



attoAFM

Low Temperature Scanning Probe Microscopes

Retrieve nano-features over millimeter ranges!

closed loop scanning & global sample coordinates

Science and technology delve deeper and deeper into the nanoworld. In particular, scanning probe & confocal microscopy have been concerned with features on the nanoscale ever since its invention. Reliably scanning over tens of micrometers range down to a few hundred nm is comparatively easily achieved by using piezo based scanners.

However, using piezo-based scanners usually relies on the assumption that the relation between applied voltage and displacement is linear. In reality, most scanners show large non-linear behaviour and hysteresis, especially for large scan ranges. Creep, i.e. drift in position after approaching a certain location, is a further phenomenon which is common to all piezo scanners.

In many experiments, reproducibly locating a small feature on a surface is crucial, and sometimes hysteresis and non-linearity in the acquired image are not acceptable. Sometimes, SPM images need to be evaluated for particularly and for the specific mutual distances of certain features, and hence, any distortions due to those nonlinearities may impede such analyses significantly.

Much more often, however, finding a certain region of interest or a particular feature on a macroscopic sample at all, or retrieving such locations repeatedly is a critical task.

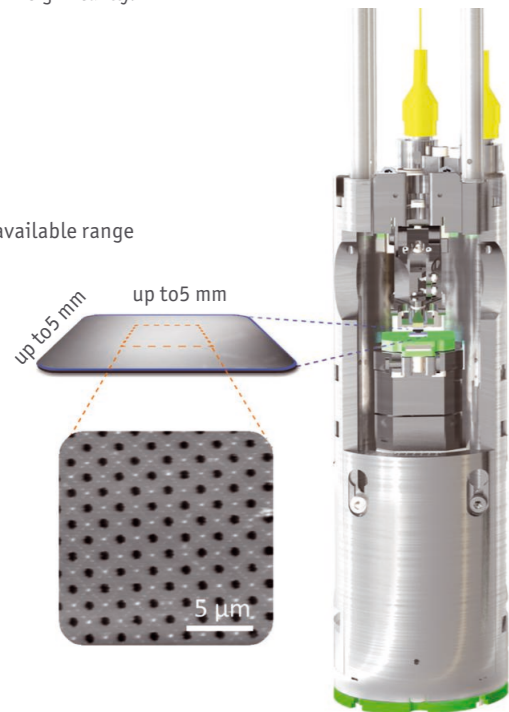
Based on our patented FPSensor, a fiber-based interferometer, our microscopes can now be equipped with position closed loop sensors with featuring a steady-state resolution of down to 1 nm even in a, despite the cryogenic working environment.

At the same time, we implemented a fully digital scan engine in the ASC500 SPM controller, which now features location based data acquisition (as opposed to time-triggered data acquisition on open loop systems). In closed loop mode, this results in perfectly linearized images. The sophisticated scan engine even allows for an adjustment of the scan acceleration to smoothen the scanning motion at the turning points, which can be especially useful especially for higher scan speeds.

The most useful new features however is that since the FPSensor covers the full 5 mm x 5 mm range of the positioners, the scan widget now contains 'global' sample coordinates: usually, the maximum range accessible in closed loop mode is limited by the maximum range of the scanners. If the user wants to scan outside of this area, he can simply use the global sample coordinate system for navigation. To further facilitate this, any measured SPM images can simply be decorated onto the scan widget's sample 'canvas' via drag-and-drop, where they are put exactly at the measured coordinates. Hence, a virtual map of the whole sample gradually evolves within the scan widget.

Retrieving regions of interest on the nanoscale, which has always been extremely difficult and time consuming especially at low temperatures, is now an easy task thanks to this global sample coordinate system.

total available range



CUSTOMER FEEDBACK

Prof. Dr. Peter Michler

*Our attoCFM I LT-lithography setup is not only the best choice when it comes to stability requirements. Its closed loop scanning feature also allows us to optically pre-select quantum dots suitable for desired experiments and mark them in-situ via lithography with nanometric precision.**

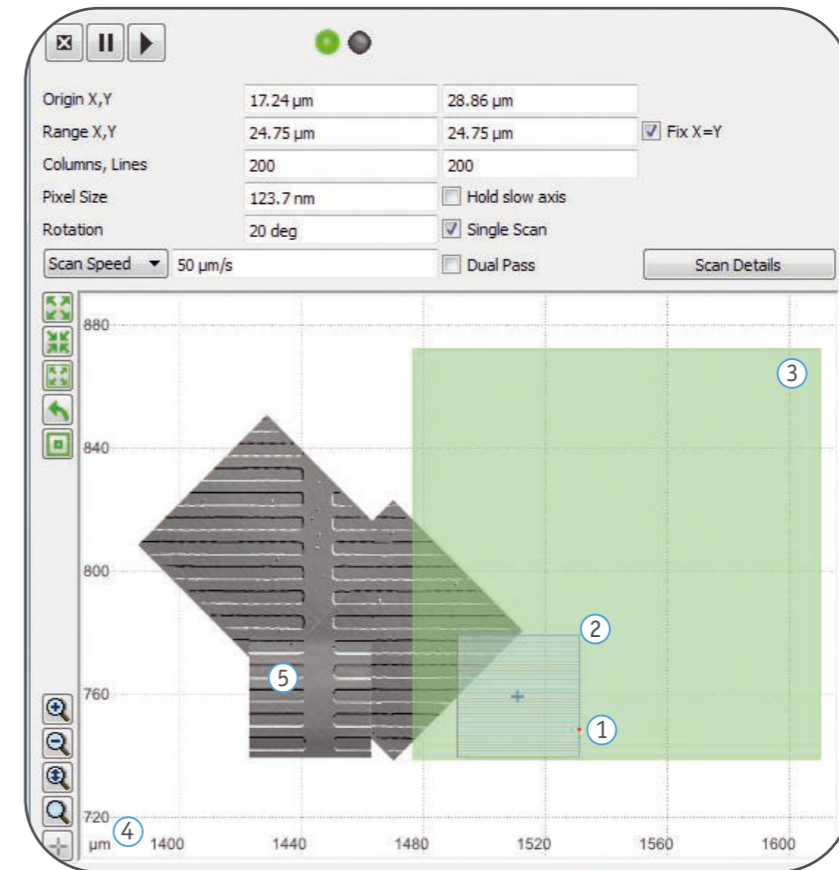
(University of Stuttgart, Germany)

For more details, see
* [1] Sartison et al. Scientific Reports 7, 39916 (2017)

AFM with Built-In Sample GPS

closed loop scanning & global sample coordinates

NEW



- 01 SPM tip position indicated by red dot
- 02 current scan area
- 03 max. scan range at this position

- 04 global sample coordinate system
- 05 SPM image decoration in global sample coordinate system

ASC500
fully digital SPM Controller



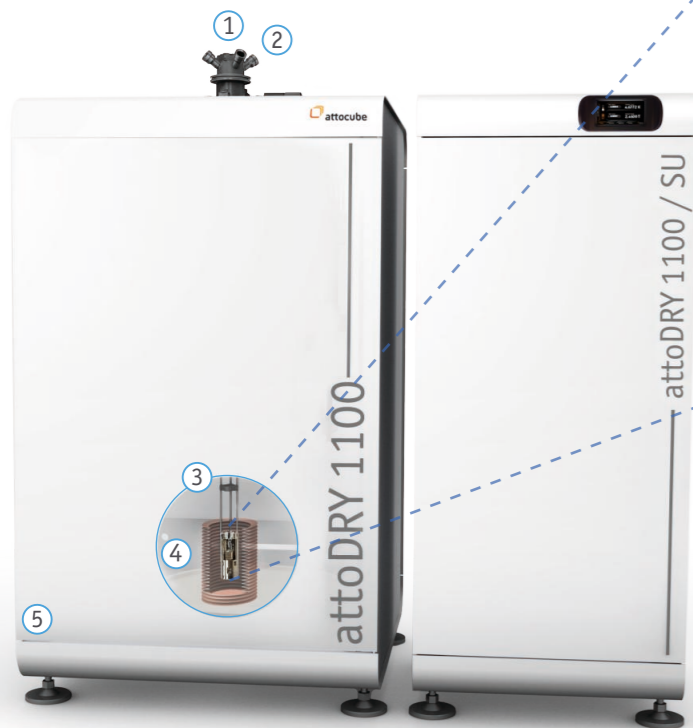
attoAFM I

low temperature atomic force microscope, cantilever based

The attoAFM I is a compact atomic force microscope designed particularly for applications at low and ultra low temperatures. The instrument works by scanning the sample below a fixed cantilever and by measuring its deflection with highest precision using a fiber based optical interferometer. Both contact and non-contact mode are applicable. Furthermore, this system is suited for magnetic force microscopy (MFM), electric force microscopy (EFM), and other imaging modes.

The extreme stability of the measurement head allows also for combinations with cryogen free pulse-tube based cooling systems for applications where liquid helium is not available or desired. The attoAFM I is available with an optional interferometric encoder for closed loop operation.

The microscope uses a set of xyz-positioners for coarse positioning of the sample over a range of several mm. Developed particularly for cryogenic applications, the piezo-based scanner provides a large scan range of 50 μm x 50 μm at room temperature, and 30 μm x 30 μm at liquid helium temperature. The exceptional combination of materials allows absolutely stable high resolution imaging of surfaces. Possible applications are the measurement of local sample properties such as topography, magnetic forces, or elasticity of surface structures.



Schematic drawing of the low temperature attoAFM I and the attoDRY1100 cryostat (optional)

- 01 vacuum window
- 02 LT and HV compatible feedthroughs
- 03 microscope insert including single mode fiber
- 04 superconducting magnet (optional)
- 05 attoDRY1100 cryostat (optional)
- 06 attoFPSensor based closed loop sensors (optional)
- 07 attoAFM I+ head incl. alignment-free cantilever holder
- 08 quick exchange sample holder with 8 electrical contacts
- 09 ultra-large range xyz scanner 125 μm x 125 μm x 15 μm @ 4 K (optional)
- 10 xyz coarse positioners 5 mm x 5 mm x 5 mm
- 11 ultra stable titanium housing

CUSTOMER FEEDBACK

Dr. N. Andreeva

The attoAFM I is great for Piezoresponse Force Microscopy of both large crystals and thin films because the microscope integrates flawlessly with external electronics and gives access to all the relevant signals. The system maintained regular weekly cooling cycles for a 2 year stretch and still works great!

