

Thermodynamique des Processus Irréversibles
Quiberon, 16-22 sept. 2018

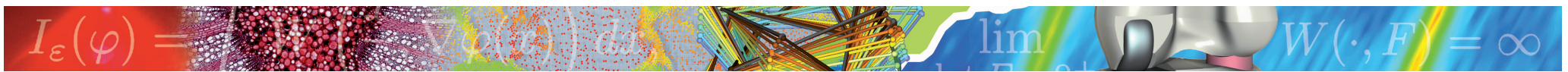
7ème école d'été de mécanique théorique

Effets de couplage et effets dissipatifs accompagnant la déformation des matériaux solides

(2^{ème} partie)

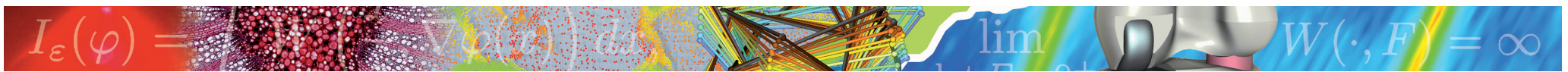
André Chrysochoos
LMGC, UMR 5508 CNRS-UM





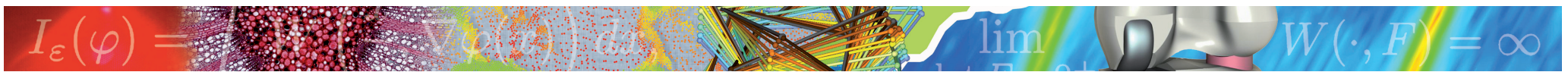
Programme

- 1 - Cadre thermomécanique et bilan d'énergie
(TPI-MSG)
- 2 - Quelques éléments rhéologiques à la sauce MSG
(d'une vision mécanique à vision thermomécanique)
- 3 - Analyse expérimentale des bilans d'énergie
(imagerie quantitative)
- 4 - Effet du temps : couplage thm et/ou viscosité ?
(interaction forte et/ou irréversibilité)
- 5 - Effet dissipatif dans les métaux
(fatigue : HCF & VHCF)



- 3 -

Analyse expérimentale des bilans d'énergie (imagerie quantitative)



Motivations – stratégie

Observer les effets cinématiques, thermiques et calorimétriques accompagnant le processus de déformation.

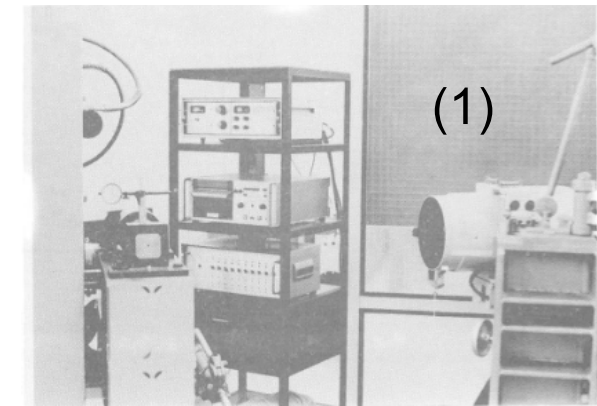
Utilisation combinée de techniques de corrélation (DIC) et de thermographie (IRT)

Domaine d'activités : « Quantitative imaging techniques – full field measurements »

DIC - Mechanics	IRT - Thermodynamics
<ul style="list-style-type: none">- displacement fields- strain and strain rate,- kinetic energy rate- deformation energy rate	<ul style="list-style-type: none">- temperature fields- heat source (via the heat equation)- intrinsic dissipation- coupling heat sources

Thermomécanique expérimentale

Très bref historique ...



1805, Gough, caoutchouc naturel

...
1857, Joule, métaux vs. caoutchouc, μ calorimètre (a)

...
1900, Charbonnier & Galy Aché, métaux en compression + μ calorimètre

...
1933, Taylor & Quinney, 1933, métaux en torsion → μ calorimètre

...
1965, Scanner IR Agema IR Systems

...
1975, J.J. Moreau, P. Germain, Q. S. Nguyen & B. Halphen, MSG/TPI

...
1976, Saix, XC38, flexion, radiomètre (1)

...
1978, naissance de FLIR

...
1982, LMA, Thèse de P. Brémond, fatigue, fissure, PVC, Aga 780 (2)

1982, Lemaître & Chaboche, Greco 47 GDE



(a) (Joule, 1857) J.P. Joule, On some thermodynamic properties of solids, *Phil. Mag. 4th Ser.* **14**, p.227 (1857)

Très bref état des lieux ...

