

Microscopie en champ proche

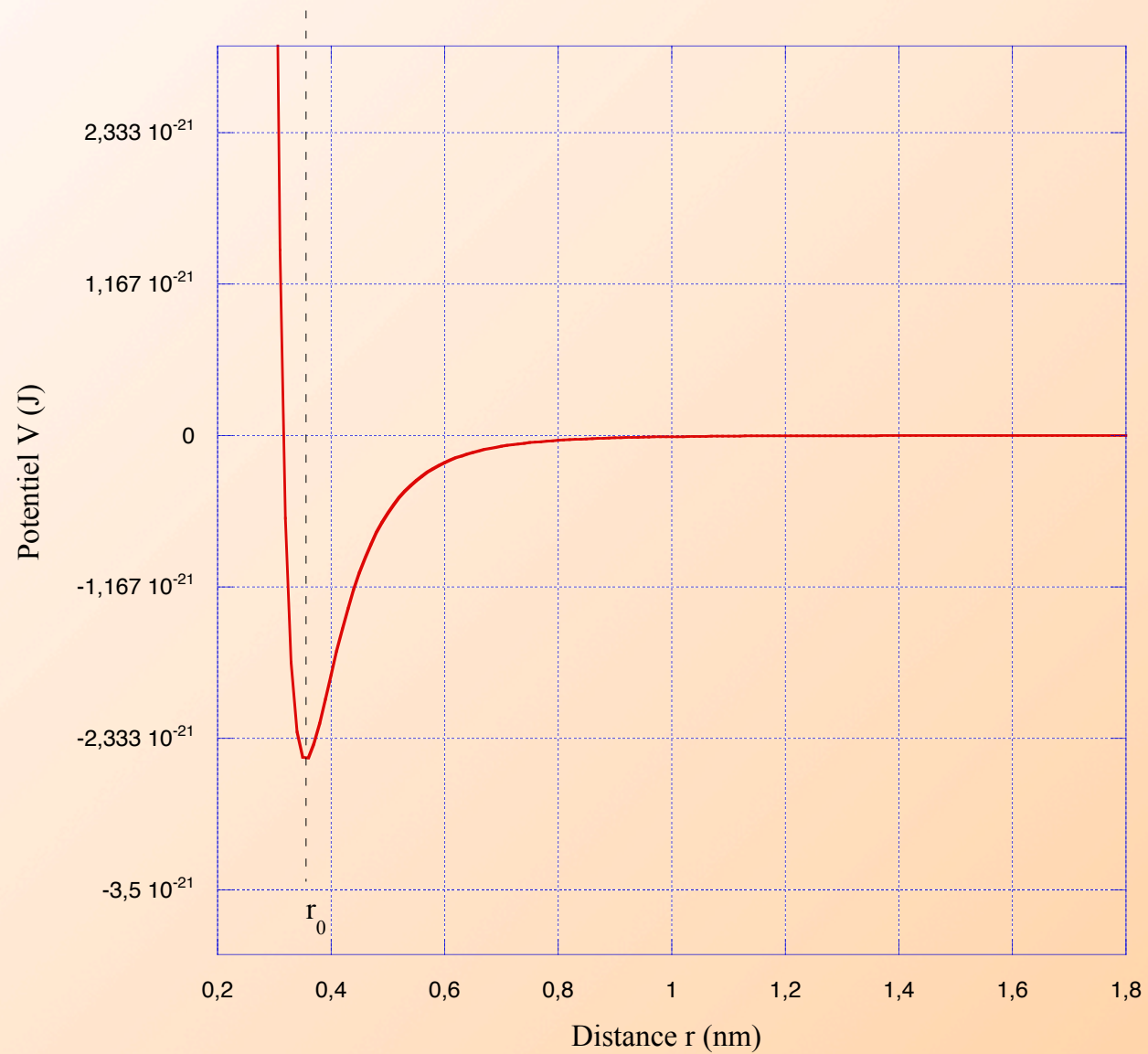
Microscopie à sonde locale

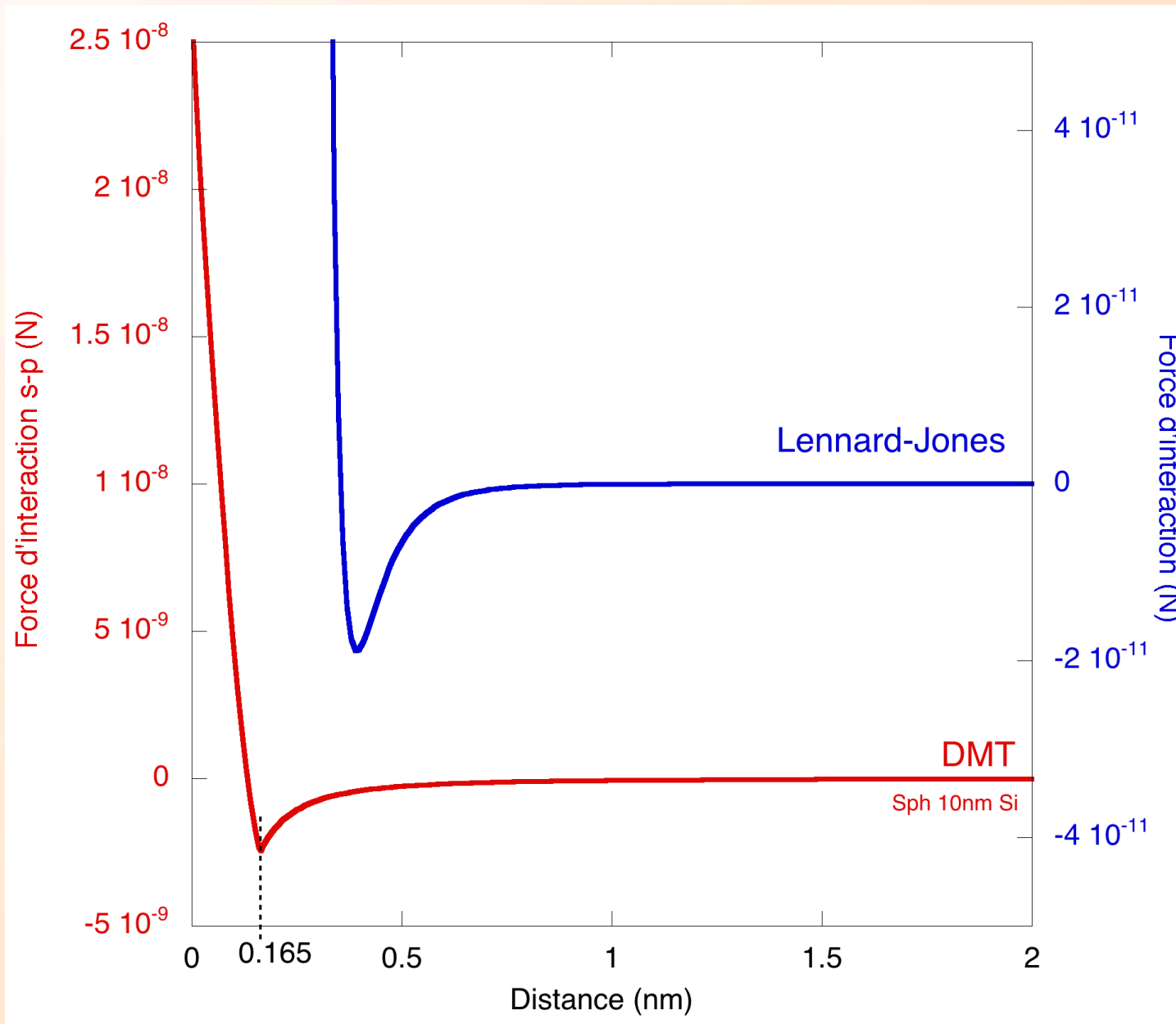
Microscope à Force Atomique

Atomic Force Microscope

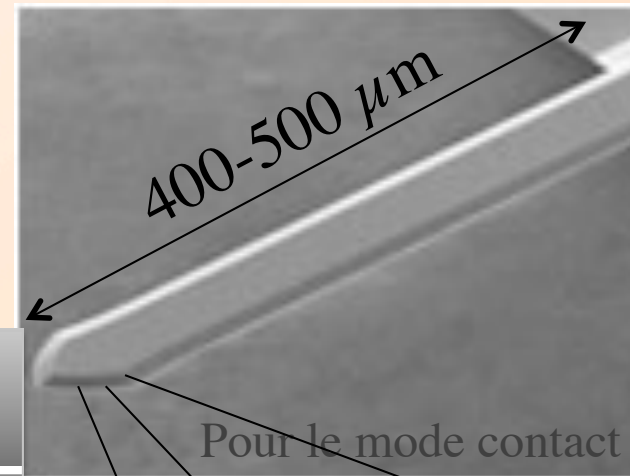
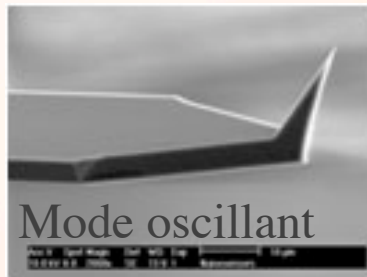
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Potentiel de type Lennard-Jones



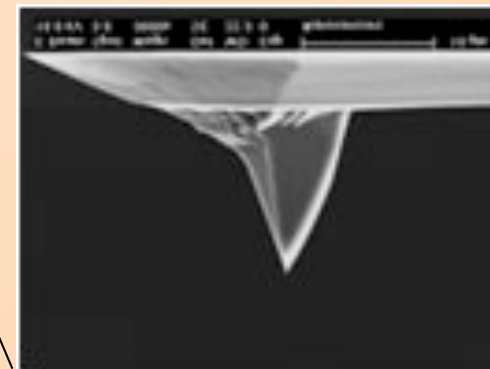
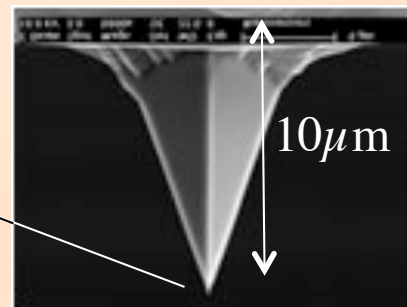


