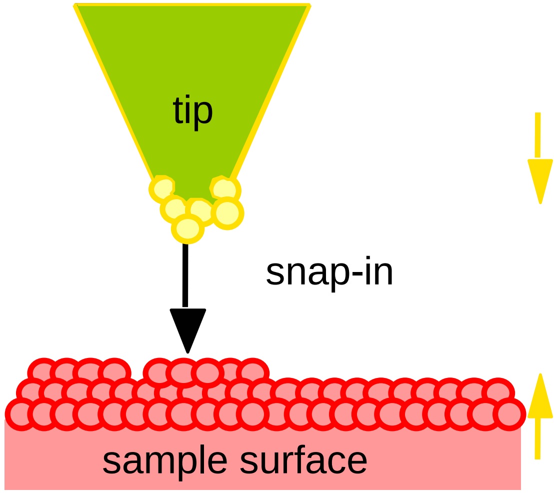
3.3.1. Principles and Instrumentation

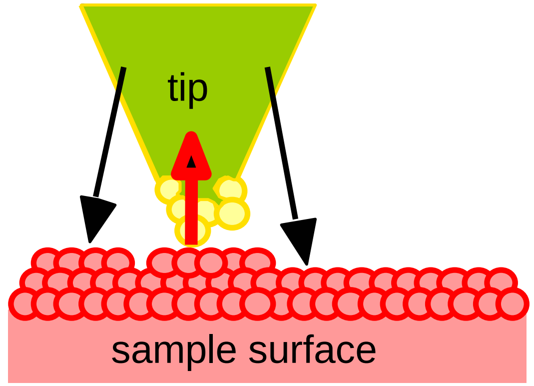
Snap to Contact

critical tip-sample distance



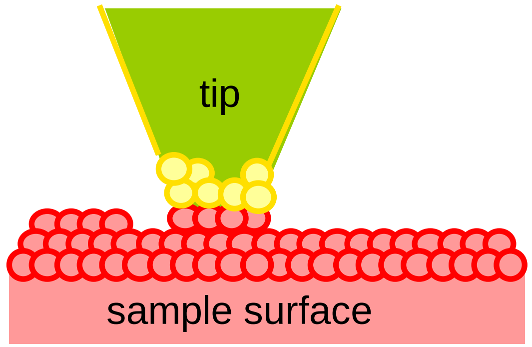
tip snaps to surface @ critical tip-sample distance due to attractive van der Waals force.

tip in contact with sample

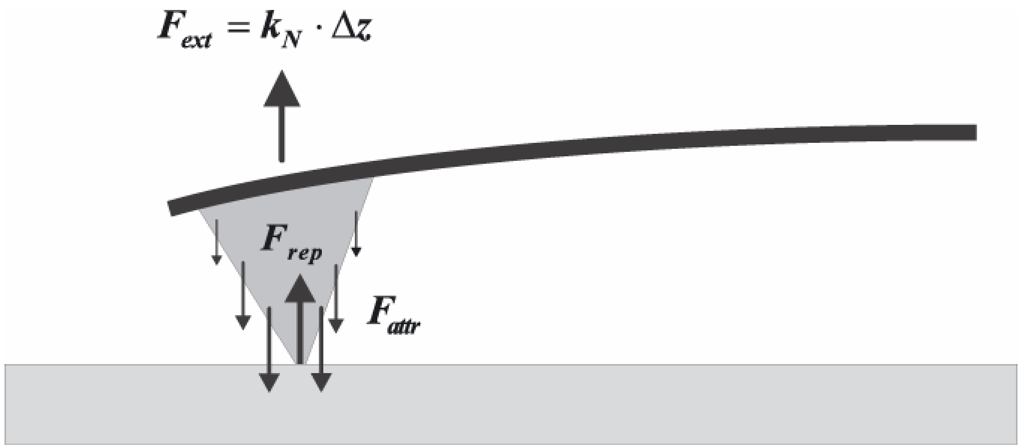


attractive van der Waals force acting on tip are compensated by local repulsive force at the tip apex.

multi-atom tip-sample contact



large repulsive force at tip apex leads to re-ordering of atoms at the tip apex. A multi-atom contact is formed. The imaging of single atoms and atomic defects is not possible under this condition.



