Interleave Scanning and LiftMode

Interleave is an advanced feature of NanoScope software that allows the simultaneous acquisition of two data types. Enabling **Interleave** alters the scan pattern of the piezo: after the trace and retrace of each main scan line (in which topography is typically measured), a second trace and retrace is inserted to obtain non-topographical information.

The Interleave commands use a set of Interleave controls that allow several scan controls (**Drive Amplitude**, **{** HYPERLINK "javascript:void(0);" **}**, and various **{** HYPERLINK "javascript:void(0);" **}**) to be set independently of those in the main scan controls.

Typical applications of interleave scanning include **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Magnetic%20Force%20Microscopy%20(MFM).htm" \o "Link to Magnetic Force Microscopy (MFM)" **}** and **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Electric%20Force%20Microscopy%20(EFM).htm" \o "Link to Electric Force Microscopy (EFM)" **}** measurements. There are two forms of Interleave scanning available:

LiftMode

Enabling Interleave with the mode set to Lift enacts **LiftMode**. During the interleave scan, the feedback is turned off and the tip is lifted to a user-selected height above the surface to perform far field measurements such as magnetic or electric forces. By recording the cantilever deflection or resonance shifts caused by the magnetic or electric forces on the tip, an image map of force changes can be produced. LiftMode was developed to isolate purely MFM and EFM data from topographic data.

Interleave Mode

Interleave can also be used in **Interleave Mode**. In this mode, the feedback is kept on while additional topography, phase lateral force, or data is acquired.

How Interleave Mode Works

Enabling **Interleave** changes the scan pattern of the tip relative to the imaged area. With Interleave mode disabled, the tip scans back and forth in the fast scan direction while slowly moving in the orthogonal direction as shown on the left of figure 1, below. This is the standard scan pattern of NanoScope systems.

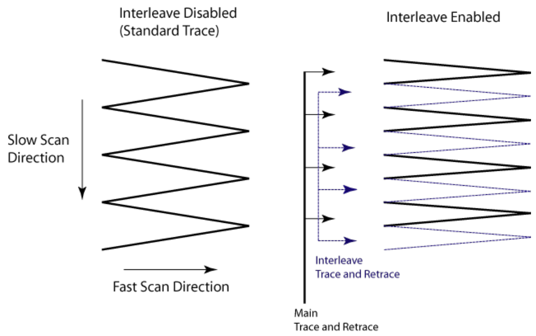
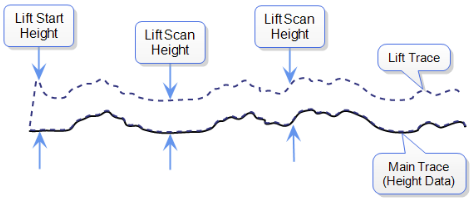


Figure 1: Comparison of standard (left) and Interleave (right) raster scan patterns.

With Interleave mode enabled, the system first performs a standard trace and retrace with the main Feedback controls in effect. The tip moves at half the normal rate in the slow scan direction. An additional trace and retrace are then performed with the Interleave feedback controls enacted. The frame rate halves because twice as many scan lines are performed for the same scan rate. This modification of the scan pattern is illustrated to the right in figure 1, above.

Two modes are possible for Interleave scan: Interleave and Lift. With **Interleave** selected, the feedback remains on during the interleave pass with the values under Interleave feedback controls (**{** HYPERLINK "javascript:void(0);" **}**, **{** HYPERLINK "javascript:void(0);" **}**, etc.) in effect. In **Lift** mode the feedback is turned off and the tip is lifted off the surface and scanned at a user-selected height for the interleave trace and retrace. Topography data recorded during the main pass is used to keep the tip a constant distance from the surface during the Interleave trace and retrace:



The tip first moves to the **Lift Start Height**, then to the **Lift Scan Height**. A large Lift Start Height can be used to pull the tip from the surface and eliminate sticking. The Lift Scan Height is the distance maintained between the sample topography and the tip during the scan. This value is added point-by-point to the height data obtained during the Main topography trace and retrace. Values can be positive or negative.

NOTE: A new feature in NanoScope 8.15 allows the user to run a lifted scan at a set distance from the sample surface, ignoring the sample topography during the lifted, interleaved, scan lines. To enable this parameter, set Interleave Mode to **Linear** in the Interleave parameter list.

Operation of Interleave Scanning and LiftMode

These instructions apply to **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\STM\\Scanning%20Tunneling%20Microscopy%20(STM).htm" \o "Link to Scanning Tunneling Microscopy (STM)" **}**, **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Contact%20AFM\\Contact%20AFM.htm" \o "Link to Contact AFM" **}**, or **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\TappingMode%20AFM\\TappingMode%20AFM.htm" \o "Link to TappingMode AFM" }. You must be familiar with TappingMode or Contact AFM to obtain good images of surface topography. The interleave scanning procedure is described below; further detail is given for specific modes elsewhere: see { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Magnetic%20Force%20Microscopy%20(MFM).htm" \o "Link to Magnetic Force Microscopy (MFM)" } and { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Electric%20Force%20Microscopy%20(EFM).htm" \o "Link to Electric Force Microscopy (EFM)" }.

1. Obtain a topography scan using the appropriate method (usually Contact or TappingMode).

   When using LiftMode, it is important that the { HYPERLINK "javascript:void(0);" } and { HYPERLINK "javascript:void(0);" } under Feedback controls be adjusted to give a faithful image of the surface. Because the height data is used in the lift pass to trace the topography, a poor measurement of surface height may give inaccurate measurement during the lift pass or cause the tip to strike the surface. Typically, the height data is displayed on **Channel 1**.
2. Choose the Interleave Mode (**Interleave**, **Lift**, or **Linear**) appropriate for the measurements to be performed.

3. Adjust the Interleave controls panel to the desired settings.

   When using TappingMode, the { HYPERLINK "javascript:void(0);" }, { HYPERLINK "javascript:void(0);" }, gains, and **Amplitude Setpoint** can be set differently in the Interleave panel than in the main Feedback panel. However, it is often convenient to begin with the main and interleave controls set to the same values. Do this by toggling the parameters of the appropriate Interleave parameters to an “off” (grayed) condition. The values can be changed once the probe is engaged.

- If you are using **LiftMode** or **Linear Lift Mode**, set the Lift Scan height.

- If you are using **Interleave** mode, set the Gains and Amplitude Setpoint. For more information, refer to { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Use%20of%20LiftMode%20with%20TappingMode.htm" \o "Link to Use of LiftMode with TappingMode" }.

NOTE: Certain constraints are imposed: scan sizes, offsets, angles, rates and numbers of samples per scan line are the same for the main and interleave data, and the imaging mode (Contact, TappingMode, or force modulation) must also match.

3. Choose the Interleave **Data Type**.

   Depending on the type of microscope, Interleave mode allows the options of amplitude, phase, frequency, potential, input potential, or data types for doing far-field (MFM or EFM) imaging. Auxiliary channels are also available for some applications.

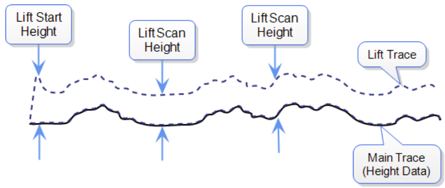
Once the Interleave **Scan Line** is chosen, Interleave mode is automatically enabled, triggering interleave scanning. Interleave data typically displays as the second image. Notice that the scan rate in the slow direction is halved.

4. Display the interleave data by switching **Scan Line** (in the Channel panels) to **Interleave**.

Final Considerations

- **Lift Scan Height:** The lateral and vertical resolutions of the Lift data depend on the distance between tip and sample: the lower the tip, the higher the resolution. However, the Lift Scan Height must be high enough that the tip does not contact the sample during the Lift trace and retrace.

- **Tip Shape:** As shown below, the tip separation in the LiftMode is defined in terms of the Z direction only. The Lift Scan Height is added to the height values taken from previous scan lines point-by-point. However, the tip may be closer to the sample than the Z separation indicates. On features with steep edges, the tip may get very close to the sample even though the Z separation is constant.



- **Line Direction:** The Line Direction should be set to Retrace for both the main and interleaved scans. If it is set instead to Trace, a band may appear along the left side of the images due to the ramp between the surface and the Lift Scan Height.

Use of LiftMode with TappingMode

Additional considerations when using LiftMode with **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\TappingMode%20AFM\\TappingMode%20AFM.htm" \o "Link to TappingMode AFM" **}** are discussed below.

Main Drive Amplitude and Frequency selection

As usual, these parameters are set when you tune the cantilever prior to engaging. It is helpful to keep in mind the measurements to be done in LiftMode when setting these values. For example, if Amplitude data will be monitored during the Lift scan for **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Magnetic%20Force%20Microscopy%20%28MFM%29.htm" \o "Link to Magnetic Force Microscopy (MFM)" **}**, the **Drive Frequency** should be set to the side of the resonance (however, certain parameters can be set independently for the interleave scan; see below.)

Setpoint Selection

When the main and interleave **{** HYPERLINK "javascript:void(0);" **}** and **{** HYPERLINK "javascript:void(0);" **}** are set to the same value (i.e., when these parameters in the Interleave panel are grayed out), the cantilever oscillation amplitude increases to the free oscillation amplitude when the tip is lifted off the surface in LiftMode. If a small **{** HYPERLINK "javascript:void(0);" **}** value forces a large decrease in oscillation amplitude while the feedback is running, the amplitude can grow considerably when the tip is lifted free of the sample surface. The change can also be large if the main Drive Amplitude was increased or the main Drive Frequency altered after the tip was engaged. The vibration amplitude remains at the setpoint during the main scan even if these parameters are changed. This could result in the tip hitting the surface in the lift scan for small Lift Scan Heights.

Interleave Drive Amplitude and Frequency Selection

The cantilever **Drive Amplitude** for the Lift scan can be set independently of the main Drive Amplitude. Click on the parameter in the Interleave panel to enable it (turns green) and adjust the value. This allows the tuning of a measurement in the Lift scan lines without disturbing the topography data acquired during the Main scan lines. The Interleave Drive Amplitude must be set low enough that the tip does not strike the surface during the Lift pass.

Caution/Attention/Vorsicht:

- Before enabling the Interleave Drive Amplitude, check that its value is not much larger than the main Drive Amplitude value to prevent possible damage to the tip.

The Interleave Drive Frequency can also be adjusted, which may be useful if acquiring amplitude data in LiftMode.

Amplitude Data Interpretation

When monitoring amplitude data in LiftMode, brighter regions correspond to larger amplitude, and darker regions to smaller amplitude.

Cantilever Oscillation Amplitude

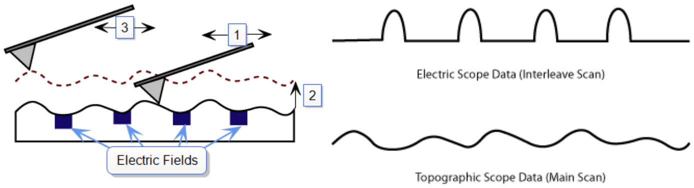
The selection of the oscillation amplitude in LiftMode depends on the quantity to be measured. For force gradients that are small in magnitude but occur over relatively large distances (sometimes hundreds of nanometers, as with magnetic or electric forces), the oscillation amplitude can be large, which for some applications may be beneficial. The Lift Scan Height must be correspondingly large so that the tip does not strike the surface. However, the lateral resolution of far field (MFM or EFM) measurements decreases with distance from the surface. Typically, the resolution is limited to a value (in nm) roughly equal to the Lift scan height.

Small amplitudes must be used to sense force gradients, such as Van der Waals forces, which occur over short distances (typically a few nm). As much of the cantilever travel as possible should be within the range of the force gradient.

Electric Techniques

The two most common electric techniques used with the Dimension Icon microscope are Electric Force Microscopy (EFM) and Surface Potential Detection. Both modes make use of **Interleave** and **LiftMode** procedures. Ensure you are familiar with before attempting electric measurements.

Electric techniques are similar to . The two-pass LiftMode measurement allows the imaging of relatively weak but long-range electrostatic interactions while minimizing the influence of topography. In the case of MFM, the system is measuring long-range magnetic fields. LiftMode records measurements in two passes, each consisting of one trace and one retrace, across each scan line. First, LiftMode records topographical data in TappingMode on one trace and retrace. Then, the tip raises to the Lift Scan Height, and performs a second trace and retrace while maintaining a constant separation between the tip and local surface topography.



1. Cantilever measures surface topography on first (main) scan (trace and retrace).

2. Cantilever ascends to lift scan height.

3. Cantilever follows stored surface topography at the lift height above the sample while responding to electric influences on second (interleave) scan (trace and retrace).

Electric Force Microscopy Overview

measures variations in the electric field gradient above a sample. The sample may be conducting, nonconducting, or mixed. Because the surface topography shapes the electric field gradient, large differences in topography make it difficult to distinguish electric field variations due to topography or due to a true variation in the field source. The best samples for EFM are samples with fairly smooth surface topography. The field source could be trapped charges, applied voltage, and so on. Samples with insulating layers (passivation) on top of conducting regions are also good candidates for EFM.