1992

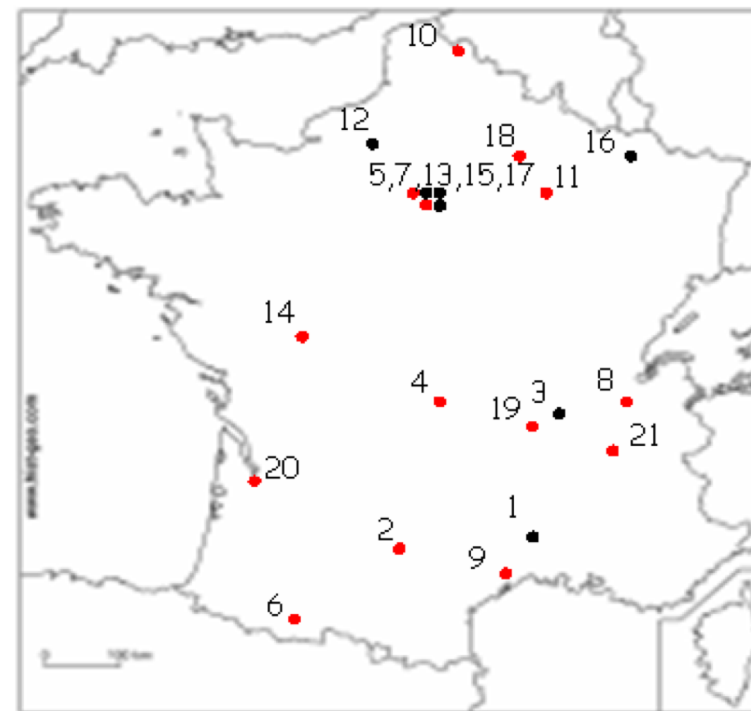
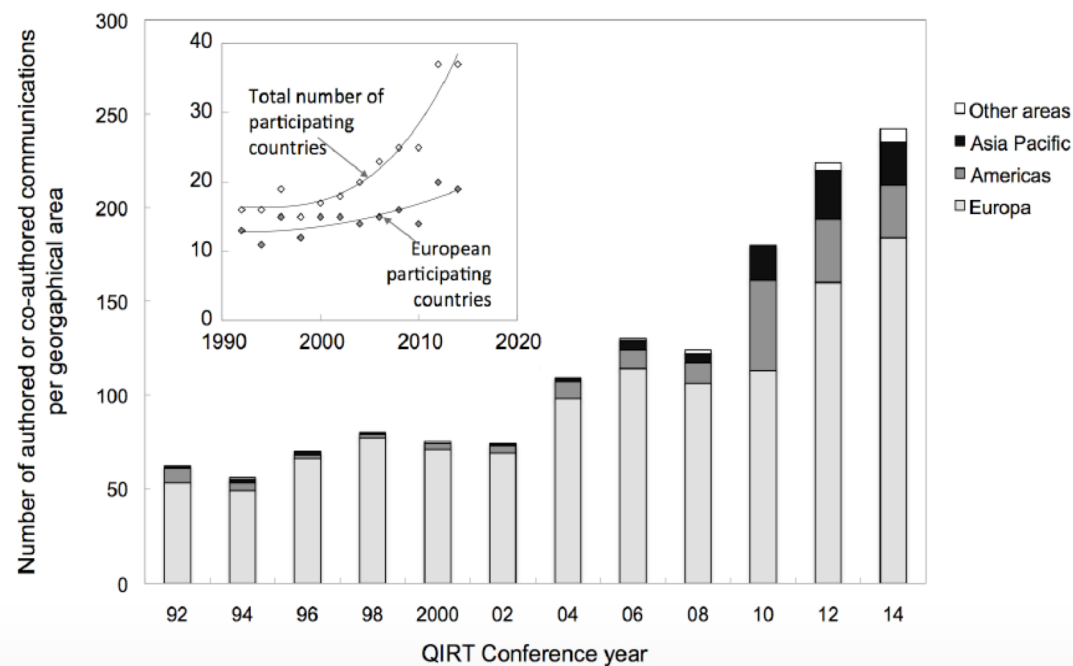
QIRT

Quantitative InfraRed Thermography

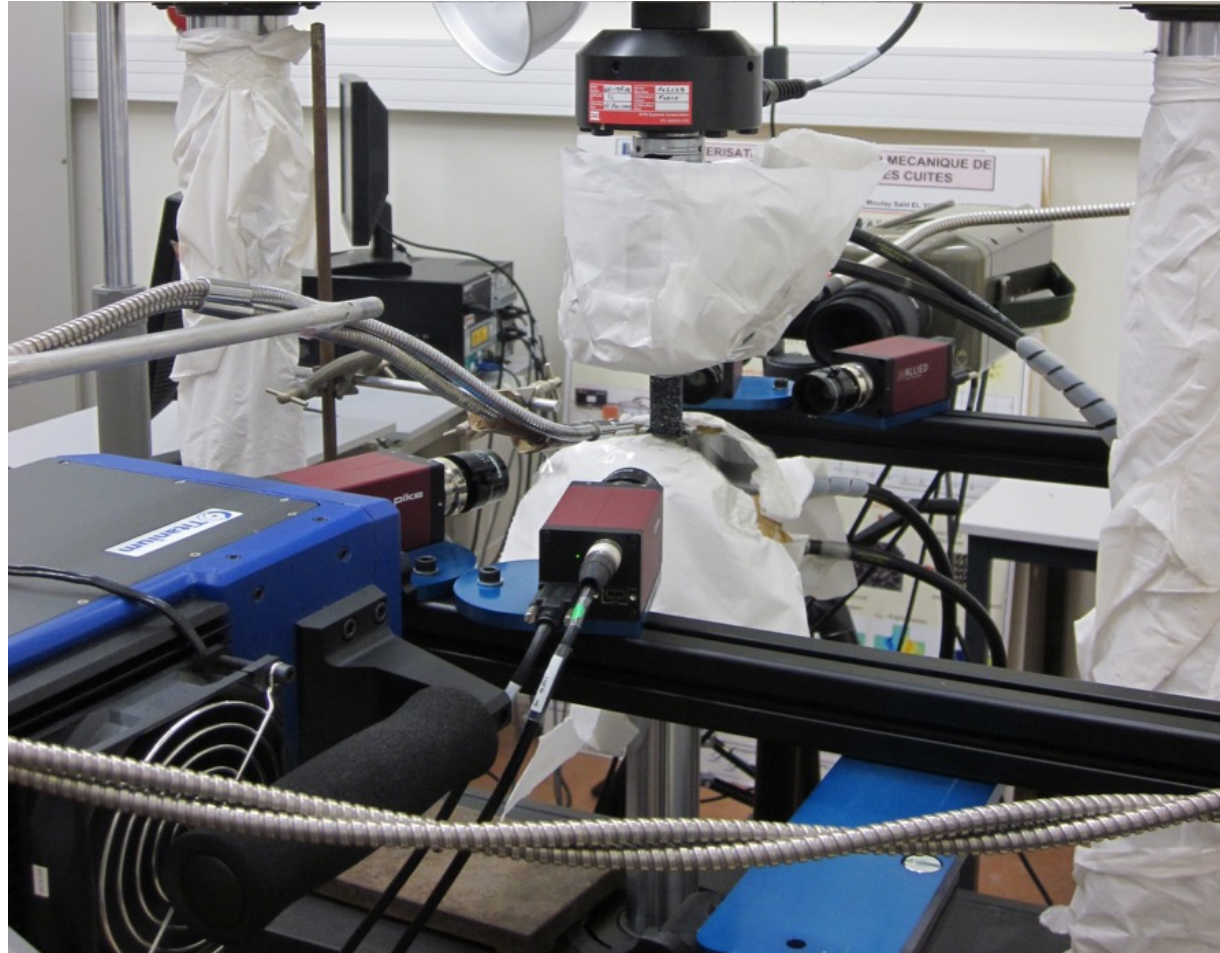
2003-2014



Renouvelé 2 fois !



