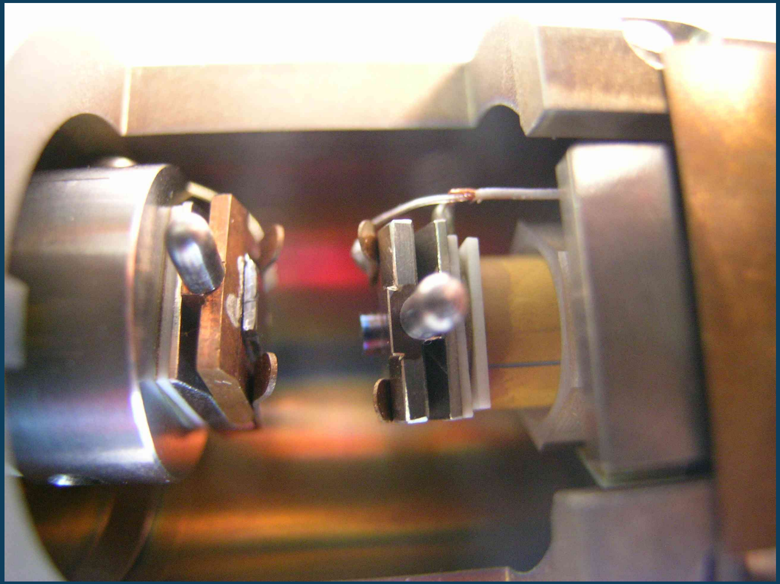
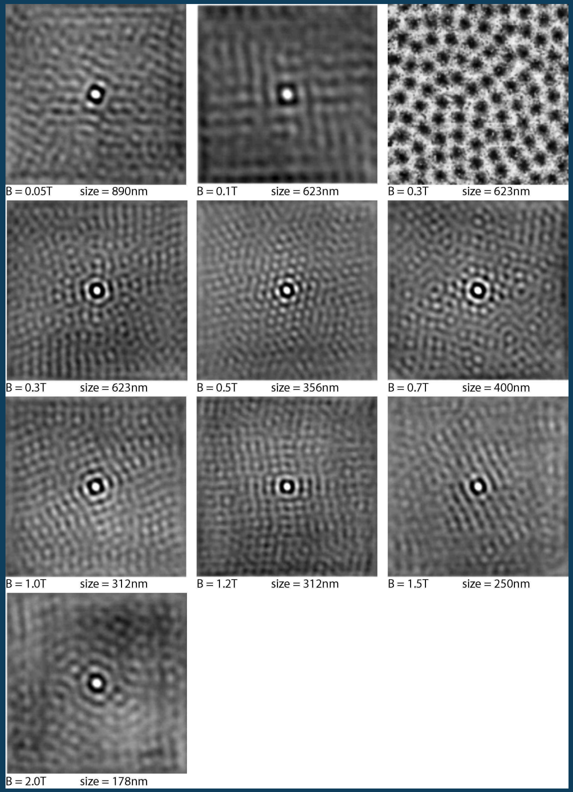
STM on (structured) Strongly Correlated Electron systems.

Federica Galli, (G. van Baarle), S. Kelly

=> Vortex studies on heterostructures by STM

=> Development of a new low-T STM





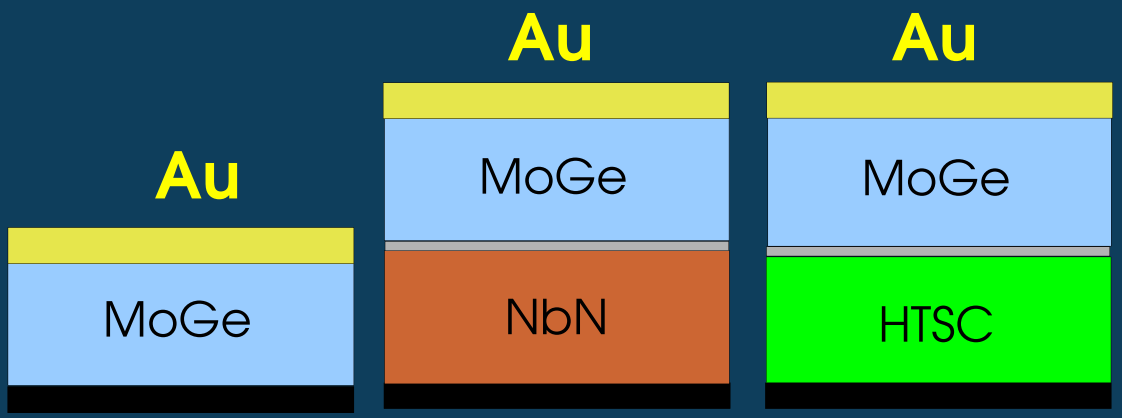
Vortex imaging by STM/STS in HTSC: issues

=> Small vortex core ($\xi \sim$ few Å).

=> Intrinsically insulating surface after treatment (cleaving or etching).

=> Surface roughness of films and non-cleaveable crystals.

A solution: imaging through a *a*-MoGe/Au layer



HTSC=$(LaSr)_2CuO_4$

$Bi_2Sr_2CaCu_2O8+\delta$

— = interface layer

Coupling Mechanisms

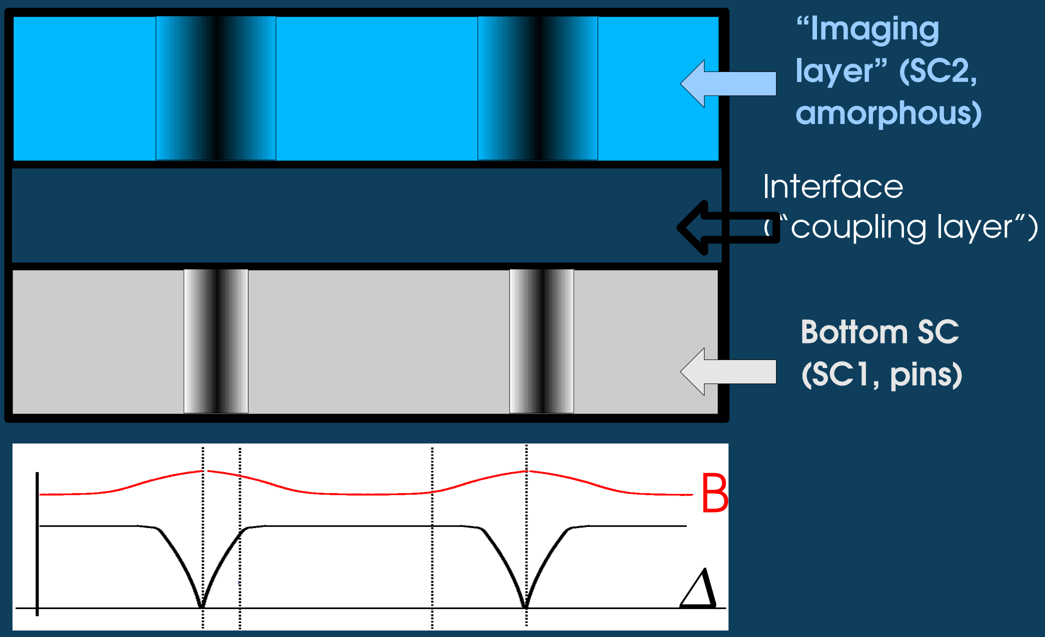
1. Electro-Magnetic coupling: Due to the variation of the magnetic field inside and outside (above) the superconductors, induced by the vortex state. The decay of this modulation from the surface of both SC (exp(-s/a_0)) is relevant for the coupling through the insulating interface [J. Low Temp. Phys. 5, p.465 (1971), Phys. Rev. B 9, p.898 (1974)]. The penetration depth λ, which defines the magnetic length scale, strongly affects the coupling.

2. Josephson coupling: Due to the misalignment of the vortex lines in the two parallel superconducting layers. This causes a phase difference of the superconducting order parameter [Phys. Rev. B 57, p.8026 (1998)], which results in a force strongly dependent on the separation layer thickness (~ 1/s) and on λ.

