

Mesures de propriétés thermophysiques

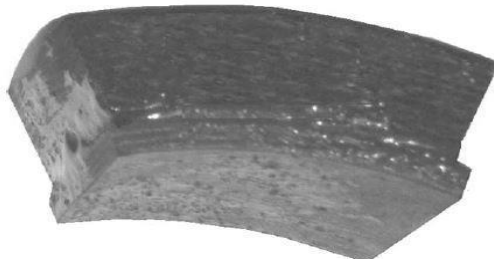
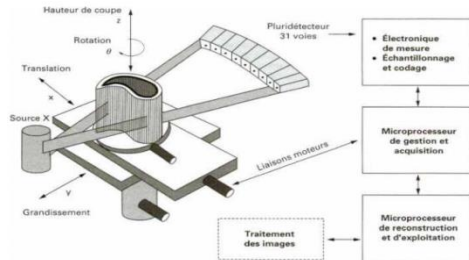
C. Pradere

^a I2M-TREFLE, UMR CNRS 5295, Bordeaux, France.

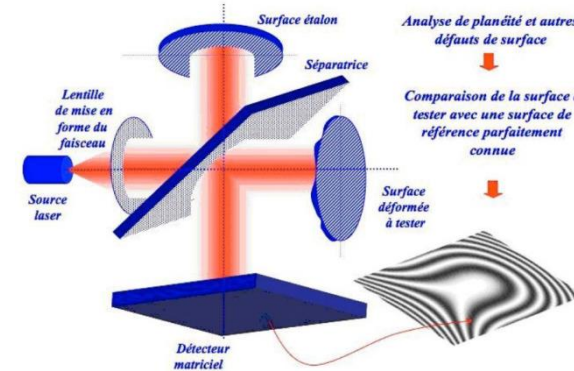
Cas de la fabrication additive métallique



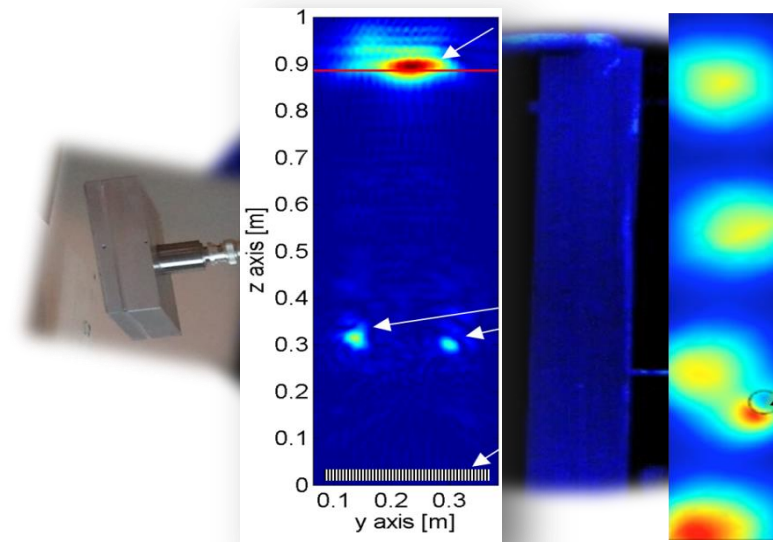
Rayons X, tomographie



Optique visible



Acoustique





Cas de la fabrication additive métallique

Modélisation du transfert de chaleur lors du procédé

$$a_{xx} \frac{\partial^2 T}{\partial x^2} + a_{yy} \frac{\partial^2 T}{\partial y^2} + a_{zz} \frac{\partial^2 T}{\partial z^2} + \sum_i \frac{C_i \Delta H_i}{\rho C_p} \frac{\partial \tau}{\partial t} = \frac{\partial T}{\partial t}$$

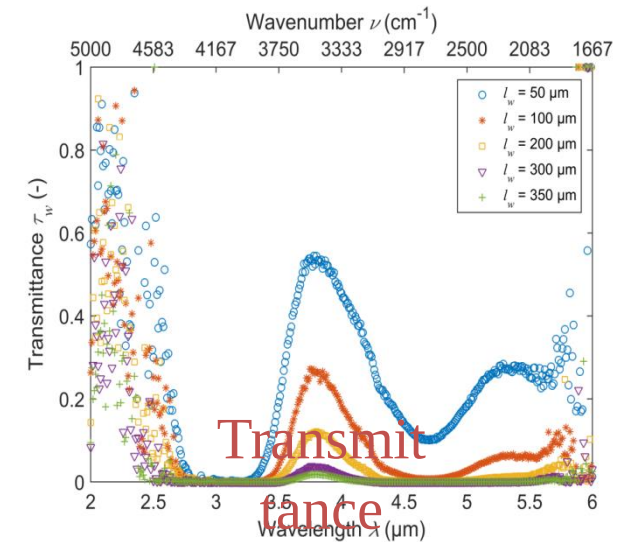
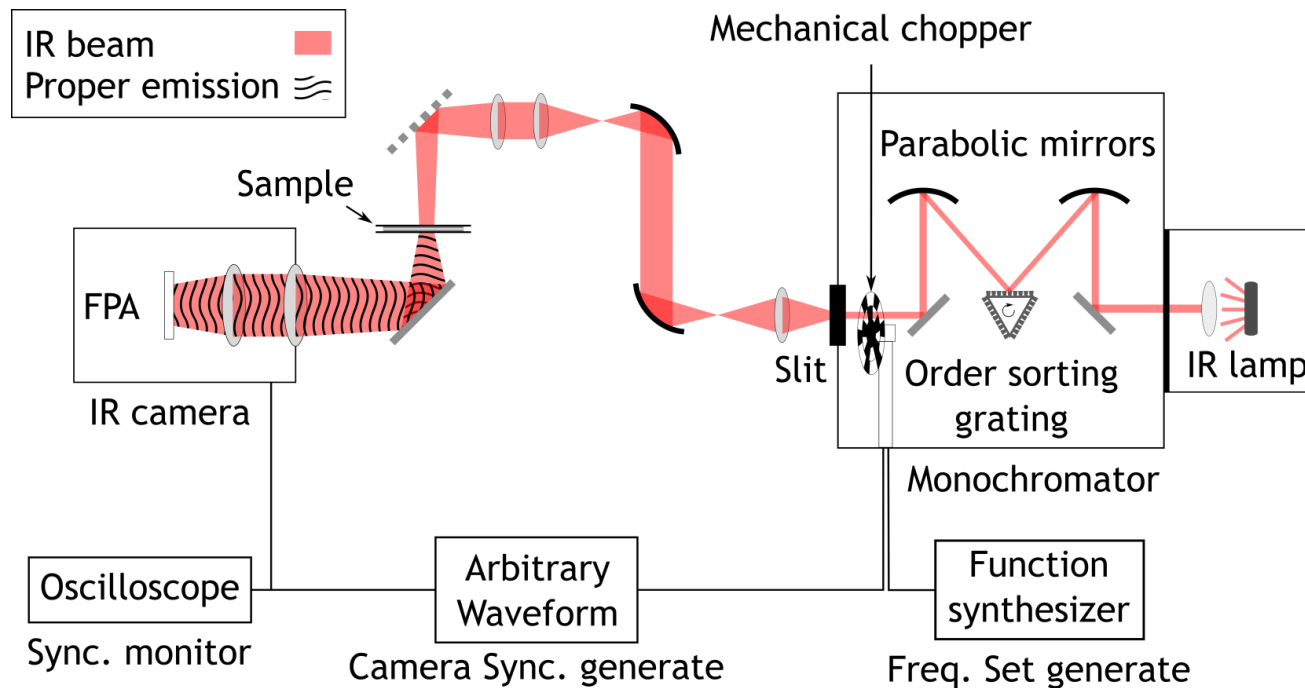
$$T(x, y, z, t = 0) = 0$$

$$-\lambda_{zz} \frac{\partial T}{\partial z} \Big|_{z=0} = P_0 (1 - R - \Gamma) f(t) - \varepsilon \sigma (T^4 - T_a^4) - h(T - T_a)$$

$$\lambda_{yy} \frac{\partial T}{\partial y} \Big|_{x=\pm l} = \varepsilon \sigma (T^4 - T_a^4) + h(T - T_a);$$

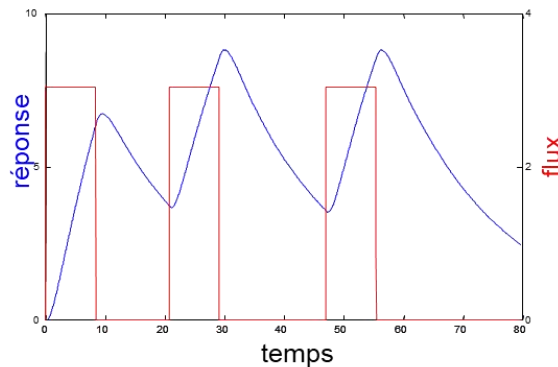
$$-\lambda_{zz} \frac{\partial T}{\partial z} \Big|_{z=e} = 0; -\lambda_{xx} \frac{\partial T}{\partial x} \Big|_{x=\pm\infty} = 0;$$

Liées au rayonnement: réflectivités, émissivités,
Transmittance, absorbance....

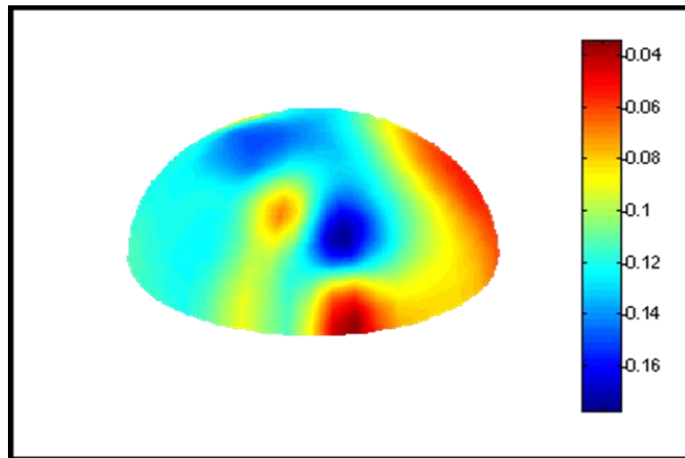


Liées à la convection: coefficients d'échange par convection, viscosité, coefficients de diffusion

Confort thermique du cycliste



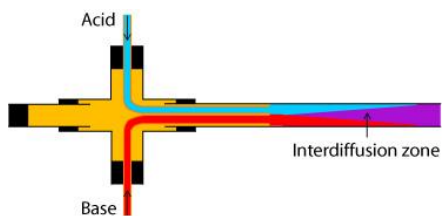
Cartographie de coefficients d'échange thermique (en s^{-1}), modèle Xirtès, vitesse de l'air : 40 km.h⁻¹



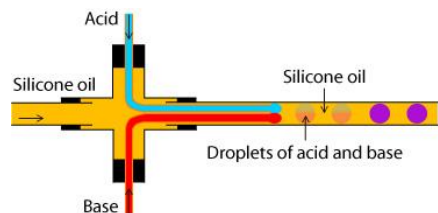
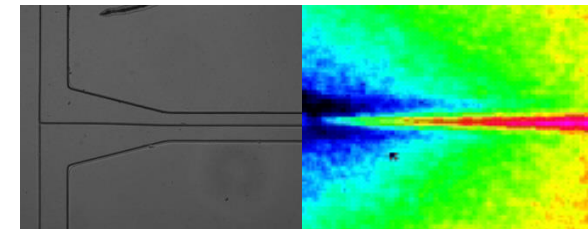
Coment E., Batsale J.C., Ladevie B., Caillibotte M., *Cartography and ventilation index for bicycle helmets*, ICEE, Dortmund, July 2000.

Liées au changement de phase ou réaction chimique: enthalpies

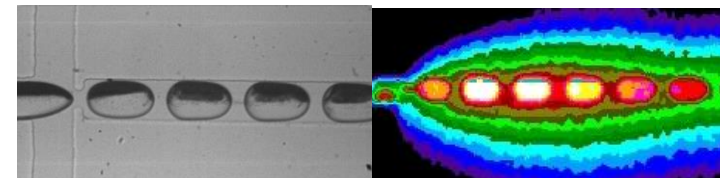
Applications : Chemical reaction or phase change in co-flow or droplet flow



*Laminar flow (low Reynolds number)
Mixing by species diffusion
Steady state ($x = vt$)*



*Mixing is faster
1 droplet = 1 microreactor*



Tools : *Temperature fields measurements at microscales* (InfraRed camera), *analytic and numerical modelisation* (quadripole, finite difference...) and *inverse methods* (nodal: OLS, TLS and modal: SVD approaches)

Liées à la conduction thermique: la conductivité, la diffusivité, l'effusivité thermique, la capacité thermique volumique.

Les différentes propriétés thermiques des solides :

Conductivité thermique λ ($W.m^{-1}.K^{-1}$)	→	Résistance au passage d'un flux de chaleur
Diffusivité thermique a ($m^2.s^{-1}$)	→	Vitesse de propagation d'un flux de chaleur (ϕ)
Effusivité thermique E ($W.m^{-2}.K^{-1}.s^{1/2}$)	→	Elévation de la température de surface d'un corps soumis à un flux de chaleur
Capacité thermique volumique ρc ($J.m^{-3}.K^{-1}$)	→	Quantité d'énergie nécessaire pour élever la température d'un volume de $1m^3$

2 propriétés indépendantes :

$$a = \frac{\lambda}{\rho c}$$

$$E = \sqrt{\lambda \rho c}$$

Moyens d'excitations

Lampe Halogène (Modulée, 100 W)

Diode Laser (800 nm, 1 W)

Résistance chauffante (Modulée...)

Modules Peltier

Lampe Flash, à venir

Matériel

Alim 200 W

Générateur De Signaux

Platines motorisées XYZ

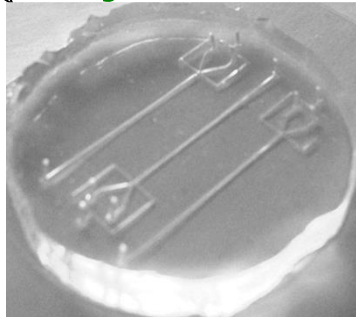
Dispositifs

μ Calorimètre

μ scope optique visible

Enceinte sous vide...

Système



Systèmes de mesures

Capteur solide (Flux, T)

Peltier (Mesure du flux)

Thermocouple ... (°C)

Caméra IR (Température ??)

CEDIP, Orion multispectrale, JADE III

FLIR, A10 et A40

Monocapteur IR (Flux)

IMPORTANT

Résolution spatiale 10 μ m au cm

Echelle temporelle MHz

Température -20 à 2000 °C

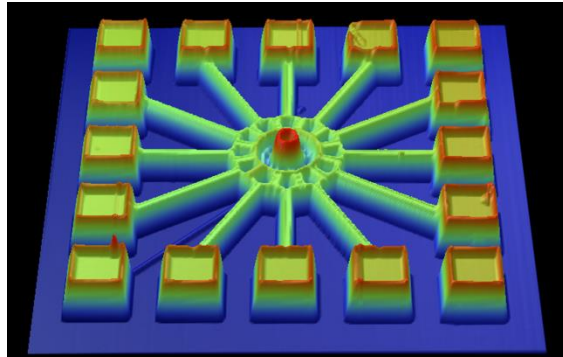
Microscope thermique

Instrumentation pour la mesure
de champ de température

Multiéchelle

μm -cm

Thermique-Energétique



Conversion d'énergie

Electronique (μ puce)

Chimique (μ réacteurs)

Milieus dispersés (matériaux, biologie...)

Systeme

Acquisition de données



Traitement masse d'informations

Méthodes inverses

Propriétés thermophysiques

Maîtrise de l'énergie

Définition:

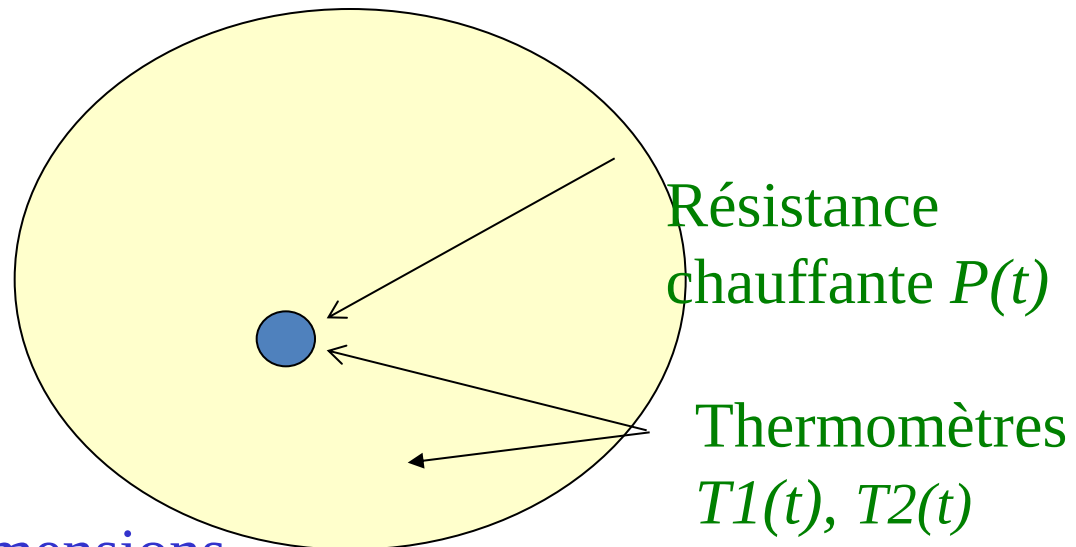
Dispositif de caractérisation thermique dans lequel la source de chaleur excitatrice (par effet Joule) et le thermomètre sont réunis en un seul et même capteur.

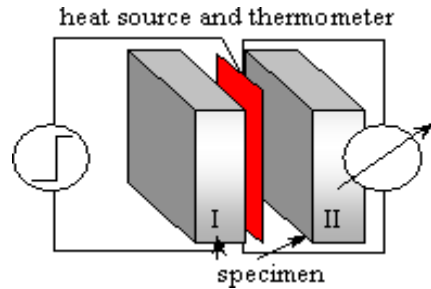
Quelques exemples:

- Plan chaud
- Fil chaud
- Sphère chaude
- Sondes “composites”

Avantages:

- Energie maîtrisée
- Echantillons de grandes dimensions
- Simplicité, robustesse
- Pilotage, acquisition, traitement
- Estimation simultanée de conductivité et diffusivité

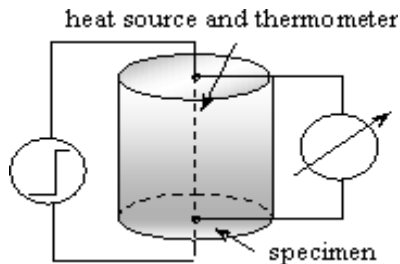




plan chaud (Isothermes planes)

$$T(0,t) - T_{\infty} = \frac{2P_a}{S\sqrt{\lambda\rho c}\sqrt{\pi}}\sqrt{t}$$

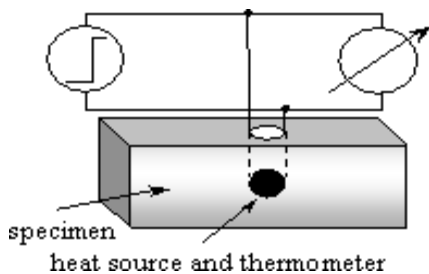
Mesure de l'effusivité thermique: $\sqrt{\lambda\rho c}$ en $Jm^{-2} K^{-1} s^{-1/2}$



fil chaud (Isothermes cylindriques)

$$T(r_0,t) - T_{\infty} = \frac{P_0}{4\pi\lambda l} \ln(t) + \ln\left(\frac{4a}{r_0^2 c_p}\right)$$

Mesure de la conductivité thermique: λ en $Wm^{-1} K^{-1}$



sphère chaude

$$T(0,t) - T_{\infty} \approx \frac{P_0}{4\pi\lambda R}$$

Signal stationnaire corrélé avec les propriétés de la sonde et du contact.

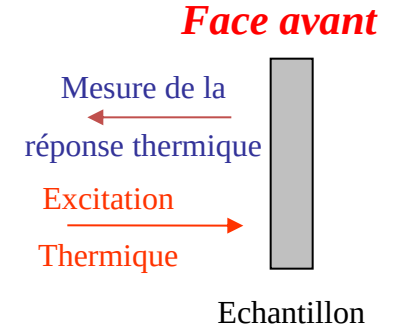
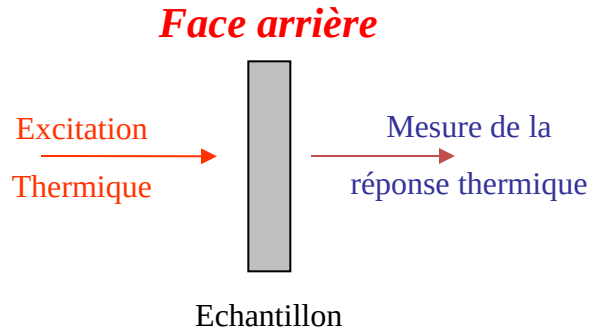
Difficile à mettre en œuvre en pratique!

2 types de configurations expérimentales

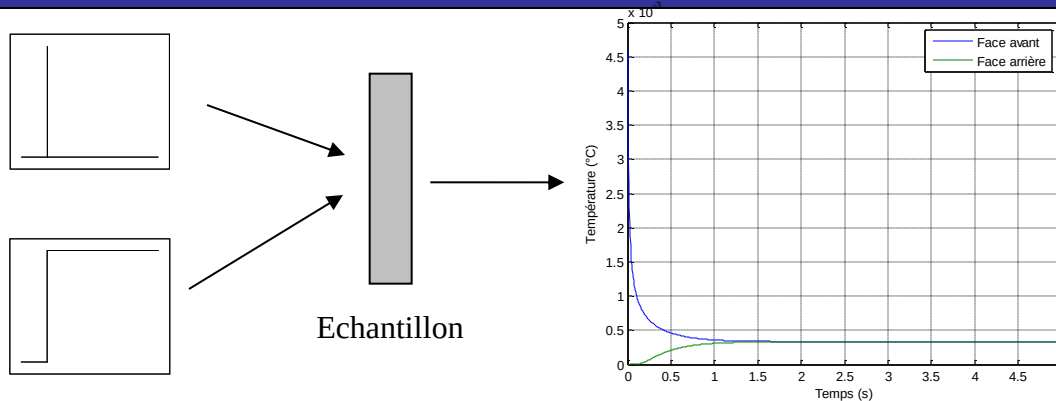
Transitoire

$$\rho C_p \frac{\partial T(x, y, z, t)}{\partial t} = \text{div}(\lambda \vec{\text{grad}}(T(x, y, z, t)))$$

$$x=0, -\lambda S \frac{dT}{dx} = \varphi(t)$$



Méthodes impulsionsnelles ou type échelon



Espace de Laplace

$$\begin{Bmatrix} \theta_{AV} \\ \Phi_{AV} \end{Bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{Bmatrix} \theta_{AR} \\ \Phi_{AR} \end{Bmatrix}$$

$$A = D = \cosh(\sqrt{p/ae});$$

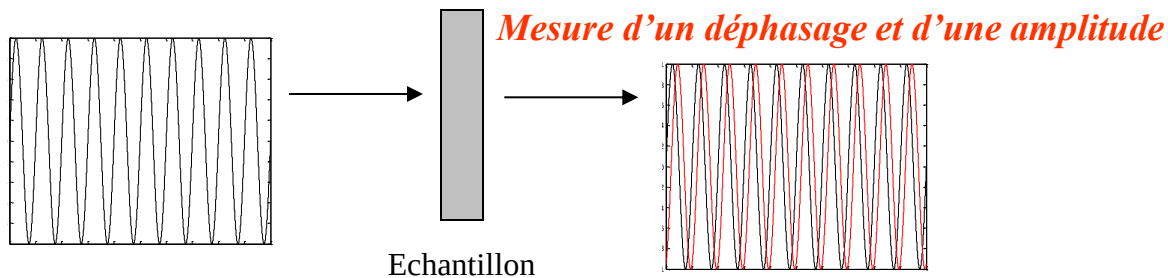
$$B = \sinh(\sqrt{p/ae}) / (\lambda S \sqrt{p/a})$$

$$C = (\lambda S \sqrt{p/a}) \sinh(\sqrt{p/ae})$$

Inversion

a, h

Méthodes modulées ou périodiques



Espace Complexe

$$\begin{Bmatrix} \theta_{AV} \\ \Phi_{AV} \end{Bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{Bmatrix} \theta_{AR} \\ \Phi_{AR} \end{Bmatrix}$$

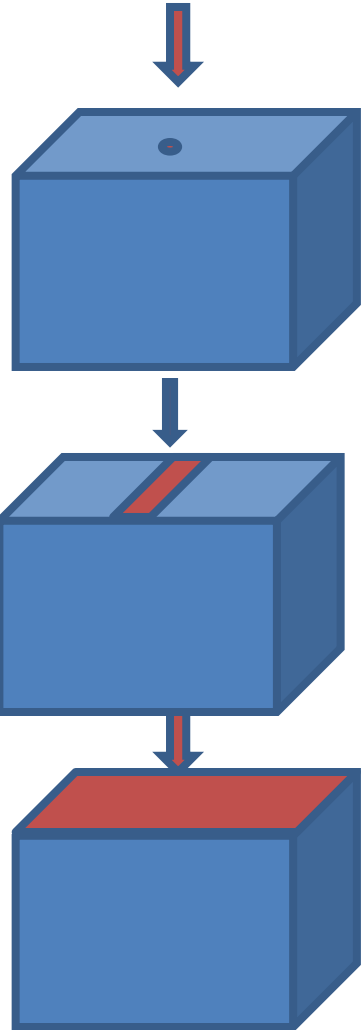
$$A = D = \cosh(\sqrt{j\omega/ae});$$

$$B = \sinh(\sqrt{j\omega/ae}) / (\lambda S \sqrt{j\omega/a})$$

$$C = (\lambda S \sqrt{j\omega/a}) \sinh(\sqrt{j\omega/ae})$$

Inversion

a, h



$$T(x, y, z, t) = \frac{Q}{\rho c} \frac{\exp(-x^2/(4a_x t))}{\sqrt{\pi a_x t}} \frac{\exp(-y^2/(4a_y t))}{\sqrt{\pi a_y t}} \frac{\exp(-z^2/(4a_z t))}{\sqrt{\pi a_z t}}$$

Hot spot

$$T(x=0, y=0, z=0) = K \times t^{3/2}$$

Averaging vs y = Hot wire vs x

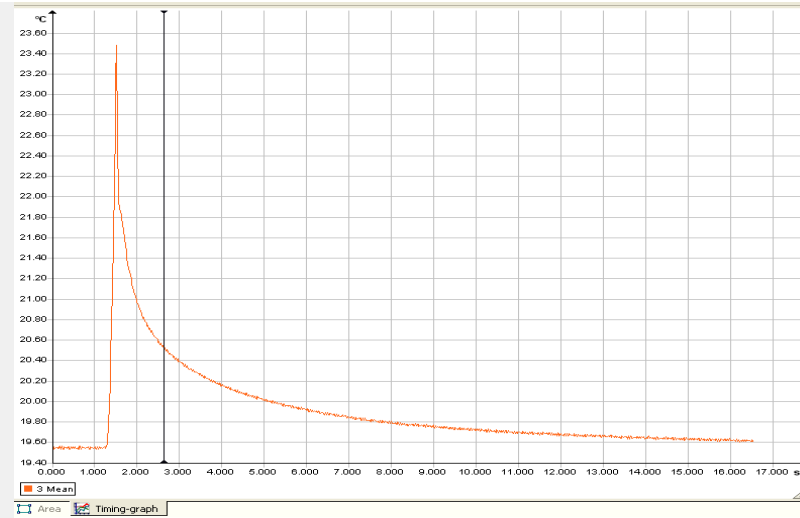
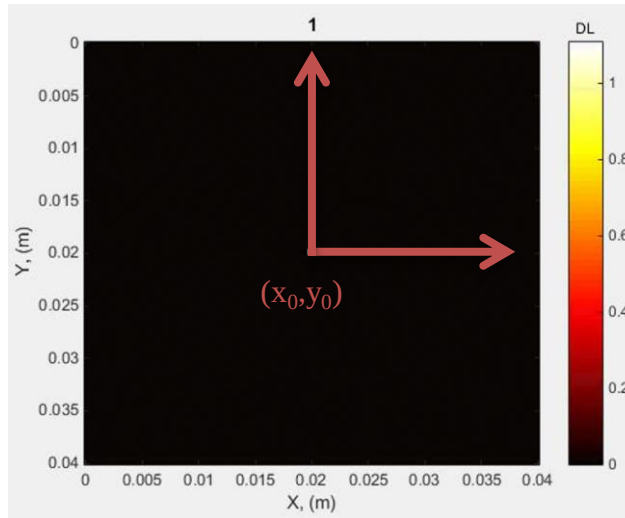
$$\langle T(y, z=0, t) \rangle_x = \frac{Q}{\rho c L} \frac{1}{\sqrt{a_z \pi t}} \frac{\exp(-y^2/(4a_y t))}{\sqrt{a_y \pi t}}$$

$$T(x=0, y=0, z=0) = K \times t^1$$

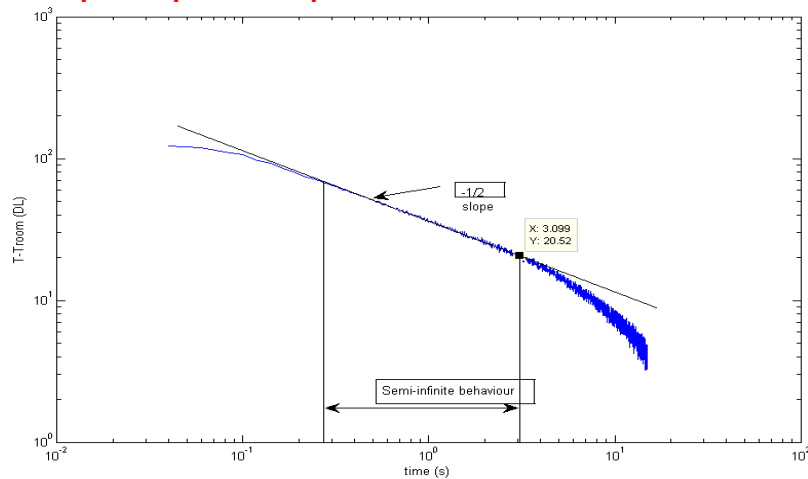
Averaging vs x and y

$$\langle \langle T(z=0, t) \rangle_x \rangle_y = \frac{Q}{\rho c L l} \frac{1}{\sqrt{a_z \pi t}}$$

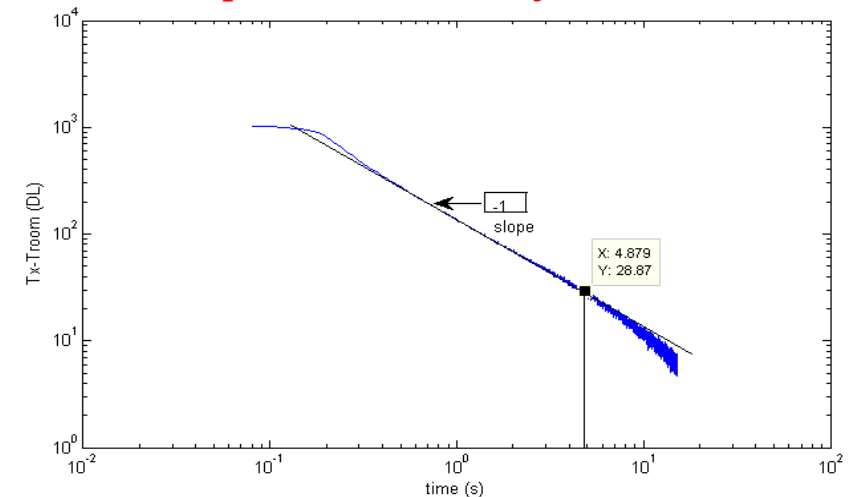
$$T(x=0, y=0, z=0) = K \times t^{1/2}$$



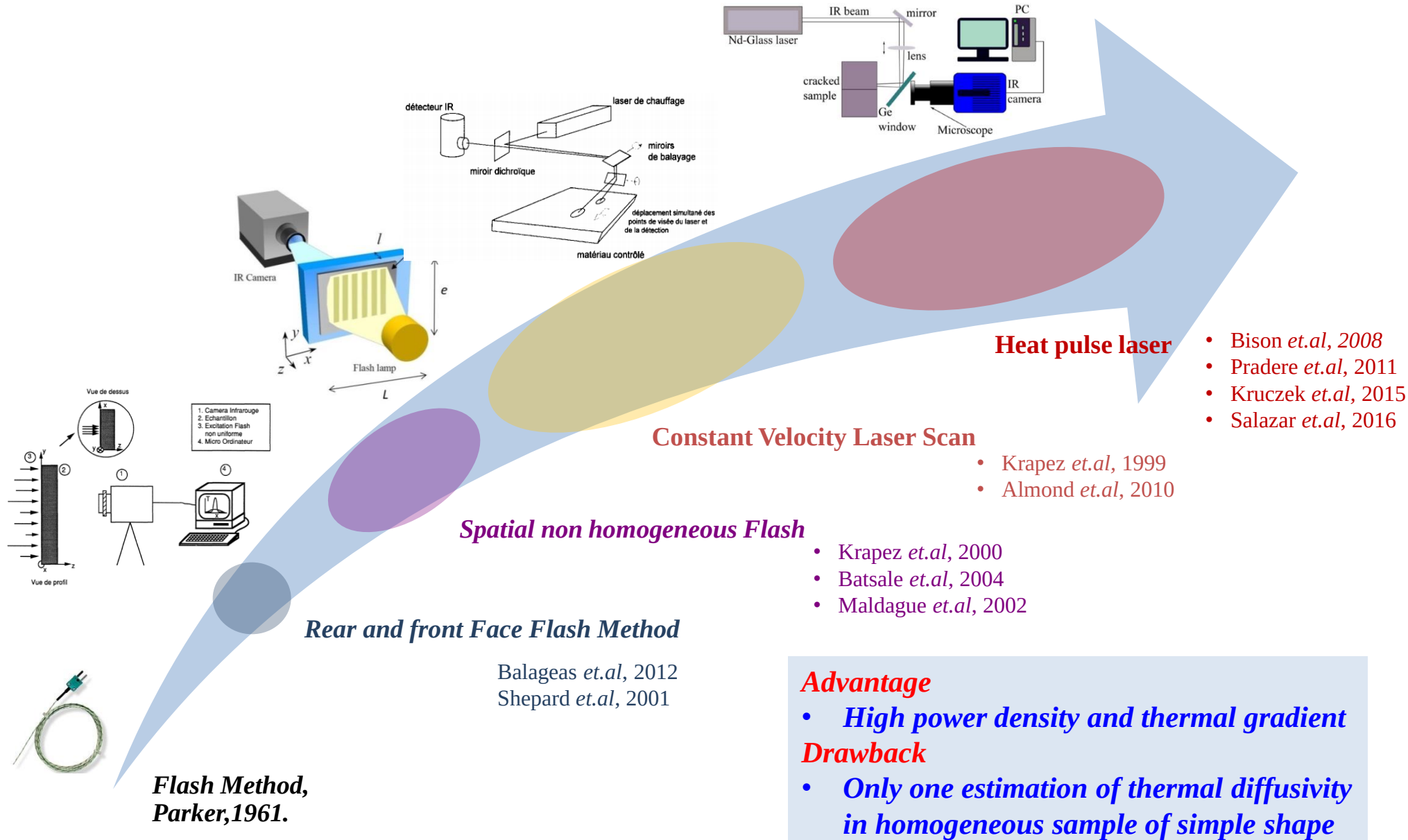
Average temperature evolution of sample's surface for the pixels inside the circle



Study of partial spatial average value of temperature in x or y direction



Logarithm spatial average value of the temperature ($T - T_{\text{room}}$) is plotted versus $\log(t)$



Méthodes de type transformées intégrales

Approches 2D, 3D sur milieu homogène

Tout type d'excitation impulsionnelles (périodique spatiale, aléatoire, point source...)

Estimation de la diffusivité thermique

Méthodes de type nodales et modales

Approches 2D, 3D sur milieu hétérogène

Tout type d'excitation impulsionnelles (périodique spatiale, aléatoire, point source...)

Estimation de la diffusivité thermique

Flying spot

Approches 2D, 3D sur milieu hétérogène

Tout type d'excitation transitoire (périodique spatiale, aléatoire, point source...)

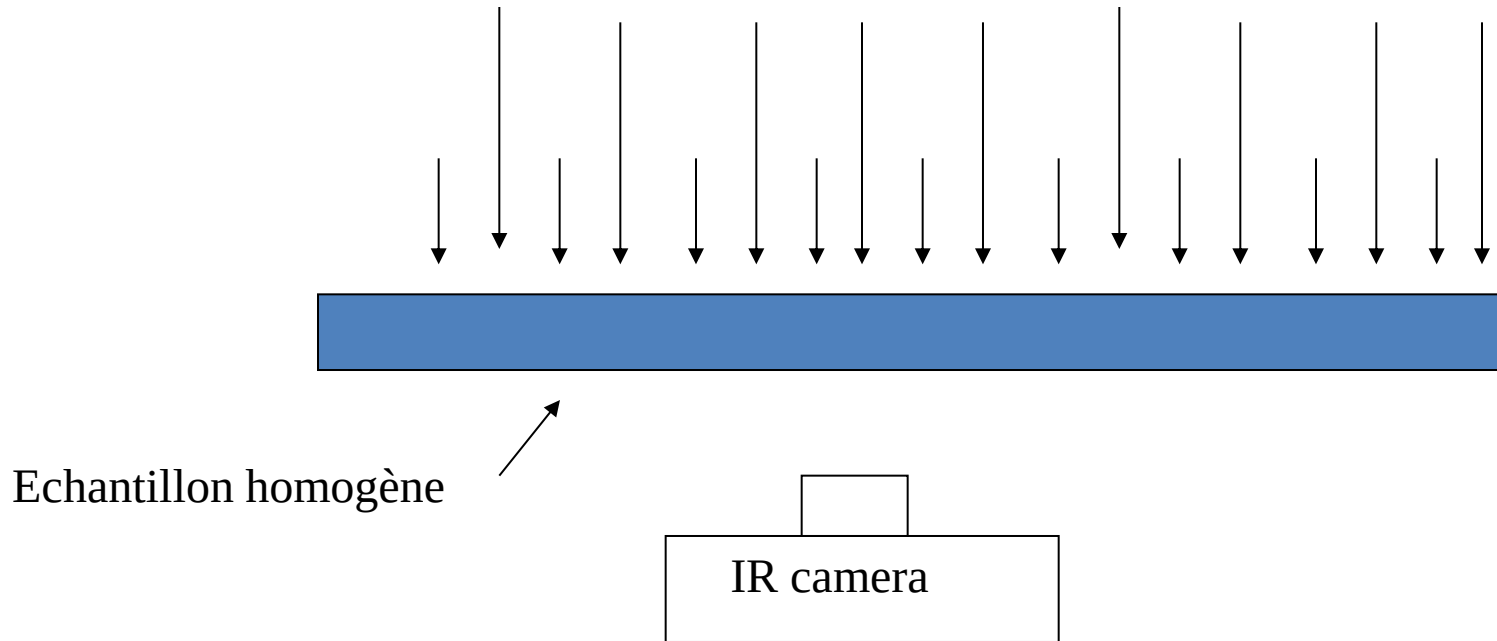
Estimation de la diffusivité thermique et du terme source

Périodique hétérodyne

Approches 2D, 3D sur milieu hétérogène, excitation périodique, grande résolution spatiale et temporelle

Estimation de la diffusivité thermique

Application avec caméra IR au cas impulsionnel en milieu homogène



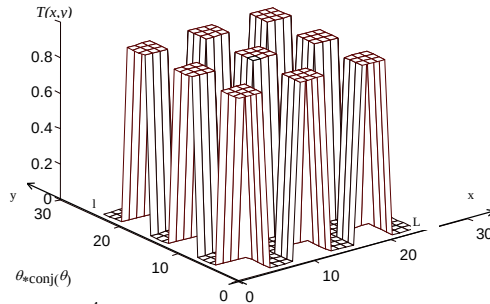
➡ Analyse de la transformation de Fourier spatiale du champ de température

Philippi I., Batsale J.C., Maillet D. et Degiovanni A. : (1995) Measurement of thermal diffusivity through processing of infrared images processing, Rev. Sci. Instru., 66(1), pp182-192.
Krapez J.C., 1999 Mesure de diffusivité longitudinale de plaques minces par méthode de grille-
 Journée SFT: "Thermographie IR quantitative" ONERA Mars 1999

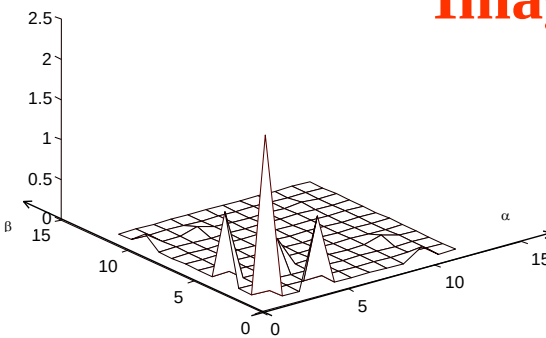
Application avec caméra IR au cas impulsionnel en milieu homogène

Images réelles

$t=0$



Images transformées



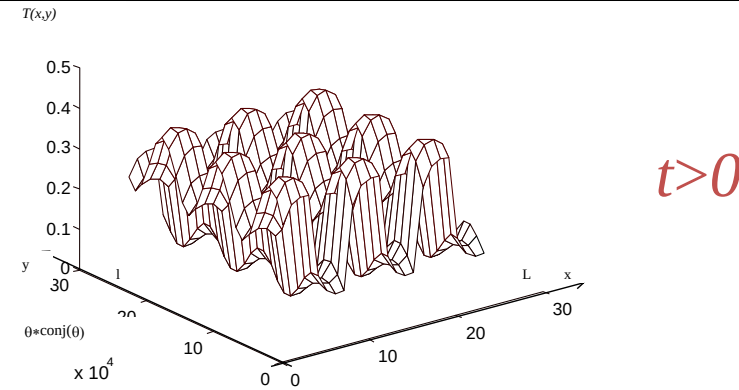
Transformée de Fourier

$$\Theta(\alpha_n, \beta_m, z, t) = \int_0^L \int_0^L \cos(\alpha_n x) \cos(\beta_m y) \cdot T(x, y, z, t) \cdot dx dy$$

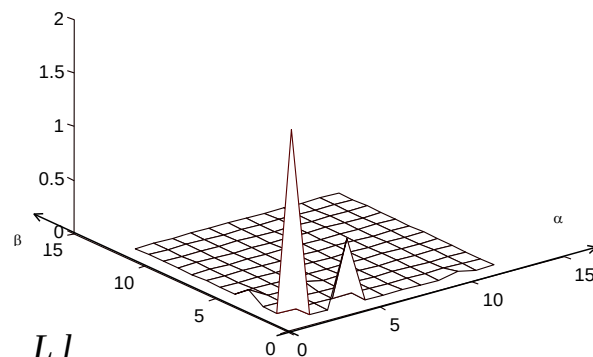
Expression 1D espace de Fourier $\theta(t, \alpha) = \theta(t=0, \alpha) * \exp(-a\alpha^2 t - ht)$

Méthode d'estimation

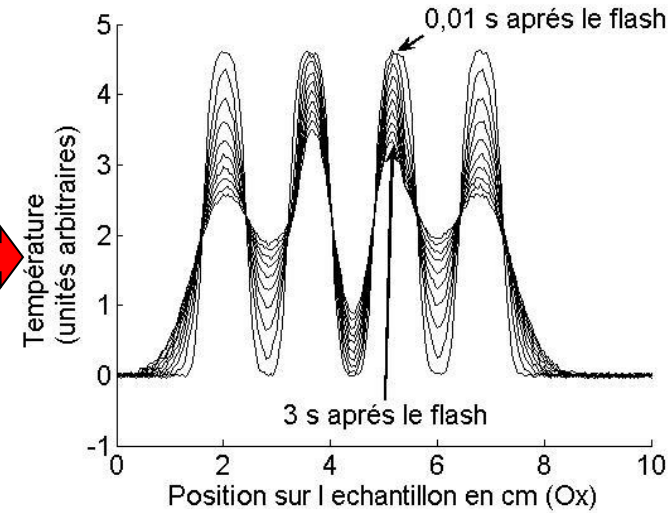
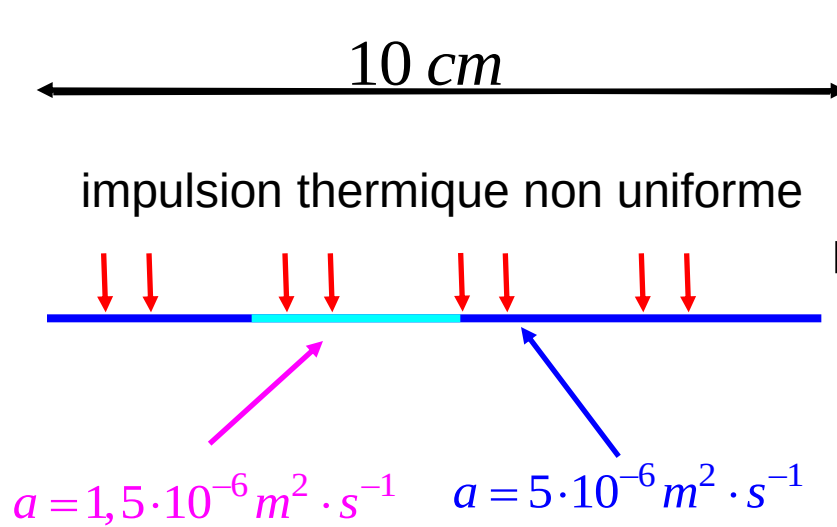
$$\ln \frac{\theta(\alpha, e, t_2)}{\theta(\alpha, e, t_1)} = \ln \frac{\theta(0, e, t_2)}{\theta(0, e, t_1)} - a_x \cdot \alpha^2 \cdot (t_2 - t_1)$$



$t>0$



Matériau ou milieu hétérogène (thèse M. Bamford 2007)

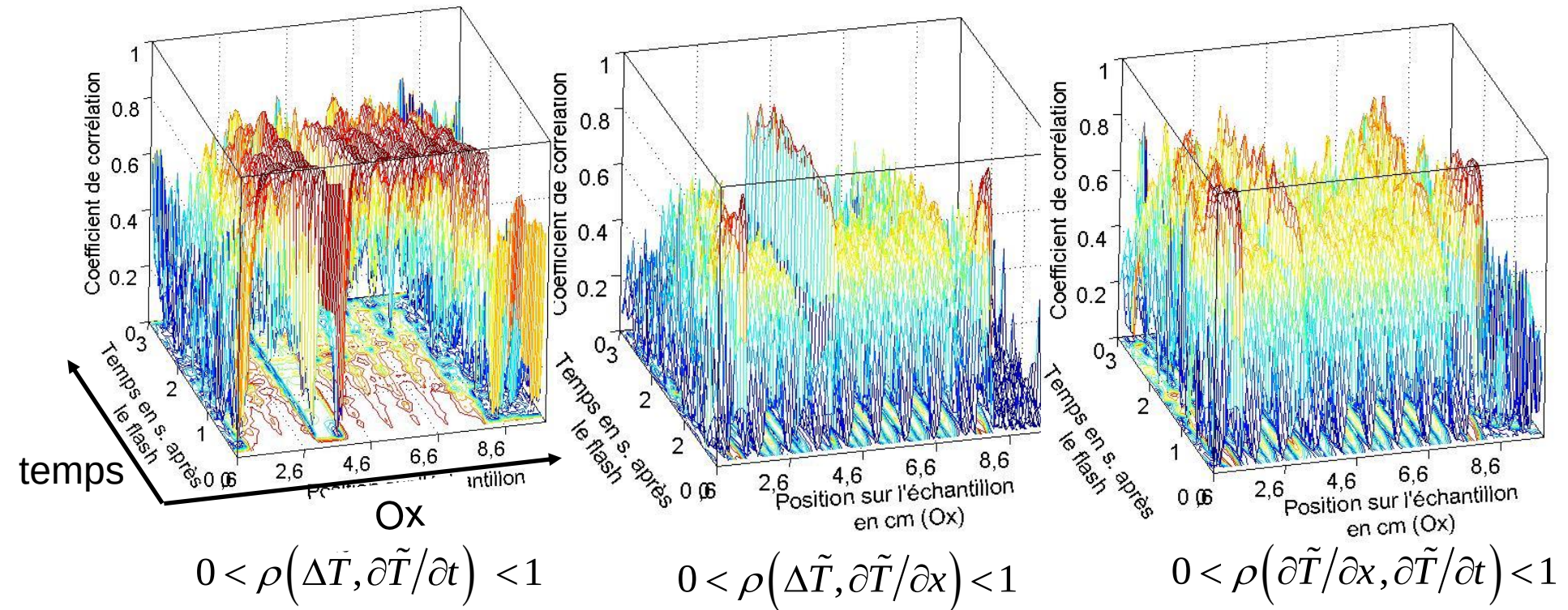


diffusion plane 1D

$$\frac{\partial \tilde{T}}{\partial t}(x,t) = a(x) \cdot \Delta \tilde{T}(x,t) + \frac{\partial a}{\partial x}(x) \cdot \frac{\partial \tilde{T}}{\partial x}(x,t)$$

Simulation proche des données expérimentales

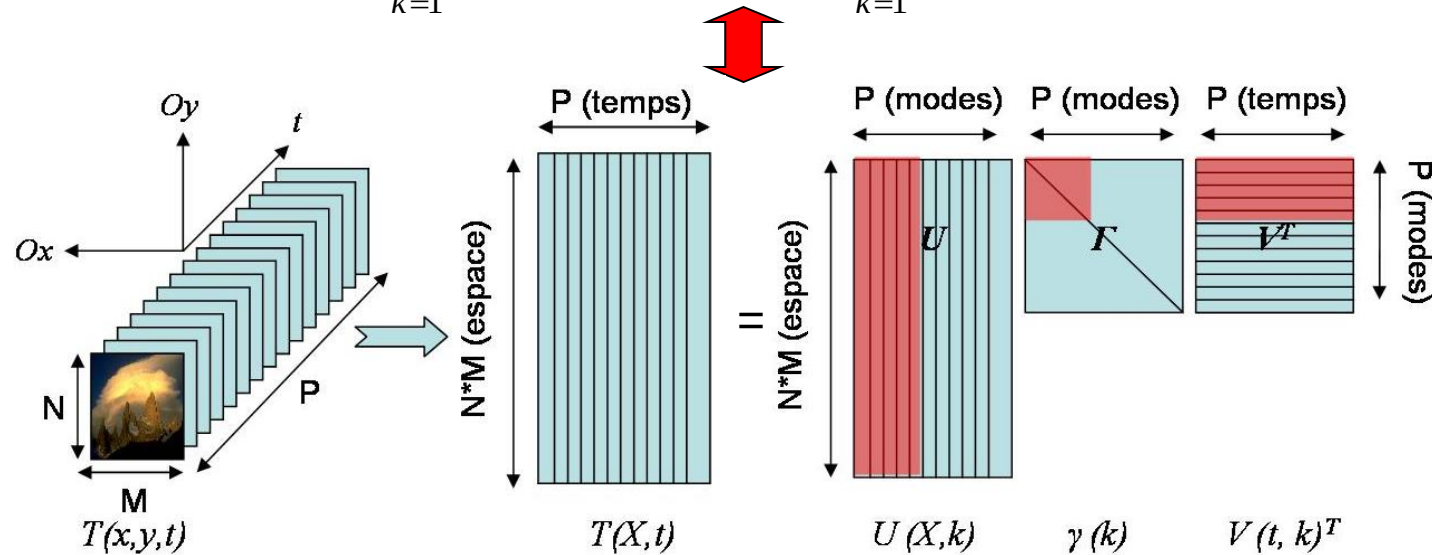
Approche nodale par les corrélations



Déterminer les parties où le modèle est valide, coûteux en temps de calcul

Approche modale par la SVD

$$T(x, t) = \sum_{k=1}^P \lambda_k \cdot U_k(x) \cdot V_k(t)^T \approx \sum_{k=1}^{\tilde{n}} \lambda_k \cdot U_k(x) \cdot V_k(t)^T$$



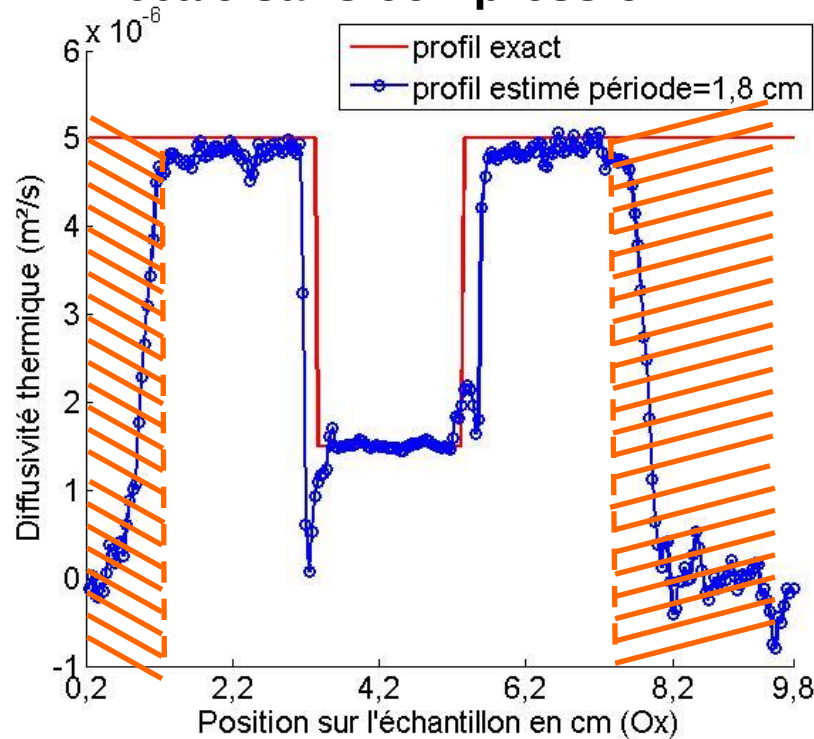
Equations identiques dans l'espace modal et dans l'espace de départ

$$\tilde{U}_k(x) = a(x) \cdot \Delta U_k(x) + \partial a / \partial x(x) \cdot \partial U_k / \partial x(x)$$

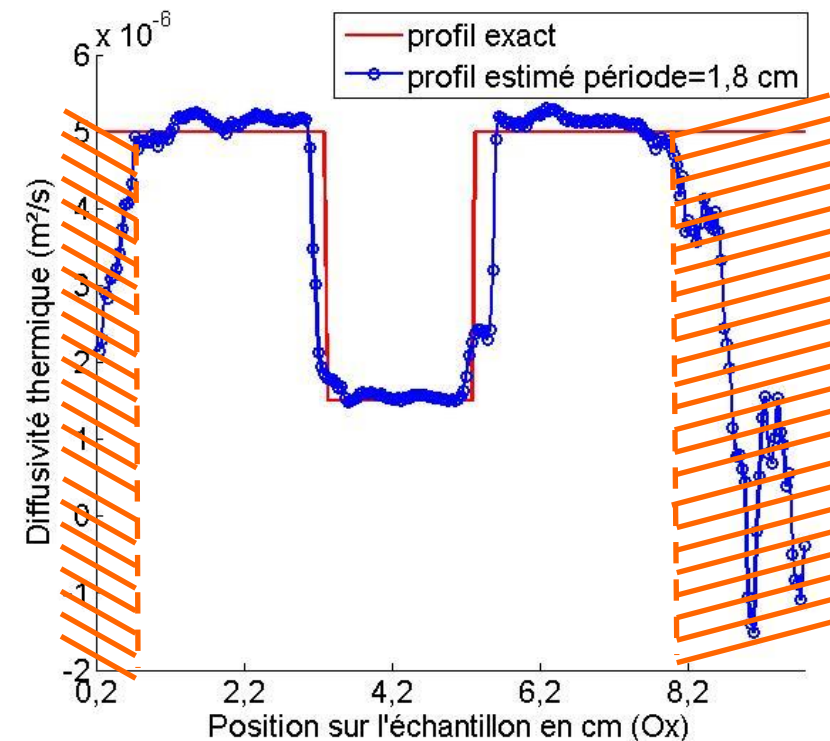
Même stratégie que précédemment, sur données compressées

Résultats

Profil diffusivité longitudinale
locale **sans compression**



Profil diffusivité longitudinale
locale **avec compression**



Résultats similaires, temps calcul / 100

Méthode en transformée intégrale



La transformée de Fourier apporte une « réduction » de la quantité d'information.
L'expression analytique s'écrit plus « simplement » dans l'espace transformé.
L'influence du bruit de mesure est diminuée par le fait que les signaux sont moyennés.



La transformation de Fourier spatiale = solutions dans le cas d'un matériau homogène.
Traitement de toute l'image alors qu'en nodal, uniquement quelques pixels sont « utilisables ».
Le signal est plus sensible à « certaines » fréquences spatiales.

Approche nodale et modale



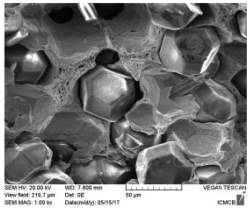
Estimation de la diffusivité en chacun des pixels
Corrélation = vérification de la validité du modèle thermique
SVD = Compression de l'information



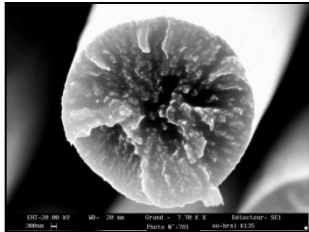
Ces méthodes ne s'appliquent qu'à une excitation de type impulsionnelle

Study thermal characterization of multiscale heterogeneous materials

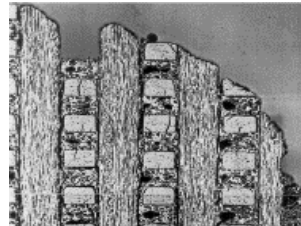
Copper-Diamond
Composite $L \approx 10 \text{ nm}$



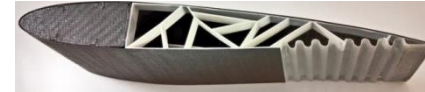
Carbon fibers
Diameter $L \approx 10 \text{ }\mu\text{m}$



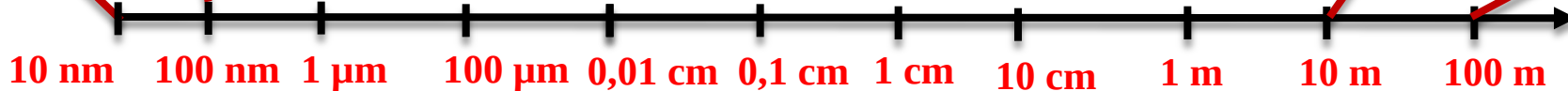
3D stratified composite
 $L \approx 1 \text{ cm}$



Aircraft Wing
 $L > \text{m}$



Spaceship
 $L > 10 \text{ m}$

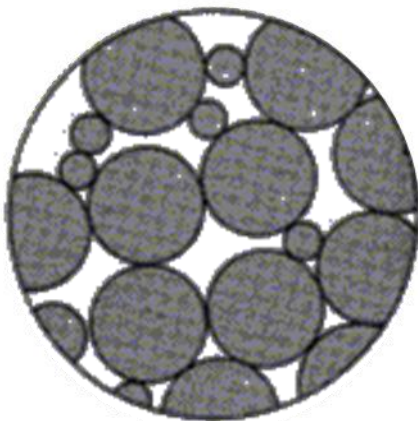


Difficulties:

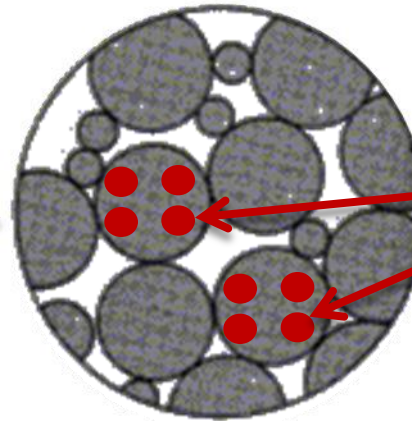
To perform quantitative estimations of in-plane thermal diffusivities fields on multiscale, heterogeneous and anisotropic materials

Break down the problem into homogeneous media by parts

Heterogeneous and anisotropic media



Laser Heat Pulse in Representative Elementary Volume (R.E.V)



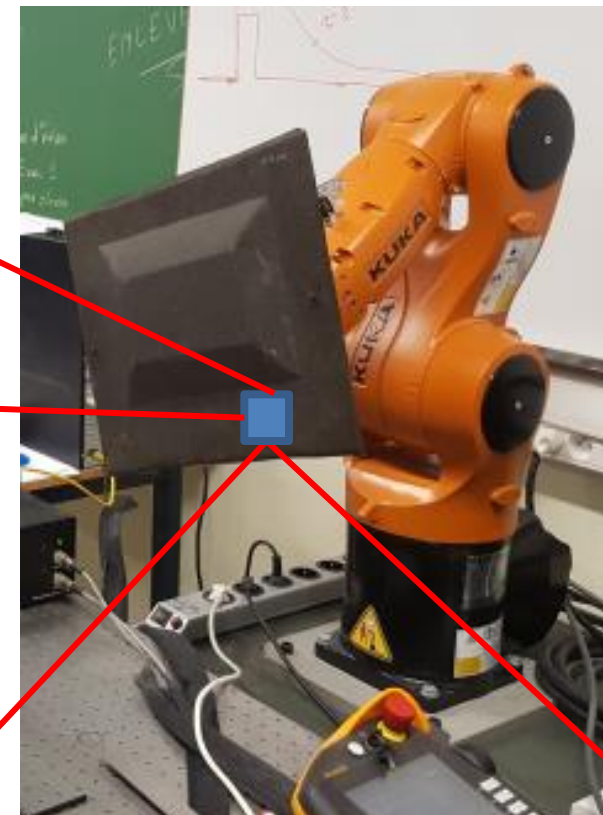
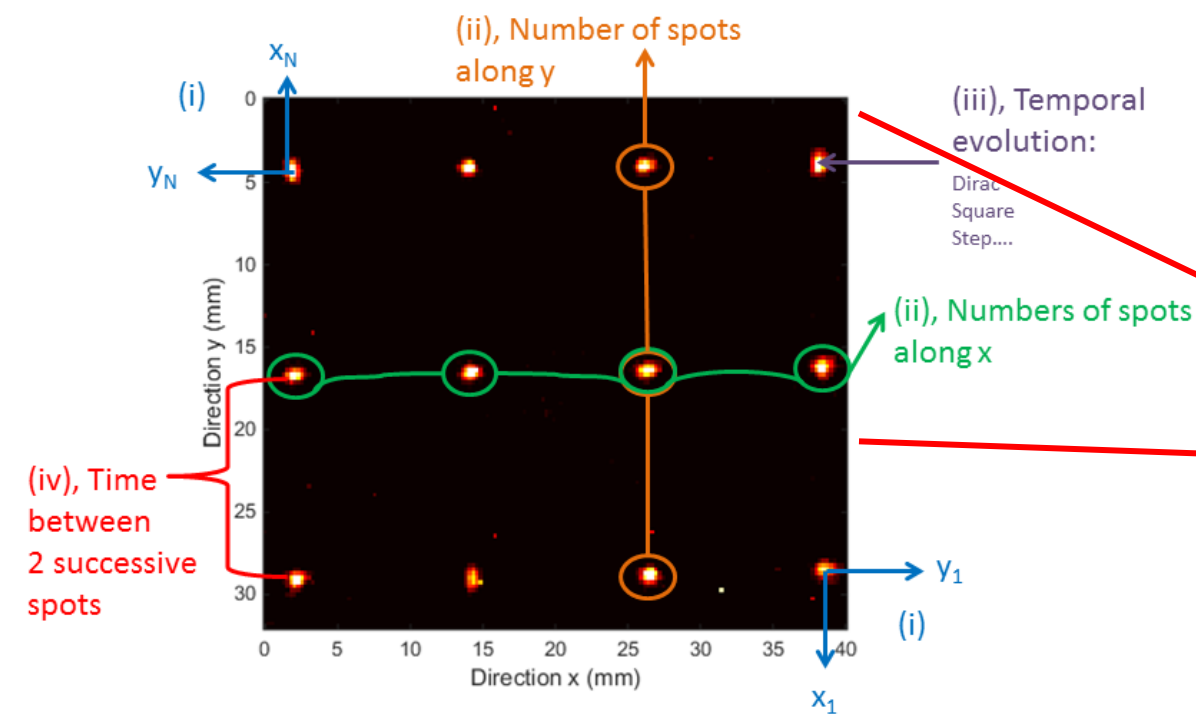
High thermal gradient at the surface of the sample

Use IR thermography for fields imaging and estimation



To develop set-up and methods :

Laser optical scanner for positioning in REV
Infrared camera for multiscale imaging
Analytical methods based on separable solutions



Scanning performances :

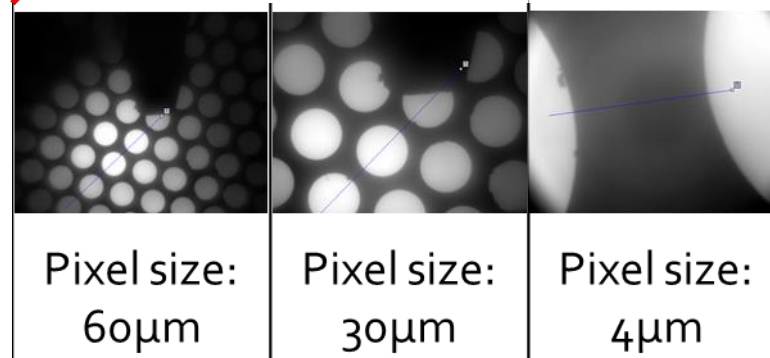
Scanning area : 60 mm x 40 mm

Laser spot: < 18 μm

Scanning rate: up to 1000 Hz

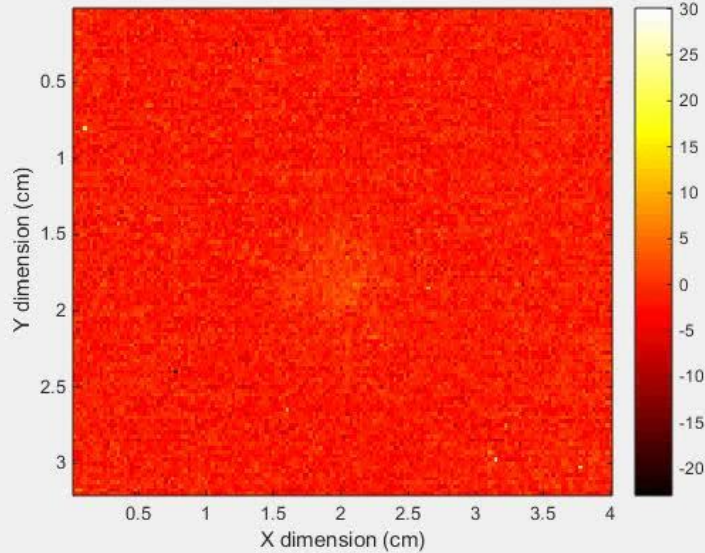
Spatial image resolution: from 4 μm to 250 μm

Robot: 6 axes, up to 2 m/s and 360°/s



Flying Spot « the most versatile set-up »

Time = 0.01 s



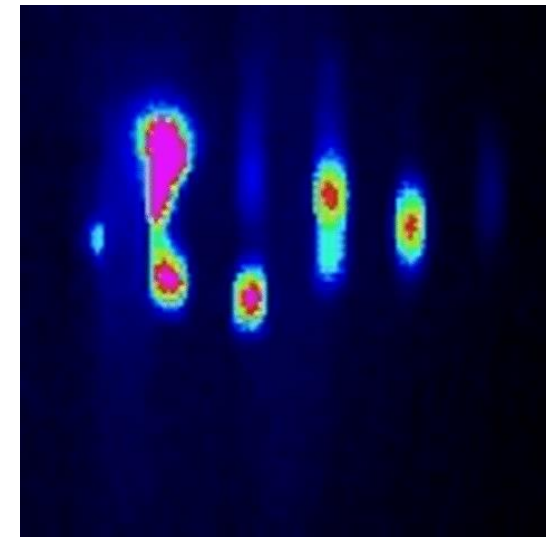
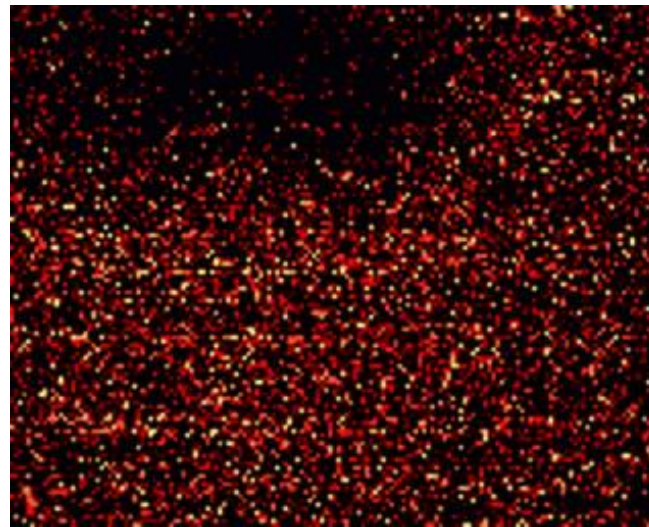
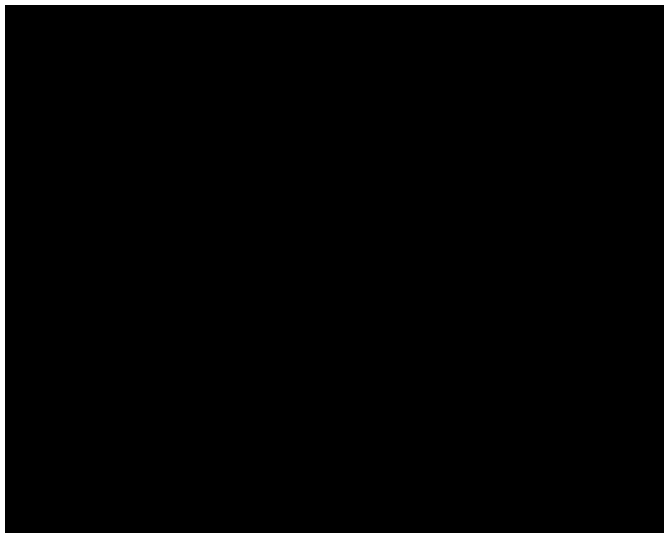
From Pulsed Spot (PS)

To Grid Pulsed Flying Spot (GPFS)

To Lock-in Pulsed Flying Spot (LPFS) 1994, Busse et al.

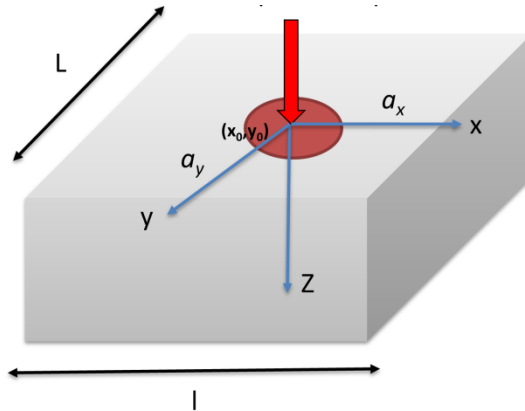
To Constant Velocity Flying Spot (CVFS)

To Random Pulsed Flying Spot (RPFS)



Direct thermal problem

Heat Pulsed Spot



Analytical solution of the 3Dt temperature field [1]

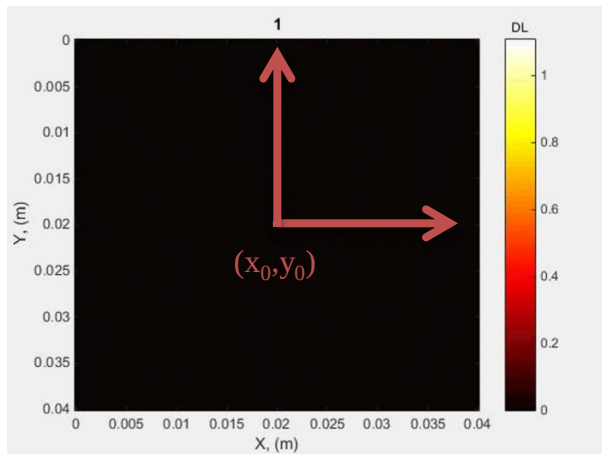
$$T(x, y, z, t) = \frac{Q}{\rho c} \frac{\exp\left(-\frac{(x-x_0)^2}{4a_{xx}t}\right)}{\sqrt{\pi a_{xx}t}} \frac{\exp\left(-\frac{(y-y_0)^2}{4a_{yy}t}\right)}{\sqrt{\pi a_{yy}t}} \frac{\exp\left(-\frac{z^2}{4a_{zz}t}\right)}{\sqrt{\pi a_{zz}t}}$$

Separability properties along x, y and z

$$T(x, y, z, t) = T_x \cdot T_y \cdot T_z$$

Space average following the x and y directions is considered

IR temperature field



$$\begin{cases} \bar{T}_y = \frac{Q}{\rho c} \frac{\exp\left(-\frac{(x-x_0)^2}{4a_{xx}t}\right)}{\sqrt{\pi a_{xx}t}} \frac{1}{\sqrt{\pi a_{zz}t}} \\ \bar{T}_x = \frac{Q}{\rho c} \frac{\exp\left(-\frac{(y-y_0)^2}{4a_{yy}t}\right)}{\sqrt{\pi a_{yy}t}} \frac{1}{\sqrt{\pi a_{zz}t}} \end{cases}$$

[1] Carslaw, H. S., & Jaeger, J. C. (1959).

Direct thermal problem

Expression analytique du champ de température à la surface de l'échantillon

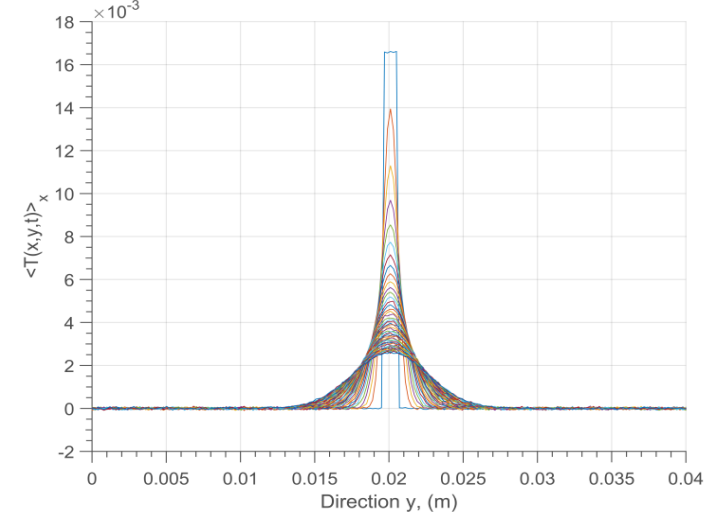
$$T(x, y, z = 0, t) = \frac{Q}{\rho c} \frac{\exp\left(-\frac{(x - x_0)^2}{4a_{xx}t}\right)}{\sqrt{\pi a_{xx}t}} \frac{\exp\left(-\frac{(y - y_0)^2}{4a_{yy}t}\right)}{\sqrt{\pi a_{yy}t}} \frac{1}{\sqrt{\pi a_{zz}t}}$$



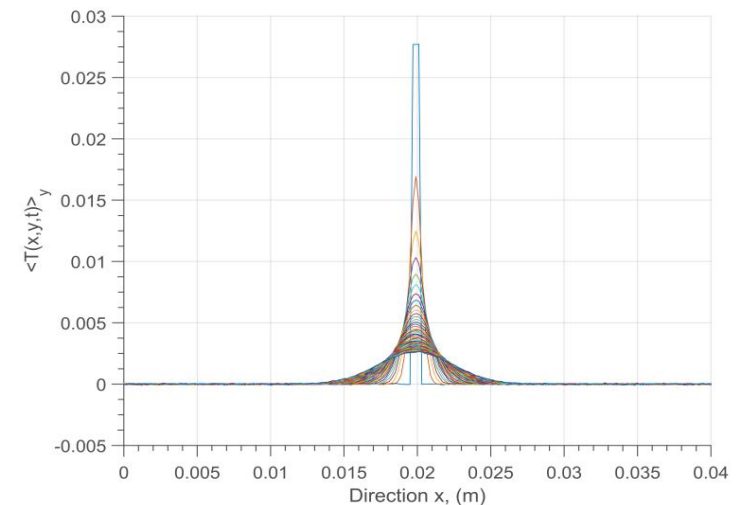
Moyennes marginales selon les directions x et y

$$\begin{cases} \bar{T}_y = \frac{Q}{\rho c} \frac{\exp\left(-\frac{(x - x_0)^2}{4a_{xx}t}\right)}{\sqrt{\pi a_{xx}t}} \frac{1}{\sqrt{\pi a_{zz}t}} \\ \bar{T}_x = \frac{Q}{\rho c} \frac{\exp\left(-\frac{(y - y_0)^2}{4a_{yy}t}\right)}{\sqrt{\pi a_{yy}t}} \frac{1}{\sqrt{\pi a_{zz}t}} \end{cases}$$

Moyenne marginale selon x



Moyenne marginale selon y



Inverse processing

Moyennes marginales selon les directions x et y

$$\begin{cases} \bar{T}_y = \frac{Q}{\rho c} \frac{\exp\left(-\frac{(x-x_0)^2}{4a_{xx}t}\right)}{\sqrt{\pi a_{xx}t}} \frac{1}{\sqrt{\pi a_{zz}t}} \\ \bar{T}_x = \frac{Q}{\rho c} \frac{\exp\left(-\frac{(y-y_0)^2}{4a_{yy}t}\right)}{\sqrt{\pi a_{yy}t}} \frac{1}{\sqrt{\pi a_{zz}t}} \end{cases}$$

Seuillage de la gaussienne du bruit de mesure au cours du temps

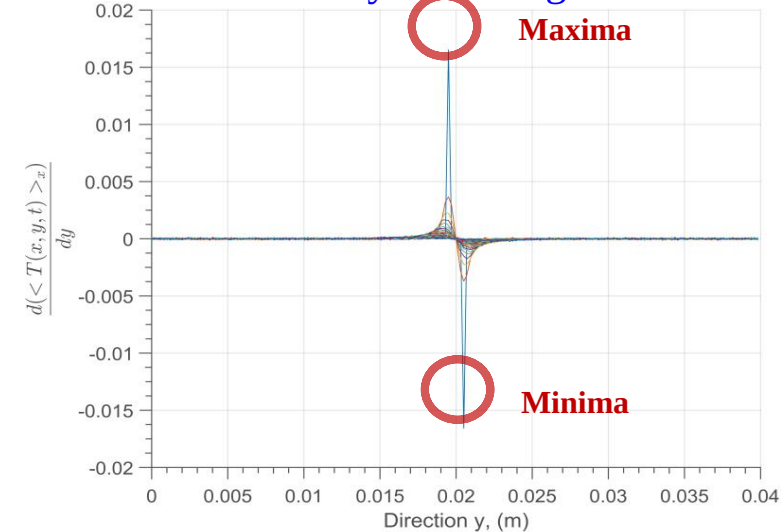
Borne max

$$\begin{cases} \max\left(\frac{d\bar{T}_y}{dx}\right) \\ \max\left(\frac{d\bar{T}_x}{dy}\right) \end{cases}$$

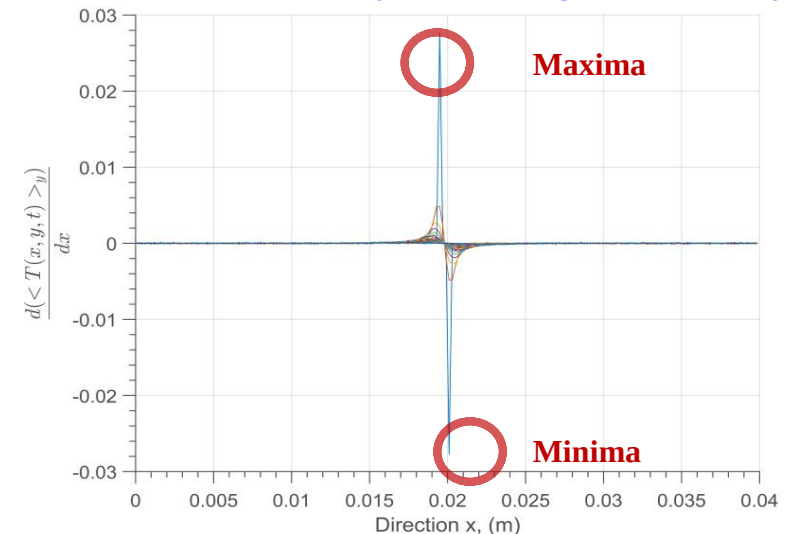
Borne min

$$\begin{cases} \min\left(\frac{d\bar{T}_y}{dx}\right) \\ \min\left(\frac{d\bar{T}_x}{dy}\right) \end{cases}$$

Dérivée de la moyenne marginale selon x



Dérivée de la moyenne marginale selon y



Inverse processing

Moyennes marginales selon les directions x et y

$$\begin{cases} \bar{T}_y = \frac{Q}{\rho c} \frac{\exp\left(-\frac{(x-x_0)^2}{4a_{xx}t}\right)}{\sqrt{\pi a_{xx}t}} \frac{1}{\sqrt{\pi a_{zz}t}} \\ \bar{T}_x = \frac{Q}{\rho c} \frac{\exp\left(-\frac{(y-y_0)^2}{4a_{yy}t}\right)}{\sqrt{\pi a_{yy}t}} \frac{1}{\sqrt{\pi a_{zz}t}} \end{cases}$$

Seuillage de la gaussienne du bruit de mesure au cours du temps

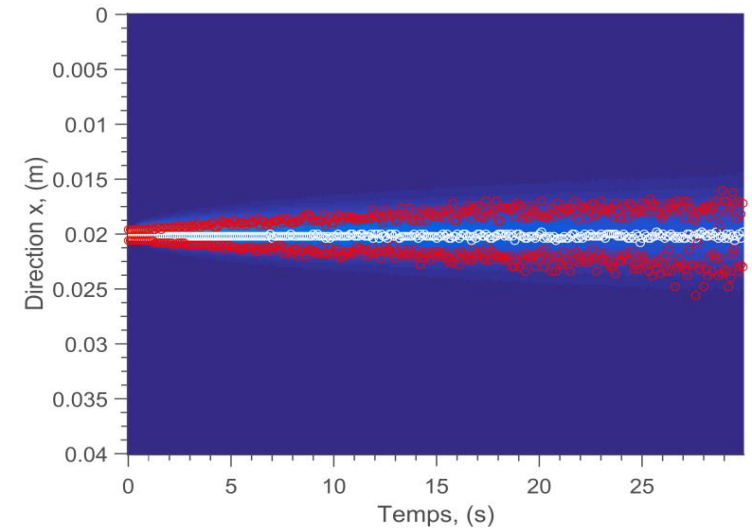
Borne max

$$\begin{cases} \max\left(\frac{d\bar{T}_y}{dx}\right) \\ \max\left(\frac{d\bar{T}_x}{dy}\right) \end{cases}$$

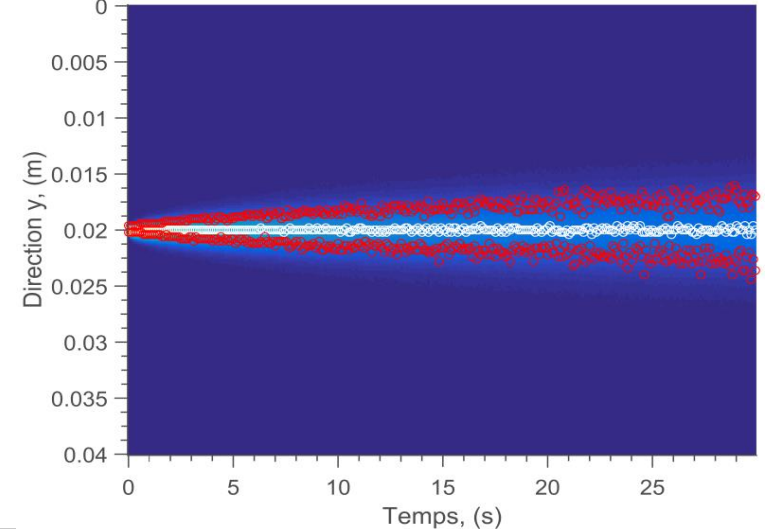
Borne min

$$\begin{cases} \min\left(\frac{d\bar{T}_y}{dx}\right) \\ \min\left(\frac{d\bar{T}_x}{dy}\right) \end{cases}$$

Seuillage de la zone d'intérêt selon x



Seuillage de la zone d'intérêt selon y



Inverse processing

Logarithmic decomposition

$$\begin{cases} \ln(\bar{T}_y) = \ln\left(\frac{Q}{\rho c \sqrt{\pi a_{zz} t}}\right) - \frac{(x - x_0)^2}{4a_{xx}t} \\ \ln(\bar{T}_x) = \ln\left(\frac{Q}{\rho c \sqrt{\pi a_{zz} t}}\right) - \frac{(y - y_0)^2}{4a_{yy}t} \end{cases}$$

Gauss-Markov theorem

Inverse processing

$$\hat{\beta} = (X^T W X)^{-1} X^T W \ln(\bar{T}_\xi)$$

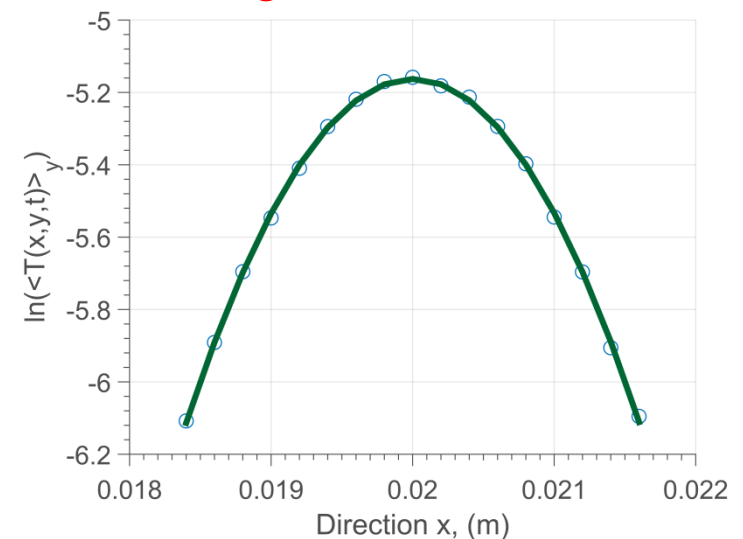
Parabolic formulation

$$\begin{cases} \ln(\bar{T}_y) = \beta_0(t) + \beta_1(t)x + \beta_2(t)x^2 \\ \ln(\bar{T}_x) = \beta_0(t) + \beta_1(t)y + \beta_2(t)y^2 \end{cases}$$

Analytic formulation of the parabolic coefficients

$$\begin{cases} \beta_2(t) = -\frac{1}{4a_{xx}t} \text{ ou } -\frac{1}{4a_{yy}t} \\ \beta_1(t) = \frac{x_0}{2a_{xx}t} \text{ ou } \frac{y_0}{2a_{yy}t} \\ \beta_0(t) = -\frac{x_0^2}{4a_{xx}t} + \ln\left(\frac{Q}{\rho c \sqrt{\pi a_{zz} t}}\right) \\ \text{ou } -\frac{y_0^2}{4a_{yy}t} + \ln\left(\frac{Q}{\rho c \sqrt{\pi a_{zz} t}}\right) \end{cases}$$

Estimation of parabolic coefficients
along x direction at fixed time



Inverse processing

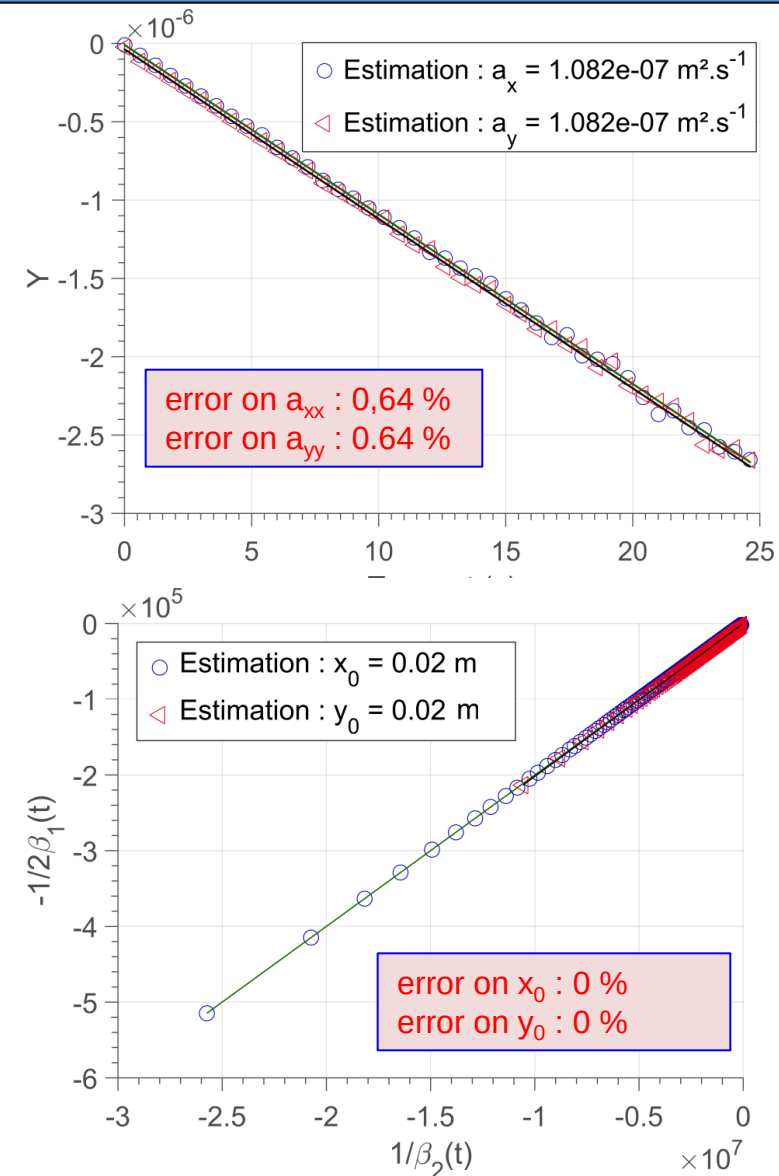
Estimation of thermal diffusivities tensor (a_{xx} , a_{yy})

$$-\frac{l}{4\beta_2(t)} = a_{xx}t \quad \text{and} \quad -\frac{l}{4\beta_2(t)} = a_{yy}t$$

Estimation of the laser spot x_0 et y_0 positions

$$\left. \begin{aligned} \beta_1(t) &= \frac{x_0}{2a_{xx}t} \text{ ou } \frac{y_0}{2a_{yy}t} \\ \beta_2(t) &= -\frac{1}{4a_{xx}t} \text{ ou } -\frac{1}{4a_{yy}t} \end{aligned} \right\} -\frac{1}{2\beta_2(t)} = \frac{x_0}{\beta_1(t)} \text{ ou } -\frac{1}{2\beta_2(t)} = \frac{y_0}{\beta_1(t)}$$

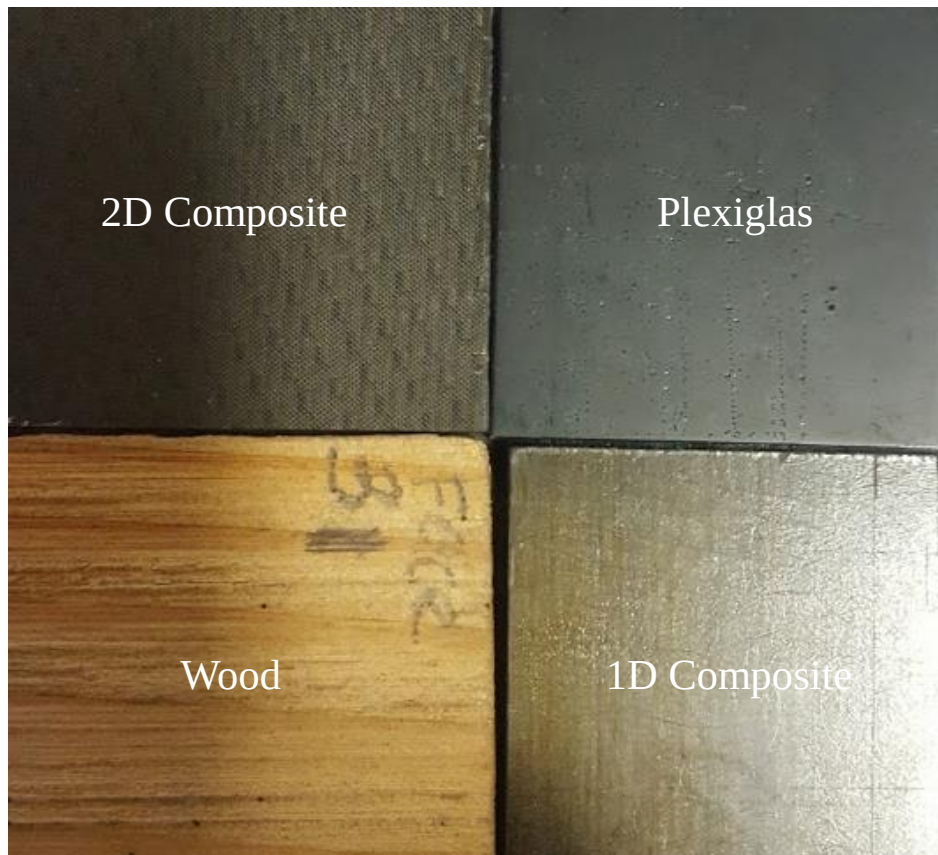
Two parameters estimation:
Laser spot location
Thermal diffusivities tensor



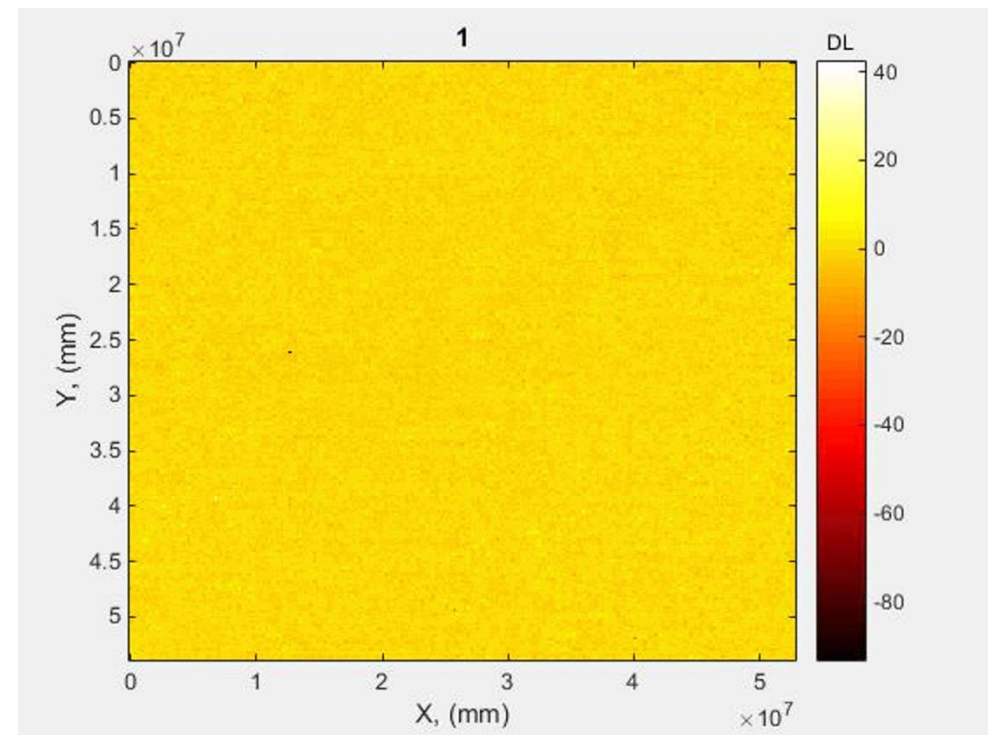
Heterogeneous and orthotropic sample

Scanning with Grid Pulsed Flying Spot (GPFS)
Huge amount of laser spot

Heterogeneous sample

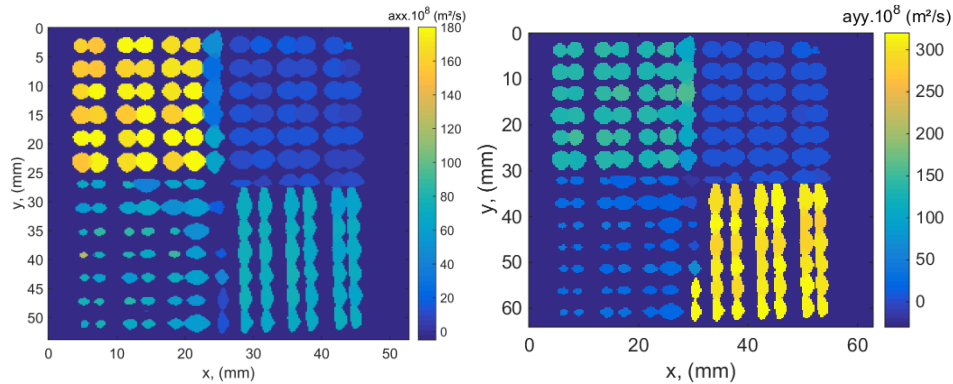


Grid Pulsed Flying Spot



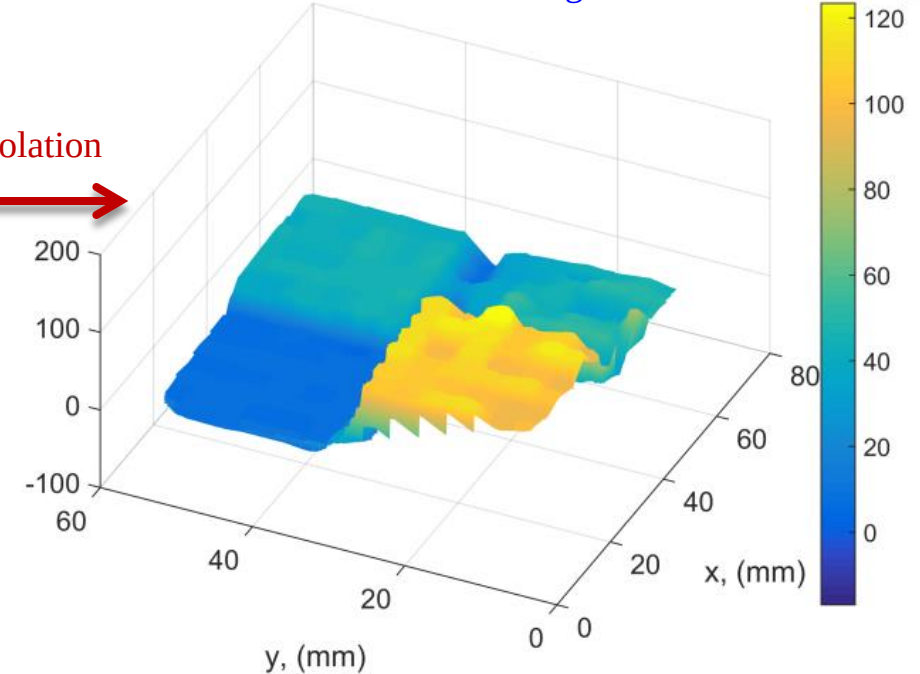
Heterogeneous and orthotropic sample

Thermal diffusivities fields after 196 scans

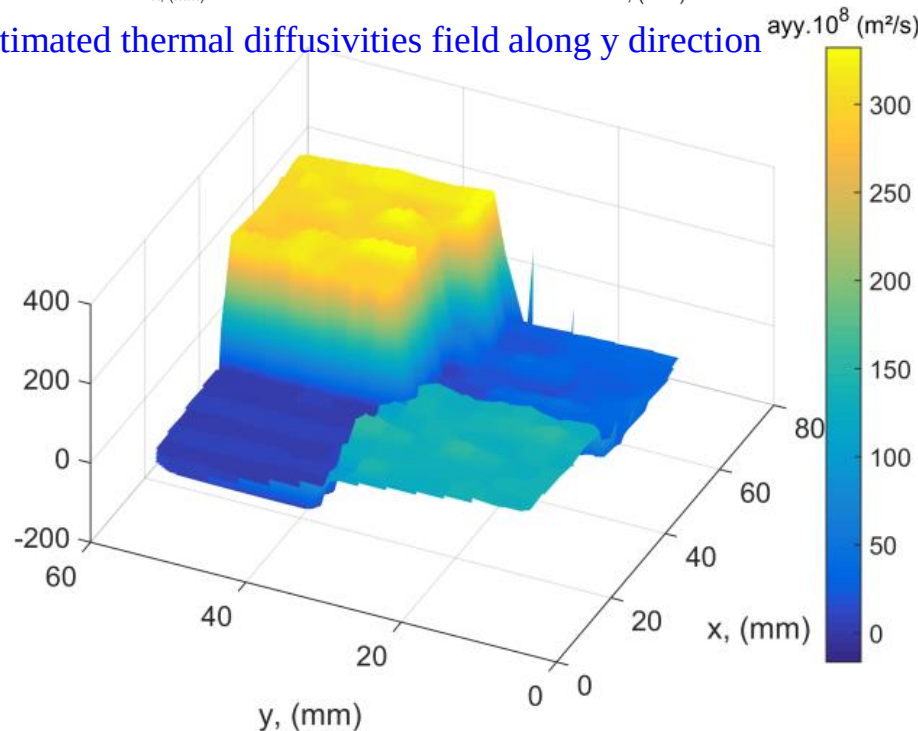


Estimated thermal diffusivities field along x direction $axx \cdot 10^8 \text{ (m}^2/\text{s)}$

Interpolation



Estimated thermal diffusivities field along y direction



Measurements duration: 10 s
Processing: 1 s
196 estimations of in-plane diffusivities fields

Direct thermal problem

[1] Chang, et al. (1973).

