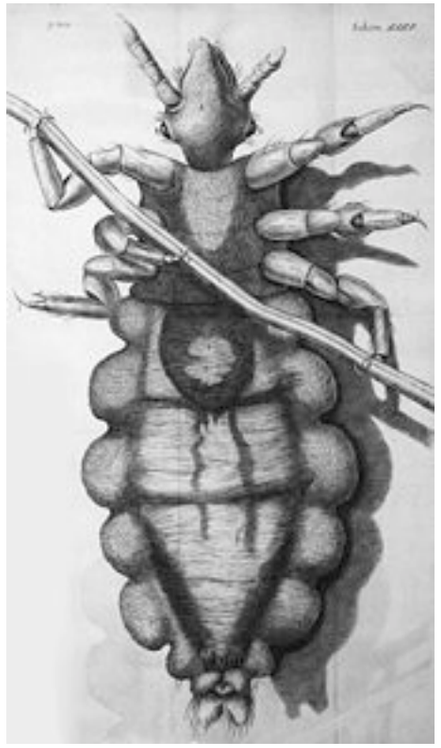
Robert Hooke
Micrographia
(1665)

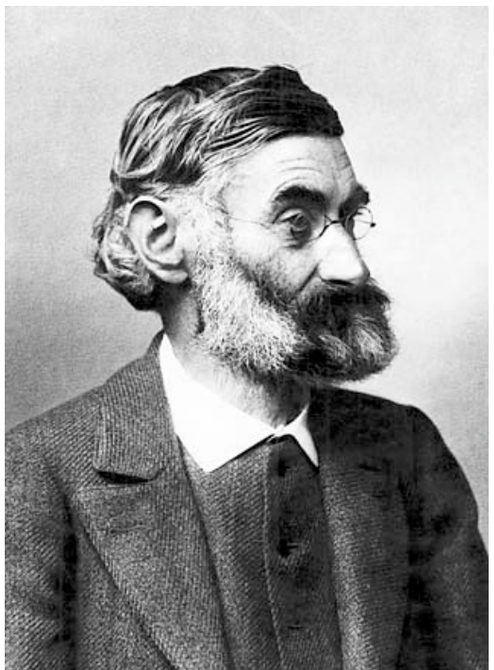


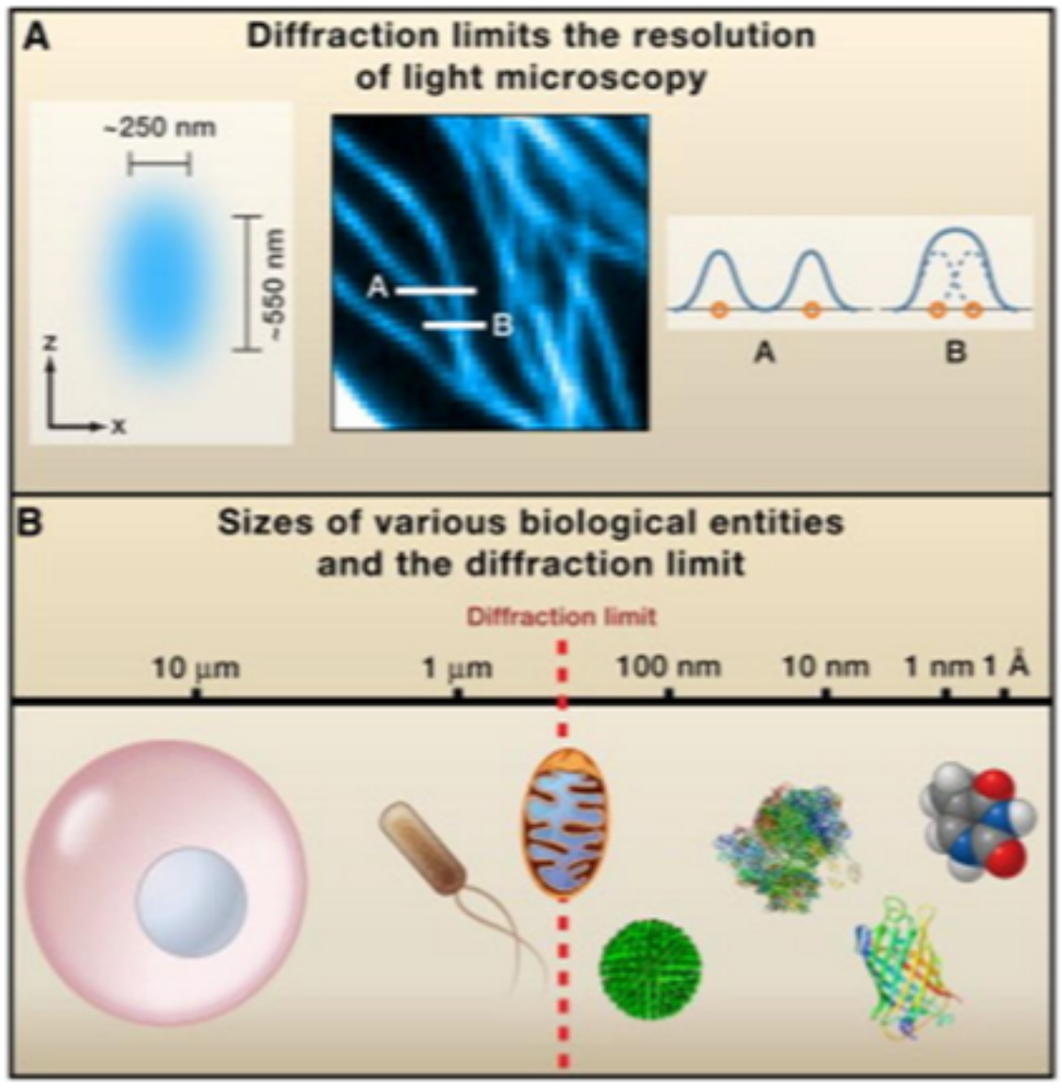
Uklonska limita:

$$d = \frac{\lambda}{2n \sin \theta}$$

Ernst Abbe, 1873

Vidna svetloba: λ=400-700nm

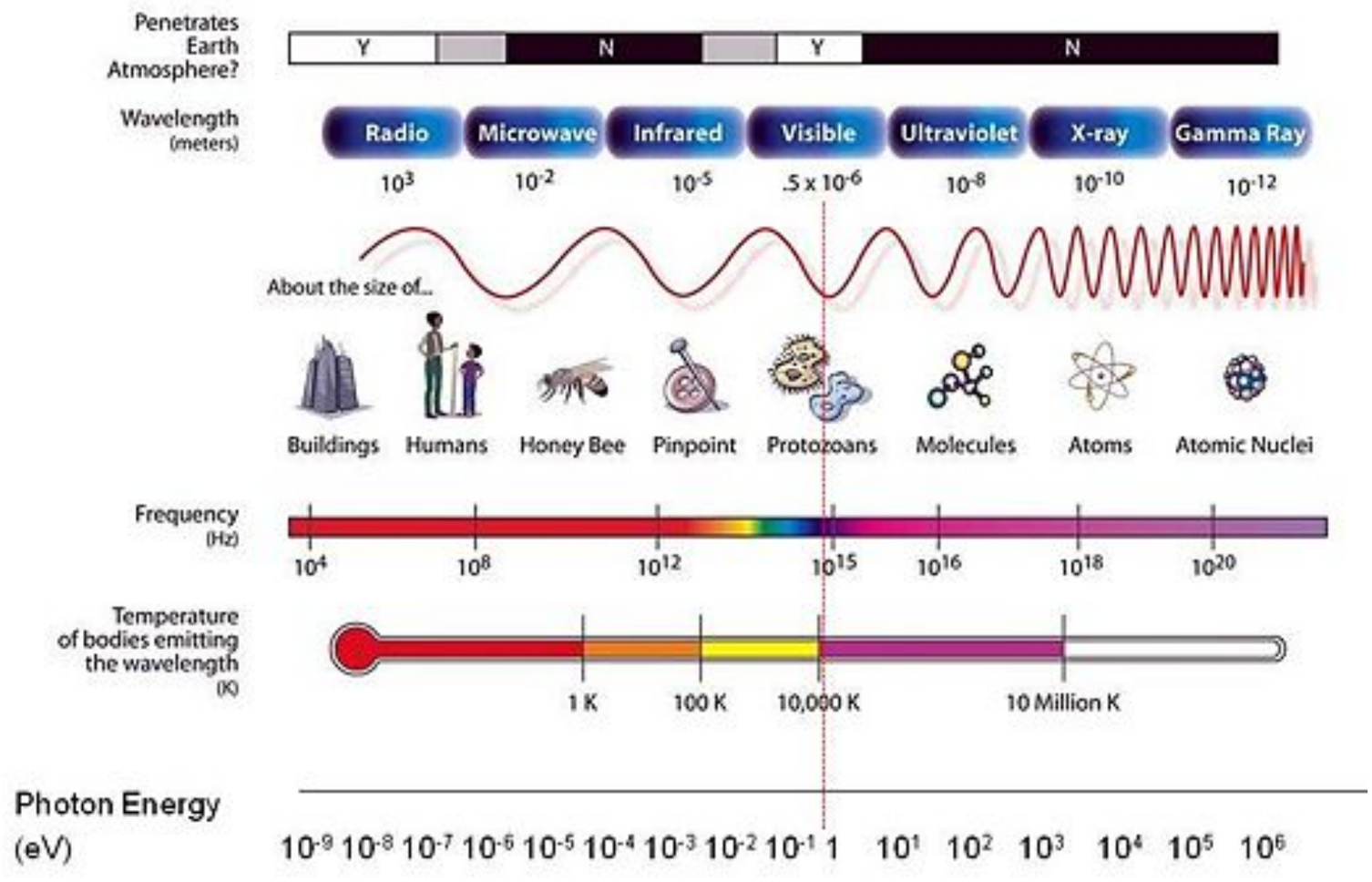


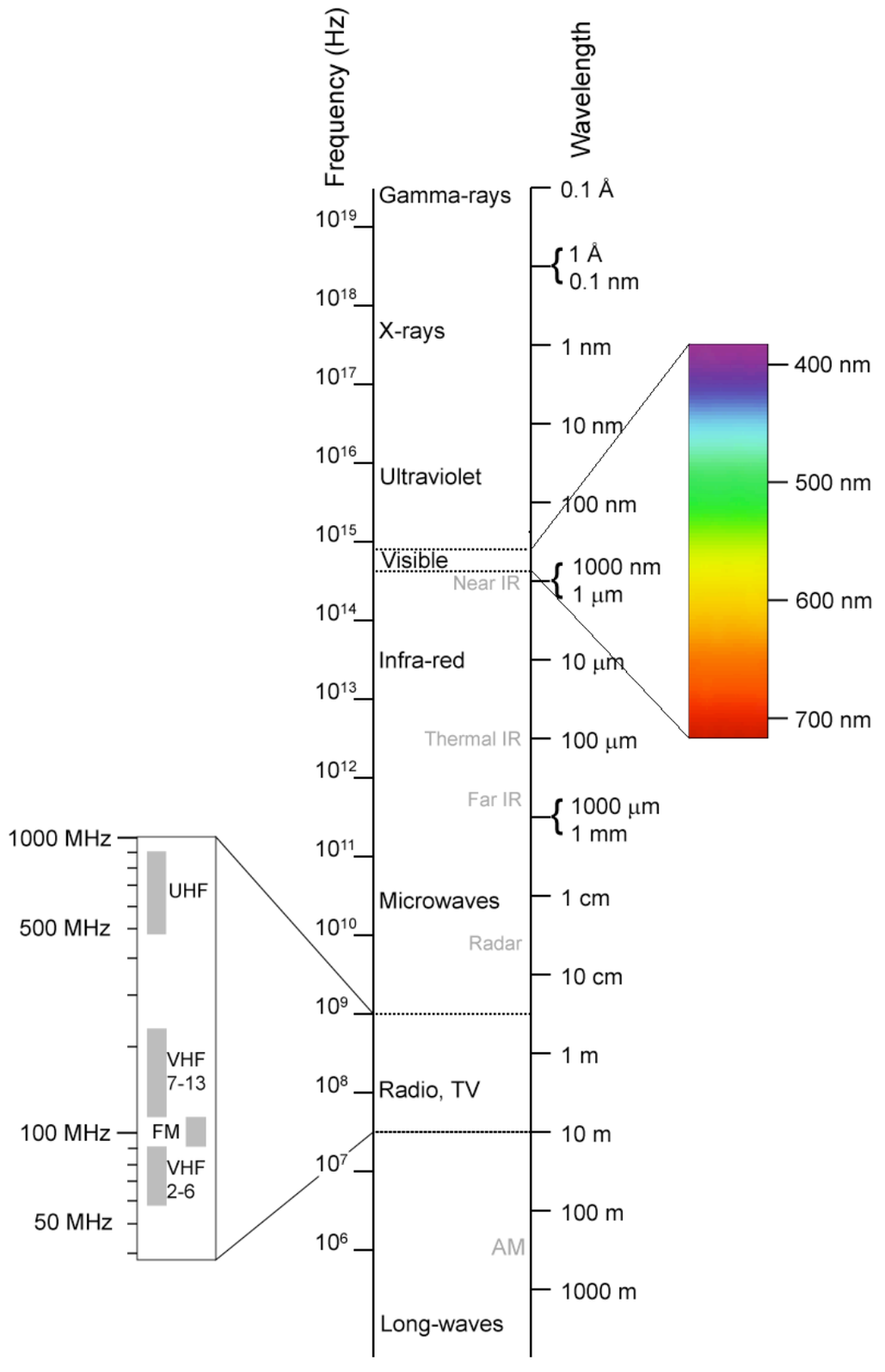


(Huang *et al.*, 2010, Cell, 143, 1047 – 57)

Opomba: iz istega razloga se ne da fokusirati laserskega žarka v piko velikosti pod λ/2.

THE ELECTROMAGNETIC SPECTRUM





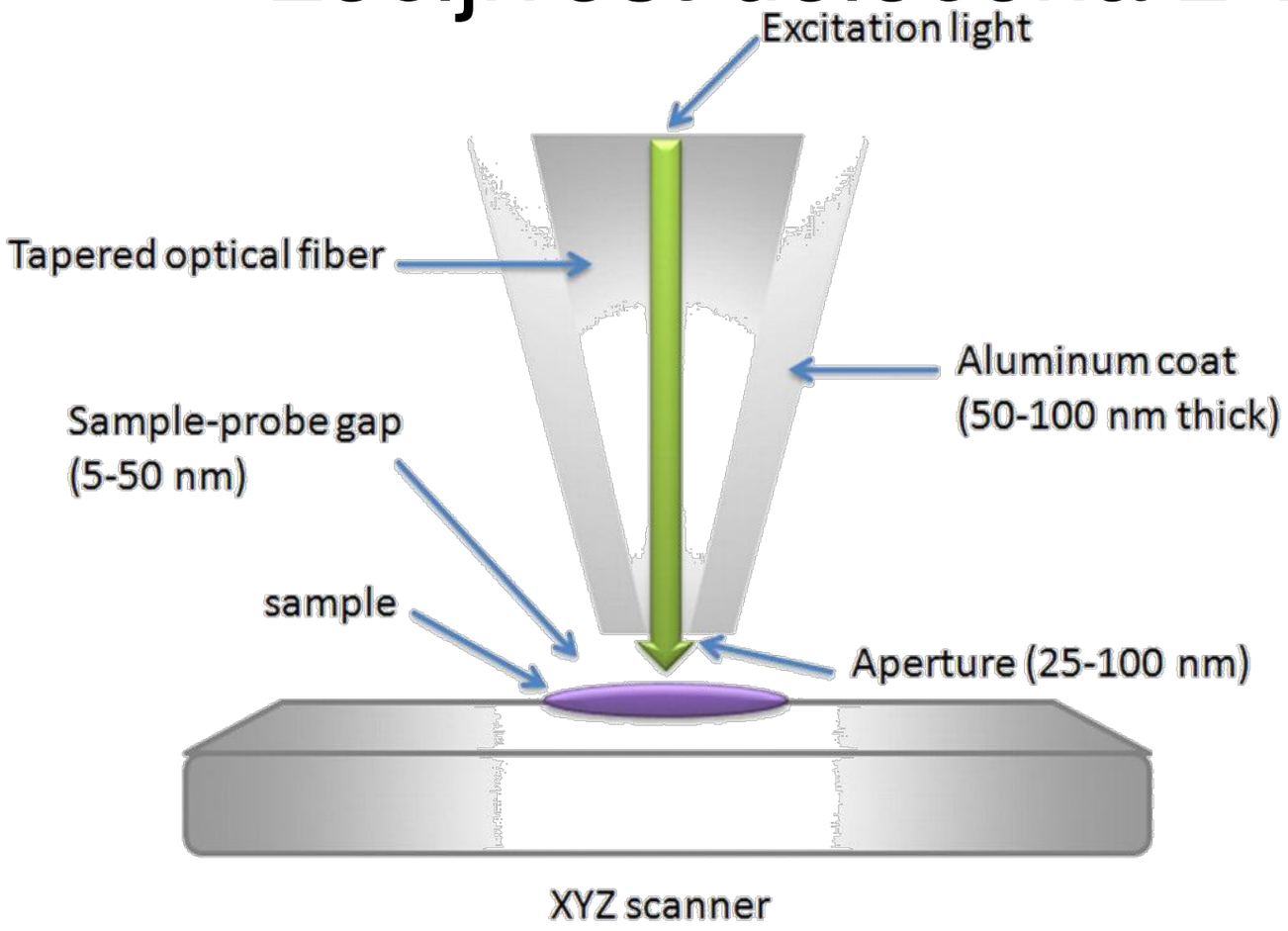
Onkraj Abbejeve uklonske limite: near-field optika

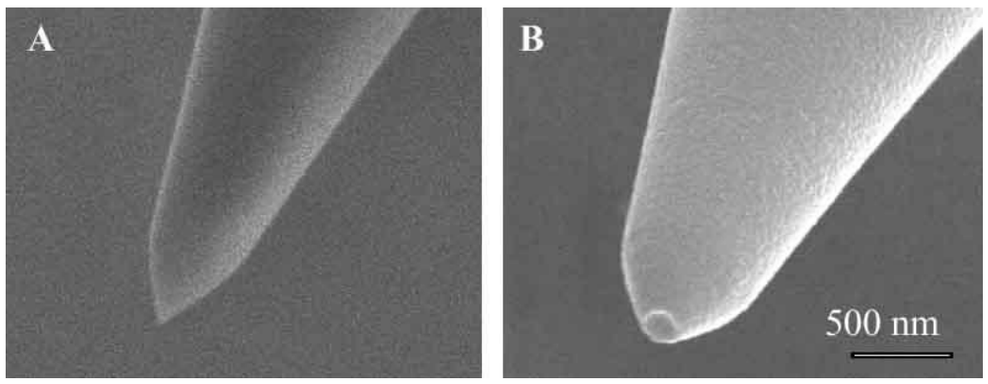
Odprtina vira za osvetljevanje manjša od valovne dolžine.

Vzorec v neposredni bližini odprtine (manj kot λ/2).

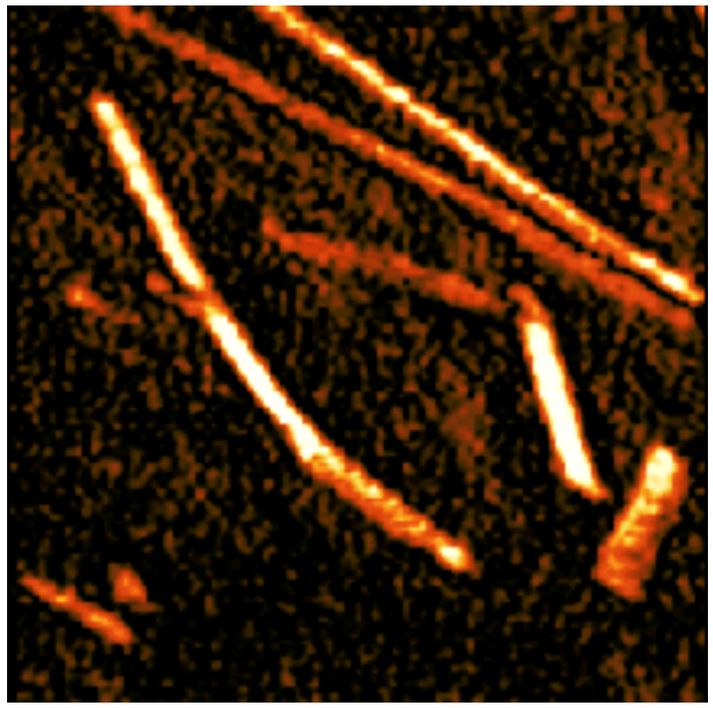
Premajhna razdalja, da bi lahko prišlo do uklona.

Ločljivost določena z velikostjo odprtine.

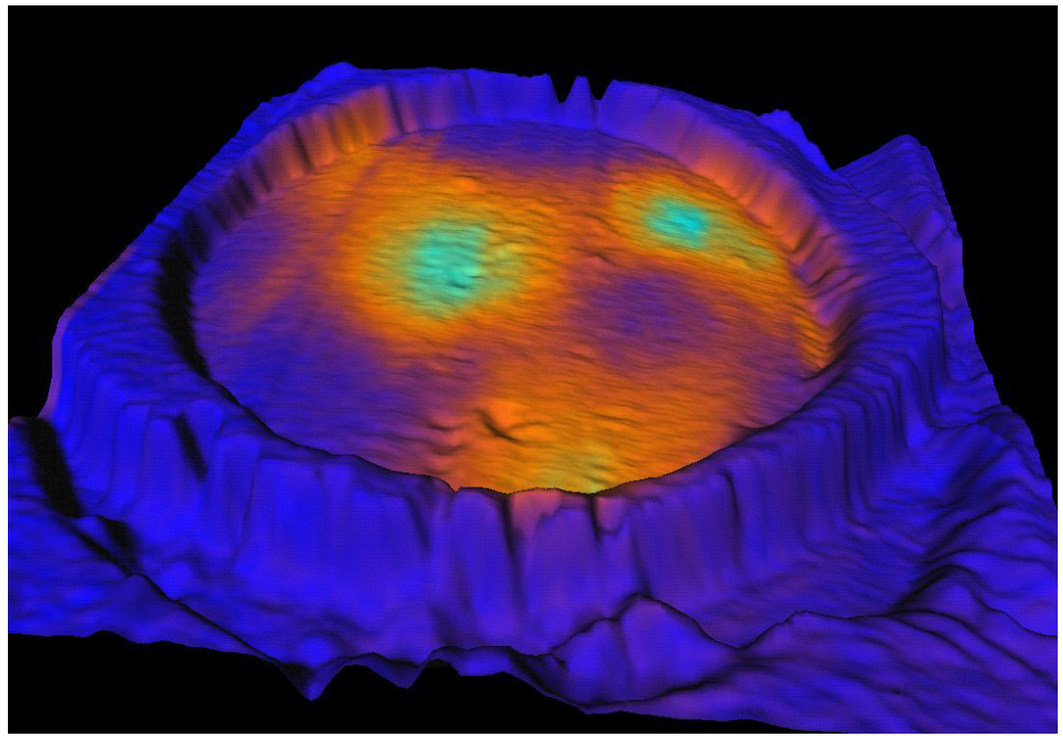




Ločljivost: 20 nm v najboljšem primeru



1 um x 1 um Tobacco Mosaic Virus



20 nm x 20 nm intensity distribution of a Vertical-Cavity Surface-Emitting Laser (VCSEL)

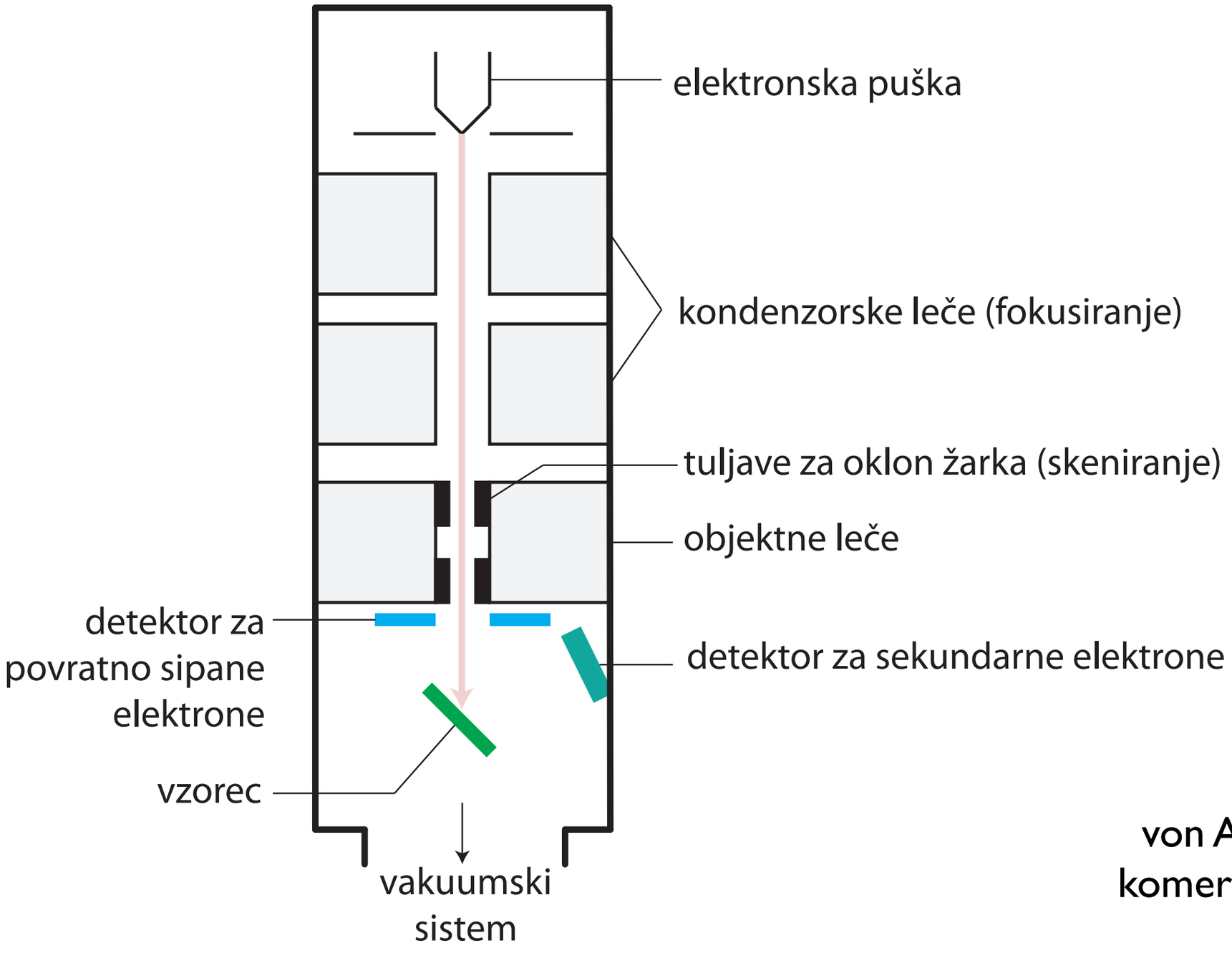
- SEM = scanning electron microscope
  vrstični (rasterski) elektronski mikroskop
- TEM = transmission electron microscope
  presevni (transmisijski) elektronski mikroskop

} gledanje

- STM = scanning tunneling microscope
  vrstični tunelski mikroskop
- AFM = atomic force microscope
  mikroskop na atomsko silo

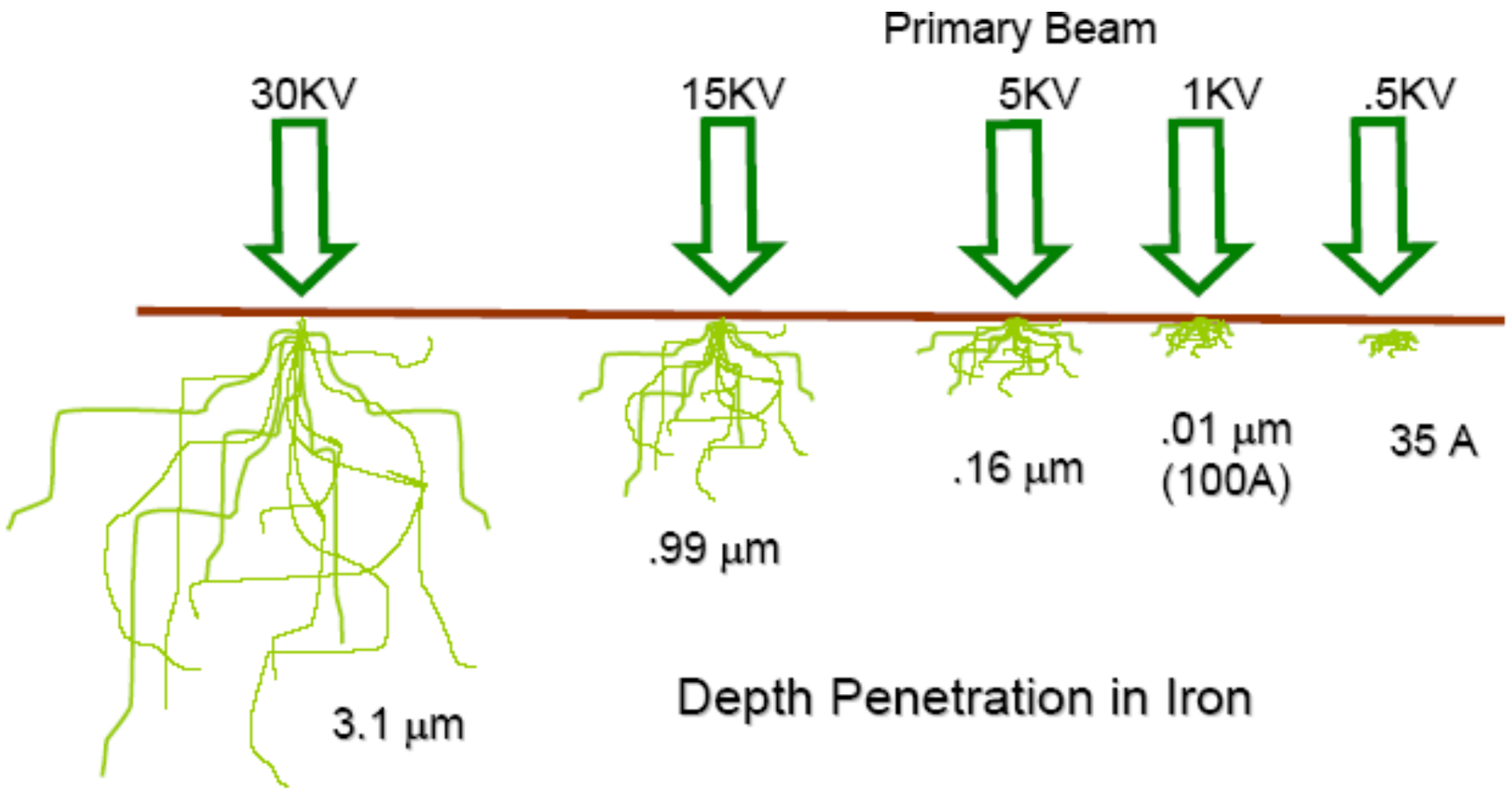
} tipanje

SEM = scanning electron microscope
rasterski (vrstični) elektronski mikroskop



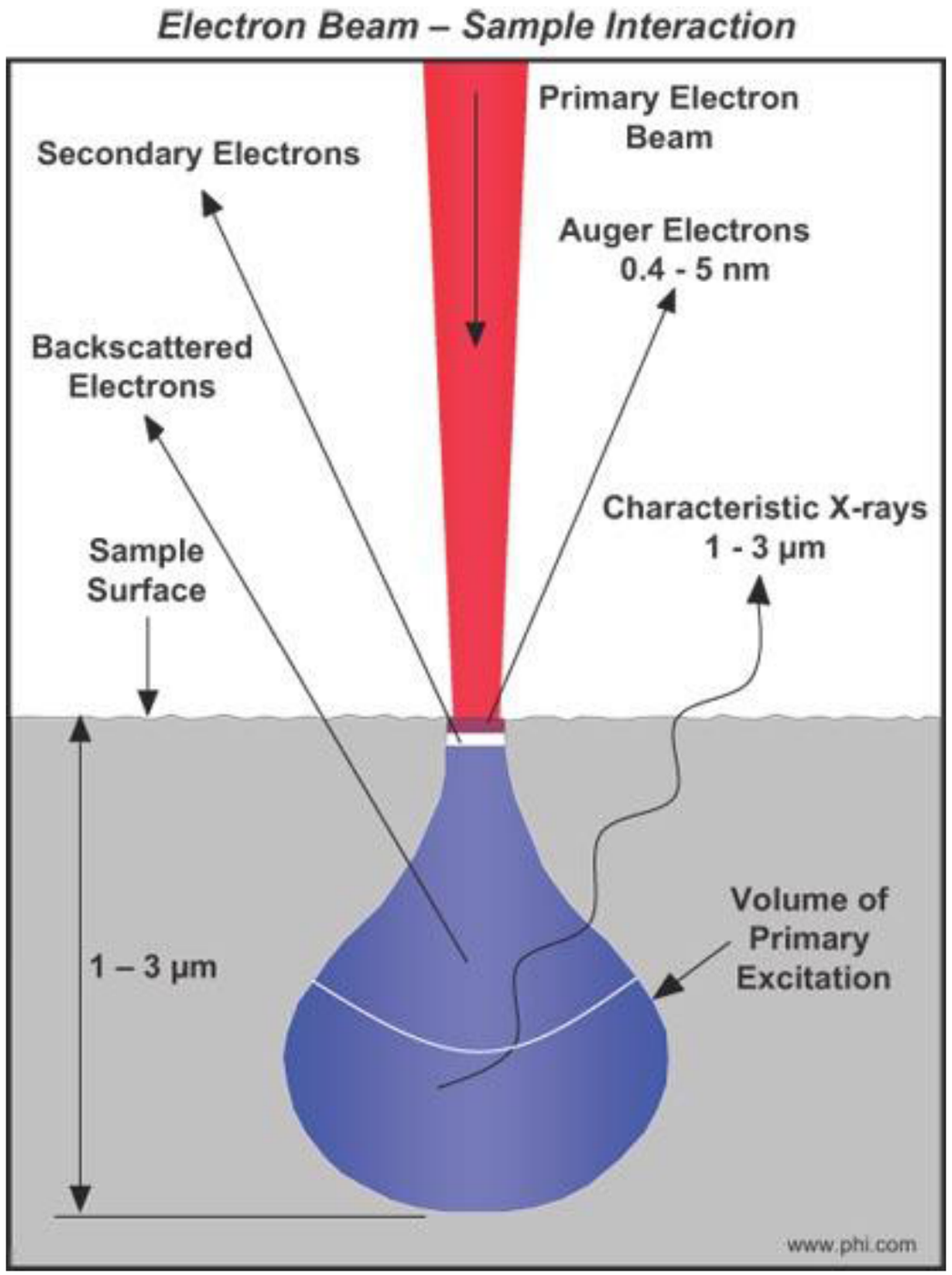
von Ardenne (1936)
komercialni okoli 1965