3. Proximity effects: Not considered because of the poor interface transparency/insulating layer.

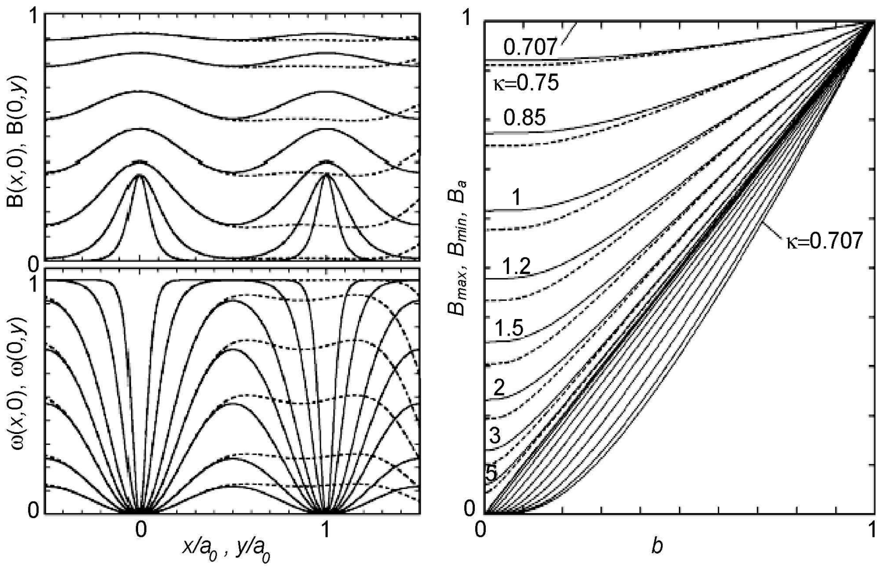
λ (thin films: $\lambda_{eff}=2\lambda_{bulk}^2/t$)

ξ, SC coherence length



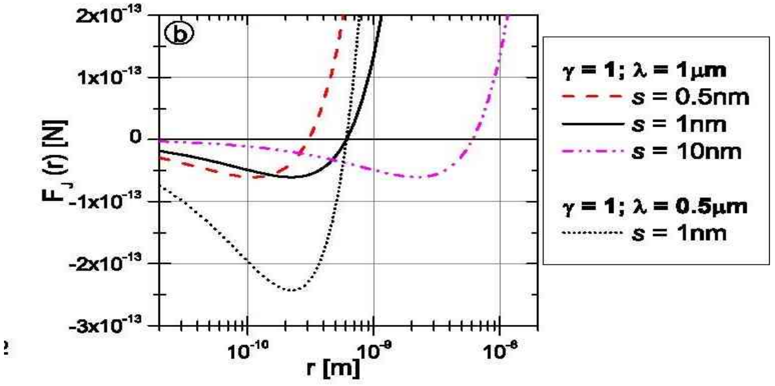
1

Spatial variation of the order parameter and of the magnetic field for triangular VL (ref:ELMC) for different values of the reduced induction (b=B'/B_{c2}) and Ginzburg-Landau parameter κ. Note that for a-MoGe, t=50nm, $\kappa \simeq 180$.



For NbN-50nm, κ ~120. This means that the field modulation inside MoGe is strongly reduced for b > 0.05.

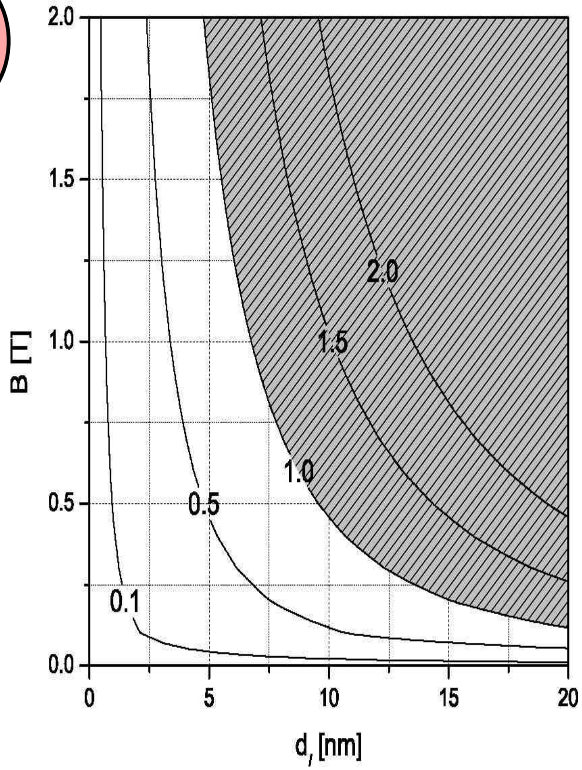
2



Magnitude of the Josephson force for different values of s (interface/coupling layer thickness – Fj ~ 1/s) and of λ, in function of misalignment r. It is evident that the attractive force is significant for small displacements and small λ.

(ref:JC)

3



Contour plot of the product $k(B)d_i$, where k(B)=2π/a_0 (a_0 contains the B-dependence) and d_i is the thickness of the interface/coupling layer (ref:ELMC). The shaded area indicates the range where significant degradation of magnetic flux density modulation occurs. It is assumed $d_i << a_0$

Intermezzo: vortex lattice (VL) imaging via STS (1)

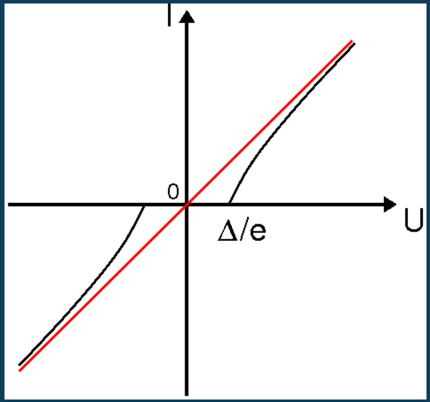
$V_b \cong$ 100/100 mV (1 mV), $I_t \cong$ 10-25 pA

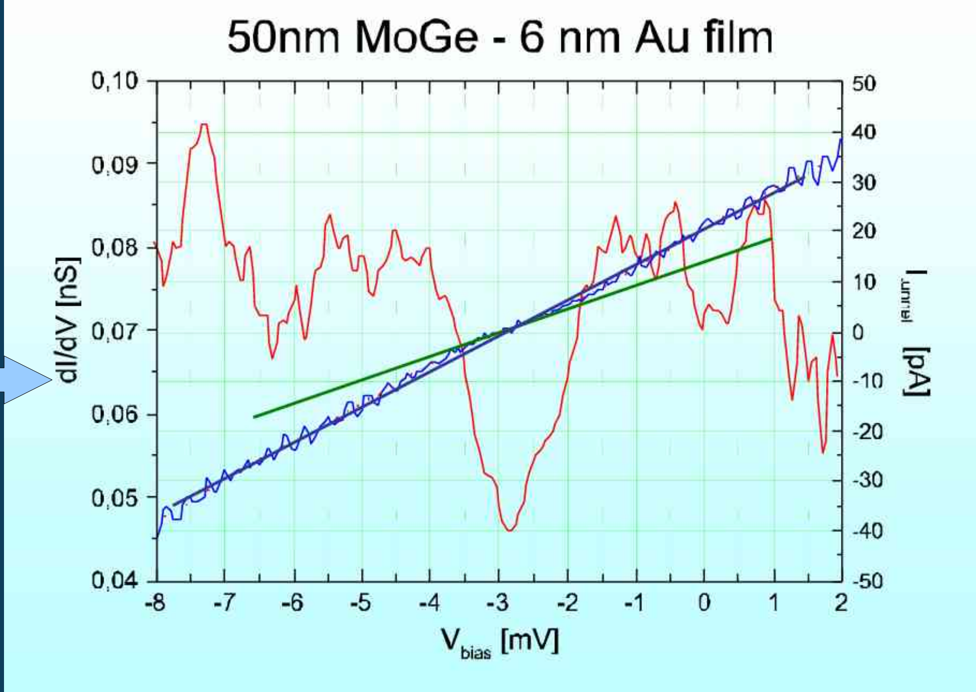
Constant Height Mode: Sample-tip d stabilized at $V_b > \Delta$ **=>** feedback off (or very slow) => scan “fast” with $|V_b| < \Delta$ and record I_t. *(Drawback: Possible only when atomically flat surface, VL imaging in* $NbSe_2$*)*

Constant Current Mode: Stabilize sample-tip d with given I_s at every pixel, with $V_b > \Delta$ => feedback off (sample-tip d = constant) => set $V_b < \Delta$ => measure I. Move to next pixel. *(Drawback: if isolation from mechanical vibration is not good, too much noise on the measured tunneling current.)*

Full I-V spectroscopy method: Similarly to above: stabilize feedback => feedback off => measure full I-V by sweeping through $-\Delta$ and $+\Delta$. More than 1 I-V per pixel (3 or 4) or AC-lock-in technique can be used to improve SNR.