Analytical temperature field out of the main axes [1]

$$T(x, y, z, t) = \frac{Q}{4\pi\rho c_p t} \cdot |a^{i,j}|^{\frac{1}{2}} \cdot \exp\left(-\frac{1}{|a_{i,j}|} \left(\frac{a_{yy}(x-x_0)^2}{4t} - \frac{a_{xy}(x-x_0)(y-y_0)}{2t} + \frac{a_{xx}(y-y_0)^2}{4t} \right)\right) \cdot f_z(t)$$

LEM formulation

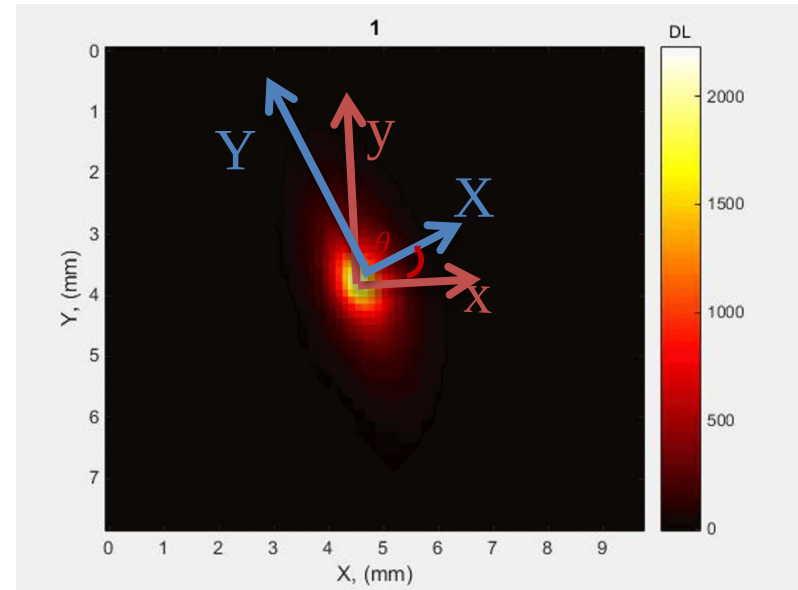
$$\ln(T(x, y, z, t)) = \beta_0(t) + \beta_1(t)x + \beta_2(t)y + \beta_3(t)x^2 + \beta_4(t)xy + \beta_5(t)y^2$$

LEM formulation centered on the spot mark

$$\ln(T(x, y, t)) = \beta_3(t)x^2 + \beta_4(t)xy + \beta_5(t)y^2$$

Matricial formulation

$$\begin{pmatrix} a_{xx} & a_{xy} & 0 \\ a_{yx} & a_{yy} & 0 \\ 0 & 0 & a_{zz} \end{pmatrix} = PDP^{-1} = \begin{pmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} a_{xx} & 0 & 0 \\ 0 & a_{yy} & 0 \\ 0 & 0 & a_{zz} \end{pmatrix} \begin{pmatrix} \cos(\theta) & \sin(\theta) & 0 \\ -\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



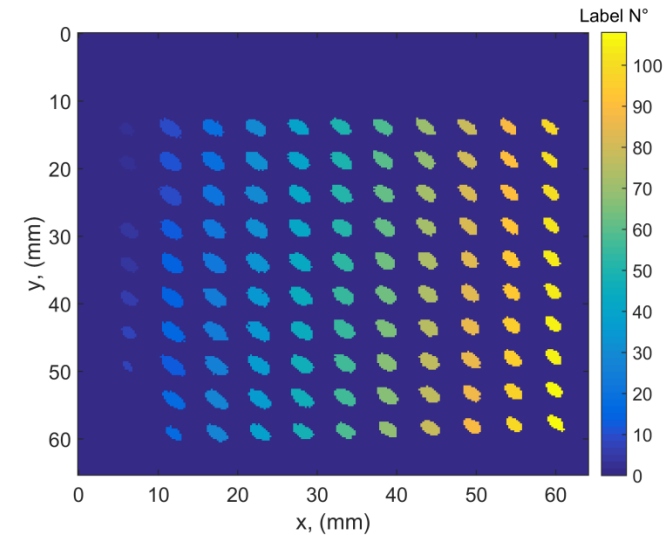
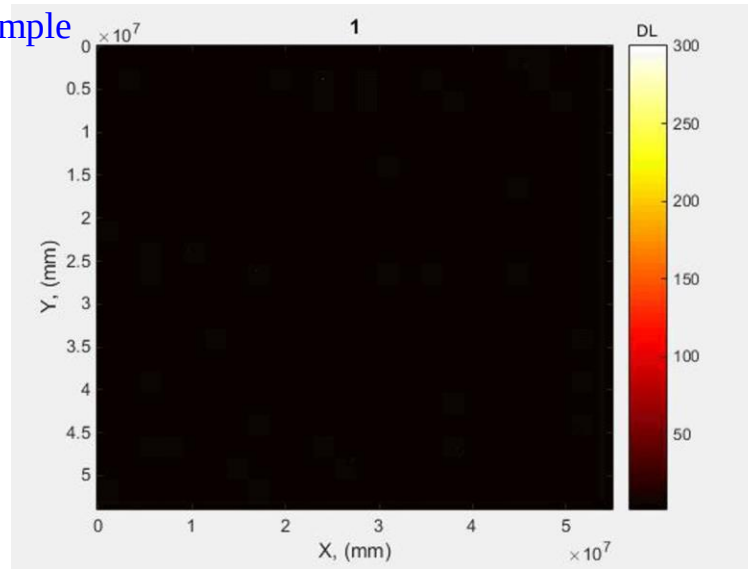
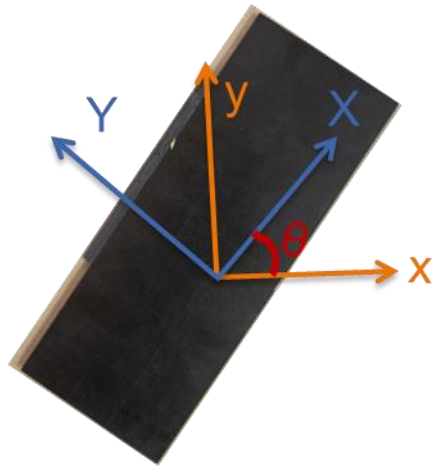
$$a_{xx} = -\frac{1}{4\lambda_1 t} \quad \text{et} \quad a_{yy} = -\frac{1}{4\lambda_2 t}$$

$$\theta = \text{Arc tan}\left(\frac{x_{21}}{x_{11}}\right) = \text{Arc tan}\left(-\frac{x_{12}}{x_{22}}\right)$$

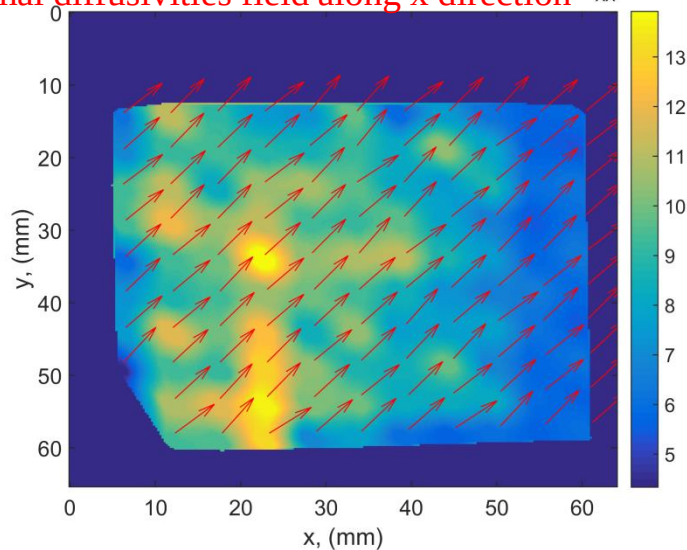
Estimation of the thermal diffusivities tensor
And the rotation angle between the axes

LEM on Oriented Orthotropic Composite Sample

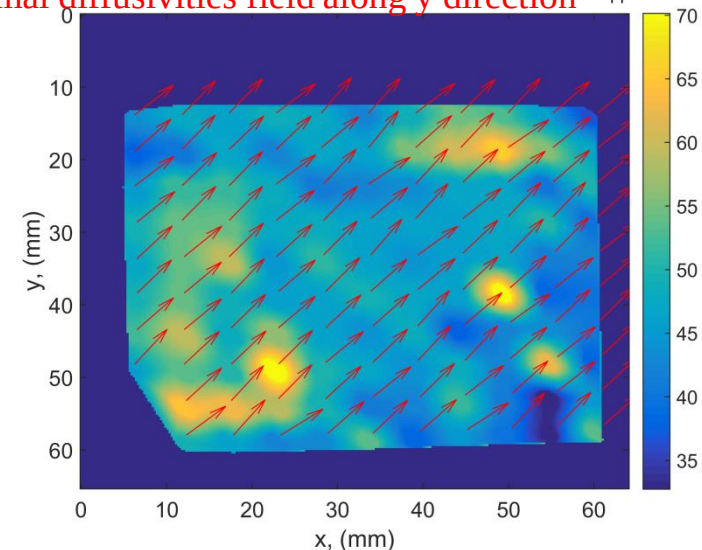
110 laser spots on 1D composite sample



Estimated thermal diffusivities field along x direction $a_{xx} \cdot 10^7 \text{ m}^2 \cdot \text{s}^{-1}$

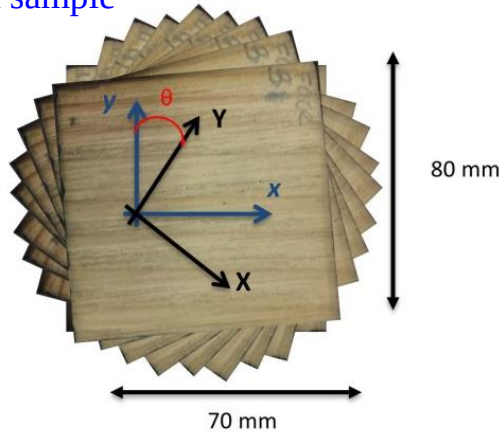


Estimated thermal diffusivities field along y direction $a_{yy} \cdot 10^7 \text{ m}^2 \cdot \text{s}^{-1}$

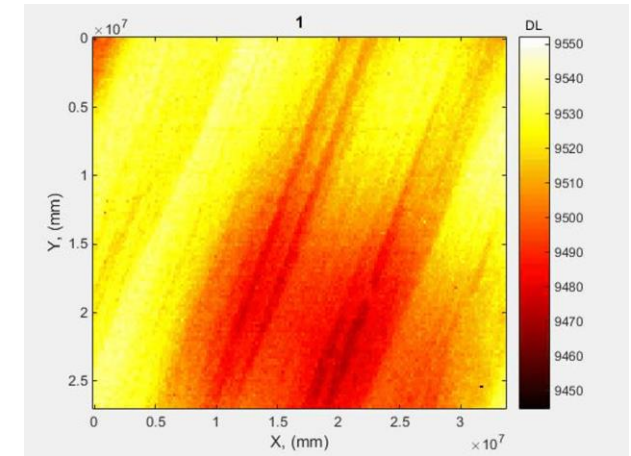
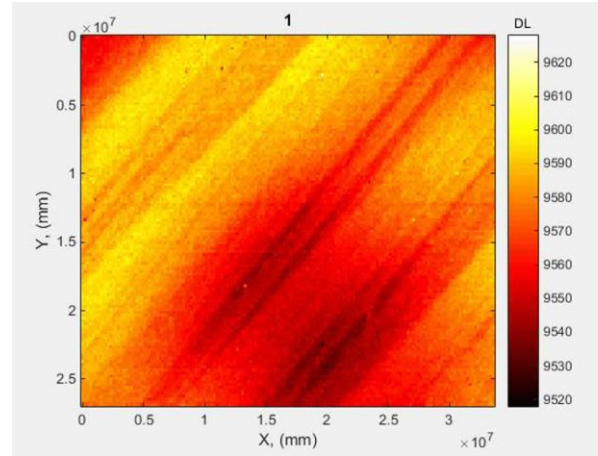


LEM on Oriented Anisotropic Wood Sample

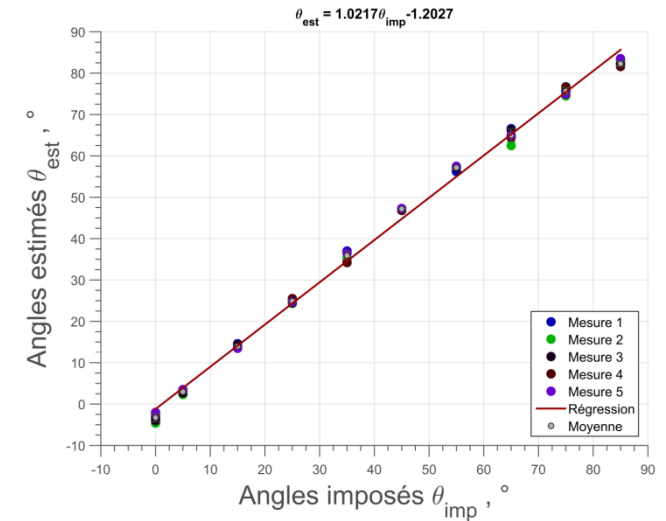
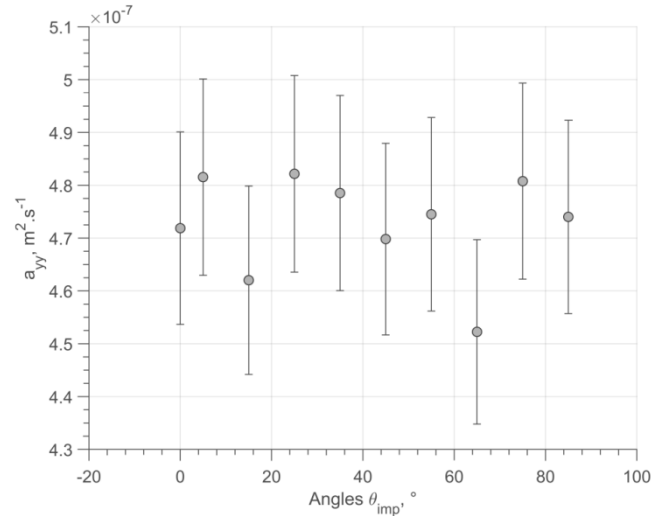
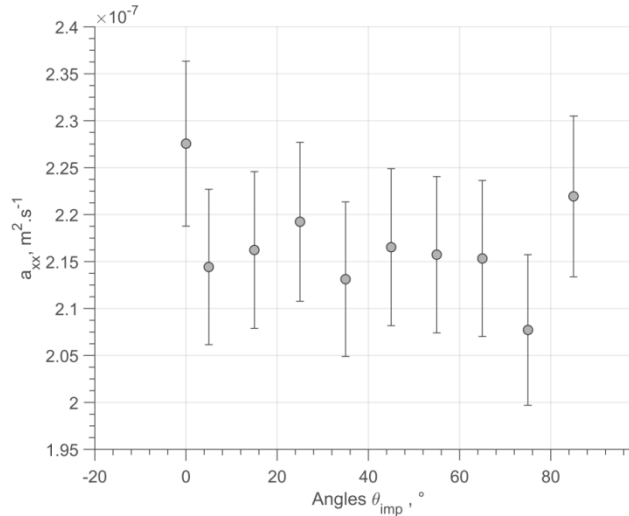
Wood sample



IR measurement as function of the sample angle

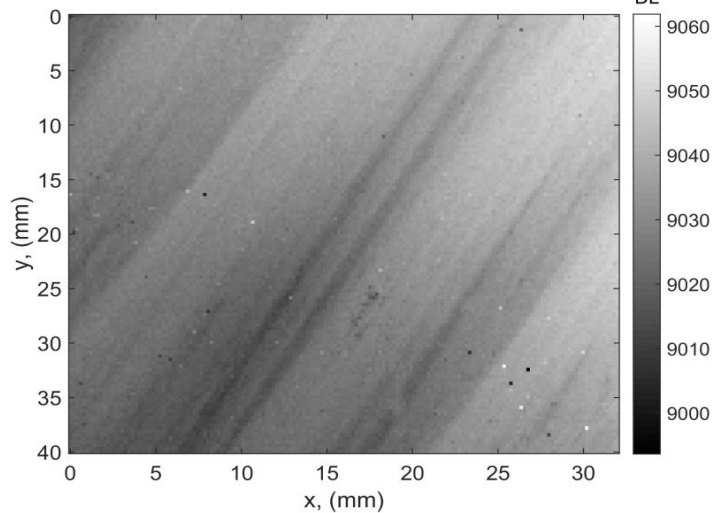


Estimated thermal diffusivities fields along x and y directions and angle

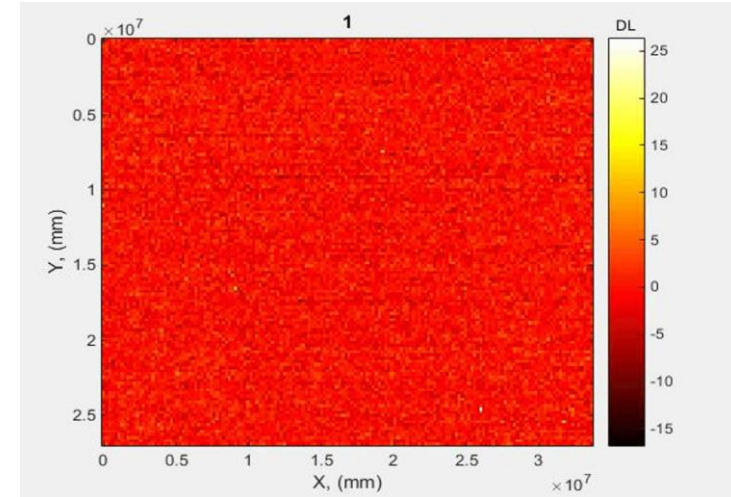


LEM on Oriented Anisotropic Wood Sample

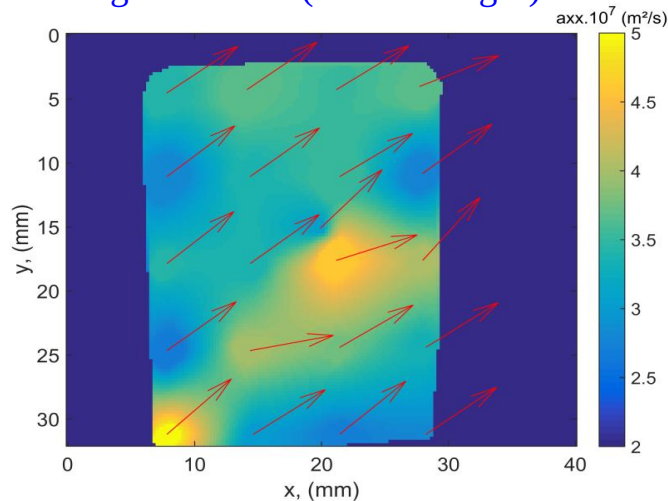
Image thermique du pin maritime orienté



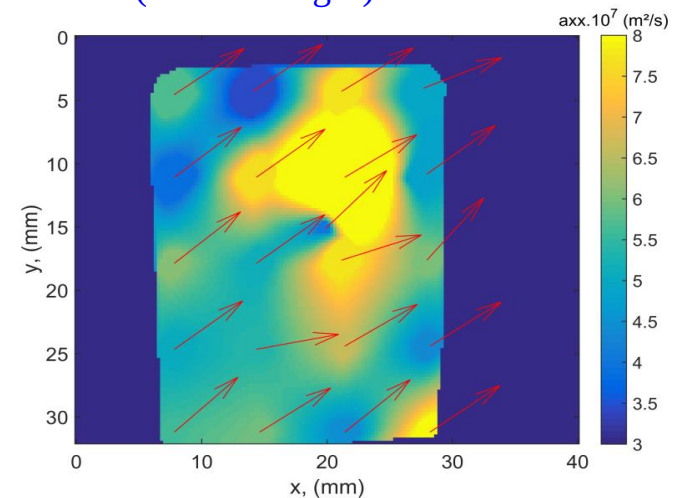
Grid Pulsed Flying Spot laser



Cartographie de diffusivité thermique selon x et les angles estimés (flèches rouges)



Cartographie de diffusivité thermique selon y et les angles estimés (flèches rouges)



Development of high versatile Flying Spot set-up

*Logarithmic analytical method for in-plane thermal diffusivities
fields estimation of anisotropic materials*

Applications

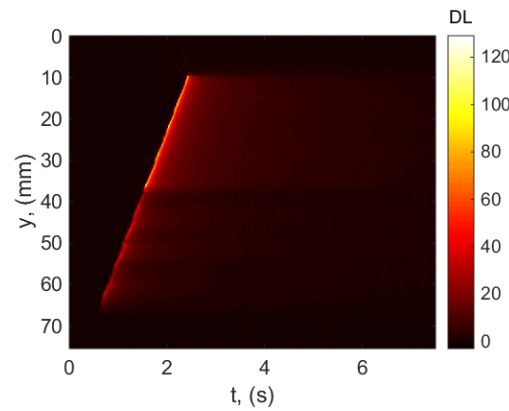
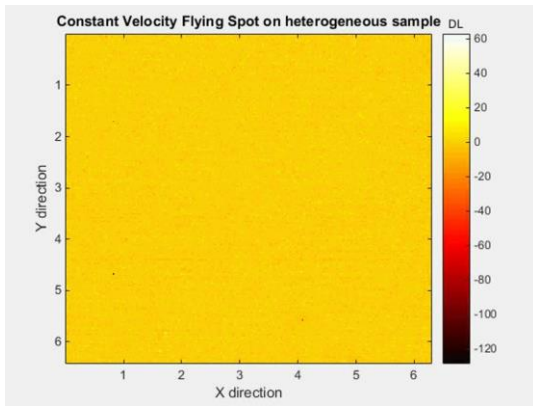
Tools for real time industrial Quantitative NDT

Performances and drawback

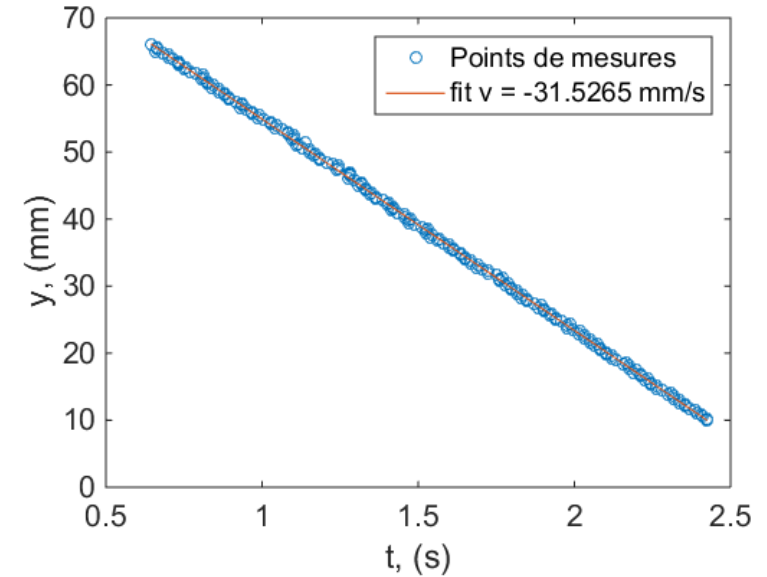
Very good spatial resolution down to 1 mm

Time analysis strongly linked to the sample thermal properties

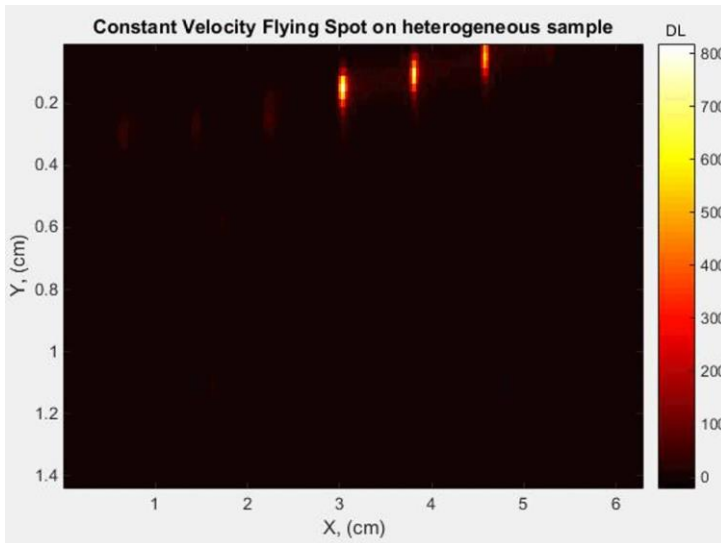
From Grid Pulsed Flying Spot



Change of mark by velocity estimation



To Constant velocity Flying Spot

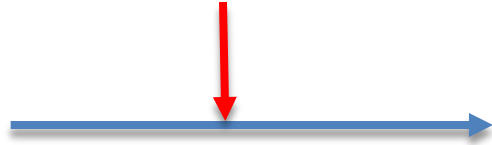


New formulation, of the thermal problem....

$$T(x, y, z) = \frac{Q}{\rho c e} \frac{\exp\left(-\frac{v(x-x_0)^2}{4a_{xx}y}\right)}{\sqrt{\frac{\pi a_{xx}y}{v}}} \frac{\exp\left(-\frac{vz^2}{4a_{zz}y}\right)}{\sqrt{\frac{\pi a_{zz}y}{v}}}$$

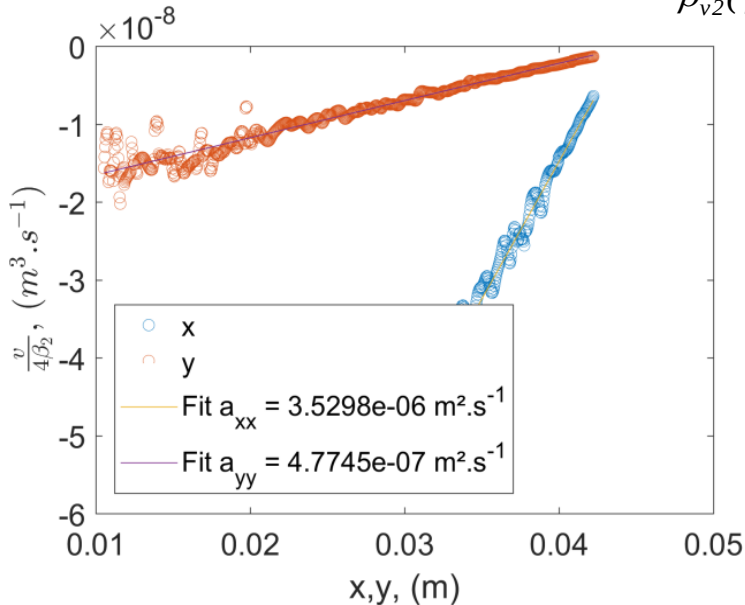
Formulation of the
logarithmic coefficient
of the parabola

Gauss-Markov



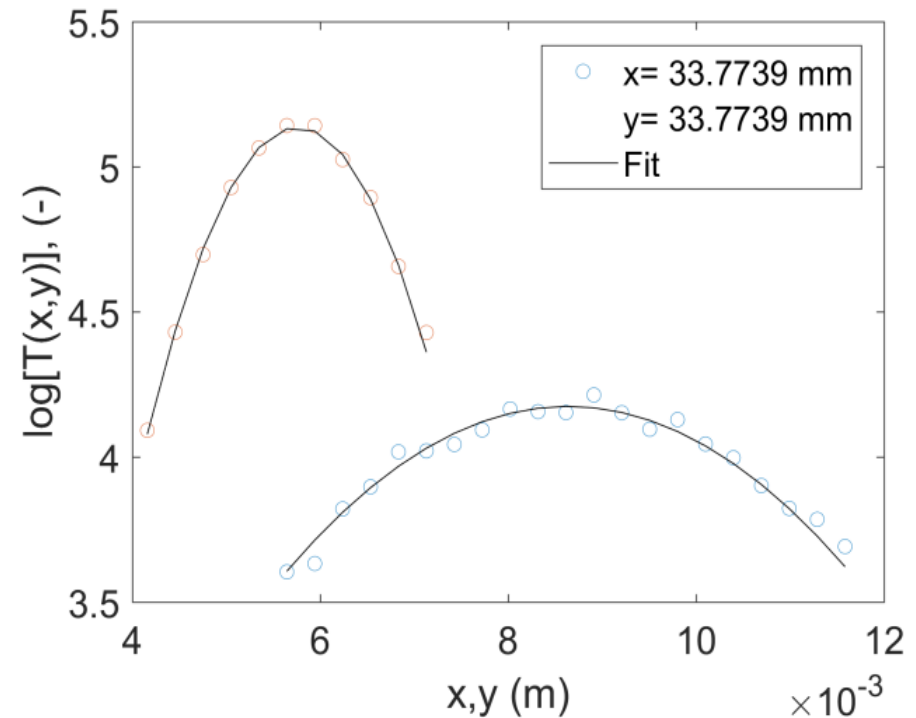
$$\begin{cases} \beta_{v2}(y) = -\frac{v}{4a_{xx}y} \\ \beta_{v1}(y) = \frac{vx_0}{2a_{xx}y} \\ \beta_{v0}(y) = -\frac{vx_0^2}{4a_{xx}y} + \ln(K) \end{cases}$$

Real time estimation



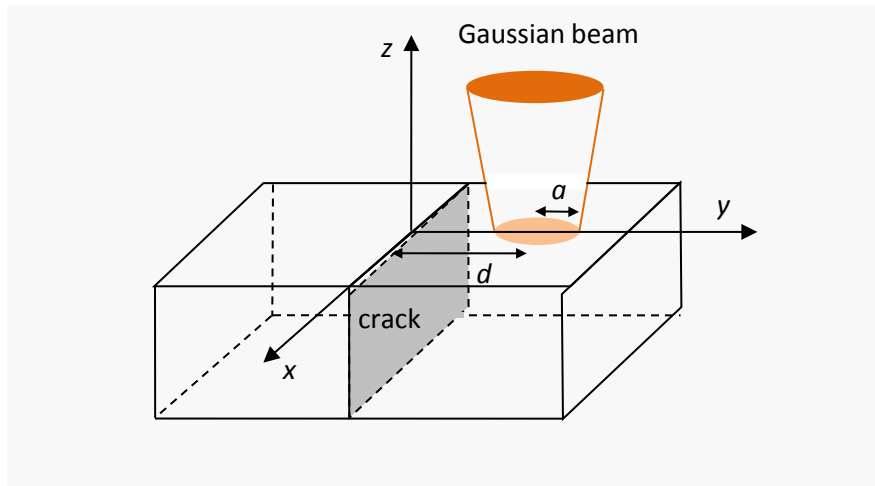
$$\frac{1}{\beta_{v2}(y)} = -\frac{4a_{xx}}{v} y$$

Estimation of parabolas for the two media



**Real time thermal diffusivities
tensor estimation: 10 s
Up to 1000 estimations
of in-plane diffusivities fields
in heterogeneous media**

2.1-Theory



Pulsed laser

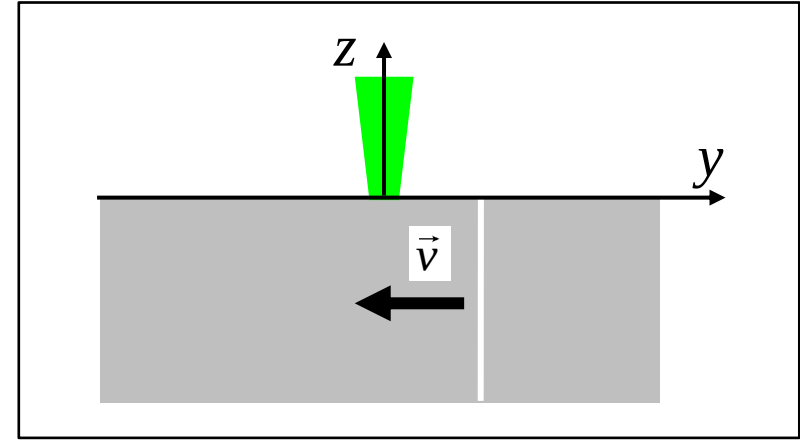
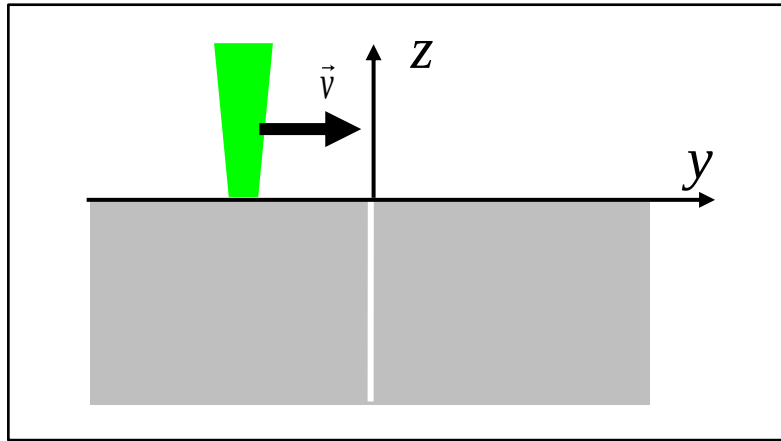
Isotropic, opaque, semiinfinite sample, **infinite vertical crack**, no heat losses

$$R_{th} = L / K_{air}$$

$$T(0, y, 0, t) = \frac{2Q_o}{\varepsilon\sqrt{\pi^3 t}} \frac{e^{-\frac{2(y-d)^2}{a^2 + 8Dt}}}{a^2 + 8Dt} \pm \frac{Q_o}{\varepsilon\pi^2 at\sqrt{D}\sqrt{a^2 + 8Dt}} \int_{-\infty}^{\infty} dy_o e^{-\frac{2(y_o-d)^2}{a^2} - \frac{u^2}{4Dt}} \left[1 - \frac{\sqrt{4\pi Dt}}{KR_{th}} e^{\left(\frac{\sqrt{4Dt}}{KR_{th}} + \frac{u}{\sqrt{4Dt}}\right)^2} \operatorname{erfc}\left(\frac{\sqrt{4Dt}}{KR_{th}} + \frac{u}{\sqrt{4Dt}}\right) \right]$$

N.W. Pech-May et al., NDT&E Int. 77, 28 (2016)

Opaque, infinite crack, no heat losses

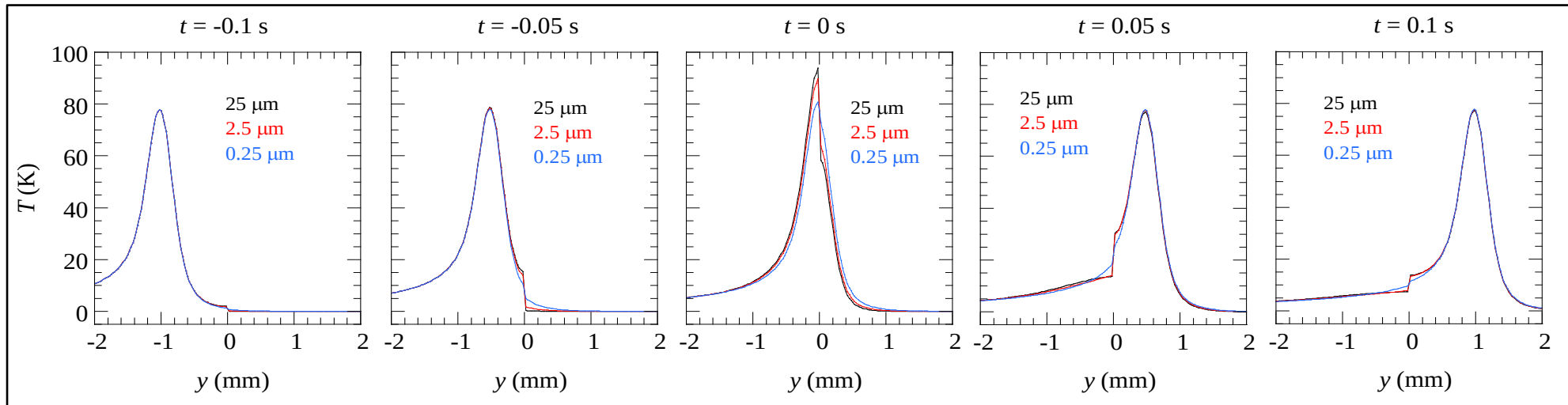


$$\begin{aligned}
 T(0, y, 0, t) = & \frac{2P_o}{\varepsilon\sqrt{\pi^3}} \int_{-\infty}^t \frac{1}{\sqrt{t-\tau}} \frac{e^{-\frac{2(y-v\tau)^2}{a^2+8D(t-\tau)}}}{a^2+8D(t-\tau)} d\tau + \\
 & + \text{sign}(y) \frac{P_o}{\varepsilon\pi^2 a \sqrt{D}} \int_{-\infty}^{\infty} dy_o \int_{-\infty}^t d\tau \frac{\text{sign}(y_o)}{t-\tau} \frac{e^{-\frac{2(y_o-v\tau)^2}{a^2} - \frac{u^2}{4D(t-\tau)}}}{\sqrt{a^2+8D(t-\tau)}} \times \\
 & \times \left[1 - \frac{\sqrt{4\pi D(t-\tau)}}{KR_{th}} \exp\left(\frac{\sqrt{4\pi D(t-\tau)}}{KR_{th}} - \frac{u}{\sqrt{4\pi D(t-\tau)}}\right)^2 \right] \text{erfc}\left(\frac{\sqrt{4\pi D(t-\tau)}}{KR_{th}} + \frac{u}{\sqrt{4\pi D(t-\tau)}}\right)
 \end{aligned}$$

→
→

AISI-304 ($D = 4 \text{ mm}^2/\text{s}$, $K = 15 \text{ W/mK}$), $P_o = 1 \text{ W}$, $a = 0.3 \text{ mm}$

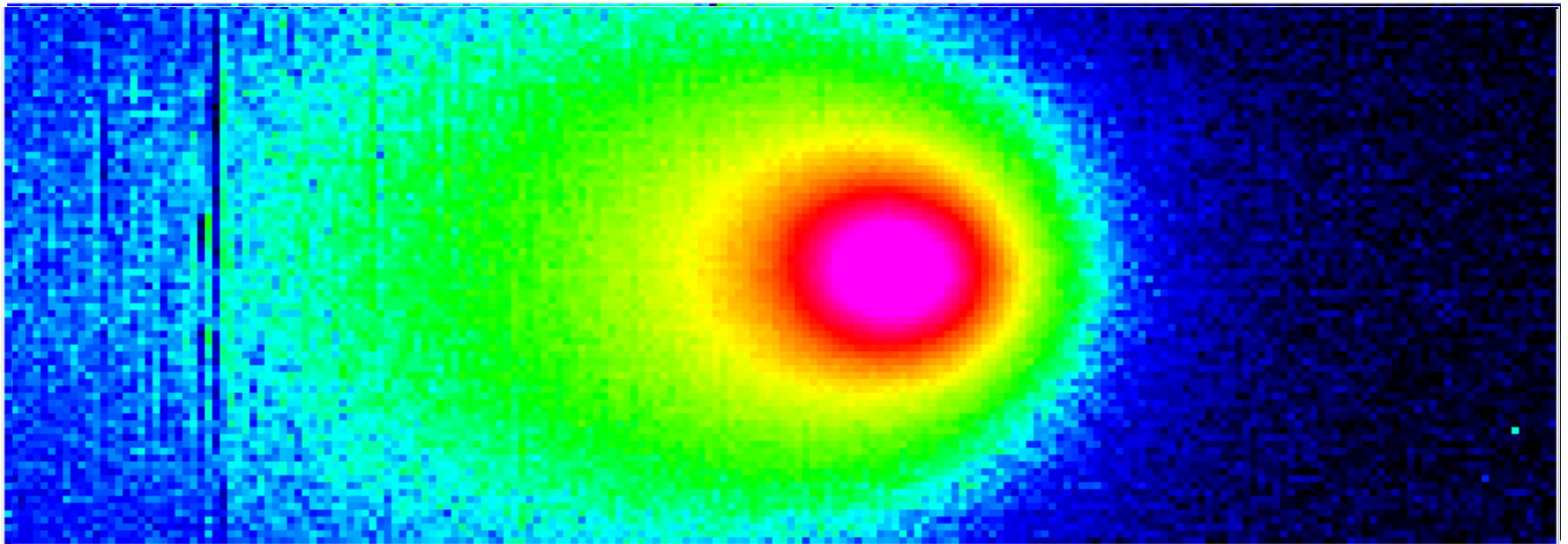
$v = 10 \text{ mm/s}$



Temperature
contrast

$$\Delta T = \frac{T(y = 0_-) - T(y = 0_+)}{T(d = vt)}$$

AISI-304, $L = 0 \text{ } \mu\text{m}$, $L_{lock-in} = 0.56 \text{ } \mu\text{m}$, $v = 3.5 \text{ mm/s}$



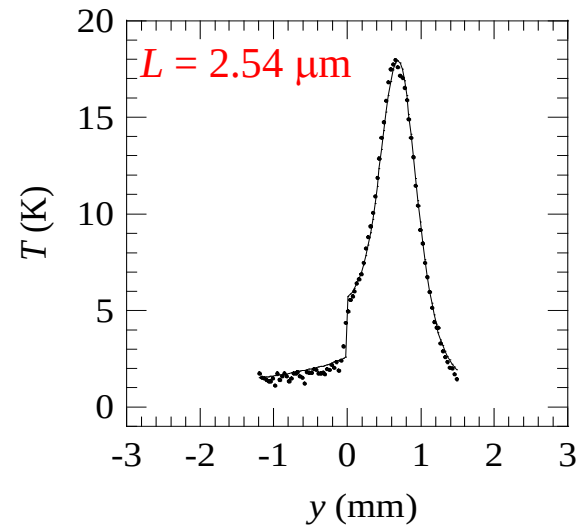
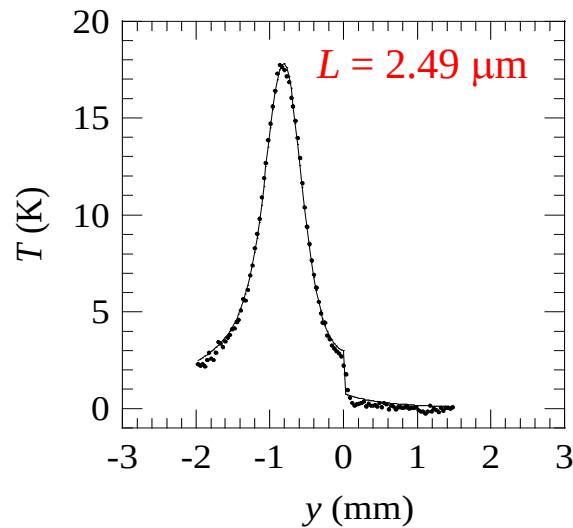
2.3 Experimental results

AISI-304

$L = 2.5 \mu\text{m}$

$L_{\text{lock-in}} = 2.72 \mu\text{m}$

$v = 3.5 \text{ mm/s}$

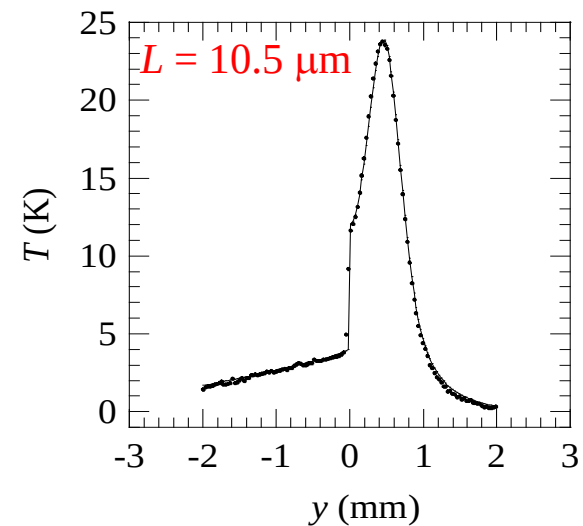
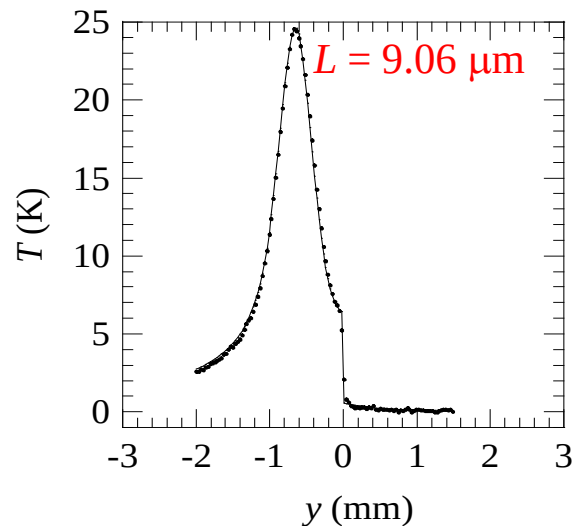


AISI-304

$L = 10 \mu\text{m}$

$L_{\text{lock-in}} = 10.5 \mu\text{m}$

$v = 3.5 \text{ mm/s}$



Spectro Imagerie Terahertz

De la source aux applications



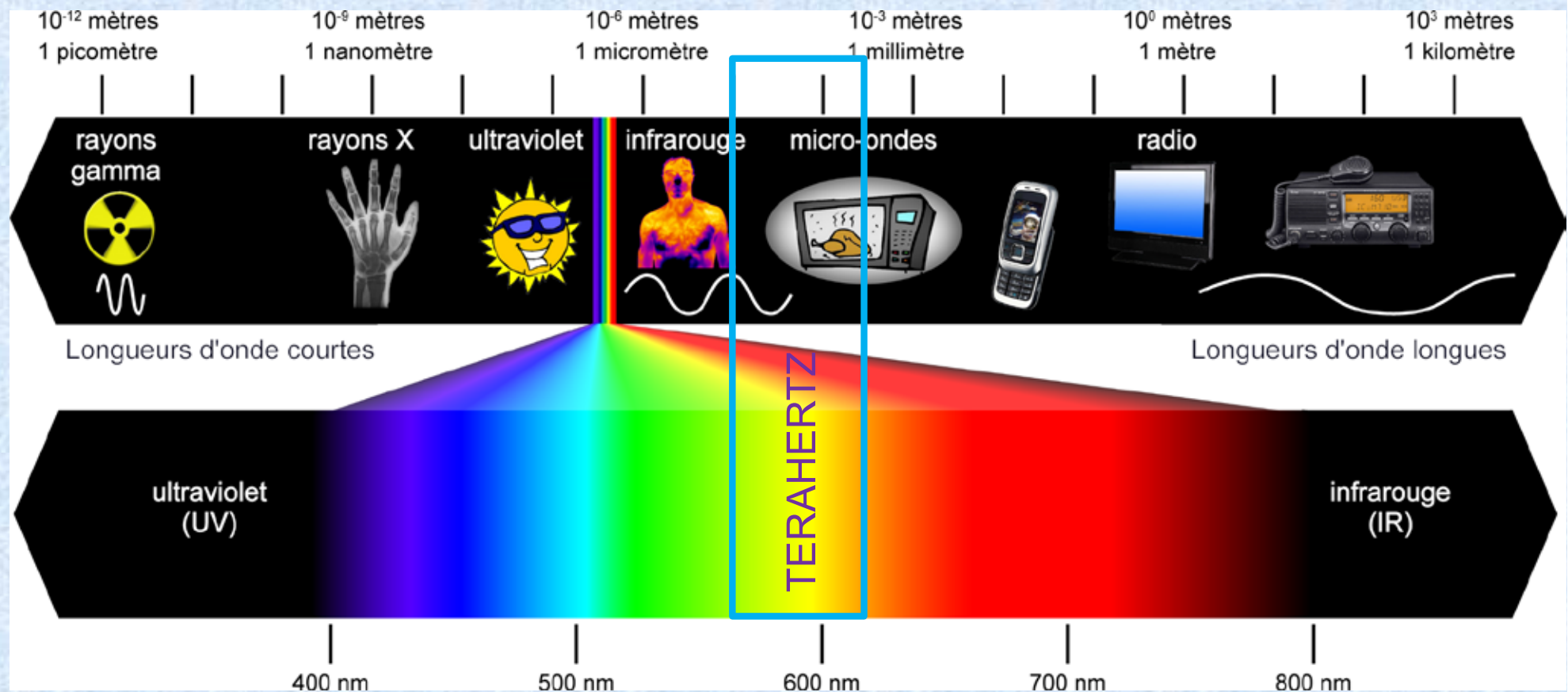
Patrick Mounaix

Laboratoire IMS- UMR 5218 CNRS, Université Bordeaux, 33405, FRANCE

Plan

- ✓ Contexte and Technique
- ✓ Génération & détection : Electronic versus optique
- ✓ La spectroscopie THz
- ✓ L'imagerie THz : Active et passive
- ✓ Exemples
- ✓ Conclusion

Présentation



- Rayonnement non ionisant , pas destructif , imagerie sans contact
- Transparence de nombreux matériaux, forte interaction avec les molécules polaires
- Substances présentant des spectres d'absorption uniques
- Imagerie multispectrale

Freq. 0.1-10 THz, Longueur d'onde 0.03-3 mm; Energie 0.4-40 meV

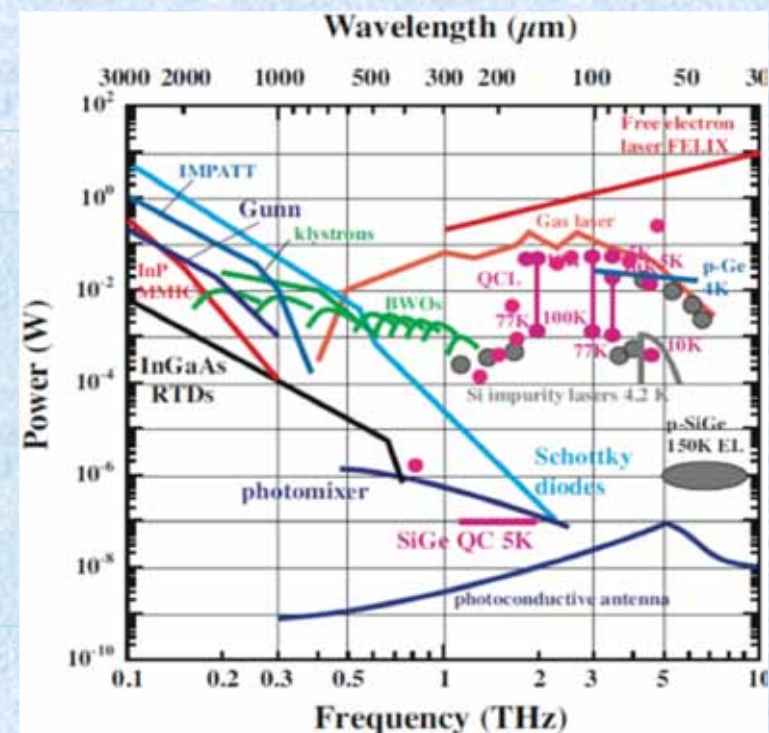
Terahertz : one word for several technologies

Sources

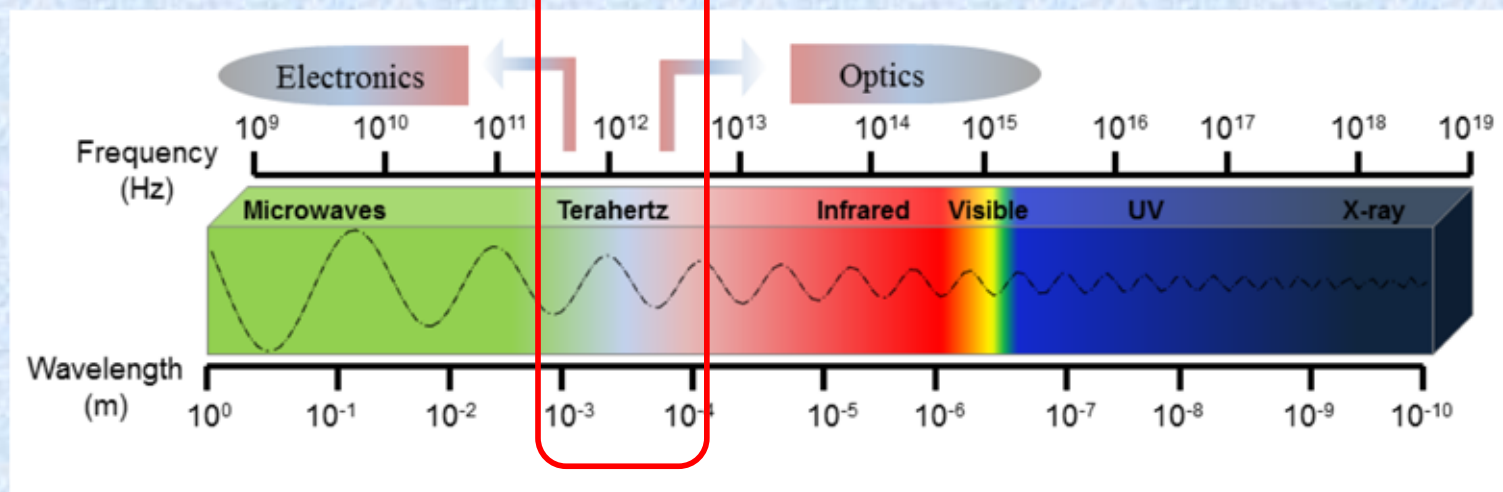
Oscillator
Optically
Laser
Wave
Quantum
THz
plasma
sources
Air
Time domain
Backward
propagating

Detectors

Golay
Bolometer
Photoconductive
Pyroelectric
Heterodyne
Schottky
HEMT



Terahertz gap



Famille de detecteurs THz

Single-pixel THz detectors



He-cooled bolometer



Golay cell

Pyroelectric detectors

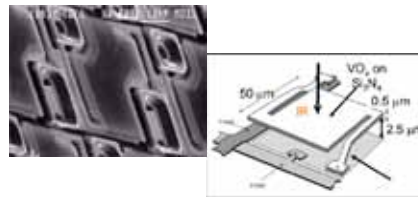


Schottky diodes



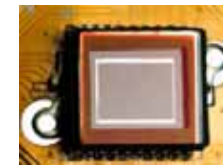
THz detector arrays

Spiricon Pyrocam

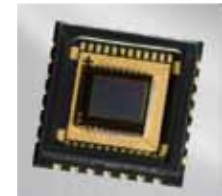


Microbolometer array

IR and visual imaging sensors



CCD chip



CMOS chip



NEC



Devices are typically

- Bulky
- High maintenance costs
- Expensive fabrication

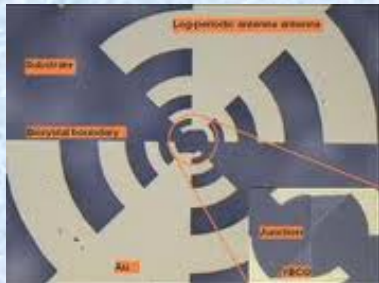
Specialized process technology

- Expensive
- Low volume
- Low integration levels

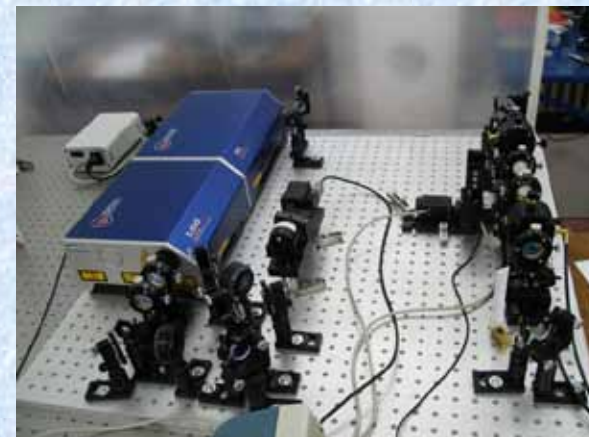
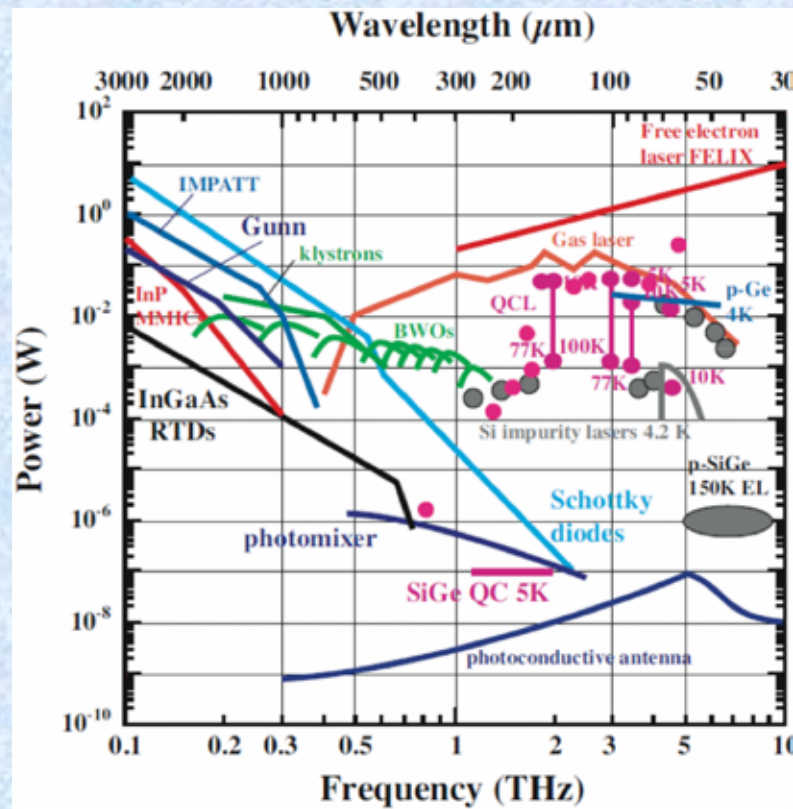
Based on silicon technology

- Low costs at high volumes
- High level of integration
- Applicability to THz electronics?

Variétés des sources Terahertz



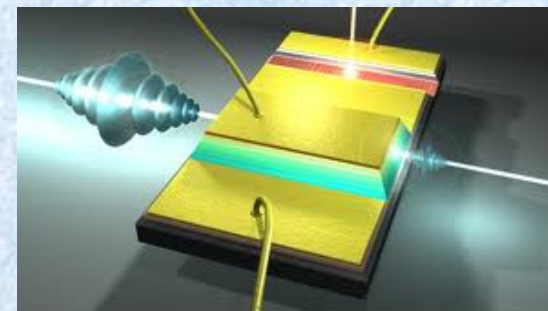
Composants ultrarapides



Laser Fs+ SC



Sources électroniques



QCL



Applications

Automotive Paint



Mobile Electronics



Food Safety



Cancer Detection



Clean Energy



Drug Development



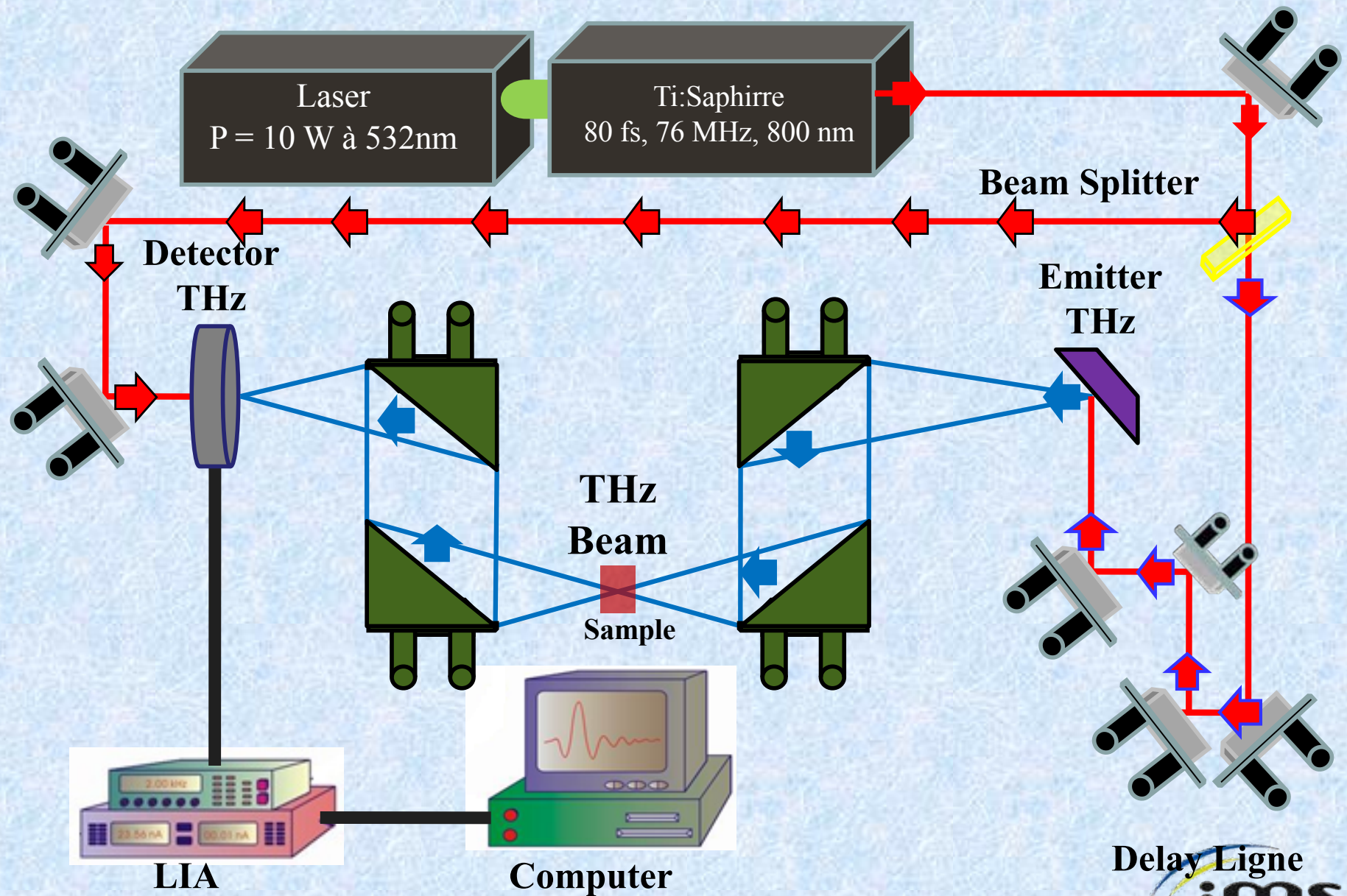
Security



Transportation
Security
Administration

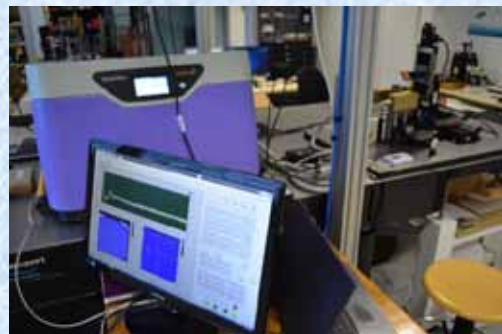


Spectromètre térahertz



Experiment

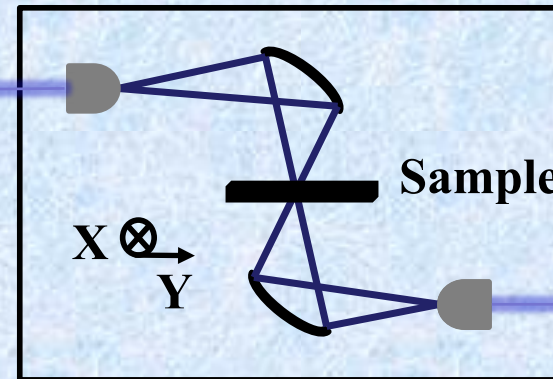
TPS spectra 3000 (Teraview)



TPS spectra 4000

Femtosecond
laser

Purged chamber

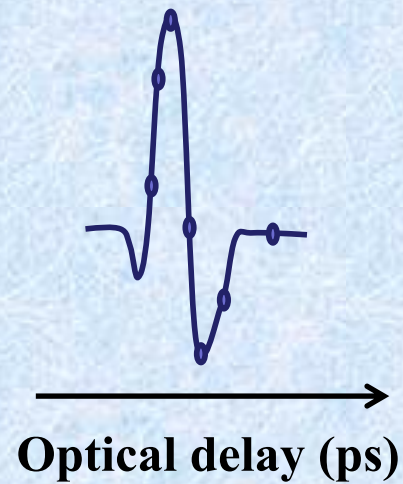


Lab

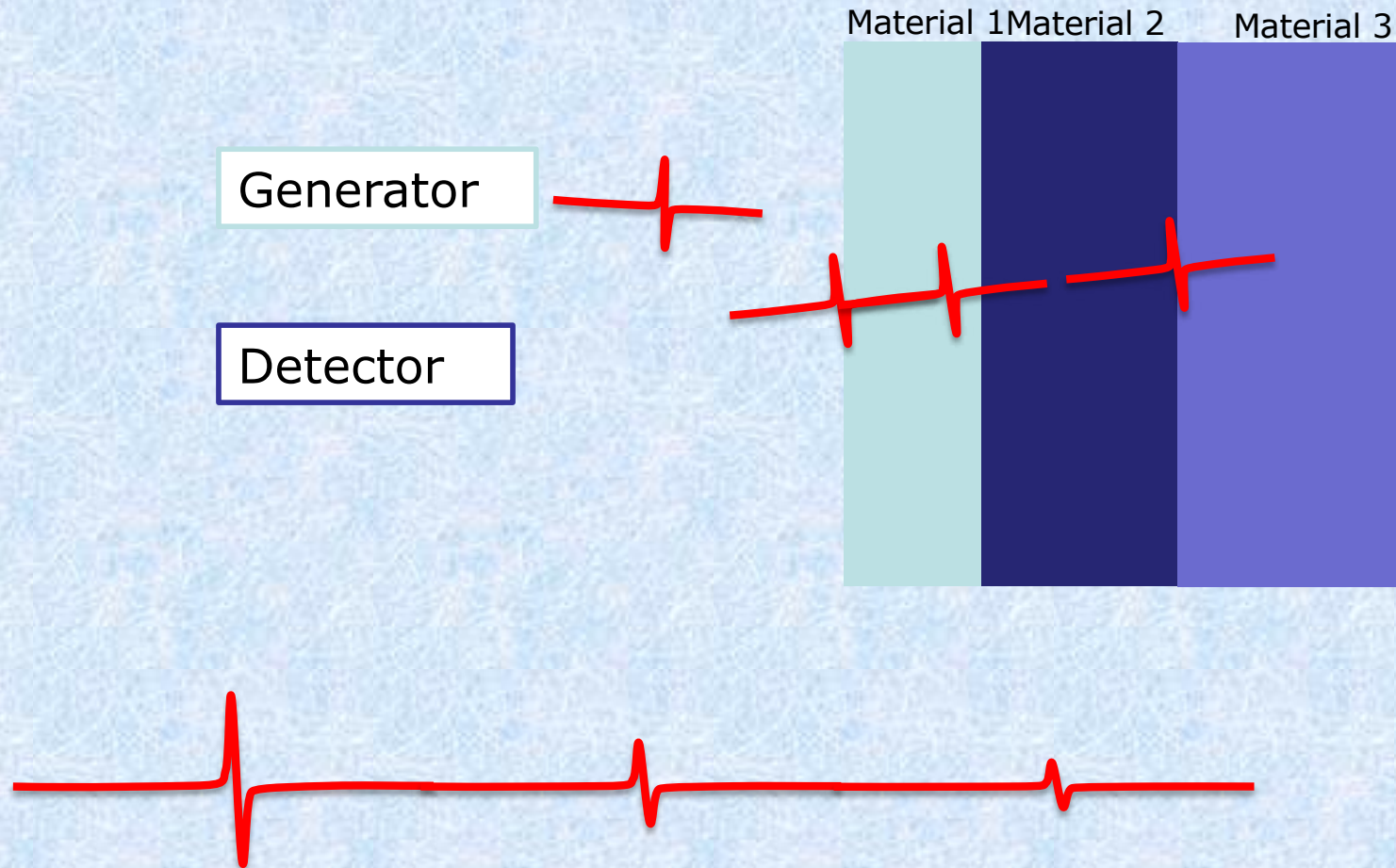
Hospital



Optical
delay



Time domain systems applications



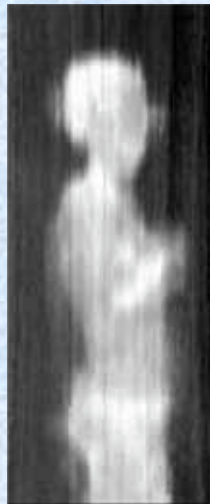
Imaging by millimeter 2D and 3D imaging

Passive

Millicam MC2



- 8 receiver array
- Frequency: 90 GHz
- Mechanical scanning
- Scan time: few sec
- Image size: 2x1 m² at 2.5 m distance



Continuous Wave (CW)



- Sources: Gunn diode
84 GHz, 50 mW
287 GHz, 14 mW
- Detectors: Schottky diode
- Lock-in detection
- Transmission
- Module
- (X, Y, Θ)

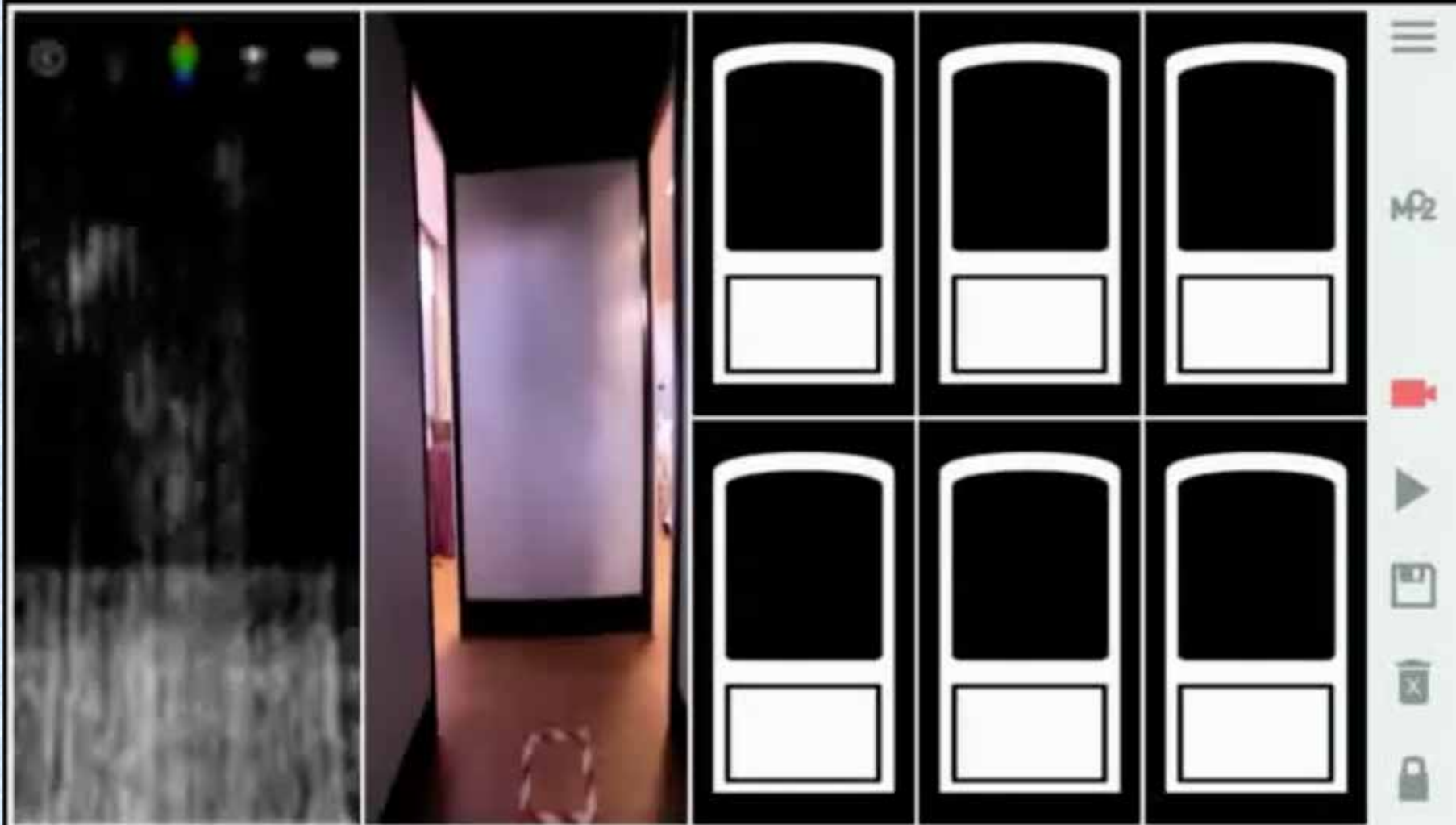
Frequency modulated CW



- Frequency range
Head 100: [60 - 110] GHz
Head 300: [230 - 320] GHz
- Transmission & reflection
- Module & phase
- (X, Y, Θ)

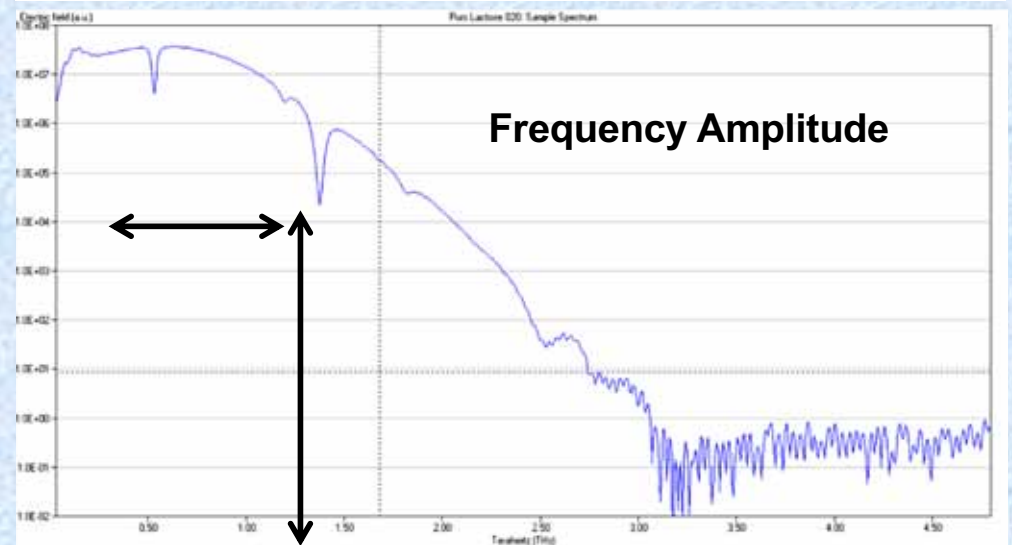
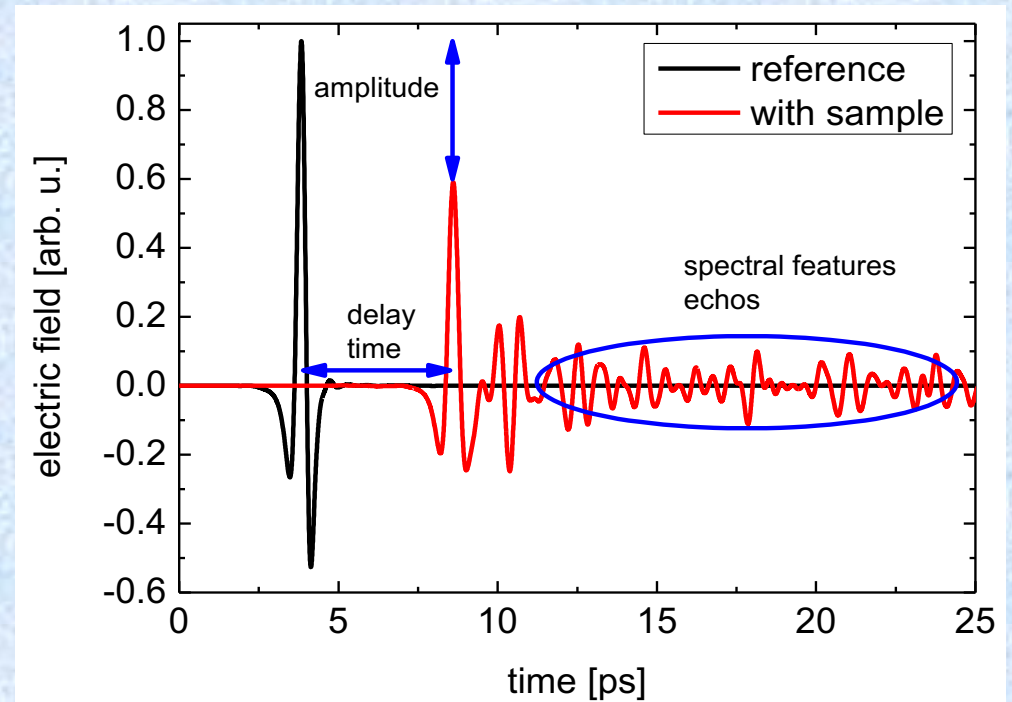
Synview



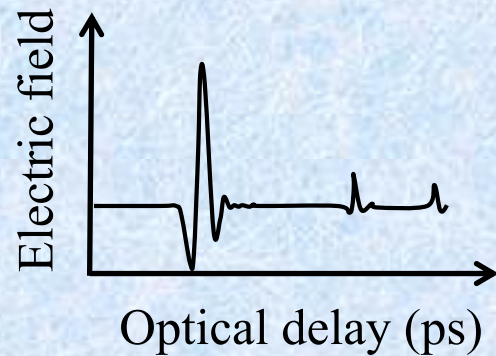


Potentiel d'analyses

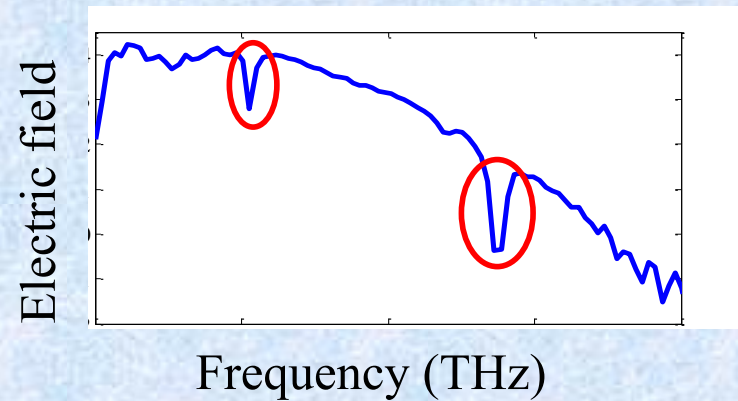
- Mesures de l'évolution de $E(t)$
- Détection cohérente : fort S/N
- Information sur :
 - Amplitude/intensité
 - Retard de phase
 - Analyse spectrale



Terahertz spectroscopy



Fast Fourier Transform



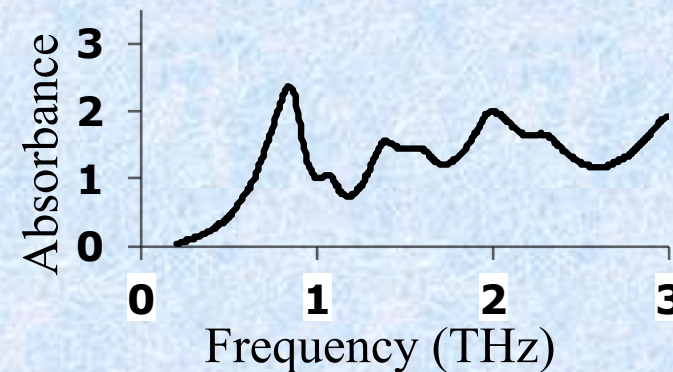
Amplitude
&
Phase

Optical properties

- Refractive index **n**
- Extinction coefficient **k**
- Absorption coefficient **α**

Transmission

$$\text{Absorbance} = -\log \left(\frac{E_{\text{sample}}}{E_{\text{reference}}} \right)$$



Bandwidth

0.1-4THz Transmission

0.1-2.5 THz Reflexion

Explosives analysis: Terahertz spectroscopy



Oxygen



Nitrogen

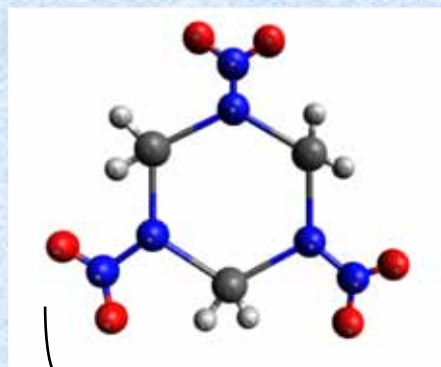


Carbon



Hydrogen

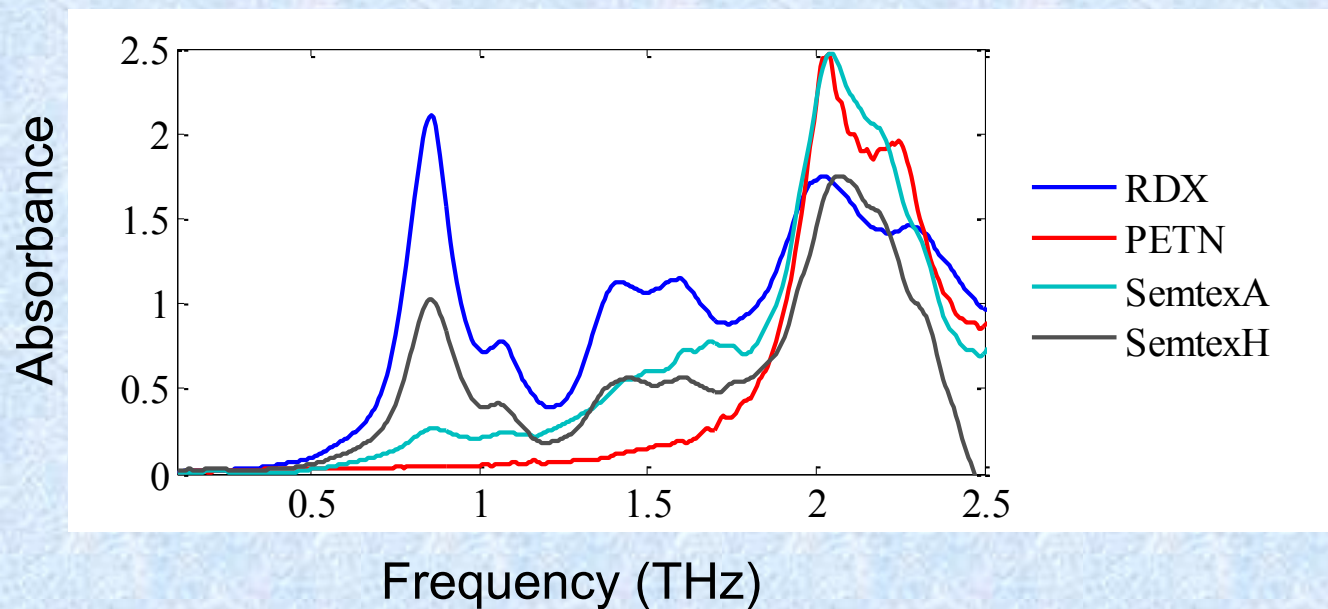
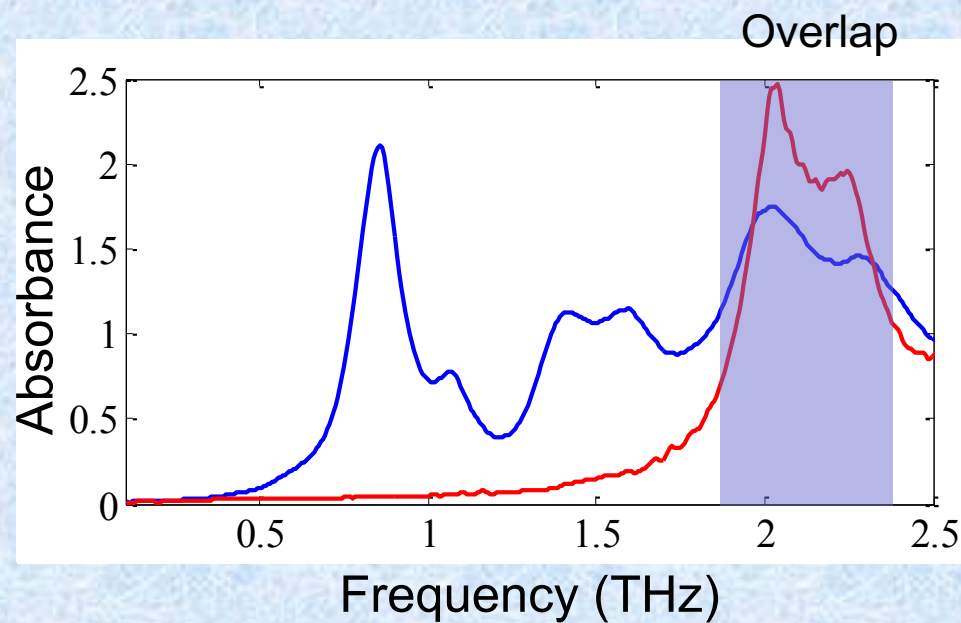
RDX



PETN



Semtex



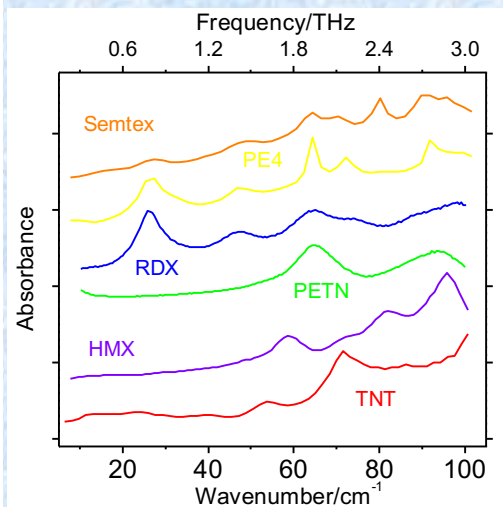
Analysis of
components in
mixtures



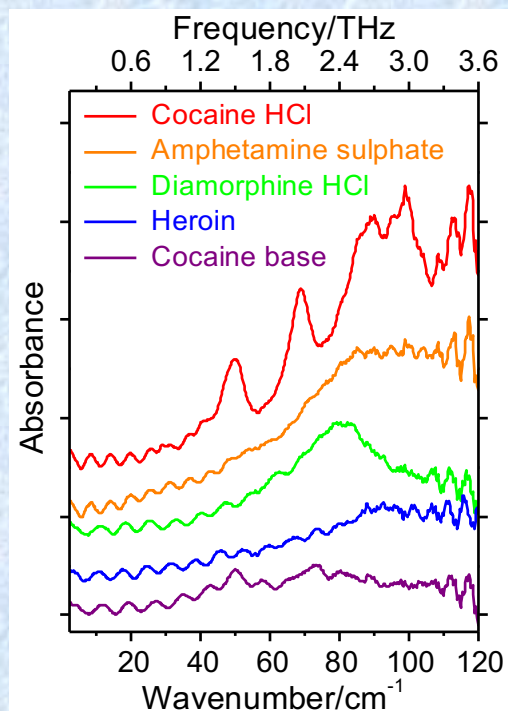
Need of chemometrics

Spectroscopic Analysis

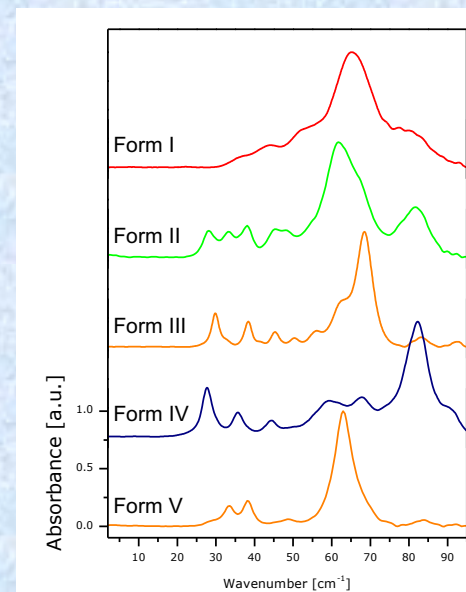
Explosives detection & analysis



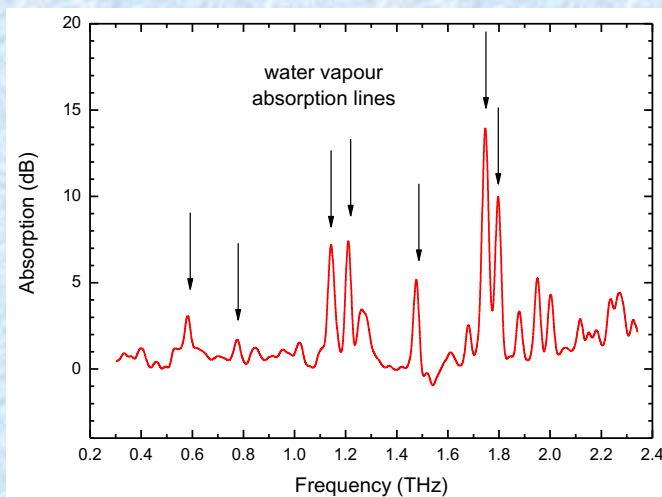
Illicit drugs



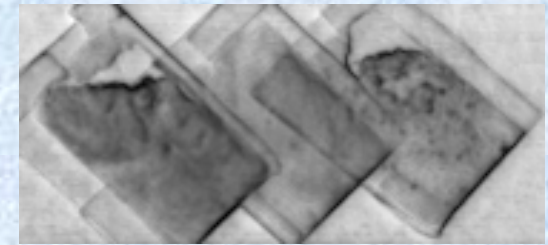
Pharmaceutical drugs: crystalline and amorphous



Airborne agents

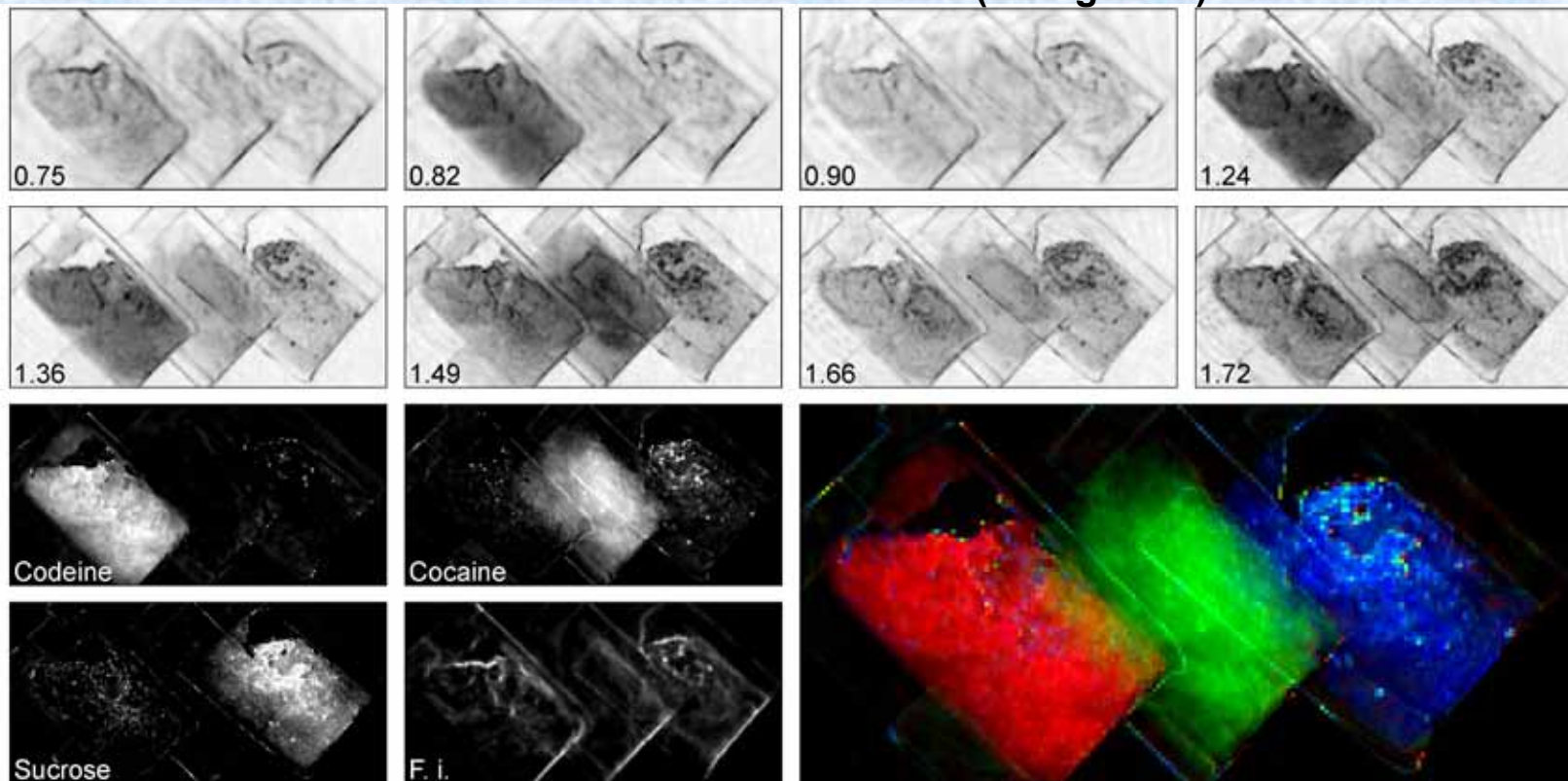


Spectro Imagerie de stupéfiants ou explosifs



Kawaze et al

codeine / cocaïne / sucrose (60 mg each)



Identification et affichage en fausses couleurs

Absorbance spectral images

Spectro imaging

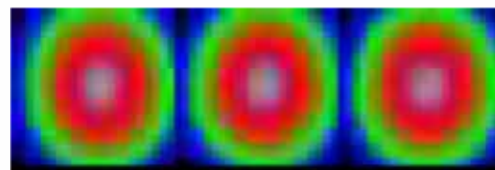
Explosives
mixed with PE
as binder

XY images at
different
frequencies

No difference between
the pellets signal

Different
signal for
each pellet

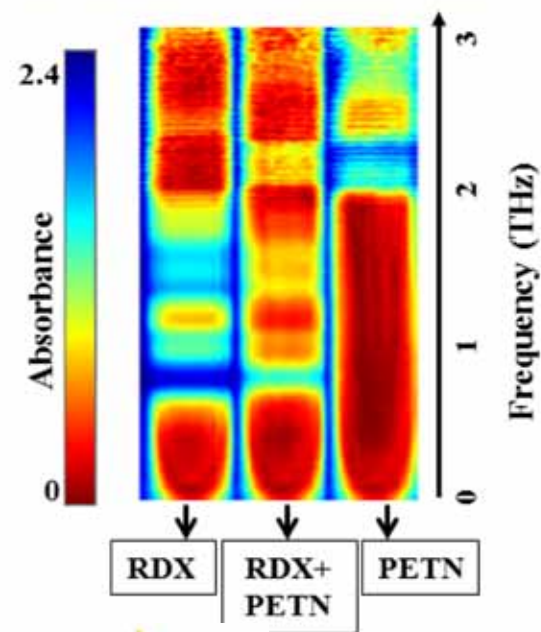
Frequency (THz)



(a)

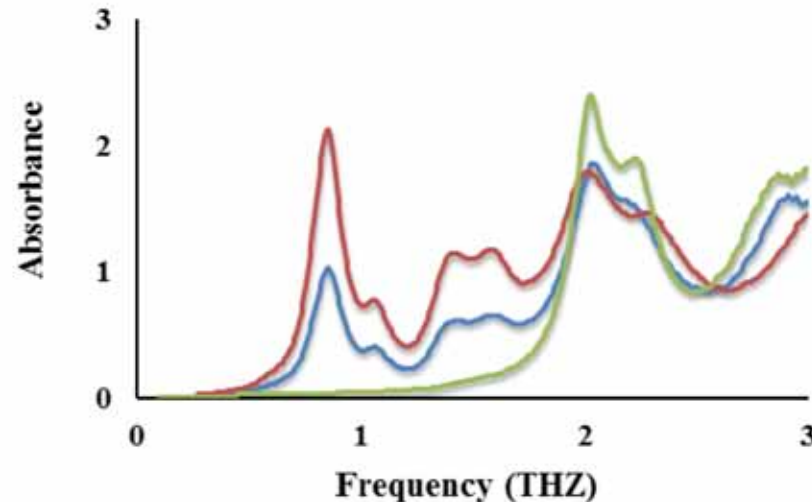


(b)



(c)

— 80 mg RDX/320 mg PE
— 40 mg RDX/40 mg PETN/320 mg PE
— 80 mg PETN/320 mg PE



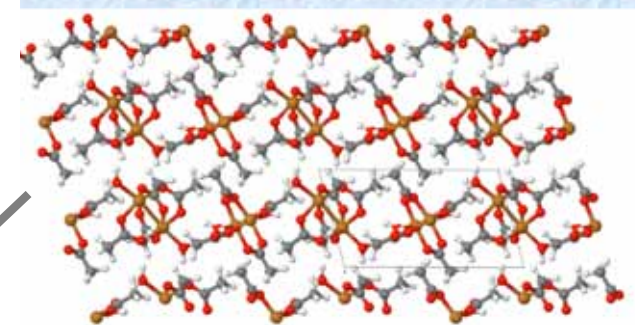
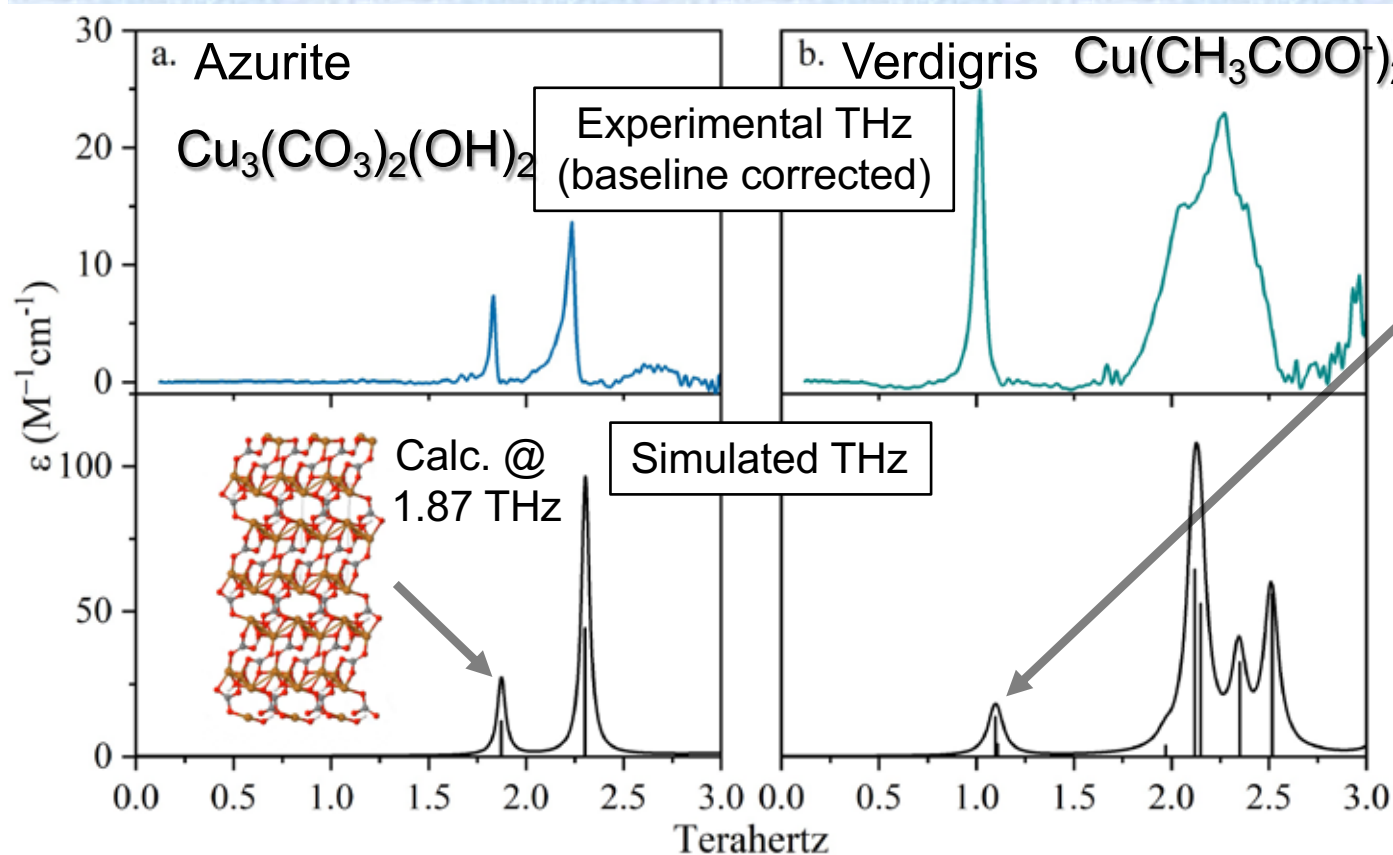
Need of automatic selector → XY
image of best contrast between
substances



Simulation of the Azurite & Verdigris THz Spectra

Optimized solid-state DFT structures are used for vibrational analyses and assignments of the normal modes of motion of the crystals.

Malachite (not shown)
has no *significant* IR-active modes predicted <3 THz, and matches experiment.

