attoDRY LAB
Dry Measurement Systems

Magnetic Force Microscopy Specifications in attoDRY1100 on par with Liquid Cryostats

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Introduction

As supplies of liquid helium are getting ever more expensive and less reliable, the importance of cryogen-free cooling systems grows. While such alternatives have been around for quite some time, they usually failed to meet the requirements of researchers in need of low vibration environments, such as those working in the field of scanning probe microscopy. It is in this field of research in particular, where the attoDRY1100 cryogen-free magnet system determines the state of the art. In this application note, we show examples of magnetic force microscopy measurements performed in a pulse-tube based cooling system, with specifications close to those reached in a regular liquid bath cryostat.

attoDRY1100

The attoDRY1100 (see Figure 1) builds the cryogen-free basis of the attoDRY LAB platform, offering a truly unique low temperature measurement platform with a fully automated gas handling system. The integrated touchscreen allows for conveniently setting the desired field (*B*) and temperature (*T*) without even using a PC. More elaborate measurement schemes such as programmable sweeps of *B* and *T* are easily possible via a USB/Ethernet connection and a LabVIEW interface.

The top-loading design enables quick and easy sample exchange while offering a generous sample space of 49.7 mm in diameter, which makes it compatible with a whole variety of different measurement options offered by attocube. The unmatched cooling performance via exchange gas coupling enables probe cooldown times as fast as 1-2 hours, with the initial cooldown time of the complete system being around 10-12 hours including a 9 T magnet. The temperature stability was measured to be better than ±5 mK over 14 hours at 4 K.

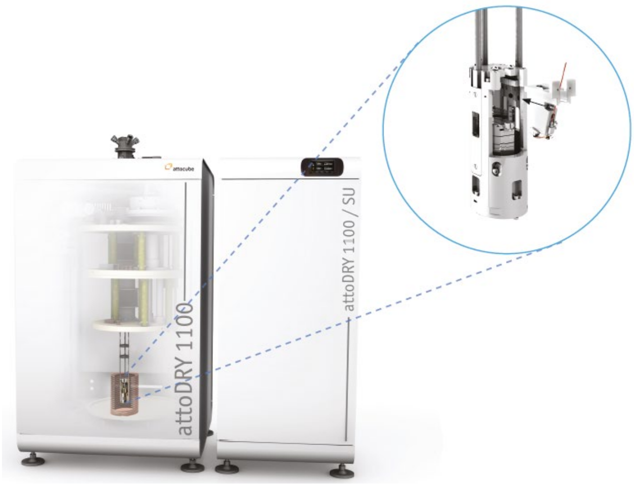

Figure 1: *The attoDry1100 platform. The inset shows the attoAFM/MFM setup.*

attoAFM/MFM I

Magnetic force microscopy (MFM) is a technique derived from atomic force microscopy (AFM), in which an etched silicon cantilever/ tip combined with optical deflection detection is used to precisely measure local interactions such as van der Waals or Coulomb forces. MFM takes advantage of tips with magnetic coatings, typically NiCr or cobalt, making them sensitive to the magnetic interaction between tip and sample. Figure 2 below shows a schematic of attocube's cantilever-based attoMFM, designed particularly for low temperature and high magnetic field applications. The attoMFM uses a single-mode, fiber-based interferometer to detect the tip deflection. As with most MFMs, the attoMFM applies an AC modulation technique to achieve highest detection sensitivity. More details can be found in [1].

Example MFM measurements

Single magnetic vortices in superconducting materials such as freshly cleaved $Bi_2Sr_2CaCu_2O_{8+x}$ (BSCCO-2212), a cuprate superconductor, represent reproducible features with low moment. A vortex consists of a circular supercurrent, which allows for a quantized flux of exactly one flux quantum to penetrate the superconductor. Hence, these substrates are ideal candidates for MFM characterization measurements.

The measurements in Figure 3 show how the density of vortices varies with applied magnetic field when changing it from -40 Oe to +50 Oe. For each field value, the sample was field-cooled in the respective field. In these images, the orientation of the vortices with respect to the moment of the tip is indicated by the color of the vortices: Bright (dark) colors indicate repulsive (attractive) forces. Here, the tip was scanned in a constant height of about 30 nm above the surface of a freshly cleaved piece of BSCCO-2212 [2].

Note that the applied field was always much lower than the coercitivity of the hard-magnetic tip (≈400 Oe), hence the orientation of the tip moment was kept unchanged. While at low vortex densities pinning effects are comparable, one can see at higher densities the hexagonal Abrikosov pattern [3].