Intermezzo: vortex lattice (VL) imaging via STS (2)

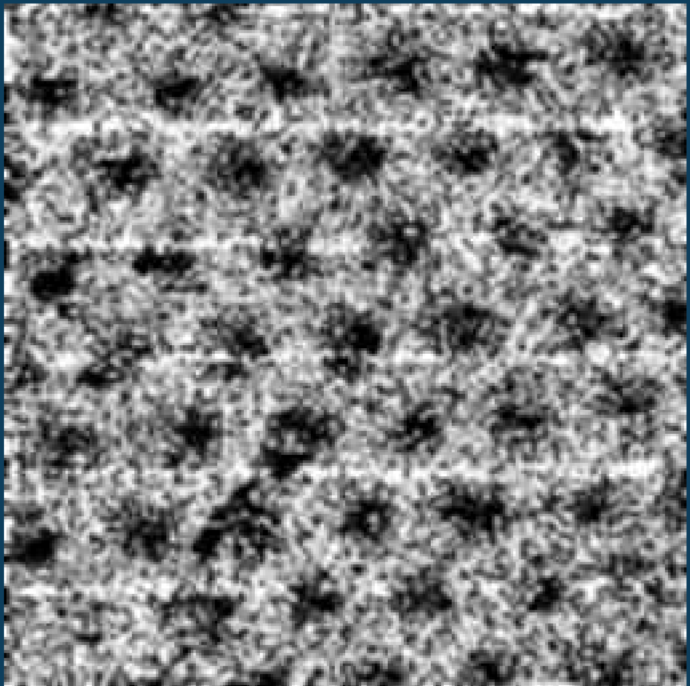




Gray scale:

dI/dV for $|V_b| > \Delta$

dI/dV for $|V_b| < \Delta$



Parameters (films)

NbN

T_c=11 K

λ ~ 500 nm

ξ ~ 5 nm

t = 67 nm

reactive RF-sputtering in Ar(95%)/N_2(5%).

Oxide

1. letting O_2 (20mbar, 15 mins)
2. Al_2O_3

RF-sputtering in Ar

a–$Mo_{70}Ge_{30}$

T_c= 6.5 K

λ = 900 nm

ξ ~ 8 nm

t = 50 nm

RF-sputtering in Ar

Au

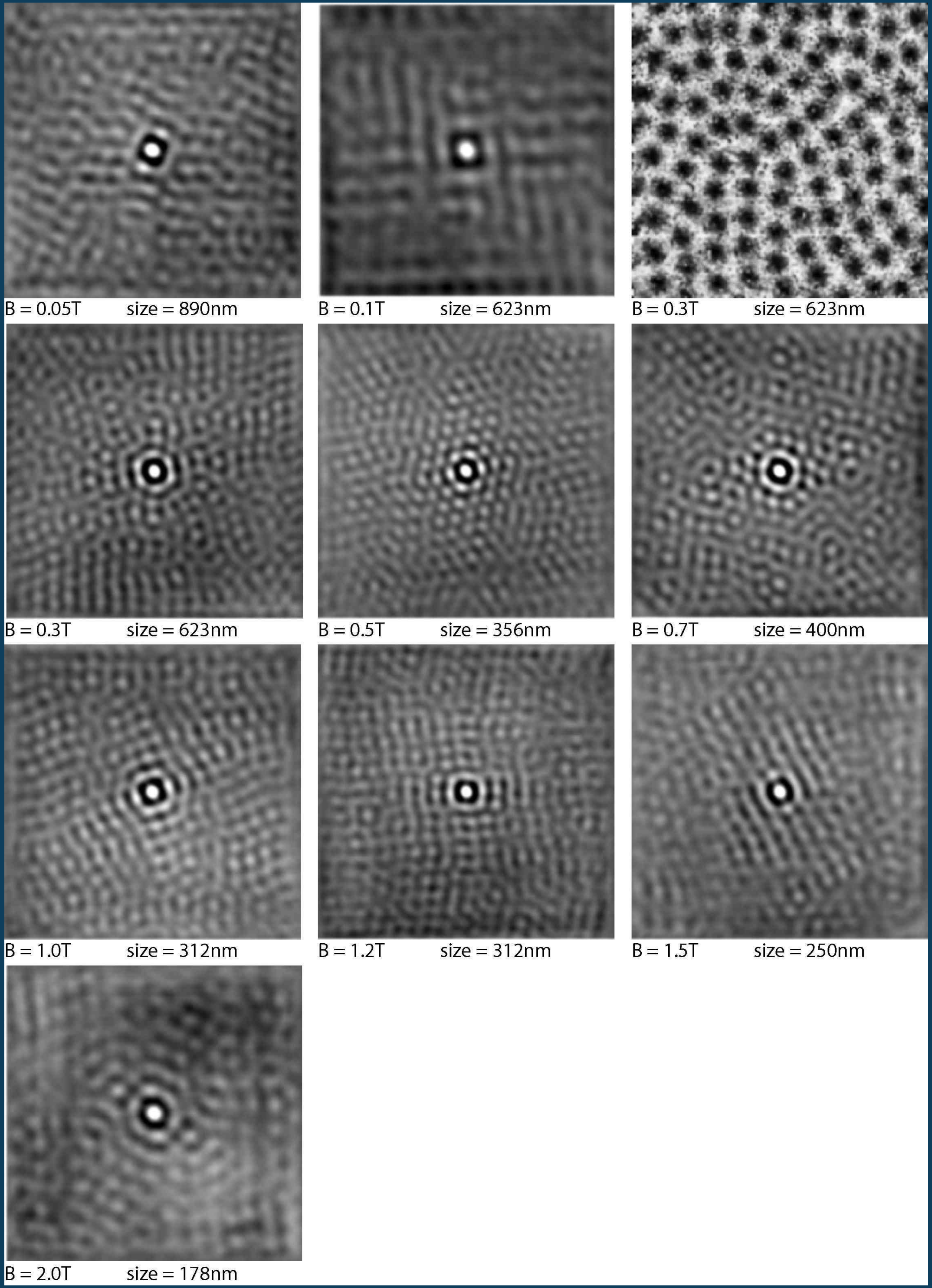
2nm (Ar)

2nm (Ar(95%)/O_2(5%))

NbN/NbN(NO)/MoGe/Au(2nm)

Results of the VL imaging via STM/STS and autocorrelation analysis as a function of increasing applied magnetic field (perpendicular to the film plane). For fields < 0.2 Tesla, there is hardly correlation (small ring for $r<a_0$) . For fields bigger than 0.3 Tesla there develops translational and angular correlation on a short range. The intermediate fields (0.5 Tesla) clearly show *short range order*.

This result suggests that the oxidized interface reduces the coupling, but does not eliminate it. Both the Josephson force and the electronic proximity contribute to the coupling between the VL and they are decreased by the reduced transparency of the interface, as expected.

