ZABRE

QSM | Quantum Scanning Microscope

NV-MAGNETOMETER: FASTER. VERSATILE. EASY TO USE.

Our NV Magnetometer and its Applications

Meet Our Turn-key Scanning NV Microscope: The QSM

The QSM unites user-friendliness with flexibility and high performance. From large area megapixel images to high resolution, high sensitivity maps, the QSM is the right tool for the job. Delivering perfomance close to the shot noise limit, its flexible platform makes it a versatile tool for studying magnetic phenomena at the nanometer scale, from stray fields and vortices over domain boundaries to current densities.

Flexibility at the Core of Our Design

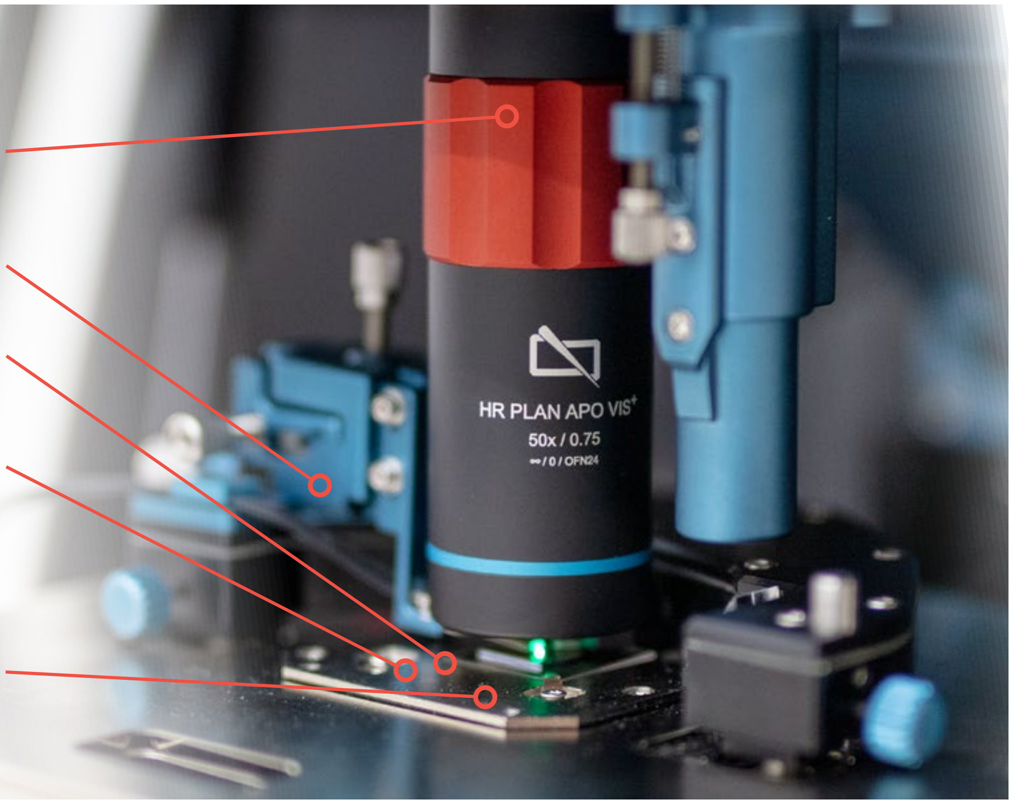
Custom optics compatible with multiple colors

Broad microwave band

Large scanner footprint for any sample geometry

Stitching extends the 85 x 85 µm² scanner range to cover feature sizes up to several millimeters

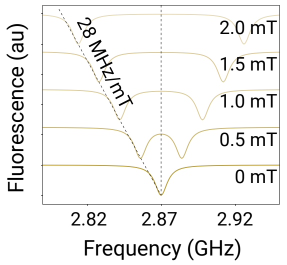
Custom DC and RF lines for manipulating sample properties



Measurement for Scanning Modes

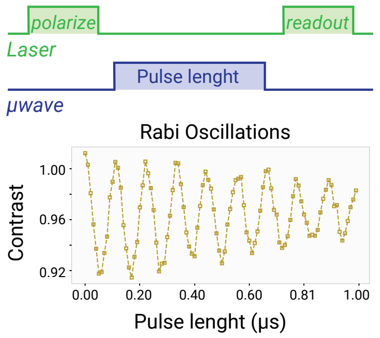
NV-CONTINUOUS WAVE (CW)

Qualitative: PL, Iso-B
Quantitative: ODMR



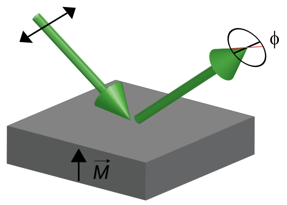
NV-PULSED

Pulsed ODMR, Ramsey, CPMG, arbitrary user-defined



MOKE

Magneto-optical Kerr Effect



ADDITIONAL

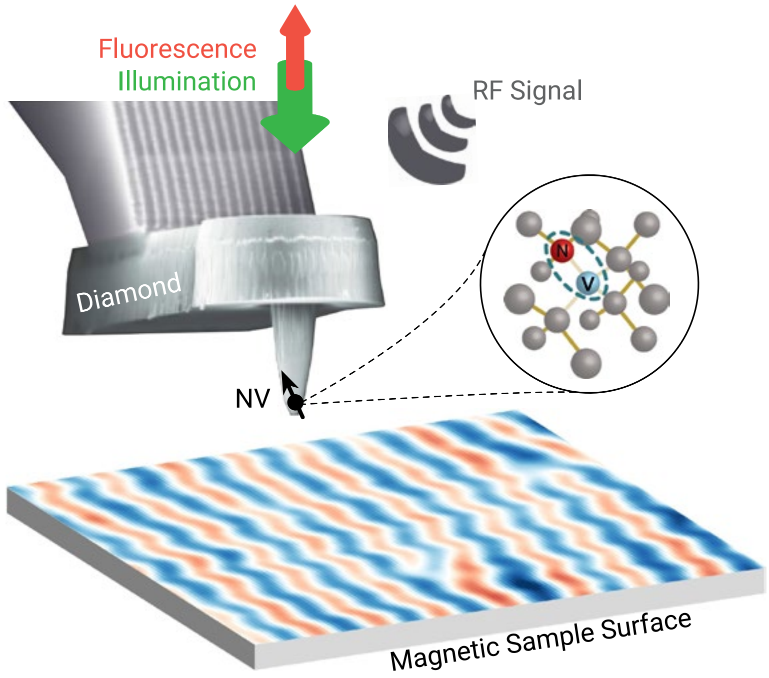
AFM topography with height control (two-pass mode and fixed plane)

