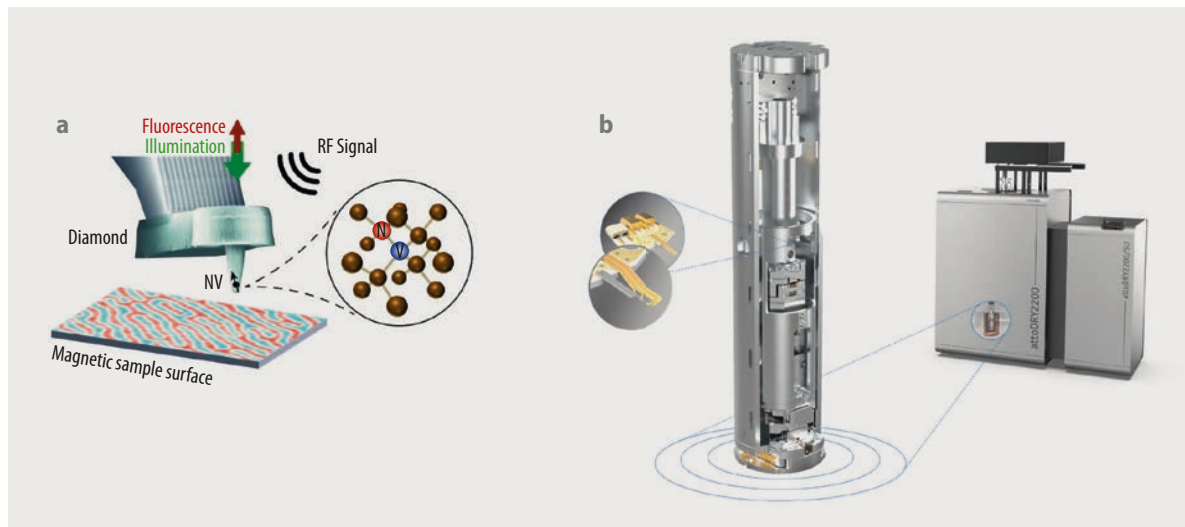


Making quantum magnetism visible

Cryogenic NV magnetometry opens a new window into quantum materials.

Florian Otto, Ankit Sharma, Andrea Morales, and Clemens Schäfermeier



Magnetism underpins countless modern technologies, ranging from data storage and sensors to emerging quantum devices. Yet many of the most intriguing magnetic and quantum phenomena occur only at cryogenic temperatures and on nanometer length scales. In quantum materials, local magnetic textures can encode phase transitions, defects, and collective states that remain hidden in measurements averaged over an entire sample. Understanding these systems requires experimental tools that combine exceptional magnetic sensitivity with nanoscale spatial resolution.

Nitrogen-vacancy magnetometry (NVM) addresses this gap by turning an individual atomic defect in diamond into a scanning magnetic field sensor. The method combines quantitative magnetic imaging and nanoscale spatial resolution and can operate non-invasively without

electrically contacting or modifying the sample. Recent progress in cryogenic integration now makes it possible to apply this approach more routinely to superconductors, van der Waals magnets and antiferromagnetic systems. This article first explains how scanning NVM works and what is required to operate it at low temperature, then illustrates its use in real measurements of quantum materials.

The method: a quantum sensor at the end of a probe tip

The sensor is the negatively charged nitrogen-vacancy (NV) center, a point defect in the diamond lattice consisting of a substitutional nitrogen atom adjacent to a vacant lattice site. Its electronic spin can be initialized and read out optically because the fluorescence of the NV center depends on its spin state. The fluorescence is typically excited with a 515 or 532 nm laser. Additionally applying microwave radiation

▲ **Fig. 1** In cryogenic scanning NV magnetometry (a) a diamond probe hosting a single NV center is scanned above the sample surface while optical excitation and microwave control enable quantitative magnetic field measurements. In a cryogenic NV magnetometer setup (b) a combined confocal and atomic force microscope hosting the NV tip with integrated rf antenna is hosted inside an ultra-low vibration, top-loading magnet cryostat, including a room-temperature optics platform on top of the cryostat.

while monitoring the fluorescence reveals the spin-resonance frequencies in a measurement known as optically detected magnetic resonance (ODMR, **Fig. 1a**).

