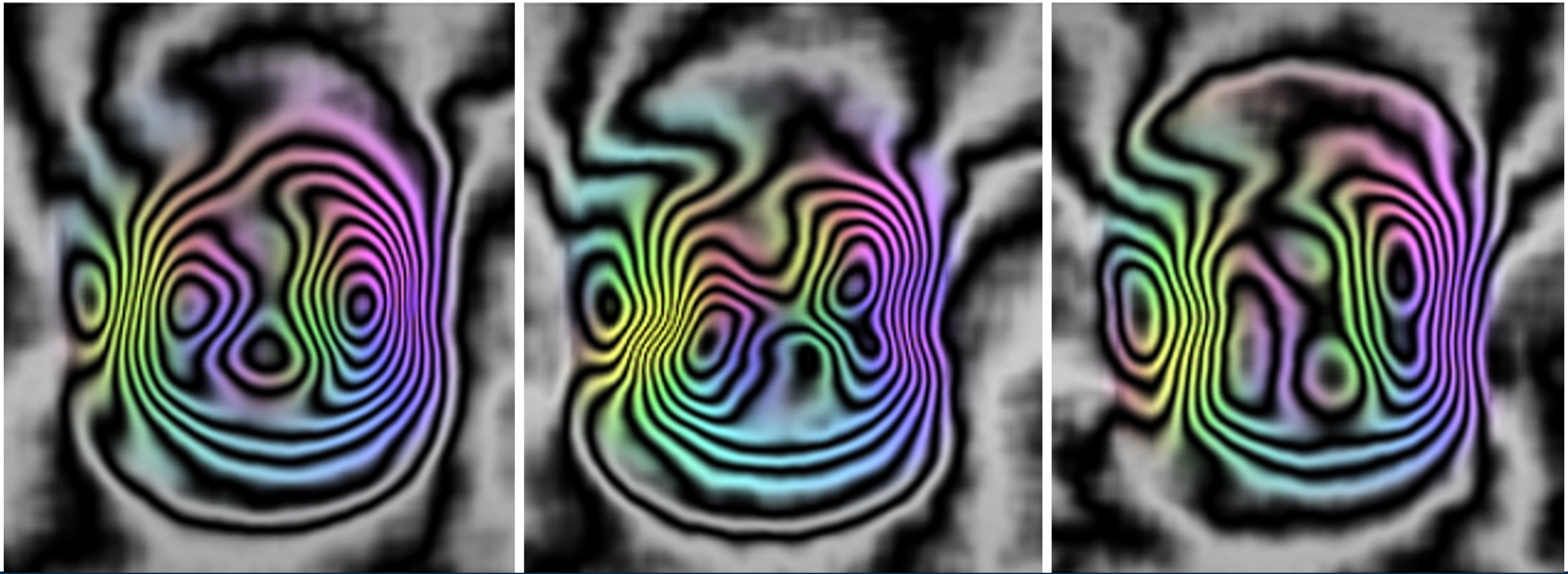


CHARACTERIZATION OF MAGNETIC TEXTURES IN MATERIALS FOR SPINTRONICS-BASED DEVICES USING TRANSMISSION ELECTRON MICROSCOPY

RAFAL E. DUNIN-BORKOWSKI, FENGSHAN ZHENG, ANDRÁS KOVÁCS, TREVOR ALMEIDA, QIANQIAN LAN, THIBAUD DENNEULIN, WEN SHI, LUYAN YANG, GIULIO POZZI, DIETER WEBER, ALEXANDER CLAUSEN, JOSEPH VAS, BENJAMIN ZINGSEM, AMIR TAVABI, FILIPP RYBAKOV, NIKOLAI KISELEV, ANDRII SAVCHENKO, STEFAN BLÜGEL

Member of the Helmholtz Association

JÜLICH Forschungszentrum

ERNST RUSKA-CENTRE FOR MICROSCOPY AND SPECTROSCOPY WITH ELECTRONS

Outline

- Transmission electron microscopy of nanoscale magnetic textures
- Towards three-dimensional imaging of magnetization
- Instrumentation development and future directions

Magnetic imaging in (S)TEM

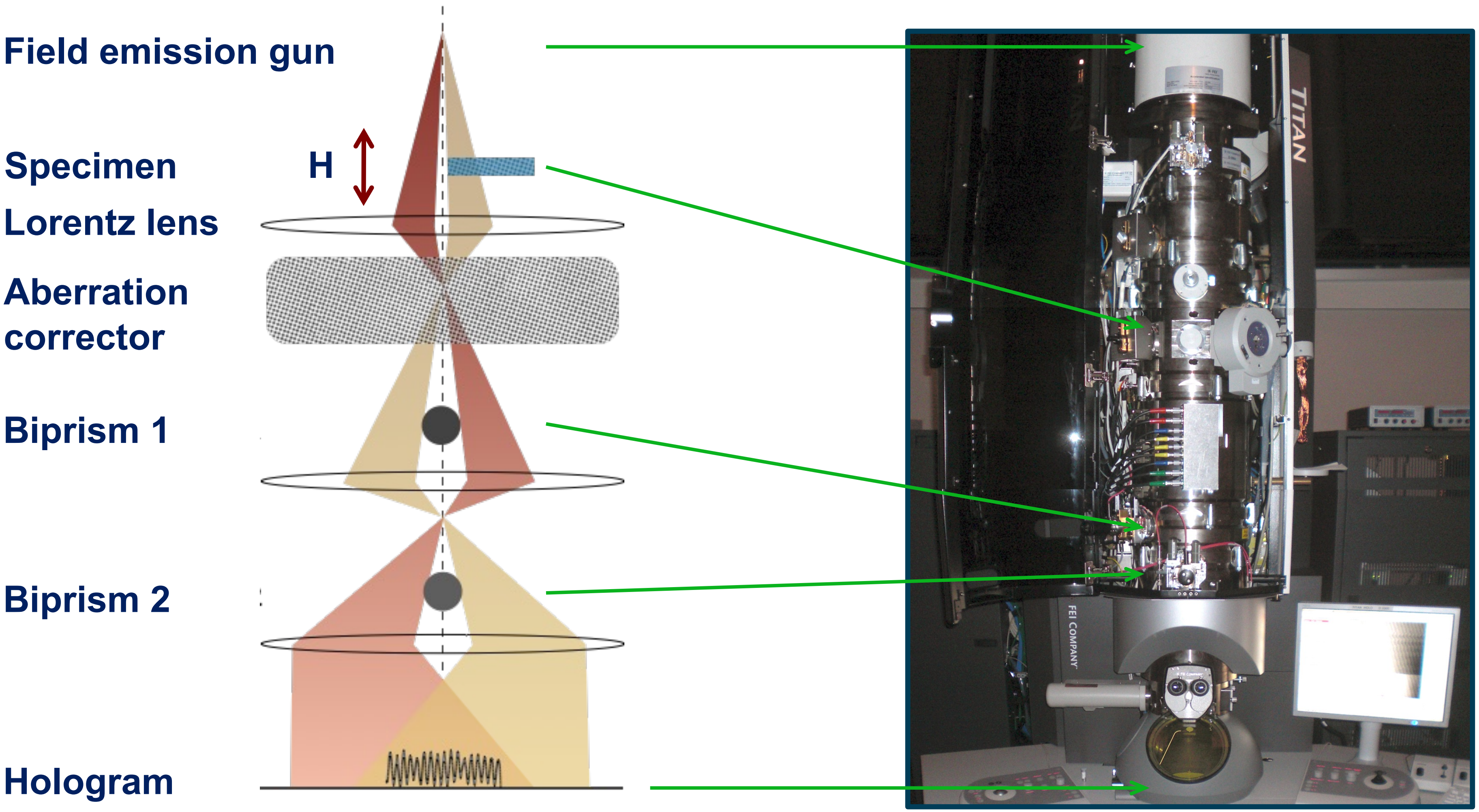
Spectroscopic techniques:

- **Electron magnetic circular dichroism**

Phase contrast (imaging and diffraction) techniques:

- **Lorentz imaging (Fresnel and Foucault modes)**
- **Off-axis electron holography**
- **STEM differential phase contrast imaging**
- **STEM ptychography**
- **Coherent diffractive imaging**

