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IAEA International Atomic Energy Agency

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19 - 24 October 2009

Why is graphite so slippery? Gathering clues from three-dimensional lateral forces measurements

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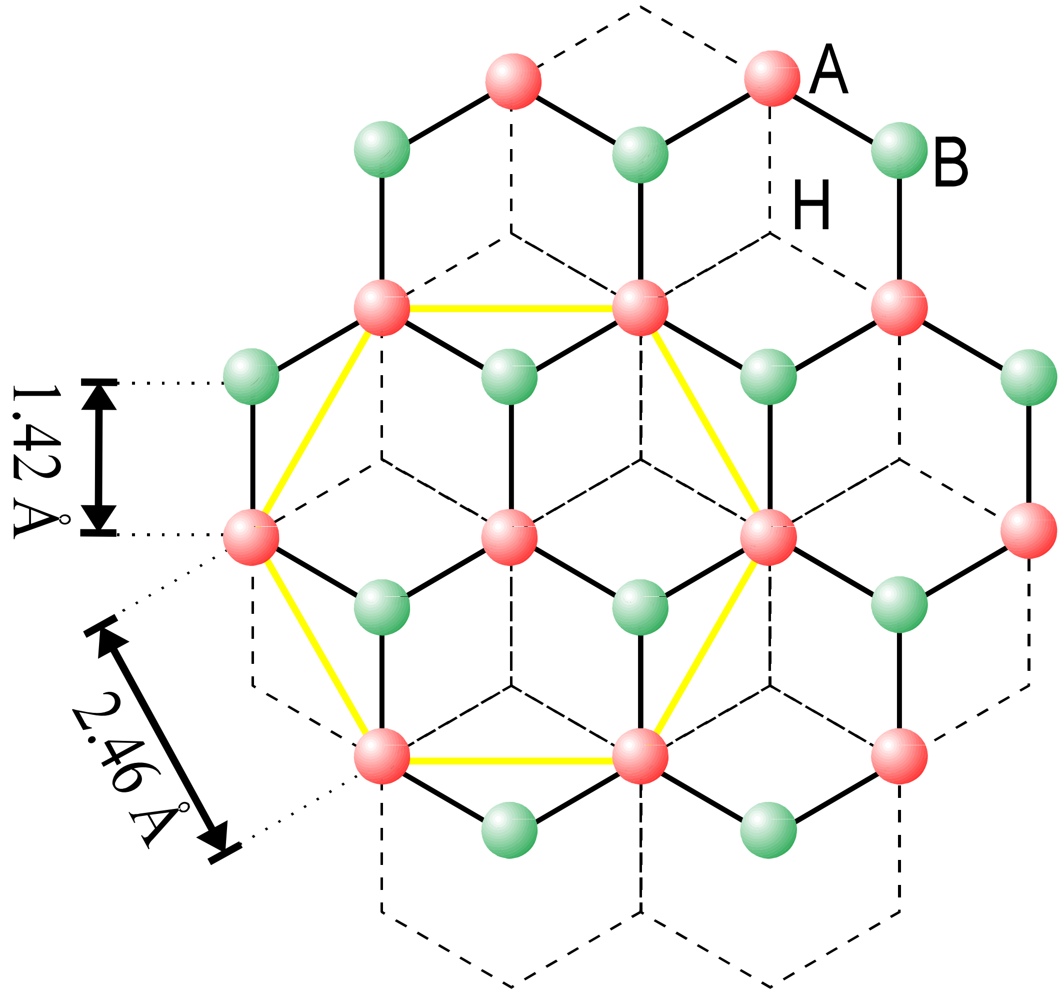
Why is Graphite so Slippery? Gathering Clues from 3D Lateral Force Microscopy

Udo D. Schwarz

Yale University, New Haven, USA

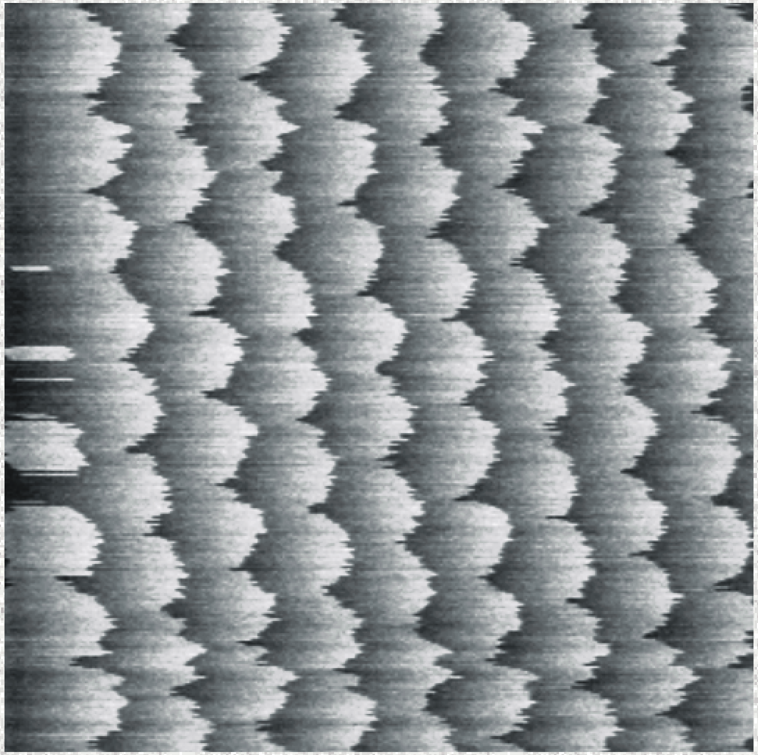
Talk given at the TIN ICTP-FANAS Conference, Trieste, Italy, October 19, 2009

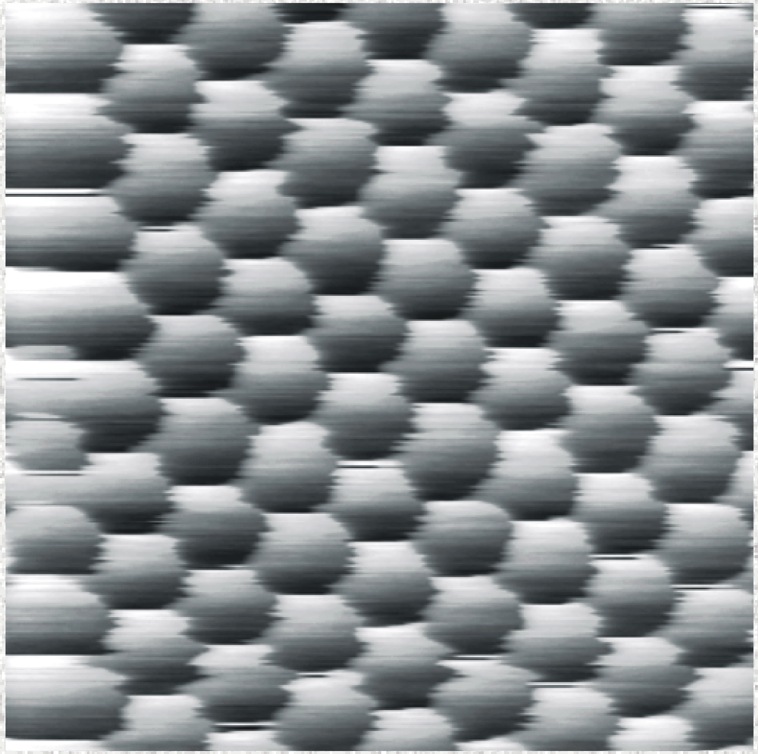
The Structure of Graphite



Atomic Scale Movement of the Atoms at the Interface during FFM Experiments

Example: Silicon tip/graphite sample





F_x Image size: 20 Å × 20 Å F_y

Udo Schwarz • Department of Mechanical Engineering • Yale University

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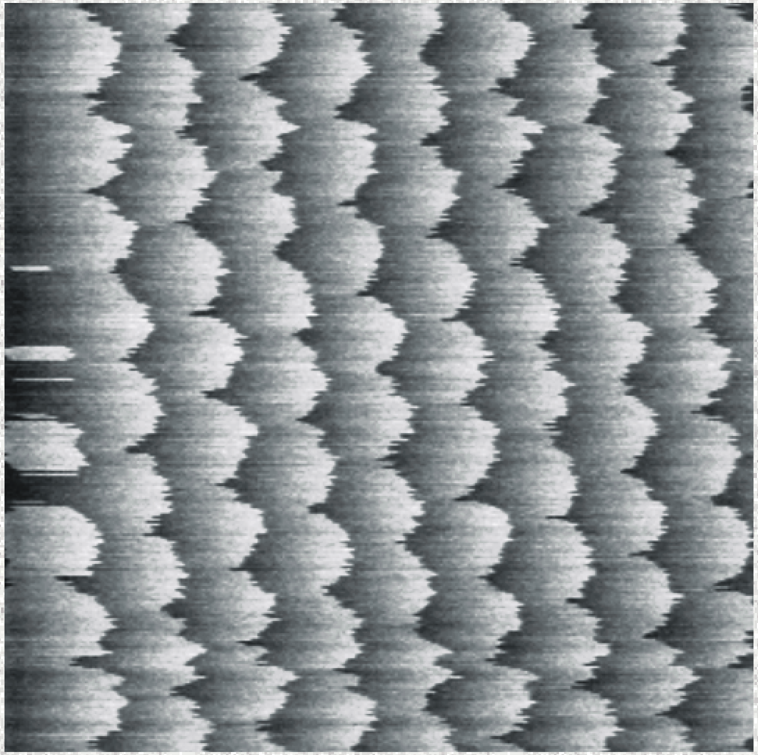

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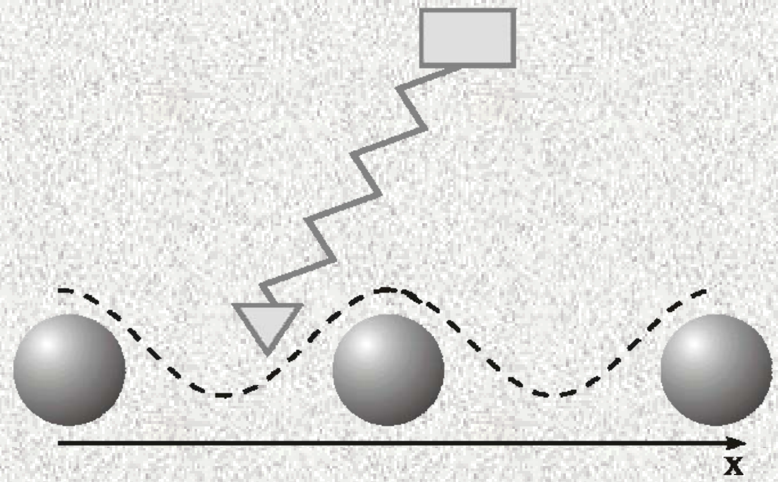

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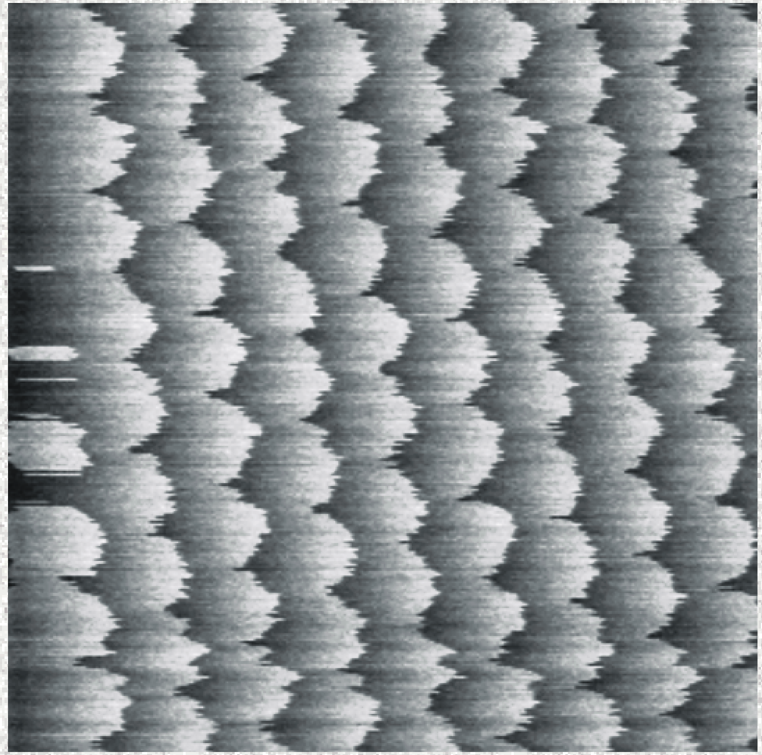
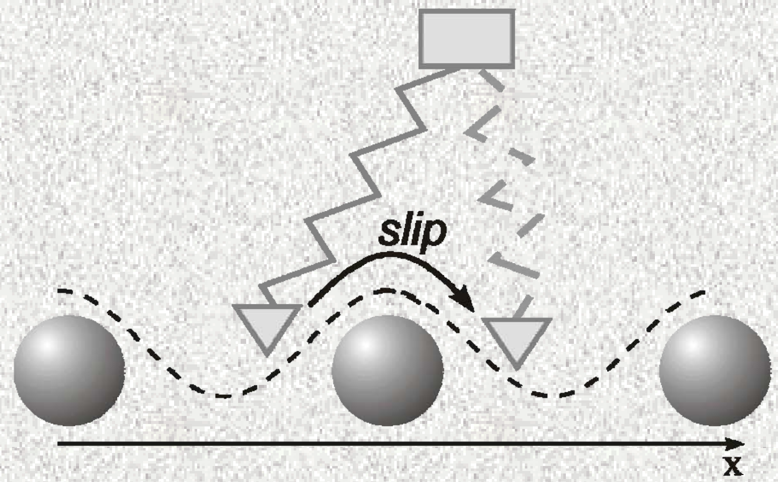


F_x Image size: 20 Å × 20 Å



Atomic Scale Movement of the Atoms at the Interface during FFM Experiments

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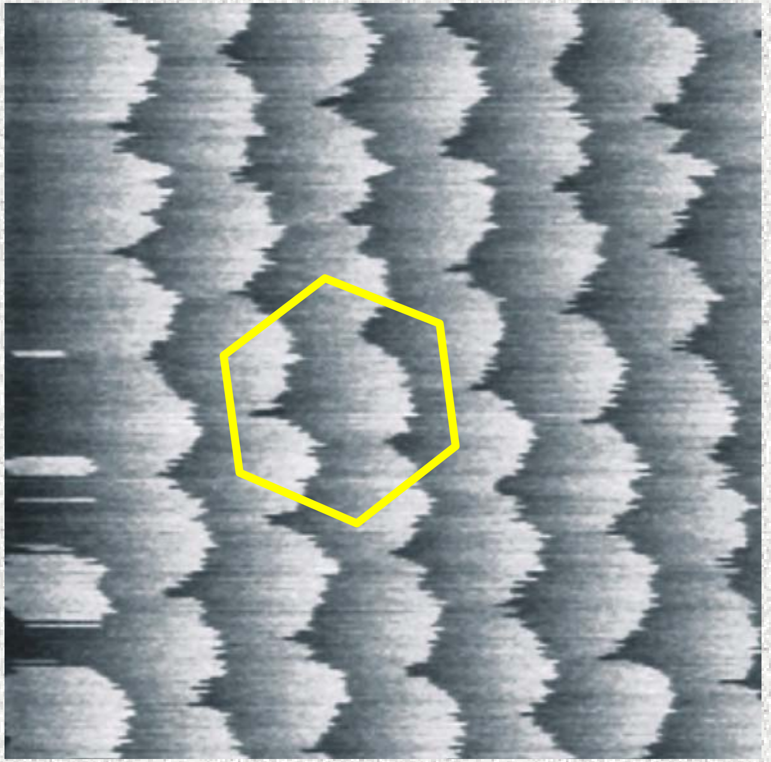
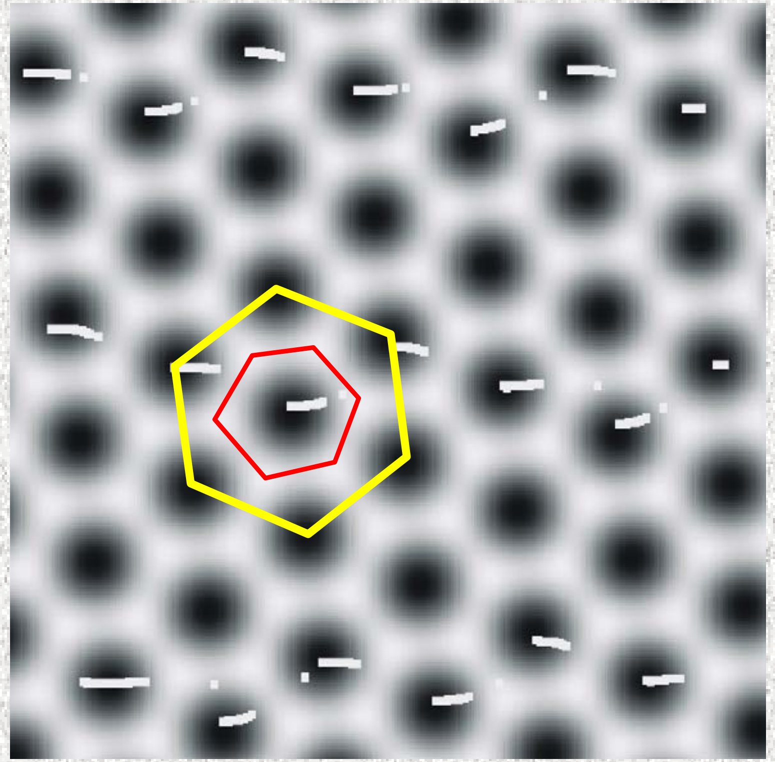