Widefield & confocal

Multiple experiments per pixel possible (example: ODMR, Rabi, CPMG)

Working Principle

We use a single defect in diamond, a Nitrogen Vacancy (NV) center, as an atomic size quantum sensor. By scanning it in close proximity over a sample surface, we can quantitatively map magnetic fields and more with high sensitivity and better than 40 nm resolution. All of this works in ambient conditions, in the desktop sized QSM.

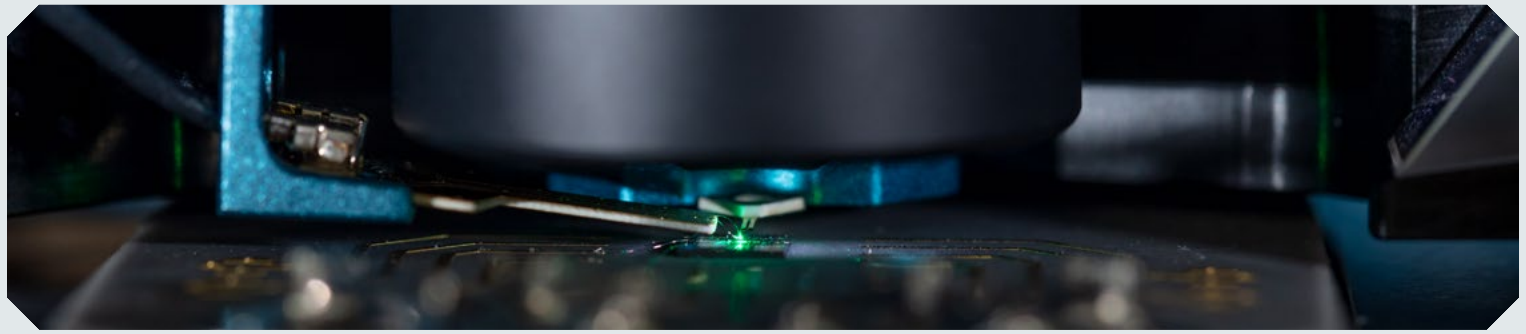


Removing two adjacent carbon atoms from the diamond crystal lattice and placing a nitrogen atom at one of the sites creates an NV center. This "artificial atom" has several unique properties:

- It is a room temperature qubit
- The levels can be readout via an optical signal
- The gyromagnetic ratio of 28 GHz/T makes it very sensitive to magnetic fields
- The measured magnetic fields are absolute

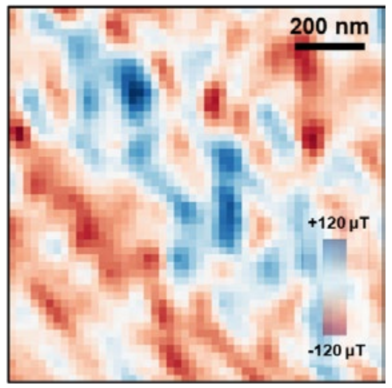
Applications at a Glance

NV SENSOR FOR	PURPOSE	MATERIALS / DEVICES
Magnetic Fields	Failure Analysis	2D Materials
Currents	Materials Characterization	Antiferromagnets
Electrical Fields	Nano NMR	Hydrodynamic Tr.
More	Radical Sensing	Ion Traps
	RF SOIC R&D	Multiferroics
	Surface Characterization	Optoelectronics
	Thermometry	Phase Transitions
	Transistor R&D	Skyrmions
	Waveguide Characterization	Spintronics
		Surface Potentials
		Topological Materials



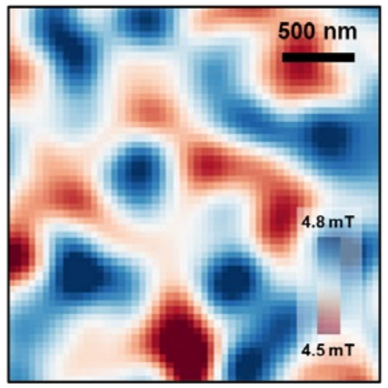
Use Cases

ANTIFERROMAGNETS
Domains in CuMnAs



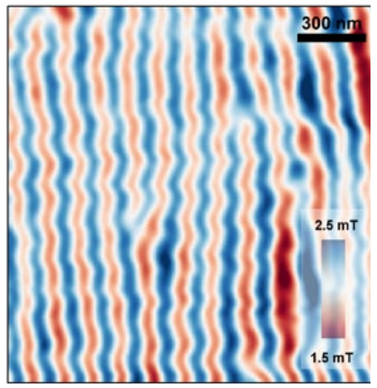
Resolve the challenging, weakly varying magnetic signals.