A local magnetic field shifts the NV spin-resonance frequencies through the Zeeman effect. The resulting Zeeman splitting in the ODMR spectrum provides a direct measure of the local magnetic field at the NV center projected onto

its quantization axis. Because the measured quantity is a frequency shift governed by well-established spin physics, quantitative magnetic field maps can be obtained directly without complex sensor calibration. Depending on the measurement protocol, NV centers can probe static and alternating magnetic fields and track spin dynamics across a broad range of timescales. To achieve nanoscale imaging, a single NV center is incorporated into a diamond scanning probe mounted on an atomic force microscope (AFM, **Fig. 1a**). As the probe scans the sample's surface, both topography and local magnetic fields are recorded simultaneously.

Because the sensing volume is defined by a single defect located near the diamond surface, local magnetic fields can be mapped with a spatial resolution of a few tens of nanometers and sensitivities in the microtesla-per-square-root-hertz range. The NV center is typically situated approximately 10 nm below the diamond surface, allowing the quantum sensor to be positioned in close proximity to the sample while preserving the optical and spin properties required for sensing. The exact spatial resolution is not a fixed instrument specification: it depends strongly on the NV depth, the tip-to-sample distance, the signal-to-noise ratio, and the characteristic length scales of the magnetic structures under investigation. Using sensing protocols originally developed for magnetic resonance imaging, the sensitivity can be further enhanced to reach the low-nanotesla range.

The measurement is non-invasive in the sense that it requires neither electrical contact nor a magnetic coating or patterned sensor structure on the specimen. Nevertheless, careful interpretation remains essential, as NVM measures the stray magnetic fields above the sample rather than the magnetiza-

tion directly. Inferring the underlying current or magnetization distribution is therefore generally an inverse problem and may require assumptions about geometry, dimensionality, and sensor height. The method is most powerful when quantitative field data, topography, and a well-defined sample model are considered together.

Bringing quantum sensing into the cryostat

Low-temperature operation is considerably more demanding than room-temperature NV imaging. The experiment must maintain nanometer-scale tip control and precise optical alignment while the cryostat is in operation. In addition, because an RF spectrum typically has to be recorded at every pixel together with the optical response, image acquisition times are often long, making drift and vibrational stability of paramount importance. Furthermore, optical

access, radio-frequency delivery, sample exchange, and magnetic-field control all compete for the limited space available around the microscope.

The attoNVM integrates confocal optics, AFM control, microwave electronics, and automated measurement software into a closed-cycle cryogenic platform optimized for long-term stability (**Fig. 1b**). Continuous-wave ODMR measurements can be performed at temperatures below 4 K. Temperatures below 1.8 K are accessible in quench mode with the microwave excitation switched off, while pulsed protocols for AC sensing and coherence measurements can be applied above 2 K. These operating modes highlight an important practical consideration: the lowest achievable temperature depends on the optical and microwave heat loads imposed by the selected sensing protocol. In addition, optical access, radio-frequency delivery, sample exchange, and magnetic-