Vpliv pospeševalne napetosti



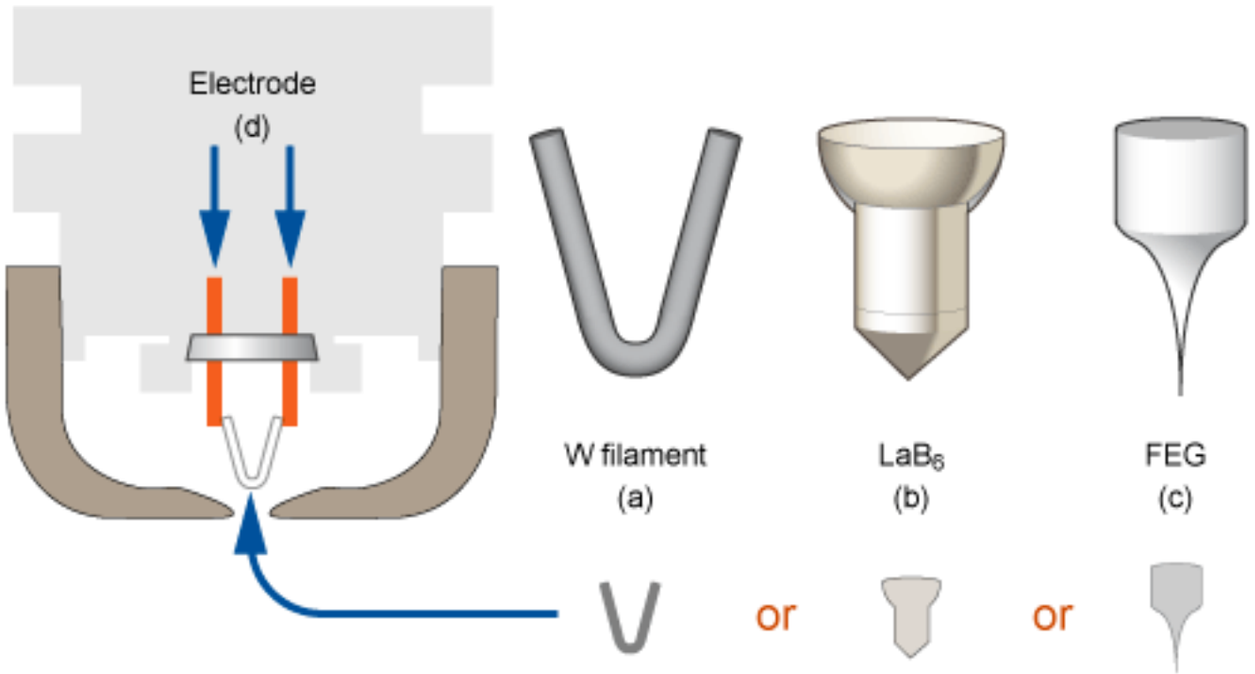
(predictions from the KO formula)

Interakcijsko območje

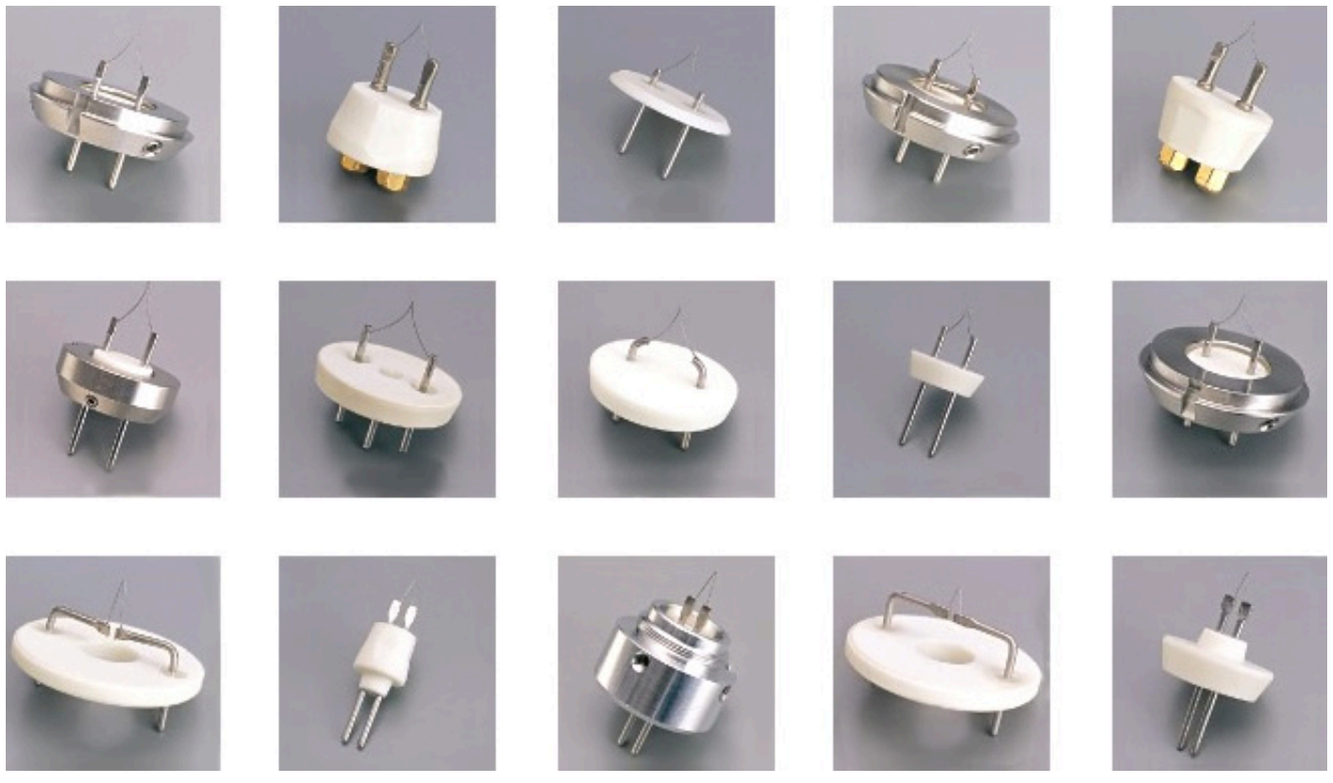


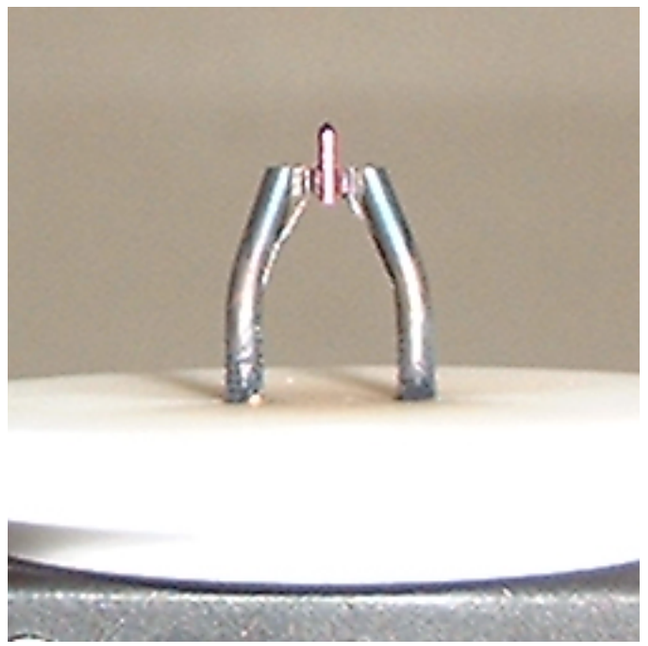
JEOL 6700F Ultra High Resolution Scanning Electron Microscope

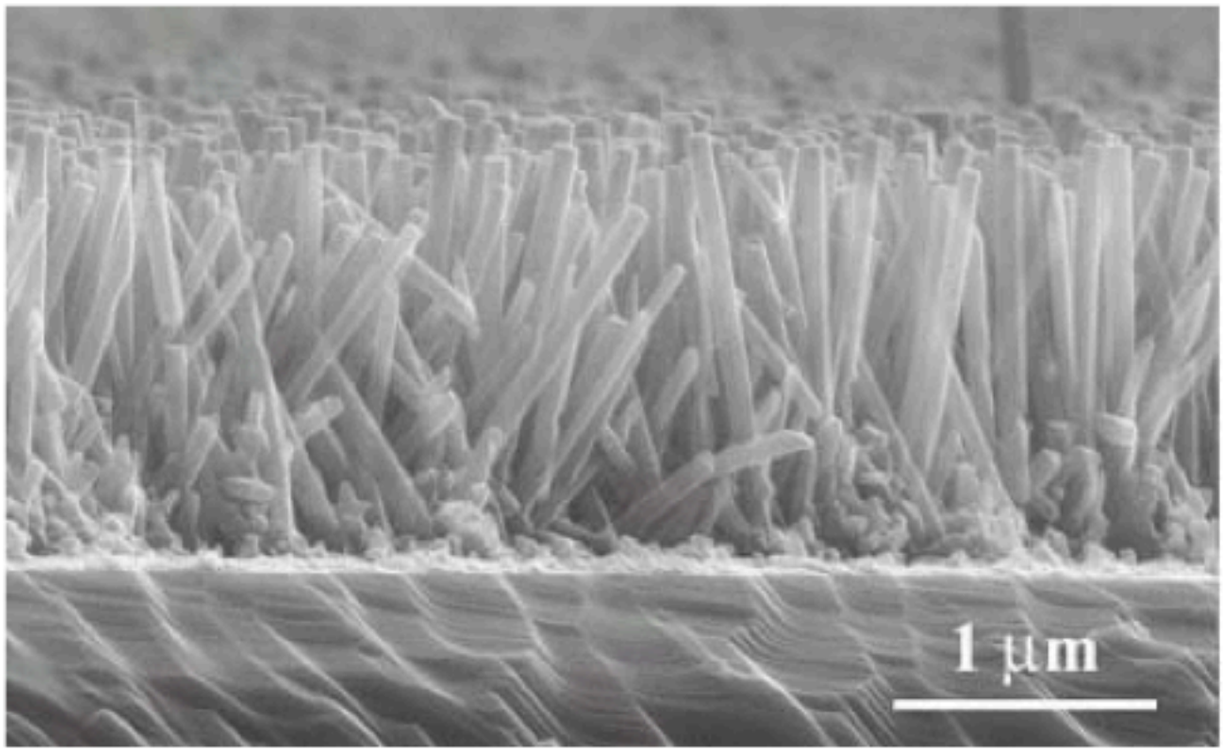
Ločljivost je določena z velikostjo curka elektronov.

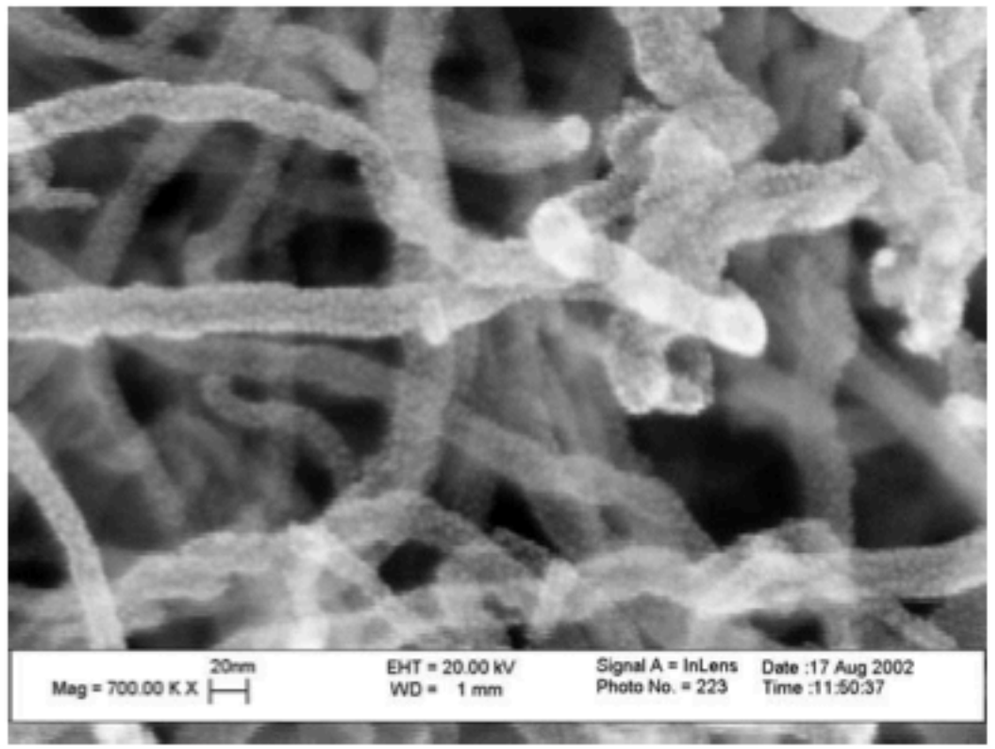


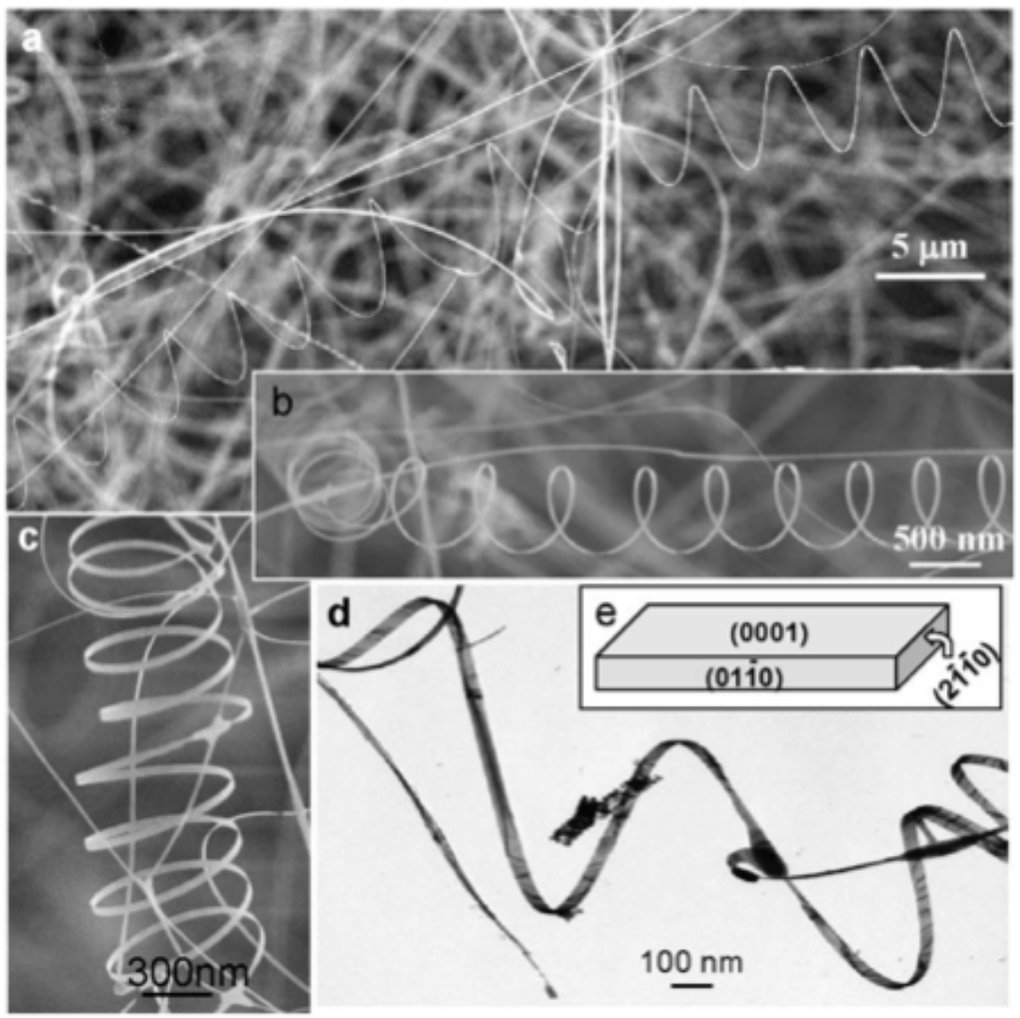
FEG
=
field emission gun



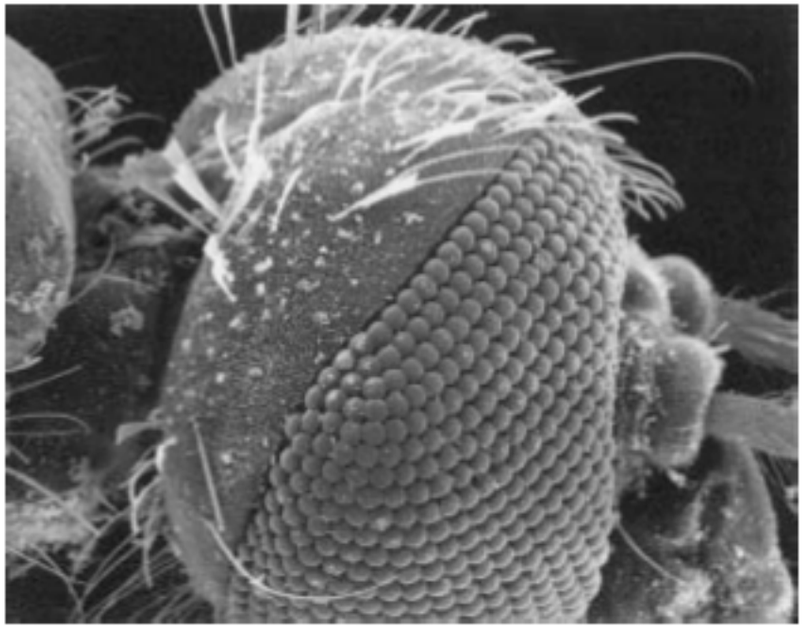


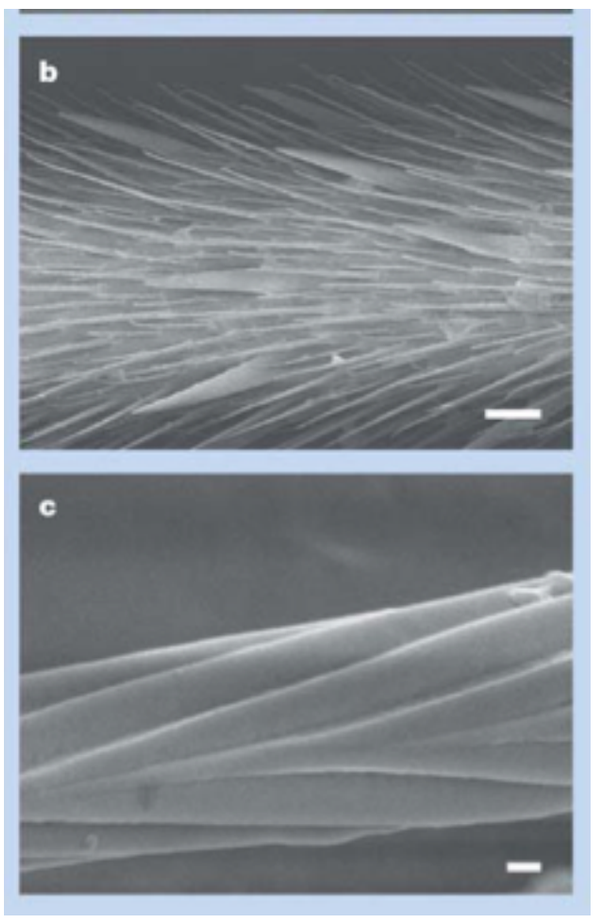

1 μm


Mag = 700.00 K X
20nm
EHT = 20.00 kV
WD = 1 mm
Signal A = InLens
Photo No. = 223
Date :17 Aug 2002
Time :11:50:37


a
5 μm
b
500 nm
c
300nm
d
100 nm
e
(0001)
(01$\bar{1}$0)
(2$\bar{1}\bar{1}$0)


2 μm




b
c

+

- Vzorec ne rabi biti tanek, ker slikamo direktno površino
- Vzorec lahko obračamo in slikamo v vseh smereh
- Globinska ostrina
- Različne povečave

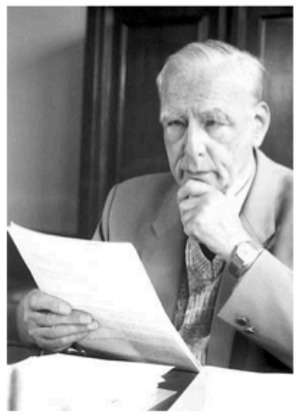
-

- Potreben je vakuum
- Vzorec mora biti prevoden (vsaj na površini)

TEM = transmission electron microscope
presevni (transmisijski) elektronski mikroskop

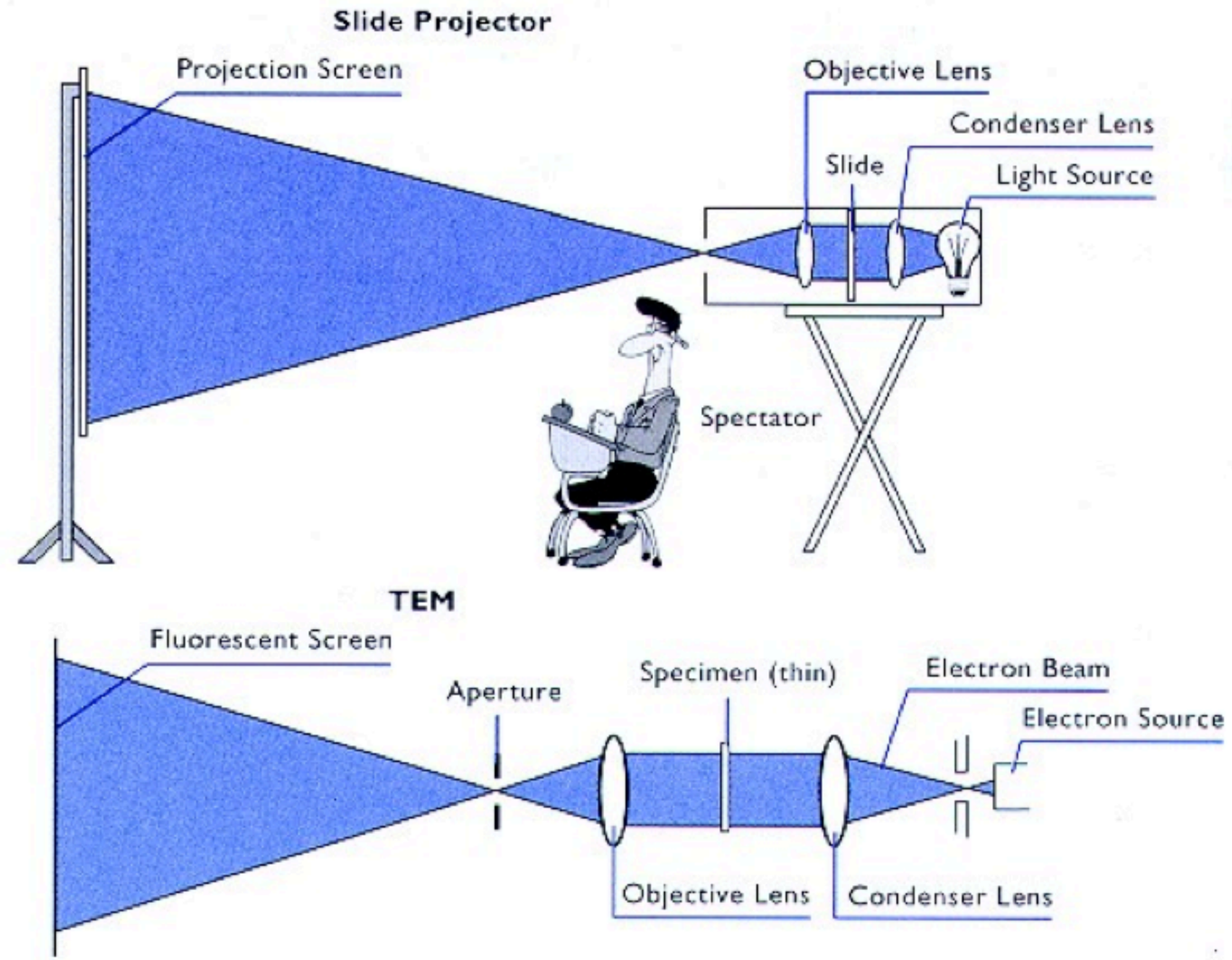
1926: elektronska leča (Bursch)
1931: prvi mikroskop (Ruska, Knoll)
1939: prvi komercialni TEM (Siemens)