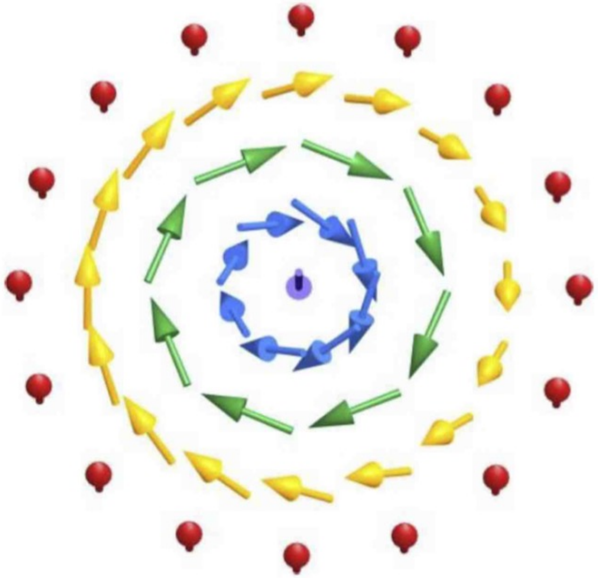
Off-axis electron holography in the TEM



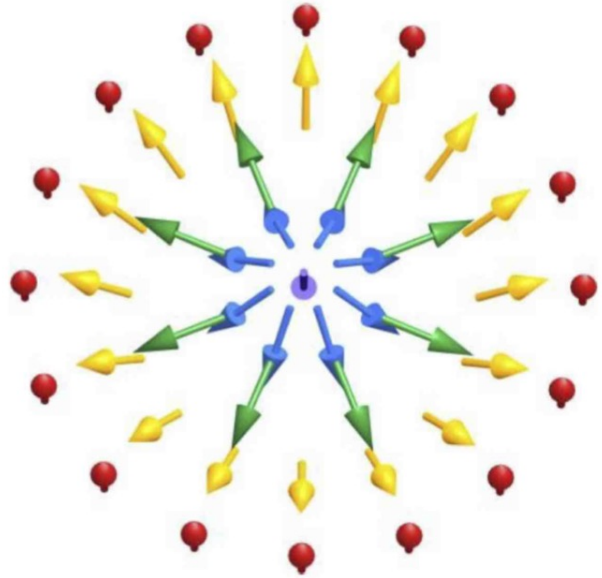
Electron holography provides direct access to the phase shift of the electron wave that passes through a specimen. The phase shift can be related to the in-plane magnetic induction and to the electrostatic potential projected in the electron beam direction.

Topological magnetic textures in confined sample geometries

Magnetic skyrmions



Spin configuration of a Bloch-type skyrmion.



Spin configuration of a Néel-type skyrmion.

The 2020 Skyrmionics Roadmap

C. Back *et al.* J. Phys. D: Appl. Phys. 53 (2020) 363001

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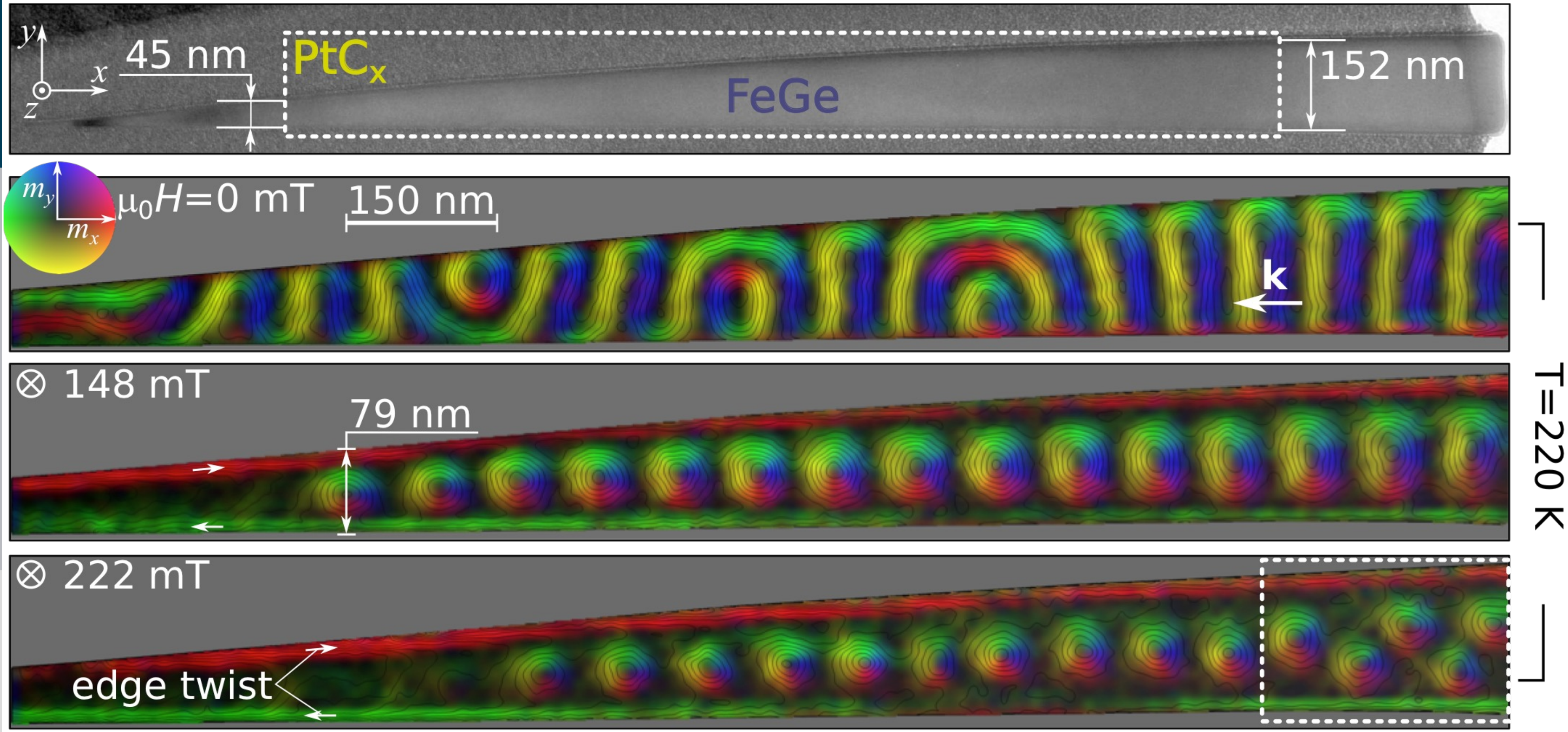
More complicated three-dimensional magnetic textures of skyrmions

- **Confined sample geometries**
- **Magnetic singularities**
- **Magnetic superstructures**
- **More complex magnetic textures**
- **Mixed Bloch-type and Néel-type character**

Magnetic skyrmions in confined sample geometries

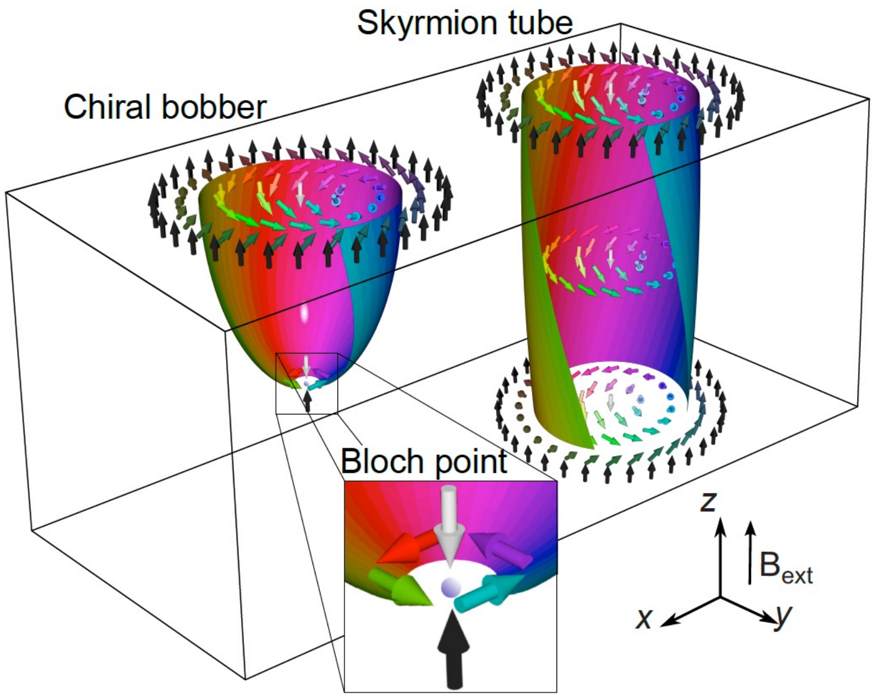
Magnetic field dependence at 220 K after zero field cooling