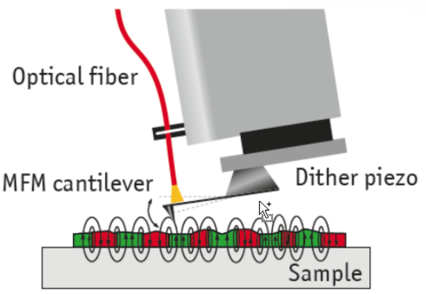

Figure 2: *Sketch of the AFM/MFM setup. An AFM tip (here: magnetically coated), is brought into close vicinity of the sample. The deflection of the cantilever due to forces on the tip can be read using a built-in fiber interferometer.*

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Performance characterization

In order to further test and quantify the performance of the microscope, certain key specifications are measured for every attoAFM/MFM I. The most important are:

(a) RMS z-noise: this number characterizes the level of vertical vibrations experienced between the AFM/MFM tip and the sample surface during a typical measurement. While the tip is in contact with the sample surface, a so-called noise-scan (at 4 K) is performed, in which the scanner is practically scanning only one and the same point (the scan size is below detectable limits). In this way, vibration data of the fully enabled system are acquired over time without any topographic influence. This 100 x 100 pixel noise scan hence acquires noise statistics of the tip deflection over 10,000 points. The sample time is set to 5 ms, which corresponds to a measurement bandwidth of 200 Hz. After subtracting slow drifts (using a line-by-line filter), the RMS z-noise value can now be easily determined from the image or the respective histogram. For the attoDRY systems attocube systems expects a z-noise value < 100 pm RMS and guarantees < 150 pm RMS, while for liquid helium systems these numbers are < 50 pm RMS (expected) and < 120 pm RMS (guaranteed).

(b) Signal-to-noise ratio (SNR): the SNR in MFM measurements on standard samples is also an indicator for the performance of the system. The SNR can easily be determined from the relative peak height of the visible structures and the noise determined in a separate noise scan with otherwise same conditions. attocube systems expects the SNR on such standard sample to exceed 20:1 and guarantees 10:1, measured in a bandwidth of 10 ms.

Performance Test Results in the attoDry1100

(a) The result of a respective performance test done in attocube Application Labs is shown in form of a histogram in Figure 4, which demonstrates a measured value of 65 pm RMS (5 ms sample time, feedback loop enabled). This value is close to what is being achieved in attocube's liquid systems and demonstrates the superior performance of the attoDRY product line.

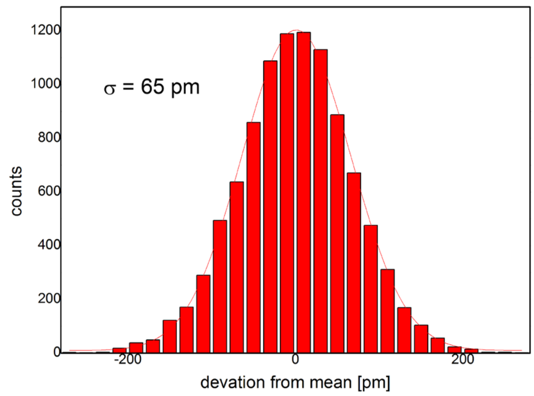

Figure 4: *Histogram of z-height values over 10,000 points (or 50 s) measured with a bandwidth from 1 to 200 Hz. The standard deviation results in 65 pm.*

(b) The typical SNR in the attoDRY LAB MFM can be determined from the MFM measurements discussed above and shown in Fig. 3. The S/N ratio was determined from the peak height of isolated vortices (e.g. at B = 10 Oe) to be above 20:1. In low noise liquid helium cryostats for comparison, the SNR is expected to exceed 20:1 as well.

Summary

In this application note, we demonstrate that extremely sensitive scanning probe techniques such as magnetic force micros-copy are now routinely possible inside the cryogen-free attoDRY1100. Most remarkably, the specifications reached are close to those achieved in liquid systems, hence opening the door to a whole new class of experiments without the need for liquid helium.

References

[1] M. Zech, C. Bödefeld, F. Otto, and D. Andres, Microscopy Today **19**, pp. 34-38 (2011). doi: 10.1017/S1551929511001180.
[2] Sample courtesy of A. Erb, TU Munich.
[3] A. A. Abrikosov, Zh. Eksp. i Teor. Fiz. **32**, 1442 (1957); Soviet Phys. JETP **5**, 1174 (1957).

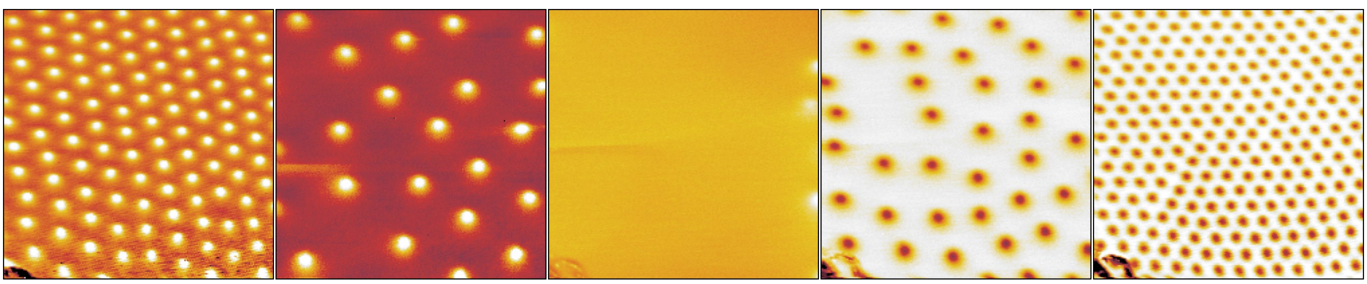

Figure 3: *MFM measurements at different magnetic fields: Left to right: B = -40 Oe, -10 Oe, 0 Oe, +10 Oe, +50 Oe. Scan size is 10 x 10 µm², color span is 2 Hz for all images.*