Surface Potential Imaging Overview

Bruker provides several methods for surface potential imaging:

- **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Surface%20Potential%20Detection.htm" \o "Link to Surface Potential Detection" **}** (aka AM-KPFM) measures the effective surface voltage of the sample by adjusting the voltage on the tip so that it feels a minimum electric force from the sample.

- **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-KPFM.htm" **}** combines the **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Surface%20Potential%20Detection.htm" **}** mode with Bruker's proprietary **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\PeakForceQNM\\Operation\\OperatingPrinciples.htm" \l "Peak" **}**.

- { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\FM-KPFM.htm" } uses a frequency modulation technique to measure surface potential. FM-KPFM is generally more accurate and has higher spatial resolution than AM-KPFM.

- { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-FM-KPFM.htm" } combines { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\FM-KPFM.htm" } with Bruker's proprietary { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\PeakForceQNM\\Operation\\OperatingPrinciples.htm" \l "Peak" }, combining the benefits of both modes.

- { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-KPFM%20HV%20Imaging.htm" } combines Bruker's proprietary { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\PeakForceQNM\\Operation\\OperatingPrinciples.htm" \l "Peak" } with an AC technique that enables measurement of surface potentials up to approximately ±200 V.

Electrical Sample Preparation

The sample should be electrically connected directly to the chuck, so that it can be held at ground potential (normal operation) or biased through the chuck. The sample can either be mounted directly on the chuck or onto a standard sample puck using conductive epoxy or silver paint as shown below:

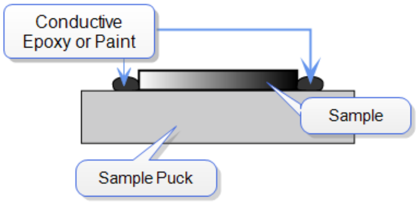


Figure 1: Schematic diagram showing how to electrically connect a sample onto a sample puck.

HINT: If the surface of your sample is conductive and the base of the sample is insulative, you will need to ensure that the conductive epoxy or paint contacts one edge of the sample surface and one edge of the conductive mount (either sample puck or the chuck itself). Ensure that the large "glob" of glue/paint required is *NOT* located directly underneath the cantilever substrate, as the substrate may come in contact with the glue/paint, completing the circuit and preventing the tip from contacting the sample:

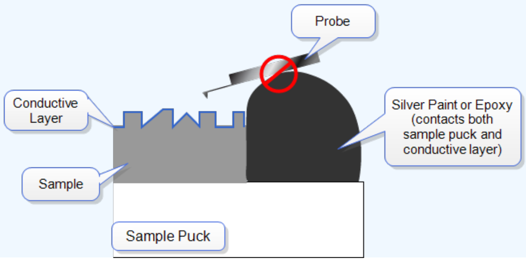


Figure 2: Schematic diagram showing how NOT to electrically connect a sample onto a sample puck.

Surface Potential Detection

Bruker provides several methods for surface potential imaging:

- **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\LiftMode%20SurfacePotentialDetectionPrinciples.htm" \o "Link to Surface Potential Detection" **}** (aka AM-KPFM) measures the effective surface voltage of the sample by adjusting the voltage on the tip so that it feels a minimum electric force from the sample. (In this state, the voltage on the tip and sample is the same.) Samples for surface potential measurements should have an equivalent surface voltage of less than ±10 V, and operation is easiest for voltage ranges of ±5 V. The noise level of this technique is typically 10 mV. Samples may consist of conducting and nonconducting regions, but the conducting regions should not be passivated. Samples with regions of different materials will also show contrast due to contact potential differences. Quantitative voltage measurements can be made of the relative voltages within a single image.

- **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-KPFM.htm" **}** combines the **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Surface%20Potential%20Detection.htm" **}** mode with Bruker's proprietary **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\PeakForceQNM\\Operation\\OperatingPrinciples.htm" \l "Peak" **}**.

- **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\FM-KPFM.htm" **}** uses a frequency modulation technique to measure surface potential. FM-KPFM is generally more accurate and has higher spatial resolution than AM-KPFM.

- **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-FM-KPFM.htm" **}** combines **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\FM-KPFM.htm" **}** with Bruker's proprietary **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\PeakForceQNM\\Operation\\OperatingPrinciples.htm" \l "Peak" **}**, combining the benefits of both modes.

- **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-KPFM%20HV%20Imaging.htm" **}** combines Bruker's proprietary **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\PeakForceQNM\\Operation\\OperatingPrinciples.htm" \l "Peak" **}** with an AC technique that enables measurement of surface potentials up to approximately ±200 V.

Lift Mode Surface Potential Imaging (AM-KPFM)

Lift Mode surface potential imaging, also referred to as Amplitude Modulated KPFM (AM-KPFM), is a two-pass procedure where the surface topography is obtained by standard **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\TappingMode%20AFM\\TappingMode%20AFM.htm" \o "Link to TappingMode AFM" **}** in the first pass and the surface potential is measured on the second pass. The two measurements are interleaved: that is, they are each measured one line at a time with both images displayed on the screen simultaneously. A block diagram of the this Surface Potential measurement system is shown in **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\LiftMode%20SurfacePotentialDetectionPrinciples.htm" \l "SPoMBlockDiagram" **}**.

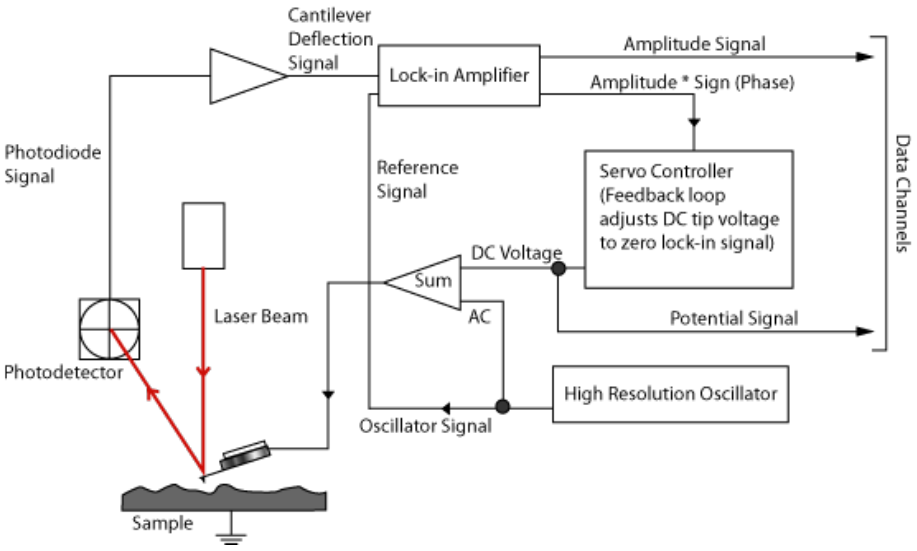
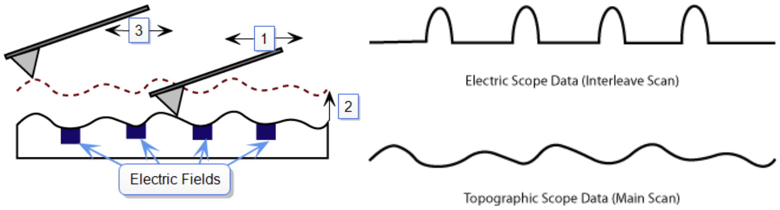


Figure 1: Block diagram of signals for Lift Mode Surface Potential Detection

On the first pass, in TappingMode, the cantilever is mechanically vibrated near its resonant frequency by a small piezoelectric element. On the second pass, the tapping drive piezo is turned off and an oscillating voltage $V_{AC}\sin(\omega t)$ is applied directly to the probe tip. If there is a DC voltage difference between the tip and sample, then there will be an oscillating electric force on the cantilever at the frequency ω. This causes the cantilever to vibrate, and an amplitude can be detected.



1. Cantilever measures surface topography on first (main) scan (trace and retrace).
2. Cantilever ascends to lift scan height.
3. Cantilever follows stored surface topography at the lift height above the sample while responding to electric influences on second (interleave) scan (trace and retrace).

If the tip and sample are at the same DC voltage, there is no force on the cantilever at frequency ω and the cantilever amplitude will go to zero. Local surface potential is determined by adjusting the DC voltage on the tip, V_{tip}, until the oscillation amplitude becomes zero and the tip voltage is the same as the surface potential. The voltage applied to the probe tip is recorded by the NanoScope Controller to construct a voltage map of the surface.

Surface Potential Detection Theory

{ HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Surface%20Potential%20Detection.htm" \o "Link to Surface Potential Detection" } microscopy can be modeled as a parallel plate capacitor. When two materials with different work functions are brought together, electrons in the material with the lower work function flow to the material with the higher work function (see **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Surface%20Potential%20Detection%20Theory.htm" \l "UnequalEnergies" **}**). If these materials are charged, the system can be thought of as a parallel plate capacitor with equal and opposite surface charges on each side. The voltage developed over this capacitor is called the contact potential. Measuring the contact potential is done by applying an external backing potential to the capacitor until the surface charges disappear. At that point the backing potential will equal the contact potential. In surface potential microscopy (scanning Kelvin probe force microscopy), this "zero-charge" point is determined by adjusting the tip voltage so the electrical force felt by the AFM cantilever is "0".

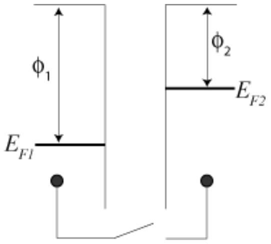


Figure 1: The electric energy level diagram for 2 conducting specimens, where Φ_1 and Φ_2 are the respective work functions. E_{f1} and E_{f2} are the respective Fermi energies.

If an external electrical contact is made between the two electrodes, their Fermi levels equalize and the resulting flow of charge (in the direction indicated in **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Surface%20Potential%20Detection%20Theory.htm" \l "EqualPotentials" **}**) produces a potential gradient, termed the contact potential V_c, between the plates. The two surfaces become equally and oppositely charged.

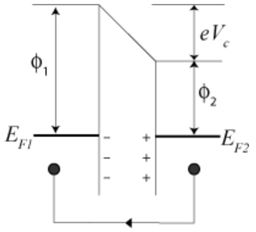


Figure 2: Electrical contact between 2 specimens

Inclusion of a variable backing potential, V_b, in the external circuit permits biasing of one electrode with respect to the other. When $V_b = Vc = (\Phi_1 - \Phi_2)/e$, the electric field between the plates vanishes (see **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Surface%20Potential%20Detection%20Theory.htm" \l "VariablePotential" **}**).

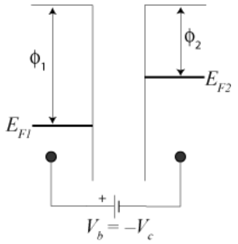


Figure 3: Variable backing potential, V_b, added

A good way to understand the response of the cantilever during Surface Potential operation is to start with the energy in a parallel plate capacitor:

$$U = \frac{1}{2} C (\Delta V)^2$$

Equation 4:

where C is the local capacitance between the AFM tip and the sample and ΔV is the voltage difference between the two.

The force on the tip and sample is the rate of change of the energy with separation distance:

$$F = -\frac{dU}{dZ} = -\frac{1}{2}\frac{dC}{dZ}(\Delta V)^2$$

Equation 5:

The voltage difference, ΔV, in Surface Potential operation consists of both a DC and an AC component. The AC component is applied from the oscillator, $V_{AC}\sin\omega t$, where ω is the resonant frequency of the cantilever:

$$\Delta V = \Delta V_{DC} + V_{AC}\sin\omega t$$

Equation 6:

ΔV_{DC} includes applied DC voltages (from the feedback loop), work function differences, surface charge effects, etc. Squaring ΔV and using the relation $2\sin^2 x = 1 - \cos(2x)$ produces:

$$F = \underbrace{-\frac{1}{2}\frac{dC}{dZ}\left(\Delta V_{DC}^2 + \frac{1}{2}V_{AC}^2\right)}_{\text{DC term}} \underbrace{-\frac{dC}{dZ}\Delta V_{DC}\, V_{AC}\sin\omega t}_{\omega\text{ term}} \underbrace{+\frac{1}{4}\frac{dC}{dZ}V_{AC}^2\cos(2\omega t)}_{2\omega\text{ term}}$$

Equation 7:

The oscillating electric force at ω acts as a sinusoidal driving force that can excite motion in the cantilever. The cantilever responds only to forces at or very near its resonance, so the DC and 2ω terms do not cause any significant oscillation of the cantilever. In regular TappingMode, the cantilever response (RMS amplitude) is directly proportional to the drive amplitude of the tapping piezo. Here the response is directly proportional to the amplitude of the F_ω drive term:

$$\textit{amplitude of } F_\omega = \frac{dC}{dZ}\,\Delta V_{DC} V_{AC}$$

Equation 8:

The goal of the Surface Potential feedback loop is to adjust the voltage on the tip until it equals the voltage of the sample ($\Delta V_{DC}=0$), at which point the cantilever amplitude should be zero ($F_\omega = 0$).

The larger the DC voltage difference between the tip and sample, the larger the driving force and resulting amplitude will be. But the F_ω amplitude alone does not provide sufficient information to adjust the voltage on the tip. The driving force generated from a 2 V difference between the tip and sample is the same as from a –2 V difference (see { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Surface%20Potential%20Detection%20Theory.htm" \l "ForceVsVoltage" }).