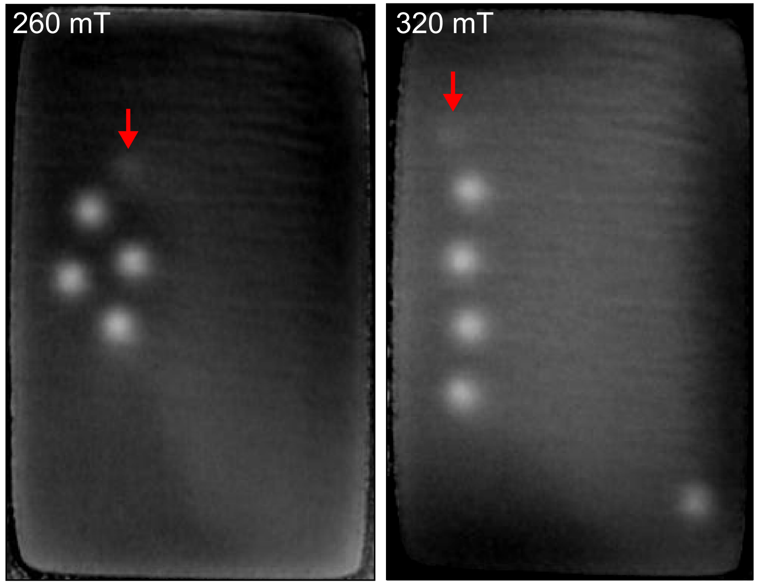


C Jin, Z-A Li, A Kovács, J Caron, F Zheng, F N Rybakov, N S Kiselev, H Du, S Blügel, M Tian, Y Zhang, M Farle and R E Dunin-Borkowski

Nature Communications 8 (2017), 15569

Magnetic singularities: Chiral magnetic bobbers





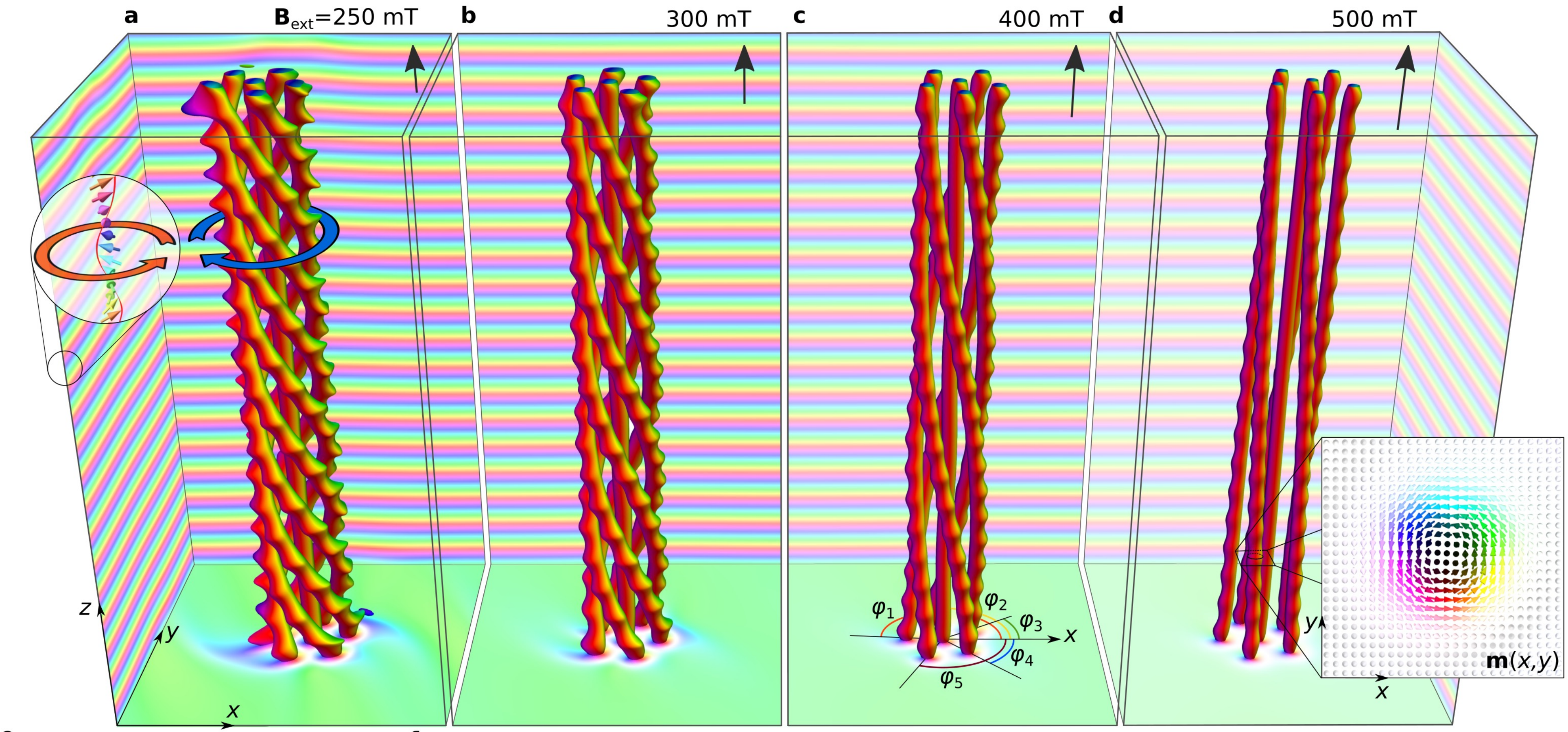
Magnetization vector field and corresponding isosurfaces for a skyrmion tube and a chiral bobber.

Experimental magnetic phase images of skyrmions and chiral bobbers in an FeGe plate in different applied magnetic fields.

F. Zheng, F. N. Rybakov, A. B. Borisov, D. Song, S. Wang, Z.-A. Li, H. Du, N. S. Kiselev, J. Caron, A. Kovács, M. Tian, Y. Zhang, S. Blügel, R. E. Dunin-Borkowski
Nature Nanotechnology 13 (2018), 451-455.

Magnetic superstructures: Skyrmion braids

Braided rope-like superstructures of 6 skyrmion strings in a chiral magnet, represented by isosurfaces of $m_z = 0$. The color modulation at the edges indicates the presence of the conical phase.