Le microlevier de Si : Cantilever

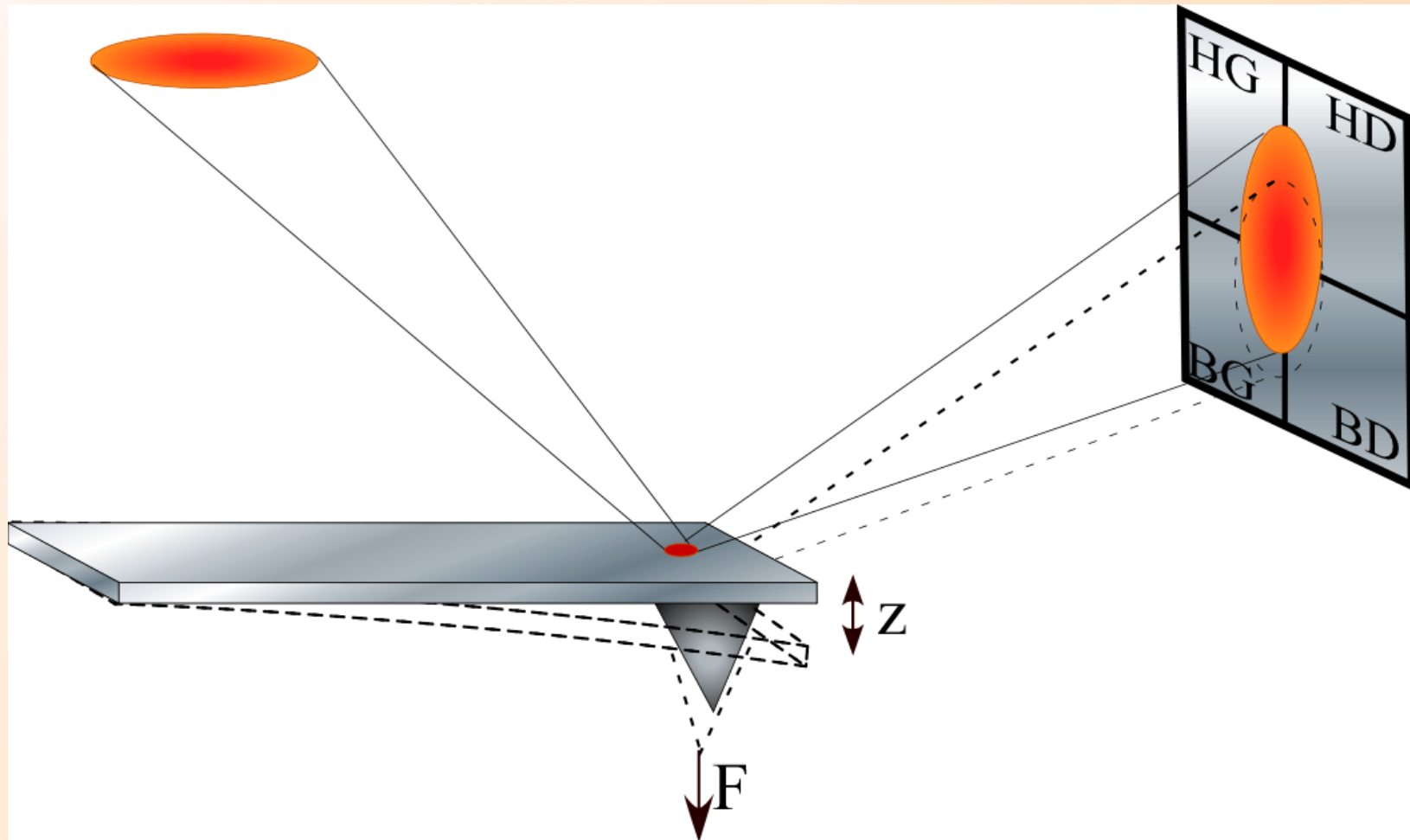


Levier contact	$L=450 \mu\text{m}$	$k=0.1 \text{ N/m}$	$f = 6 \text{ kHz}$
Levier oscillant	$L=225 \mu\text{m}$	$k=40 \text{ N/m}$	$f= 150 \text{ kHz}$