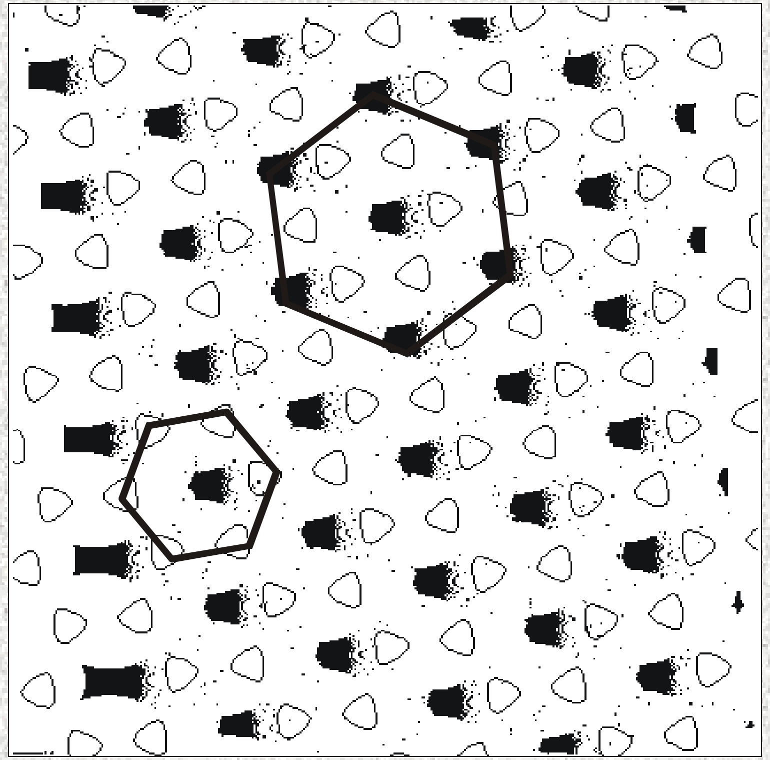
F_x - Experiment

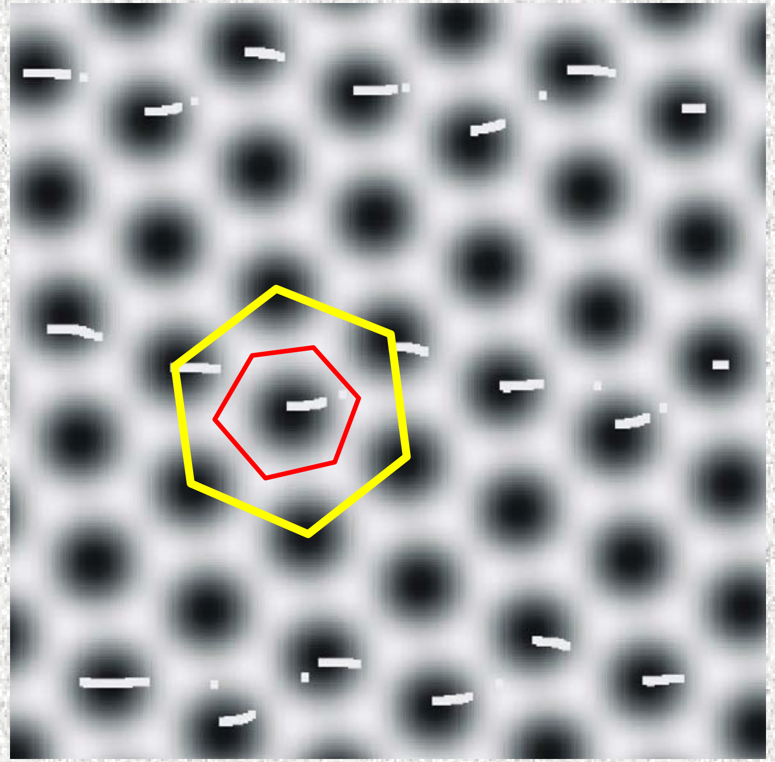
Image size: 15 Å × 15 Å

Path of the tip

Atomic Scale Movement of the Atoms at the Interface during FFM Experiments

Example: Silicon tip/graphite sample





Probability density   Image size: 15 Å × 15 Å   Path of the tip

=> H. Hölscher, U. D. Schwarz, O. Zwörner, and R. Wiesendanger, Phys. Rev. B **57**, 2477 (1998)

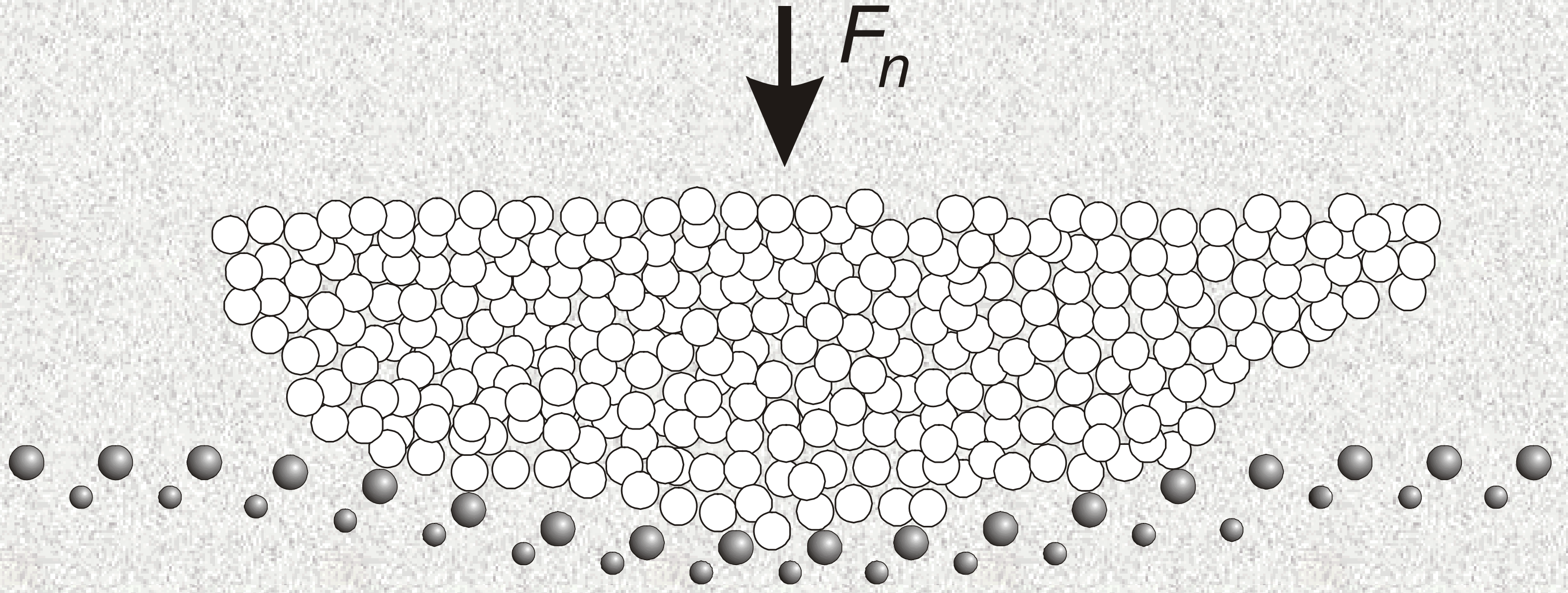
Measurement of Lateral Forces with Picometer and Piconewton Resolution

How do we *not* jump over parts of the tip-sample interaction potential?

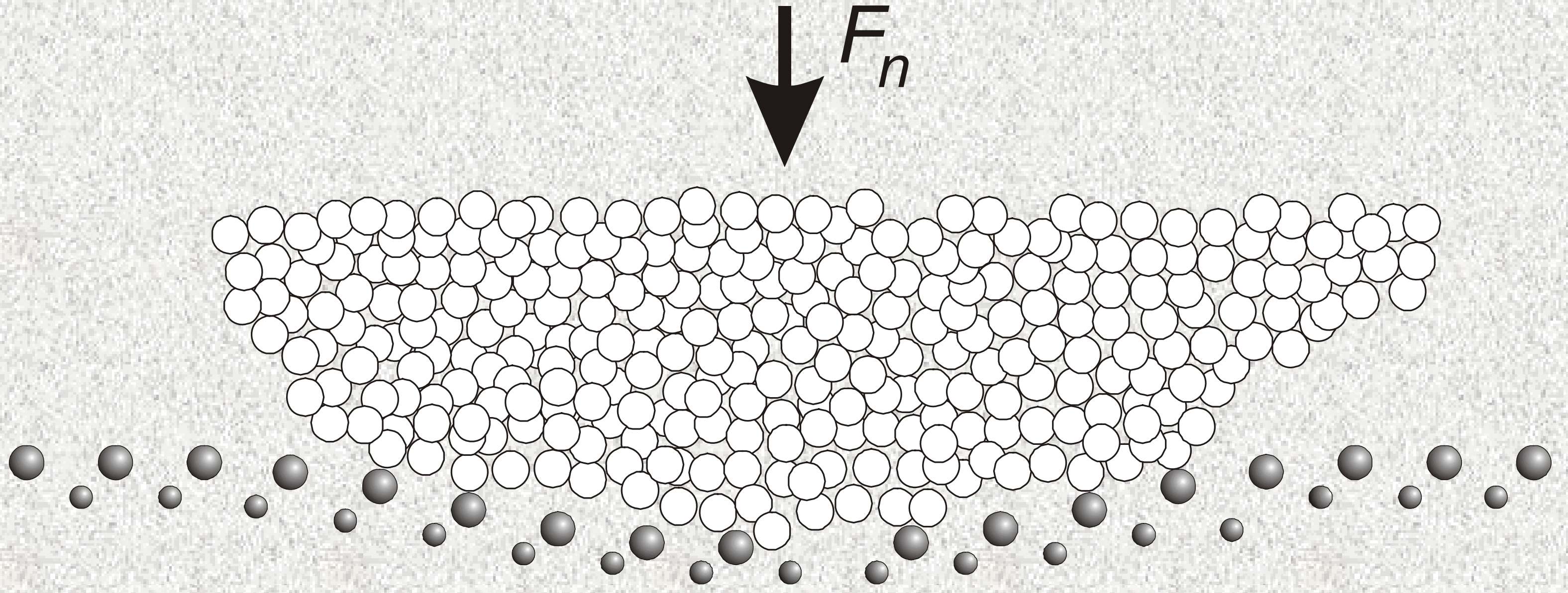
OUR APPROACH:

- ***Employ noncontact atomic force microscopy with atomic resolution***
- **Measure full 3D force field**

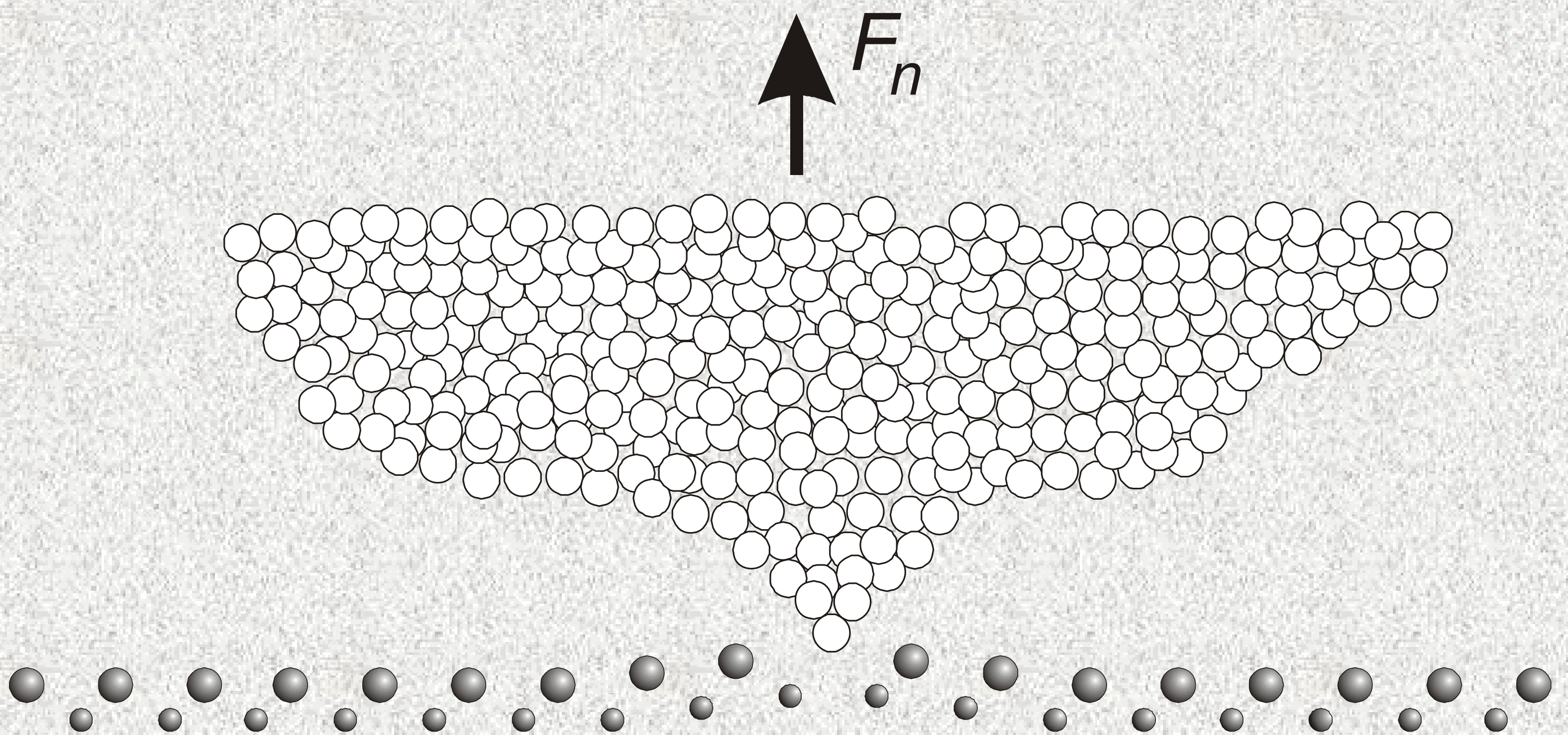
Imaging of Individual Atoms with „Traditional“ AFM (Contact, Tapping)?



Imaging of Individual Atoms with „Traditional“ AFM (Contact, Tapping)?



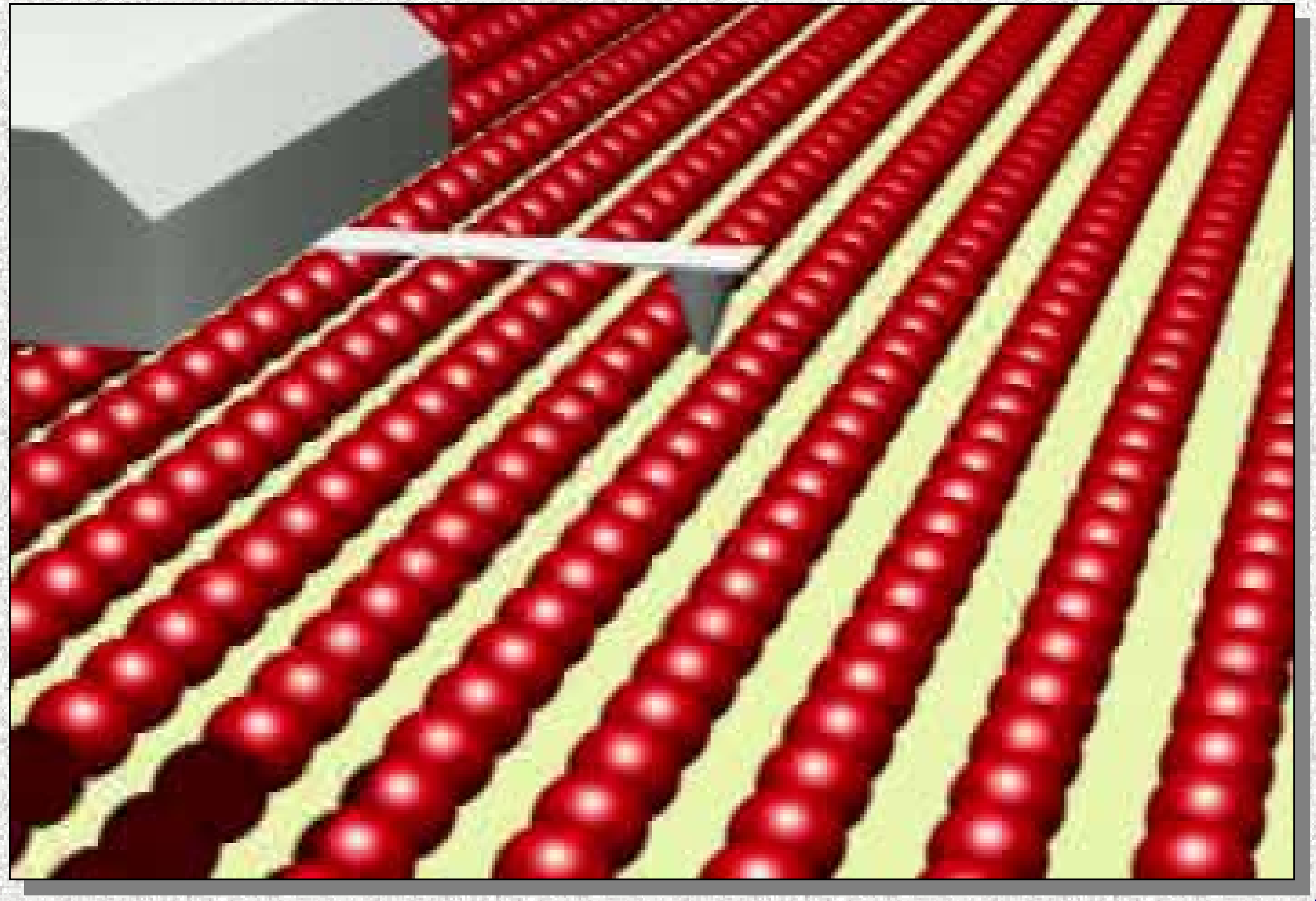
Imaging of Individual Atoms with Atomically Sharp Tip in Noncontact Mode (Vacuum)



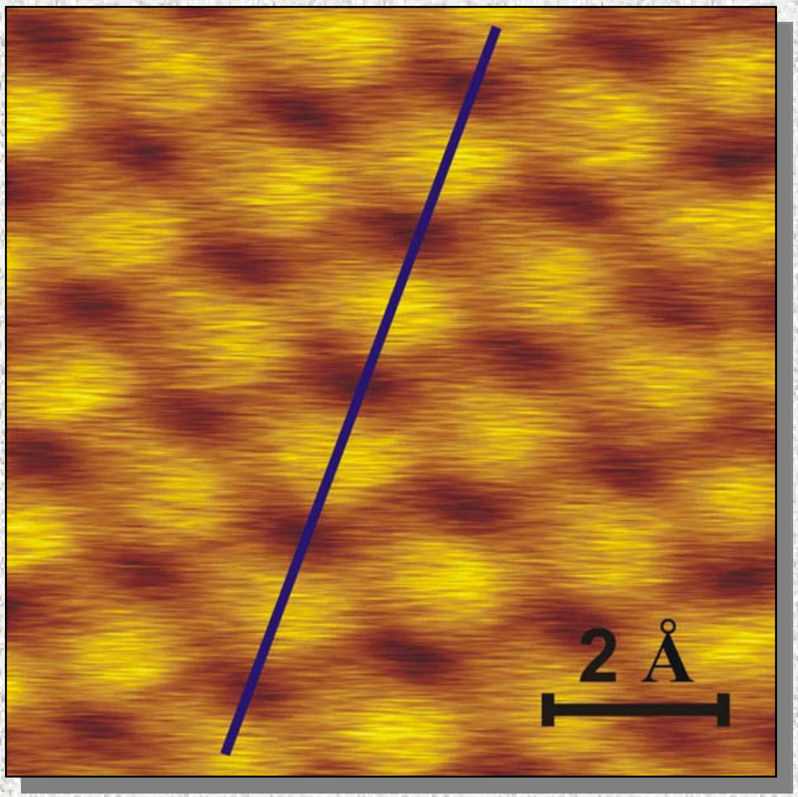
Attractive interaction, noncontact operation