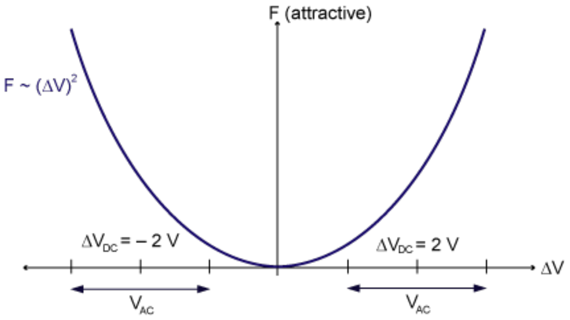


Figure 9: Force as a function of voltage

What differentiates these states is the phase. The phase relationship between the AC voltage and the force it generates is different for positive and negative DC voltages (see { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Surface%20Potential%20Detection%20Theory.htm" \l "VatW" } through { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Surface%20Potential%20Detection%20Theory.htm" \l "OutOfPhase" }).

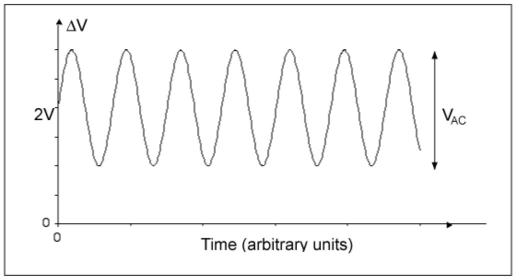


Figure 10: V_{AC} at ω, ΔV_{DC}= 2 V

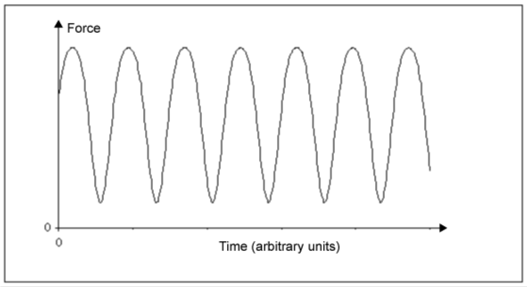


Figure 11: Major force component in phase with V_{AC} at Frequency ω, ΔV_{DC}= 2 V

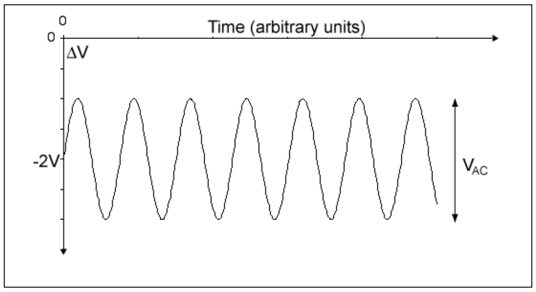


Figure 12: ΔV_{AC}at ω, ΔV_{DC}= –2 V

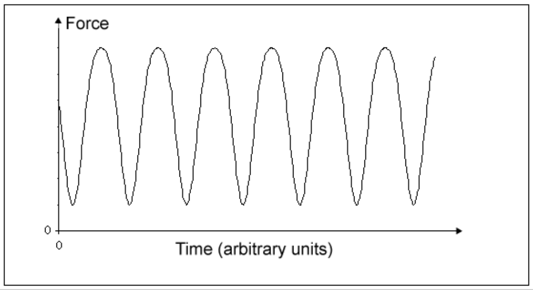


Figure 13: Major force component 180° out of phase with V_{AC} at Frequency ω, ΔV_{DC}= –2 V

In the case where ΔV_{DC} = 2 V, the force is in phase with V_{AC}. When ΔV_{DC} = –2 V, the force is out of phase with V_{AC}. Thus, the cantilever oscillation will have a different phase, relative to the reference signal V_{AC}, depending on whether the tip voltage is larger or smaller than the sample voltage. Both the cantilever amplitude and phase are needed for the feedback loop to correctly adjust the tip voltage. The input signal to the Surface Potential feedback loop is the cantilever amplitude multiplied by the sign of its phase (i.e., positive value voltage for phase ≥ 0 degrees, negative value voltage for phase < 0 degrees). This signal can be accessed in the software by selecting **Potential Input** (interleave scan line) in one of the channel panels.

If ΔV_{DC} = 0, the electric drive force is at the frequency 2ω. The component of the force at ω is zero so the cantilever does not oscillate (see **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Surface%20Potential%20Detection%20Theory.htm" \l "DVis0" **}** and **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Surface%20Potential%20Detection%20Theory.htm" \l "2W" **}**). The Surface Potential feedback loop adjusts the applied DC potential on the tip, V_{tip}, until the cantilever's response is zero. V_{tip} is the Potential data that is used to generate a voltage map of the surface.

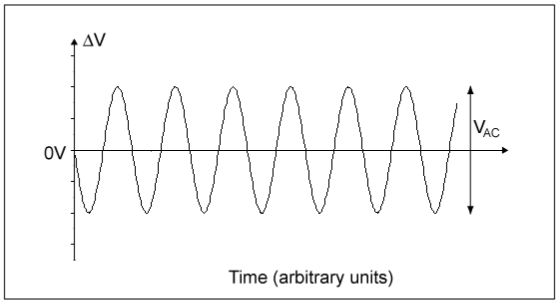


Figure 14: V_{AC} at ω, ΔV_{DC}= 0 V

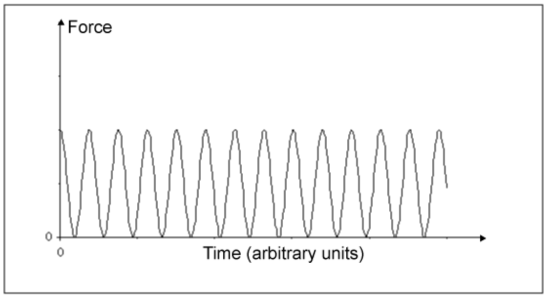


Figure 15: Force at Frequency of 2ω, ΔV_{DC}= 0 V

LiftMode Surface Potential Detection (AM-KPFM) Procedure

Sample Preparation

Prepare the sample as described in **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Electric %20Techniques.htm" \l "Sample_Preparation" **}**.

Probe Selection

- **{** HYPERLINK "http://www.brukerafmprobes.com/p-3309-mesp.aspx" \t "_blank" \o "Link to MESP probe information on brukerafmprobes.com" **}** (cost-effective electrically conductive probes coated with cobalt/chromium)

- Custom-coated **{** HYPERLINK "http://www.brukerafmprobes.com/p-3259-fesp.aspx" \t "_blank" \o "Link to FESP probe information on brukerafmprobes.com" **}** silicon TappingMode cantilevers (ensure that any deposited metal you use adheres strongly to the silicon cantilever)

- **{** HYPERLINK "http://www.brukerafmprobes.com/p-3392-scm-pit.aspx" \t "_blank" \o "Link to SCM-PIT information on brukerafmprobes.com" **}** (platinum/iridium coated probes)

- **{** HYPERLINK "http://www.brukerafmprobes.com/p-3379-oscm-pt.aspx" \t "_blank" \o "Link to information about OSCM-PT tips at brukerafmprobes.com" **}** (platinum coated probes)

- FESP or **{** HYPERLINK "http://www.brukerafmprobes.com/p-3297-ltesp.aspx" \t "_blank" \o "Link to information about LTESP tips at brukerafmprobes.com" **}** (uncoated, highly-doped Si)

Procedure

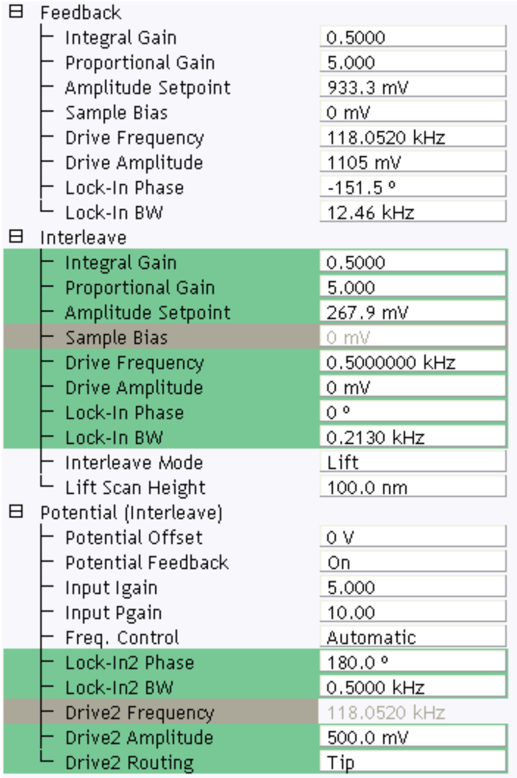
1. Mount a sample onto the sample holder.
2. Mount a metal-coated cantilever into the standard probe holder (see **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Basic%20AFM%20Operation\\Prepare%20and%20Load%20the%20Cantilever%20Holder.htm" \o "Link to Prepare and Load the Cantilever Holder" **}** for details).
3. Click the **Select Experiment** icon.
4. Select the following:
    - **Experiment Category**: Electrical & Magnetic
    - **Experiment Group**: Electrical & Magnetic Lift Modes
    - **Select Experiment**: Surface Potential (AM-KPFM)
5. Click **Load Experiment**.
6. Set up the AFM for **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\TappingMode%20AFM\\Basic%20TappingMode%20Operation.htm" \o "Link to basic TappingMode AFM procedure" **}**.
7. Use the **AutoTune** button in the Tune Cantilever panel of the Setup view to locate the cantilever's resonant peak.

   If you were to click the **Manual Tune** button, the Cantilever Tune window would appear displaying 2 peaks—the amplitude curve and the phase curve. In the event you find more than one resonance, use Manual Tune and select a resonance that is sharp and clearly defined, but not necessarily the largest. It is also helpful to select a resonant peak where the lock-in phase also changes very sharply across the peak. Multiple peaks can often be eliminated by making sure the cantilever holder is clean and the cantilever is tightly secured. See **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\TappingMode%20AFM\\Manual%20Cantilever%20Tuning.htm" \o "Link to Manual Cantilever Tuning" **}** for more information.

8. **Engage** the AFM and make the necessary adjustments for a good TappingMode image while displaying height data.
9. Activate the **Expanded Mode** to see all the Interleave parameters available (in the Check Parameters or Scan view from the workflow toolbar).

10. In the ***Interleave*** panel, set the following:

    - **Integral Igain**: 0.5
    - **Proportional Gain**: 5
    - **Interleave Mode**: Lift
    - **Lift Scan Height**: 100 nm (can be optimized later)



Feedback	
Integral Gain	0.5000
Proportional Gain	5.000
Amplitude Setpoint	933.3 mV
Sample Bias	0 mV
Drive Frequency	118.0520 kHz
Drive Amplitude	1105 mV
Lock-In Phase	-151.5 °
Lock-In BW	12.46 kHz
Interleave	
Integral Gain	0.5000
Proportional Gain	5.000
Amplitude Setpoint	267.9 mV
Sample Bias	0 mV
Drive Frequency	0.5000000 kHz
Drive Amplitude	0 mV
Lock-In Phase	0 °
Lock-In BW	0.2130 kHz
Interleave Mode	Lift
Lift Scan Height	100.0 nm
Potential (Interleave)	
Potential Offset	0 V
Potential Feedback	On
Input Igain	5.000
Input Pgain	10.00
Freq. Control	Automatic
Lock-In2 Phase	180.0 °
Lock-In2 BW	0.5000 kHz
Drive2 Frequency	118.0520 kHz
Drive2 Amplitude	500.0 mV
Drive2 Routing	Tip

11. In the **Potential (Interleave)** panel, set the following:

- **Potential Feedback**: On
- Leave the **Drive2 Frequency** at the main Feedback value (gray)

11. Enter a **Drive2 Amplitude**.

This is the AC voltage that is applied to the AFM tip. Higher Drive Amplitude produces a larger electrostatic force on the cantilever and this makes for more sensitive potential measurements. Conversely, the maximum total voltage (AC + DC) that may be applied to the tip is ±10 V, so a large Drive Amplitude reduces the range of the DC voltage that can be applied to the cantilever. If the sample surface potentials to be measured are very large, it is necessary to choose a small Drive Amplitude, while small surface potentials can be imaged more successfully with large Drive Amplitudes. A suggested starting Drive Amplitude is 500 mV.

12. Ensure the the **Channel 4 image Data Type** is set to Potential.

13. Set the scan **Line Direction** for the main and interleave scans to Retrace.

    Remember to choose the Retrace direction because the lift step occurs on the trace scan and can cause artifacts in the data.

14. Set the **Channel 4 Scan Line** to Interleave.

15. Adjust the Input gains.

    As with the topography gains, the scan can be optimized by increasing the gains to maximize feedback response, but not so high that oscillation sets in. See **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Troubleshooting%20the%20Surface%20Potential%20Feedback%20Loop.htm" \o "Link to Troubleshooting the Surface Potential Feedback Loop" **}** for more information.

16. Optimize the lift heights.

    Set the **Lift Scan Height** at the smallest value possible that does not make the Potential feedback loop unstable or cause the tip to crash into the sample surface. When the tip crashes into the surface during the Potential measurement, dark or light streaks appear in the Potential image. In this case, increase the Lift Scan Height until these streaks are minimized.