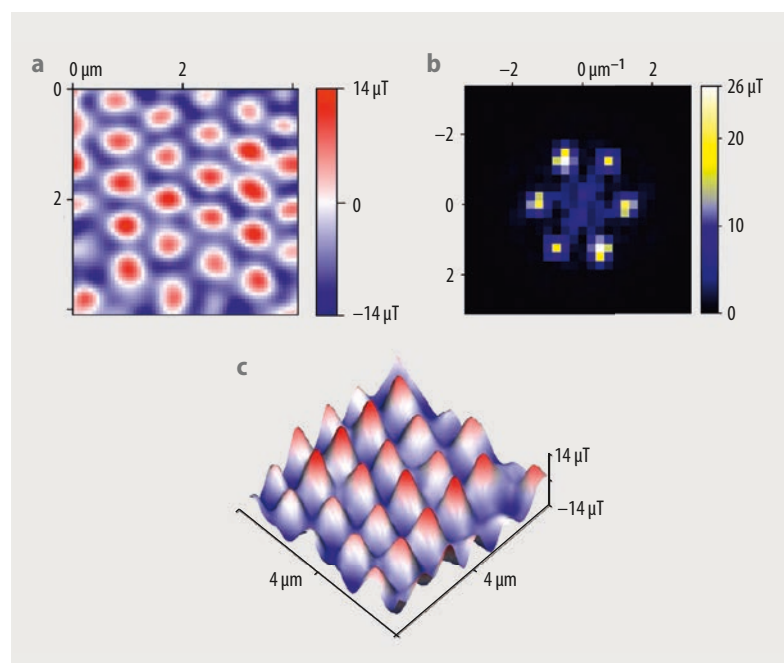


Fig. 2 Abrikosov vortices (a) in a high-temperature superconductor were imaged quantitatively at cryogenic temperatures [3]. The resulting real-space image (b), Fourier representation, and three-dimensional rendering reveal the ordered vortex lattice (c).

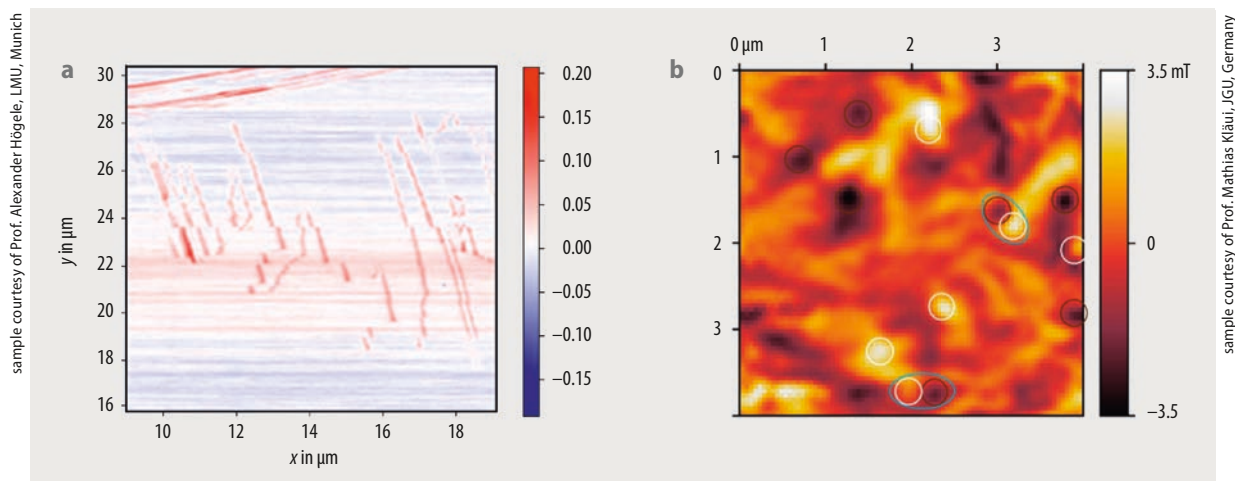


Fig. 3 Nanoscale magnetic imaging provides access to complex spin structures in quantum materials. The images reveal magnetic domains in twisted double-bilayer CrSBr (a) and meronic spin textures in a synthetic-antiferromagnet multilayer (b).

field control all compete for the limited space available around the microscope.

A key innovation is the use of diamond probes with integrated microwave antennas. By eliminating the need to pattern microwave structures directly onto the sample surface, this approach significantly simplifies sample preparation and broadens the range of materials that can be studied, from small flakes and thin films to devices with existing contact geometries. The integrated architecture further seeks to replace the assembly of individually optimized laboratory components with a reproducible workflow that covers probe positioning, NV-center localization, sam-

ple approach, and the acquisition of correlated topographic and magnetic data.