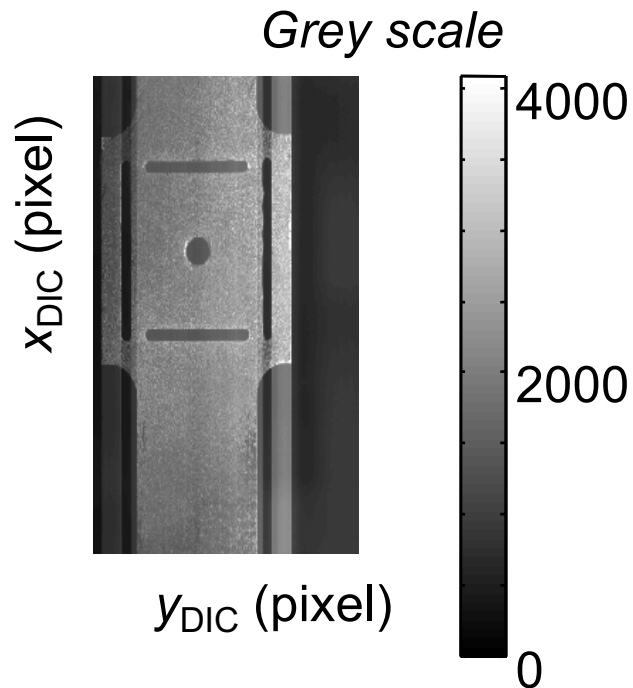
Exemple de dispositif expérimental



Vue d'ensemble d'un dispositif

Utilisation combinée de la «DIC» et de la «IRT»

image de granularité

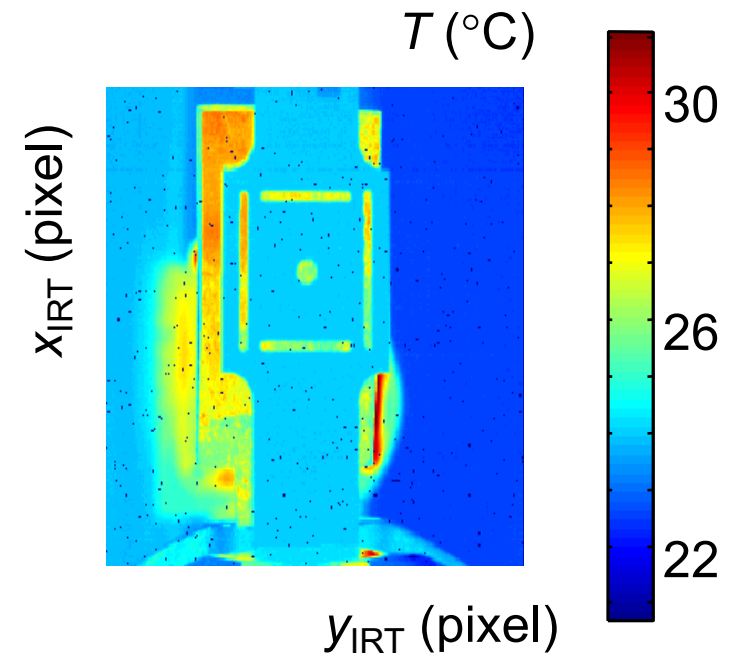


$$U(t_{DIC}, x_{DIC}, y_{DIC})$$

t_{DIC}

(x_{DIC}, y_{DIC})

image infrarouge



$$T(t_{IRT}, x_{IRT}, y_{IRT})$$

t_{IRT}

(x_{IRT}, y_{IRT})

Synchrocam (*)

cible

Correspondance entre données cinématiques et thermiques

Quelques mots sur la DIC (2D)

Rq : la 2D^{1/2} et la 3D existent déjà ...

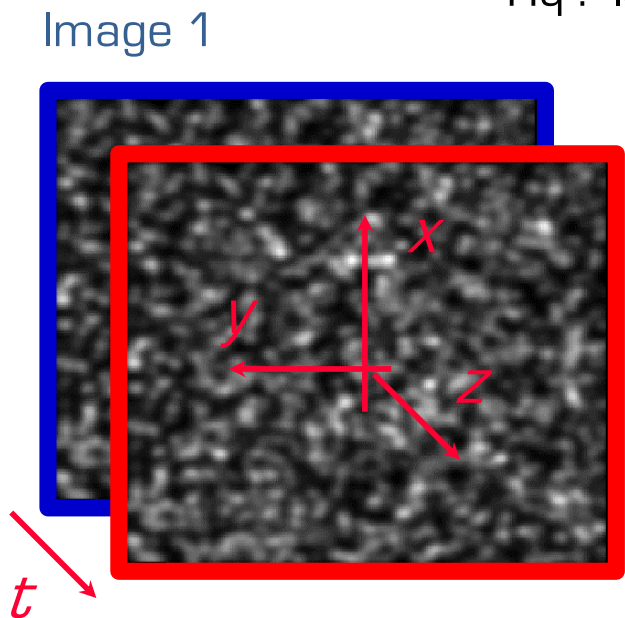
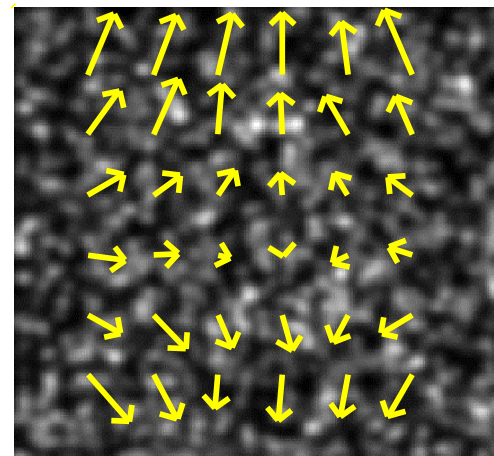