SKYRMIONS
Vortices with applied magnetic field

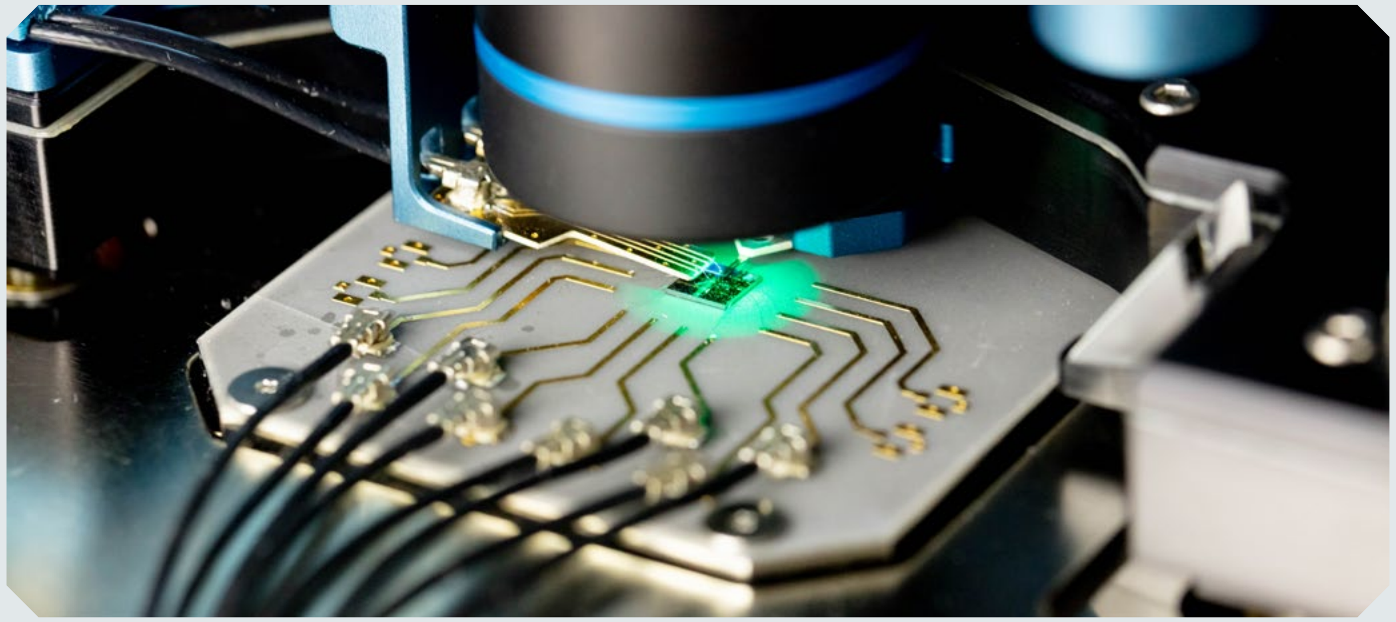


Tune the magnetic field to induce vortex nucleation.

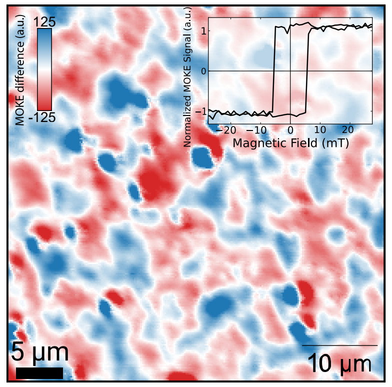
MULTIFERROICS
Cycloids in strained BiFeO



Study spin cycloid domains with high sensitivity and resolution



MOKE
Correlate magnetic field and magnetization



Quickly scan large sample areas to identify features of interest and use the additional data for a better understanding of the material.

TRACING CURRENTS
Correlate topography with currents and more

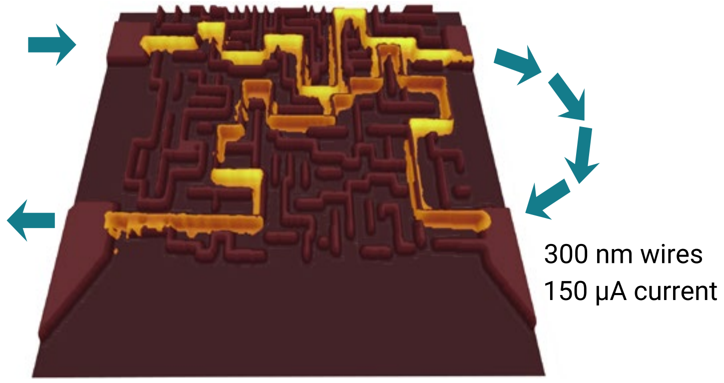


Image currents in a running device via the magnetic fields they generate to reveal defects and hot spots or verify the design.

QUICKSCAN MODE
Stripe features in Hematite (Fe_2O_3)

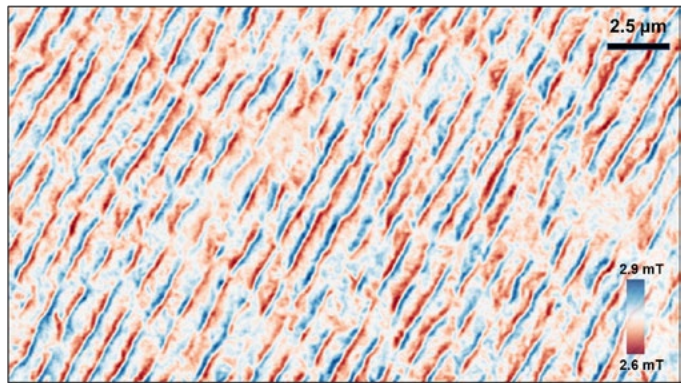
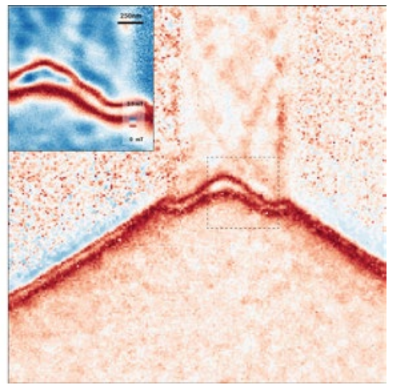