17. Optimize the drive phase by clicking the **Set Phase** icon in the ***NanoScope*** toolbar.

    As discussed in **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Surface%20Potential%20Detection%20Theory.htm" \o "Link to Surface Potential Detection Theory" **}**, the correct phase relationship must exist between the reference and the input signals to the lock-in for the potential feedback loop to perform correctly. **Lock-In Phase** adjusts the phase of the reference signal to the lock-in amplifier and depends on the mechanical properties of the cantilever.

18. For large sample voltages or qualitative work, set a **Data Type** to Phase (in addition to Channel 4 Data Type set to Potential).

    When the controller has been configured for surface potential measurements, the “phase” signal is actually the cantilever amplitude signal, as measured by a lock-in amplifier. If the feedback loop is not enabled by selecting the Data Type = Potential, the lock-in cantilever amplitude depends on the voltage difference between the tip and sample in a roughly linear fashion. (The lock-in amplifier produces a voltage that is proportional to the cantilever amplitude.) Qualitative surface potential images can be collected using this lock-in signal. Also, if the sample has a surface potential that exceeds ±10 V (greater than the range of the “Potential” signal), it is possible to use the lock-in signal to provide qualitative images that reflect the sample surface potential. To view the lock-in signal with the reconfigured controller, select the Data type = Phase.

Determination of Lock-in Phase

For surface potential microscopy (also called scanning Kelvin probe force microscopy, SKPFM) measurements, the feedback adjusts the DC voltage applied between the tip and sample to compensate their intrinsic potential difference. The DC voltage map across the surface thus reflects surface potential variations of the sample surface.

When the difference is perfectly compensated, the tapping oscillation amplitude of the metal coated AFM cantilever (excited by an AC bias field) approaches “0”—the very reason this technique is called a *nulling* technique. In doing so, the feedback uses the tapping amplitude and phase to determine whether to increase or decrease the DC voltage.

To facilitate setting the **Phase** parameter, NanoScope Version 8.15 software now features a **Set Phase** tool, which enables the user to determine the lock-in phase with a single click.

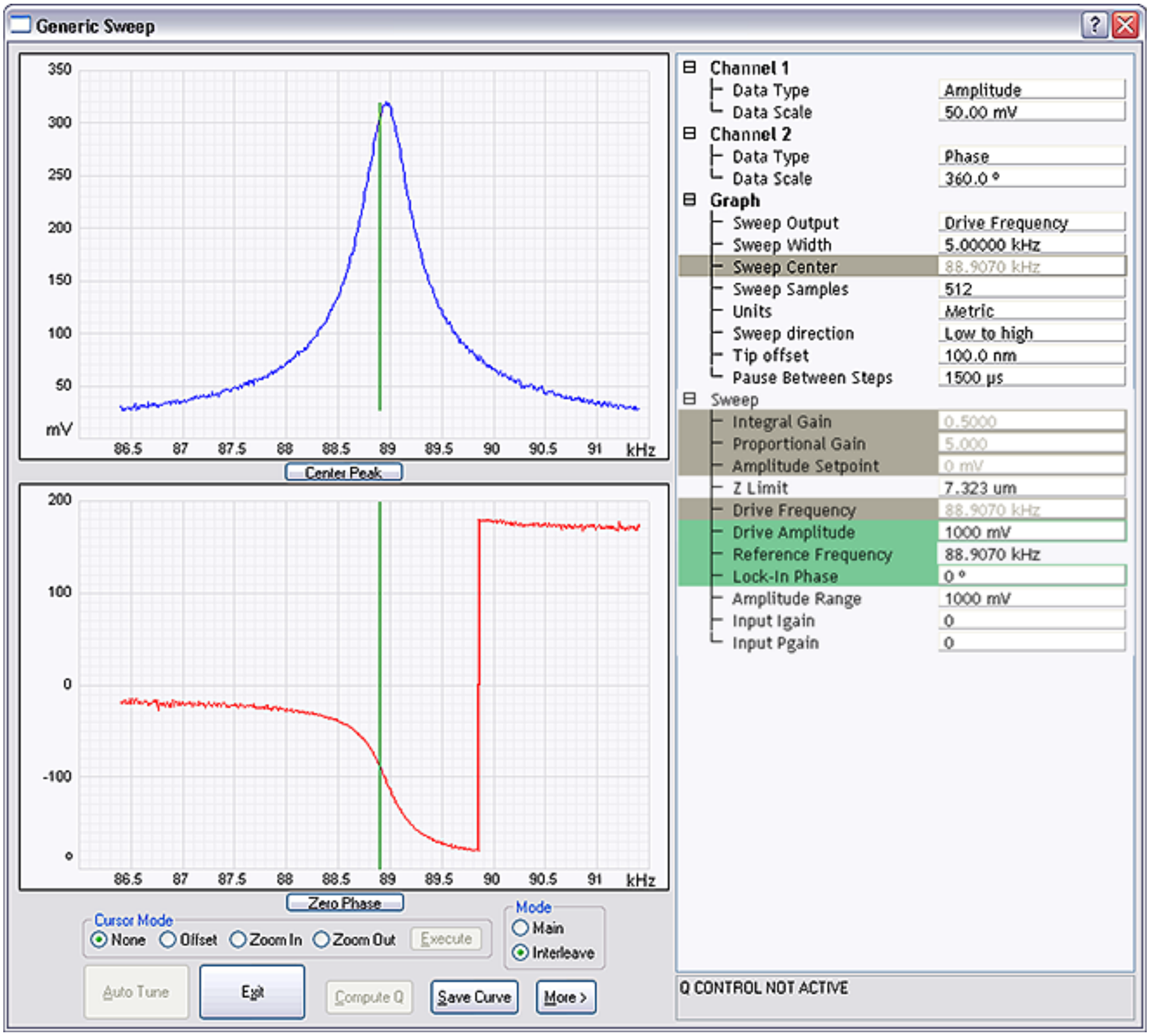
The following describes the NanoScope procedures initiated by the Set Phase tool:

NOTE: Knowledge of the inner workings of Set Phase is generally not necessary.

Generic Sweeps are taken on Interleave. In some cases, it is helpful to switch back and forth between Main and Interleave for the sweep parameters to take effect. Some inconsistency may occur—for instance, potential feedback may not actually be on when **Input Igain** and **Input Pgain** are non-zero.

{ HYPERLINK "javascript:void(0);" **}**

A phase difference (–90° in the lower graph in **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Determination%20of%20Lock-in%20Phase.htm" \l "InterleaveTuneCurve" **}**) is usually seen between tip oscillation signal and the AC bias driving signal. This phase lag varies from tip to tip, with operating frequency, and the potential difference between the tip and the spot on the sample.



Channel 1
- Data Type: Amplitude
- Data Scale: 50.00 mV

Channel 2
- Data Type: Phase
- Data Scale: 360.0 °

Graph
- Sweep Output: Drive Frequency
- Sweep Width: 5.00000 kHz
- Sweep Center: 88.9070 kHz
- Sweep Samples: 512
- Units: Metric
- Sweep direction: Low to high
- Tip offset: 100.0 nm
- Pause Between Steps: 1500 µs

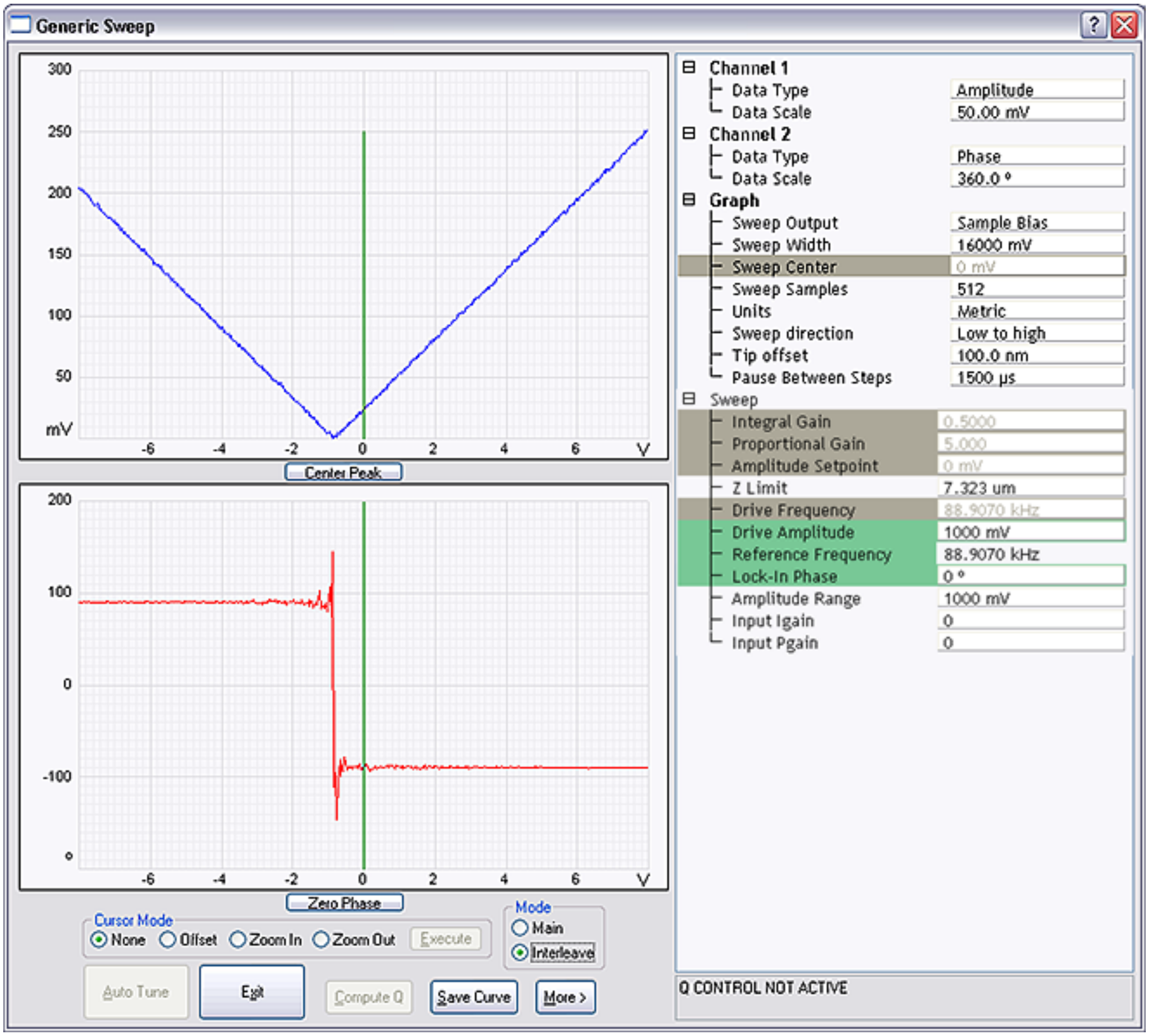
Sweep
- Integral Gain: 0.5000
- Proportional Gain: 5.000
- Amplitude Setpoint: 0 mV
- Z Limit: 7.323 um
- Drive Frequency: 88.9070 kHz
- Drive Amplitude: 1000 mV
- Reference Frequency: 88.9070 kHz
- Lock-In Phase: 0 °
- Amplitude Range: 1000 mV
- Input Igain: 0
- Input Pgain: 0

Q CONTROL NOT ACTIVE

Figure 1: Interleave Tuning Curve - Phase Lag

{ HYPERLINK "javascript:void(0);" }

{ HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Determination%20of%20Lock-in%20Phase.htm" \l "AmplitudeAndPhaseVsBias" } shows a Generic Sweep of Sample Bias while the potential feedback is turned off. Note that Input Igain and Input Pgain are 0.