Visualizing Abrikosov vortices

One area where cryogenic NV magnetometry demonstrates its strengths is superconductivity research. Type-II superconductors provide a direct test of both the spatial and quantitative capabilities of cryogenic NVM. When an applied field lies between the lower and upper critical fields, magnetic flux penetrates the superconductor as Abrikosov vortices (Fig. 2). Each vortex carries one magnetic-flux quantum. The arrangement of vortices reflects inter-vortex interactions, material

anisotropy, disorder and pinning, all of which influence dissipation and the performance of superconducting materials and devices.

In measurements with the attoNVM, individual vortices can be imaged directly and quantitatively. Measurements of BSCCO-2212 at 71 K revealed a well-ordered triangular vortex lattice, whose symmetry and spacing were confirmed by two-dimensional Fourier analysis. By contrast, YBCO thin films measured at 3 K exhibited a markedly more disordered vortex arrangement, consistent with stronger vortex pinning. In both cases, the measured vortex densities were in excellent agreement with the values expected from magnetic-flux quantization, highlighting the quantitative nature of the technique.

This comparison highlights not only the ability to image individual vortices but also the efficiency of the technique. Quantitative vortex maps with nanoscale resolution can be acquired within approximately two to four hours, making systematic studies across a range of magnetic fields, temperatures, and sample regions practical for a broader research community.

Webinar on cryogenic NV magnetometry

Readers interested in learning more about cryogenic scanning NV magnetometry, its experimental implementation, and recent application examples in quantum materials research are invited to join an upcoming webinar. A recording will be available afterward.

Event Details

Thursday, October 22, 2026, 14:30 (CEST)

| 08:30 (EDT) | 20:30 (CST)

Duration: approximately 45 minutes + Q & A

More information: <https://www.attocube.com/en/resources/webinar-attoNVM>



Magnetic textures in quantum materials

The impact of cryogenic NV magnetometry extends well beyond superconductivity. The technique is increasingly being applied to the study of van der Waals magnets, antiferromagnets, moiré materials, and topological spin textures. These systems often exhibit magnetic states that are difficult or impossible to access with conventional magnetic-imaging techniques. For example, in van der Waals magnets, scanning NVM can resolve domains and domain walls in micron-sized exfoliated flakes, where spatial averaging would otherwise obscure local variations. Real-space magnetic-field mapping can thus reveal structures that cannot be inferred unambiguously from transport measurements or bulk magnetometry alone.

Antiferromagnets are compelling targets, as their magnetic moments cancel on a macroscopic scale, making the combination of high sensitivity and nanometer-scale spatial resolution essential. Recent studies have used NV magnetometry to reveal antiferromagnetic domain structures, emergent magnetic charges, and novel spin textures that were previously inaccessible to experimental observation.

The technique is also valuable for the investigation of twisted van der Waals materials, where subtle magnetic interactions govern exotic quantum phases (Fig. 3). Here, real-space magnetic imaging provides direct insight into phenomena that are otherwise inferred only indirectly through transport or optical measurements.

From specialist method to shared research tool

Cryogenic scanning NV magnetometry combines two equally important advances: a quantum-

sensing technique that provides quantitative magnetic-field maps with nanoscale resolution, and an integrated low-temperature implementation that makes the technique applicable to real quantum-material systems. Neither aspect alone is sufficient. While the sensor physics determines what can be measured, mechanical, optical, and cryogenic engineering determine whether those measurements can be performed stably and reproducibly over many hours.

By integrating these capabilities into a robust commercial platform, the attoNVM lowers the barrier to adopting quantum sensing in everyday research. Researchers can now investigate superconductors, quantum magnets, and spintronic materials with a level of detail that was previously accessible only in highly specialized laboratory environments requiring substantial instrumentation development and system integration. As quantum materials continue to evolve from subjects of fundamental research into building blocks of future technologies, tools capable of directly visualizing their otherwise hidden magnetic structures will play an increasingly important role.

References

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