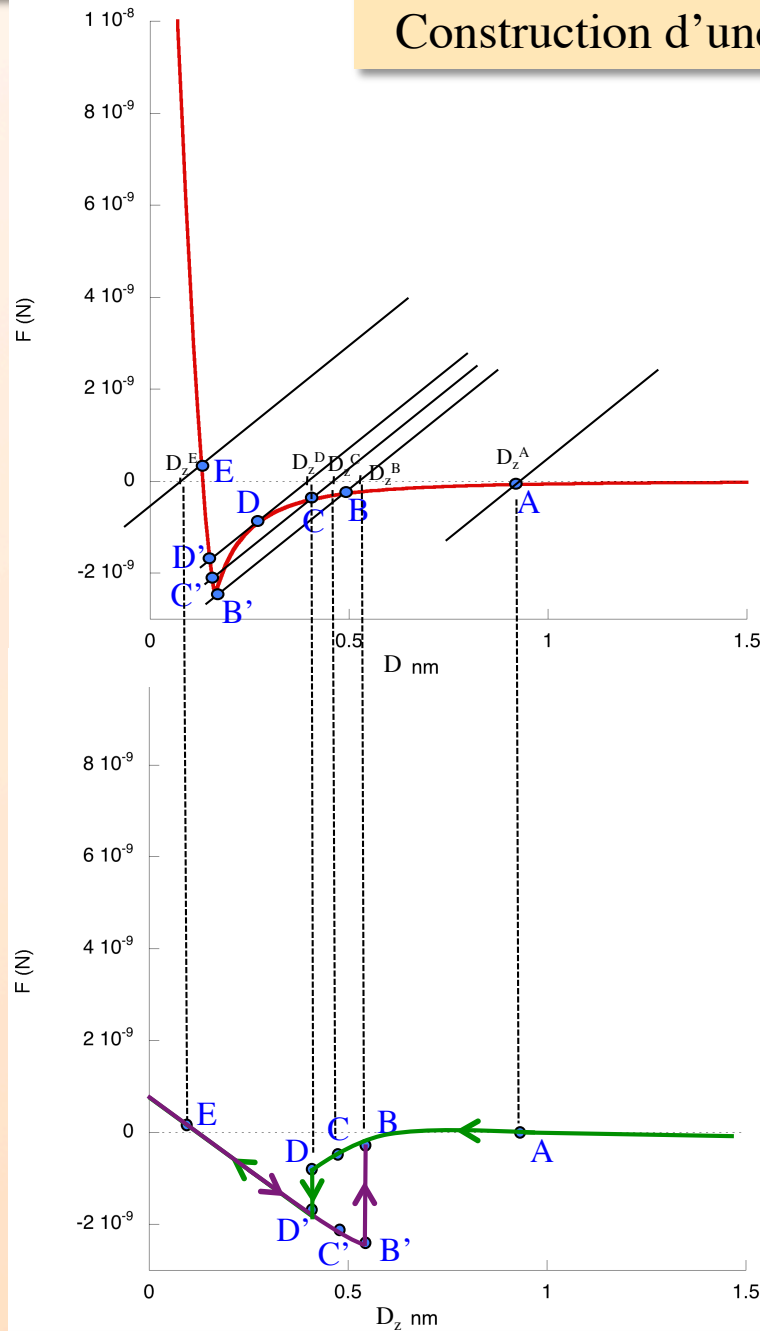
Rayon de courbure de l'apex 10 nm



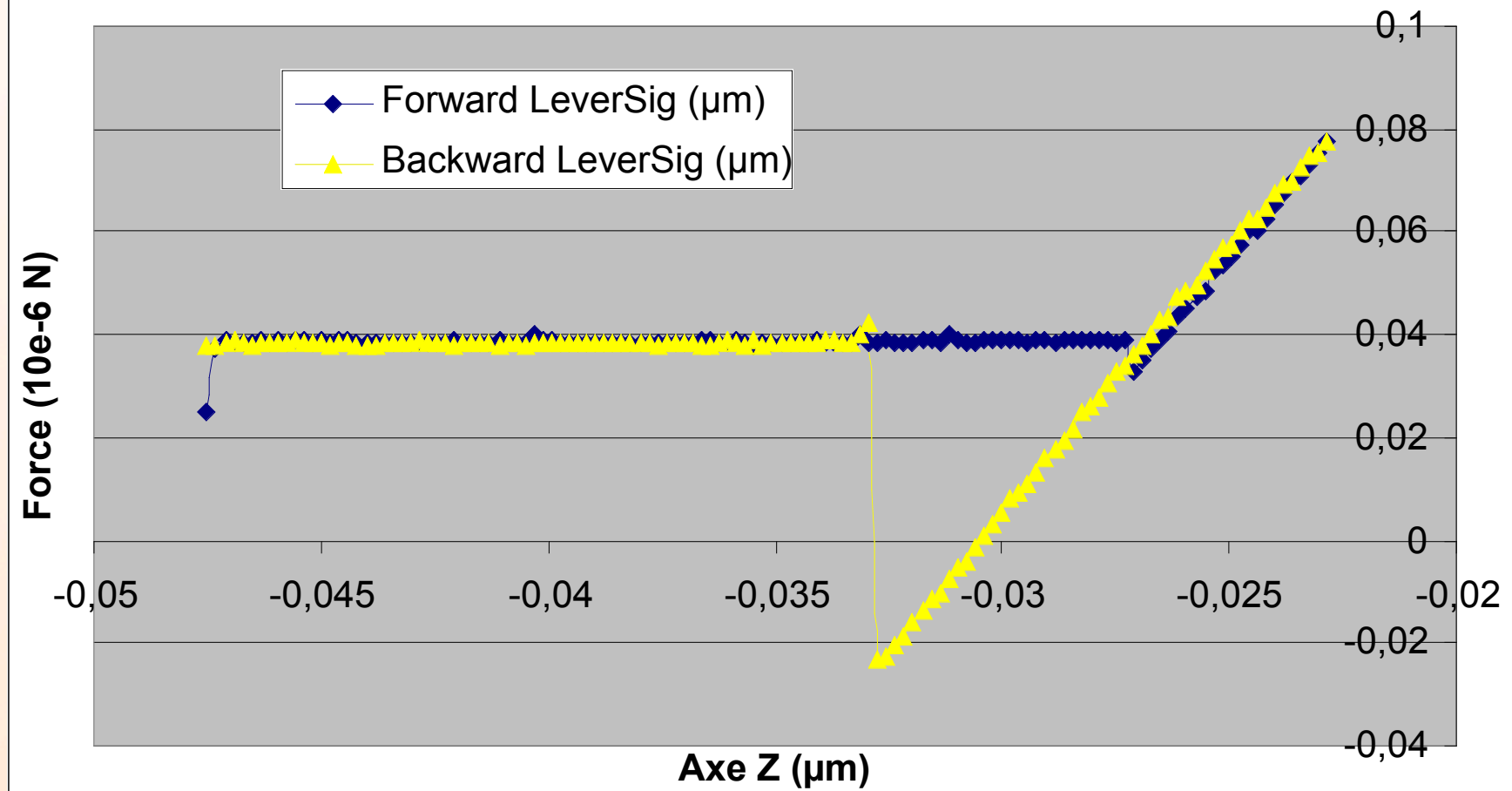
Mesure optique de la déflexion



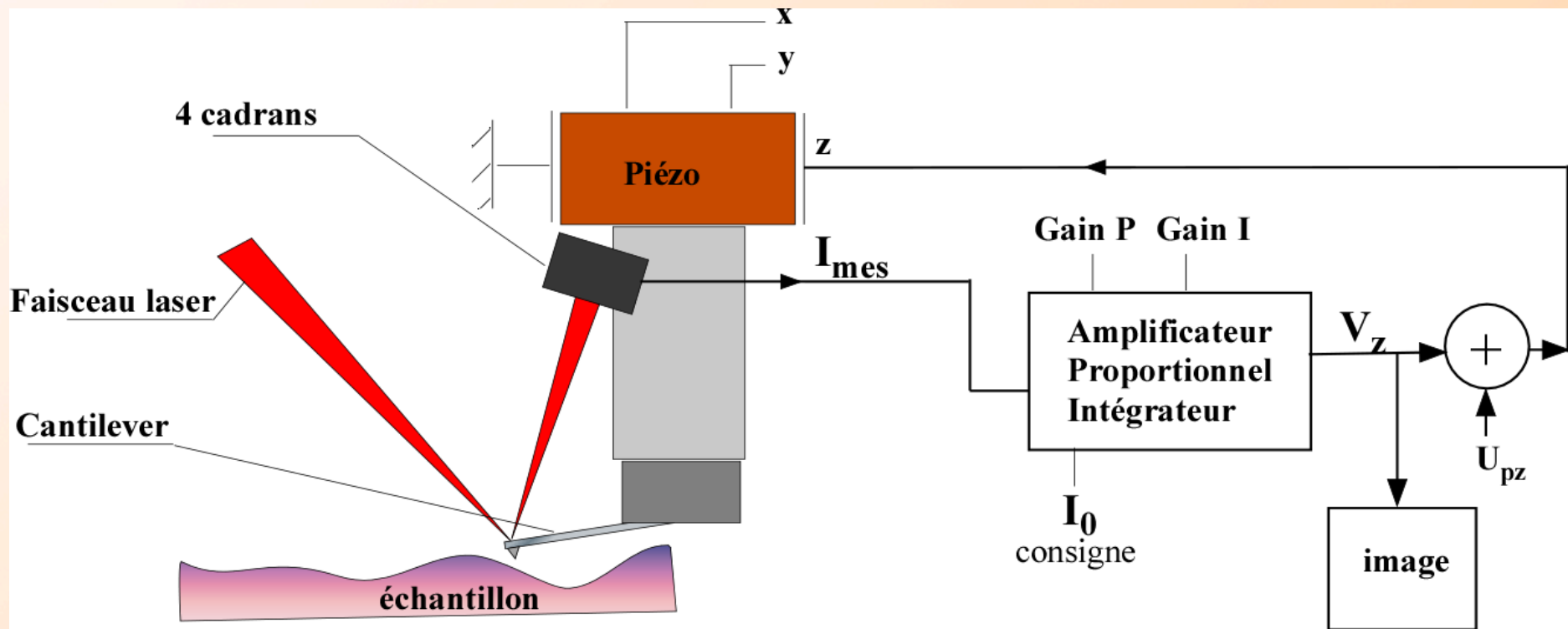
Construction d'une courbe de force $F(D_z)$



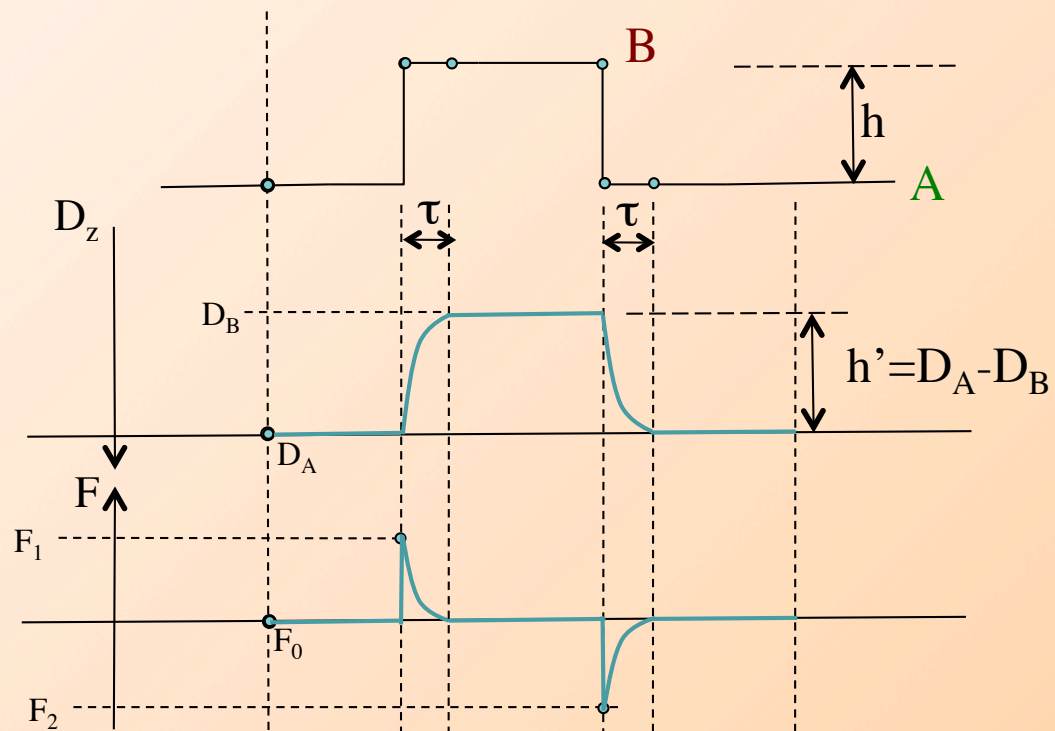
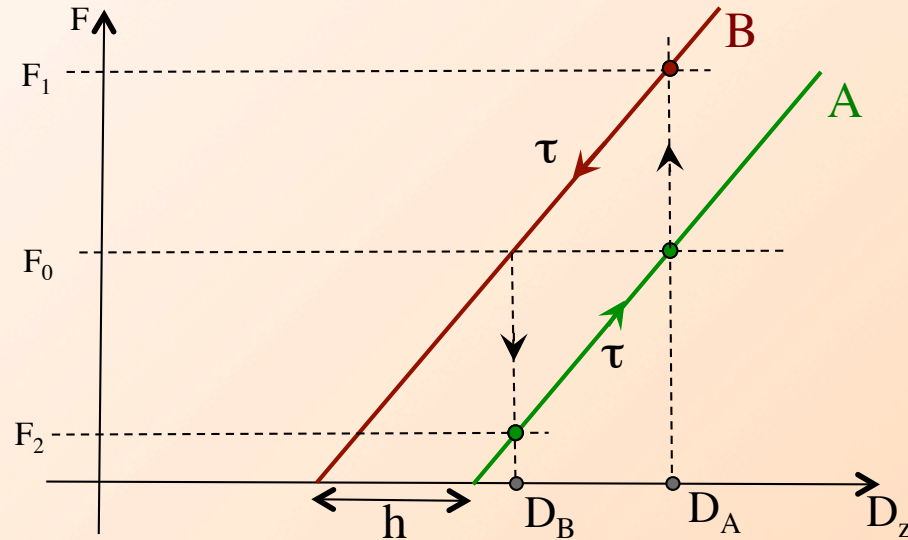
Zoom DVD courbe de force



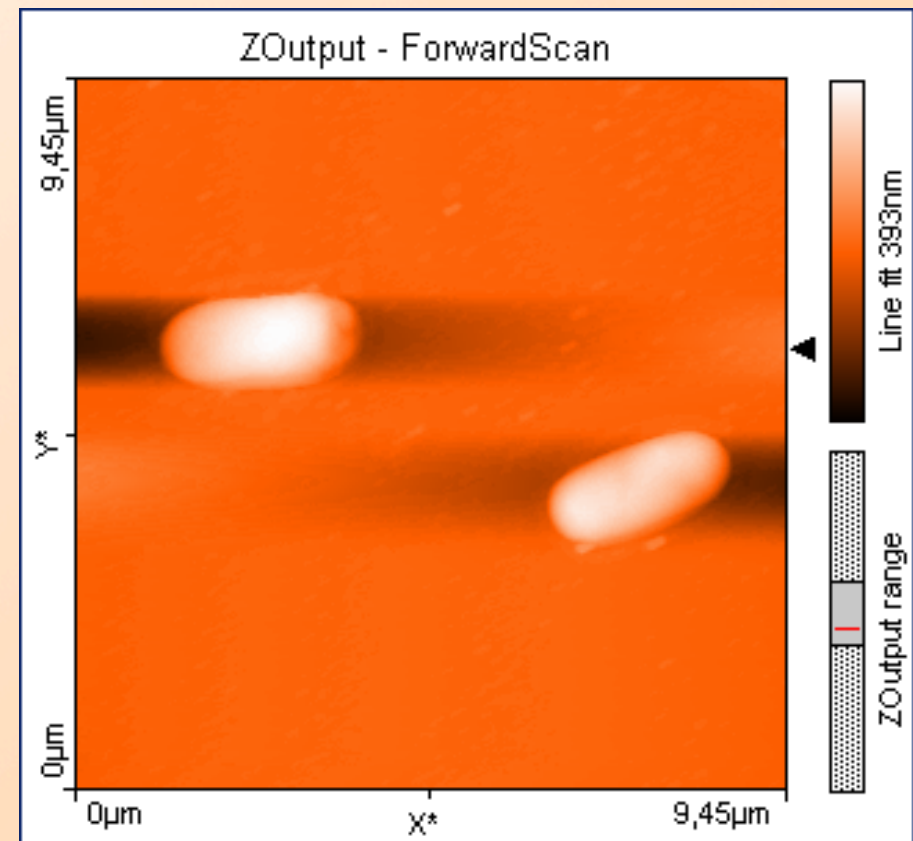
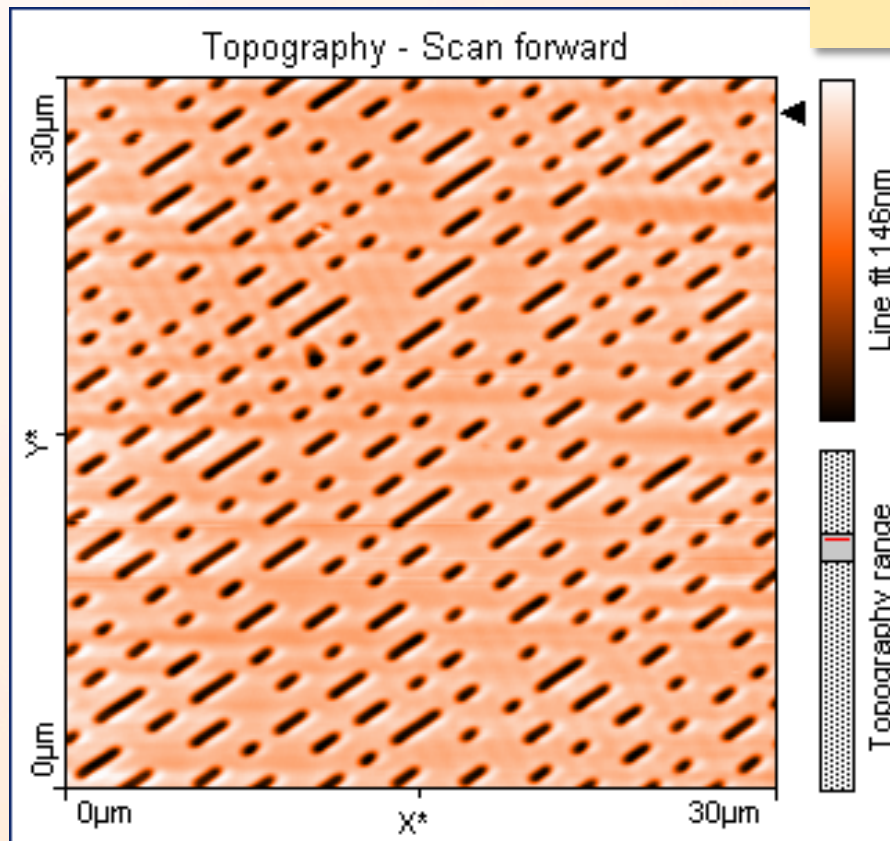
Fonctionnement du microscope Imagerie à Force constante