(St. Petersburg State Polytechnical University, Russia)

PRODUCT KEY FEATURES

- interferometric encoders for closed loop scanning with 1 nm resolution (optional)
- 125 μm scan range @ 4 K (optional)
- attoAFM I+ head feat. alignment-free cantilever holder
- quick exchange sample holder with 8 electrical contacts
- ultra compact, highly rigid MFM head
- highly sensitive interferometric deflection detection
- adjustment of the cantilever outside the cryostat prior to cooling the microscope

BENEFITS

- easy tracking of regions of interest & distortion-free images (optional)
- tip exchange in less than 2 minutes
- high spatial resolution imaging
- simultaneous ultra high resolution topographic & magnetic force imaging
- compatible with Nanosensors'XY-auto alignment AFM tips

APPLICATION EXAMPLES

- investigation of superconductors
- domain structure studies
- materials science

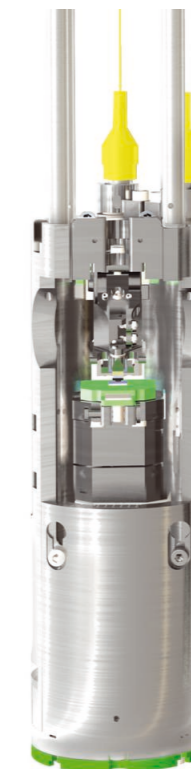
COMPATIBLE COOLING SYSTEMS

- attoDRY1000/1100/2100, attoDRY800 (on request)
- attoLIQUID1000/2000/3000/5000

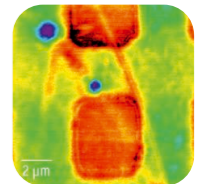


Available Upgrade Options

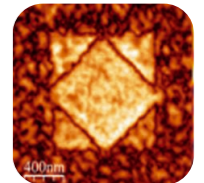
- closed loop scanning & global sample coordinates
 - ultra large scan range (125 μm @ 4 K)
 - inspection optics
 - closed loop upgrade for positioners
- ...for further details, see accessories section



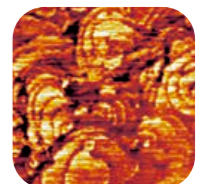
The attoAFM I microscope module



Kelvin Probe Force Microscopy



Piezoresponse Force Microscopy



Conductivity Mapping

attoAFM I+ Head

featuring an alignment-free cantilever holder

The attoAFM I+ head features an alignment-free cantilever holder for tip exchange, and hence takes over the complete mechanical alignment of the cantilever with respect to the fiber used for deflection readout. A folding mechanism allows for easy extraction of the cantilever holder for tip exchange without dismantling the AFM head itself.

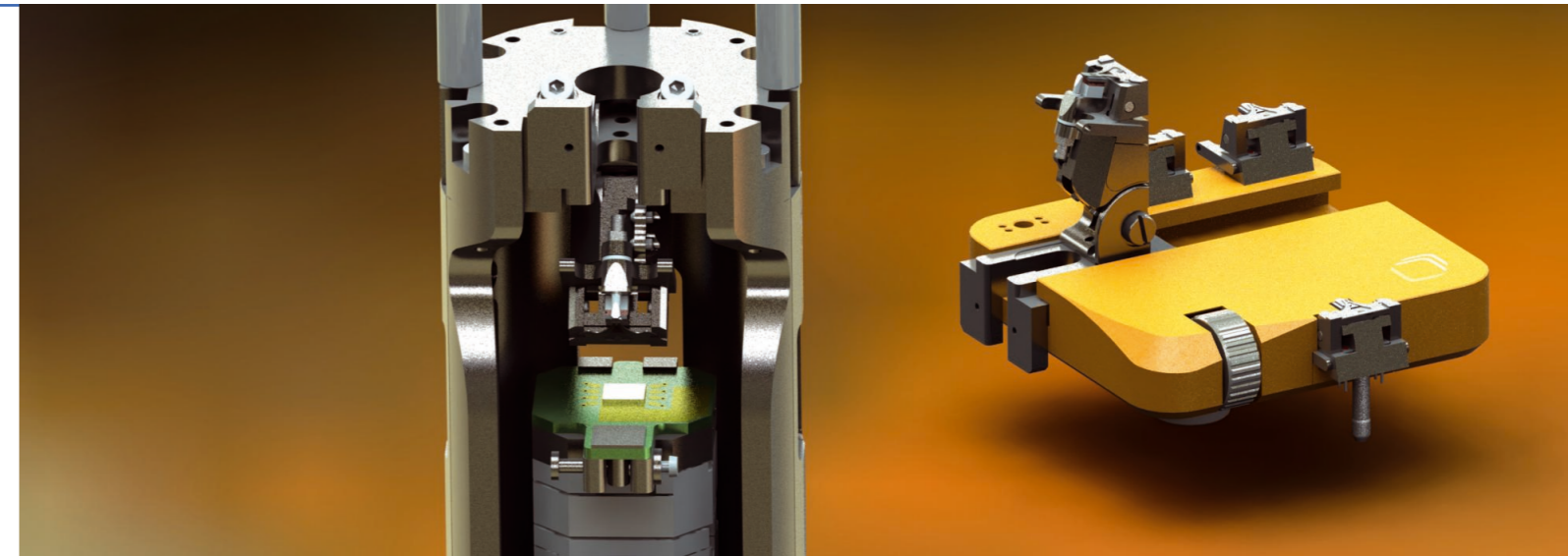
To exchange the tip, the holder is simply put into an exchange basis with a leveled platform. This enables to easily slide in and out cantilevers, thus minimizing the danger of damaging the costly and valuable tips during handling. The tip itself is held in place by a spring blade, which can be slid open and closed via another clever quick folding mechanism.


This way, the tip can be replaced within tens of seconds. During re-attachment, a guiding rod automatically centers the cantilever holder. When folding the head back into its initial parking position, the fiber end is perfectly aligned with respect to the cantilever. The desired interference pattern with ideal contrast is thus automatically achieved without any further mechanical alignment.

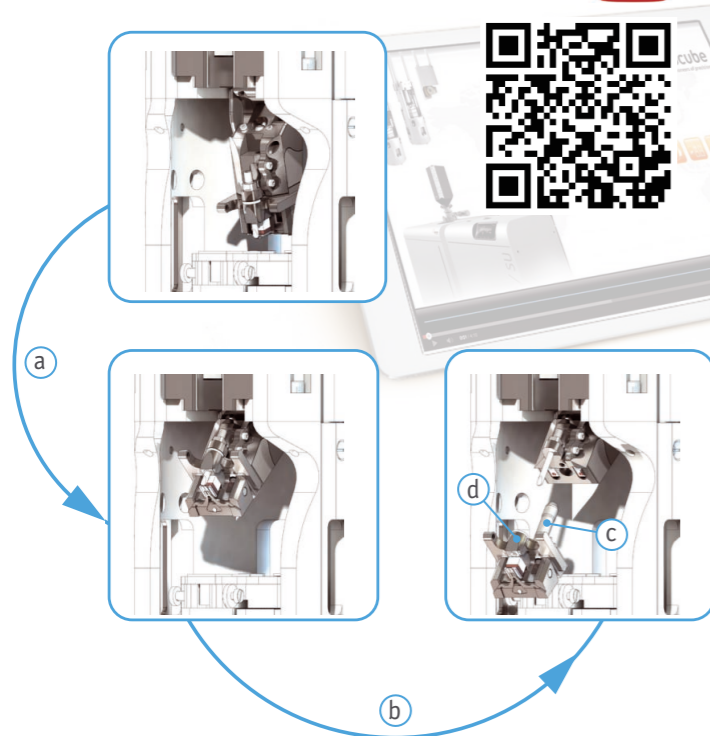
The attoAFM I+ head incl. the alignment-free cantilever holder is included with every attoAFM I (2" and 1" version), as well as any upgrades such as MFM, PFM, KPFM and ct-AFM), and is compatible with all commercially available XY-auto alignment AFM tips (patented technology by NANOSENSORS ^{AG} The World Leader in Scanning Probes).

Quick. Intuitive. Efficient.

AFM/MFM tip exchange in less than 2 minutes



Tip exchange in < 2 minutes! Watch the video on 



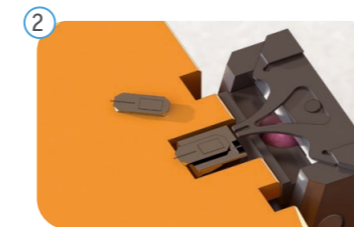
1. Flip the AFM head upwards. (a)
2. Remove the cantilever holder. (b)
3. Perform the AFM tip exchange (for details, see description of the cantilever holder on the right)
4. Once the new tip is mounted, reattach the cantilever holder:
A guiding rod (c) automatically centers the cantilever holder by fixing one degree of freedom, while the fiber ferrule is still far away from any potentially harmful obstacle.
5. Feed the ferrule into the cantilever holder through another guiding sleeve (d). The ferrule is protected by a soft sleeve.
6. Tilt the head back into the housing – it flips conveniently and firmly into its dedicated parking position.

Done.

There is no further mechanical alignment necessary – perfectly aligned, yielding the desired interferogram used for the deflection detection of the cantilever.



Put the cantilever holder into the exchange basis.



Slide back the spring blade.



Perform the cantilever exchange; alignment grooves on chip guarantee perfect positioning.



Close the holder and remove holder from the exchange basis, and insert it back into the AFM head.



MAIN ADVANTAGES

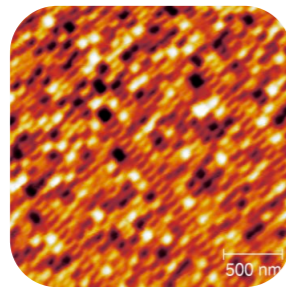
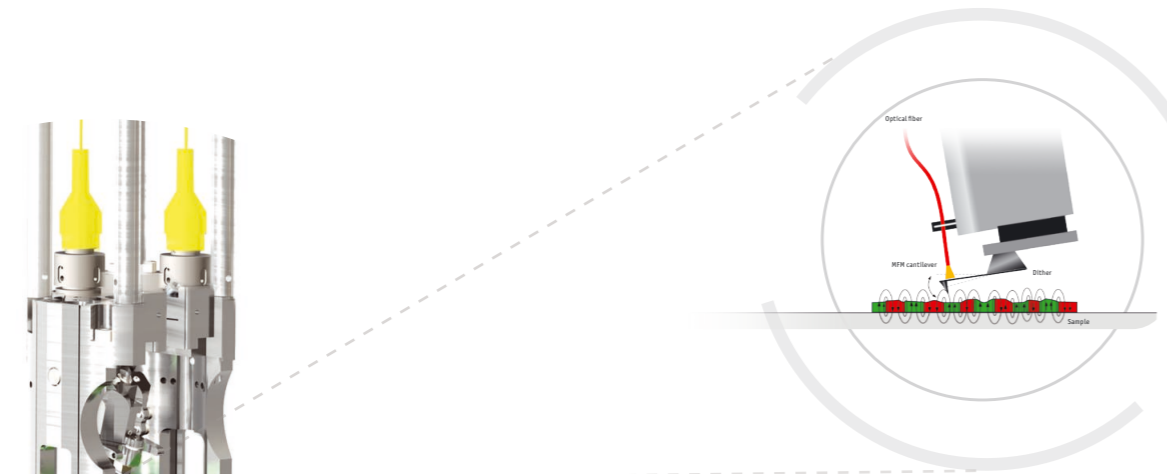
- compact design
- ultra-stable
- easy to use
- no special tools needed
- fully pre-aligned
- no re-alignment needed after cantilever exchange
- electrical pin contacts included, no wires to be detached

Magnetic Force Microscopy (MFM)

additional AFM mode upgrades

Magnetic Force Microscopy (MFM)

MFM is one of the most widely used AFM techniques, and makes use of a magnetic tip to map out the z-component of the gradient of the magnetic stray field.