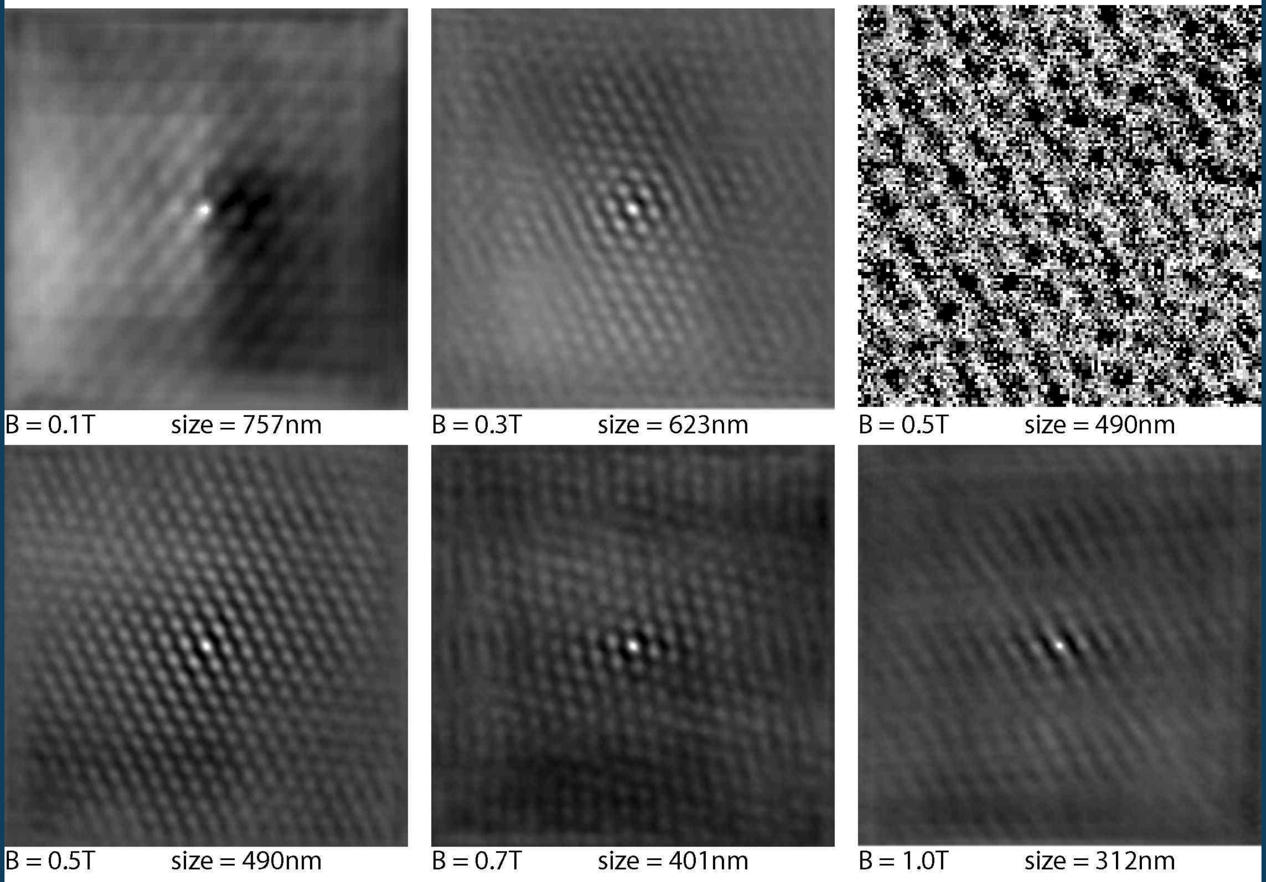

B = 0.05T size = 890nm
B = 0.1T size = 623nm
B = 0.3T size = 623nm
B = 0.3T size = 623nm
B = 0.5T size = 356nm
B = 0.7T size = 400nm
B = 1.0T size = 312nm
B = 1.2T size = 312nm
B = 1.5T size = 250nm
B = 2.0T size = 178nm

NbN/Al_2O_3/MoGe/Au(2nm)

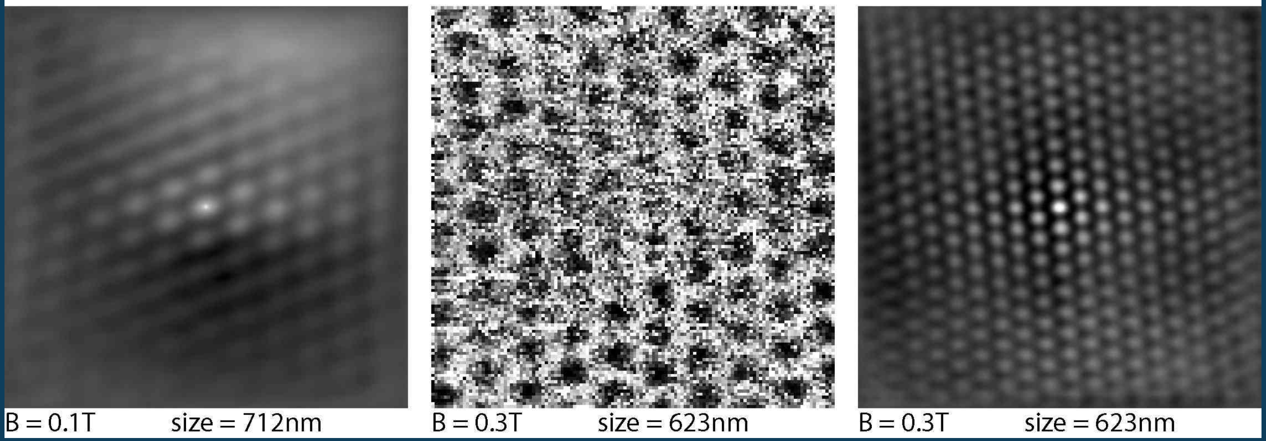
Results of the VL imaging via STM/STS and autocorrelation analysis, as a function of increasing applied magnetic field (perpendicular to the film plane), for film1: Al_2O_3(1nm) and film2: Al_2O_3 (4nm). The first spacer thickness models the situation of La-214, where the 1^{st} superconducting layer would be at a distance of ~ 1nm or less under an insulating sheet, after surface treatment.

A clearly developed *long range order* can be seen. This indicates that the Josephson coupling is reduced by the 1nm-interface. The results are comparable to [ref:Baarle03], where single MoGe films capped with Au are studied via STM. For the 4nm-Al_2O_3 the long range order appears even more clearly. Here the coupling (Josephson) is further reduced because of thicker separation layer. As discussed, we do not expect the ELM-coupling to play a significant role here, because of the relatively large λ and κ of NbN and MoGe, which make the field modulation profile very flat.