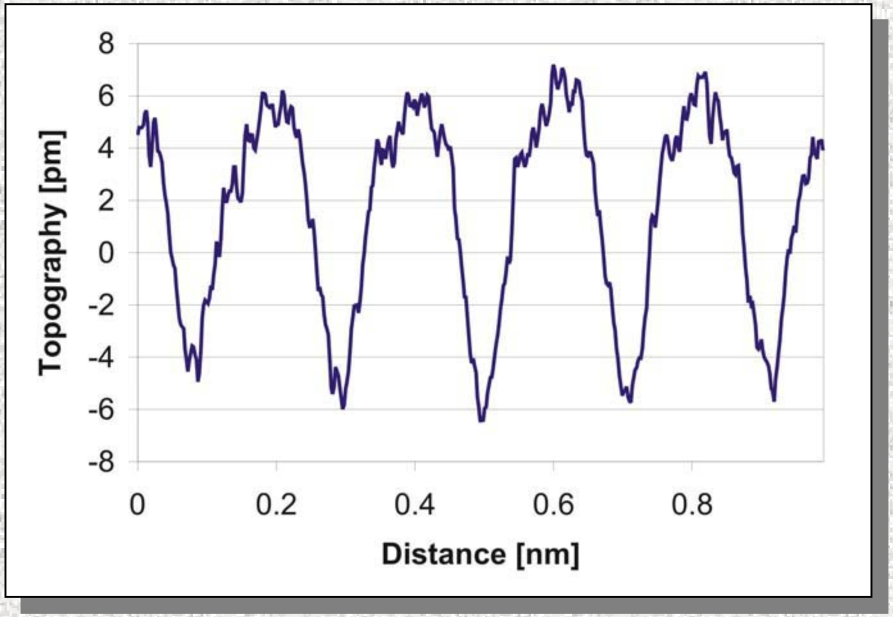
=> *Atomic resolution possible!*

Principle of Noncontact Atomic Force Microscopy (NC-AFM) in Vacuum



Atomic Resolution Results: HOPG(0001) Imaged with NC-AFM

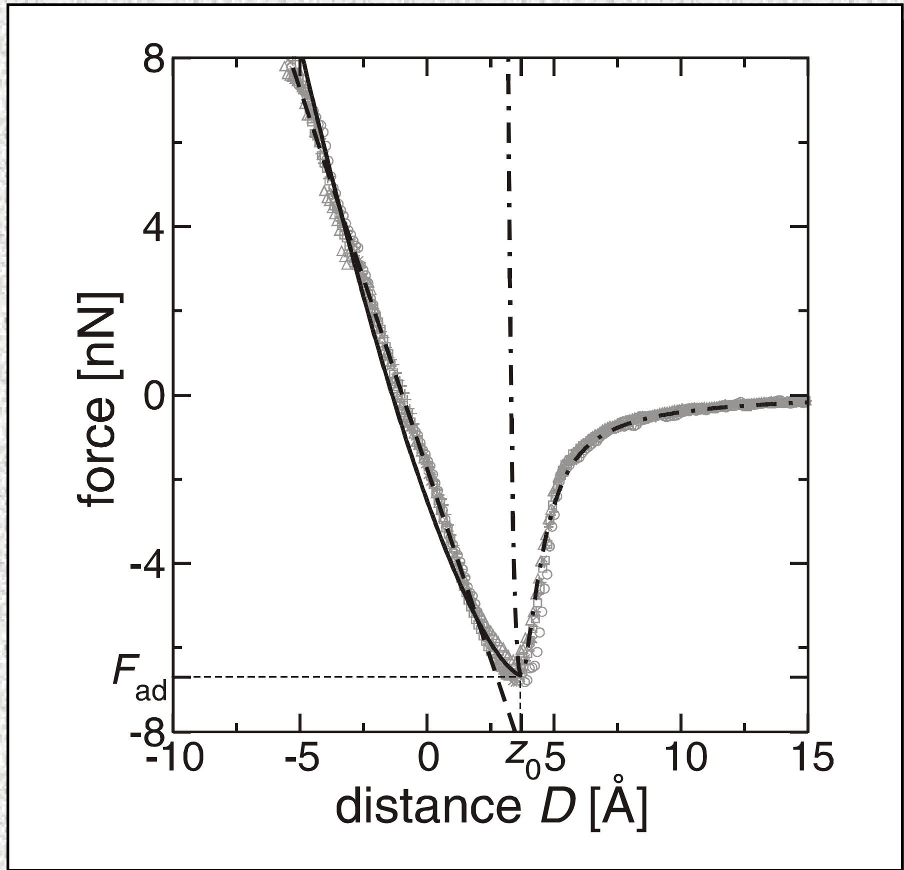




1.0×1.0 nm^2, Δf = -2.9 Hz,
f_0 = 29529 Hz, Amplitude = 0.25 nm

How do I get force information in NC-AFM?

Atomic resolution images reflect **PLANES OF CONSTANT Δf !**



Silicon tip on graphite surface

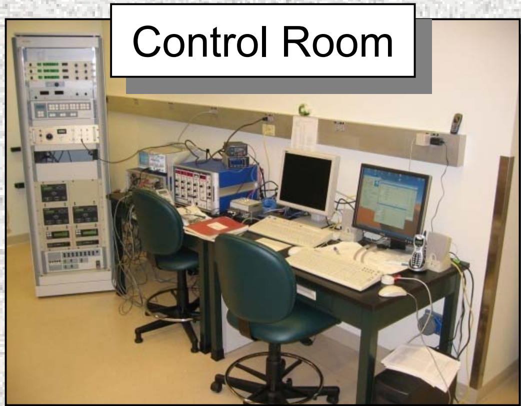
=> H. Hölscher, A. Schwarz, W. Allers, U. D. Schwarz, and R. Wiesendanger, Phys. Rev. B **61**, 12678 (2000)

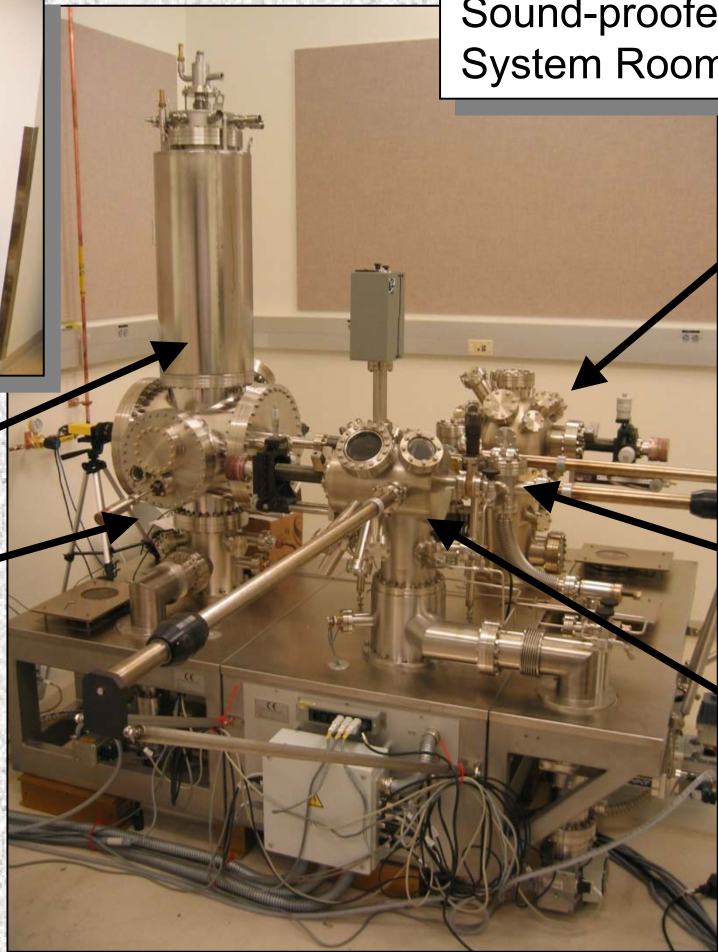
How do I get force information in NC-AFM?

Publications with either 2D or 3D force/energy maps:

- *H. Hölscher et al., Appl. Phys. Lett.* ***81****, 4428 (2002)*
- *S. Langkat et al., Surf. Sci.* ***527****, 12 (2003)*
- *A. Schwarz et al., AIP Conf. Proc.* ***696****, 68 (2003) (32 x 32)*
- M. Heyde et al., *APL* **89**, 263107 (2006)
- A. Schirmeisen et al., *PRL* **97**, 136101 (2006)
- M. Abe et al., *APL* **90**, 203103 (2007)
- B. J. Albers et al., *Rev. Sci. Instrum.* **79**, 033708 (2008)
- K. Ruschmeier et al., *Phys. Rev. Lett.* **101**, 156102 (2008)
- Y. Sugimoto et al., *Phys. Rev. B* **77**, 195424 (2008)
- M. Ternes et al., Science **319**, 1066 (2008)
- M. Ashino et al., Nature Nanotechnology **3**, 337 (2008) (41 x 41)
- M. Ashino et al., *Nanotechnology* **20**, 264001 (2009) (41 x 41)
- L. Gross et al., *Science* **325**, 1110 (2009) (80 x 40)

Low Temperature Ultrahigh Vacuum NC-AFM/STM for 3D-AFM Imaging





analysis chamber (LEED, Auger)

dewar

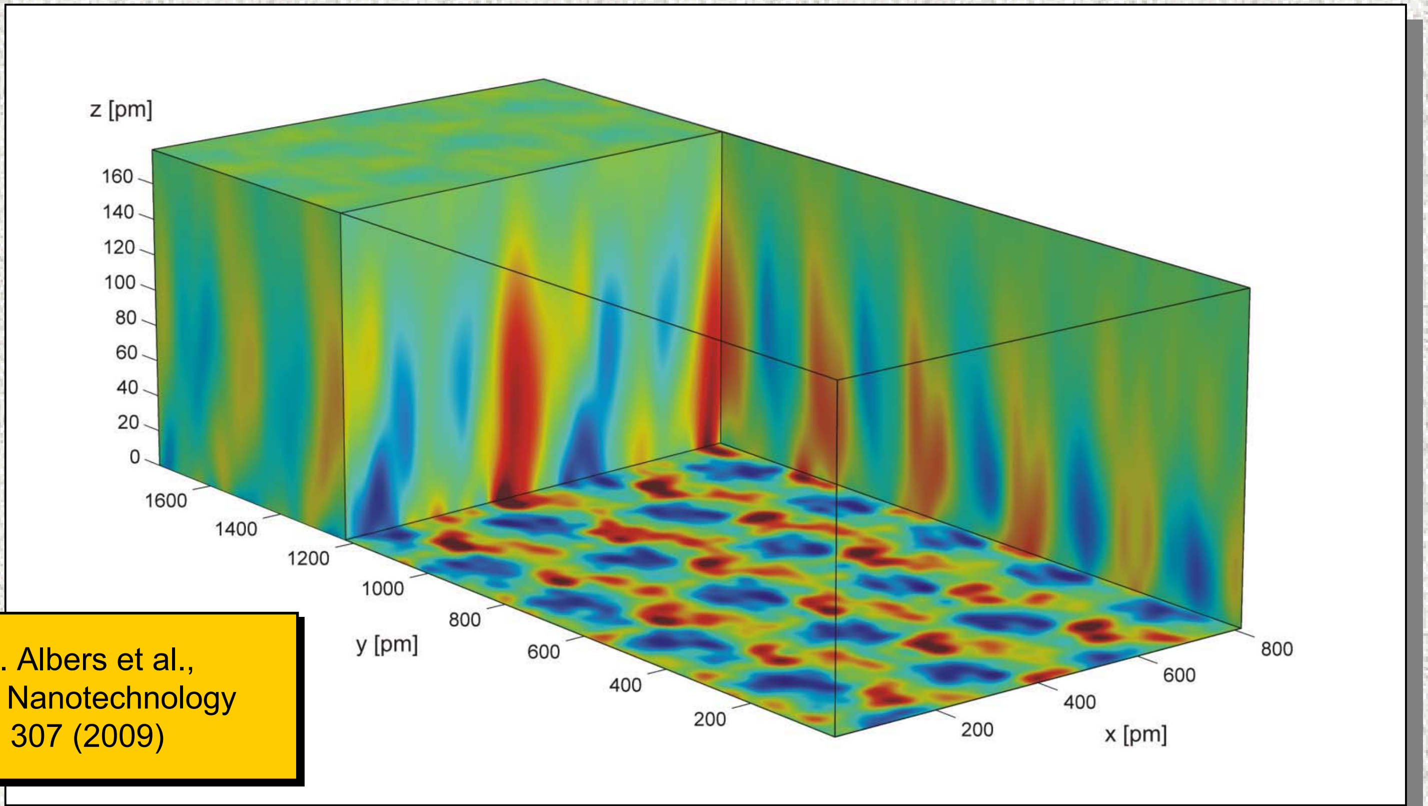
load lock

microscope chamber

preparation chamber

📖 B. J. Albers et al., Rev. Sci. Instrum. **79**, 033708 (2008)

3D-AFM:
Measuring Full (*x*, *y*, *z*, *F*) Arrays on Graphite

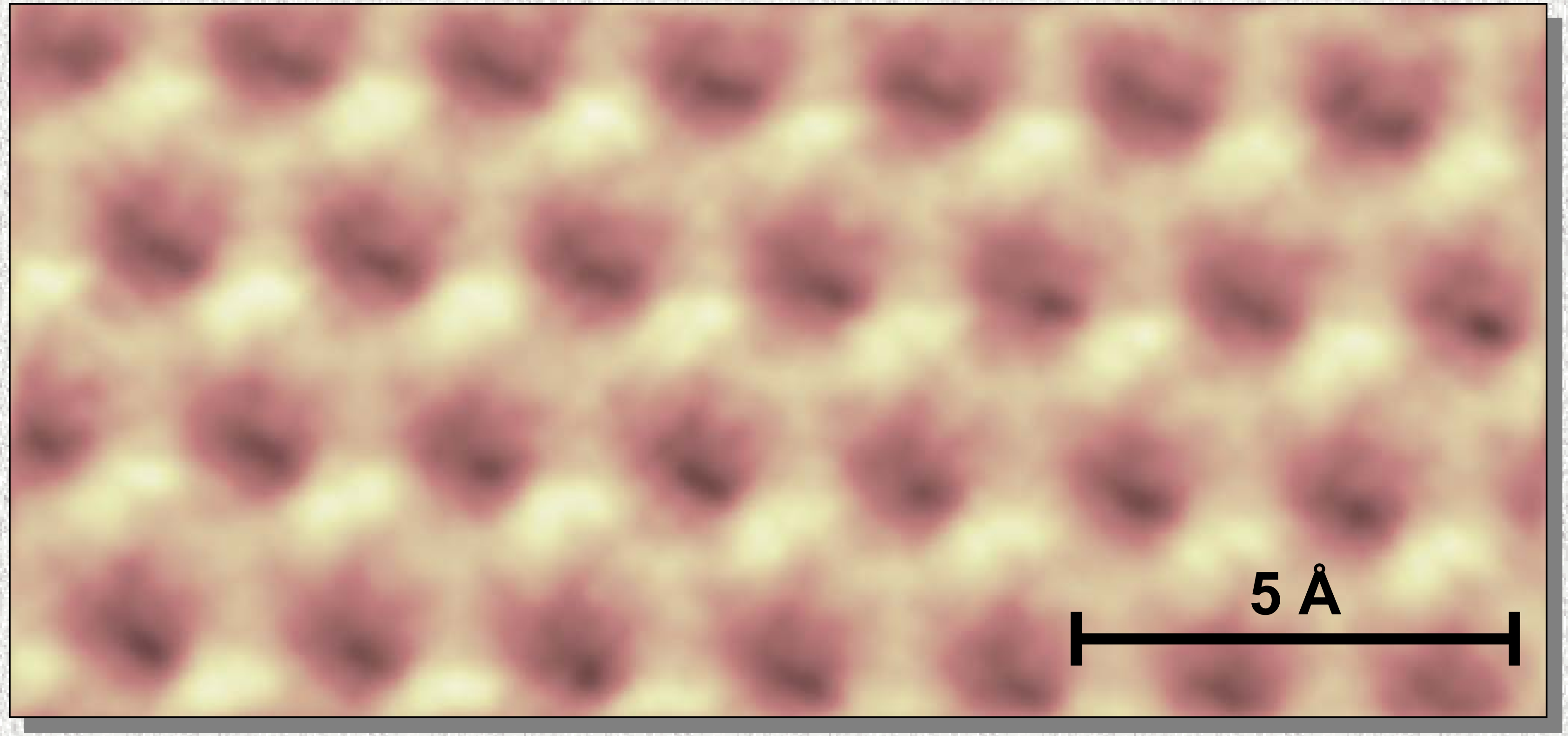


B. J. Albers et al.,
Nature Nanotechnology
4, 307 (2009)

Grid of 119 × 256 force curves = 30464 force curves, T = 6 K
acquisition time 40 hours, average force for each height subtracted

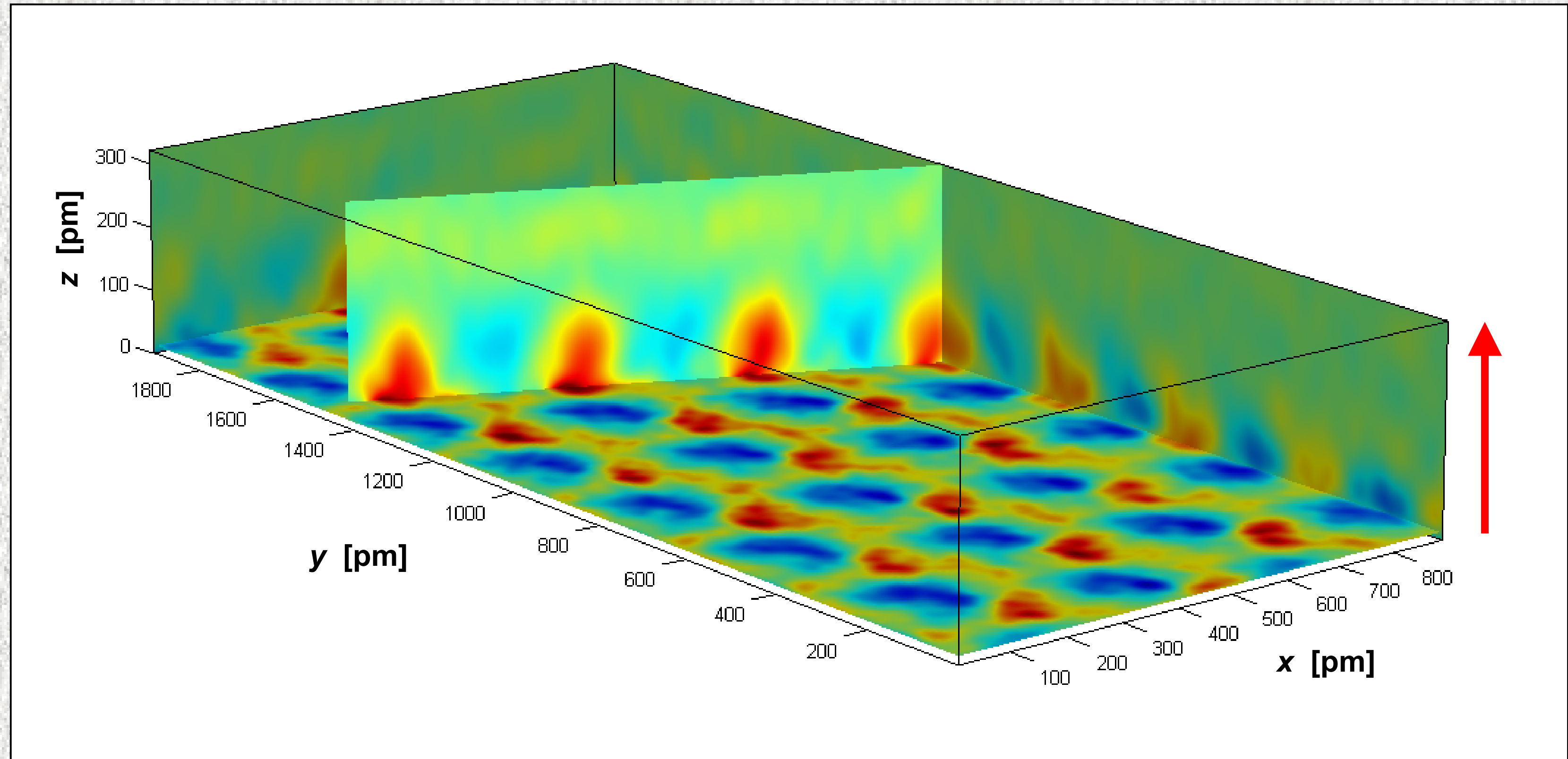
“True“ Force Imaging with Atomic Resolution on Graphite