MFM image of hard disc

The MFM upgrade contains

- 10 MFM tips
- MFM test sample
- MFM factory test at room temperature and low temperature
- MFM demonstration and training during the installation

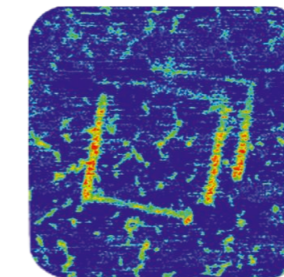
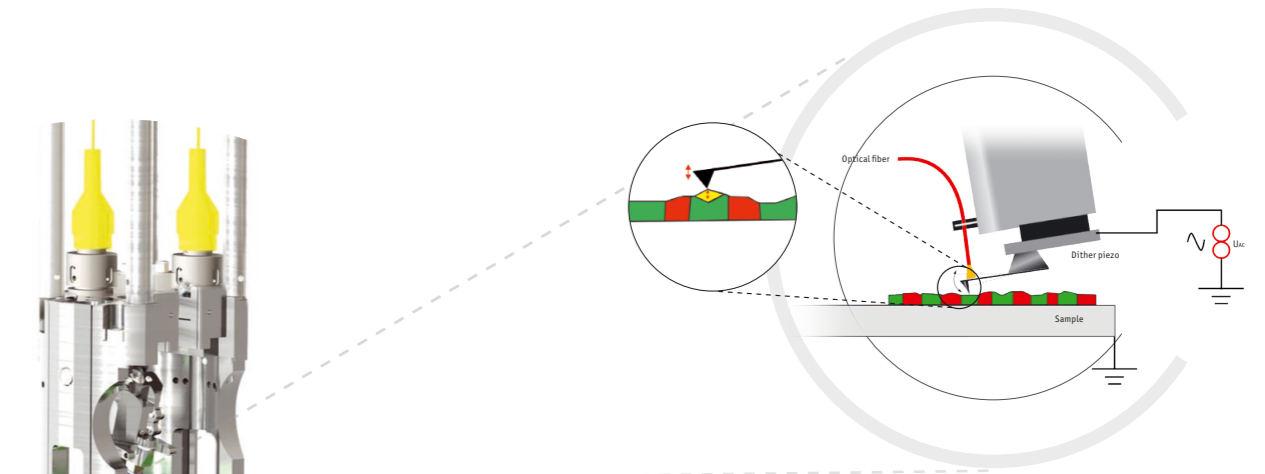
Article	Art.No.
MFM upgrade	1012468

Piezoresponse Force Microscopy (PFM)

additional AFM mode upgrades

Piezoresponse Force Microscopy (PFM)

PFM is capable of imaging the local deformation of a multiferroic material in response to a local electric field caused by a voltage supplied to the AFM tip.



attocube logo written into BFO by PFM

The PFM upgrade contains

- 10 conductive AFM tips
- PFM test sample
- PFM factory test at room temperature and low temperature
- PFM demonstration and training during the installation

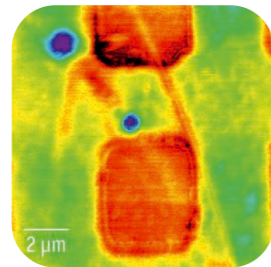
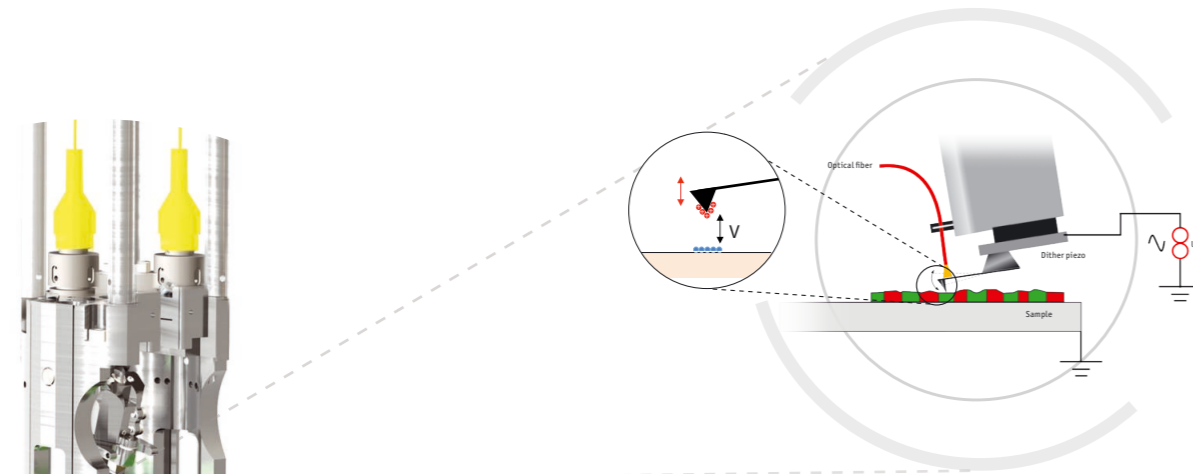
Article	Art.No.
PFM upgrade	1009869

Kelvin Probe Force Microscopy (KPFM)

additional AFM mode upgrades

Kelvin Probe Force Microscopy (KPFM)

KPFM yields information about the local variations of the work function of a material with respect to the AFM tip.



KPFM image of Au-on-Pt pattern

The KPFM upgrade contains

- KPFM software upgrade
- 10 conductive AFM tips
- KPFM test sample
- KPFM factory test at room temperature and low temperature
- KPFM demonstration and training during the installation

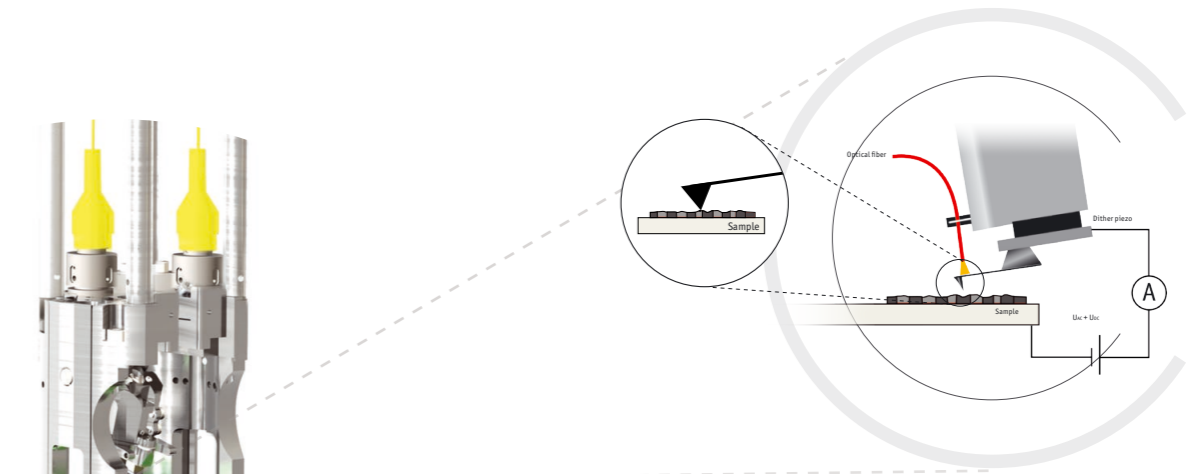
Article	Art.No.
KPFM upgrade	1009977

Conducting-tip Atomic Force Microscopy (ct-AFM)

additional AFM mode upgrades

Conducting-tip Atomic Force Microscopy (ct-AFM)

Ct-AFM allows to map out the local electric response of a sample to an applied bias voltage via the AFM tip.



ct-AFM on Ruthenium

The ct-AFM upgrade contains

- Low noise current amplifier
- 10 conductive tips
- Ct-AFM test sample
- Ct-AFM factory test at room temperature and low temperature
- Ct-AFM demonstration and training during the installation

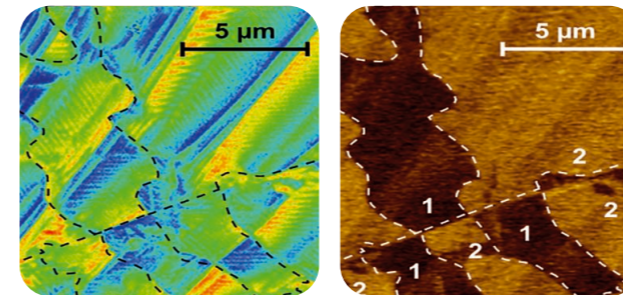
Article	Art.No.
Ct-AFM upgrade	1008504

General Specifications	
type of instrument	cantilever based AFM with interferometric deflection detection
sensor head specifics	attoAFM I+ head feat. alignment-free cantilever holder tip exchange in less than 2 minutes
alignment-free cantilever holder (default)	compatible with PointProbe® Plus XY-Alignment Series by Nanosensors
conventional cantilever holder (optional)	compatible with standard commercial cantilevers
Operation Modes	
imaging modes	contact mode, non-contact mode, constant height, constant force
slope compensation	2 axis scan plane correction
z feedback	PI feedback loop for amplitude modulation (AM), phase modulation (PM) or frequency modulation (FM) using included PLL, constant force
incl. standard techniques	AFM
optional upgrades	KPFM, PFM, conductive-tip AFM
Resolution*	
measured RMS z-noise (constant force @ 4 K, 5 ms pixel time)	< 0.05 nm (expected for attoLIQUID) < 0.10 nm (expected for attoDRY) < 0.15 nm (guaranteed)
z deflection noise density	< 3 pm/√Hz (dependent on laser system)
lateral magnetic resolution	< 20 nm (attoLIQUID), < 50 nm (attoDRY)
z bit resolution @ 4 K	57 pm at 15 μm scan range
Sample Positioning	
total travel range	5 x 5 x 5 mm ³ (open loop)
step size	0.05..3 μm @ 300 K, 10..500 nm @ 4 K
fine scan range	50 x 50 x 24 μm ³ @ 300 K 30 x 30 x 15 μm ³ @ 4 K
closed loop scanning	optional
sample holder	ASH/QE/4CX quick-exchange sample holder with 8 electrical contacts, integrated heater calibrated temperature sensor
Suitable Operating Conditions	
temperature range	1.5 K..300 K (dependent on cryostat); mK compatible setup available on request
magnetic field range	0..15 T+ (dependent on magnet)
operating pressure	designed for He exchange gas (vacuum compatible version down to 1E-6 mbar on request)
Suitable Cooling Systems	
titanium housing diameter	48 mm
bore size requirement	designed for a 2" (50.8 mm) cryostat/magnet bore
compatible cryostats	attoDRY1000/1100/2100 attoLIQUID1000/2000/3000/5000



