high Q-factor two-pass mode [1]. In the first pass, the cantilever's Q-factor is artificially lowered to ensure stable non-contact topography imaging. In the second pass, a phase-locked loop (PLL) measures the frequency shift, maintaining the maximum Q-factor for optimal sensitivity in magnetic field measurements. This approach prevents tip crashes during the first pass and eliminates nonlinear phase response in the second pass, ensuring robust and precise measurements. [1] Rev. Sci. Instrum. 95, 113704 (2024).