Simulation des images
en imagerie à force
constante (F_0)



Quelques images en mode contact



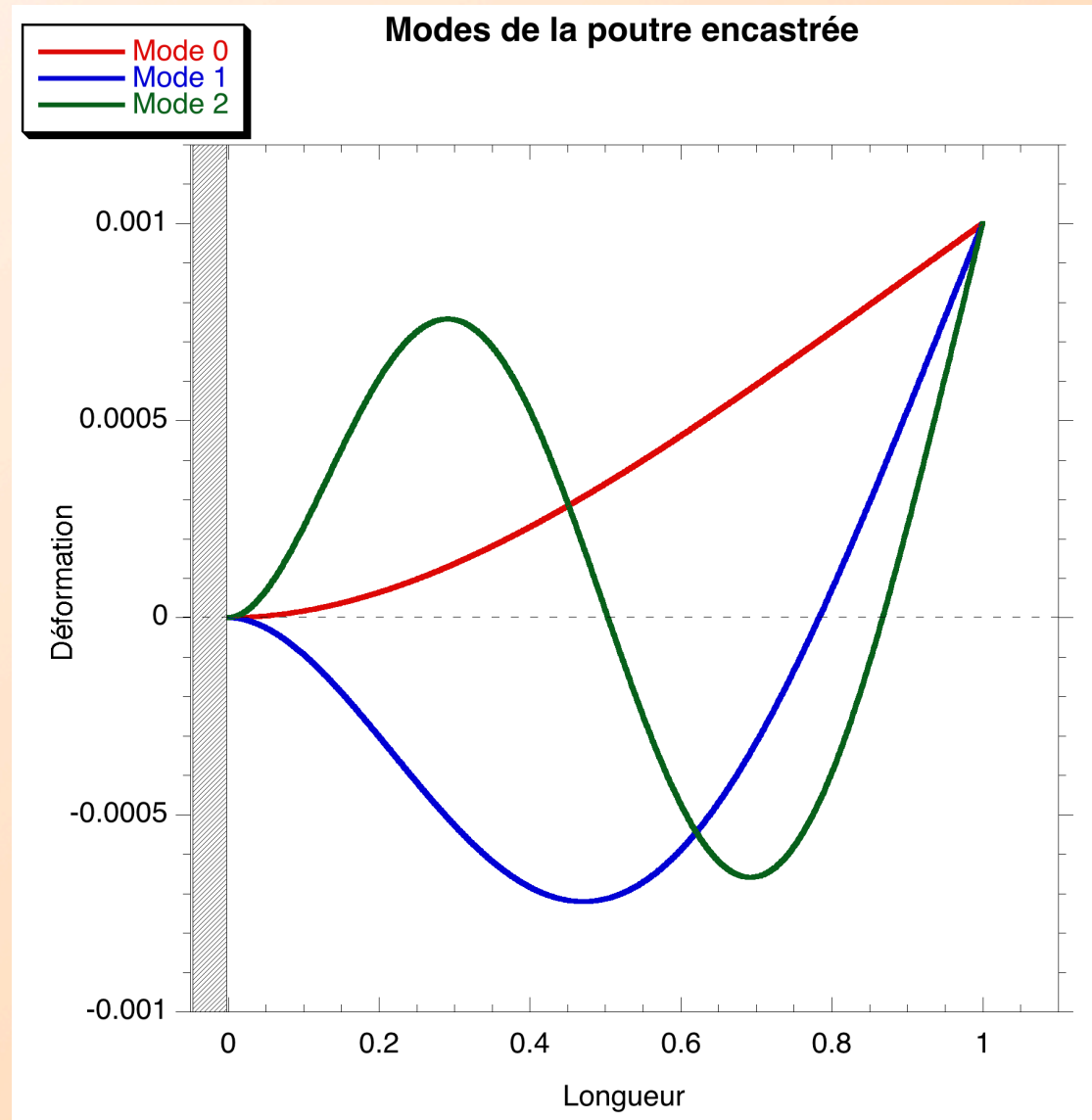
Équation différentielle de la poutre

$$EI \frac{\partial^4 z}{\partial x^4} + \kappa \frac{\partial z}{\partial t} + \rho S \frac{\partial^2 z}{\partial t^2} = 0$$

Solution :

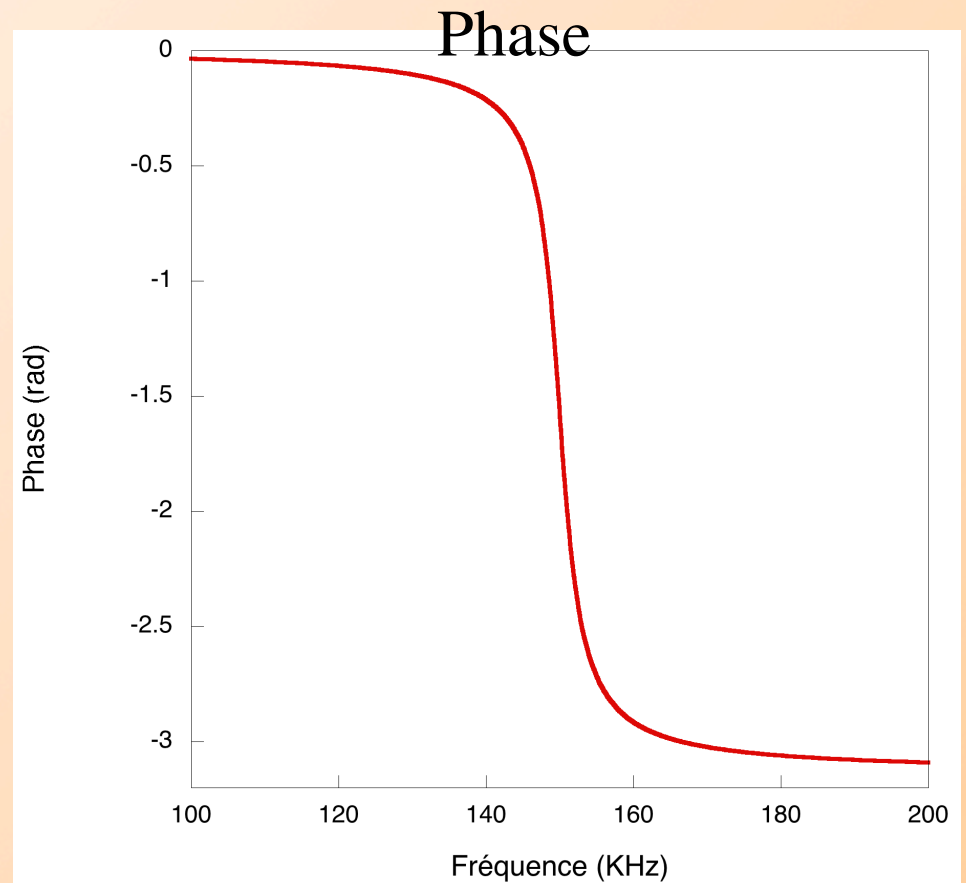
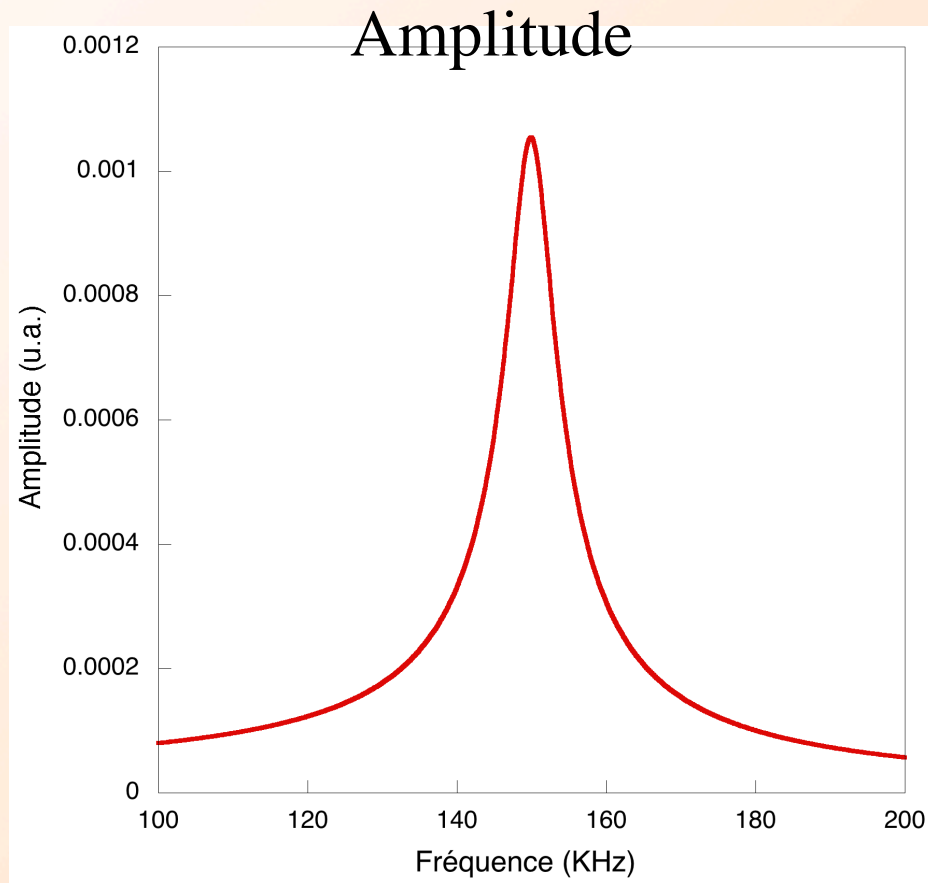
$$z(x,t) = (Ae^{\beta x} + Be^{i\beta x} + Ce^{i\beta x} + De^{-i\beta x}) e^{i\omega t} e^{-\frac{\Gamma}{2}t}$$

avec $\omega = \sqrt{\frac{EI}{\rho S}} \beta^2$ et $\Gamma = \frac{\kappa}{\rho S}$