Contact Radius:

- in atmosphere: 2-10nm @ 1nN < F < 100nN
- in UHV: 1-4nm @ 0.1nN < F < 10nN

How to achieve True Atomic Resolution?

Concept

• reduce long-range force (sharp and single atom tip)
• avoid strong bonding or reaction of tip apex atom with surface (no wear)

Experimental Realization

• reduce van der Waals force by immersing in polar liquid (repulsive forces < 0.1nN !)
• in UHV: keep tip close to surface (~ 5 Å), but avoid jump to contact !

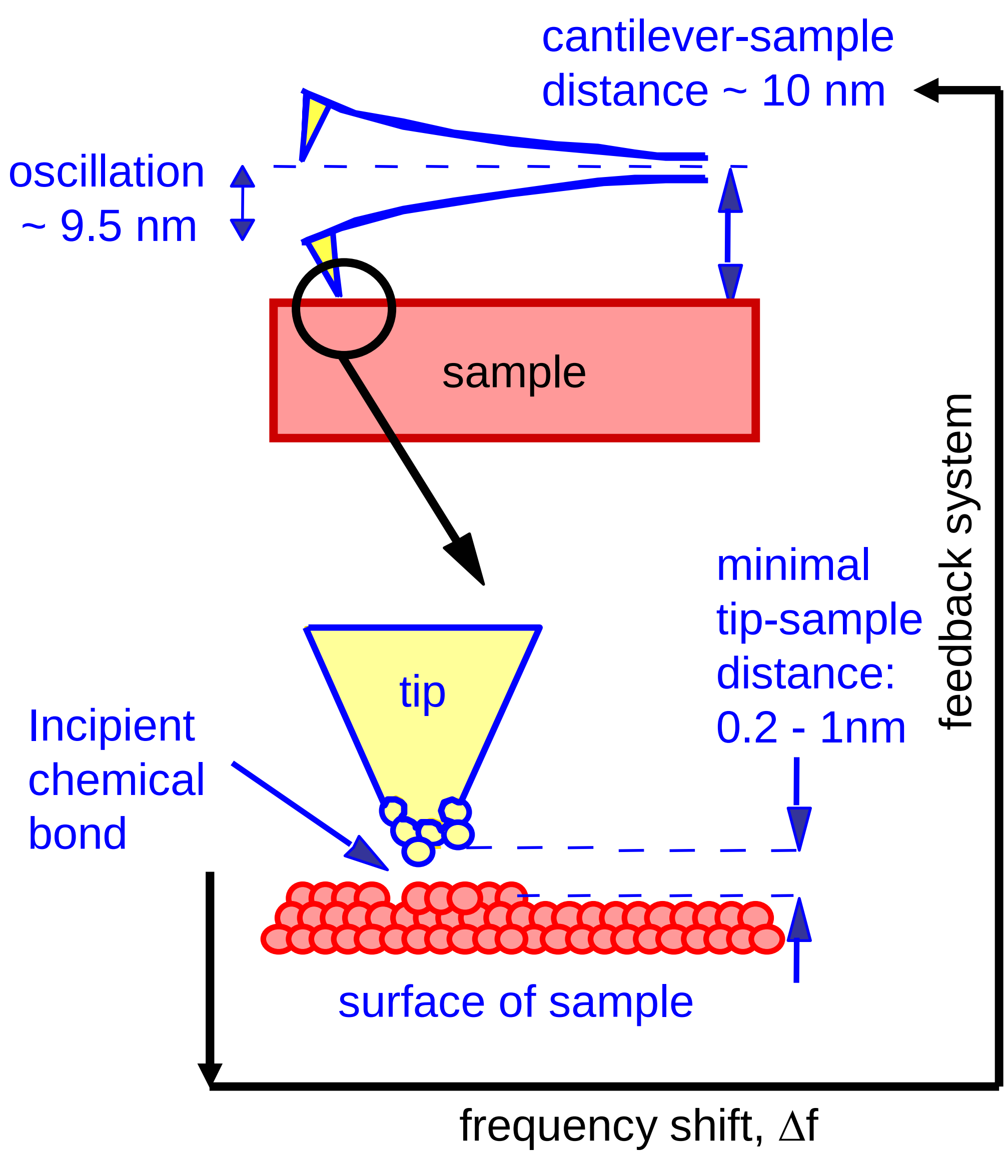
Stability criterion (avoiding jump to contact, JTC)

$$c_L > \frac{\partial F_{TS}}{\partial z}$$ or $$c_L \cdot A_0 > -F_{TS}$$

- use hard levers c_L and measure deflection or frequency shift
- use any lever at sufficiently large oscillation amplitude, A_0 and measure frequency shift