Example: Force image recorded at constant height



F_{av} = -2.306 nN, force corrugation ≈70 pN, T = 6 K

3D-AFM:
Plotting the Force for Every *z* Distance



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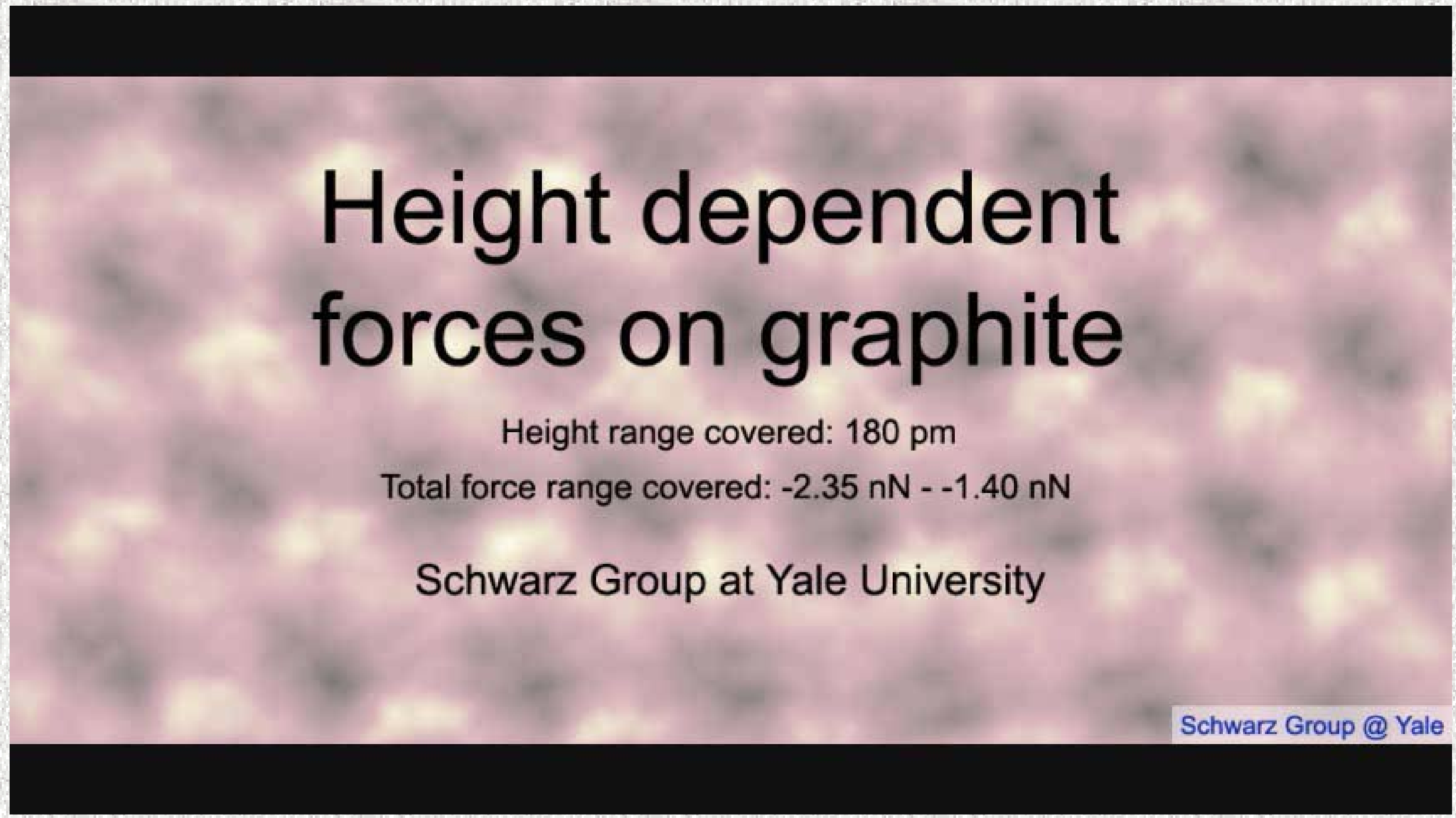
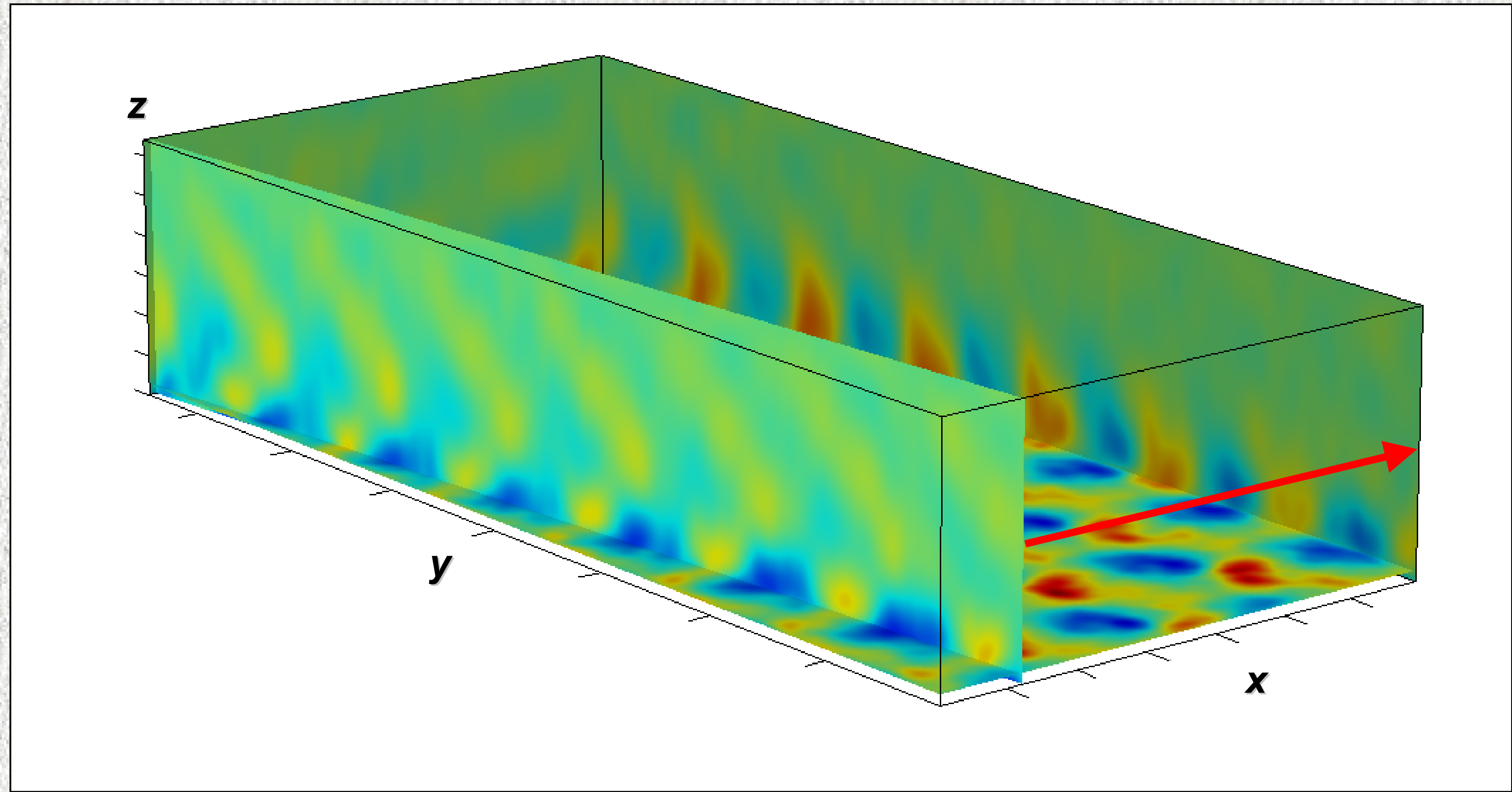


3D-AFM:
Plotting the Force for *yz* Planes



3D-AFM:
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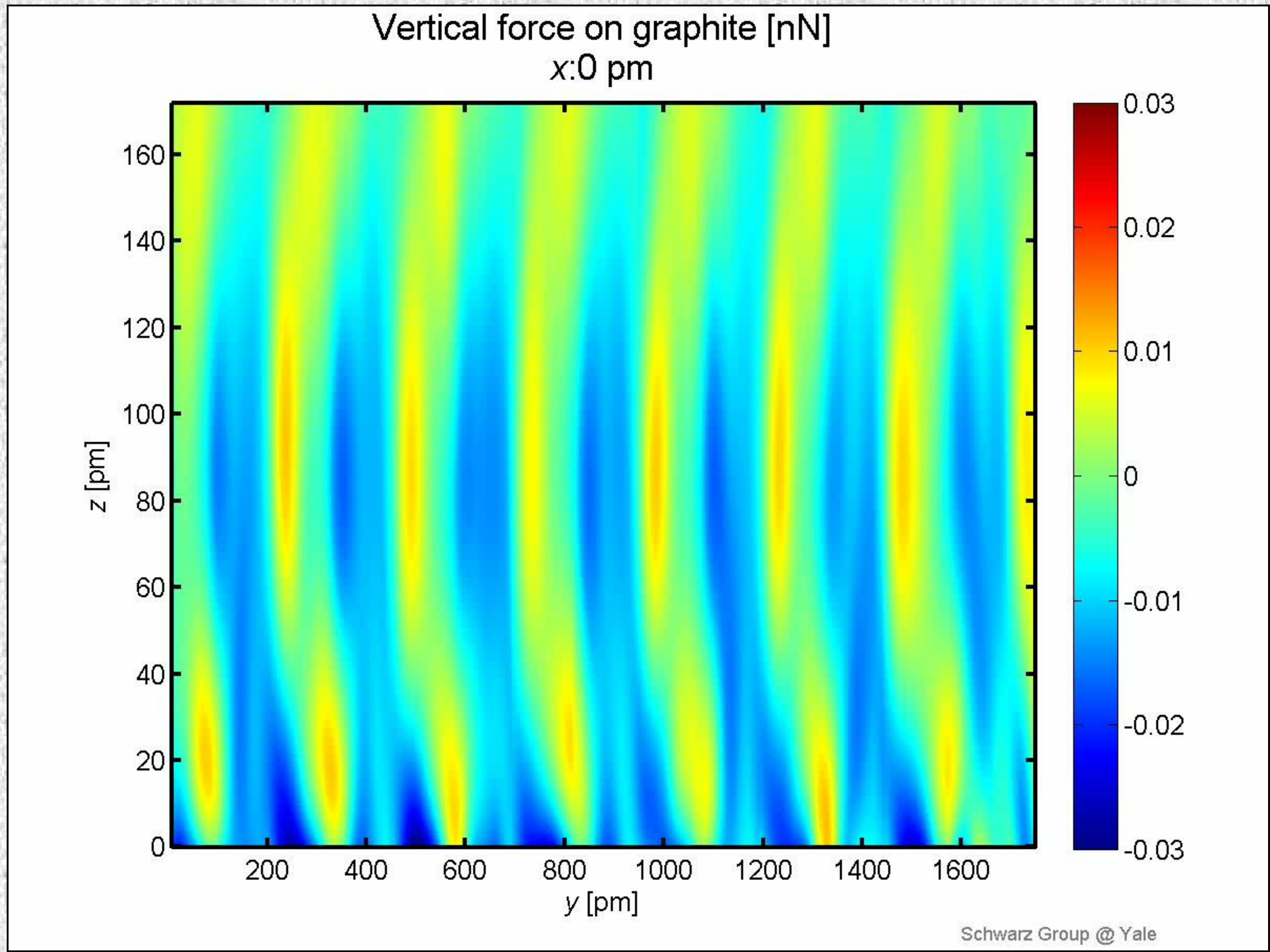
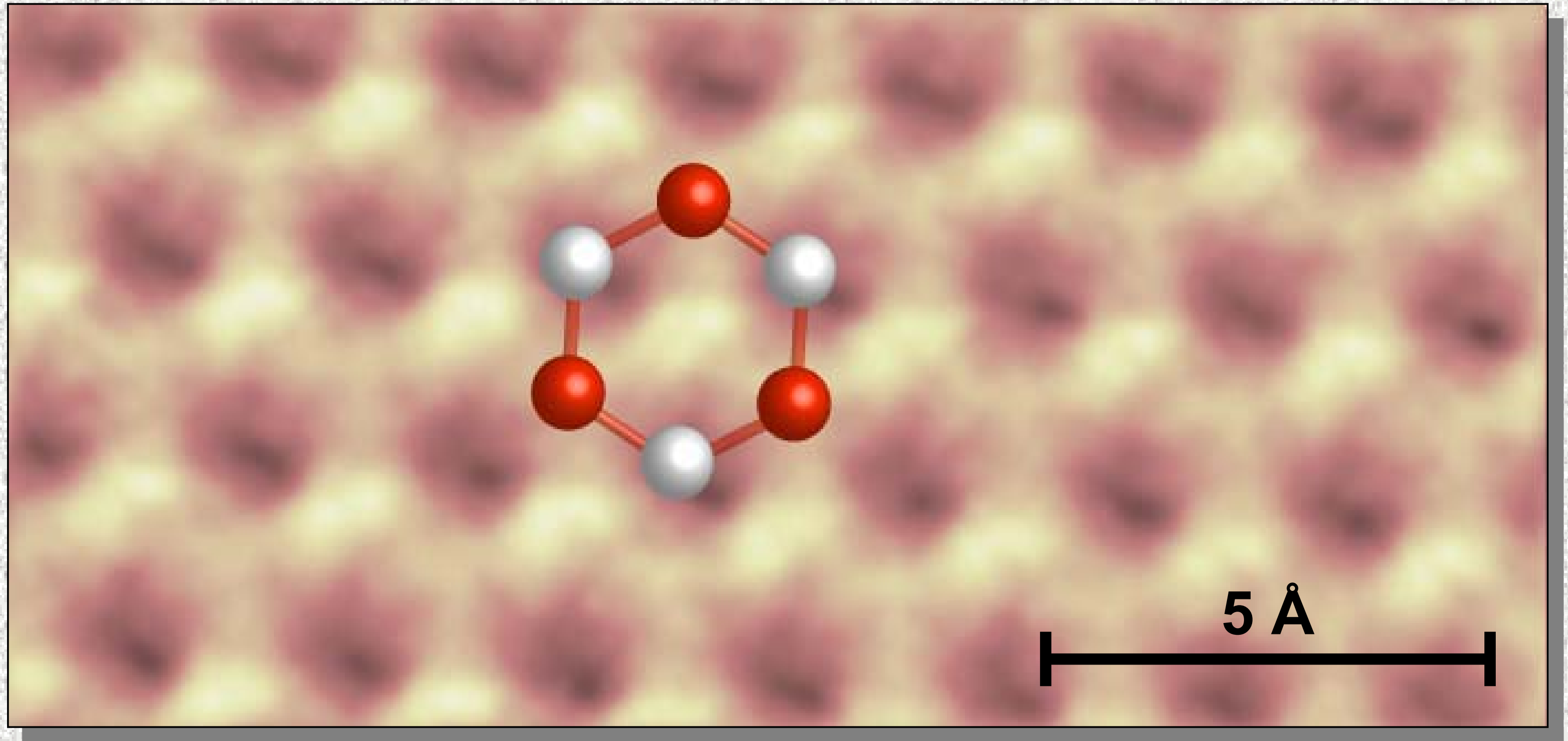


Characterization of Site-Specific Interactions

Interactions at A-, B-, and H-sites



F_{av} = -2.306 nN, force corrugation ≈70 pN, z = 12 pm, T = 6 K

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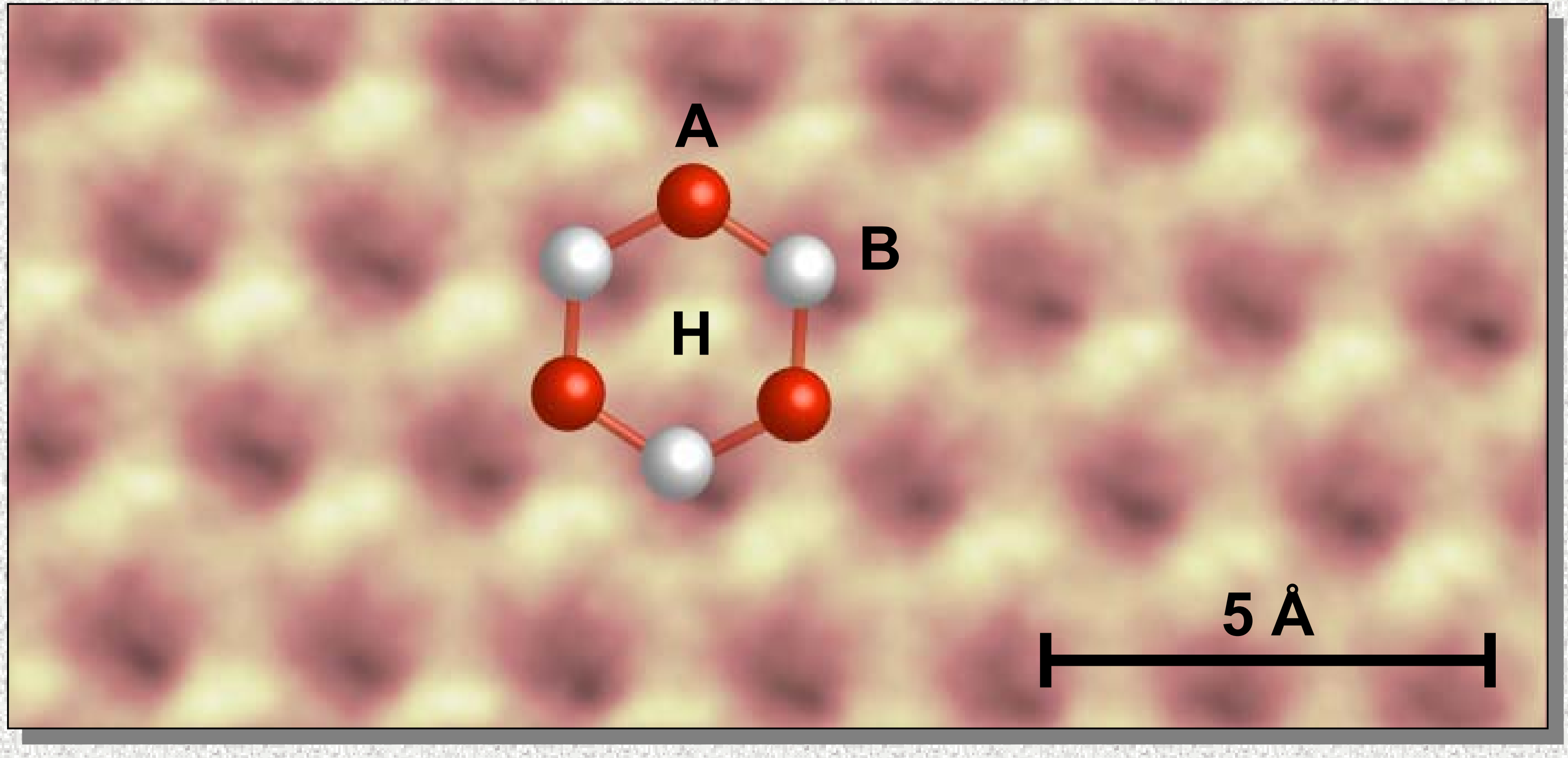