Mode oscillant

Résonance du mode fondamental du cantilever



Principe de la moindre action

L, Lagrangien du système :

$$L(z, \dot{z}, t) = \frac{1}{2} m^* \dot{z}(t)^2 - \left[\frac{1}{2} k_c z(t)^2 - z(t) F_0 \cos(\omega t) + V_{\text{int}} \right] - \Gamma m^* z(t) \underline{\dot{z}(t)}$$

Pour retrouver l'équation différentielle on applique :

$$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{z}} \right) - \frac{\partial L}{\partial z} = 0$$

On cherche des solutions de la forme :

$$z(t) = A \cos(\omega t + \varphi)$$

$$S = \int_{t_1}^{t_2} L(z, \dot{z}, t) dt$$

Dans le cas de l'oscillateur le Principe de moindre action devient :

$$\begin{cases} \frac{\partial S}{\partial A} = 0 \\ \frac{\partial S}{\partial \varphi} = 0 \end{cases}$$

Avec $S = S_0 + S_{dissip} + S_{int}$

$$S_0 = \int_0^{\frac{2\pi}{\omega}} \left(\frac{1}{2} m^* \dot{z}(t)^2 - \frac{1}{2} k_c z(t)^2 + z(t) F_0 \cos(\omega t) \right) dt$$

$$S_{int} = - \int_0^{\frac{2\pi}{\omega}} V_{int} dt$$

$$S_{dissip} = - \int_0^{\frac{2\pi}{\omega}} \Gamma m^* z(t) \underline{\dot{z}(t)} dt$$

Le système s'écrit :

$$\begin{cases} \cos \varphi = \frac{m^*}{F_0} A(\omega_0^2 - \omega^2) - \frac{\omega}{\pi F_0} \frac{\partial S_{\text{int}}}{\partial A} \\ \sin \varphi = -\frac{\Gamma m^*}{F_0} \omega A \end{cases}$$

Attractif pur

$$S_{\text{int}} = -\int_0^{\frac{2\pi}{\omega}} \frac{HR}{6(D - A \cos(\omega t + \varphi))^2} dt$$

$$\frac{\partial S_{\text{int}}}{\partial A} = \frac{HR\pi}{3\omega} \frac{A}{(D^2 - A^2)^{3/2}}$$

Répulsif pur

$$S_{\text{int}} = -k_s \int_0^{\tau} (A \cos(\omega t + \varphi) - D)^2 dt$$

$$\frac{\partial S_{\text{int}}}{\partial A} = -\frac{k_s D}{\omega} \frac{4\sqrt{2}}{3} \left(\frac{A}{D} - 1 \right)^{3/2}$$

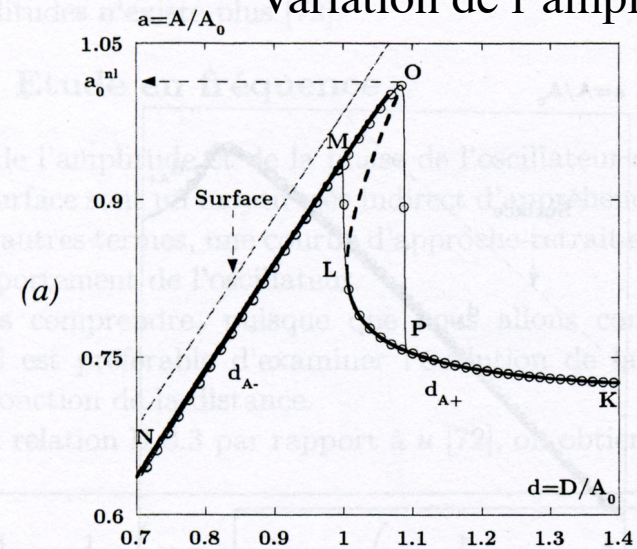
Attractif pur

$$\begin{cases} \cos \varphi = Qa(1 - u^2) - \frac{aQ\kappa}{3(d^2 - a^2)^{3/2}} \\ \sin \varphi = -ua \end{cases}$$

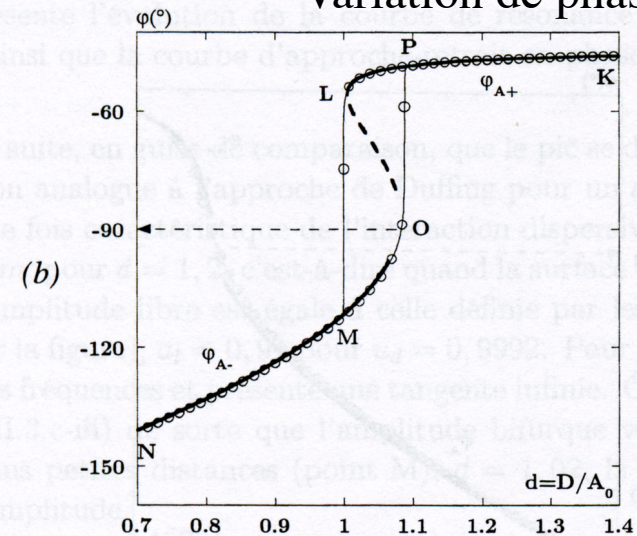
$$d_{\pm} = \sqrt{a^2 + \left(\frac{Q\kappa}{3(Q(1 - u^2) \mp \sqrt{1/a^2 - u^2})} \right)^{2/3}}$$

$$\varphi_{\pm} = \arctan \left(\frac{u}{Q(u^2 - 1) + \frac{Q\kappa}{3(d_{\pm}^2 - a^2)^{3/2}}} \right)$$

Variation de l'amplitude



Variation de phase



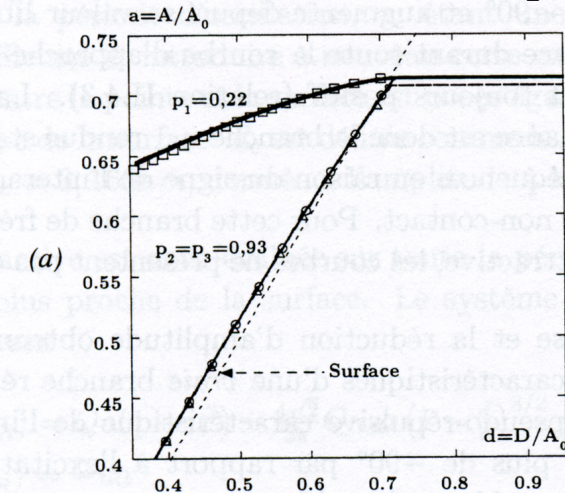
Répulsif pur

$$\begin{cases} \cos \varphi = Qa(1 - u^2) + \frac{4\sqrt{2}}{3\pi} Q\kappa_c a \left(1 - \frac{d}{a}\right)^{3/2} \\ \sin \varphi = -ua \end{cases}$$

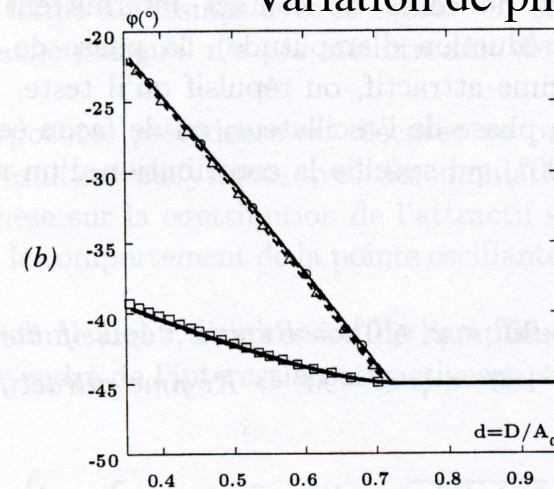
$$d = a \left(1 - \left(\frac{3\pi}{4\sqrt{2}} \frac{Q(u^2 - 1) + \sqrt{1/a^2 - u^2}}{Q\kappa_c} \right)^{2/3} \right)$$

$$\varphi = \arctan \left(\frac{u}{Q(u^2 - 1) - \frac{4\sqrt{2}}{3\pi} Q\kappa_c \left(1 - \frac{d}{a}\right)^{3/2}} \right)$$