The attoAFM I microscope stick

Electronics	
scan controller and software	ASC500 (for detailed specifications please see attoCONTROL section)
laser	LDM1300 laser/detector module (for detailed specifications please see attoCONTROL section)
Options	
closed loop upgrade for coarse positioners	resistive encoder, range 5 mm, sensor resolution approx. 200 nm, repeatability 1-2 μm
ultra-large scan range upgrade	80 x 80 @ 300 K 125 x 125 @ 4 K
<i>in-situ</i> inspection optics	tip/sample monitoring via <i>in-situ</i> LT-LED for illumination, mirrors, lenses and CCD camera (outside of cryostat) field of view approx. 3 mm x 2 mm, resolution approx. 20 μm (depending on cryostat: distance top-flange to field center)
closed loop scanning upgrade	interferometric encoders available (see attoDRY LAB -> attoMFM I+)
additional AFM head with manual alignment	conventional cantilever holder, compatible with standard commercial cantilevers



Ferroelectric Domains at Low-Temperature Phase Transitions in BTO

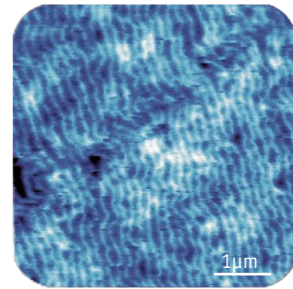
Ferroelectric barium titanate (BTO) exhibits several ferroelectric phase transitions at low temperatures, resulting in severe structural changes and domain formation. Using an Attocube AFM I, the group of Prof. Eng (Institute of Applied Physics, Dresden University of Technology, Dresden, Germany) has investigated this domain dynamics in BTO single crystals applying both piezoresponse force microscopy (PFM) and Kelvin probe force microscopy (KPFM) down to 10 K. The two images display the PFM signal (a) and surface potential measured by KPFM (b) in contact and non-contact mode, respectively, over the same 15 μm x 15 μm sample area at T=220 K (orthorhombic BTO phase).

(J. Döring, L.M. Eng, and S.C. Kehr. "Low-temperature piezoresponse force microscopy on barium titanate." *J. Appl. Phys.* 120, 84103 (2016))

* Resolution may vary depending on applied tip, sample, and cryostat

Selected Applications

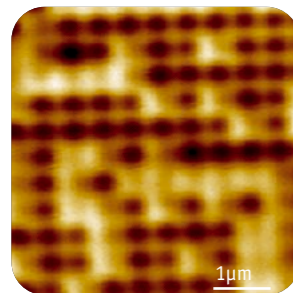
attoAFM I



Helimagnetic Phase of Fe_{0.5}Co_{0.5}Si

Real space imaging of exotic magnetic phases provides a level of understanding that cannot be achieved with indirect techniques. The figure on the left shows one of the first observations of a helimagnetic phase using the attoMFM I. The periodicity of the stripes is around 100 nm. This phase is of particular interest because of its proximity to a skyrmion phase. Skyrmions are exotic magnetic excitations, studied extensively because of their potential use in spintronic applications. The measurement was performed on a FeCo_{0.5}Si_{0.5} sample at 4 K using an attoMFM I in attocube application labs.

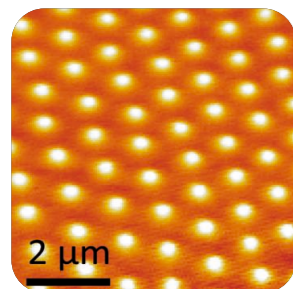
(attocube application labs, 2013; sample courtesy of A. Bauer and C. Pfleiderer, Technical University of Munich, Garching, Germany)



High Resolution MFM on Bit Patterned Media Co-Pd at 10 K

MFM measurement on Co-Pd dots with 50 nm diameter at 10 K using the attoMFM I. The image demonstrates the high magnetic resolution achievable with the attoMFM. Variations in magnetic field perpendicular to the surface allows switching domains from one magnetic state to the other (here recorded at 6250 Oe). For this measurement, the attoMFM was operated at constant height with the frequency shift measured using a phase-locked loop.

(attocube application labs, 2010; sample courtesy of Hitachi Global Storage Solutions, San Jose, USA)



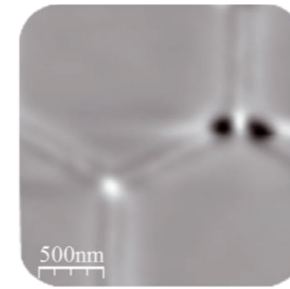
MFM on Superconducting Vortices in BSCCO

This measurement shows a dominantly hexagonally ordered Abrikosov vortex lattice, at a magnetic field of -40 Oe (the sample was field-cooled). The orientation of the vortices with respect to the moment of the tip is indicated by the color of the vortices: Bright colors indicate repulsive forces. The tip was scanned in a constant height of about 30 nm above the surface of a freshly cleaved piece of BSCCO-2212. Note that the applied field is much lower than the coercivity of the hardmagnetic tip (≈ 400 Oe), hence the orientation of the tip moment is unchanged. Scan size is $10 \times 10 \mu\text{m}^2$, color span is 2 Hz.

(attocube applications labs, 2013; sample courtesy of A. Erb, TU Munich, Germany)

Selected Applications

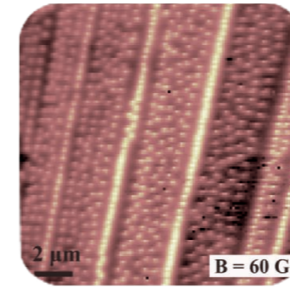
attoAFM I



Low Temperature MFM on Artificial Spin Ice

Frustrated systems are intriguing for physicists since they possess highly degenerate ground states with non-zero entropy at 0 K, which can give rise to interesting new phenomena. A prominent example which has been widely studied in condensed matter physics is artificial spin ice. Using Magnetic Force Microscopy (MFM), the group of W. Branford (Imperial College, UK) have studied the magnetic reversal of a nanostructured permalloy honeycomb lattice, demonstrating the breakdown of the artificial spin ice regime at low temperatures and in high magnetic fields.

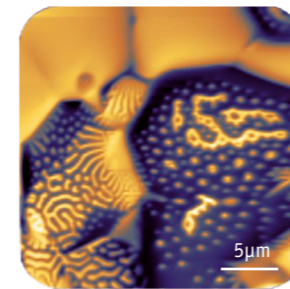
[Data courtesy of W.R. Branford, Imperial College, UK; for more details, see K. Zeissler et al., Scientific Reports 6, 30218 (2016)]



Vortex Barriers in Iron Pnictides

Iron-pnictide high-temperature superconductors are widely studied, but many open questions still remain. Using an attoAFM I for magnetic force microscopy, the group of O. Auslaender (Technion, Israel); for more information, see A. Yagil et al., Phys. Rev. B 94, 064510 (2016)]

[Data courtesy of O. Auslaender (Technion, Israel); for more information, see A. Yagil et al., Phys. Rev. B 94, 064510 (2016)]



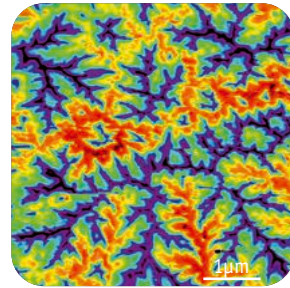
MFM for Optimization of Sintered Magnets

MFM image of a NdFeB sintered magnet with the nominal c-axis orientation perpendicular to the surface. The sample is in the remanent state but some surface grains show already magnetization reversal. High resolution imaging allows deeper insights into the magnetic reversal mechanism and the optimization of magnetic properties. Image size is $30 \times 30 \mu\text{m}^2$.

(Image courtesy of T. Helbig and O. Gutfleisch, Functional Materials Group, TU Darmstadt, Germany and Fraunhofer IWKS Hanau, Germany.)

Selected Applications

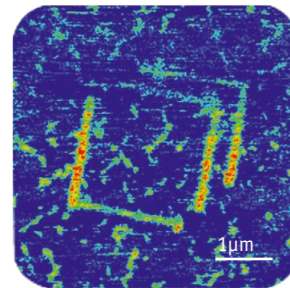
attoAFM I



MFM on Co Doped Mn₂Sb Single Crystal

Magnetic domain structure in the ferrimagnetic state of Co doped Mn₂Sb single crystal imaged using an attoAFM Ixs Magnetic Force Microscopy (here at 290 K). The image was taken in constant distance mode with the height above the sample surface set to 50 nm. The area shown in the figure corresponds to 15 μm x 15 μm with a size of 800 x 800 pixel.

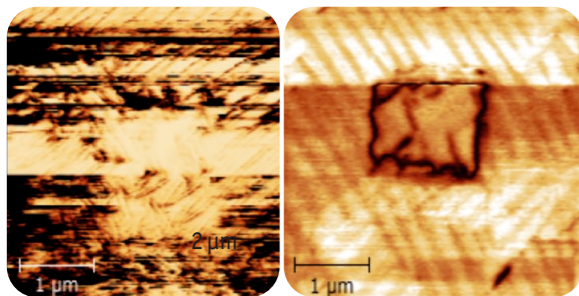
(Image courtesy of Rajeev Rawat, UGC-DAE Consortium for Scientific Research, Indore, India)



Piezoresponse Force Image on BFO

This image shows the attocube logo electrically written into a BaFeO₃ substrate next to natural domains of the sample. The data were taken at 4K in piezoresponse force mode using an attoAFM/MFM I. Image size is 5x5 μm².

(attocube application labs, 2014; Sample courtesy of Marin Alexe, Functional Materials Group, Department of Physics, University of Warwick, Coventry, UK)



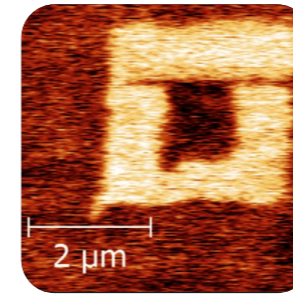
Local Conductivity Mapping and PFM on BFO Thin Film

In this application, the versatility of the attoAFM I was demonstrated on an ultra-thin film of BFO. A simple box writing and reading measurements was performed. During the writing phase, a DC voltage of -10V was applied to write a box. During the reading, a 5 V_{pp} AC excitation at ~42 kHz on top of a -2V DC voltage was used. Using both AC and DC voltage at the same time allows for a simultaneous measurement of PFM (right image) and local conductivity (left image).

(attocube application labs, 2014; sample courtesy of N. Domingo, ICN Barcelona, Spain)

Selected Applications

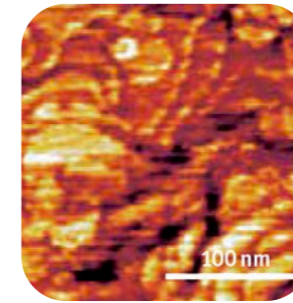
attoAFM I



Low Temperature Piezoresponse Force Microscopy on BiFeO₃

Piezoresponse Force Microscopy (PFM) is a standard tool at room temperature to investigate new materials, especially multiferroics. However in many cases the scientifically interesting phases only exist at low temperatures or high magnetic fields, what demands the extension of this technique to extreme conditions. In collaboration with our customers, we adapted our attoAFM based on the general purpose ASC500 for PFM measurements. In the measurements here we investigated BiFeO₃ a well know room temperature multiferroic. The figure shows piezoresponse amplitude after a box in the box writing at 160 K on the sample.