Refs.:
[1] F. Ohnesorge and G. Binnig, Science 260, 1451 (1993)
[2] U. Dürig in NATO ASI Series E: applied sciences 286 (1995)
[3] P. M. Hoffmann, Proc. R. Soc. Lond. A 457, 1161 (2001)
[4] F.J. Giessibl, , Science 267, 68 (1995)

Principle of Dynamic Force Microscopy with Atomic Resolution



First demonstration of true atomic resolution:

F.J. Giessibl, , Science 267, 68 (1995),

S. Kitamura et al.,
Jpn. J. Appl. Phys., 34, L145 (1995)

H. Ueyama et al.,
Jpn. J. Appl. Phys., 34, L1086 (1995)

FM Detection:

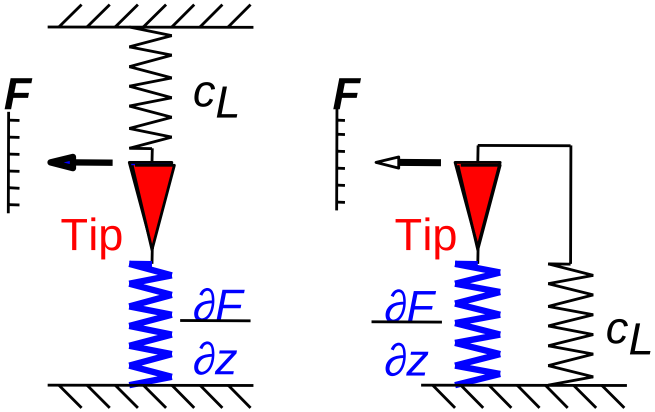
T.R. Albrecht et al., J. Appl. Phys. 69, 668 (1991)
describe an FM demondulation technique for fast measurement of frequency shift.

U. Dürig et al., J. Appl. Phys. 82, 3641 (1997),
Ch. Loppacher et al., Appl. Phys. A66, 215 (1998)

- adjust frequency of oscillation circuit to keep phase between excitation and cantilever oscillation constant (phase locked loop)
- keep cantilever oscillation amplitude constant, i.e. cantilever excitation signal is proportional to energy dissipation
- conservative and non-conservative interactions can be separated