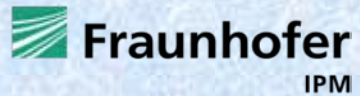


Calc. @ 1.09 THz

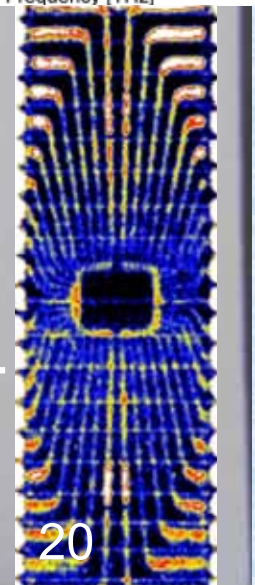
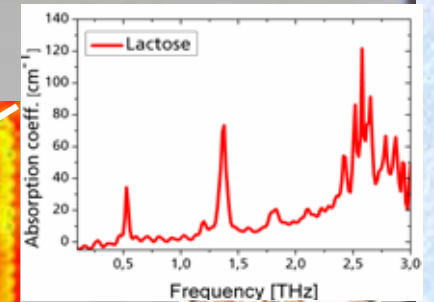
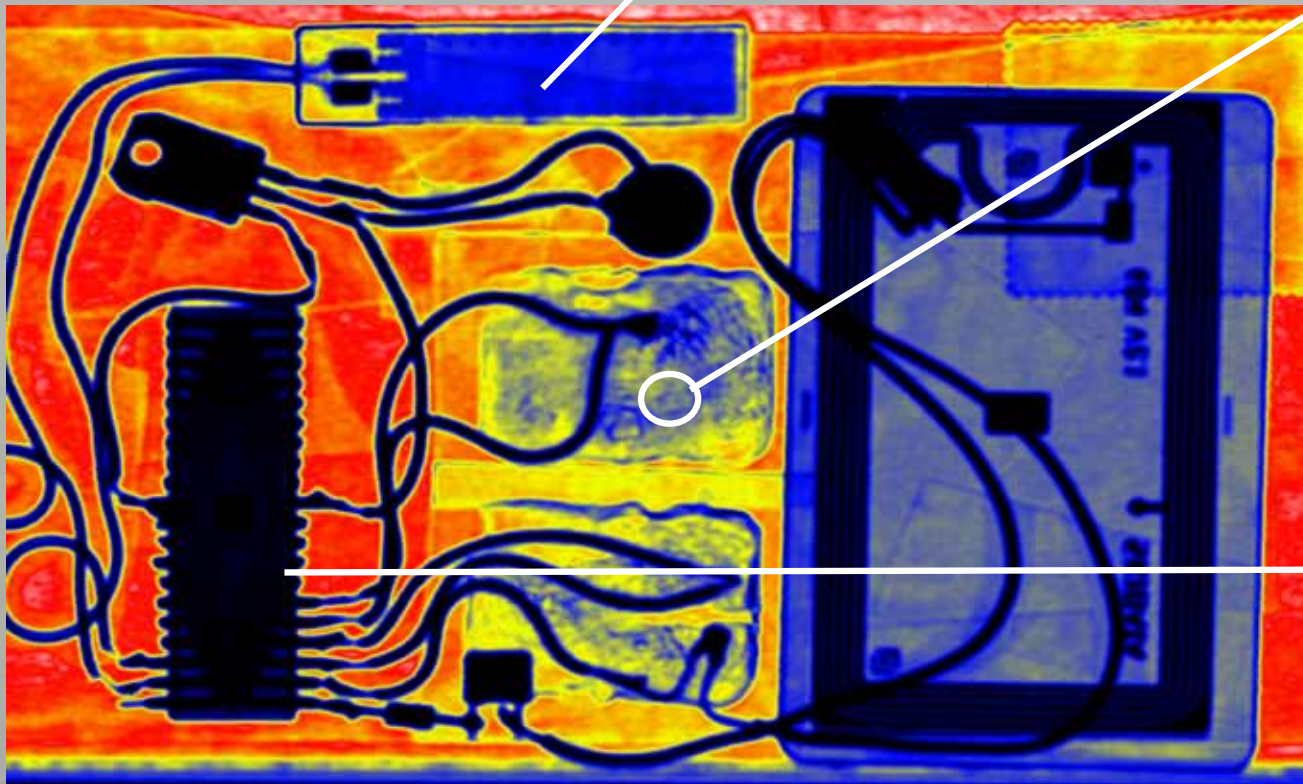
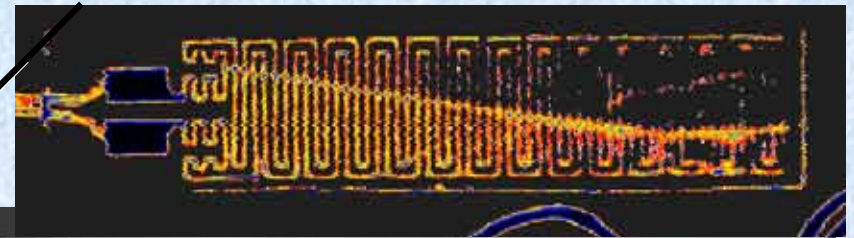
- ☒ Chemical Formula
- ☒ Solid Structure
- ☒ Terahertz Spectra
- ☐ Raman Spectra

Imaging and Identification d'objets cachés

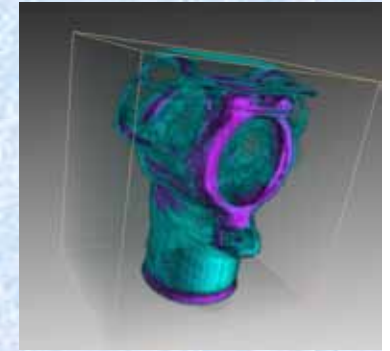
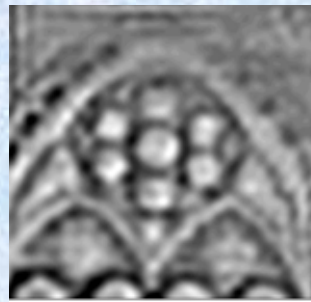
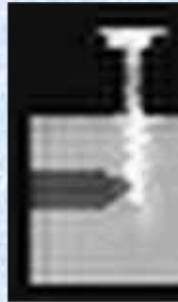
Mock-up letter bomb



R. Beigang et al

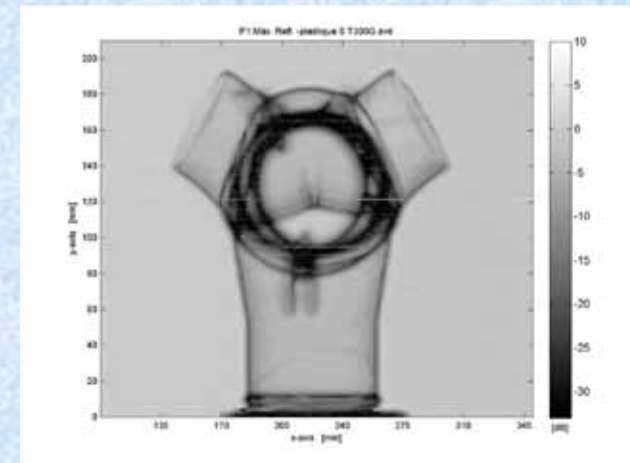
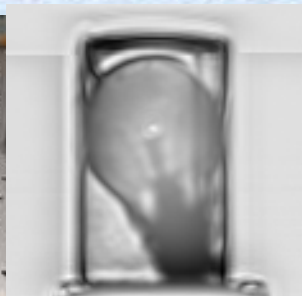


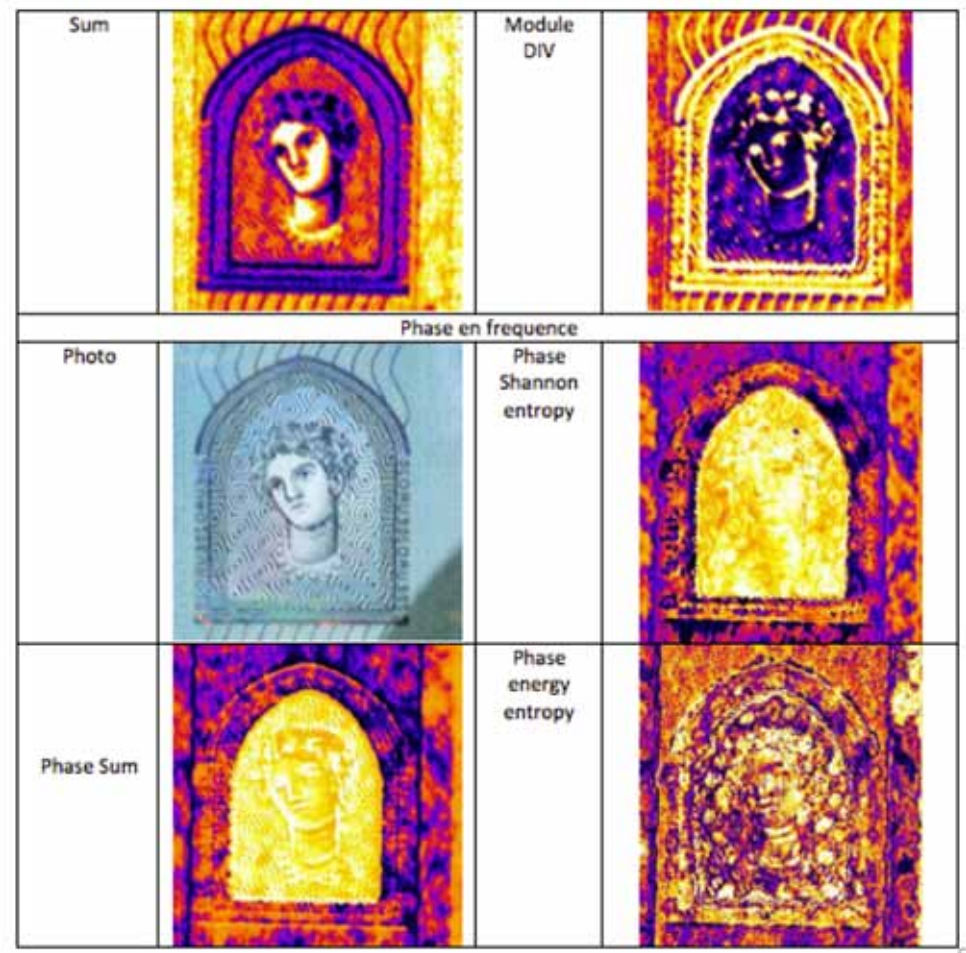
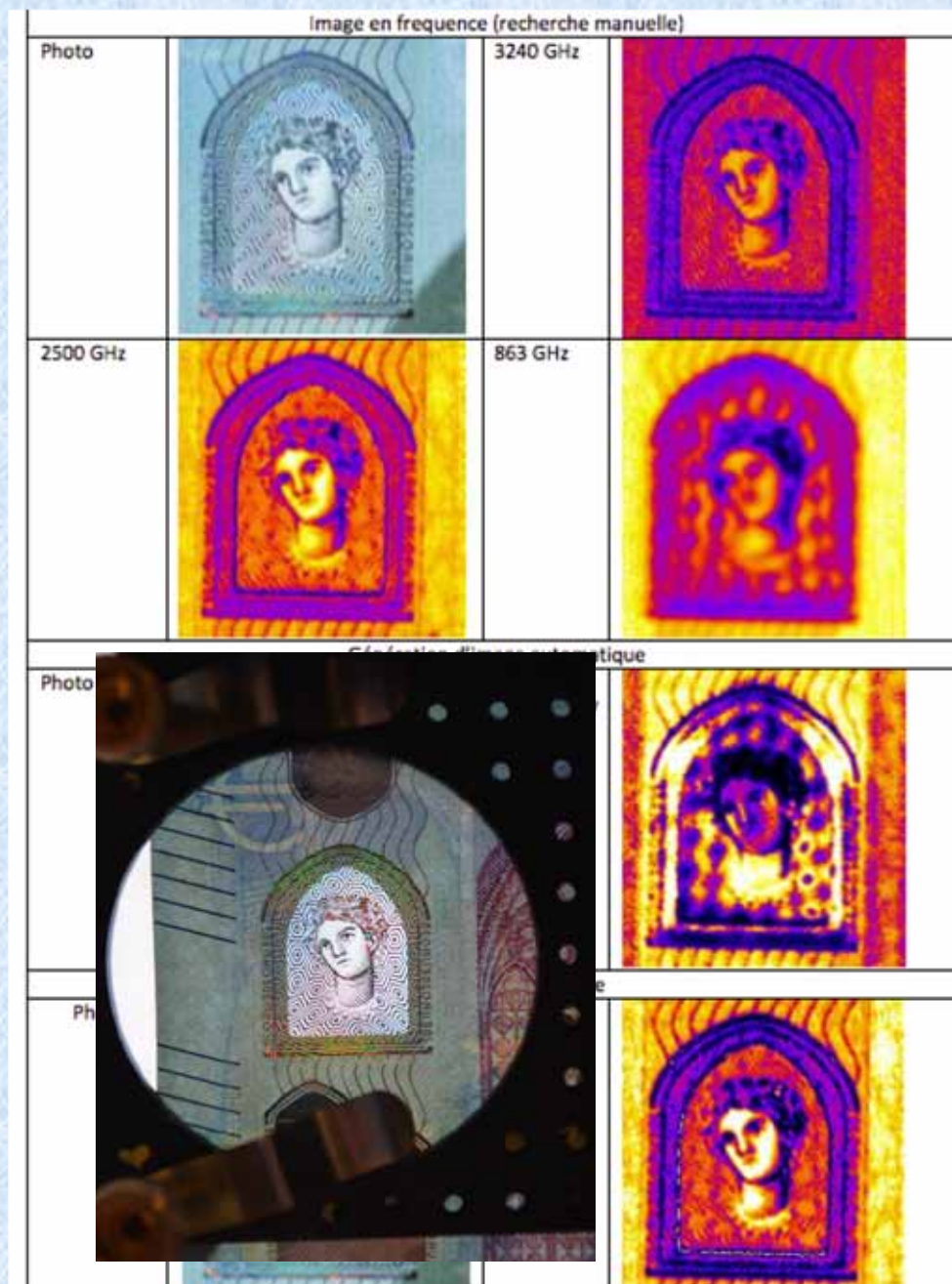
2D or 3D : Imaging /Tomography



Penetration

Resolution





MULTISPECTRAL IMAGING

How to see in 3D with terahertz?



Continuous waves imaging

- Monochromatic waves (One frequency for each emitter)
- Signal amplitude
- 2D projection at different angles
- 2D tomograph → 3D reconstruction
 - Radon Algorithms or iteratives
- 3D inner inspection

Frequency Modulated Continuous Wave

- Monochromatic waves but frequency change as function of time
- Frequency difference between emitted and received signal depends on time of flight
- 2.5D data
- Longitudinal resolution in same order than lateral

Time domain spectral imaging

- Polychromatic wave
- One temporal pulse → Fourier transform → spectrum
- 2.5D data
- Longitudinal resolution better than lateral
- Mask effect , knowlegde of $(n(w), e)$
- Chemical imaging

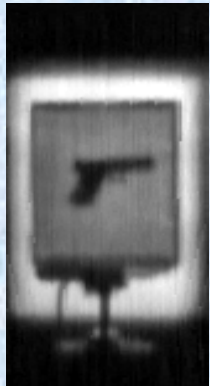
3D Terahertz imaging

+ Shape From Focus

millimeter 2D and 3D imaging

Passive

Metallic gun Metallic gun
& knife



Rotational
stage

Continuous Wave (CW)

Plastic Gun

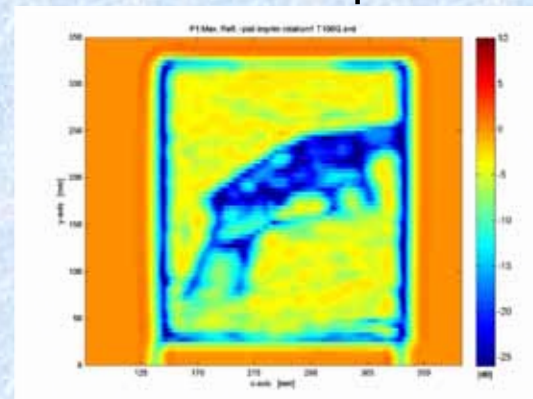
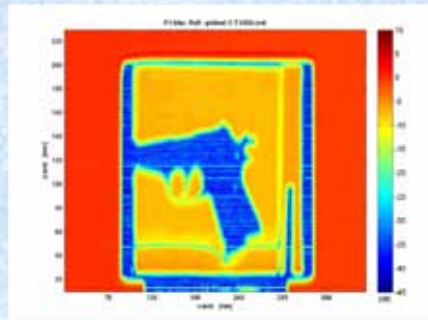


Transmission 100 GHz



Plastic Gun inside parcel

Metallic gun



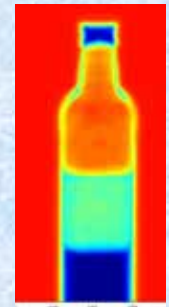
300 GHz reflection

Frequency modulated CW

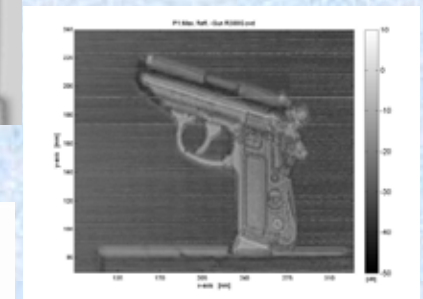
Sharpen
objects



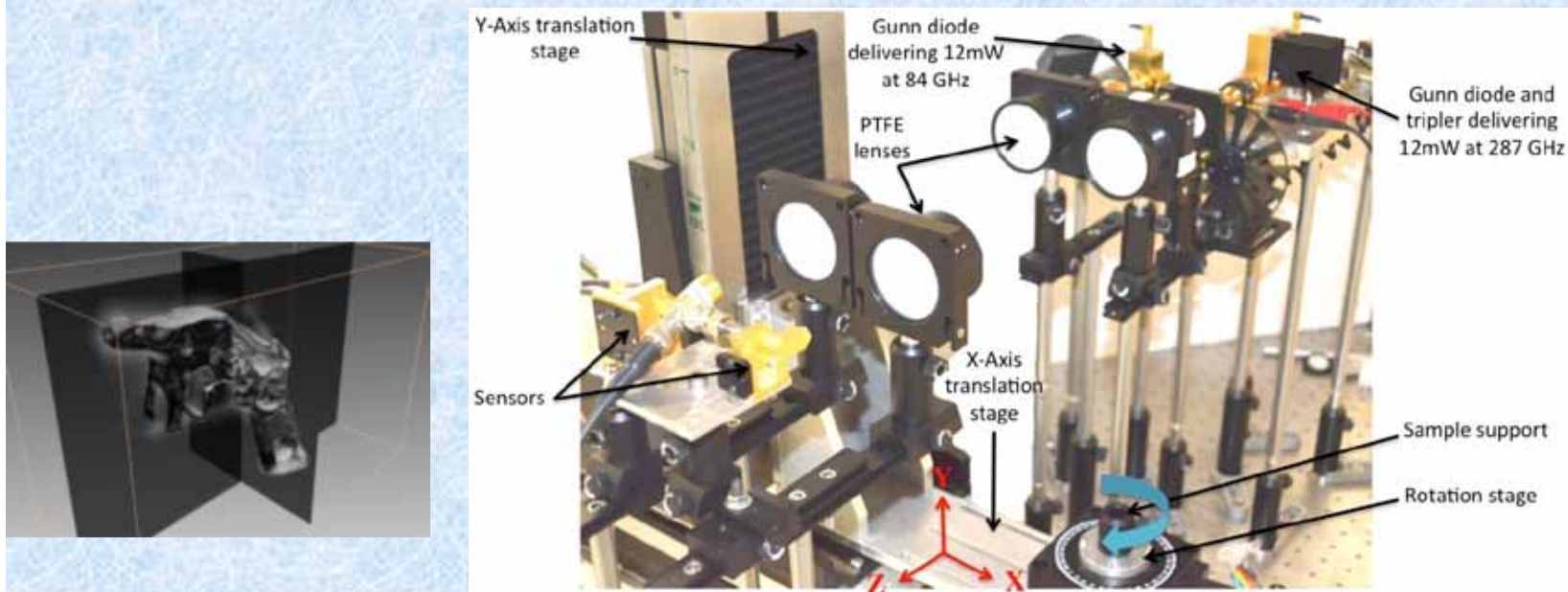
Liquide



Transmission
300 GHz



3D THz tomographic acquisition setup



Setup : Gunn diodes deliver subTHz beams at 84 GHz and 287 GHz, collimated and focused by a pair of PTFE lenses. Sample positioned on a (X,Y, θ) motorized stage.



Gun in resin
By 3D printer



100 GHz proj.



300 GHz proj.

Advanced Processing Sequence



Original object



THz acquisition



Reconstruction



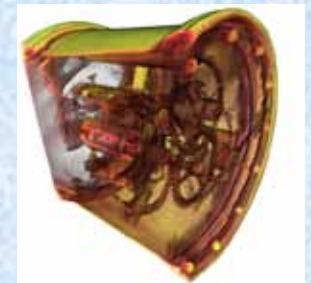
Segmentation



Labeling

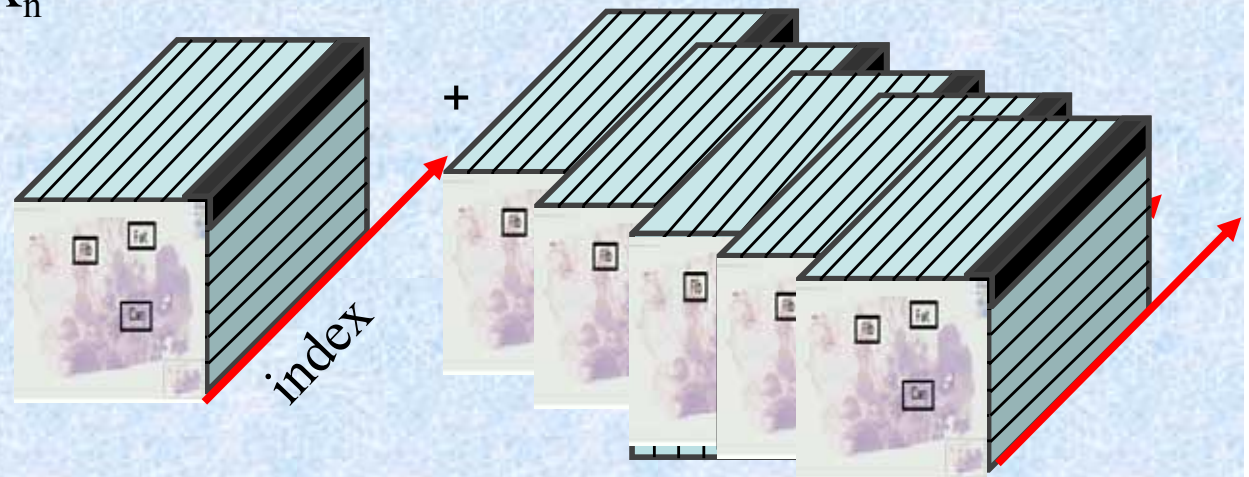
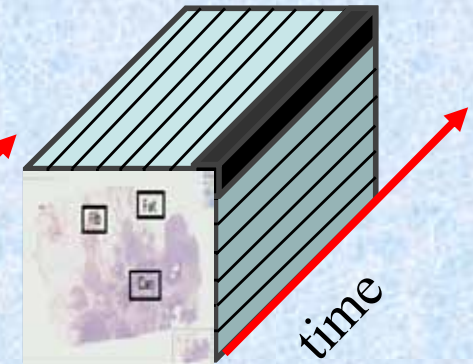
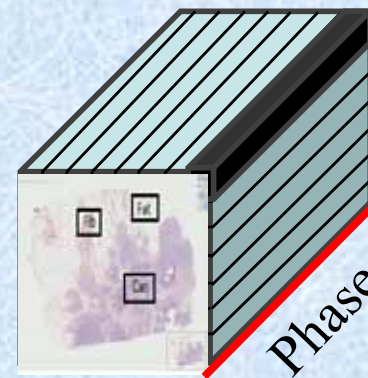
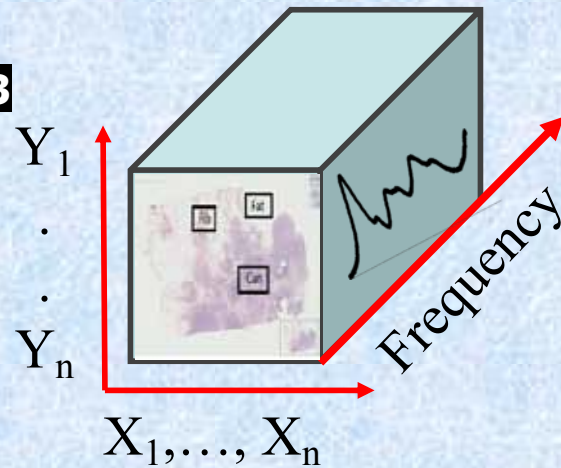
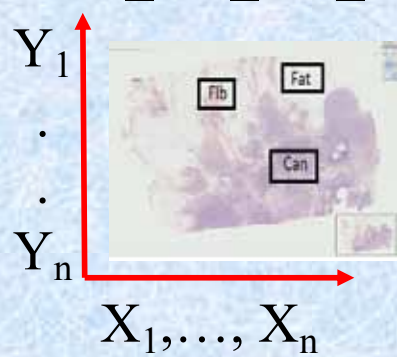
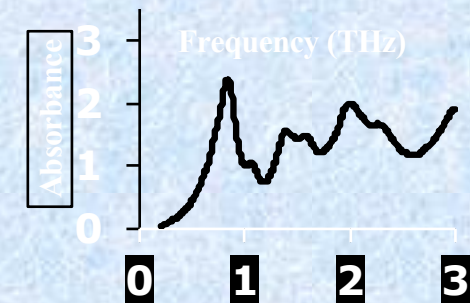


Surface & volume rendering



Analysis

Data: 3D : 100x100x2000 values

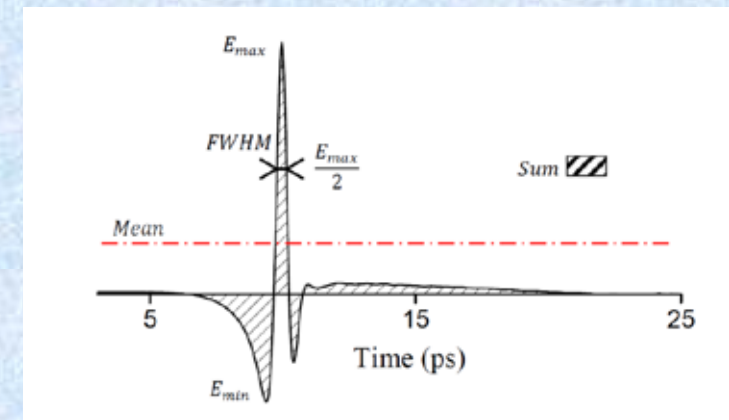


Transmittance , reflectance,.....;

Data processing for spectro imaging applications : time domain



$E_{\max}$, $E_{\min}$, $E_{\max}/E_{\min}$, $E_{\min}*E_{\max}$
Time of flight (max) , time of flight (min)
Peak to Peak , *Peak to Peak in time slice*
Time slice , diff time slice ,
Sum , *Optimal Sum Optimal difference*,
Average
derivative of time,
time delay of pulse maximum (artifact with absorption)
FWHM (min-max) (0-max) (0-min)
Relative pulse width (origin of pulse width ?)
Relative reduction of pulse maximum (unphysical)
Relative power loss (good SNR)
Spectrally weighted time delay (Shift of the center energy)
Shannon Entropy (compressive data)
Sure Entropy (compressive data)
Threshold entropy (compressive data)
PCA (compressive data)



T. Löffler, K. Siebert, S. Czasch, T. Bauer, and H. G. Roskos,
"Visualization and classification in biomedical terahertz pulsed imaging,
" *Physics in Medicine and Biology*, vol. 47, p. 3847, 200

Data processing for spectro imaging applications : Frequency domain



FFT Amp Best

Sum , *Optimal Sum*

Optimal, difference ,

Average

Time delay at fTHz

Relative power loss at fTHz (frequency dependance of losses)

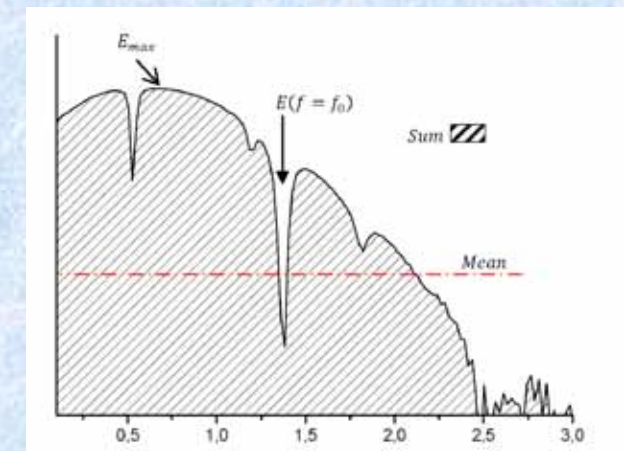
Module Shannon Entropy (dispersion sensitive)

Module Sure Entropy (compressive data)

Module Threshold entropy(compressive data)

PCA (compressive data)

Energy Entropy (compressive data)



$$T = \frac{\Phi_e^t}{\Phi_e^i},$$

$$R = \frac{\Phi_e^r}{\Phi_e^i},$$

$$A = \log_{10} \left(\frac{\Phi_e^i}{\Phi_e^t} \right) = -\log_{10} T,$$

Same Tools for FFT phase ,

Transmittance , T

Reflectance, R

Absorbance , A

Data processing for spectro imaging applications : TAG

Time domain imaging

From Left to right

Up to down

Time domain difference

Time domain div

Energy Entropy

FWHM

Max

Mean

Min

Multiplication

Relative Power loss

Relative pulse width

Reduction of pulse maximum

Time domain Shannon entropy

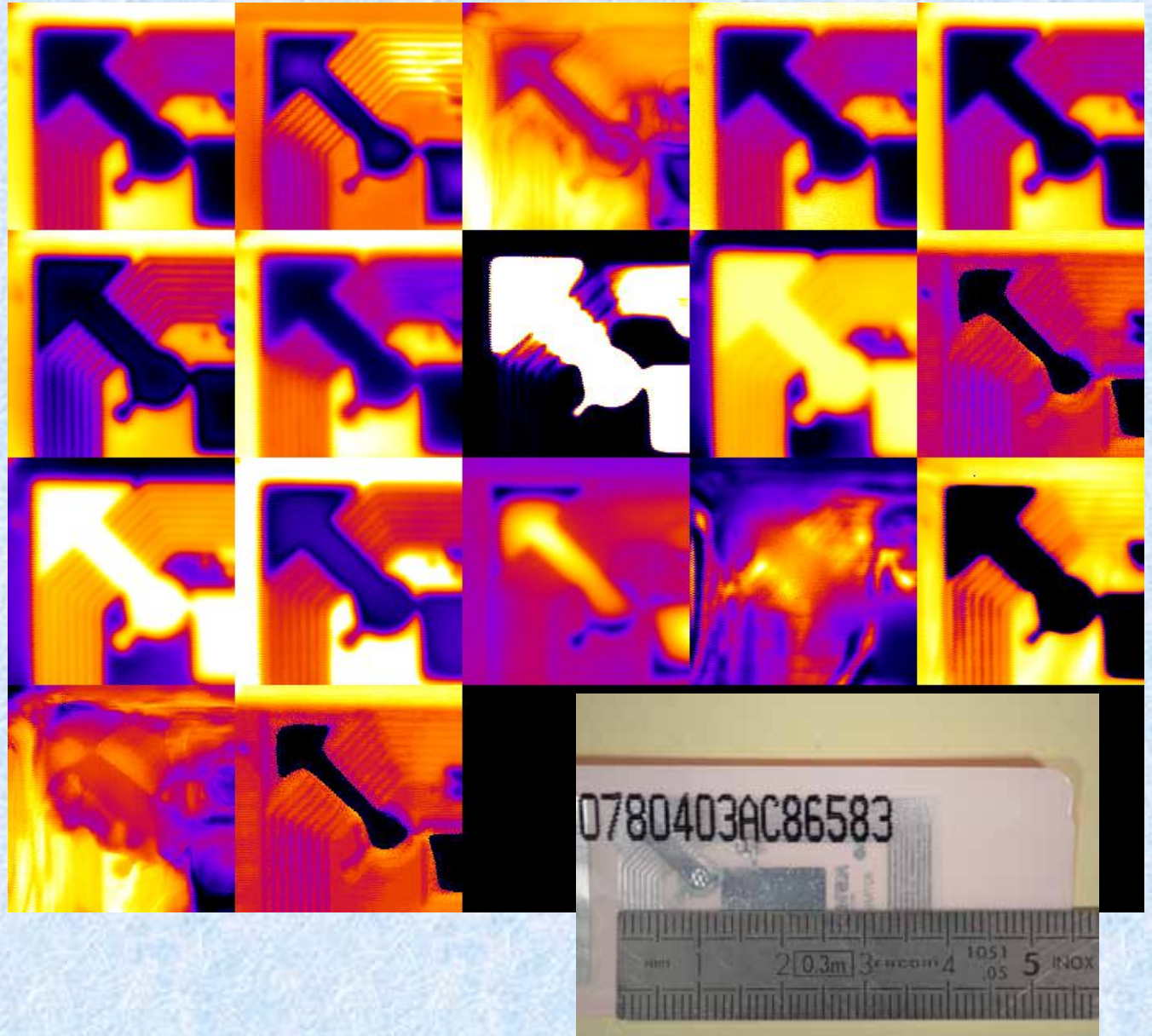
Spectrally weight time delay

Sum

Sure entropy

Threshold entropy

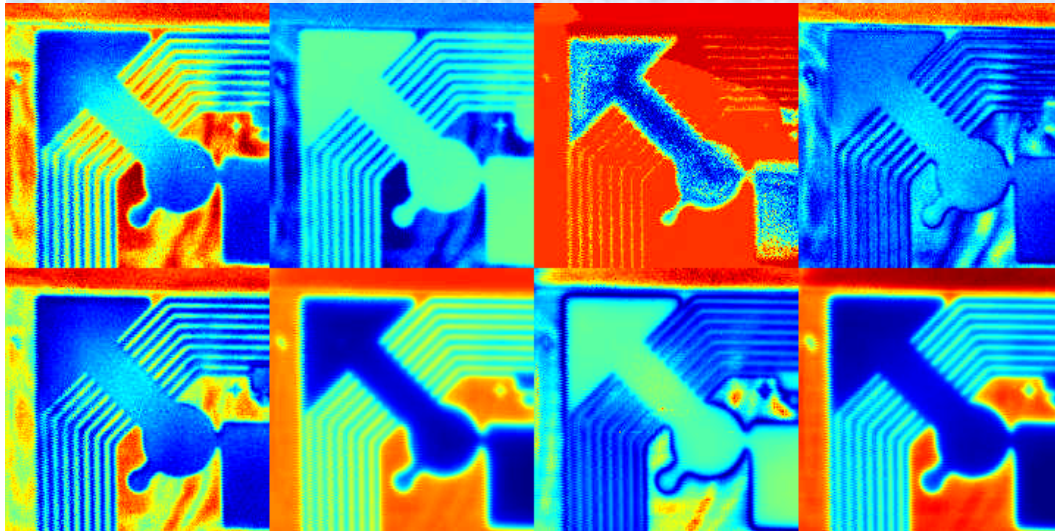
Time delay of pulse maximum



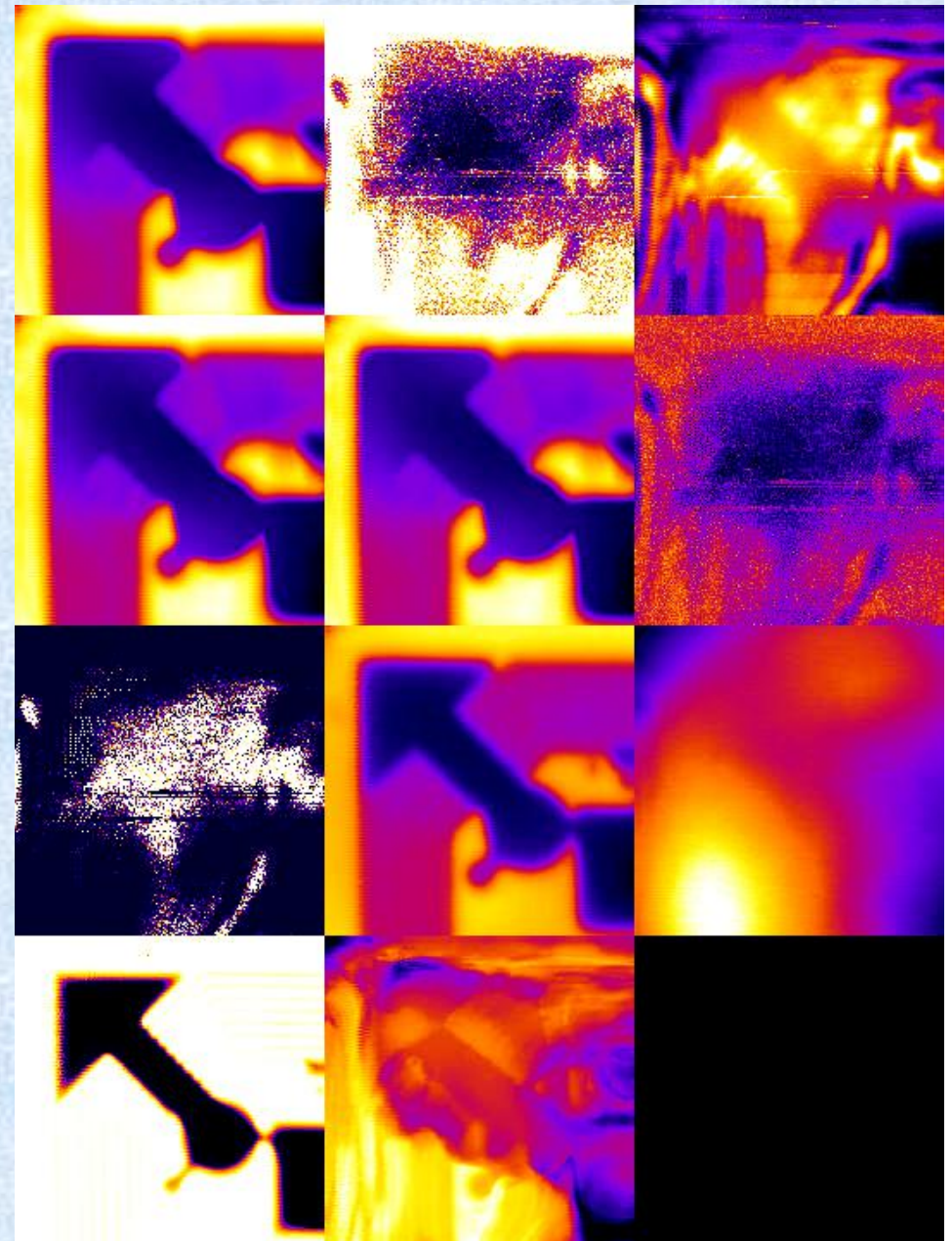
Data processing for spectro imaging applications : TAG

Frequency domain

difference
division
energy entropy
Max , mean, min
multiplication
Shannon entropy
sum
sure entropy
Threshold entropy

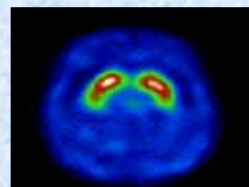
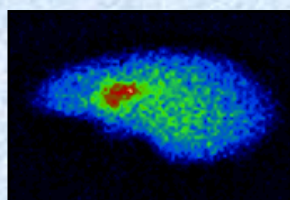


Best F, Best F relative loss, best F time delay , Freq
Transmittance, Energy, Shannon E , Best Sum F



Tomographie THz 3D

The Radon inverse transform



Reconstructed images
 $f(x,y)$

$p(u,\Theta)$

Fourier
Transform

$P(r,\Theta)$

Sinograms

Filtering

$|r| P(r,\Theta)$

inverse
Fourier transform

$p'(u, \Theta)$

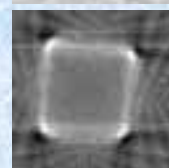
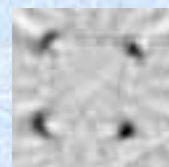
Back projection



Transparent plastic cell

Amplitude image

Delay image

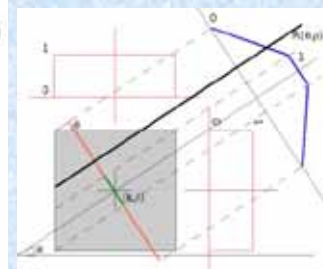
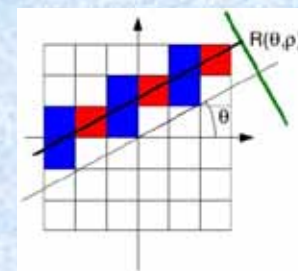


Advantages & drawbacks Experimental

Amplitude
Phase

} Images

Absorption and refraction
losses Numerical

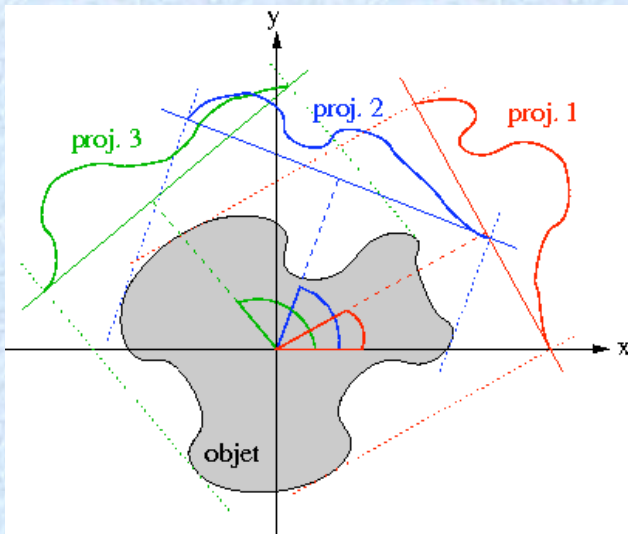


Trade off: complexity, precision
Time acquisition

For each pixel, the THz waveform as a function of time.
Final tomographic THz images can be obtained
maximum value of the THz amplitude signal (amplitude)
time delay : average of the different peaks (delay image).

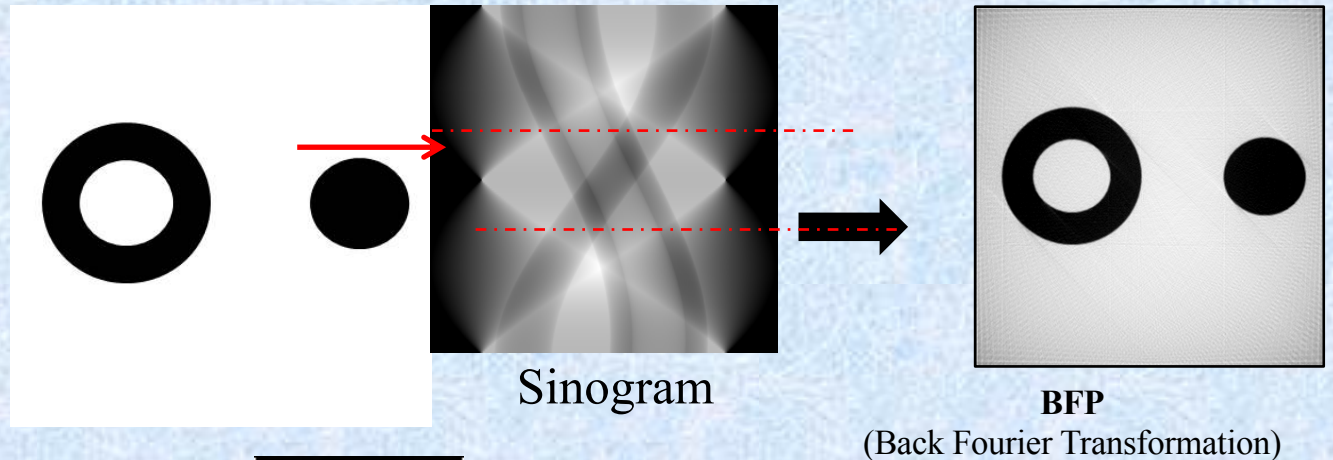
Computed tomography

Principle of computed tomography

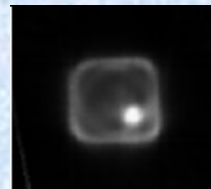


Radon's Theorem (1917)

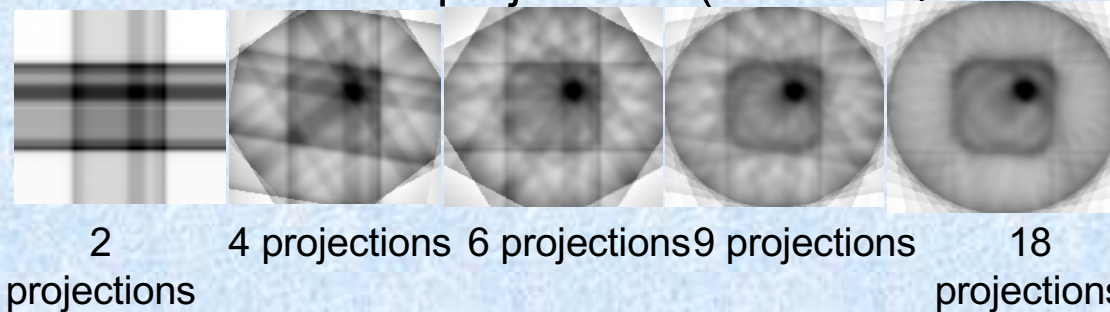
$$f(x,y) = \int_{\theta=0}^{2\pi} \int_{\rho=-\infty}^{+\infty} R(\theta,\rho) \delta(\rho - x \cos \theta - y \sin \theta) d\theta d\rho$$



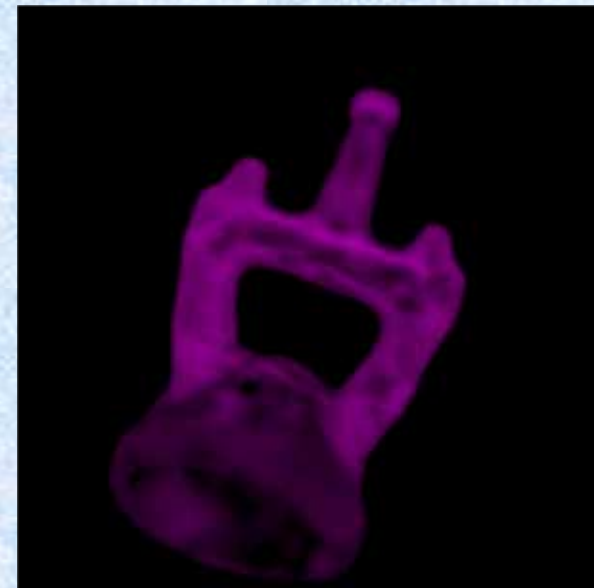
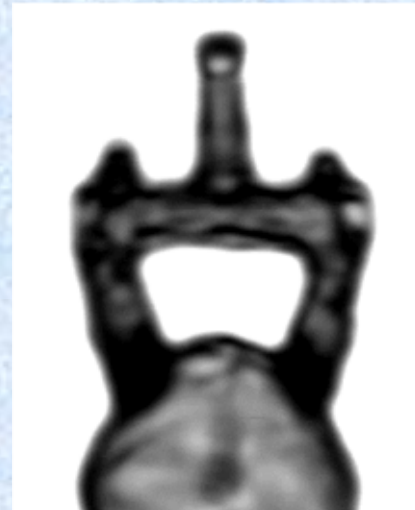
Foam cube/metallic bar metal



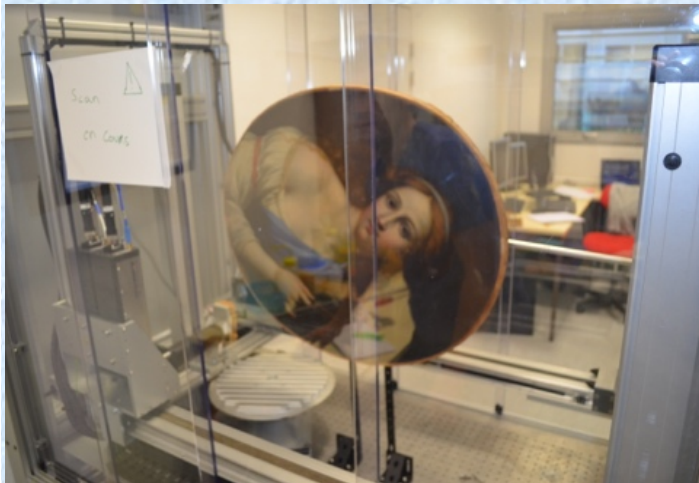
Number of projections (287 GHz)



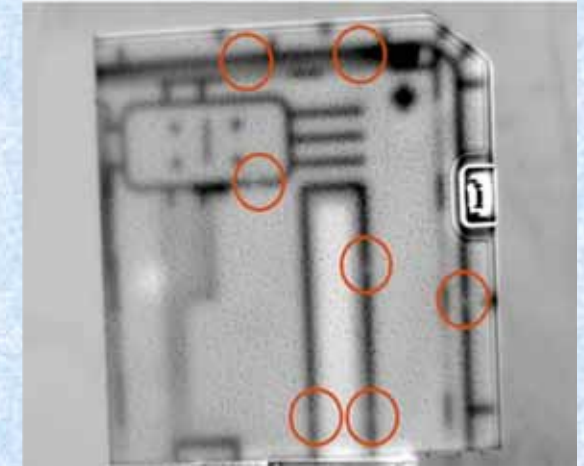
Imagerie en 3D : contrôle industriel



FMCW system

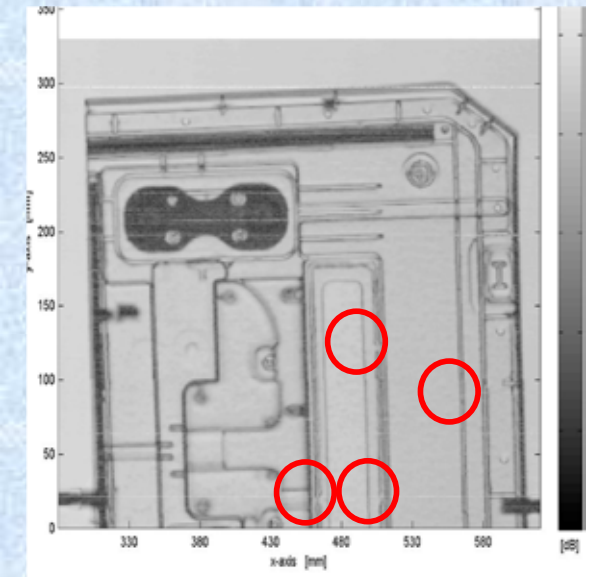


IR thermography



- Frequency modulated Continuous Wave system
- Transmission and reflection 100 GHz and 300 GHz
- Scan Area 600 × 800 mm
- Faster than TDS but resolution in the millimeter range
- Can give direct 2.5D images with frequency difference reconstruction

300 GHz FMCW

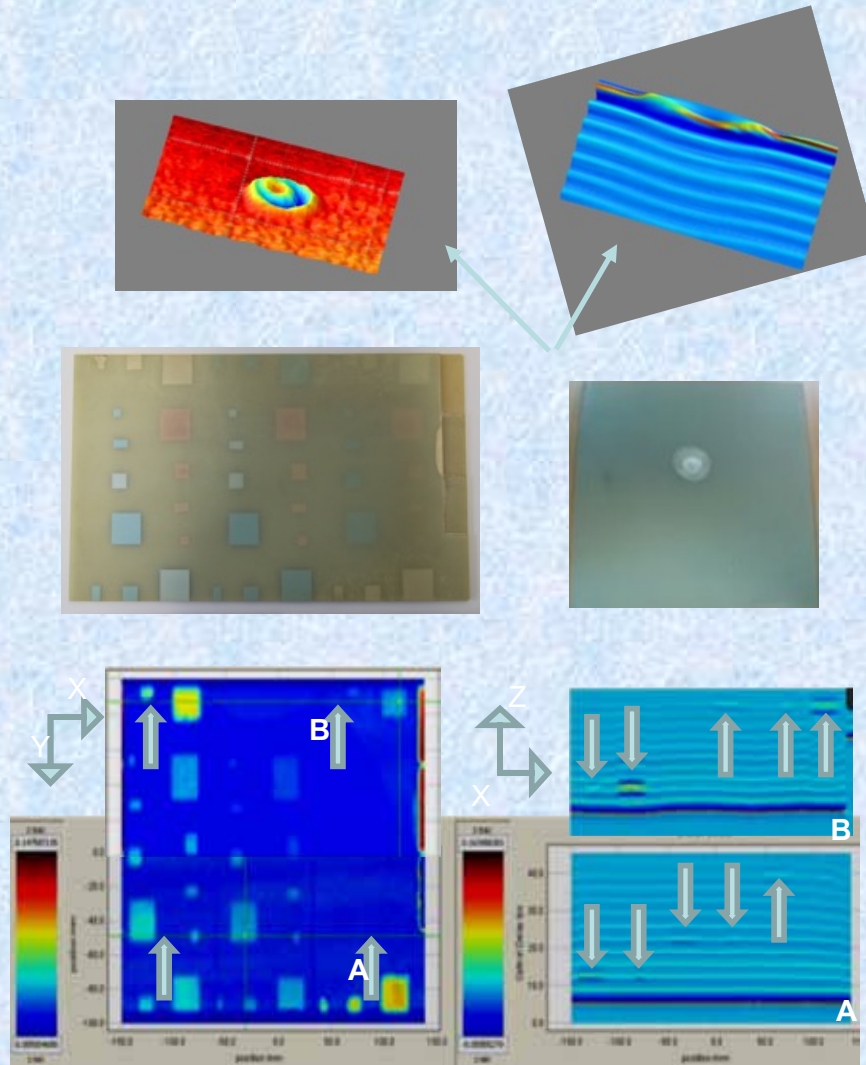


Automotive industry



Time of Flight system

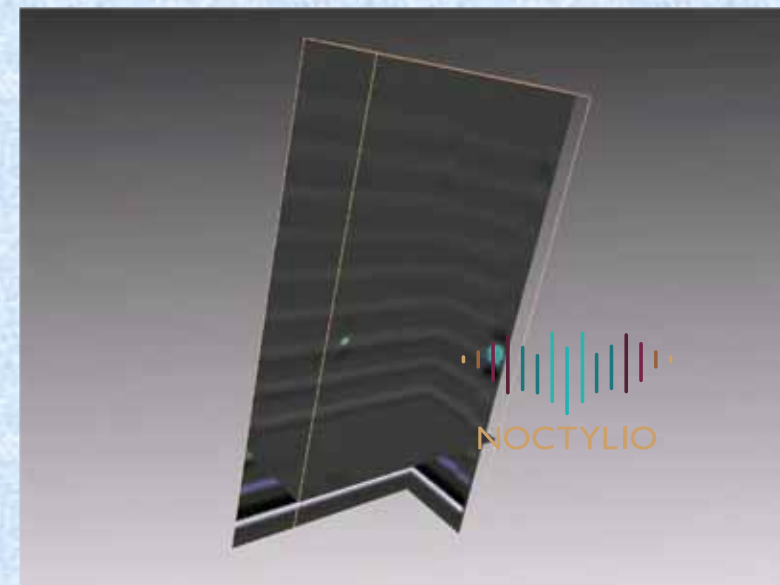
Glass Fiber Reinforced Plastic



defects localised en 3D

Defect localisation by TDS TOF

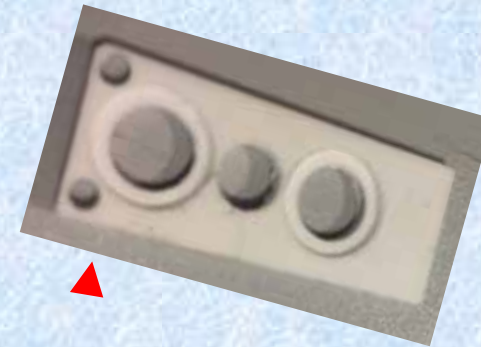
- Intentional defects for **calibration**
- Water inclusion
- Simulation of delaminations and debonding
- Impact damage



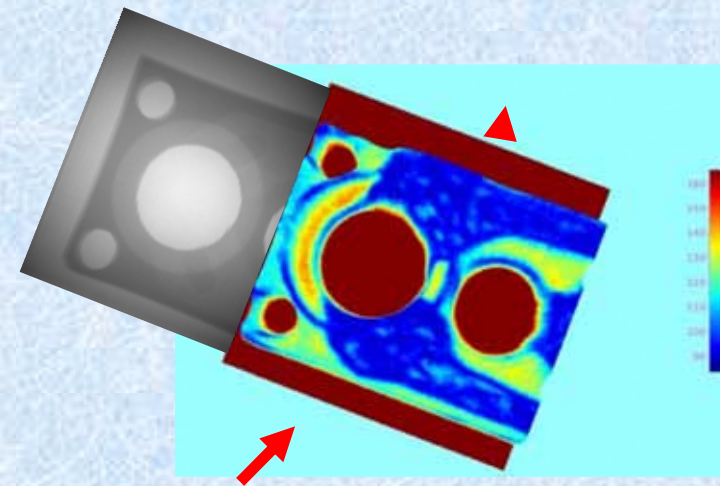
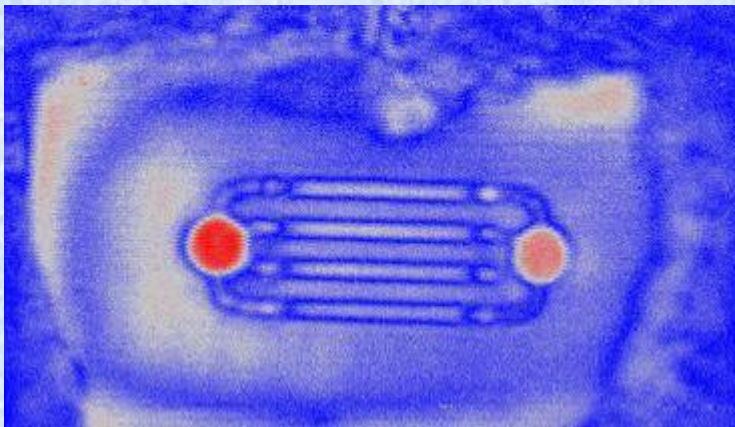
Time of Flight system



Detail of a zirconia piece with cavities



Ceramics



Micro Channels revealed and inspected



3D terahertz Real time Imaging

Real-time terahertz imaging systems

- ◆ Compact QCL laser @ 2.5 THz (3mW) cooled @ 44 K from Lytid society
- ◆ CEA-LETI uncooled micro-bolometer array based camera (320*240 pixels) from I2S society
- ◆ f/0.8 lens with a 200 mm working distance and 64*48 mm² object field of view
- ◆ Homogenizer to limit interferences effects due to the laser source coherency [4]



HDPE head
spray as sample



750 projections acquired
from 0 to 180 ° in 30s



Terahertz
tomography

3D Tomographic
reconstruction



Sectional view



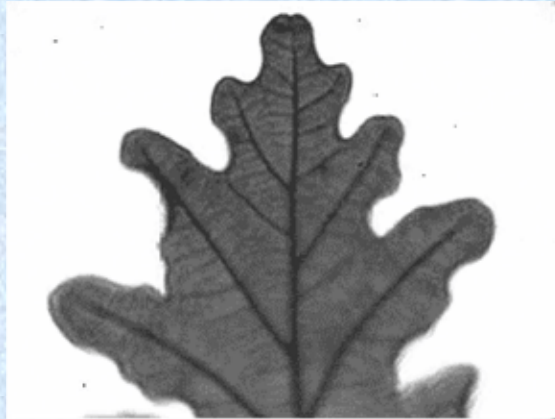
Terahertz computed tomography for 3D reconstruction

- ◆ With a terahertz adapted algorithm included in Noctylio software from Noctylab society
- ◆ High resolved reconstruction for « 3D type » objects

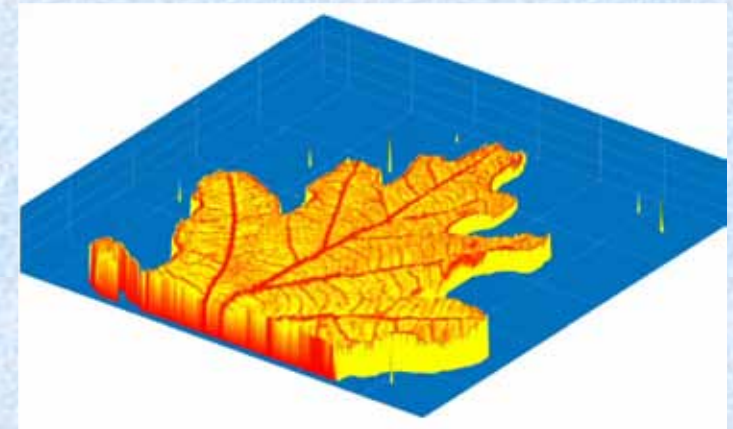
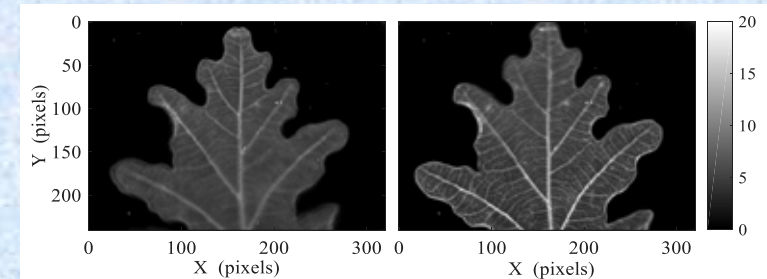
2.5 THz real-time full field imaging

- One bended oak leaf

Samples



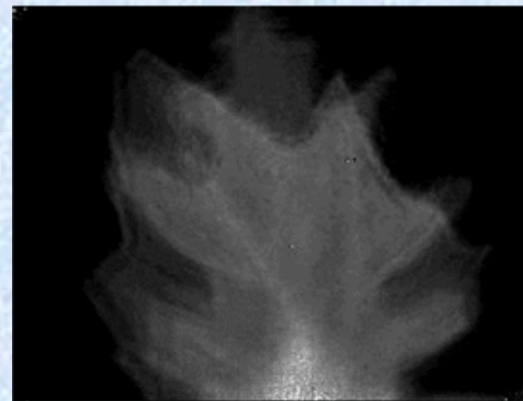
Absorban
ce



- Two stacked bended leaves : A maple leaf and the previous oak leaf behind



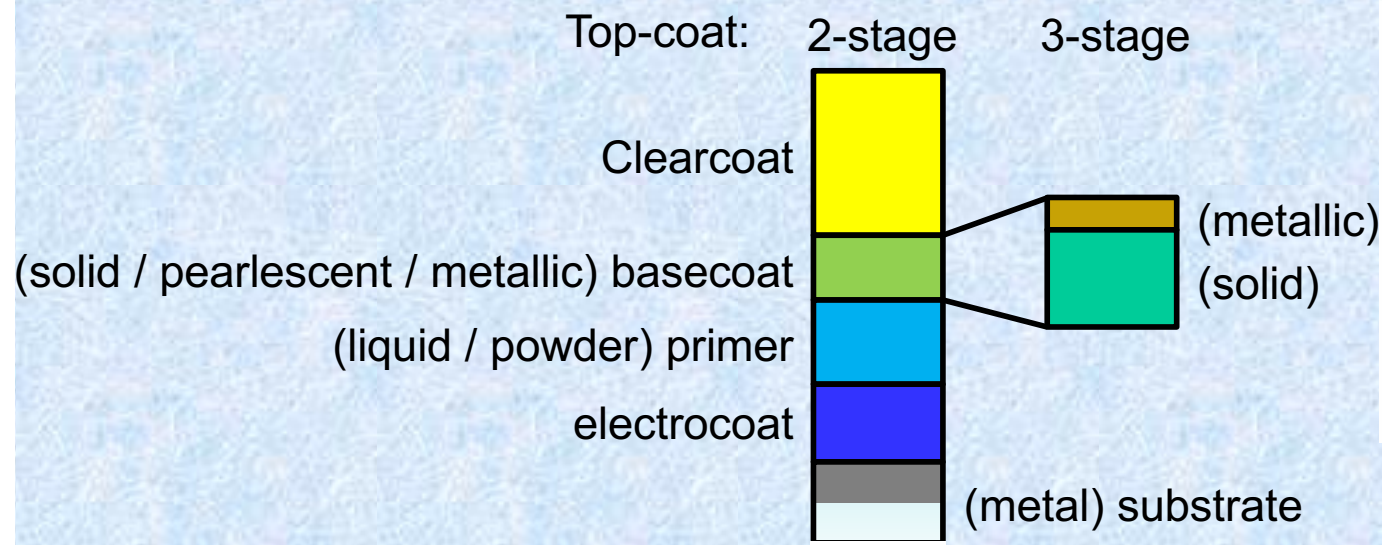
f/0,8 lens



Overview of paint film build

Goal:

- to reliably determine **dry film thickness** of all individual layers
- to report when individual builds are **outside of specification**
- to operate reliably in an **industrial environment**
- to provide self-calibration



film builds: 10 – 55 μm

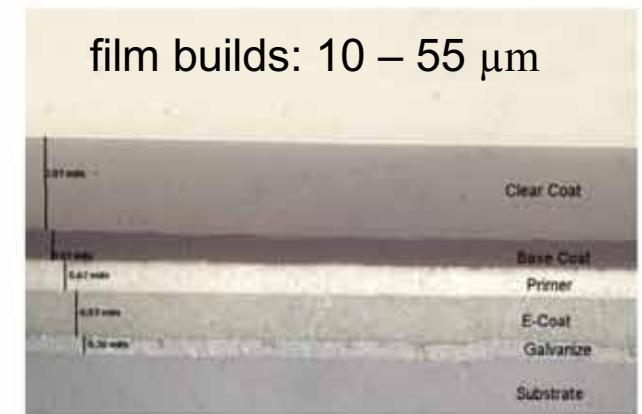
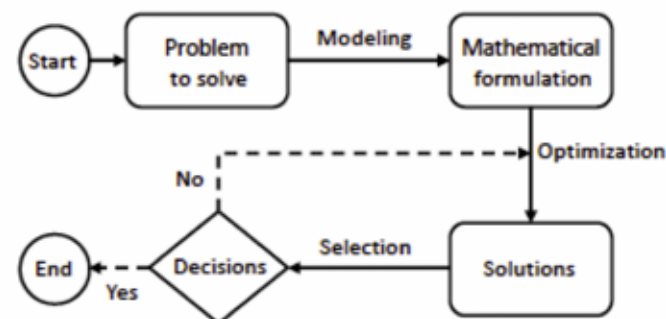
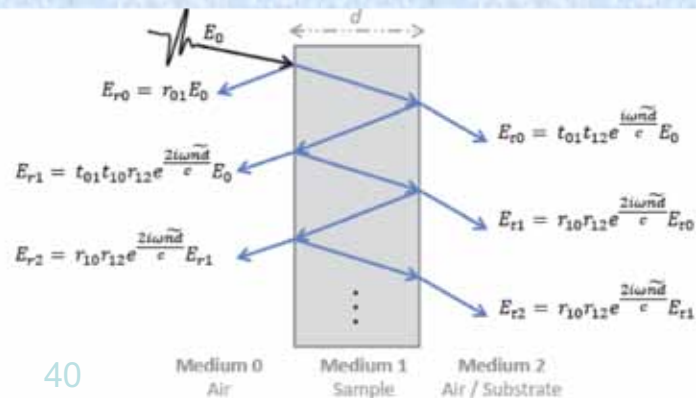
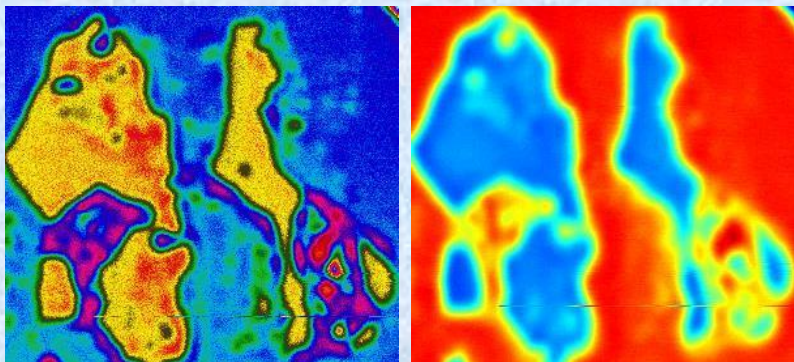


image: www.dupont.com

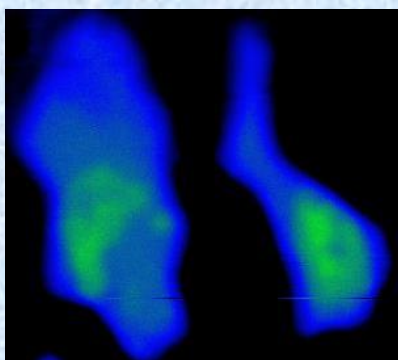


Data processing for spectro imaging applications :

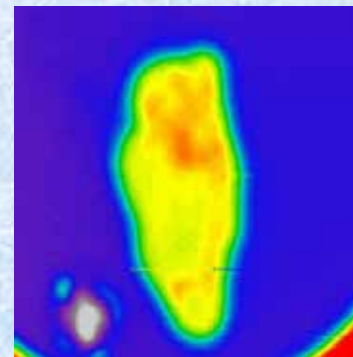
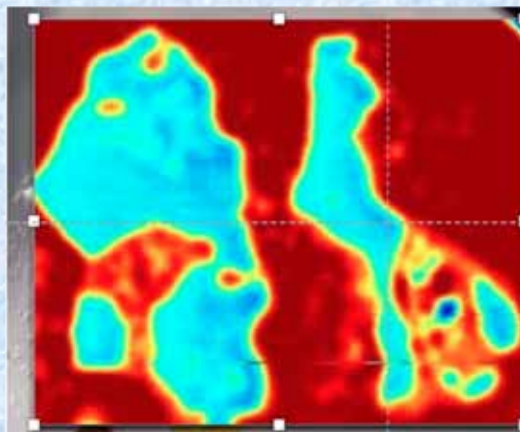
Example of extraction #1



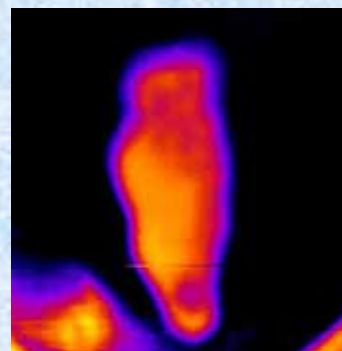
Frequency domain



Time domain

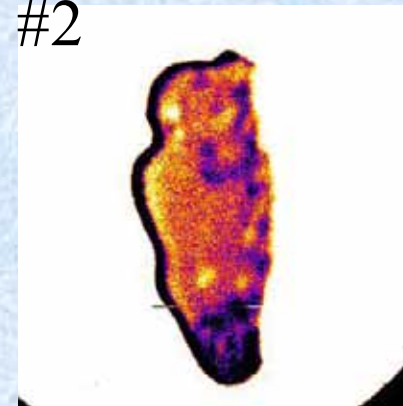


Frequency domain

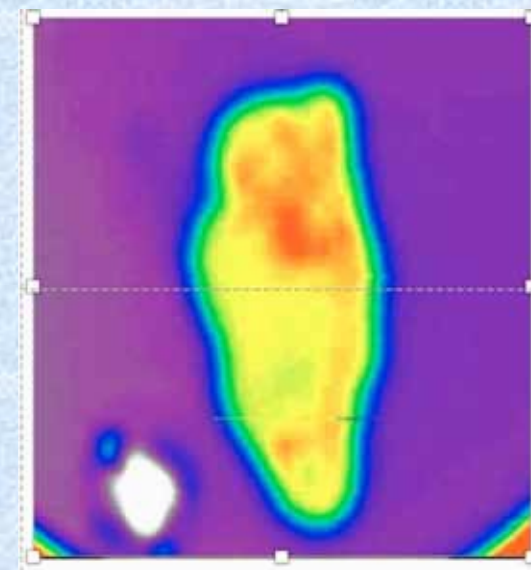


Time domain

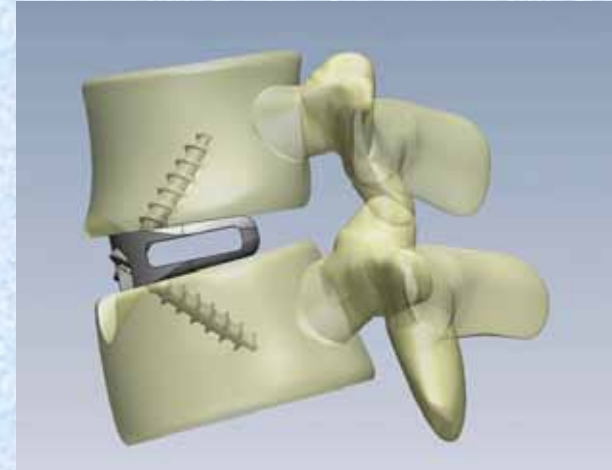
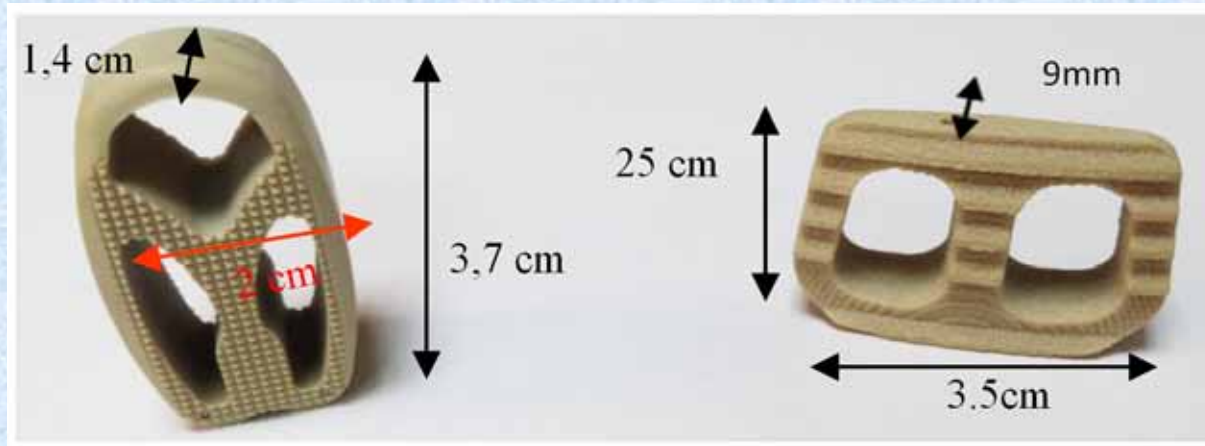
#2



Transmittance

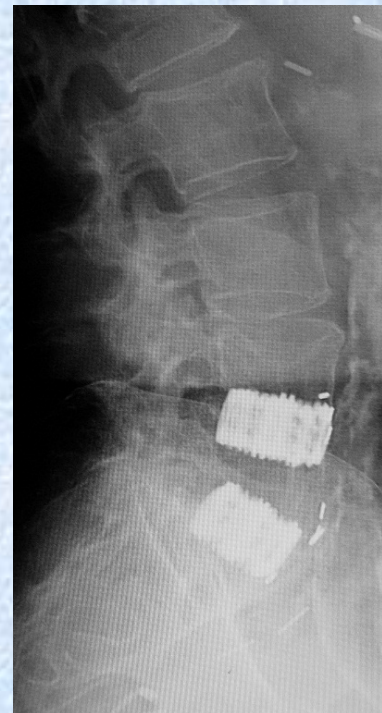


3D image Rendering Lumbar interbody devices implant

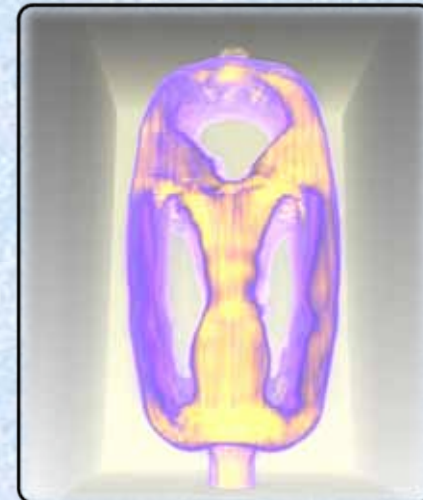


Lumbar Interbody Devices

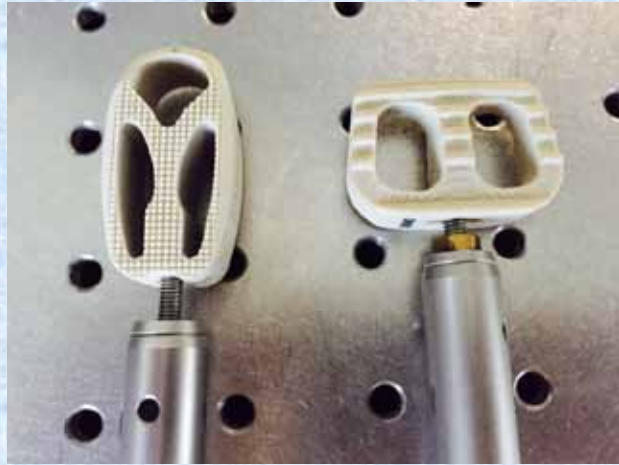
Lumbar fusion is commonly performed to alleviate chronic low back and leg pain secondary to disc degeneration, spondylolisthesis with or without concomitant lumbar spinal stenosis



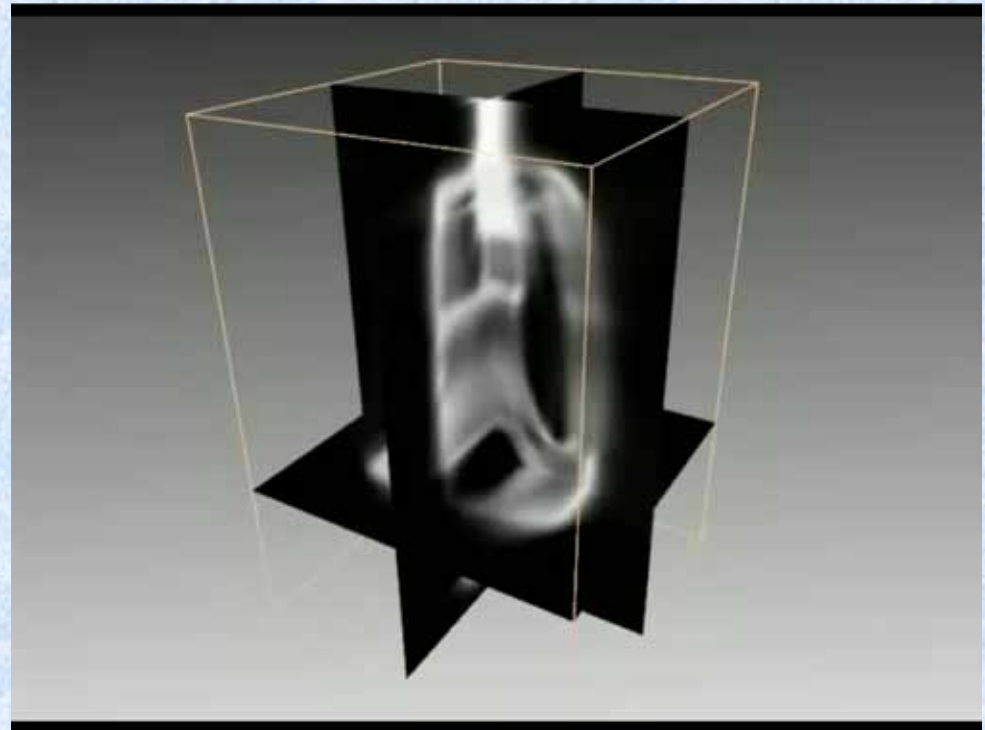
2D sinogram & reconstruction



3D image Rendering



Medical Implant
By Additive manufacturing

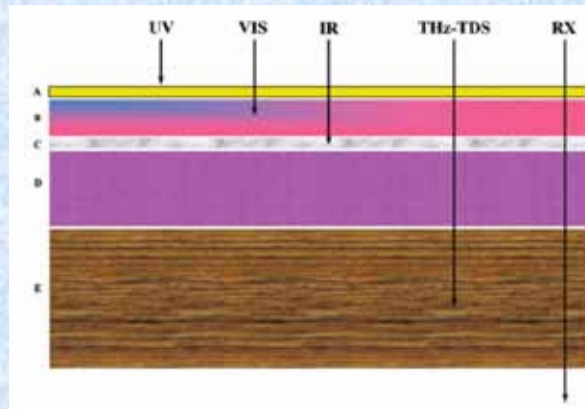


3D image Rendering

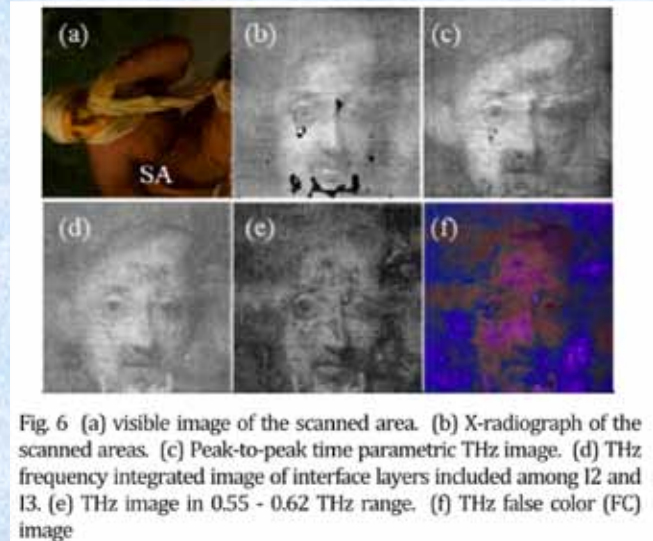
Processing Sequence To Analyse 3D THz Images , Benoit Recur; Hugo Balacey; Jean Baptiste Perraud; Patrick Mounaix
IEEETST, Appl,Optics

THz & art : mainly TDI

Painting → hidden layers, pigments
Egyptian papyrus
Manuscript
Etc...



Fukunaga, K., & Picollo, M. (2012).
Characterisation of works of art. In *Terahertz Spectroscopy and Imaging* (pp. 521-538).
Springer Berlin Heidelberg.



Koch-Dandolo, C. L., Filtenborg, T., Fukunaga, K., Skou-Hansen, J., & Jepsen, P. U. (2015). Reflection terahertz time-domain imaging for analysis of an 18th century neoclassical easel painting. *Applied optics*, 54(16), 5123-5129.

Scanning systems : FMCW

Frequency modulated continuous wave system (FMCW) with a large scan area : 600 x 800 mm (Synview[®])

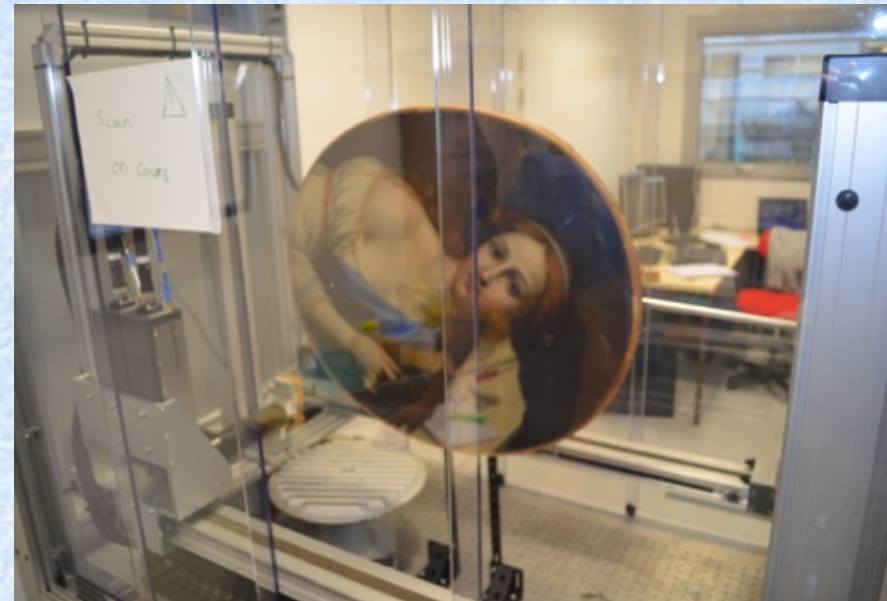
Four heads :

- two both emitting and receiving
- two only receiving signals

Two frequency ranges, from 75 to 110 GHz and from 220 to 330 GHz

The spatial resolution 5 mm at 100 GHz and 2 mm at 300 GHz

50 to 70 dB dynamic range depending topology and frequency



FMCW measurements

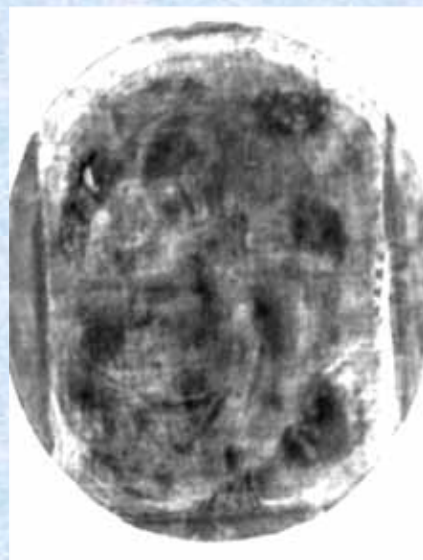
Visible image



Transmission 300 GHz



Reflection 100 GHz



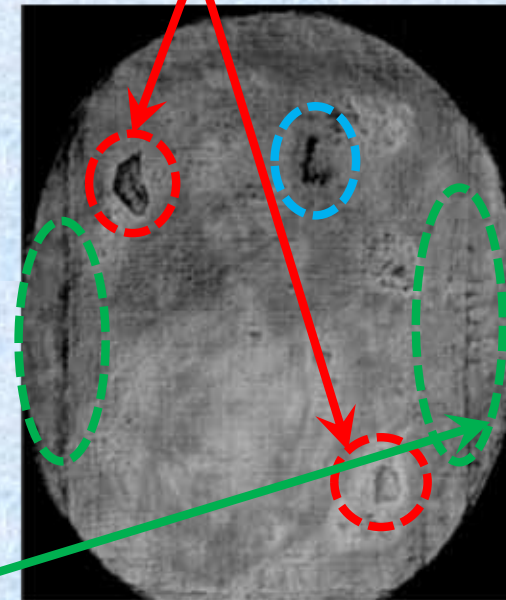
Reflection 300 GHz



Art conservation Large surface , defect detection



50% superimposition



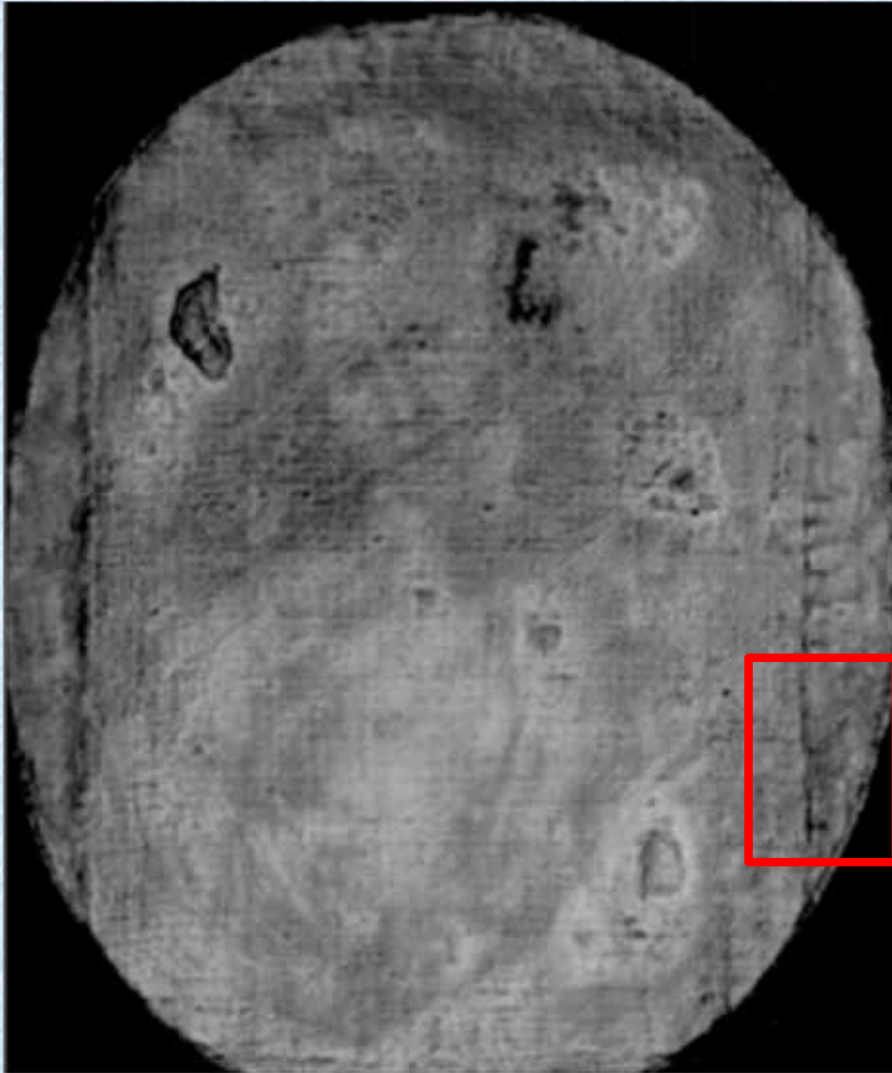
Voids

Rip of the canvas

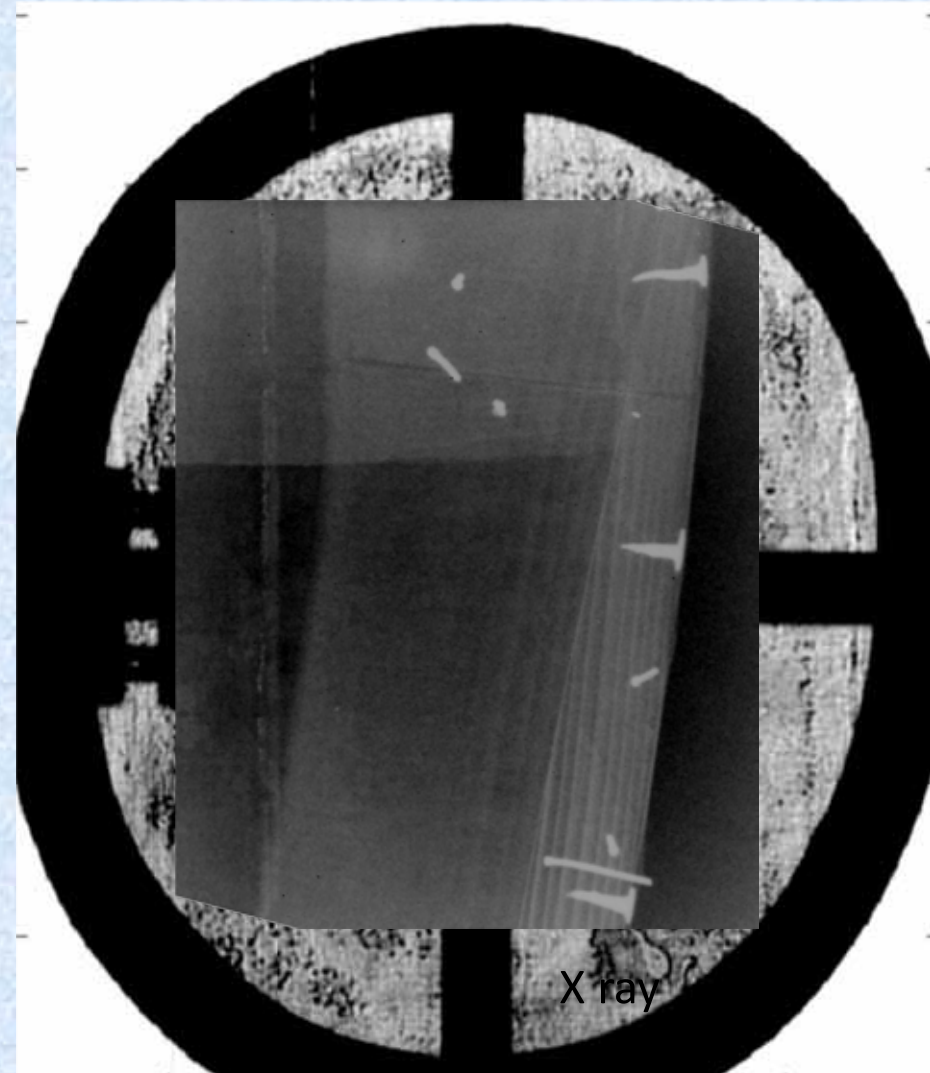
Cracking of the canvas close to the extension

300 GHz reflection

Cracks

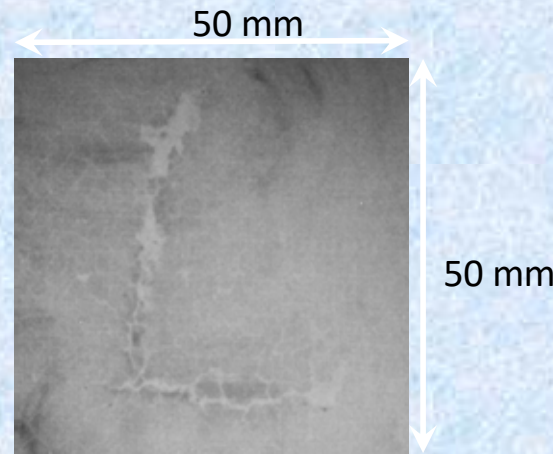


300 GHz reflection



100 GHz reflection

Crack of the canvas



X Ray image



Raking visible light

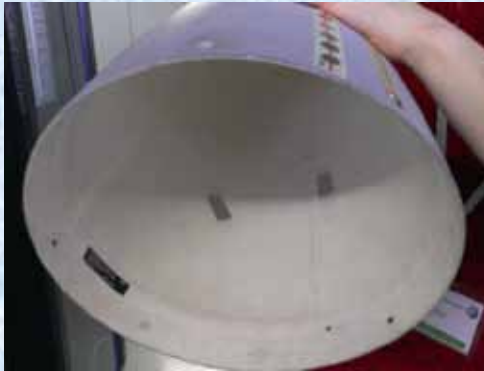
FMCW give the best result for this defect with X Ray



THz-TDI image axis after flattening with alignment of waveform to maximum and using a slice

3D Visualization

Longitudinal resolution

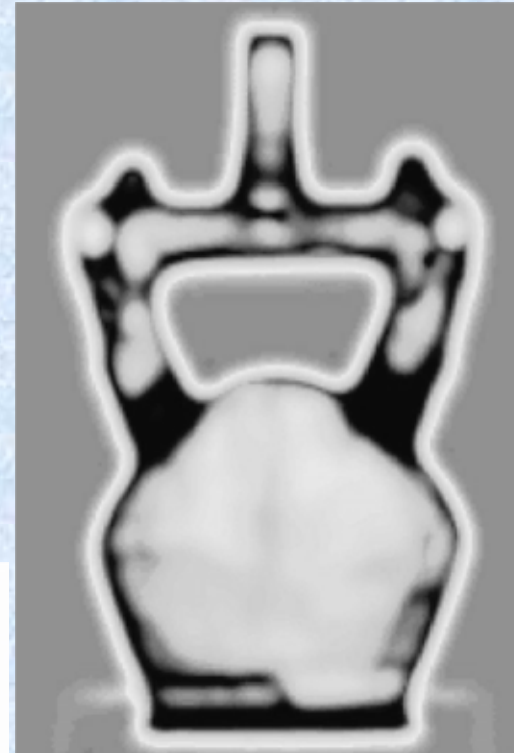


From 2D THz to 3D



Mochica
pottery

@ 84 GHz

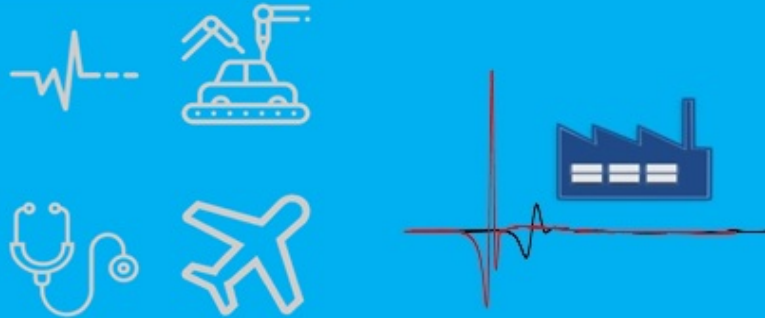


Synview 100 GHz

@ 287GHz



TERAHERTZ FOR INDUSTRY



Le laboratoire IMS UMR CNRS 5218 et la société Teraview Ltd, en partenariat avec le pôle de compétitivité ALPHA - Route des Lasers & des Hyperfréquences et le cluster LAPHIA, organisent **les 19 et 20 février 2019 à l'Université de Bordeaux**

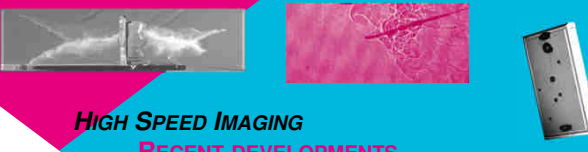
la 2ème édition du forum
sur l'emploi des ondes terahertz dans l'industrie
<http://terahertzforindustry.com>

Au programme :

- > Cycle de **conférences** et exemples de transferts technologiques dans l'industrie,
- > **Stands** d'industriels,
- > **Session posters** d'académiques et de professionnels autour des projets terahertz en lien avec l'industrie,
- > Visite et démonstrations des **systèmes Terahertz de la plateforme ATLAS** du laboratoire IMS.

2 jours pour :

- Présenter aux industriels un état des lieux sur le Terahertz,
- Rassembler la communauté scientifique et industrielle du domaine,
- Découvrir des exemples d'applications Terahertz et les opportunités industrielles correspondantes,
- Réseauter avec des spécialistes de ce domaine émergent.



High Speed Imaging

Recent Developments & Applications

Prof. Pierre R.L. Slangen



<http://hisians.wp.mines-telecom.fr/>
pierre.slangen@mines-ales.fr

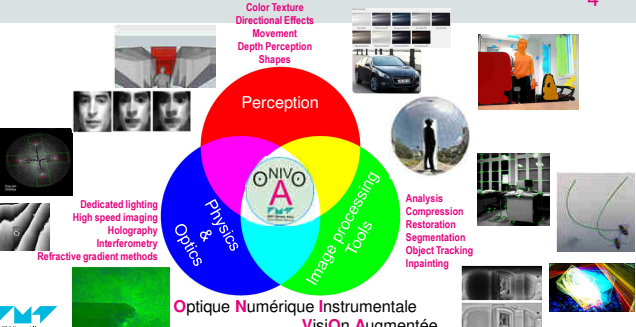


ALÈS SCHOOL OF MINES ECOLE DES MINES D'ALÈS NETWORK *INSTITUT MINES TELECOM*

Higher education and research Institute
with 175 years of history, 1300 students
Master Degree in Engineering + PhD
Civil engineering, Mechatronics, Environment,
Materials, Informatics-Productics
Located in the South of France



ONIVO: COMPUTATIONAL PHOTOGRAPHY FACILITY



Perception
Color Texture
Directional Effects
Movement
Depth Perception
Shapes

Image processing Tools
Analysis
Compression
Restoration
Segmentation
Object Tracking
 inpainting

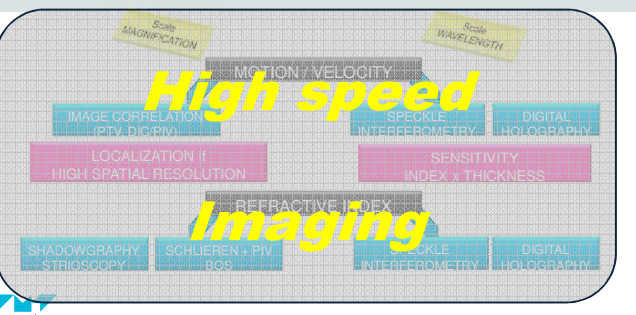
Optics & Physics
Dedicated lighting
High speed imaging
Holography
Interferometry
Refractive gradient methods

Optique Numérique Instrumentale
VisiOn Augmentée

OPTICAL MEASUREMENTS

Measurement type	Measured quantity	Measurement methods
Direct imaging	Velocity, Size, Shape, Refraction index	PIV / PTV, Shadowgraphy, PILS
Intensity, intensity ratio	Size, Temperature	Extinction/Absorption, LIF, Speckle
Interferometry	Velocity, Size, Refraction index, temperature	Laser Doppler, Phase Doppler (PDA), Speckle, Holography
Time offset	Velocity, Size, Shape	Time of Flight, etc...
Pulse delay	Size, Temperature	Femtosecond laser
Raman diffusion	Temperature, concentration	Raman spectroscopy, Raman Holography

MAIN VISUALIZATION TECHNIQUES



High speed
MOTION / VELOCITY
IMAGE CORRELATION (PTV, DIC, PIV)
LOCALIZATION if HIGH SPATIAL RESOLUTION
SPECKLE INTERFEROMETRY
DIGITAL HOLOGRAPHY

Imaging
SHADOWGRAPHY
STRIOSCOPY
SCHLIEREN + PIV
BOSS
SPECKLE INTERFEROMETRY
DIGITAL HOLOGRAPHY

Scale MAGNIFICATION
Scale WAVELENGTH
REFRACTIVE INDEX
SENSITIVITY INDEX x THICKNESS



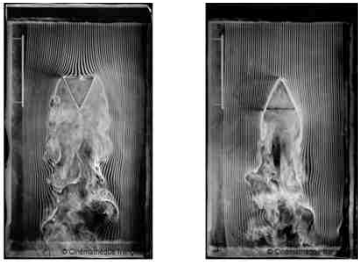
BEHIND HIGH SPEED IMAGERS



FREEZING MOVEMENT : CHRONOPHOTOGRAPHY

8

57 channels smoke machine
Laminar flow



Etienne-Jules Marey (1830-1904), 42 images/s
Prisme triangulaire présentant au courant ses arêtes, quatrième et dernière version de la machine à fumée, équipée de 57 canaux.
Agrandissement moderne d'après la plaque négative au gélatino-bromure sur verre (1901)

Paris, Cinématique française

TOO FAST TO BE SEEN

9

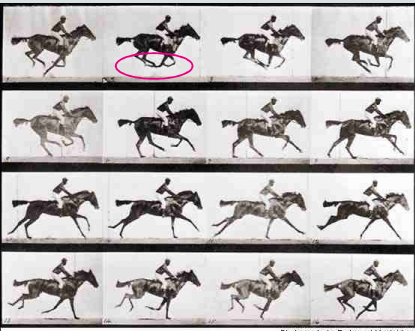


Do you have your four legs on the floor while running ???