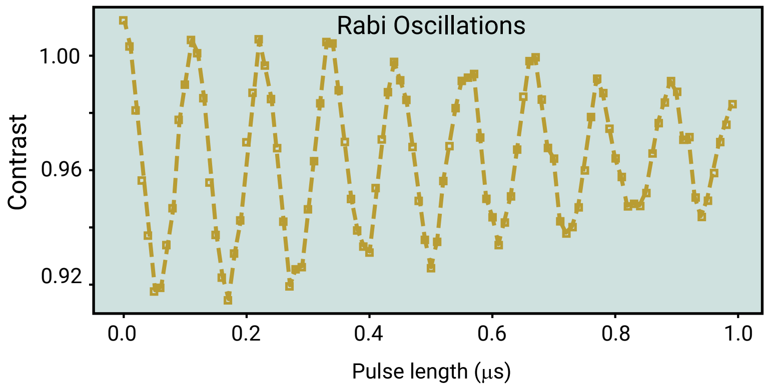
Image large areas while retaining high pixel density in a short amount of time with Quickscan. Resolve both short- and long range features.

DOMAIN WALLS
Extract domain wall chirality and width

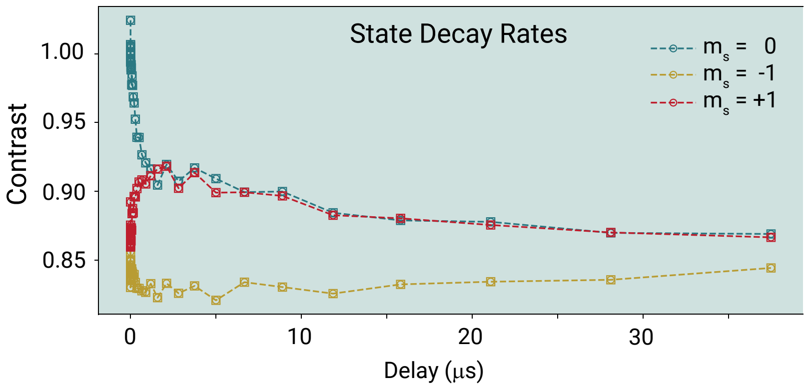


Characterize domain walls directly from the data, which is the projection of the sample magnetic field onto the defined NV axis.

RELAXOMETRY
Different spin decay rates due to surface-magnons coupling in YIG

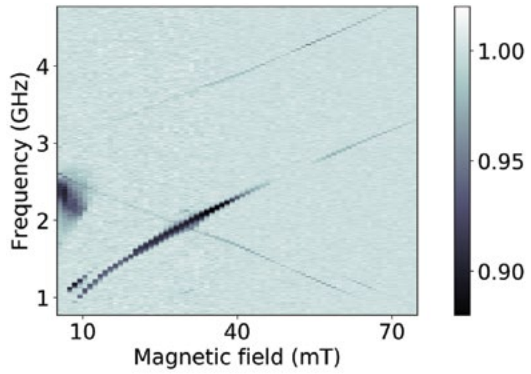


The QSM can achieve Rabi rates exceeding 40 MHz.



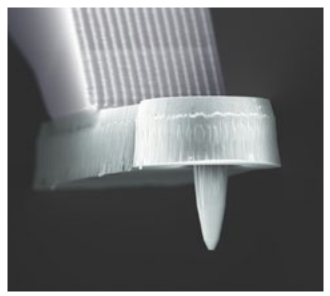
Extend the QSM with multiple microwave sources, for example to perform spin selective readout.

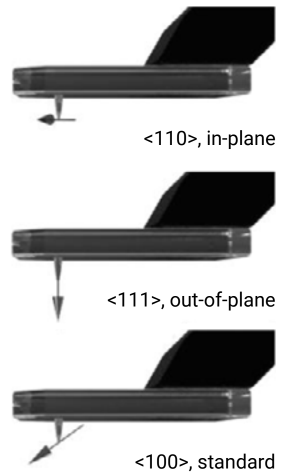
SPECTROSCOPY
Ferromagnetic Resonance in YIG



Measure at high magnetic fields with our magnet options and broad microwave band.

NV ORIENTATIONS
In-plane, out-of-plane and standard orientation





We offer different NV orientations for optimum projection of the stray field or measuring at high bias.

System Overview

MONITOR
Display real-time temperature and humidity data over up to 24 hours

ISOLATING ENCLOSURE
Temperature stabilized and acoustically isolated enclosure, active vibration isolation

OPTICS HEAD
Scanning confocal optics for NV excitation and readout, scanning MOKE and widefield imaging

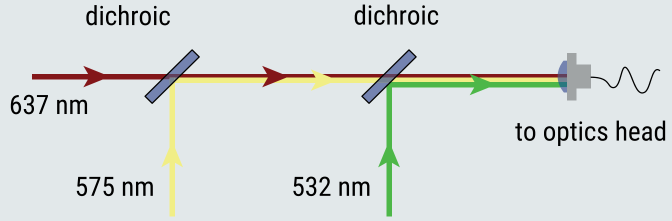
AFM STAGE
AFM head with manual 3D stage for microwave excitation for NV scanning probes

MAGNET STAGE
Mechanical magnet or electro vectormagnet for biasing the NV and/or sample

SUPPORT RACK
Quantum Control Console, AFM controller, PC, UPS

QSM Highlights

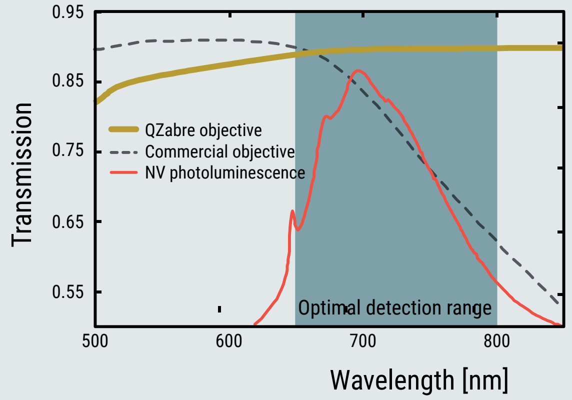
MULTI-COLOUR EXCITATION
The QSM optical setup and its control electronics can handle multiple wavelengths, as well as multi-colour excitation pulses and pulse sequences.