Image 2

intercorrelation



interpolation



$[u_x, u_y]$
in-plane
components

$[u_x, u_y]$
+ $\det F = 1$
+ *depthwise uniform strain field*

$= U_z$
out-of-plane components



fitting



derivation

$$H_{iK} = \frac{\partial u_i}{\partial X_K}$$

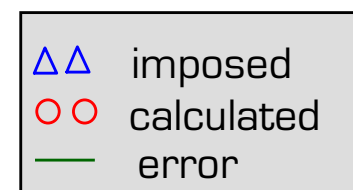
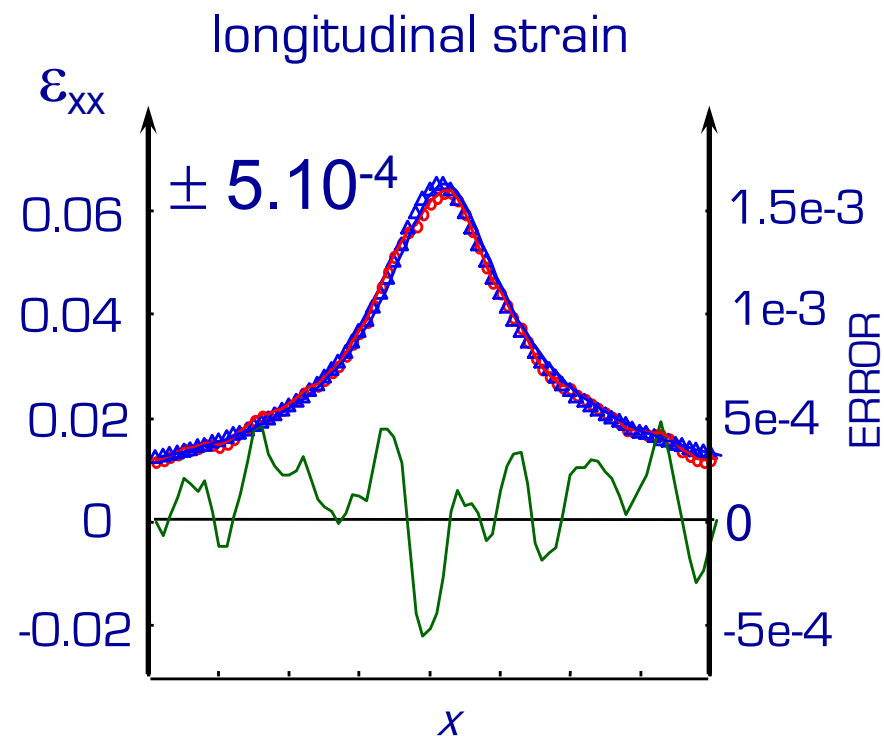
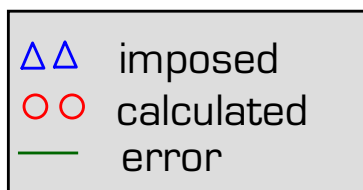
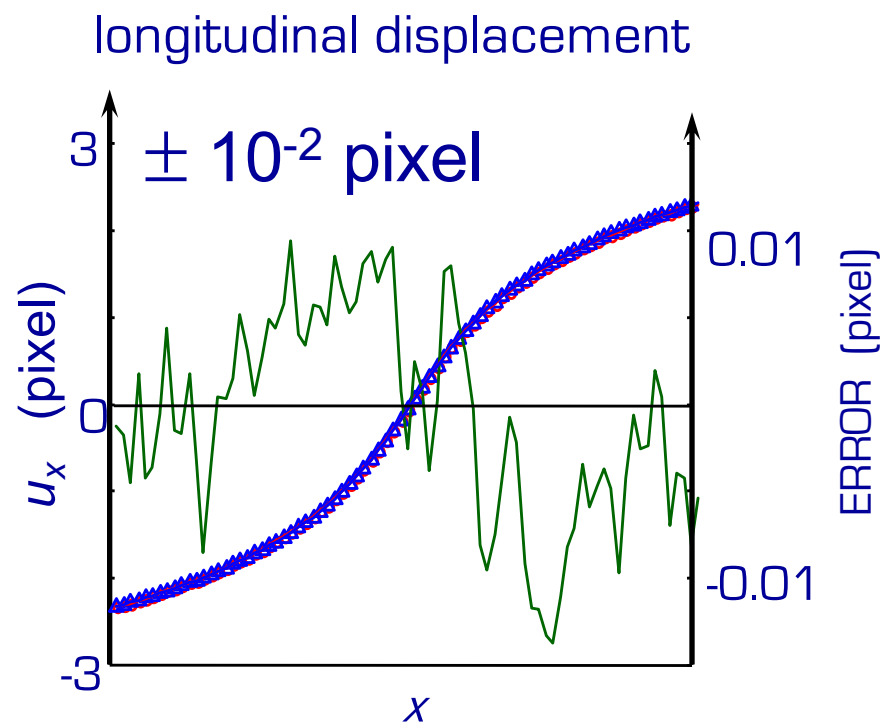
displacement gradient tensor

DIC (2) : précision des mesures cinématiques

Utilisation d'images de granularité « artificielles »

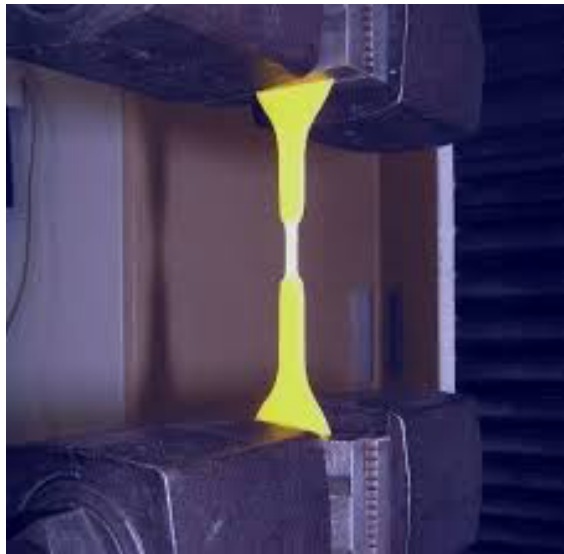
Champ de déplacements donné

[Bornert et al., Assessment of Digital Image Correlation Measurement Errors: Methodology and Results, Exp. Mech., 2009] - Prix SEM 2011.