Ask Joe Goodman...
In Stanford he knows!!

TOO FAST TO BE SEEN:

11



First motion analysis by photography (1887)
Eadweard Muybridge, « The farm », Stanford.
16 photographic plate cameras aligned // horse riding triggered by a rope
"Loco" motion

TOO FAST TO BE SEEN...24FPS

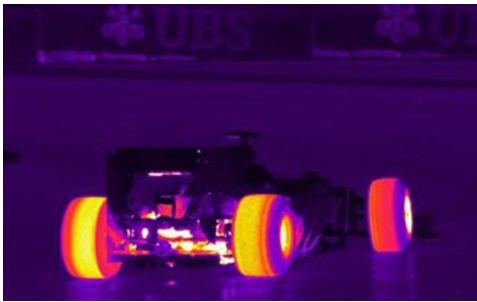
12



FASTER ROAD RUNNER, MORE HORSE POWER

13

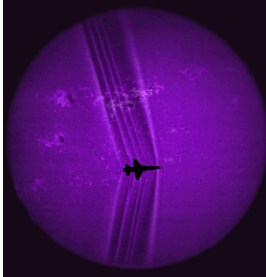
Formula 1 racing (2018)
NIR HSI



SEEING INVISIBLE WITH HSI

14





Vision Research : Hi speed color imaging

NASA Sonic boom visualization : BOSCO
(Background Oriented Schlieren using Celestial Objects)

15

HIGH SPEED IMAGING

- High speed recording frequency, lower speed replay...
sometimes called "Slow Mo or MoCap"
- Current range: 60 < HSI < 100 000fps and UHSI up to 200Mfps
- Main parameters:
 - Speed fps : frame per second... linked to exposure time
 - Exposure Time T_{exp} (s) : the shortest... and so high sensitivity
 - High sensitivity S : big pixels (20-30µm)... or binning small pixels (10µm)
 - Resolution R_p : number of pixels, sometimes downsized
 - Throughput (from active image to Memory) T (pix/s) : constant by camera
 - Onboard Memory M_o (GB) : images storage, linked to architecture

16

HSI: W4?

Event	Frequency	Duration
Golf Swing	125 fps	1 second
Milk drop	250 fps	200 ms
Eye Blink	500 fps	100 ms
Machine	1000 fps	~ 500 ms
Airbag	5000 fps	30 ms
Welding Spark	15000 fps	5ms
Small Gunshot	50 000 fps	1 ms
Glass Break	250 000 fps	10µs
Hypervelocity	1 000 000 fps	1µs

HSI RULES
RULE #1
"Don't try the object !"
with the light spots
RULE #2
"Freeze the object !"
with exposure time or flash
RULE #3
"XX fps ⇔ 1/XX s exposure"
RULE #4
"Heisenberg is always right"

17

THE PERFECT IMAGE

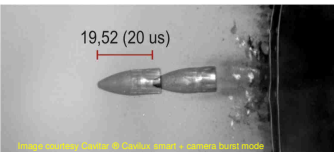
Working distance

Recording time

Trade-off

- Camera optics
 - Aperture, Focal length
 - Magnification
 - Sharp focus
 - Depth of field
- Camera Triggering
 - FIFO Rolling Memory
 - Sharp trigger to avoid
- Camera Exposure time
 - Long enough to see: "Lux is lux ! ...but Black is Black!" (adjust bit shift)
 - Short enough for fps and blur free (ns or ps flashlight): "Frozen !"

The possibility to launch multiple (up to five) light pulses with freely adjustable delays between the pulses into each image enables the acquisition of quantitative information from each image (track, velocity, acceleration etc.).



Rifle bullet with a velocity of 682 m/s. Illumination by two laser pulses (20 µs delay between the pulses).

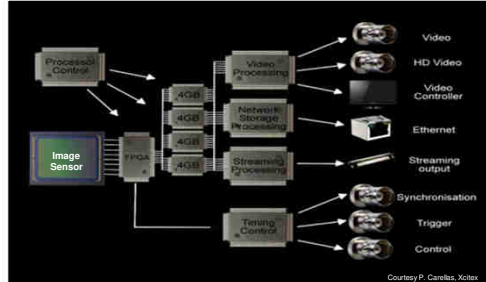
18

MAIN PARAMETERS

- Pixel blur B (pix)
 - $B = V_p \times T_{exp} \times (N_p / ROI) = V_p \times T_{exp} / M \Rightarrow \text{Blur free } B \leq 1: T_{exp} = M / V_p$
 - V_p (m/s), T_{exp} (s), N_p (pix), ROI (m), M (m/pix)
 - Appli: $V_p = 1 \text{ cm/s}$, $T_{exp} = 33 \text{ ms}$, 640 pixels for ROI=10cm, $B=2, 1 \text{ pix}$
- Throughput (pix/s or MB/s)
 - $H \times V \times FPS = \text{Gpx/sec} = \text{Camera } C'$ (pixel weight 8, 10, 12 bits)
 - 1920x1080 @ 30 fps = 0,062 Gpx/s
 - 1920x1080 @ 2000 fps = 4,2 Gpx/s
 - 1920x1080 @ 12500 fps = 25,9Gpx/s

19

ANATOMY OF HI SPEED CAMERA

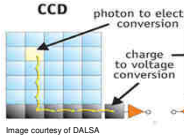


20

MAIN ARCHITECTURES : SENSORS

- Photoelectric effect : Electric charge generation from photon
 - CCD: Transport then charge to conversion on dedicated site
 - CMOS: Charge to voltage conversion on creation site

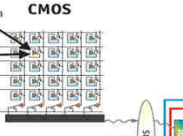
CCD



photon to electron conversion

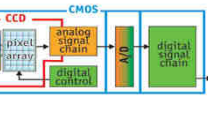
charge to voltage conversion

CMOS



photon to electron conversion

charge to voltage conversion



MAIN ARCHITECTURES : SENSORS

21

CCD Full Frame (photogates)

CCD Frame Transfer (photogates)

CCD Interline Transfer (photodiodes)

CMOS Active Pixels (photodiodes)

CMOS On-chip A/D

Higher fill factor

Higher complexity

Image courtesy of DALSA

MAIN ARCHITECTURES : SYSTEMS

22

Different goals... different configurations

- Large public
 - Basic sensor and electronics
- Machine Vision
 - Simple architecture (1 ou 2 TAPs)
 - No onboard memory
- Integrated Camera
 - Complex Architecture (multi TAPs)
 - Memory image nearby Active image
- Ultra high speed Camera
 - Very complex architecture
 - Sometimes with intensifier
 - ONBOARD memory

Image courtesy of P. Carlier, J. Chouinard

INFORMATION SIZE

23

Pixel weight

Number of pixels

Image

Speed

Throughput

Storage

Standard Video

Scientific

High Speed

36 Mo/s

630 Mo/s

30 Go/s

MAIN ARCHITECTURES : SYSTEMS

24

Throughput and interfacing

- Information size: 1280x1024@224fps@8bits=294MB/s
- Direct connection without NIC (Network Interface Card)
- NIC Connection internal or external (Thunderbolt box) to PC
 - Careful with cables (quality, length... PRICE)
 - Influence on throughput (Cat5 ou Cat6), motherboard fast slot
 - Power plugging (e.g. Cameraink POCL)

Intel Pro 1000 drivers

Thunderbolt 3@30Gbit/s

Thunderbolt 2@20Gbit/s

USB3.1@10Gbit/s

n-Base T@5Gbit/s

	GIGE VISION	USB3	Camera Link	CoaxPress
Bandwidth (Mbytes/sec)	117	400	255-635	120-3600
Cable type	Ethernet	USB 3.0	Camera link	Coax
Cable lengths (possible)	100 meters	3-5 meters	10 meters	35-105 meters
Frame grabber required	No	No	Yes	Yes

Same sensor faster for different interfacing...

- GigE@51fps - USB3@165fps

	GigE	1920	1200	10	51	CoaxPress EXTENSION 2008
USB 3.0	1920	1200	10	145	5008	CoaxPress EXTENSION 2008

HIGH-SPEED CAMERA : 2 BIG FAMILIES

25

CMOS + Rolling Memory Buffer

CCD CMOS + In Situ Storage

- Rolling buffer, variable Resolution
- In Situ Image Storage (ISIS)

Images Pre-trigger

Trigger

Images Post-trigger

- Memory $\leq 288\text{GB}$, 26Gpx/s (V2512)
- External SSD disk drive
 - "CineMag, FastD" $\leq 2\text{TB}$
- Memory to PC: 10GB/s or CoaxPress
- Straddle time $\geq 293\text{ns}$ (Photon SAZ)

Frequency limited by interframe time

Frame 1

Frame 2

Camera

Laser

HIGH-SPEED CAMERA : 2 BIG FAMILIES

26

CMOS + Rolling Memory Buffer

CCD CMOS + In Situ Storage

- Rolling buffer, variable Resolution
- In Situ Image Storage (ISIS)

Images Pre-trigger

Trigger

Images Post-trigger

- Memory $\leq 288\text{GB}$, 26Gpx/s (V2512)
- External SSD disk drive
 - "CineMag, FastD" $\leq 2\text{TB}$
- Memory to PC: 10GB/s or more
- Straddle time $\geq 293\text{ns}$ (Photon SAZ)

Frequency limited by interframe time

Frame 1

Frame 2

Camera

Laser

Image number limited by 130nm In situ footprint

THE PERFECT CAMERA

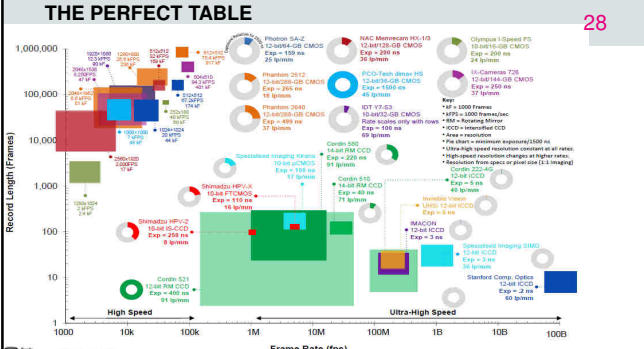
27

- Optical mount
 - Nikon, Canon, C mount, *focus remote control*
- Memory Triggering and Throughput
 - In Situ Image Storage : up to **240 images...but Mfps**
 - FIFO Rolling Memory: up to **288GB... but 26kfps**
 - Long time recording: High throughput to **distant SSD disc (CoaXPress)**
- Exposure time
 - From **5ns ISIS** to **195ns FIFO Memory... with "FAST" Option (+5k€!!!)**
 - Sensitivity...choose your ref e.g. **EMVA** (up to 100 000 ISO 12232 SAT mono)
 - Pixel size from **7µm up to 30µm** (the wider the more sensitive: **BINNING**)
- Drag&Drop, Shock & Harsh, Weight and Size, Battery-powered



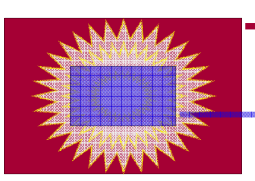
THE PERFECT TABLE

28



RMB: RESOLUTION / THROUGHPUT

29



Adjust Magnification & Sensor Resolution

Resolution		v2511	v2011	v1611	v1211
Horizontal	Vertical	fr/s	fr/s	fr/s	fr/s
1280	720	28,500	25,500	18,400	14,000
1024	800	30,500	26,900	19,700	15,000
1024	512	47,300	41,800	30,700	23,400
896	800	33,600	29,800	21,800	16,600
768	768	39,100	34,700	25,300	19,300
640	480	68,900	62,400	45,500	34,700
512	512	75,400	67,700	49,100	37,500
512	384	99,500	89,000	65,000	49,600
384	256	170,600	154,200	112,300	85,700
256	256	205,000	187,200	135,400	103,600
256	128	375,700	343,500	253,000	193,900
128	64	764,700*	708,800*	538,400	415,500*
128	32	1,000,000*	1,000,000*	840,000*	653,000*
128	16	1,000,000*	1,000,000*	1,000,000*	820,000*

IMAGE DOWNSIZING IN UHSI

30

- 2015: Shimadzu HPV X2, FTCMOS2 sensor
 - 5 - 10 Mega fps (Half Pixel or Full Pixel mode)
 - 400 x 250 pixels
 - Rolling buffer...128 images or 256 images in HP

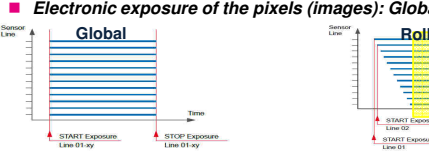
HP (Half Pixel) Mode	FP (Full Pixel) Mode
10 million frames/second	5 million frames/second
50,000 pixels	100,000 pixels
256	128

Storage: FTCMOS2 instead CCD – ISIS : Sensitivity >> as S_{pixels}

GLOBAL AND ROLLING SHUTTER

31

- Electronic exposure of the pixels (images): Global or Rolling



Pixel shifting if objects move fast, avoided by flashlight

NOISE AND BLACK REFERENCE

32

- Noise
 - Linked to technology, CCD or CMOS
 - Quantization noise : weak as sensors are 10 or 12bits
 - Photon noise : quite weak, depending on exposure time
 - Dark current : negligible as very short exposure time
- Black reference
 - Offset noise from each pixel amplifier (or from the TAPs)
 - Fixed pattern for every parameters set: **Fixed Pattern Noise**
 - Mandatory Reset after any change (**Temp, fps, ROI**)
 - Shielding sensor from light by **mechanical or electromechanical shutter**
 - Important to reach the good grey values distribution
 - Mandatory for **multipulses** ou double frame acquisition

33



34

-
- The graph shows Output on the vertical axis and Input on the horizontal axis. A piecewise linear function starts at the origin. The first segment, from the origin to a point, is labeled 'Dark areas' in purple. The second segment, from that point to the end of the graph, is labeled 'Bright areas' in red. The function is concave, meaning the slope decreases as input increases.

35



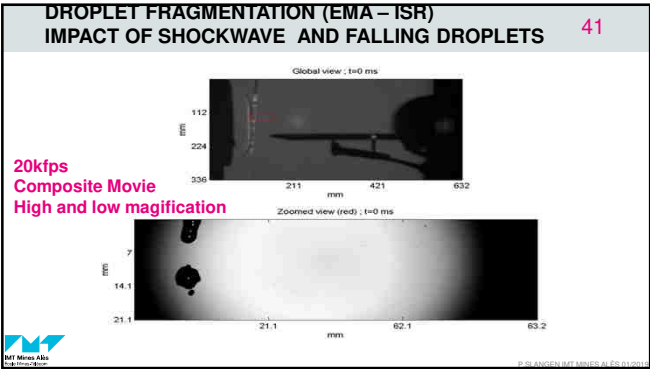
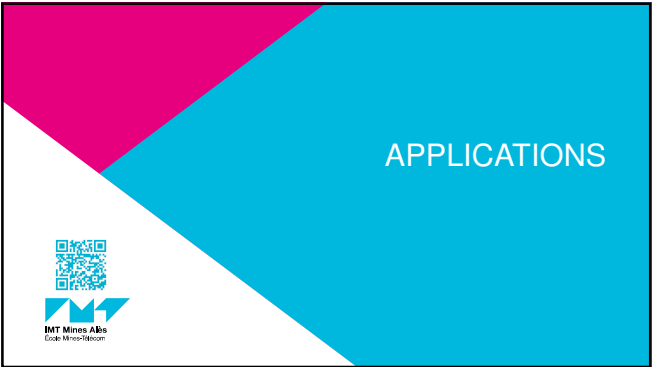
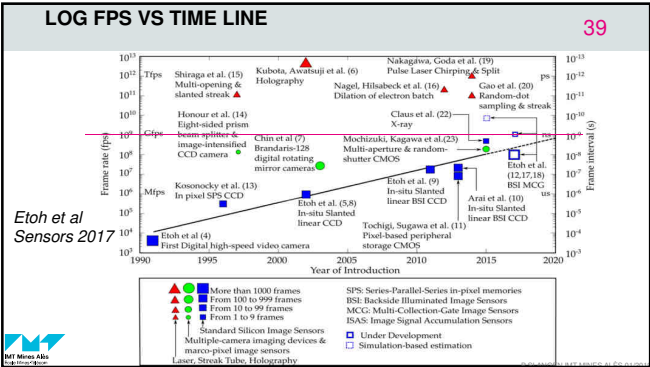
36

- Session 1

38

-
- The diagram illustrates a 3D multi-layered microarray structure. The layers, from top to bottom, are: AOC (Memory), Storage gates, Transfer gates, In-situ storage gates, Light shield, Oxides (Silicon: 5-10um), Electrodes, and Metal layers/Microchannels. The structure is shown in a cross-section view, with a top-down view of the gates and a side view of the layers.

Figure 2 A cross-section structure of a pixel of a backside-illuminated (BSI) image sensor and trajectories of signal electrons. A: light shield; B: oxide; C: interface between the backside oxide layer and the silicon layer; D: backside hole accumulation layer; E: p⁺ layer; F: n⁺ layer; G: p-well; H: p⁺ layer.



APPLICATIONS

Breaking falling droplets with shockwave in Time Resolved In-Line Digital Holography

42

- Leak of containment in industrial accident: liquid jets/drops and shock
- TR In-Line Digital Holography versus 1:1 TR Shadowgraphy or 5:1 TRS
 - Increasing resolution of very small particles
 - Reconstructing the particles field in 3D
- Questions
 - Interaction of shockwave and droplets ???
 - Size, speed and distribution of secondary "droplets"
 - Changing We, the Weber number, by chemphys properties of the falling drops

laser

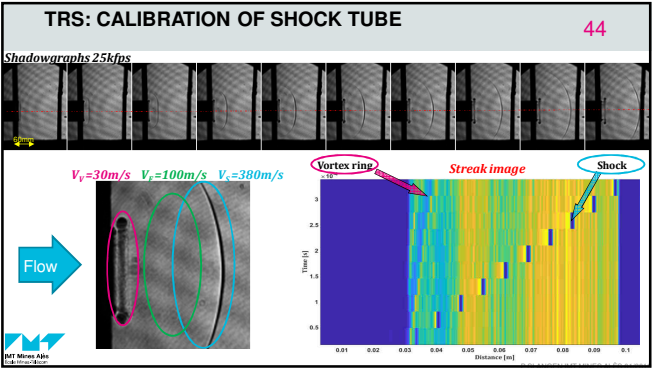
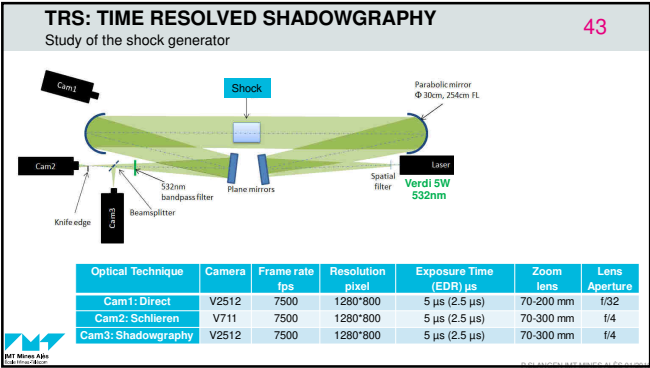
Spatial Filter

Lens

Drops dispenser

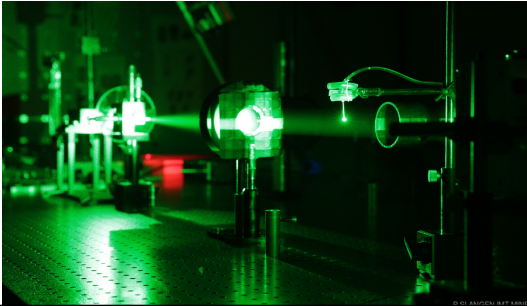
Shockwave

Camera



TR DIGITAL IN-LINE HOLOGRAPHY : SET UP45

YAG laser
100mW
532nm
+ Spatial Filter

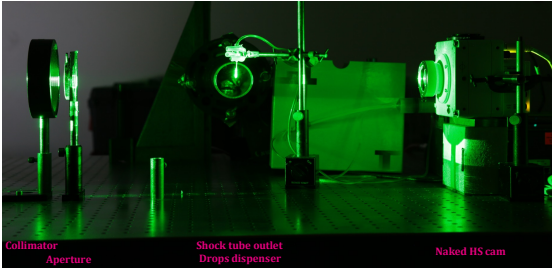


TR IN-LINE DIGITAL HOLOGRAPHY : SET UP46

VE0710
20µm Pixel
1280x800
7100fps
1µs
512x512
105mm²
25kfps
1µs

V2512
28µm Pixel
1280x800
26kfps
1µs
896x704
495mm²
38kfps
1µs

Collimator
Aperture
Shock tube outlet
Drops dispenser
Naked HS cam



TRILDHI: RESULTS47

Shockwave from shadowgraphy
Ø_{tube} = 63mm, V_s ~ 380m/s

Flow

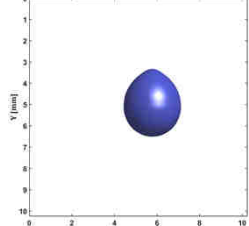
V_f ~ 100m/s
Ø_p ~ 1.5mm
Ethanol
We ~ 314

Isopropanol
We ~ 409

H₂O 100%
PEG 10% H₂O 90%
PEG 20%
...
PEG 100%

165 < We < 480
Water
100%
PEG
100%

H₂O droplet from TRILDHI: just falling

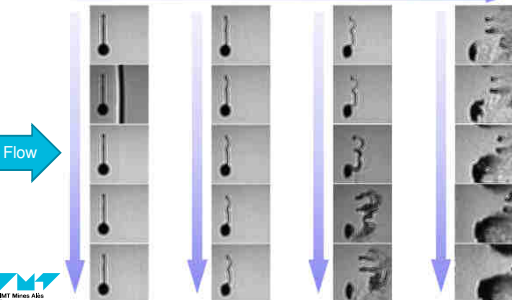


Y [mm]
X [mm]

Ø_p ~ 2mm, V_f ~ 2.5m/s (No shock)

TRILDHI: RESULTS 25000FPS -- PEG 100%48

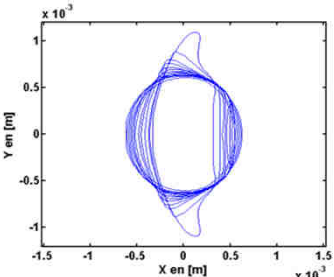
Flow



Twin image
not filtered
Todo List:
Off axis DHI
Mach – Zehnder
+ spatial phase shift

TRILDHI: PROFILE EVOLUTION OF PEG DROP49

Flow



Y en [m]
X en [m]

TRILDHI: IMPROVEMENTS50

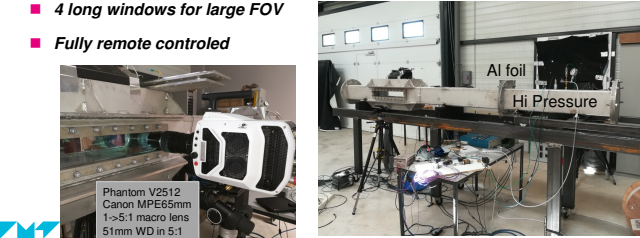
■ Large scale and hi pressure shock tube: 2m HP + 3m GP, 30cm, up to 8bars

■ 4 long windows for large FOV

■ Fully remote controlled

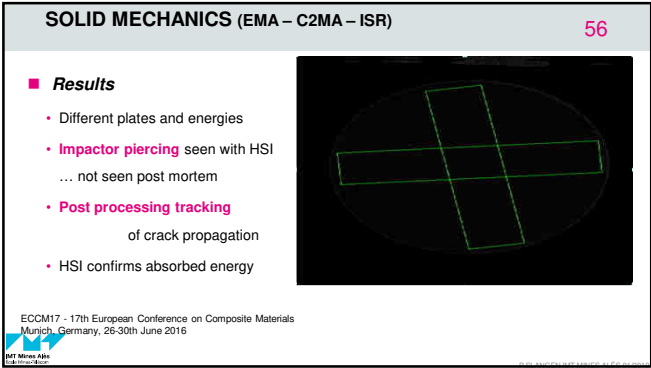
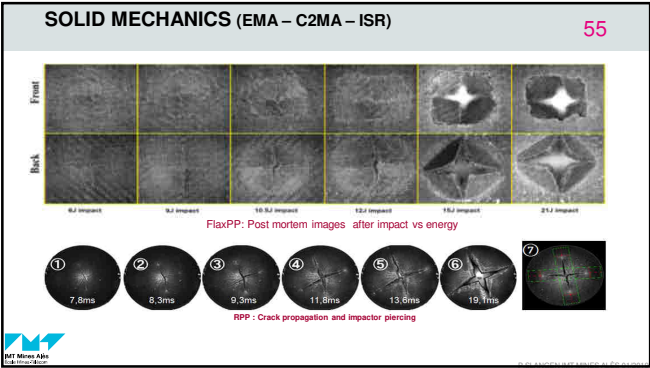
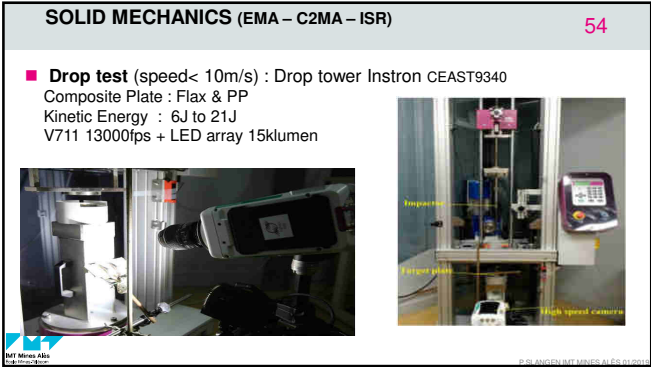
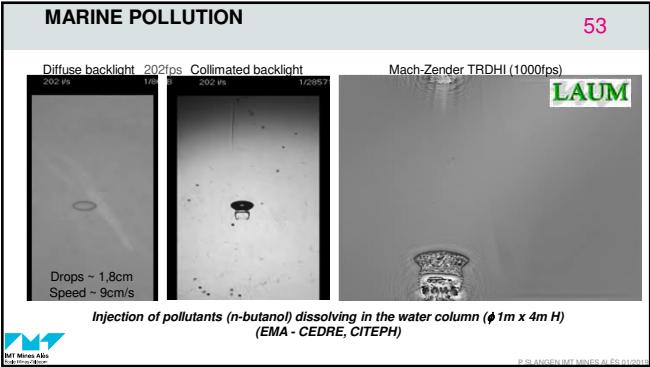
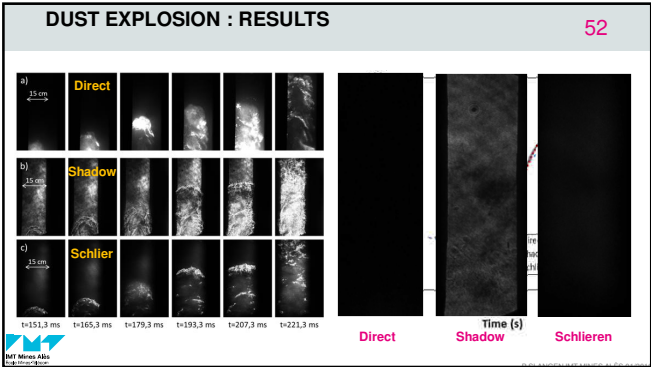
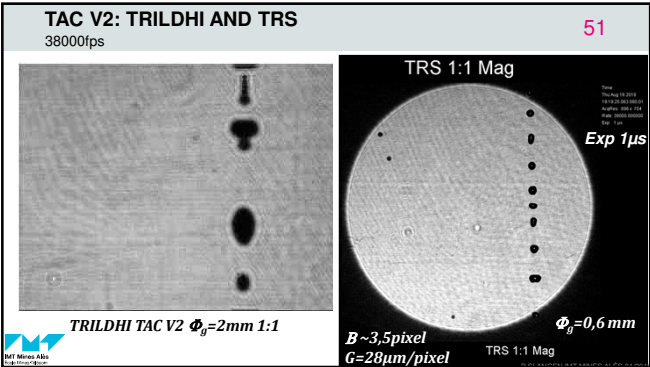
Phantom V2512
Canon MPE65mm
1->5:1 macro lens
51mm WD in 5:1

Al foil
Hi Pressure



HSI Prof. Pierre Slangen IMT Mines Alès

8



AND NOW...


IMT Mines Alès
Code MinesAlès.com

HIGH-SPEED CAMERA : EXAMPLES AND WISHES60


Kira, sCMOS, 30µm
2Mf/s, 150 images, 9247768pixels
416x228x192mm, 10.5kg


Phantom V2512, CMOS, 28µm
26kF/s, 1865s, 1380100pixels
273x190x170mm, 7.7kg


AVT Pike, CCD, 7.4µm
2026/s, 0 Mo, 640'480pixels
96.8x44x44mm, 250g

■ Need Color ???

■ Need Speed/Res ???

■ Need More SRC

Bayer filtering or 3cam

Hyper spectral cams

Flex4K: global shutter...

• Camera arrays

• Smaller pixels

• Hybrid sensors



CONCLUSIONS AND FUTURE DEVELOPMENTS61

Rules #1, 2, 3, 4: "Don't fry, just freeze, in 5ns for 200Mfps..."

Increased Speed@constant Resolution: Asynchronous HSI cameras

Timer Box + Interface + PC + SSD disk + Cloud

Increased Resolution@constant Speed: Plenoptic HSI cam array

Increased Color@constant Speed: Common path filter HSI cams

Check your Pixel size and Throughput... as $2 \times 14\mu\text{m} = 28\mu\text{m} !!$

HSI is everywhere...even in the smartphones with EXMOR stacked CMOS

HSI + Questions= Friends@11Gfps

THANK YOU

SPECIAL THANKS

P. Carellas, Xciter USA

M. Hargather, NewMexicoTech USA

N. Long, Trinoma F

M. Ortlieb, Shimadzu D

P. Reu, Sandia Lab USA

a.m.o. ...

1 SECOND @ 3600FPS

RECORDING

=

1 HOUR @ 1FPS

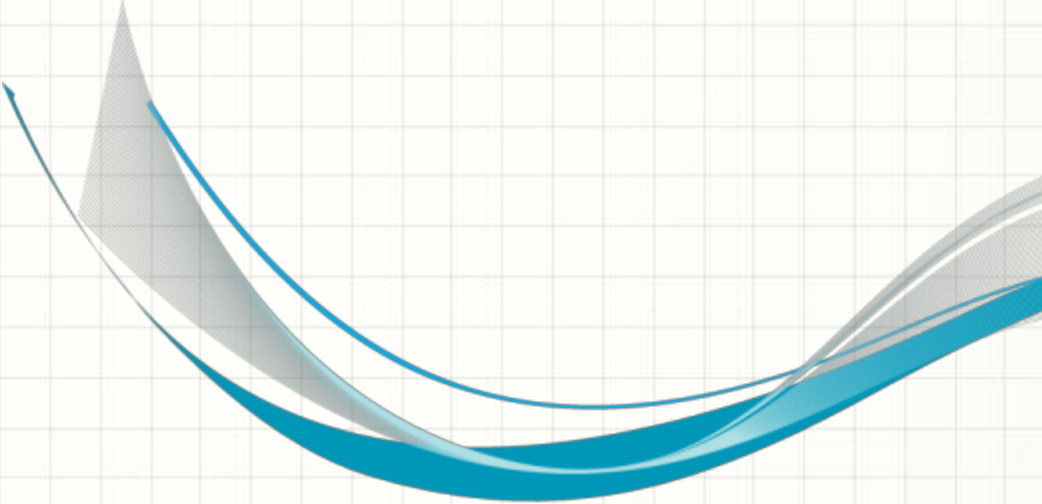
PLAYING



SCANNING THERMAL MICROSCOPY

J.-L. Battaglia, A. Kusiak, A. Sommer, C. Pradère
A. Saci (PostDoc), I. De (PhD)

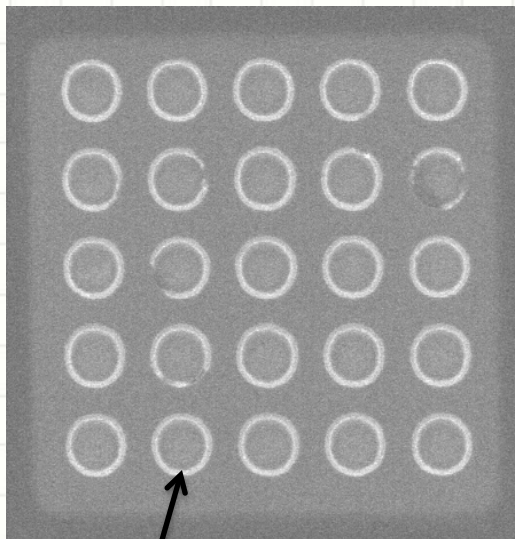
I2M Lab., UMR 5295
University of Bordeaux
29/01/2019



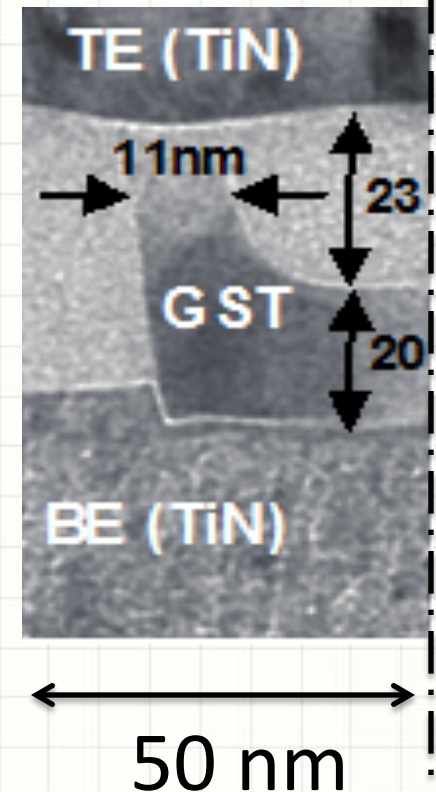
Applications

Application Objectives 1/3

Electronic devices: what is the thermal boundary resistance between constitutive elements ?

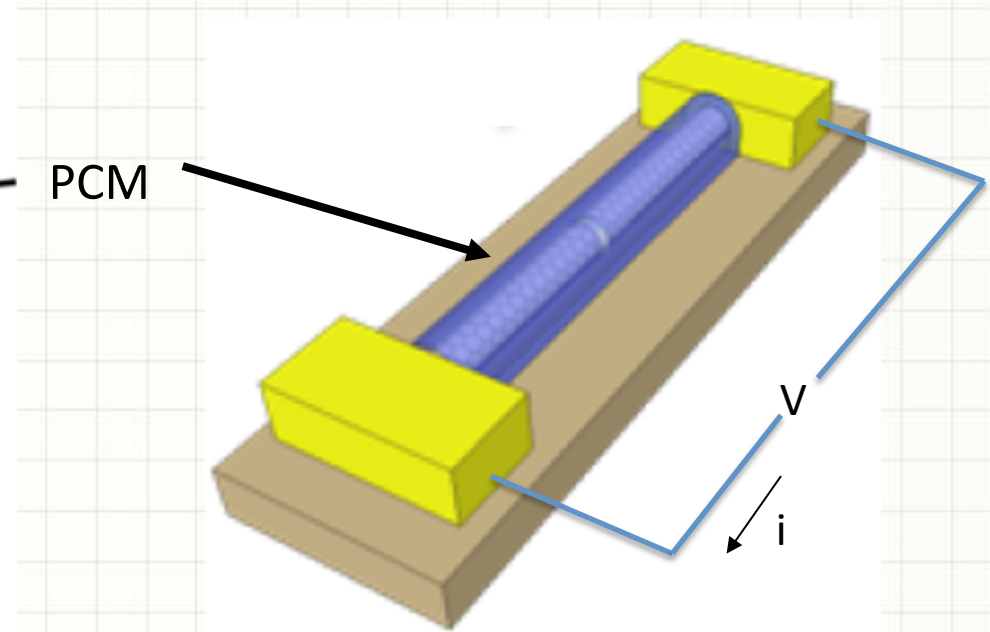
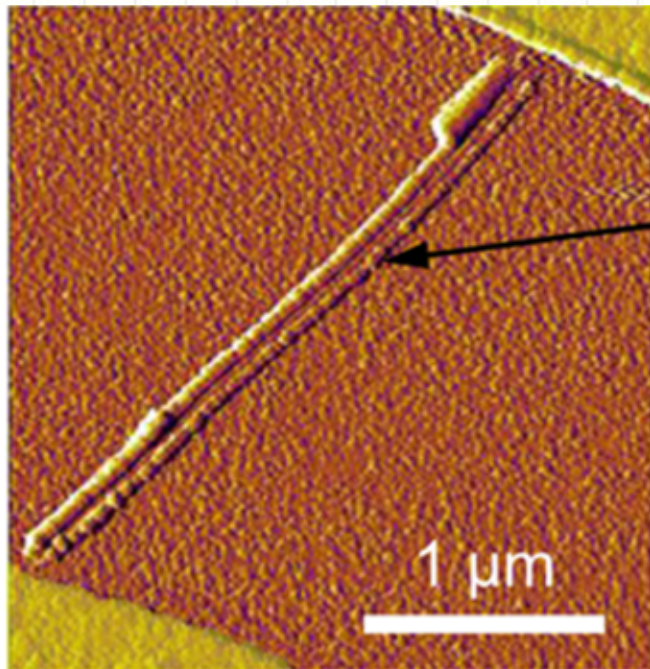


Cell diameter: 100 nm



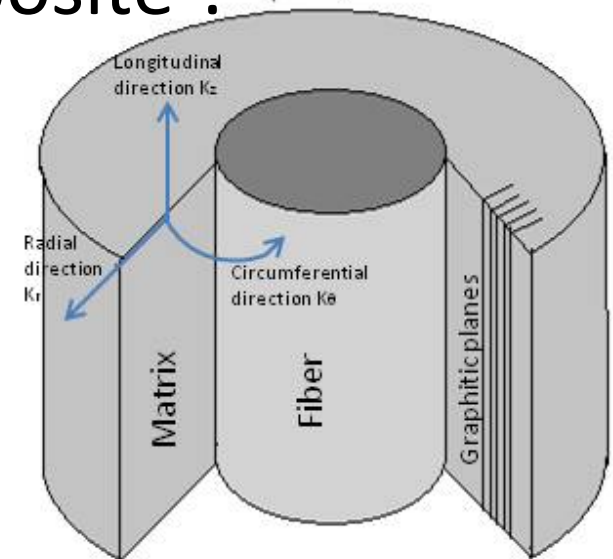
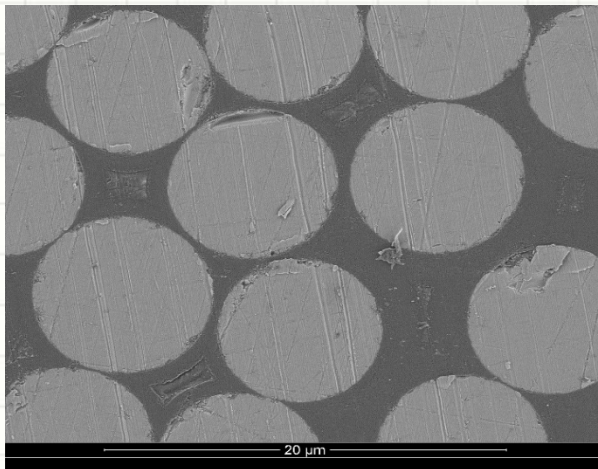
Application Objectives 2/3

Thermal conductivity of another new and more advanced PCM device based on nanowire, 100 nm diameter

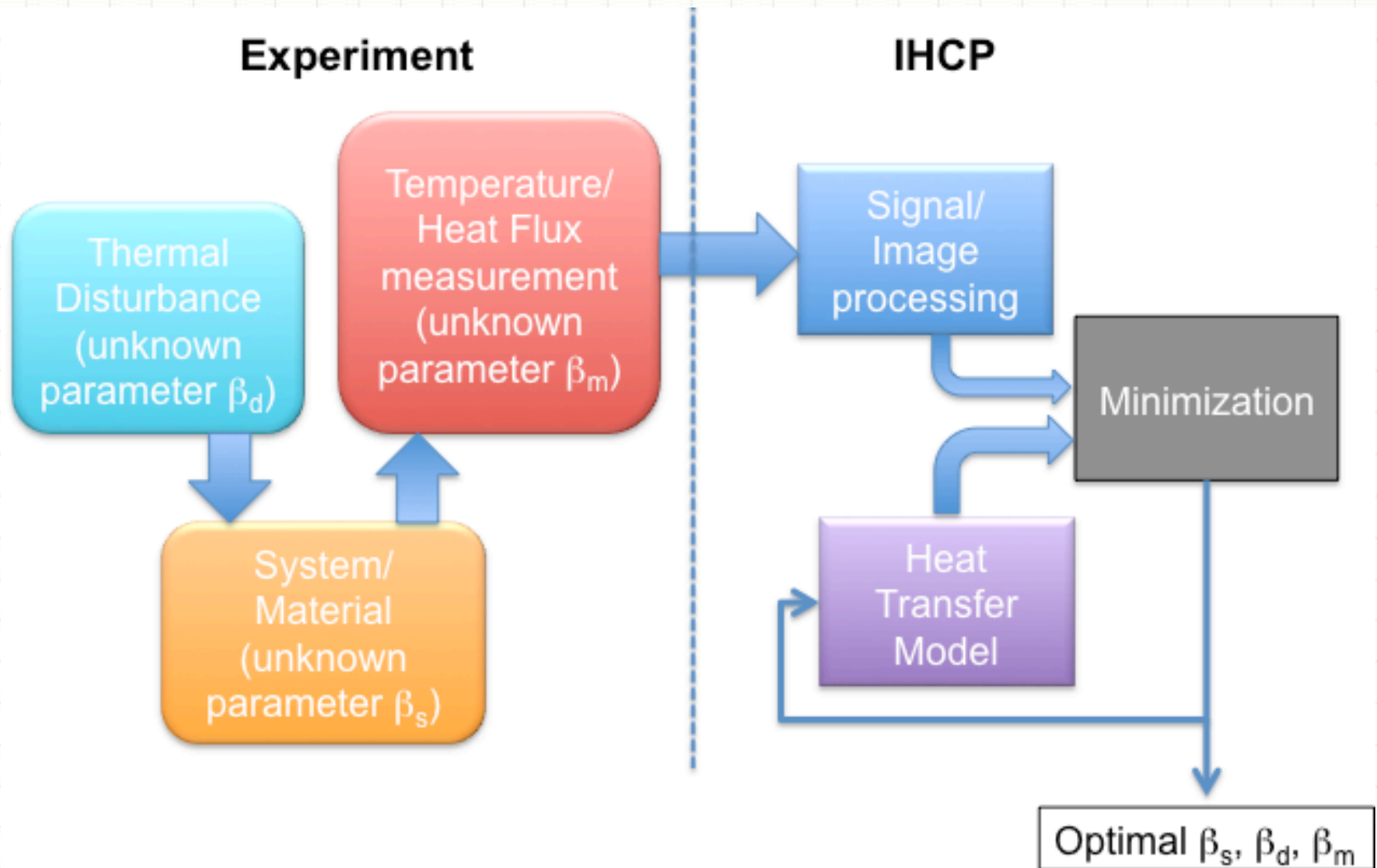


Application Objectives 3/3

Modern Composite Structure with Carbon Matrix and Silicon Fiber: What is the thermal boundary resistance between the fiber (diameter $10\mu\text{m}$) and the matrix of a complex pyrocarbon composite ?



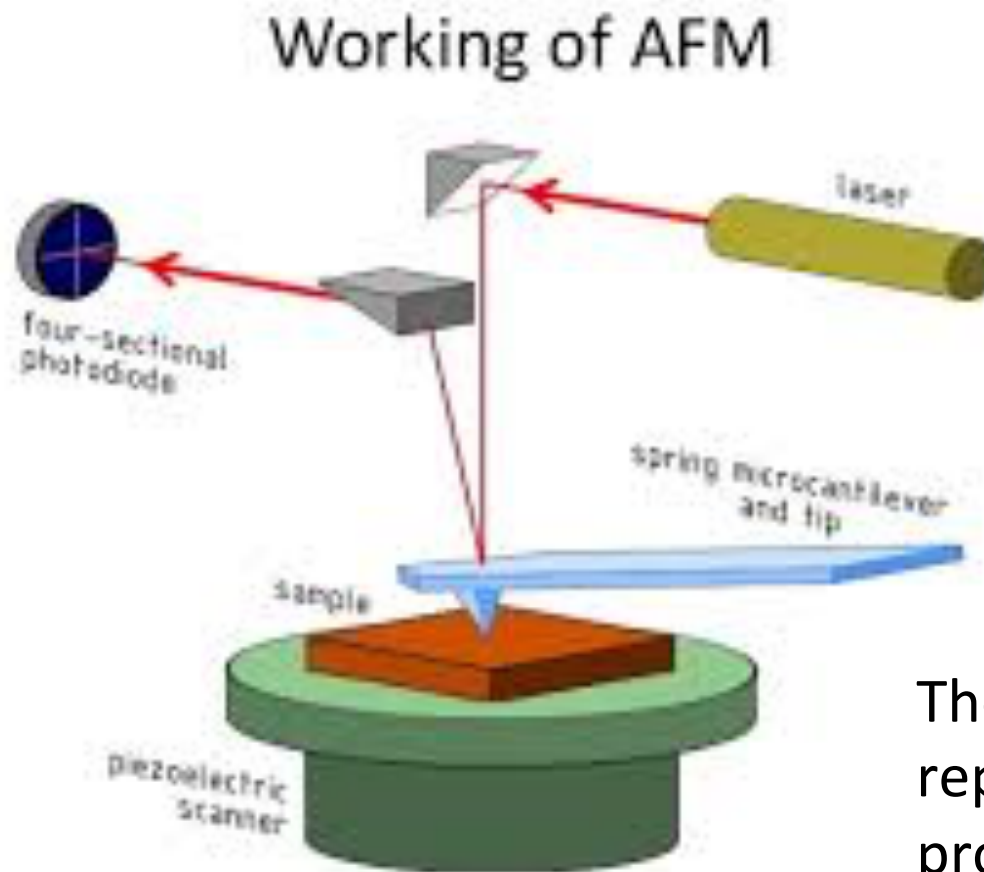
Thermal Characterization Principle



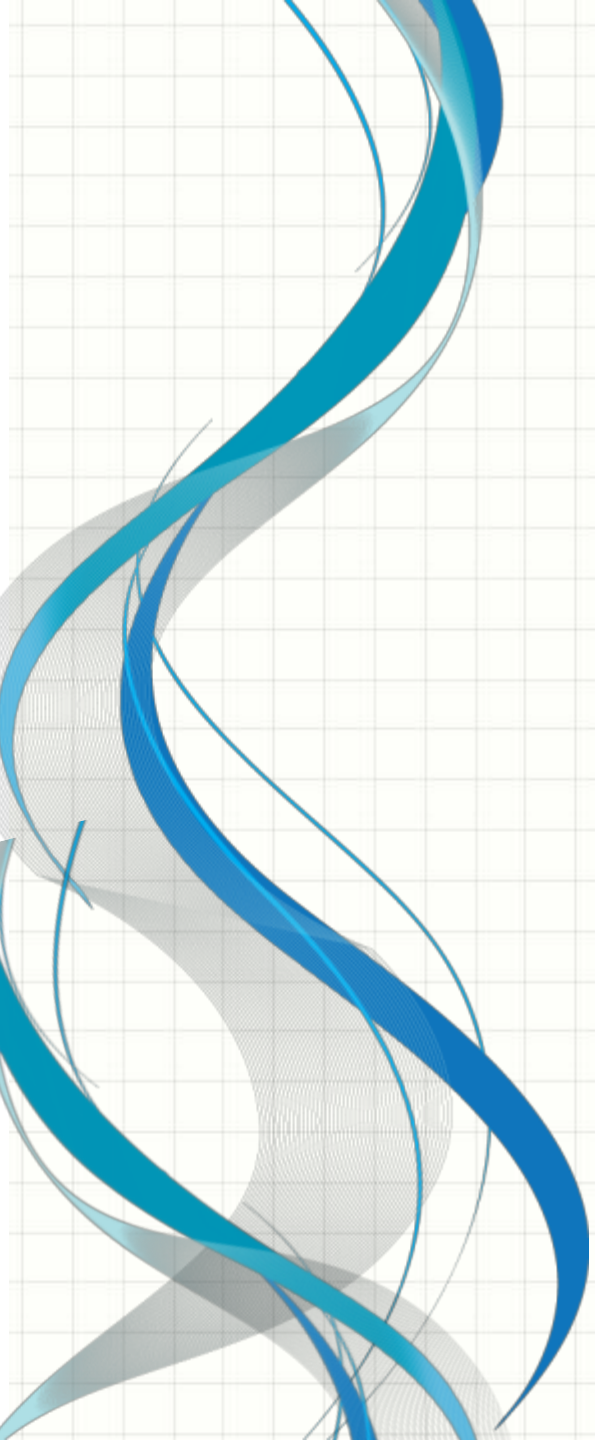


Suited Experiment: The Scanning Thermal Microscopy (SThM)

Scanning Thermal Microscopy (SThM) is based on AFM

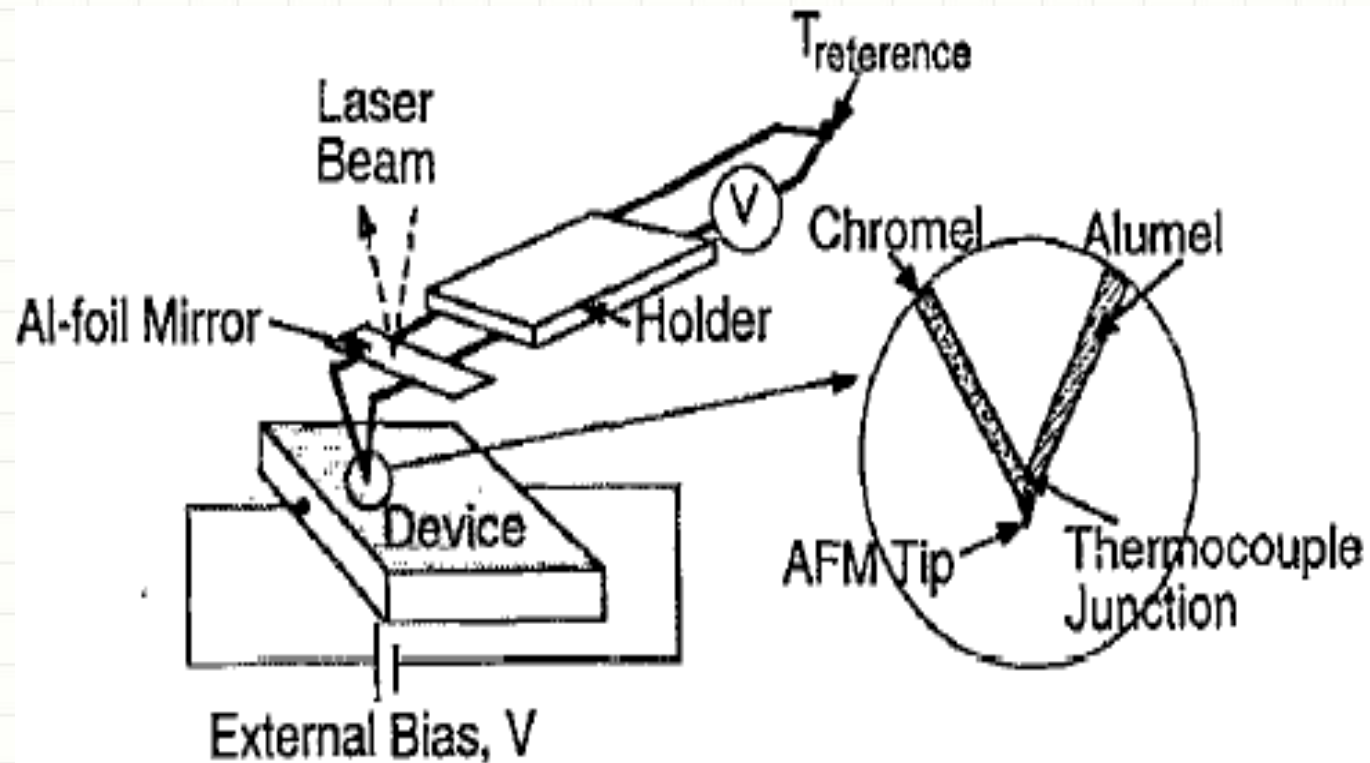


The AFM probe is replaced by a thermal probe



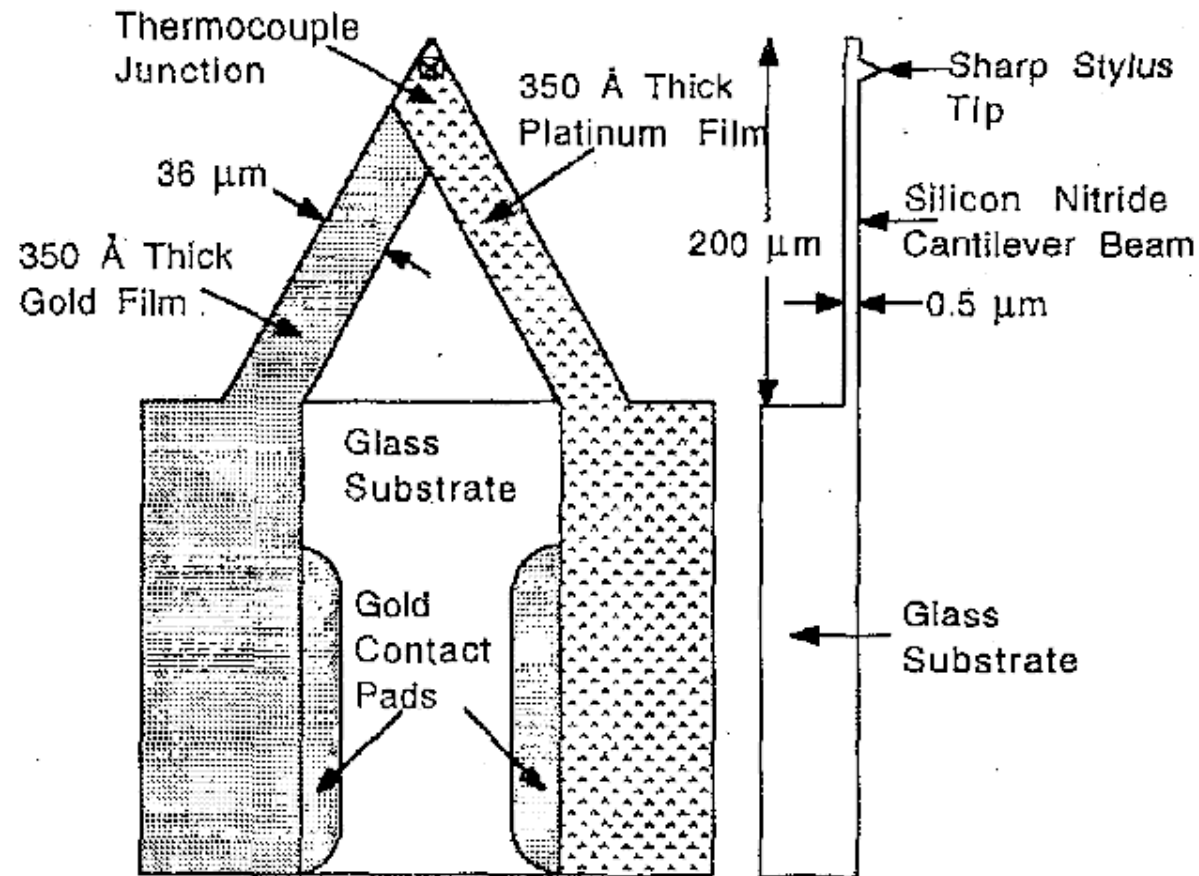
Passive mode: measuring the surface temperature

Thermocouple probe 1/4



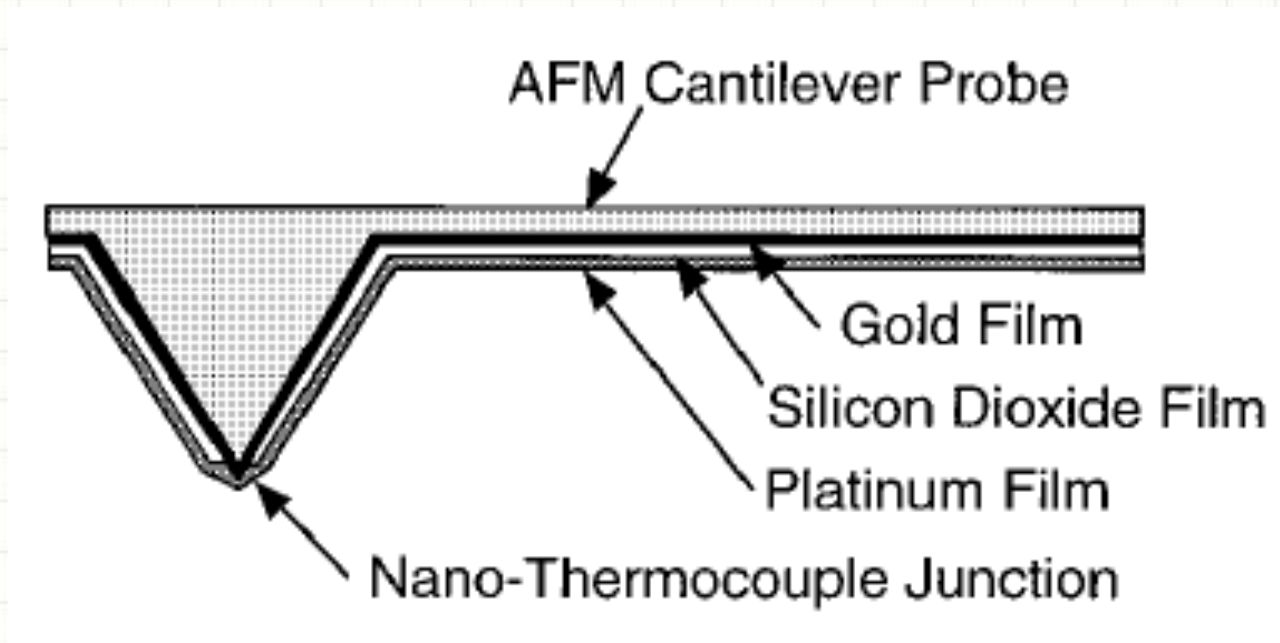
Thermocouple Probe developed by A. Majumdar in 1993 based on a K-type thermocouple

Thermocouple probe 2/4



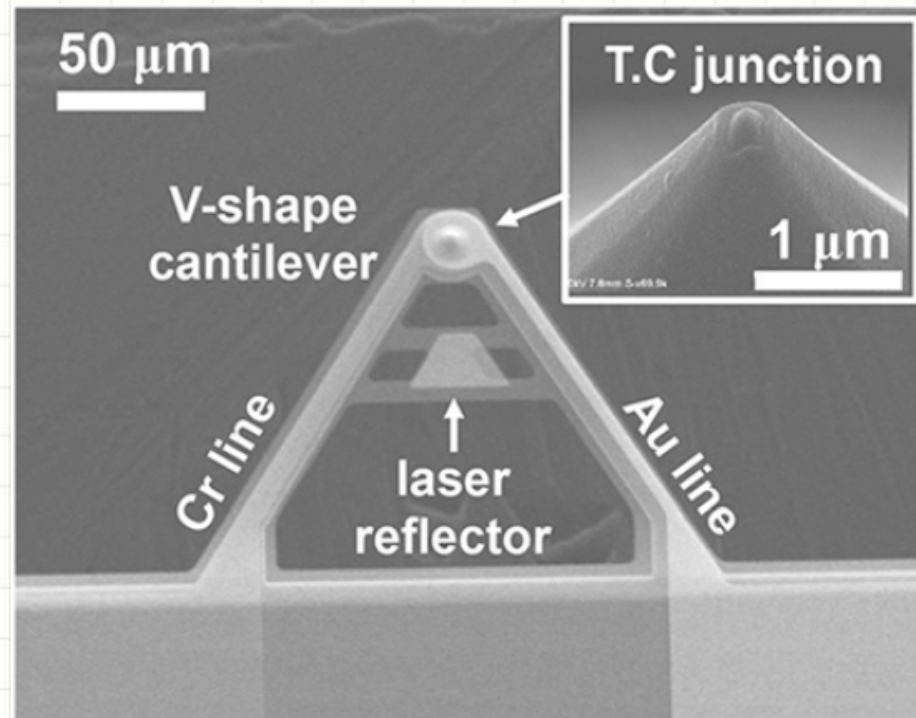
The Diamond tip Thermocouple Probe Introduced by A. Majumdar in 1995

Thermocouple probe 3/4

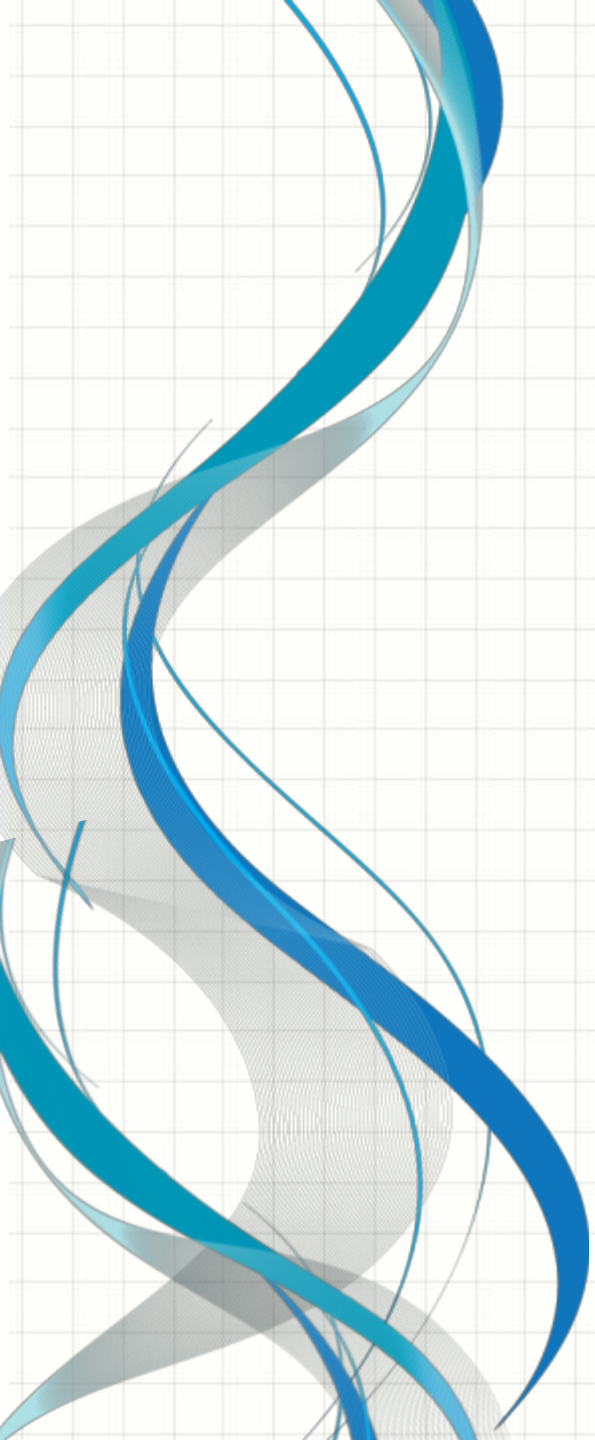


Thermocouple Probe tip demonstrated by K. Luo in 1996

Thermocouple probe 4/4

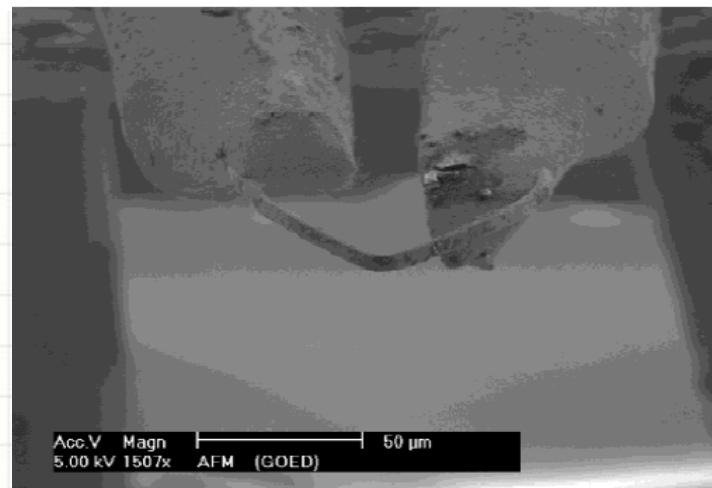
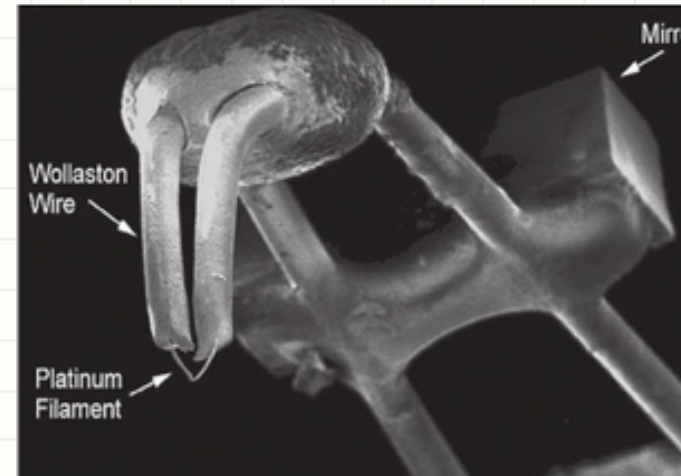
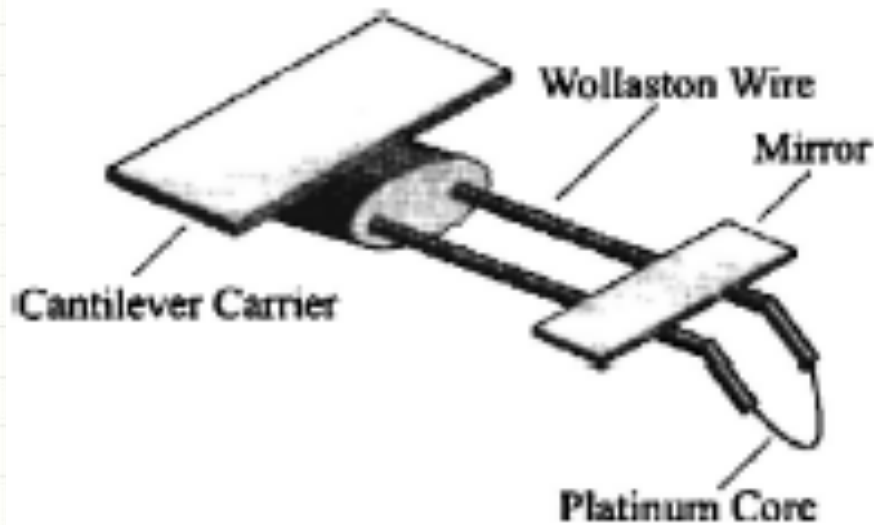


Thermocouple probe demonstrated by K. Kim et al. in 2014

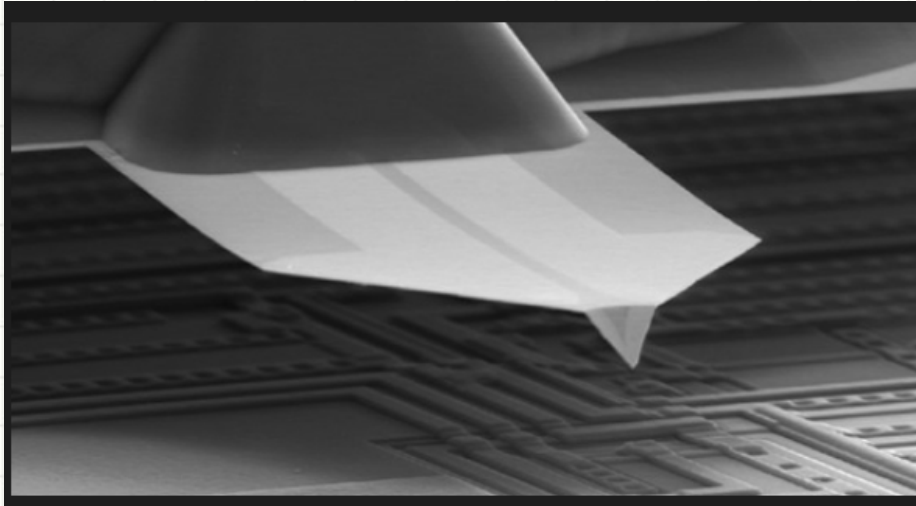


Active mode: heating
the probe and
measuring the
surface temperature
→ Measuring thermal
properties

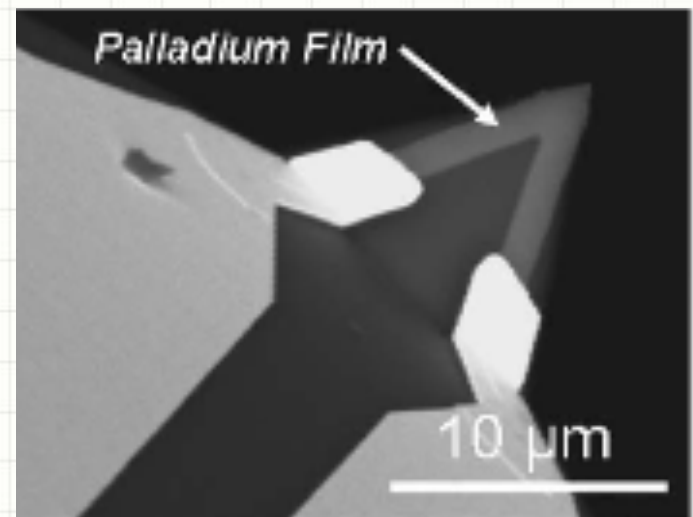
Thermoresistive Probes 1/4



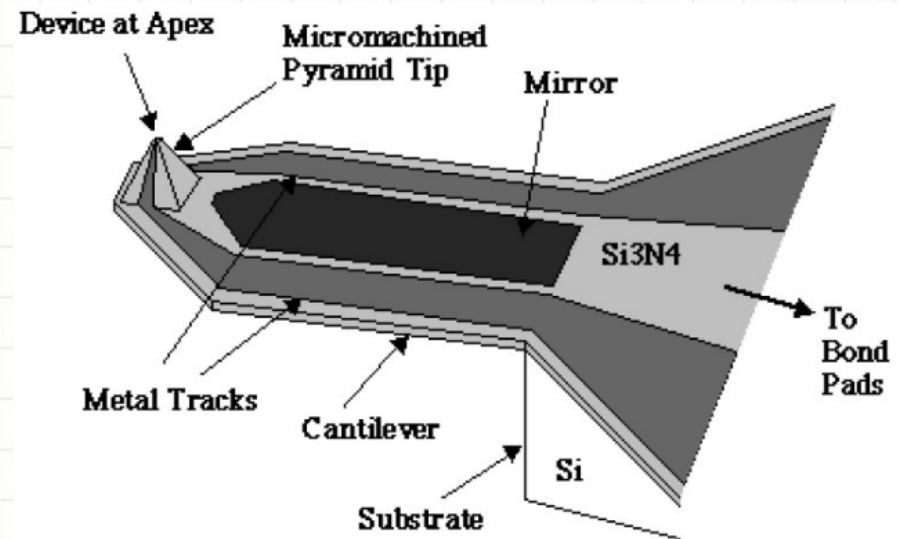
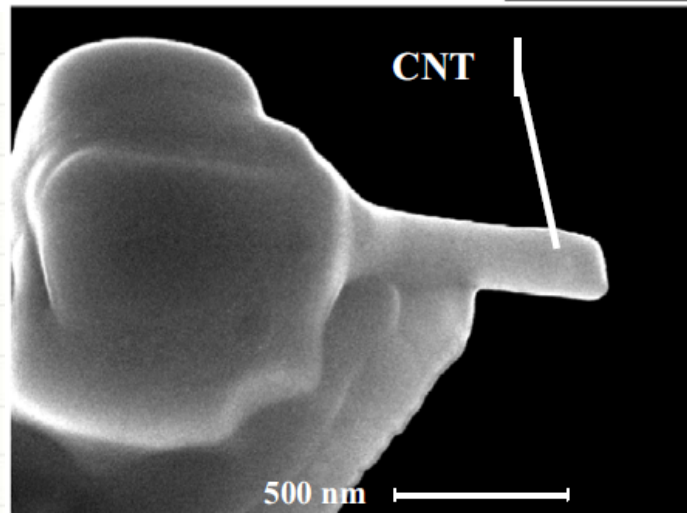
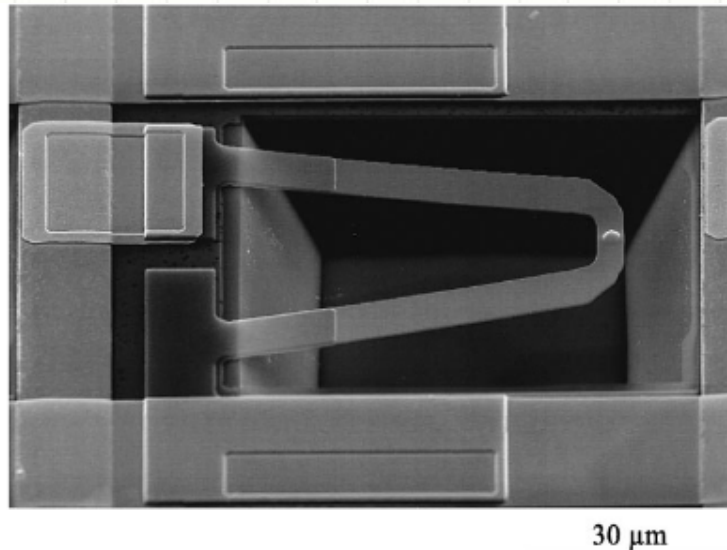
Thermoresistive Probes 2/4



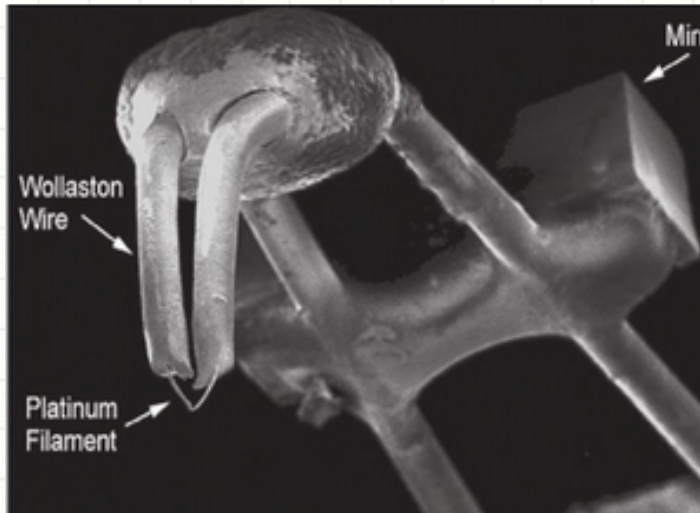
Micro-fabricated probes



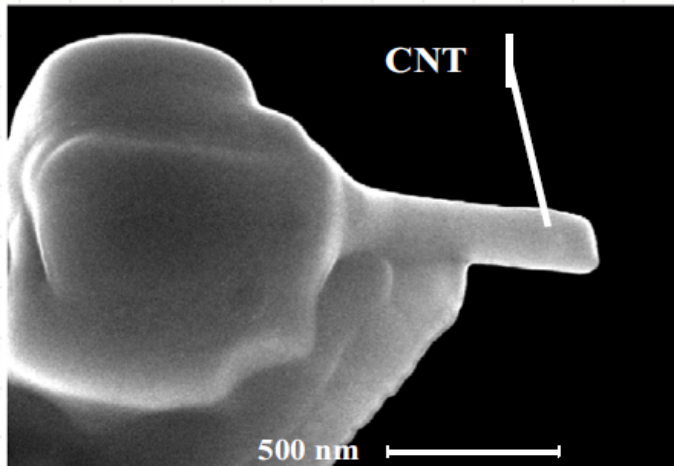
Thermoresistive Probes 3/4



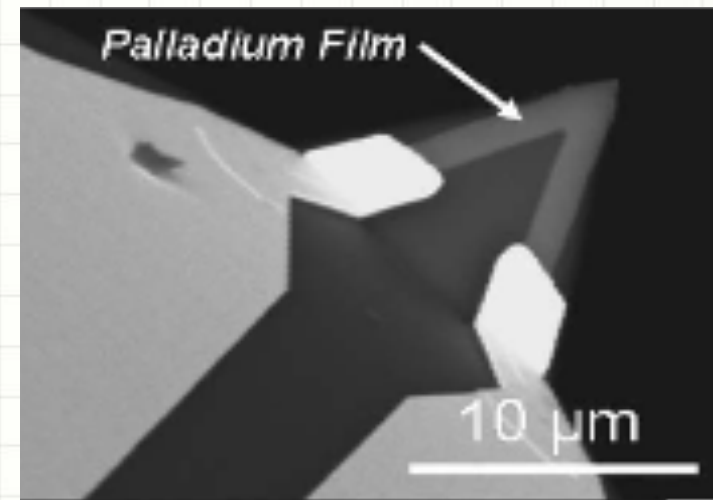
Thermoresistive Probes 4/4



5 μm



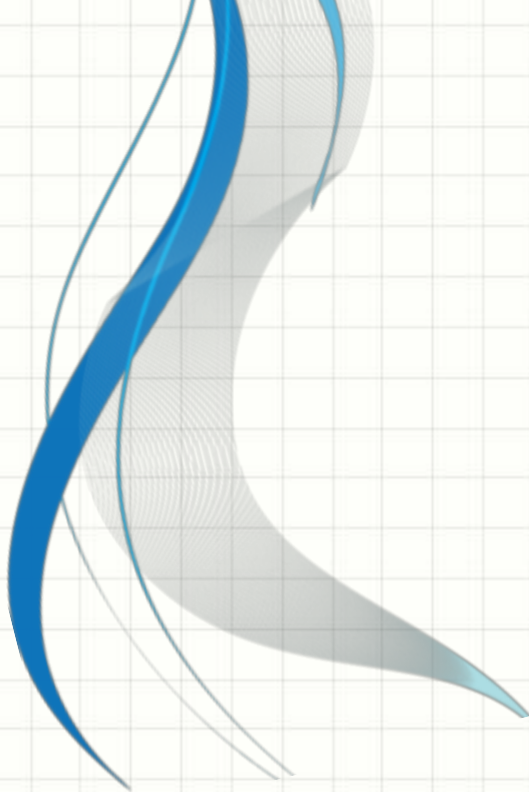
0.01 μm



0.1 μm

Type of Probe Used

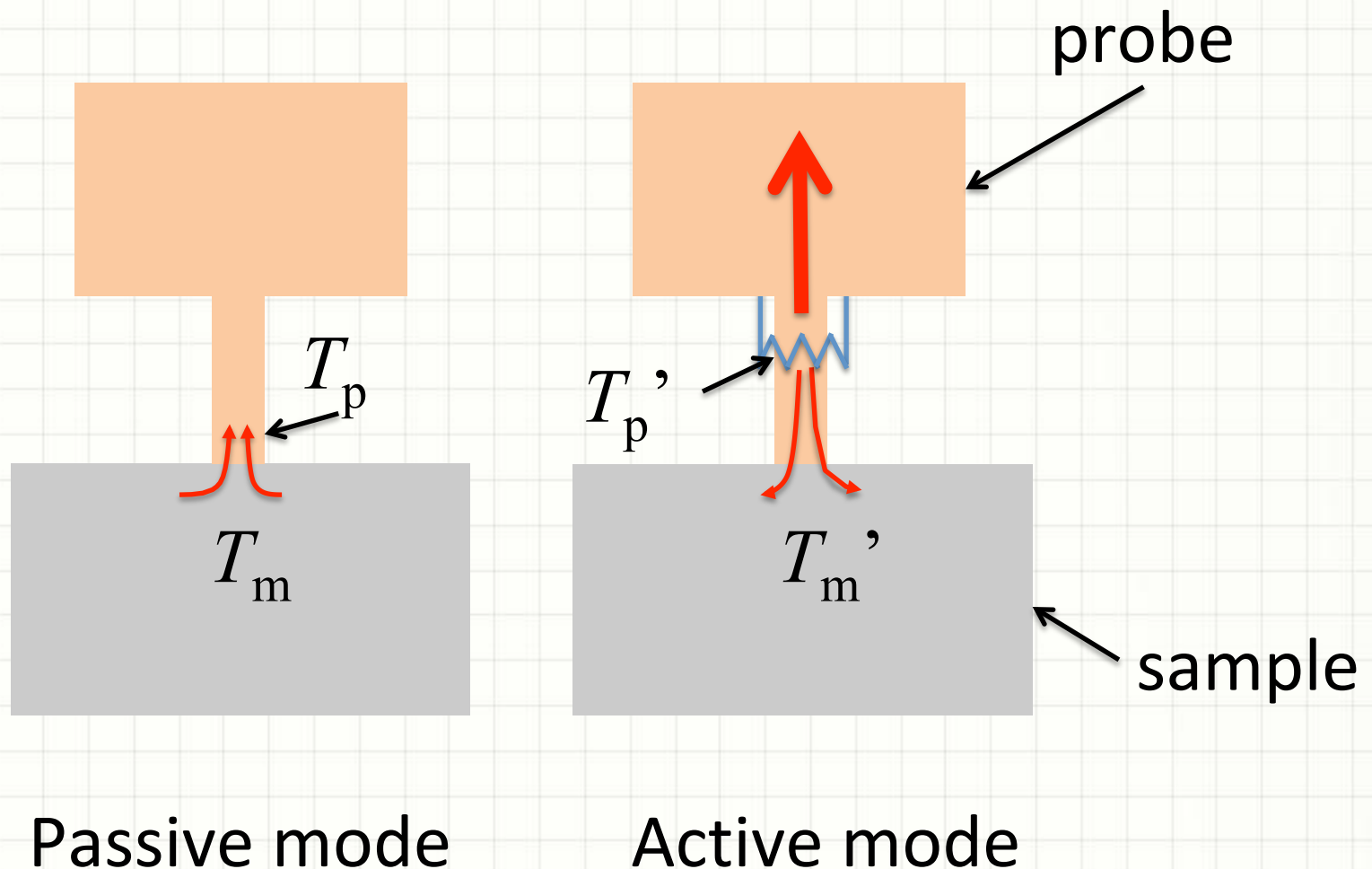
Probe Type	Thermocouple	Thermoresistive	Bimetallic	Fluorescent
Thermal sensor	Chromel-alumel ThC Au-Cr ThC Pt-Cr THc	Pt thermoresistor Pd thermoresistor Si thermoresistor	Al/Si bimetal	Er/Yb co-doped fluoride glass
Temperature change measurement principle	Electrical (Seebeck effect)	Electrical (resistance)	Frequency change	Optical
Mode	Passive	Passive & Active	Passive	Passive
Tip size	Usually < 50 nm	100 nm – 5 µm	<20 nm	200 nm
Spatial resolution	Even below 20 nm	About 100 nm	Unknown	< 1 µm
Durability	Medium	High	Unknown	Unknown



Heat transfer between probe and sample

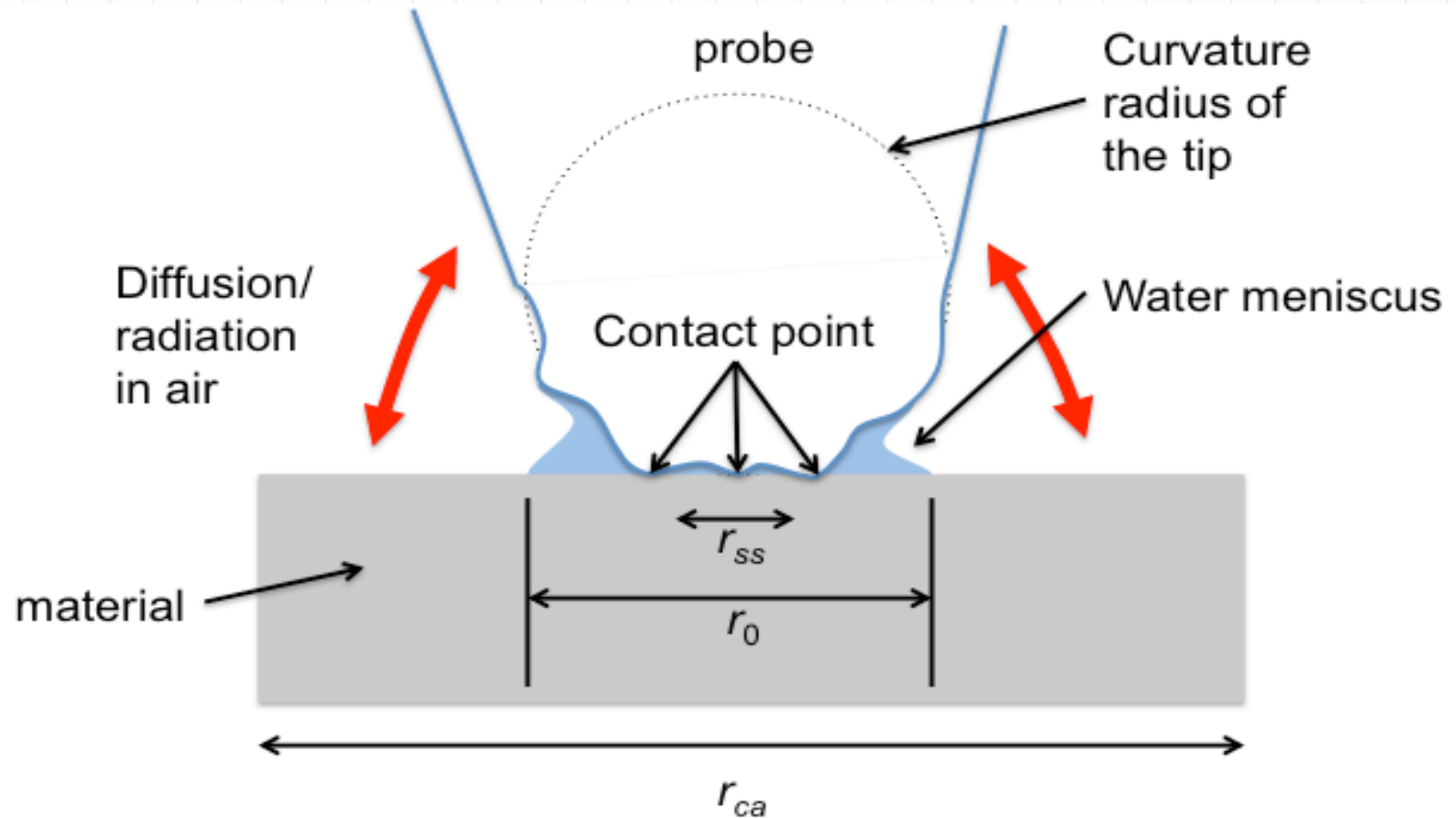
Physical Phenomena at the interface

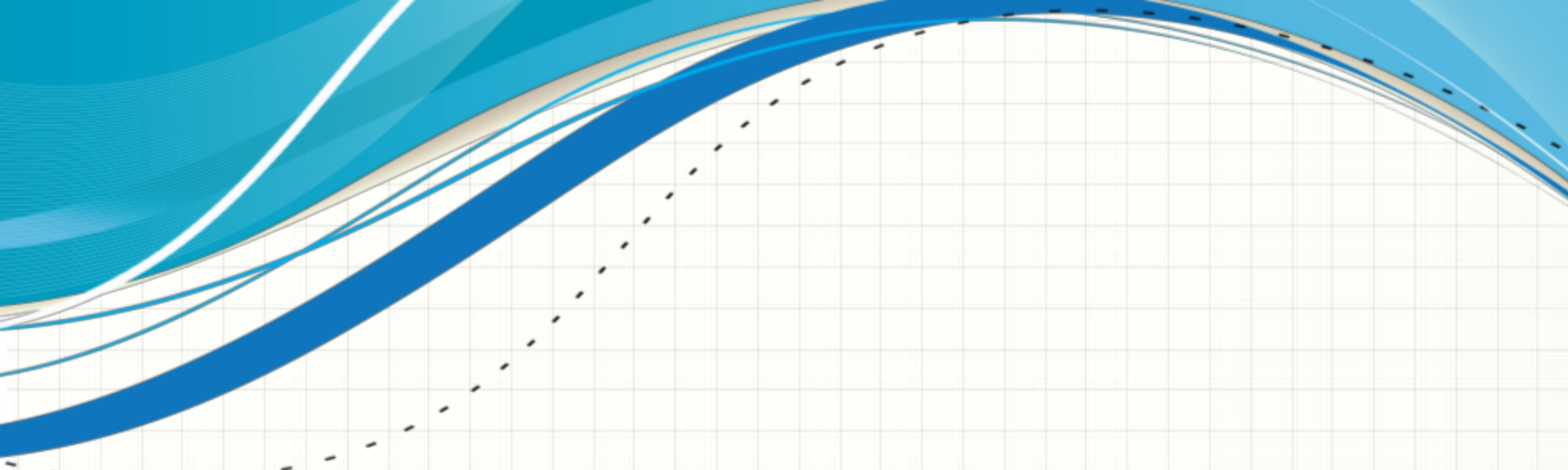
1/2



Physical Phenomena at the interface

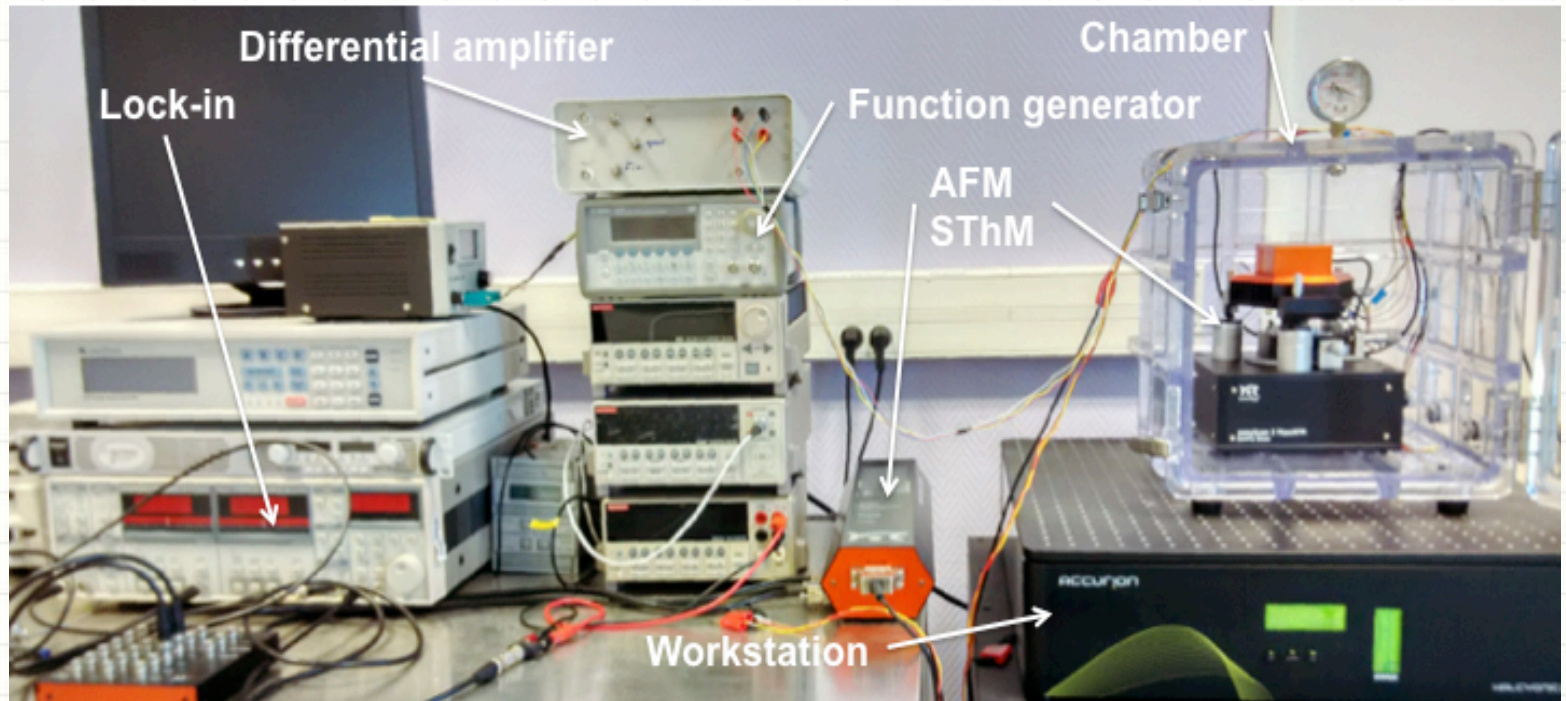
2/2





EXPERIMENTAL SETUP

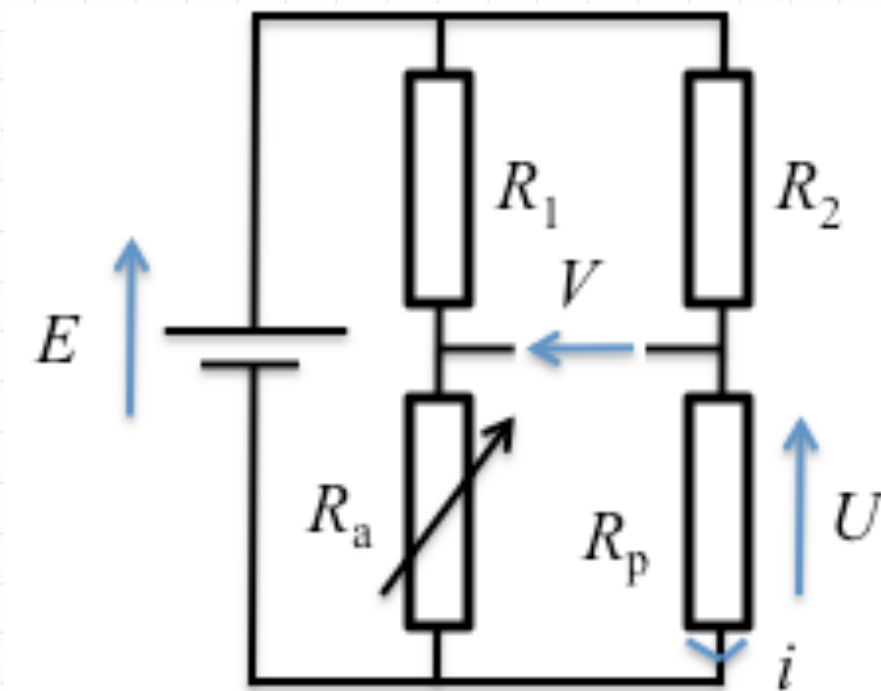
SThM Setup



AFM Nanosurf
Easyscan 2



SThM passive mode



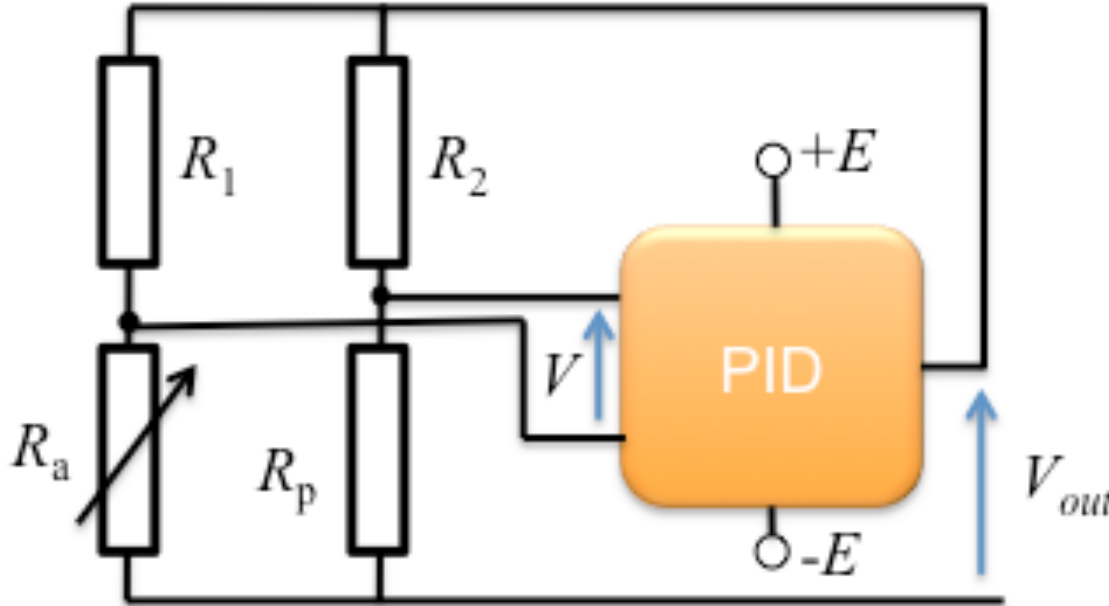
$$\Delta T = \frac{1}{\alpha_R} \frac{4V}{E - 2V}$$

$$\alpha_R = \left(1/R_0\right) dR/dT$$

Temperature
coefficient (TCR)

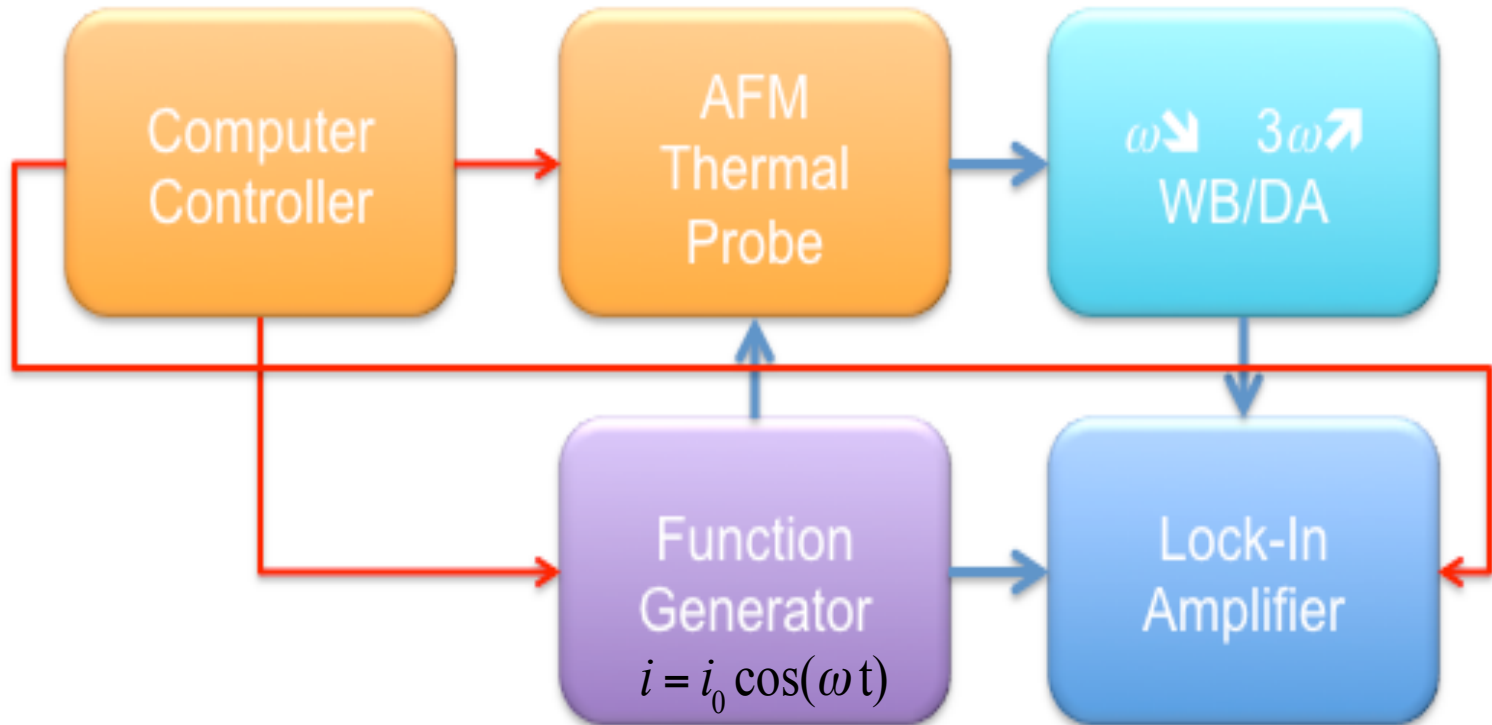
SThM active mode and continuous wave

$$\frac{P_{in} - P_{out}}{P_{in}} = \frac{\Delta P}{P_{in}} = \frac{V_{sec}^2 - V_{shc}^2}{V_{sec}^2} = f(k_m)$$



The probe in the probe is adjusted in order to have its temperature constant
 k_m is the sample thermal conductivity