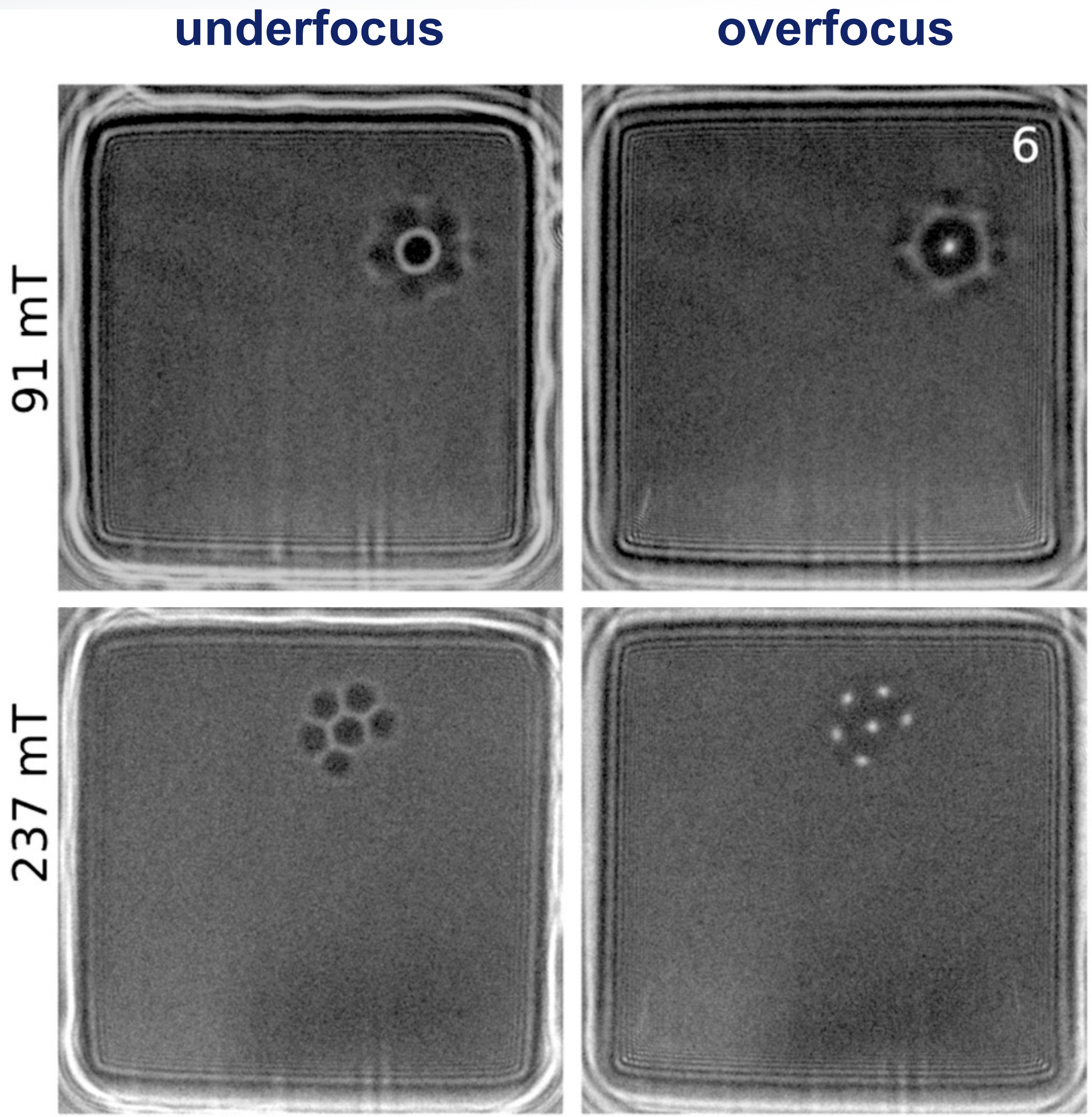


F Zheng, F N Rybakov, N S Kiselev, D Song, A Kovács, H Du, S Blügel, R E Dunin-Borkowski
Nature Communications 12 (2021), 5316.

Magnetic superstructures: Skyrmion braids

Experimental Lorentz TEM images in an FeGe plate of thickness 180 nm at 95 K in two different perpendicular magnetic fields:

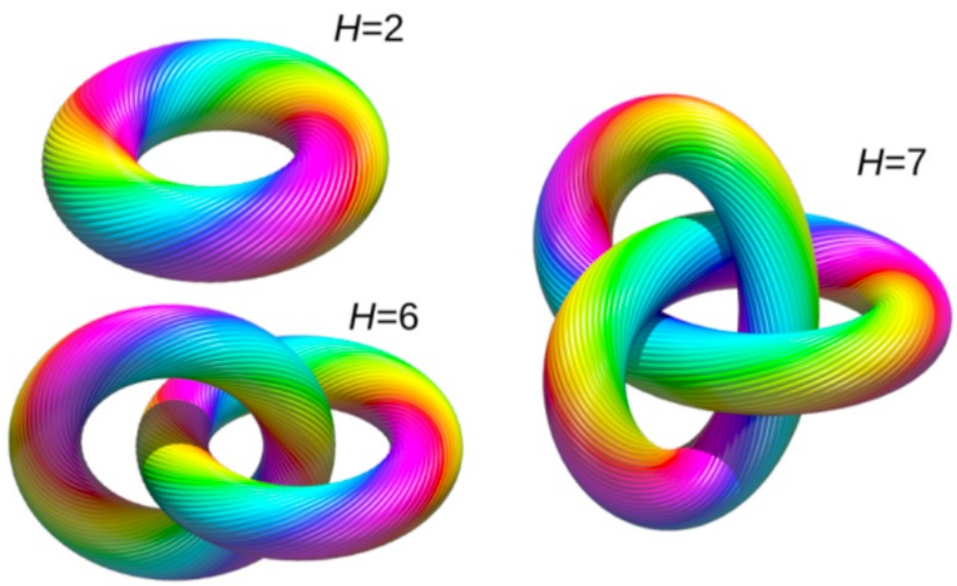
- 6 skyrmion braid (upper row)
- Untwisted skyrmions (lower row).



F Zheng, F N Rybakov, N S Kiselev, D Song, A Kovács, H Du, S Blügel, R E Dunin-Borkowski
Nature Communications 12 (2021), 5316.

Magnetic hopfions

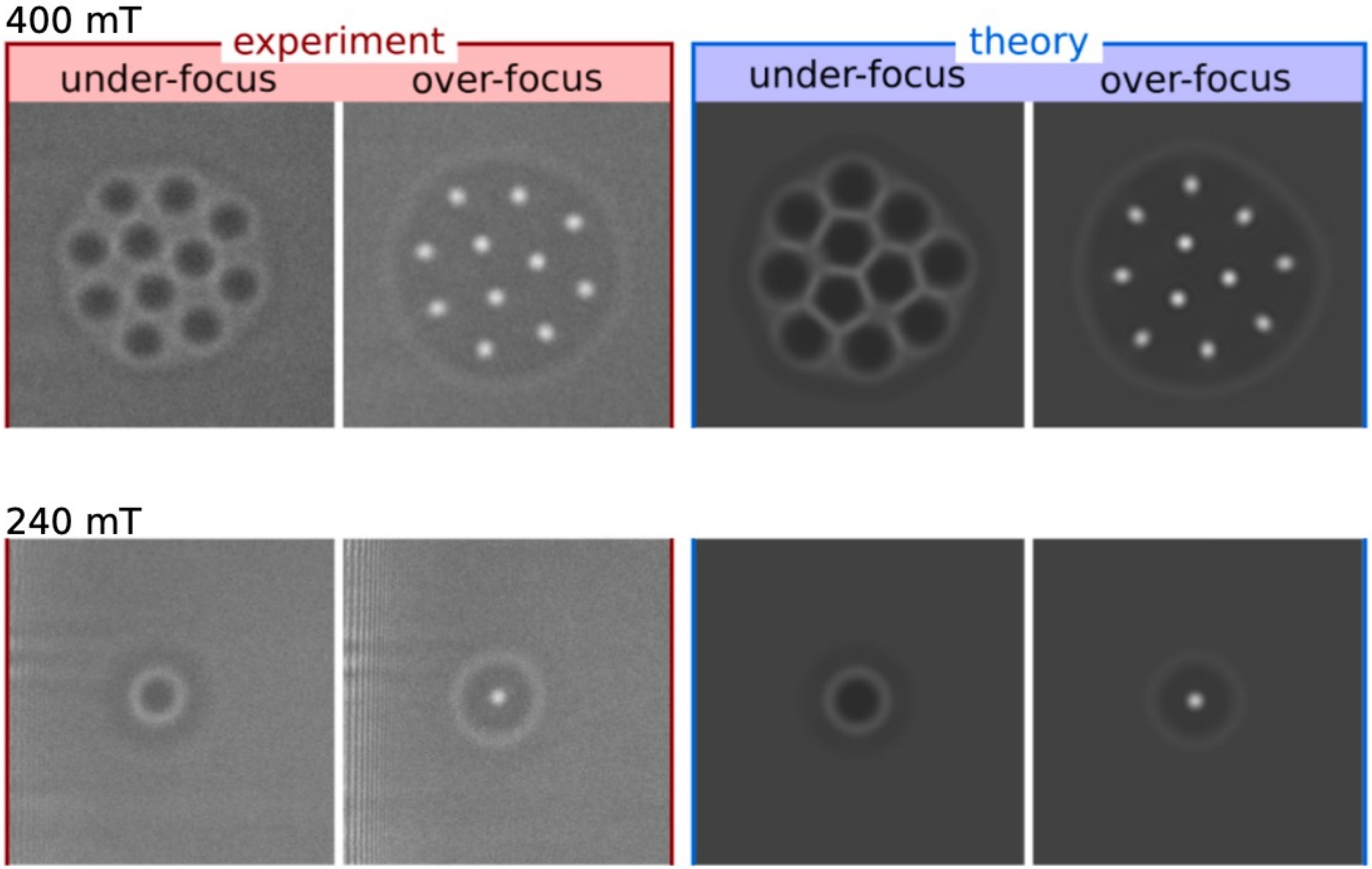
Hopfions can be considered as closed twisted skyrmion strings that take the shape of a ring in the simplest case.