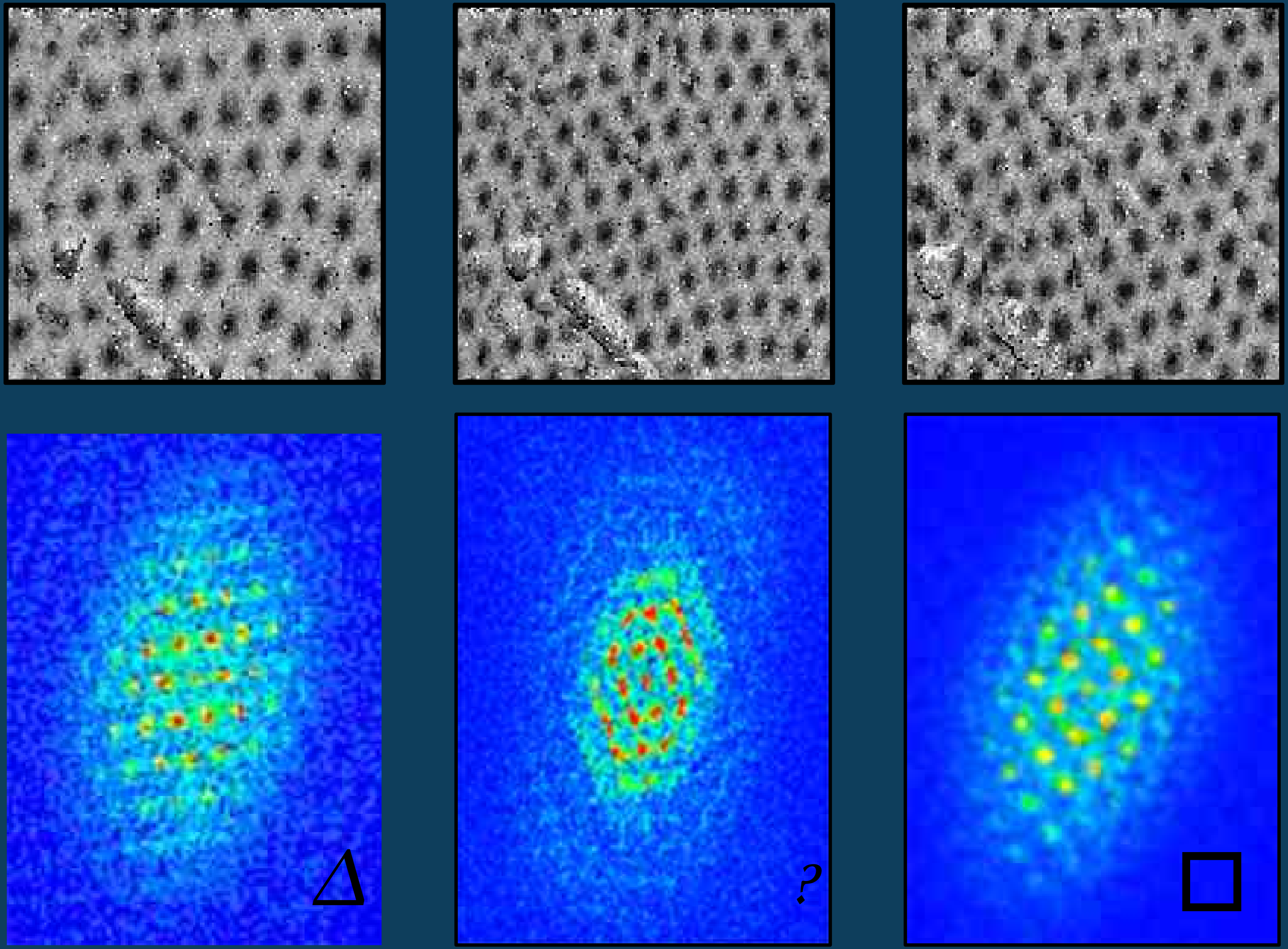
1 nm Al_2O_3



4 nm Al_2O_3



STM/STS on La-214/MoGe/Au (van Baarle et al.)



VL

2D-FFT

0.3 Tesla

0.5 Tesla

0.7 Tesla

Neutron scattering, Gilardi, Forgan 2002

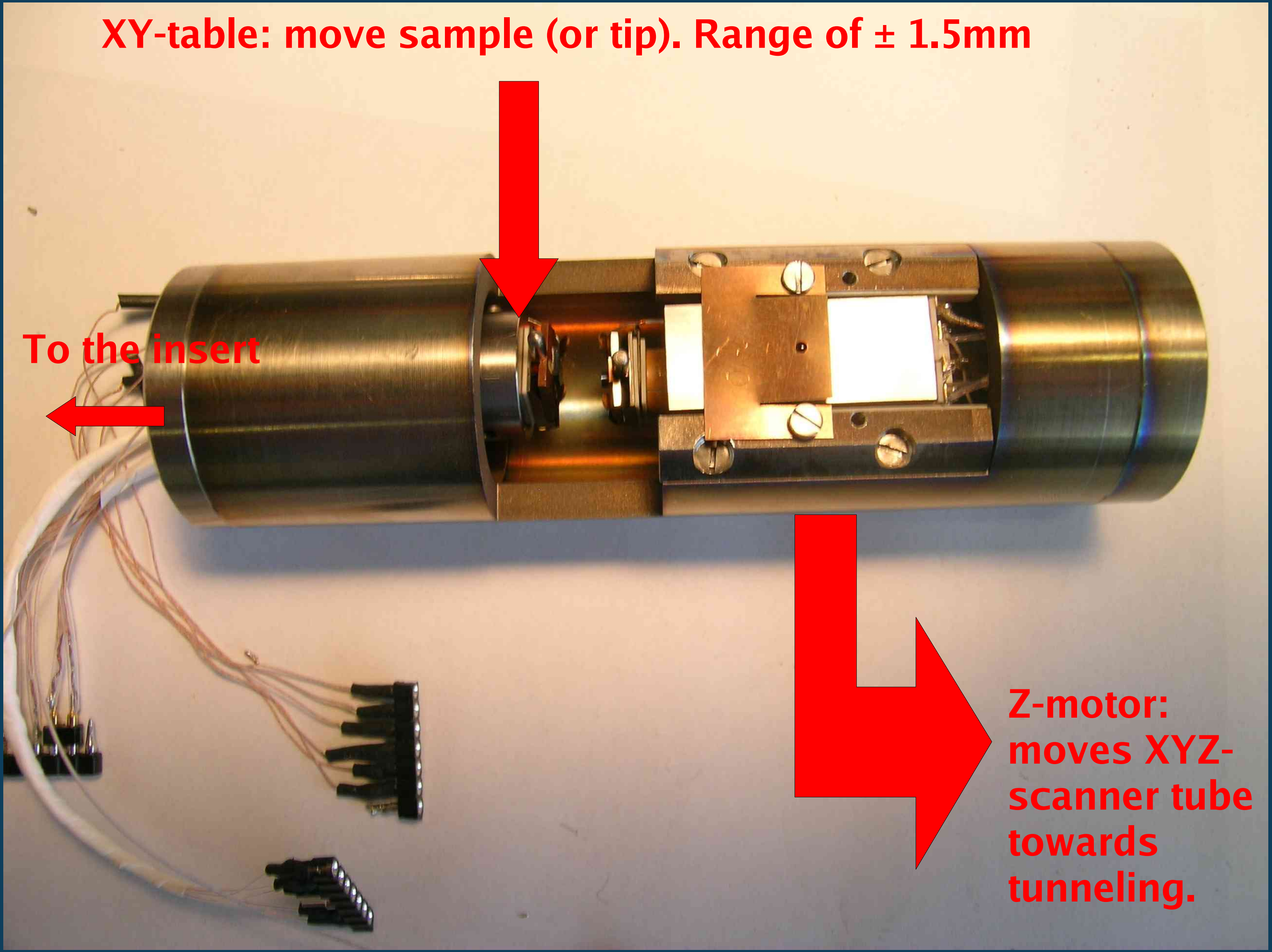
Conclusions

We have studied the vortex lattice in NbN/Oxide/MoGe/Au and La-214/MoGe/Au heterostructures, using the *a*-MoGe(50nm)/Au(2nm) bilayer as “imaging layer”.

We found that the success of such method critically depends on the physical parameters of both superconductors like the magnetic penetration depth, the thickness of MoGe and the thickness and properties of the interface between the two.

In the La-214/MoGe/Au heterostructure the method is definitively successful due to the smaller λ of La-214 with respect to NbN. Also, here the insulating interface is expected to be rather thin (sub-nanometer).