Channel 1	
Data Type	Amplitude
Data Scale	50.00 mV
Channel 2	
Data Type	Phase
Data Scale	360.0 °
Graph	
Sweep Output	Sample Bias
Sweep Width	16000 mV
Sweep Center	0 mV
Sweep Samples	512
Units	Metric
Sweep direction	Low to high
Tip offset	100.0 nm
Pause Between Steps	1500 µs
Sweep	
Integral Gain	0.5000
Proportional Gain	5.000
Amplitude Setpoint	0 mV
Z Limit	7.323 um
Drive Frequency	88.9070 kHz
Drive Amplitude	1000 mV
Reference Frequency	88.9070 kHz
Lock-In Phase	0 °
Amplitude Range	1000 mV
Input Igain	0
Input Pgain	0

Q CONTROL NOT ACTIVE

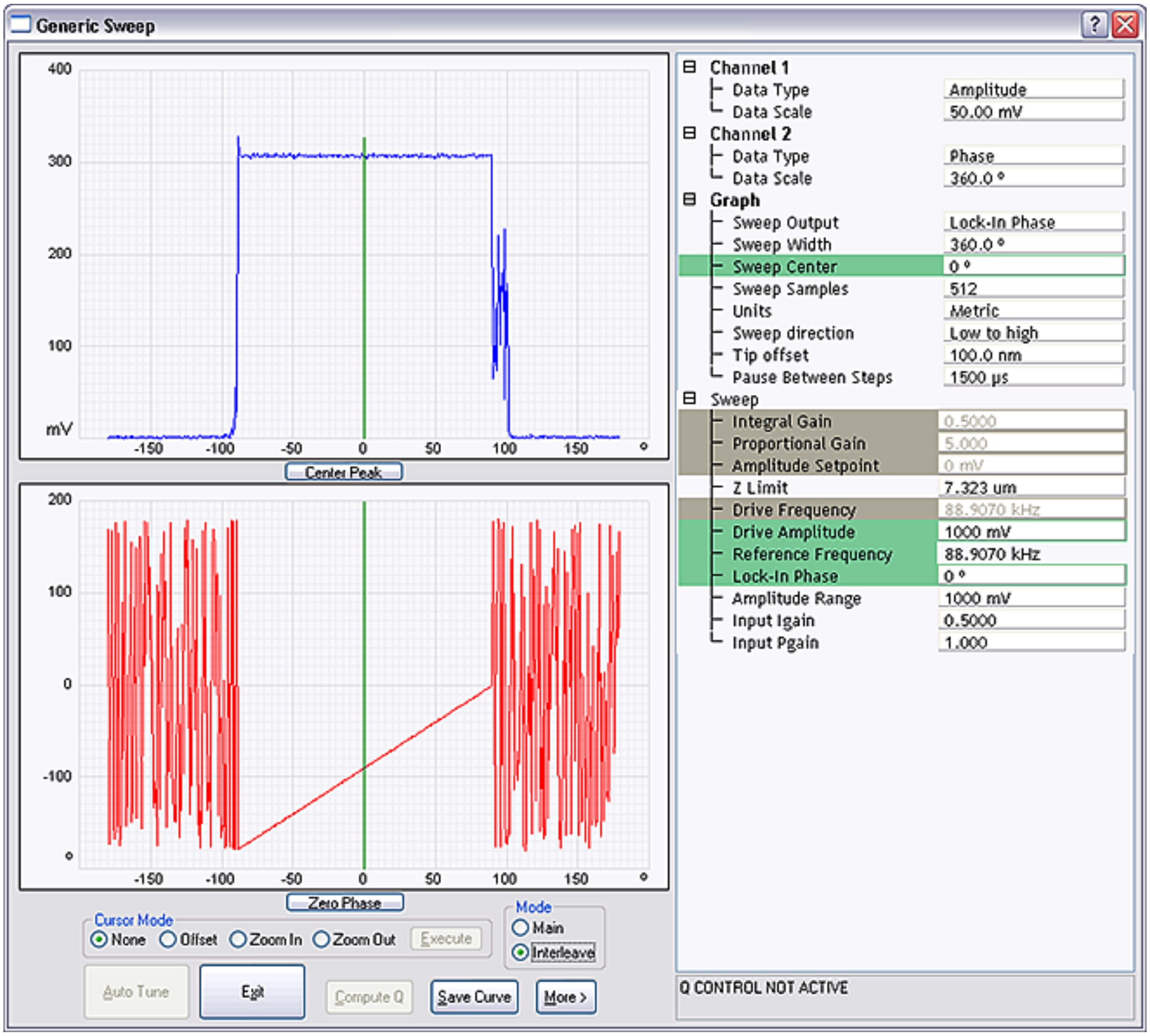
Figure 2: Amplitude and Phase vs. Sample Bias (Feedback Off)

The amplitude, shown in the upper plot, dips to 0 when the sample is biased to match the tip potential; as the bias voltage moves away from that point, the amplitude increases. Potential feedback seeks that zero point. Because amplitude alone can not determine whether one is on the left side or right side of that zero amplitude point, the feedback relies on the phase to determine which direction to move the DC bias.

The bottom graph in { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Determination%20of%20Lock-in%20Phase.htm" \l "AmplitudeAndPhaseVsBias" } shows the phase changing by 180° across “0” amplitude. Choose a Lock-In Phase to offset the oscillation phase so that the phase is negative when the tip voltage is positive relative to the sample. As you can see in { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Determination%20of%20Lock-in%20Phase.htm" \l "AmplitudeAndPhaseVsBias" }, when the sample bias is –2 V (tip is positive), the output Lock-In Phase is 90°. The Interleave Lock-In Phase then needs to be set to –180° to make it –90°.

{ HYPERLINK "javascript:void(0);" }

It is logical to sweep the lock-in phase in a full circle to determine the phase range where feedback is working while the feedback is turned on (Input Igain and Input Pgain are non-zero).



⊟ Channel 1	
Data Type	Amplitude
Data Scale	50.00 mV
⊟ Channel 2	
Data Type	Phase
Data Scale	360.0 °
⊟ Graph	
Sweep Output	Lock-In Phase
Sweep Width	360.0 °
Sweep Center	0 °
Sweep Samples	512
Units	Metric
Sweep direction	Low to high
Tip offset	100.0 nm
Pause Between Steps	1500 µs
⊟ Sweep	
Integral Gain	0.5000
Proportional Gain	5.000
Amplitude Setpoint	0 mV
Z Limit	7.323 um
Drive Frequency	88.9070 kHz
Drive Amplitude	1000 mV
Reference Frequency	88.9070 kHz
Lock-In Phase	0 °
Amplitude Range	1000 mV
Input Igain	0.5000
Input Pgain	1.000

Q CONTROL NOT ACTIVE

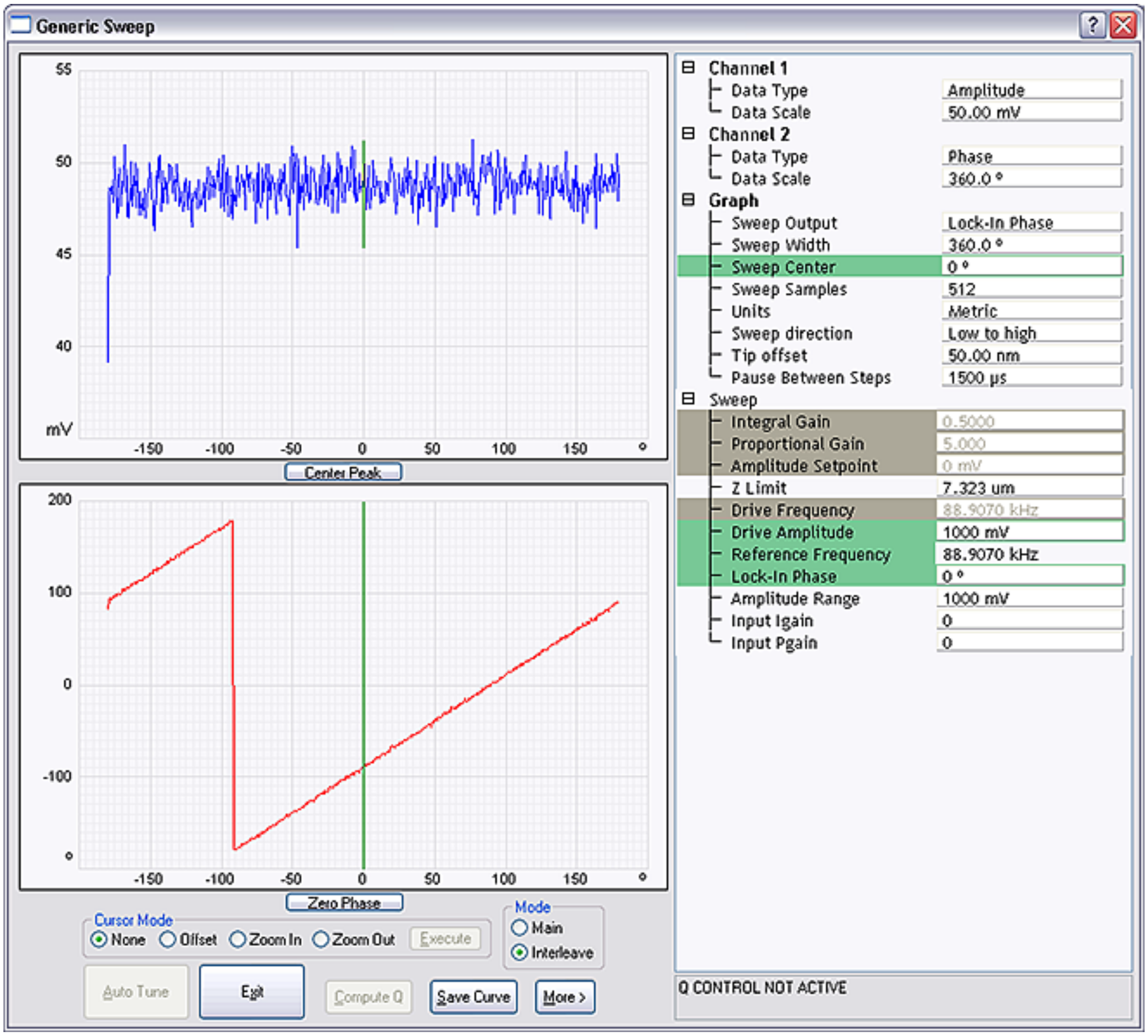
Figure 3: Phase vs. Lock-in Phase (Feedback On)

The top plot in { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Determination%20of%20Lock-in%20Phase.htm" \l "PhaseVsLockIn" } shows how the amplitude changes while lock-in phase is swept. In the mid-range of the phase sweep (approximately –100° to +100°), the amplitude stays non-zero, indicating that the phase is not correct for the feedback to work properly. On both ends, the amplitude remains around “0”, implying that feedback is working properly in “nulling” the amplitude. In principle, it is fine to choose any lock-in phase in these two regions 100° ~ 180° and –180° ~ –90° (equivalent to 180° ~ 270°); actually a combined region of 100° ~ 270°. It makes practical sense, however, to choose a value somewhere in the middle to have a good margin, e.g. –170°.

The lower plot in { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Determination%20of%20Lock-in%20Phase.htm" \l "PhaseVsLockIn" } shows phase changing linearly in the middle of the sweep range, while jumping around when feedback is working on either end. This is explained above under *Amplitude and Phase vs. Sample Bias—Feedback Off*.

{ HYPERLINK "javascript:void(0);" }

{ HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Determination%20of%20Lock-in%20Phase.htm" \l "AlternativePhase" } depicts a Generic Sweep of Lock-in phase while potential feedback is off and Input Igain and Input Pgain are “0”.



Channel 1
- Data Type: Amplitude
- Data Scale: 50.00 mV

Channel 2
- Data Type: Phase
- Data Scale: 360.0 °

Graph
- Sweep Output: Lock-In Phase
- Sweep Width: 360.0 °
- Sweep Center: 0 °
- Sweep Samples: 512
- Units: Metric
- Sweep direction: Low to high
- Tip offset: 50.00 nm
- Pause Between Steps: 1500 µs

Sweep
- Integral Gain: 0.5000
- Proportional Gain: 5.000
- Amplitude Setpoint: 0 mV
- Z Limit: 7.323 um
- Drive Frequency: 88.9070 kHz
- Drive Amplitude: 1000 mV
- Reference Frequency: 88.9070 kHz
- Lock-In Phase: 0 °
- Amplitude Range: 1000 mV
- Input Igain: 0
- Input Pgain: 0

Cursor Mode: ● None ○ Offset ○ Zoom In ○ Zoom Out

Mode: ○ Main ● Interleave

Q CONTROL NOT ACTIVE

Figure 4: Alternative Phase vs. Lock-in Phase (Feedback Off)

The top plot in { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Determination%20of%20Lock-in%20Phase.htm" \l "AlternativePhase" } shows the amplitude remaining unchanged while the Lock-In Phase is swept.

The bottom plot shows the phase changing linearly as the lock-in phase is swept. There is one exception where the phase jumps from 180° to –180°, so-called phase wrapping.

In case the plots in the previous section were not obtained (due to software inconsistency), do the following:

- From the left bottom plot, choose a lock-in phase where oscillation phase falls within –180°~0° (or 0~180°), e.g. 10° (–170°)
- If this does not work, add/subtract 180°, e.g. –170° (10°)

Of course, you can simply pick any lock-in phase, if it works, fine. Otherwise, change the phase by 180°. The difference is that with the above outlined approach you know what kind of margin you have.

Recall: Lock-In Phase depends on the mechanical properties of the cantilever. For cantilevers with resonant frequencies from 60–80 kHz (such as MESP, SCM-PIT, and FESP), use an interleave Lock-In Phase of 170 degrees. For cantilevers with higher resonant frequencies, increased electronics phase lag must be compensated. For cantilevers with resonant frequencies around 300 kHz (such as TESP, RTESP) an interleave Lock-In Phase near 130 degrees often works well.

FM-KPFM Imaging

FM-KPFM (Frequency Modulated-Kelvin Probe Force Microscopy) applies an AC signal to the probe at a low frequency, f_m, while mechanically driving the probe at its resonant frequency, f_0, and uses the amplitude of the 1st sideband at $f_0 + f_m$ as the error signal to drive a DC voltage that nulls that signal.

FM-KPFM is a **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\TappingMode%20AFM\\TappingMode%20AFM.htm" **}** single-pass technique and, unlike other electric modes, does not use **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Interleave%20Scanning.htm" \l "LiftMode" **}**. FM-KPFM has higher spatial resolution than **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\LiftMode%20SurfacePotentialDetectionPrinciples.htm" **}** but its signal-to-noise ratio is frequently lower.