The complexity of the hopfion shape and size increases with the Hopf index *H*.

Magnetic hopfions in solids
F N Rybakov, N S Kiselev, A B Borisov, L Döring, C Melcher, S Blügel
APL Materials 10 (2022), 111113.

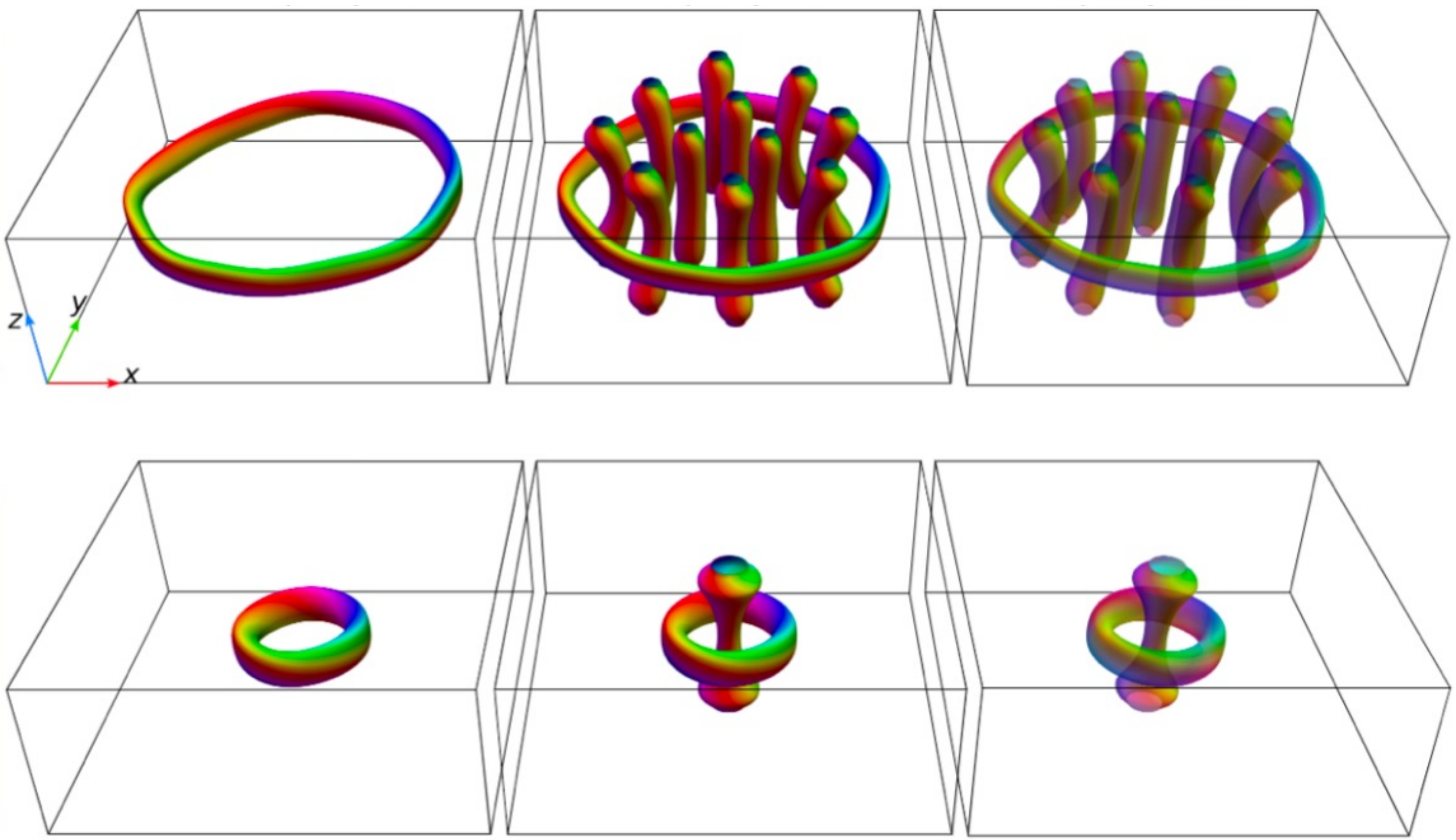
Coupled states of skyrmion strings and hopfions in FeGe plates of thickness 180 nm at 95 K



Hopfion rings in a cubic chiral magnet
F Zheng, N S Kiselev, F N Rybakov, L Yang, W Shi, S Blügel, R E Dunin-Borkowski
Nature 623 (2023), 718-723.

Magnetic hopfions

Simulations of $m_z = 0$ isosurfaces for hopfion rings with Q = −11 and −1.
Left: hopfion ring alone. Right: semitransparent isosurfaces.



Hopfion rings in a cubic chiral magnet
F Zheng, N S Kiselev, F N Rybakov, L Yang, W Shi, S Blügel, R E Dunin-Borkowski
Nature 623 (2023), 718-723.

Challenges

- **3D imaging of magnetization with nm spatial resolution**
- **Improved spatial & temporal resolution in magnetic measurements**
- **Improved control over sample geometry and damage**
- **Improved control over sample temperature and other stimuli**
- **Improved automation and correlative experiments**

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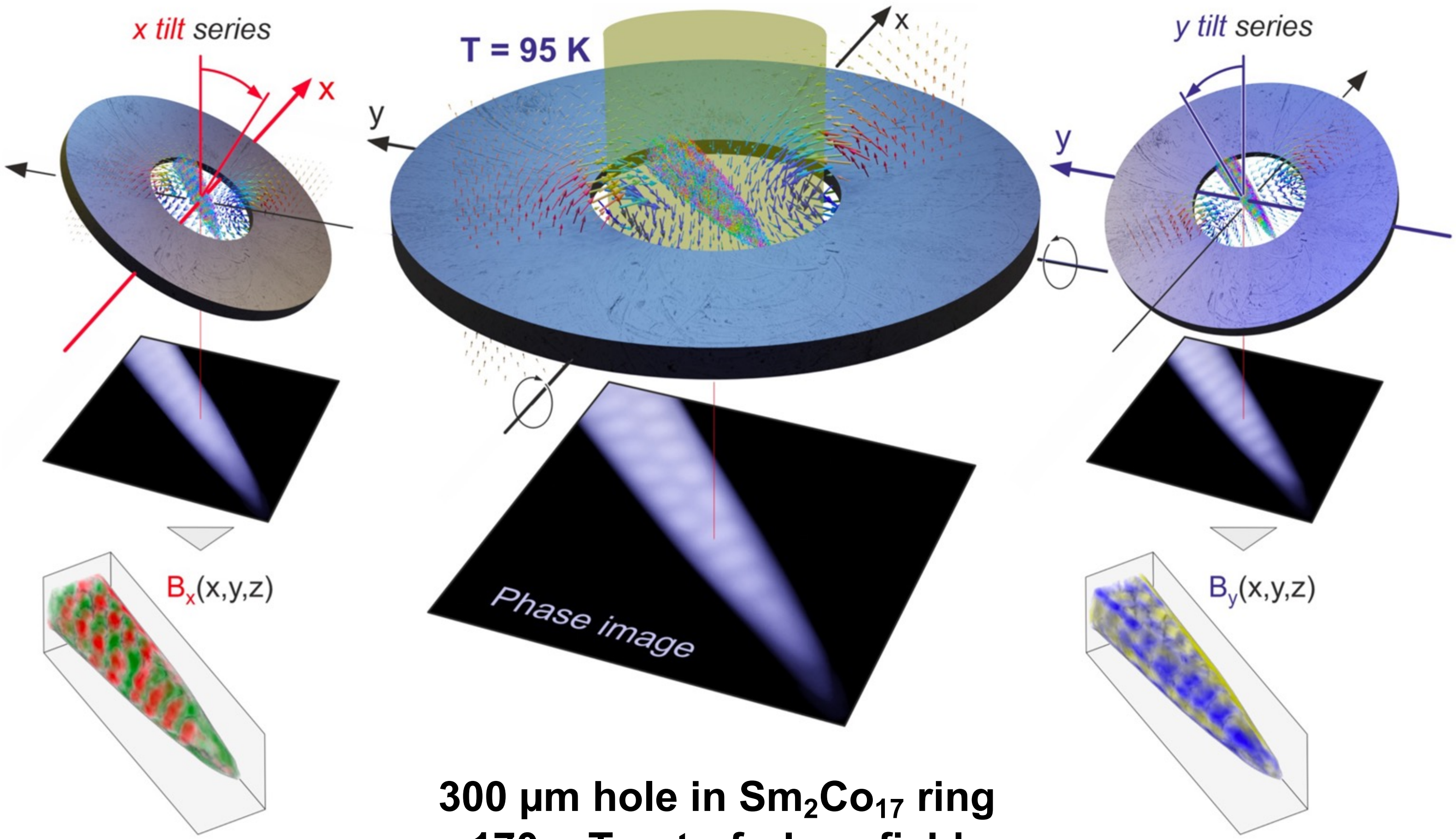
3D magnetic vector field tomography

Magnetic skyrmions in 3D in an applied magnetic field

Two tilt axes, applied field and low temperature.