The Nobel Prize in Physics 1986

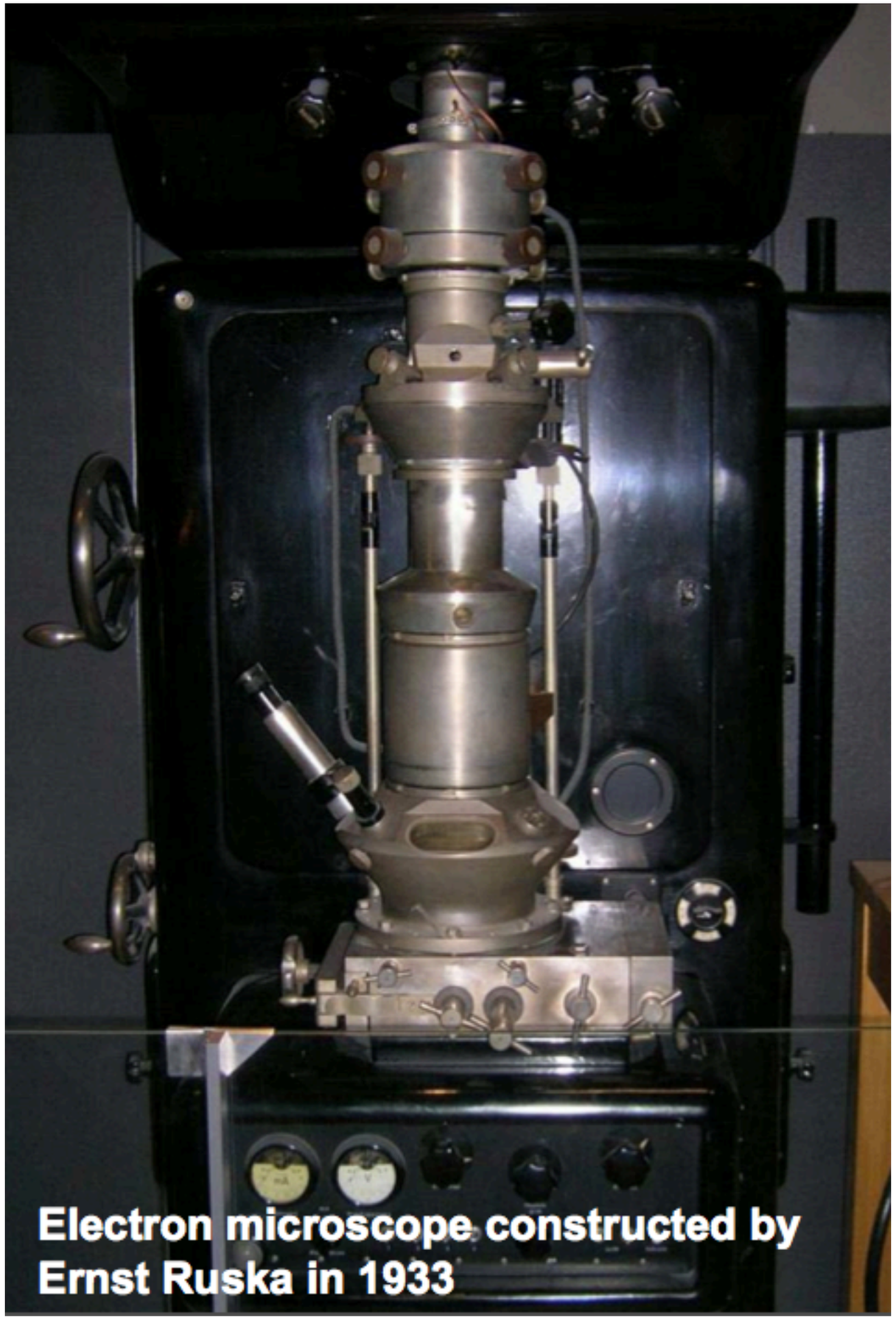


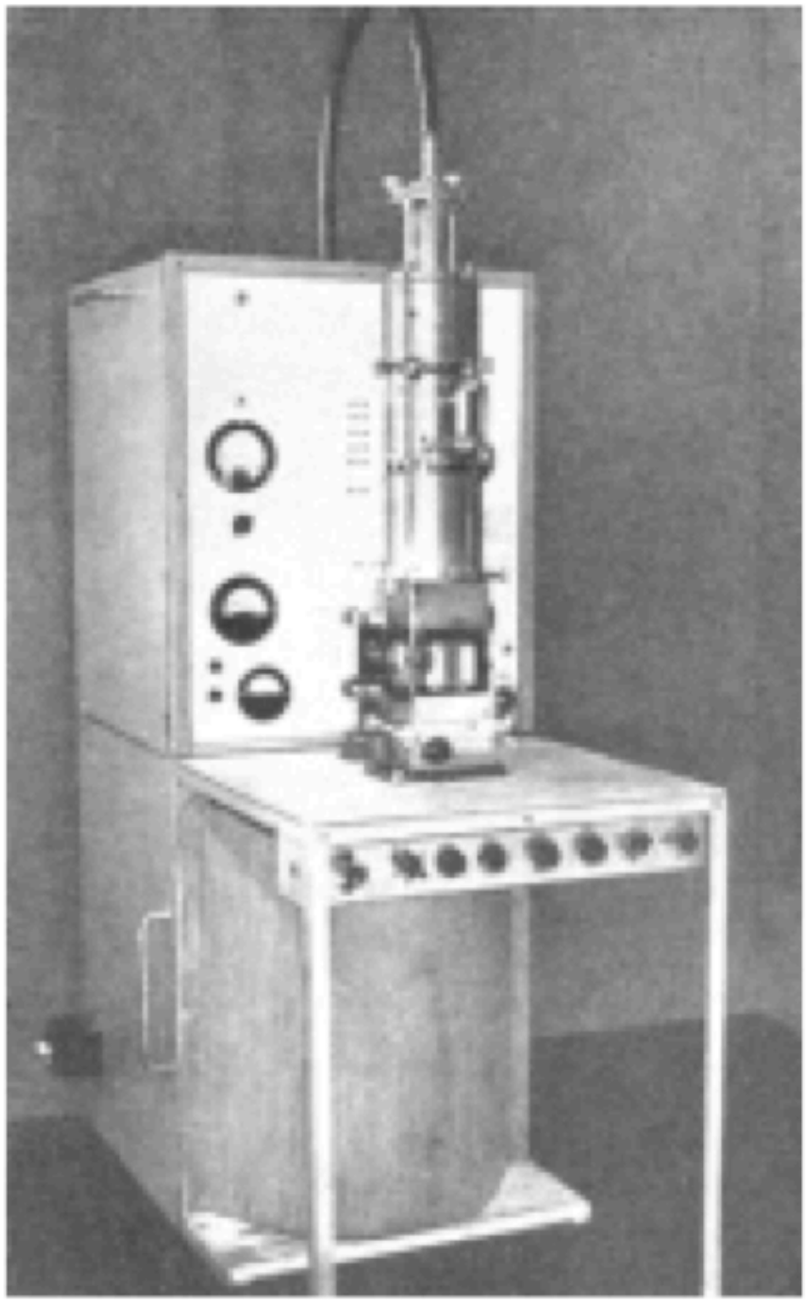
"for his fundamental work in electron optics, and for the design of the first electron microscope"

Ernst Ruska
Born: 25 December 1906, Heidelberg, Germany
Died: 27 May 1988, West Berlin, Germany
Affiliation at the time of the award: Fritz-Haber-Institut der Max-Planck-Gesellschaft, Berlin, Federal Republic of Germany



tanek vzorec, <200nm

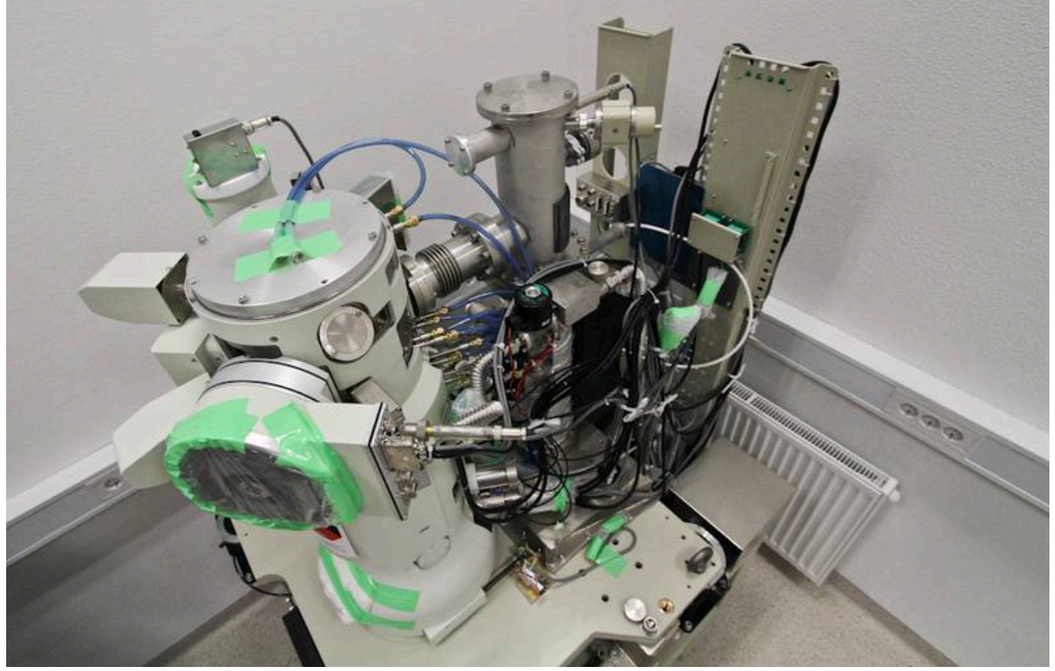

Electron microscope constructed by
Ernst Ruska in 1933



Strojnikov 50 kV elektronski mikroskop iz leta 1955

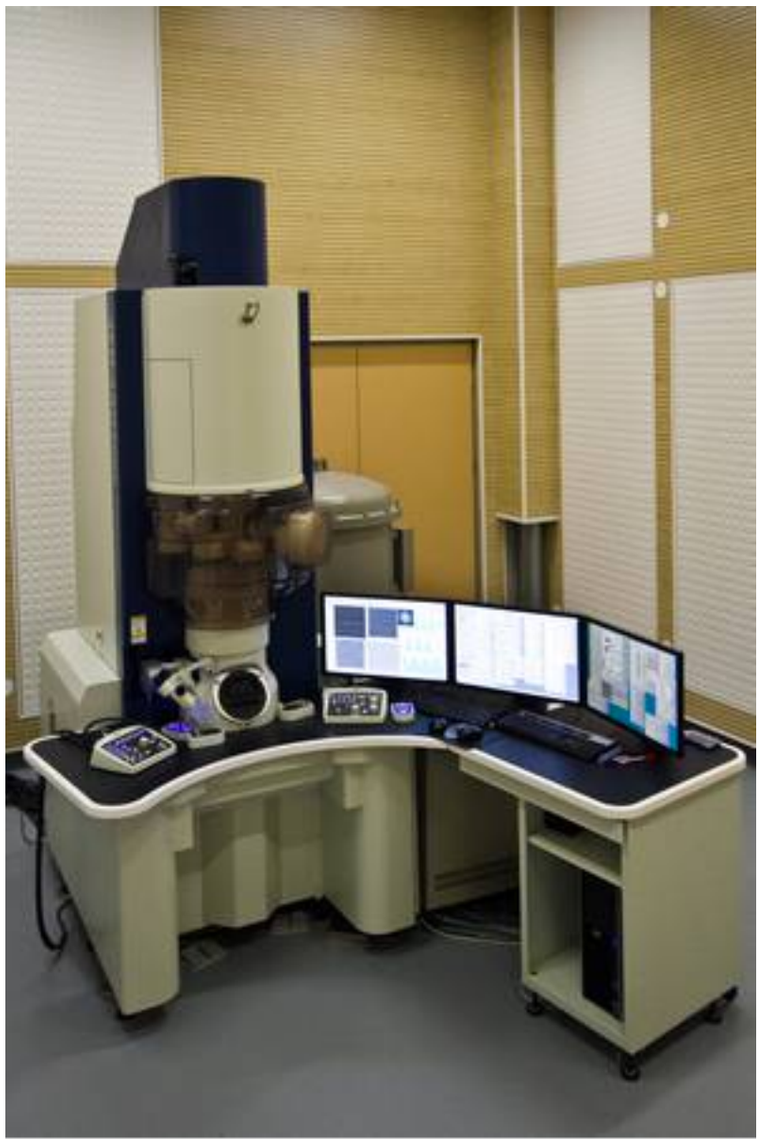
Aleš Strojnik

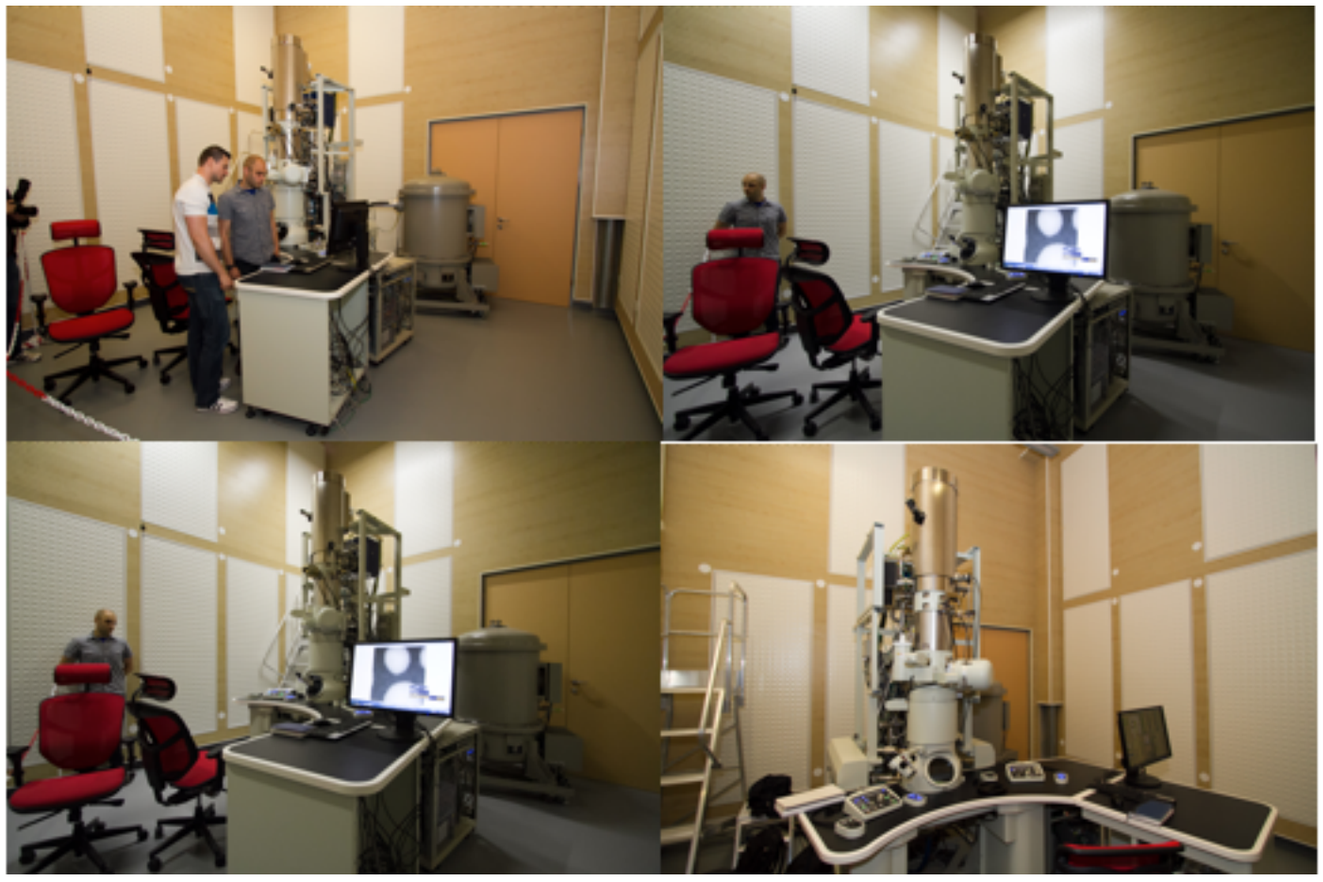
Redni profesor na ljubljanski Elektrotehniški fakulteti



http://microscopy.ki.si/

JEOL
JEM ARM 200 CF
AR-STEM

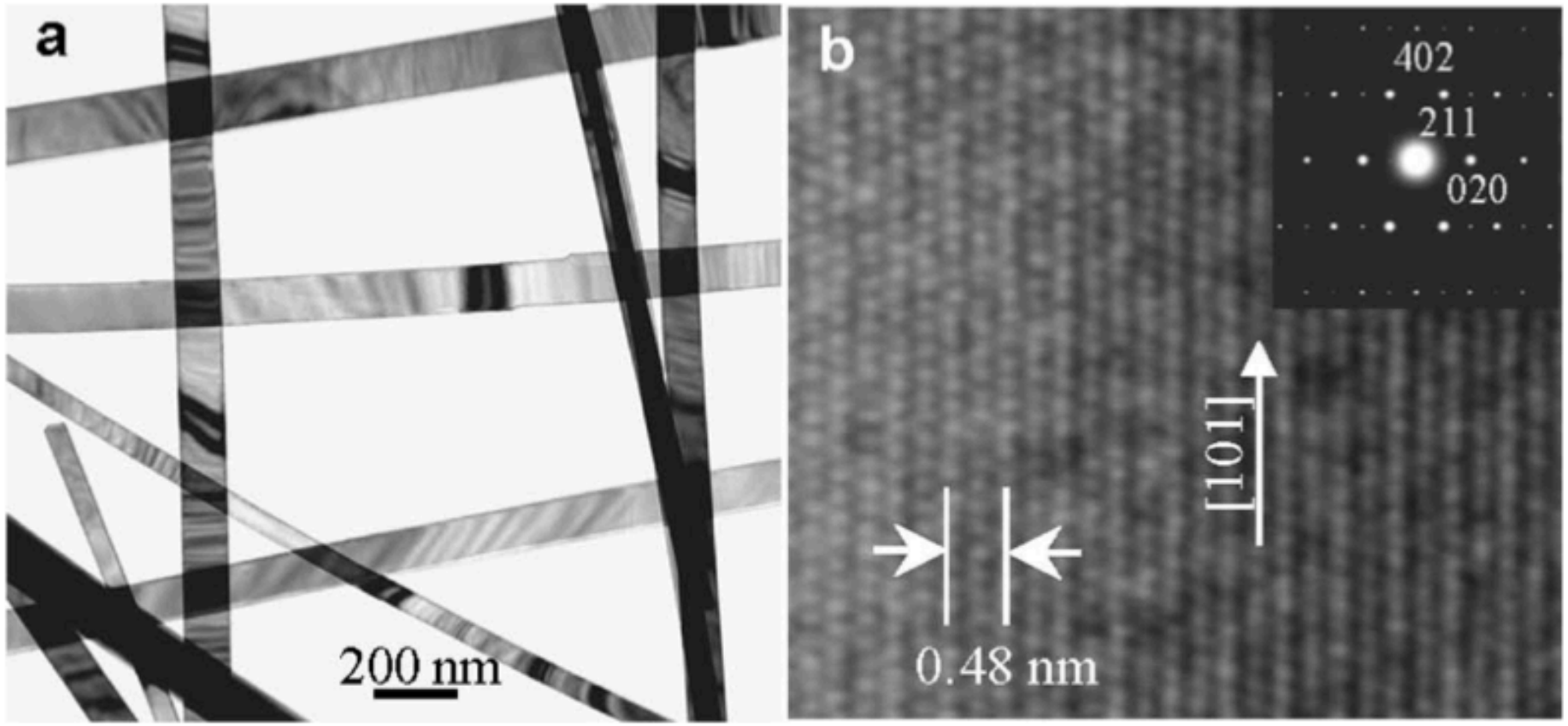


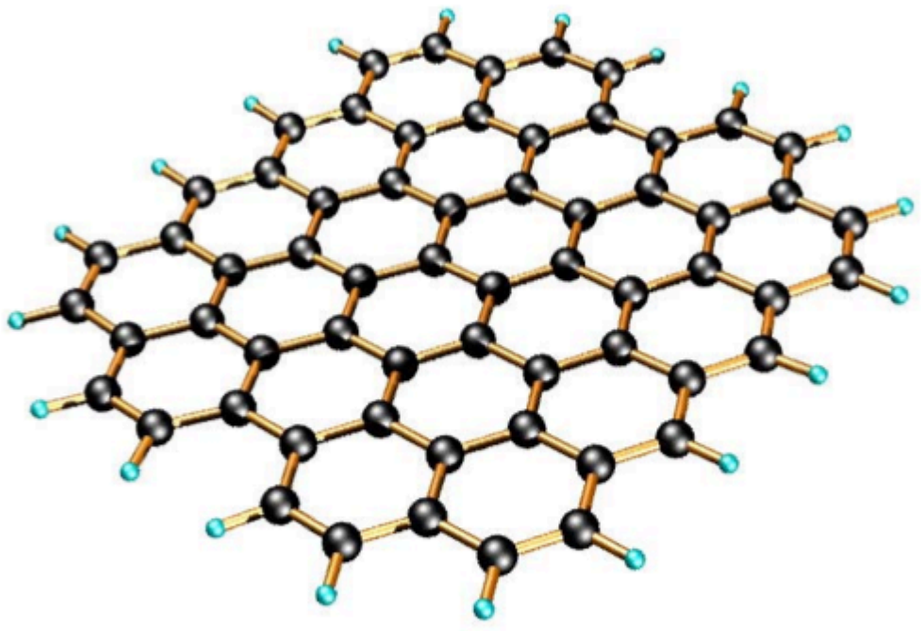


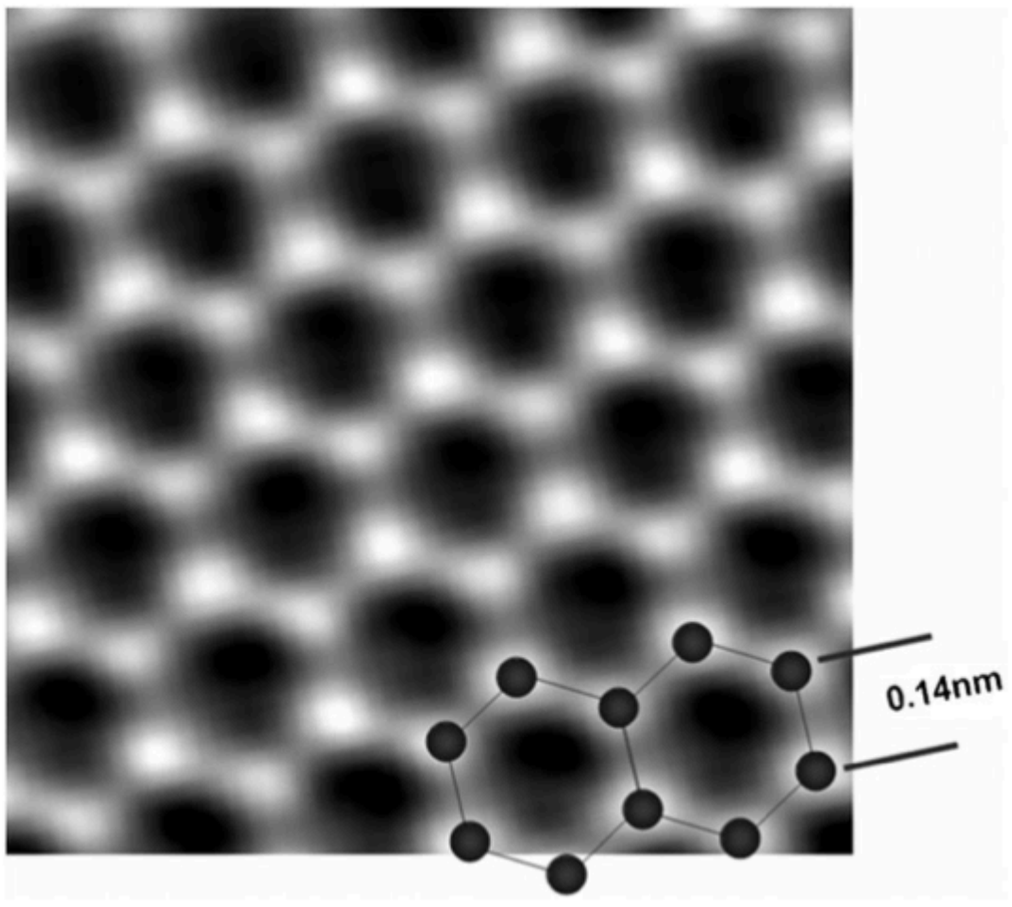
Kemijski inštitut, Ljubljana (2013)

JEOL HVTEM

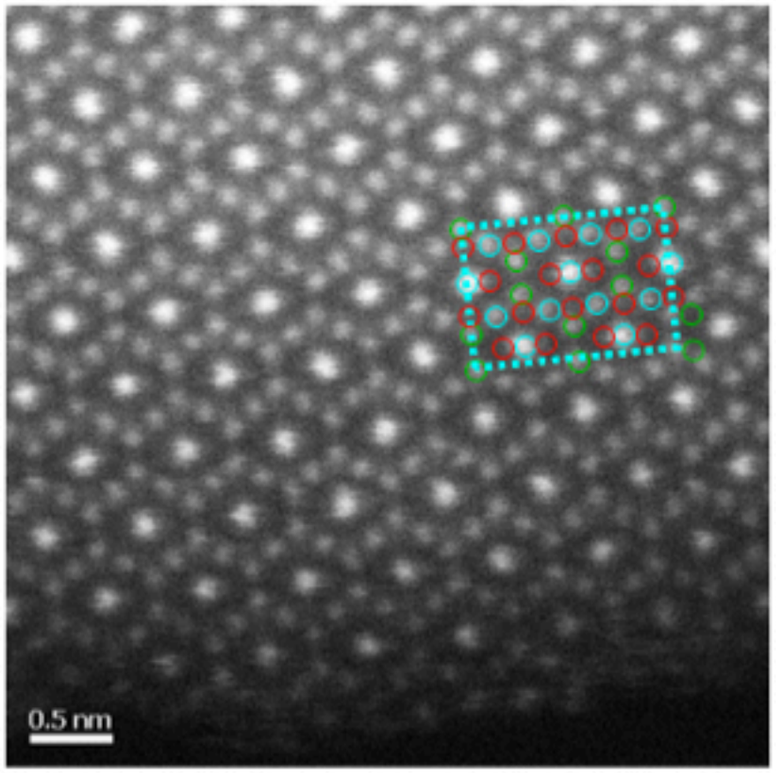
1 MV


a
200 nm
b
402
211
020
[101]
0.48 nm

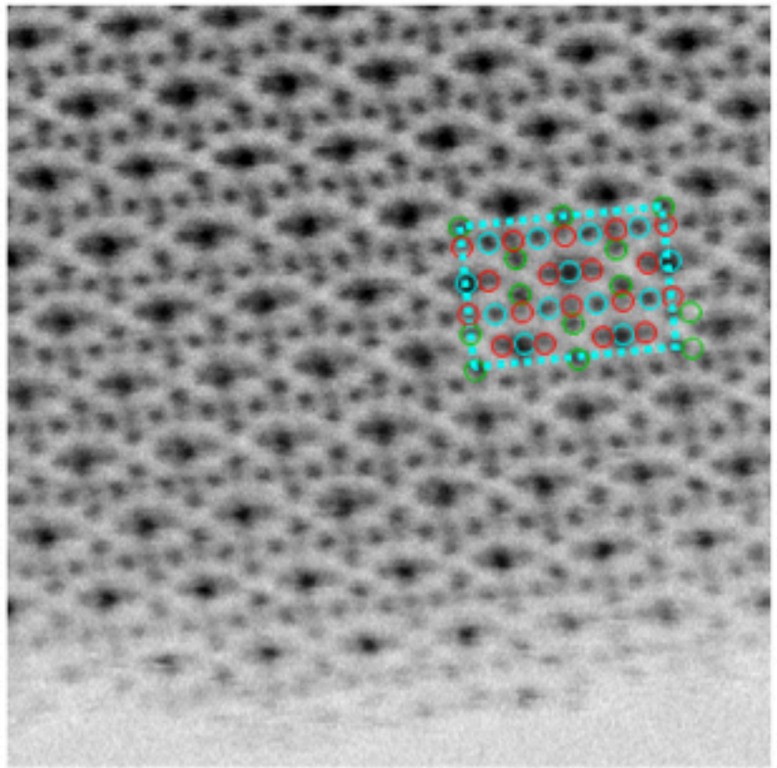



0.14nm

STEM-HAADF image

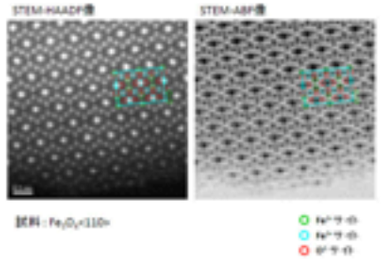


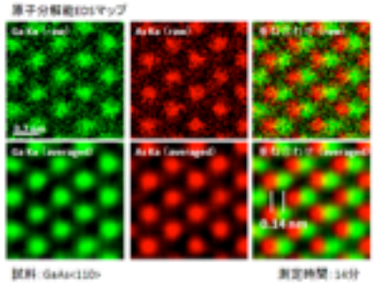
STEM-ABF image

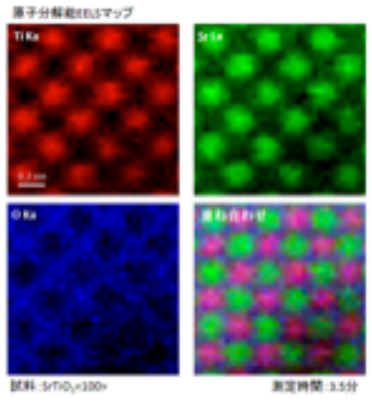


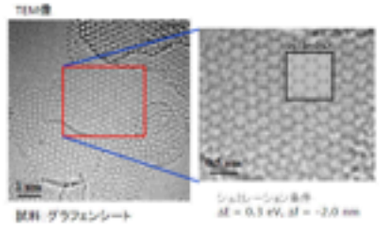
Specimen : Fe_3O_4<110>

- Fe^{2+} site
- Fe^{3+} site
- O^{2-} site









Tipalni mikroskopi

Kaj se zgodi, ko približamo dva kosa snovi na izjemno majhno medsebojno razdaljo?

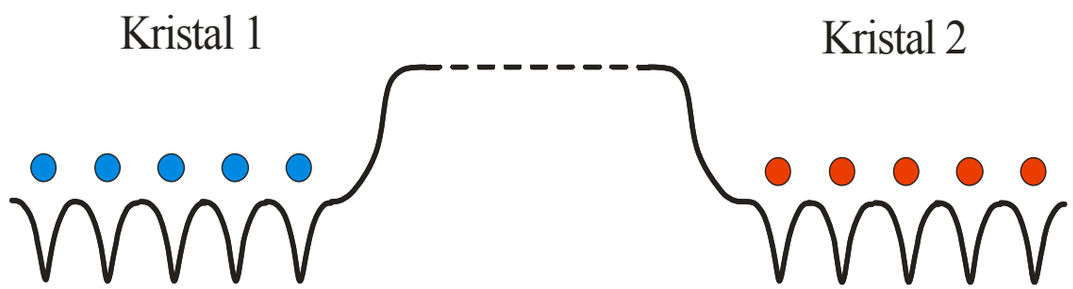
- Sile med površinama
  - privlačna van der Waalsova
  - kemijska vezava (kovalentna vez)
  - odbojna sila ob mehanskem kontaktu
- Tunelski pojav in električni tok med kosoma snovi

Tunelski pojav

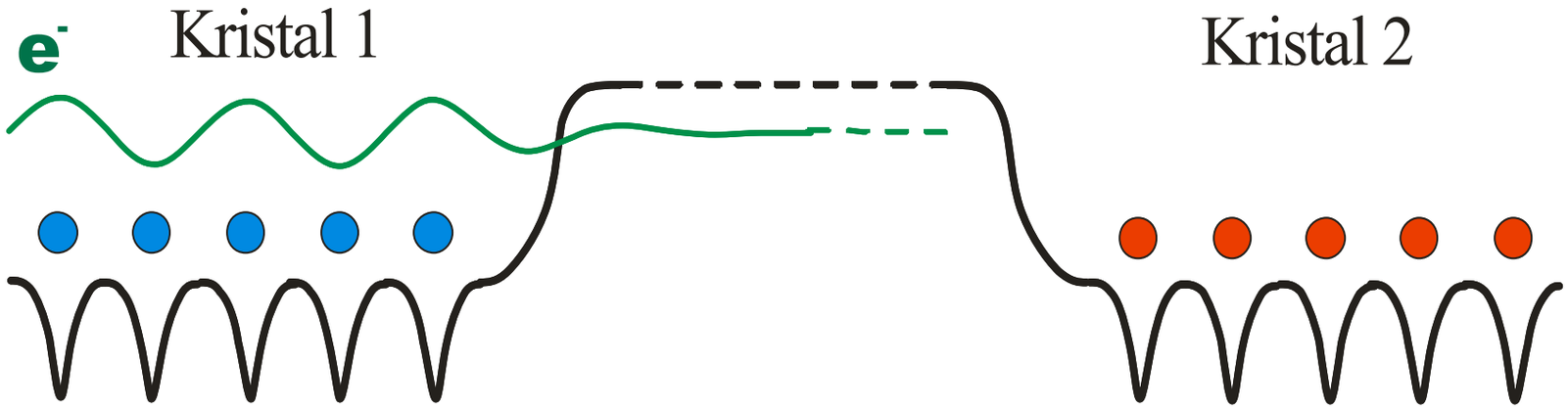
- Elektroni se obnašajo kot **valovanje** in/ali kot delci (dualnost) → valovni paketi.
- Valovanje lahko prodre skozi tanko oviro, v katero klasični delec ne bi mogel vstopiti. Rečemo, da tunelira skozi prepovedano območje.
- Neposredna posledica zakonov **kvantne fizike**, nima analogije v klasični mehaniki.