F_{av} = -2.306 nN, force corrugation ≈70 pN, z = 12 pm, T = 6 K

H. Hölscher *et al., Phys. Rev. B* **62**, 6967 (2000);

M. Ashino *et al., Nanotechnology* **16**, S134 (2005).

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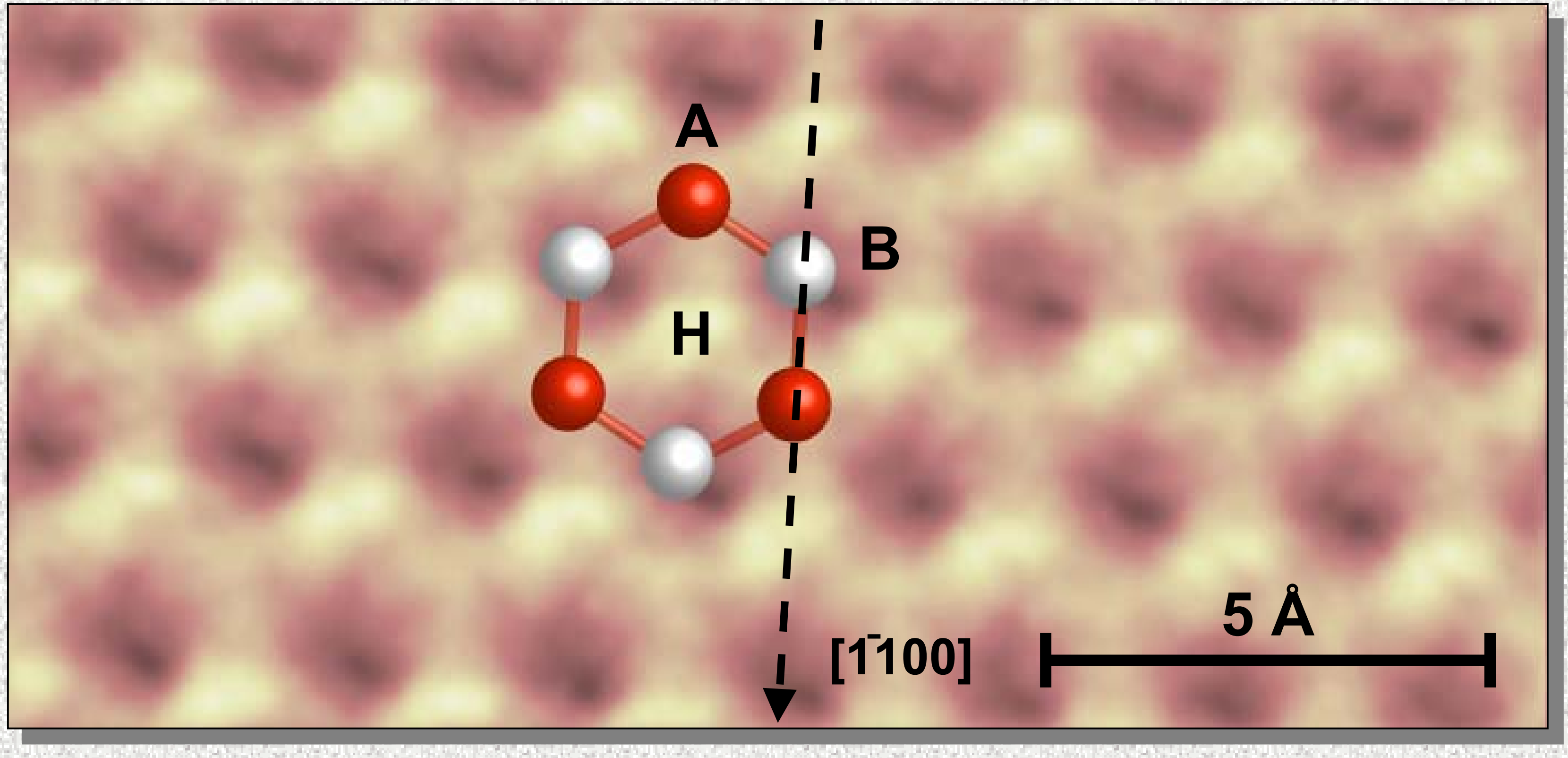

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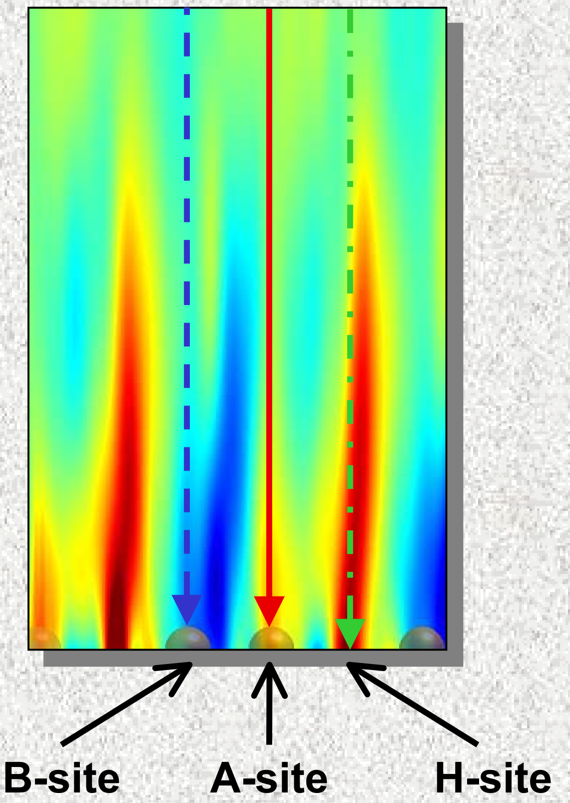

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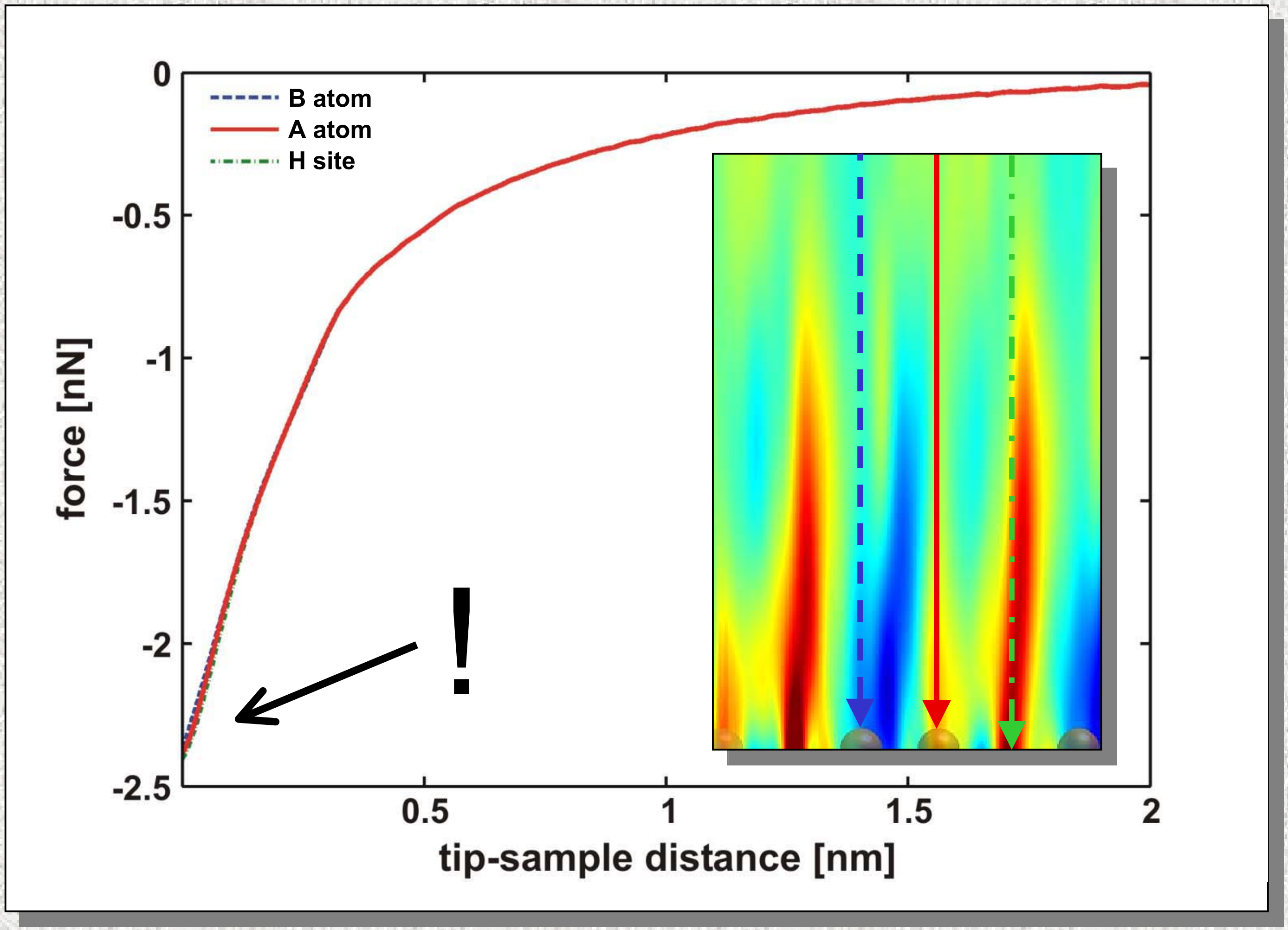

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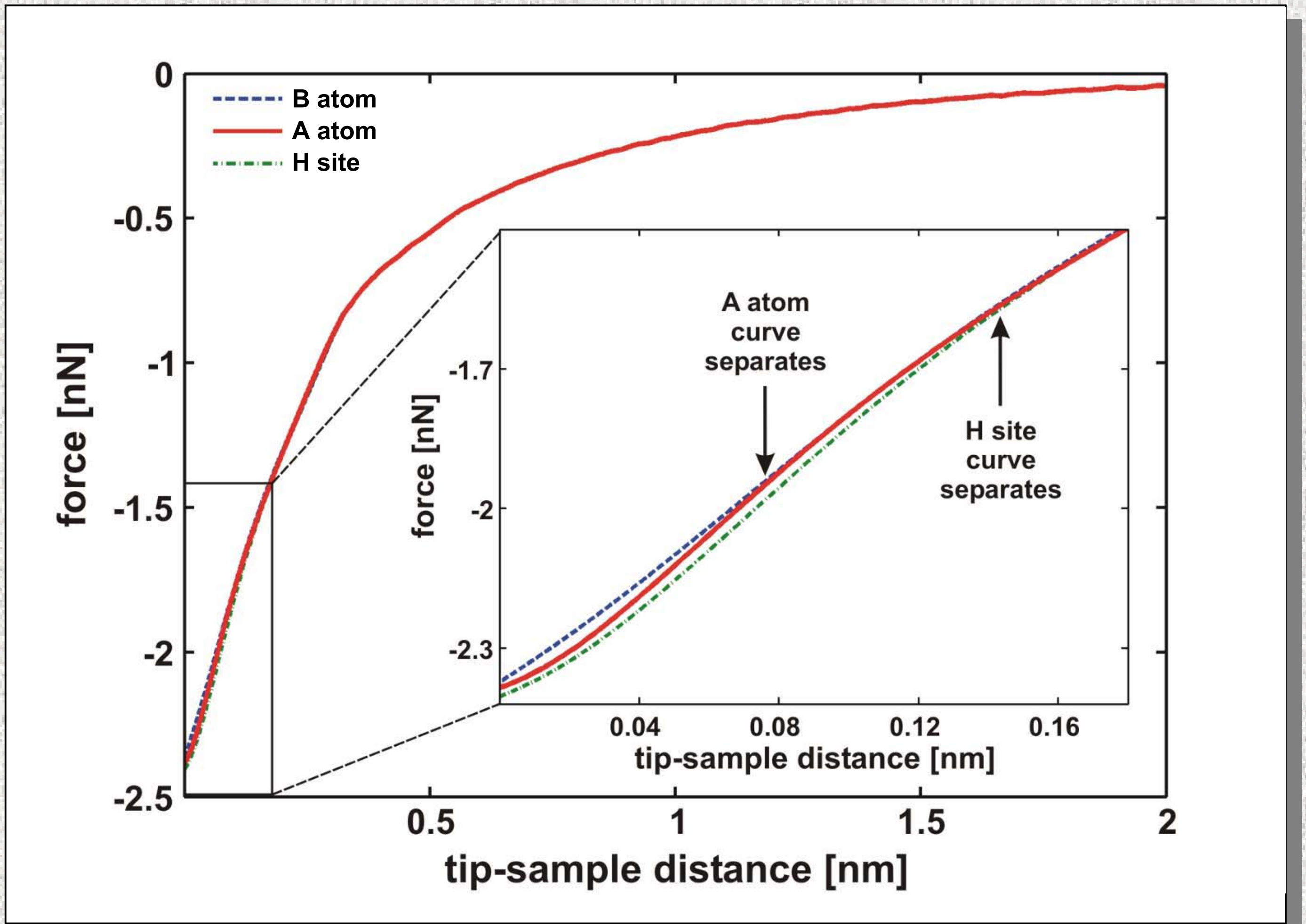
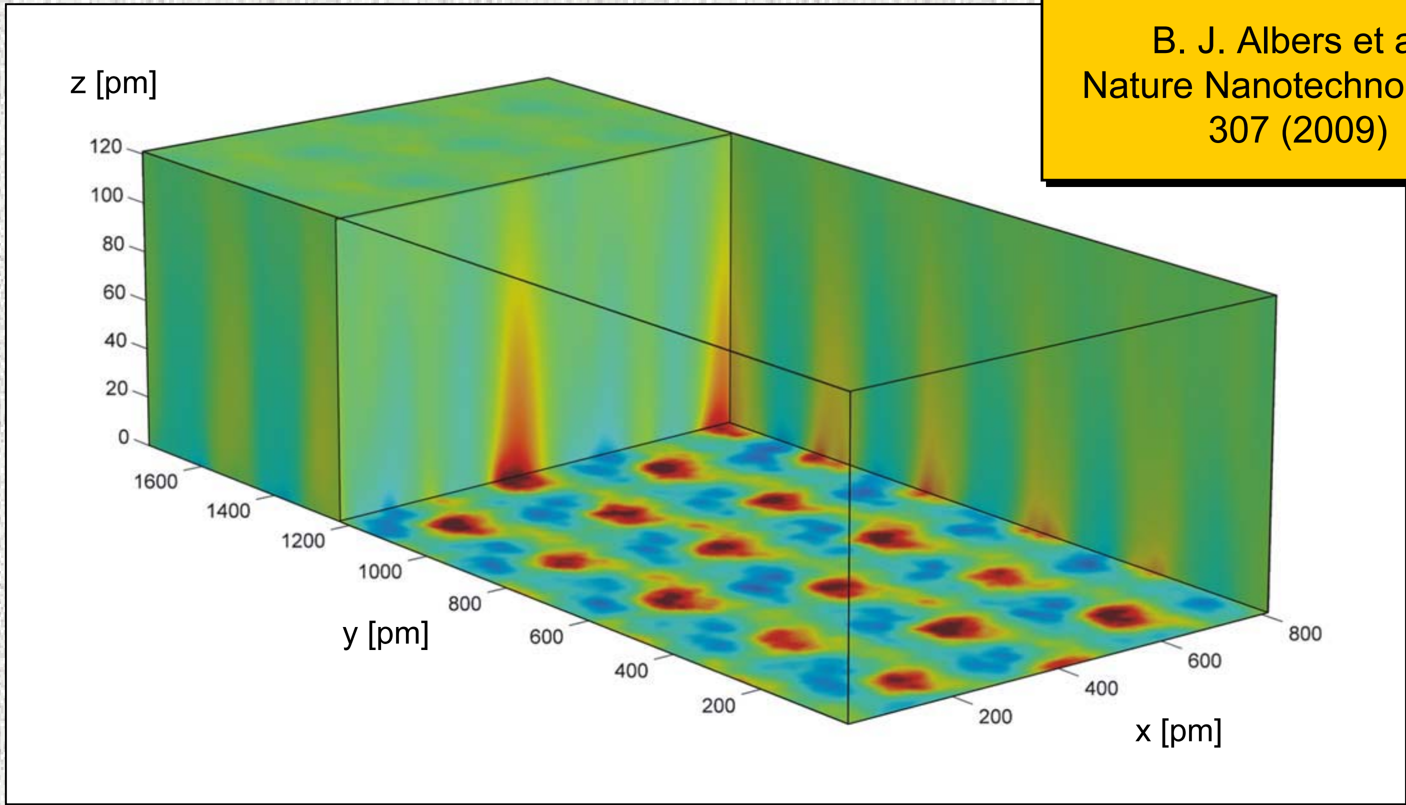


3D-AFM: Measuring Full (*x*, *y*, *z*, *E*) Arrays on Graphite

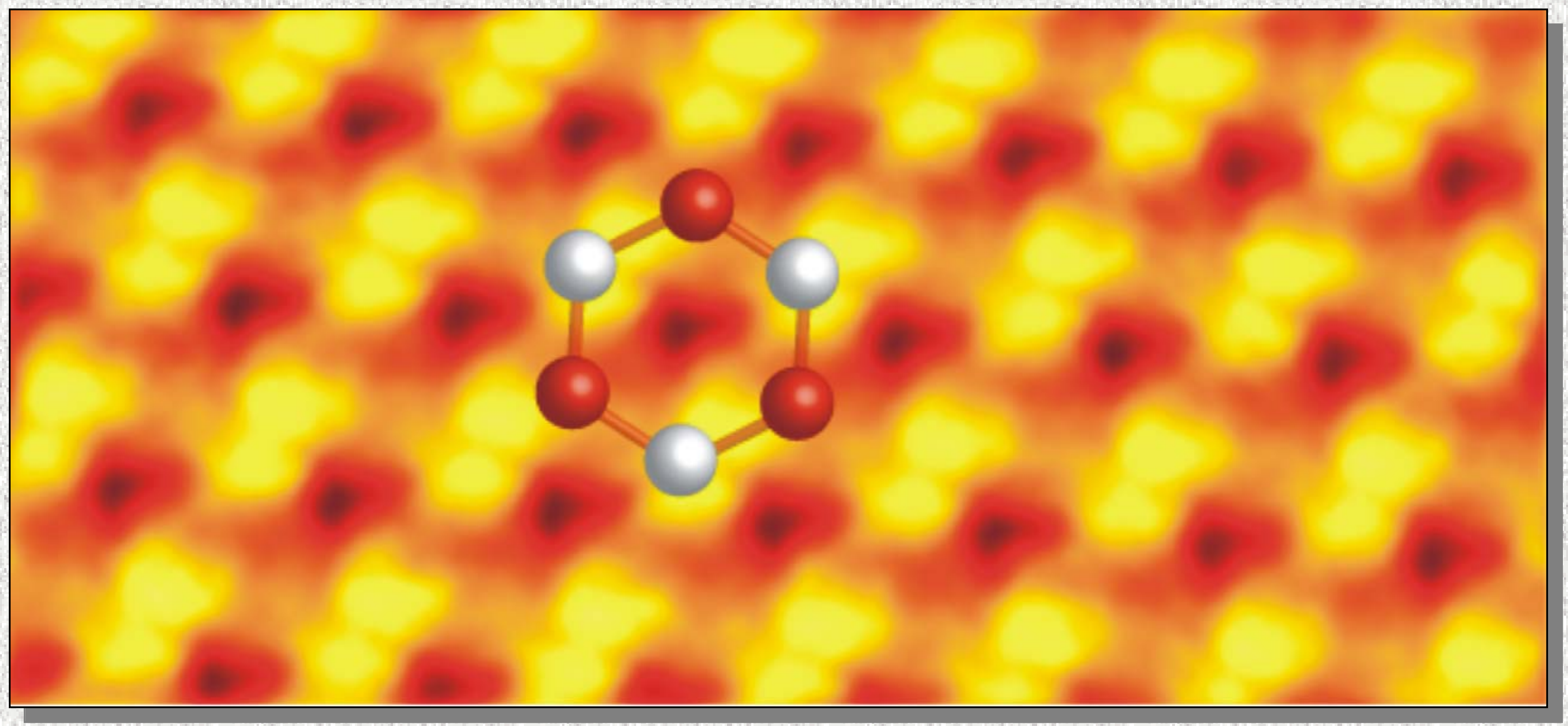


B. J. Albers et al., Nature Nanotechnology **4**, 307 (2009)

Grid of 119 × 256 energy curves = 30464 energy curves, *T* = 6 K
acquisition time 40 hours, average energy for each height subtracted