Cryo holographic vector-field electron tomography of skyrmion tubes in FeGe.

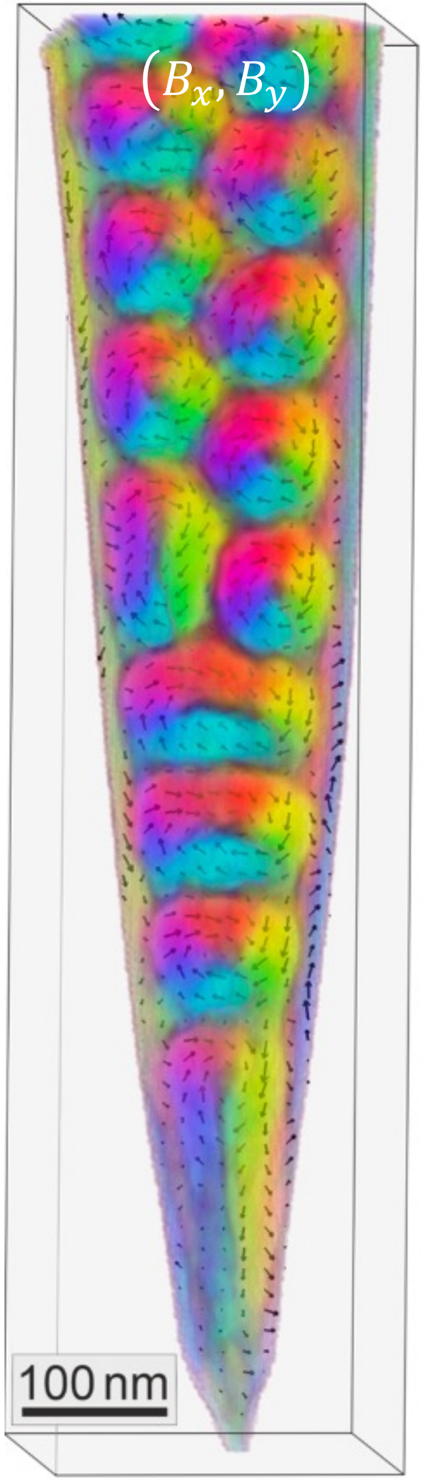


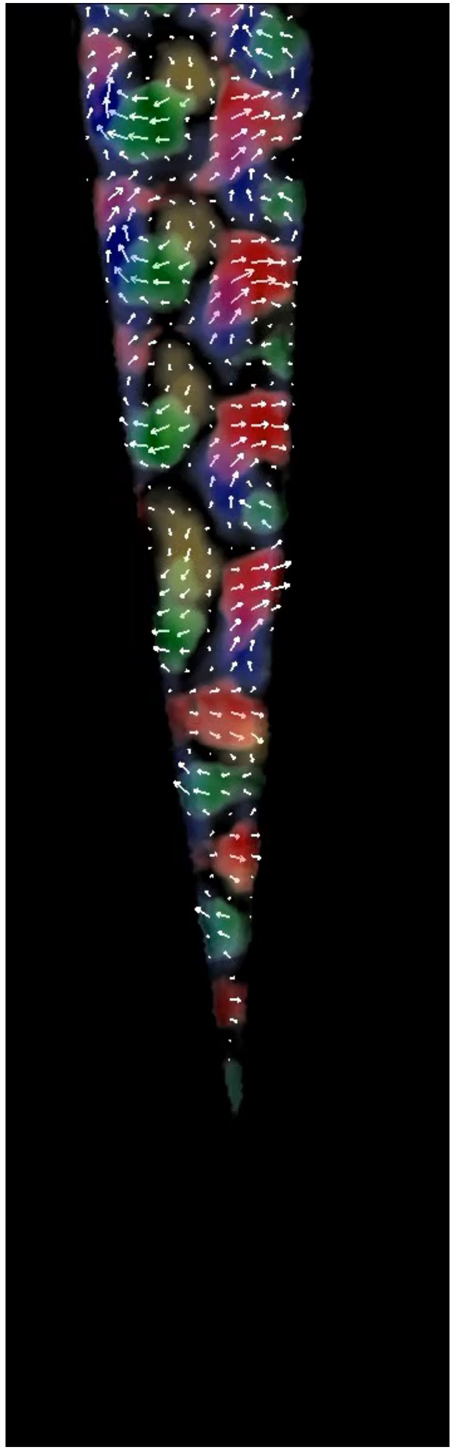
300 µm hole in Sm_2Co_{17} ring
170 mT out-of-plane field

D Wolf, S Schneider, U K Rößler, A Kovács, M Schmidt, R E Dunin-Borkowski, B Büchner, B Rellinghaus, A Lubk, Nature Nanotechnology 17 (2022), 250-255

- **Local deviations from Bloch character.**
- **Collapse of skyrmion texture at surfaces.**
- **Tilts of elongated SkTs at the tip.**
- **Correlated modulations of SkTs along their axes.**

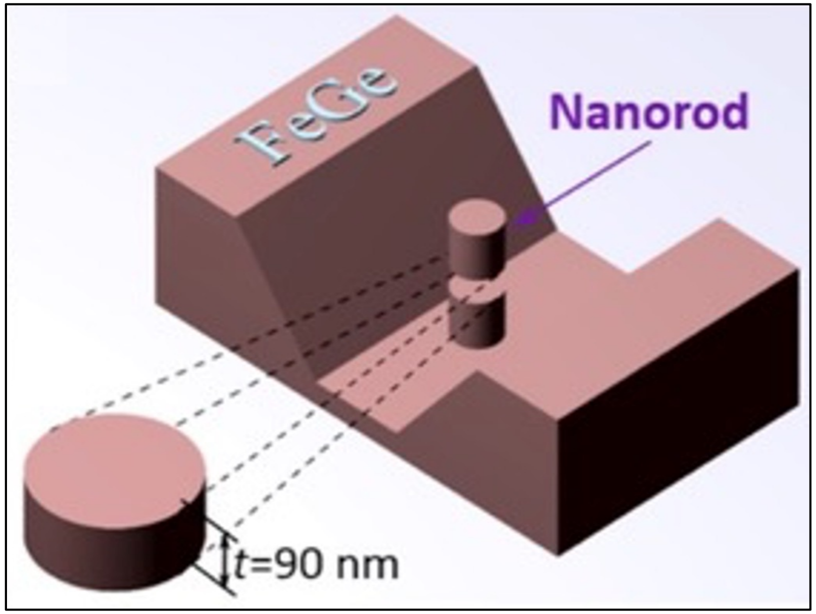
D Wolf, S Schneider, U K Rößler, A Kovács, M Schmidt, R E Dunin-Borkowski, B Büchner, B Rellinghaus, A Lubk, Nature Nanotechnology 17 (2022), 250-255