Tunelski pojav

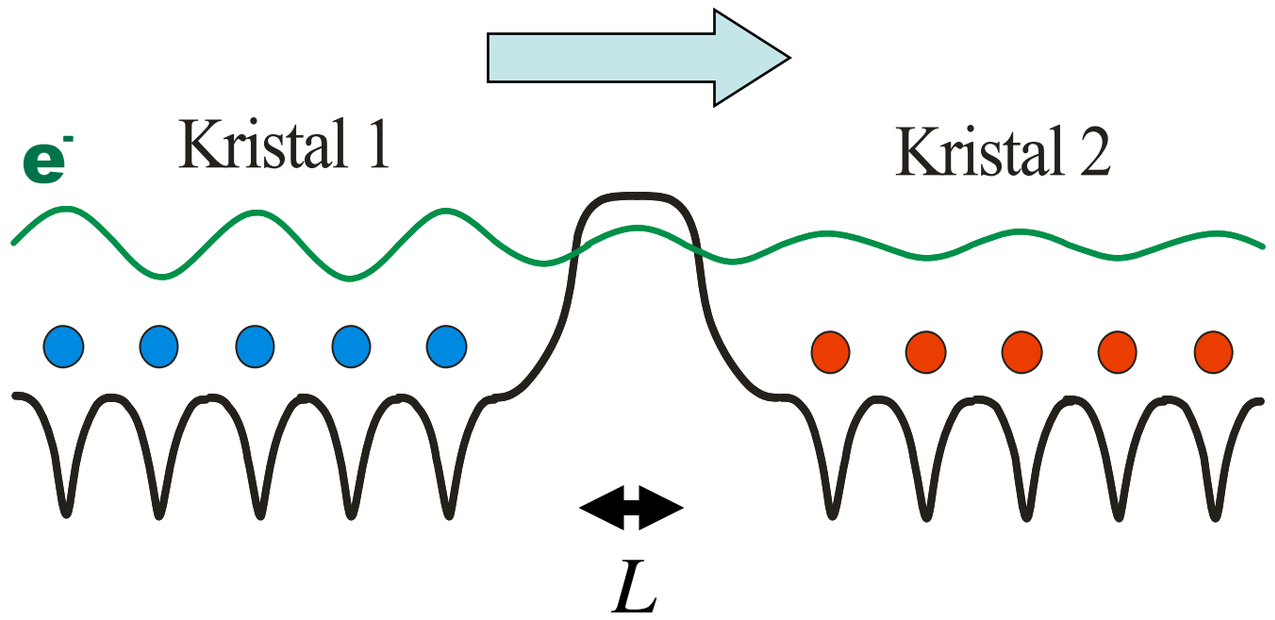
Tunelski pojav



Tunelski pojav



Tunelski pojav



$$I \propto e^{-2\kappa L}$$

1/2 Nobelove nagrade leta 1973 za “eksperimentalna odkritja o tunelskem pojavu v polprevodnikih oziroma v superprevodnikih”.

Leo Esaki

Ivar Giaever

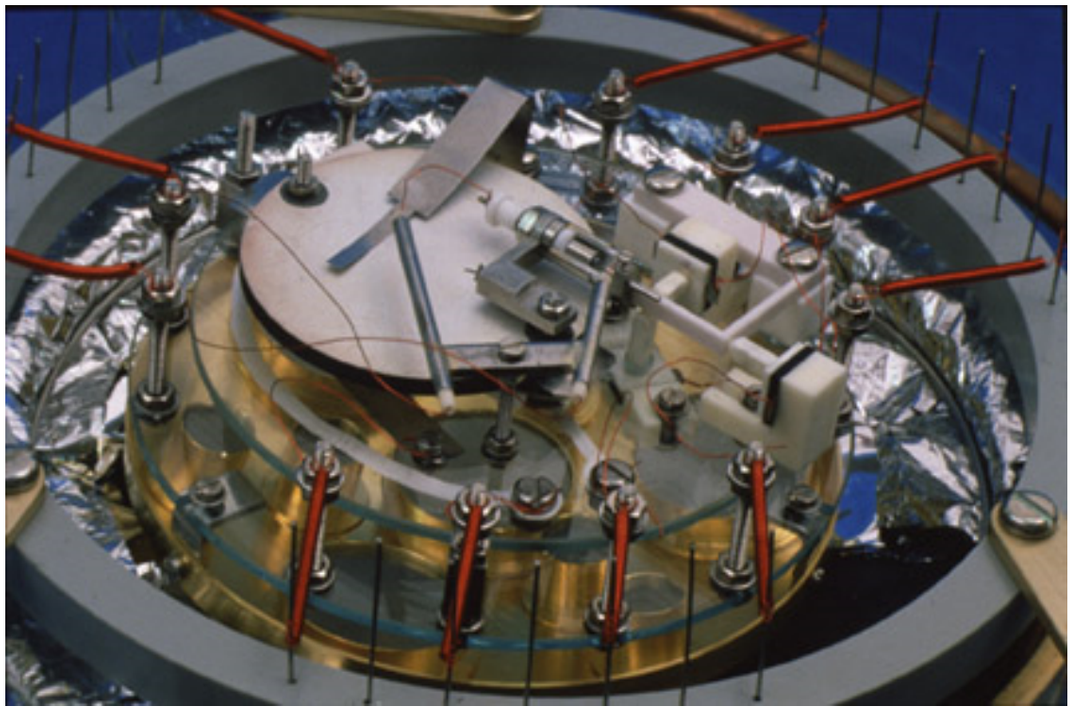
1/2 Nobelove nagrade za “teoretično napoved lastnosti supertokov skozi tunelsko pregrado, oziroma bolj natančno za tiste pojave, ki so v splošnem znani kot Josephsonov pojav”.

Brian David Josephson

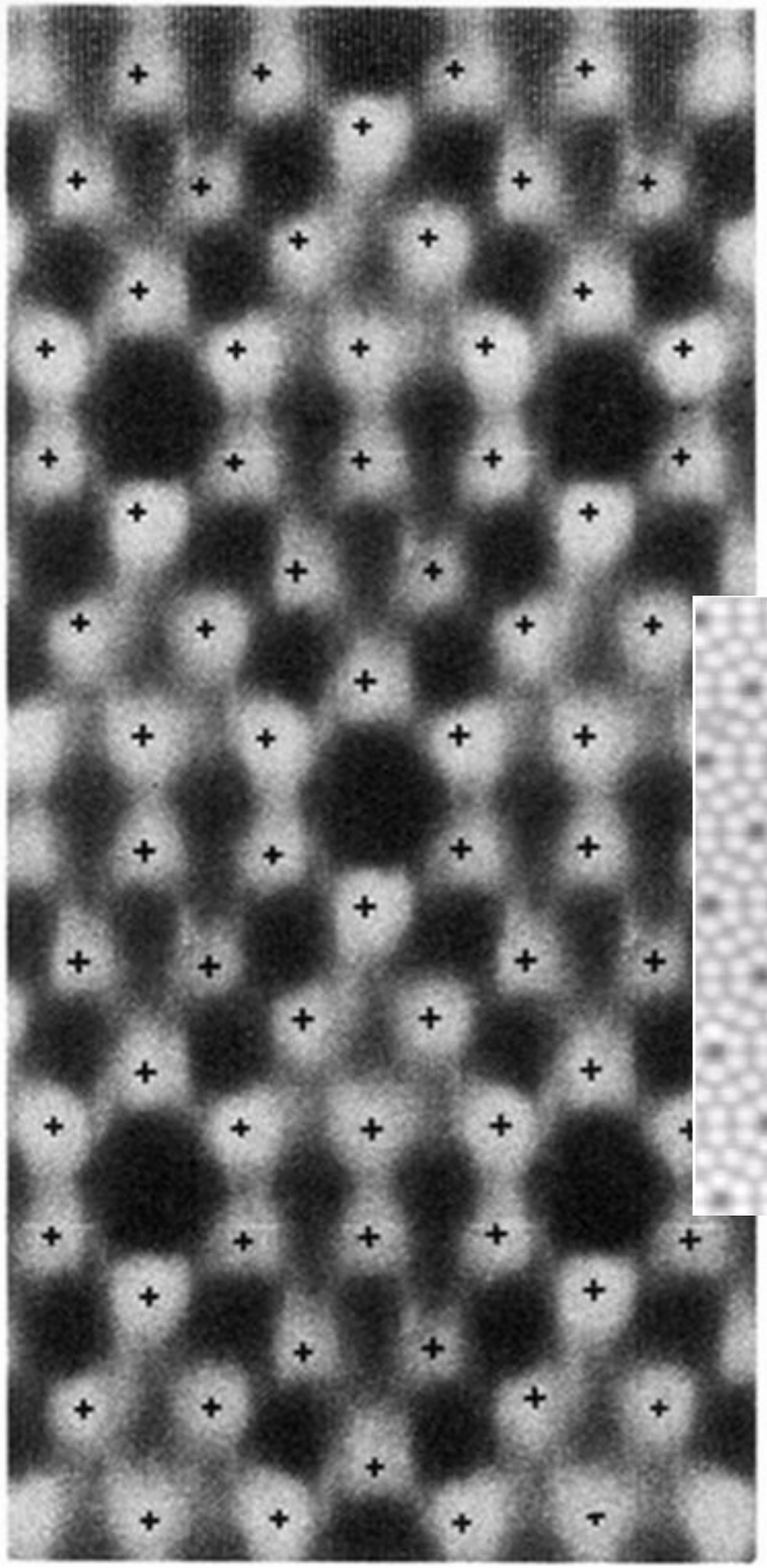
Vrstični tunelski mikroskop

Nobelova nagrada leta 1986 za “izdelavo vrstičnega tunelskega mikroskopa”.

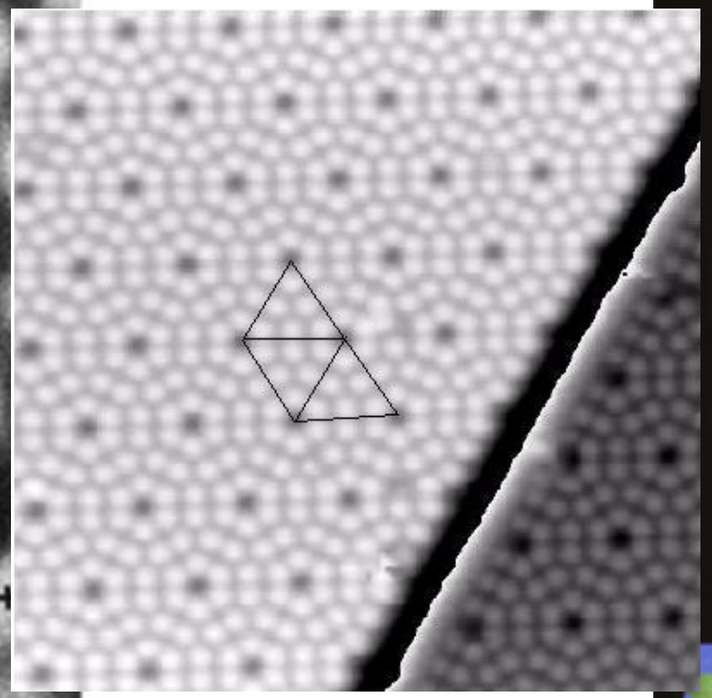
Heinrich Rohrer, Gerd Binnig

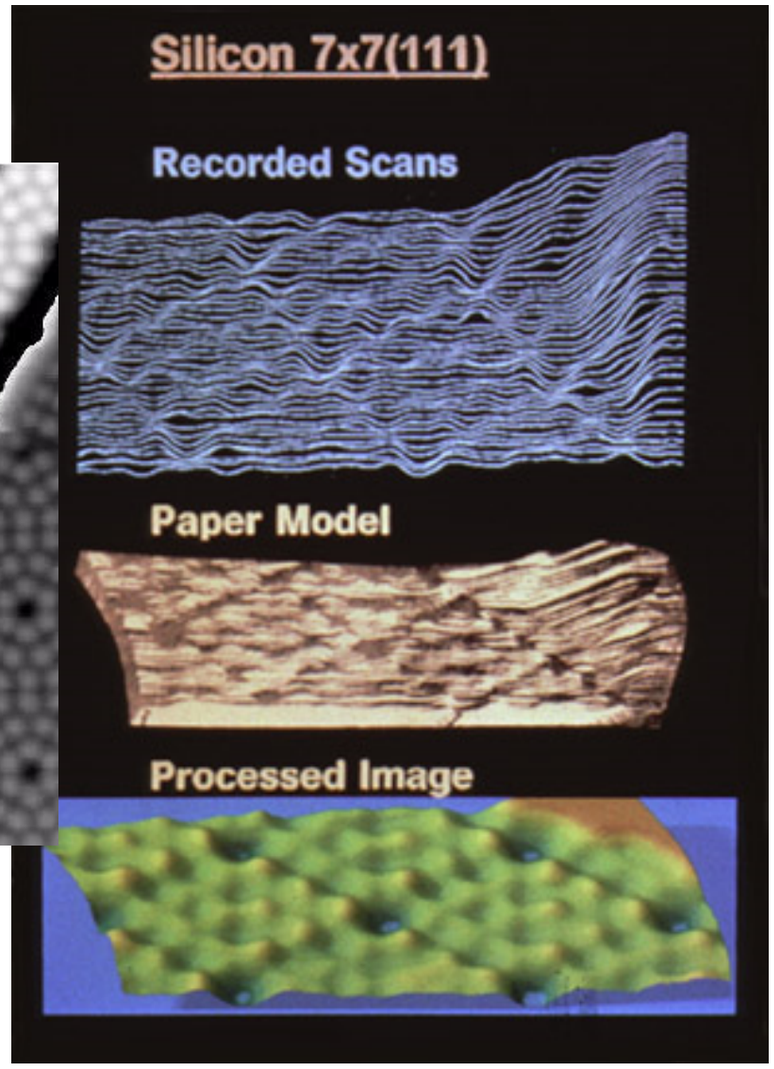


Prvi tunelski mikroskop (1981)



G. Binnig, H. Rohrer, Ch. Gerber, and E. Weibel
“7 × 7 Reconstruction on Si(111) Resolved in Real Space”
Phys. Rev. Lett. **50**, 120 - 123 (1983)

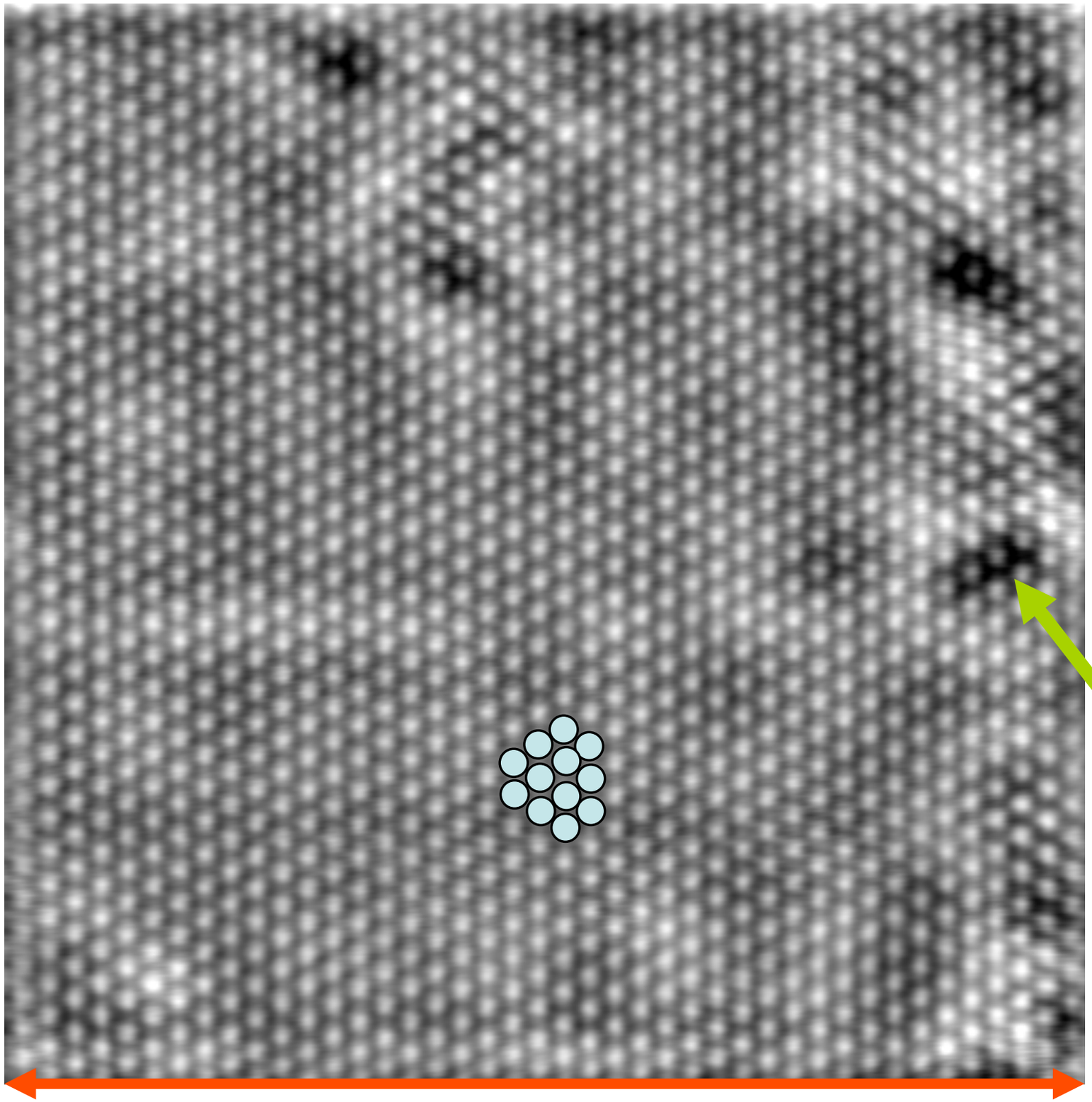




Si(111)-7x7

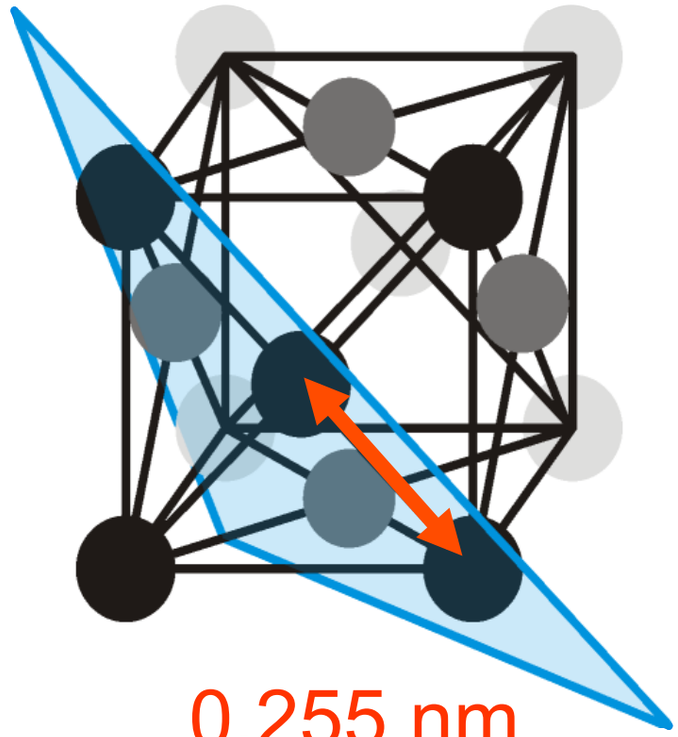
Vir: IBM Zürich

Atomska ločljivost na bakru pri T=25 K (2005)



9,2 nm

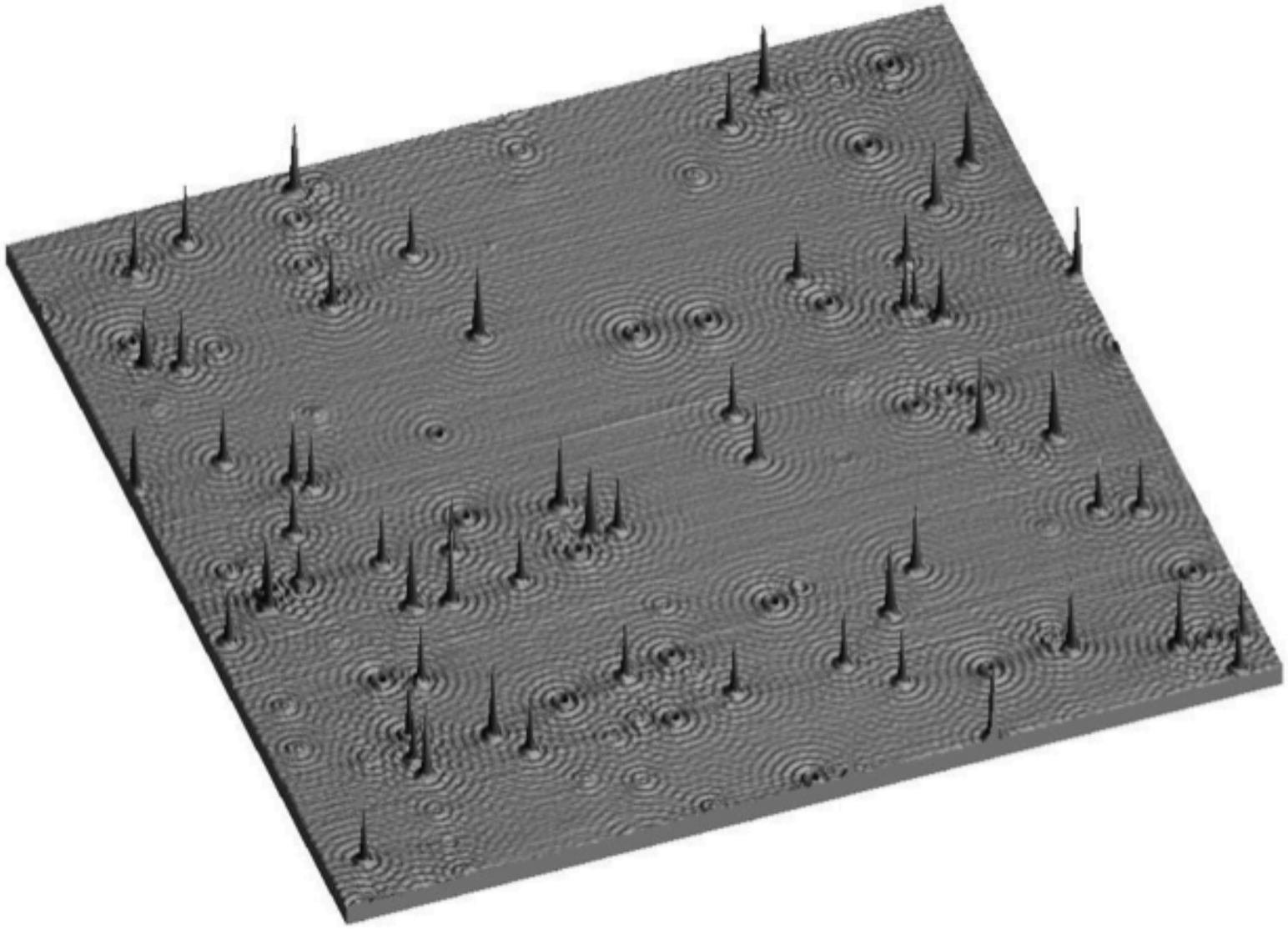
Površina bakra
Cu(111)



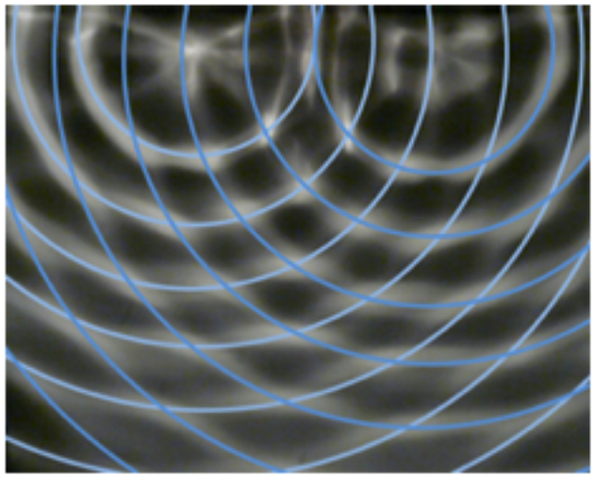
0,255 nm

Pod površino so napake v kristalu.