Interaction Energy Imaging with Atomic Resolution on Graphite

Example: Energy image recorded at constant height

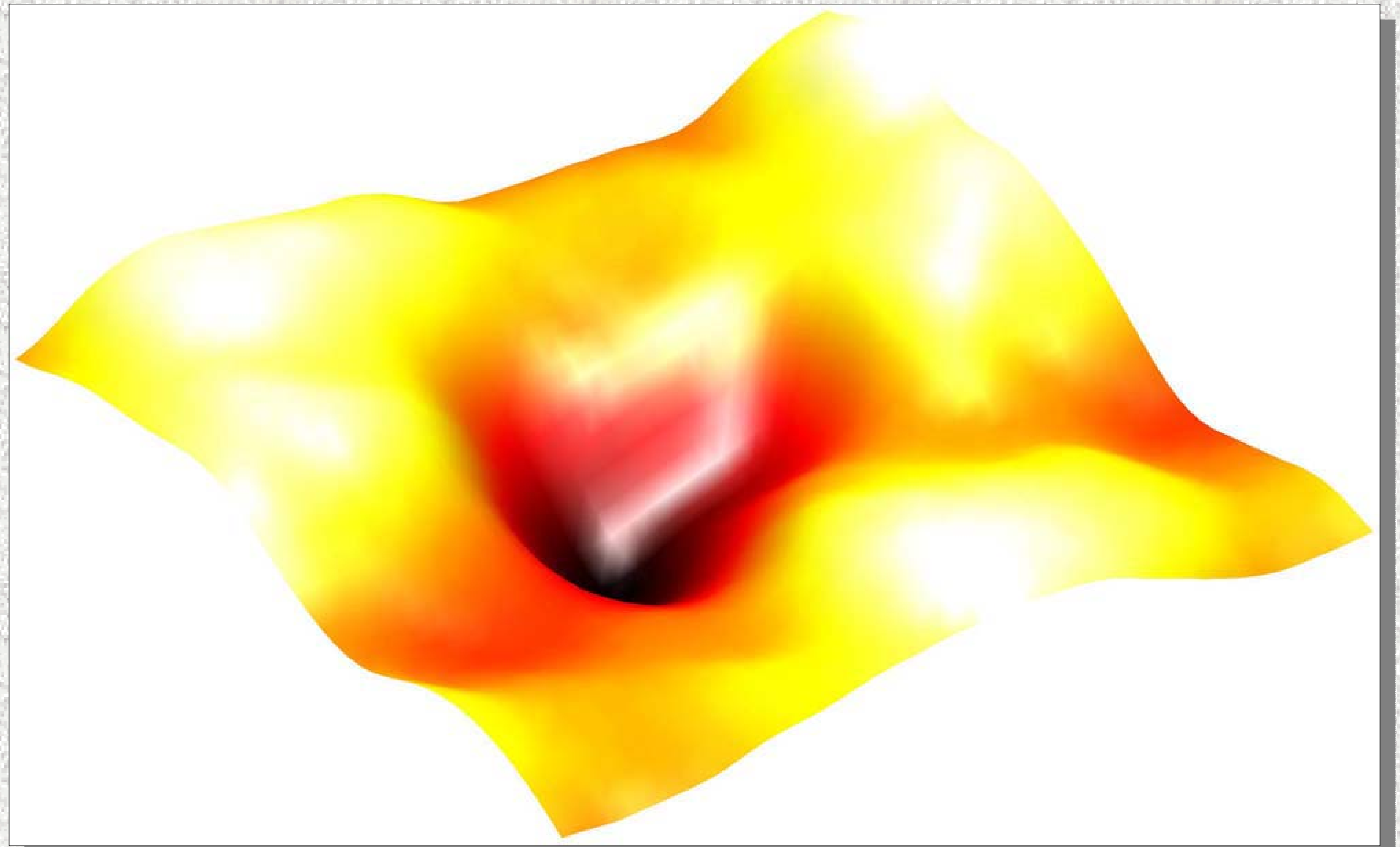


E_{av} = -5.47 eV, energy corrugation ≈38 meV, z = 12 pm, T = 6 K

Darker colors mean lower (i.e., higher negative) potential energies

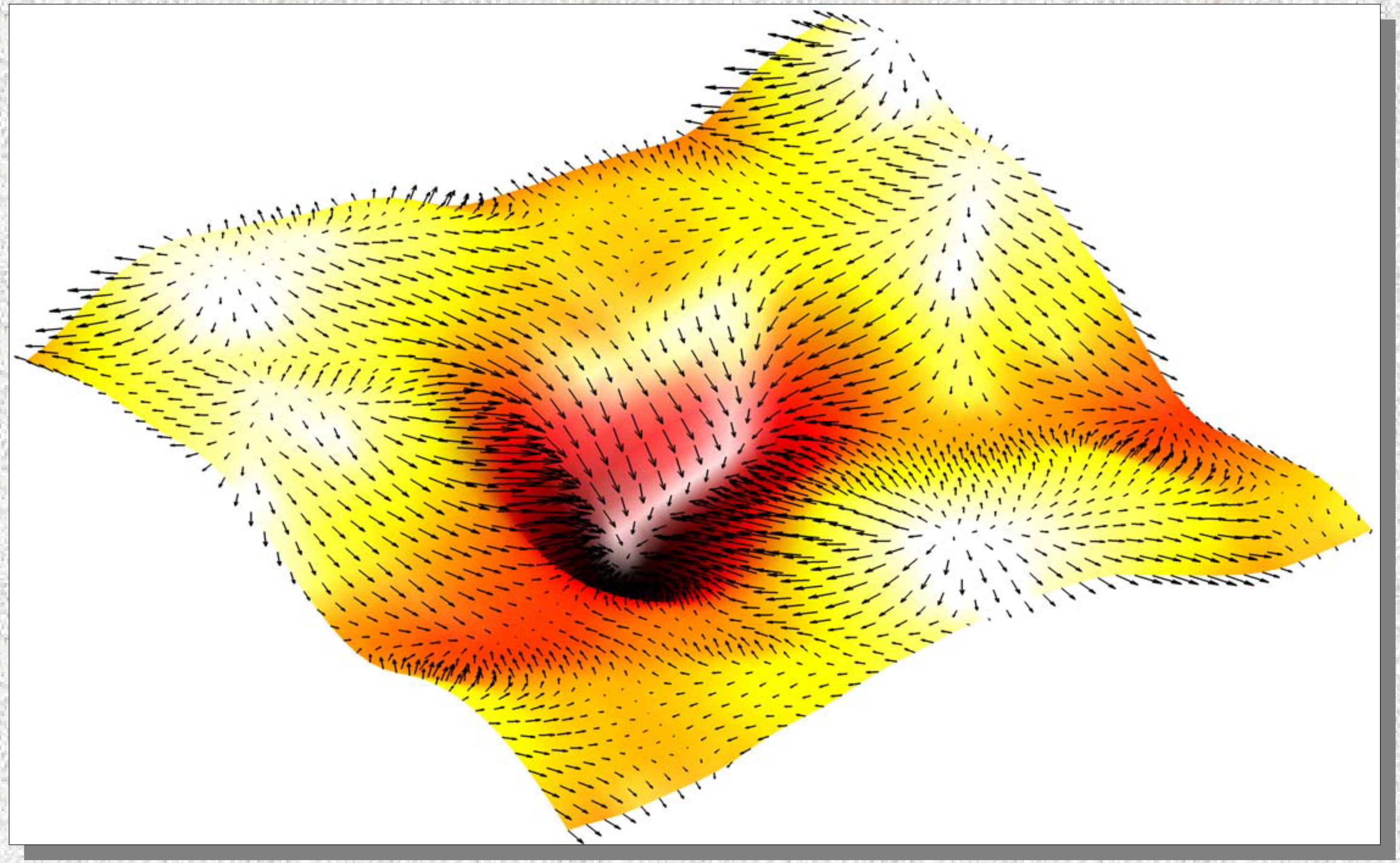
Potential Energy Well on a Hollow Site

Measured with 3D-AFM at 6 K in UHV



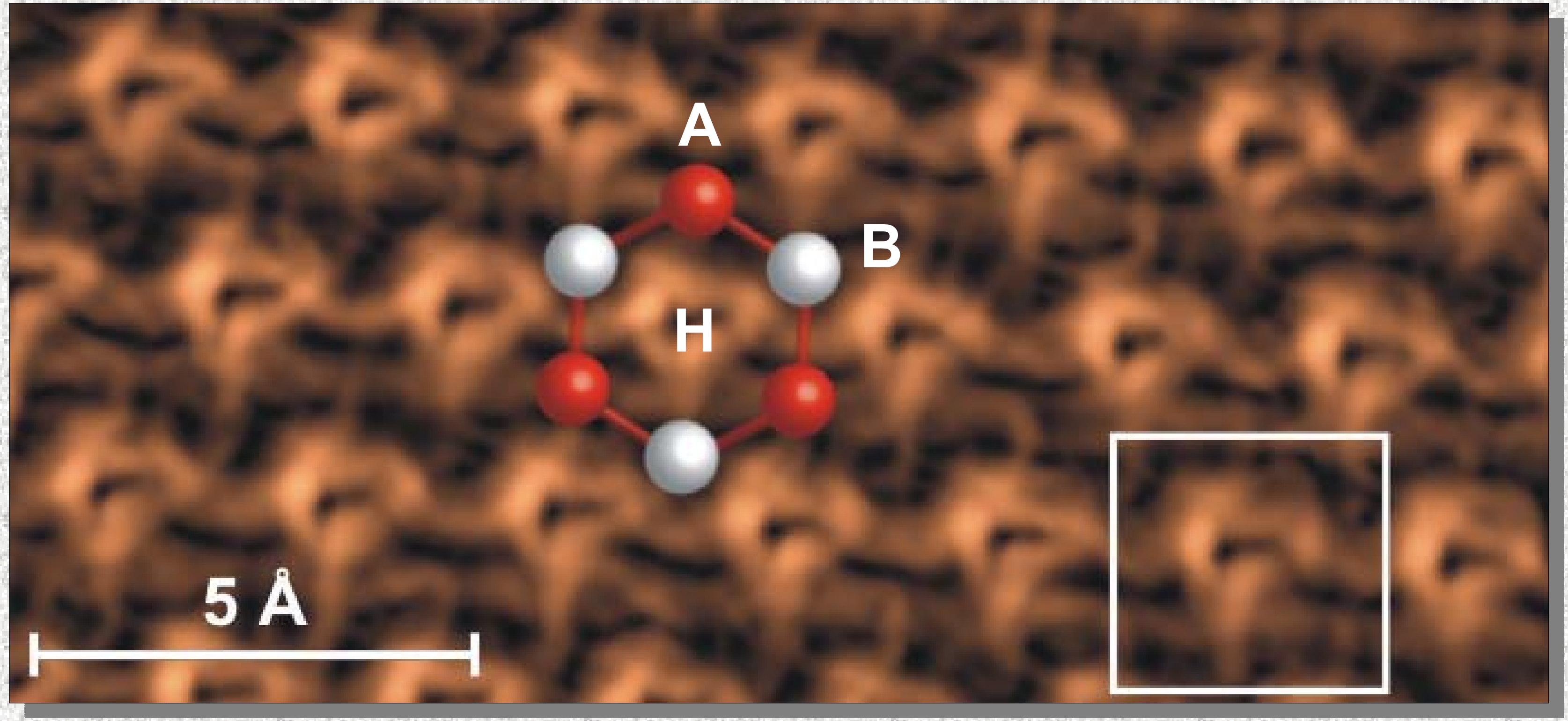
Potential Energy Well with Lateral Forces