SThM active mode and 3-omega signal

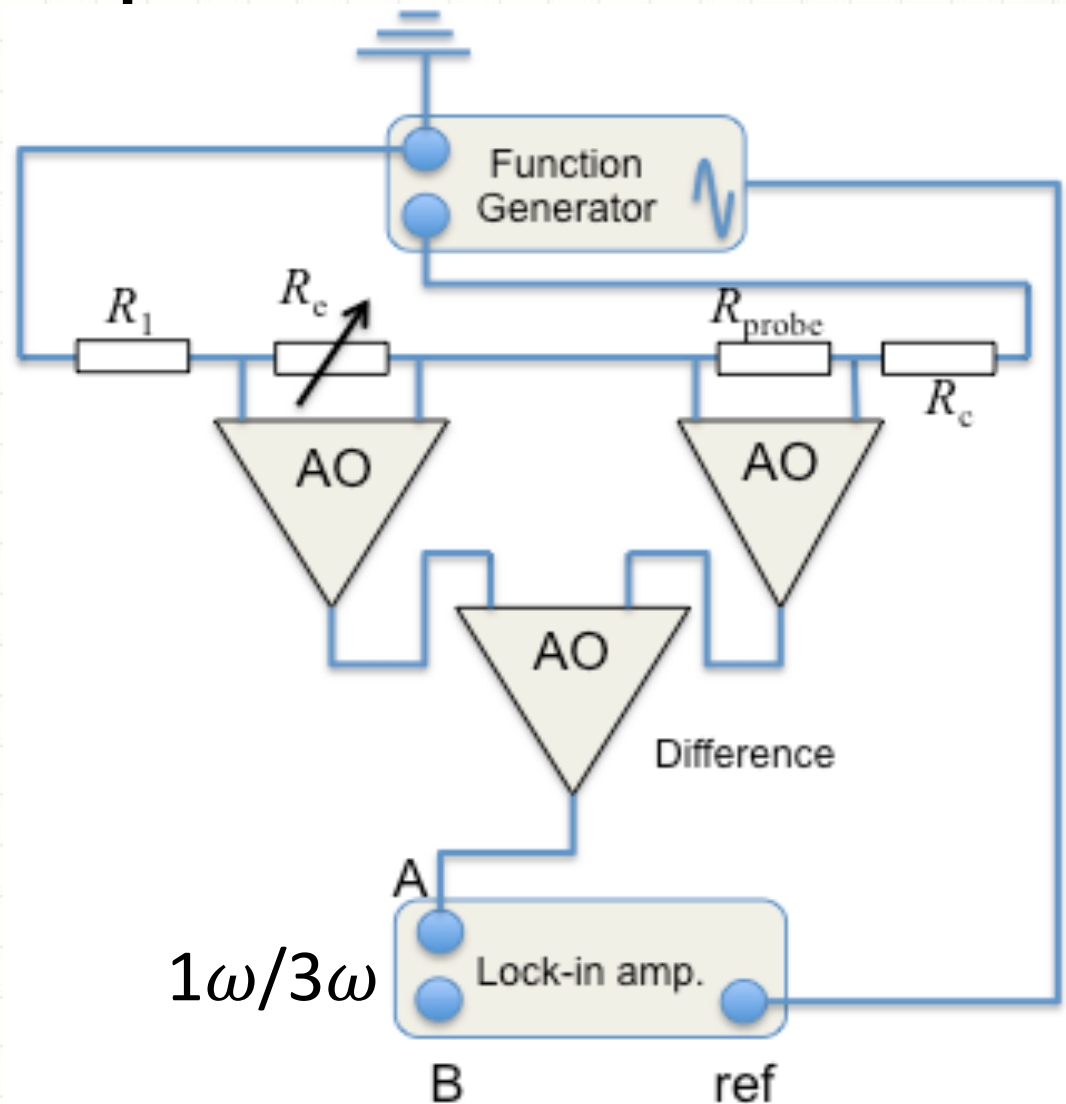


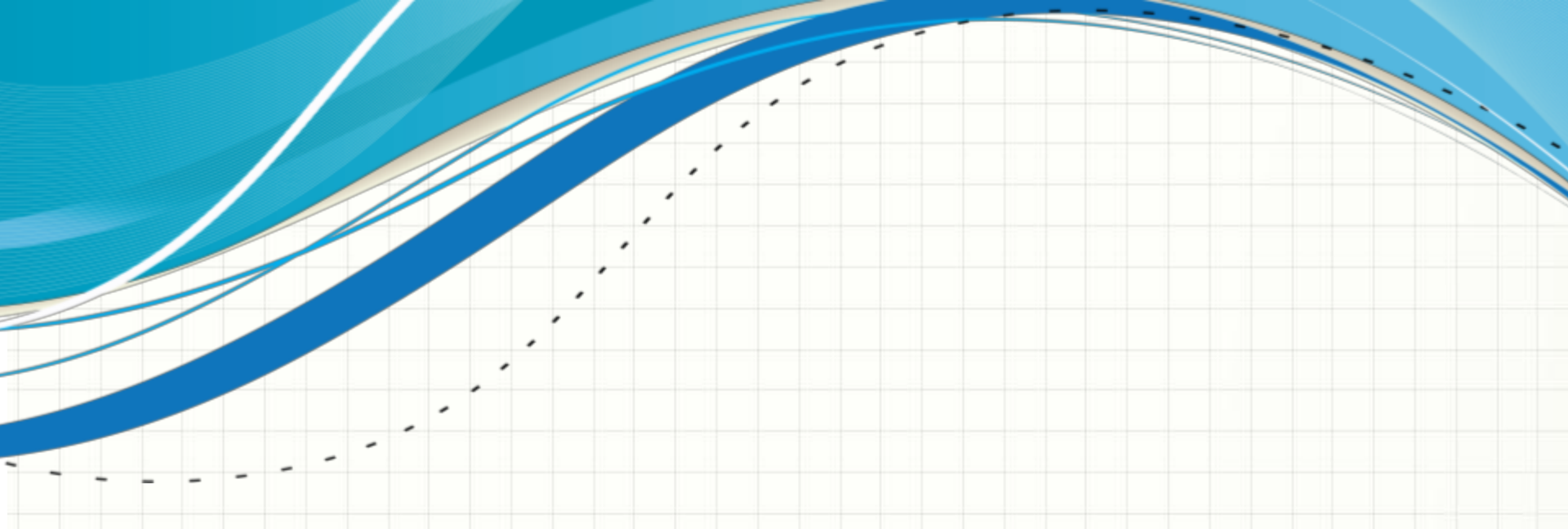
$$\Delta T_{2\omega} = \frac{2}{\alpha_R R_0 i_0} V_{3\omega} = \frac{2}{\alpha_R} \frac{V_{3\omega}}{V_0} = f(k_m)$$

Differential amplifier and lock-in

The goal is to minimize the 1-omega component with respect the 3-omega one

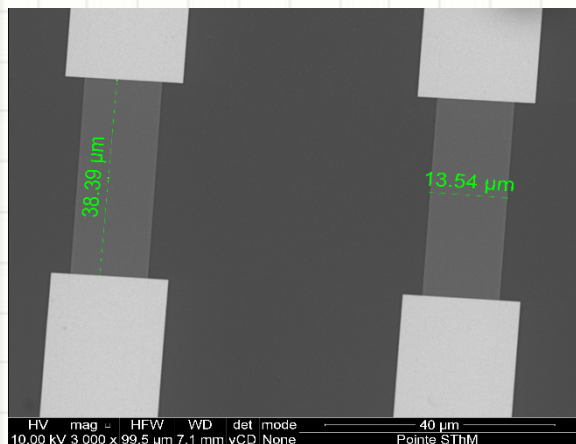
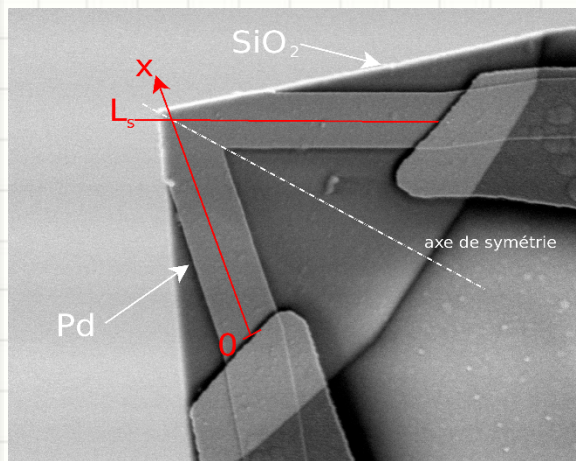
The lock-in leads to the amplitude and phase with the 3ω harmonic





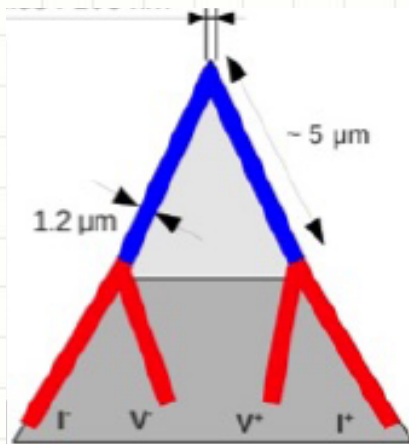
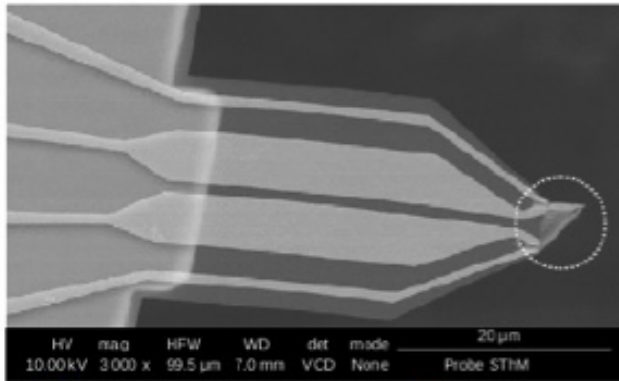
CALIBRATION

2-point probe



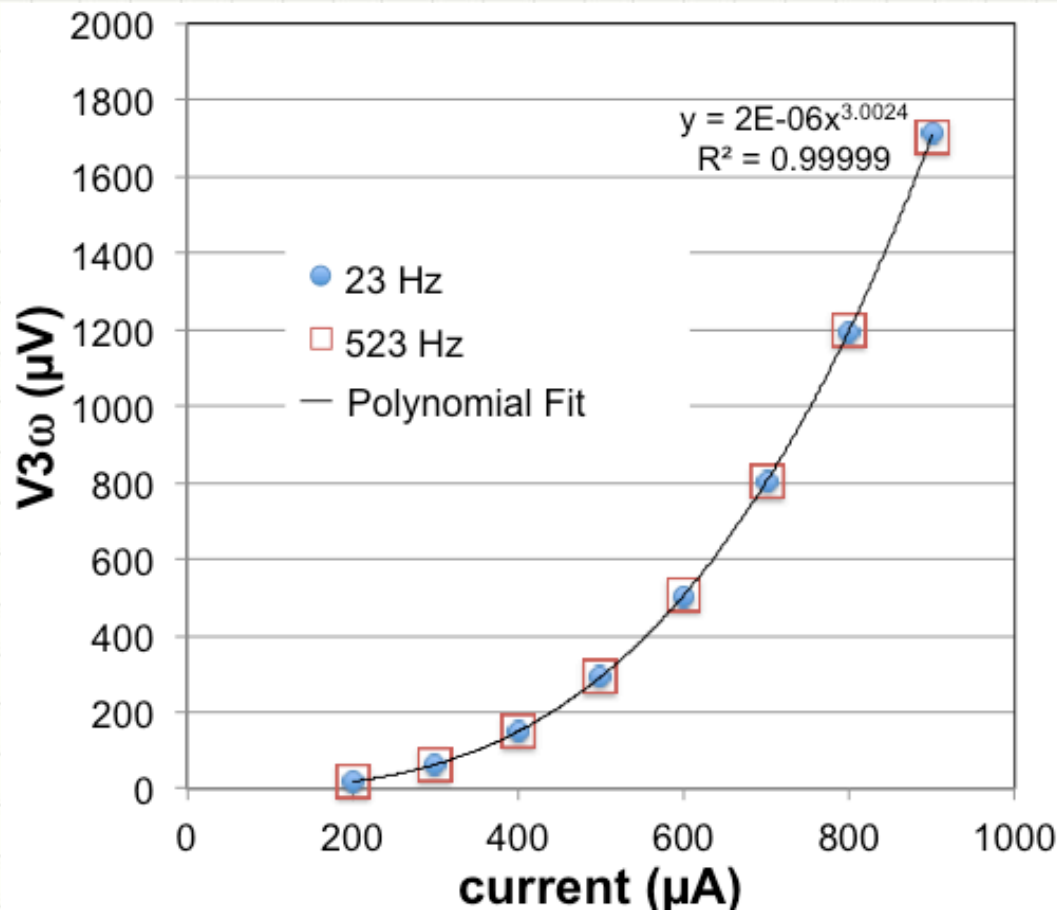
Provider	Anasys/ NanoAndMore	NT-MDT
Cantilever	Si ₃ N ₄	SiO ₂
Resistance metal	5 nm NiCr – 40 nm Pd	5 nm NiCr – 40 nm Pd
	5 nm NiCr – 140 nm Au	5 nm NiCr – 140 nm Au
Length x width	150 x 60 μm	150 x 60 μm
Thickness	0.4 μm	1 μm
Tip Height	10 μm	10 μm
Spring Constant	0.25 N/m	0.45 N/m
Resonant Frequency	50 kHz	48 kHz
Resistance	250-400 W (typ. 320 W)	300-500 W
Sensitivity	Approx. 1 W/°C	Approx. 1 W/°C
Tip Radius	< 100 nm	< 100 nm
Maximum controllable temperature	160 °C	160 °C

4-point probe



Probe base	2 mm x 3 mm
Cantilever (Si_3N_4)	150 μm x 60 μm x 1 μm
Resistor metal	5 nm NiCr – 40 nm Pd
Track and pad metal	5 nm NiCr – 140 nm Au
Resistance	300 – 500 Ohm
Tip Radius	< 100 nm
Maximum Temperature	160 °C
Tip height	10 μm
Si_3N_4 Spring Constant	0.25 N/m
Fo	48 kHz
Sensitivity	app. 1 Ohm/°C

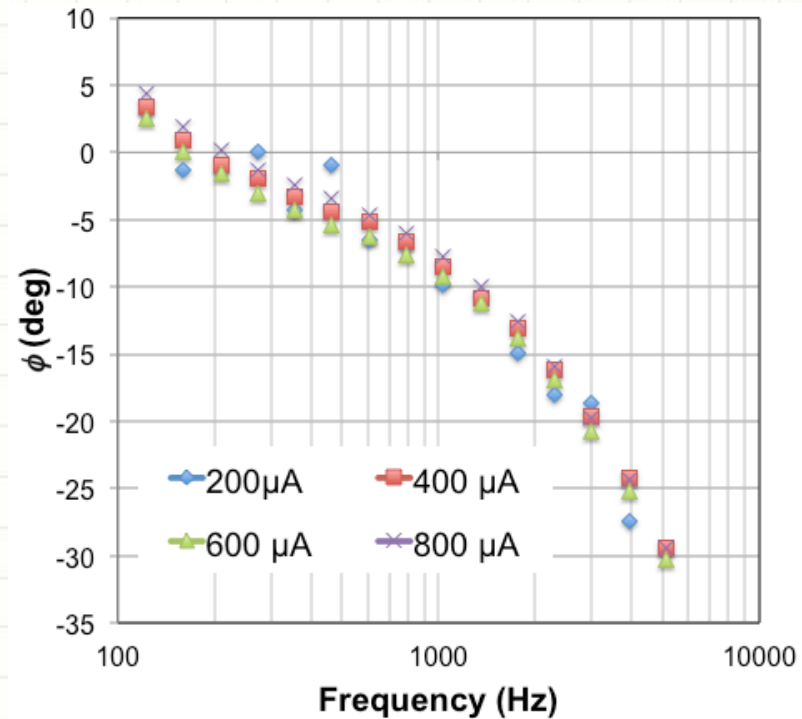
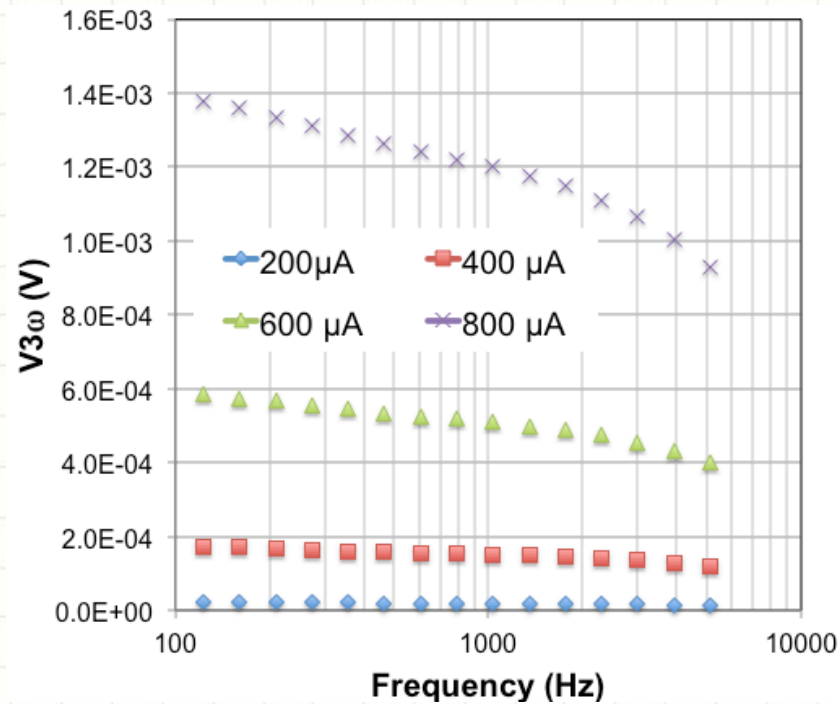
Checking the 3ω



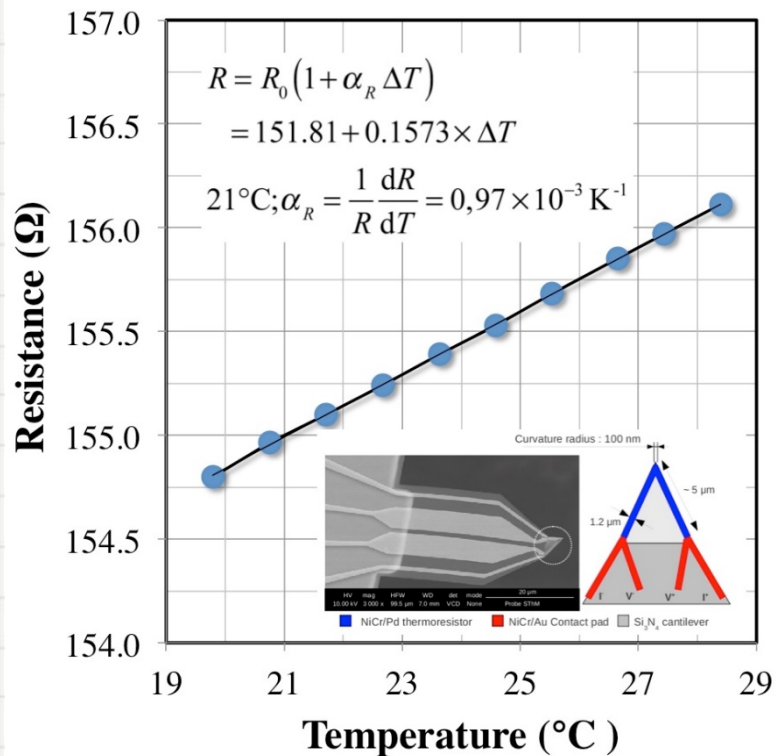
$$\left. \begin{array}{l} \Delta T_{2\omega} \propto P = \frac{Ri^2}{2} \\ Ri^2 \propto \frac{V_{3\omega}}{Ri} \end{array} \right\} \Rightarrow V_{3\omega} \propto i^3$$

$$V_{3\omega} = 2 \times 10^{-6} i^{3.0024}$$

Checking the linearity



TCR calibration

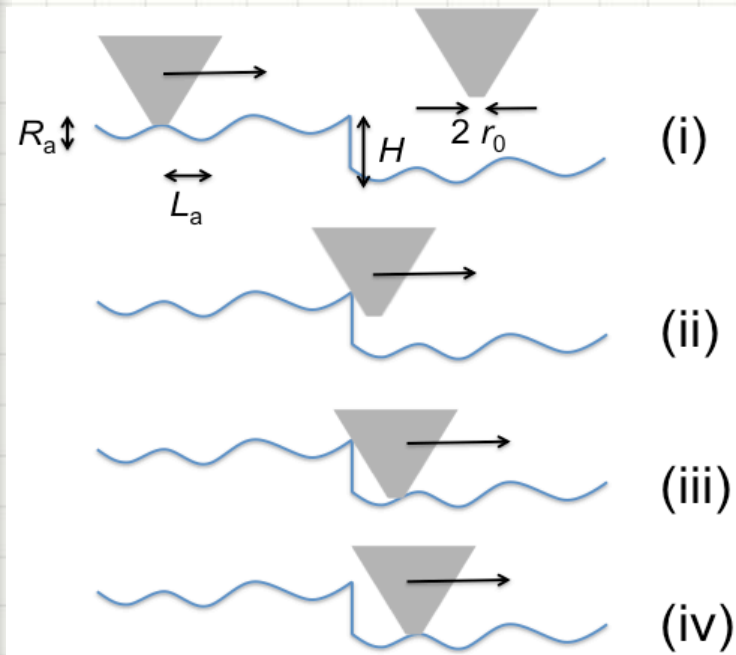


$$\alpha_R(Pd_{bulk}) = 3 \times 10^{-8} \text{ K}^{-1}$$

TCR	Associated Work	Manufacturer
$(1.3-1.6) \times 10^{-3} \text{ K}^{-1}$	Present work (2 point probe)	Anasys Instruments & NanoandMore
$1.2 \times 10^{-3} \text{ K}^{-1}$	Puyoo et <i>al.</i>	Anasys Instruments
$1.37 \times 10^{-3} \text{ K}^{-1}$	A. Assy et <i>al.</i>	Kelvin Nanotechnology
$0.97 \times 10^{-3} \text{ K}^{-1}$	Present Work (4 point probe)	Kelvin Nanotechnology

Scanning → Surface preparation

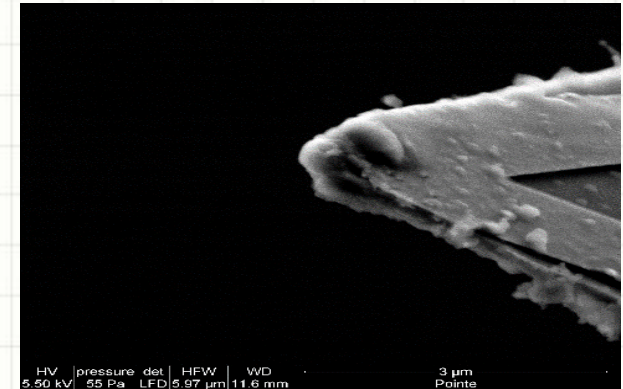
Sample Irregularities



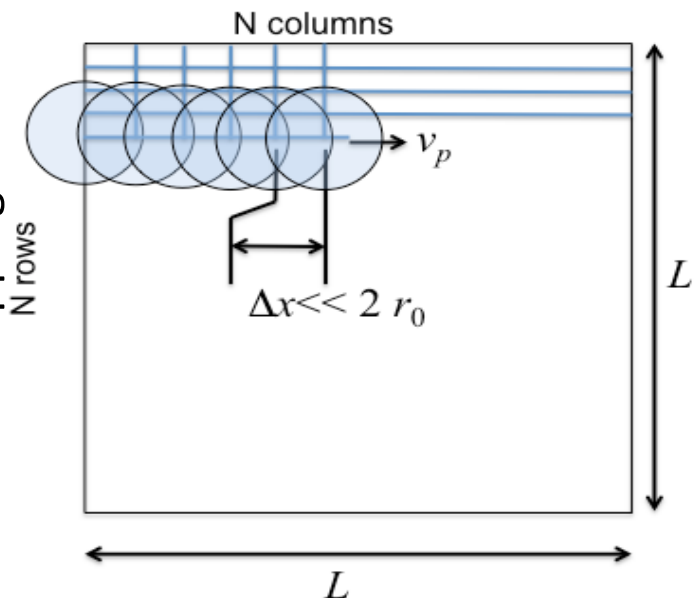
Classic solid-solid contact

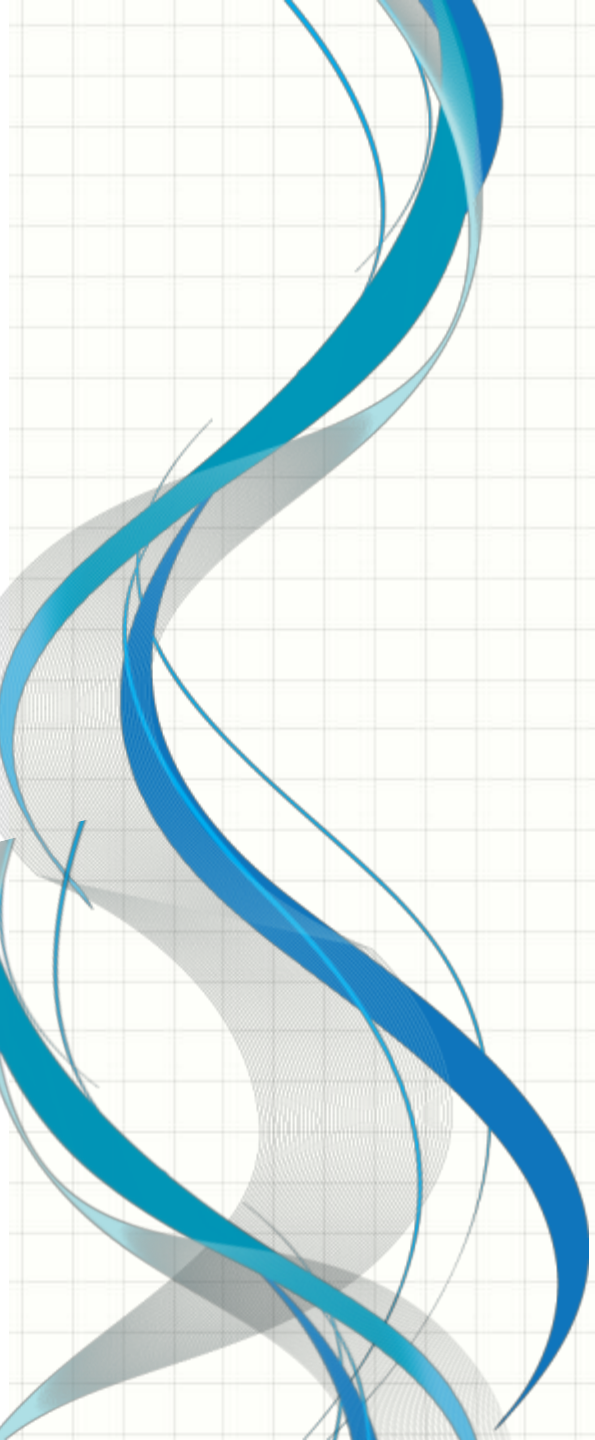
$$\begin{cases} 2r_0 < L_a \\ 2r_0 > R_a \end{cases}$$

Probe After Use



Overlapping

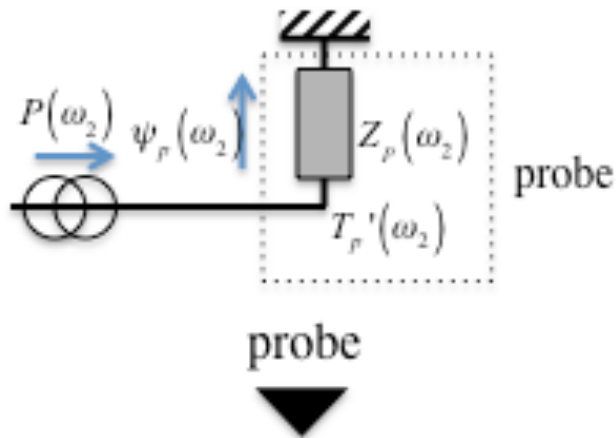




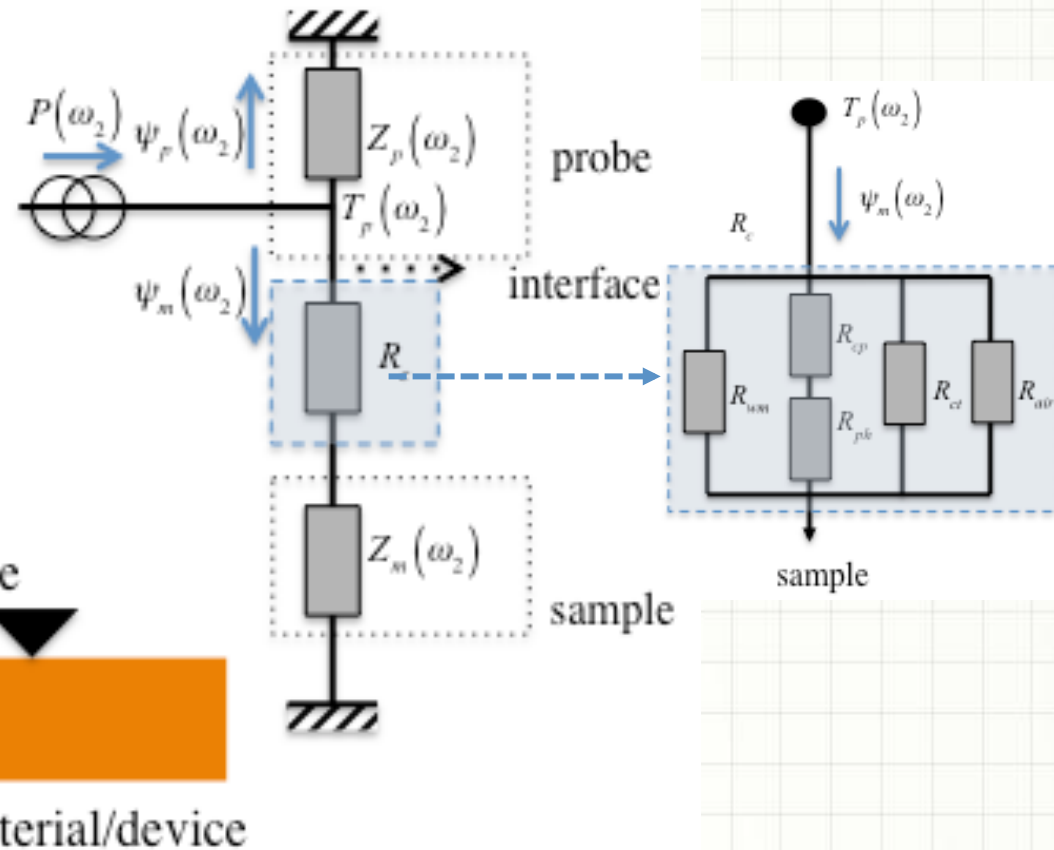
Heat transfer model

Heat Transfer Model

Non Contact mode



Contact mode



$$\|T_p(\omega)\| = \left\| \frac{P_0}{1/Z_p + 1/(R_c + Z_m)} \right\|$$

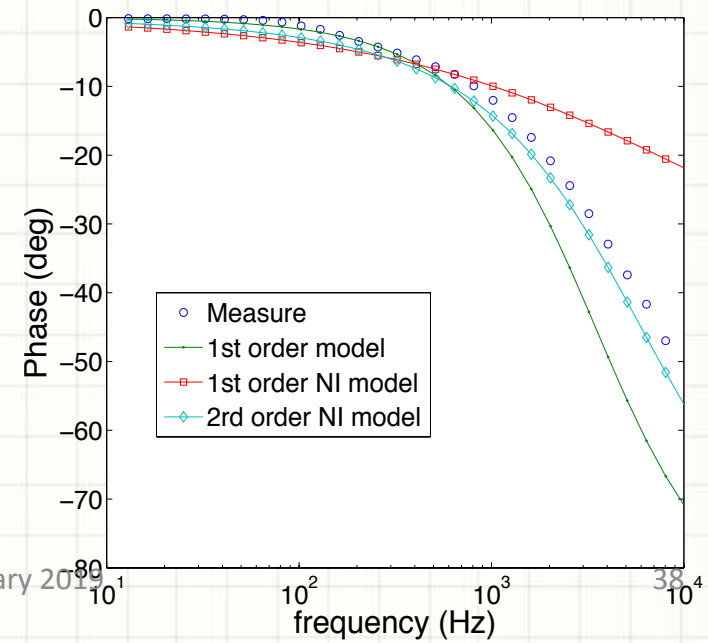
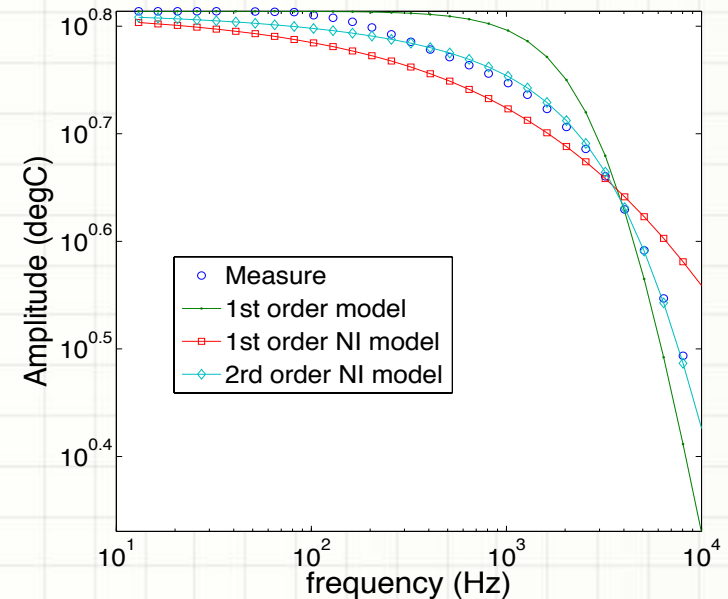
$$\delta(\omega) = \arg \left(\frac{P_0}{1/Z_p + 1/(R_c + Z_m)} \right)$$

$Z_p(\omega)$ and $Z_m(\omega)$

- The probe thermal impedance is identified experimentally (out-of-contact mode). We showed that

$$Z_p(\omega) = \frac{a_0}{1 + b_0 \sqrt{j\omega} + b_1 j\omega}$$

- The probe thermal impedance can be slightly modified when in contact with the surface → we assumed this additional constriction resistance is included within R_c .
- The material thermal impedance is either analytical (integral transforms) or discrete (FEA with semi infinite behavior)



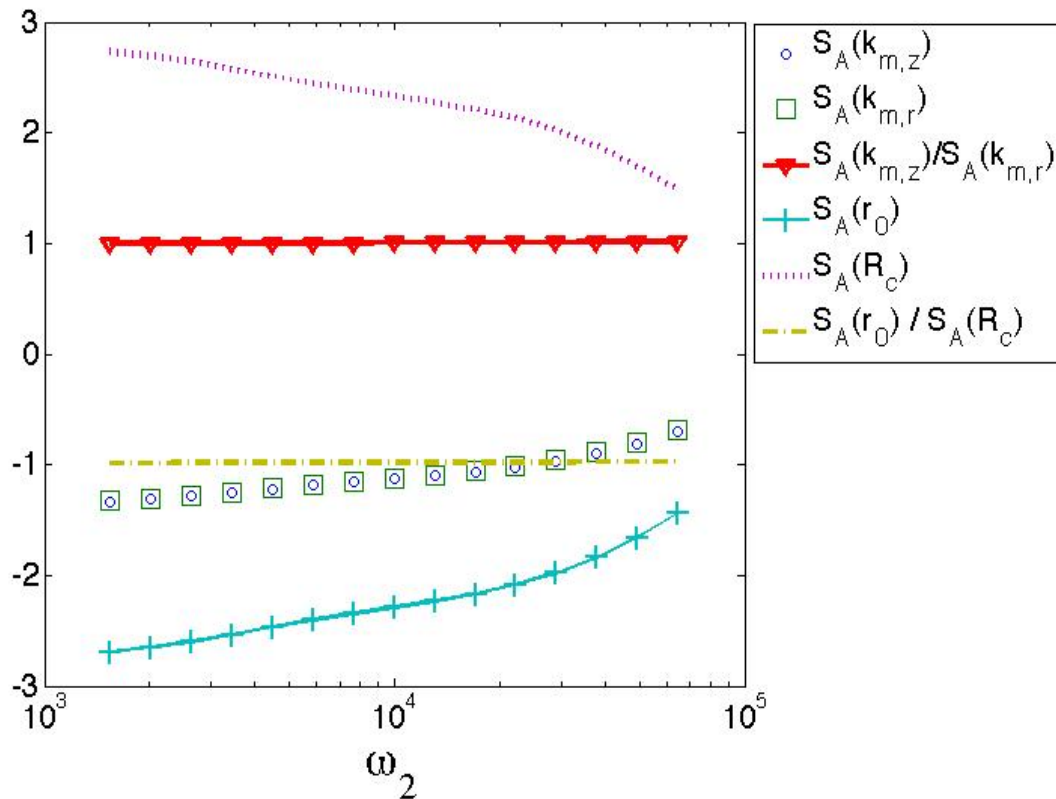
Unknown Parameters - Sensitivity analysis

Related to probe
& sample contact

$$r_0, R_c$$

Related to
sample
properties

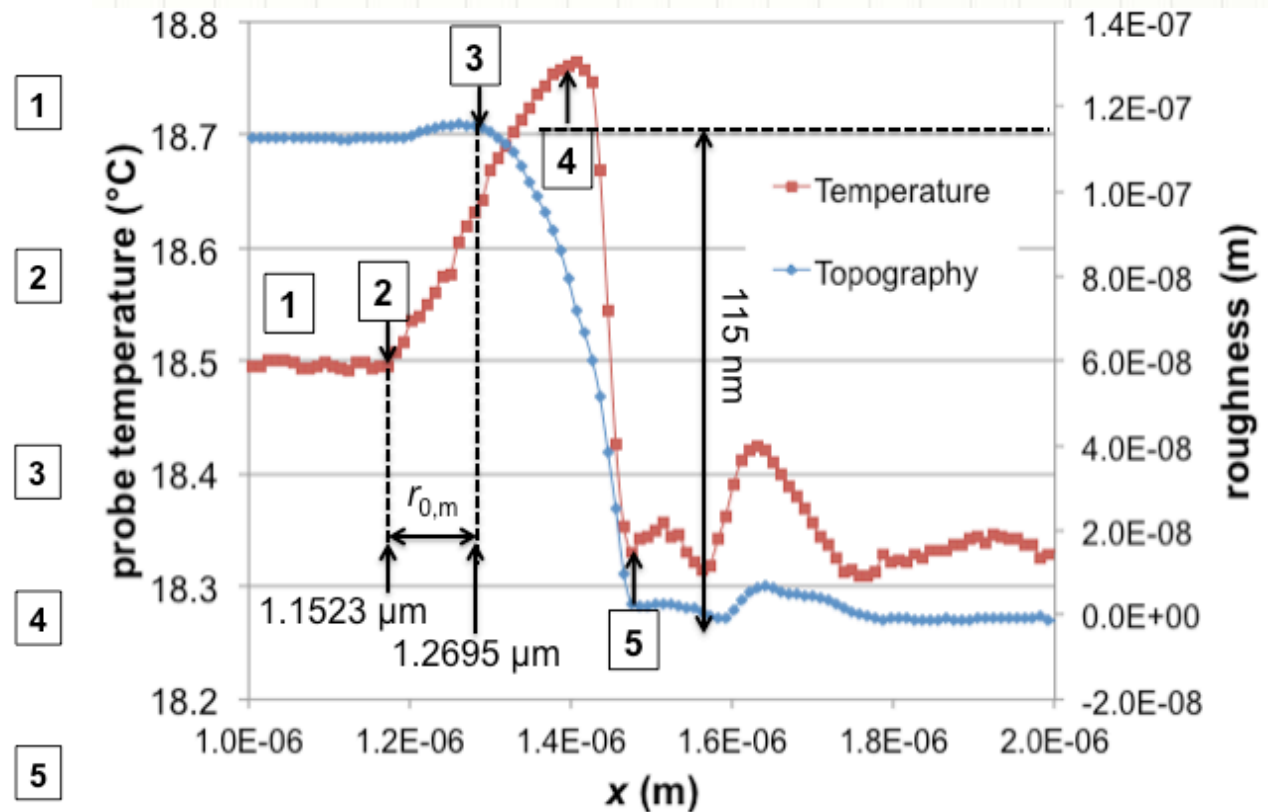
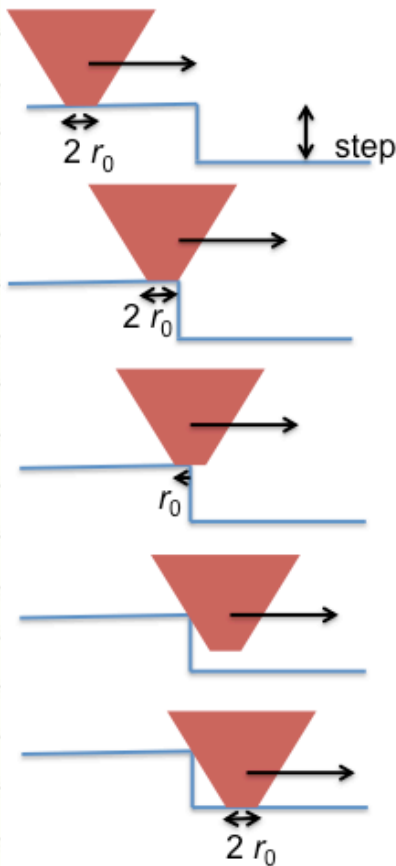
$$k_m, \text{TBR}$$



The sensitivity functions are linearly dependent $\rightarrow$ The simultaneous identification of the parameters is impossible

We need to define a way to identify them separately or using another set of experimental data

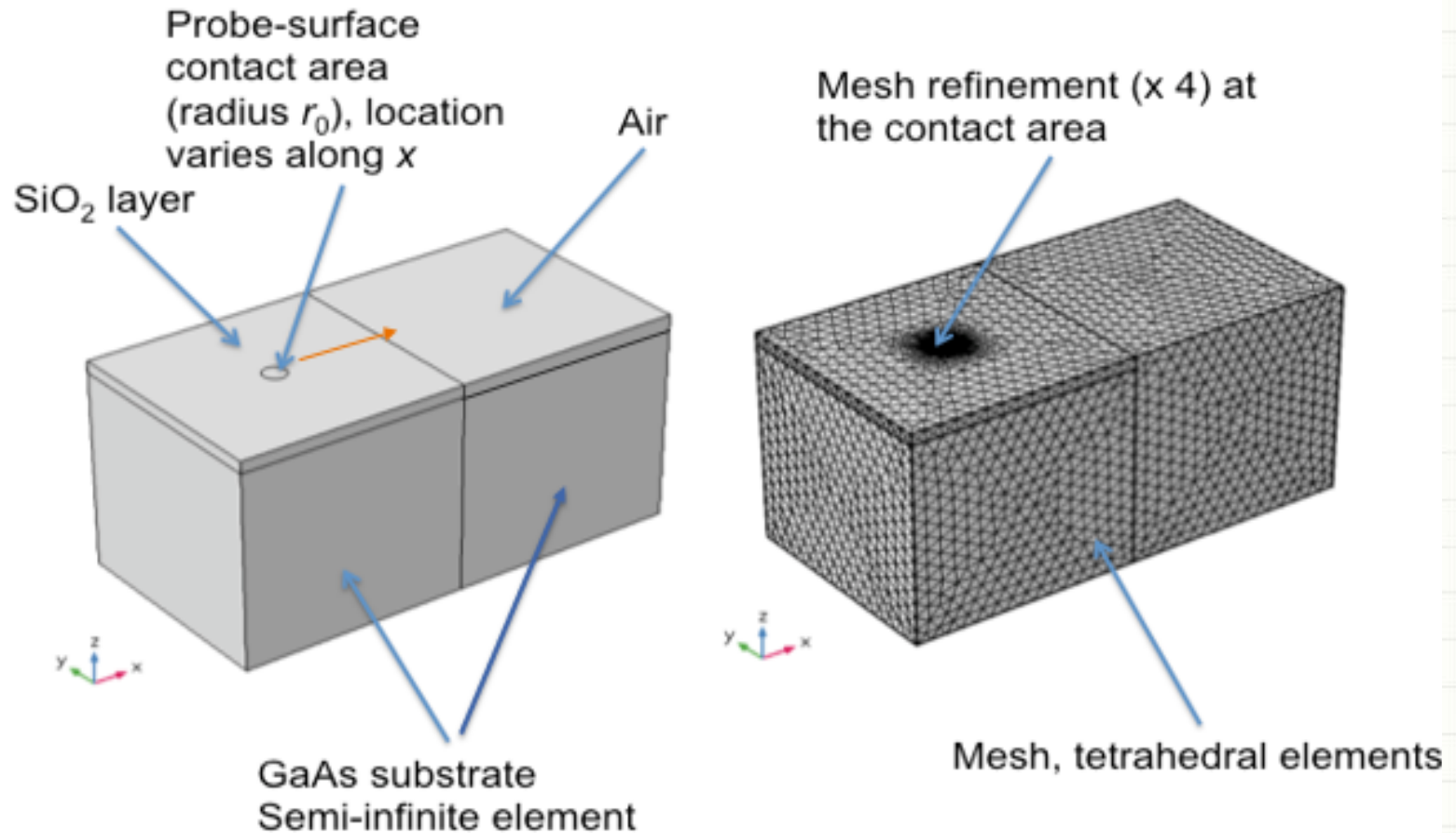
Radius direct measurement



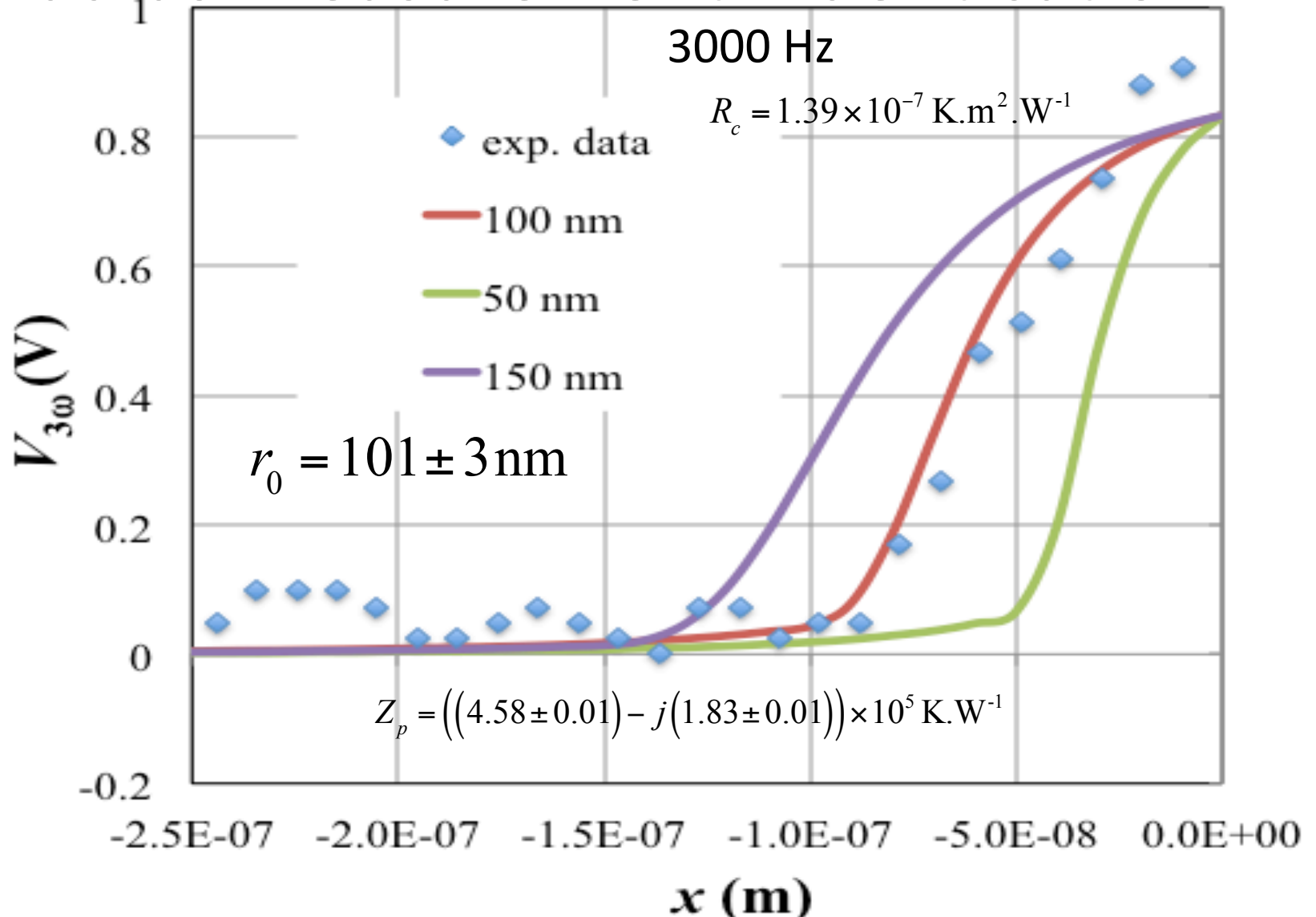
$$r_0 = 117 \text{ nm}$$

Radius Measurement – Identification

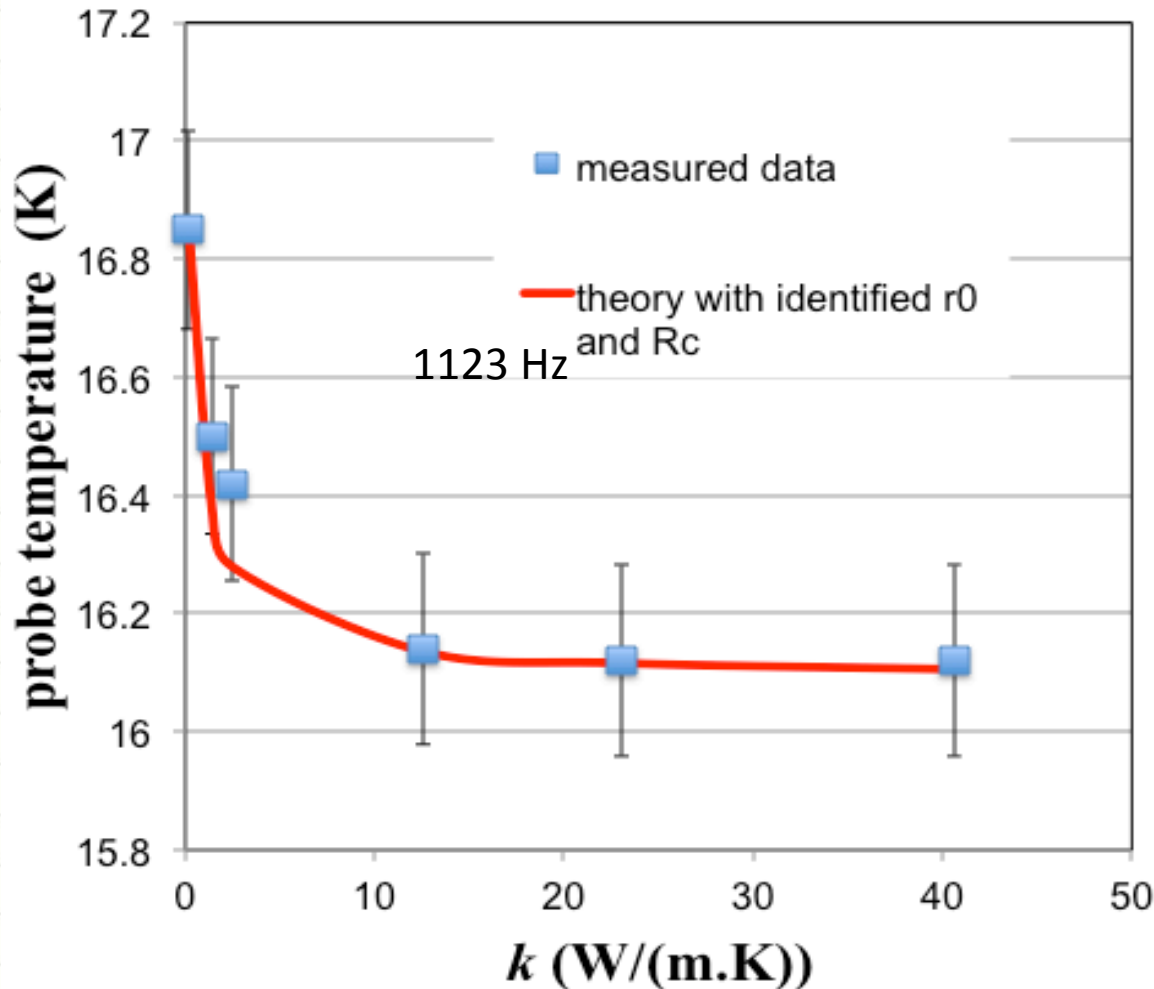
1/2



Radius Measurement - identification

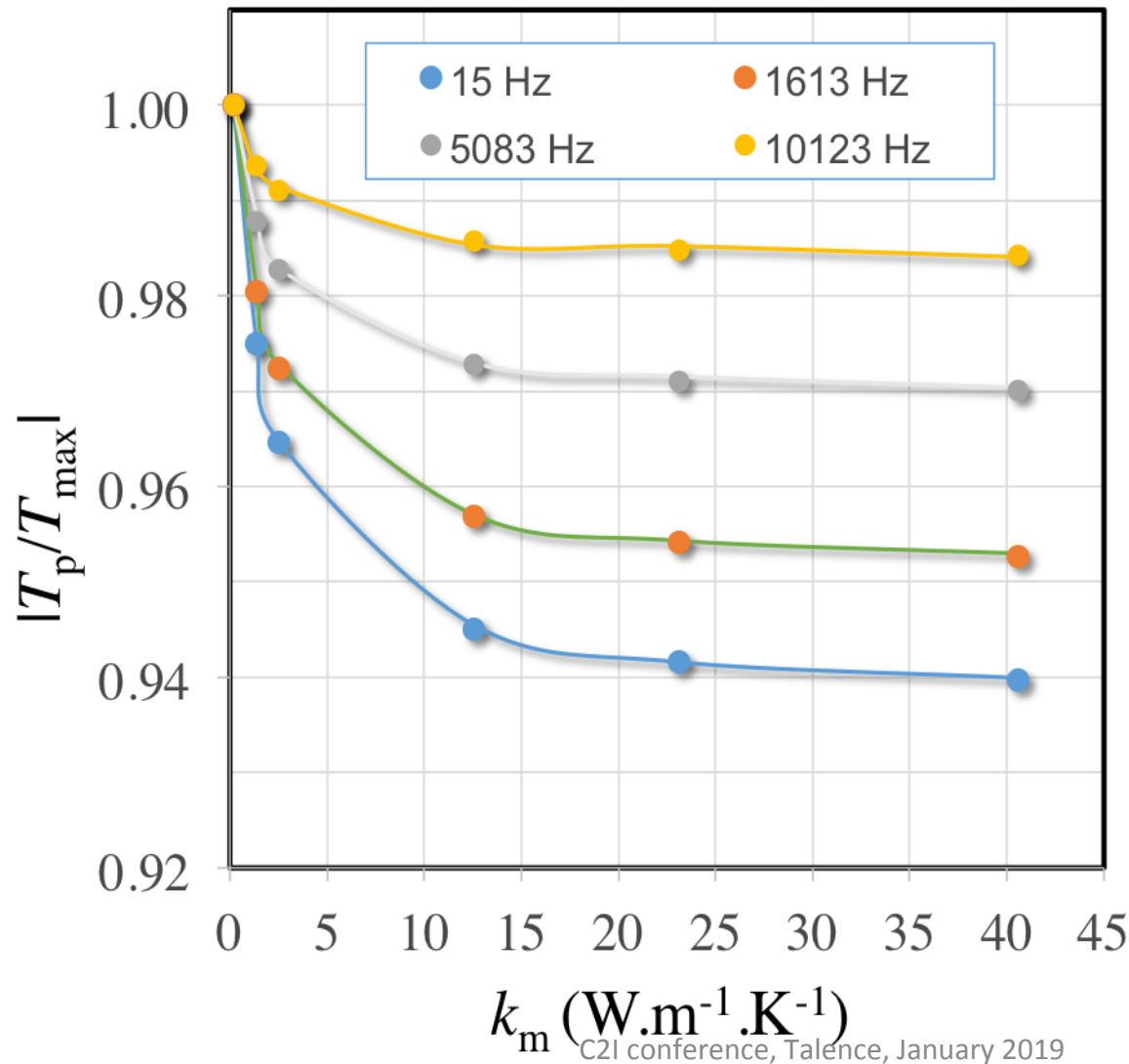


Sensitivity

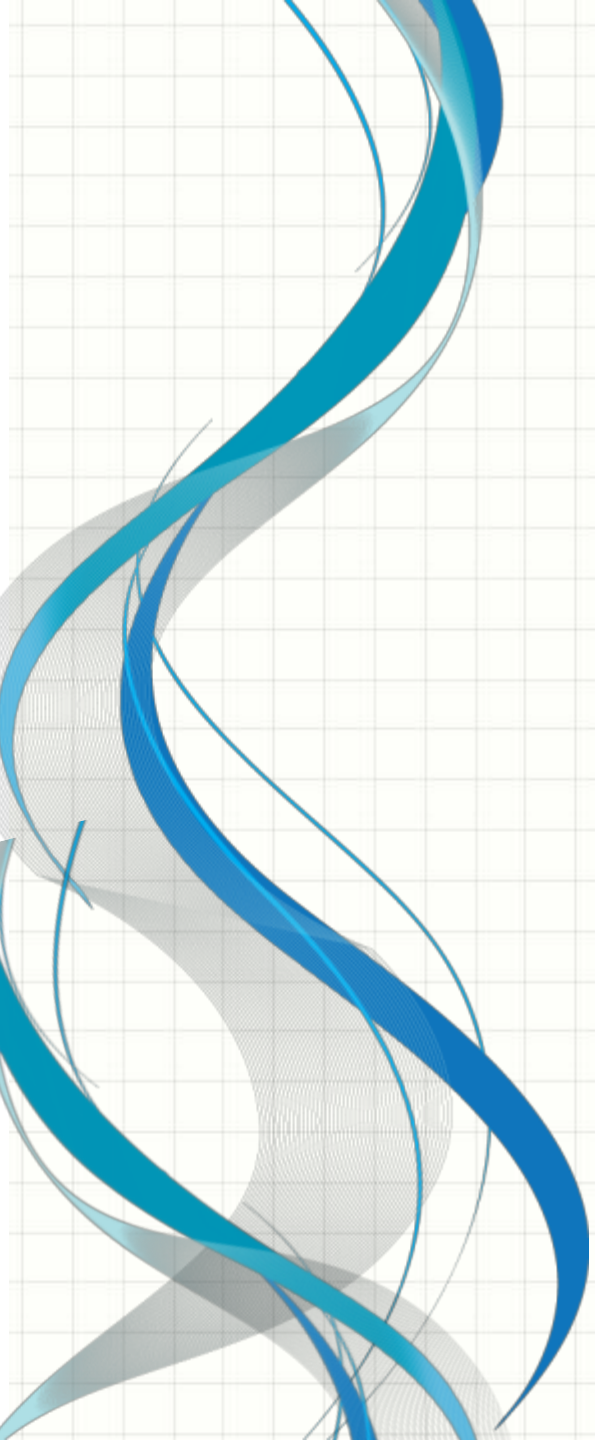


Probe: 2 point
Status: Motion
Condition:
Atmosphere

Sensitivity



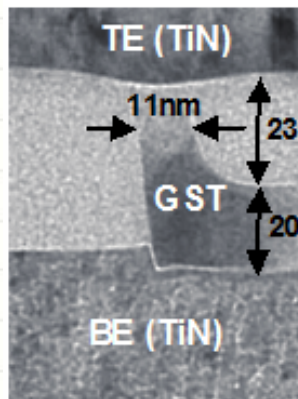
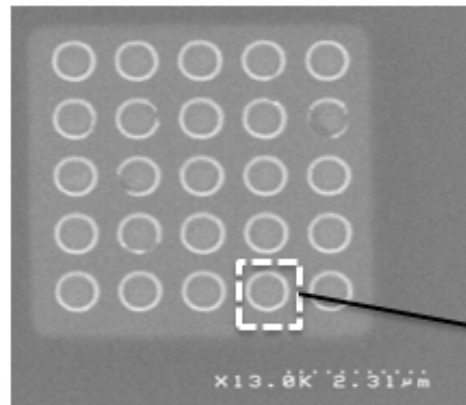
Probe: 4 point
Status:
Motionless
Condition:
Vacuum



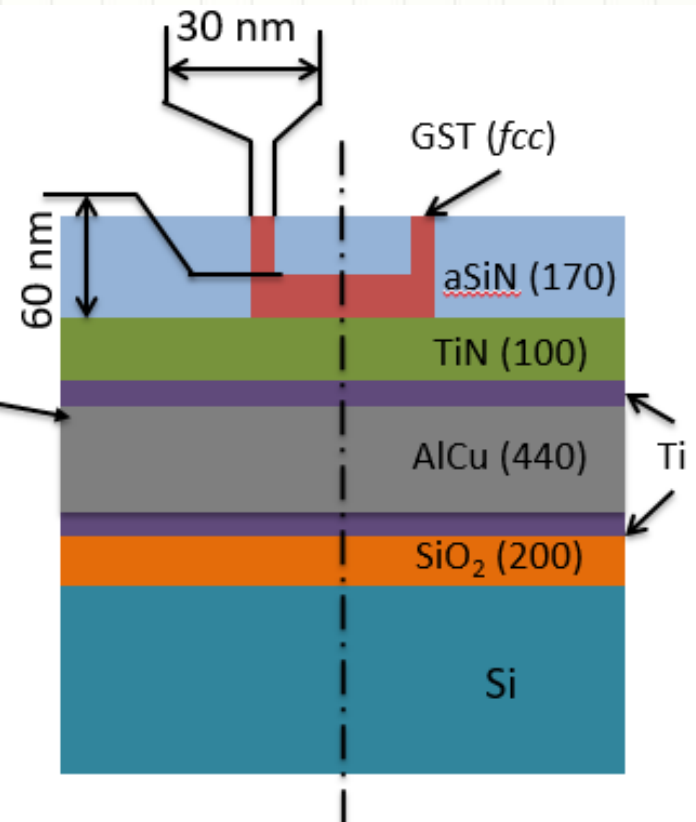
Applications

Application: Phase Change Memory Device

Pattern top view

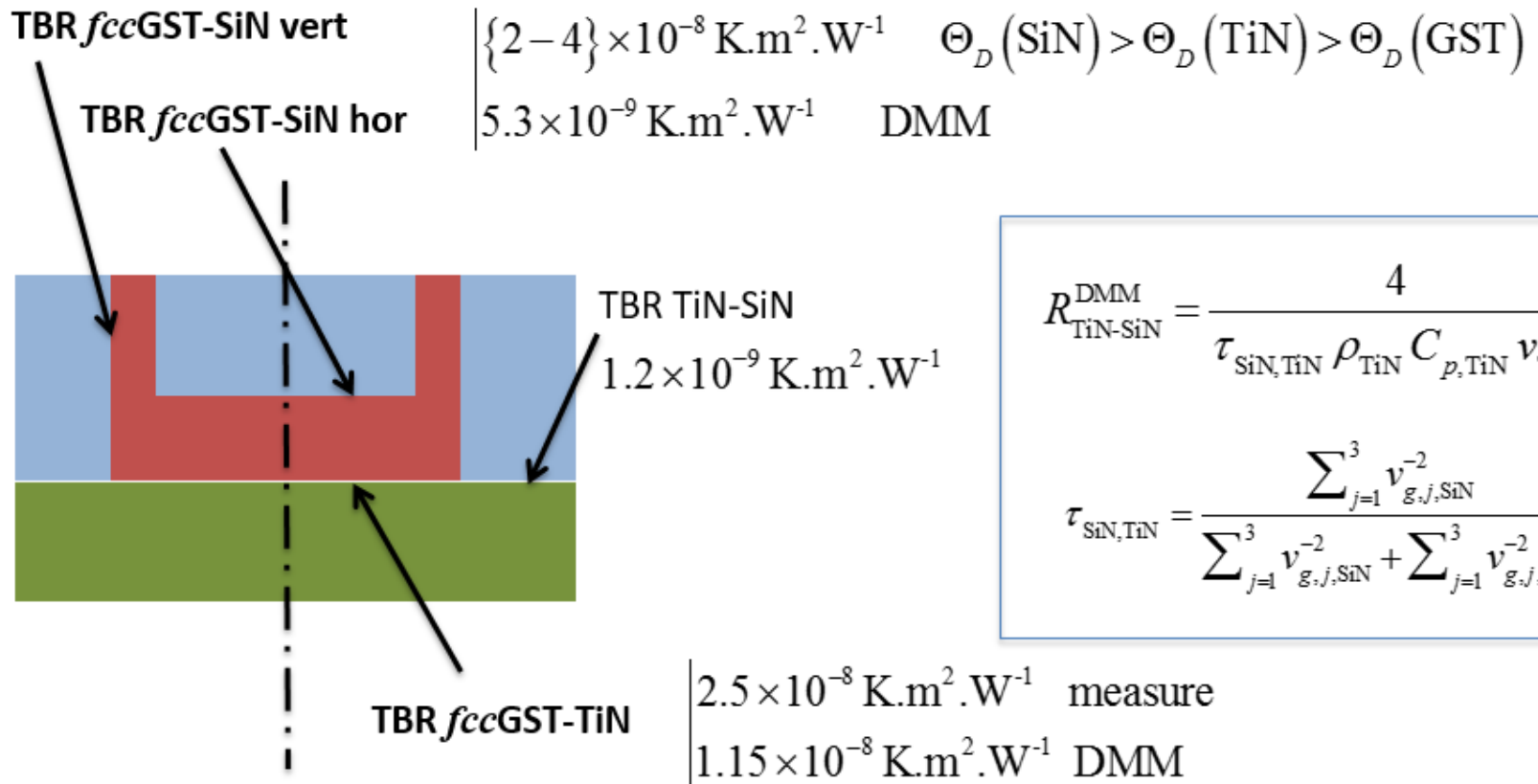


S. C. Lai et al., Symp. VLSI Tech Dig., p.132-133, 2013



Cell cross section view

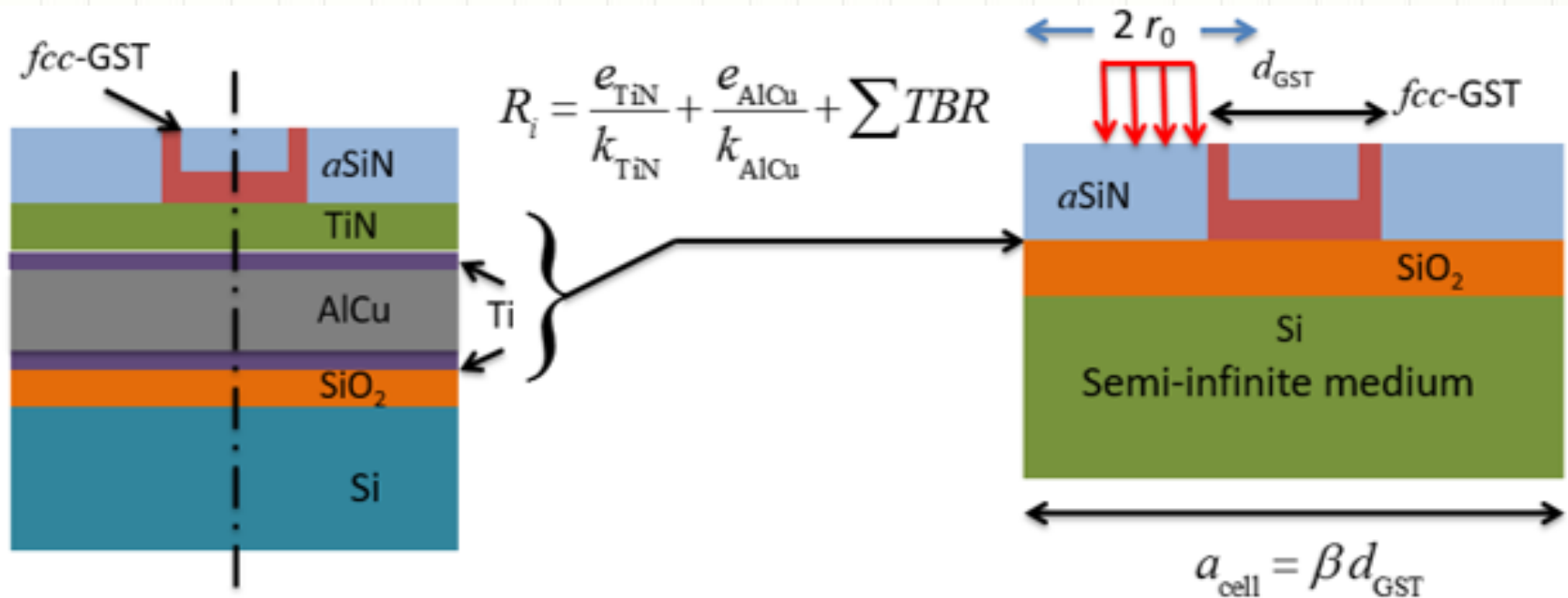
Known parameters



Reifenberg J. P., Kencke D. L. and Goodson K. E., *IEEE Electron. Device Lett.* **29** 1112–4 (2008).

J.-L. Battaglia et al., *Appl. Phys. Lett.* **105**, 121903 (2014).

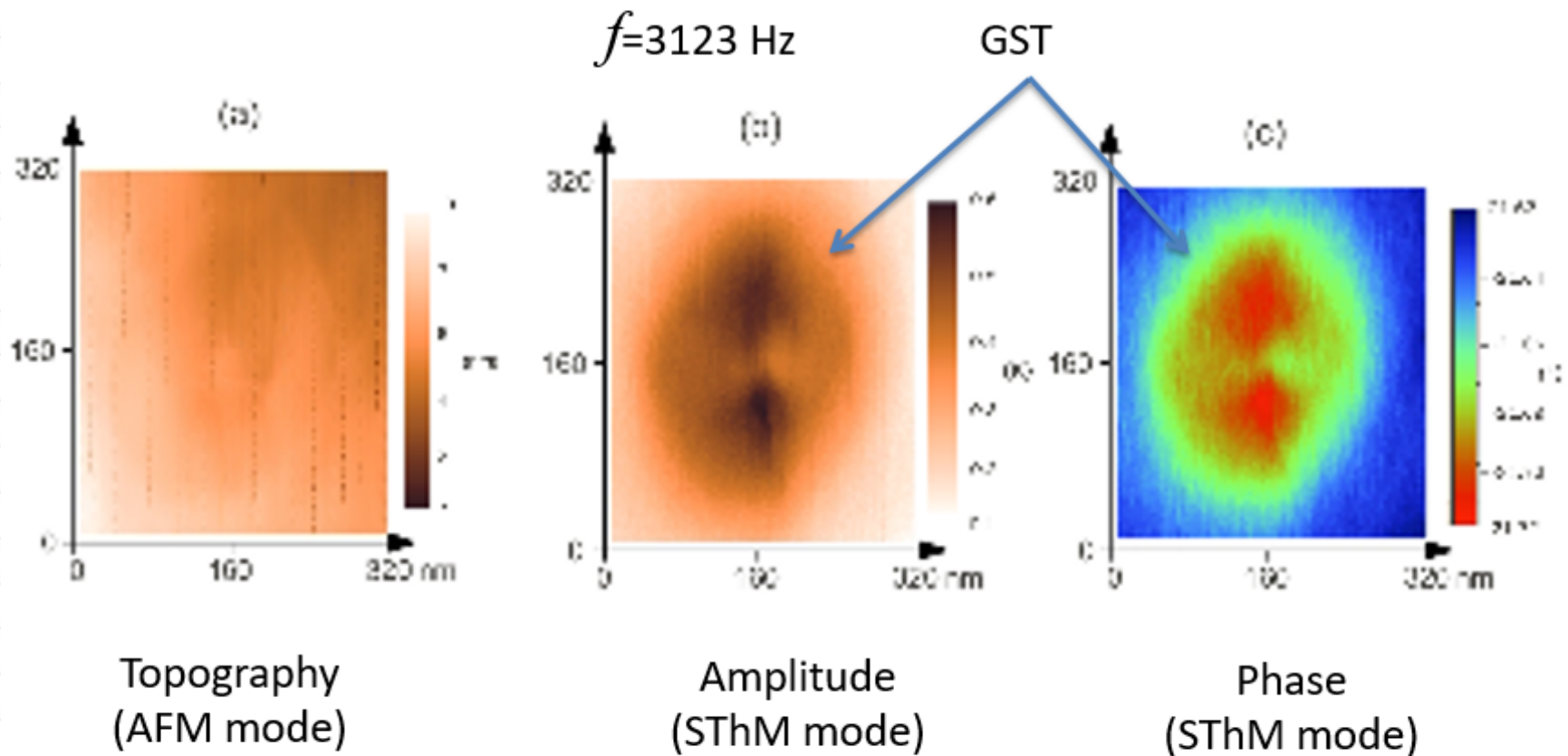
Geometry simplification



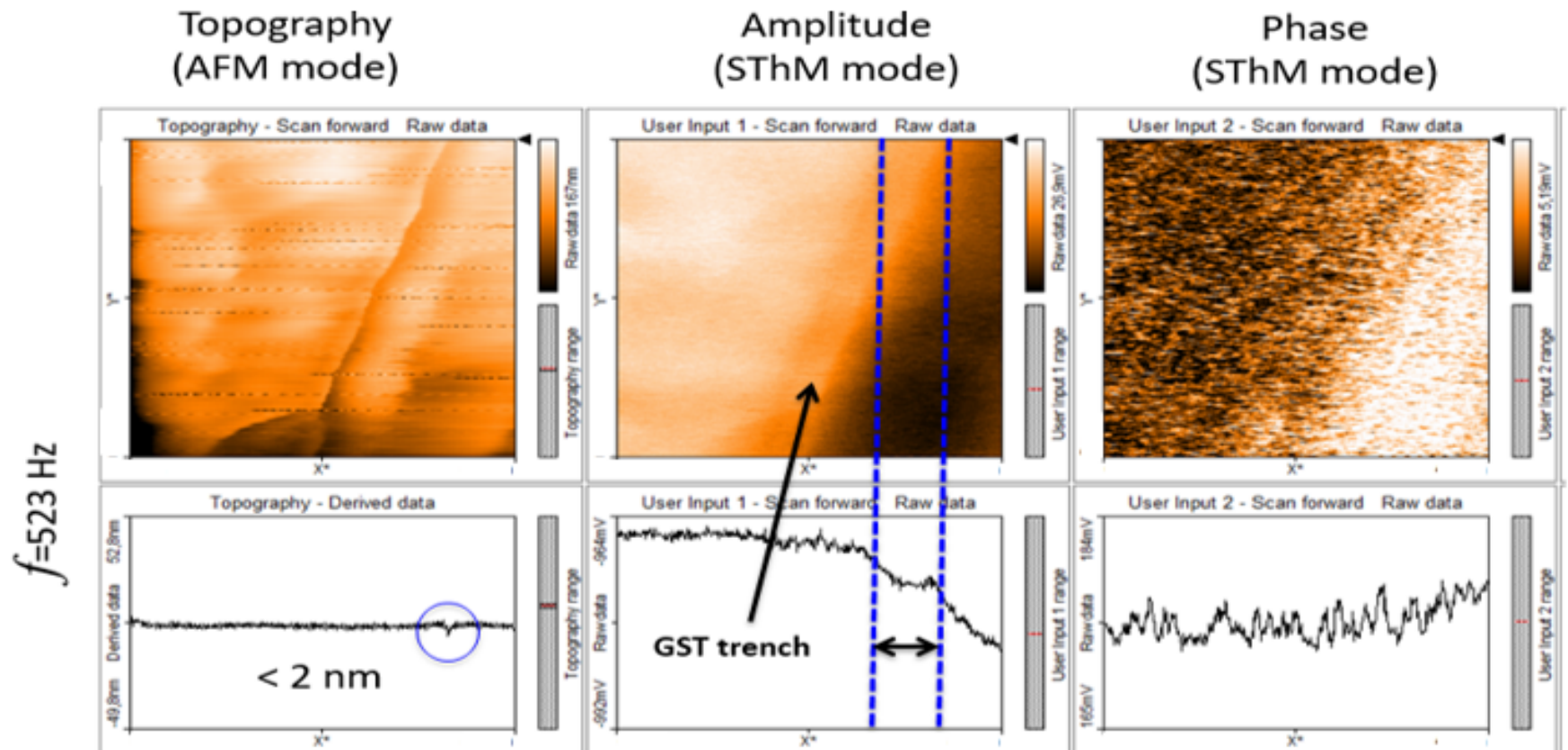
$Z_m(\omega)$ is calculated using the FEM

- Tetrahedral elements (458096 DoF)
- Multi-Grid solver (GMRES, with Newton scheme for convergence)
- Integration over the heated area πr_0^2 (order 4)

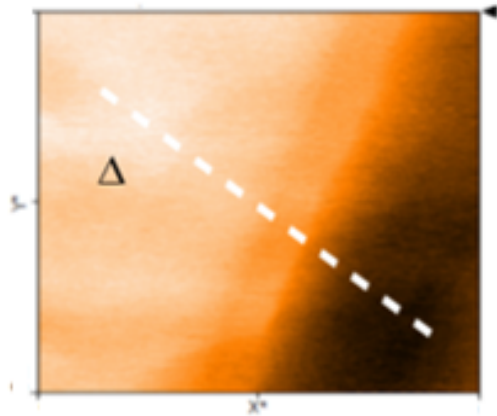
Experimental measurements



Zoom on the trench



Simulation results



Identified parameters

$$Z_p(523\text{Hz}) = (11.10 \pm 0.025) / P_0 \text{ K.W}^{-1}$$

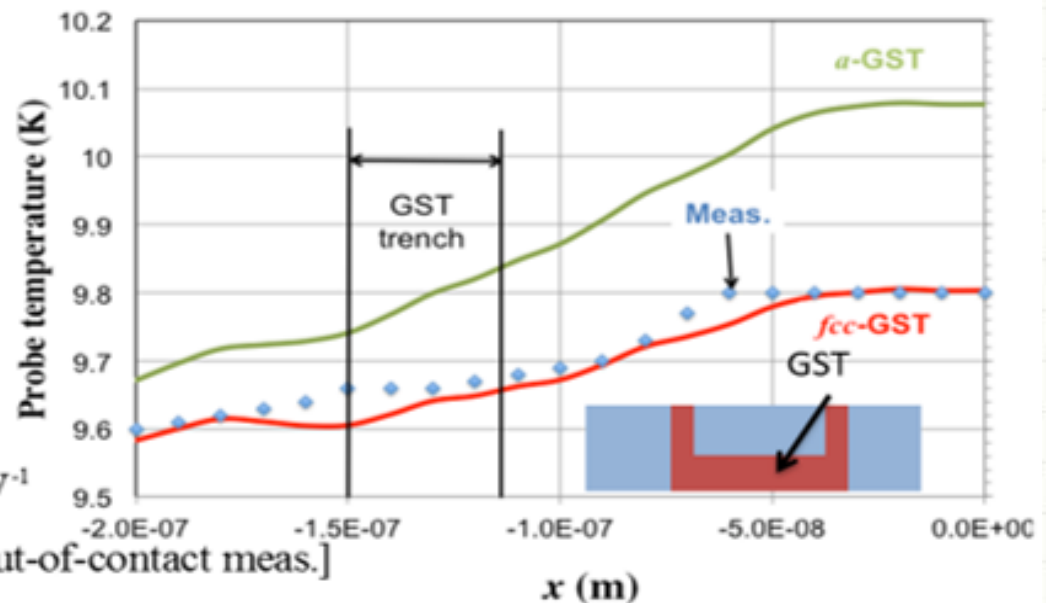
$$[(11.11 \pm 0.1) / P_0 \text{ K.W}^{-1} \text{ out-of-contact meas.}]$$

$$TBR_{\text{SiN-GST}} = (2.0 \pm 0.2) \times 10^{-8} \text{ K.m}^2.\text{W}^{-1} > \text{DMM value}$$

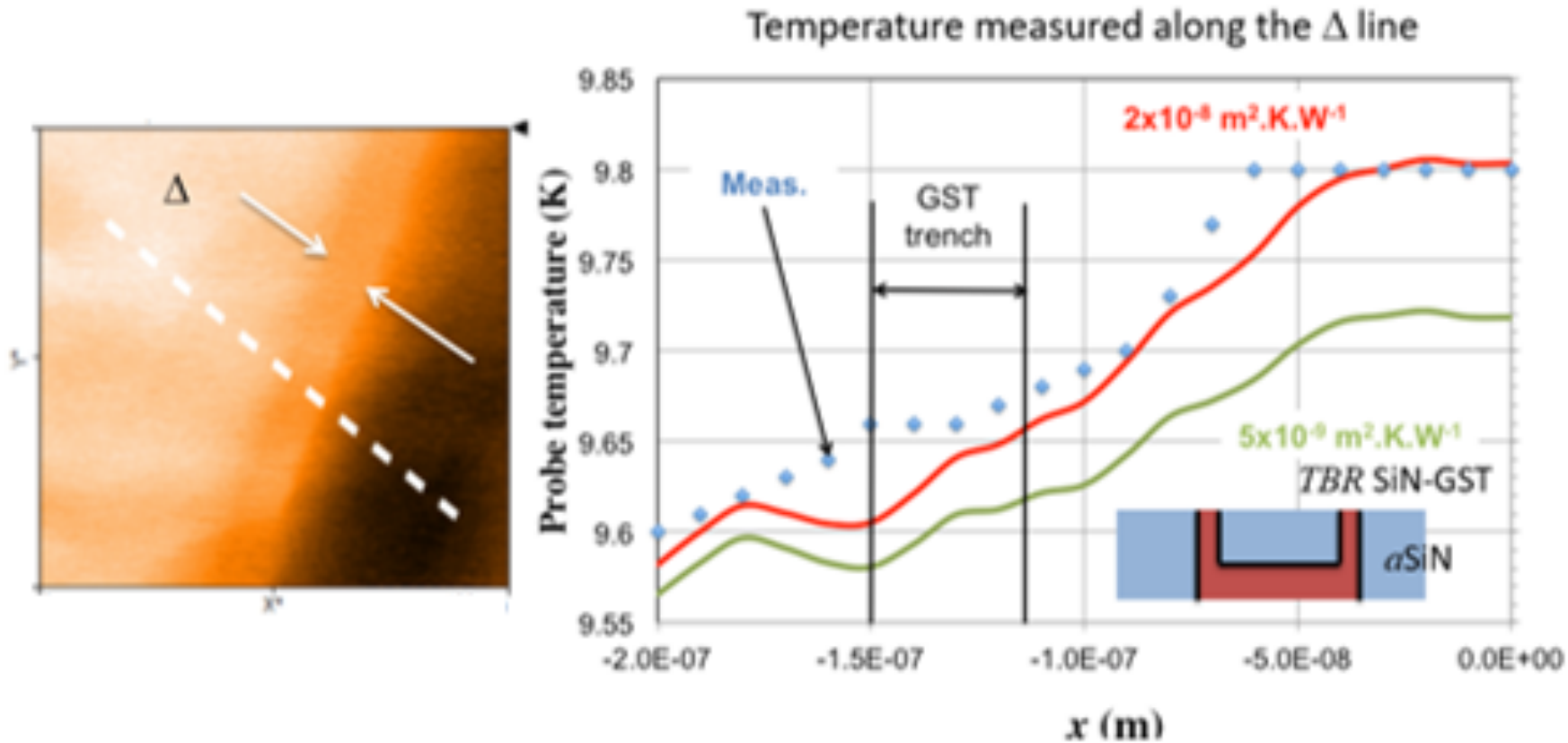
$$k_{\text{GST}} = 0.46 \pm 0.1 \text{ W.m}^{-1}.\text{K}^{-1} \text{ (fcc-GST)}$$

$$\beta = 3.3 \pm 0.1$$

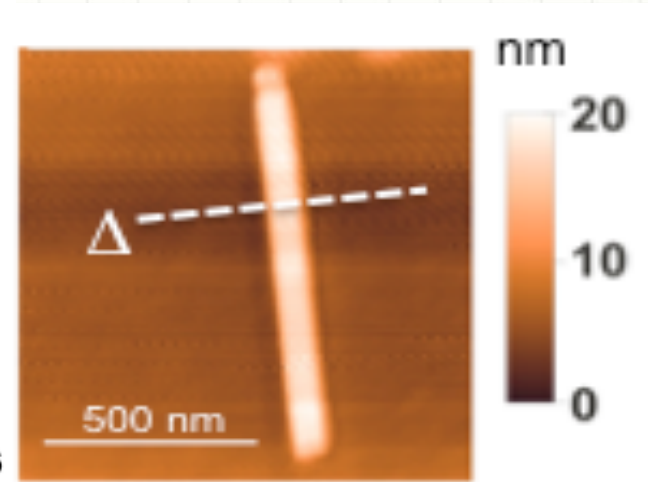
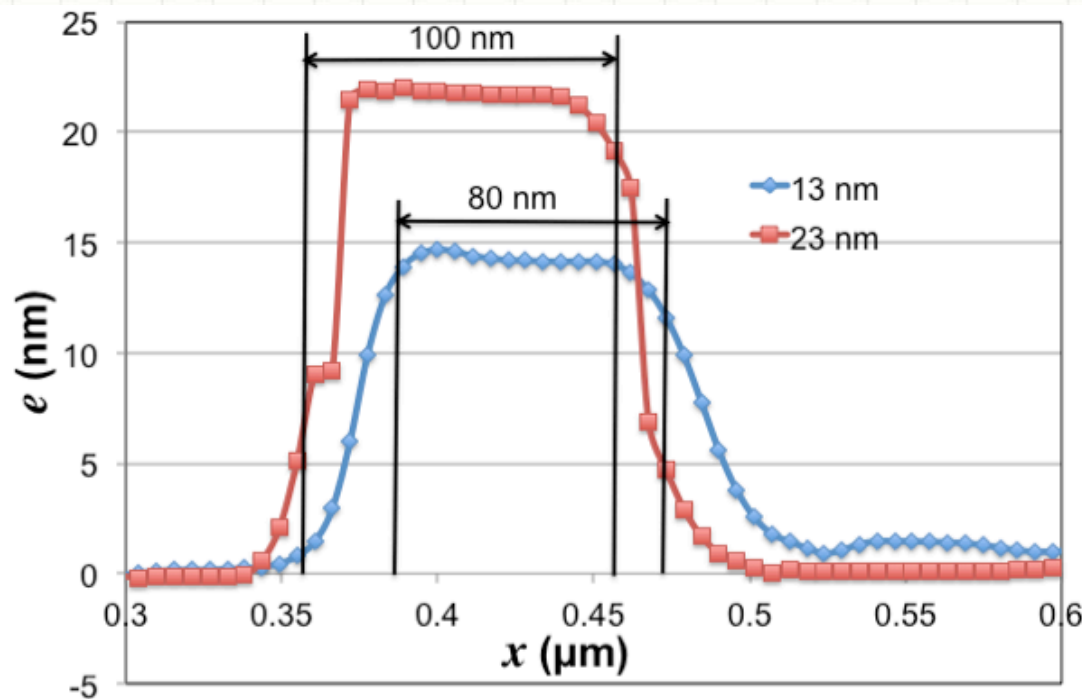
Temperature measured along the Δ line



Sensitivity on the TBR

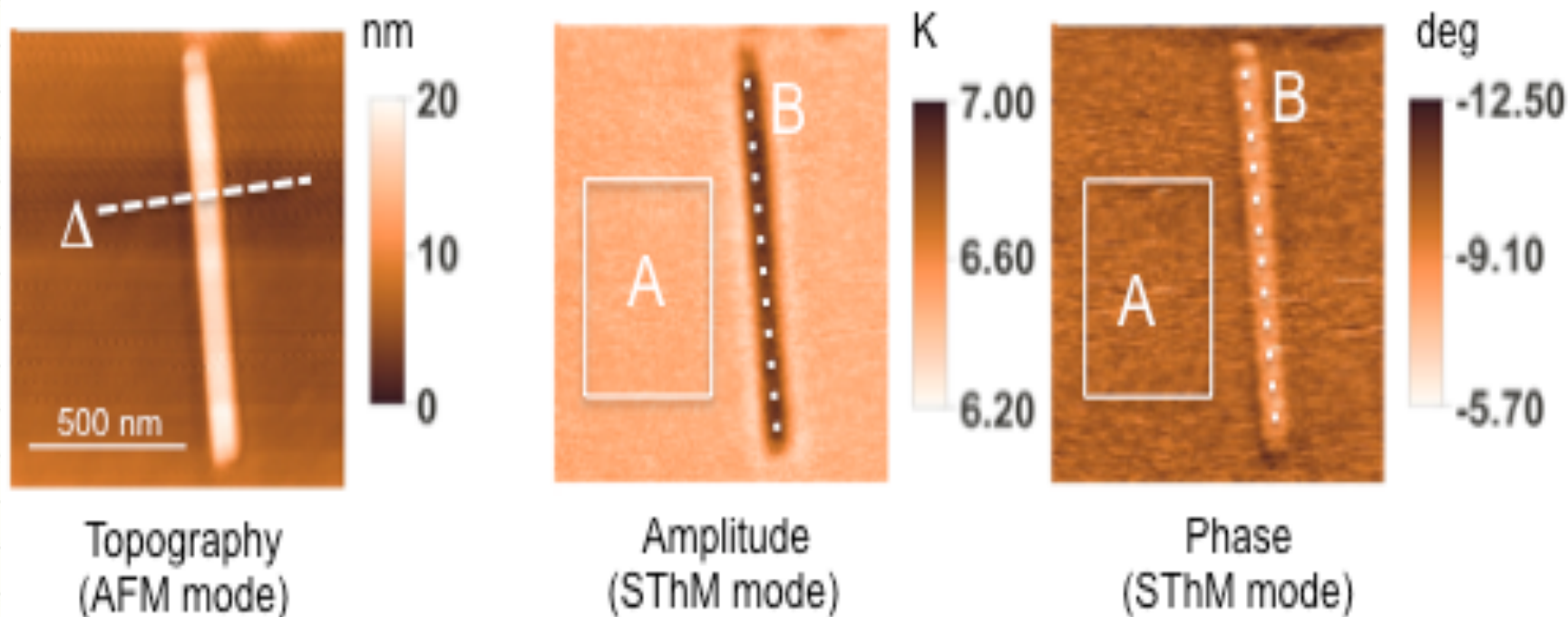


Application – In_3SbTe_2 Nanowires



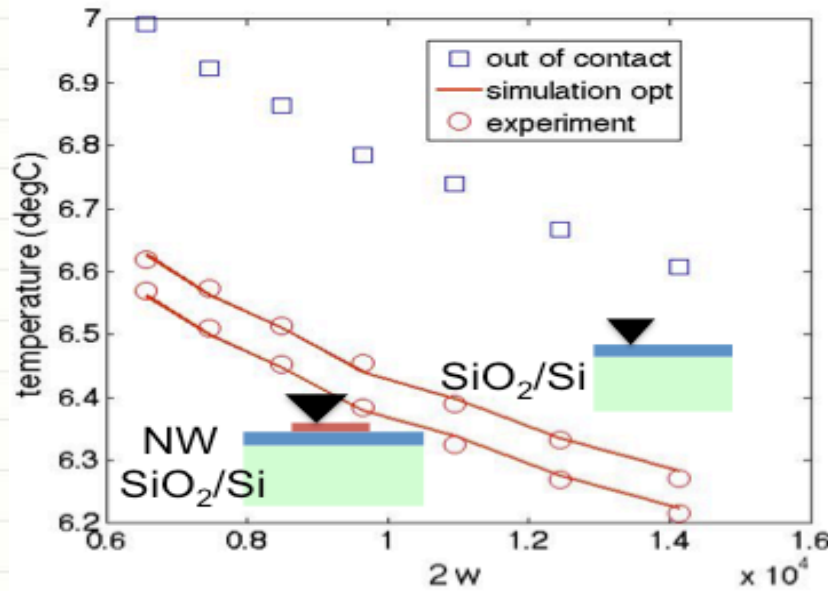
Cross-sectional area measurement of the Nanowire across the Δ line

Application – In_3SbTe_2 Nanowires

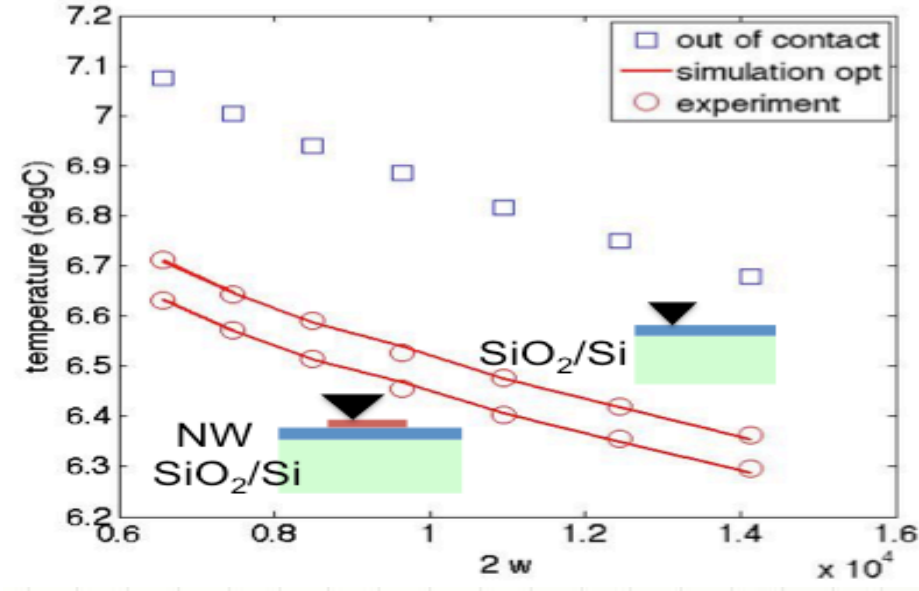


Topography, Amplitude and Phase at 523Hz. The dotted line (Δ) has been used to plot the 23 nm thick nanowire cross-section profile. Areas A and B are used to average the measured temperature with the probe in contact with the SiO_2/Si layer and the NW respectively

Application – In₃SbTe₂ Nanowires



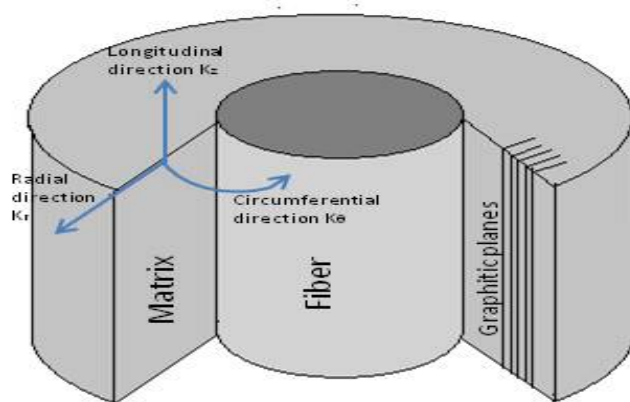
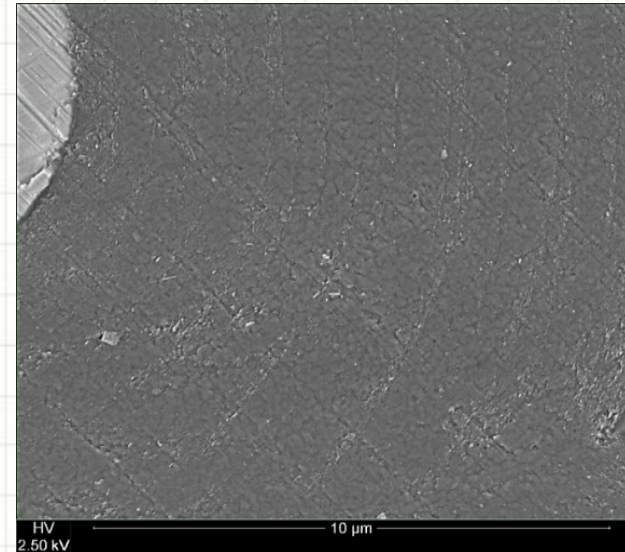
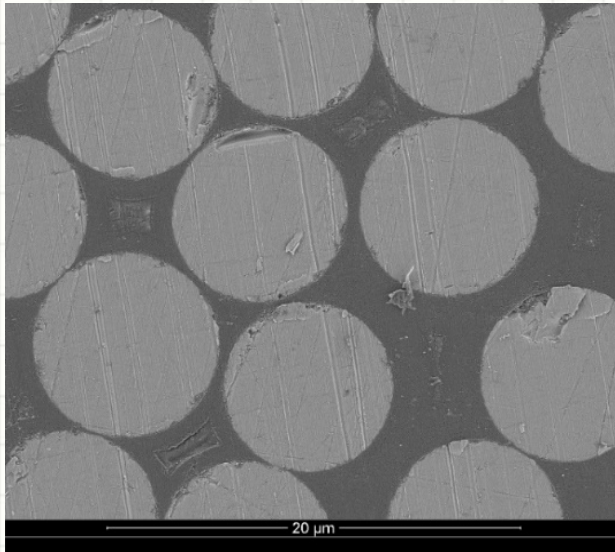
13 nm



23 nm

	13 ($l_{NW}=80$ nm)	23 ($l_{NW}=100$ nm)
R_{NW} (K.m ² .W ⁻¹)	$(3.4 \pm 0.7) \times 10^{-9}$	$(6.4 \pm 1.3) \times 10^{-9}$
R_{NW} (K.m ² .W ⁻¹)	6.19×10^{-10}	1.09×10^{-9}

Application – Pyro-Carbon Composite



Glass Fiber Properties

Thermal conductivity (k)	$1.1 \text{ W.m}^{-1}.\text{K}^{-1}$
Density (r)	2200 Kg.m^{-3}
Specific heat (C_p)	$748 \text{ J.kg}^{-1}.\text{K}^{-1}$

Application – Pyro-Carbon Composite

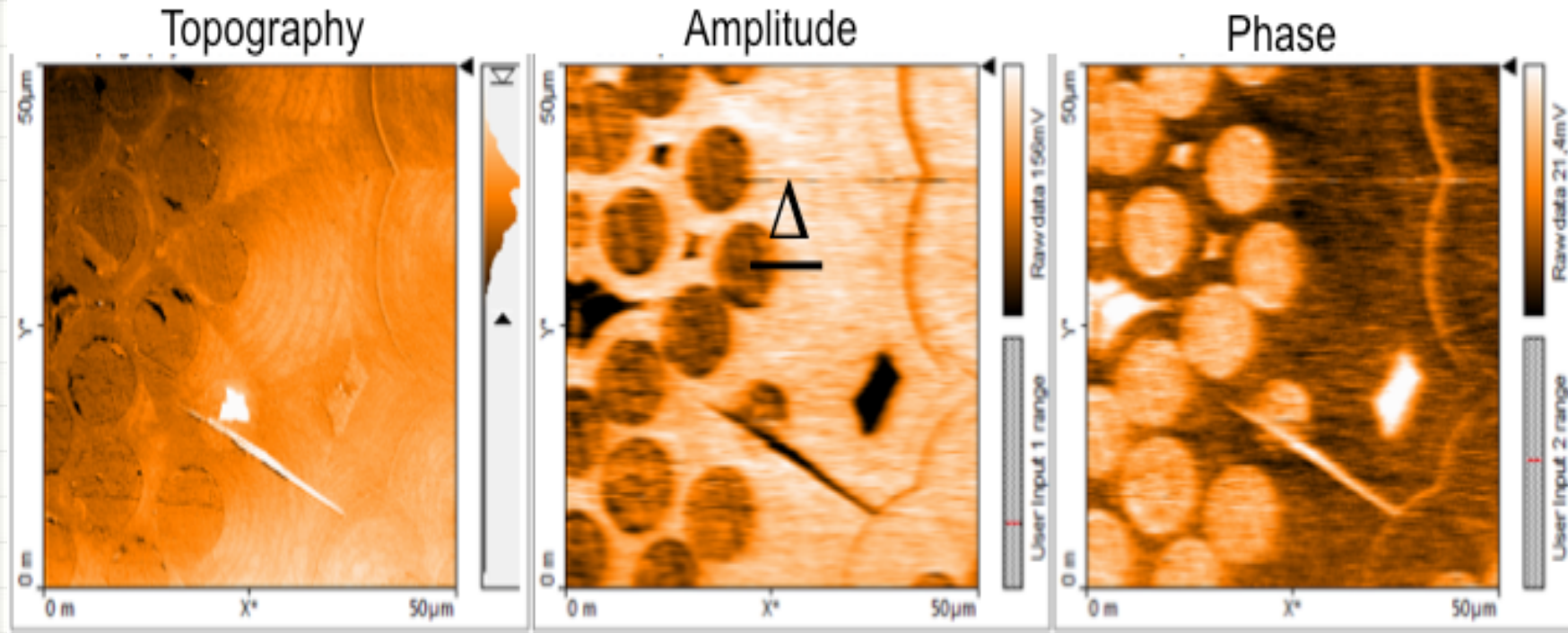
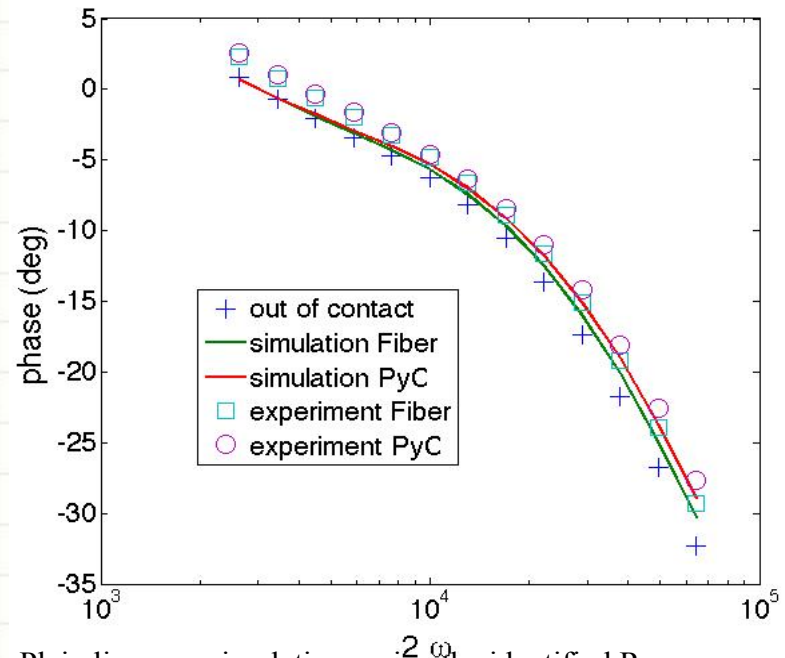
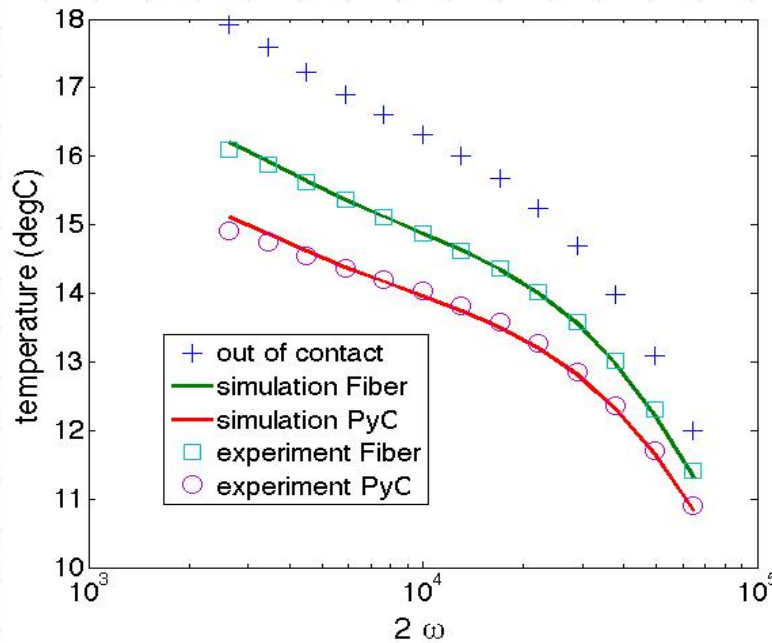


Image Size: 50μm
Contact Force: 10 nN
Current: 750 μA
Frequency : 1125 Hz

Application – Pyro-Carbon Composite

Simulated Results



Measured temperature (left) and phase (right) against 2ω . Plain lines are simulations using the identified R_c when the probe is in contact with the silica fiber and the identified k_{eff} of the PyC when the probe is in contact with the PyC.