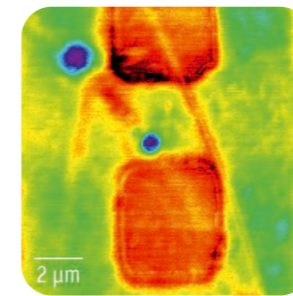
(attocube application labs, 2013; Sample courtesy of Neus Domingo & Gustau Catalan, CIN2 Barcelona, Centre d'Investigació en Nanociència i Nanotecnologia, Bellaterra, Spain)



Conductive-Tip AFM Measurements on Ruthenium

In this application, atomic steps on Ruthenium were investigated using conductive-tip AFM. Atomic steps as well as spiral dislocations can be identified on the molecular beam epitaxy-grown sample. The contrast in this measurement is highly enhanced due to a difference in conductance between edges and flat plateaus. Such high contrast was not observed in the accompanying topographic image. A voltage of +10 mV was applied to the standard Pt-coated AFM tip, while the sample was grounded via a current amplifier with gain 10⁶ V/A. The measurement was performed at room temperature in a 20 mbar He atmosphere.

(Sample and measurement courtesy of V. Da Costa, J.-F. Dayen, B. Doudin, IPCMS-DMONS, CNRS/University of Strasbourg, France)



Kelvin Probe Force Microscopy of Au-on-Pt Pattern

The measurements shown here were performed on a test sample consisting of a Au layer on a Pt substrate in dual pass mode. The KPFM image was recorded during the second line with a lift height of about 50 nm. The color scale spans approximately 130 mV, and the image size is 11.9 μm x 11.9 μm.

We found a KPFM contrast of approx. 35 mV, and a KPFM resolution (noise level) of approx. 2.6 mV.

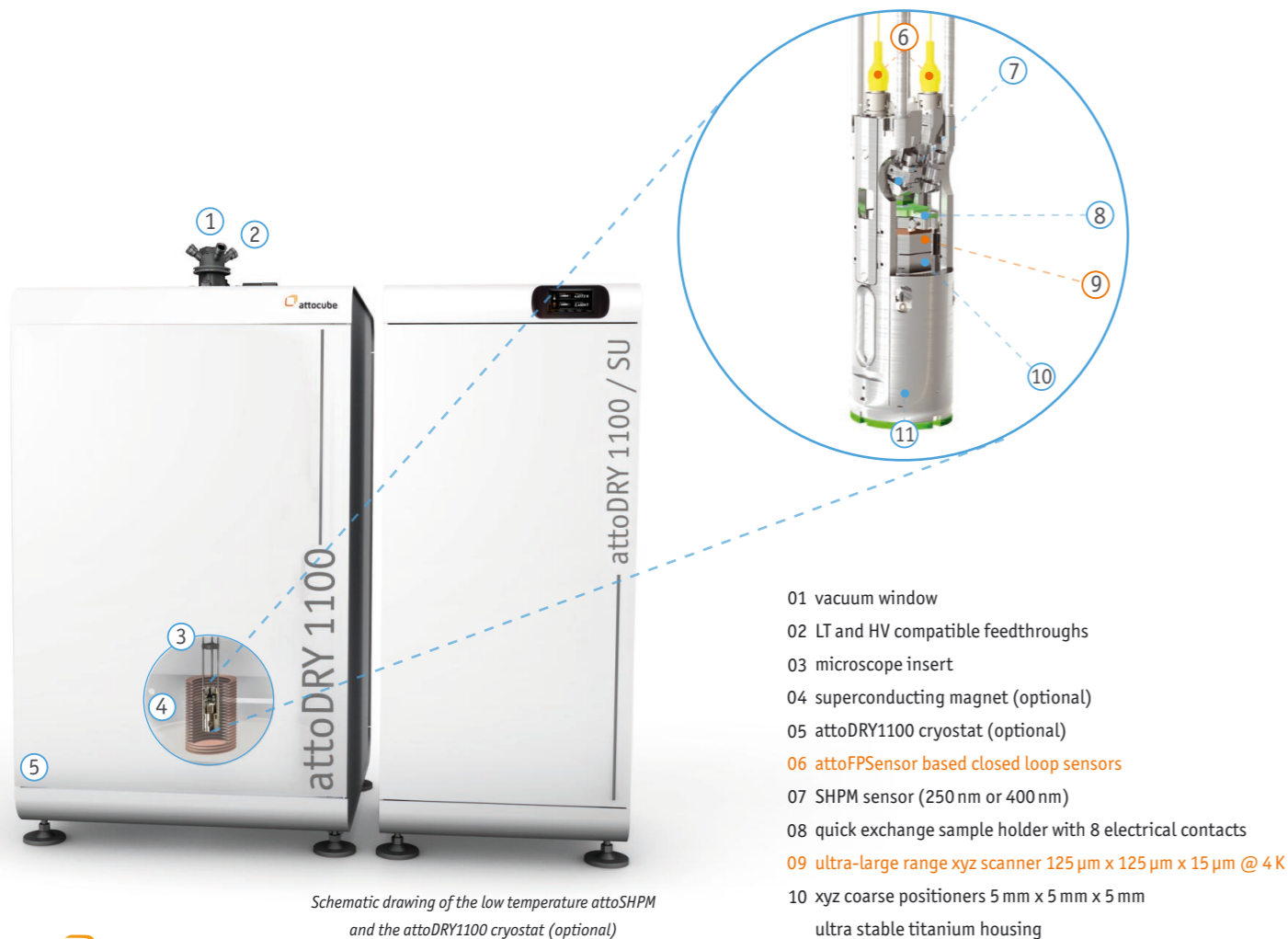
(attocube application labs 2014)

attoSHPM

Low temperature scanning Hall probe microscope

The attoSHPM+ is a compact scanning Hall probe microscope, designed particularly for operation at low temperature and high magnetic fields. At the heart of the attoSHPM+, a molecular beam epitaxy (MBE) grown GaAs/AlGaAs Hall sensor measures magnetic fields with unrivalled sensitivity. Local measurements of the magnetization of a sample are obtained by scanning the sample underneath the Hall sensor and simultaneously recording the Hall voltage, directly yielding the local magnetic stray field.

While other local probes may outperform the Hall sensor with respect to its lateral resolution, its ability to non-invasively obtain quantitative values for the local magnetic field makes the Hall sensor a unique tool for the study of superconductors and magnetic materials. The attoSHPM+ features an interferometric encoder for closed loop operation with 1 nm resolution, and an ultra large range scanner with 125 μm scan range at 4 K.



Schematic drawing of the low temperature attoSHPM and the attoDRY1100 cryostat (optional)

PRODUCT KEY FEATURES

- interferometric encoders for closed loop scanning with 1 nm resolution
- 125 μm scan range @ 4 K
- quick exchange sample holder with 8 electrical contacts
- STM distance tracking for conductive samples
- high spatial resolution: 250 nm & 400 nm sensors available
- noise-equivalent magnetic field: 15 nT/ $\sqrt{\text{Hz}}$ @ 4 K (40 μA Hall current)
- typ. attainable field detection limit: 15 μT (bandwidth 10 Hz @ 277 Hz)
- (ultra-) large cryogenic scan range: 30 μm x 30 μm x 15 μm @ 4 K (incl.) 125 μm x 125 μm x 15 μm @ 4 K (optional)

BENEFITS

- easy tracking of regions of interest & distortion-free images
- gain quantitative & non-invasive magnetic information
- ultra-high field sensitivity combined with sub-micron resolution
- easily identify and relocalize regions of interest (ROIs) on your sample
- fits standard cryogenic and magnet sample spaces
- compatible with high magnetic fields

APPLICATION EXAMPLES

- vortex distribution and pinning measurements in pnictides, cuprates and other superconductors
- local field measurements on magnetic nanoparticles, bit patterned media, and other materials
- local hysteresis and susceptibility measurements

COMPATIBLE COOLING SYSTEMS

- attoDRY1000/1100/2100
- attoLIQUID1000/2000/3000, attoLIQUID5000 (on request)

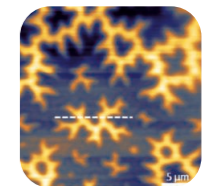


Available Upgrade Options

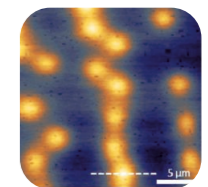
- closed loop scanning & global sample coordinates
 - ultra large scan range (125 μm @ 4 K)
 - inspection optics
 - closed loop upgrade for positioners
- ...for further details, see accessories section



The attoSHPM microscope module



Magnetic Domain Imaging



Vortex Imaging

Specifications

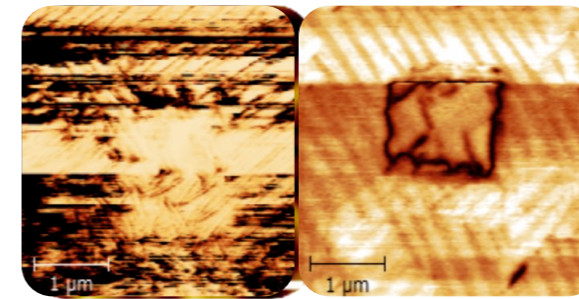
attoSHPM

General Specifications	
type of instrument	Scanning Hall Probe Microscope with STM tip for tip-sample distance control
sensor head specifics	MBE grown hall cross sensor (GaAs/AlGaAs heterostructure) on a 2-axis tiltable sensor mount
Operation Modes	
imaging modes	constant height
slope compensation	2 axis scan plane correction
z feedback	STM distance tracking (usually only for autoapproach)
Resolution*	
size of Hall cross on sensor	400 nm (high resolution); 250 nm (ultra high resolution)
field sensitivity @ 4 K	1500 V/AT
noise-equivalent magnetic field (theoretical)	15 nT/√Hz @ 4 K and 40 μA Hall current 80 nT/√Hz @ 77 K and 40 μA Hall current
typical attainable field detection limit (measured)	15 μT typ. (bandwidth 10 Hz @ frequency 277 Hz)
z bit resolution @ 4 K	57 pm at 15 μm scan range
Sample Positioning	
total travel range	5 x 5 x 5 mm ³ (open loop)
step size	0.05..3 μm @ 300 K, 10..500 nm @ 4 K
fine scan range	50 x 50 x 24 μm ³ @ 300 K 30 x 30 x 15 μm ³ @ 4 K
closed loop scanning	optional
sample holder	ASH/QE/4CX quick-exchange sample holder with 8 electrical contacts, integrated heater calibrated temperature sensor
Suitable Operating Conditions	
temperature range	1.5 K..300 K (dependent on cryostat); mK compatible setup available on request
magnetic field range	0..15 T+ (dependent on magnet)
operating pressure	designed for He exchange gas (vacuum compatible version down to 1E-6 mbar on request)
Suitable Cooling Systems	
titanium housing diameter	48 mm
bore size requirement	designed for a 2" (50.8 mm) cryostat/magnet bore
compatible cryostats	attoDRY1000/1100/2100 attoLIQUID1000/2000/3000/5000
Electronics	
scan controller and software	ASC500 (for detailed specifications please see attoCONTROL section)
Options	
closed loop scanning & global sample coordinates	interferometric encoders for scan linearization and closed loop sample navigation
ultra-large scan range upgrade	80 x 80 @ 300 K 125 x 125 @ 4 K
<i>in-situ</i> inspection optics	tip/sample monitoring via <i>in-situ</i> LT-LED for illumination, mirrors, lenses and CCD camera (outside of cryostat) field of view approx. 3 mm x 2 mm, resolution approx. 20 μm (depending on cryostat: distance top-flange to field center)
closed loop upgrade for coarse positioners	resistive encoder, range 5 mm, sensor resolution approx. 200 nm, repeatability 1-2 μm