Measured with 3D-AFM at 6 K in UHV



3D-AFM: Lateral Force Mapping

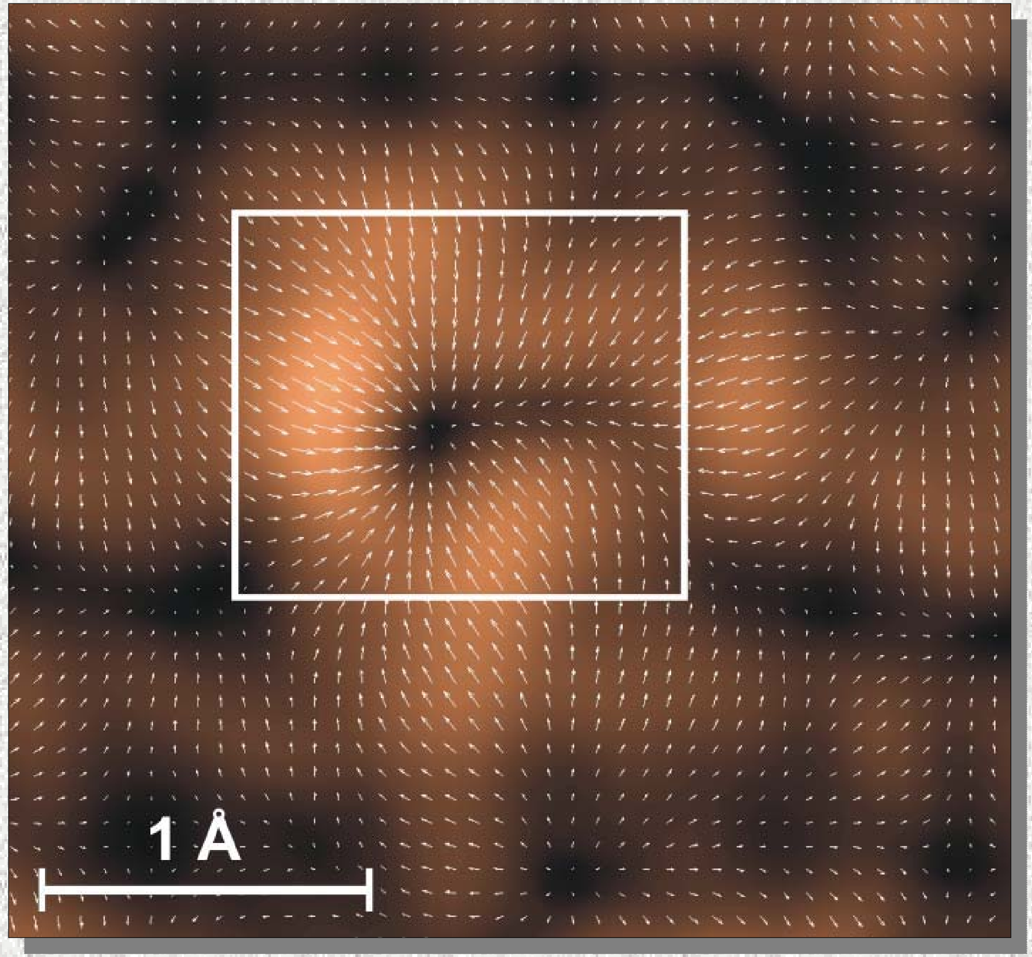
Lateral Force Image of Graphite



Lateral force corrugation ≈100 pN, T = 6 K

Local Lateral Forces on Graphite

Measured with 3D-AFM at 6 K in UHV



Local Lateral Forces on Graphite

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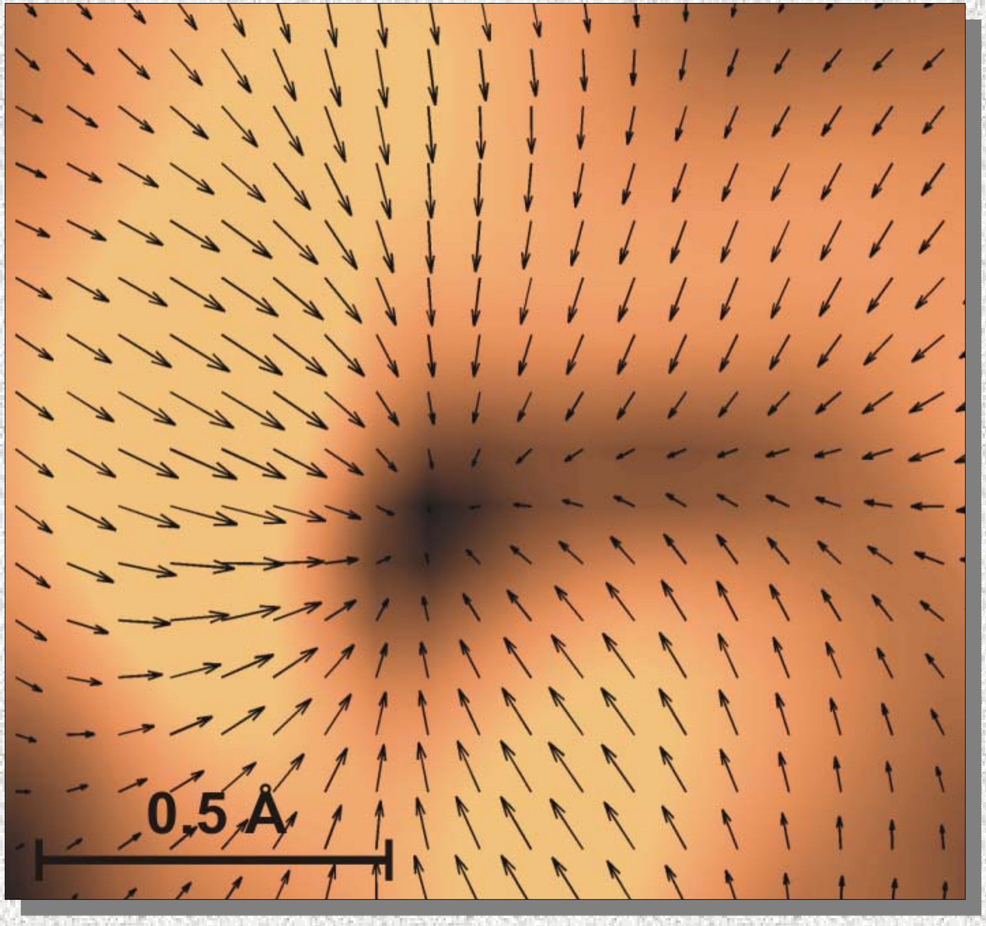
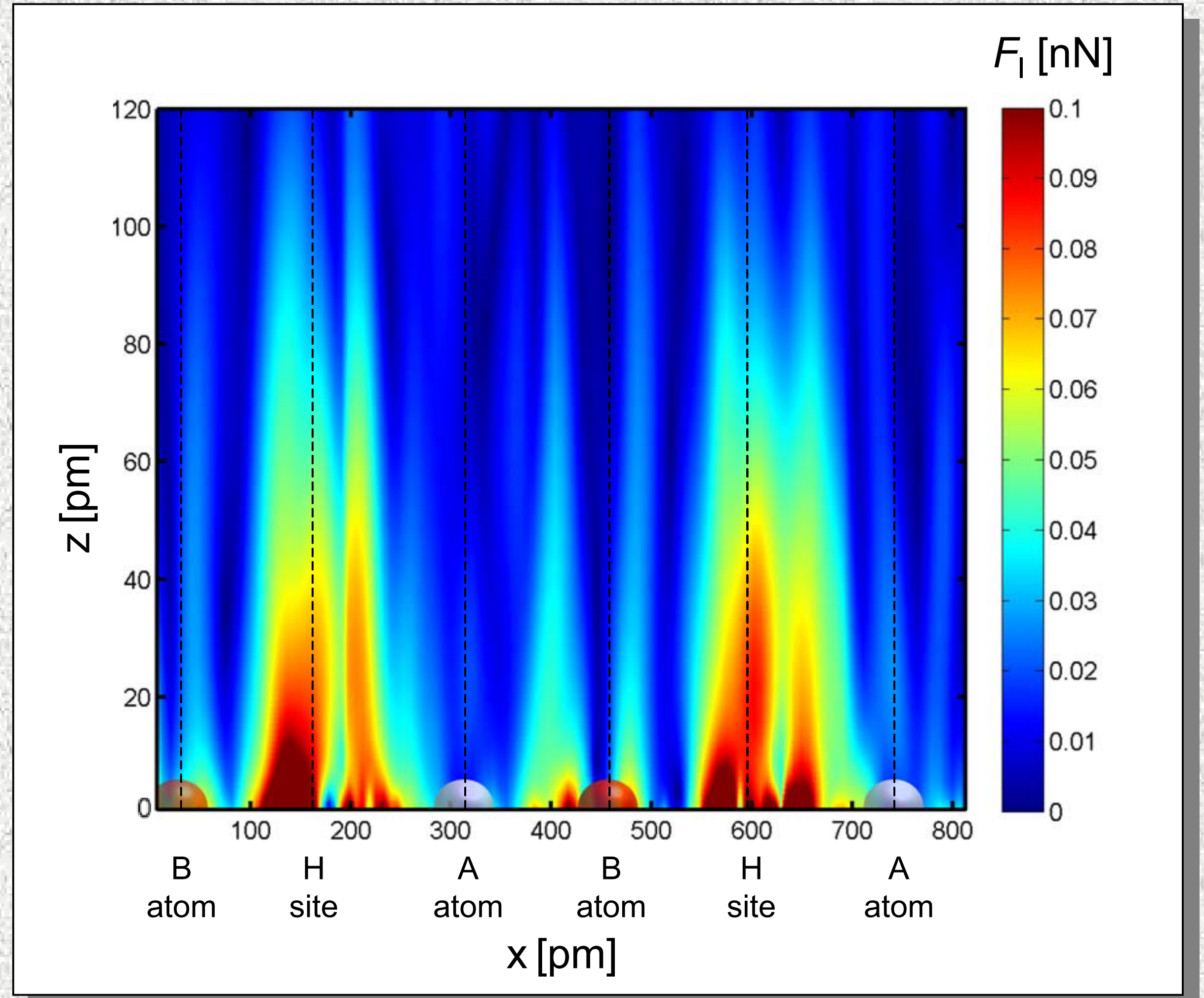
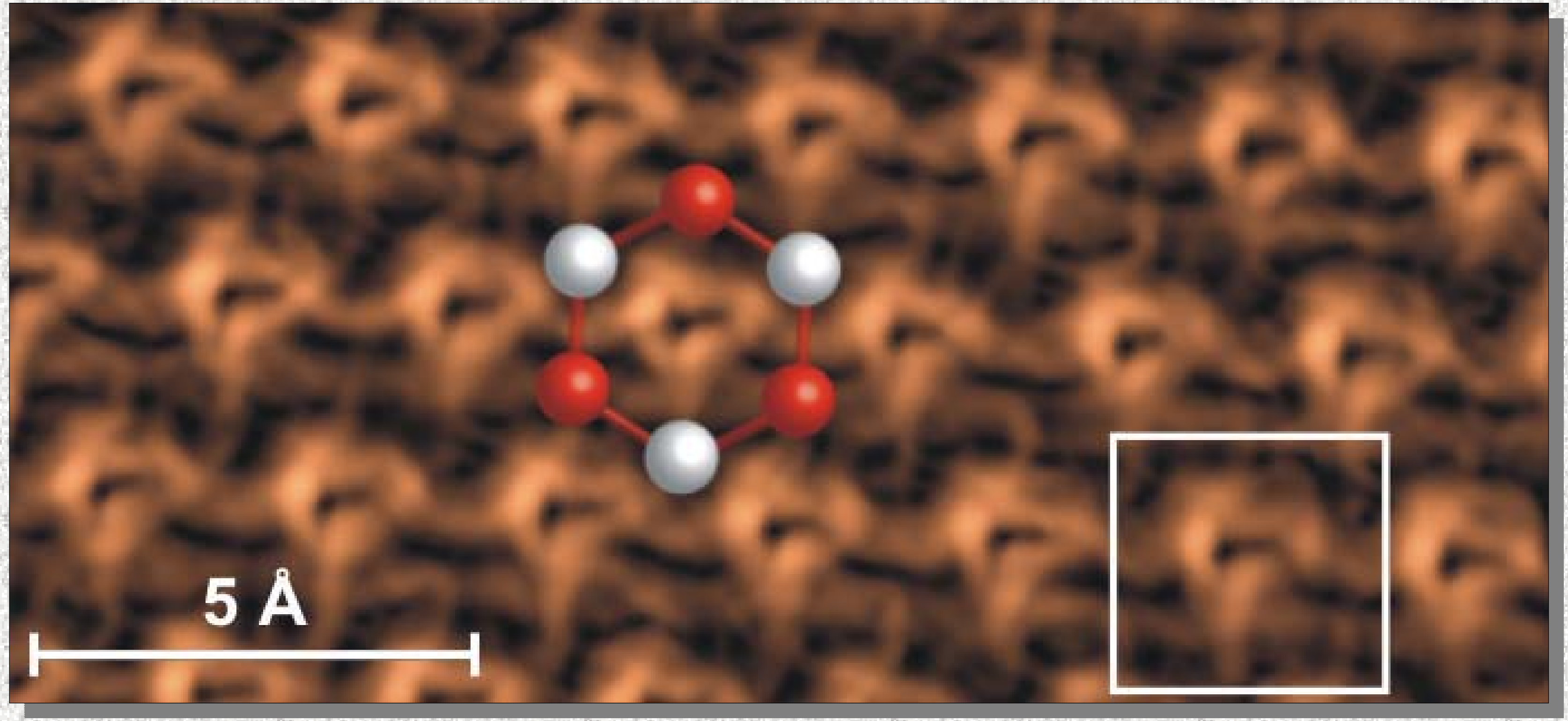


3D-AFM:
Lateral Force Contour Along [$\bar{1}$100]



3D-AFM:
Lateral Force Mapping

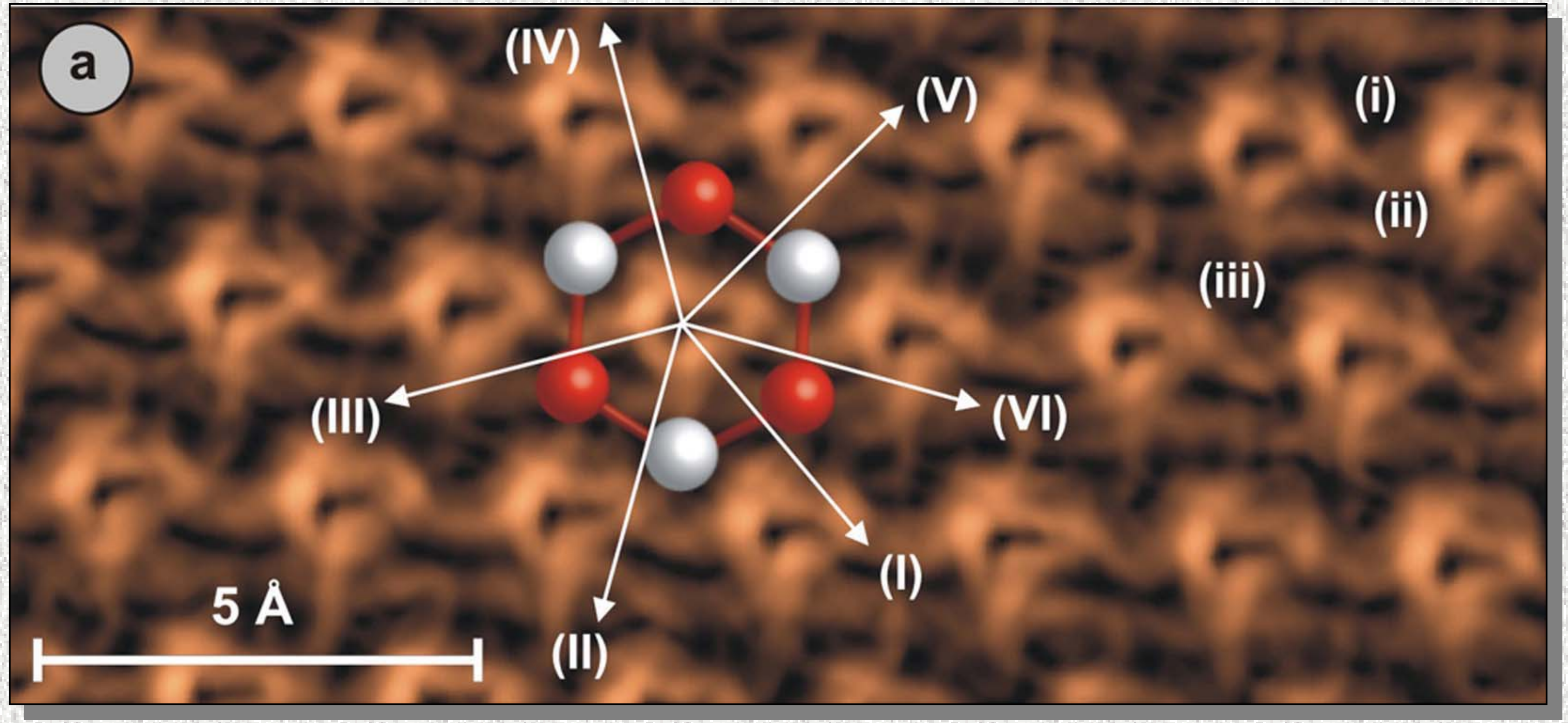
Lateral Force Image of Graphite



Lateral force corrugation ≈100 pN, T = 6 K

Lateral Forces for Constant Load: Paths of Least Resistance

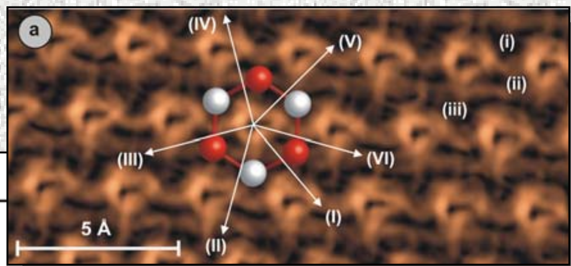
Lateral Force Image of Graphite for constant normal force –2.31 nN

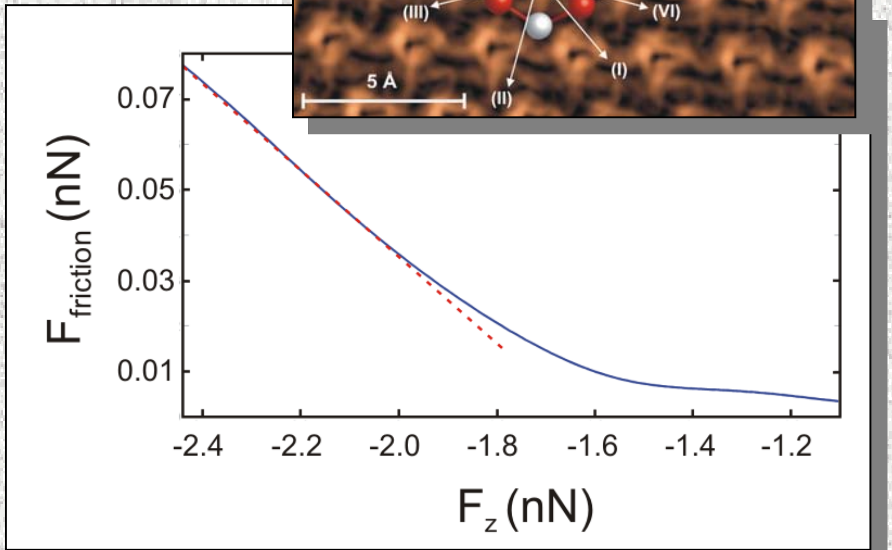


Lateral force corrugation ≈100 pN, T = 6 K

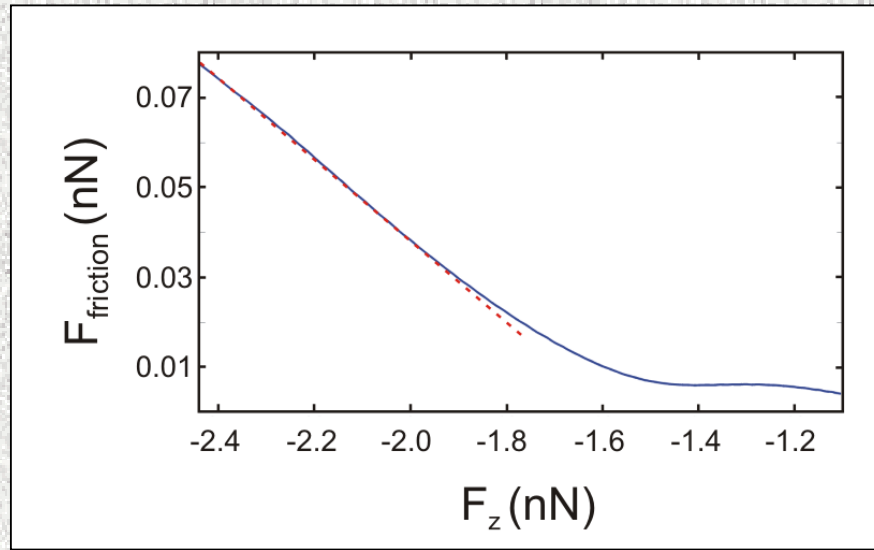
Transitioning to "Attractive Static Friction": $F_{friction}$ vs F_{load} along Paths of Least Resistance

Maximum Lateral Force vs. Load Curves along path (I)





Curve averaged over all paths (I) of inset map



Curve along path (I) as given in inset map

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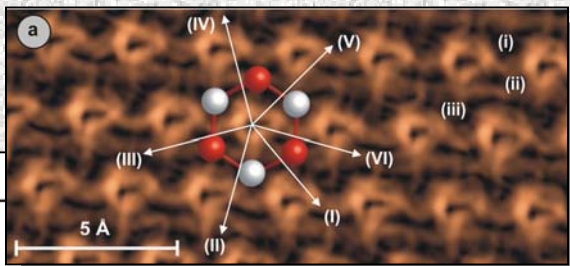
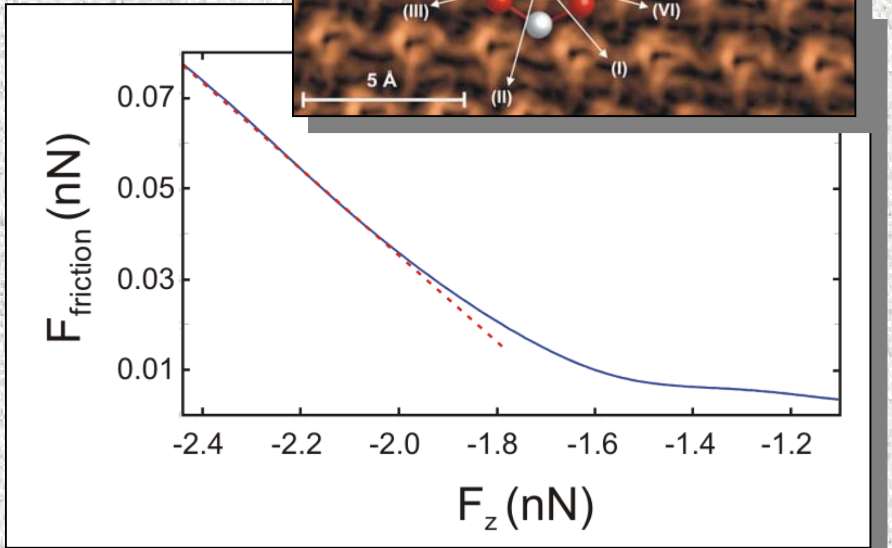
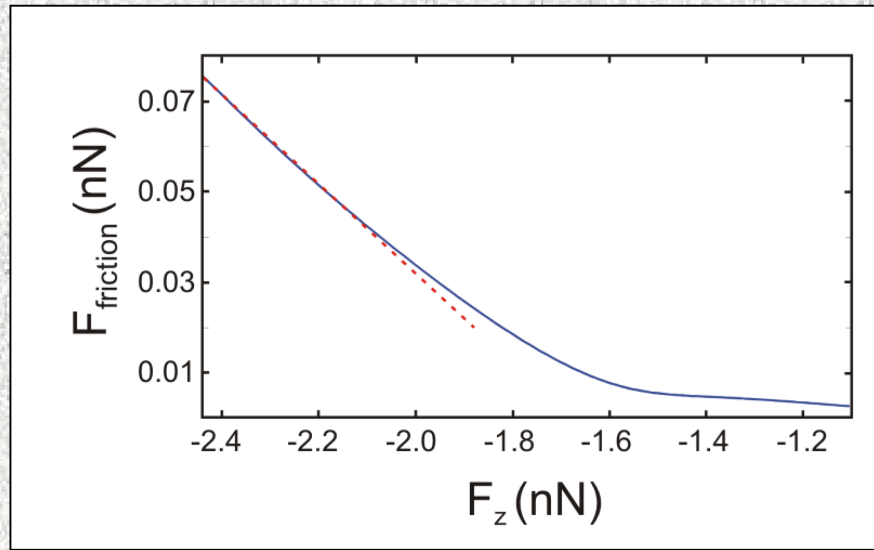
Transitioning to "Attractive Static Friction": $F_{friction}$ vs F_{load} along Paths of Least Resistance

Maximum Lateral Force vs. Load Curves along path (I)





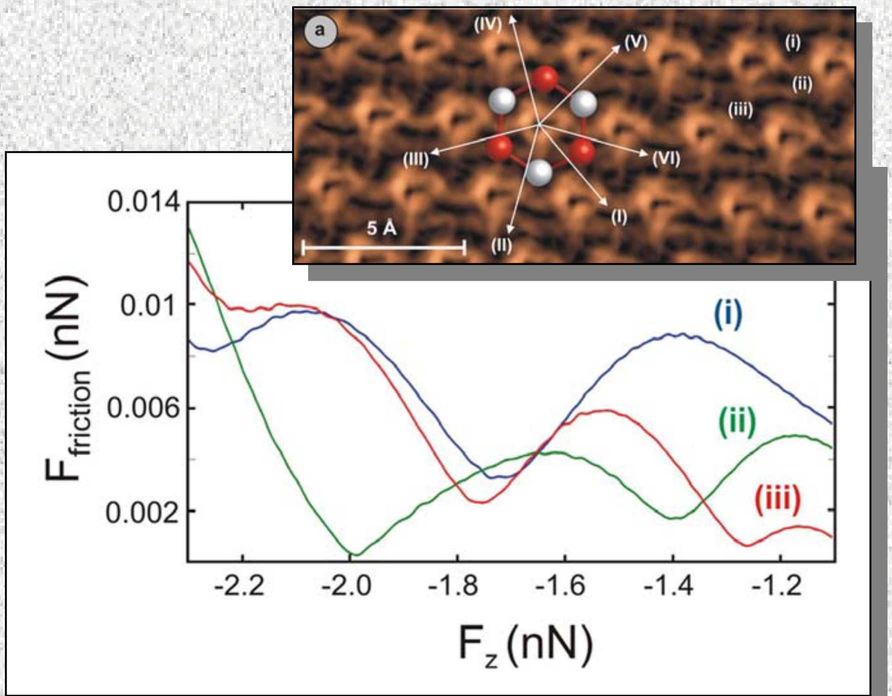


Curve averaged over all paths (I) of inset map

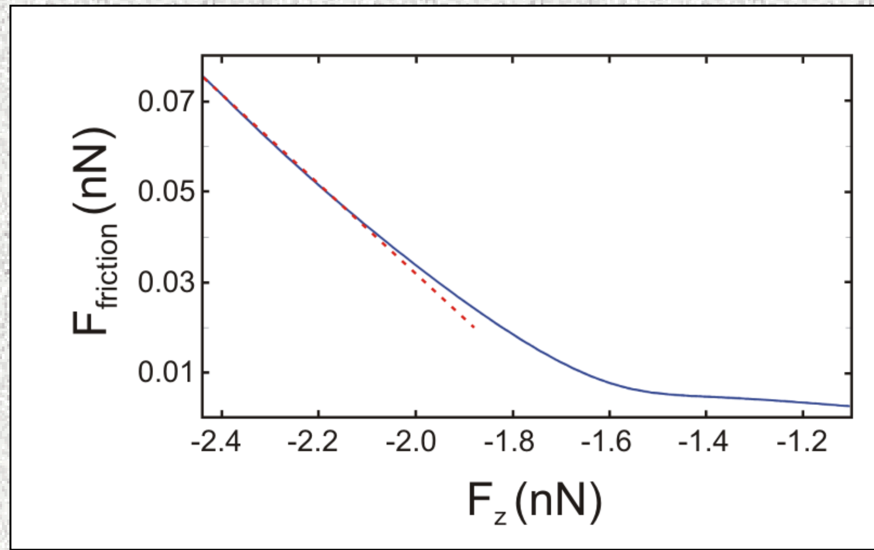
Curve averaged over all paths given in inset map