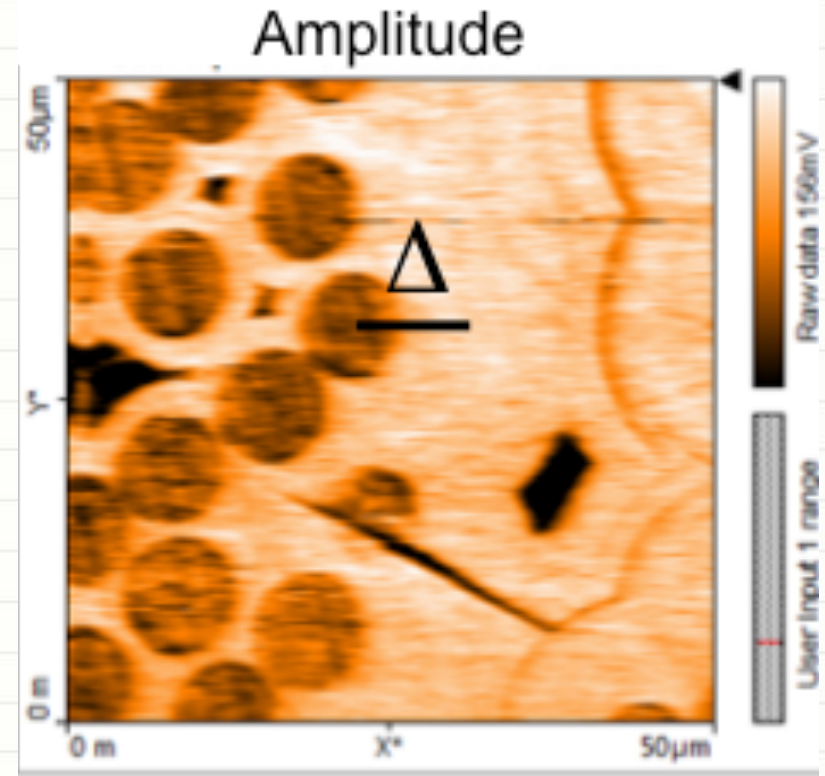
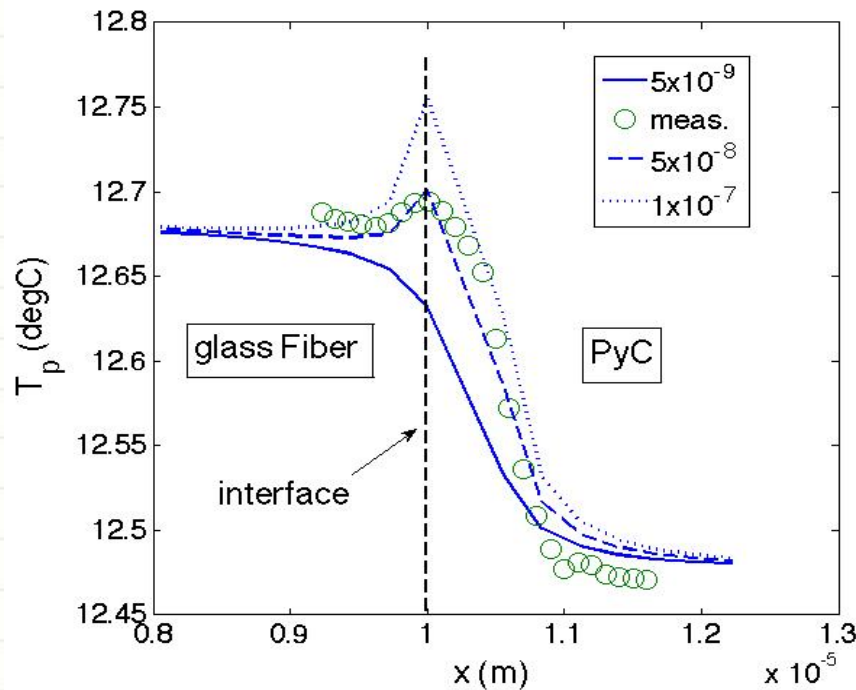
Probe in Contact with Fiber

$$R_c = (8.80 \pm 0.3) \times 10^{-8} \text{ K.m}^2.\text{W}^{-1}$$

Probe in Contact with PyC Matrix

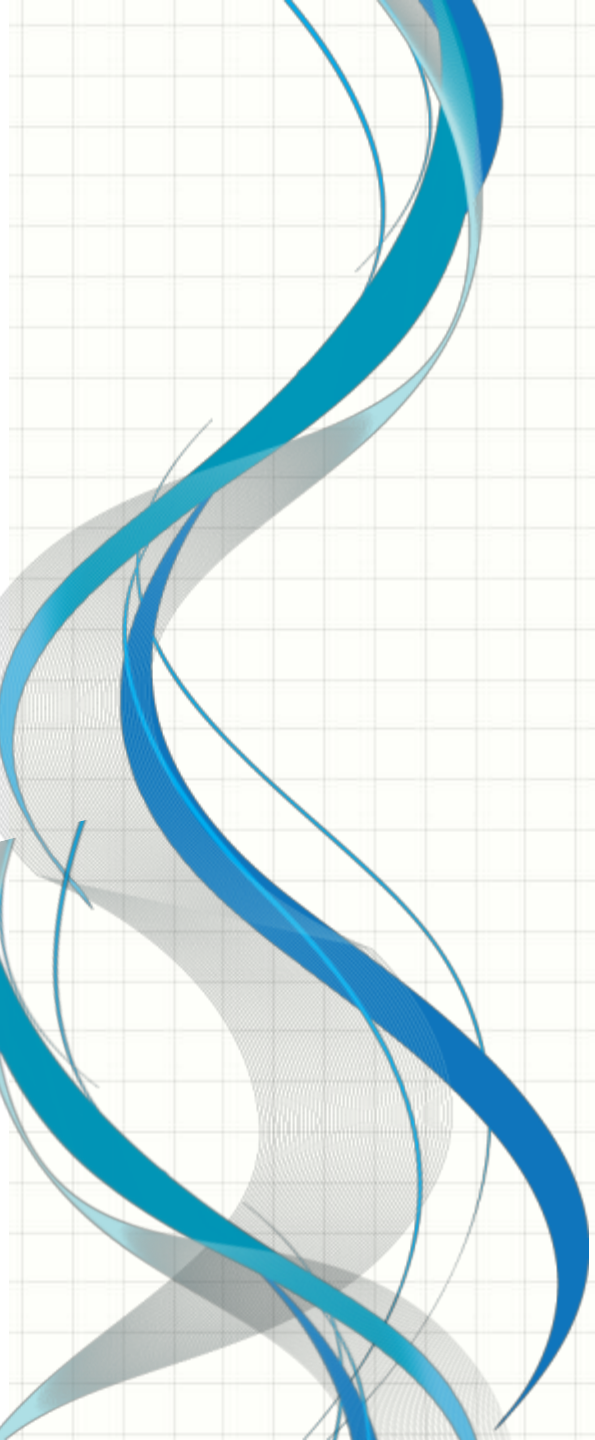
$$k_{eff} = 21.01 \pm 4.2 \text{ W.m}^{-1}.\text{K}^{-1}$$

Application – Pyro-Carbon Composite



Measured probe temperature along the Δ line and simulated probe temperature values considering three different values for Effective Thermal Boundary Resistance (RTH) (in $\text{K.m}^2.\text{W}^{-1}$).

$$RTH = (5 \pm 1) \times 10^{-8} \text{ K.m}^2.\text{W}^{-1}$$



Conclusions Perspectives

Conclusions 1/2

- The probe are micro-fabricated thermoresistive devices that allow to heat the investigated surface and measure the temperature change of the resistive element with spatial accuracy of 100 nm (atmos. Cond.) and lower (overlapping and/or vacuum)
- The probe thermal impedance is derived experimentally from the out-of-contact configuration when the probe is far away from the investigated surface
- The thermal contact resistance at the interface between the probe and the surface includes all the physical phenomena occurring in this region (solid-solid contact, water meniscus formation, diffusion and radiation through the air in ambient configuration) as well as the influence of the contact on the probe thermal impedance

Conclusions 2/2

- We demonstrated a constant contact area and thermal contact resistance when the probe scan heterogeneous surface. This seems to be true with a class of materials including dielectrics and semiconductors.
- The unknown parameters are identified from the resolution of the inverse heat conduction problem using the frequency and spatial dependent probe temperature.
- Quantitative SThM has been achieved in three applications involving very different configurations.

Perspectives

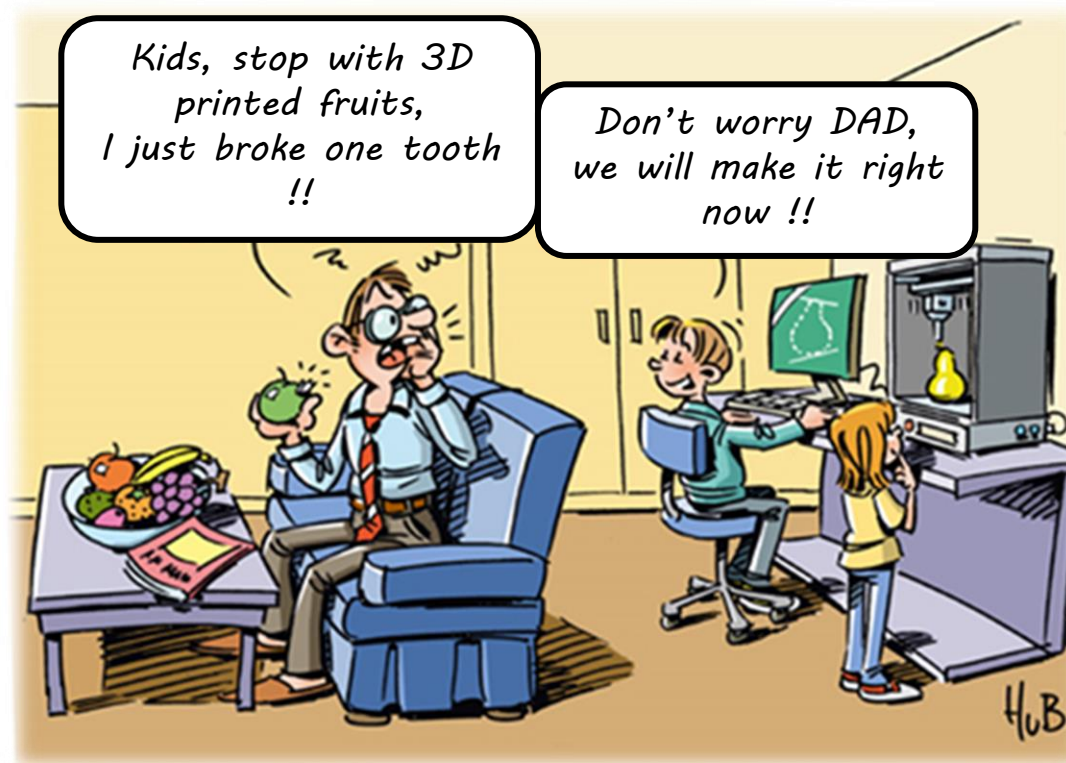
- The main improvements reside in the quantification and sensitivity
- Development of new probes in order to make the heating very local at the tip and then increasing the heat flux part into the sample.
- Multi-probes development for in-plan thermal characterization

Short Introduction to the Additive Manufacturing

Robin KROMER, Associate Professor

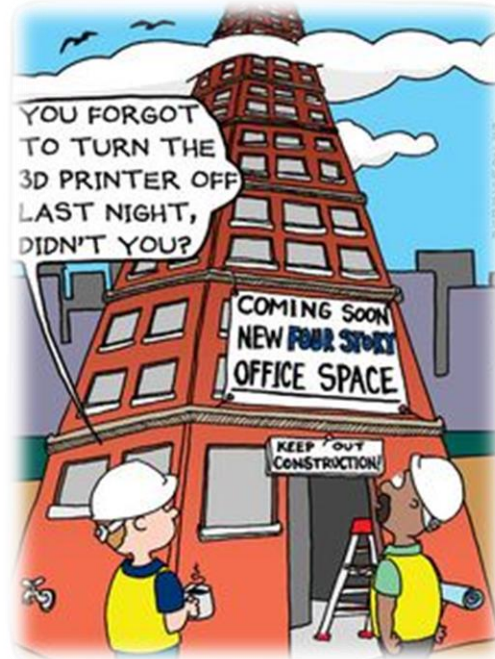
What if ...

... anyone could make almost **anything** they need, **anywhere** ?



What if ...

... all it took to set up an advanced manufacturing facility was **electricity**, access to some **raw materials**, and a **computer**?



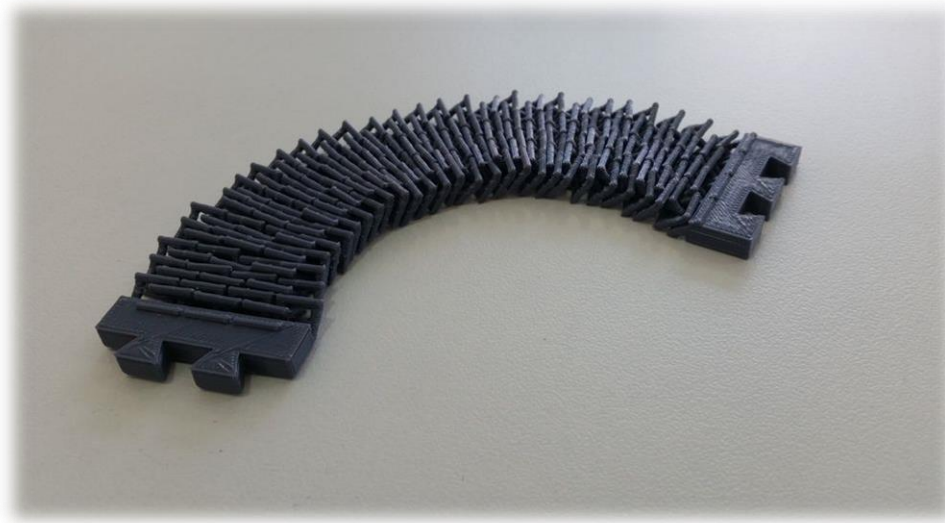
What if ...

... an entrepreneur could **start selling** a new product **without** ever needing to buy a **machine**, purchase a **tool** or prove out a **mold**; and could **start shipping** products the day after the design is finalized?



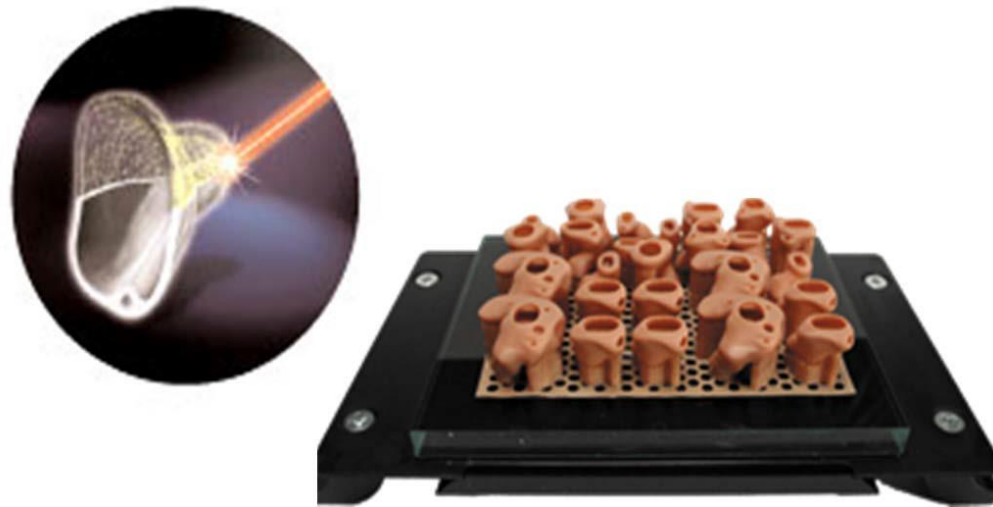
What if ...

... part of your watch broke and you don't want to buy a new watchband, so you use a free sketching tool to design a replacement, which you upload on a website and which is **shipped to your house a couple of days later, in the material of your choosing, for less than \$5?**



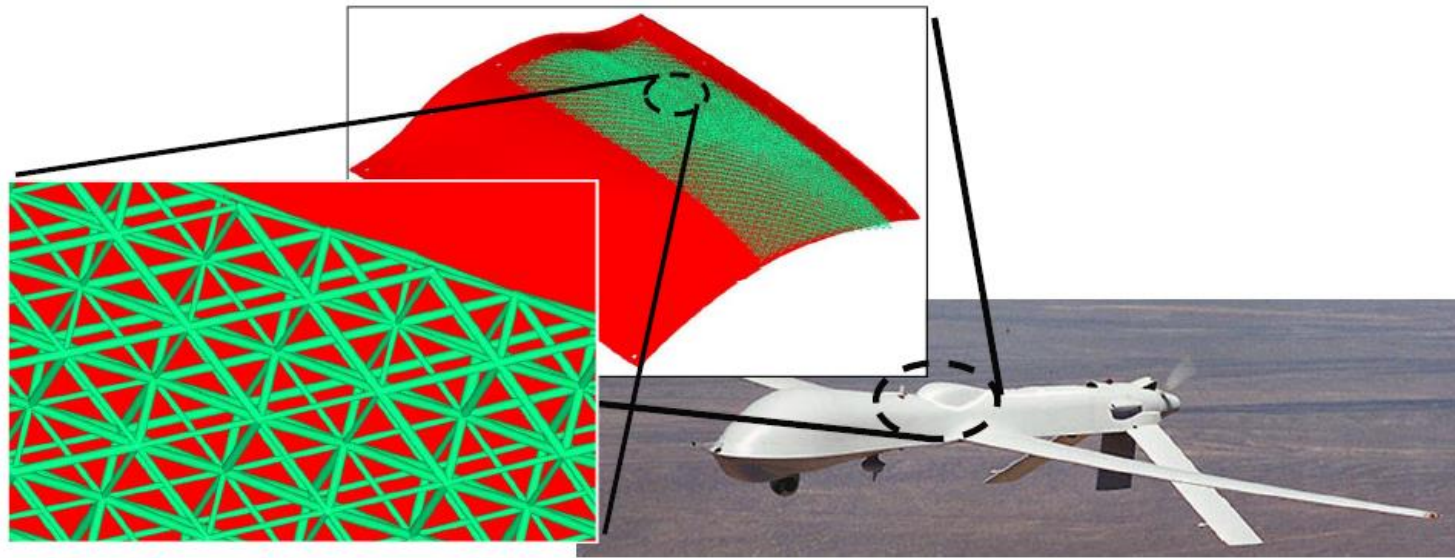
What if ...

... you automated the manufacture of hearing aids so that you simply scanned the ear, printed out a custom-fitted hearing aid, inserted the electronics, and shipped them by the millions?



What if ...

... you wanted to **control** the overall **geometry** of a part, which is made up of a **truss** network, where each truss has an **optimized thickness** and could have an individually **controllable microstructure or material**?



What if ...

... all of these activities were already happening and most people had no clue?

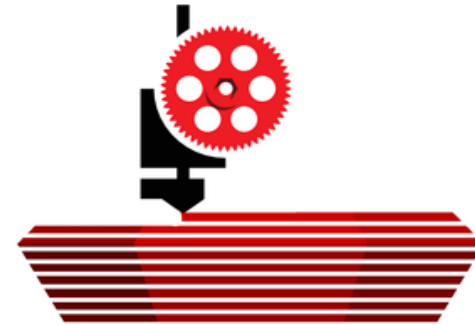
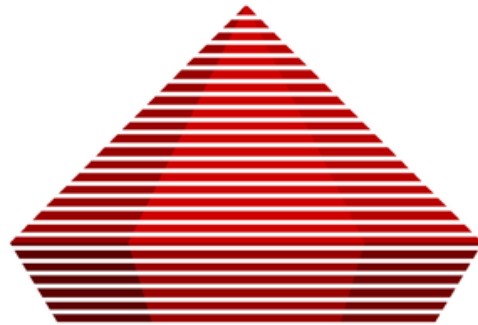


All of this is possible and is currently being done with
Additive Manufacturing Technologies

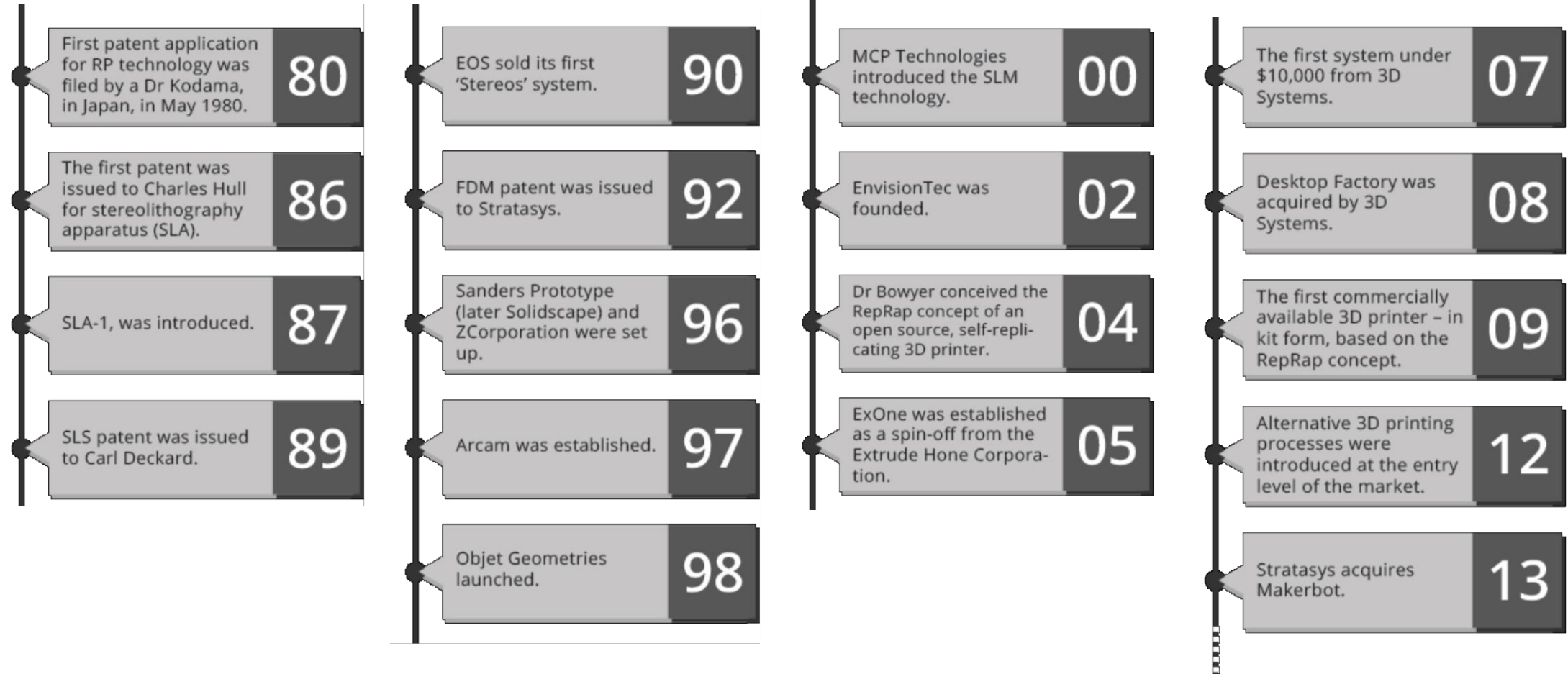
*« The right **quantity** of the right **material** at the right **place**
and for the good **reason** »*

Introduction

- Additive Manufacturing by ASTM (American Society for Testing and Materials): “Process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining”

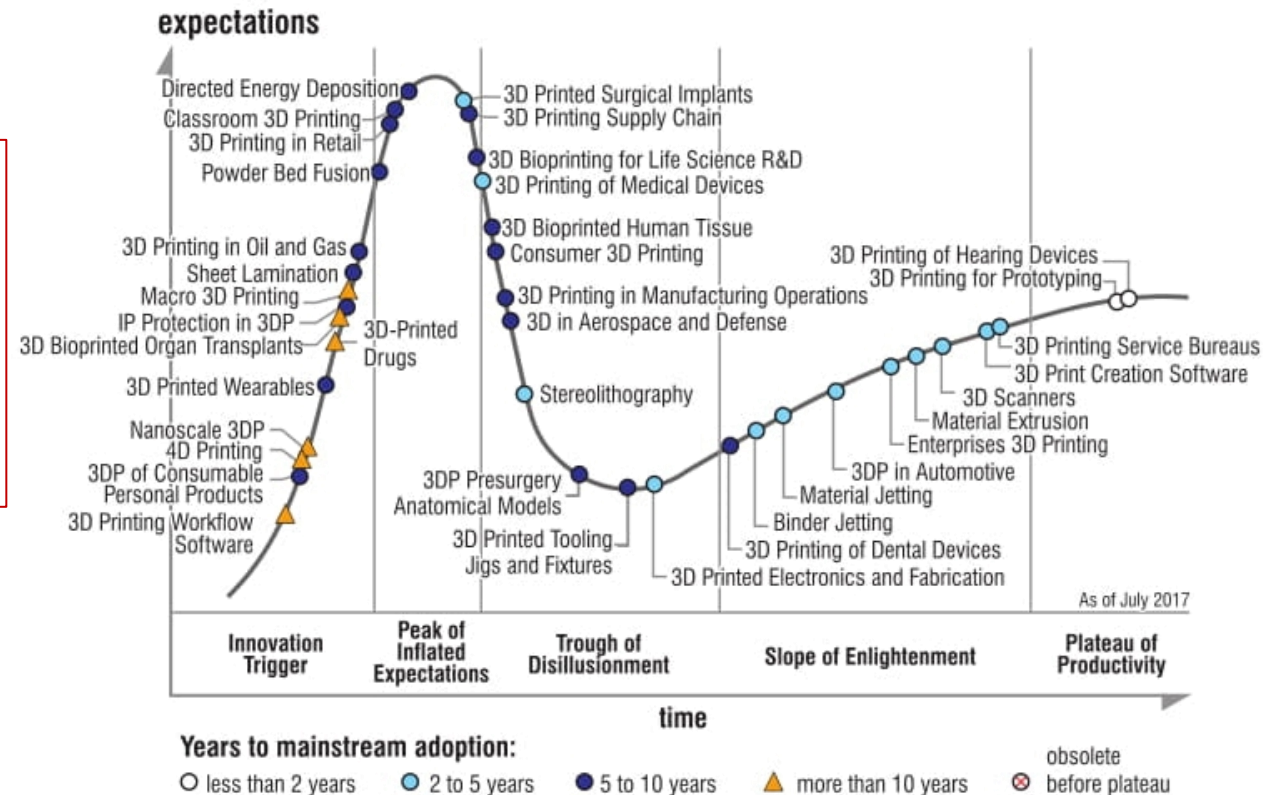


History



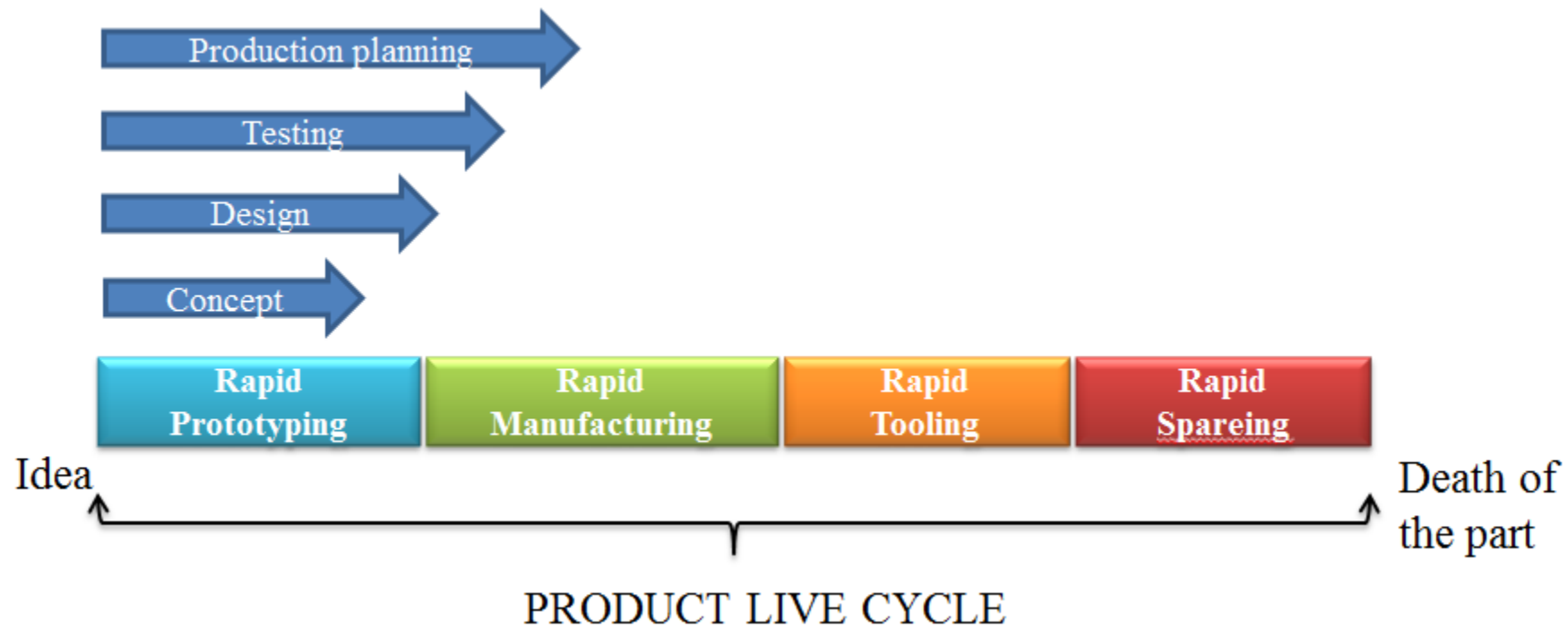
Development

“3D PRINTING’S POTENTIAL
TO REVOLUTIONIZE
MANUFACTURING IS QUICKLY
BECOMING A REALITY.”



Past ...

- Over the last years, AM technology became valid for the whole lifecycle of a product



Now ...

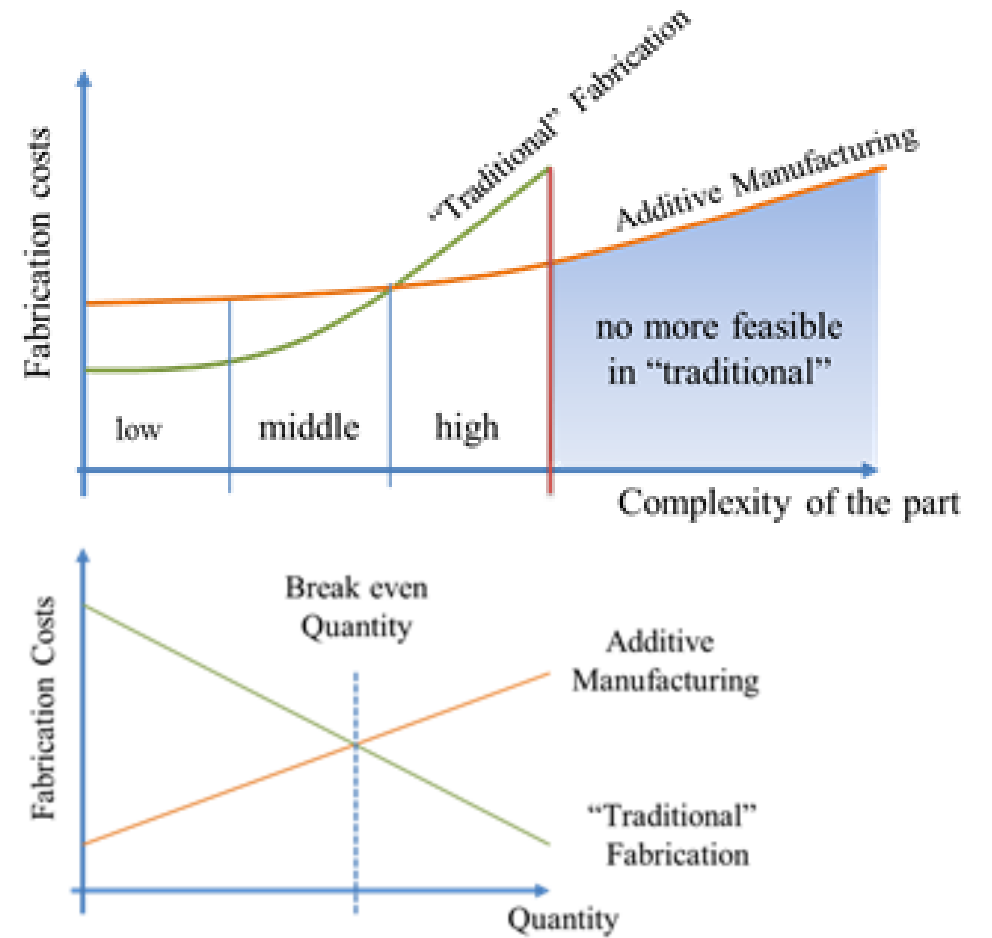
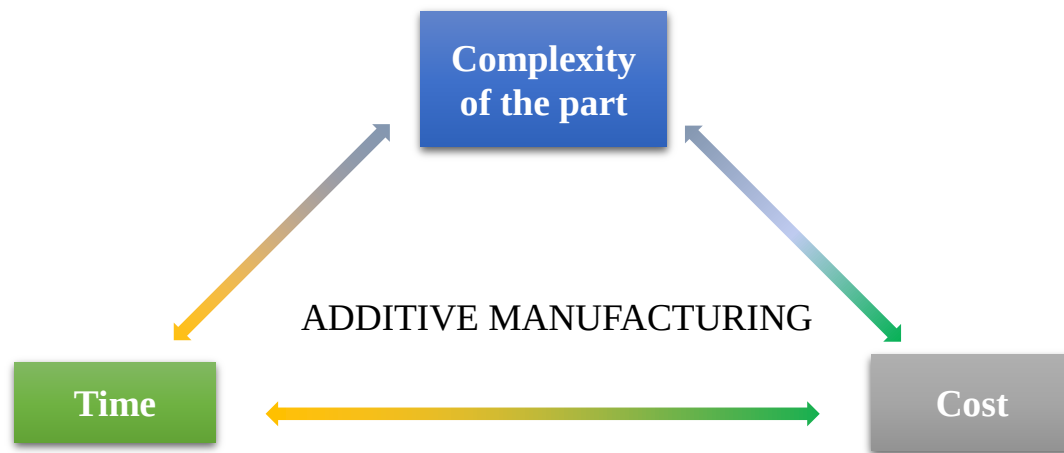


Table of contents

1. Process
2. Design
3. Perspectives

Process

Classification based on
raw materials nature

AM Processes

Liquid Based

- Stereolithography
- Jetting Systems
- Direct Light Processing

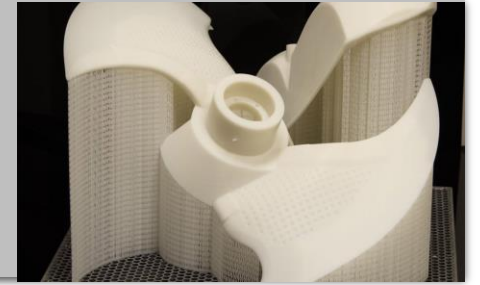
Powder Based

- Selective Laser Sintering
- Fused Metal Deposit Systems
- Electron Beam Melting
- Selective Laser Melting
- Selective Masking Sintering
- Selective Inhibition Sintering

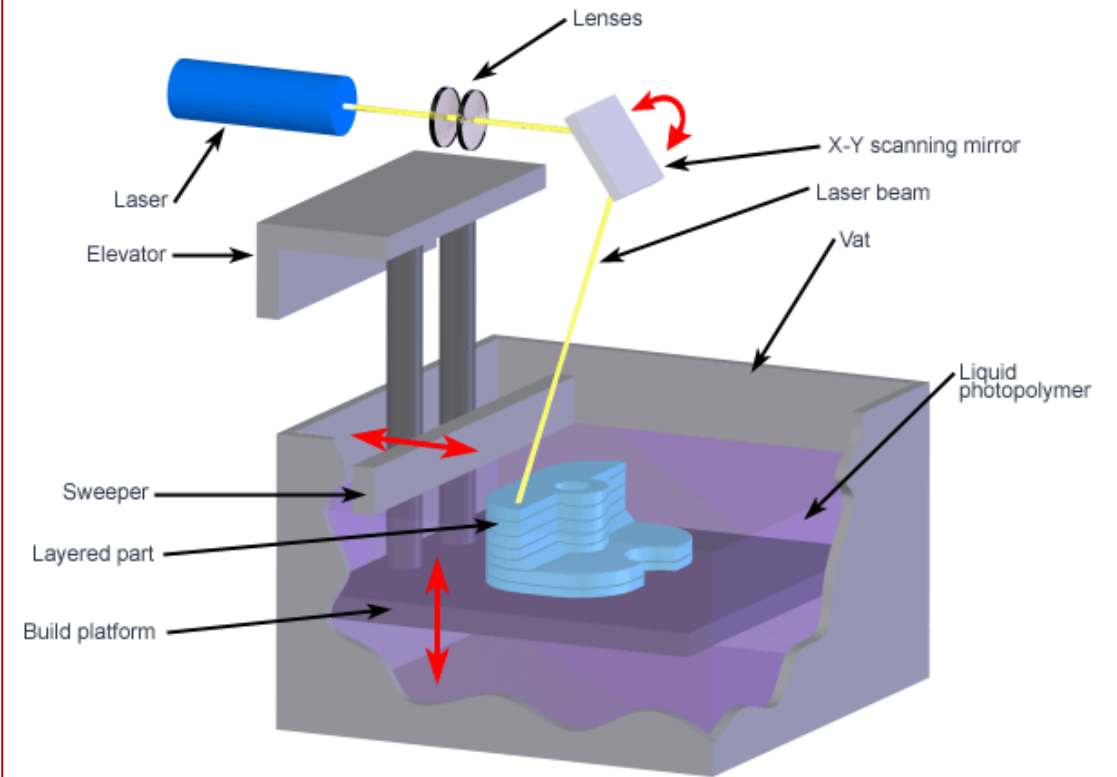
Solid Based

- Fused Deposition Modelling
- Sheet Stacking Technologies

Stereolithography

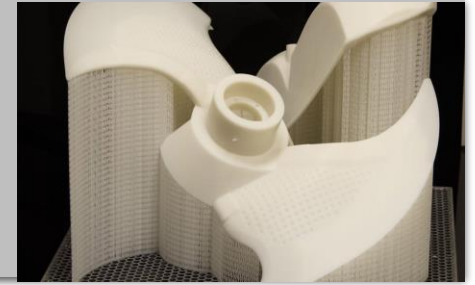


- UV laser cures resin
- Build platform lowers with the part into the resin vat (or rises from it in some cases)
- New layer of resin is cured and process repeated
- Materials:
 - UV curable resins
 - Waxes
 - Ceramic
- Manufacturers:
 - 3D Systems, DWS, Lithoz...

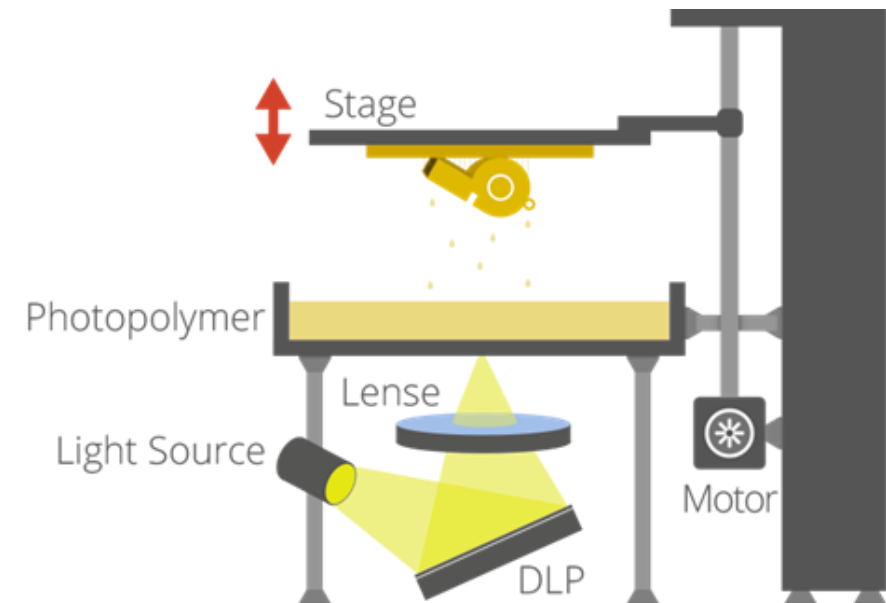


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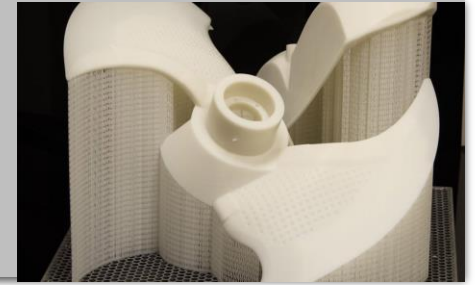
Direct Light Processing



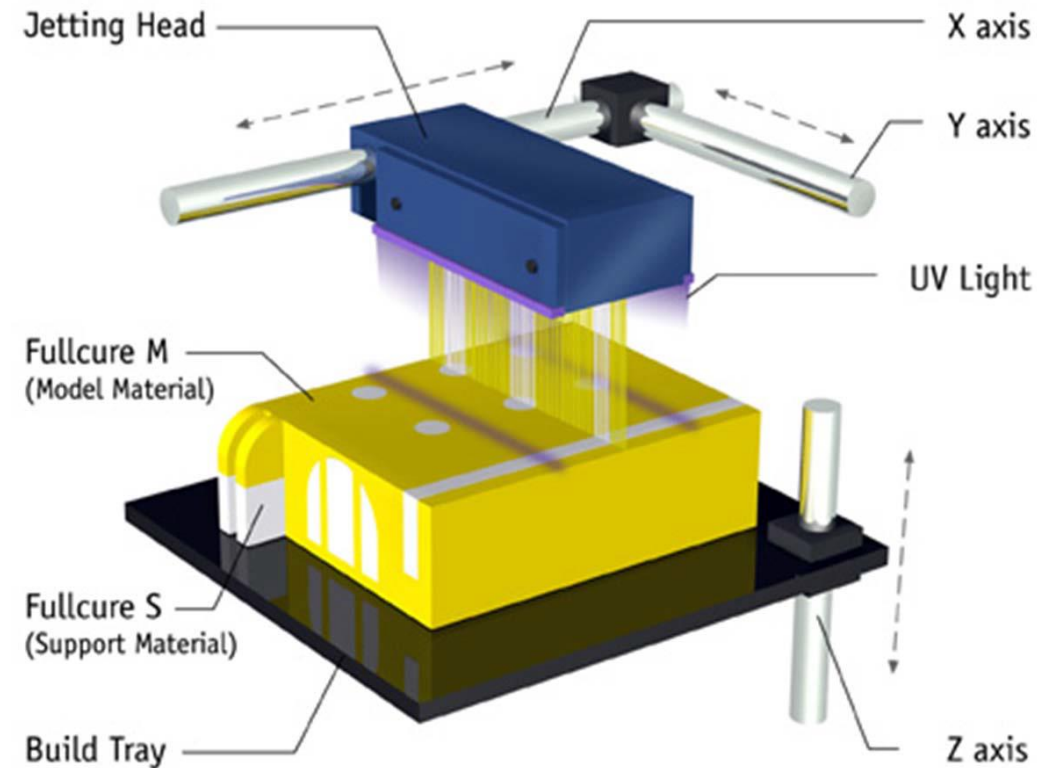
- The major difference is the light source: conventional light source
- Liquid crystal display panel or a deformable mirror device (DMD): apply entire surface of the vat of photopolymer resin
- Materials:
 - UV curable resins
 - Waxes
 - Ceramic
- Manufacturers:
 - 3D Systems, DWS, Lithoz,
 - +few hobbyist oriented



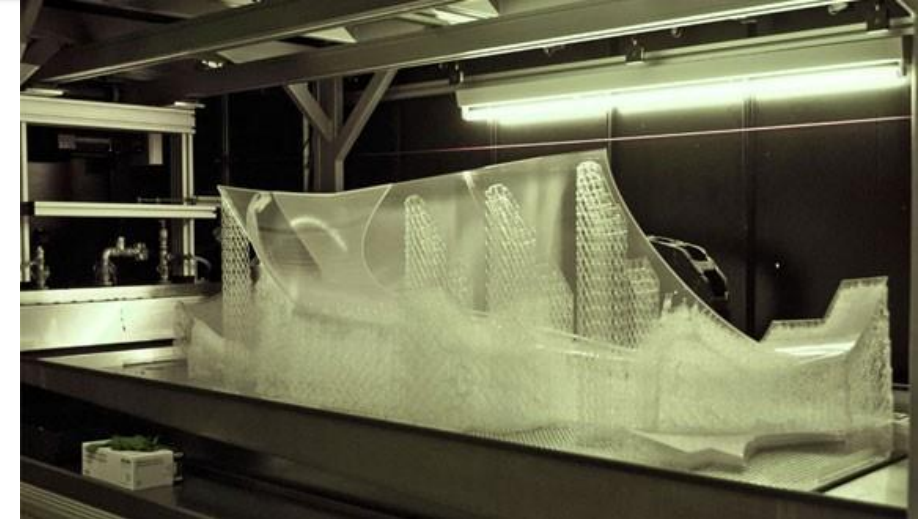
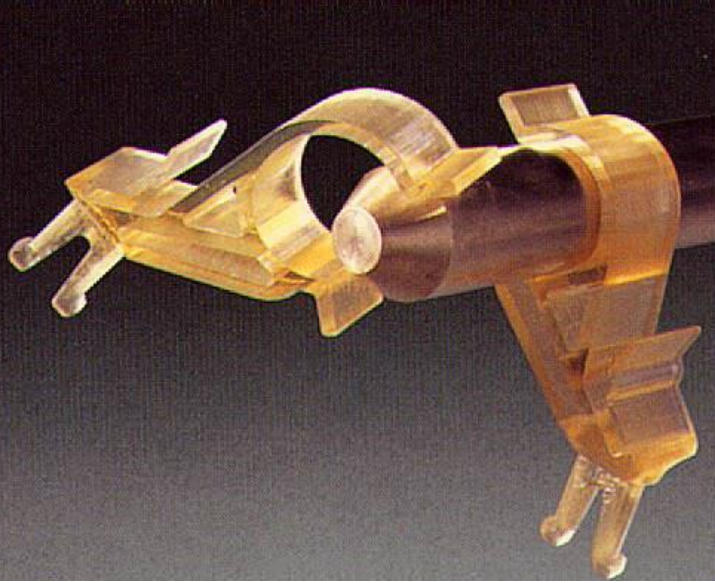
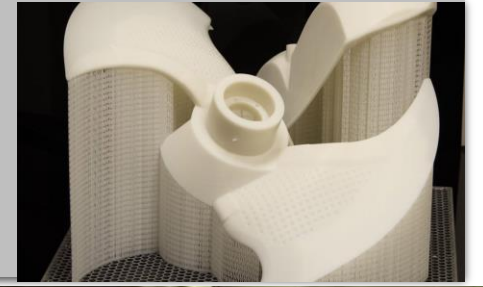
Jetting System



- Droplets are selectively deposited
- Materials layers are cured and hardened using UV light
- Bi-material: support & model
- Materials:
 - Photopolymers
 - Waxes
- Manufacturers:
 - Trimaker, Rapishare



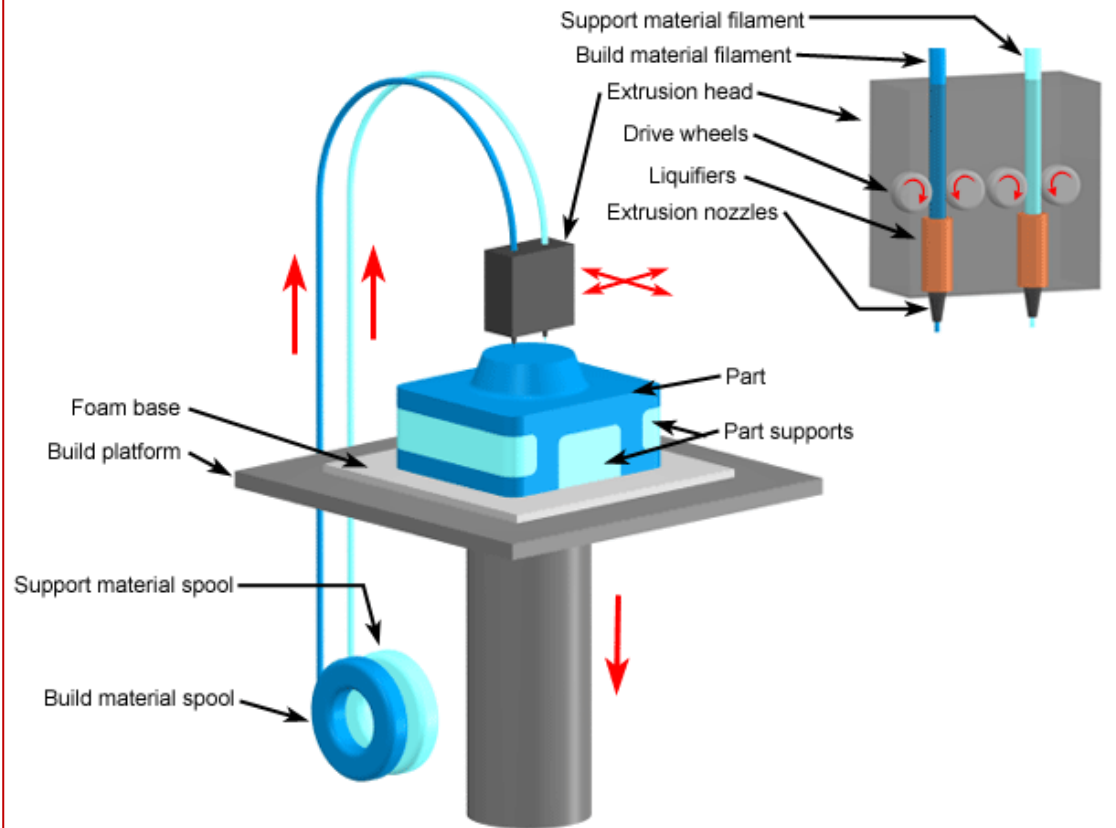
Stereolithography



Fused Deposition Modeling

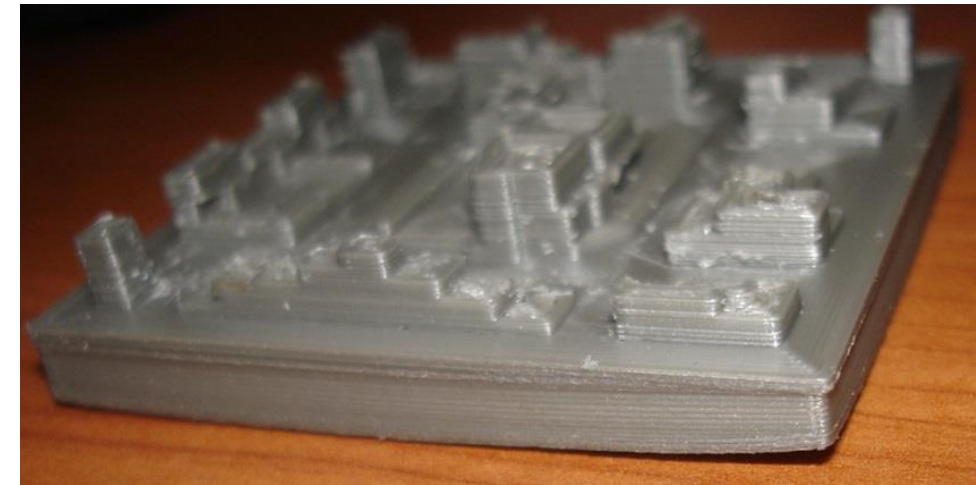
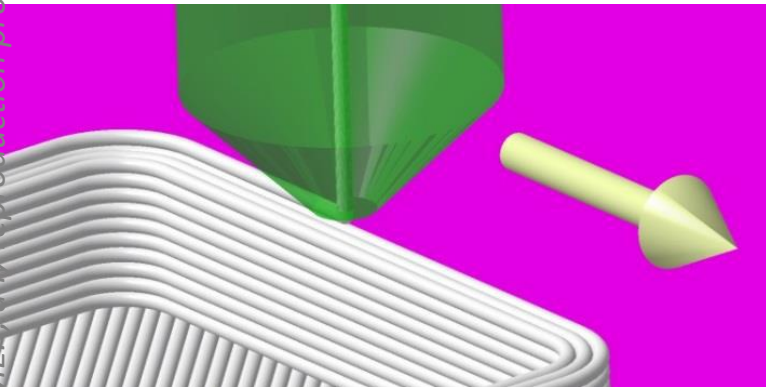
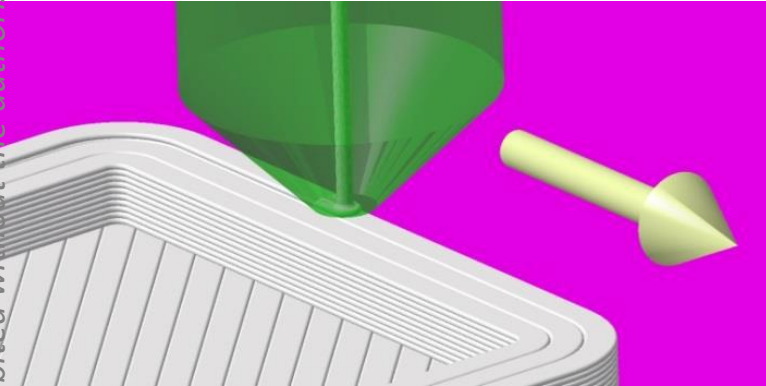


- Molten plastic is extruded to form a layer of the part (or matter droplet)
 - Build platform lowers with the part and process repeats
 - Special support material with second nozzle – washed away
-
- **Materials:**
 - ABS
 - Polycarbonate
 - Nylon
 - **Manufacturers:**
 - Stratasys, 3D systems, Mixshop



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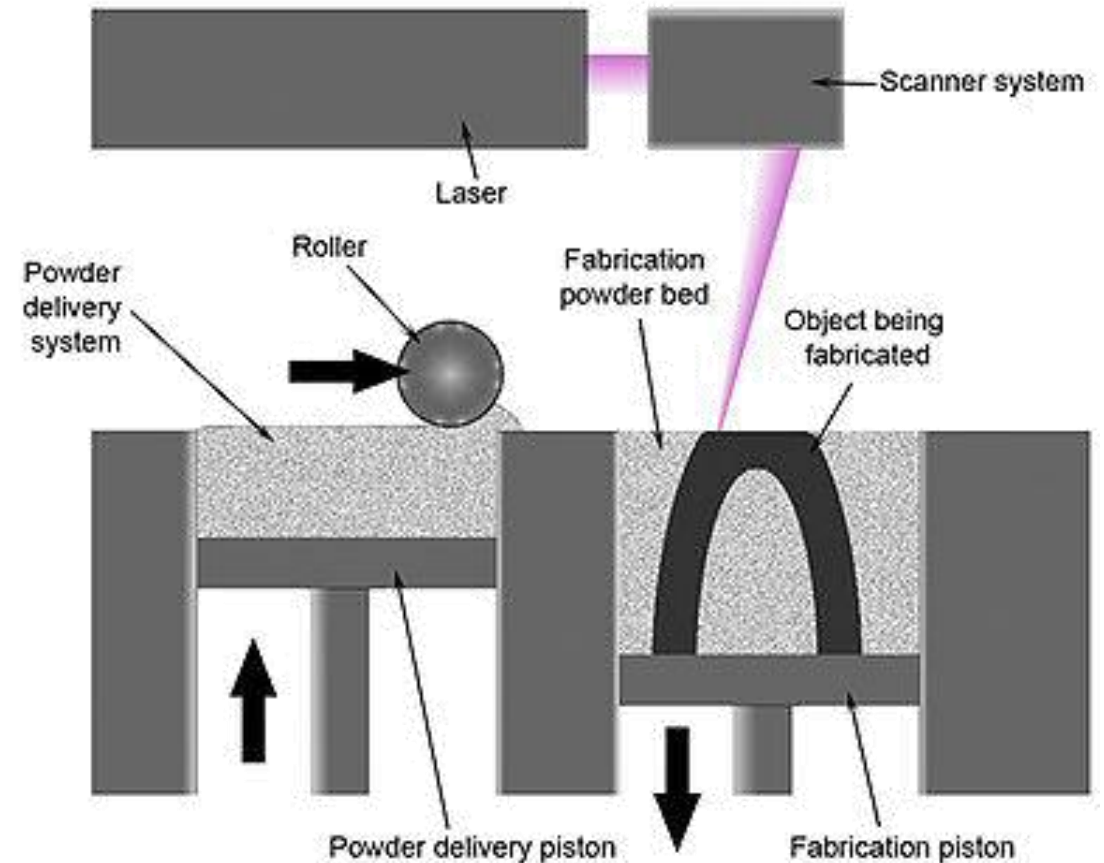
Fused Deposition Modeling



Selective Laser Sintering/Melting



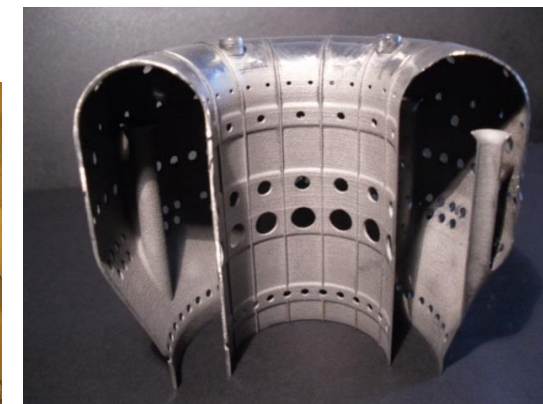
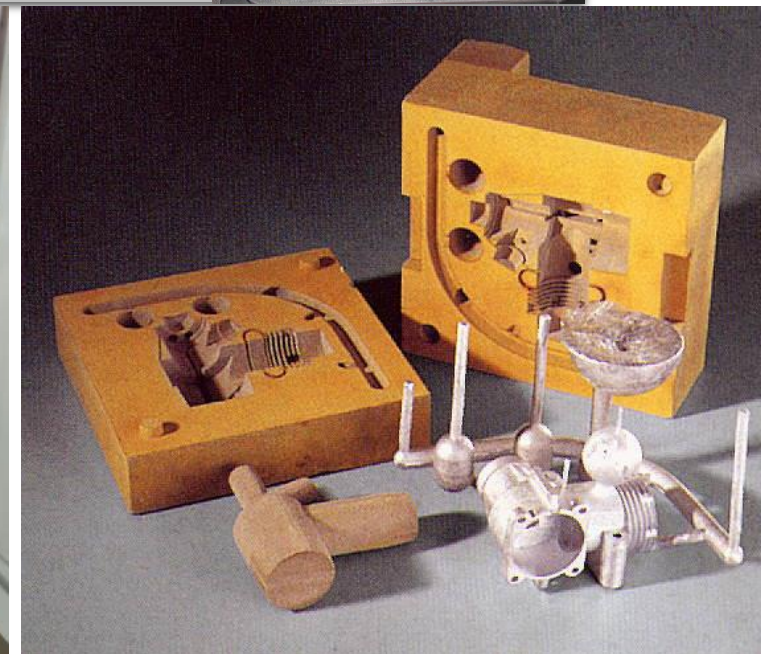
- Laser track is traced across a powder bed according to the 3D data in the X-Y axes.
 - As the laser interacts with the surface of the powdered material it sinters, or fuses, the particles to each other forming a solid.
 - Powder bed is layered and next pass of the laser fused with the previous layer.
 - Build chamber is completely sealed (temperature, environment)
-
- **Materials:**
 - Thermoplastic : ABS, PA, PEEK,
 - Metallic : Al, Ti, Ni, SS , Cr and alloys
 - Sand
 - **Manufacturers:**
 - SLM, EOS, Renishaw...



Selective Laser Sintering/Melting



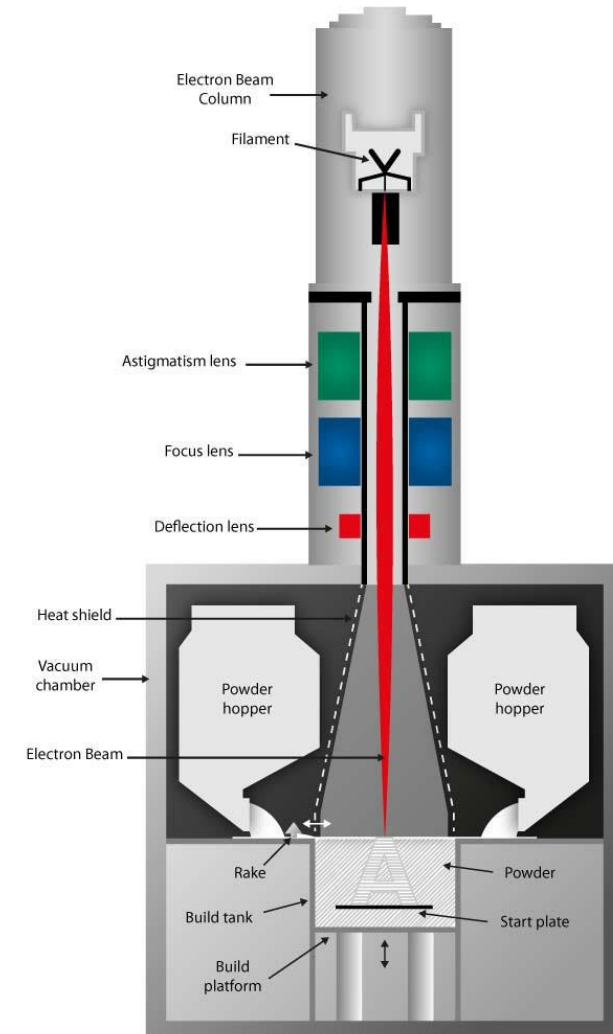
- + Precision and tolerance
- + Mechanical properties
- - Volume max.
- - Residual stress
- - Support



EBM



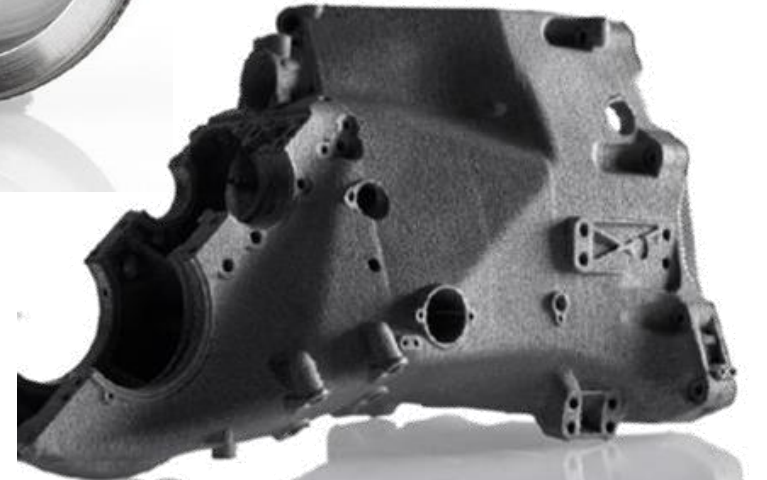
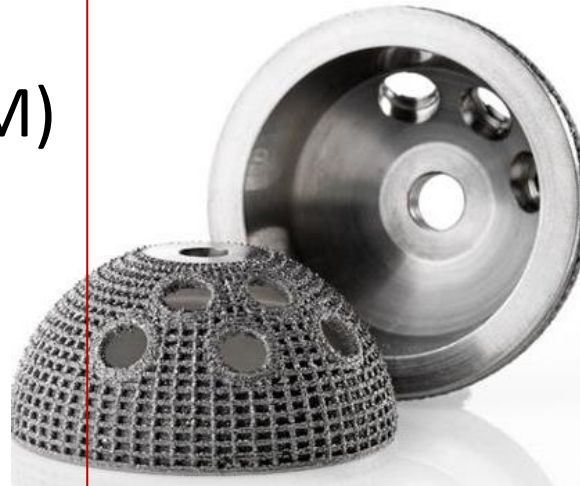
- Similarities with SLM but the energy source is electron beam
- Powder bed sintering before melting
- Materials:
 - Metallic : Al, Ti, Ni, SS and alloys
- Manufacturers:
 - ARCAM



EBM



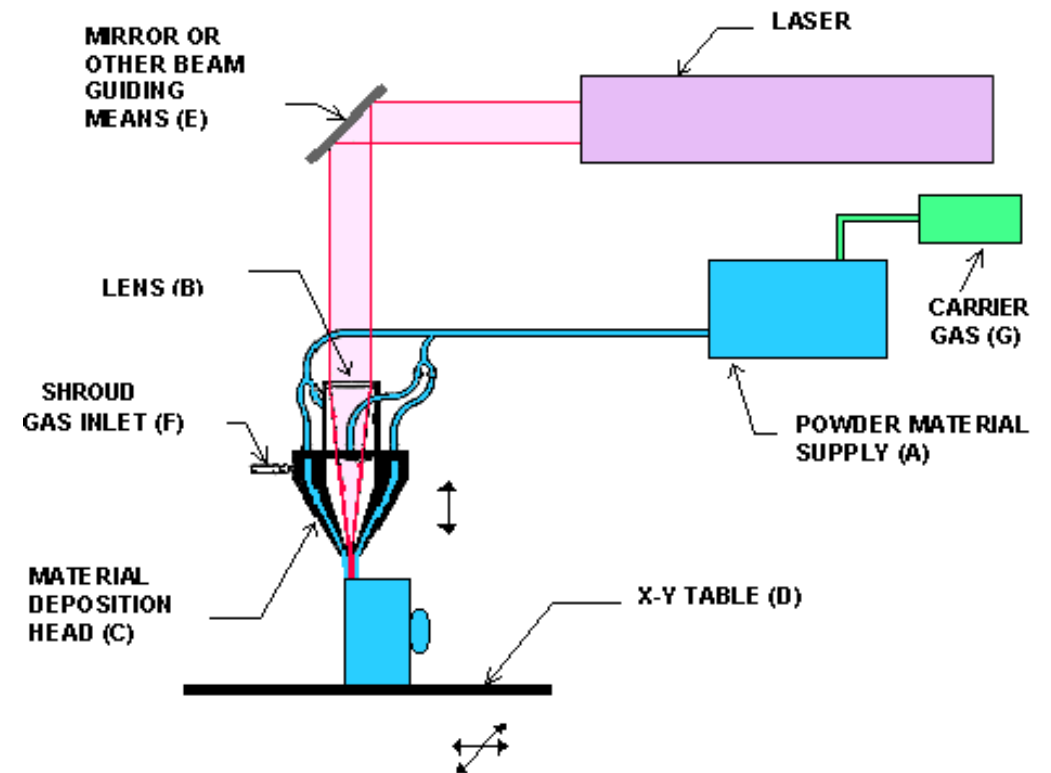
- + Process faster (2x/SLM)
- + Better homogeneity (20%/SLM)
- - In-situ analysis
- - Roughness
- - Residual stresses



Laser Powder Forming



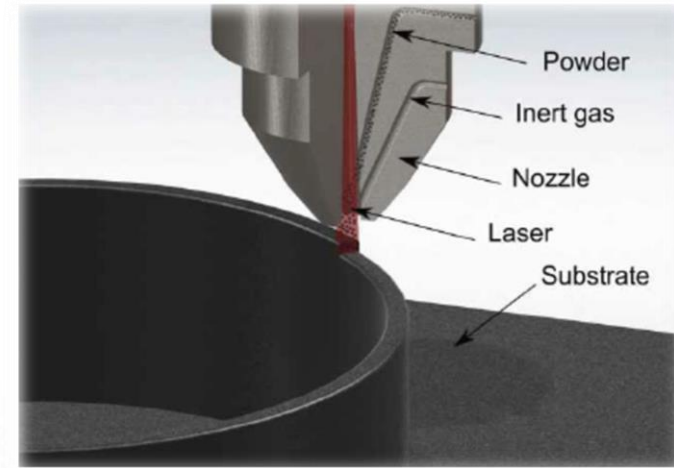
- Consists of a nozzle mounted on a multi axis arm
- Material is provided (wire or powder)
- And melted upon deposition with a laser or electron beam
- Materials:
 - Metallic : Al, Ti, Ni, SS and alloys
- Manufacturers:
 - BeAM, Optomec, InssTek



Laser Powder Forming



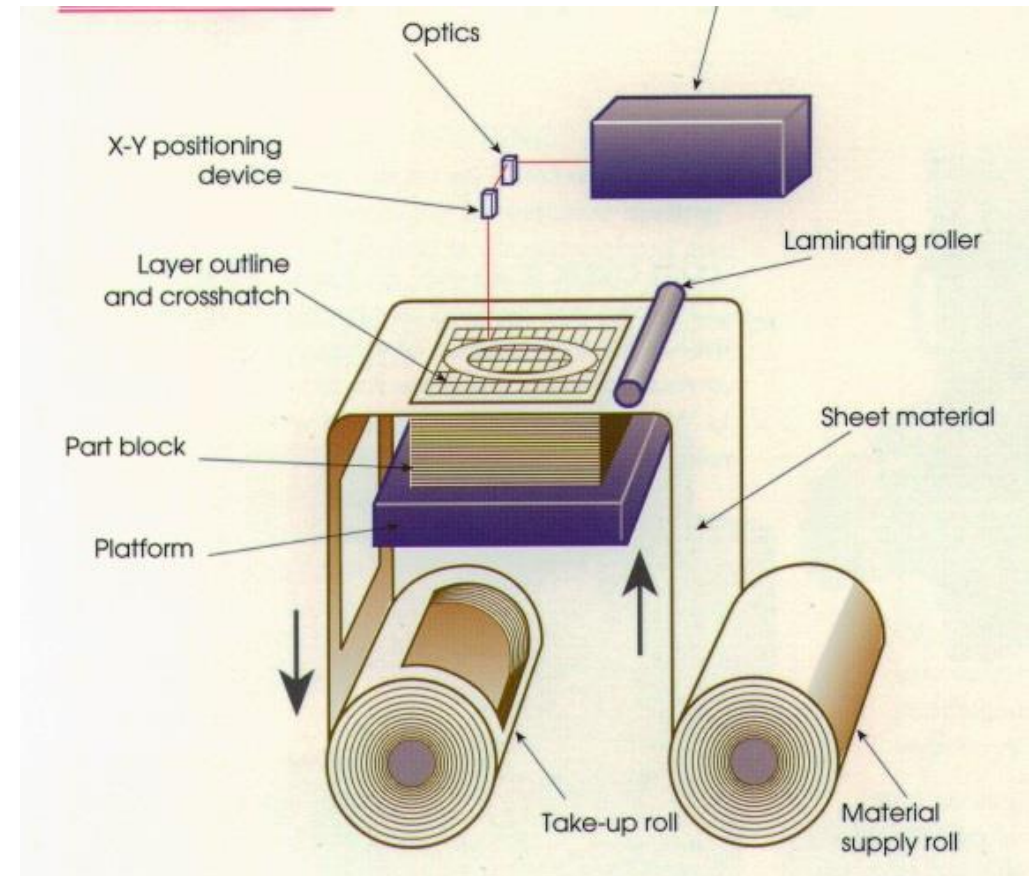
- + no support, multi-material and coating
- + Dimension and Fast (4x/SLM)
- - Roughness and residual stress
- - Fatigue endurance
- - In-situ control complex



Sheet Stacking Technology



- Sheets are used
- Laser beam cuts the contour of each layer
- Glue activated by hot rollers
- Materials:
 - Metal, Wood, Plastic
- Manufacturers:
 - Amkor, 3D systems, EOS



CATEGORIES	TECHNOLOGIES	PRINTED "INK"	POWER SOURCE	STRENGTHS / DOWNSIDES
Material Extrusion	Fused Deposition Modeling (FDM)	Thermoplastics, Ceramic slurries, Metal pastes	Thermal Energy	• Inexpensive extrusion machine • Multi-material printing • Limited part resolution • Poor surface finish
	Contour Crafting			
Powder Bed Fusion	Selective Laser Sintering (SLS)	Polyamides /Polymer	High-powered Laser Beam	• High Accuracy and Details • Fully dense parts • High specific strength & stiffness • Powder handling & recycling • Support and anchor structure • Fully dense parts • High specific strength and stiffness
	Direct Metal Laser Sintering (DMLS)	Atomized metal powder (17-4 PH stainless steel, cobalt chromium, titanium Ti6Al-4V), ceramic powder		
	Selective Laser Melting (SLM)			
	Electron Beam Melting (EBM)		Electron Beam	
Vat Photopolymerization	Stereolithography (SLA)	Photopolymer, Ceramics (alumina, zirconia, PZT)	Ultraviolet Laser	• High building speed • Good part resolution • Overcuring, scanned line shape • High cost for supplies and materials
Material Jetting	Polyjet / Inkjet Printing	Photopolymer, Wax	Thermal Energy / Photocuring	• Multi-material printing • High surface finish • Low-strength material
Binder Jetting	Indirect Inkjet Printing (Binder 3DP)	Polymer Powder (Plaster, Resin), Ceramic powder, Metal powder	Thermal Energy	• Full-color objects printing • Require infiltration during post-processing • Wide material selection • High porosities on finished parts
Sheet Lamination	Laminated Object Manufacturing (LOM)	Plastic Film, Metallic Sheet, Ceramic Tape	Laser Beam	• High surface finish • Low material, machine, process cost • Decubing issues
Directed Energy Deposition	Laser Engineered Net Shaping (LENS) Electronic Beam Welding (EBW)	Molten metal powder	Laser Beam	• Repair of damaged / worn parts • Functionally graded material printing • Require post-processing machine

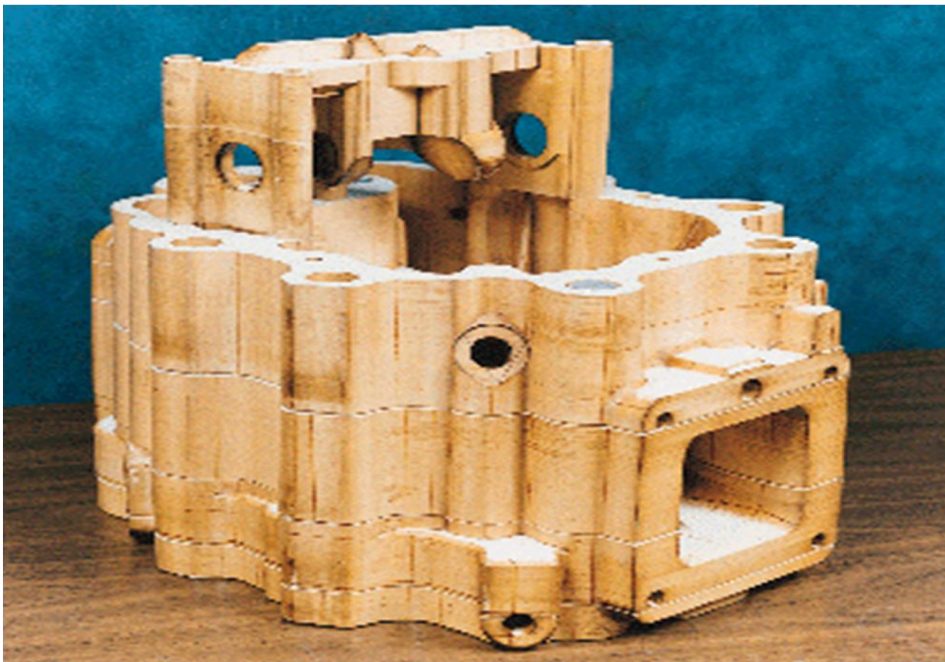
Touch and Feel



Form, Fit and Function



Patterns or Molds for Casting



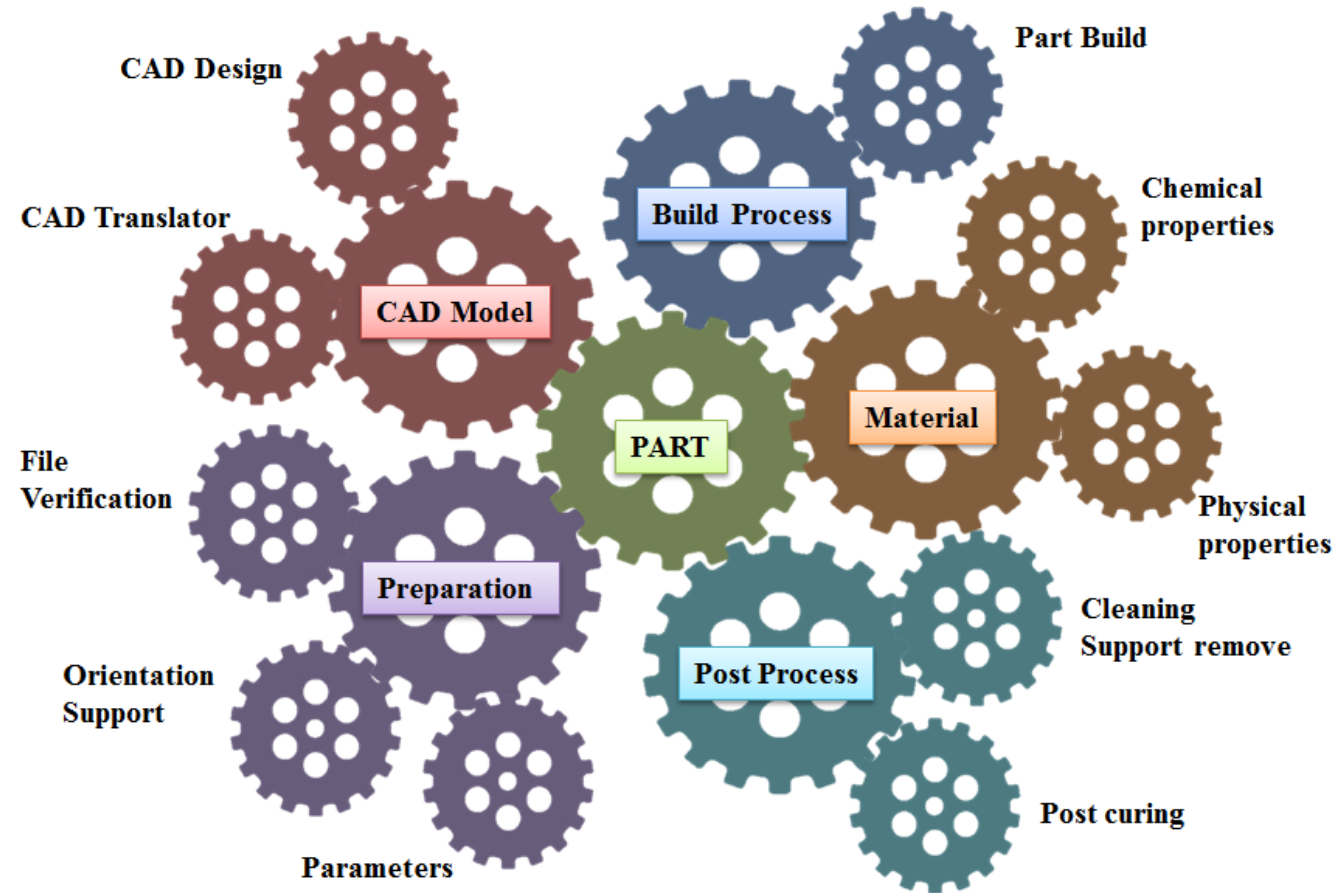
Direct Tooling and Prototypes



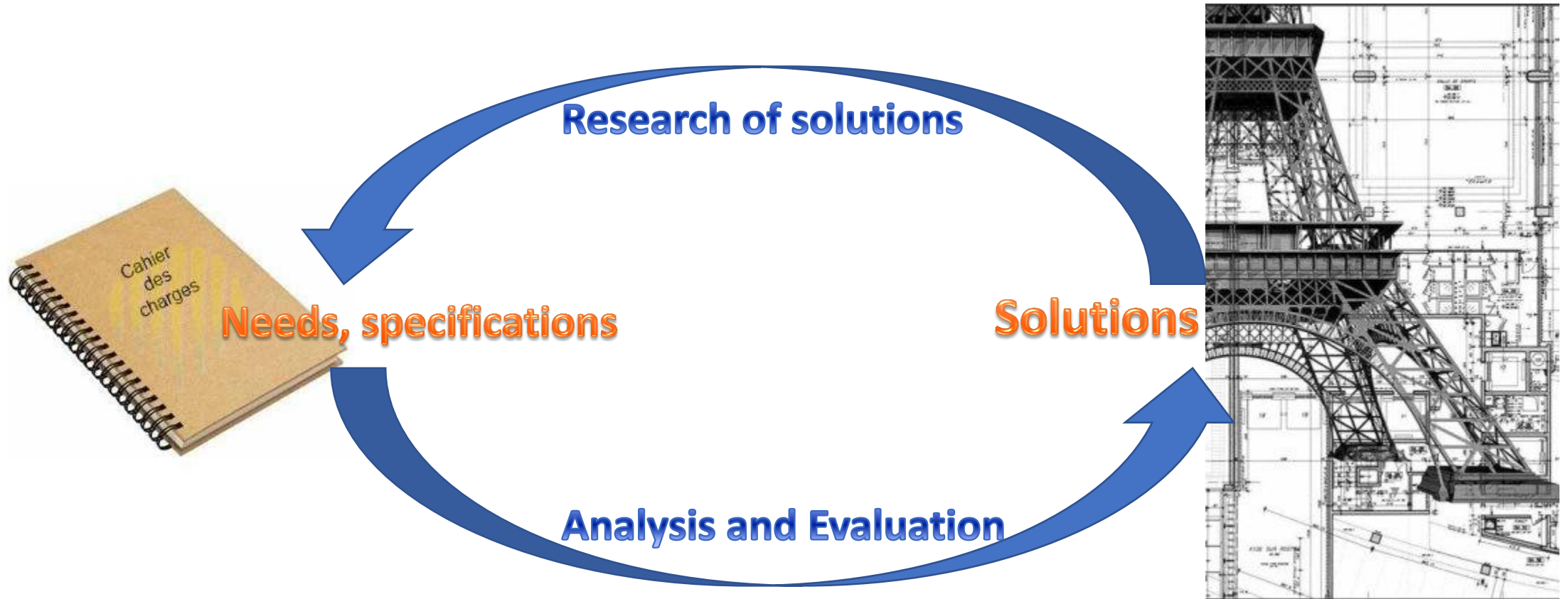
Table of contents

1. Process
2. Design
3. Perspectives

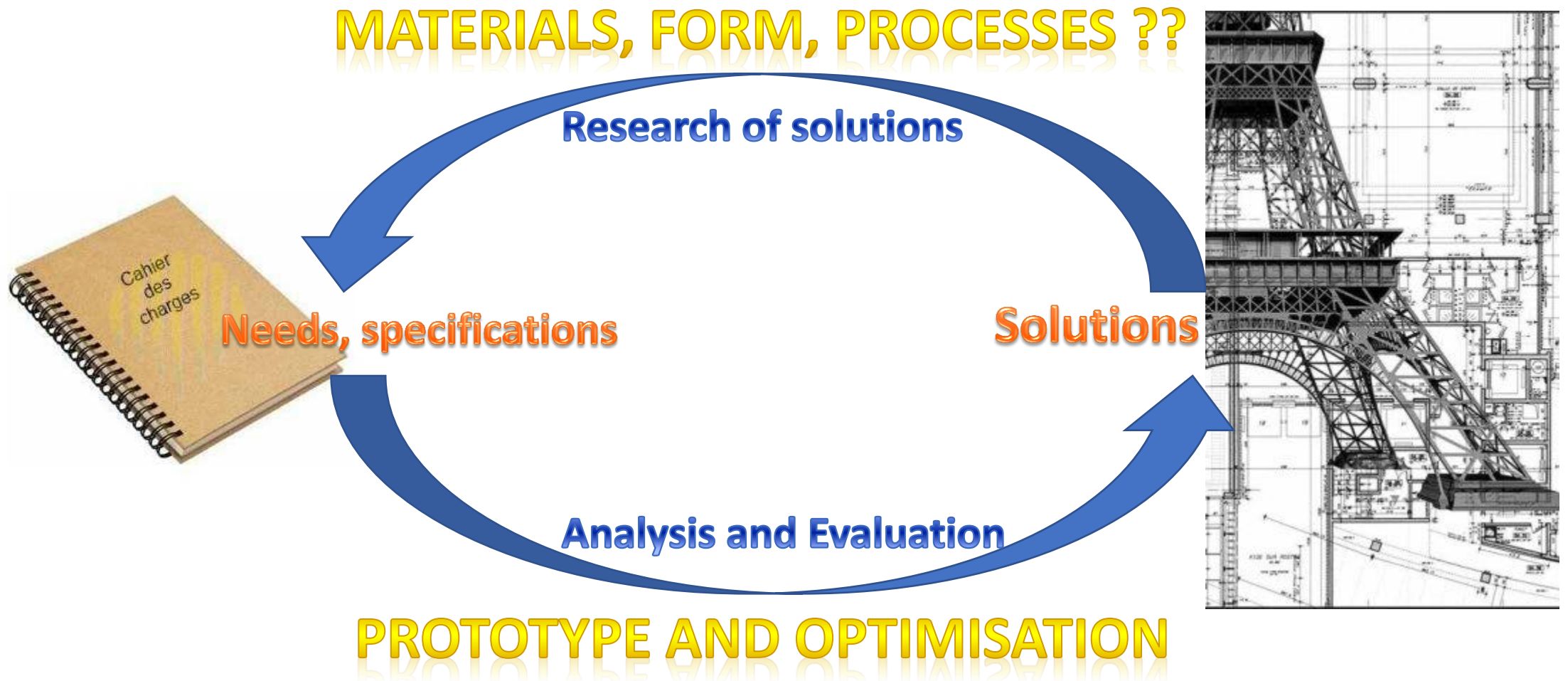
Application Design



Design phases: past



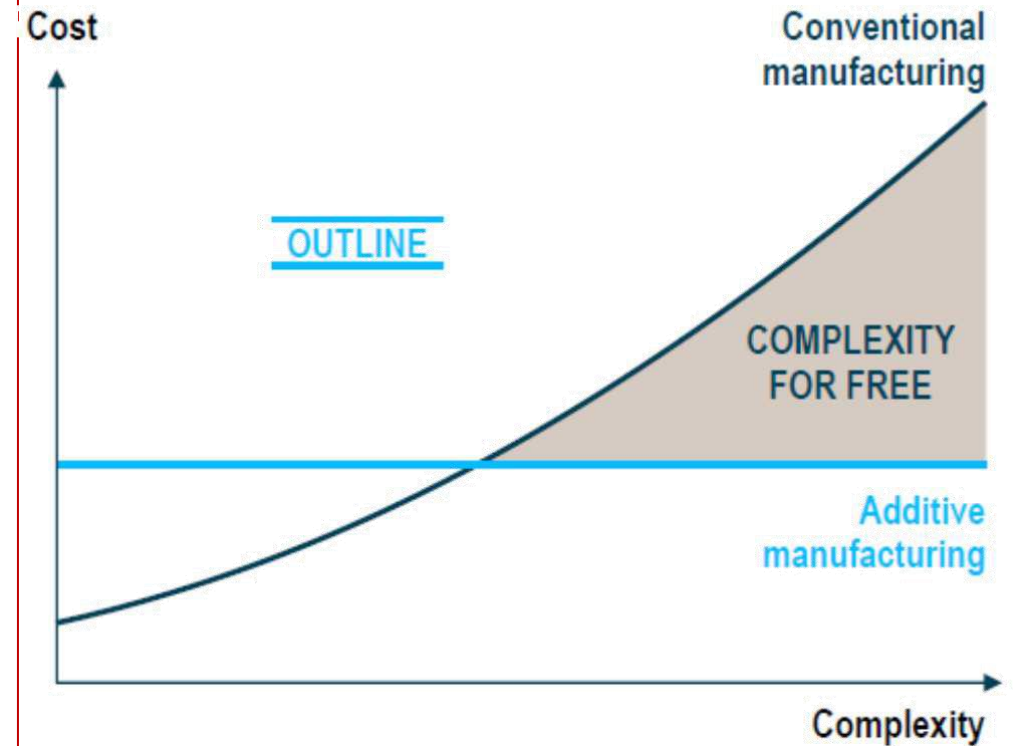
Design phases : now



Value optimisation

1. Regroup parts
2. New functions
3. Personlization
4. Energy saving
5. Mass reduction
6. Esteem

→ **Complexity** does not change the **Cost**

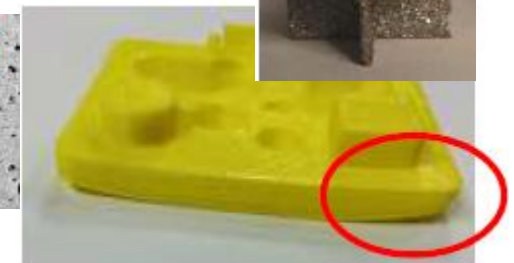
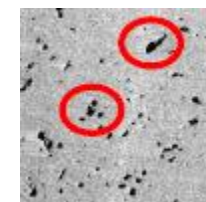


Design methodology

Freedom without rules doesn't work → Material & Process !

- Direction of process and reference
- Link between shape and properties
- Supports
- Post-treatments

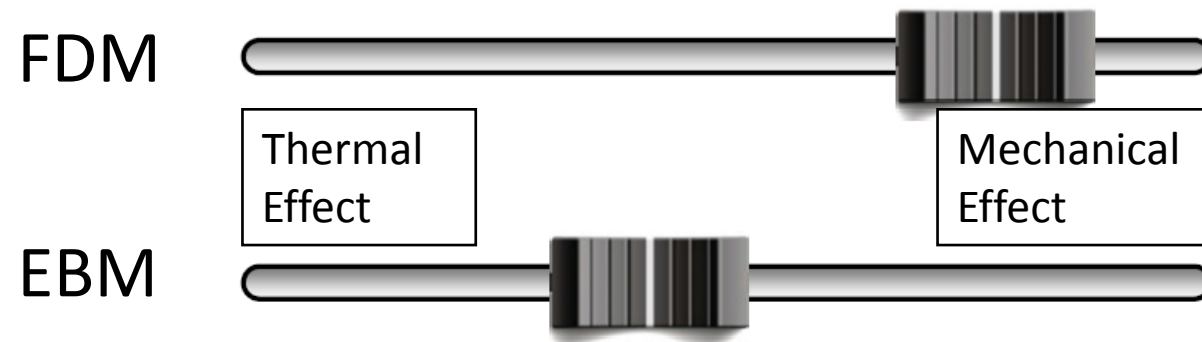
• → Curling, Warping, Porosity, Cracks, Shape deviation...