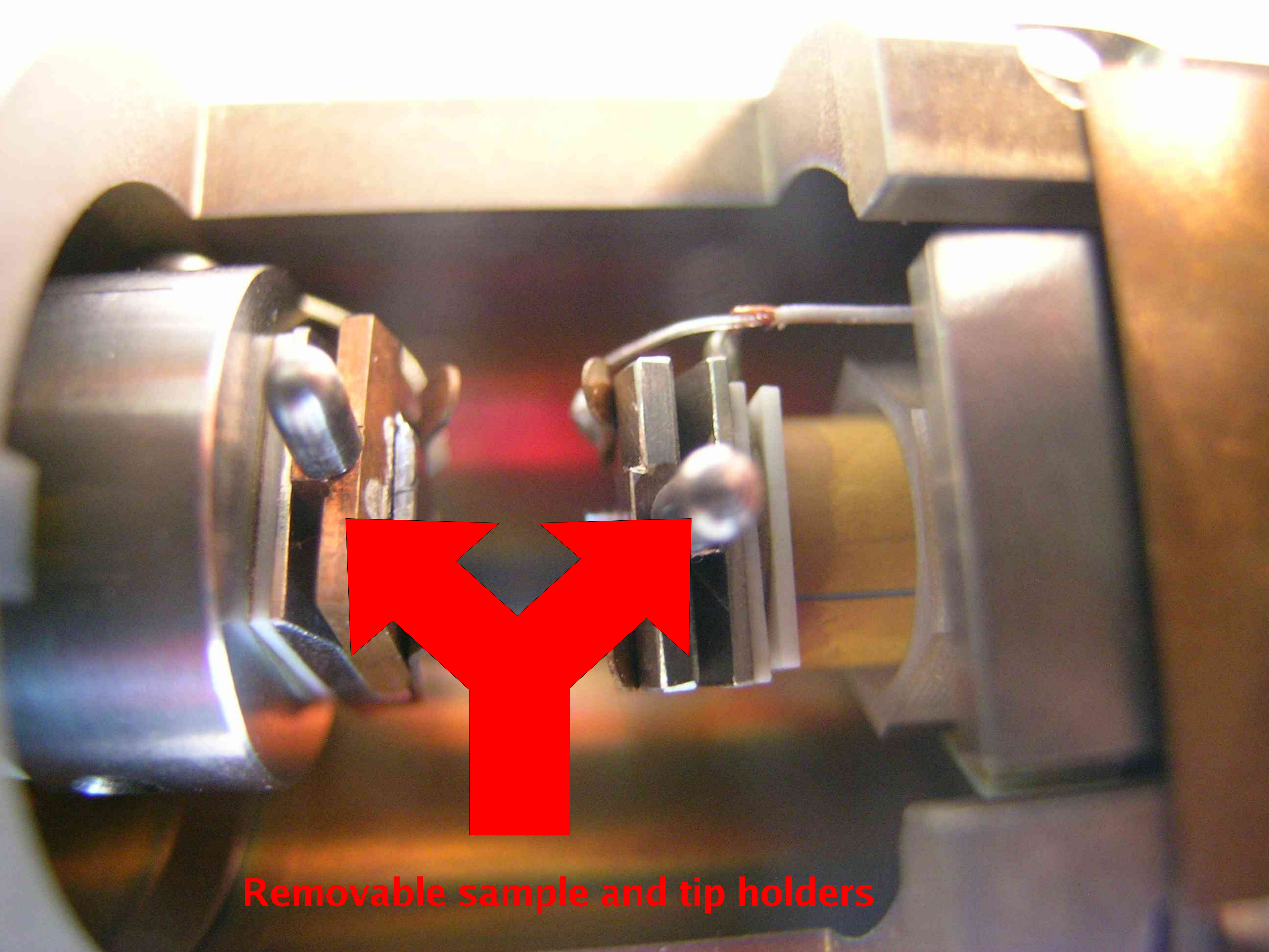
Development of a new low-T/UHV STM



XY-table: move sample (or tip). Range of ± 1.5mm

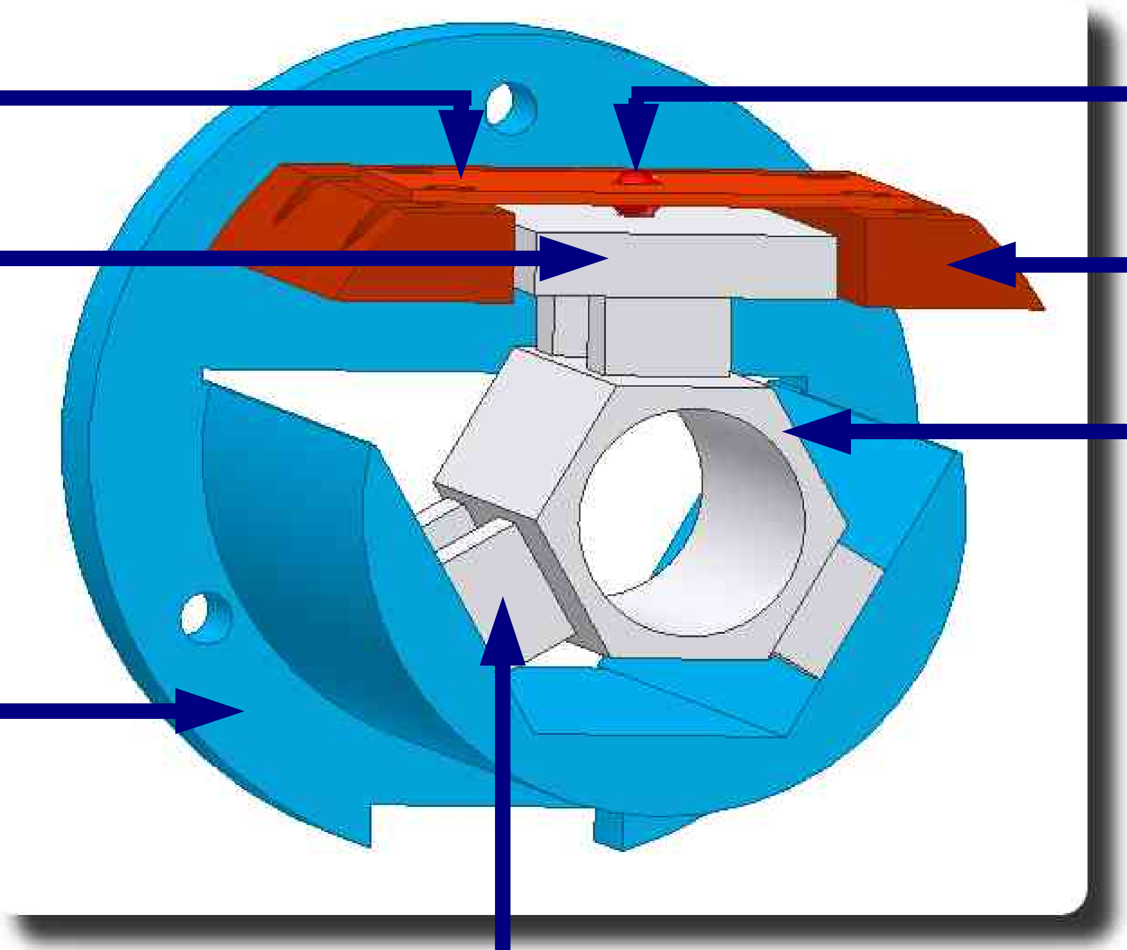
To the insert

Z-motor: moves XYZ-scanner tube towards tunneling.