* Resolution may vary depending on applied tip, sample, and cryostat

Selected Applications

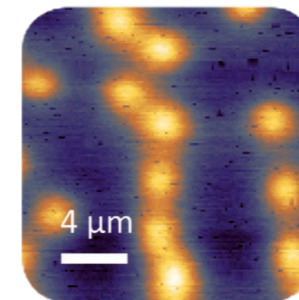
attoSHPM



Domain Imaging in BaFeO

The 15 μm x 15 μm sized image shows a sample of BaFeO recorded with an attoSHPM, recorded at 4.2 K. The SHPM sensor was kept in a constant height of about 200 nm. The color scale spans 106 mT (dark to bright), while the S/N ratio of this measurement yields an exceptional 50 000:1. Note that SHPM records absolute field strength as opposed to MFM techniques, that record only field gradients.

(attocube application labs, 2011; sample courtesy of R. Kramer, Institut Néel, CNRS, Grenoble)



Vortex Imaging via Scanning Hall Probe Microscopy

SHPM measurements on a degraded Bi₂Sr₂CaCu₂O_{8+x} substrate have been performed demonstrating strong surface pinning effects at 4.2 K and 2.5 Gauss external magnetic field. The figure shows the vortex distribution measured in constant height of approx. 100 nm above the surface.

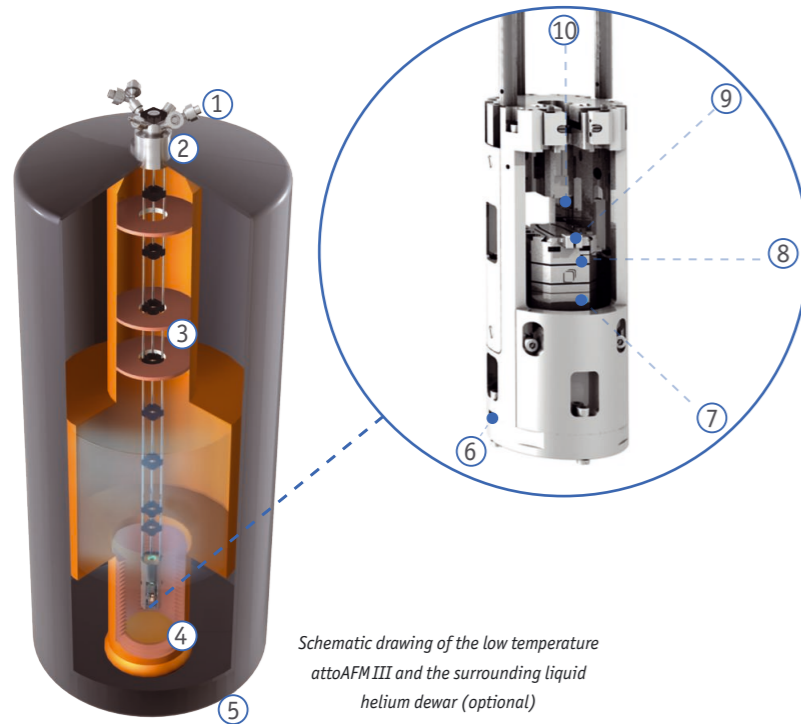
(attocube applications labs, 2011; sample courtesy of A. Erb, TU Munich, Germany)

attoAFM III

tuning fork based, low temperature atomic force microscope

The attoAFM III is an atomic force microscope designed particularly for applications at low and ultra low temperature. Due to the non-optical shear force detection based on a tuning fork, this system is ideally suited for applications where input of light is problematic. A typical application of the attoAFM III microscope is scanning gate microscopy (SGM) on semiconductor structures. This microscope is compatible with the commercially available tuning fork tips, and is available with optional interferometric encoder for closed loop scanning.

The attoAFM III uses a tuning fork sensor as detection mechanism for the tip-sample forces, allowing high resolution non-contact mode imaging without the need for any optical deflection detection techniques. An AFM tip is glued onto one prong of a small quartz tuning fork, which is then excited to oscillate in horizontal direction. The decrease in amplitude due to tip-sample interaction when approaching the sample is monitored and/or used as a feedback signal. The force resolution of this technique is typically 0.1 pN.



Schematic drawing of the low temperature attoAFM III and the surrounding liquid helium dewar (optional)

- 01 LT and HV compatible feedthroughs
- 02 vacuum window
- 03 microscope insert
- 04 superconducting magnet (optional)
- 05 liquid He dewar (optional)
- 06 ultra stable Titanium housing
- 07 xyz coarse positioners
- 08 xyz scanner
- 09 quick-exchange sample holder
- 10 tuning fork AFM sensor

CUSTOMER FEEDBACK

Dr. Stefan Heun

Directly after the set up in our labs, the attoAFM III in a 3He cryostat - used for scanning gate microscopy experiments - has started to produce great data for us. It runs more than 5 years now, and we have published several papers since then. The instrument worked within specifications from the first day and we really appreciate the excellent attocube support throughout the years.

(Istituto Nanoscienze-CNR and Scuola Normale Superiore, Pisa, Italy)

PRODUCT KEY FEATURES

- ultra compact AFM head with unprecedented stability
- interferometric encoders for closed loop scanning (optional)
- highly sensitive, non-optical tuning fork sensor
- large cryogenic scan range:
30 μm x 30 μm x 2 μm @ 4 K

BENEFITS

- ultra high resolution imaging in non-contact mode
- high Q factor for high sensitivity measurements
- optimized S/N ratio due to LT compatible preamplifier
- no optical alignment necessary

APPLICATION EXAMPLES

- materials science: ultra-high resolution topographic imaging
- scanning gate microscopy at mK temperatures
- investigations of semiconductor structures

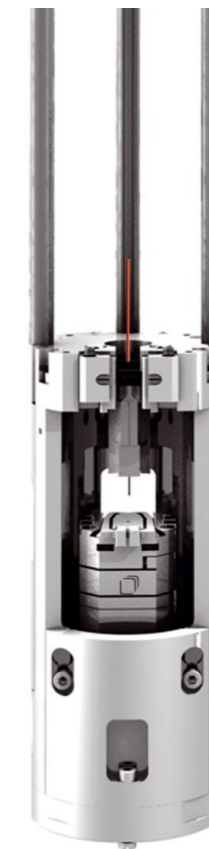
COMPATIBLE COOLING SYSTEMS

- attoDRY 1000/11000/2100
- attoLIQUID1000/2000/3000/5000

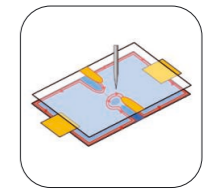


Available Upgrade Options

- closed loop scanning & global sample coordinates
 - ultra large scan range (125 μm @ 4 K)
 - inspection optics
 - closed loop upgrade for positioners
- ...for further details, see accessories section



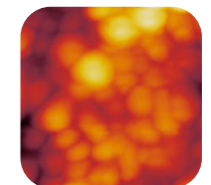
The attoAFM III microscope module



Scanning Gate Microscopy



High resolution AFM



Kelvin Probe Force Microscopy

Specifications

attoAFM III

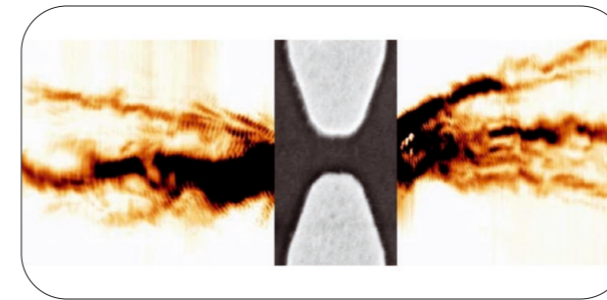
Selected Applications

attoAFM III

General Specifications	
type of instrument	tuning-fork based AFM with shear-force or standard detection
sensor head specifics	etched metal wires, etched or pulled optical fiber probes, STM tips, Akiyama probes (also compatible with NaugaNeedles commercial tips)
Operation Modes	
imaging modes	non-contact mode AFM, EFM, SGM
slope compensation	2 axis scan plane correction
z feedback	PI feedback loop for amplitude modulation (AM), phase modulation (PM) or frequency modulation (FM) using included PLL
optional upgrades	AFM/STM mode
Resolution*	
measured z-noise density	< 16 pm/√Hz
z bit resolution @ 4 K	7.6 pm at 2 μm scan range
Sample Positioning	
total travel range	5 x 5 x 5 mm ³ (open loop)
step size	0.05..3 μm @ 300 K, 10..500 nm @ 4 K
fine scan range	50 x 50 x 4.2 μm ³ @ 300 K 30 x 30 x 2 μm ³ @ 4 K
sample holder	ASH/QE/0 quick exchange sample holder and integrated heater with calibrated temperature sensor
Suitable Operating Conditions	
temperature range	1.5 K..300 K (dependent on cryostat); mK compatible setup available on request
magnetic field range	0..15 T+ (dependent on magnet)
operating pressure	designed for He exchange gas (vacuum compatible version down to 1E-6 mbar on request)
Suitable Cooling Systems	
titanium housing diameter	48 mm
bore size requirement	designed for a 2" (50.8 mm) cryostat/magnet bore
compatible cryostats	attoDRY1000/1100/2100 attoLIQUID1000/2000/3000/5000
Electronics	
scan controller and software	ASC500 (for detailed specifications please see attoCONTROL section)
Options	
sample holder upgrade	ASH/QE/4CX quick-exchange sample holder with 8 electrical contacts and integrated heater with calibrated temperature sensor
closed loop upgrade for coarse positioners	resistive encoder, range 5 mm, sensor resolution approx. 200 nm, repeatability 1-2 μm
ultra-large scan range upgrade	80 x 80 @ 300 K 125 x 125 @ 4 K
in-situ inspection optics	tip/sample monitoring via in-situ LT-LED for illumination, mirrors, lenses and CCD camera (outside of cryostat) field of view approx. 3 mm x 2 mm, resolution approx. 20 μm (depending on cryostat: distance top-flange to field center)
closed loop scanning upgrade	interferometric encoders available