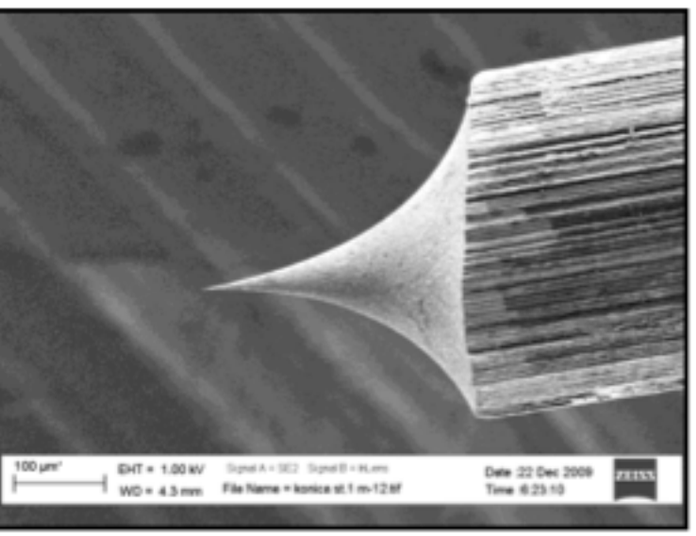
Odsek F5,
IJS

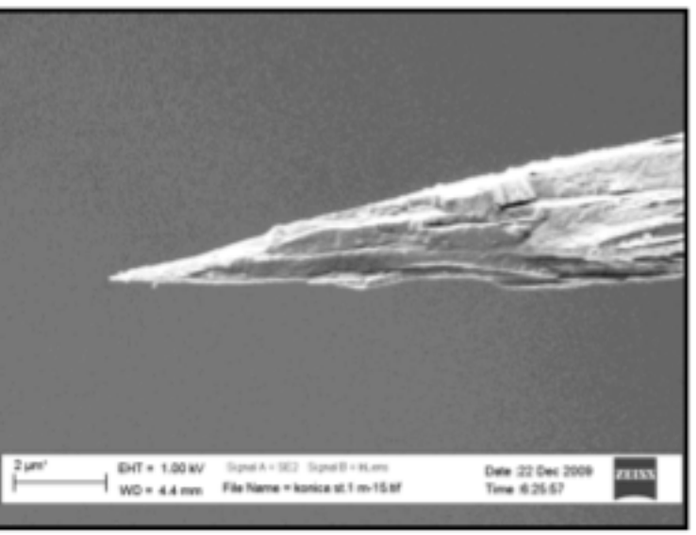


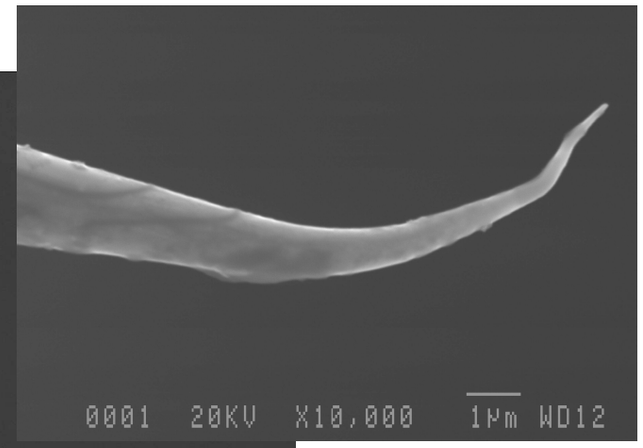
150 x 150 nm^2



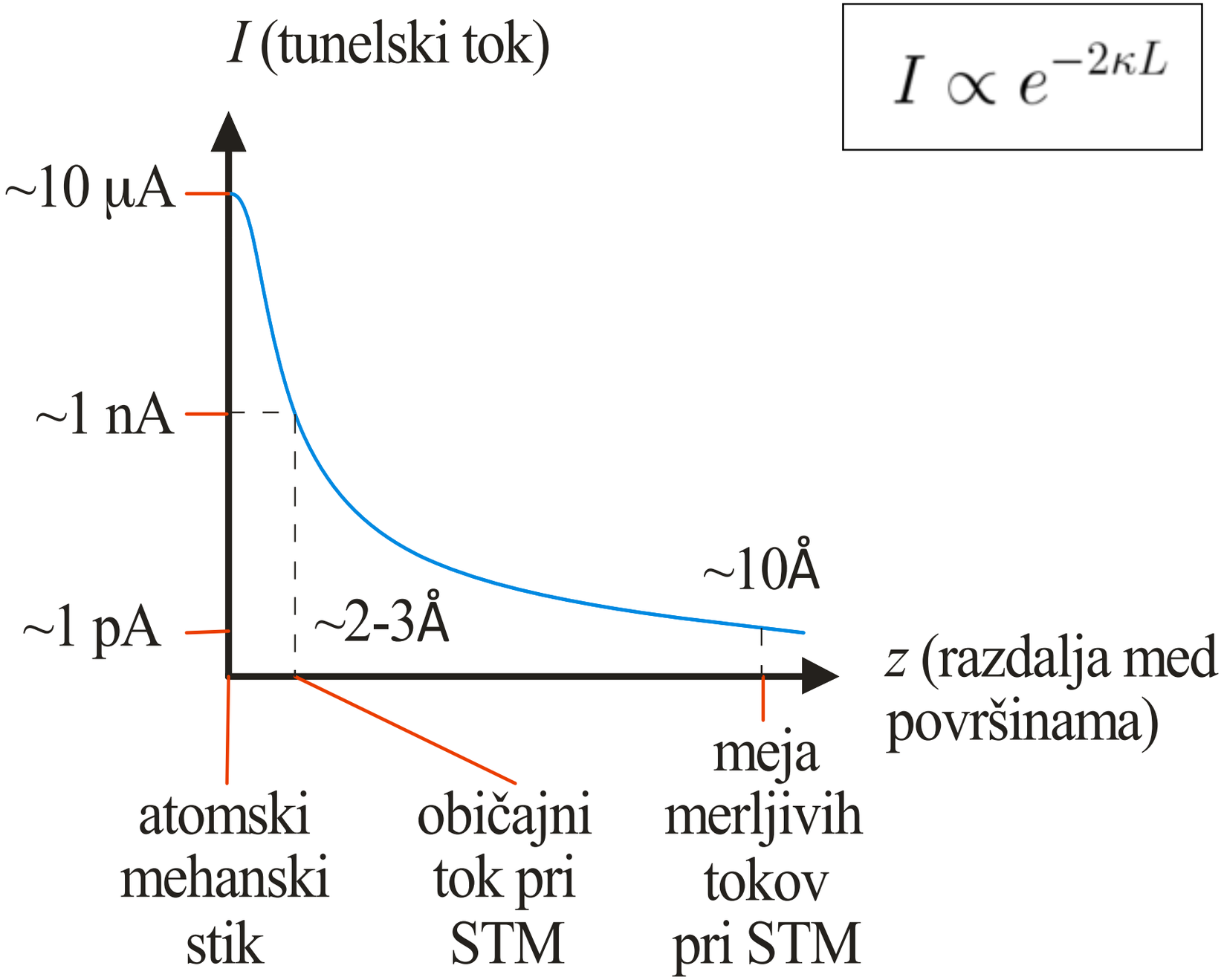
Tipalo mikroskopa: ostra konica iz W



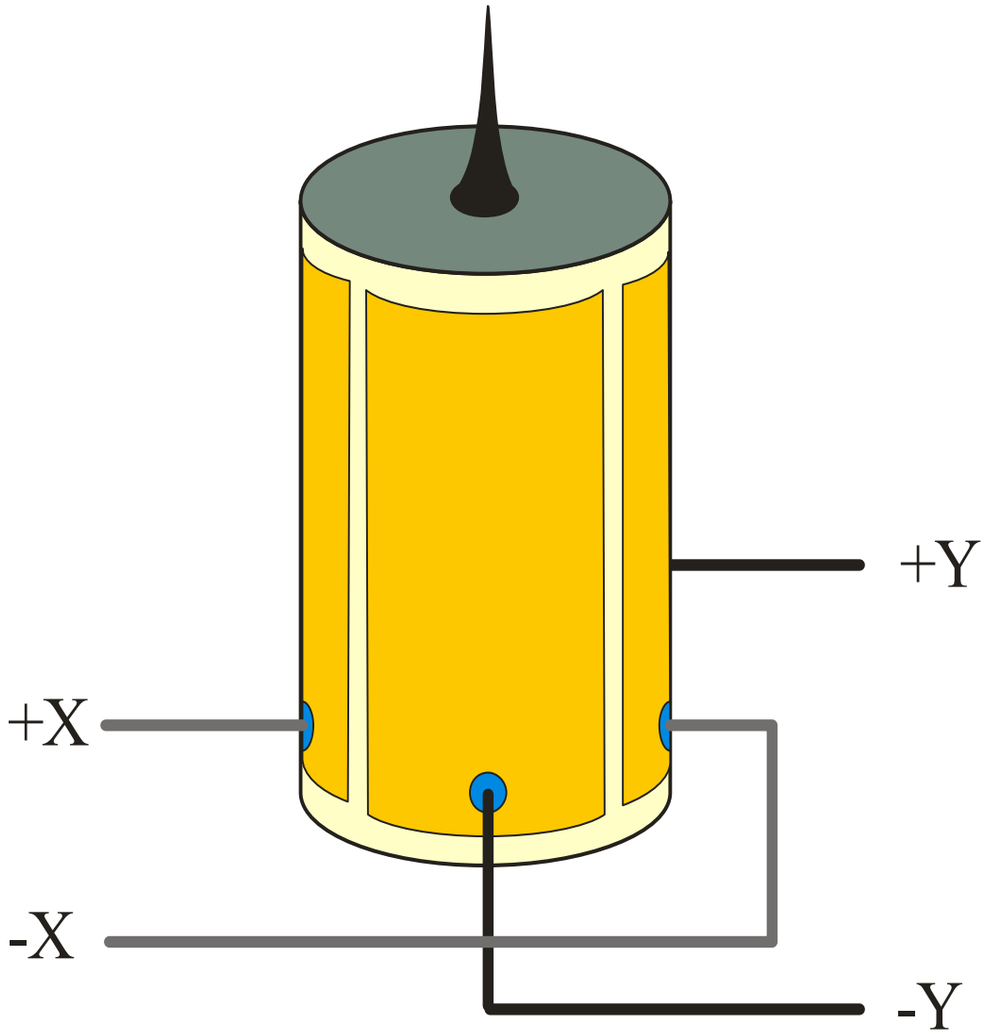


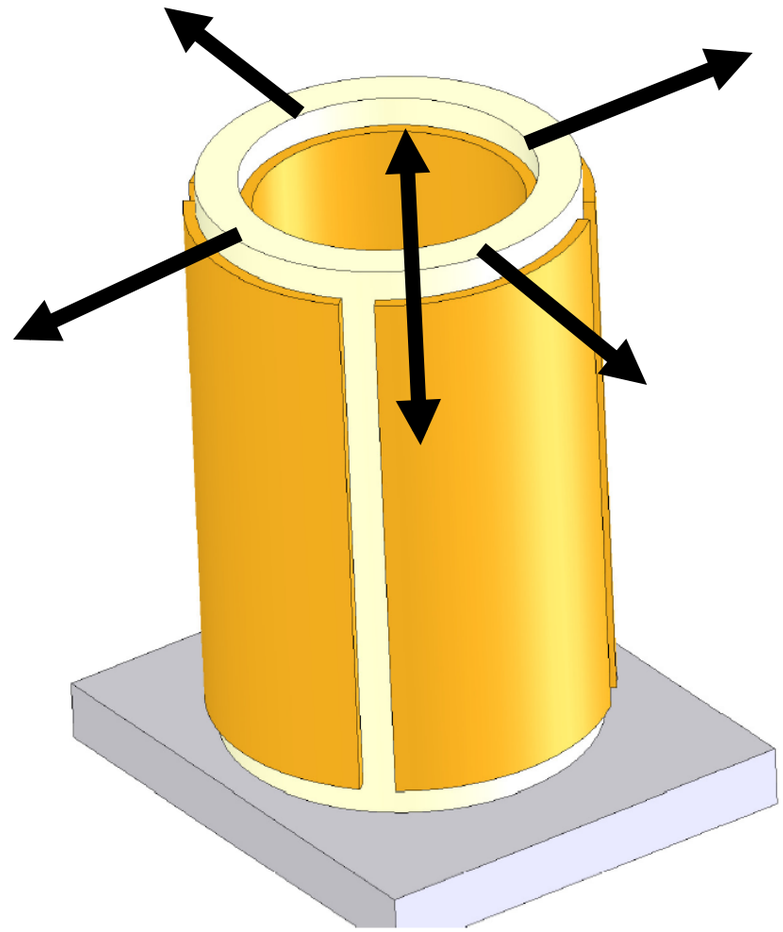


$$I \propto e^{-2\kappa L}$$

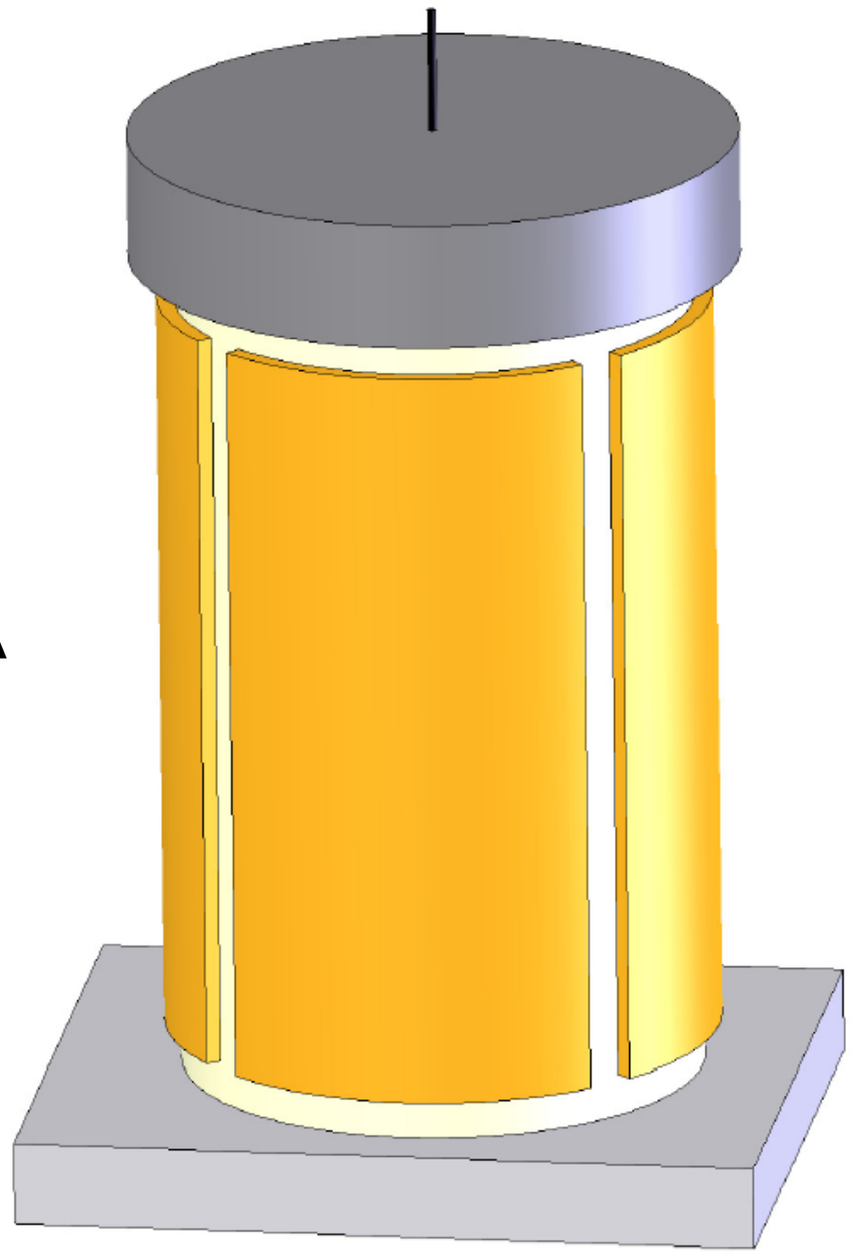


Kako posnamemo sliko?





Premikanje tipala s (pod)atomsko natančnostjo

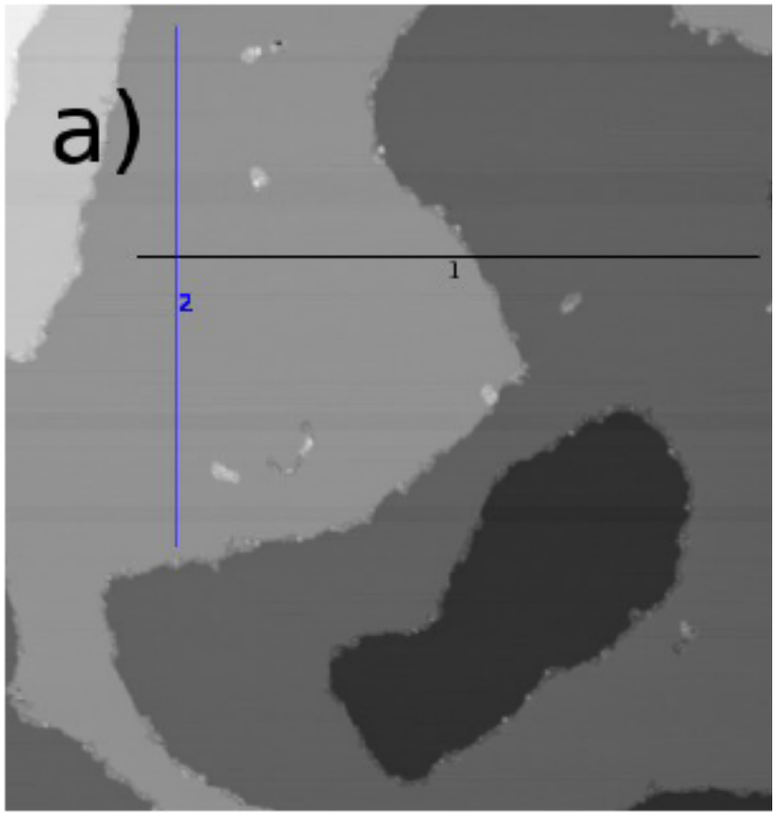


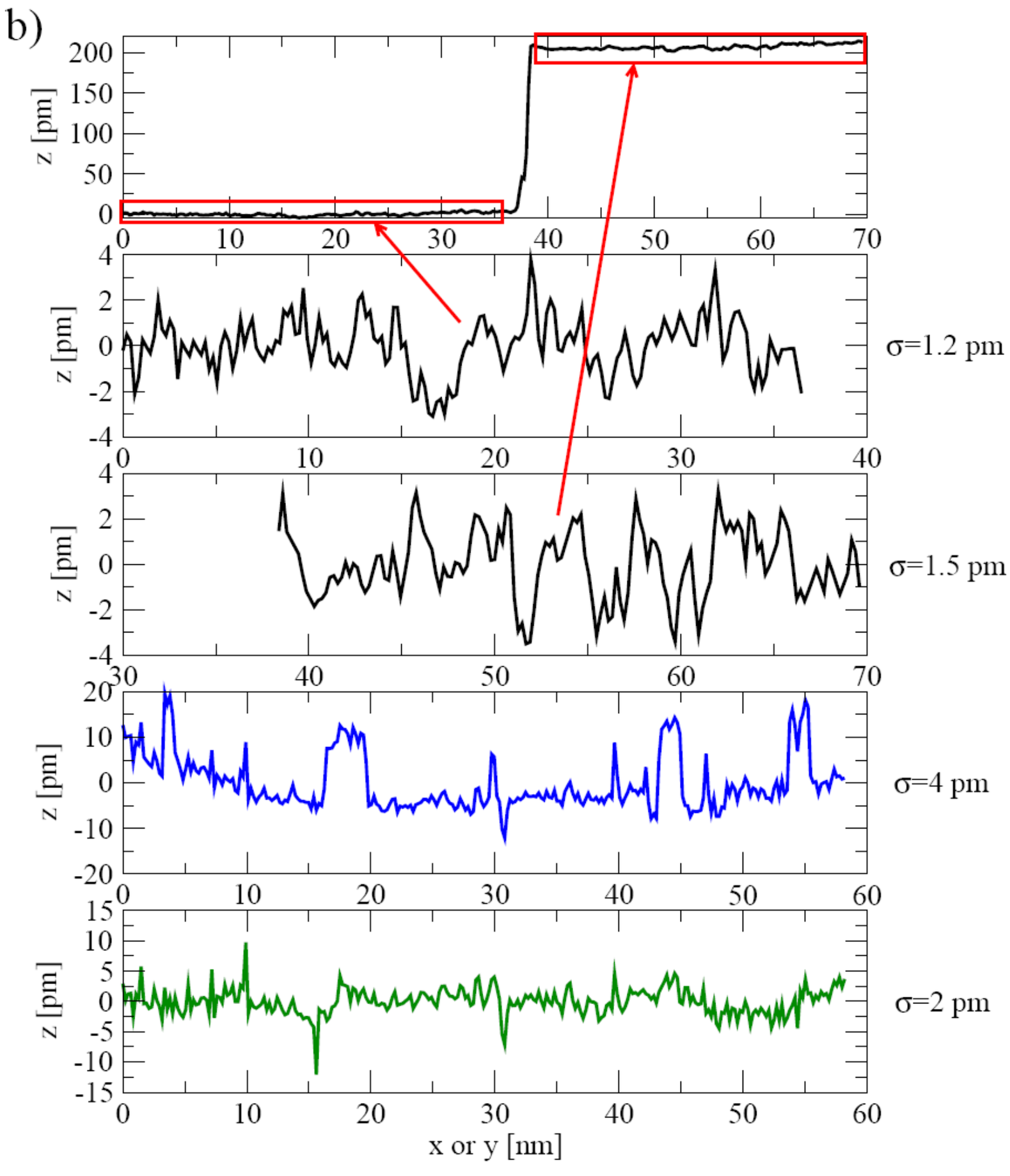
Velikost cevke: 1 cm

Natančnost premika: 0.01 Å

Razmerje: $1:10^{10}$

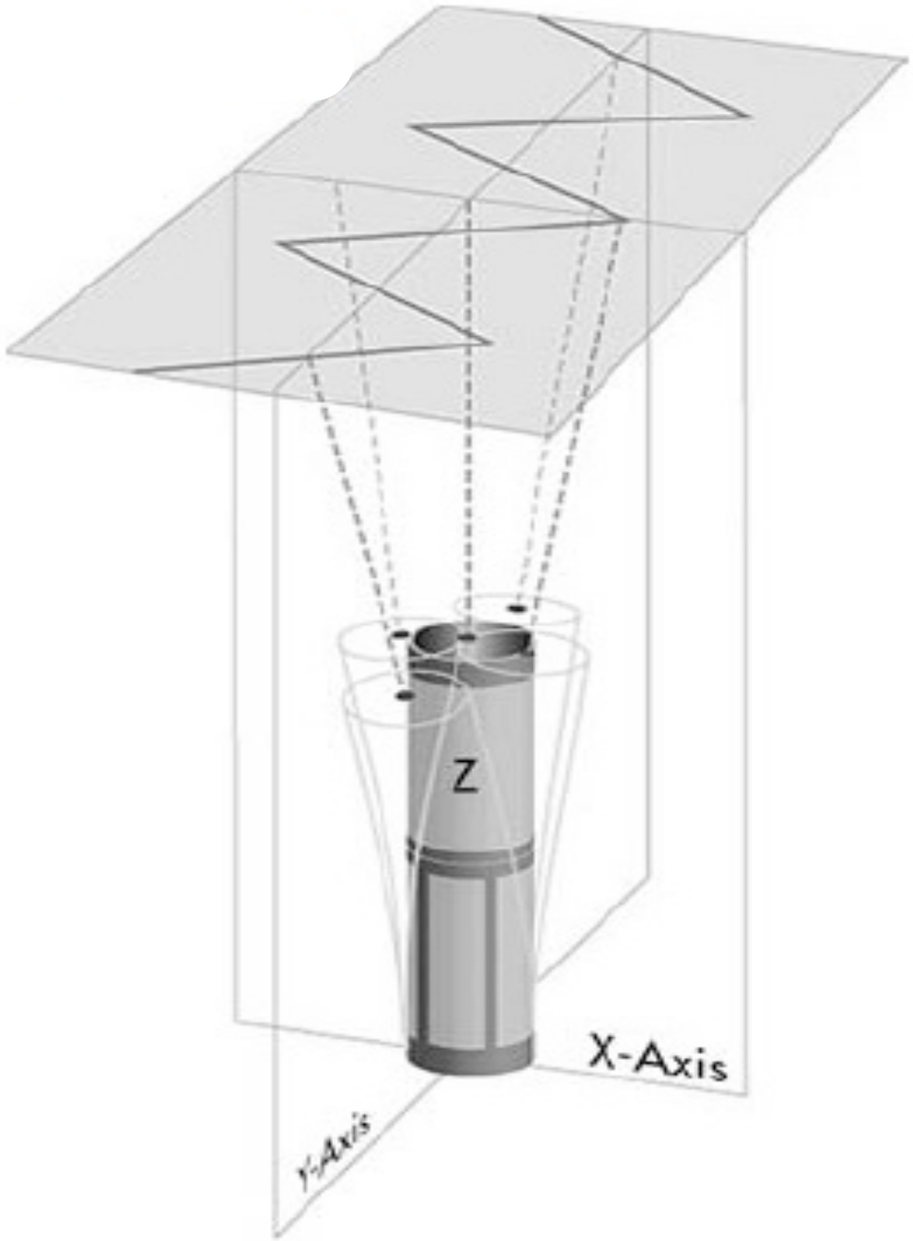
1 mm : Ljubljana-Los Angeles

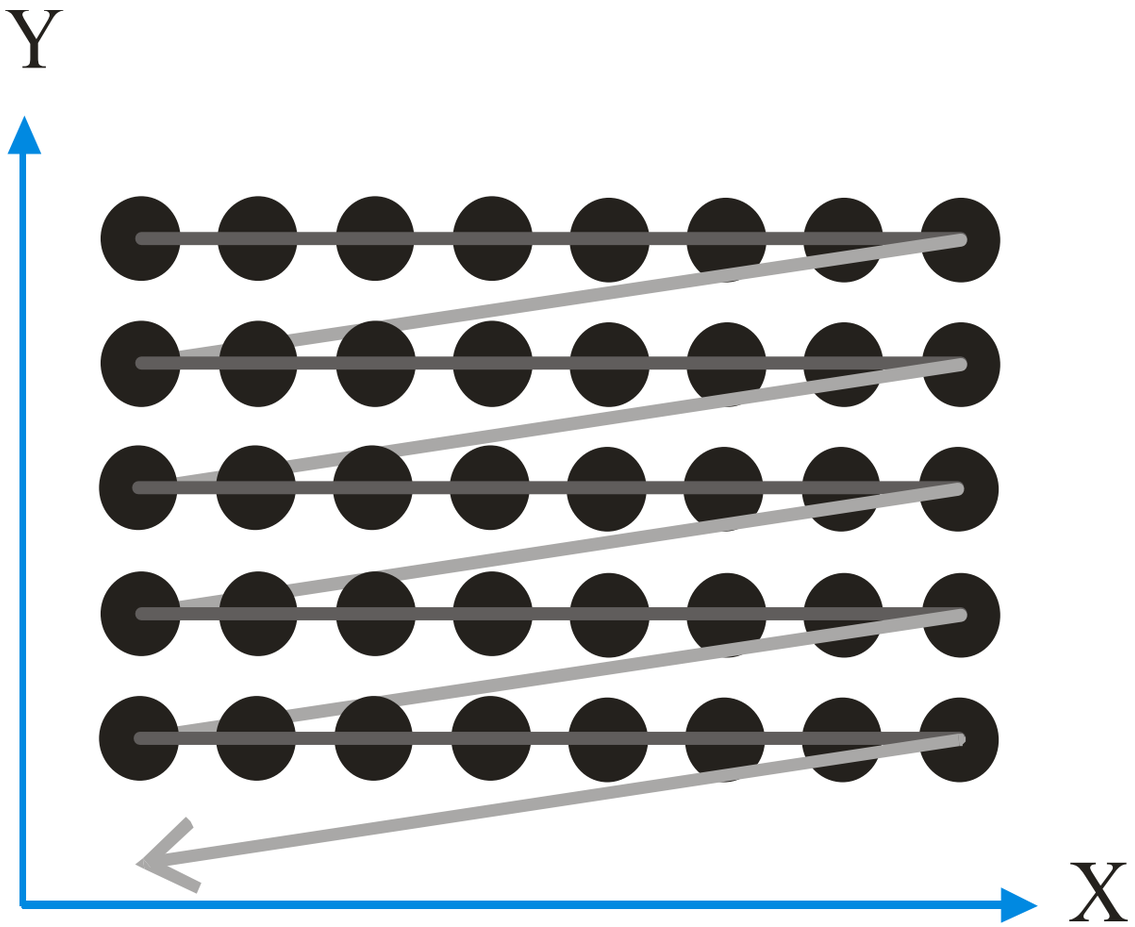




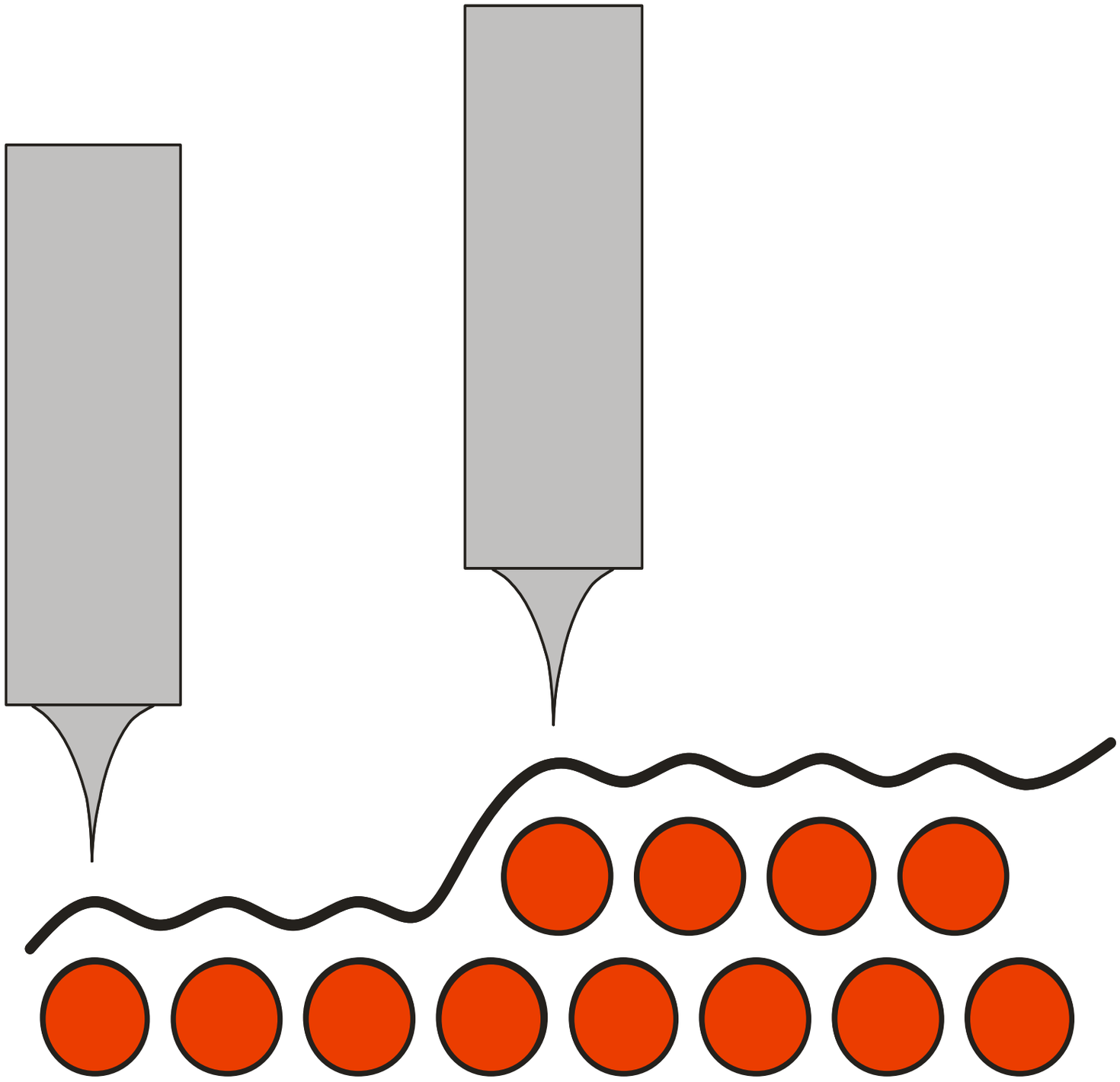
High mechanical stability!

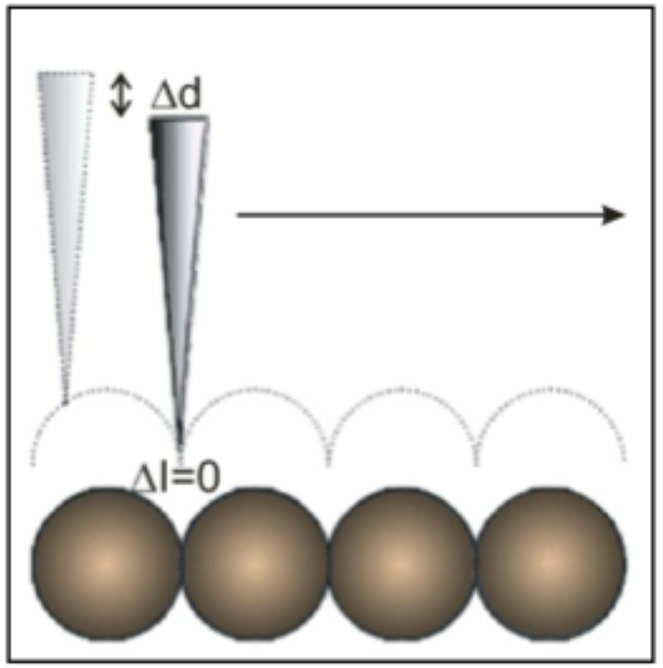
Kako posnamemo sliko?