Variation de l'amplitude

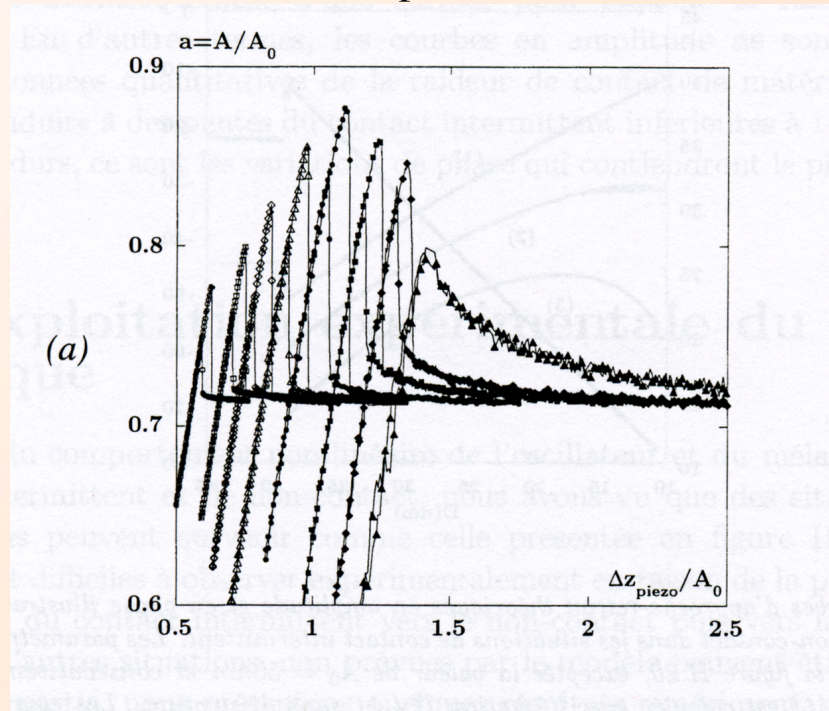


Variation de phase

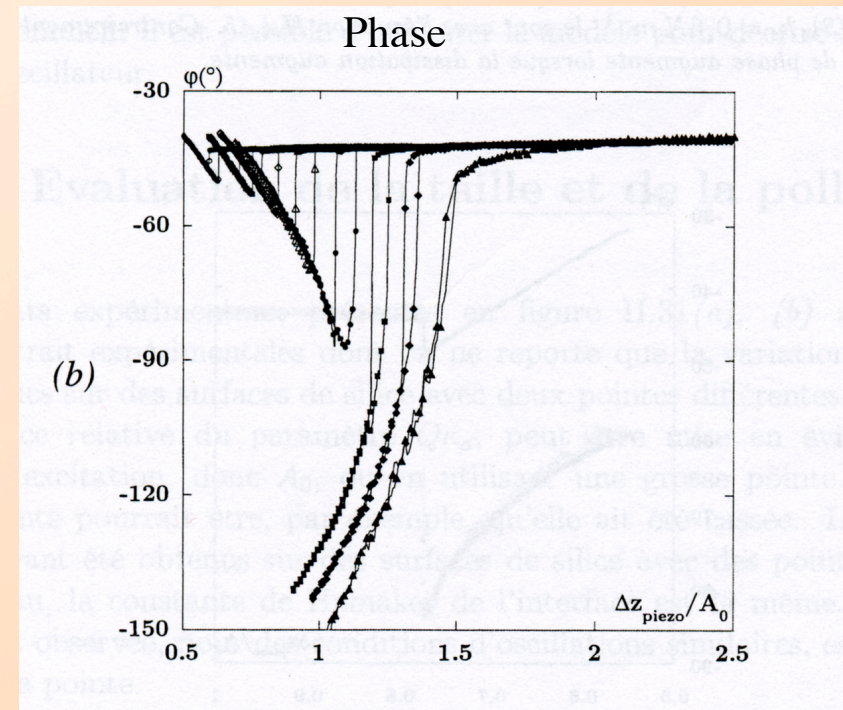


Transition entre mode attractif et mode répulsif

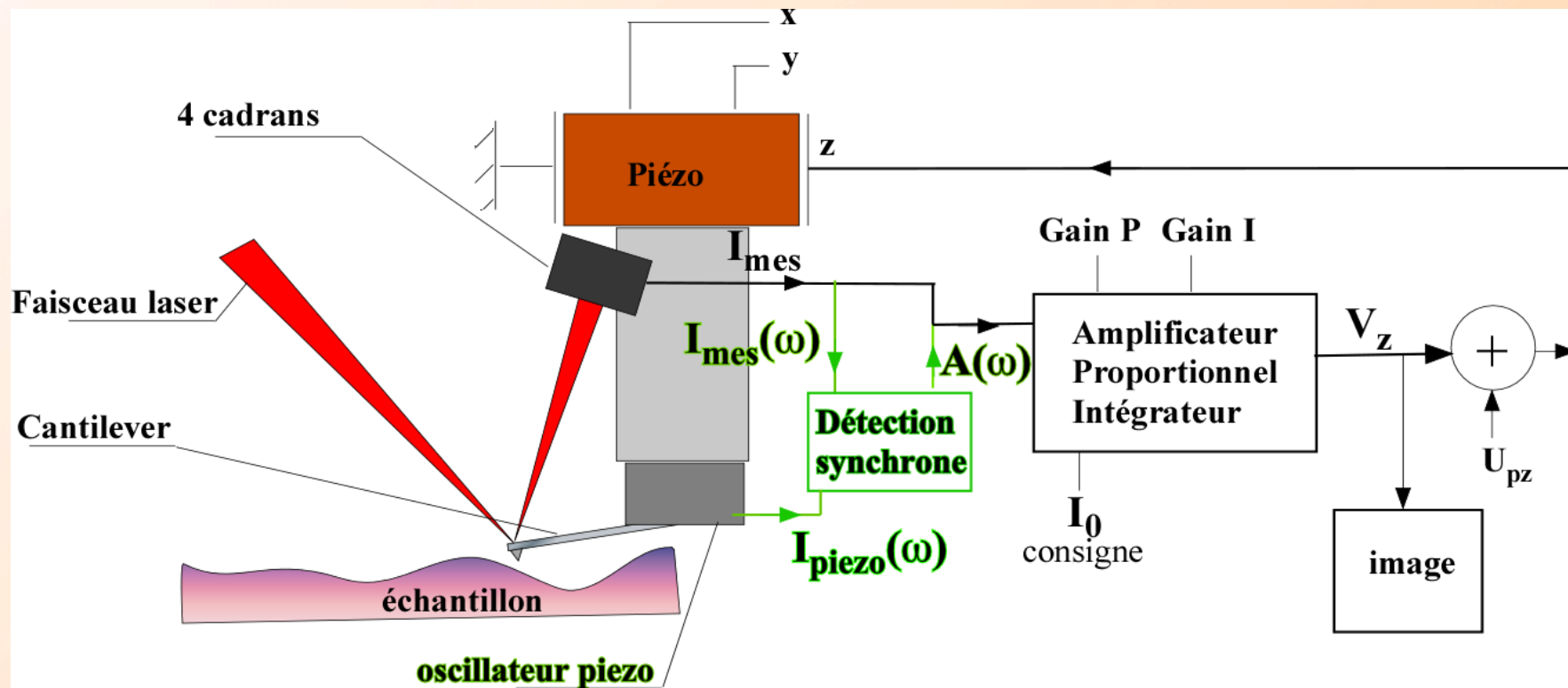
Amplitude



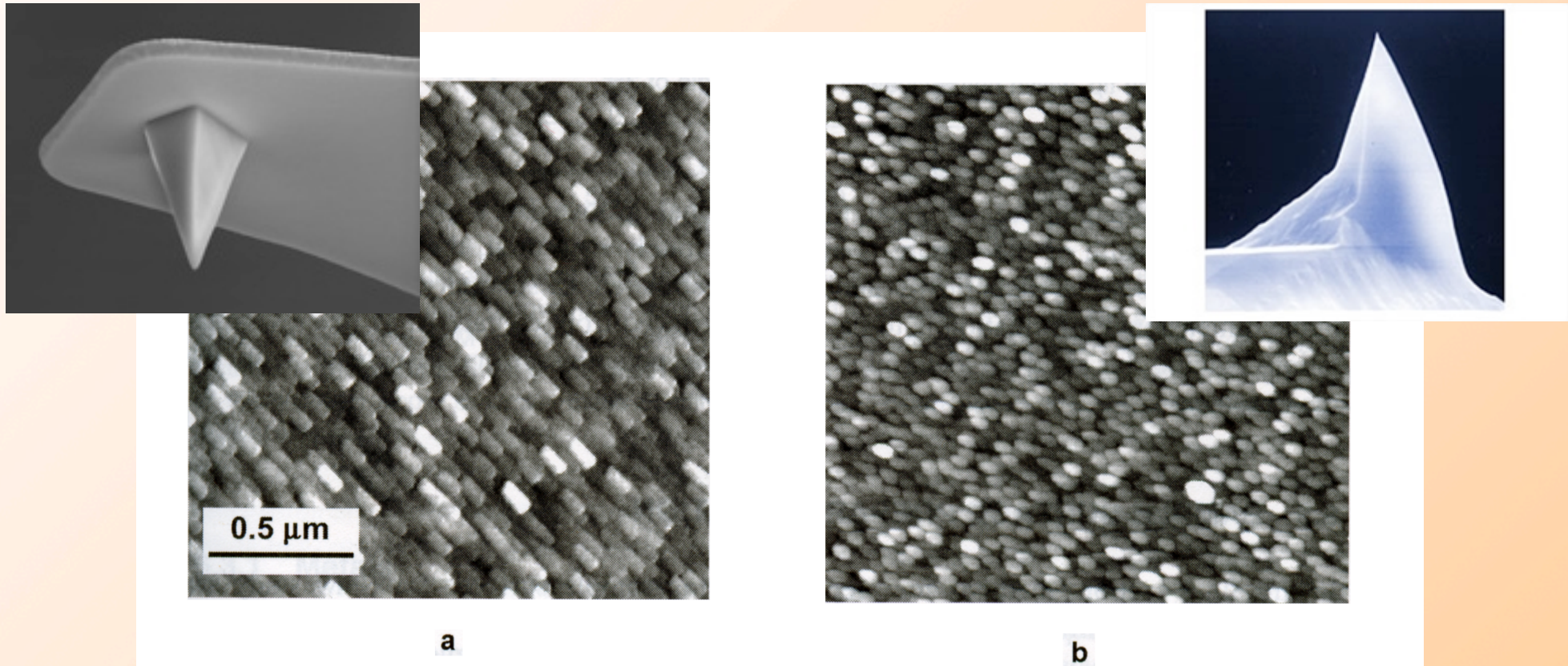
Phase



Fonctionnement du microscope Imagerie à Amplitude constante



Notion de résolution et de convolution de la pointe



Contact AFM images of the same area of a (001) oriented TiO₂ thin film deposited on an Al₂O₃(10 $\bar{1}$ 0) substrate by sputtering. **a**, AFM image acquired with a pyramidal Si₃N₄ tip (Digital Instruments). **b**, Image acquired with a conical, etched Si tip (Digital Instruments). Both images are on the same scale and in the same surface orientation. In both cases, when the sample was rotated, the orientation of the surface features did not change. Clearly, the tip shape is convoluted into the surface morphology in both images.

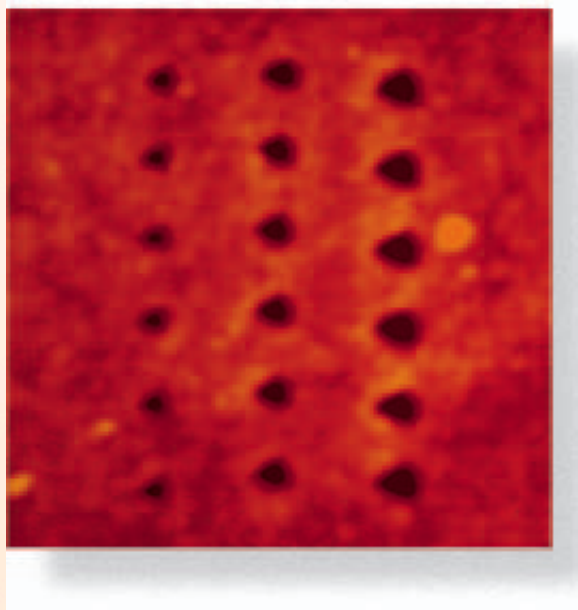
Image AFM en mode dynamique



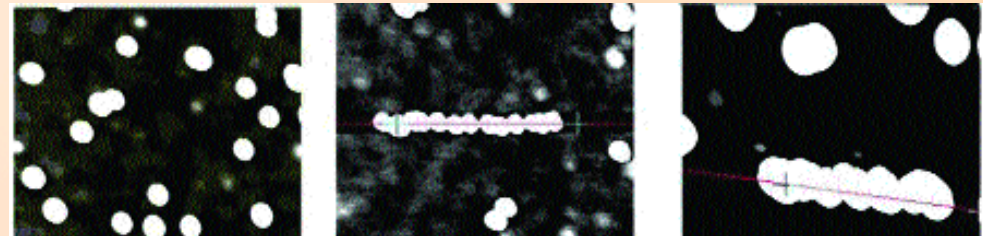
ADN (100nm x 100 nm)

Les autres modes de fonctionnement

❖ Nanolithographie et nanomanipulation



Nanoindentation (15 nm)
dans un film de polymère
(800nm x 800 nm)



Manipulation de particule d'or (8nm)
sur surface de silice

Imagerie de phase d'un copolymère

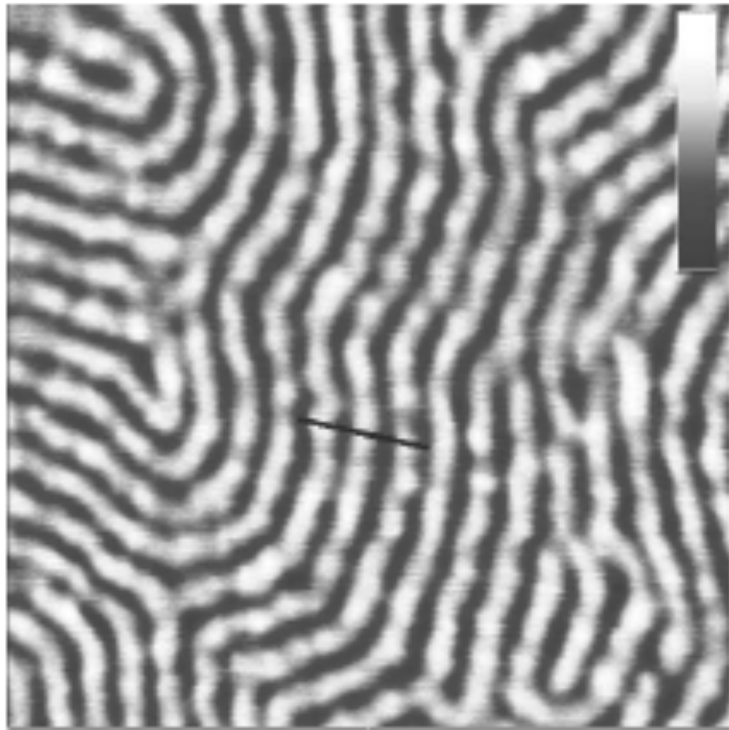


Fig. 10. Phase image of the copolymer ($500\text{nm} \times 500\text{nm}$). The contrast bar (upper right) corresponds to 5 degrees. The fits are carried out on curves recorded on different locations along the black line.