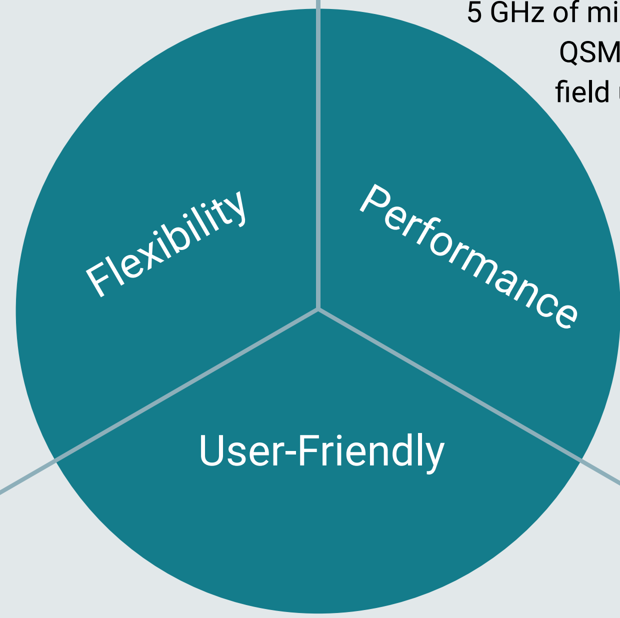
MAGNET OPTIONS
Mechanical magnet for bias fields exceeding 200 mT or vector electromagnet for fast sweeps.

MOKE MEASUREMENT SETUP
MOKE provides additional data in the form of sample surface magnetization and allows quicker identification on a larger size scale.

OPTIMIZED OPTICS
Our custom optical design significantly boosts the optical performance. The NV emission overlaps the visible and near IR region, which means standard components are not optimal. Each element in the QSM is optimized for the NV band, even the objective.



BROADBAND MW EXCITATION FOR A LARGE RANGE OF MAGNETIC FIELD BIASES
5 GHz of microwave bandwidth means that the QSM can measure at any magnetic bias field up to 110 mT. Both magnet options allow full vector control of the bias field, giving you maximum measurement flexibility.

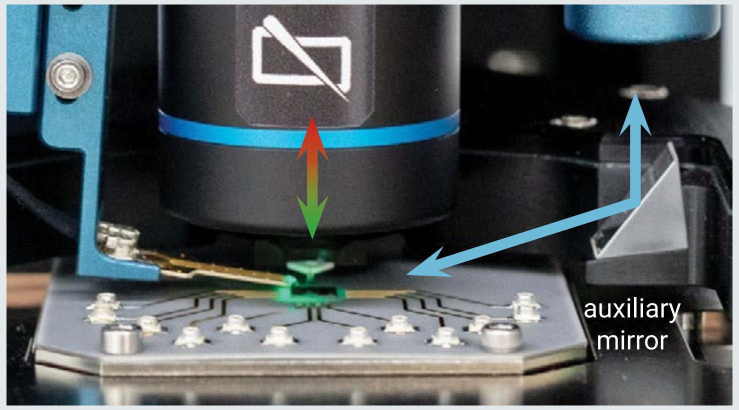


QUICKSCAN
ODMR at pixel rates up to 200 Hz means 100 x 100 pixels scans in less than one minute and Megapixel scans in less than 2 hours. Optimized software algorithms decrease software overhead close to zero.

UNIFIED USER INTERFACE
The QS3 software interface gives you full control of the QSM microscope, from the AFM to the NV part. It features unique measurement protocols such as Quickscan ODMR, is open source, and allows scripting within the same GUI.

BRIGHT FIELD IMAGING WITH HIGH RESOLUTION AND LARGE FIELD OF VIEW (FOV)
By switching between these two independent systems, you can easily identify larger and smaller landmarks on your chip. Approaching the surface is safe and easy.