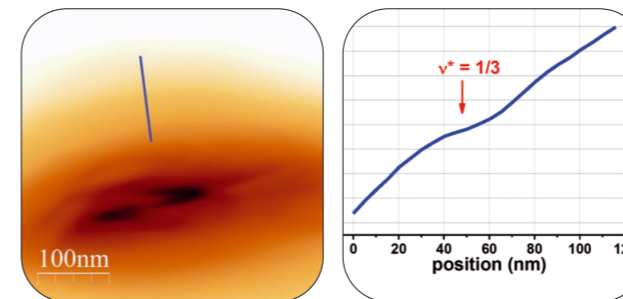
The attoAFM III microscope stick



Scanning Gate Microscopy at 300 mK

In this measurement, an attoAFM III was operated inside an attoLIQUID3000 cryostat at 300 mK in scanning gate microscopy mode (SGM) - investigating the trajectory and interaction of edge channels of a split-gate quantum point contact (QPC) device in the Quantum Hall (QH) regime. By scanning the SGM tip over the surface of the QPC at constant height and by simultaneously measuring and plotting the source-drain current, conductance maps were obtained. The image to the left is an example of such a conductance map depicting the characteristic branched-flow of electrons at zero magnetic field, which in turn shows electron interference fringes and the actual electron path ($T = 400$ mK, 2DEG density $n_{2D} = 3.37 \times 10^{11} \text{ cm}^{-2}$).

(Data and images were generously provided by S. Heun et al., NEST, CNR-INFM and Scuola Normale Superiore, Pisa, Italy.)



Imaging Fractional Incompressible Stripes in Quantum Hall Systems

In newer measurements, the group performed SGM measurements at the temperature and magnetic field conditions required to observe the fractional quantum Hall effect. The goal is to image for the first time the presence of fractional incompressible stripes, i.e. the existence of an inner structure within the integer edge channel. The measurements were performed at bulk filling factor $\nu = 1$ ($B = 8.23$ T, $T = 300$ mK). The corresponding SGM map in the region close to the QPC center is depicted in the lower Figure (a). Analogously to the $\nu = 4$ case, one expects to find plateaus when the local electron phase is gapped, i.e. when the local filling factor ν^* equals a robust fraction. The scan profile depicted in the right figure reveals a clear shoulder for $G_{sd} = e^2/3h$ (corresponding to points where $\nu^* = 1/3$). A more careful analysis [1] allows to determine the occurrence of incompressible phases for $\nu^* = 1/3, 2/5, 2/3$, and $3/5$, i.e. the two most robust fractions and their hole-particle conjugates, respectively. The SGM maps allow not only to reveal the fractional incompressible stripes, but also to measure their width and correlate it with the local electron density slope. The agreement between the data and a reconstruction model is remarkable, especially in light of the uncertainty on the fractional-gap value, which is known to be rather sensitive to the details of disorder potential.

(Data and images were generously provided by N. Paradiso, S. Heun et al., NEST, CNR-INFM and Scuola Normale Superiore, Pisa, Italy.)

[1] N. Paradiso et al., Phys. Rev. Lett. 108, 246801 (2012). See also the Supplemental Material.

* Resolution may vary depending on applied tip, sample, and cryostat

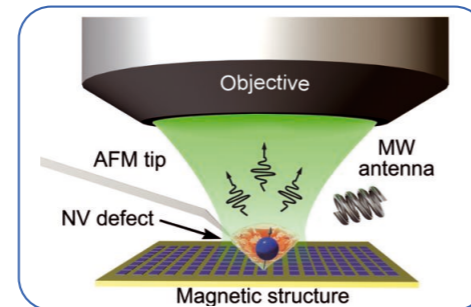
attoAFM/CFM

combined low temperature atomic force and confocal microscope, tuning fork based

The tuning fork based attoAFM/CFM not only allows fast optical investigation of the sample prior to detailed AFM studies, it also enables precise positioning of the AFM tip over small structures and optical control of the scanning process or any surface manipulation. Also, optical experiments such as Raman spectroscopy and tip enhanced Raman spectroscopy (TERS) can be conducted. Needless to say that all of these tasks can be performed in extreme environments, such as ultra low temperature, high vacuum and magnetic fields.

The attoAFM/CFM uses an Akiyama probe tip to investigate tip-sample interaction forces on the nanometer scale. The Akiyama probe is typical-

ly operated in non-contact mode using a phase-locked loop to excite the probe at resonance and track any shift in frequency due to tip-sample interactions. An additional PI controller keeps the frequency shift at a constant value while scanning over the surface. Simultaneously to the information provided by the Akiyama probe, the CFM reveals complementary optical information of the sample surface. Since the z-scanning motion is provided by a dedicated scanner on the side of the AFM, the focal distance between the low-temperature compatible lens and the sample does not change.



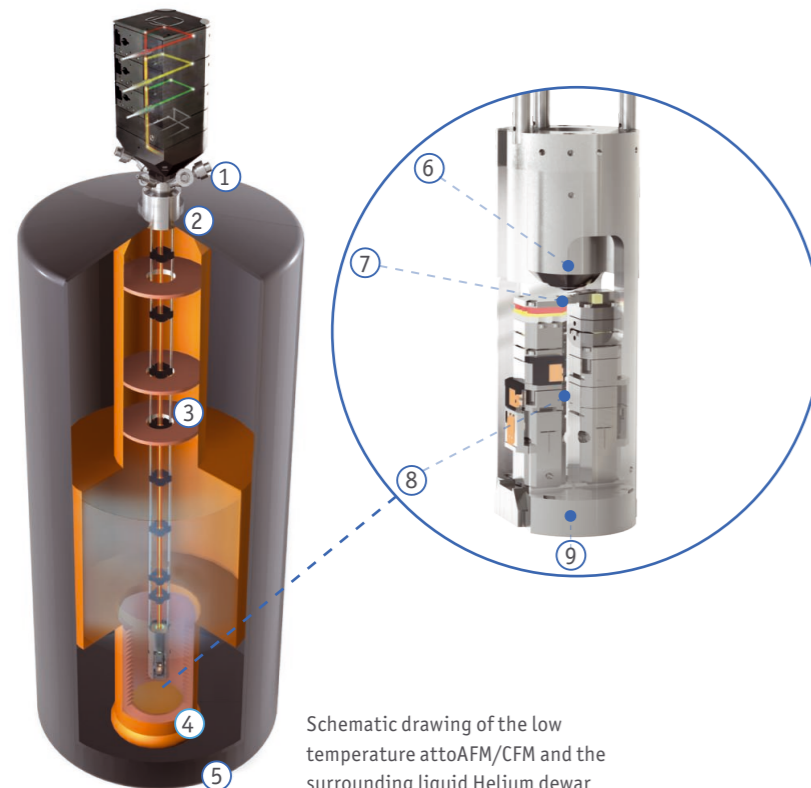
Principle of atomic-sized magnetic sensors using NV centers.



Available Upgrade Option

- closed loop scanning & global sample coordinates
- ...for further details, see accessories section

- 01 LT and HV compatible feedthroughs
- 02 vacuum window
- 03 microscope insert
- 04 superconducting magnet (optional)
- 05 liquid He dewar (optional)
- 06 confocal microscope objective
- 07 AFM Akiyama probe
- 08 two xyz coarse positioners and xyz scanner units
- 09 ultra stable Titanium housing



Schematic drawing of the low temperature attoAFM/CFM and the surrounding liquid Helium dewar (optional)

CUSTOMER FEEDBACK

Prof. Dr. Patrick Maletinsky

Our attoLIQUID1000-based attoAFM/CFM system was a complete game-changer for starting up my research group. Instead of spending years developing a highly complex technical system on our own, we had a fully operational, high-performance cryogenic AFM/CFM system at hand within a relatively short timespan. This allowed us to plunge into our scientific endeavours with highest efficiency. As always, this attocube product stands out due to its reliability, ease of use and excellent performance. A particular further asset is the systems versatility - interfacing it with our existing experiments was straight-forward due to the clever system design and excellent support from attocube's application engineers.

(Department of Physics, University of Basel, Switzerland)

CUSTOMER FEEDBACK

Prof. Dr. Vincent Jacques

Owing to the high stability and easy operation of the attoAFM/CFM, we were able to perform first magnetometry experiments within only a few months. Support from attocube engineers was always very prompt and efficient. The system is now operated since two years and I must say that it has been the cornerstone of the rapid development of scanning probe magnetometry in our group.

(LPQM, ENS-Cachan, France)

PRODUCT KEY FEATURES

- scan area at 4 K: 12 x 12 μm^2
- independent sample scanning and scanning of the AFM module
- tuning fork based and PLL controlled systems available
- non contact measurement mode
- objectives with various working distances available

BENEFITS

- suitable for conducting and non-conducting samples
- enables exact positioning of AFM tip
- optical access to the sample with high magnification

APPLICATION EXAMPLES

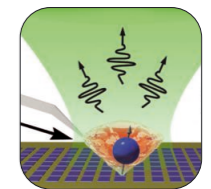
- solid state physics and quantum dot optics
- fluorescence observation
- highly stable long term experiments on single quantum dots

COMPATIBLE COOLING SYSTEMS

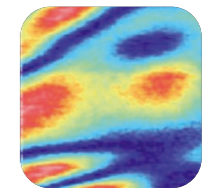
- attoDRY1000/1100/2100, attoDRY800(on request)
- attoLIQUID1000/2000, attoLIQUID3000/5000 (on request)