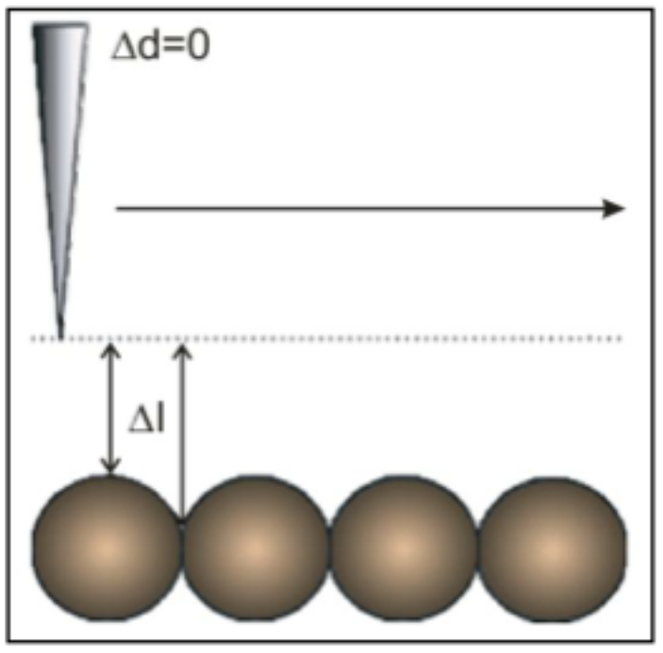




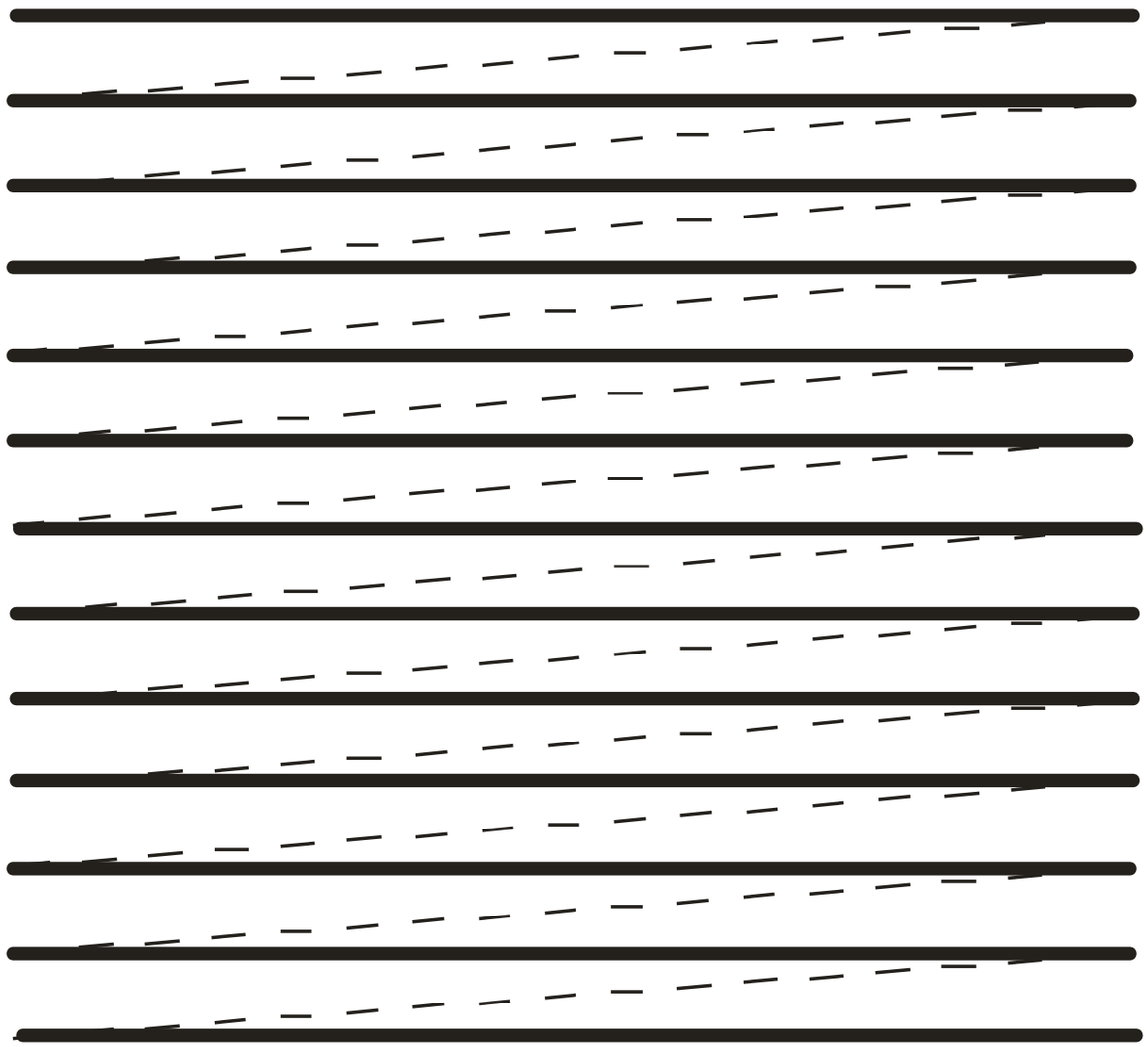
Povratna zanka

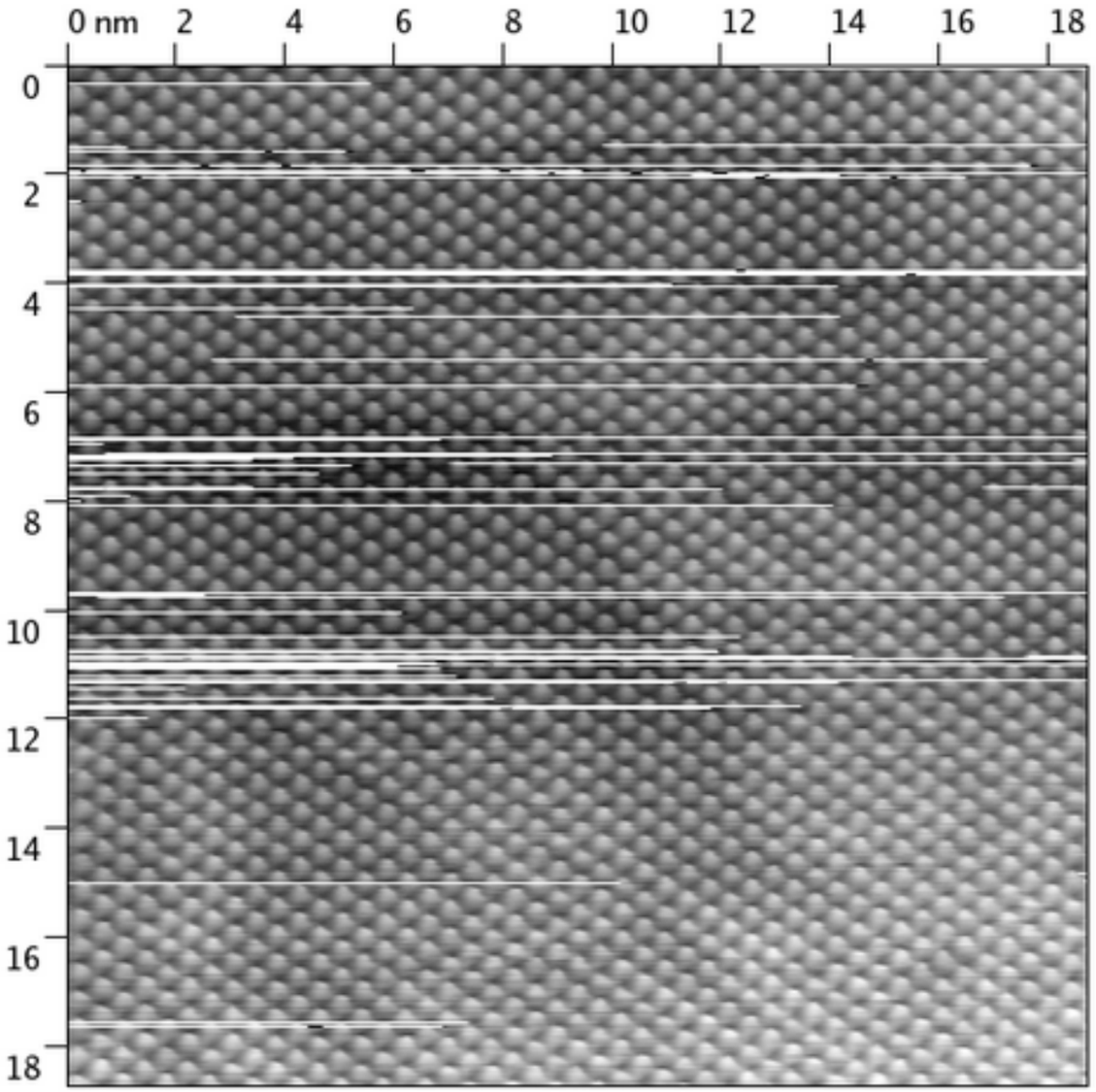






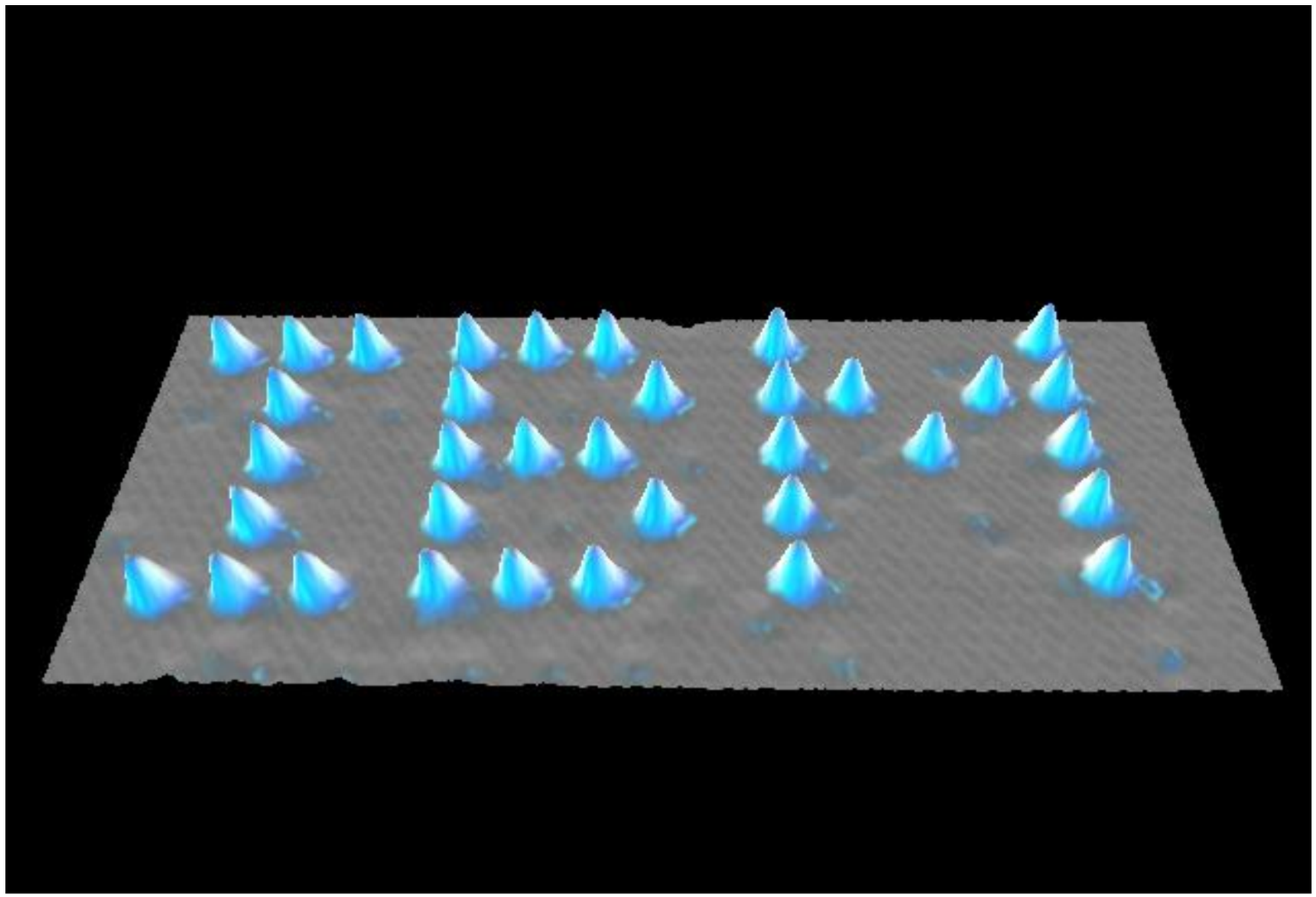
Tvorjenje slike





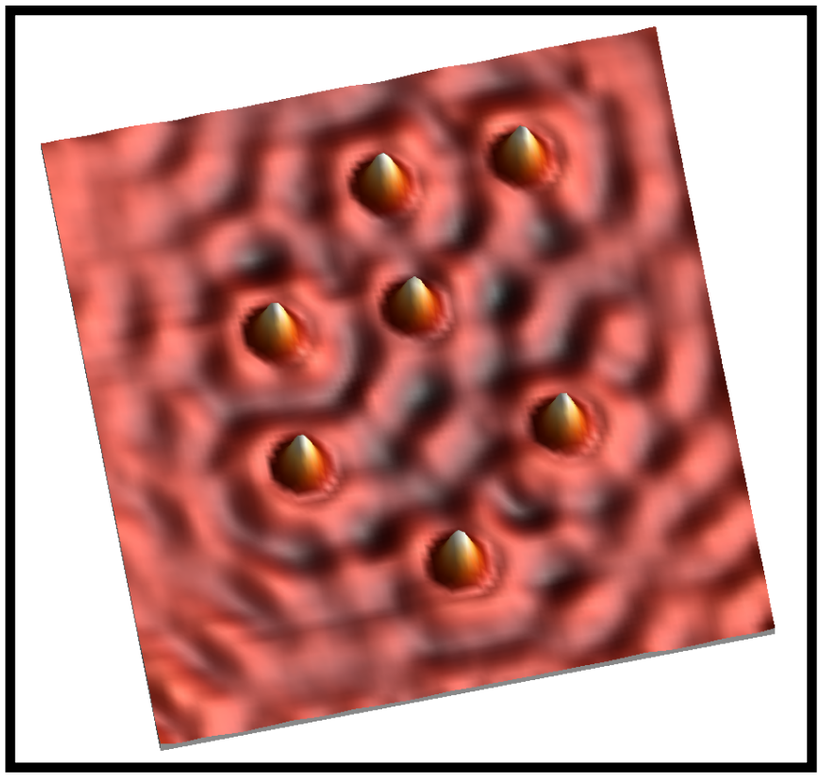
Atomska ločljivost na površini bakra Cu(111)

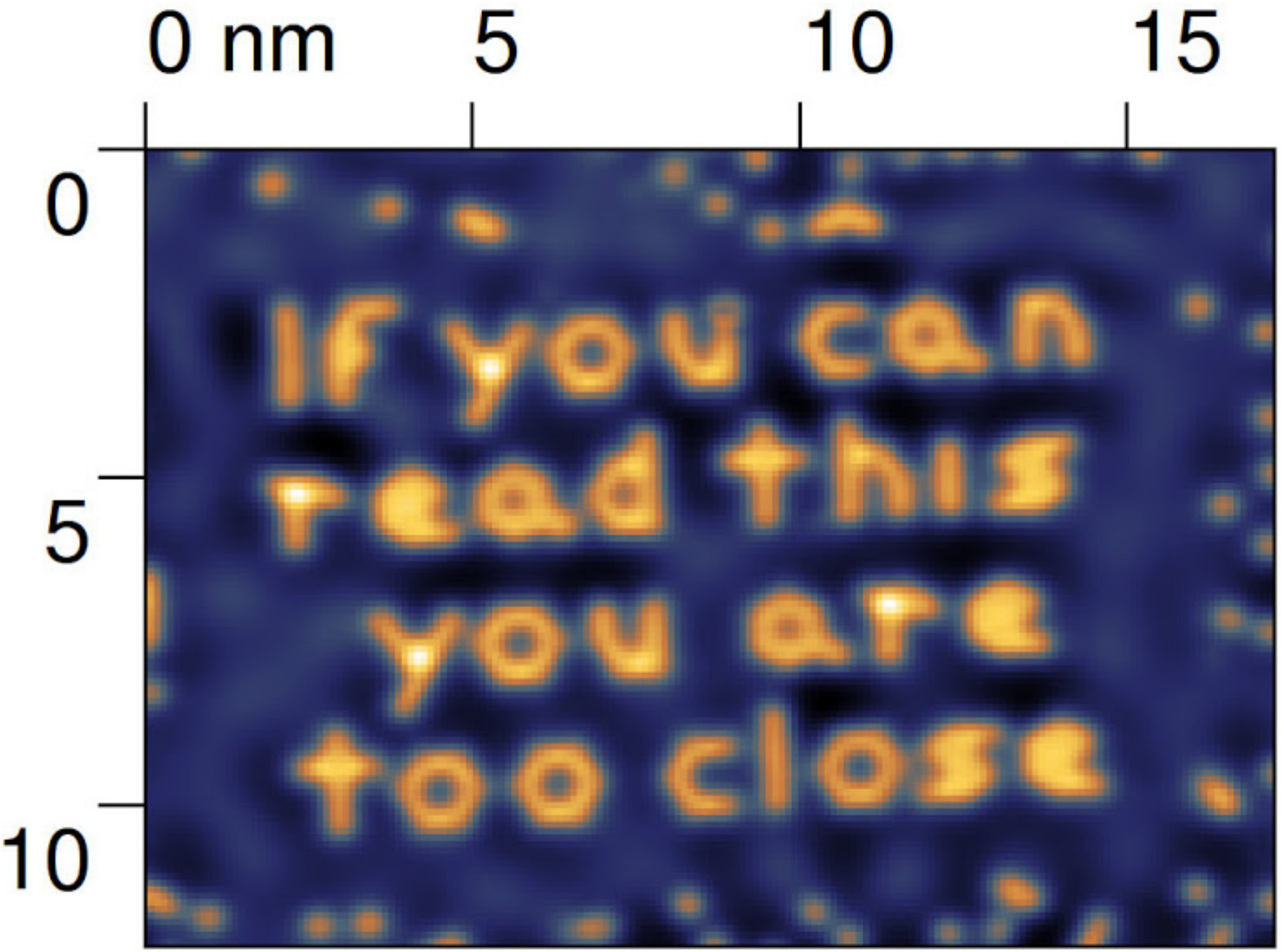
Premikanje atomov



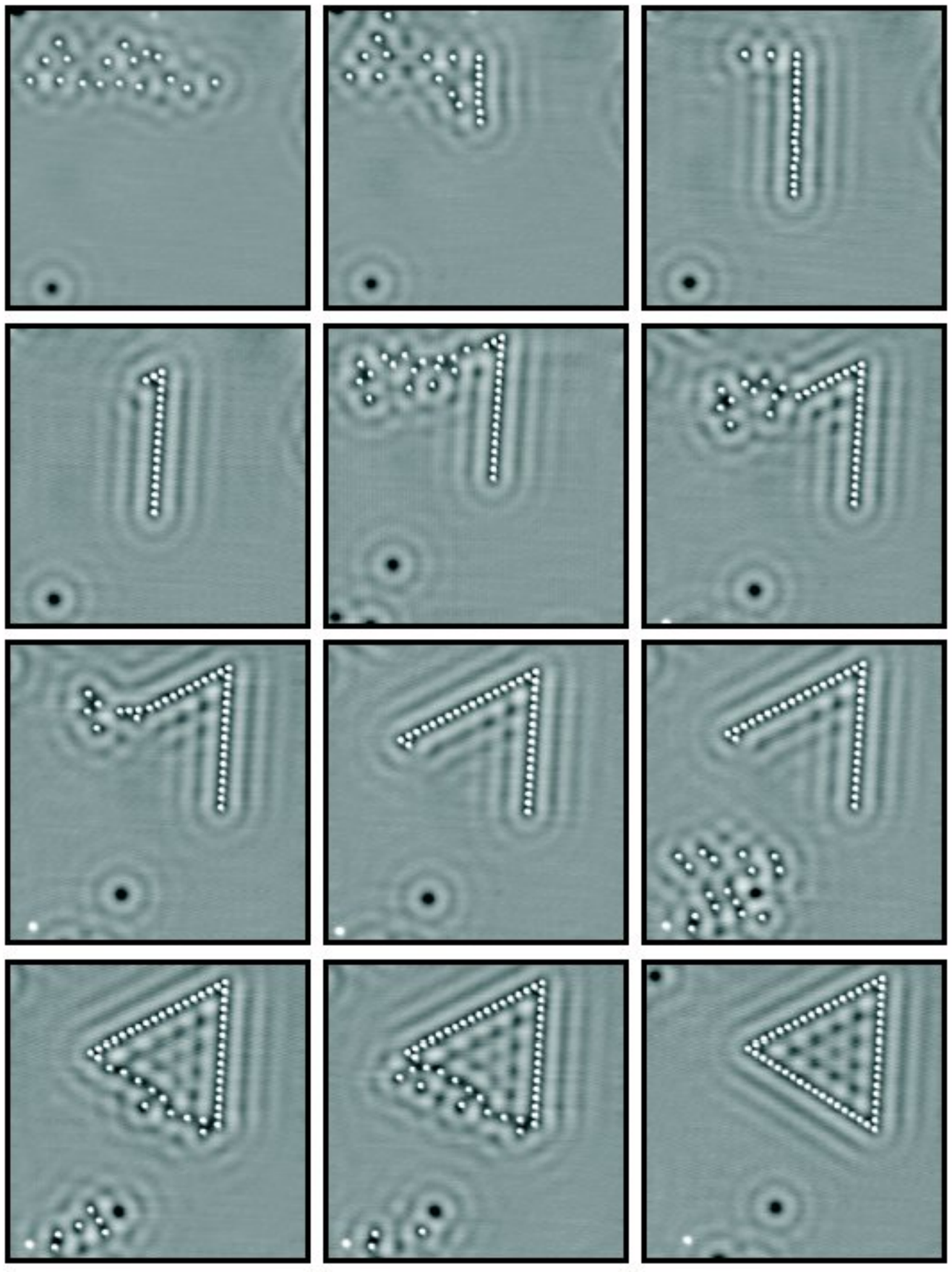
Atomi ksenona na površini kristala niklja

D.M. Eigler, E.K. Schweizer. **Positioning single atoms with a scanning tunneling microscope.** *Nature 344, 524-526 (1990).*

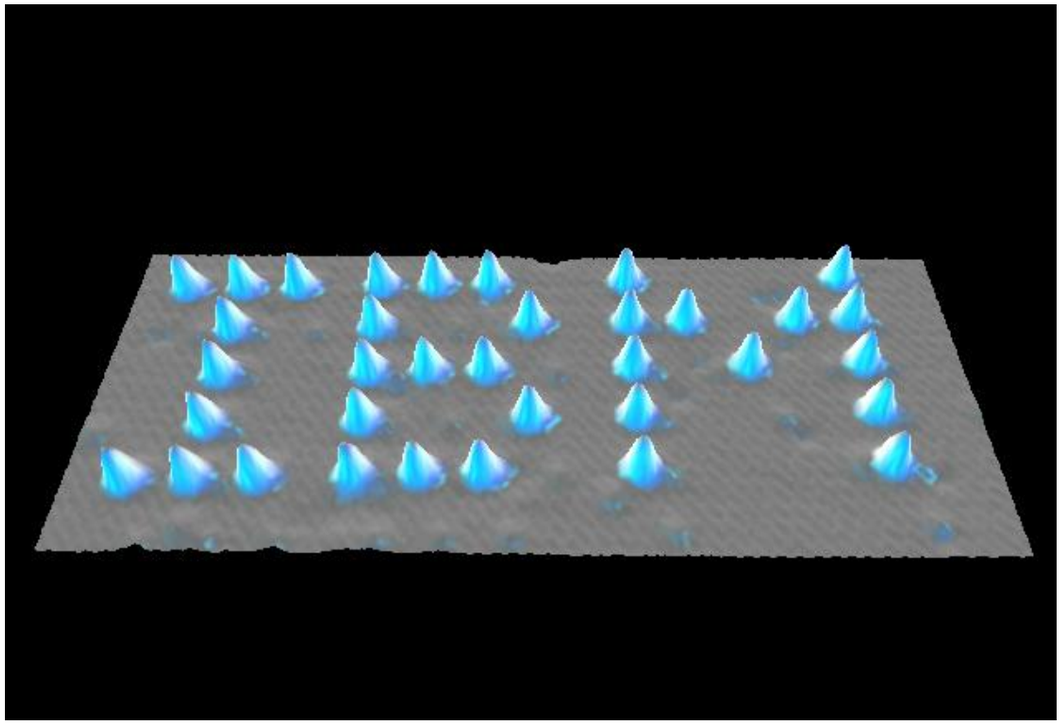


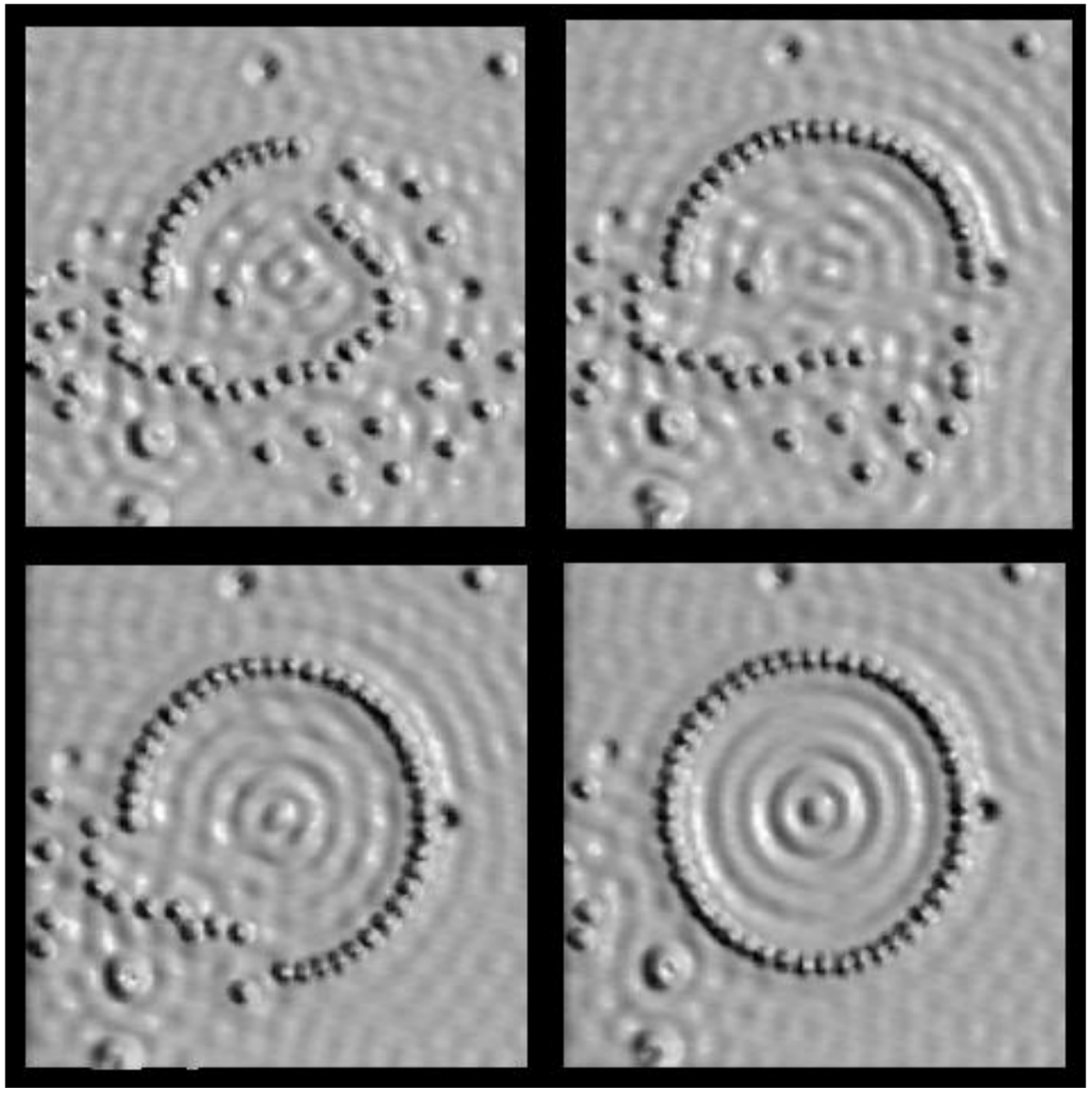


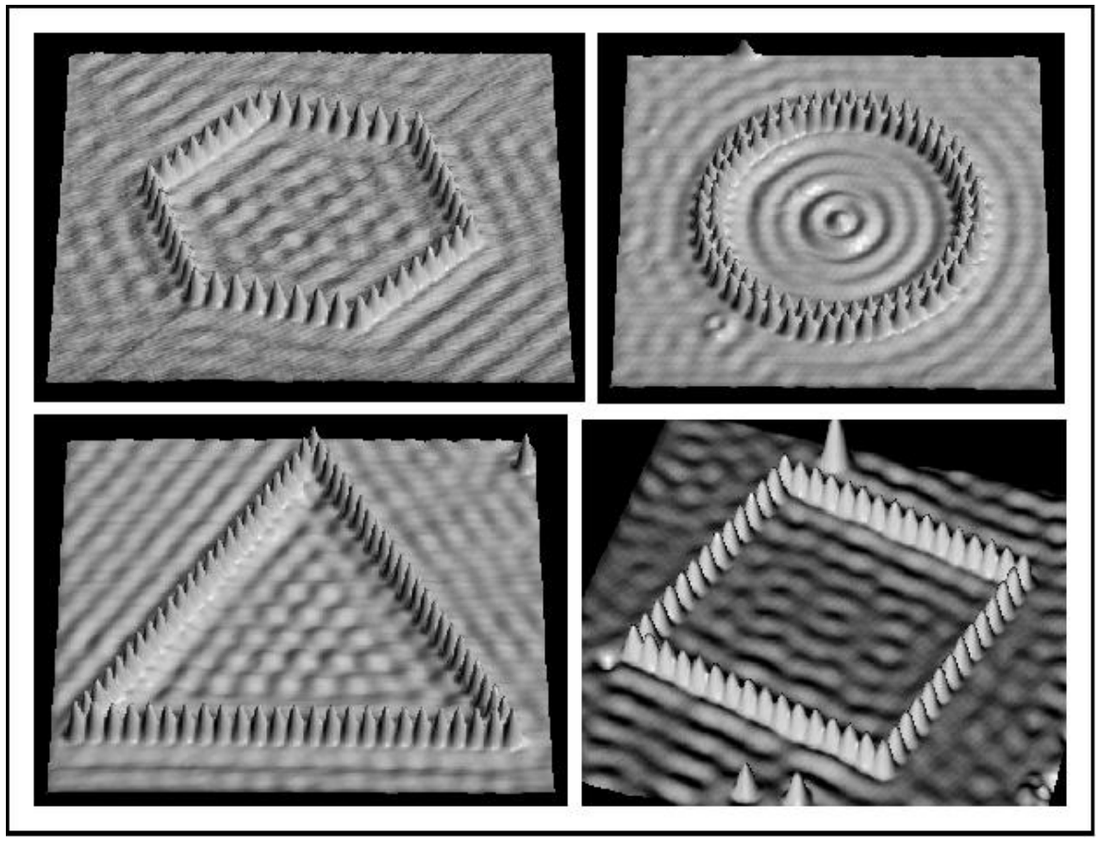
IBM, CO/Cu



Vir: Kai-Felix Braun,
Freie Universität Berlin,
disertacija.





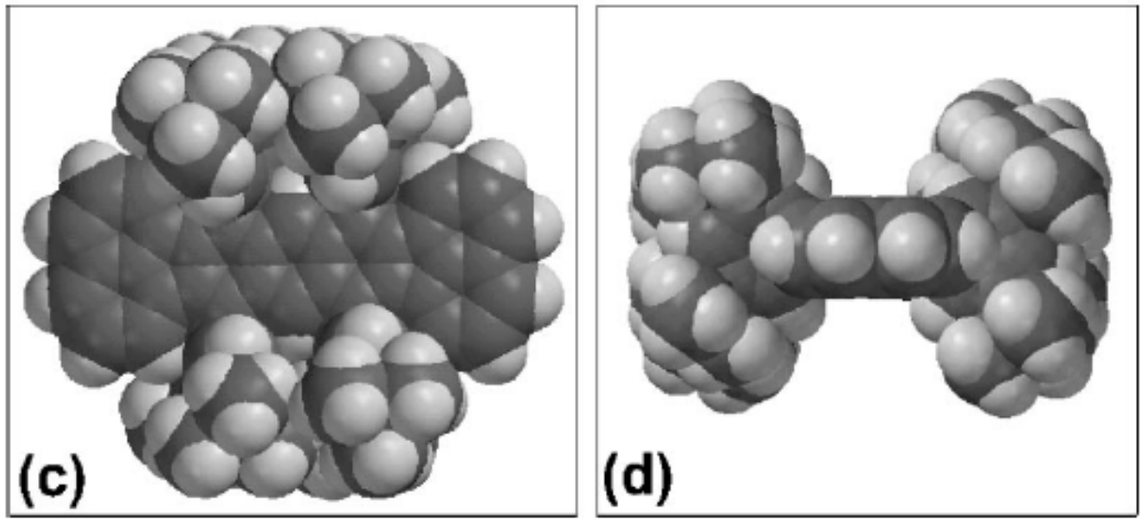


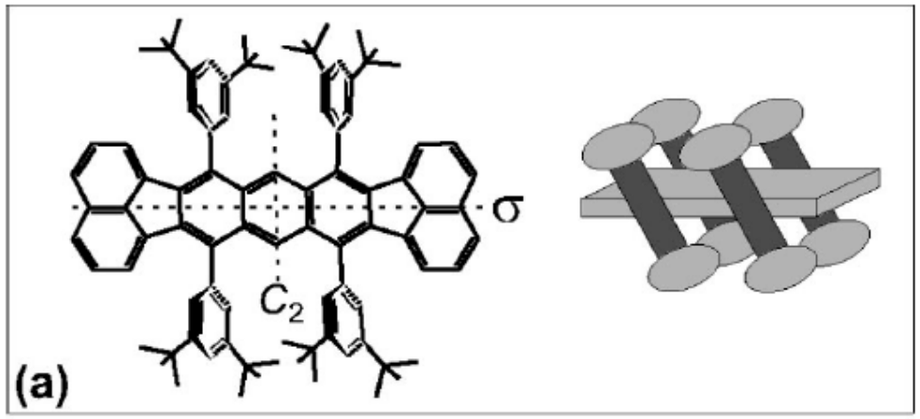
Source: IBM

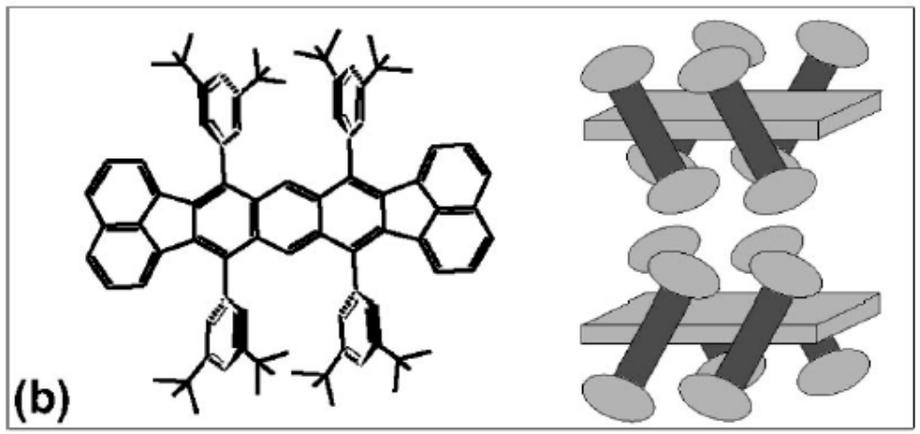
Atomski smeško premera 32 nm

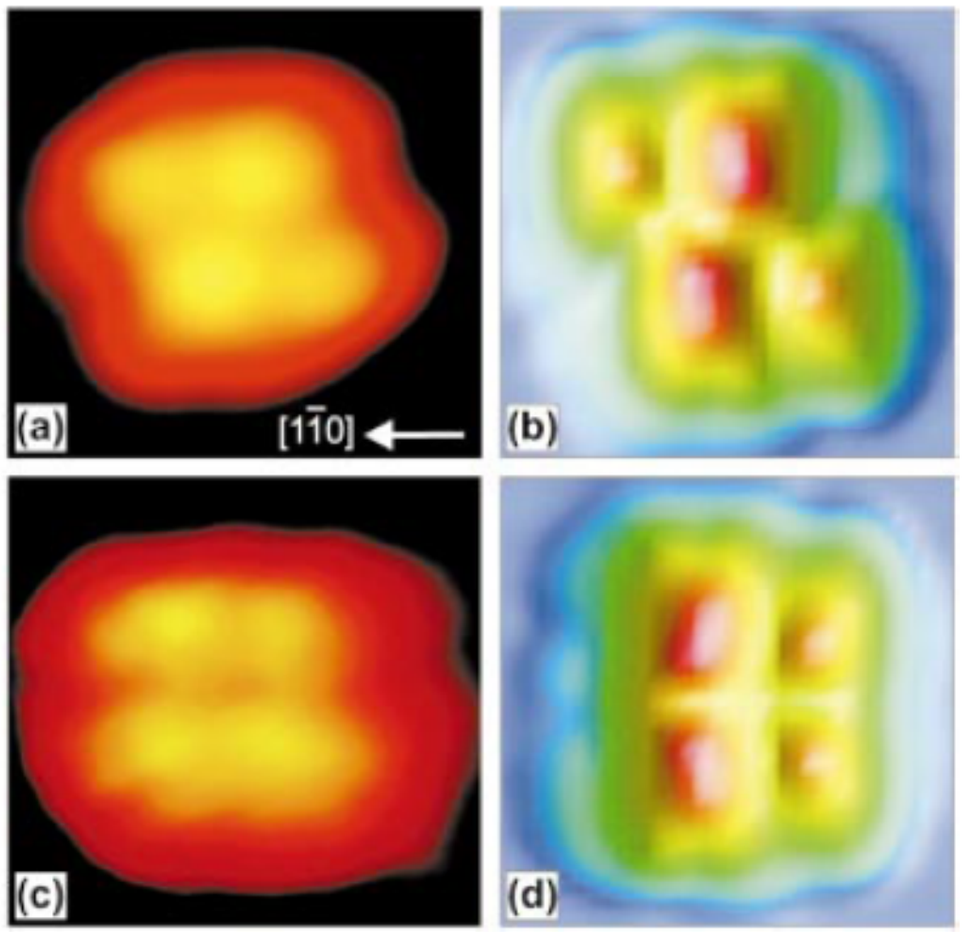
Saw-Wai Hla, J. Vac. Sci. Tech. B **23** 1351 (2005).