Removable sample and tip holders

Z-COARSE APPROACH MODULE



Ruby ball

Leaf spring

Spring spacer

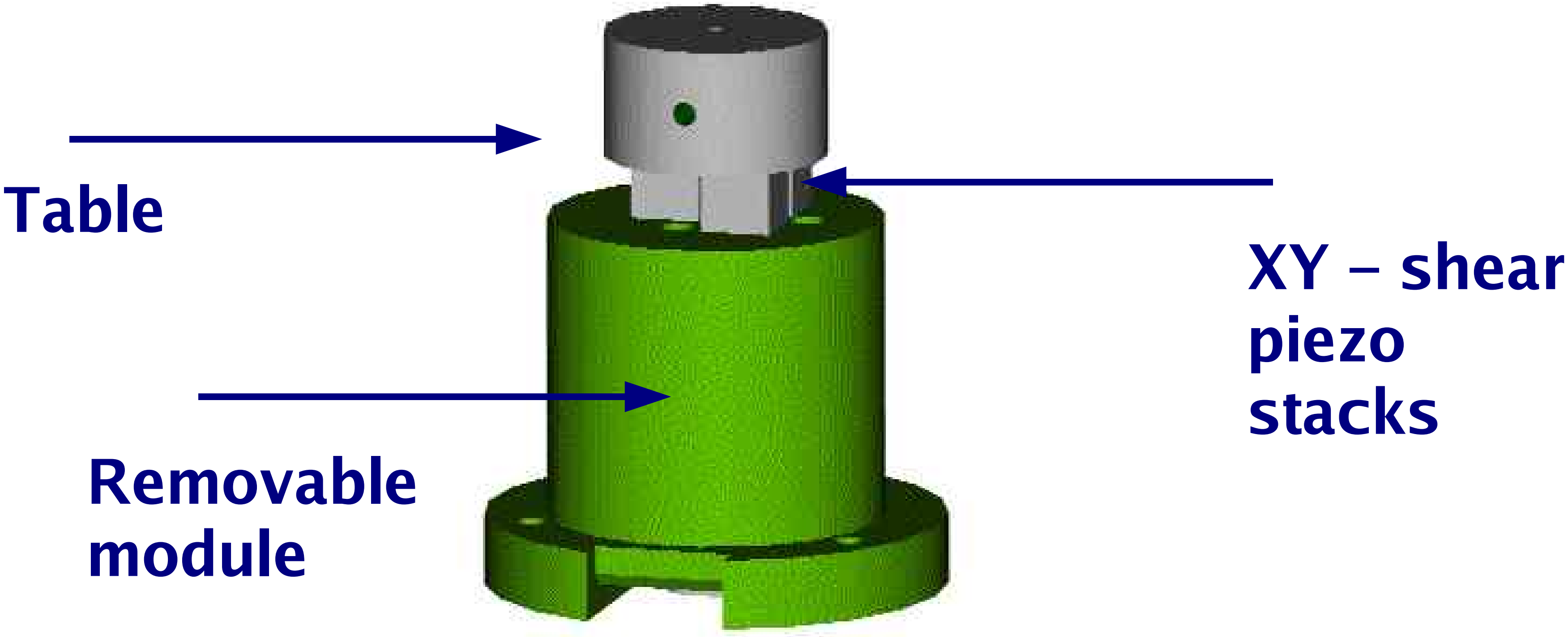
Upper piezo beam

Sapphire slider
(scanner holder)

Coarse approach
housing
(removable
module)

Shear piezo stack

XY-TABLE MODULE



Table

XY – shear piezo stacks

Removable module

Coarse Approach: working principle.

The moving shaft ("slider", blue in figure) is clamped in position between a set of stacked shear piezos ("legs", yellow in figure). When a slowly rising voltage is applied to all 4 legs the slider will be displaced 1 step forward, by being dragged by the legs. In this phase the static friction limit between the legs and the slider is not exceeded because the acceleration is low. Afterwards, each leg is retracted very fast, *one by one,* by dropping the voltage very quickly.

"Slip-stick"=> $t_1 \neq t_2 \neq t_3$

"Inertial Slip-stick"=> $t_1 = t_2 = t_3$

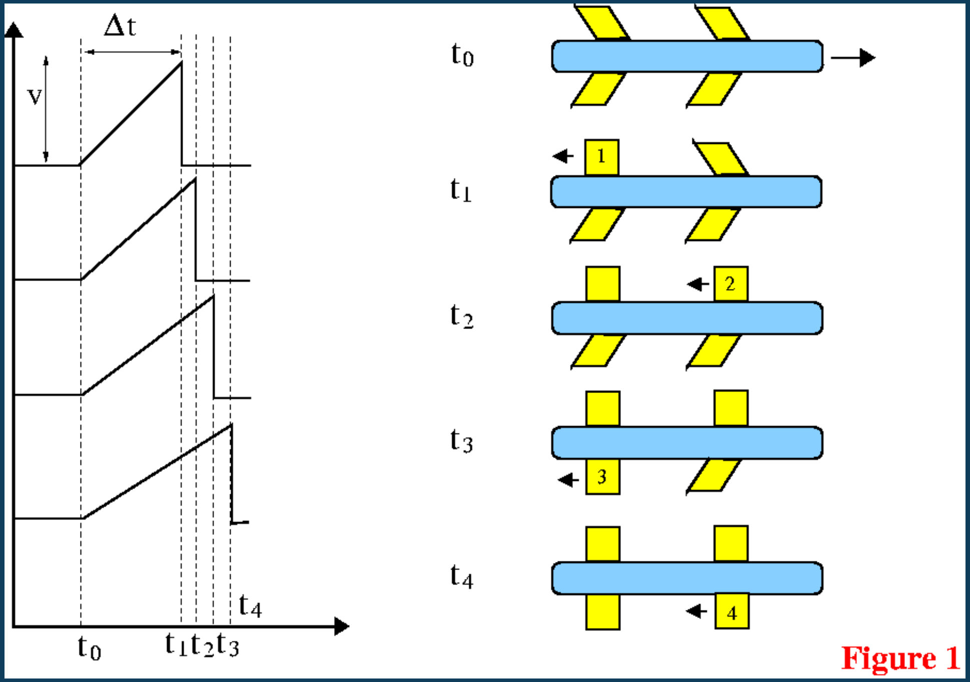


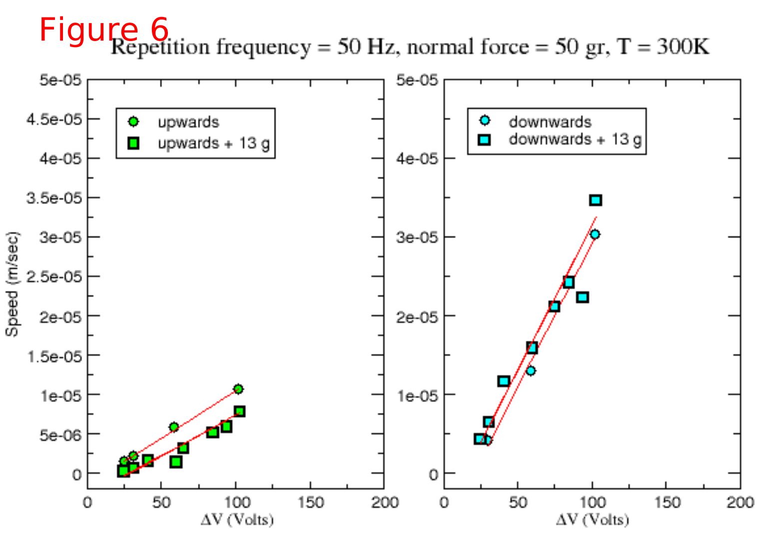
Figure 1

For the operation of both motors we use a "saw-tooth" like shape of the voltage pulses (with V=30 to 250 Volts, Δt=5ms, slew-rate~V/100μs=, t4-t3=t3-t2=t2-t1=0.5ms and a step repetition frequency between 50 and 200 Hz) or a parabolic shape, with frequency up to 500 Hz and $t_1 = t_2 = t_3$ (inertial).