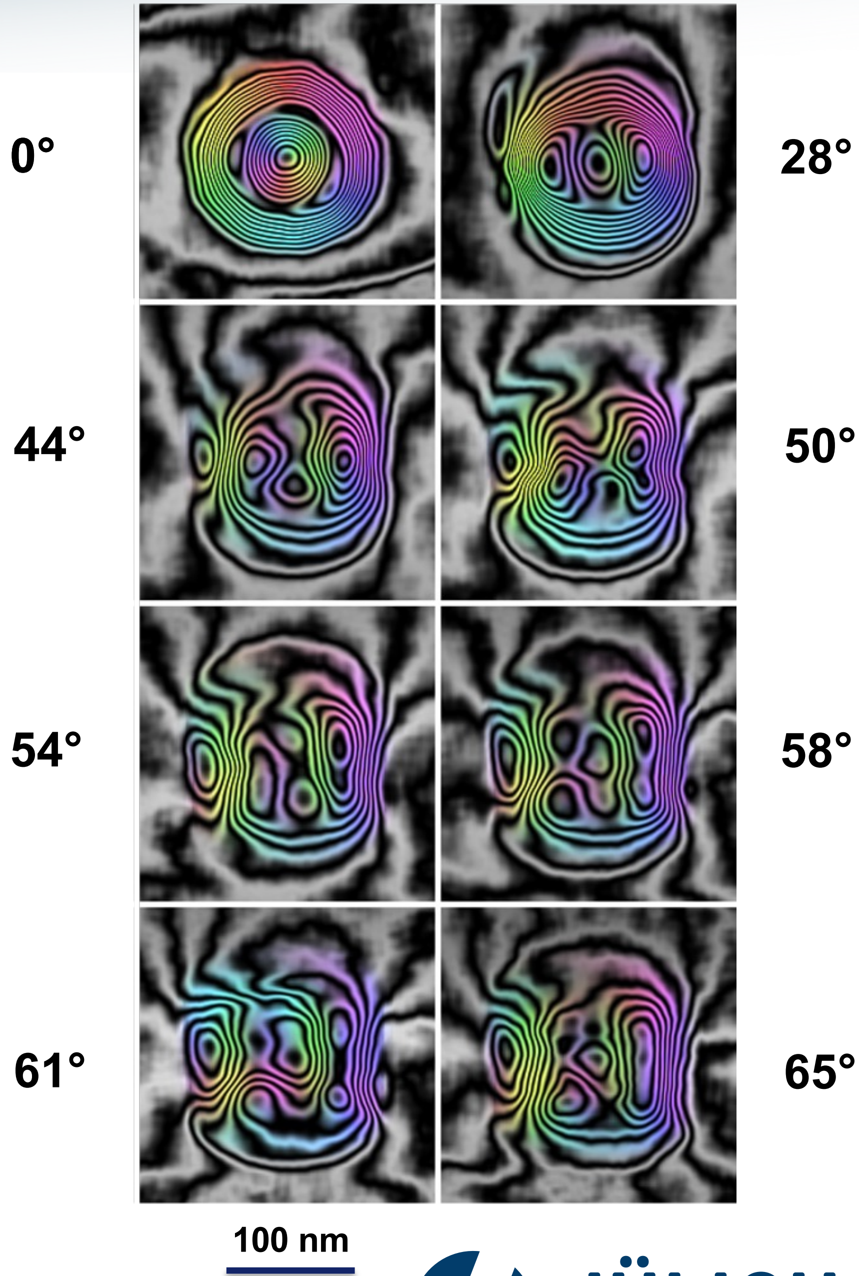




Mixed Bloch & Néel: Target skyrmion

Target skyrmion in FeGe

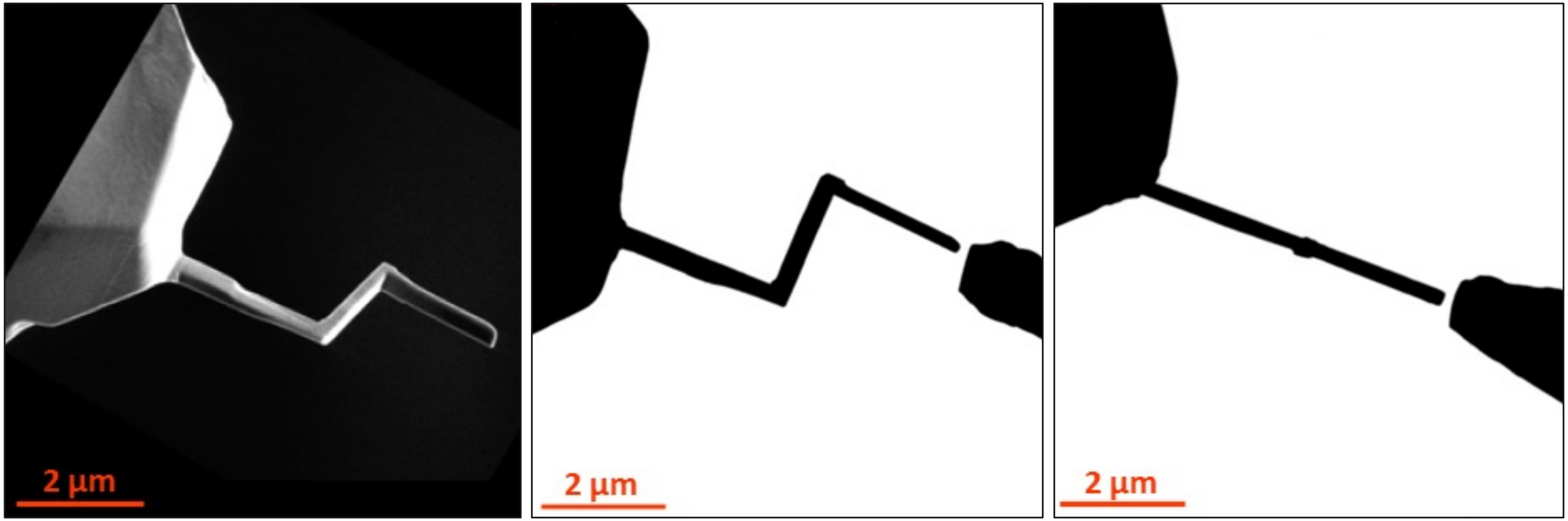




Collaboration with Haifeng Du, Jiadong Zang and colleagues.

Oersted field of a current

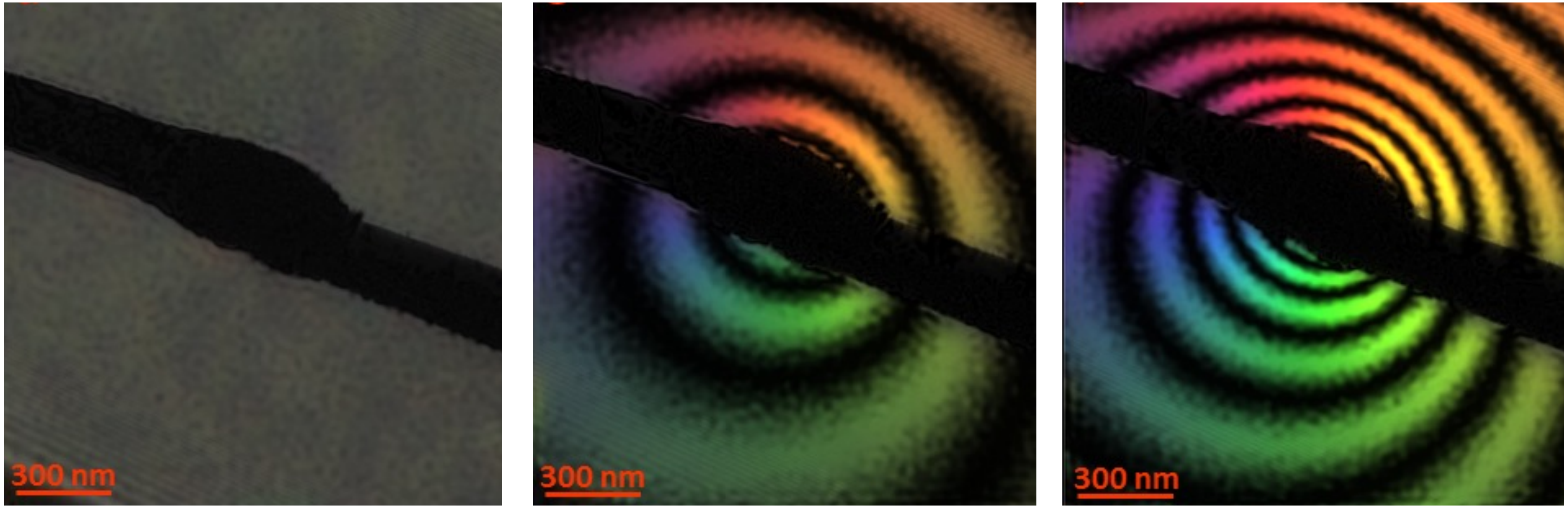
Magnetic field of a current-carrying wire



FIB milling and bright-field TEM images of Au needle and hook in a TEM-STM specimen holder with the tilt set first to 70° and then to 0° (with the hook arm parallel to the electron beam direction).