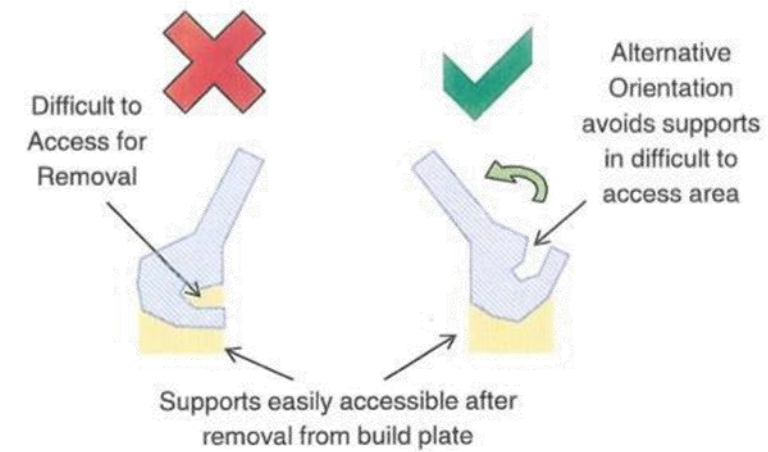
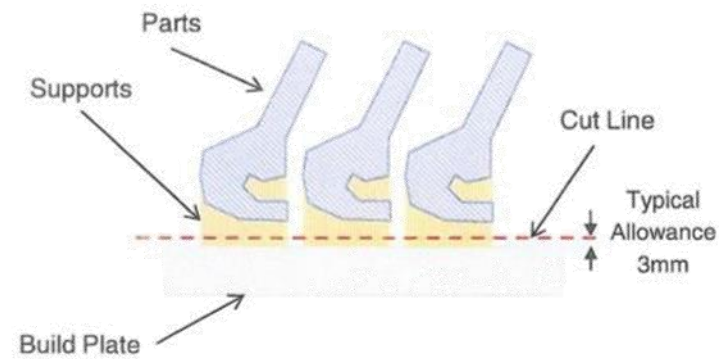
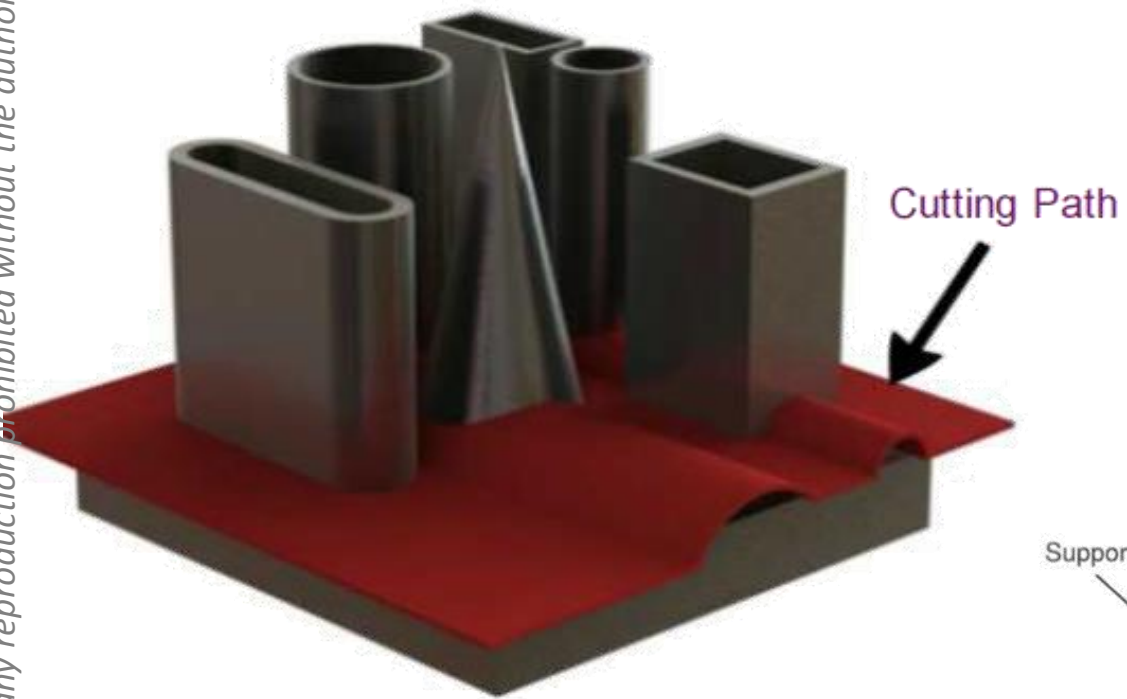
Design Methodology

1. Rules not well defined
2. Not formalized
3. Strong link to a process, a machine, material even manufacturer

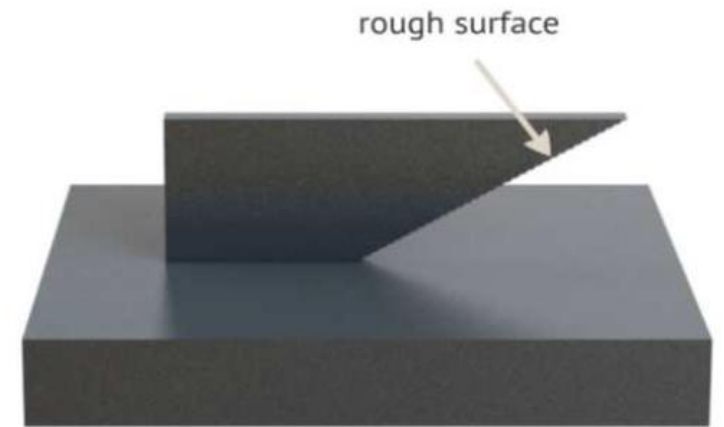
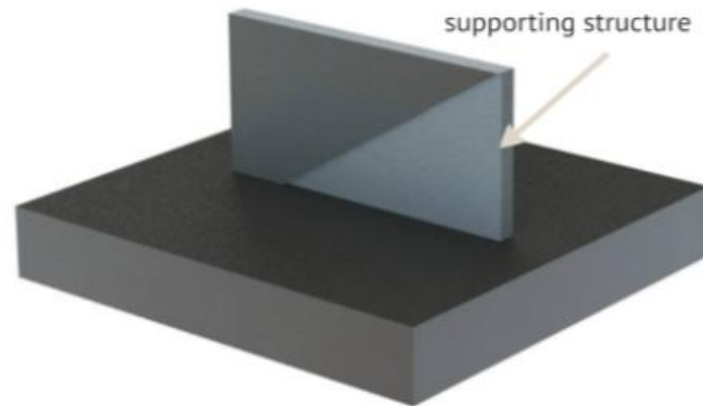
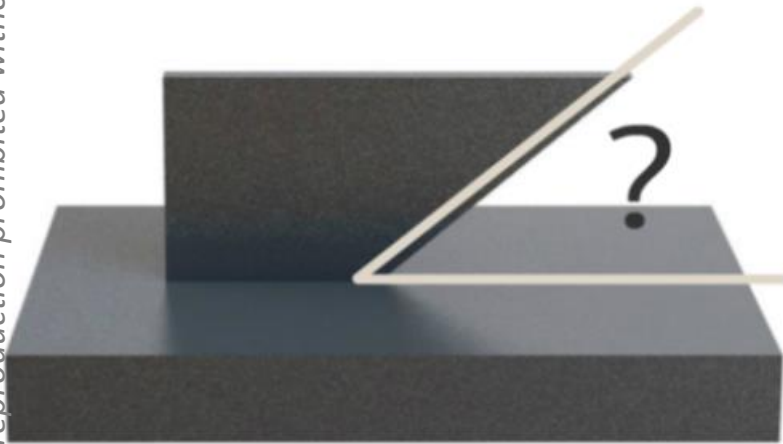
Ex:



Examples



Examples



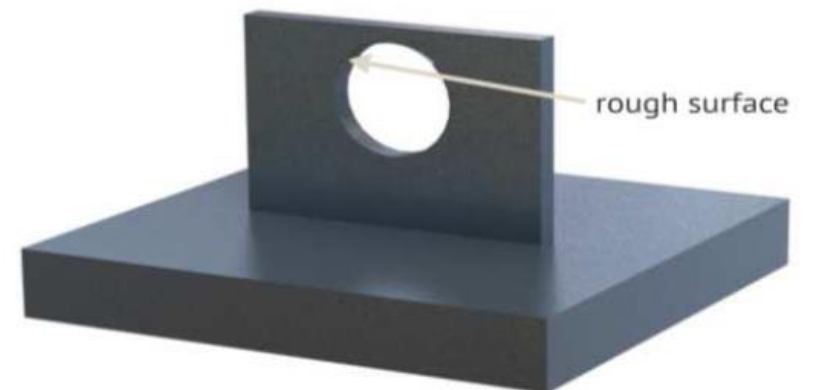
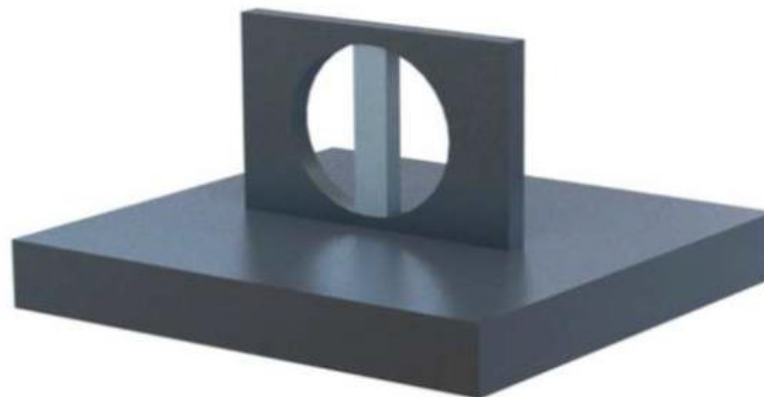
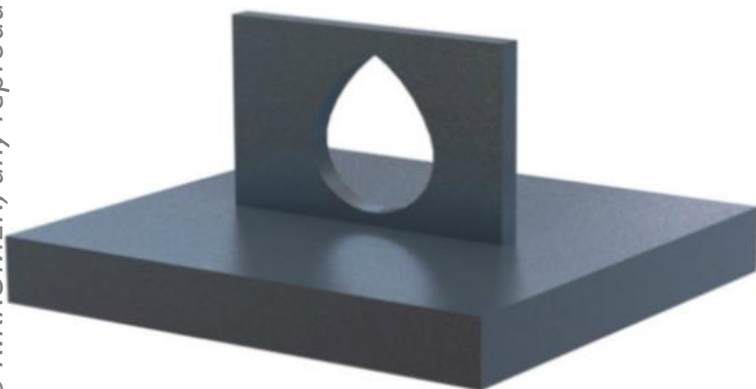
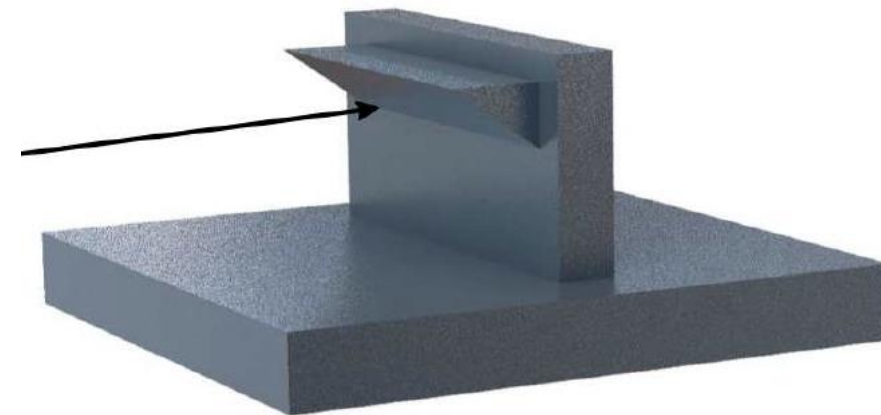
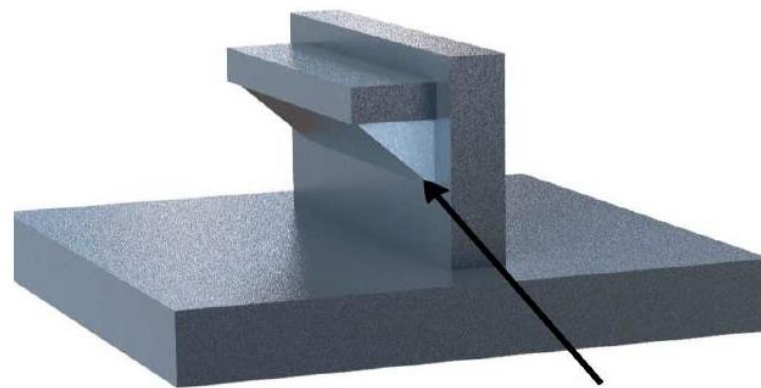
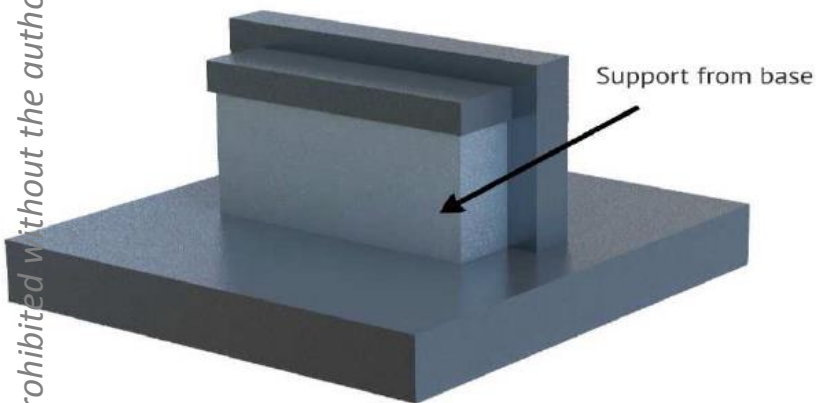
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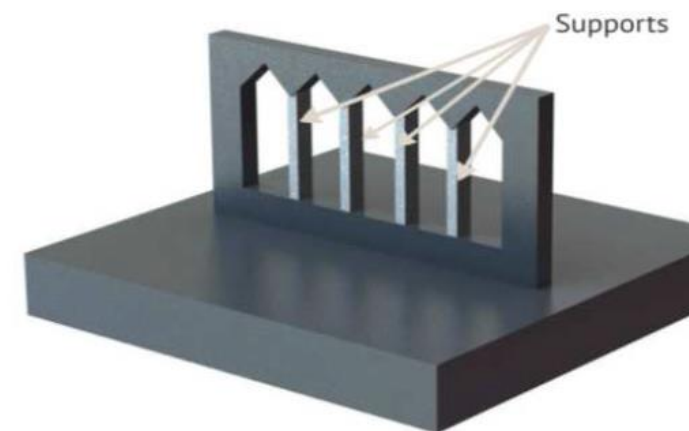
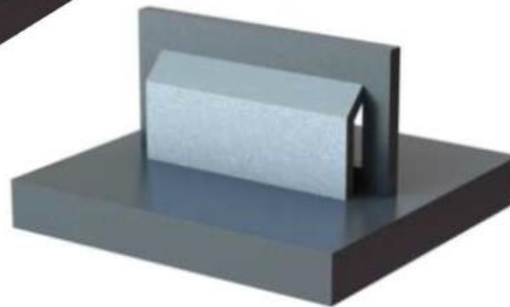
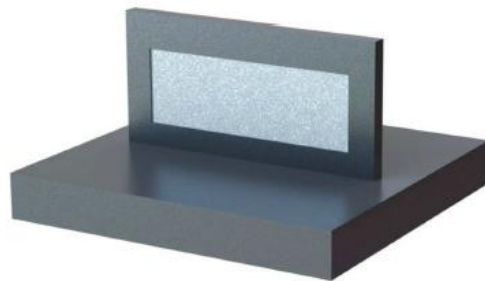


Ti64

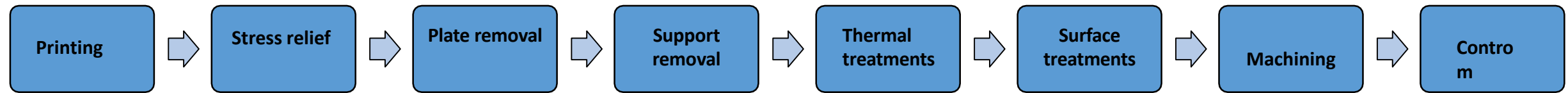
Examples



Examples

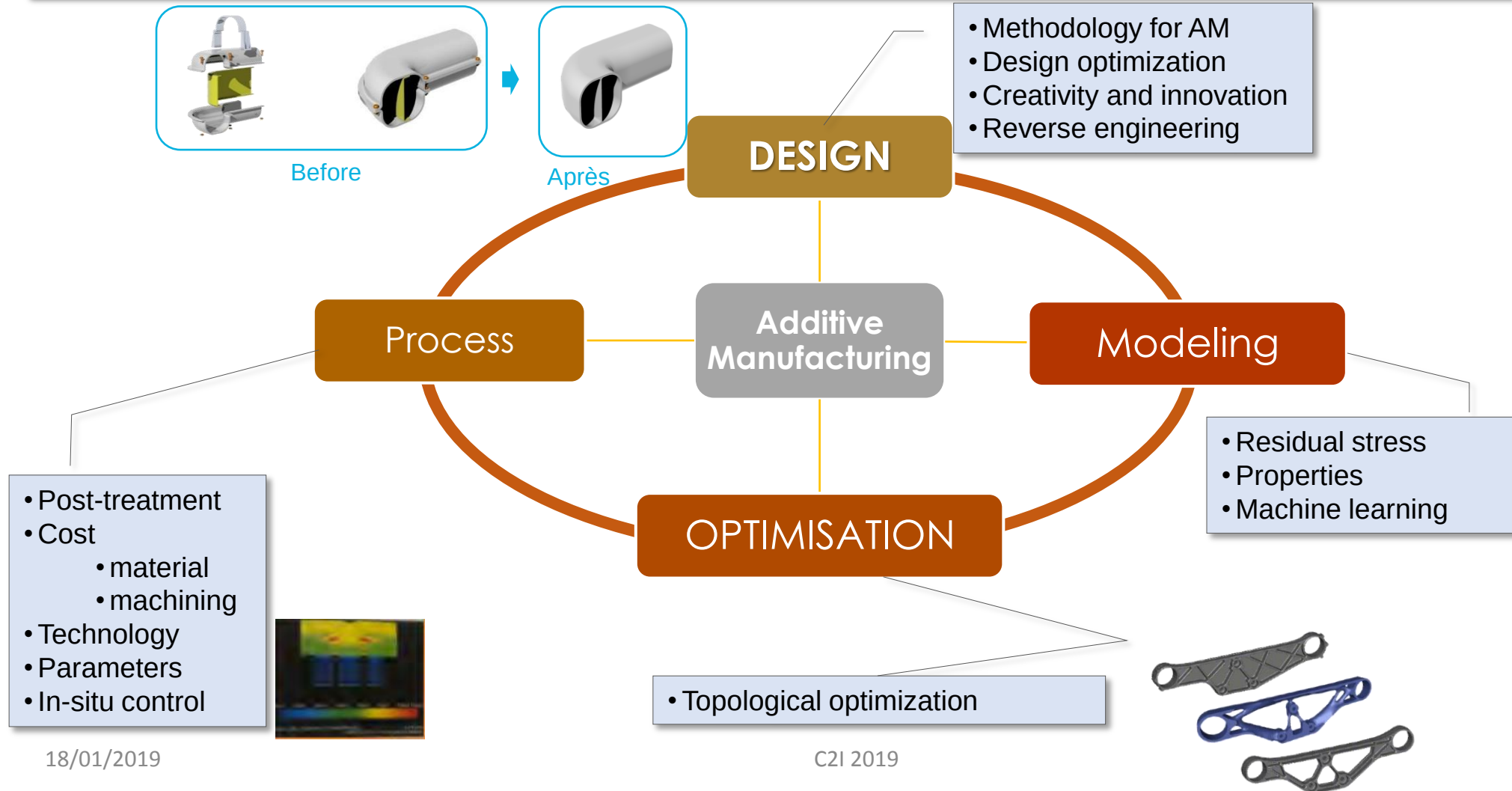


Design for Additive Manufacturing

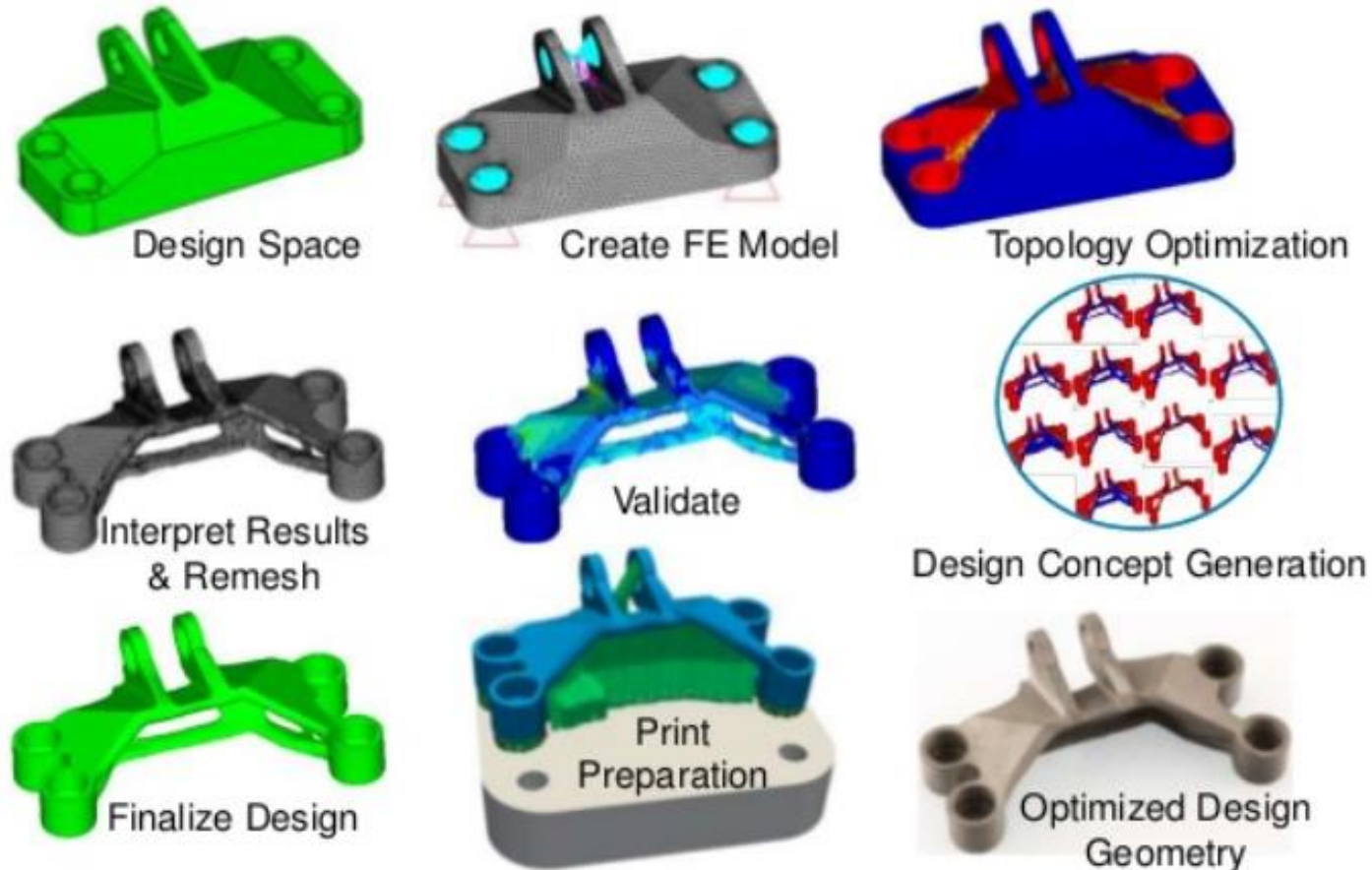


Steps need to be anticipated at the design phase due to limitation according to the process, the machine and the materials

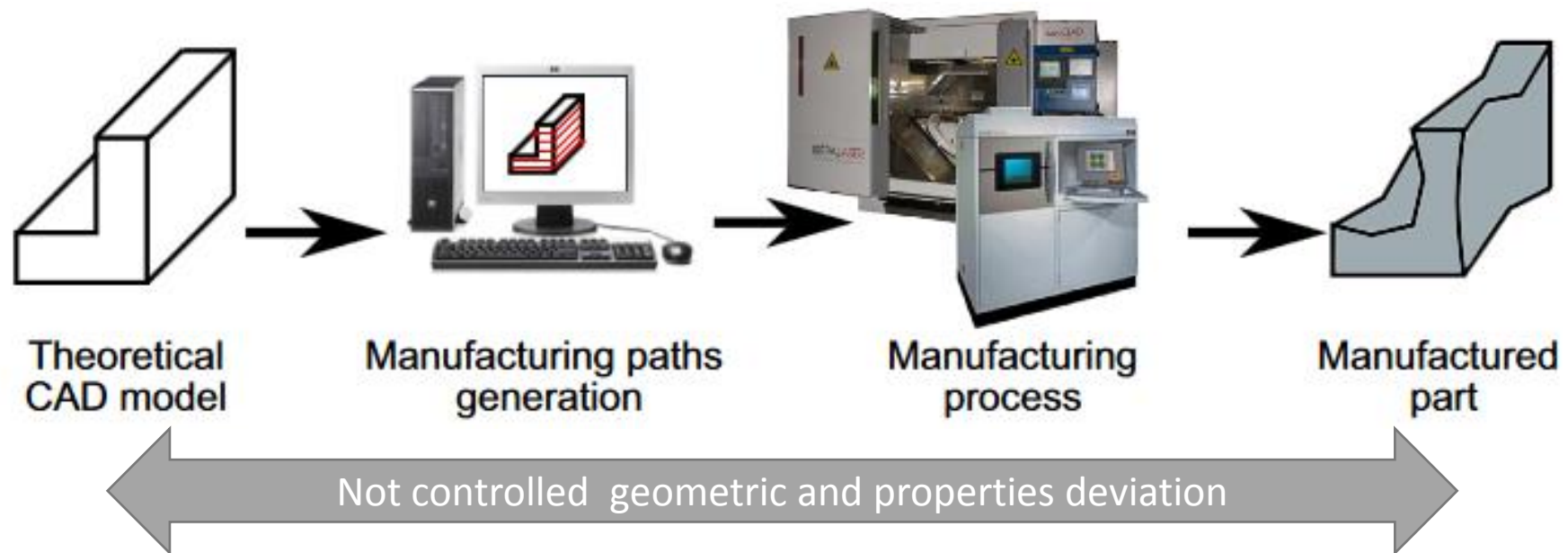
Design for Additive Manufacturing



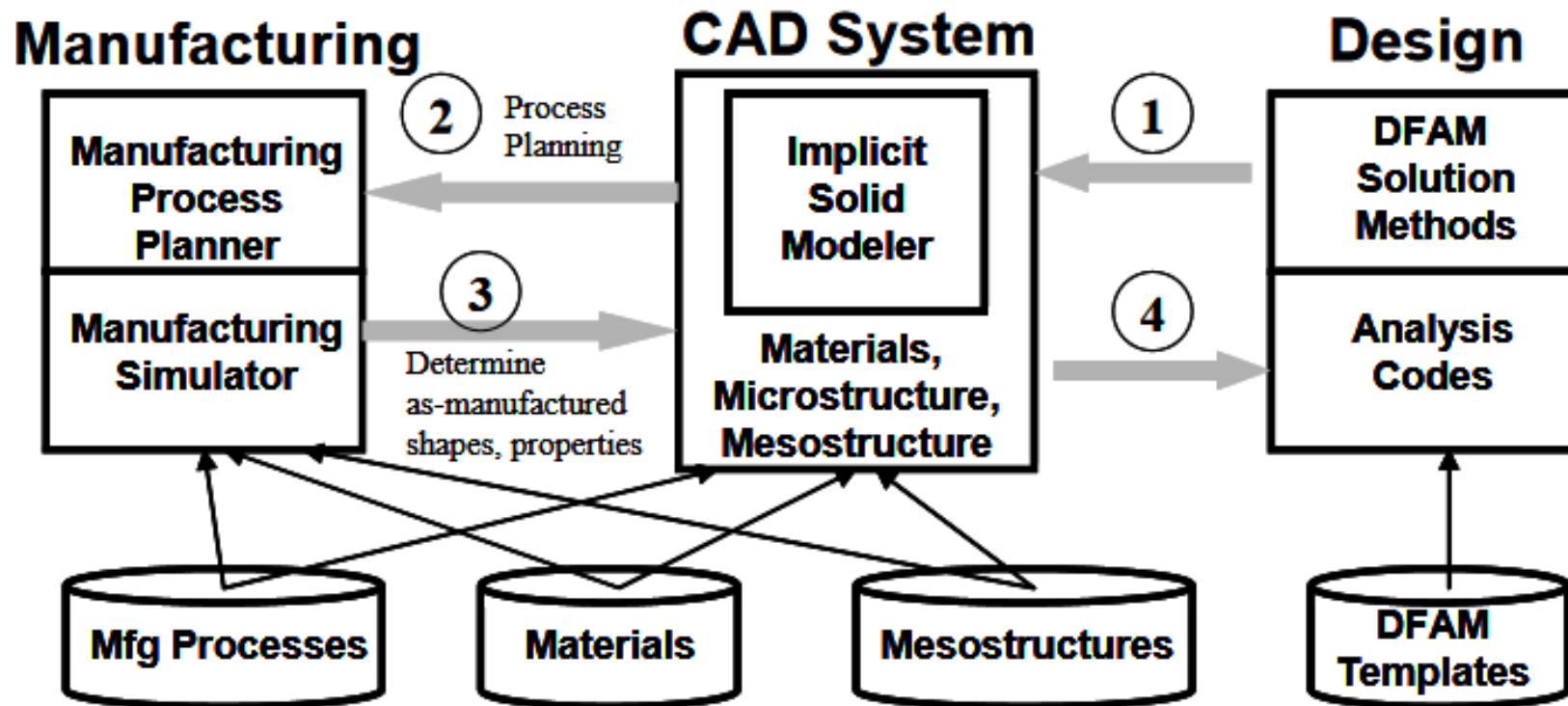
Perspective : Take advantage for optimization



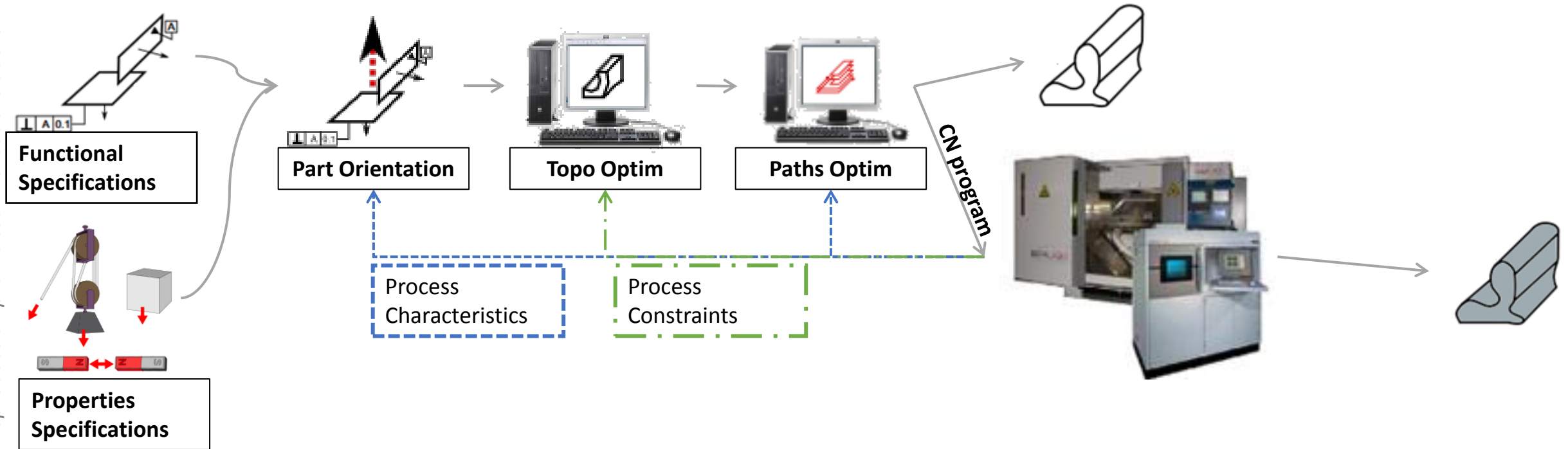
Perspectives : links ??



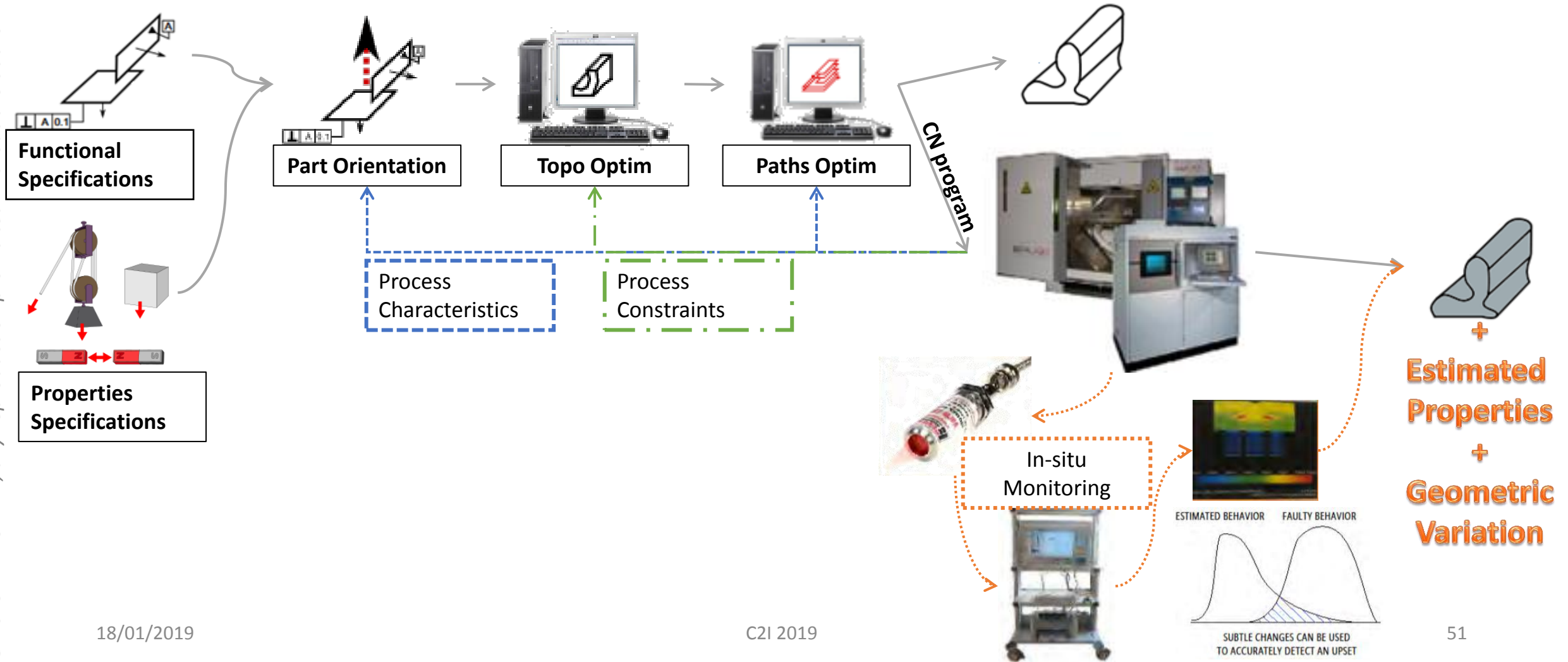
Perspectives : Design Methodology for Additive Manufacturing



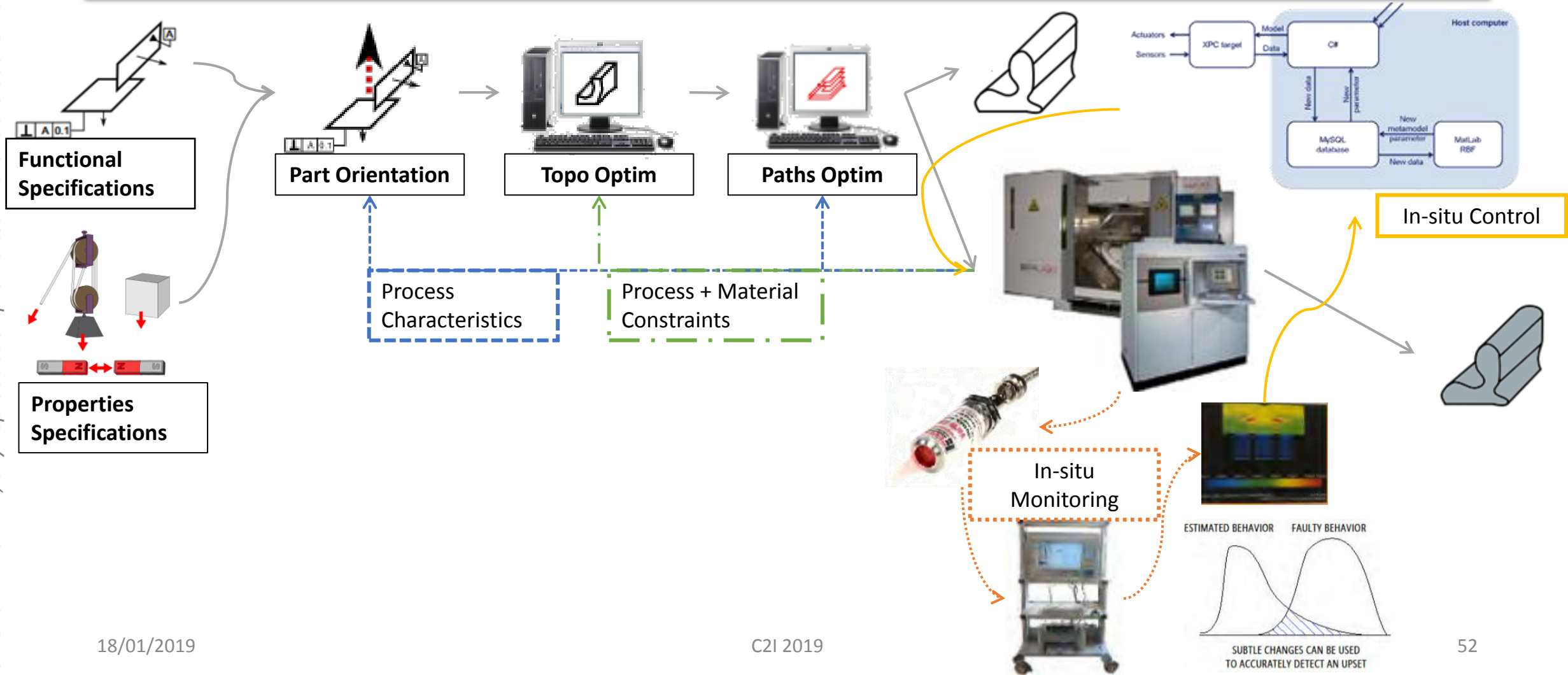
Perspectives : DFAM Example



Perspectives : In-situ Analysis



Perspectives : In-situ Controlled → Cyber-Enabled Manufacturing Systems



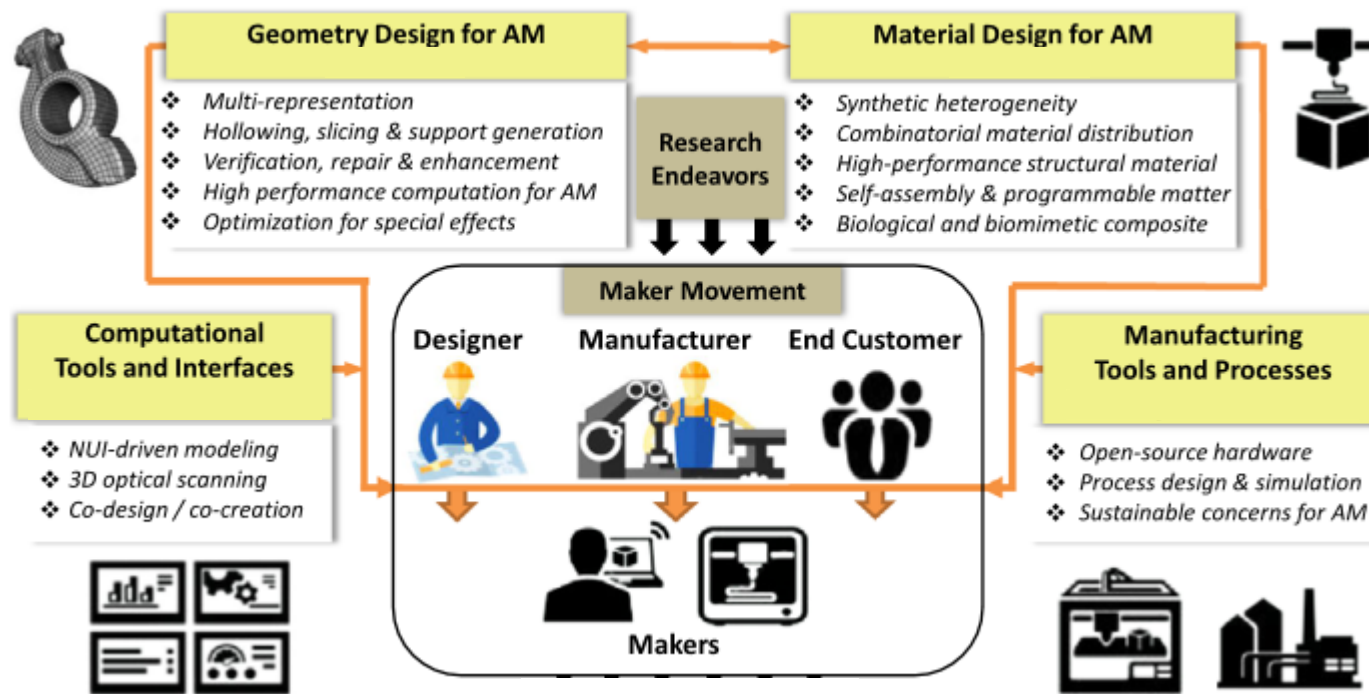
Perspectives : To day needs

1. Physical phenomena understanding
2. Sensors implentation in machine
3. Transfer function from data to properties
4. Link process/material with geometry
5. Accurate physics-based dynamics models for control and defect detection

- Lab bench for LPBF
- Machine learning development + physical modeling
- In-situ evaluation and data mining
- Prediction tools

Conclusion

Additive Manufacturing is an **exciting** and emerging field, but there is much yet **to do** to reach its ***potential ...***



**“WHEN OBSTACLES
ARISE, YOU CHANGE
YOUR DIRECTION TO
REACH YOUR GOAL;
YOU DO NOT CHANGE
YOUR DECISION TO
GET THERE.” - ZIG ZIGLAR**

Merci !

Robin KROMER, Associate Professor

REFERENCE

- <http://aim.gov.in/>
- Metal binder jetting: de la production unitaire à la fabrication série, P.Calves
- Impression 3D, de l'idée au produit, A. Bernard
- Conception pour la fabrication additive, GSCOP, F.Pourroy
- Fabrication additive, ENSIL, IUT Limoges

CONTRÔLE NON DESTRUCTIFS PAR ULTRASONS

ANISSA MEZIANE

MAÎTRE DE CONFÉRENCES À L'UNIVERSITÉ DE BORDEAUX
INSTITUT DE MÉCANIQUE ET D'INGÉNIERIE DE BORDEAUX (I2M, UMR5295)

- **Généralités sur les ondes acoustiques**
- **Ultrasons pour la caractérisation mécanique**
 - ✓ Caractérisation par ondes de volumes
 - ✓ Caractérisation par ondes guidées
- **Contrôle non destructif par ultrasons**
 - ✓ Ondes de volumes
 - ✓ Ondes guidées
 - ✓ Acoustique non-linéaire

Définition d'une onde élastique

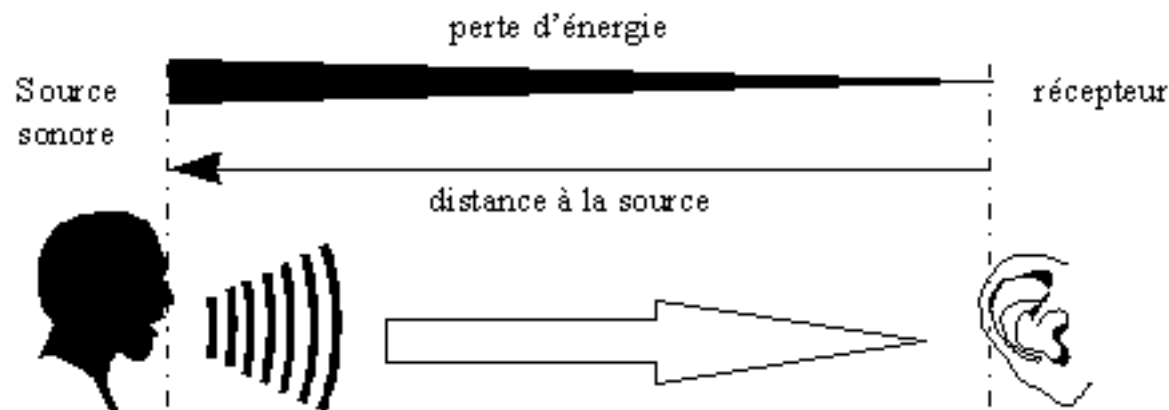
Contrairement aux ondes électromagnétiques (lumière, rayons X,...), les **ondes élastiques** (ou ondes mécaniques) ne peuvent pas exister dans le vide. Elles requièrent un support matériel (fluide ou solide) pour se propager. En effet, l'onde élastique est une **perturbation mécanique de la matière** (dilatation, compression, cisaillement, vibration,...) qui se propage de proche en proche *via* des **forces d'interaction** entre les particules du milieu.

L'existence d'une onde élastique requiert donc une **source excitatrice** et **un milieu matériel de propagation**. Un **récepteur** complète alors ce système pour assurer la détection, voire l'analyse, de l'onde propagée.

Propagation du son (parole, musique, bruits divers)

Le son est généré par **nos cordes vocales** (un instrument ou tout objet susceptible de faire vibrer localement l'air).

=> Le son **se propage** via les particules d'air qui bougent tour à tour autour de leur position d'équilibre, jusqu'au **récepteur** qui peut être notre tympan, un microphone, les ailes ou antennes d'un insecte, etc...



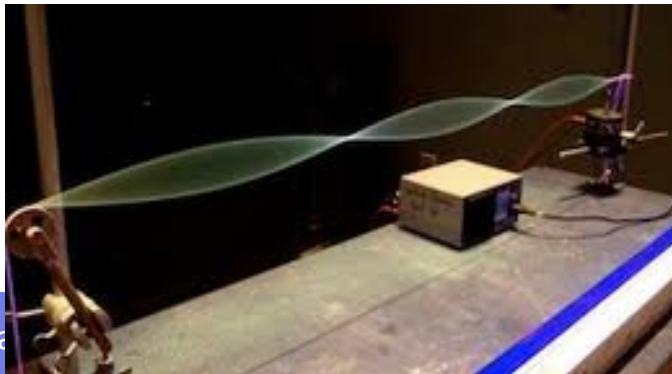
On est en présence d'une **onde dite « acoustique »** à cause du côté audible des fréquences associées à ce son (voir plus loin la définition des domaines en fréquence).

La propagation d'une vibration le long d'une corde de guitare

La source sera le **pincement par les doigts du guitariste**, le milieu de propagation est la **corde**, le détecteur est **notre oreille** qui reçoit le son (acoustique) rayonné par la corde vibrante.

L'onde élastique se propage le long de la corde, sous la forme d'une **onde stationnaire** car ce sont une infinité d'ondes qui font des allers et retours le long de cette corde pour la faire entrer en résonance et la faire vibrer à sa fréquence propre.

Le couplage mécanique entre cette corde (solide) et l'air environnant (fluide) entraîne la vibration des particules d'air situées au voisinage immédiat de la corde. Le mouvement de ces particules d'air se transmet donc aux particules voisines, via les forces de contact évoquées plus haut, jusqu'à notre tympan.



Anissa Mezia

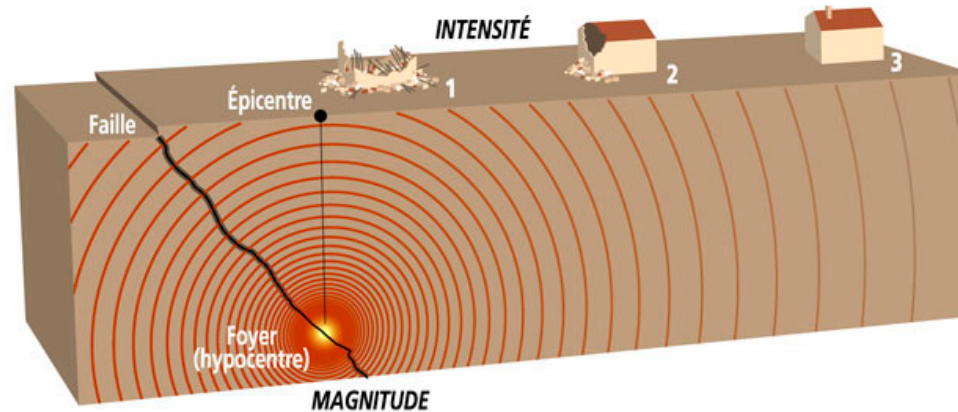
28/01



La propagation d'une onde sismique dans le sol

La source est **l'hypocentre** (ou foyer) qui est activé par une rupture/glissement de faille (par exemple). Les ondes sismiques proviennent du foyer et se dirigent (entre autres) vers la surface de la terre. Le **sol** constitue donc le milieu de propagation.

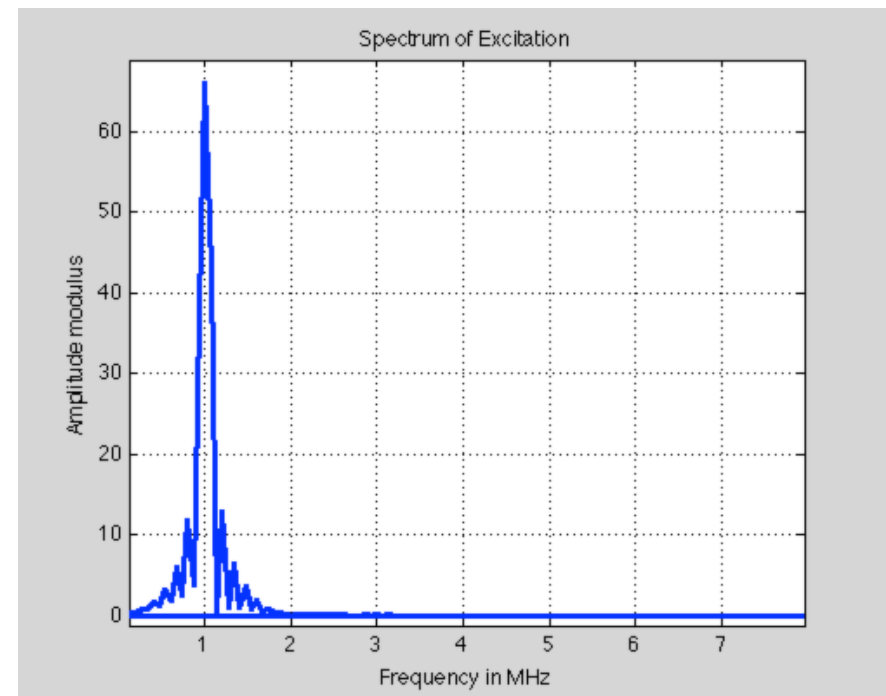
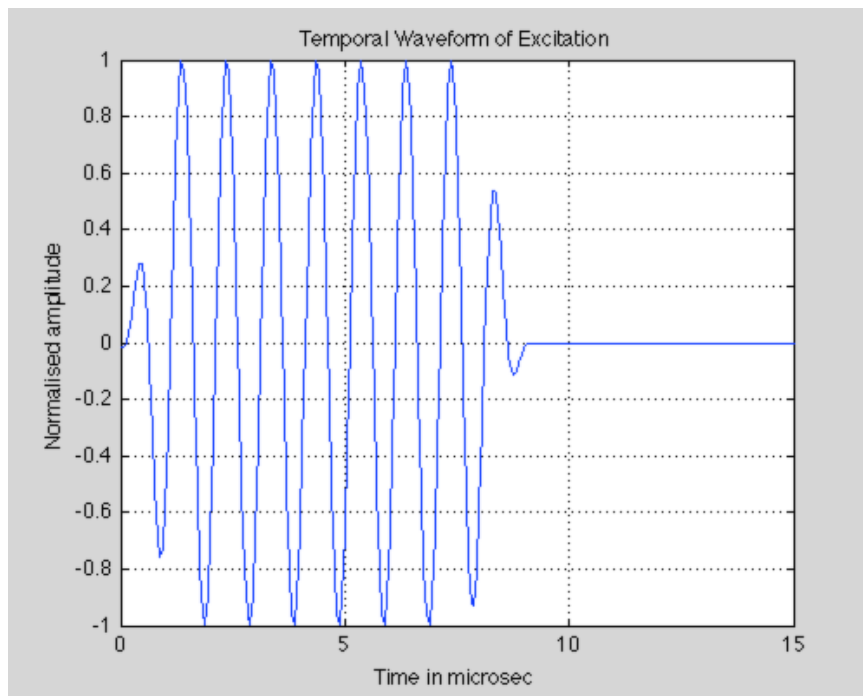
Les détecteurs sont les personnes ou habitations en surface, les sismographes qui surveillent et mesurent les ondes terrestres, etc...



Onde sismique

<http://www.mementodumaire.net/les-risques-naturels/rn-6-seismes-et-tsunami/>

La perturbation possède une certaine **forme temporelle** (puisque les particules oscillent autour de leur position d'équilibre). Si cette forme est sinusoïdale et de durée infinie, alors le phénomène est dit harmonique ou monochromatique (une seule fréquence).



Elle peut aussi comporter plusieurs harmoniques ; elle est alors périodique mais avec plusieurs fréquences superposées.

Dans tous les cas, on distingue trois domaines de fréquences :

$f \leq 20$ Hz – Ondes basses fréquences – Domaine des **infrasons**

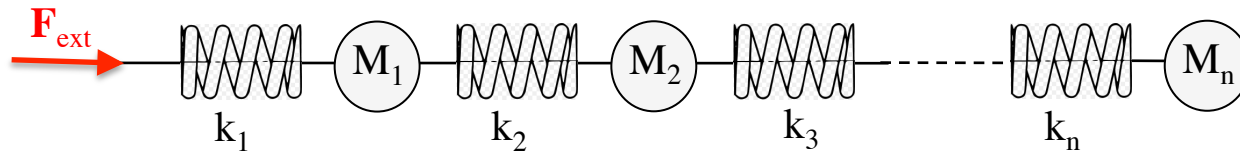
$20 \text{ Hz} \leq f \leq 20 \text{ kHz}$ – Fréquences audibles – Domaine de **l'acoustique**

$f \geq 20 \text{ kHz}$ – Ondes hautes fréquences – Domaine des **ultrasons**

Exemples de régimes fréquentiels (valeurs approximatives)

- 1 μ Hz – 1 Hz : Physique du globe, Sismologie TBF
- 10 Hz – 100 Hz : Géologie, Sismique
- 20 Hz – 20 kHz : Audible
- 10 kHz – 100 kHz : Nettoyage par US (façades, dents, ...)
- 1 kHz – 30 kHz : Génération d'US par micro-ondes
- 10 kHz – 100 kHz : Acoustique sous-marine, sonars
- 50 kHz – 500 kHz : CND ultrasons à couplage par air
- 500 kHz – 20 MHz : CND contact ou couplage eau, Emission acoustique, Médical, Echographie
- 20 MHz – 100 MHz : Microscopie acoustique (imagerie fine)
- 100 MHz – 1 GHz : Acousto-optique, Acousto-électronique
- 1 GHz – 1 TeraHz : Etude de la matière à l'échelle microscopique

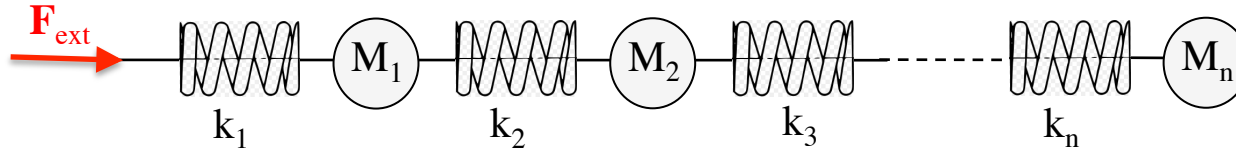
Le milieu de propagation peut être assimilé à une chaîne finie de N masses M_i reliées entre elles par des ressorts de raideurs k_i .



On a alors à faire à un **milieu discret à N degrés de liberté**.

force extérieure $\Rightarrow$ compression du premier ressort k_1 relié à la masse M_1
 $\Rightarrow$ compression du ressort k_2 qui la relie à la masse M_2
 $\Rightarrow$

$\Rightarrow$ **propagation d'une perturbation** dans un milieu discret à N ddl.



Si excitation extérieure **sinusoïdale, de période T**

=> variation temporelle des masses M de la même forme temporelle (si milieu linéaire).

=> **dimension spatiale** de la perturbation = **longueur d'onde $\lambda = C T$**

où **C** est la vitesse à laquelle se propage la perturbation, le long de la chaîne atomique.

Si la **distance** entre les masses adjacentes de la chaîne est **de l'ordre de grandeur, ou plus grande, que la longueur d'onde λ**

=> alors le système est « vu », par la perturbation qui se propage, comme un **milieu discret**.

Il faut donc autant d'équations qu'il y a de masses pour modéliser le phénomène vibratoire qui se propage. Mathématiquement, on écrit et on résout un système de N équations à N inconnues. Quand N est grand, on peut avoir recours à des méthodes numériques (différences finies par exemple ...) pour résoudre.

Si la **distance** entre les masses adjacentes de la chaîne peut être considérée comme **petite devant la longueur d'onde λ** ,

=> alors le système peut être assimilé à un **milieu continu**.

*Une seule équation, appelée **équation de propagation**, est alors nécessaire et suffisante pour modéliser le phénomène.*

- **Equation de la dynamique :**

u vecteur déplacement, **T** : Tenseur des contraintes

$$\rho \frac{\partial^2 u_i}{\partial^2 t} = \frac{\partial T_{ij}}{\partial x_j}$$

- **Loi de comportement matériaux**

=> Ex : Loi de Hooke pour un matériau élastique linéaire anisotrope
(**C** : tenseur des rigidités élastiques rang 4)

$$T_{ij} = C_{ijkl} \frac{\partial u_l}{\partial x_k}$$

=> **Equation du mouvement**

$$\rho \frac{\partial^2 u_i}{\partial^2 t} = C_{ijkl} \frac{\partial^2 u_l}{\partial x_j \partial x_k}$$

$$\Rightarrow \text{Equation du mouvement} \quad \rho \frac{\partial^2 u_i}{\partial t^2} = C_{ijkl} \frac{\partial^2 u_l}{\partial x_j \partial x_k}$$

Dans un solide infini : recherche de solution sous forme **d'une onde plane progressive** se propageant dans une direction $\mathbf{n}(n_1, n_2, n_3)$ et recherche de la vitesse de phase V et polarisation ${}^0\mathbf{u}({}^0u_1, {}^0u_2, {}^0u_3)$.

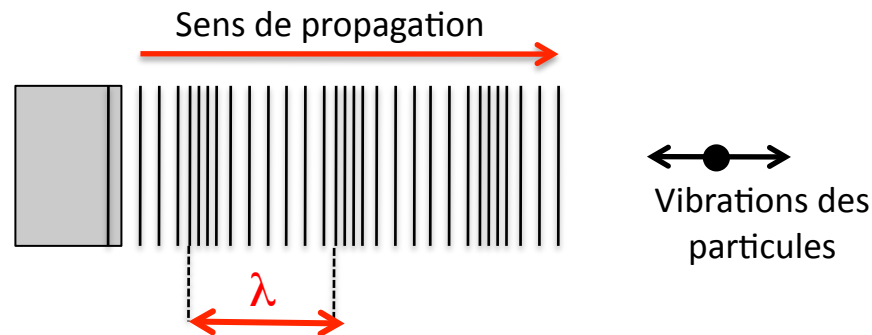
$$\Rightarrow \text{Equation de Christoffel :} \quad \rho V^2 {}^0u_i = C_{ijkl} n_j n_k {}^0u_l$$

Vitesses de phase et polarisation des ondes planes se propageant dans la direction $\mathbf{n}$ sont les valeurs propres et vecteurs propres du tenseur $\Gamma_{ij} = C_{ijkl} n_j n_k$

Il y a en général 3 solutions : **1 onde longitudinale et 2 ondes transversales**
(ou 1 quasi longitudinale et 2 ondes quasi transversales si le matériau est anisotrope).

Mouvement de compression-traction

Le déplacement des particules est parallèle à la direction le long de laquelle se propage la perturbation. On parle alors d'onde **longitudinale** ou onde de **compression**, généralement notée L.



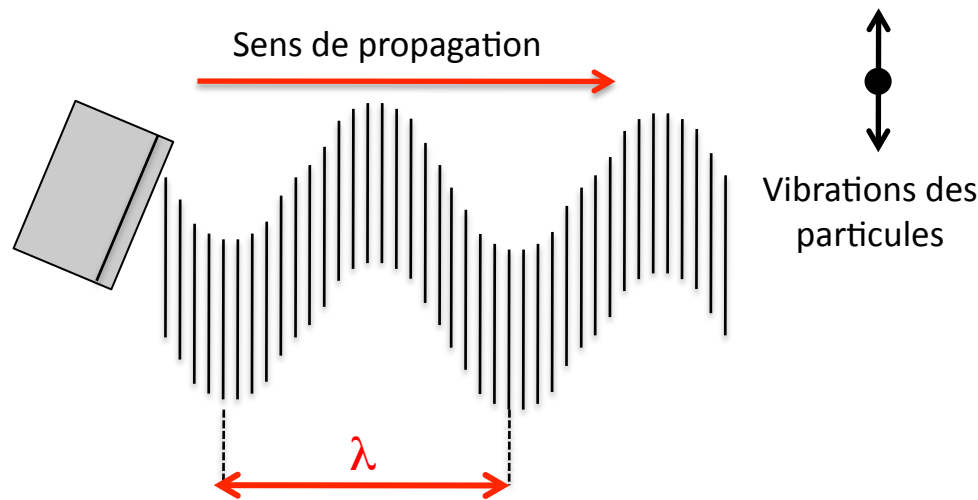
- Déplacement des particules // à la direction de propagation
- Propagation dans les fluides ou dans les solides
- Vecteurs $\mathbf{n}$ et $\mathbf{P}$ (ou $\mathbf{k}$ et $\mathbf{P}$) sont **colinéaires**.
On écrit alors : $\mathbf{k}_L \wedge \mathbf{P}_L = 0$.

Formalisme :

- **relatif à la propagation** : vecteur d'onde $\mathbf{k} = k \mathbf{n}$, direction de propagation $\mathbf{n}$ (vecteur unité), k le nombre d'onde $= \omega/C$, avec la pulsation $\omega = 2 \pi f$, (f = fréquence; C la célérité de l'onde).
- **relatif au mouvement des particules** : vecteur polarisation noté $\mathbf{P}$.

Mouvement de cisaillement – Ondes transversales

Le déplacement des particules est **perpendiculaire** à la direction de propagation de la perturbation (mouvement transverse que subirait une corde tendue, par exemple). On parle alors d'onde **transversale** ou onde de **cisaillement**, généralement notée **T**.



- Déplacement des particules perpendiculaires à la direction de propagation
- Propagation dans les solides uniquement
- Dans le cas de l'onde T, les vecteurs **n** et **P** (ou **k** et **P**) sont **orthogonaux**. On écrit alors : $\mathbf{k}_T \cdot \mathbf{P}_T = 0$.

Formalisme :

- **relatif à la propagation** : vecteur d'onde $\mathbf{k} = k \mathbf{n}$, direction de propagation $\mathbf{n}$ (vecteur unité), k le nombre d'onde $= \omega/C$, avec la pulsation $\omega = 2 \pi f$, (f = fréquence; C la célérité de l'onde).
- **relatif au mouvement des particules** : vecteur polarisation noté **P**.

Remarques :

- Généralement, ces ondes sont appelées « **ondes de volume** » car leur propagation est considérée dans un milieu infini (pas de réflexion par les bords du milieu au point où cela modifierait leur nature L ou T). Ainsi elles sont supposées exister dans un volume infini par opposition aux ondes de plaques, de structures, de surface ou d'interface qui nous verrons par la suite.
- Les ondes transversales ne peuvent pas exister dans les **fluides parfaits** (non visqueux) car le phénomène de cisaillement ne se produit pas dans ces milieux. Dans un fluide visqueux, le cisaillement se produit donc l'onde T peut exister mais elle est généralement très fortement amortie au cours de sa propagation.

Milieu **infini** (ou du moins de dimensions suffisantes par rapport aux longueurs d'onde => **Ondes de volumes (L ou T)**)

Structures solides **réelles** (même de géométrie simple), il peut y avoir certaines fréquences pour lesquelles les longueurs d'ondes ne sont pas négligeables devant les dimensions.

=> **Ondes de surface, Ondes d'interface** ou **Onde de résonance d'épaisseur**

qui résultent en fait d'une superposition complexe de plusieurs ondes L et T sous des conditions particulières.

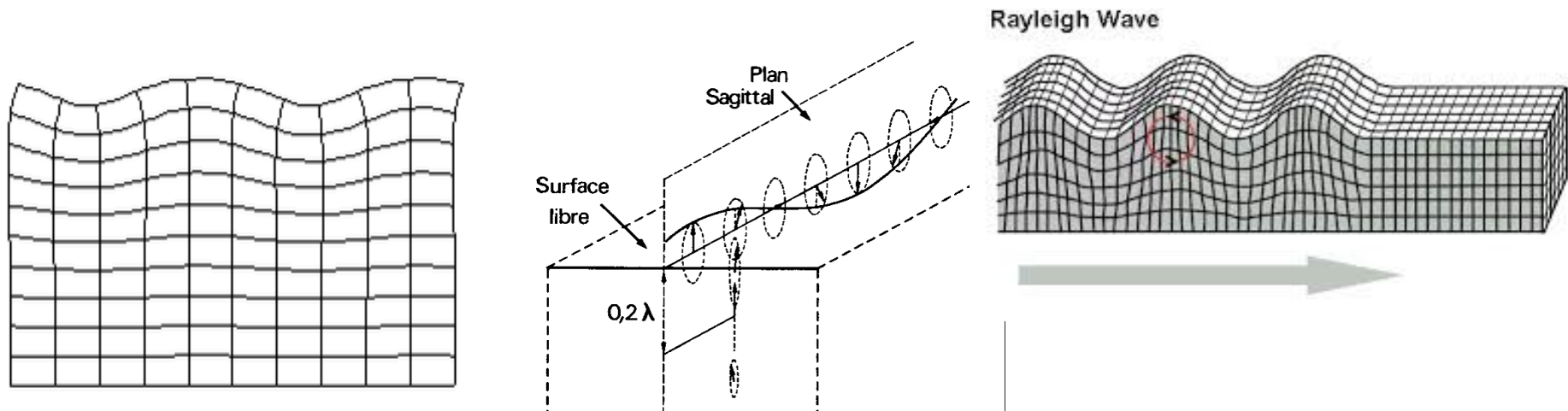
=> **Equation du mouvement**

$$\rho \frac{\partial^2 u_i}{\partial t^2} = C_{ijkl} \frac{\partial^2 u_l}{\partial x_j \partial x_k}$$

+ **Conditions aux limites**

Ondes de Rayleigh (découverte en 1885 par Lord Rayleigh)

Dans le cas simple d'un milieu isotrope couplé avec le vide, elle est constituée d'une composante **longitudinale** et d'une composante **transversale**, déphasées de $\pi/2$ et contenues dans le plan sagittal qui est formé par le vecteur d'onde et la normale à la surface.

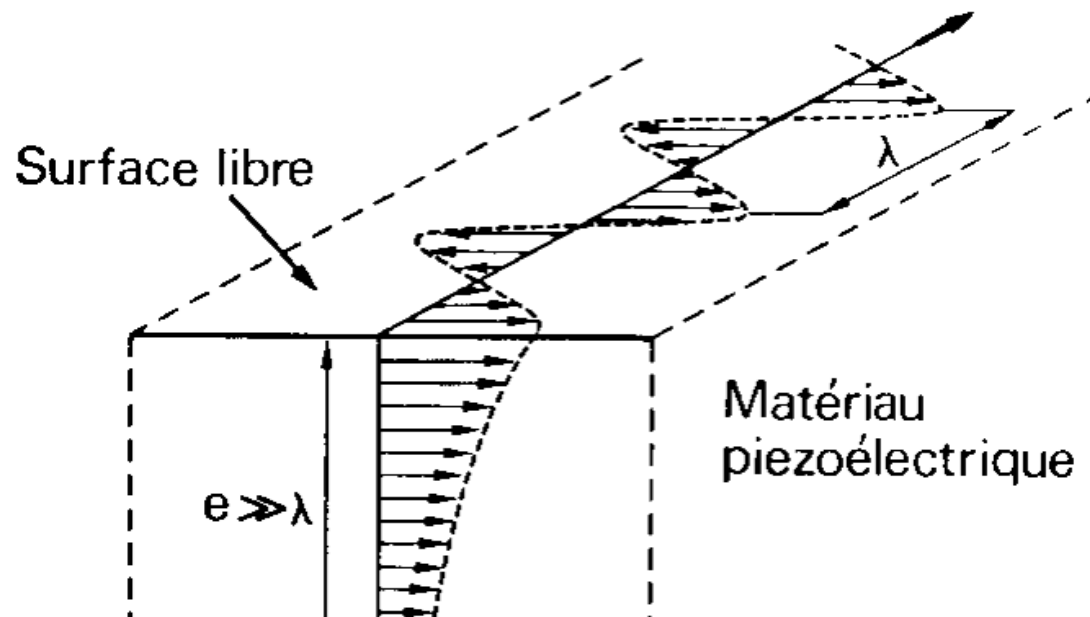


L'extrémité du vecteur polarisation décrit une **ellipse**. La composante L s'annule puis change de signe à une profondeur de 0.2λ . A cette profondeur, la polarisation est donc purement transversale. Au delà, elle devient à nouveau elliptique. Le déplacement de matière devient définitivement nul à une profondeur de 2λ .

Ondes de Bleustein-Gulyaev

A la surface d'un matériau piézoélectrique, la propagation d'une onde transversale, de polarisation parallèle à la surface, est possible.

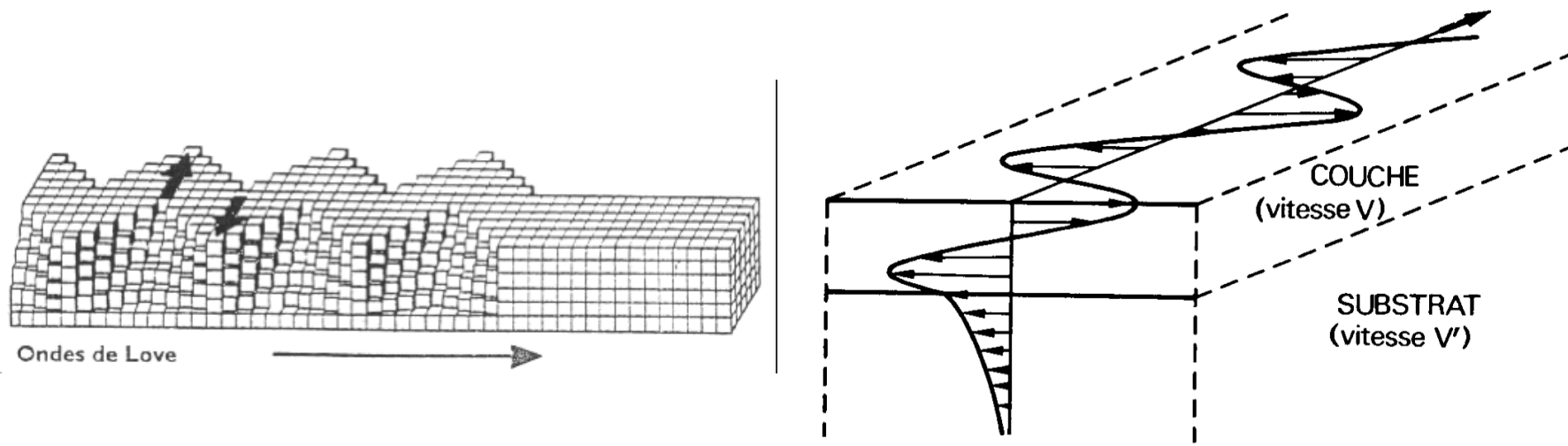
La profondeur de pénétration est d'autant plus petite que la piézoélectricité du matériau est élevée. L'épaisseur de matière mise en vibration par cette onde, appelée onde de Bleustein-Gulyaev, est de l'ordre de 100λ .



Ondes de Love

Lorsque le milieu est composé d'une couche mince déposée sur un substrat, une onde de surface à polarisation **transverse**, appelée onde de Love, peut se propager le long de l'interface séparant les deux milieux.

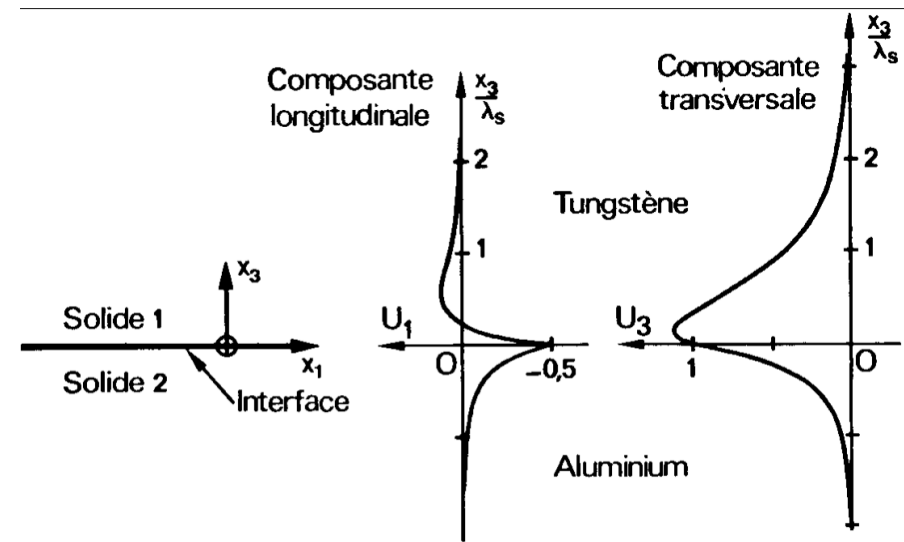
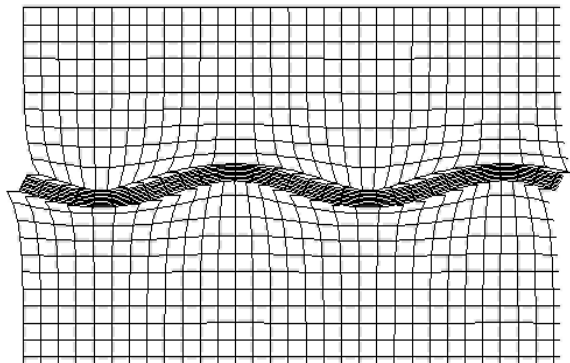
Pour que cette onde existe, il faut que la vitesse de l'onde de volume transversale dans la couche mince soit inférieure à la vitesse de l'onde de volume transversale dans le substrat.



Onde de Stoneley

Lorsque les deux matériaux sont isotropes et semi-infinis, on peut avoir à faire à une onde qui produit un déplacement de matière situé dans le plan **sagittal**, et qui décroît de part et d'autre de la surface de séparation.

Cette onde comporte 2 composantes : une **longitudinale** et une **transversale**. Ce phénomène s'apparente à la propagation d'une onde de Rayleigh de part et d'autre de l'interface solide/solide.



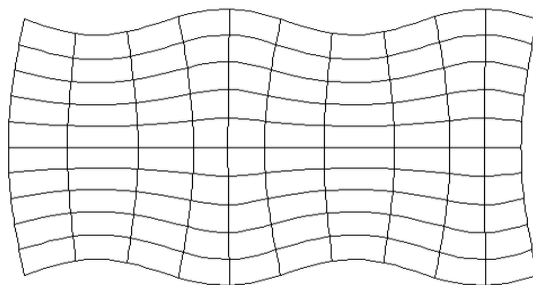
Onde de Lamb

Lorsque le matériau est limité par deux plans parallèles et libres de contraintes (matériau placé dans le vide), les ondes fondamentales L et T se multi-réfléchissent indéfiniment entre ces deux plans.

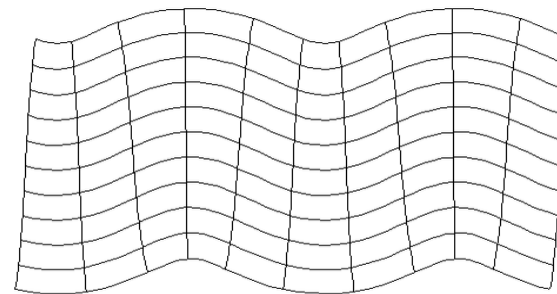
Si l'épaisseur du matériau est **de l'ordre de grandeur de la longueur d'onde λ** , le milieu devient alors fini (ou borné) : plaque, paroi d'un cylindre, ... => **Ondes de Lamb**

Ondes de Lamb = **ondes guidées** se propageant le long de la structure et produisant un déplacement de matière dans toute son épaisseur.

Il existe **une infinité de modes de Lamb**, divisés en deux familles : les modes **symétriques** et les modes **antisymétriques**.



Modes symétriques



Modes antisymétriques

Ondes guidées par les cylindres

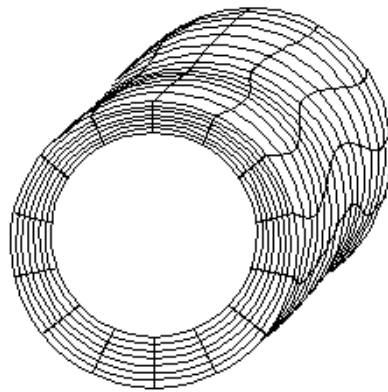
Les modes antisymétriques deviennent des modes de flexion : $F(m,n)$

Les modes symétriques deviennent des modes de compression : $L(m,n)$

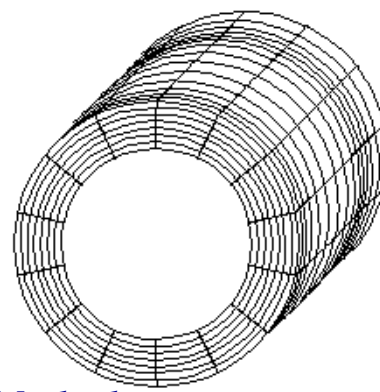
Les modes SH deviennent des modes de torsion : $T(m,n)$

m : nombre de longueurs d'onde contenues dans la circonférence

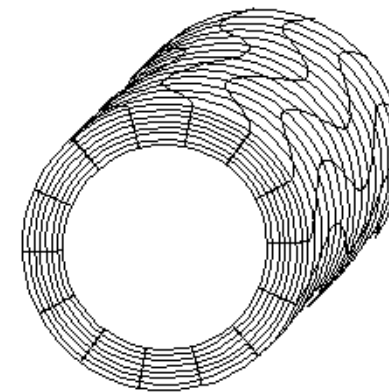
n : ordre du mode



Mode de flexion



Mode de compression



Mode de torsion

Remarques :

- Même type de modes pour les barres cylindriques pleines.
- Les modes guidés existent aussi, sous des variantes diverses, pour des guides à géométries variables : les barres à section rectangulaire ou autres, les rails de chemin de fer, raidisseurs (sections en T, en L, ...), etc.

Dispersion :

Un milieu dispersif est un milieu où la vitesse de phase de l'onde (vitesse de propagation) dépend de la fréquence :

- vitesse de phase $V_\phi = \omega/k$ ($k = \text{nombre d'onde } 2\pi/\lambda$)
- vitesse de groupe $V_g = (d\omega/dk)_{k_0}$

Si un paquet d'onde se propage dans une milieu dispersif $\Rightarrow$ « déformation » au cours de sa propagation car son déphasage dépend de la fréquence.

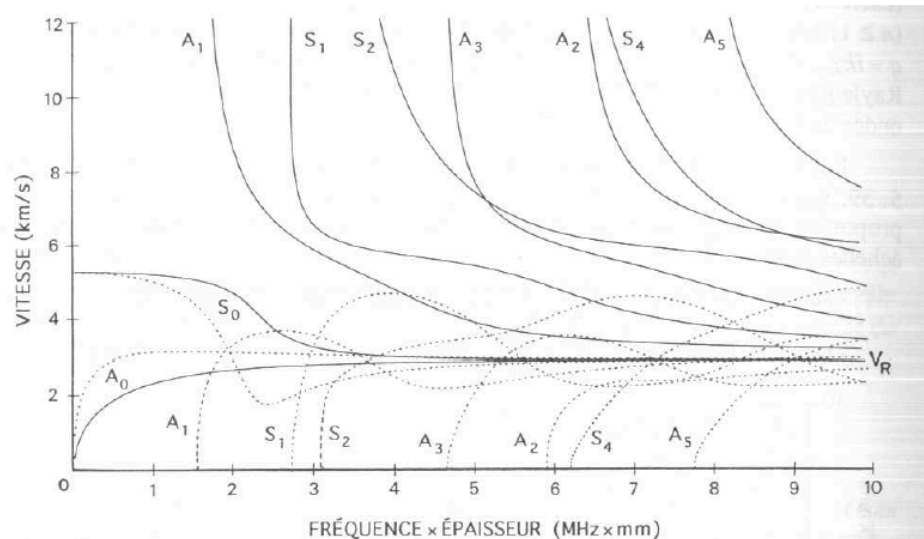


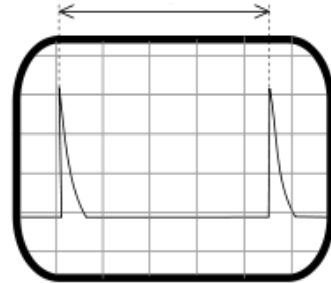
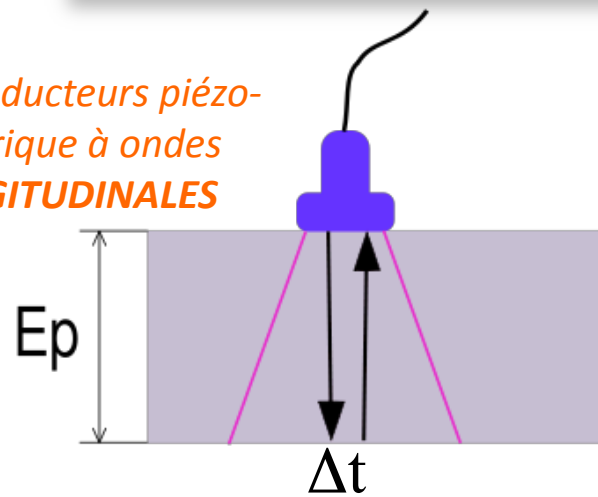
FIG. 5. 40. Onde de Lamb dans une plaque d'acier ($V_L = 5\,900$ m/s, $V_T = 3\,100$ m/s). Vitesse de phase (—) et vitesse de groupe (---) en fonction du produit fréquence $\times$ épaisseur.

COURBE DE DISPERSION DES
ONDES DE LAMB DANS L'ACIER
(*extrait du ROYER & DIEULESANT*
Tome 1)

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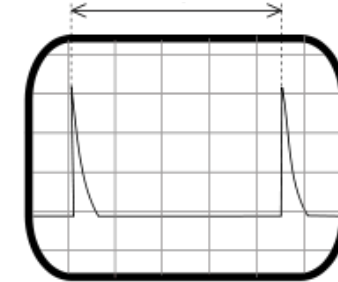
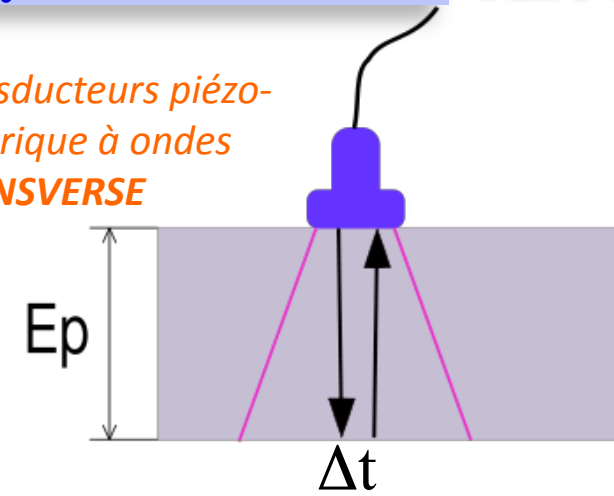
Mesure de modules élastiques pour un matériau isotrope au contact

Transducteurs piézo-
électrique à ondes
LONGITUDINALES



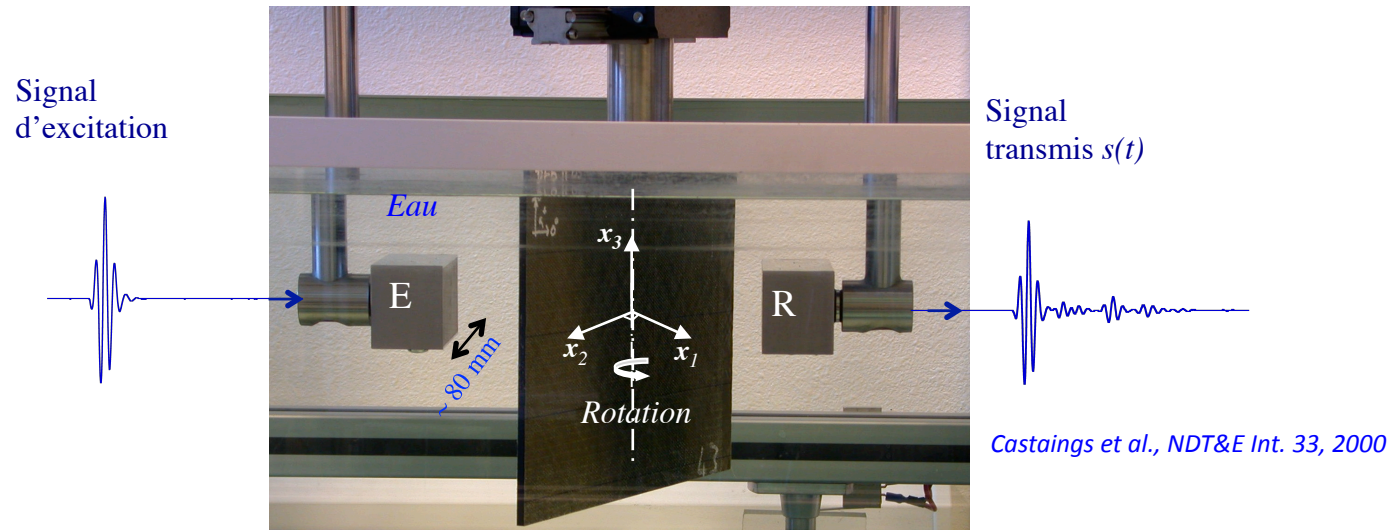
$$V_L = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}$$

Transducteurs piézo-
électrique à ondes
TRANSVERSE



$$V_T = \sqrt{\frac{E}{2\rho(1+\nu)}}$$

Détermination de E et ν (si on connaît ρ)

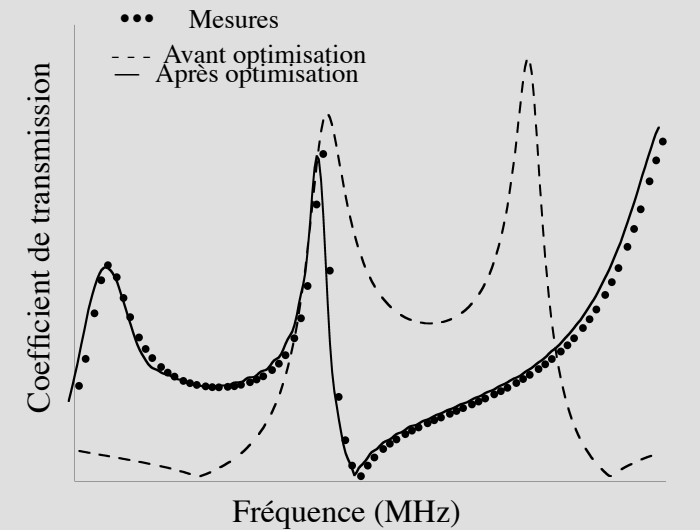


Coefficients de transmission mesurés :

$$|T^{Exp}(f_n, \theta_m)| = \frac{|A_T^{Exp}(f_n, \theta_m)|}{|A_I^{Exp}(f_n)|}$$

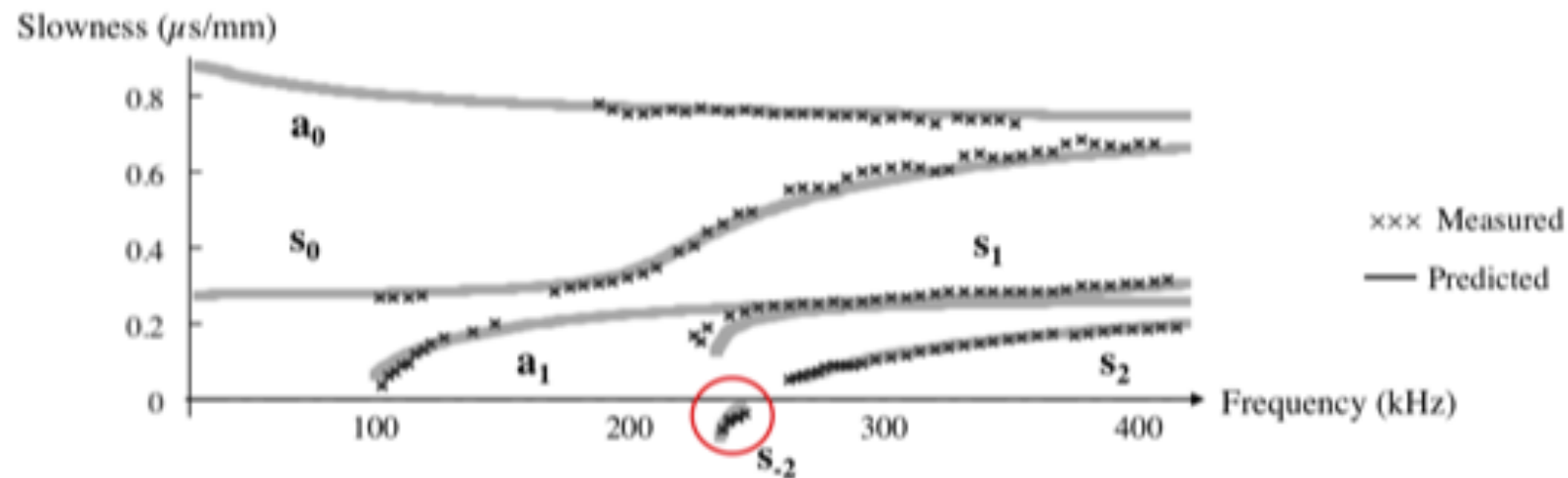
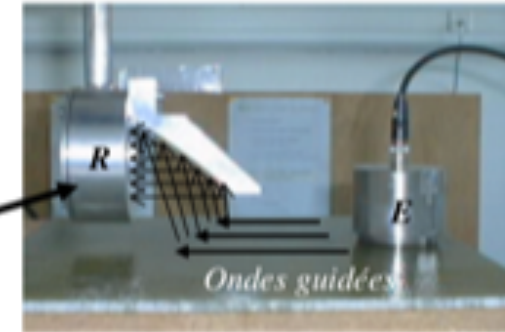
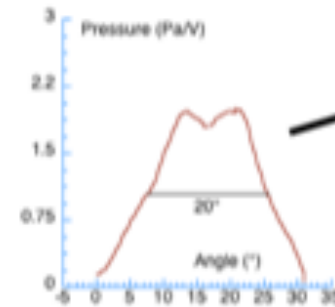
Calcul des coefficients de transmission théoriques grâce à la méthode des matrices d'impédances de surfaces (Hosten et al., Ultrasonics 41, 2003)

Une routine d'optimisation (*méthode du simplex*) est utilisée pour évaluer les modules C_{11} , C_{22} , C_{12} et C_{66} de la colle dans le plan P_{12}



Air-coupled guided waves - Material characterization

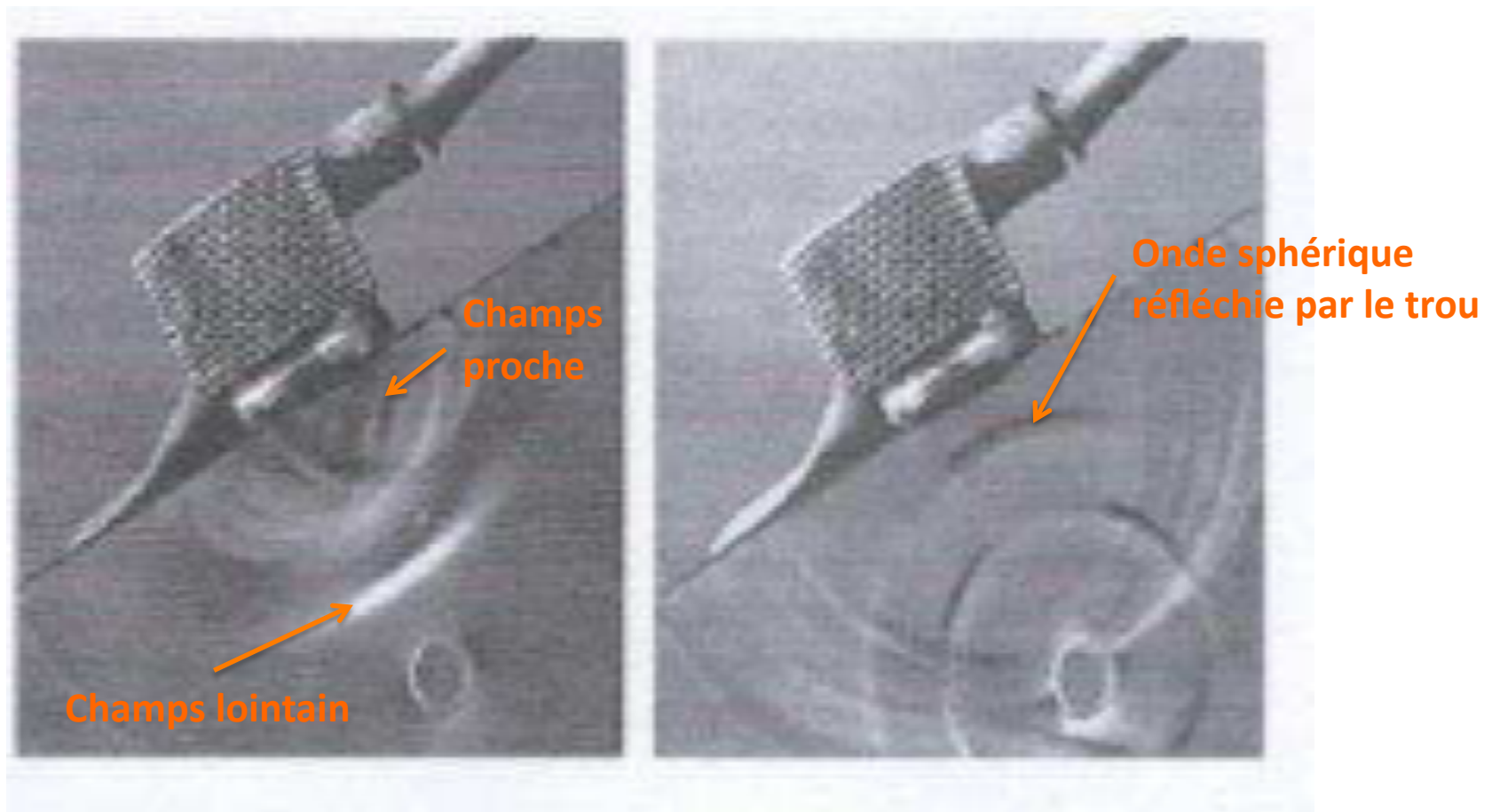
Ex. : Crossed-ply Carbone Epoxy - 5 mm



C_{11}	C_{12}	C_{22}	C_{66}	C_{13}	C_{33}	C_{55}
14	8.2	32	3.5	8.1	30	3.4

GPa

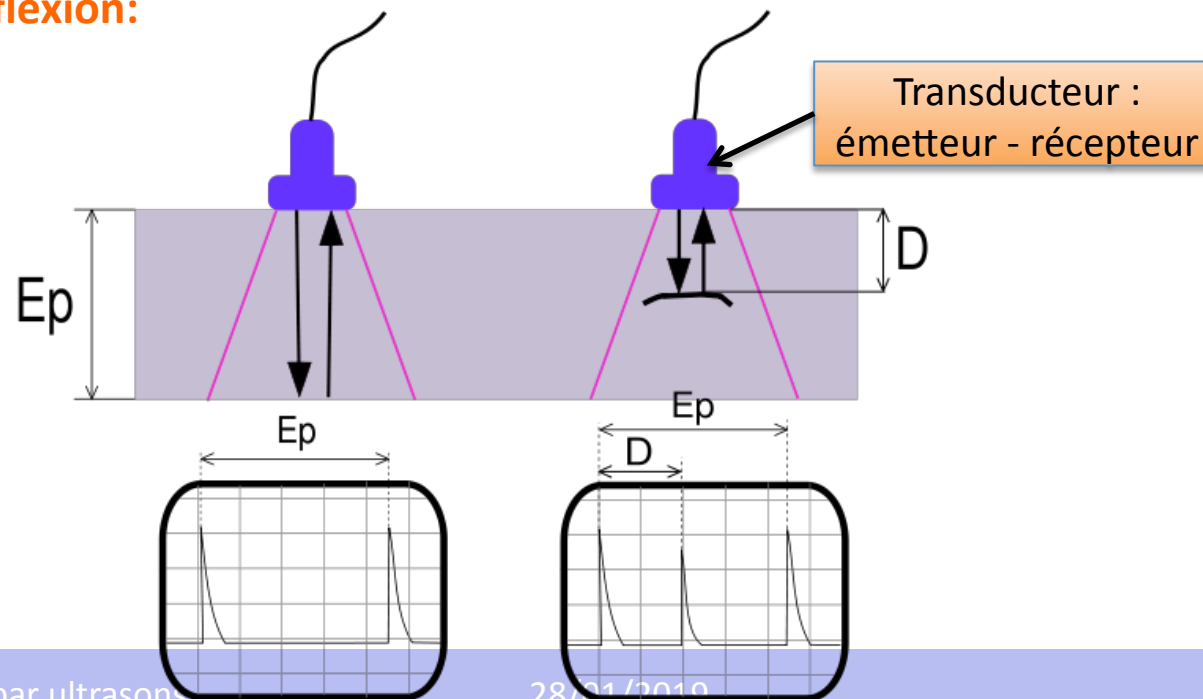
- **Généralités sur les ondes acoustiques**
- **Ultrasons pour la caractérisation mécanique**
 - ✓ Caractérisation par ondes de volumes
 - ✓ Caractérisation par ondes guidées
- **Contrôle non destructif par ultrasons**
 - ✓ Ondes de volumes
 - ✓ Ondes guidées
 - ✓ Acoustique non-linéaire

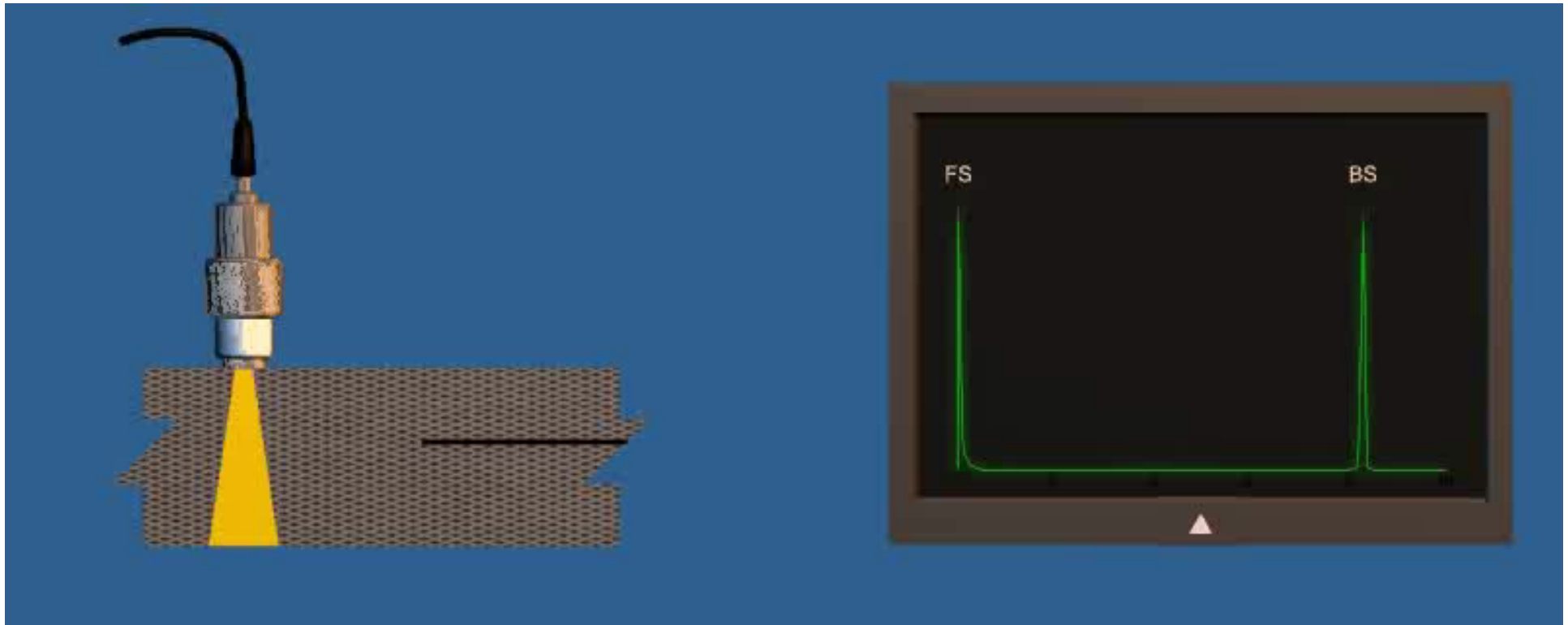


• **Précautions:**

- Nécessite la présence d'un **agent de couplage** entre la pièce et le transducteur pour éviter toute atténuation du signal à cause de l'air.
- L'interface air/pièce se comporte comme un miroir pour les ultrasons (près de 90% de l'énergie est réfléchi si il y a 1 μ m d'air entre la pièce et le transducteur)

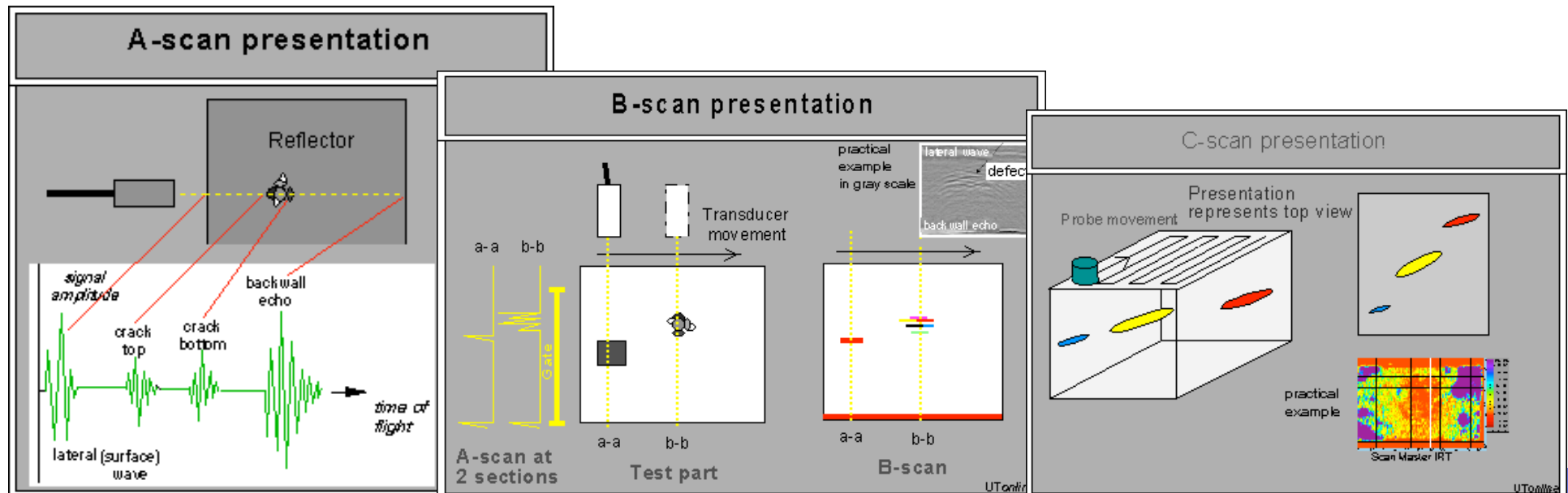
• **Examen par réflexion:**



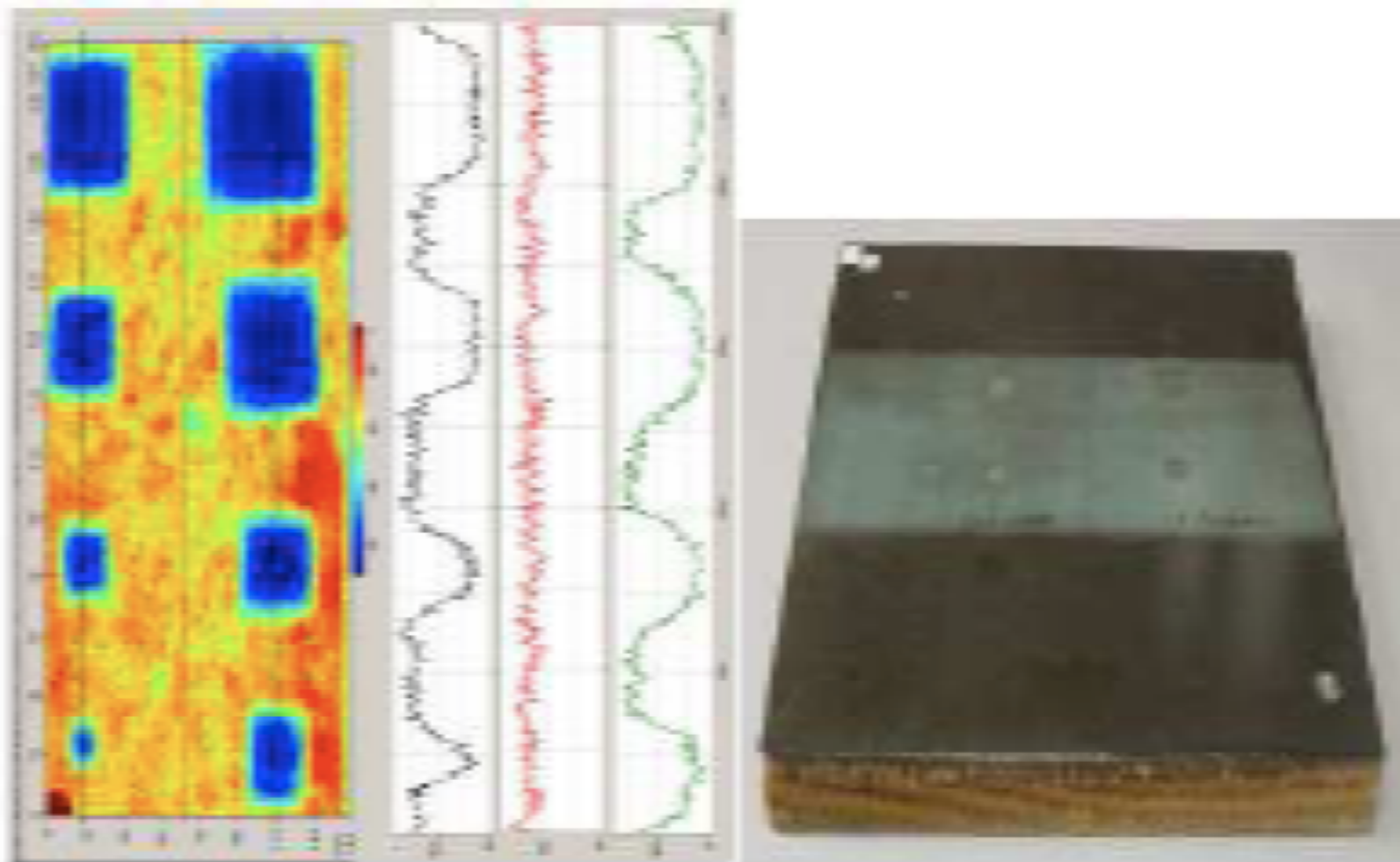


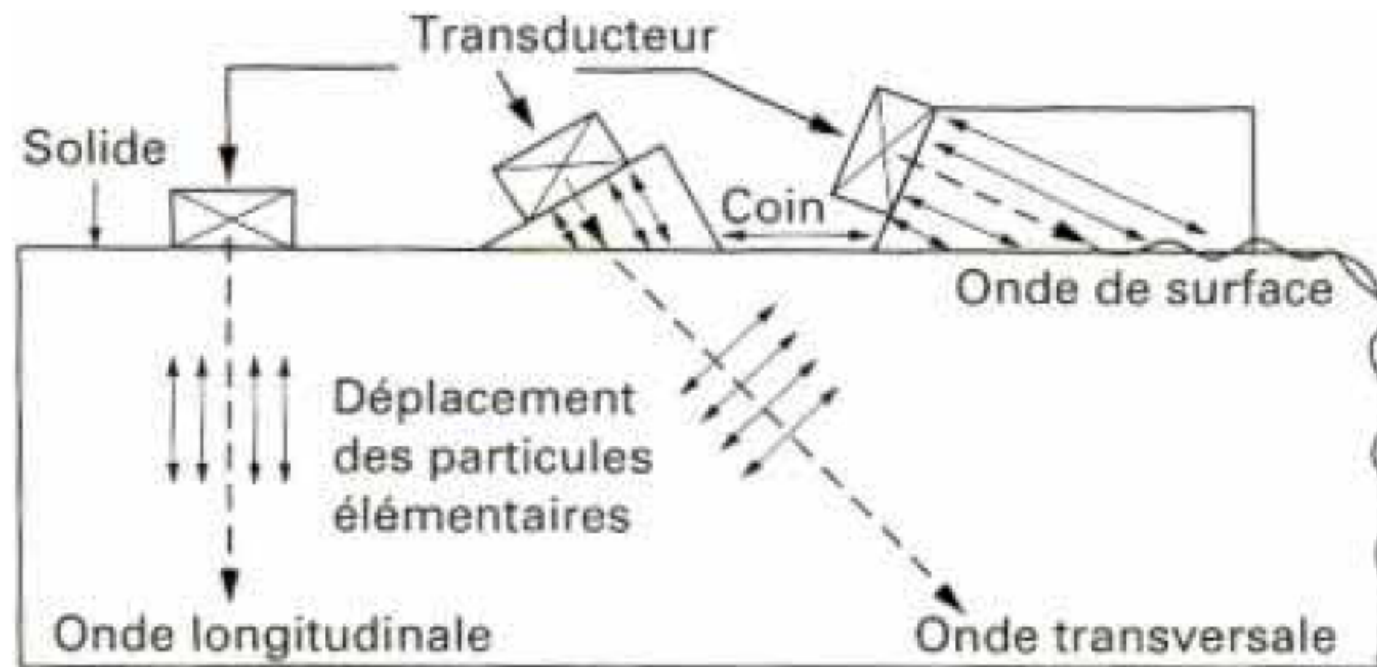
- Trois grands types d'examen par US:

- **Visualisation de type A (A-scan)** : représentation par échos amplitude/temps. L'amplitude = énergie reçue, le temps = distance parcourue
- **Visualisation de type B (B-scan)** : vue en coupe de la pièce examinée
- **Visualisation de type C (C-scan)** : vue en plan et de dessus de la pièce



C-SCAN d'une plaque en composite contenant des inserts





$$V_L = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}$$

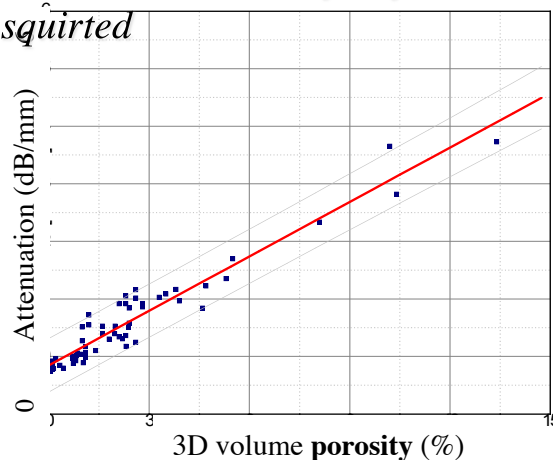
$$V_T = \sqrt{\frac{E}{2\rho(1+\nu)}}$$

Through-transmission ultrasonic technique

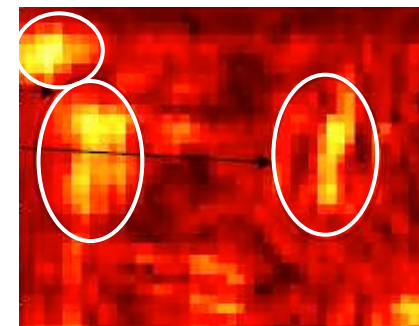
Water jet



*Ultrasonic Attenuation coefficient
Sensor 1MHz, 4mm jet of water,
squirted*



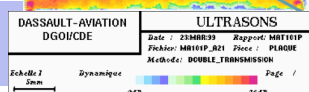
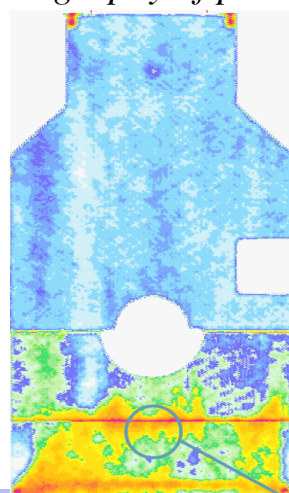
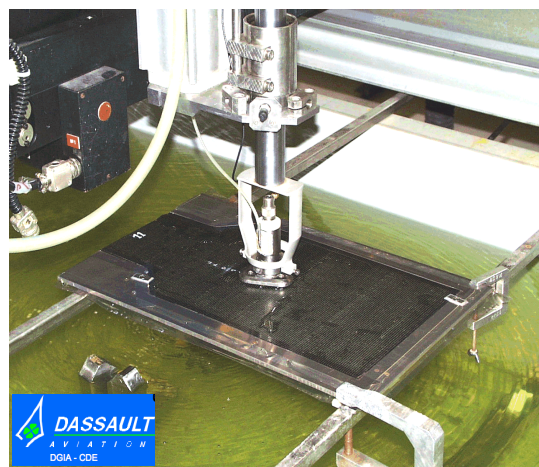
Detection of delaminations



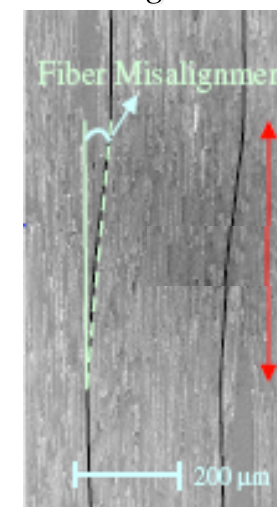
<http://www.wavelength-ndt.com/composites.htm>

Pulse-echo ultrasonic technique / Immersion tank

*US cartography of porous zone of
RTM*



Detection of fibres misalignment

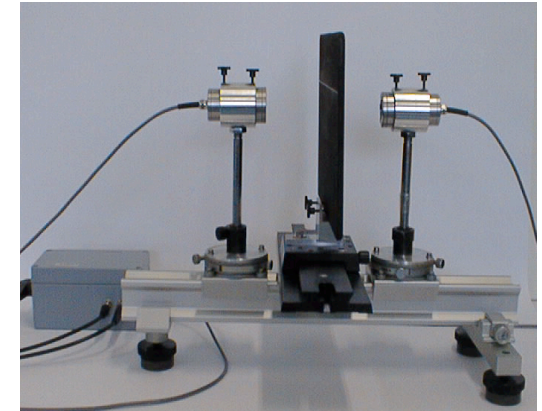


J. Cho, Scripta Materialia 56, 2006

Ex. : Impacted 3 mm Carbon Kevlar plate samples

Photo

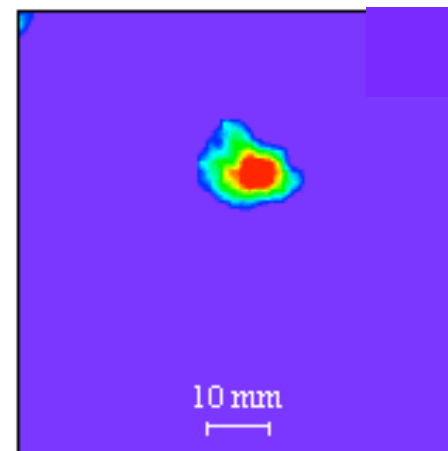
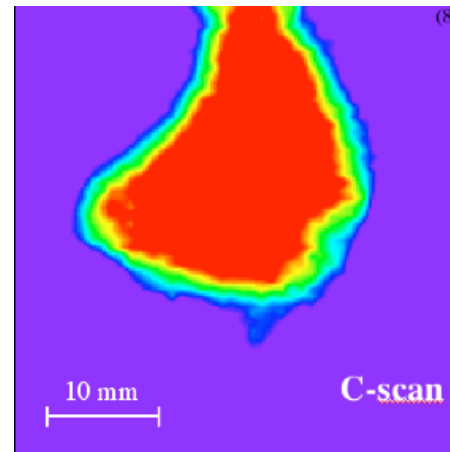
Ultrasonic C-scan / 250 kHz



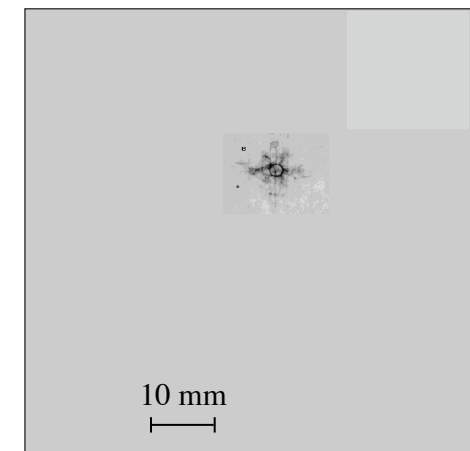
Impact 6J



Impact 2J



X-Ray inspection



Principe :

Utilisation de plusieurs éléments piézoélectriques pour focaliser et/ou générer différents types d'ondes.