(1) S.H.Pan, international Patent publication Nr. WO93/19494
(2) Rev. Sci. Instr. 68, p.3806 (1997) (3) Rev. Sci. Instr. 70, p.1459 (1999)

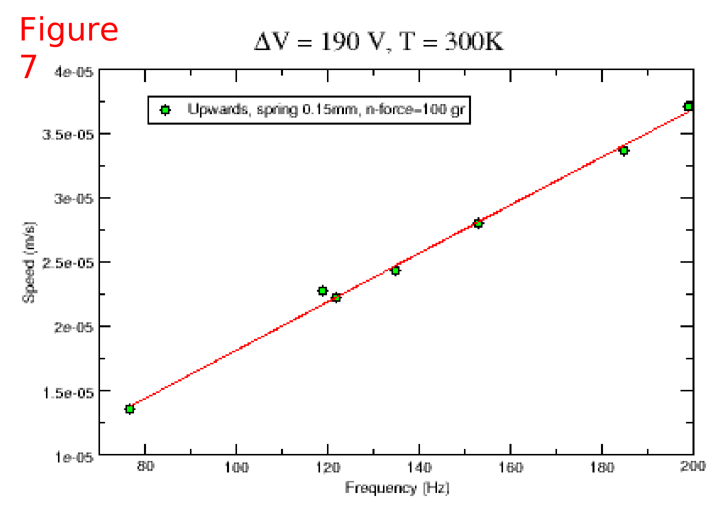
Coarse Approach: test at RT

Figure 6



Speed of the Z-coarse approach in function of driving voltage (Figure 6) and repetition frequency (Figure 7) at 300 K.

Figure 7



Coarse Approach: test at 4K

Figure 8

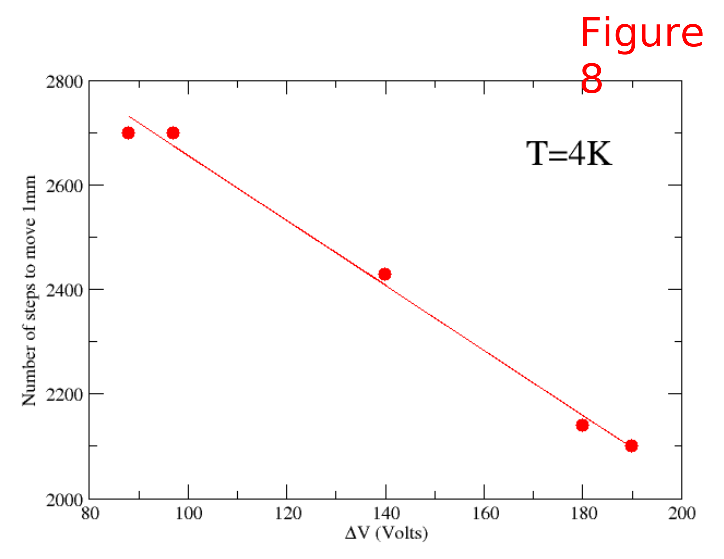
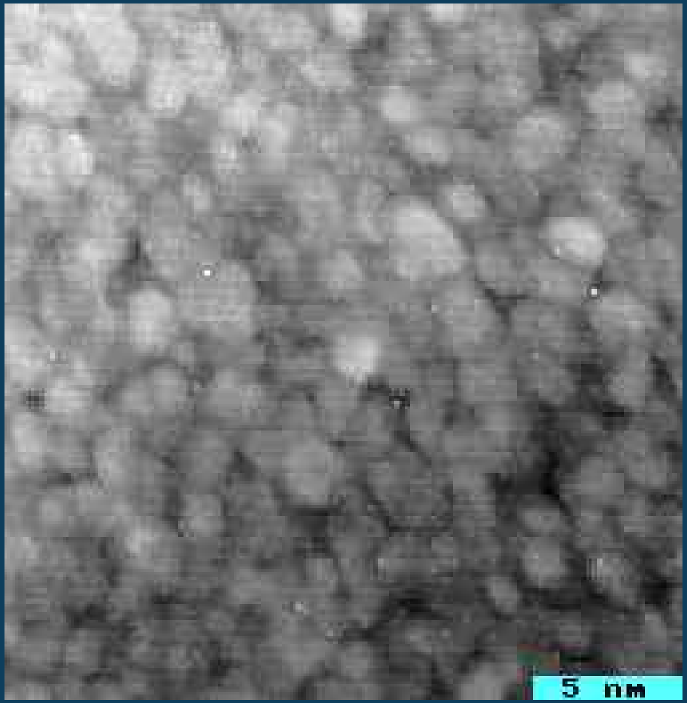


Figure 8: Time (in terms of number of steps) for the Z-coarse approach to “walk” an estimated distance (0.8mm) in function of driving voltage (repetition frequency = 50Hz) at 4 K.

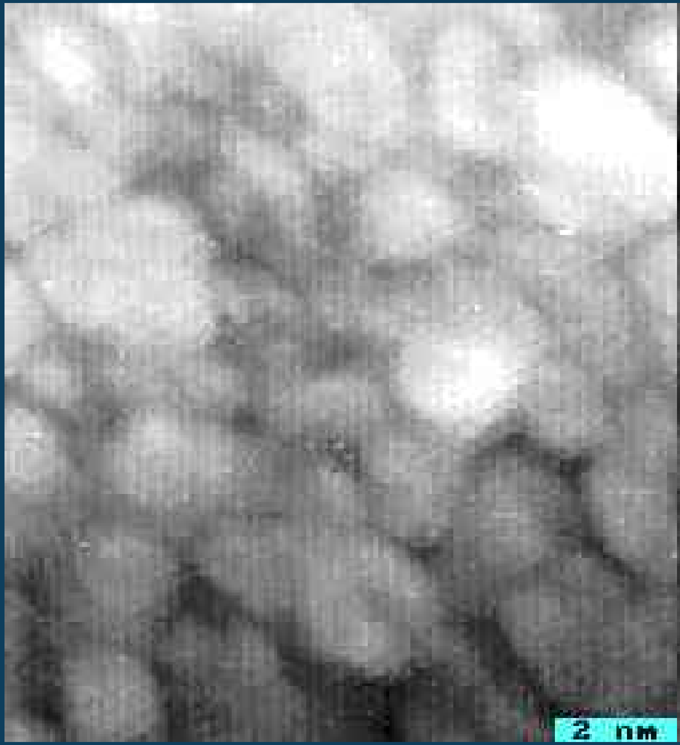
Imaging of “flat” Au surface at RT in air

Resolution: 128x128, scan speed: 1s/line, V_b= 200/100 mV
No vibration isolation.

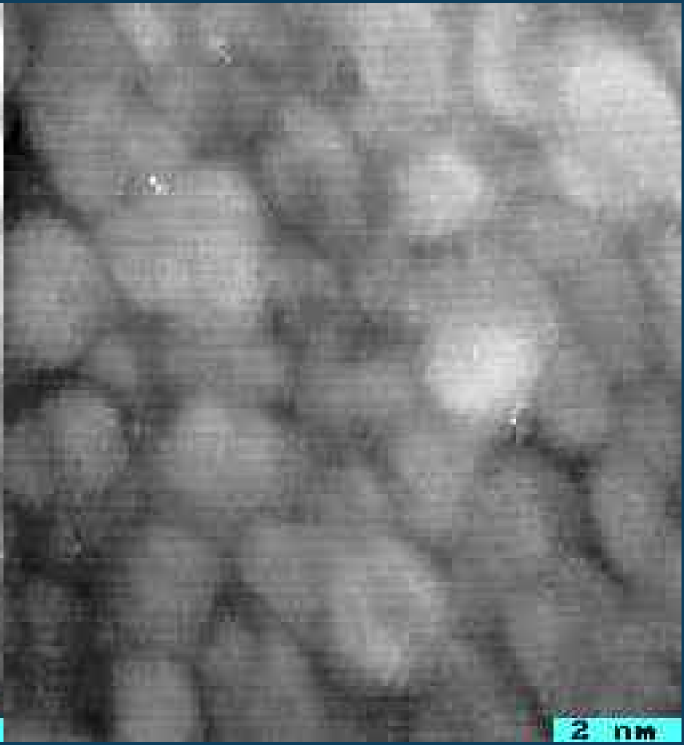
Fast scan dir. ←
Slow scan dir. ↓



Fast scan dir. ↓
Slow scan dir. ←



Fast scan dir. ←
Slow scan dir. ↓



Problems:

1. Get the Z-motor working again :-(

2. Improve vibration isolation

(Electronic noise, interferences, ground loops etc, do not seem to be a problem YET!)

Future:

1. Do 1. until works :-)

2. Strained Oxides

3. Test XY