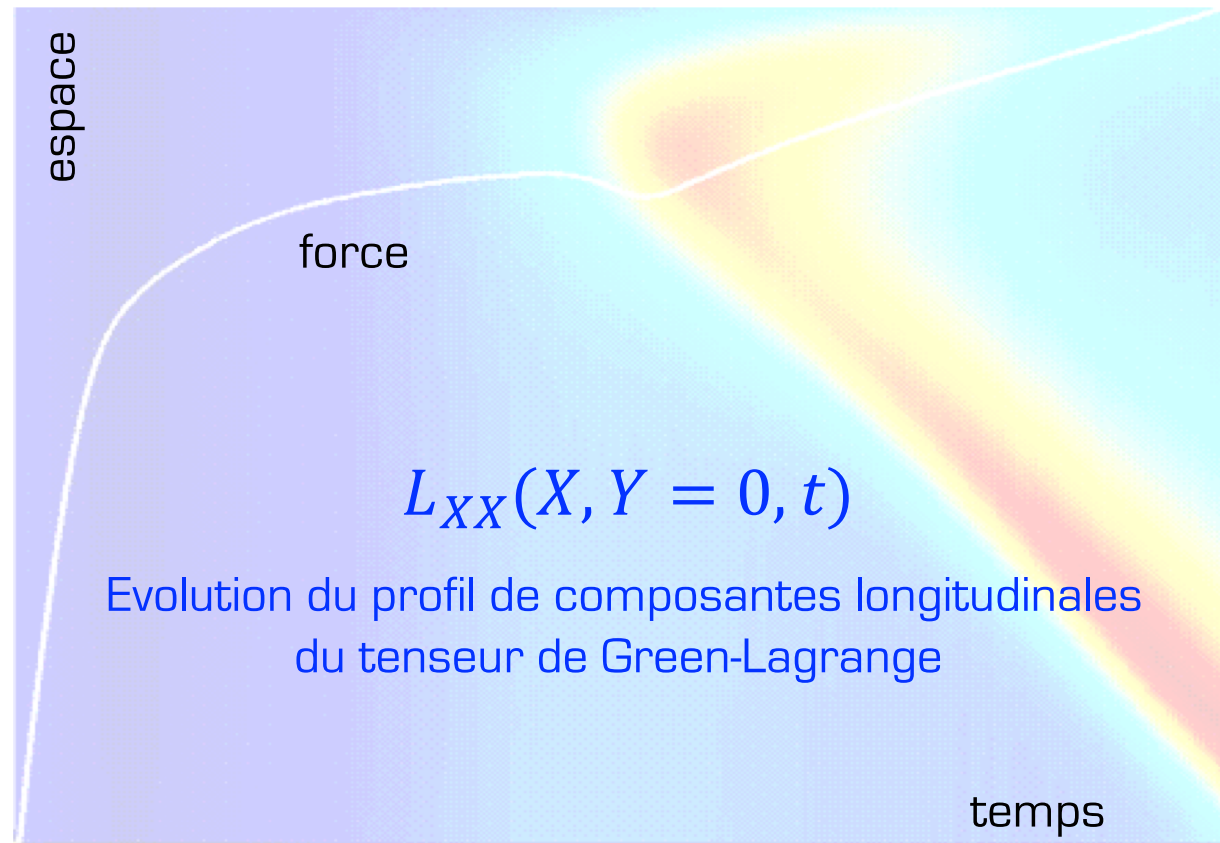


Un exemple de champ 1D au cours du temps

PA11 : thermoplastique semi-cristallin
 propagation de lèvres de striction



Allongement de la zone « strictionnée »

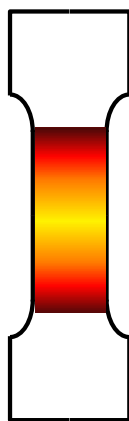


[Muracciole et al., Strain (2008)]

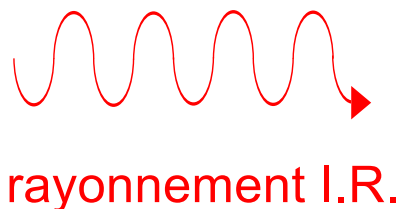
Un minimum de radiométrie IR

Objectif : mesurer des températures de surface pour estimer les sources de chaleur

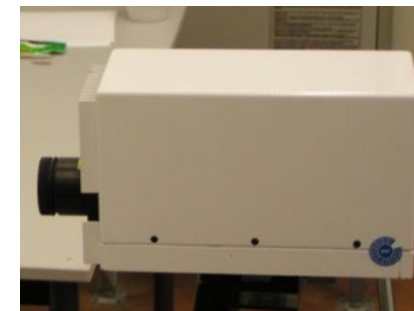
cible rayonnante



atmosphère



détecteur IR



$\Delta_\lambda = 3-5 \mu\text{m} / 4-8 \mu\text{m} / 8-12 \mu\text{m}$

Moyen : caméra IR matricielle

détecteur : délivre un signal électrique [V] lié à la puissance rayonnée [W]

émittance : flux global émis par la cible par unité de surface [$\text{W}\cdot\text{m}^{-2}$]

... pour une bande passante donnée

$$R = \int_{\Delta_\lambda} \frac{\partial R(\lambda, T)}{\partial \lambda} d\lambda$$

émittance spectrale
varie avec T !