Transitioning to “Attractive Static Friction”: $F_{friction}$ vs F_{load} along Paths of Least Resistance

Maximum Lateral Force vs. Load Curves along path (I)

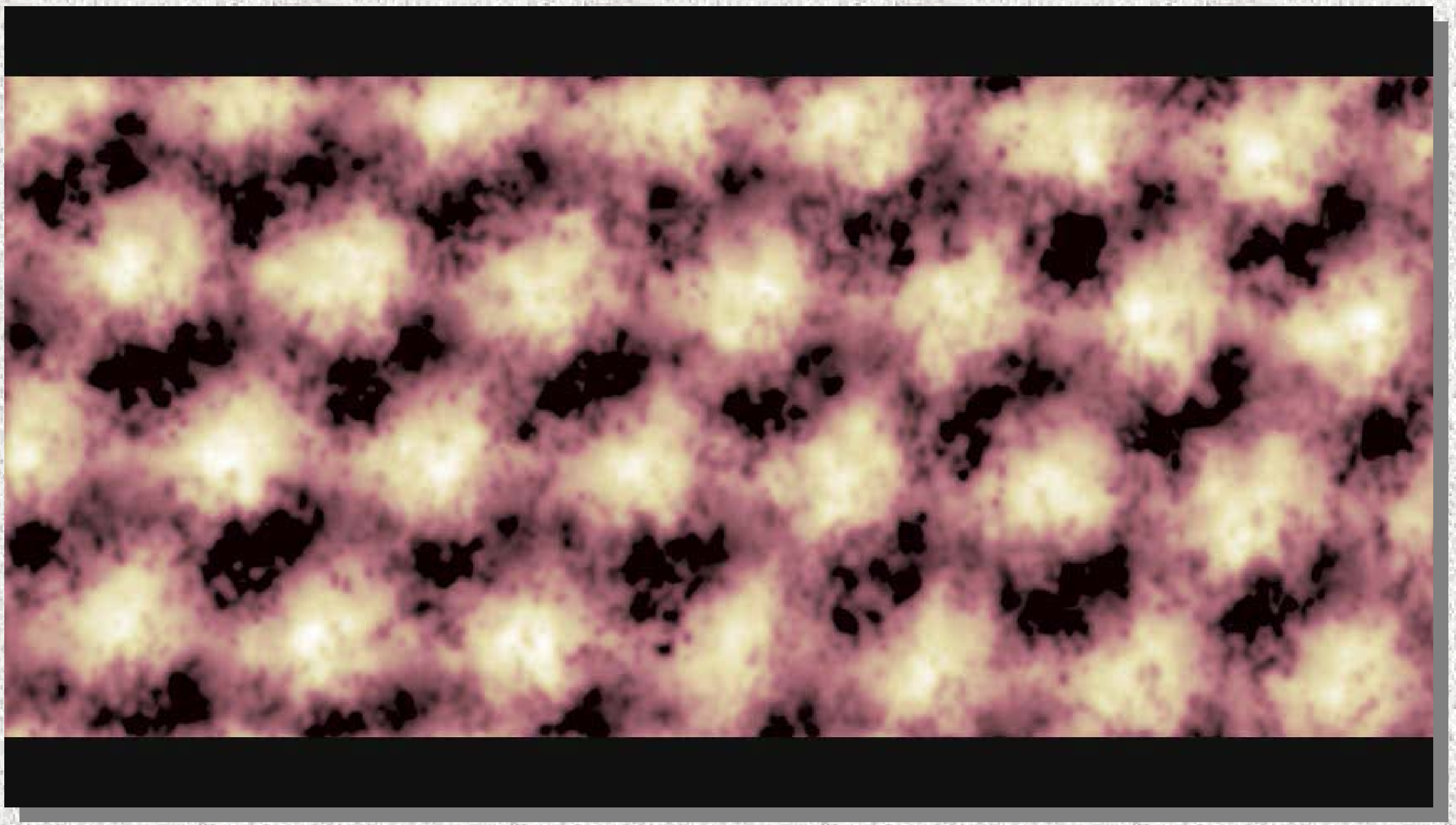


Curves acquired at the arbitrary points (i), (ii), and (iii) of inset map



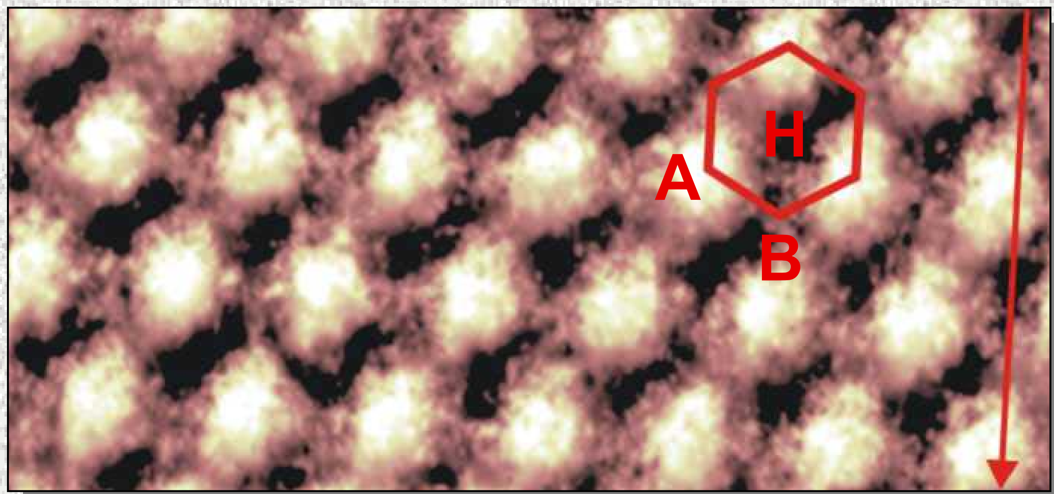
Curve averaged over all paths given in inset map

3D-AFM:
Plotting the Dissipation for Every *z* Distance

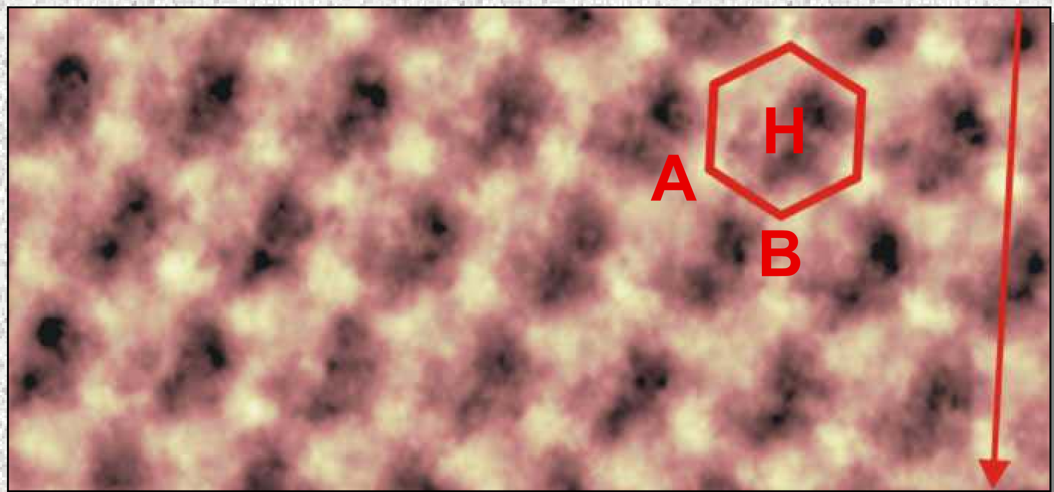


Grid of 119 × 256 force curves = 30464 force curves, T = 6 K
total height covered = 180 pm, average force for each height subtracted

Height-Dependent Image Contrast in Dissipation Signal



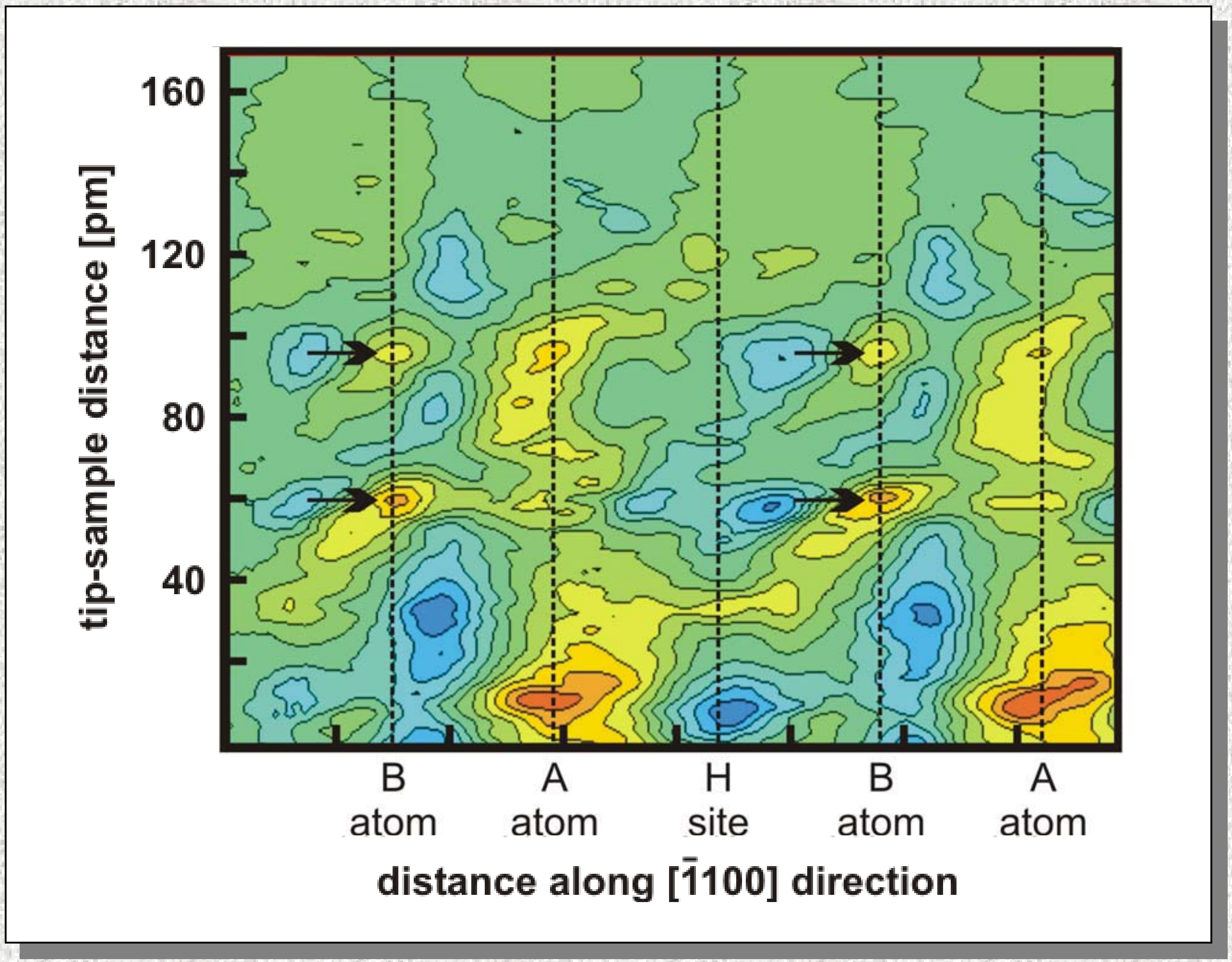
z = 12 pm
E_{diss} = 272 µeV/cycle
E_{corr} = 43 µeV/cycle



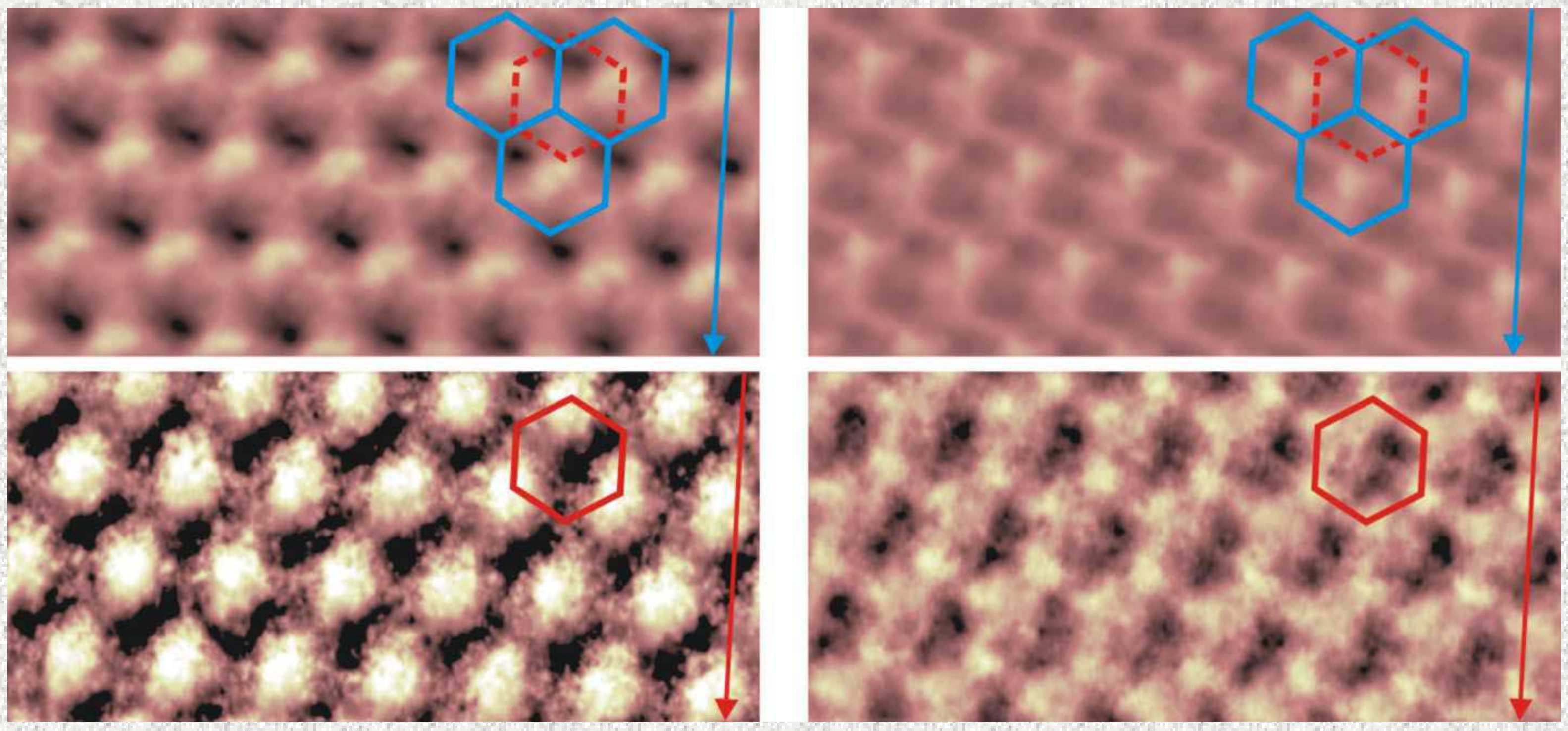
z = 97 pm
E_{diss} = 98 µeV/cycle
E_{corr} = 26 µeV/cycle

Characterization of Site-Specific Interactions

Interactions at A-, B-, and H-sites



Different Interaction Mechanisms in Dissipation and Force Signals?

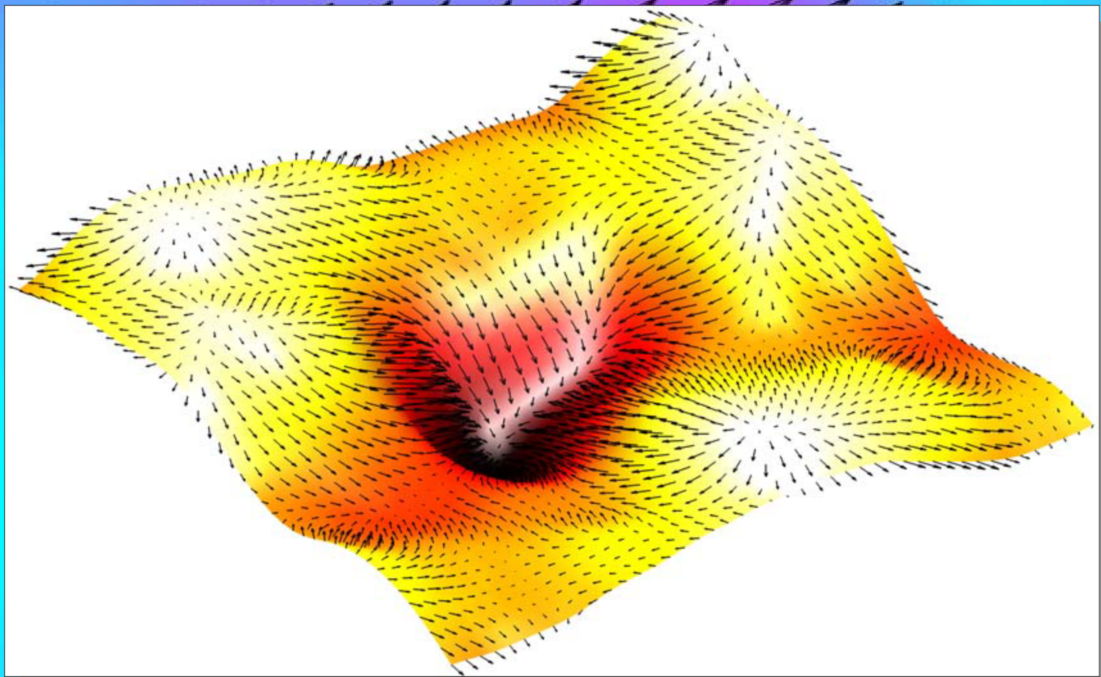


Top row: Force images; *bottom row:* dissipation images
Left column: Height z = 12 pm, *Right column:* z = 97 pm

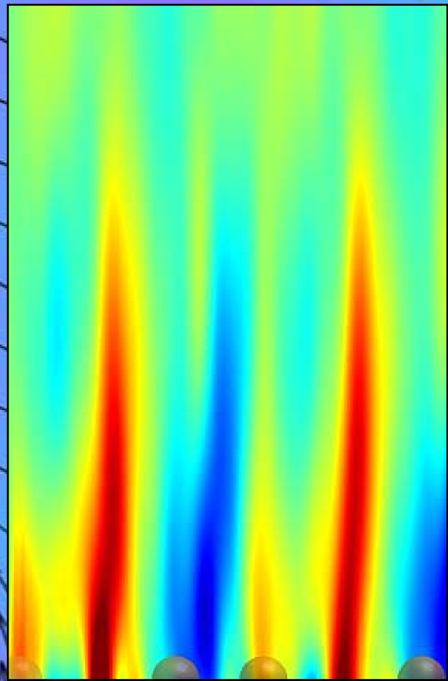
Conclusions

3D-AFM:

An ideal tool for the high-resolution investigation of local lateral forces!



energy plot with lateral forces



xz force map

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