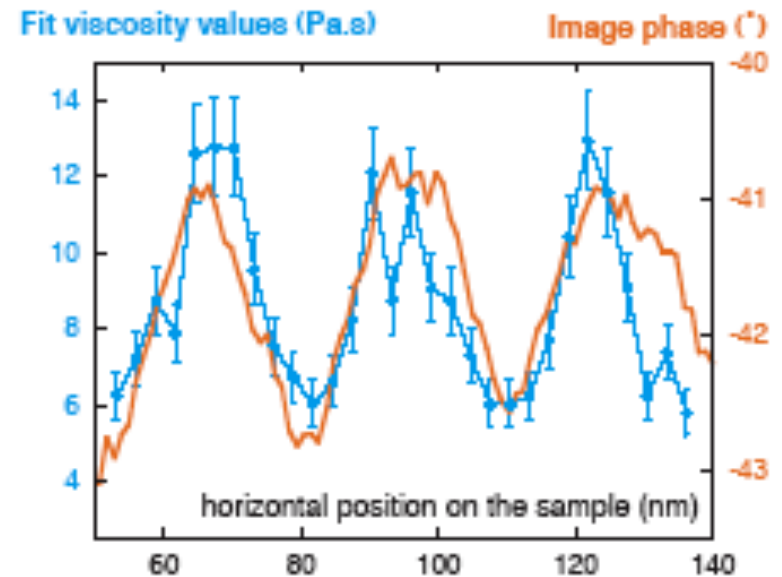
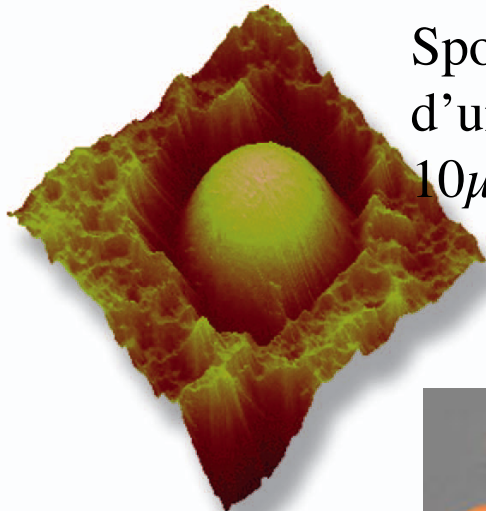


Fig. 11. Comparison of the phase image section and the viscosity values obtained from the fits. The fits values (with 10% relative error) follow the same variations as the image phase contrast, thus reproducing the local variations of the mechanical properties. The lateral resolution is close to the step between two adjacent measurements, *i.e.* about 3 nm.

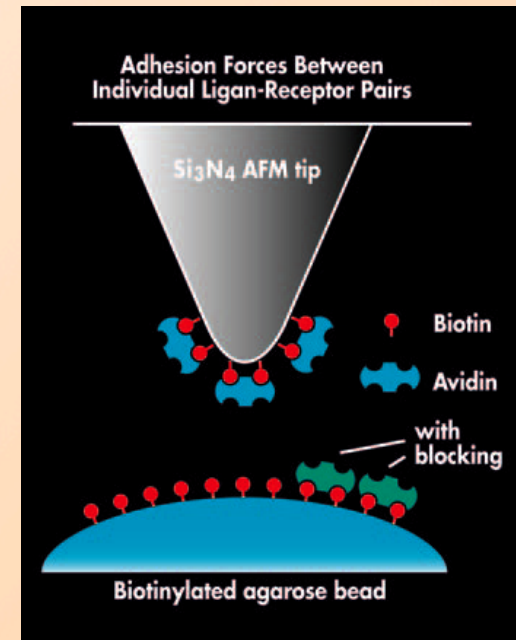
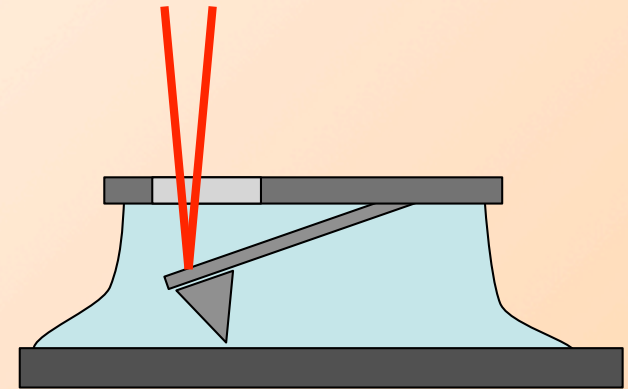
AFM en milieu liquide *Mode contact et tapping*



Spore dans la membrane
d'un champignon ($10\mu\text{m} \times 10\mu\text{m}$)



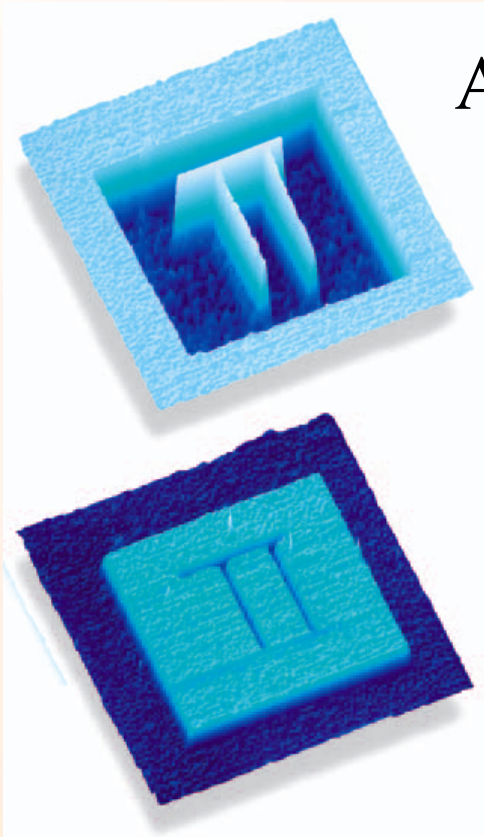
Cellule de sang humain
(mode tapping)



Étude en force volume
(fonctionnalisation des
Pointes)

❖ EFM (Electric Force Microscope)
uniquement en mode tapping

Applications en micro et nano électronique



Images EFM pour deux polarisations inversées
($15\mu\text{m} \times 15\mu\text{m}$)

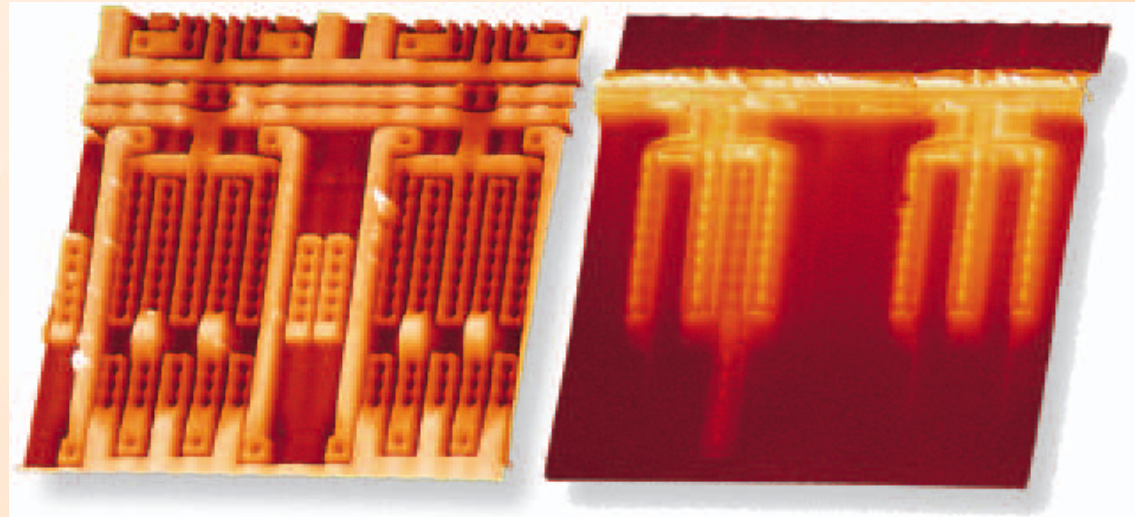
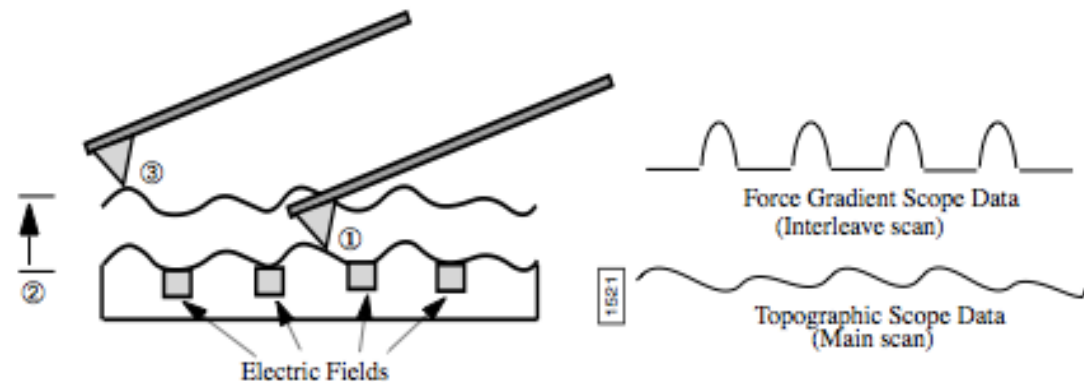