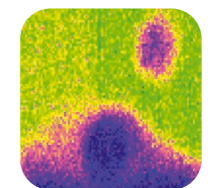
The attoAFM/CFM microscope module



Color Centers in Diamond



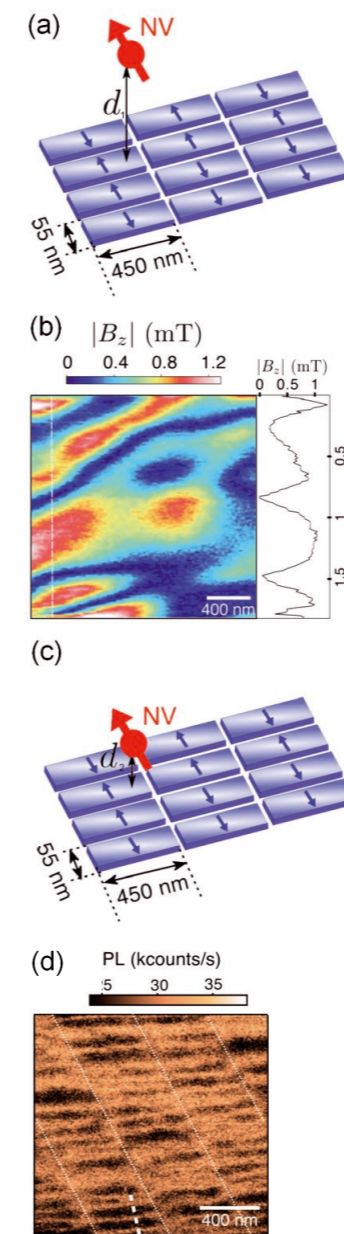
Magnetic Domain Imaging



Tip Enhanced Raman Spectroscopy

General Specifications	
type of instrument	combined confocal (CFM) and atomic force microscope (AFM)
sensor head specifics	AFM: Akiyama probe (quartz tuning fork combined with a micromachined cantilever) CFM: attoCFM I external optics head and low temperature apochromatic
Operation Modes	
imaging modes	optically detected magnetic resonance (ODMR), AFM, CFM
slope compensation	2 axis scan plane correction
z feedback	AFM: PI feedback loop for amplitude modulation (AM), phase modulation (PM) or frequency modulation (FM) using included PLL
Resolution*	
measured RMS z-noise (constant force @ 4 K, 5 ms pixel time)	< 0.2 nm (expected for attoLIQUID1000) < 0.5 nm (guaranteed for attoLIQUID1000)
z bit resolution @ 4 K	7.6 μ m at 2 μ m scan range
Confocal Unit	
configuration	compact and modular design, two or more optical channels standard configuration: 1 excitation channel, 1 detection channel
quick-exchange of optical components	beamsplitters, filter mounts for up to 4 filters/ polarizers (1" diameter), optional piezoelectric rotator with filter mount
LT-compatible objective	LT-APO/VIS, LT-APO/VISIR, LT-APO/NIR (see accessory section for more information)
inspection unit	sample imaging with large field of view: ~75 μ m (attoDRY), ~56 μ m (attoLIQUID)
Illumination	
excitation wavelength range	400 .. 1000 nm default: 650 nm (others on request)
Detection	
detection mode	e.g. optically detected magnetic resonance (ODMR), luminescence, fluorescence
Sample Positioning	
total travel range	independent degrees of freedom for tip and sample of 2 mm x 3 mm x 2.5 mm (closed loop)
step size	0.05..3 μ m @ 300 K, 10..500 nm @ 4 K
fine scan range	30 μ m x 30 μ m x 4.3 μ m @ 300 K, 12 μ m x 12 μ m x 2 μ m @ 4 K (open loop)
sample holder	Ti plate with integrated heater and calibrated temperature sensor
Suitable Operating Conditions	
temperature range	1.5 K..300 K (dependent on cryostat); mK compatible setup available on request
magnetic field range	0..15 T+ (dependent on magnet)
operating pressure	designed for He exchange gas (vacuum compatible version down to 1E-6 mbar on request)
Suitable Cooling Systems	
titanium housing diameter	48 mm
bore size requirement	designed for a 2" (50.8 mm) cryostat/magnet bore
compatible cryostats	attoLIQUID1000/2000 (attoLIQUID3000/5000 & attoDRY1000/1100/2000 on request)
Electronics	
scan controller and software	ASC500 (for detailed specifications please see attoCONTROL section)
laser	LDM600 laser/detector module (for detailed specifications please see attoCONTROL section)

* Resolution may vary depending on applied tip, sample, and cryostat



NV-Center Based Nanomagnetometry

Given its premier mechanical and thermal stability, the attoAFM/CFM is the ideal platform for nanoscale magnetic imaging employing an AFM tip with a diamond nanocrystal that contains a single nitrogen-vacancy (NV) center [1]-[4]. Local magnetic fields are subsequently evaluated by measuring the Zeeman shifts of the NV defect spin sublevels. In the particular case of NV-center magnetometry, an external microwave field is emitted and tuned in frequency such that local spin resonance occurs. This condition can subsequently be detected by a decrease in photoluminescence intensity of the NV-center, referred to as ODMR (optically detected magnetic resonance). Using a Lock-in and feedback loop technique allows to maintain spin resonance while rastering the sample, allowing to record a local magnetic field map with nanometer resolution.

In this example, magnetic imaging of a hard disk sample with random bit orientation was performed in the group of V. Jacques at LPQM, ENS-Cachan, France. [1]

Example 1 (a,b): Quantitative imaging using ODMR based method with NV-center scanned at $d_1 = 250$ nm above the sample. (a) Schematic of the measurement. (b) Quantitative magnetic field distribution recorded with the lockin technique (13 nm pixel size, 110 ms acquisition time per pixel). The inset shows a line-cut taken along the dashed white line in the image. [1]

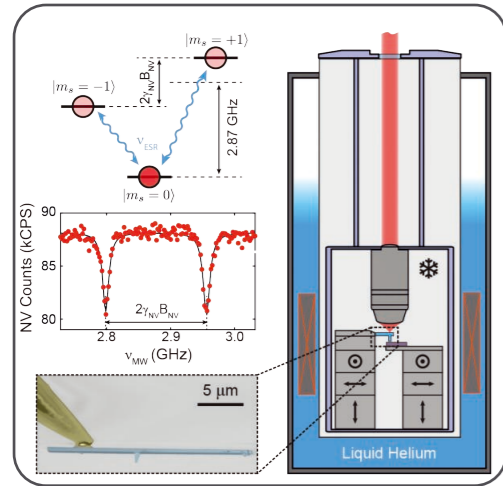
Example 2 (c,d): All-optical method with NV center closer to the sample surface. (c) Schematic of the measurement. (d) All optical photoluminescence image (no microwave field applied) recorded with the NV-scanning probe magnetometer in tapping mode (8 nm pixel size, 20 ms acquisition time per pixel). Comparisons with simulations indicates that the tip surface distance is roughly $d_2 = 30$ nm. Fine white dotted lines are plotted along the direction of the hard disk tracks as a guide for the eye. [1]

References:

- [1] L. Rondin et al., *Appl. Phys. Lett.* 100, 153118 (2012)
- Related publications based on the attoAFM/CFM (2012-2016)
- [2] L. Thiel et al., *Nature Nanotechnology* (2016). doi:10.1038/nnano.2016.63
- [3] Tétienne et al., *Science* 344, 1366 (2014)
- [4] J.-P. Tétienne et al., *Nature Communications* 6, 6733 (2015)
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- [9] J.-P. Tétienne et al., *New J. Phys.* 14, 103033 (2012)
- [10] A. Dréau et al., *Phys. Rev. B* 85, 134107 (2012)
- [11] L. Rondin et al., *Appl. Phys. Lett.* 100, 153118 (2012)

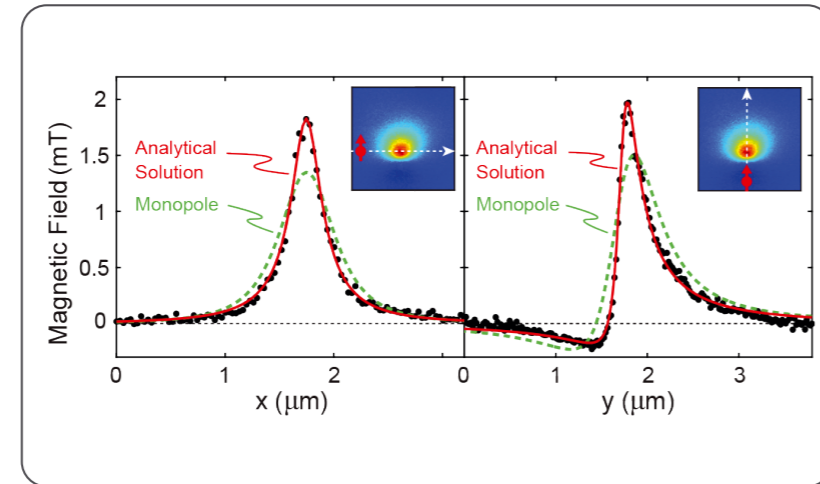
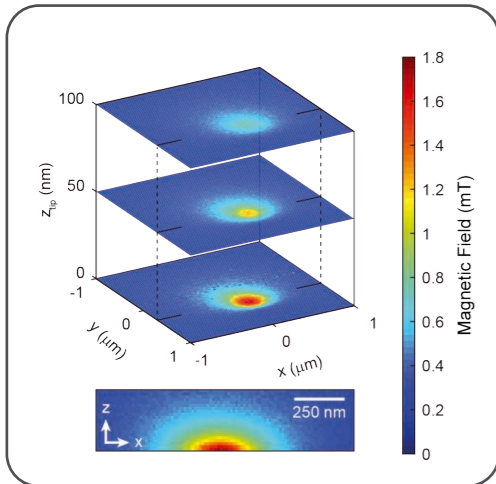
Selected Applications

attoAFM/CFM



Quantitative Nanoscale Vortex-Imaging of Superconductors

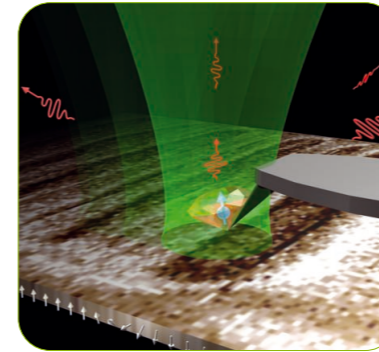
Understanding the microscopic mechanisms of superconductivity could be greatly facilitated by non-invasive tools that allow for quantitative imaging with nanometric resolution over a large range of temperatures and high magnetic fields. Based on the attoAFM/CFM, the group of Patrick Maletinsky (Univ. of Basel) reports on cryogenic measurements using NV center magnetometry. Their technique allows to extract quantitative data on the local magnetic field of individual superconducting vortices in YBCO with high sensitivity and spatial resolution. By determining the local London penetration depth, they find that the so called Pearl-vortex model explains the data much better and allows for fitting of additional parameters than the standard monopole model. Their experiments constitute an impressive example for how far the practical use of the NV center based magnetometry tools has already evolved.



Images courtesy of P. Maletinsky, University of Basel, CH; for more details, see L. Thiel et al., "Quantitative nanoscale vortex imaging using a cryogenic quantum magnetometer", *Nature Nanotechnology* (2016), doi:10.1038/nnano.2016.63

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Nanoscale Imaging and Control of Domain-Wall Hopping

Domain walls in magnetic wires may prove useful for future spintronic devices, and hence their nanoscale characterization is an important steps towards useful applications. As demonstrated by the group of Vincent Jaques in Science, their NV center microscope based on the attoAFM/CFM allows to image domain walls in a 1 nm thick ferromagnetic nanowire with high resolution as well as jumps between pinning sites of individual domain walls. At the same time, they showed that the domain walls can be moved along the wire by inducing jumps via local heating due to a high local laser power. Since the domain walls are pinned by nearest pinning site, this allows to probe and image the pinning landscape of the sample quite efficiently.



Images courtesy of V. Jaques, University of Montpellier, FR; for more details, see Tétienne et al., "Nanoscale imaging and control of domain-wall hopping with a NV center microscope", *Science* 344, 1366(2014)



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