{ HYPERLINK "javascript:void(0);" **}**

An AC voltage with amplitude V_{AC} and frequency f_m (angular frequency ω_m) superimposed on a DC voltage, V_{DC}, is applied between the probe tip and the sample. The resulting electrostatic force is given by

$$F_{el} = -\frac{1}{2}\frac{\partial C}{\partial z}(\Delta V)^2$$

Equation 1:

where

$$\Delta V = V_{DC} - \frac{\Delta\phi}{e} + V_{AC}\sin(\omega_m t)$$

Equation 2:

where Δφ is the contact potential difference between the probe and sample.

Equation 1 may be separated into three terms:

$$F_{el} = \frac{1}{2}\frac{\partial C}{\partial z}\left[\left(V_{DC} - \frac{\Delta\phi}{e}\right)^2 + \frac{1}{2}V_{AC}{}^2\right] + \frac{\partial C}{\partial z}\left[V_{DC} - \frac{\Delta\phi}{e}\right]V_{AC}\sin(\omega_m t) + \frac{1}{4}\frac{\partial C}{\partial z}V_{AC}{}^2\cos(2\omega_m t)$$

Equation 3:

The electric field gradient is given by:

$$\frac{\partial F_{el}}{\partial z} = \frac{1}{2}\frac{\partial^2 C}{\partial z^2}\left[\left(V_{DC} - \frac{\Delta\varphi}{e}\right)^2 + \frac{1}{2}V_{AC}^2\right] + \frac{\partial^2 C}{\partial z^2}\left(V_{DC} - \frac{\Delta\varphi}{e}\right)V_{AC}\sin(\omega_m t) + \frac{1}{4}\frac{\partial^2 C}{\partial z^2}V_{AC}^2\cos(2\omega_m t)$$

Equation 4:

The applied AC voltage modulates the force and force gradient at frequencies ω_m and $2\omega_m$.

Frequency Modulation

Hooke's law states:

$$F = k(z - z_0)$$

Equation 5:

Taking the derivative,

$$\frac{\partial F}{\partial z} = k$$

Equation 6:

The force gradient and spring constant are thus seen to be equivalent.

The electrostatic force shifts the resonant frequency of a cantilever with effective mass m* as follows:

$$\omega'_0 = \sqrt{\frac{k - \frac{\partial F}{\partial z}}{m^*}}$$

Equation 7:

The applied AC voltage modulates F_{el} and $\partial F_{el}/\partial z$ according to { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\FM-KPFM.htm" \l "Eqn4" }. { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\FM-KPFM.htm" \l "Eqn6" } then shows that the mechanical resonance of the cantilever is modulated with frequencies f_m and $2f_m$ with sidebands, shown schematically in { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\FM-KPFM.htm" \l "Fig1" }, appearing at $f_0 \pm f_m$ and $f_0 \pm 2f_m$.

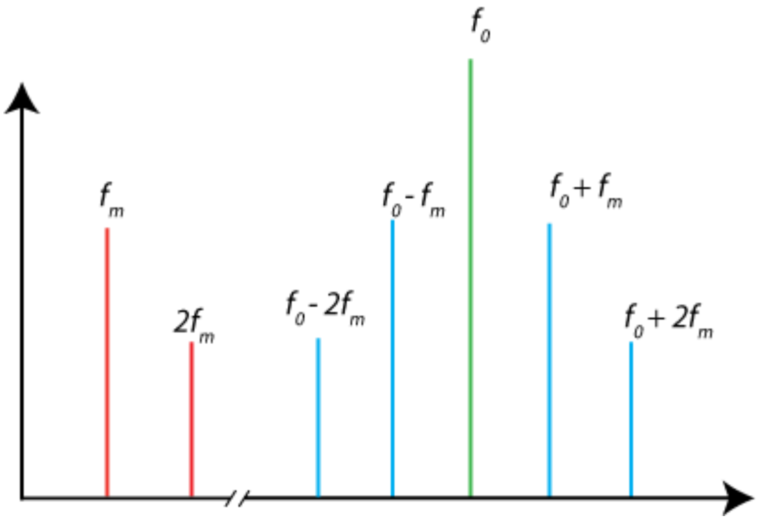


Figure 8: Schematic of the frequency spectrum of the probe tip oscillation

Resolution

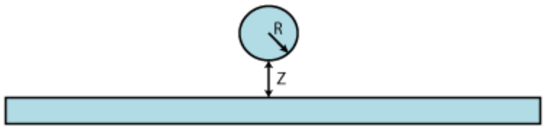


Figure 9: Charged sphere at separation z above an infinite plane

The force between a charged sphere at separation z above an infinite plane, shown in { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\FM-KPFM.htm" \l "ChargedSphere" }, is:

$$F_{el}(z) = -\pi\epsilon\left(\frac{R^2}{z(z+R)}\right)\Delta V^2$$

Equation 10:

and its derivative is:

$$\frac{\partial F_{el}}{\partial z} = \left(\frac{1}{z} + \frac{1}{z+R}\right) F_{el}(z)$$

Equation 11:

The electric force gradient has a steeper dependence on Z than the electric force. It also has a steeper dependence on X and Y.

FM-KPFM Probe Requirements

Bruker recommends **{** HYPERLINK "http://www.brukerafmprobes.com/Product.aspx?ProductID=3817" \t "_blank" **}** probes for FM-KPFM measurements.

Sample Preparation

Prepare the sample as described in **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Electric%20Techniques.htm" \l "Sample_Preparation" **}**.

FM-KPFM Procedure

1. Mount a sample onto the sample holder.
2. Mount an appropriate probe into the standard probe holder (see Prepare and Load the Cantilever Holder for details).
3. Click the **Select Experiment** icon to open the ***Select Experiment*** window, shown in **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\FM-KPFM.htm" \l "SelectExperimentWindow" **}**.
4. Select the following:
    - ***Experiment Category***: Electrical & Magnetic
    - ***Experiment Group***: Electrical & Magnetic Lift Modes
    - ***Select Experiment***: Surface Potential (FM-KPFM)
5. Click **Load Experiment**.
6. Click the **Setup** icon to open the ***Setup*** window.
7. Align the laser on the cantilever and place the crosshair there. See **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\FM-KPFM.htm" \l "AlignLaser" **}**.
8. Fast Thermal tuning, used to find the cantilever resonance, is performed when you exit the

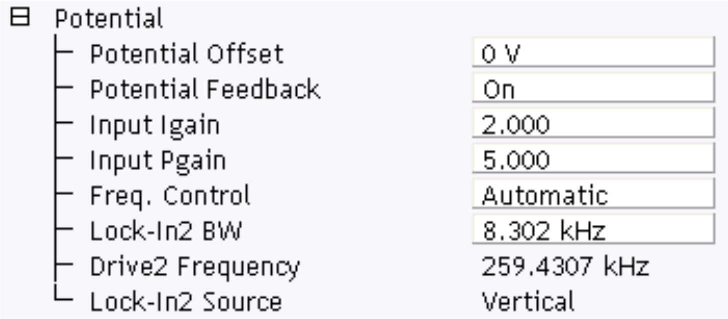
Setup view. This is made visible by the HDSC window, shown in { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\FM-KPFM.htm" \l "HSDC" }.

7. **Engage** the probe onto the sample

8. **Scan** the sample

9. Entering a value in the ***Potential Offset*** field adds that value to the measured value in the ***Potential*** channel. This can be particularly useful when measuring work functions as this function measures the difference in potential between the probe and the sample - entering the value of the work function of the probe will then provide a direct measurement of work function of the sample.

NOTE: The stored data is unaffected by the ***Potential Offset***. I.e. offline measurements do not see this input.



⊟ Potential

Potential Offset	0 V
Potential Feedback	On
Input Igain	2.000
Input Pgain	5.000
Freq. Control	Automatic
Lock-In2 BW	8.302 kHz
Drive2 Frequency	259.4307 kHz
Lock-In2 Source	Vertical

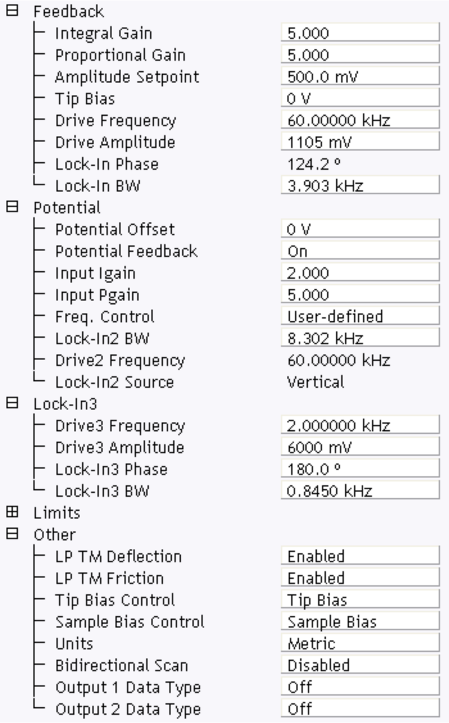
Figure 15: *Potential Offset* in the FM-KPFM ***Potential*** window

Advanced FM-KPFM Imaging

Automatic frequency selection is the default for FM-KPFM imaging. You may wish, however, to manually select an operating frequency. To do this:

12. Enter the **Expanded** mode.

13. Set ***Freq. Control*** in the ***Potential (Interleave)***, shown in { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\FM-KPFM.htm" \l "FreqControl" }, panel to **User-defined**.



Feedback	
Integral Gain	5.000
Proportional Gain	5.000
Amplitude Setpoint	500.0 mV
Tip Bias	0 V
Drive Frequency	60.00000 kHz
Drive Amplitude	1105 mV
Lock-In Phase	124.2 °
Lock-In BW	3.903 kHz
Potential	
Potential Offset	0 V
Potential Feedback	On
Input Igain	2.000
Input Pgain	5.000
Freq. Control	User-defined
Lock-In2 BW	8.302 kHz
Drive2 Frequency	60.00000 kHz
Lock-In2 Source	Vertical
Lock-In3	
Drive3 Frequency	2.000000 kHz
Drive3 Amplitude	6000 mV
Lock-In3 Phase	180.0 °
Lock-In3 BW	0.8450 kHz
Limits	
Other	
LP TM Deflection	Enabled
LP TM Friction	Enabled
Tip Bias Control	Tip Bias
Sample Bias Control	Sample Bias
Units	Metric
Bidirectional Scan	Disabled
Output 1 Data Type	Off
Output 2 Data Type	Off

Figure 16: Selecting **User-defined** ***Frequency Control***

14. You may then, if you wish, **Tune** the cantilever.

FM-KPFM Parameters

You may wish to manually adjust the parameters shown in **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\FM-KPFM.htm" \l "FMKPFMParms" **}**.

Parameter	Description
Lock-In BW	Needs to be smaller than twice the ***Drive 3 Frequency*** which is f_m in **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\FM-KPFM.htm" \l "Fig1" **}**. This lets the Lock-In respond to f_0 while filtering $f_0 \pm f_m$. If the ***Lock-In BW*** is too low, the tracking ability will be reduced. **Automatic *Freq. Control*** is thus easier to use than **User-defined *Freq. Control***.
Lock-In2 BW	Needs to be larger than four times the ***Drive 3 Frequency*** which is f_m in **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\FM-KPFM.htm" \l "Fig1" **}**. This is used to include the first and second harmonics, $f_0 \pm 2f_m$. Extra bandwidth of Lock-In2 does not degrade image quality as Lock-In3 follows.
Lock-In3 BW	Lock-In3, cascaded with Lock-In2, is used for the surface potential feedback.
Drive3	Higher ***Drive3 Amplitudes*** will result in higher signal-to-noise ratios.

Parameter	Description
Amplitude	

Table 1: Adjustable FM-KPFM parameters

PeakForce KPFM-AM Imaging

PeakForce-KPFM-AM is a is a two-pass procedure where the surface topography and nanomechanical properties are obtained using Bruker's proprietary **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\PeakForceQNM\\Operation\\OperatingPrinciples.htm" \l "Peak" **}** in the first pass and the surface potential or work function in the second pass using the **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\LiftMode%20SurfacePotentialDetectionPrinciples.htm" **}** mode:

1. The cantilever measures surface topography and nanomechanical properties on the first (main) scan (trace and retrace).
2. The cantilever ascends to the ***Lift Scan Height***.
3. The cantilever then follows the stored surface topography at the lift height above the sample while an oscillating voltage $V_{AC}\sin(\omega t)$ is applied directly to the probe tip. If there is a DC voltage difference between the tip and sample, then there will be an oscillating electric force on the cantilever at the frequency ω. This causes the cantilever to vibrate, and an amplitude can be detected on the second (interleave) scan.

PeakForce KPFM-AM leverages the advantages of PeakForce Tapping:

- Direct force control, eliminating artifacts that result from tip and sample damage
- Self-optimization using ScanAsyst
- Dramatically improved ease of use through the ScanAsyst™ imaging mode
- Spatially correlated nanomechanical information with PeakForce QNM

PeakForce KPFM-AM Probe Requirements

Bruker recommends **{** HYPERLINK "http://www.brukerafmprobes.com/Product.aspx?ProductID=3817" \t "_blank" **}** probes for PeakForce KPFM measurements.