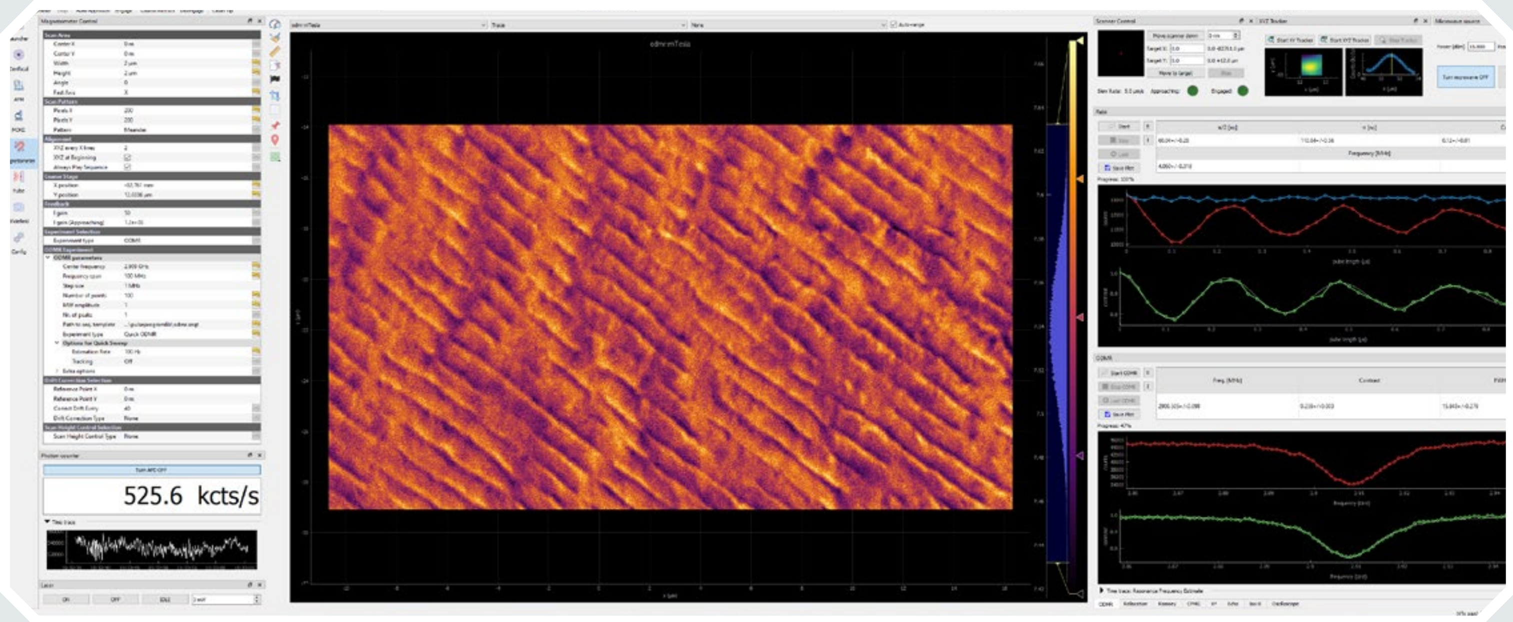
Green arrow:
A 50x high resolution system with a FOV of 150 µm
Blue arrow:
A low resolution system with a FOV of ~2 mm



Powerful Software Suite

QS3 Software - Scanning NV as simple as AFM

What you see with your eyes is just the tip of the iceberg. The QS3 software is built around the experience and the needs of our customers combining functionality, speed and usability. The intuitive software interface jump starts your entry into the world of magnetic and current imaging. A unified, turnkey solution, the software seamlessly integrates all the QSM components from the AFM to the magnetometer and the MOKE.



Quickscan - Megapixel Images in Less Than Two Hours

Measure faster with Quickscan! A unique algorithm practially eliminates the software overhead, so that the unmatched performance of our probes and optimized optical design of the QSM directly translate to faster measurements. At pixel rates of up to 200 Hz, 100 x 100 pixel scans don't take hours anymore but less than a minute. You can correlate short- and long-range features by taking megapixel scans in a few hours instead of weeks. Quickscan measures full frequency spectra at each pixel, providing the same wealth of information as conventional cw-ODMR.

Do you have a sample with highly varying field? Quickscan can also frequency track, keeping a small frequency window dynamically centered on the ODMR resonance. The small window preserves the sensitivity, which would be lost with the large frequency window necessary without tracking, keeping your scan quick!

Scripting and Pulsed Measurements

Being at the forefront of research means new and often unconventional experiments. A dedicated pulsed program interface in QS3 allows you to easily modify existing pulse sequences or even add new ones. Script custom pulse experiments controlling both the laser and the microwave source and directly use them to perform scanning measurements without additional programming.

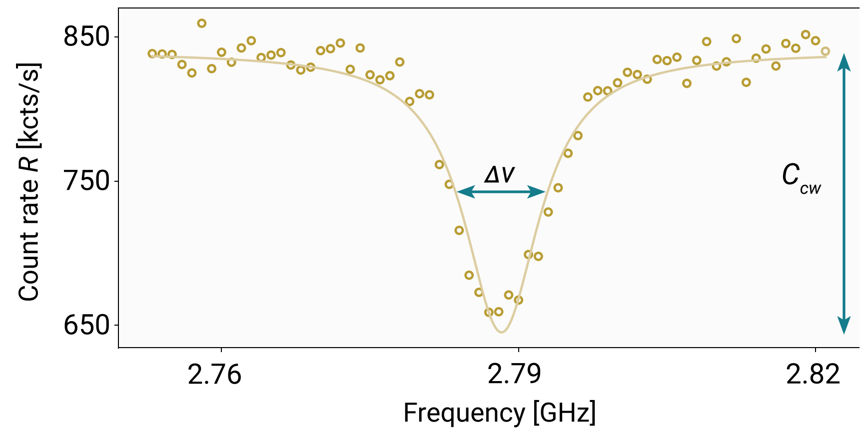
A dedicated widget gives you easy access to software resources minimizing programming overhead. QS3 automatically plots and saves the data, so that you can focus on designing your experiments. Have a look at the spectroscopy measurement of page 5 to see what the script widget can do!

Background Information

Sensitivity

Magnetic sensitivity strongly depends on the protocoll used. To start, let's look at cw-ODMR, measuring at a single point frequency point. The shot noise limited sensitivity is then given by: η_{cw}

$$\eta_{cw} = \frac{4}{3\sqrt{3}} \frac{h}{g_e \mu_B} \frac{\Delta\nu}{C_{cw}\sqrt{R}}$$



with linewidth $\Delta\nu$, contrast C_{cw}, count rate R .

In cw-ODMR, both contrast and count rate can be increased at the expense of linewidth. Optimal sensitivity is typically achieved at low linewidths rather than high contrast or count rates.

What values can you actually expect? Our top of the line sensors have a contrast of better than 25% at a linewidth of 10 MHz and a countrate of up to 1 Mcts/s at maximum contrast, leading to a theoretical sensitivity of 1 μT/ ($Hz^{1/2}$) in cw ODMR.

For real world instruments, soft- and hardware overhead as well as setting can significantly decrease the actual sensitivity. With Quickscan and tracking, the QSM can operate close to the shotnoise limit.