... où s'appliquent directement les lois du rayonnement

● Loi de Planck

$$\frac{\partial R_{cn}(\lambda, T)}{\partial \lambda} = \frac{2\pi hc^2 \lambda^{-5}}{\exp\left(\frac{hc}{\lambda kT}\right) - 1}$$

- R : exitance spectrale, $W.m^{-3}$
- h : Planck, $6,66.10^{34}$ J.s
- k : Boltzmann, $1,38.10^{23}$ J.K⁻¹
- c : lumière, 3.10^8 m.s⁻¹
- T : température, K

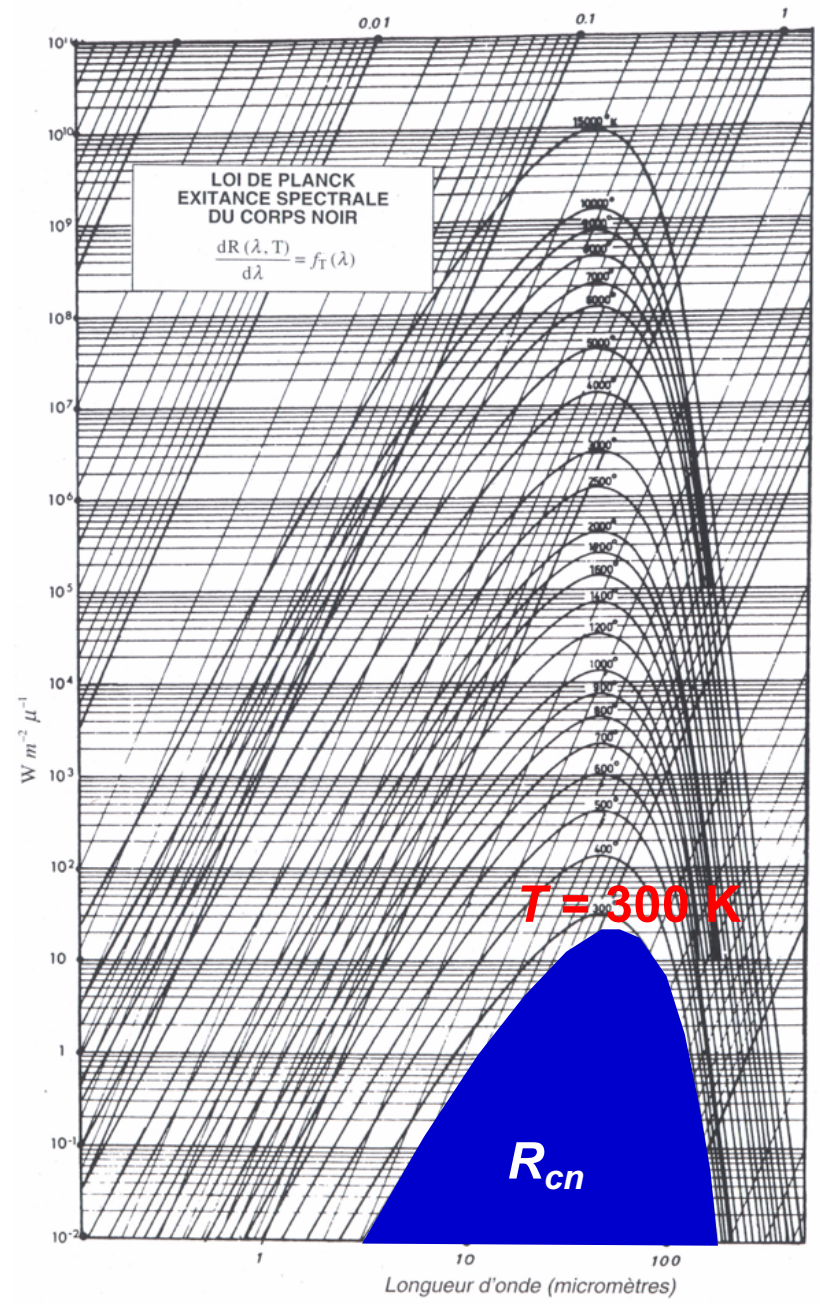
● Loi de Stefan-Boltzmann

$$R_{cn} = \sigma_s T^4$$

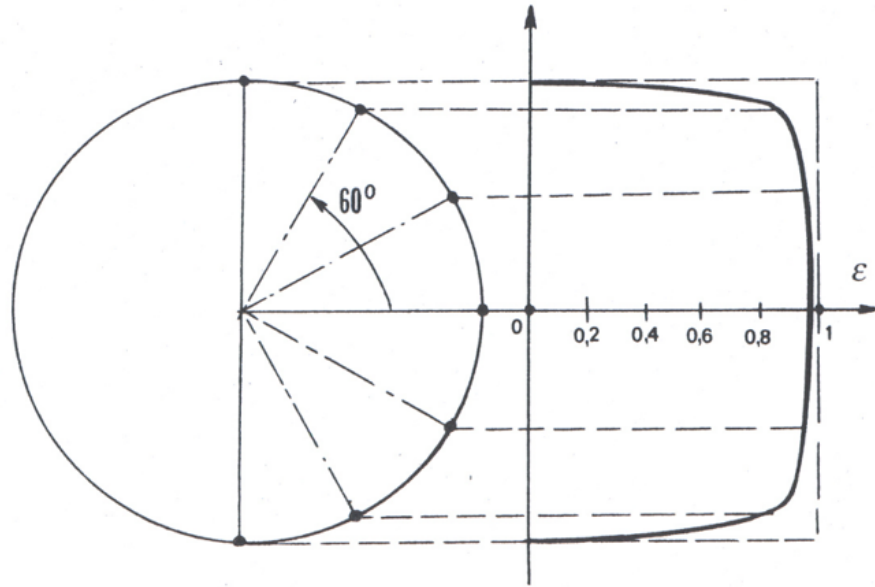
σ_s : constante de Stephan

$$\sigma_s = \frac{2\pi^5 k^4}{15c^2 h^3} = 5,67 10^{-8} W.m^{-2}.K^{-4}$$

[G. Gaussorgues]