Spreminjanje konformacij molekul



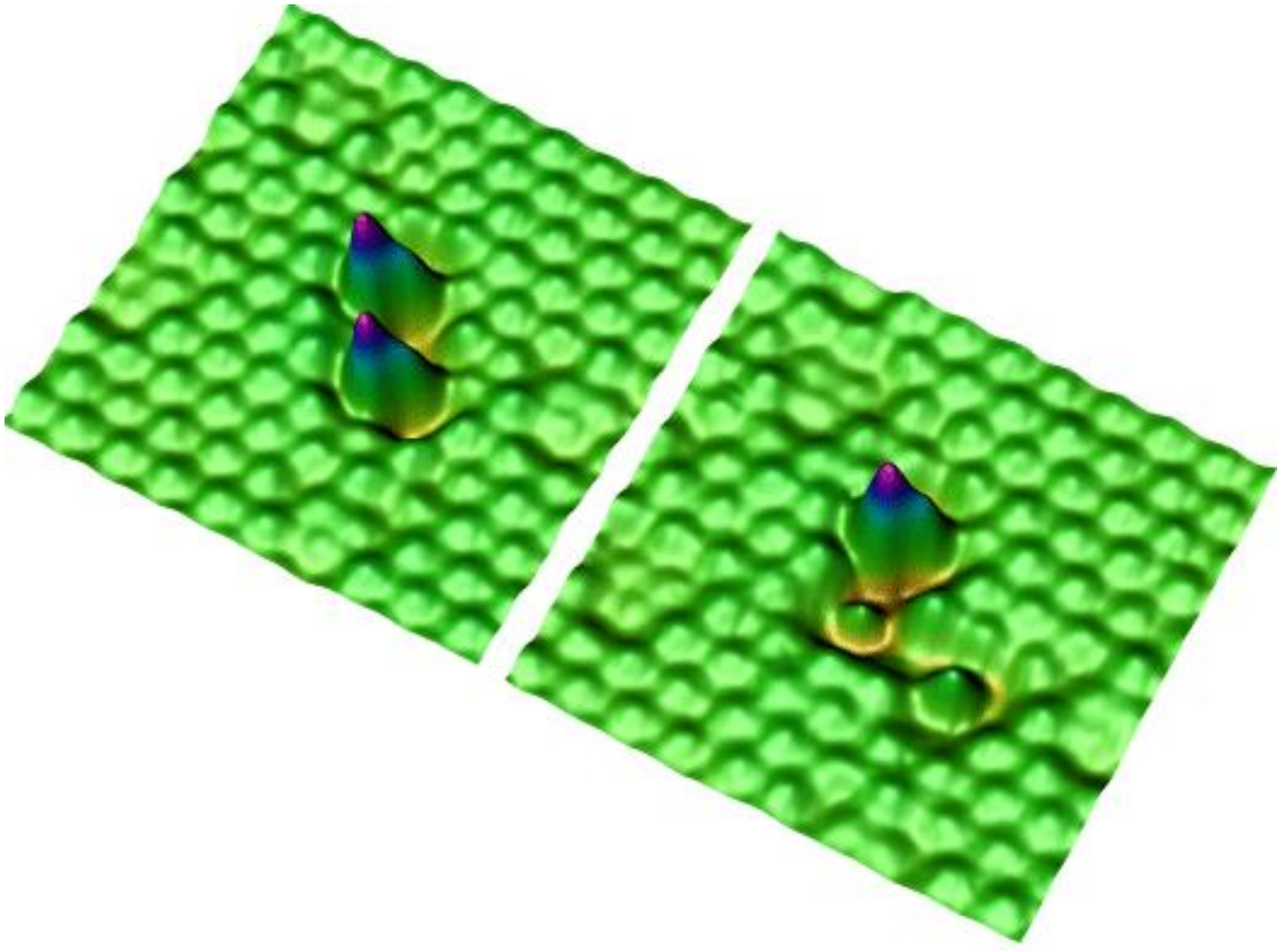






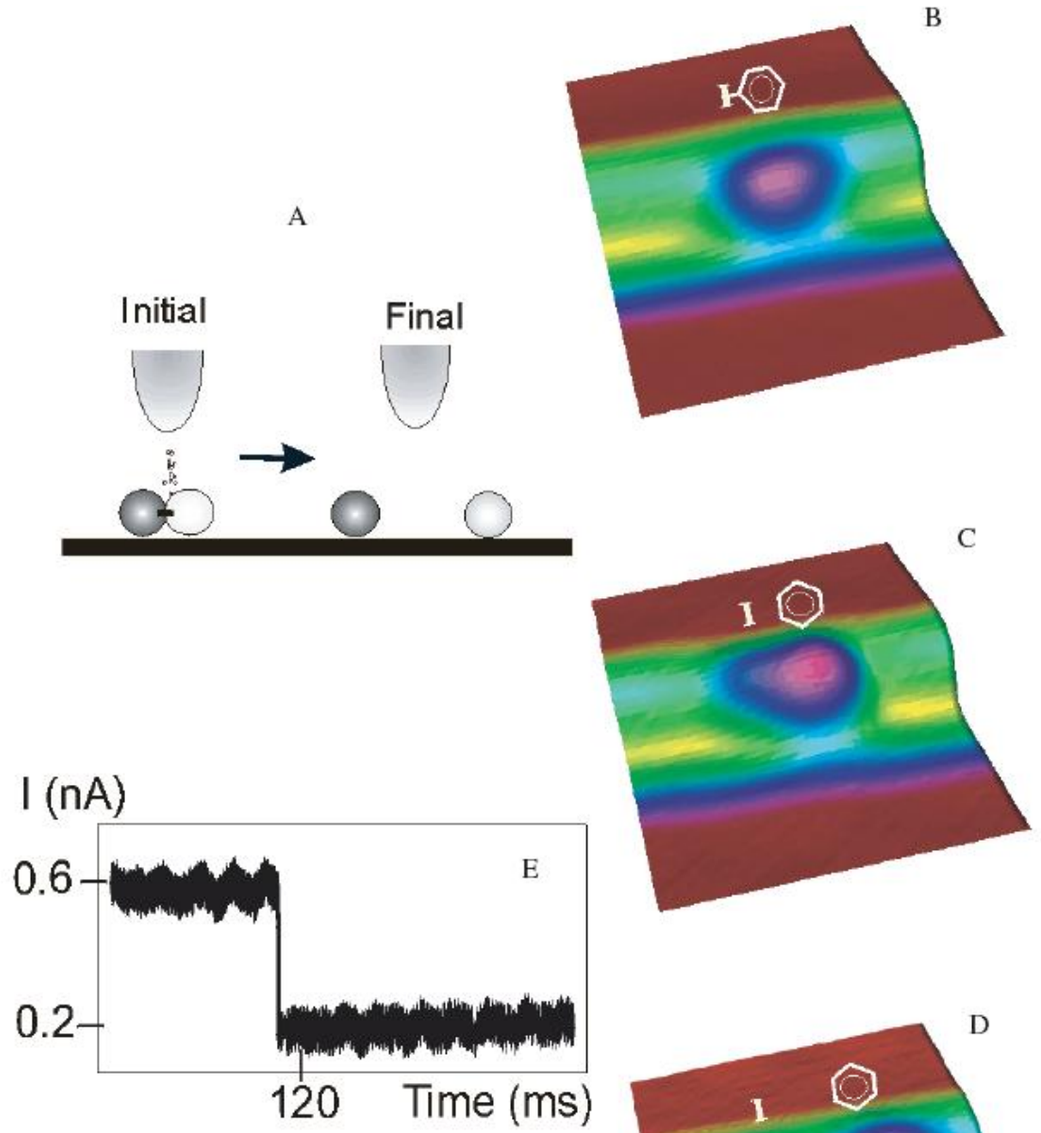
M. Schunack et al. J. Chem. Phys. **117** 6259 (2002).

Dissociation of single O_2 molecule



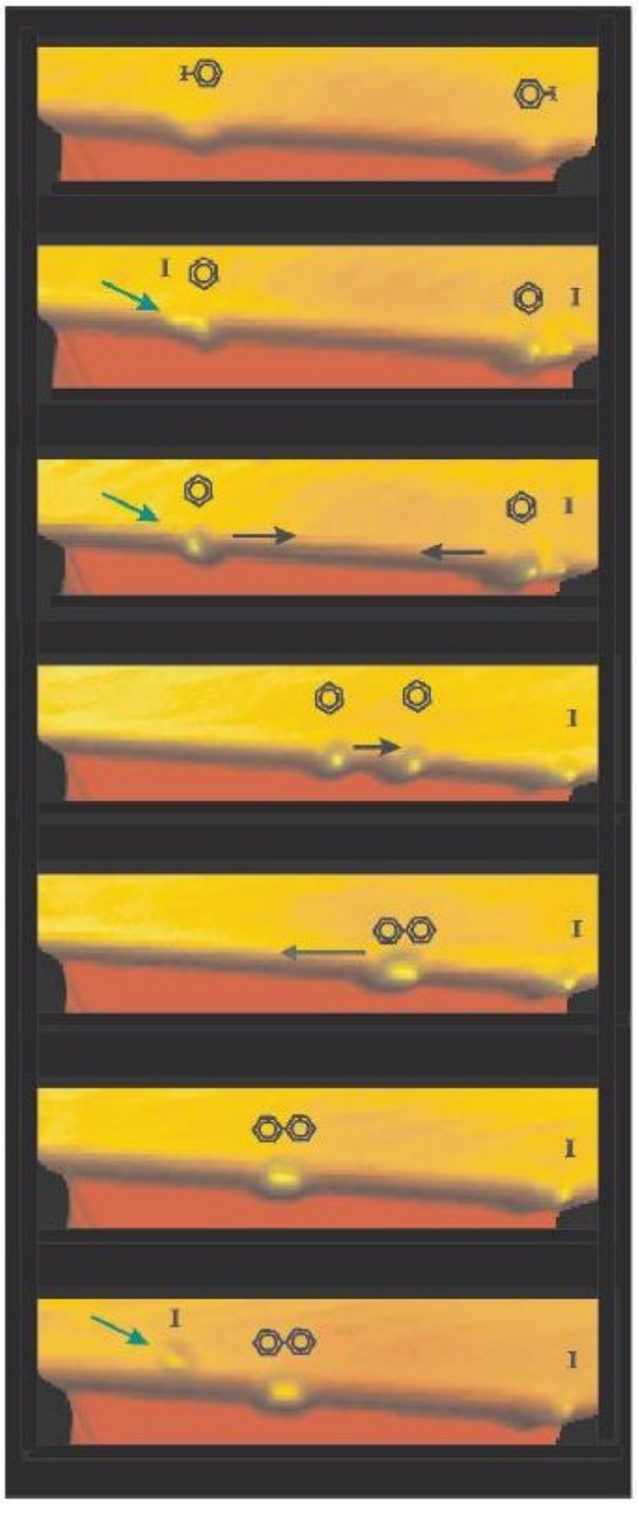
Stipe, Rezaei, Ho et al. *Phys. Rev. Lett.,* **78** 4410, 1997.

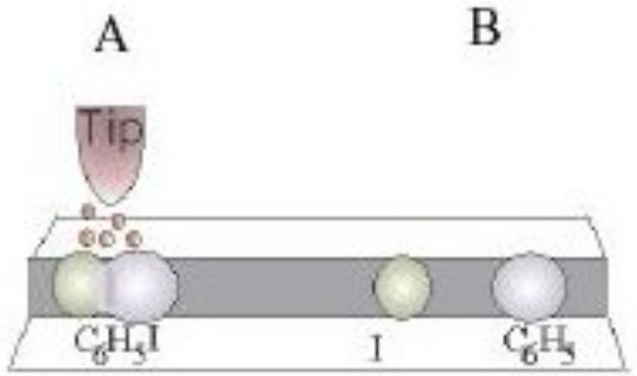
Splitting of bonds in organic molecules - iodobenzene

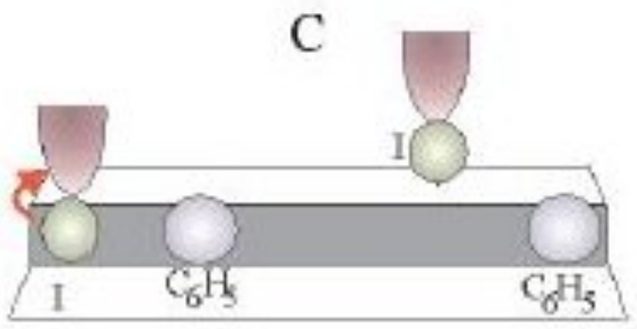


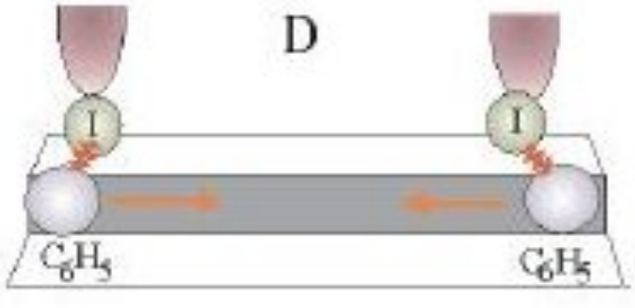
Lauhon, Ho. *Phys. Rev. Lett.*, **84** 1527, 2000.

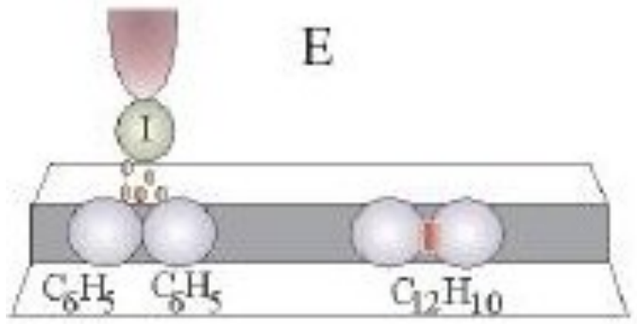
Kemijske reakcije s posameznimi molekulami

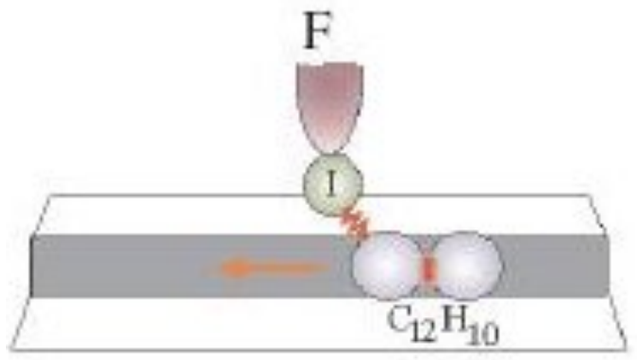


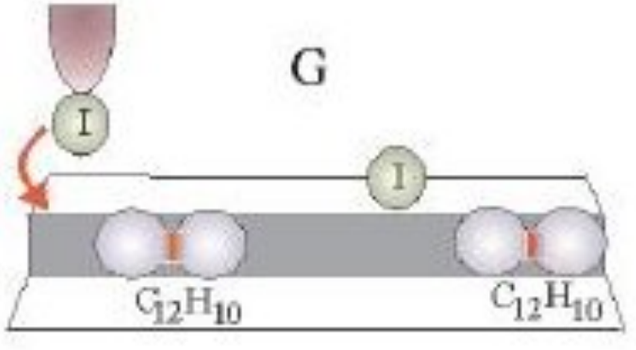






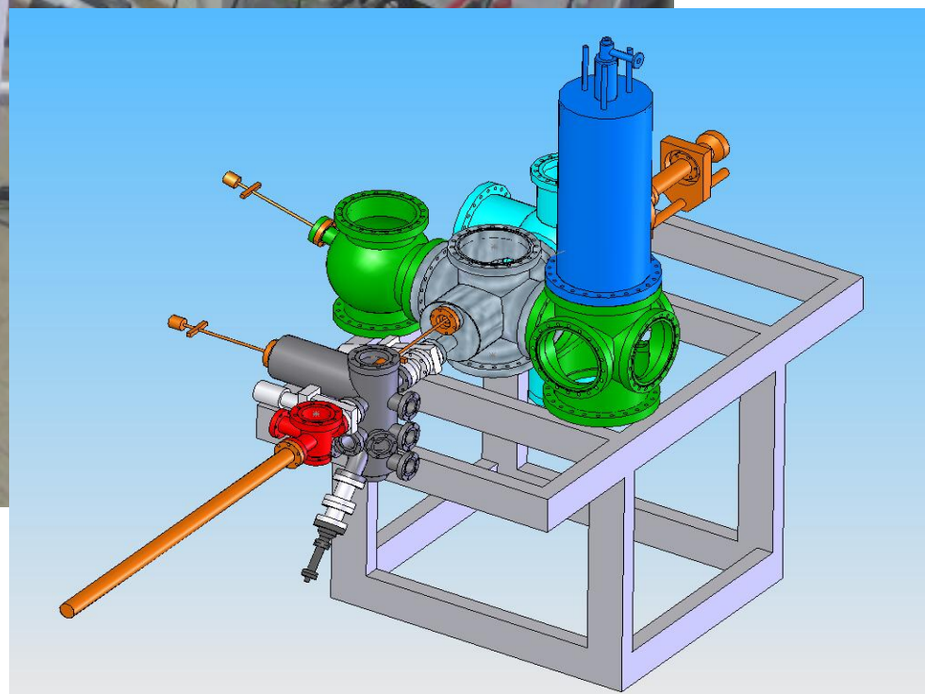


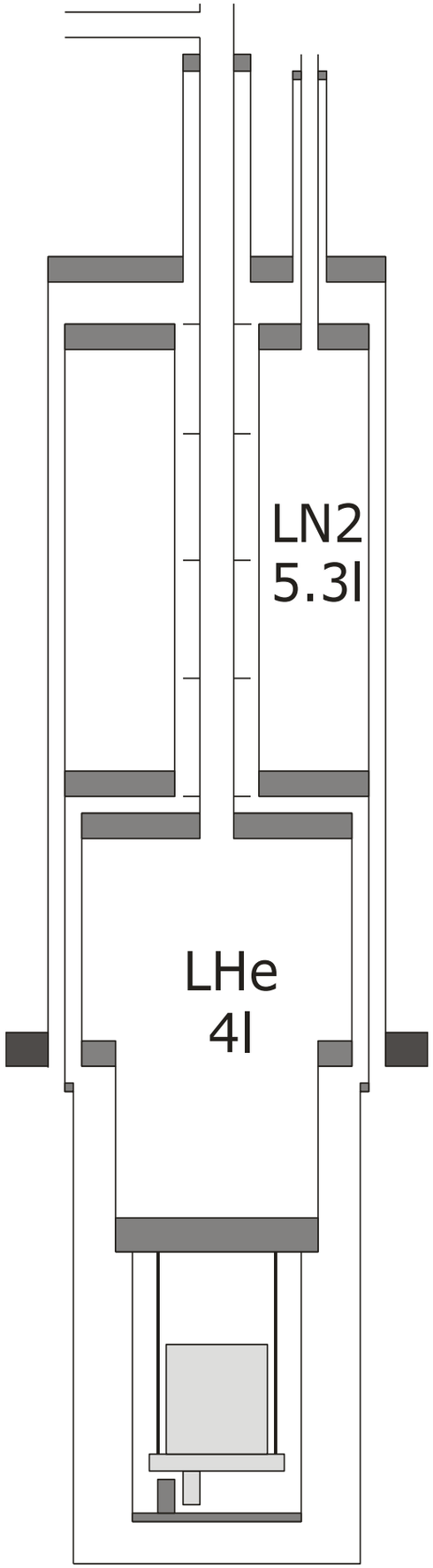




Saw-Wai Hla et al. Phys. Rev. Lett. **85** 2777 (2000)

Nizkotemperaturni STM na IJS





Zakaj vakuum?

Sobni pogoji (1bar): v vsak atom površine se zadane molekula plina 100 000 000 krat na sekundo.
(pri 10^{-6} mbar enkrat na sekundo,
pri 10^{-9} mbar enkrat na dan)

Typical temperatures:

- below 5K without the Joule-Thomson stage operation
- 1.0K in ^{4}He JT mode, <500 mK in ^{3}He JT mode
- variable temperature 1 - 100 K

Measuring times:

- LHe hold time (9.5l) over 6 days
- LN2 hold time (18l) over 4 days

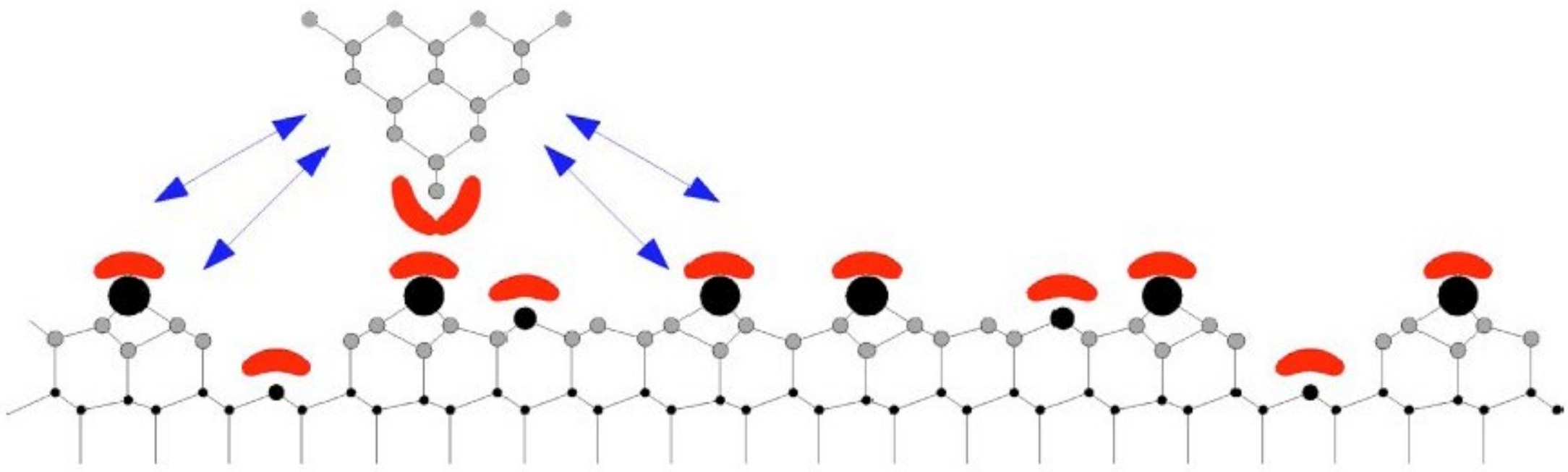
Specifications:

- X & Z coarse positioning
- in-situ tip and sample exchange
- scan range @ 1K: 1 x 1 μm
- drift rate < 100 pm/h
- sample dimensions: 10 x 10 mm

Kaj se zgodi, ko približamo dva kosa snovi na izjemno majhno medsebojno razdaljo?

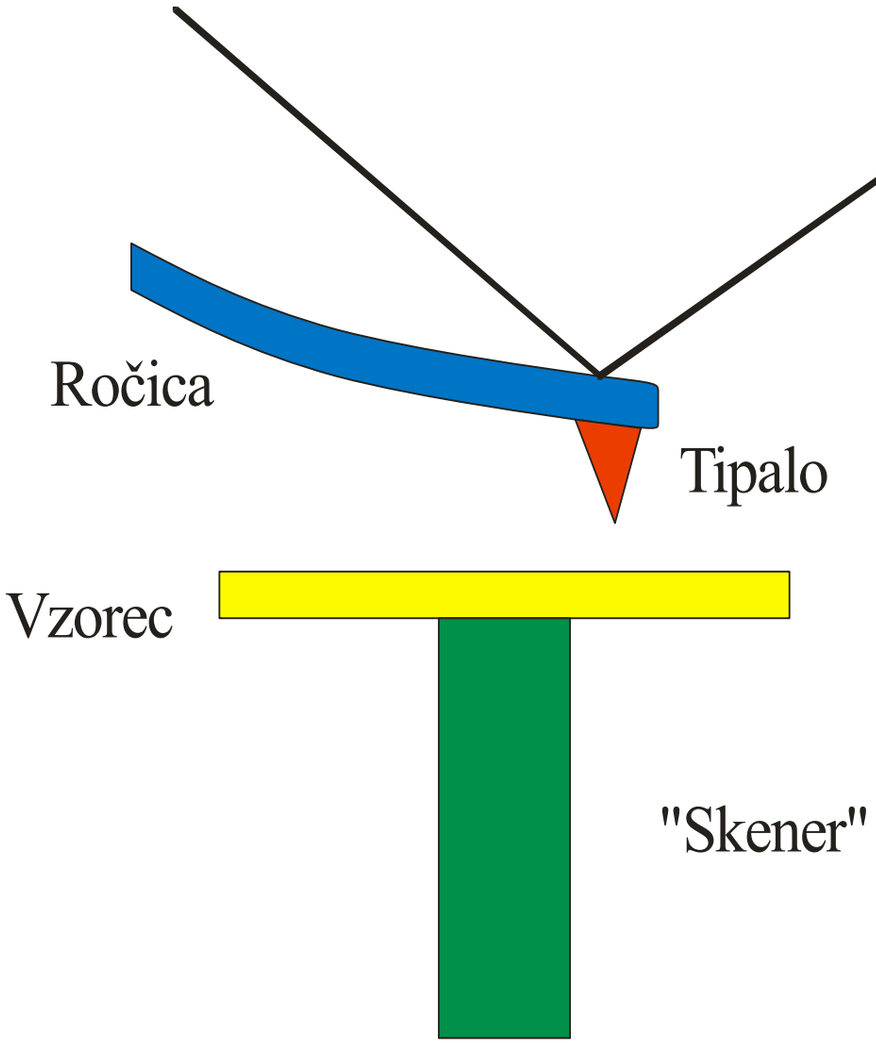
- Sile med površinama
  - privlačna van der Waalsova
  - kemijska vezava (kovalentna vez)
  - odbojna sila ob mehanskem kontaktu
- Tunelski pojav in električni tok med kosoma snovi