Measurement Modes Explained

PHOTOLUMINESCENCE

Magnetic fields modify the fluorescence rate of the NV, indicating where the field is stronger and where it is weaker. Since it only measures the fluorescence, it is a very fast, but only qualititave measurement.

ISO-B

Measures the ratio of two microwave frequency points centered around a specific frequency and about the line width apart to create contours of equal field. A fast measurement that is quantitative for small field changes.

CW-ODMR

Measures the full resonance curve by continually applying the laser and microwave field to map the fluorescence response. Fully quantitative with additional information in the contrast, countrate and linewidth.

TRACKING

Strong variations in the magnetic field shift the resonance significantly. This either requires a large frequency window for ODMR, which decreases signal-to-noise, or, to avoid this, a dynamically moving, small window.

PULSED ODMR

At each frequency point the NV is initalized with a laser pulse, followed by a microwave pi pulse and laser readout pulse. This avoids power broadening, the more narrow linewidth and higher contrast increase the sensitivity to better than 0.5 μT/ ($Hz^{1/2}$).

GRADIOMETRY

The tuning fork motion means that the NV oscillates relative to the sample. This turns gradients into AC magnetic fields, which are detected with a low noise spin echo meausurement, increasing the sensitivity down to the 100 nT/ ($Hz^{1/2}$) range.

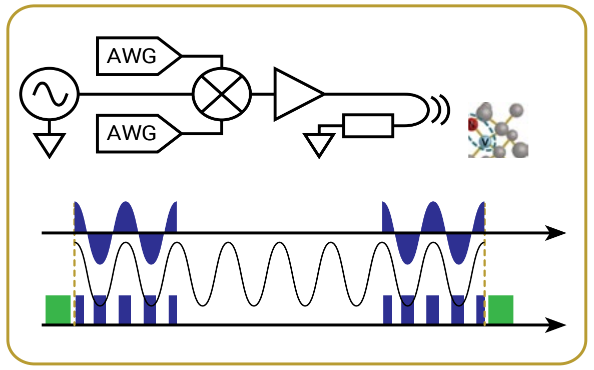
System Extensions

Analog and Digital Extension

FASTER DATA. DIFFERENT DATA.

Adding the hard- and software for pulsed measurements significantly extends the capabilities of the QSM:

- Quickscan for up to 200 pixel/s scanning rates
- Pulsed ODMR, Rabi, Ramsey, T1, relaxometry, CPMG and more standard protocols integrated into the UI
- Pulse sequence generator for arbitrary, user-defined pulse sequences
- All pulsed protocols can be run stand-alone or as maps
- Protocols can be “stacked” for mapping. Example: ODMR/Rabi/Ramsey to stay on resonace.

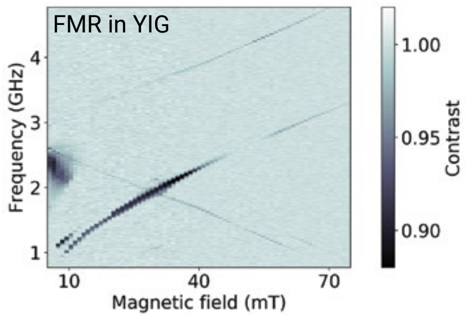


Pulsed measurements increase sensitivity and extend the measurements from DC magnetic fields to AC magnetic fields and currents, magnetic noise, relaxometry, gradiometry and much more. The additional up to 4 analog and 17 digital channels can be further used to apply stimuli or trigger additional instrumentation or hardware.

Magnetic Field Control

OPTION 1: MECHANICAL MAGNET

Interchangeable permanent magnets on a moving xyz stage offer a wide range of field strengths with orientation control. This option can generate beyond 0.5 T in- or out-of-plane for strong magnetization of samples. An algorithm aligns the magnetic field to the NV axis for measurements at bias fields beyond 100 mT.

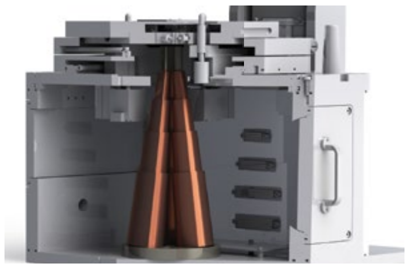


Reproduction of nanobeam data, C. Du, Science, 357, 2017

OPTION 2: VECTOR ELECTROMAGNET

The low noise, temperature stabilized design offers >80 mT in arbitrary directions with peak fields for specific directions >200 mT.

The vector magnet enables easy field sweeps and ramps for magnetizing samples, as well as optimization algorithms for maximum NV performance.



Custom PCBs

OPTIMIZED TO YOUR NEEDS

Whether you need current pulses to move a domain wall or microwave excitation to excite a ferromagnetic resonance, applying signals to a sample is often required. We offer both standardized as well as custom designed ceramic PCBs with DC and/or RF lines, including connectors.

Contact us for features such as multiple microwave or laser sources, vacuum, temperature range, additional optical beam paths, rotating sample holder or inert atmosphere housings.