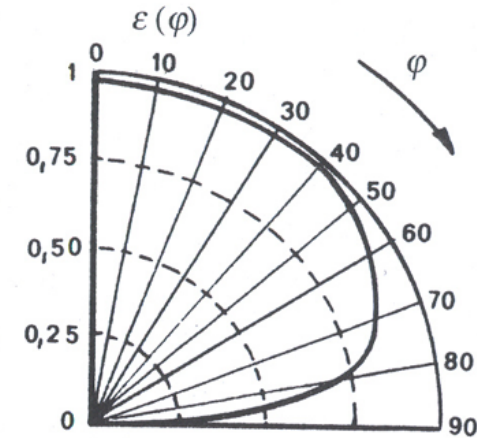


Rôle de l'incidence du rayonnement



émissivité : fonction de l'incidence

ε : émissivité



φ : angle observation

émissivité de l'eau à $\lambda = 10 \mu\text{m}$

Jusqu'à 45-50 degrés, corps lambertiens ... $\partial\varepsilon/\partial\varphi \approx 0$

Risque faibles : éprouvettes planes \perp axe optique de la caméra

+ corps gris à forte émissivité [peinture]

$$R_{\Delta\lambda}(T) \approx \varepsilon R_{cn_{\Delta\lambda}}(T)$$

Une caméra IR en quelques chiffres



Cedip MW (4-8 μm)

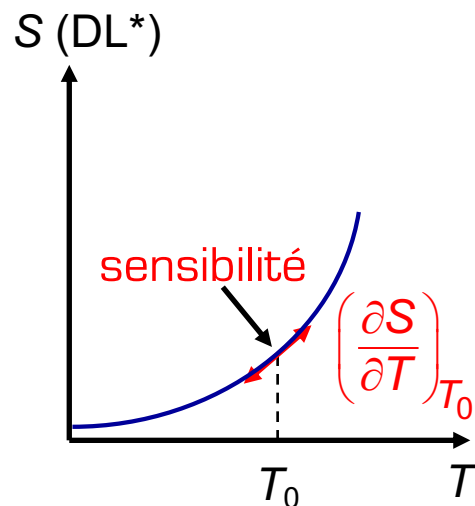
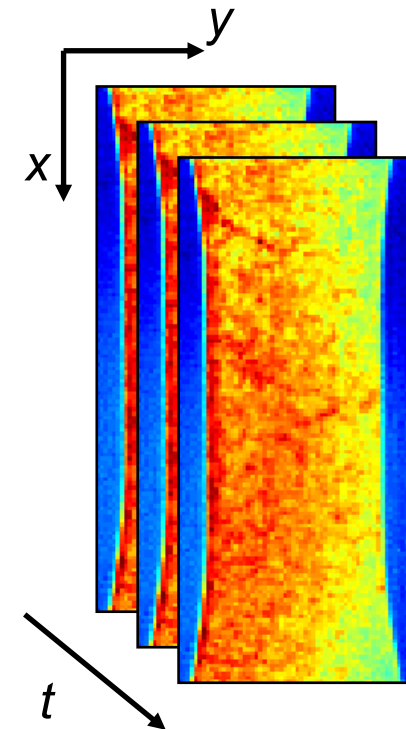
Image : 320×240 pixels

Codage : 14 bits

Fréq. Acq. : 50 images/seconde

Résolution spatiale : 100 μm/pix

NETD : 20 mK à l'ambiante



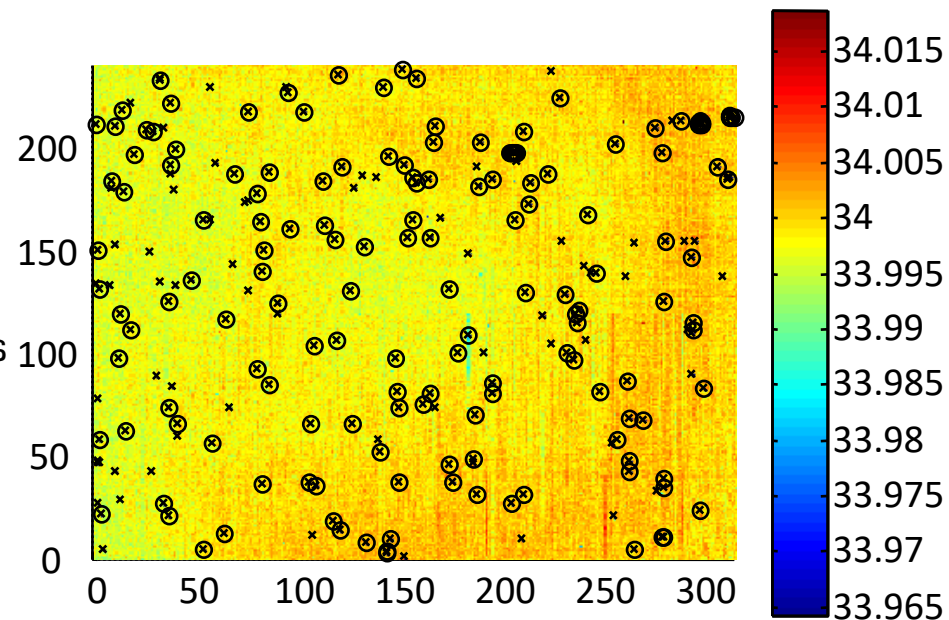
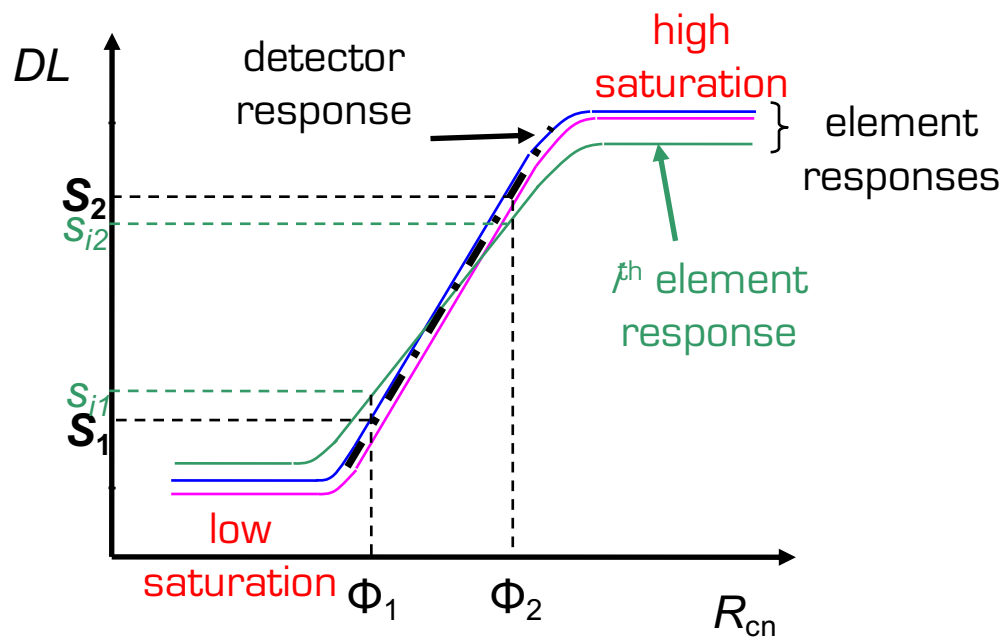
(*) DL : digital level