Sample Preparation

Prepare the sample as described in **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Electric%20Techniques.htm" \l "Sample_Preparation" **}**.

PeakForce KPFM-AM Procedure

1. Mount a sample onto the sample holder.

2. Mount an appropriate probe into the standard probe holder (see Prepare and Load the Cantilever Holder for details).

3. Click the **Select Experiment** icon to open the ***Select Experiment*** window, shown in **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-KPFM.htm" \l "SelectExperiment" **}**.

4. Select the following:
    - ***Experiment Category***: Electrical & Magnetic
    - ***Experiment Group***: Electrical & Magnetic Lift Modes
    - ***Select Experiment***: PeakForce KPFM-AM

5. Click **Load Experiment**.

4. Click the **Setup** icon to open the ***Setup*** window.

5. Align the laser on the cantilever and place the crosshair there. See **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-KPFM.htm" \l "AlignLaser" **}**.

6. Fast Thermal tuning, used to find the cantilever resonance, is performed when you exit the ***Setup*** view. This is made visible by the HSDC window, shown in **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-KPFM.htm" \l "HSDC" **}**.

7. **Engage** the probe onto the sample

8. **Scan** the sample.

9. Set the ***Lift Scan Height*** as low as possible without hitting the sample, typically 75 - 100 nm.

10. Entering a value in the ***Potential Offset*** field adds that value to the measured value in the ***Potential*** channel. This can be particularly useful when measuring work functions as this function measures the difference in potential between the probe and the sample - entering the value of the work function of the probe will then provide a direct measurement of work function of the sample.

NOTE: The stored data is unaffected by the ***Potential Offset***. I.e. offline measurements do not see this input.

11. Refer to the **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\PeakForceQNM\\Operation\\O

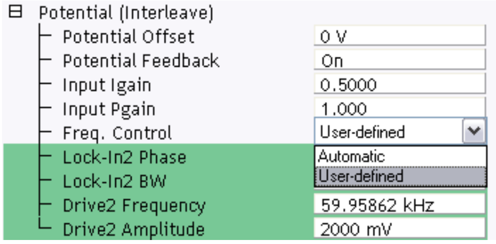
peratingProcedures.htm" **}** sections for details regarding PeakForce mode imaging.

Advanced PeakForce KPFM-AM Operation

Automatic frequency selection is the default for PeakForce KPFM imaging. You may wish, however, to manually select an operating frequency. To do this:

12. Enter the **Expanded** mode.

13. Set ***Freq. Control*** in the ***Potential (Interleave)***, shown in **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-KPFM.htm" \l "FreqControl" **}**, panel to **User-defined**.



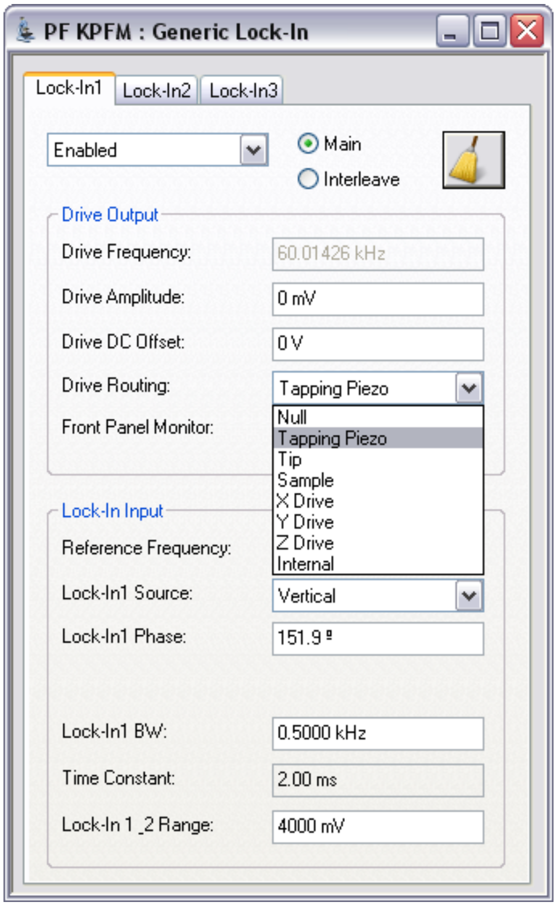
Potential (Interleave)

Potential Offset	0 V
Potential Feedback	On
Input Igain	0.5000
Input Pgain	1.000
Freq. Control	User-defined
Lock-In2 Phase	
Lock-In2 BW	
Drive2 Frequency	59.95862 kHz
Drive2 Amplitude	2000 mV

Figure 4: Selecting **User-defined *Frequency Control***

14. You will then need to manually tune the cantilever:

15. Select **Microscope** > **Generic Lockin** from the NanoScope Menu Bar. This opens the Generic Lock-In window, shown in **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-KPFM.htm" \l "LockIn" **}**.



Enabled

● Main
○ Interleave

Drive Output

Drive Frequency: 60.01426 kHz
Drive Amplitude: 0 mV
Drive DC Offset: 0 V
Drive Routing: Tapping Piezo
Front Panel Monitor:

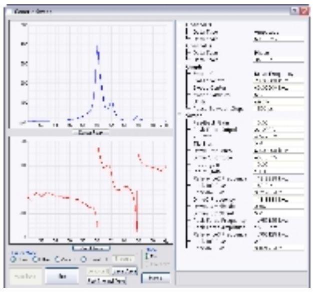
Lock-In Input

Reference Frequency:
Lock-In1 Source: Vertical
Lock-In1 Phase: 151.9 º
Lock-In1 BW: 0.5000 kHz
Time Constant: 2.00 ms
Lock-In 1 _2 Range: 4000 mV

Figure 5: The PeakForce KPFM Generic Lock-In window

16. Select **Tapping Piezo** in the ***Drive Routing*** panel of ***Lock-In1***.

17. Click **Sweep** to open the ***Generic Sweep*** window, shown in **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-KPFM.htm" \l "GenericSweep" **}**.



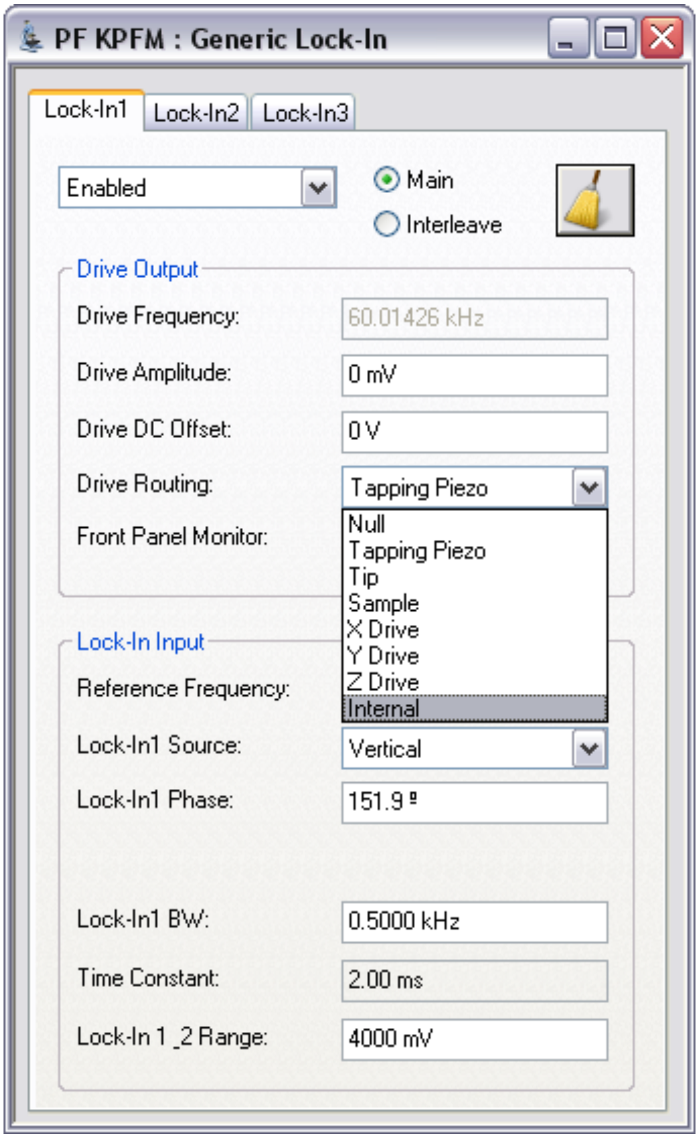
(Hover over the image to view larger)

Figure 6: The ***Generic Sweep*** window

18. Standard tune procedures, with the exception of Auto Tune, apply. You may use the **Offset** command to center the peak on the cursor...

19. You will also need to follow the manual procedures described in { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Determination%20of%20Lock-in%20Phase.htm" }.

20. Reset the ***Drive Routing*** to **Internal** before closing the ***PF KPFM Generic Lock-In*** window. See { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-KPFM.htm" \l "Internal" }.



Enabled

● Main
○ Interleave

Drive Frequency: 60.01426 kHz
Drive Amplitude: 0 mV
Drive DC Offset: 0 V
Drive Routing: Tapping Piezo
Front Panel Monitor:
Reference Frequency:
Lock-In1 Source: Vertical
Lock-In1 Phase: 151.9 º
Lock-In1 BW: 0.5000 kHz
Time Constant: 2.00 ms
Lock-In 1 _2 Range: 4000 mV

Figure 7: Set the ***Drive Routing*** to **Internal**

21. Enter your chosen frequency and amplitude into the ***Drive2 Frequency*** and Amplitude windows, shown in { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-KPFM.htm" \l "FreqControl" }.

PeakForce KPFM Imaging

PeakForce KPFM (PeakForce Frequency Modulated-Kelvin Probe Force Microscopy) is a combination of Peak Force Tapping Mode and frequency modulated KPFM (FM-KPFM) mode.

PeakForce KPFM measures surface potential or work function using a **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\LiftMode%20SurfacePotentialDetectionPrinciples.htm" **}** variation of the **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\FM-KPFM.htm" **}** mode while simultaneously providing correlated nanomechanical property information using the Bruker's proprietary **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\PeakForceQNM\\Operation\\OperatingPrinciples.htm" \l "Peak" **}**.

PeakForce KPFM leverages the advantages of PeakForce Tapping:

- Direct force control, eliminating artifacts that result from tip and sample damage
- Self-optimization using ScanAsyst™
- Dramatically improved ease of use through the ScanAsyst™ imaging mode
- Spatially correlated nanomechanical information with PeakForce QNM

Because of PeakForce's direct force control, softer probes may be used in this mode, thereby increasing sensitivity.

PeakForce KPFM Probe Requirements

Bruker recommends **{** HYPERLINK "http://www.brukerafmprobes.com/Product.aspx?ProductID=3817" \t "_blank" **}** probes for PF FM-KPFM measurements.

Sample Preparation

Prepare the sample as described in **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Electric%20Techniques.htm" \l "Sample_Preparation" **}**.

PeakForce KPFM Procedure

1. Mount a sample onto the sample holder.
2. Mount an appropriate probe into the standard probe holder (see **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Basic%20AFM%20Operation\\Prepare%20and%20Load%20the%20Cantilever%20Holder.htm" \o "Link to Prepare and Load the Cantilever Holder" **}** for details).

3. Click the **Select Experiment** icon to open the Select Experiment window.

4. Select the following:

    - ***Experiment Category***: Electrical & Magnetic
    - ***Experiment Group***: Electrical & Magnetic Lift Modes
    - ***Select Experiment***: PeakForce KPFM

5. Click **Load Experiment**.

6. Click the **Setup** icon to open the ***Setup*** window.

7. Align the laser on the cantilever and place the crosshair there. See **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-FM-KPFM.htm" \l "AlignLaser" **}**.

6. Fast Thermal tuning, used to find the cantilever resonance, is performed when you exit the ***Setup*** view. This is made visible by the HSDC window, shown in **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-FM-KPFM.htm" \l "HSDC" **}**.

7. **Engage** the probe onto the sample

8. **Scan** the sample

9. Set the ***Lift Scan Height*** as low as possible without hitting the sample, typically 75 - 100 nm.

10. Entering a value in the ***Potential Offset*** field adds that value to the measured value in the ***Potential*** channel. This can be particularly useful when measuring work functions as this function measures the difference in potential between the probe and the sample - entering the value of the work function of the probe will then provide a direct measurement of work function of the sample.

NOTE: The stored data is unaffected by the ***Potential Offset***. I.e. offline measurements do not see this input.

11. Refer to the **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\PeakForceQNM\\Operation\\OperatingProcedures.htm" **}** sections for details regarding PeakForce mode imaging.

A sample result showing the surface potentials (work functions) of three different materials is shown in **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-FM-KPFM.htm" \l "Scan" **}**.