Specifications

SPM Scanner and Coarse Stage

SAMPLE SCANNER	xyz scanner range: 85 µm x 85 µm x 15 µm (closed-loop, 0.15 nm resolution) System noise z: <50 pm RMS (dependent on environment)
COARSE STAGE	xyz range 6 mm x 6 mm x 15 mm (100 nm resolution) Stitching with scanner movement possible
SPM MODES	Tuning fork based AFM mode, NV modes: Photoluminescence, Iso-B, cw-ODMR, Quickscan, pulsed protocols
SAMPLE SIZE	25 mm diameter, (up to 50 mm x 50 mm with custom holder)
PROBE-SAMPLE DRIFT RATE	<2 nm/h over 50 h in temperature stabilized housing

Imaging Modes

NV SCANNING	Magnetic spatial resolution: theoretical <10 nm; typical 25-70 nm Magnetic sensitivity*: 0.5-3 µT/(Hz$^{1/2}$)
AFM TOPOGRAPHY	Tip dependent: NV scanning probes ~1 nm (z), ~150 nm (xy); Akiyama probes (non NV) <1 nm (z), <30 nm (xy)
CONFOCAL FLUORESCENCE	Circular scanning range: 150 µm diameter; <1 µm imaging resolution @515 nm
ADDITIONAL	MOKE, bright field imaging (150 µm and 2 mm FOV)

* Probe and protocol dependent: shot noise limit for DC sensitivity in cw-ODMR : better than 1.5 µT/(Hz$^{1/2}$), for pulsed ODMR better than 500 nT/(Hz$^{1/2}$)

Confocal Microscope Performance

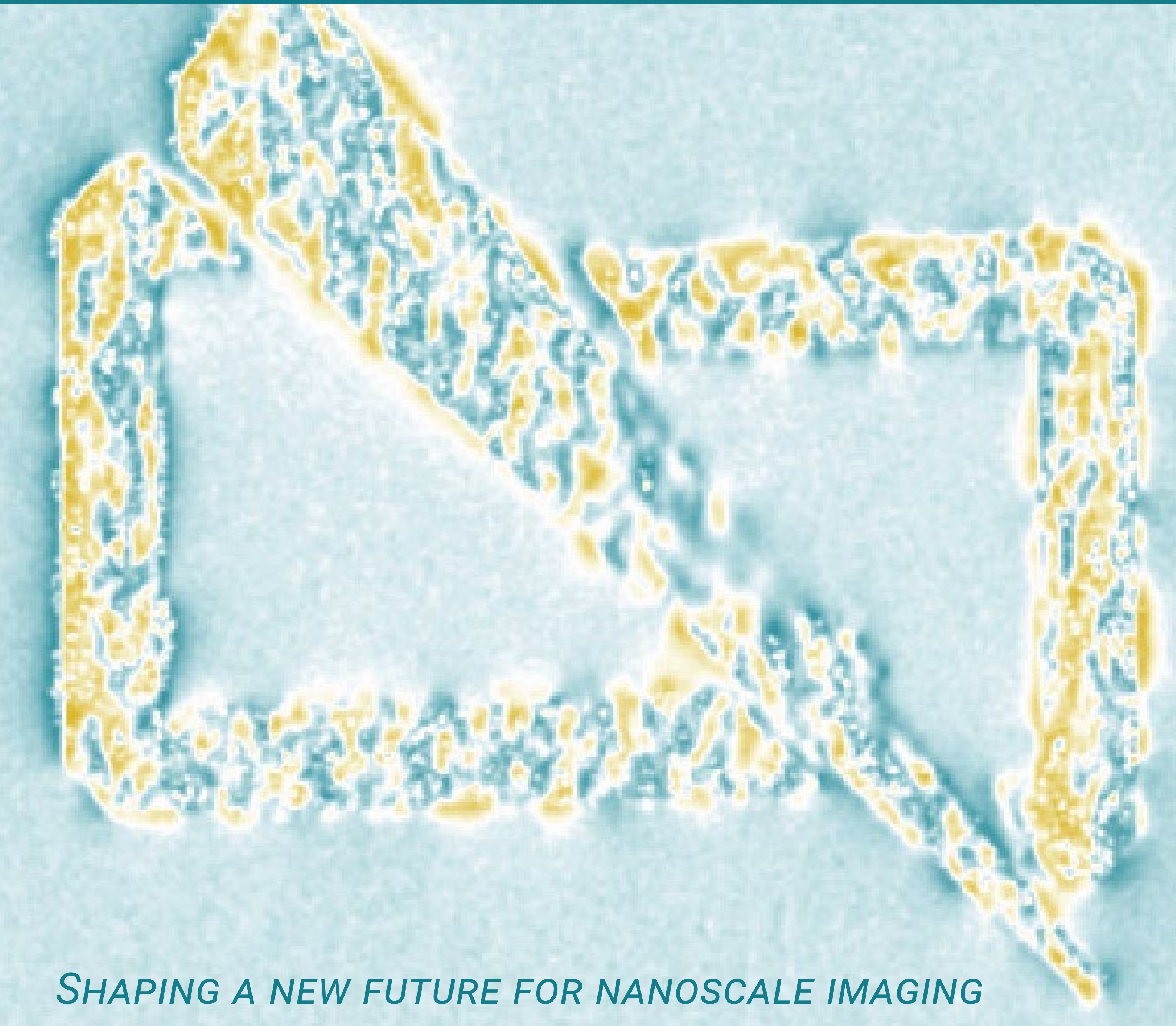
MICROSCOPE OBJECTIVE	50x magnification, NA=0.75, WD=5 mm, FOV=150 µm diameter, NV-band optimized and compatible with 515 nm, 575 nm and 637 nm
OPTICAL SCANNING RANGE	Circular aperture with 150 µm diameter FOV

Quantum Control Console

MICROWAVE SOURCE	0.6-6 GHz, up to 36 dBm (5 W), custom range and output power available on request Analog and digital extension: AWG with 1.25 GS/s, 400 MHz bandwidth Custom MW circuitry available on request
LIGHT SOURCE & DETECTION	515 nm laser source (cw & pulsed control), >10 mW, <1.5 ns rise/fall time SPAD module with high quantum efficiency

Vibration and Temperature Isolation

VIBRATION ISOLATION	Active isolation 0.7-300 Hz, passive isolation above 300 Hz Transmissibility <0.01(~40 dB) above 10 Hz
TEMPERATURE STABILIZATON	<0.1°C temperature drift



Established in 2018, QZabre AG is a pioneer in NV technology. As an ETH Spinoff from the Spin Physics Group, our vision is to make scanning NV imaging as easy to use as AFM today.

Spinoff ETH zürich

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