Dynamic SFM

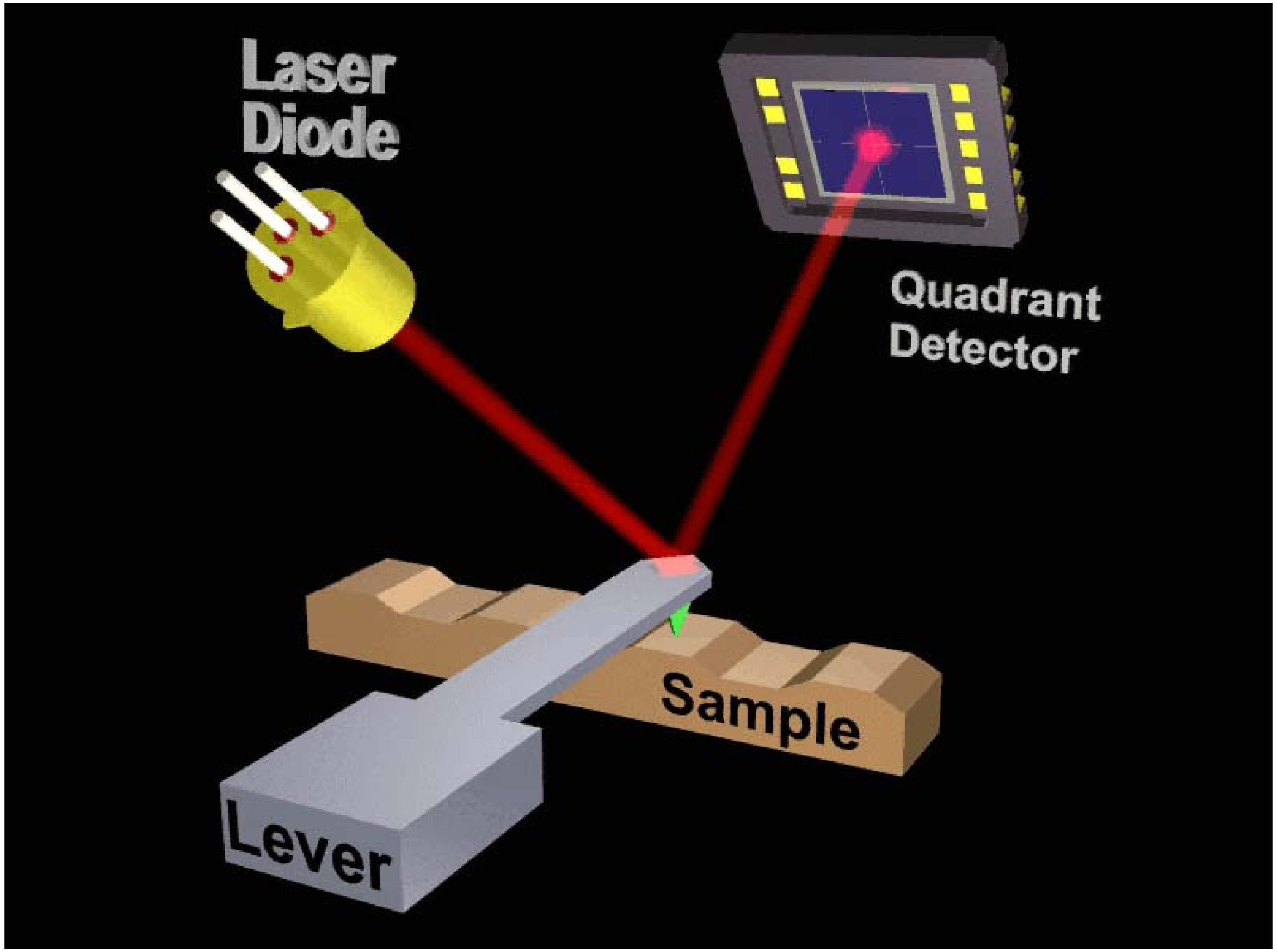
**Measurement of the dynamical properties of the cantilever:
resonance frequency shift & energy loss per oscillation period**



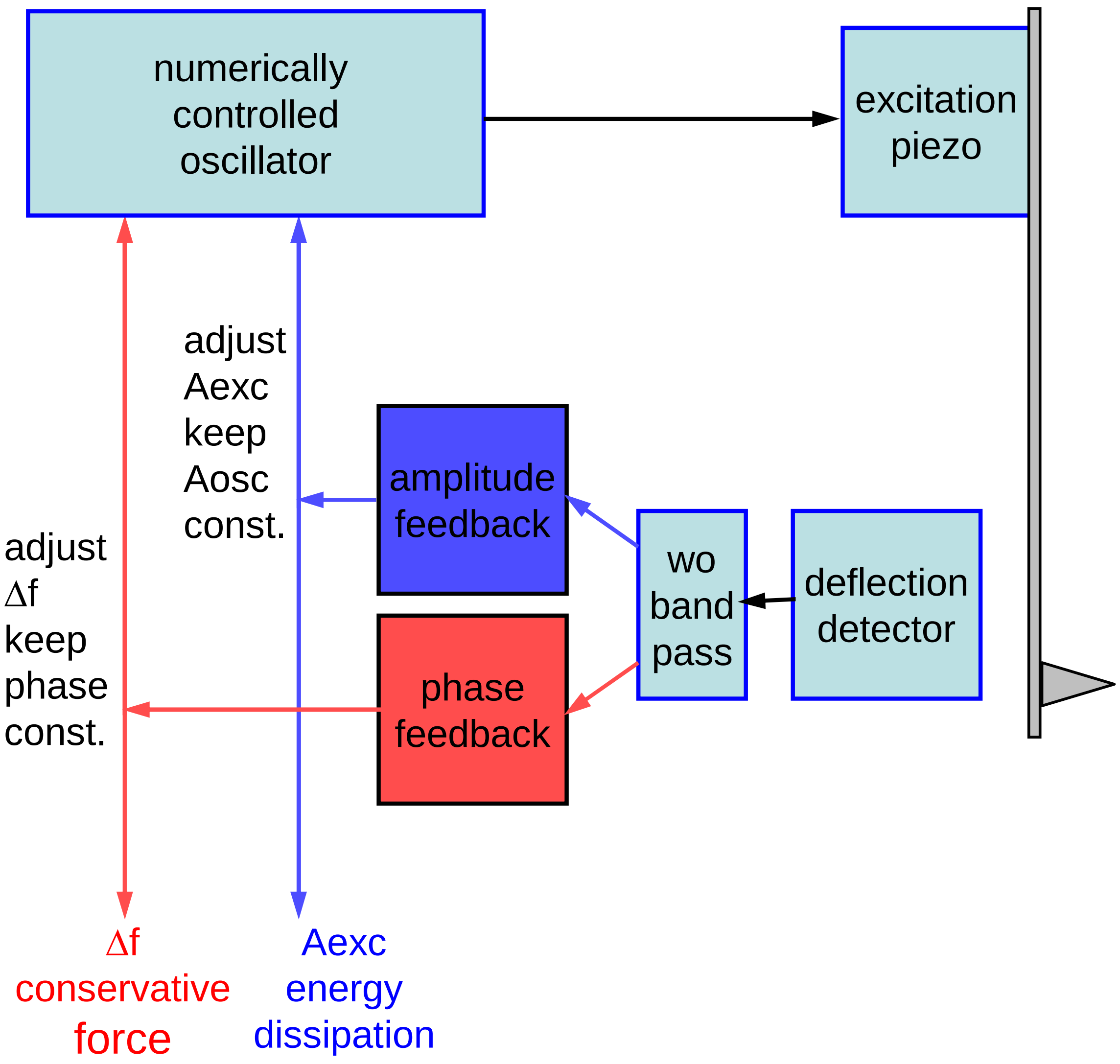
$$\omega = \sqrt{\frac{c_L - \frac{\partial F}{\partial z}}{m}}$$