Figure 1-3 Typical phased array probe assemblies

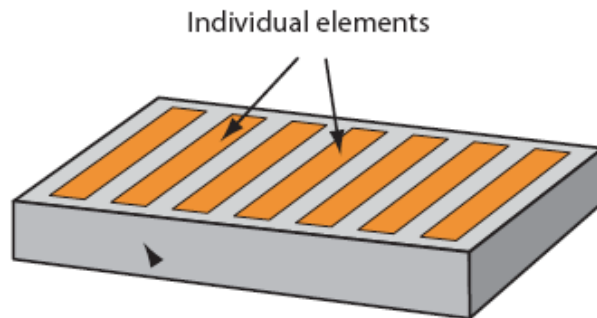


Figure 1-4 Typical multielement construction

S-SCAN d'une cale étalon

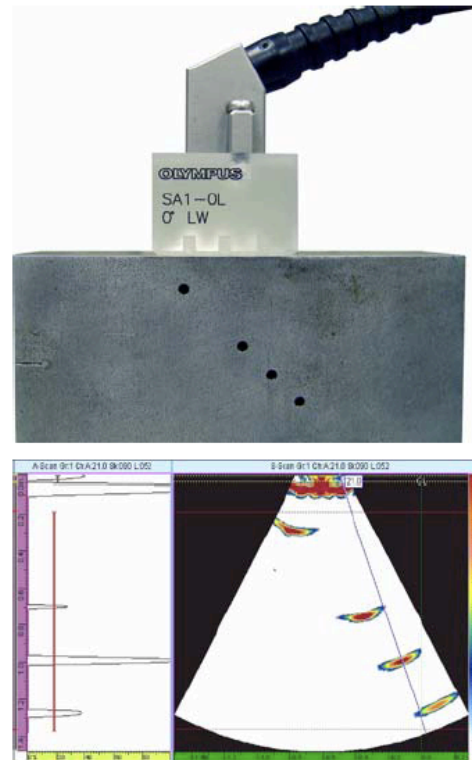


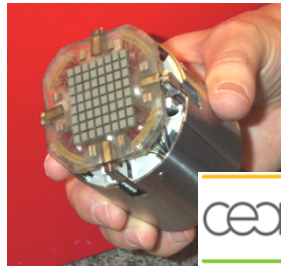
Figure 3-8 -30° to +30° S-scan

Echographie : S-SCAN



Figure 1-2 Phased arrays used for medical diagnoses

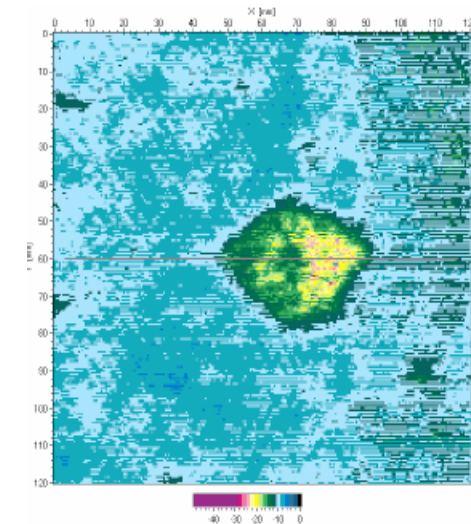
Various types of contact probes including *smart flexible Transducer*



Focussing and/or linear scanning by setting properly phase delay for each channel



Ex. Ultrasonic imaging for defects in curved composite components / *German Aerospace centre*



Shows defect size and location

- Lamb waves can penetrate large areas (long-range inspection)
- No time consuming scanning

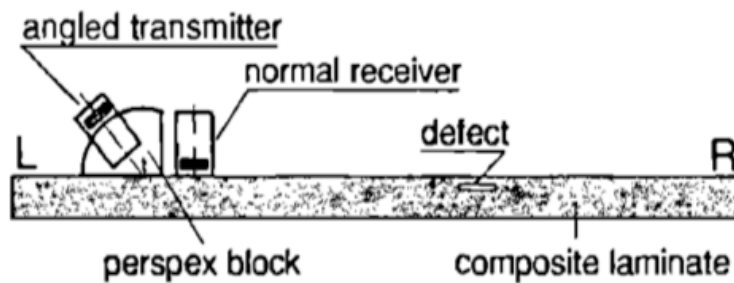
But

- For each frequency, at least two wave modes exist
- Modes are often dispersive

Therefore

- Modes have to be carefully selected depending on the type of damage and on the material of the tested component
- Specific signal processing is often required due to mode conversion phenomenon

N. Guo, P. Cawley JASA. 94 (4) 1993

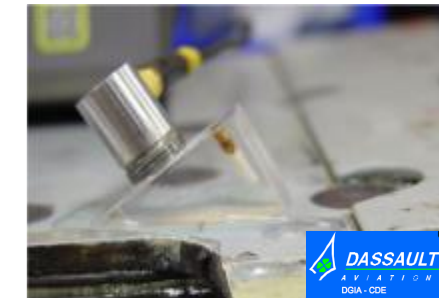


$[0/90]_{2s}$ Carbon Epoxy 1mm thick plate

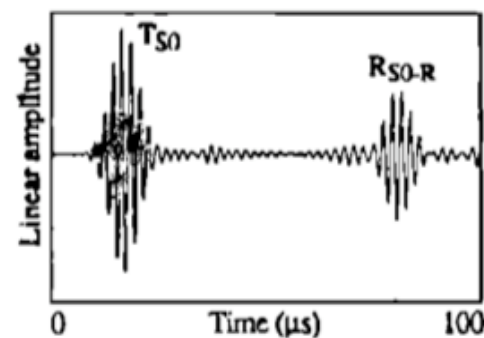
$F=0.5$ MHz / Incident S_0 mode

Defect is delamination like at various positions thru-thickness

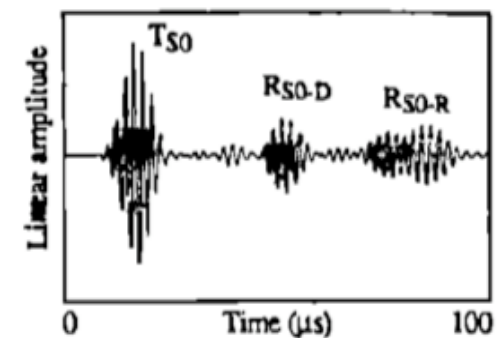
Mono-element transducers



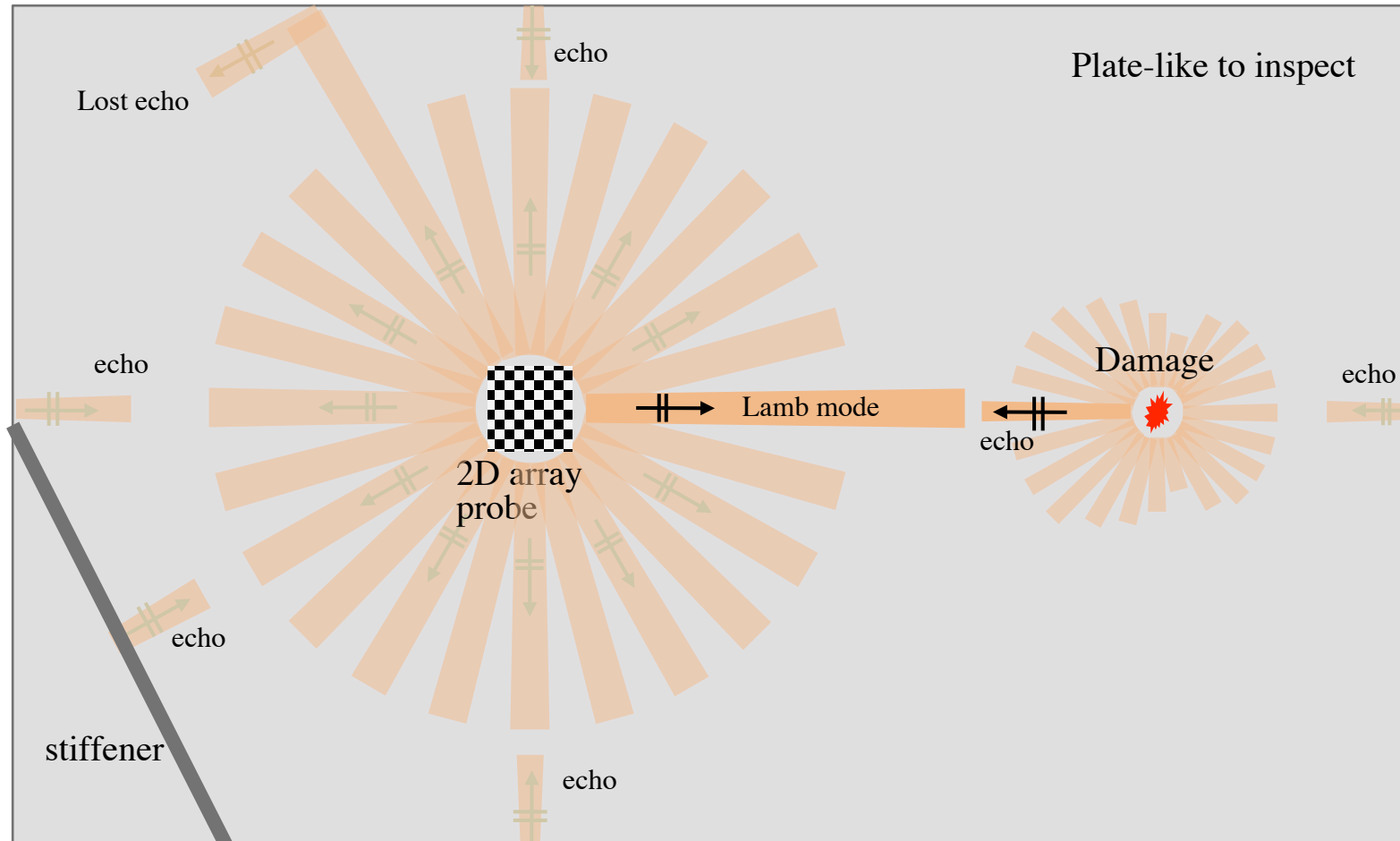
Measured time traces - No defect



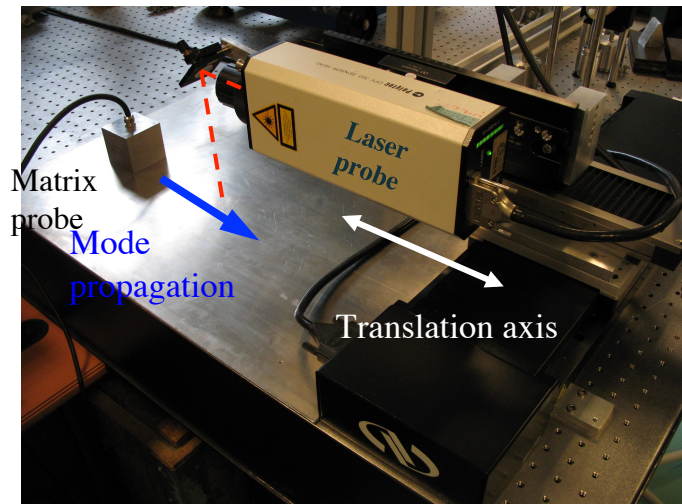
Measured time traces - Defect 7/8



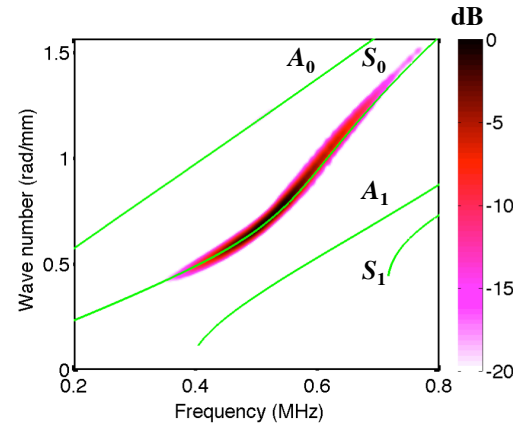
To use single, compact, removable, PZT, matrix probe for selecting pure Lamb mode sent toward (received from) given directions and for quickly inspecting these directions over long distances.



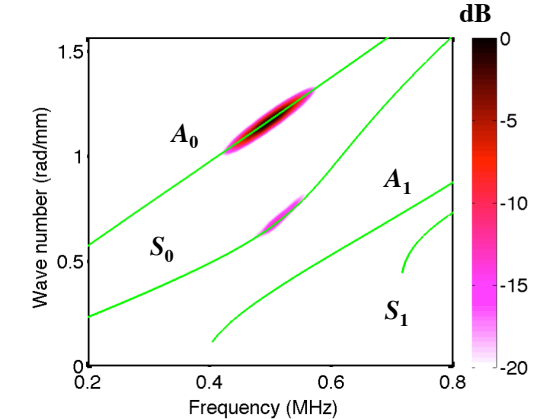
➔ Need to do 2D beam steering + modal selectivity + compensate modes dispersion for large structures.



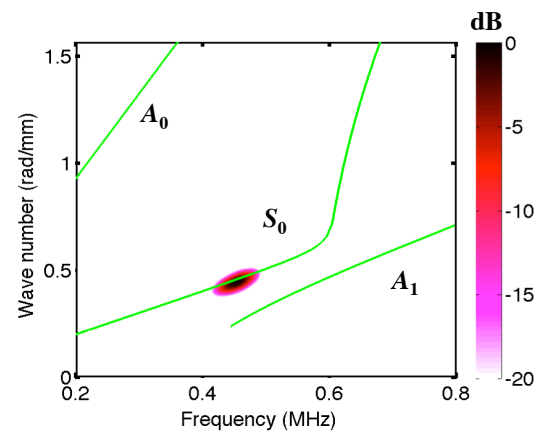
S_0 from 0.4 to 0.8 MHz (dispersive mode) in 4 mm aluminium plate



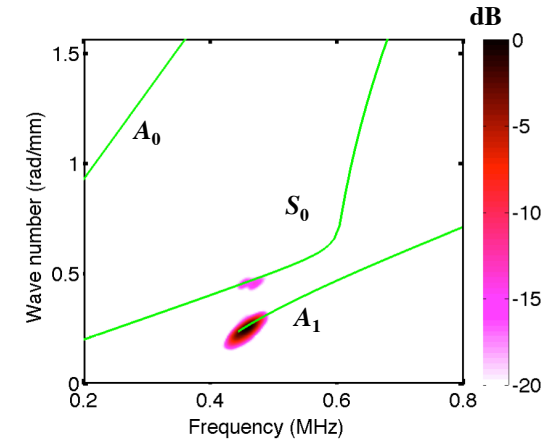
A_0 from 0.4 to 0.6 MHz (non dispersive mode) in 4 mm aluminium plate



S_0 from 0.4 to 0.5 MHz (non dispersive mode) in 2.1 mm carbon epoxy $[0^\circ/90^\circ]_4s$ composite plate – Along fibre direction



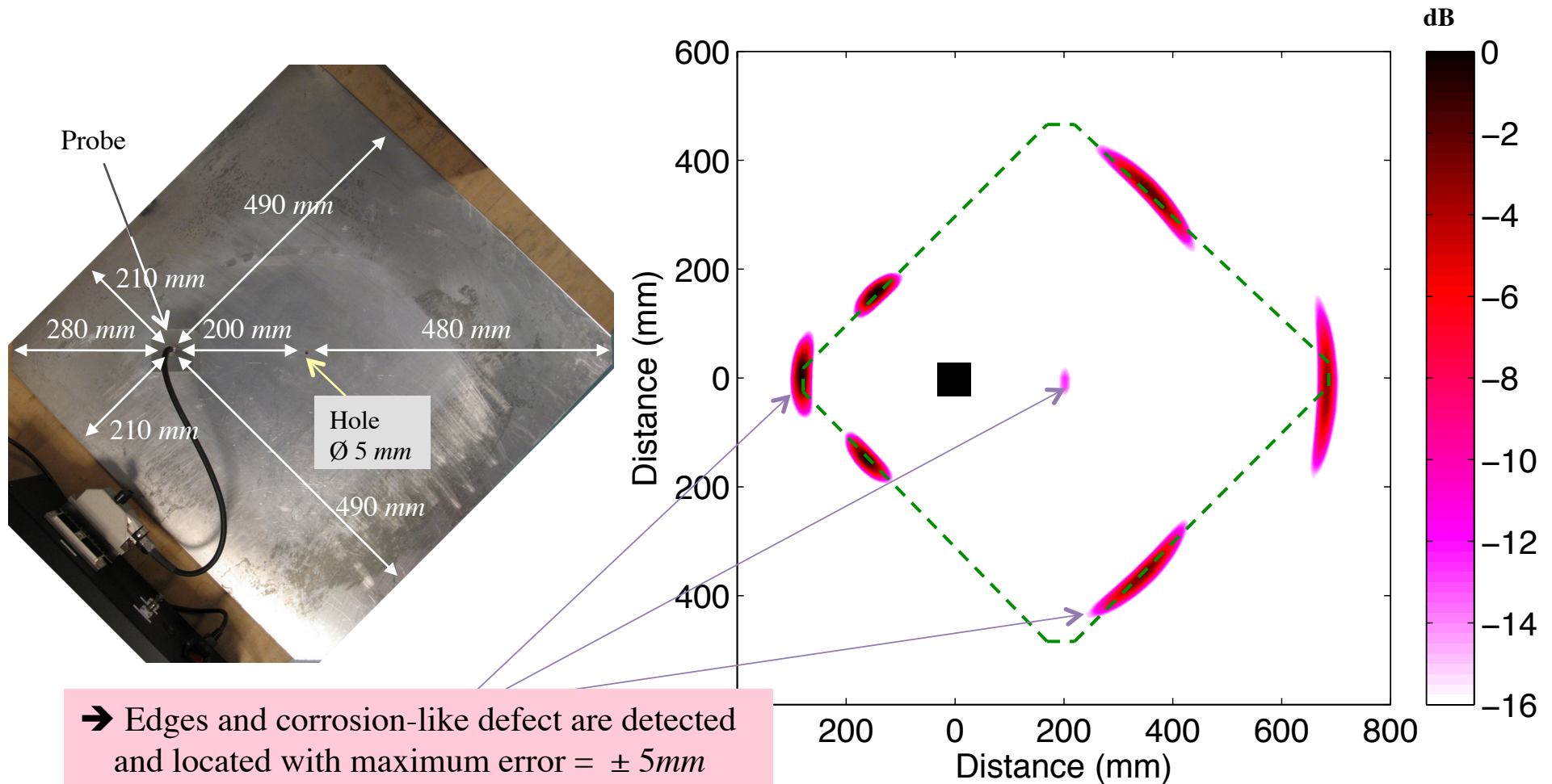
A_1 from 0.4 to 0.5 MHz (dispersive mode) in 2.1 mm carbon epoxy $[0^\circ/90^\circ]_4s$ composite plate – Along fibre direction



Sample = 4 mm thick Aluminium plate; Defect = Corrosion-like;

Excitation = 12-cycle, 0.35 MHz centre frequency toneburst;

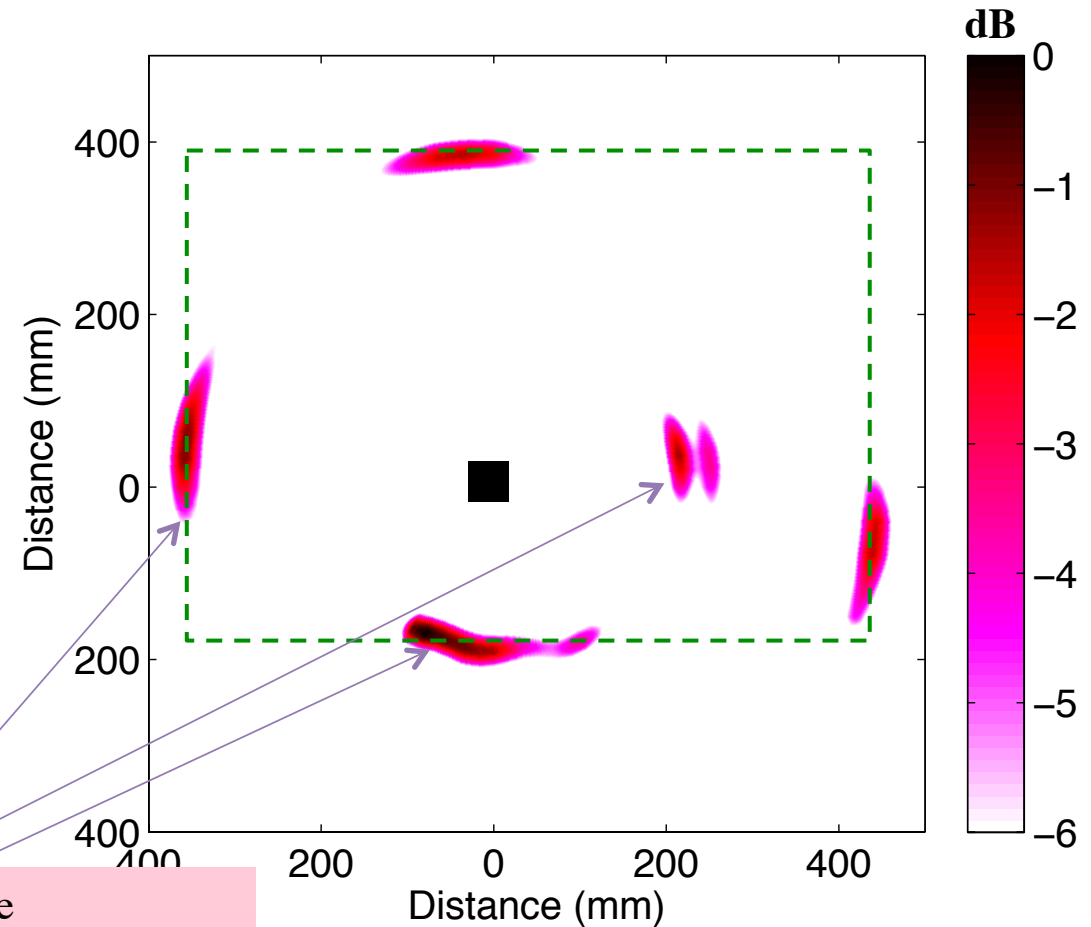
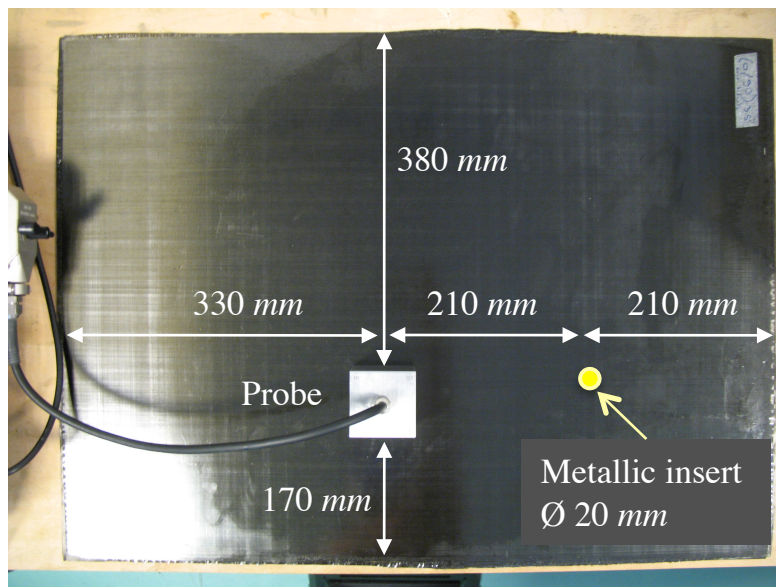
Guided wave = S_0 mode – $\lambda \approx 15$ mm – Excited in and received from all directions.



Sample = 1.6 mm thick $[0^\circ/90^\circ]_3$ s Carbon Epoxy plate

Excitation = 12-cycle, 0.35 MHz centre frequency toneburst

Guided wave = S_0 mode – $\lambda \approx 18$ mm – Excited in and received from all principal directions



→ Edges and delamination-like defect are detected and located with maximum error = ± 10 mm

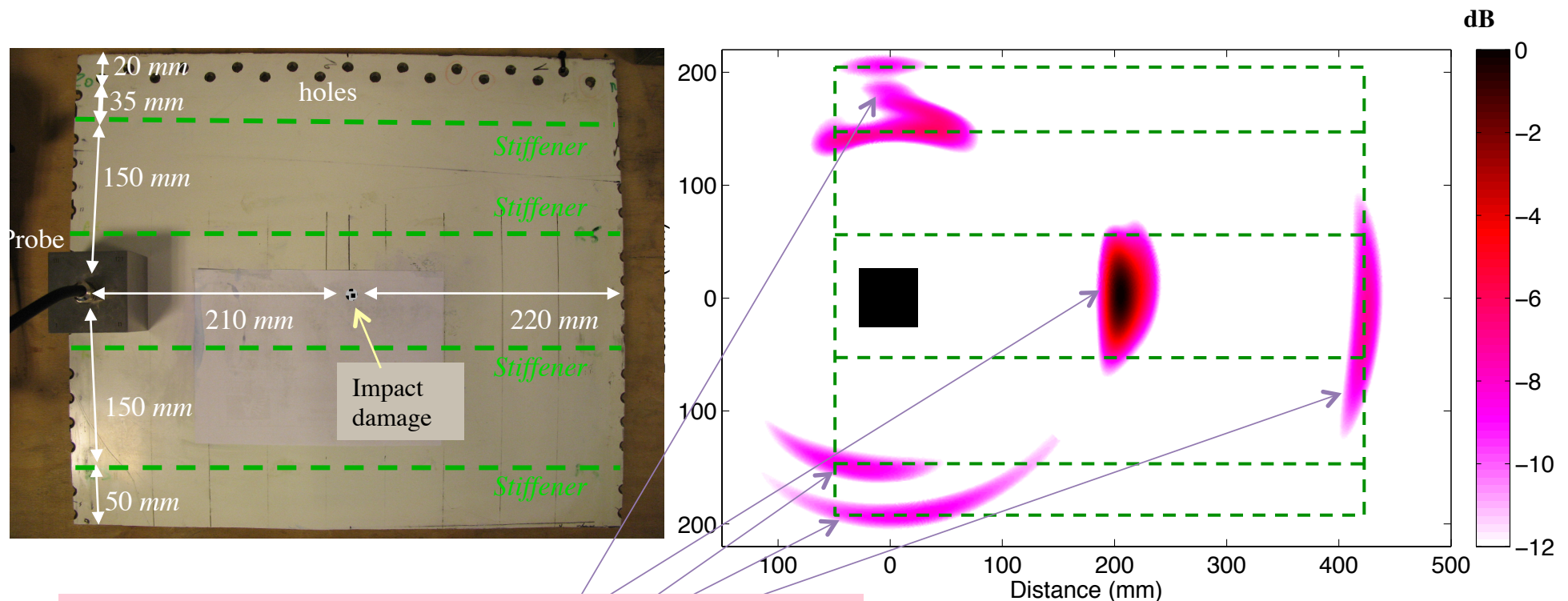
A. Leleux, P. Micheau, M. Castaings, *Journ. of NDE* 32, p. 200, 2013

Sample = 4 mm thick Carbon Epoxy curved plate with 4 composite stiffeners

Defect = Impact damage

Excitation = 12-cycle, 0.5 MHz centre frequency toneburst

Guided wave = S_0 mode – $\lambda \approx 14$ mm – Excited in and received from all principal directions



➔ Edges, “far” stiffeners, holes and impact damage are detected and located with maximum error = ± 10 mm

A. Leleux, P. Micheau, M. Castaings, *Journ. of NDE* 32, p. 200, 2013

- **Généralités sur les ondes acoustiques**
- **Ultrasons pour la caractérisation mécanique**
 - ✓ Caractérisation par ondes de volumes
 - ✓ Caractérisation par ondes guidées
- **Contrôle non destructif par ultrasons**
 - ✓ Ondes de volumes
 - ✓ Ondes guidées
 - ✓ Acoustique non-linéaire

Dans certains cas, CND linéaire peu sensible :

- Microfissures
- Fissures « fermées »
- Plasticité ...



Comportement
mécanique NON LINEAIRE

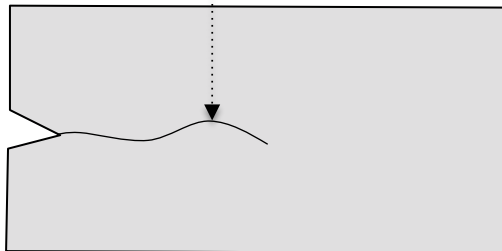
Phénomènes spécifiques lors de la propagation
d'ondes dans des milieux possédant ces défauts



Quelles informations supplémentaires peut-on obtenir en exploitant ces phénomènes ?

Pourquoi les méthodes linéaires sont peu sensibles ?

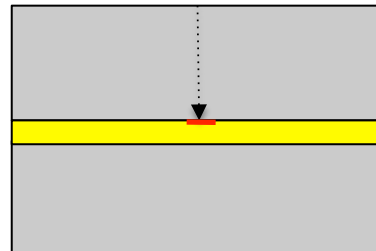
Fissure fermée (/microfissures)



Surfaces conformes
entre deux matériaux
identiques

⇒ Pas de réflexion ...
⇒ Pas d'effet notable sur
la vitesse de propagation
⇒ Peu d'effet sur
l'atténuation

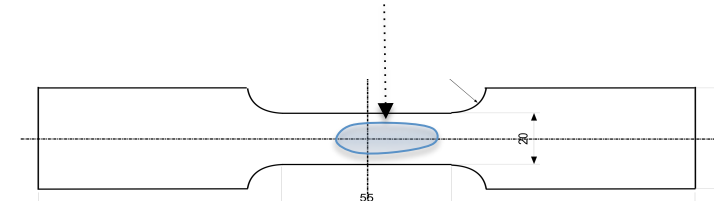
Défaut d'adhésion au
niveau d'un joint de colle



Il existe des méthodes
linéaires pour
caractériser la colle (C_{11}
et C_{66}) [1],[2]

mais
pas de méthode **linéaire**
efficace pour détecter
des défauts d'adhésion ...

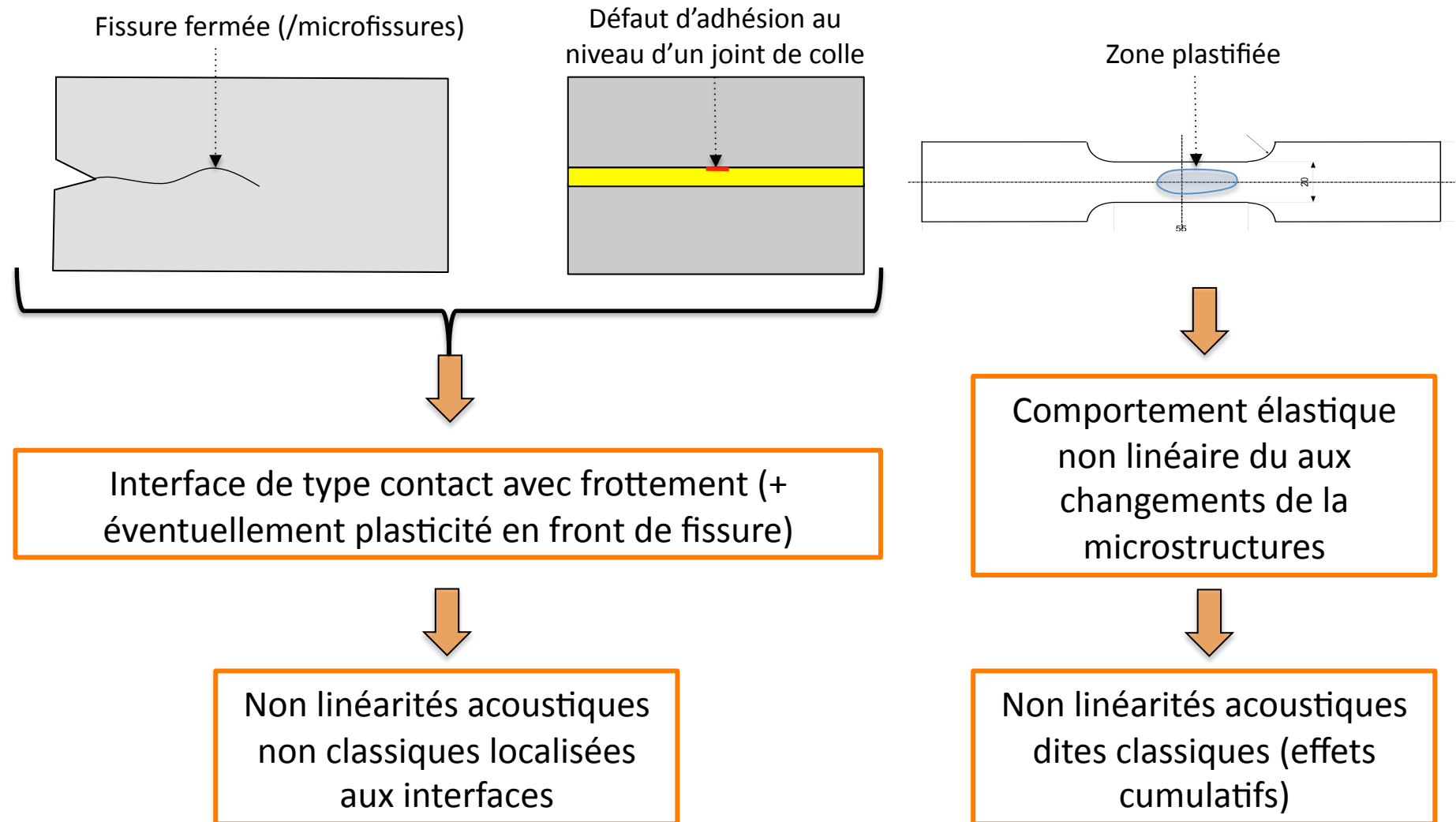
Zone plastifiée



Modification à l'échelle de
la micro-structure
(Dislocations/ bandes de
glissement / ...)

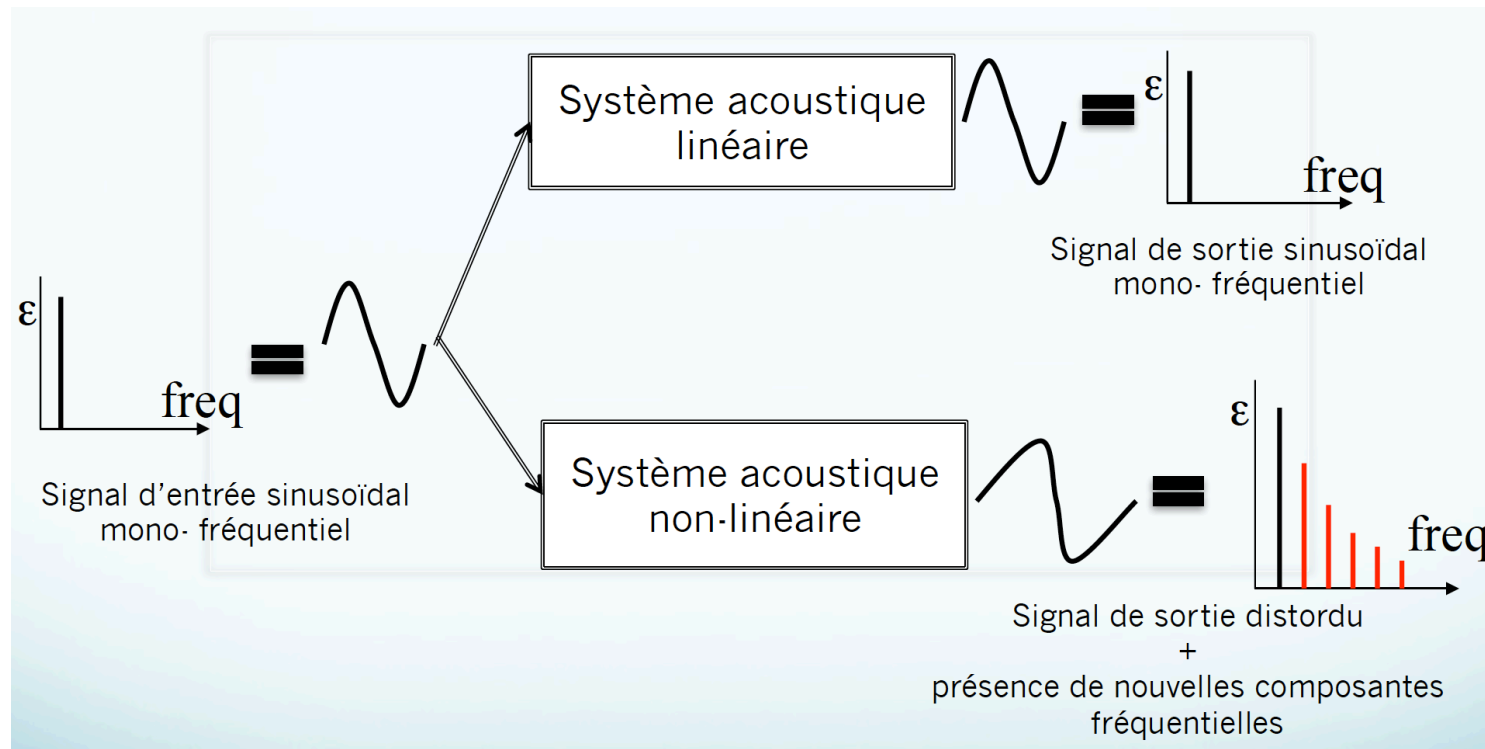
⇒ Pas de réflexion ...
⇒ Pas d'effet notable sur la
vitesse de propagation
⇒ Peu d'effet sur
l'atténuation

Pourquoi les méthodes NL sont efficaces ?



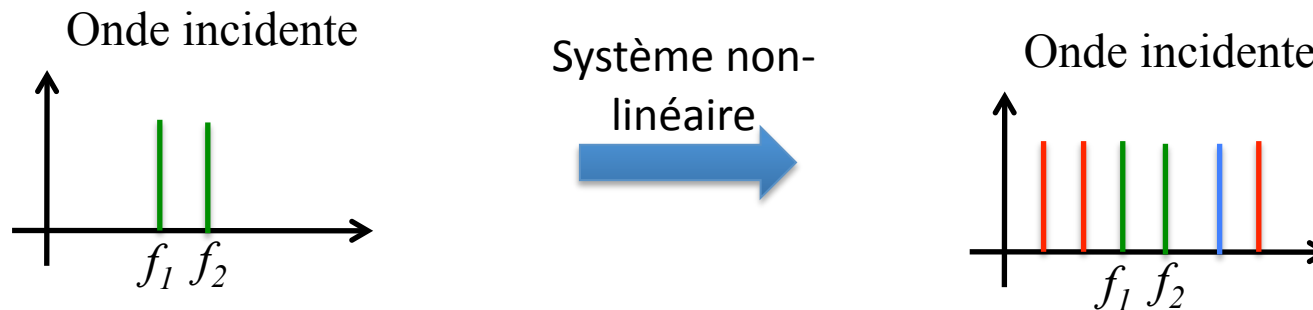
Génération d'harmoniques :

L'onde incidente a initialement un contenu fréquentiel à f . Au cours de sa propagation, si elle rencontre une non-linéarité quelconque, son contenu fréquentiel s'enrichit avec des harmoniques nf .



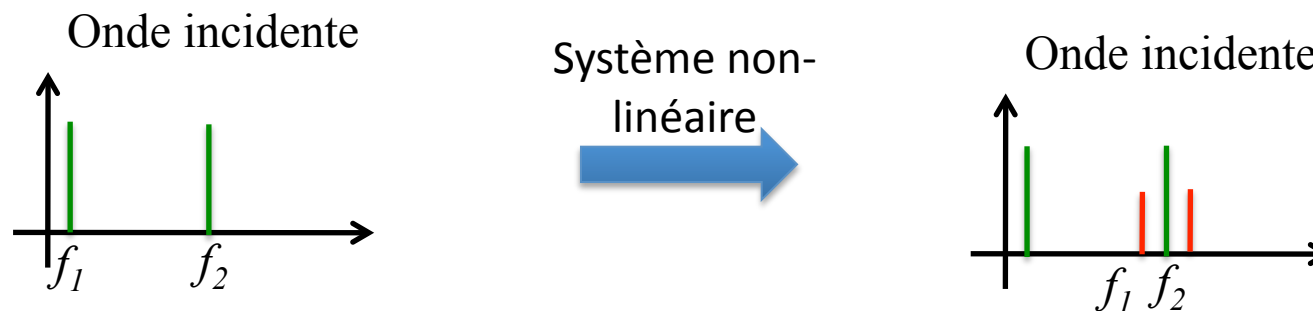
Interactions fréquentielles:

L'onde incidente a initialement un contenu fréquentiel contenant principalement 2 fréquences f_1 et f_2 . Au cours de sa propagation, si elle rencontre une non-linéarité quelconque, son contenu fréquentiel s'enrichit avec les harmoniques nf_1 et nf_2 mais également avec les fréquences $nf_1 \pm mf_2$.



Modulation de fréquence :

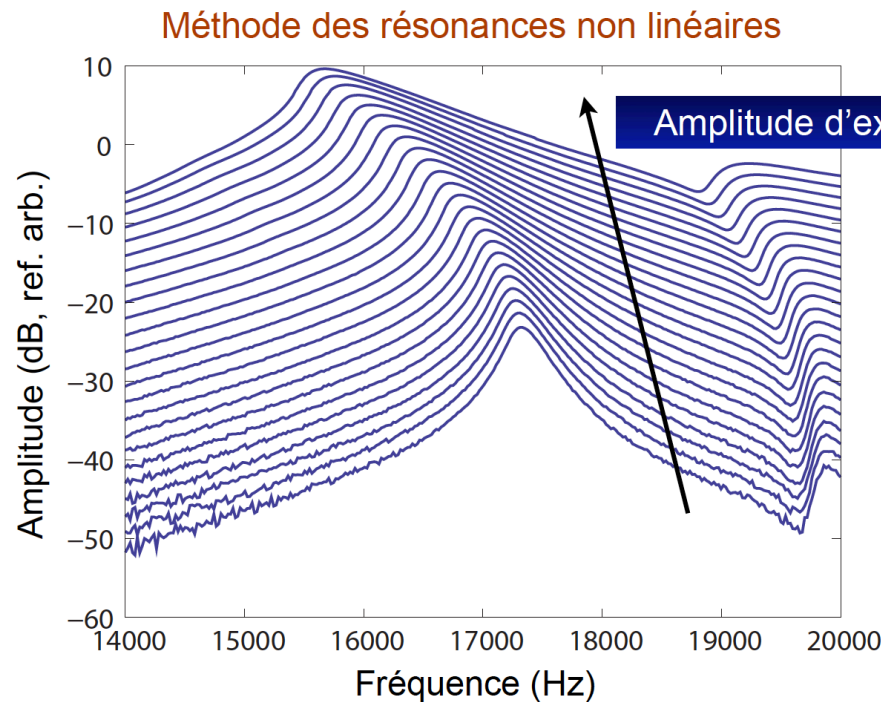
Idem sauf que $f_1 \ll f_2$.



Résonance non-linéaire:

Lorsque le système est non-linéaire, la fréquence de résonance du système peut dans certains cas varier en fonction de l'amplitude. Ce décalage de la fréquence de résonance peut être utilisée pour caractériser ou détecter des endommagements.

Processus particuliers,
propres aux solides
endommagés initialement
homogènes ou linéaires :
applications au CND



⇒ Assouplissement

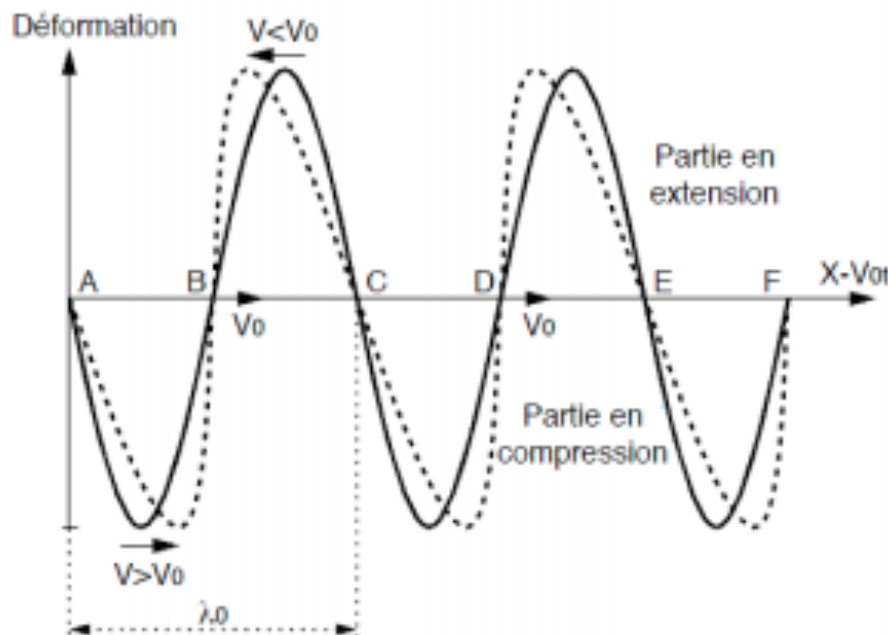
⇒ Dissipation ↗

En général, on considère que la relation **contrainte/déformation** est **linéaire**.

=> Vitesse de propagation ne dépend que du milieu de propagation $V = V_0$

Dans la réalité, la relation **contrainte/déformation** est **non-linéaire**.

=> Vitesse de propagation ne dépend que du milieu de propagation et de la valeur de la déformation : $V(\epsilon) = V_0(1 + \beta\epsilon)$, avec β coefficient de non-linéarité, ϵ la déformation.



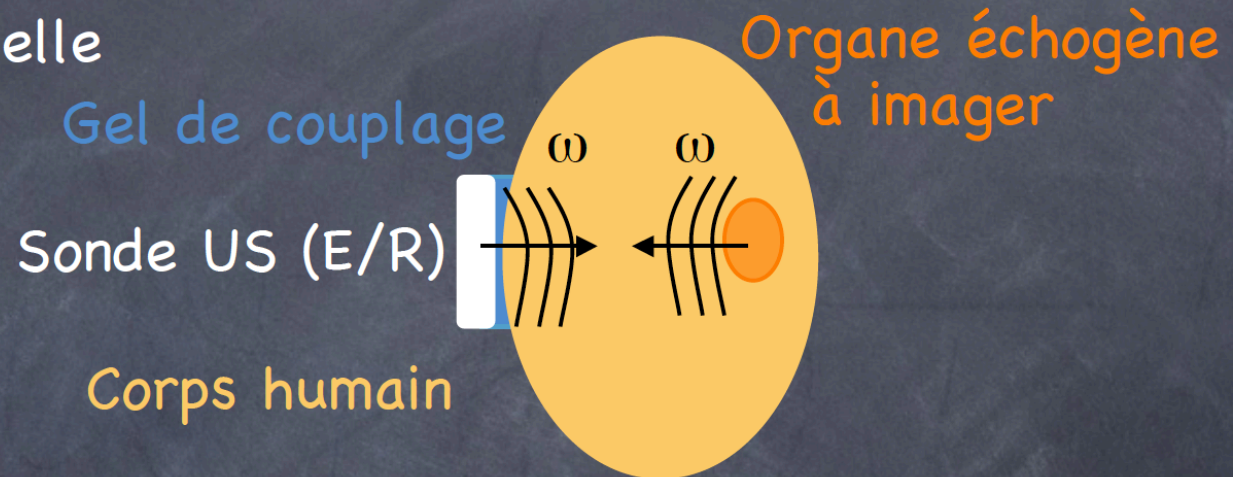
=> Distorsion de l'onde au fur et à mesure de sa propagation

=> Effet **cumulatif**

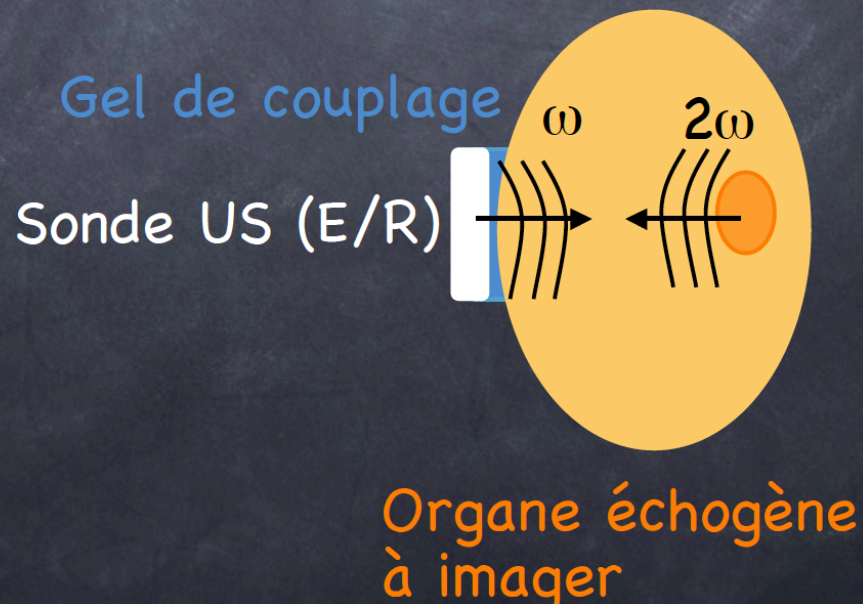
Acier [22]	$\beta = 4.4$
Granite [12]	$\beta = -441$
Béton (1) [13]	$\beta = -157$
Béton (2) [14]	$\beta = -139$
Silice [15]	$\beta = -3.75$
Air [16]	$\beta = 1.2$
Titane [15]	$\beta = 2.5$
Eau distillée à 20°C [16]	$\beta = 3.5$
Duralumine [15]	$\beta = 5.5$
Os trabéculaire [17]	$\beta = 440$

Tableau1. Différentes valeurs du coefficient de non-linéarité β

Echographie conventionnelle



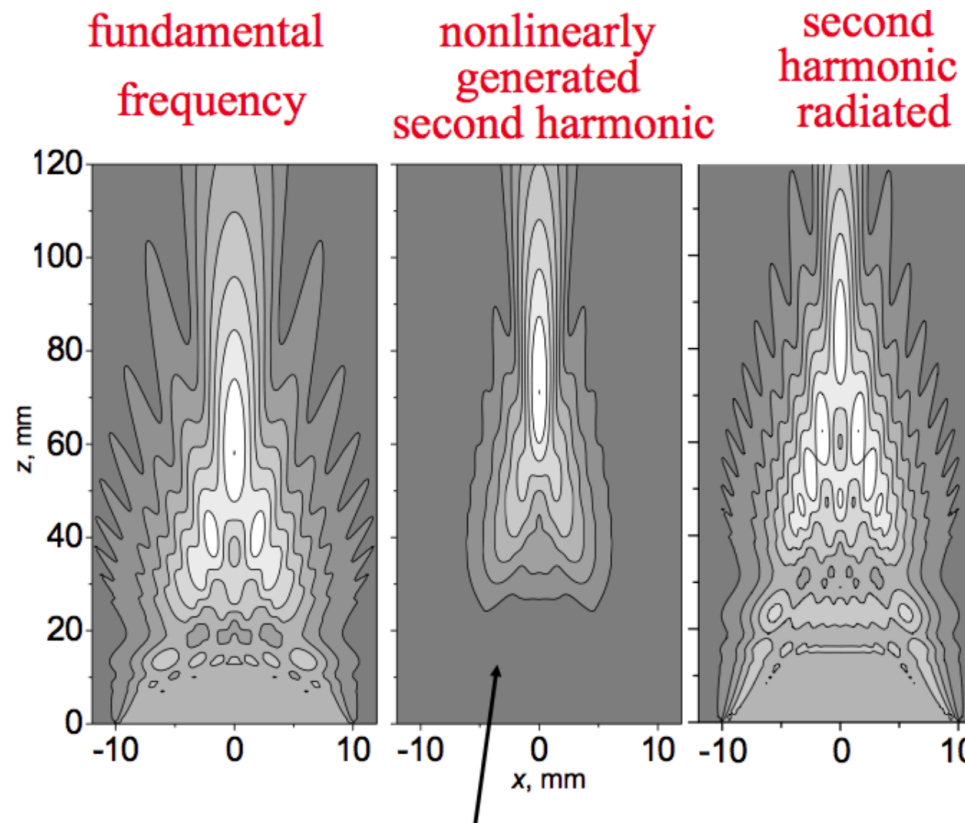
Echographie harmonique



Cours F. Coulouvrat

Avantages de l'échographie harmonique :

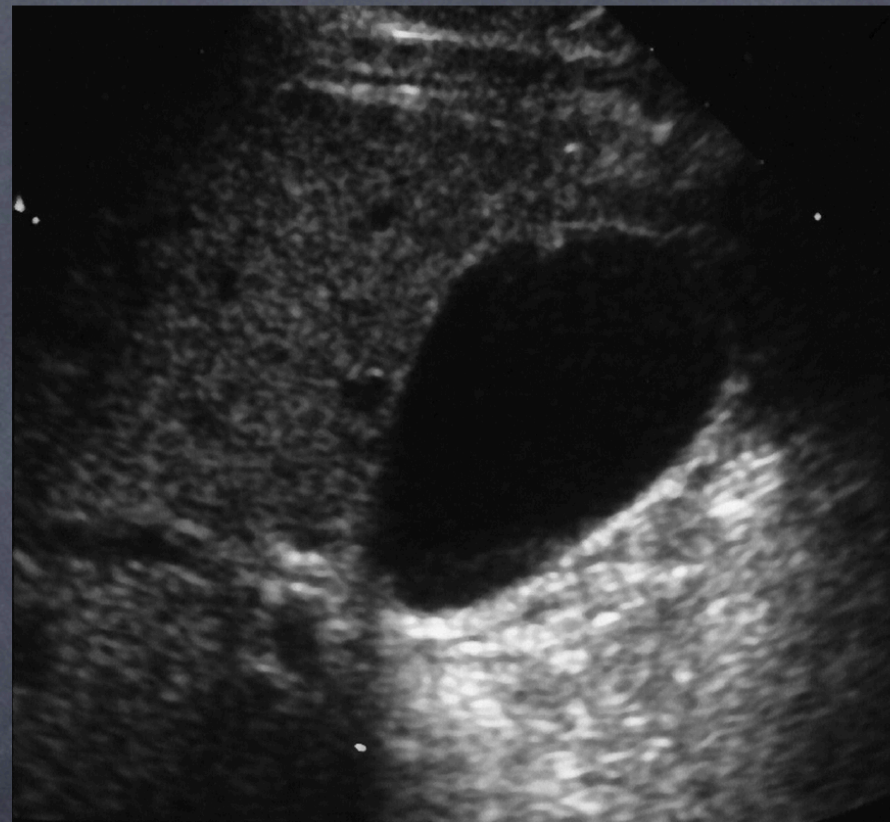
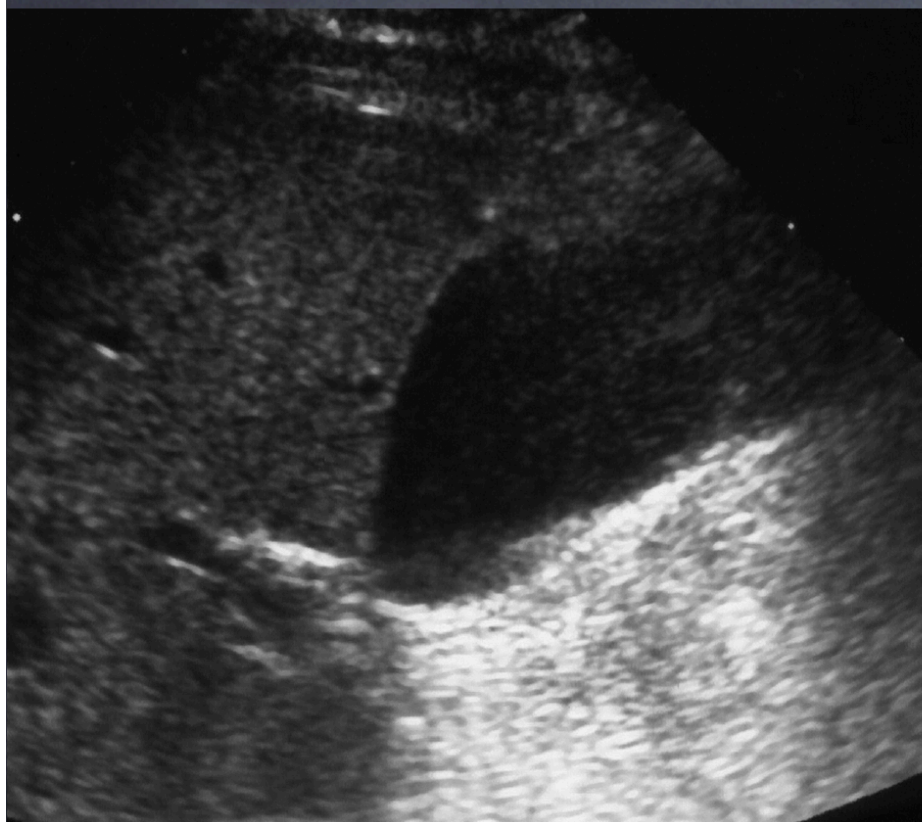
- Fréquence double $\Rightarrow$ Longueur d'onde $/2 \Rightarrow$ Meilleure résolution axiale
- Proportionnel au carré de l'amplitude $\Rightarrow$ Réduction de lobes secondaires
 $\Rightarrow$ Meilleure résolution latérale et réduction des artefacts
- Génération progressive $\Rightarrow$ Réduction des artefacts issus de la propagation directe



Cours F. Coulouvrat

Echographie **conventionnelle** (linéaire)

Echographie **harmonique** (non linéaire)



Choudhry S et al. Radiographics 2000;20:1127-1135

RadioGraphics

©2000 by Radiological Society of North America

Imagerie harmonique => composites ayant subi des cycles de fatigue

Image d'amplitude linéaire

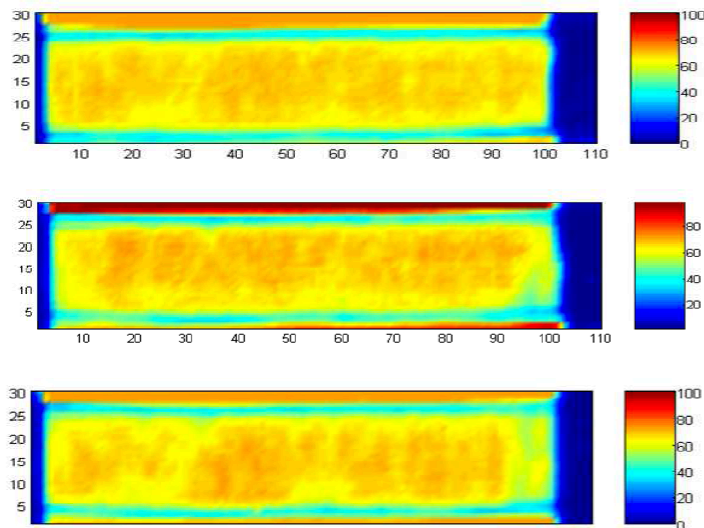
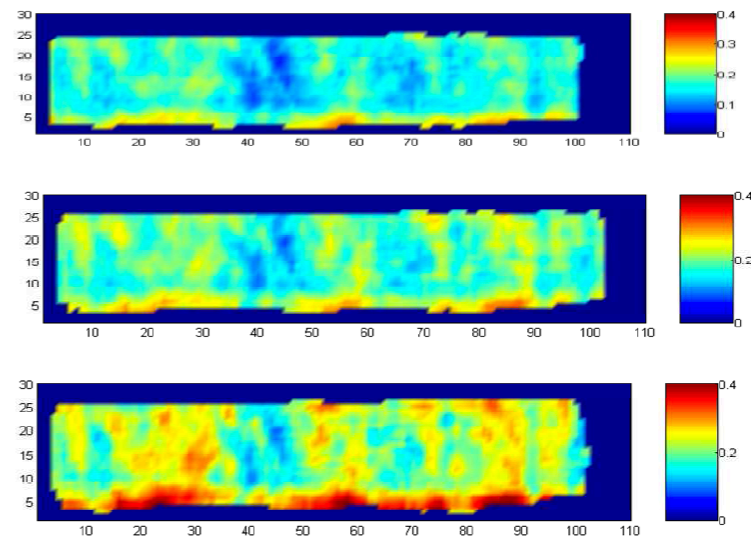


Image du deuxième harmonique
obtenue par inversion d'impulsion



0 cycles

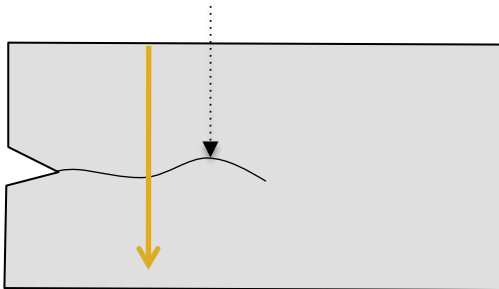
15 000 cycles

17 000 cycles

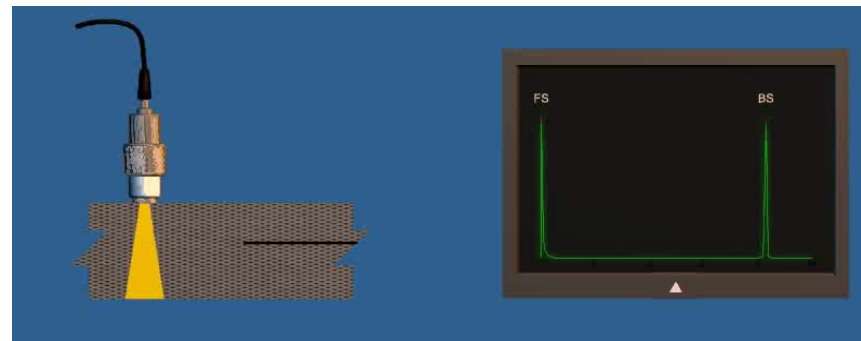
Cours O. BOU MATAR

ECND de fissures fermées ?

Fissures fermées (/microfissures)



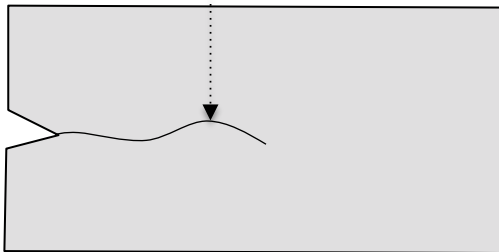
Techniques US linéaires conventionnelles



ECND de fissures fermées ?

Sensibilité limitée des techniques US linéaires

Fissures fermées (/microfissures)



Interfaces avec un comportement NON-LINEAIRE
Contact, frottement, adhésion, rugosités, plasticité
...



Effets non-linéaires lors de la propagation d'ondes acoustiques si les comportements NL sont activés

Effets observés quelque soit la nature de la non-linéarité (locale, cumulative, classique, non classique ...)

=> **Pb ouvert : différencier et caractériser les NL**

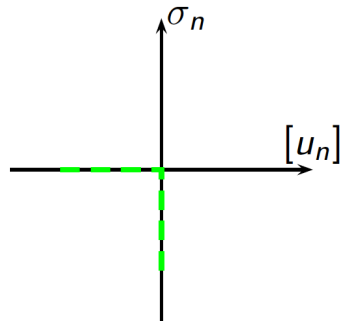
Génération d'harmoniques

Modulation de fréquence

Résonance non linéaire

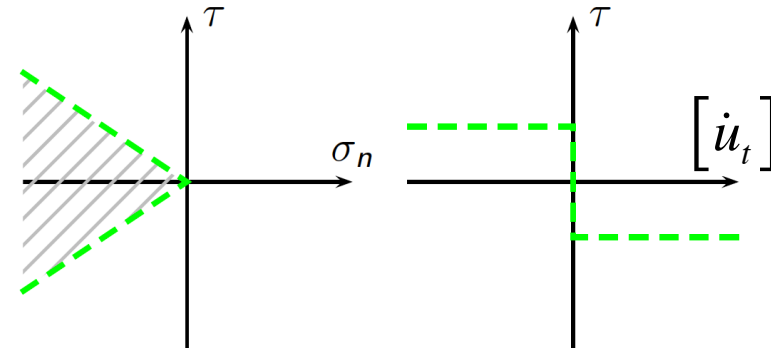
...

Comportement normal :
Contact unilatéral



$$\begin{cases} \sigma_n \leq 0 \\ [u_n] \leq 0 \\ \sigma_n [u_n] = 0 \end{cases}$$

Comportement tangentiel:
Frottement de Coulomb



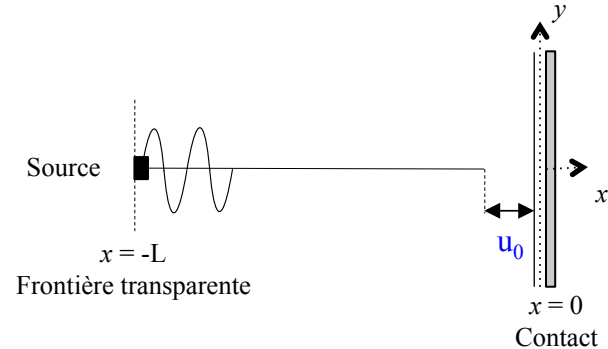
$$|\tau| \leq \mu |\sigma_n|$$

- si $|\tau| < \mu |\sigma_n|$, $\dot{u}_t = 0$ (adhésion)
- si $|\tau| = \mu |\sigma_n|$, $\tau \cdot \dot{u}_t \leq 0$ (glissement)

Un seul paramètre physique = coefficient de frottement

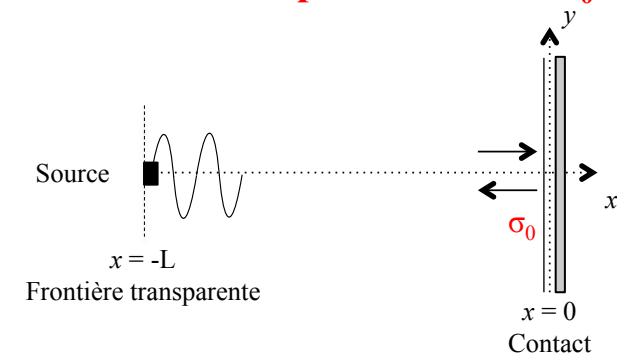
- Lois non-régulières avec résultats partiels concernant l'existence et l'unicité des solutions
⇒ Précautions pour l'implémentation numérique de la loi

Interface initialement ouverte avec
un saut de déplacement u_0



Clapping si $u_{inc_max} > |u_0|$
 $\psi_L = |u_0|/u_{inc_max}$

Interface initialement fermée
avec une précontrainte σ_0

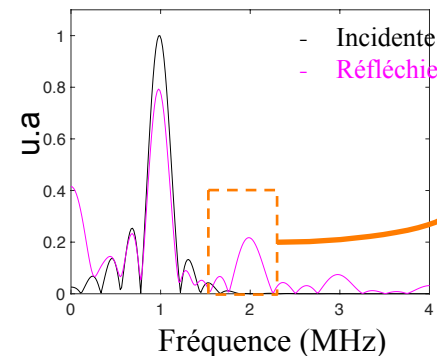
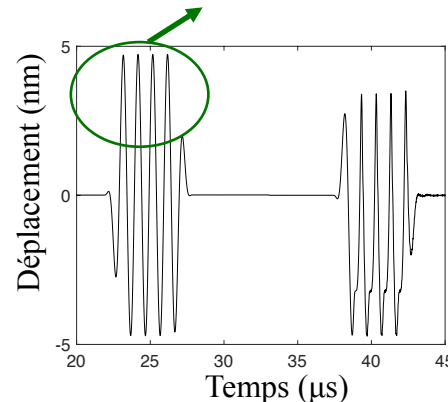


Clapping si $\sigma_{inc_max} > |\sigma_0|$
 $\xi_L = |\sigma_0|/\sigma_{inc_max}$

Méthode de
génération
d'harmoniques

Exemple (interface fermée): $\sigma_0 = -1.4$ MPa

Onde incidente : $f=1$ MHz; $N_c=5$; $\sigma_{inc_max}=3$ MPa (fenêtre rectangulaire apodisée).



$$\eta = \frac{A_2}{A_{inc}}$$

Effet du « clapping »

Interface ouverte u_0

Interface fermée σ_0

Effet du « sliding »

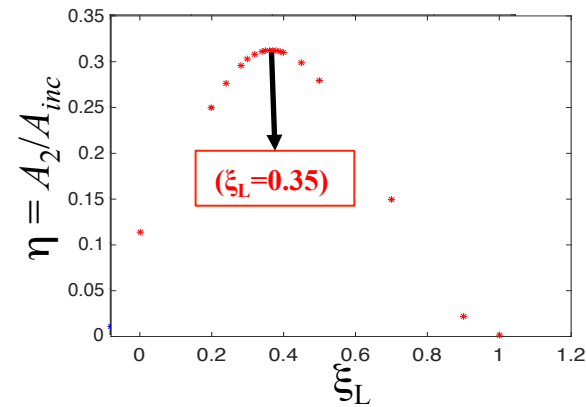
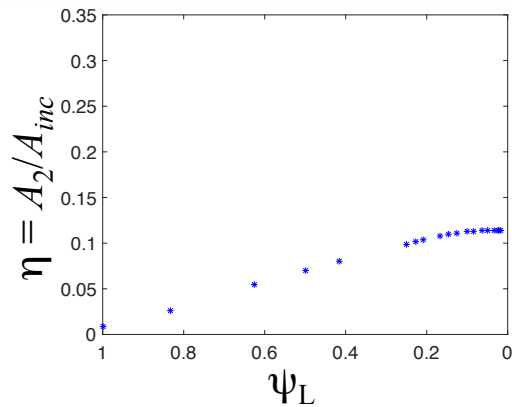
Paramètre
important

$$\psi_L = \frac{|u_0|}{u_{inc}^{int}}$$

$$\xi_L = \frac{|\sigma_0|}{\sigma_{inc}^{int}}$$

=> Génération de A_2 liée à l'intensité du « clapping »

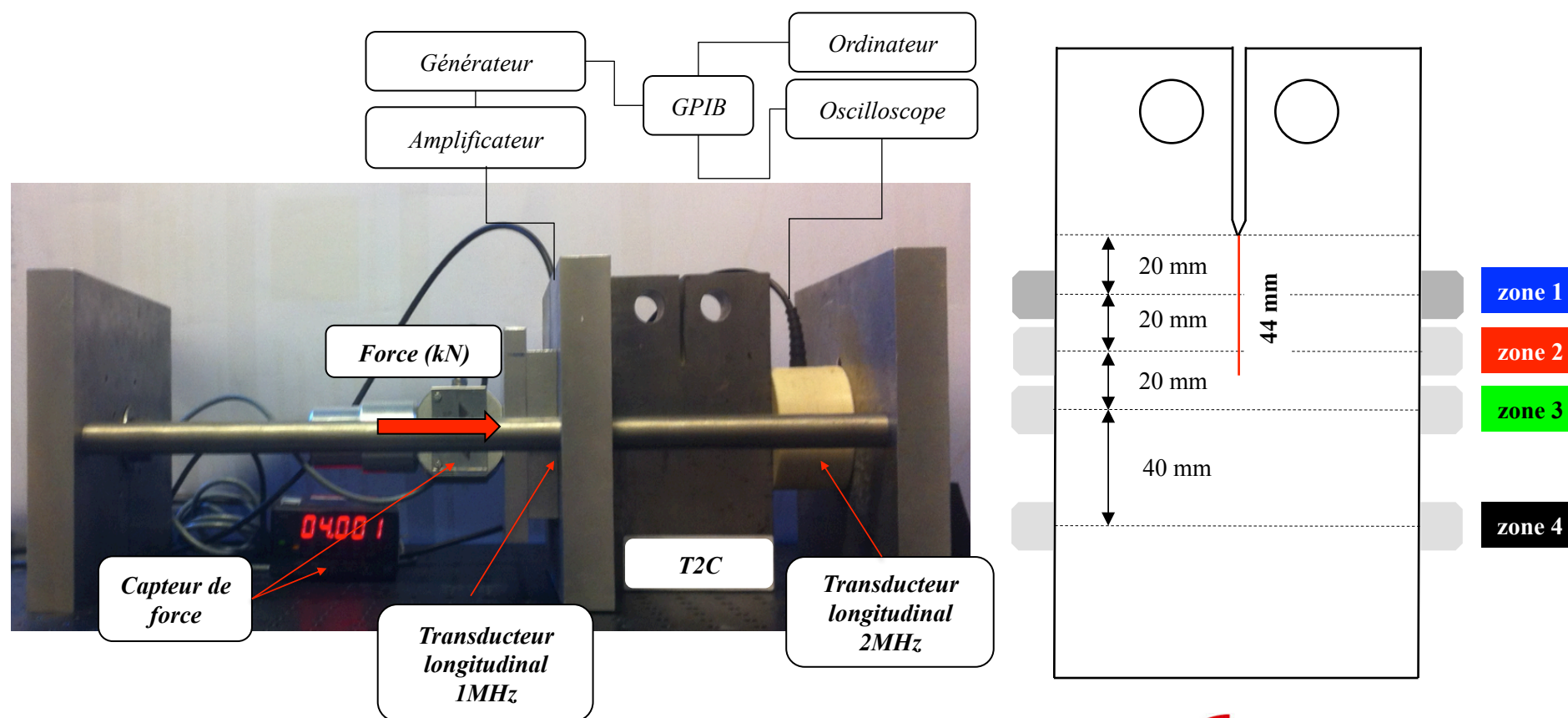
Signature CAN
numérique



Signature CAN
expérimentale

2 signatures acoustiques non-linéaires différentes

• Dispositif expérimental:



Effet du « clapping »

Interface ouverte u_0

Interface fermée σ_0

Effet du « sliding »

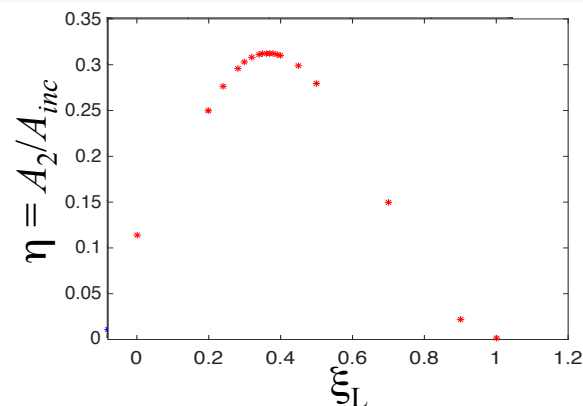
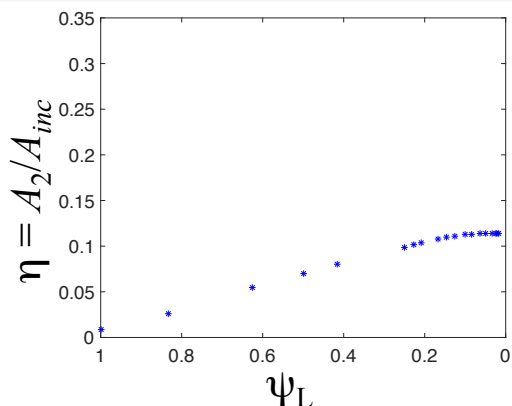
Paramètre
important

$$\psi_L = \frac{|u_0|}{u_{inc}^{int}}$$

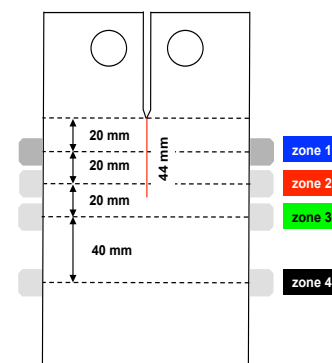
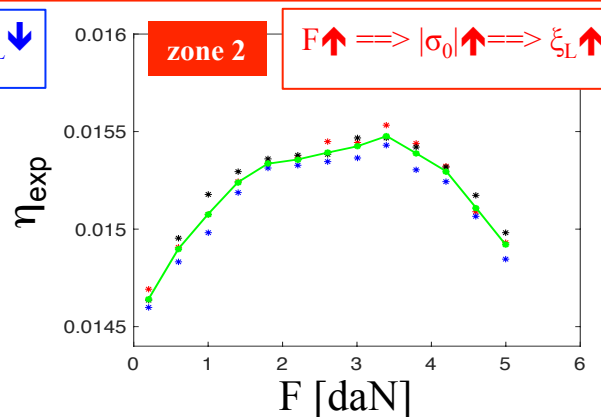
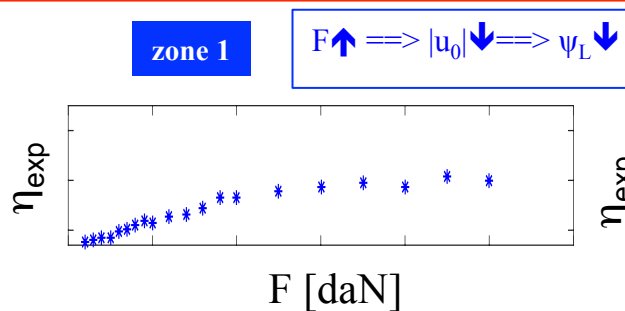
$$\xi_L = \frac{|\sigma_0|}{\sigma_{inc}^{int}}$$

=> Génération de A_2 liée à l'intensité du « clapping »

Signature CAN
numérique



Signature CAN
expérimentale



Effet du « clapping »

Interface ouverte u_0

Interface fermée σ_0

Meziane et al, JASA 130.4 2011
Blanloeuil et al. JASA 135.4 2014

Effet du « sliding »

Paramètre
important

$$\psi_L = \frac{|u_0|}{u_{inc}^{int}}$$

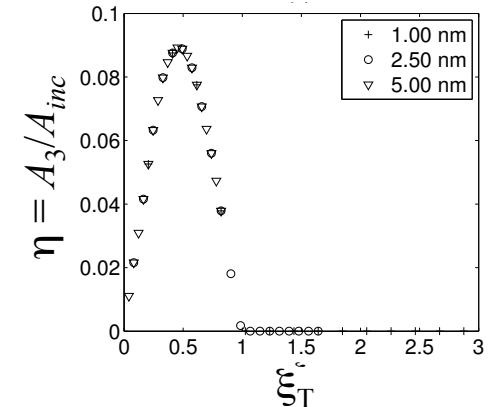
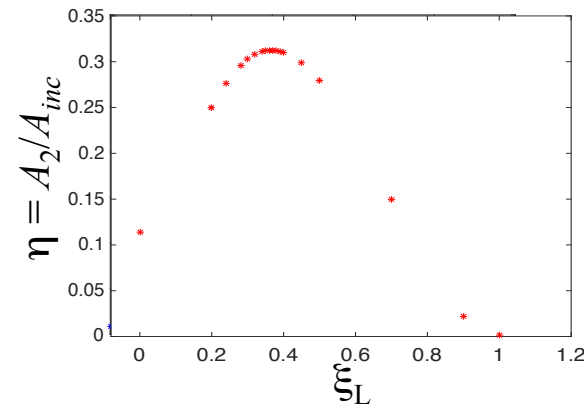
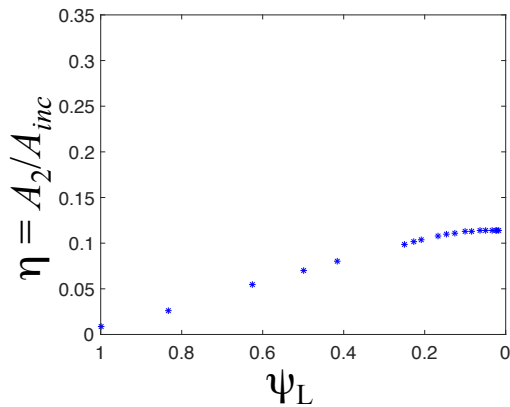
$$\xi_L = \frac{|\sigma_0|}{\sigma_{inc}^{int}}$$

$$\xi_T = \frac{\mu|\sigma_0|}{\tau_{inc}^{int}}$$

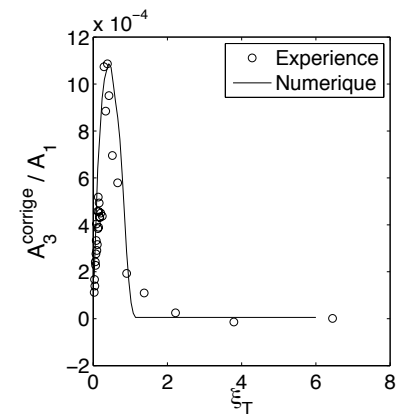
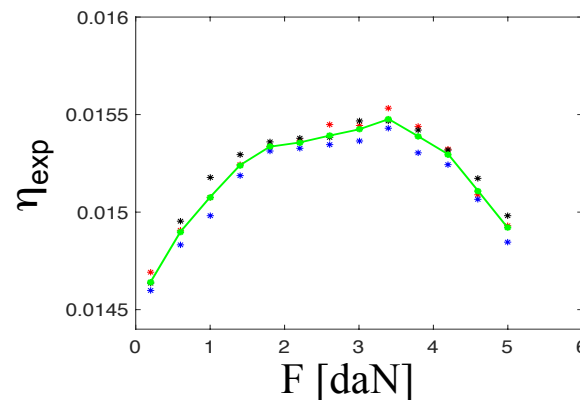
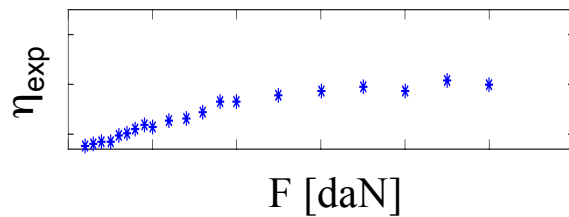
=> Génération de A_2 liée à l'intensité du « clapping »

=> Génération de A_3 liée à l'énergie dissipée par frottement

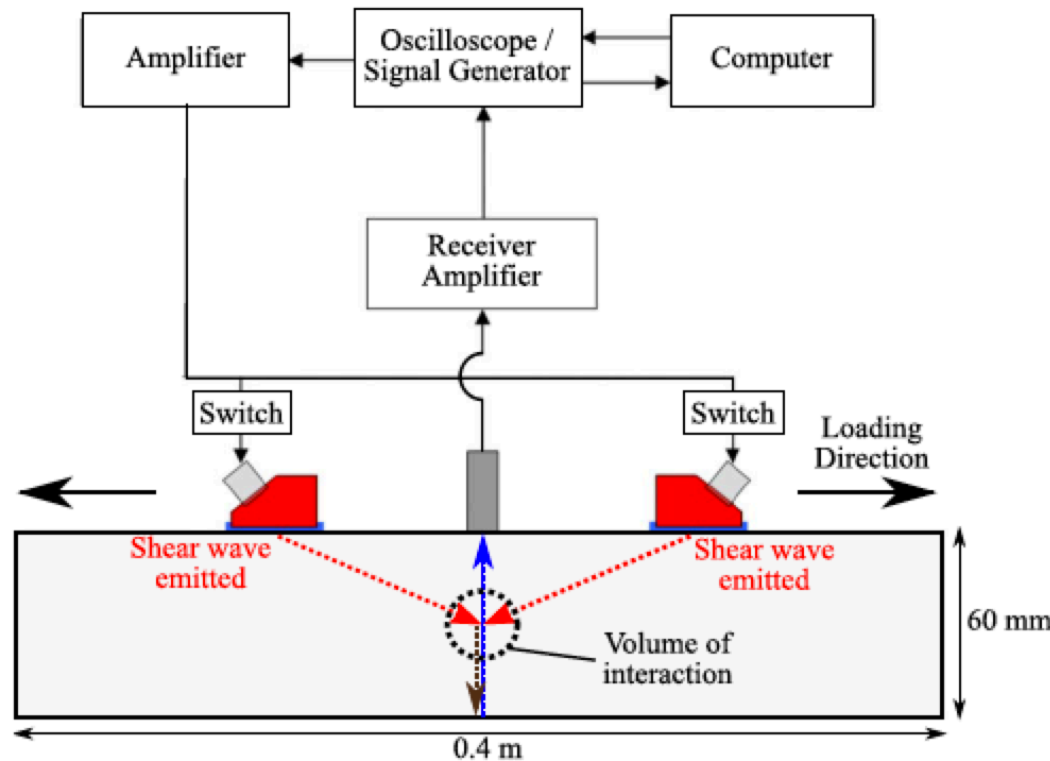
Signature CAN
numérique



Signature CAN
expérimentale



Méthode proposée par Jones et Kobet (1963) et expérimentalement testée par Rollin (1963)



[Croxford et al. JASA Express letter 2009]

Interaction de 2 ondes de
cisaillements (**incidence oblique**)
de fréquence f_0

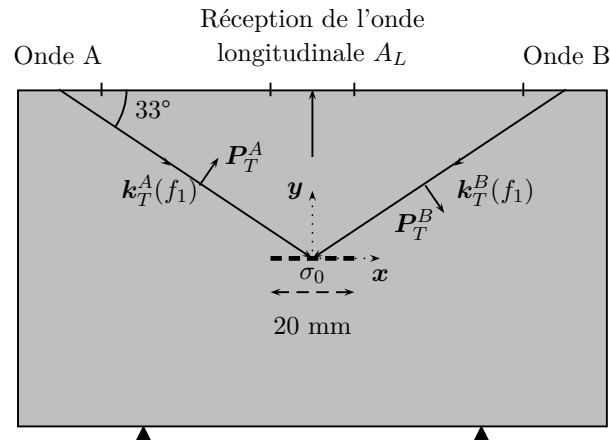
Comportement
mécanique NL
dans le volume
d'interaction

Génération d'une onde
longitudinale de fréquence $2f_0$

Moins sensible aux NL du système grâce à : la sélectivité **spatiale**, sélectivité **modale**,
sélectivité **fréquentielle** et sélectivité **directionnelle**.

Analyse numérique : Application à une fissure fermée

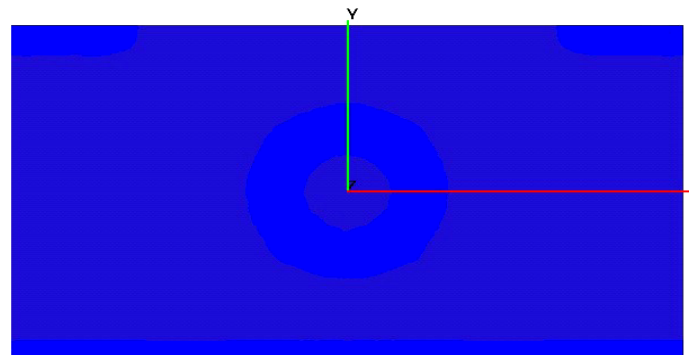
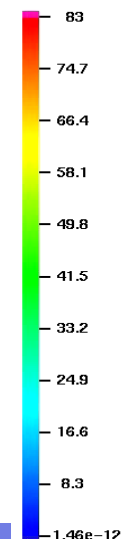
Blanloeuil et al., NDT&E
76 2015



250

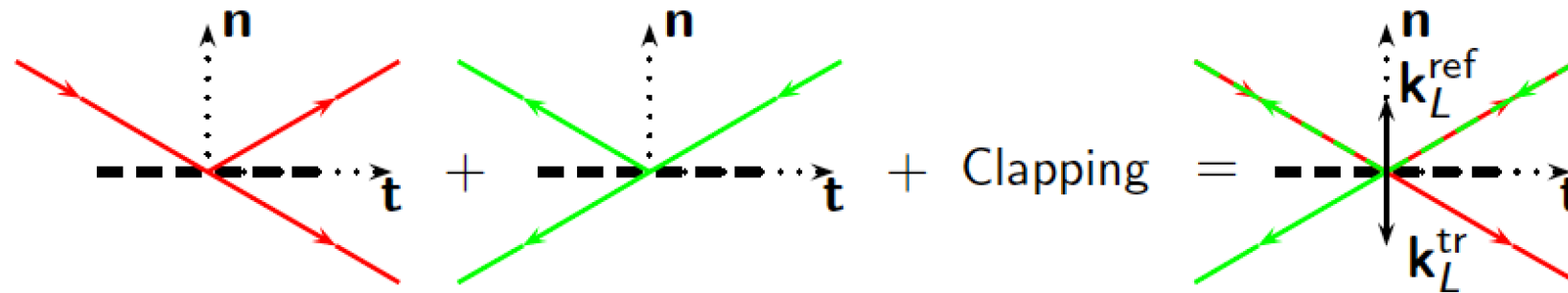
7.5e-07

Cells Vect Mag

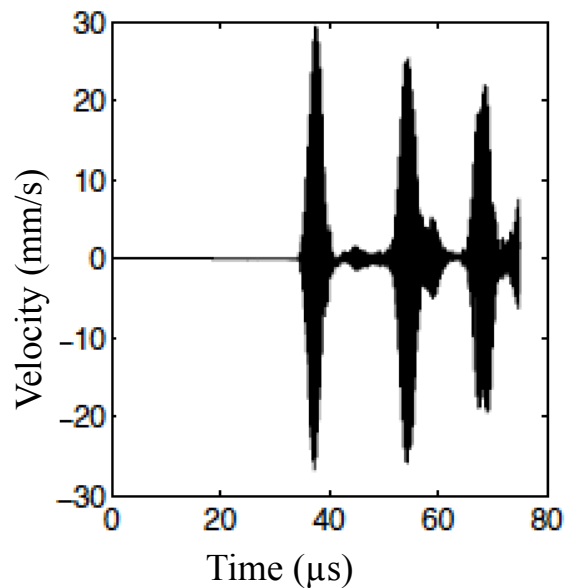


- Ondes incidentes transverses A and B;
- $\theta_I = 57^\circ$, $f_0 = 1.5\text{MHz}$, $A = 15\text{nm}$, 10 cycles;
- Loi de contact = Contact unilatéral avec frottements de Coulomb (incluant une précontrainte);
- Raffinement en pointes de fissure.

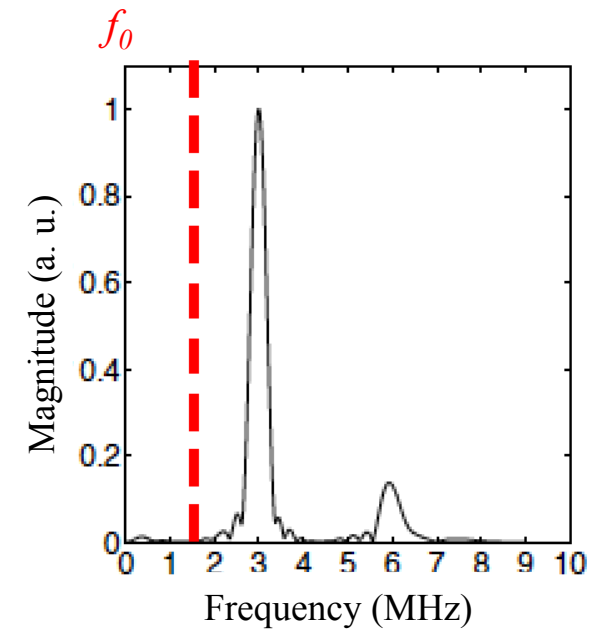
Non-linéarité de contact :



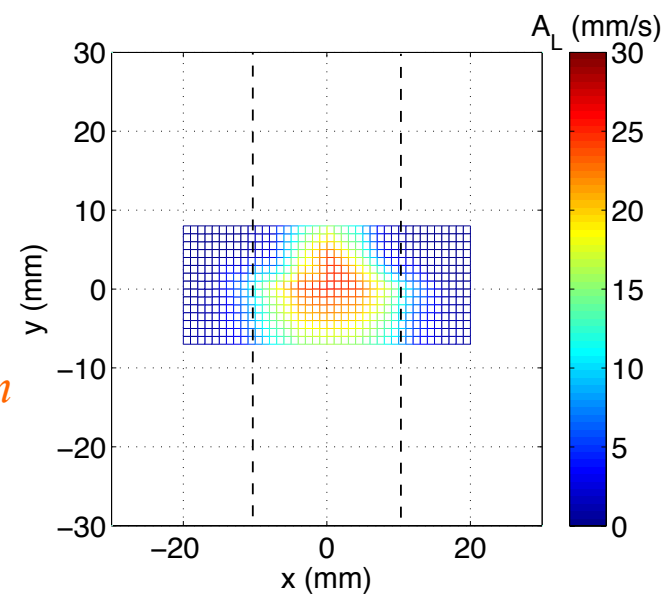
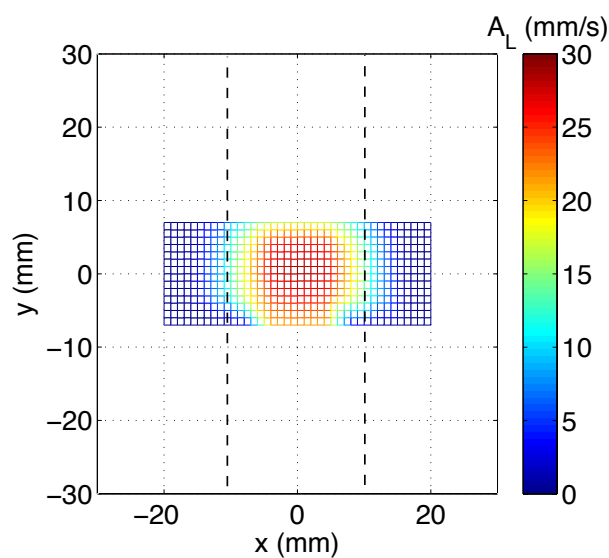
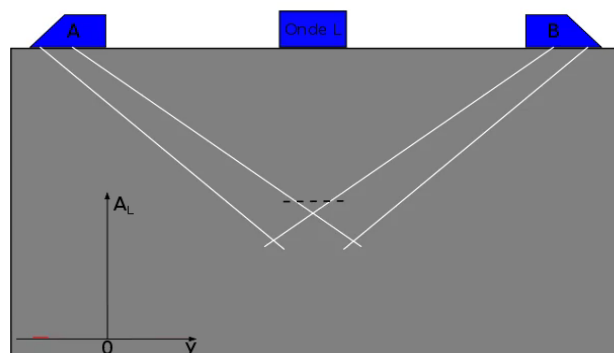
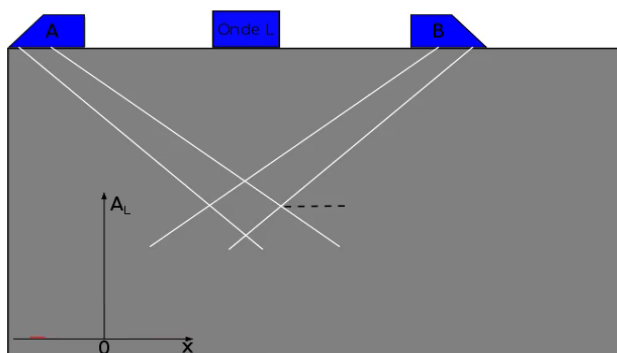
2 ondes longitudinales sont générées (réfléchié et transmise)



FFT



Potentiel pour l'imagerie



*Optimisation
de l'angle*

MERCI POUR VOTRE ATTENTION !!!

QUESTIONS