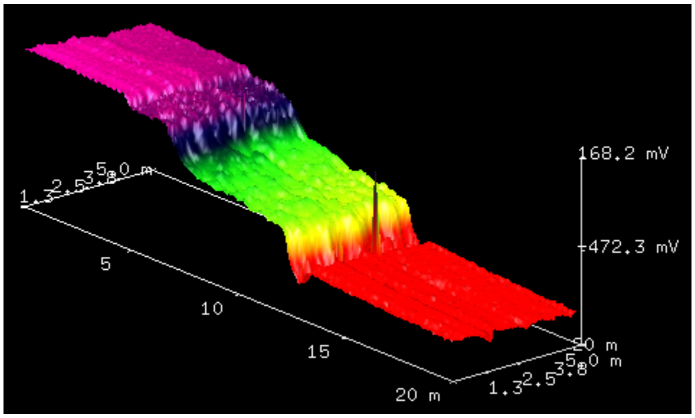


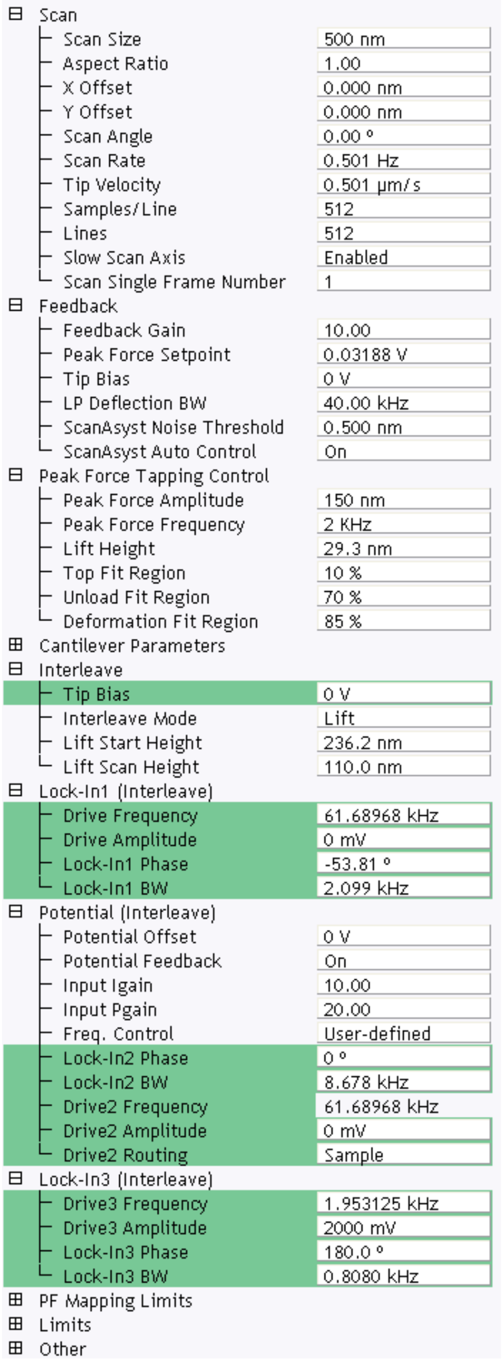
Figure 4: PeakForce KPFM scan of a Au-Si-Al (left to right) sample.

Advanced PeakForce KPFM Imaging

Automatic frequency selection is the default for PeakForce KPFM imaging. You may wish, however, to manually select an operating frequency. To do this:

12. Enter the **Expanded** mode.

13. Set ***Freq. Control*** in the ***Potential (Interleave)***, shown in **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-FM-KPFM.htm" \l "FreqControl" **}**, panel to **User-defined**.



⊟ Scan	
Scan Size	500 nm
Aspect Ratio	1.00
X Offset	0.000 nm
Y Offset	0.000 nm
Scan Angle	0.00 °
Scan Rate	0.501 Hz
Tip Velocity	0.501 µm/s
Samples/Line	512
Lines	512
Slow Scan Axis	Enabled
Scan Single Frame Number	1
⊟ Feedback	
Feedback Gain	10.00
Peak Force Setpoint	0.03188 V
Tip Bias	0 V
LP Deflection BW	40.00 kHz
ScanAsyst Noise Threshold	0.500 nm
ScanAsyst Auto Control	On
⊟ Peak Force Tapping Control	
Peak Force Amplitude	150 nm
Peak Force Frequency	2 KHz
Lift Height	29.3 nm
Top Fit Region	10 %
Unload Fit Region	70 %
Deformation Fit Region	85 %
⊞ Cantilever Parameters	
⊟ Interleave	
Tip Bias	0 V
Interleave Mode	Lift
Lift Start Height	236.2 nm
Lift Scan Height	110.0 nm
⊟ Lock-In1 (Interleave)	
Drive Frequency	61.68968 kHz
Drive Amplitude	0 mV
Lock-In1 Phase	-53.81 °
Lock-In1 BW	2.099 kHz
⊟ Potential (Interleave)	
Potential Offset	0 V
Potential Feedback	On
Input Igain	10.00
Input Pgain	20.00
Freq. Control	User-defined
Lock-In2 Phase	0 °
Lock-In2 BW	8.678 kHz
Drive2 Frequency	61.68968 kHz
Drive2 Amplitude	0 mV
Drive2 Routing	Sample
⊟ Lock-In3 (Interleave)	
Drive3 Frequency	1.953125 kHz
Drive3 Amplitude	2000 mV
Lock-In3 Phase	180.0 °
Lock-In3 BW	0.8080 kHz
⊞ PF Mapping Limits	
⊞ Limits	
⊞ Other	

Figure 5: Selecting **User-defined** ***Frequency Control***

You can manually select the operating frequency of the LiftMode. For details, refer to **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-KPFM.htm" \l "Advanced" **}**.

PeakForce KPFM Parameters

You may wish to manually adjust the parameters shown in **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-FM-KPFM.htm" \l "FMKPFMParms" **}**.

Parameter	Description
Lock-In1 BW	Needs to be smaller than twice the ***Drive 3 Frequency*** which is f_m in **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\FM-KPFM.htm" \l "Fig1" **}** of **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\FM-KPFM.htm" **}**. This lets the Lock-In respond to f_0 while filtering $f_0 \pm f_m$. If the ***Lock-In BW*** is too low, the tracking ability will be reduced. **Automatic *Freq. Control*** is thus easier to use than **User-defined *Freq. Control***.
Lock-In2 BW	Needs to be larger than four times the ***Drive 3 Frequency*** which is f_m in **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\FM-KPFM.htm" \l "Fig1" **}** of **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\FM-KPFM.htm" **}**. This is used to include the first and second harmonics, $f_0 \pm 2f_m$. Extra bandwidth of Lock-In2 does not degrade image quality as Lock-In3 follows.
Lock-In3 BW	Lock-In3, cascaded with Lock-In2, is used for the surface potential feedback.
Drive3 Amplitude	Higher ***Drive3 Amplitudes*** will result in higher signal-to-noise ratios.

Table 1: Adjustable FM-KPFM parameters

PeakForce KPFM-HV Imaging

The PeakForce Kelvin Probe Force Microscopy-HV mode maps the electrostatic potential at the sample surface by applying an AC voltage to the probe and measuring harmonics of that voltage. This AC technique extends the measurement range of AM-KPFM (see **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\LiftMode%20SurfacePotentialDetectionPrinciples.htm" **}**) up to approximately ±200 V.

PeakForce KPFM-HV also leverages the advantages of PeakForce Tapping:

- Direct force control, eliminating artifacts that result from tip and sample damage
- Self-optimization using ScanAsyst™
- Dramatically improved ease of use through the ScanAsyst™ imaging mode
- Spatially correlated nanomechanical information with PeakForce QNM

{ HYPERLINK "javascript:void(0);" **}**

The electrostatic force on the cantilever is the derivative of the potential:

$$F_{el} = -\frac{\partial U}{\partial z} = -\frac{1}{2}\frac{\partial C}{\partial z}(\Delta V)^2$$

Equation 1:

where the voltage difference is:

$$\Delta V = V_{DC} - \frac{\Delta\varphi}{e} + V_{AC}\sin(\omega_m t)$$

Equation 2:

Combining **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-KPFM%20HV%20Imaging.htm" \l "Eqn1" **}** with **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-KPFM%20HV%20Imaging.htm" \l "Eqn2" **}** we get:

$$F_{el} = \frac{1}{2}\frac{\partial C}{\partial z}\left(\left(V_{DC} - \frac{\Delta\varphi}{e}\right)^2 + \frac{1}{2}V_{AC}^2\right) + \frac{\partial C}{\partial z}\left(V_{DC} - \frac{\Delta\varphi}{e}\right)V_{AC}\sin(\omega t) + \frac{1}{4}\frac{\partial C}{\partial z}V_{AC}^2\cos(2\omega t)$$

Equation 3:

For V_{DC} = 0 we have

$$\Delta\varphi = \frac{1}{4}V_{AC}\frac{A_{\omega}}{A_{2\omega}}\bigg|_{V_{DC=0}}$$

Equation 4:

and

$$\frac{\partial C}{\partial z} = \frac{4A_{2\omega}}{V_{AC}^2}$$

Equation 5:

Measuring the amplitudes at ω and 2ω, we use **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-KPFM%20HV%20Imaging.htm" \l "Eqn4" **}** to measure the surface potential φ. **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-KPFM%20HV%20Imaging.htm" \l "Eqn5" **}** provides an additional property channel, $\partial C/\partial z$.

PeakForce KPFM HV Operation

PeakForce KPFM HV requires a PF KPFM-HV Application Module, shown in { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-KPFM%20HV%20Imaging.htm" \l "AppMod" }.

The PF-KPFM HV Application Module requires an { HYPERLINK "http://www.brukerafmprobes.com/a-3501-dtrch-am.aspx" \t "_blank" }. Either the Dimension SCM Probe Holder or the Dimension SSRM, TUNA and C-AFM Probe Holder will work.

PF KPFM-HV Probe Requirements

Bruker recommends { HYPERLINK "http://www.brukerafmprobes.com/Product.aspx?ProductID=3817" \t "_blank" } probes for PeakForce KPFM-HV measurements.

Sample Preparation

Prepare the sample as described in { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Electric%20Techniques.htm" \l "Sample_Preparation" }.

PF KPFM-HV Procedure

1. Mount a sample onto the sample holder.

2. Mount an appropriate probe into the standard probe holder (see Prepare and Load the Cantilever Holder for details).

3. Click the **Select Experiment** icon to open the ***Select Experiment*** window.

4. Select the following:

    - ***Experiment Category***: Electrical & Magnetic
    - ***Experiment Group***: Electrical & Magnetic Lift Modes
    - ***Select Experiment***: PeakForce KPFM-HV

5. Click **Load Experiment**.

4\. Click the **Setup** icon to open the ***Setup*** window.

5\. Align the laser on the cantilever and place the crosshair there. See { HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\PF-KPFM%20HV%20Imaging.htm" \l "AlignLaser" }.

7\. **Engage** the probe onto the sample

8. **Scan** the sample

9. Set the ***Lift Scan Height*** as low as possible without hitting the sample. Increase the ***Lift Scan Height*** if the probe touches the sample - symptoms will be a very noisy potential scan.

10. Refer to the **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\PeakForceQNM\\Operation\\OperatingProcedures.htm" **}** sections for details regarding PeakForce mode imaging.

Troubleshooting the Surface Potential Feedback Loop

The **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Surface%20Potential%20Detection.htm" \o "Link to Surface Potential Detection" **}** signal feedback loop can be unstable. This instability can cause the potential signal to oscillate or become stuck at either +10 V or –10 V. Below are some tips to ensure the feedback loop is working properly with no oscillation. Look at the scope display for the **Potential** signal:

- If oscillation noise is evident in the Potential signal:
  - Reduce the **{** HYPERLINK "javascript:void(0);" **}**. (The gains are scaling factors for the error signal to determine how quickly corrections should be applied in the feedback loop. There are two important gain factors: the proportional gain scales to the current value of the error signal, and the integral gain scales the aggregate of the past values of the error signal (the "area under the curve").)
  - If oscillations persist even at very low gains, try increasing the **Lift Scan Height** and/or reducing the **Drive Amplitude** until oscillation stops.
  - If the tip crashes into the surface the Lock-in signal becomes unstable and can cause the feedback loop to malfunction. Increasing the Lift Height and reducing the Drive Amplitude can prevent this problem.
  - Once oscillation stops, the gains may be increased for improved performance.
- If the Potential signal is perfectly flat and shows no noise even with a small Z-range:
  - The feedback loop is probably stuck at ±10 V—you can verify this by changing the value of **Realtime Plane Fit** to None in the Channel 1 panel.
  - Reduce the Scan Rate and watch the scope trace, which indicates the cantilever amplitude. On the topographic trace, the voltage displayed should be the **{** HYPERLINK "javascript:void(0);" **}** selected for the Main scan. On the Potential trace, this voltage drops close to zero if the cantilever oscillation is being successfully reduced.
  - If the value instead goes to a large nonzero value, the feedback loop is probably not working properly. In this case, try reducing the Drive Amplitude and increasing the Lift Scan Height or optimizing the Lock-In Phase (see **{** HYPERLINK "file:///D:\\Program%20Files\\Nanoscope\\8.15\\Help\\Icon\\Content\\Interleave%20Scanning\\Determination%20of%20Lock-in%20Phase.htm" \o "Link to Determination of Lock-in Phase" **}**).
  - It may also be helpful to momentarily turn the **Interleave Mode** to Disabled, then back to Interleave.

- Try reducing any external voltage that is being applied to the sample to stabilize the feedback loop, then turn the voltage back up.