small amplitudes
→ Taylor expansion

$$\frac{\Delta\omega}{\omega} = -\frac{1}{2c_L} \cdot \frac{\partial F}{\partial z}$$



Phase Locked Loop



Refs: U. Dürig et al., J. Appl. Phys. 82, 3641 (1997) & Ch. Loppacher et al., Appl. Phys. A66, 215 (1998)

Modelling Dynamic SFM

The system of cantilever and tip can be described as a damped harmonic oscillator [1]. Here, we use the equation of motion

$$m\ddot{z} = -k\left[z - A_{exc}\cos\left(\omega t + \varphi\right)\right] - \gamma\dot{z} + F(z)$$

where *m* is the effective mass, *z* the vertical position of the tip, *γ* the damping coefficient of the internal friction of the material, and *F*(*z*) the tipsample force. The excitation is done with an amplitude *Aexc* and a phase shift, which should always be $\varphi = 90°$.

For the constant amplitude mode, we assume that the frictional force $-\gamma\dot{z}$ is compensated by the driving force $F_0 = kA_{exc}\cos\left(\omega t + \varphi\right)$. Then, the equation of motion reduced to $m\ddot{z} = -kz + F(z)$.

For small amplitudes, a linear expansion of the force can be done and a frequency shift proportional to the force gradient is found:

$$\frac{\Delta f}{f} = -\frac{1}{2k}\frac{\partial F}{\partial z}$$

In DFM the oscillation amplitudes are usually larger than the decay length of the force. Thus this equation does not hold! However, the trajectory of the tip is almost perfectly harmonical, because a strong tip-sample interaction occurs only at the lower turning point. Inserting a harmonic solution $z = z_0 + A\sin\omega t$ and multiplying with $\sin\omega t$ yields:

$$-mA\omega^2\sin\omega t = -kA\sin\omega t - kz_0 + F(z_0 + A\sin\omega t)$$

Integration over one oscillation period results in

$$kA\left(1 - \frac{\omega}{\omega_0}\right) = \frac{1}{\pi}\int_0^{\frac{2\pi}{\omega}} \sin\omega t F(z_0 + A\sin\omega t)dt$$

For small frequency shifts one obtains

$$\frac{\Delta f}{f}kA = \frac{1}{\pi}\int_0^{\frac{2\pi}{\omega}} \sin\omega t F(z_0 + A\sin\omega t)dt$$