Sile med površinama



F. J. Giessibl, Rev. Mod. Phys. **75** 952 (2003)

Mikroskop na atomsko silo

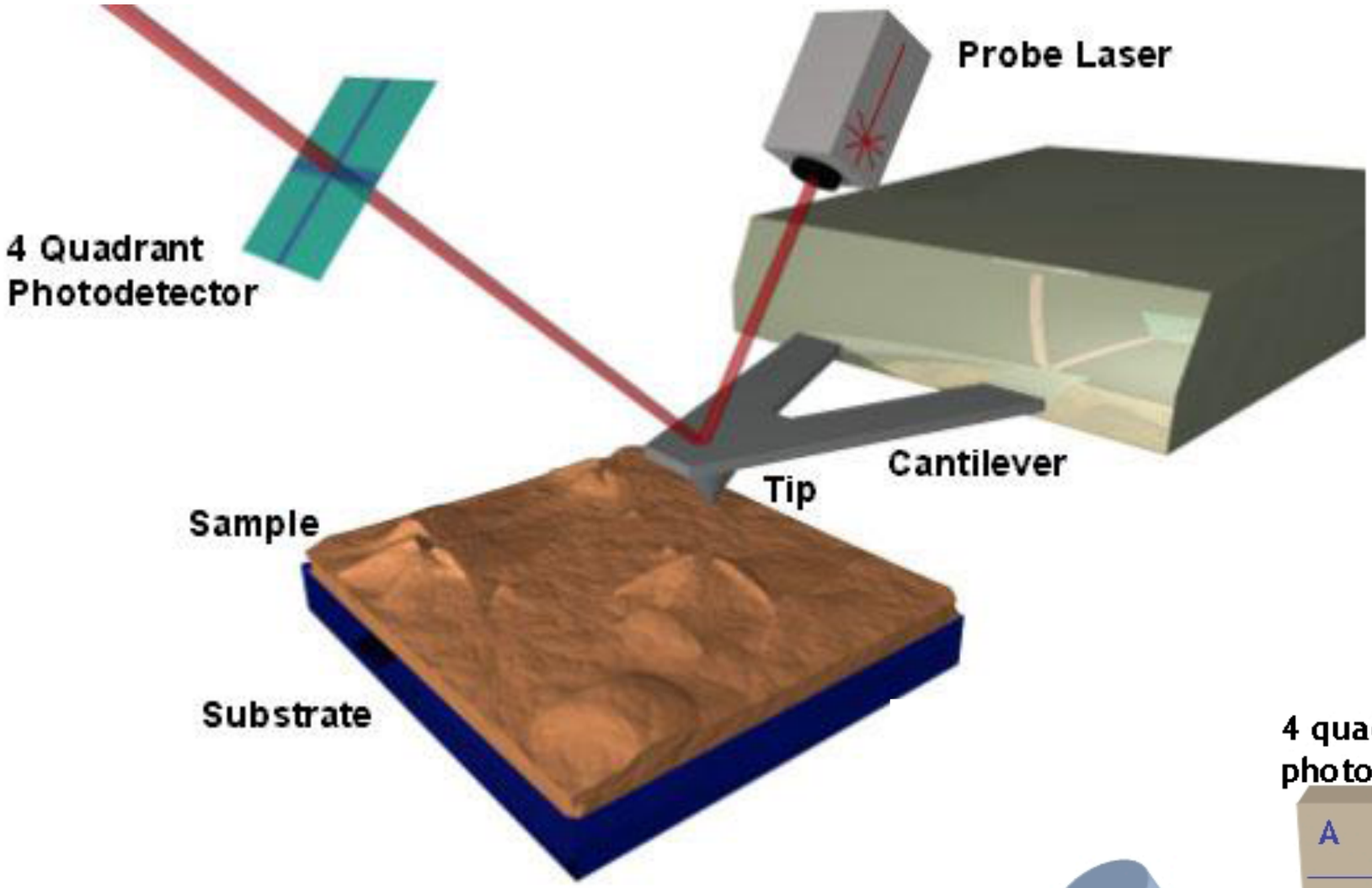


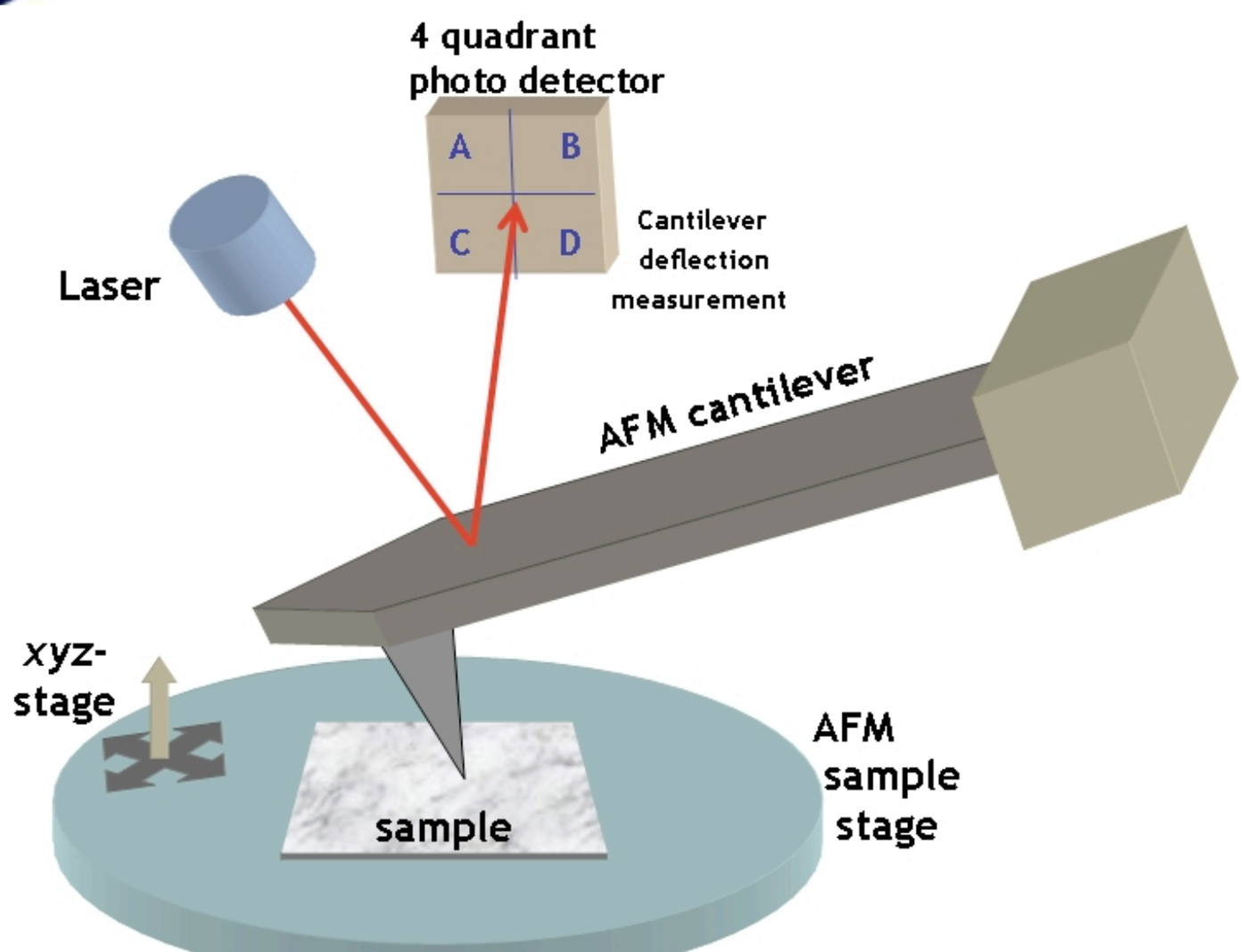
G. Binnig, C. F. Quate, Ch. Gerber
“Atomic Force Microscope”
Phys. Rev. Lett. 56, 930 - 933 (1986)

Calvin Quate

Christoph Gerber

$$F = -kx$$


Probe Laser
4 Quadrant
Photodetector
Cantilever
Tip
Sample
Substrate


4 quadrant
photo detector
A
B
C
D
Cantilever
deflection
measurement
Laser
AFM cantilever
xyz-
stage
sample
AFM
sample
stage

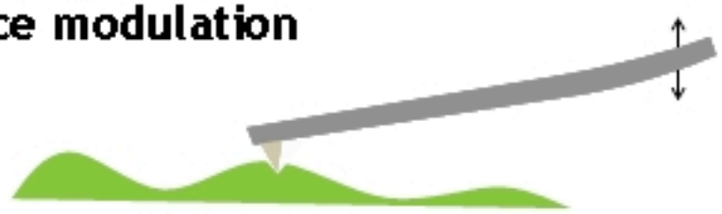
Contact mode

Non-contact

Tapping mode
/intermittent contact

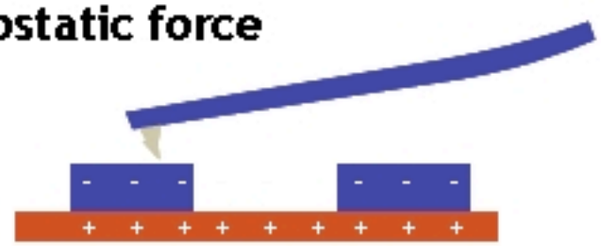
Lateral force

Force modulation

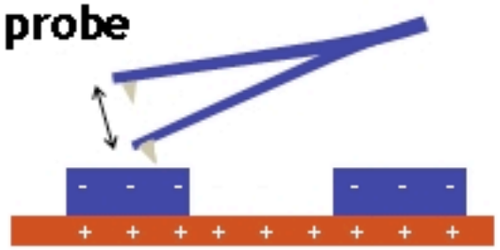


Force distance

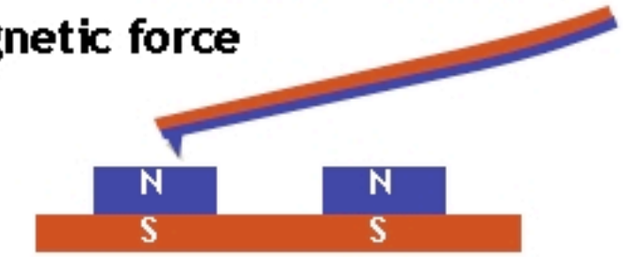
Electrostatic force



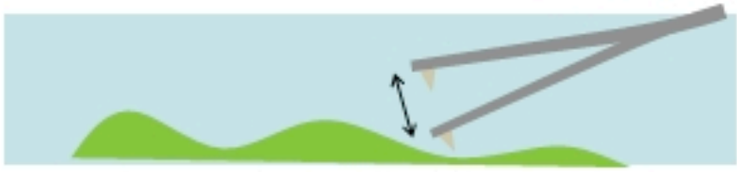
Kelvin probe



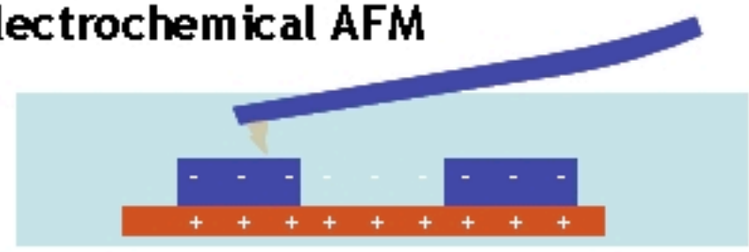
Magnetic force



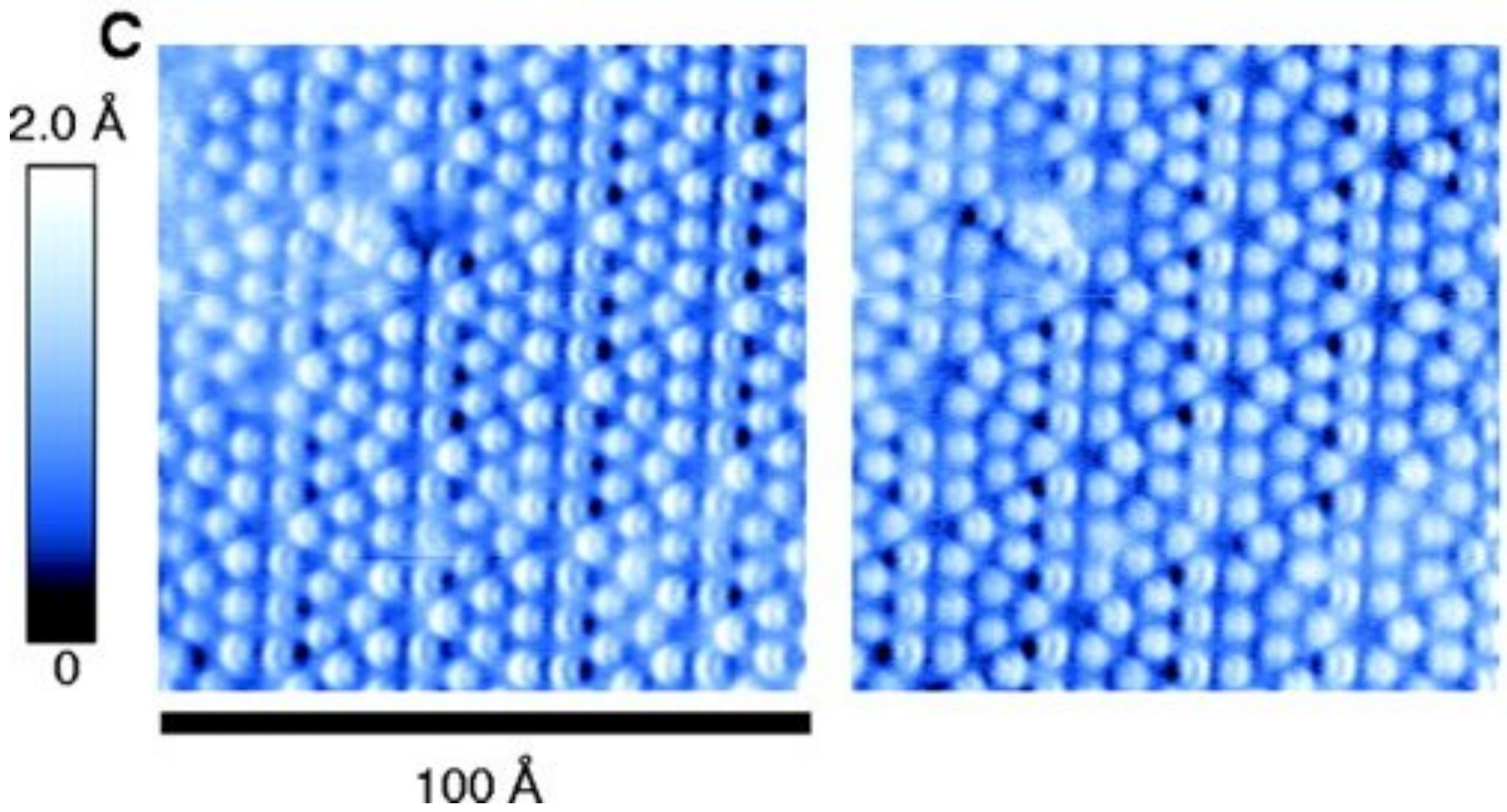
Liquid AFM



Electrochemical AFM

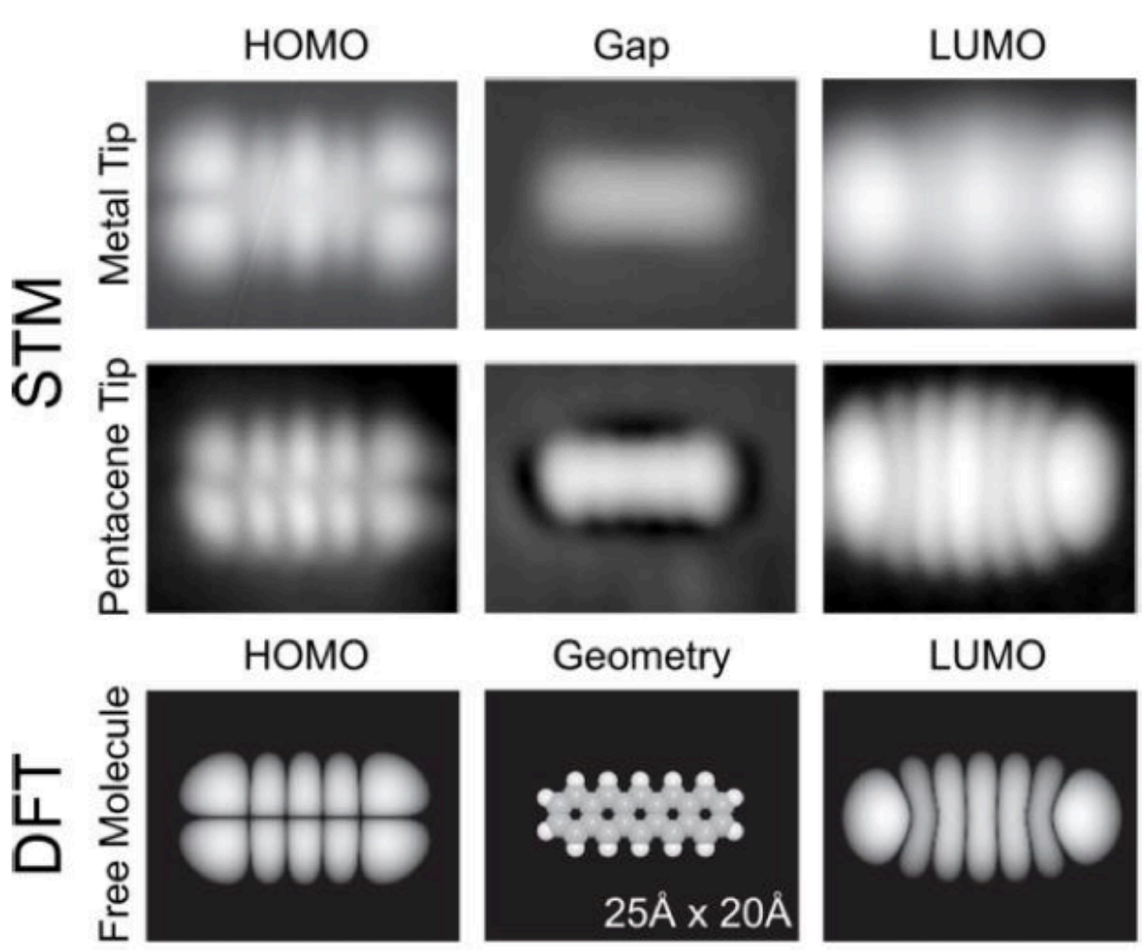


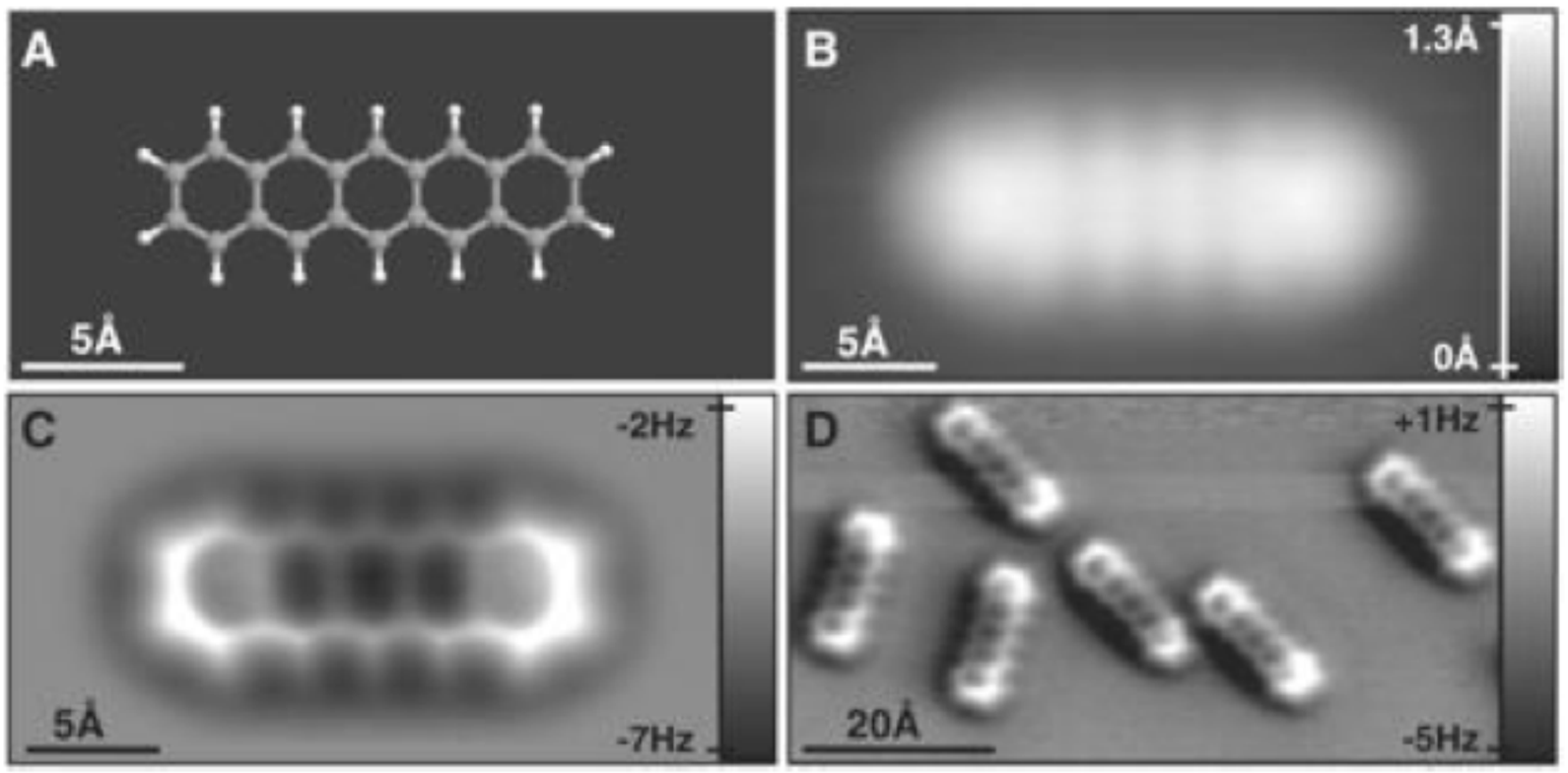
Atomska ločljivost pri AFM



Si(111)-7x7

F. J. Giessibl et al., Science **289** 422 (2000).


HOMO
Gap
LUMO
STM
Metal Tip
Pentacene Tip
HOMO
Geometry
LUMO
DFT
Free Molecule
25Å x 20Å


A
5Å
B
1.3Å
0Å
5Å
C
-2Hz
-7Hz
5Å
D
+1Hz
-5Hz
20Å

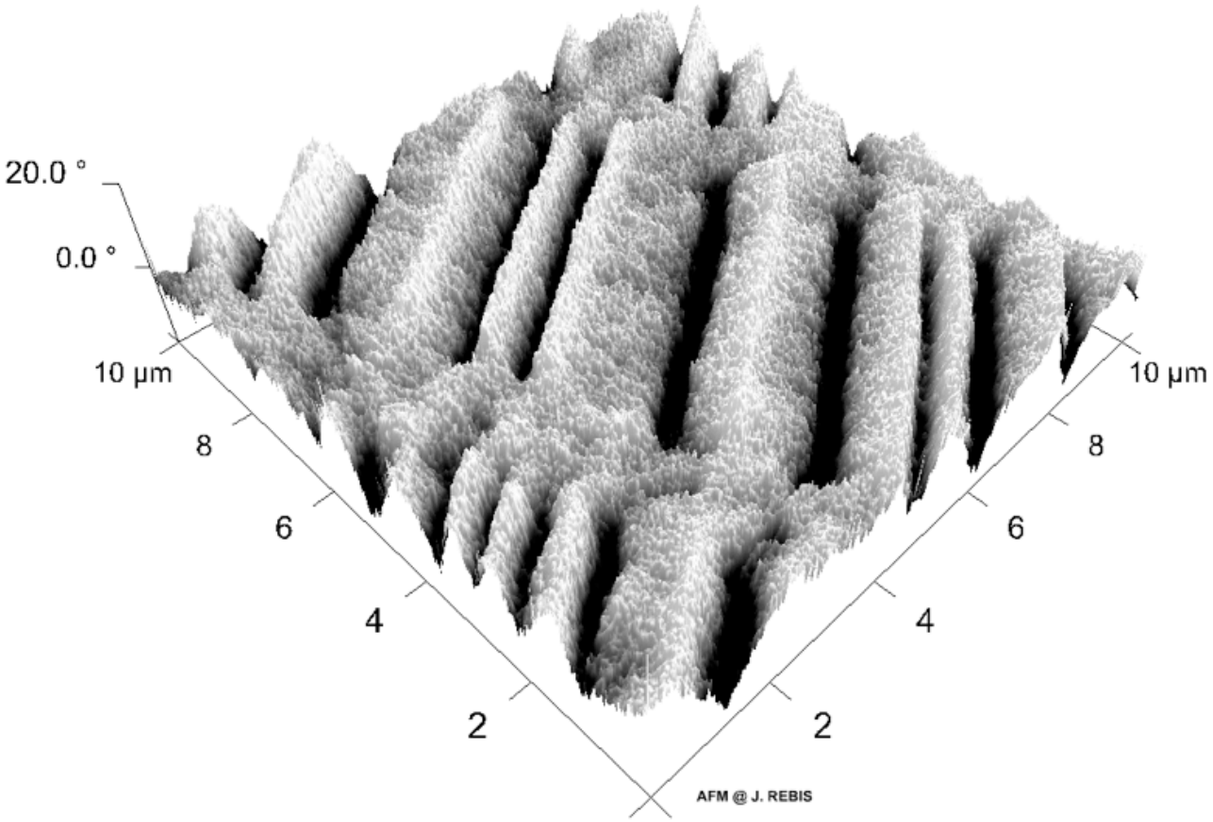
AFM

Druge vrste tipalnih mikroskopov

- magnetic force microscope (magnetne lastnosti)
- lateral force microscope (trenje)
- electric force microscopy (naboj)
- magnetic resonance force microscopy (spin)
- ...

MAGNETIC FORCE MICROSCOPY

Dysk twardy magnetyczny 3,2 Gb



Dysk twardy magnetyczny 30 Gb

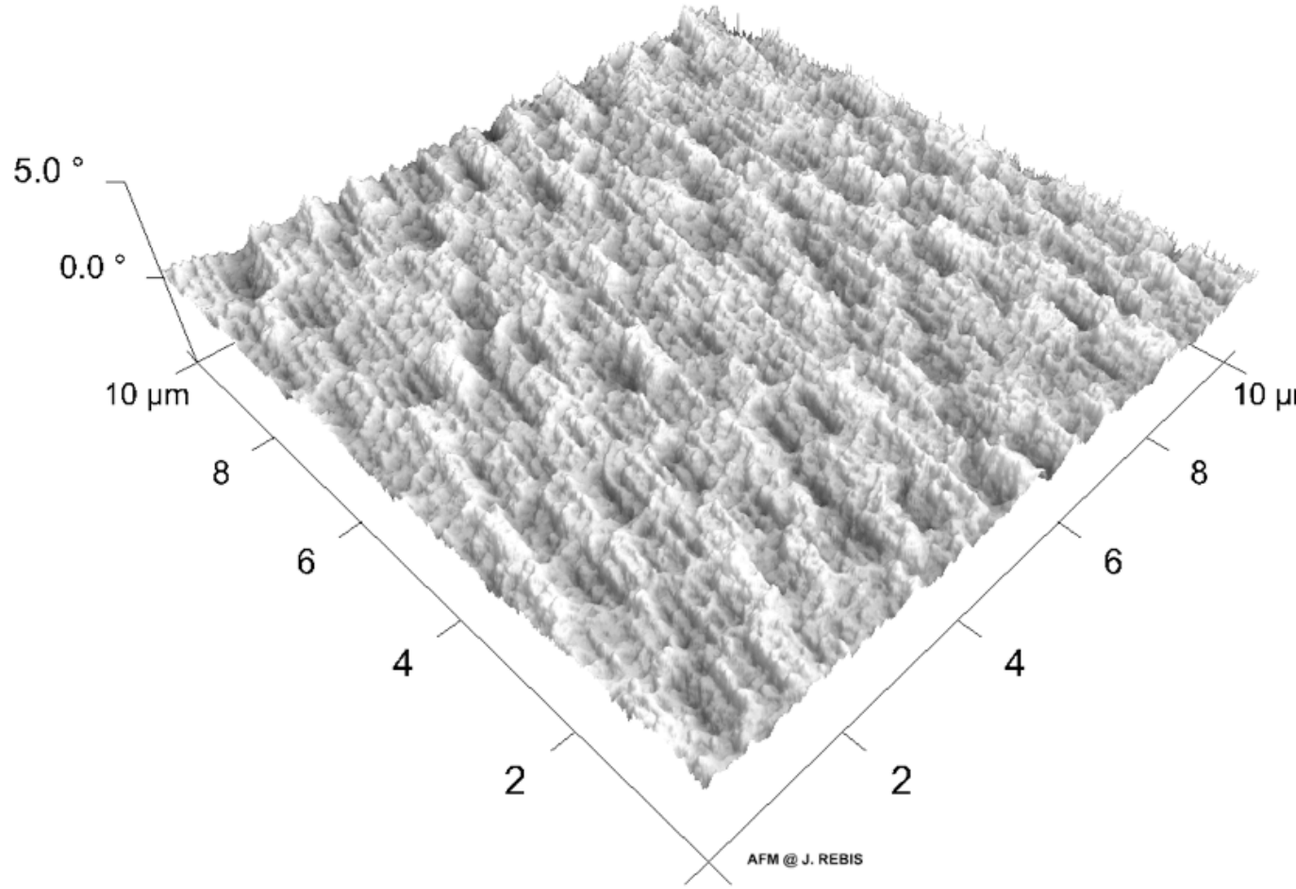
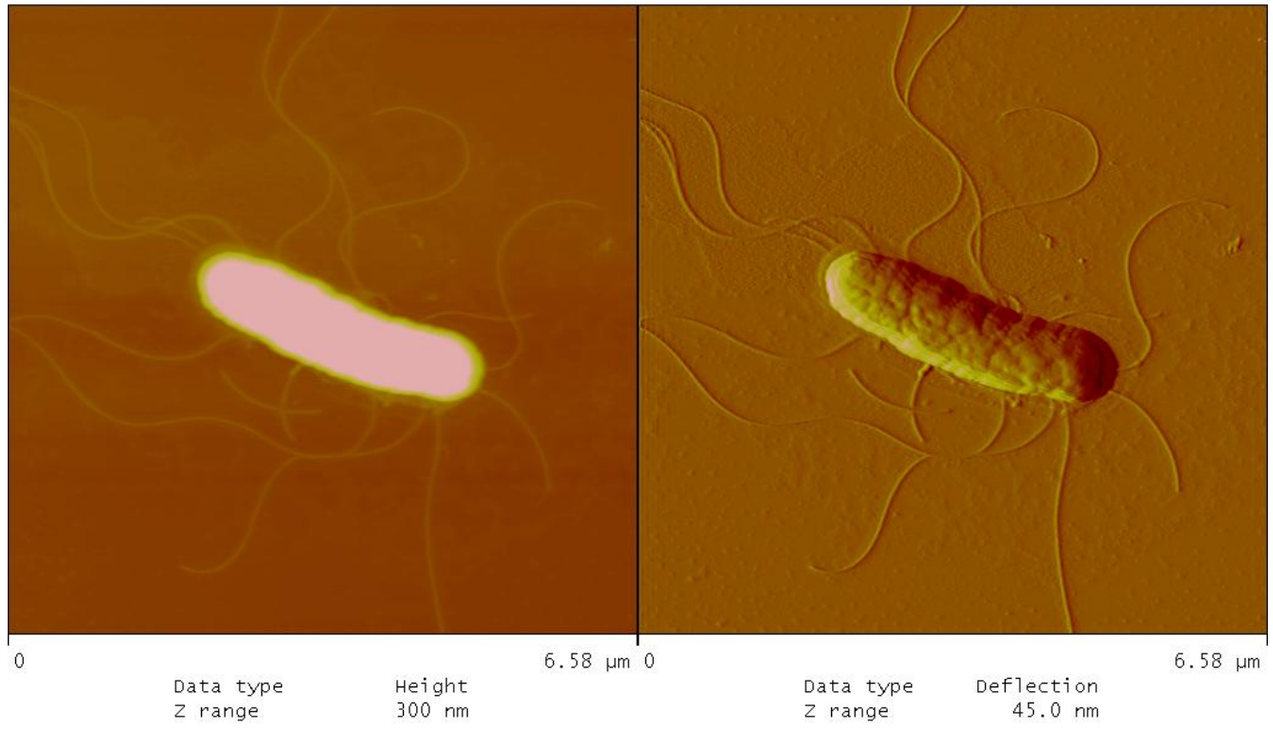


Figure 2.2. MultiMode SPM.



bakterija

Igor Muševič, Miha Škarabot, odsek F5

- tekoči kristali
- plastni materiali
- biološki vzorci

Multimode AFM Nanoscope III, DI

Microscopes