Magnetic field of a current-carrying wire

Experimental 8-times-amplified phase contour maps recorded for currents of 0, 2 and 4 mA through the wire



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New instrumentation

Ernst Ruska-Centre in Jülich: Short and medium term plans

- Existing microscope being equipped with advanced magnetizing stage, two helium flow cryostats, pulsed lasers, ultrafast beam blanker, GHz specimen holders, improved detectors and automation software.

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Titan HOLO microscope

German national perspective

Forschungszentrum

National research infrastructure

High energy resolution correlative electron and optical spectroscopy

UHV, gas injection

LHe cooled stage

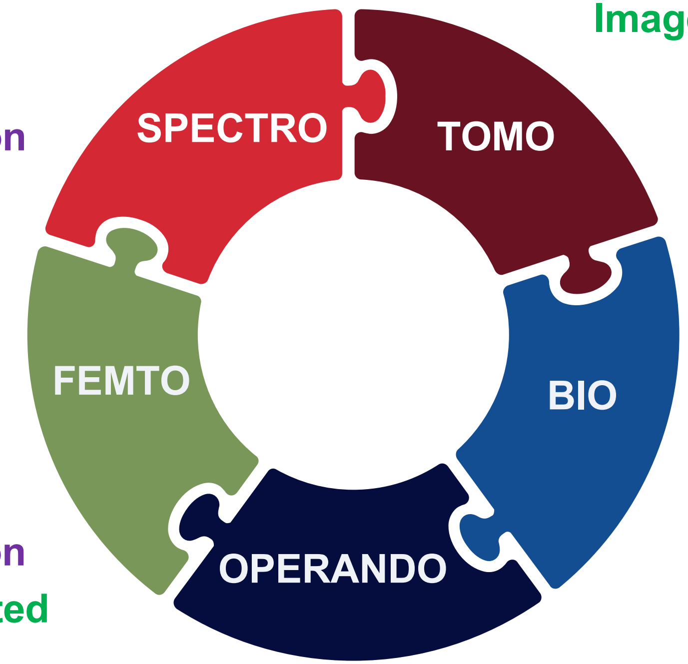
Light injection and collection

Probe Cs corrected

Integrated correlative atom probe and TEM

UHV LHe cooled stage

Image and probe Cs corrected



Ultrafast and single shot time-resolved TEM

Unique photoelectron gun

Light injection and collection

Image and probe Cs corrected

Pushing resolution and dose efficiency in biological cryo-EM

LHe cooled stage

Additional transfer lenses for novel phase plates

Image Cs/Cc corrected and probe Cs corrected

***In situ* growth and characterisation inside TEM starting from surface science base pressure**

UHV, gas injection LHe cooled stage

Image Cs corrected

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Challenges, opportunities and requirements

- Real-time three-dimensional imaging of electromagnetic fields
- Improved temporal resolution: ultrafast switching on the sub-ns scale
- Multiple stimuli (voltage, field, light, temperature, gas …)
- Atomic-resolution imaging of individual spins and charges
- Automation of workflows
- Real-time data analysis (especially for studies of dynamic processes)
- Adaptive optics (incl. pixelated phase plates)
- New dose-efficient imaging modes
- Correlative and multimodal experiments
- More modular electron microscopes
- Improved specimen stages

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Jan Caron, Patrick Diehle, Jörn Ungermann, Martin Riese, Ulrich Poppe

Kiyou Shibata, Yoshinori Tokura

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- Grant No. 823717, project “ESTEEM3”
- Grant No. 766970, project “Q-SORT”
- Grant No. 101094299, project “IMPRESS”

Deutsche Forschungsgemeinschaft:

- Project-ID 405553726 – TRR 270 “HoMMage”

SFB 917 NanoSwitches Collaborative Research Centre

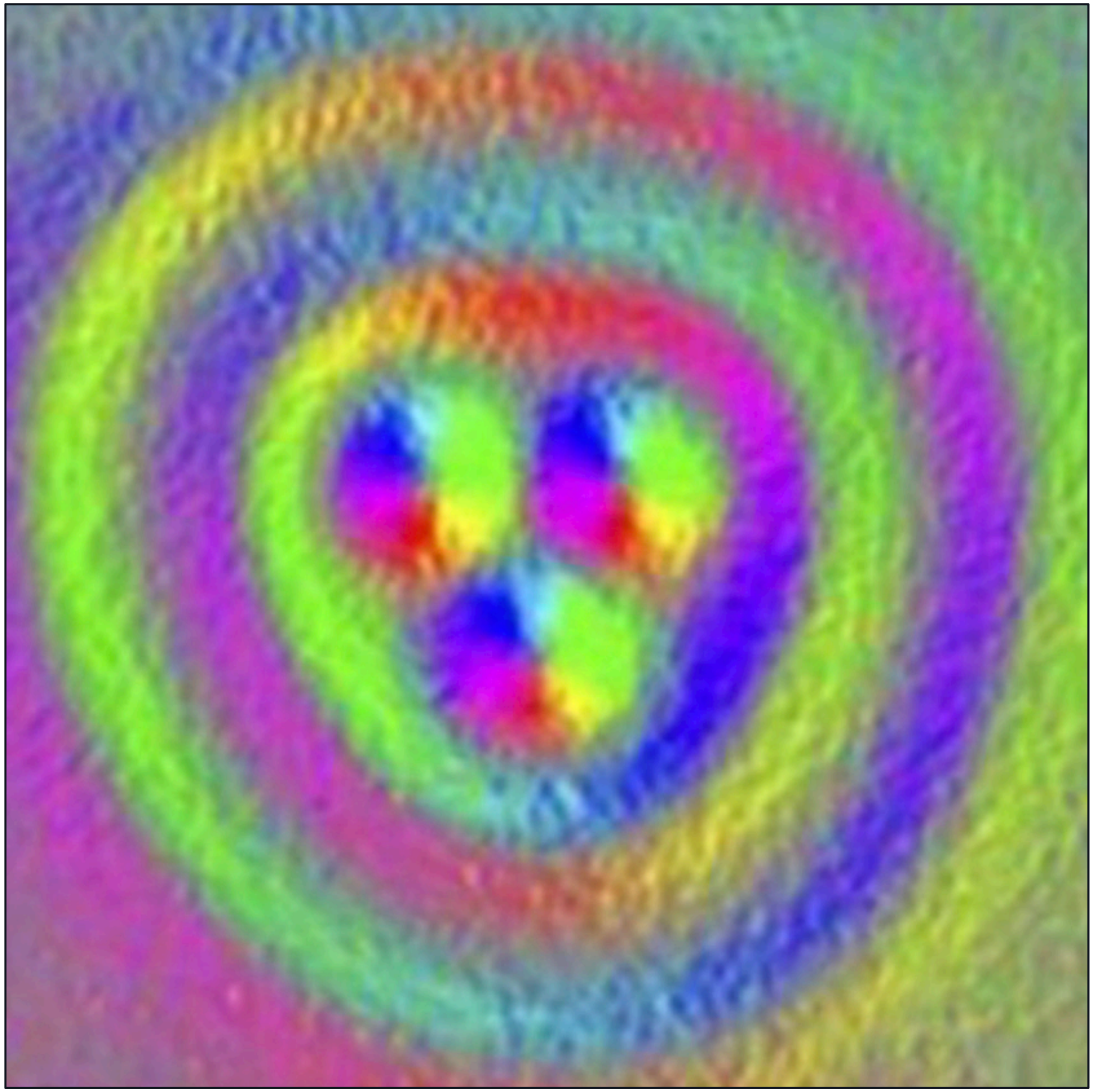
DARPA TEE program through grant MIPR# HR0011831554

The Royal Society

Ministry of Education, China

Fundamental Research Funds for the Central Universities

Magnetic hopfions



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