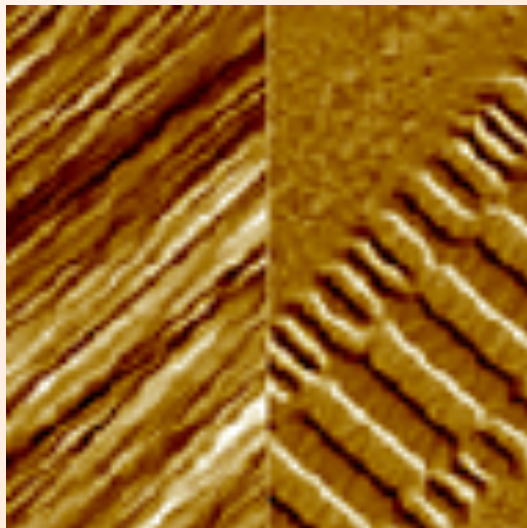
Image d'un défaut de charge dans un transistor
($80\mu\text{m} \times 80\mu\text{m}$)



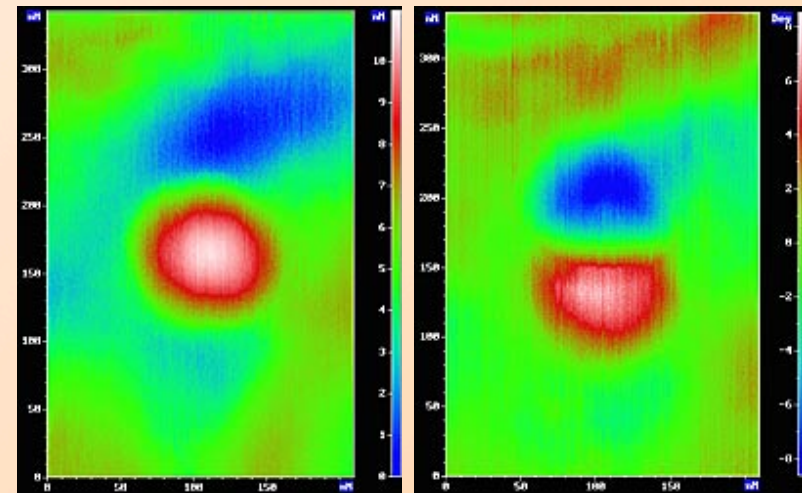
📦 MFM (Magnetic Force Microscope)

uniquement en mode tapping

Image en double passage avec lift-up



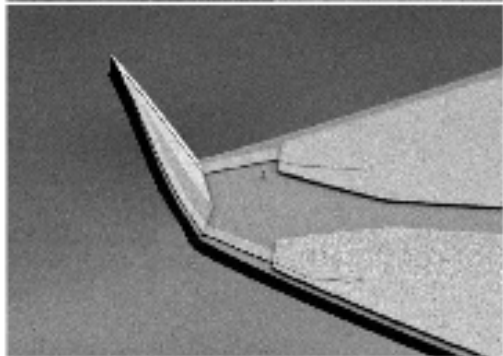
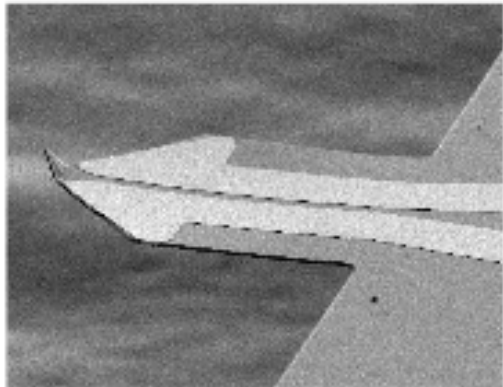
topographie MFM image
Piste de disque dur



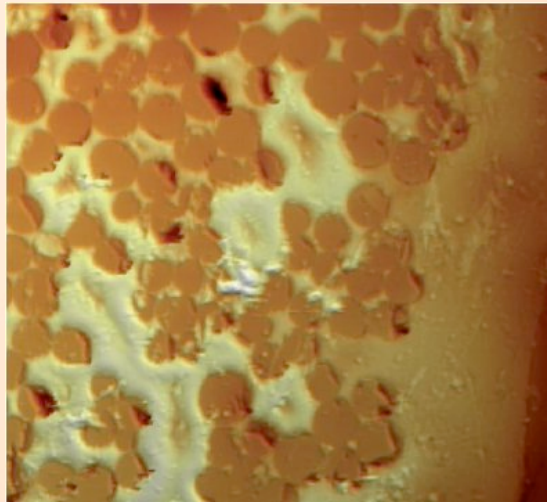
topographie MFM image
Image d'une particule de Co

🔍 SThM (Scanning Thermal Microscope)
uniquement en mode contact

Sonde AFM thermique



SEM Images of the entire cantilever (top)
and the tip (bottom)



topographie

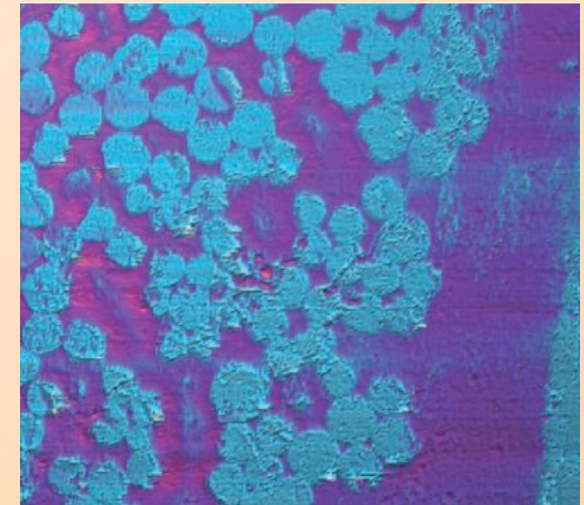


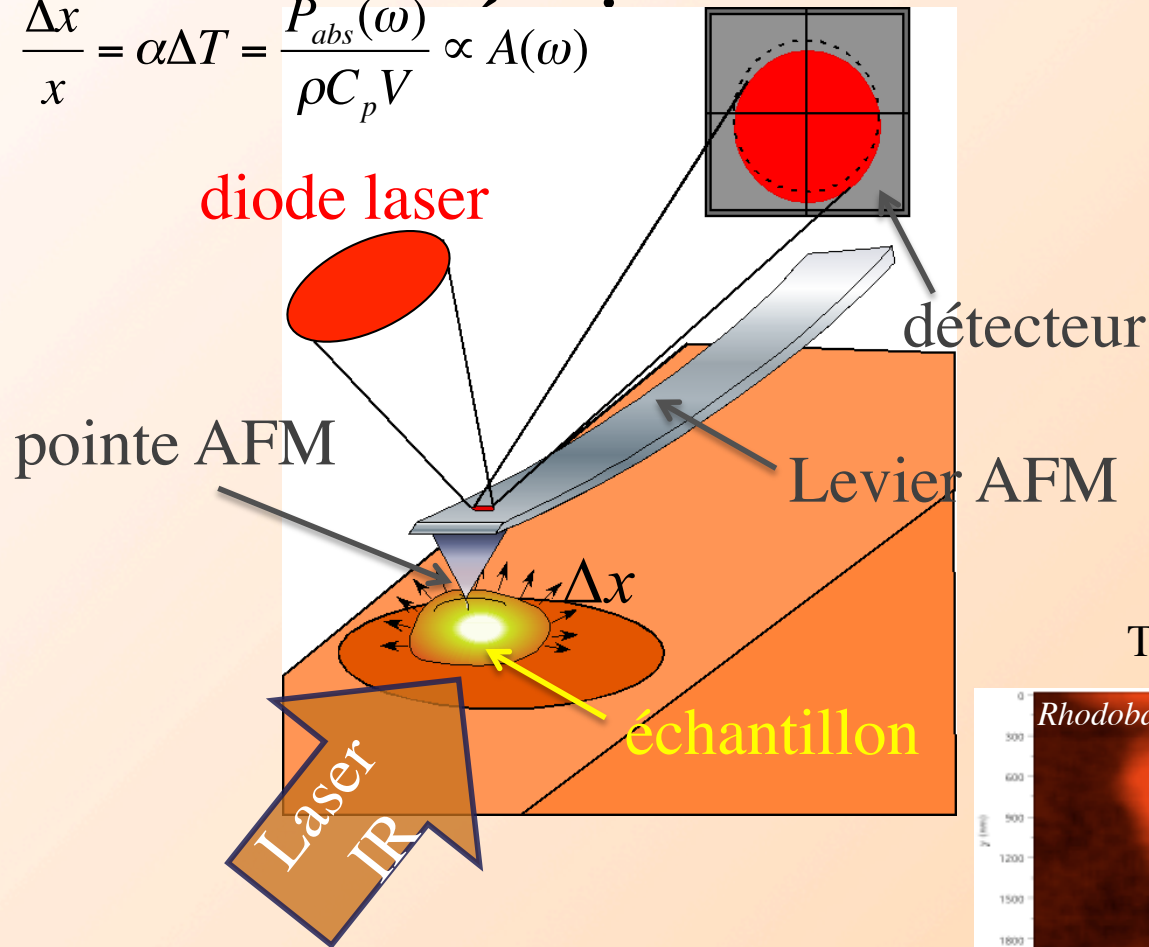
Image thermique

Surface représentant des fibres de carbones incluses dans de la résine époxy. Contraste correspondant aux différences de conductivités thermiques.

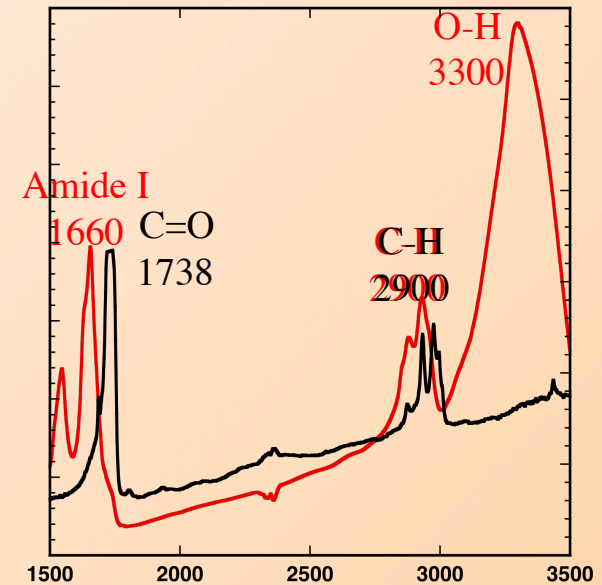
NanoIR (AFM pour la spectroscopie infrarouge)

Effet photothermique détecté par

$$\frac{\Delta x}{x} = \alpha \Delta T = \frac{P_{abs}(\omega)}{\rho C_p V} \propto A(\omega)$$



Spectre FTIR d'une bactérie



Cartographie de poches d'acide gras ($\sigma=1740 \text{ cm}^{-1}$)

Topographie