NETD : (noise equivalent temperature difference)
 Différence de Température Equivalente à la valeur efficace du bruit mesuré sur le thermosignal.

Etalonnage : constructeur

- 2 scènes thermiques uniformes (Φ_1 et Φ_2)
 feuille blanche + main ...
- 50 % de la dynamique des capteurs (partie linéaire)
- opérations NUC et BPR

$s_i = a_i \phi + b_i$ $a_i = \text{gain}$
 $b_i = \text{offset}$

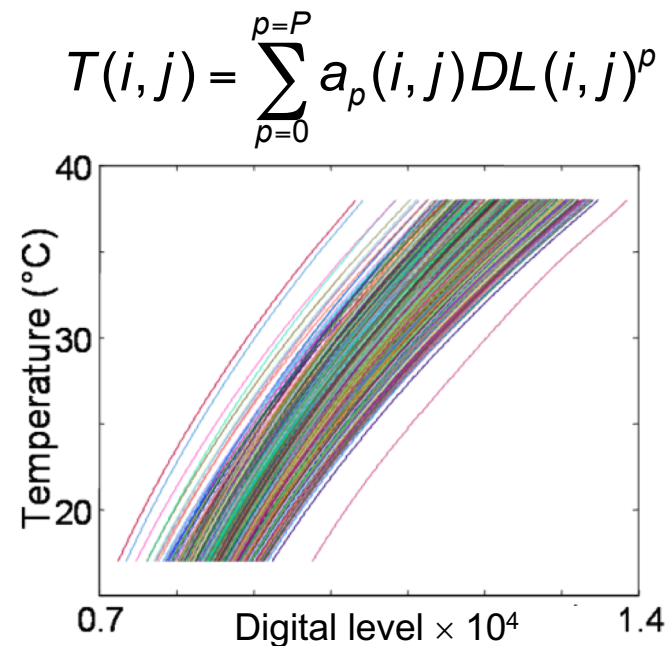
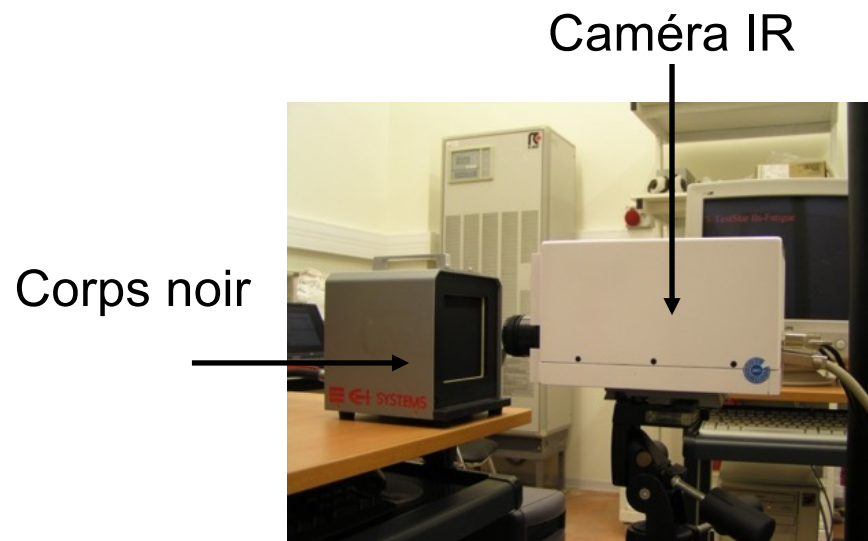


Nb pixels défectueux = 255, soit 0.29%
 $T_{cn} = 34^\circ \text{ C}$

Etalonnage : laboratoire

Calibration pixel à pixel [Honorat et al., QIRT 2005]

- nécessité d'1 corps noir plan (20 mK) + 30 k€ (+ 40-120 k€ de caméra !)
- stabilité thermique de la caméra (4-5 h) et de la salle d'essai ...
- étalonnage pixel à pixel (polynôme de degré 5)
- précision 20 mK et plus de remplacement de «bad pixel»
- à refaire dès que l'on modifie un paramètre (temps d'intégration, taille des images, objectif, ...)



Estimation des sources de chaleur

Equation de la chaleur moyennée suivant l'épaisseur d'un éprouvette mince et plate

$$\rho C \left(\frac{\partial \bar{\theta}}{\partial t} + v_x \frac{\partial \bar{\theta}}{\partial x} + v_y \frac{\partial \bar{\theta}}{\partial y} + \frac{\bar{\theta}}{\tau_{th}} \right) - k \left(\frac{\partial^2 \bar{\theta}}{\partial x^2} + \frac{\partial^2 \bar{\theta}}{\partial y^2} \right) = \bar{w}_h'$$

- *Estimation directe de sources en utilisant des données discrètes et bruitées*

- Le traitement d'image a évolué avec les performances des caméras

1980-90



- *Estimation d'opérateur aux dérivées partielles*

caméra mono-détecteur

- projection des données thermiques sur une solution spectrale analytique (1990)

caméra à matrice de détecteur

- outils de Fourier, filtrage convolutif, prolongement périodique (2000)
- lissage local par moindres carrés (2004)
- POD: préfiltrage des données thermiques (1D : 2014 - 2D : 2017)

Main refs:
 IJES : 2000
 EXP-MECH : 2007
 JoMMS : 2010
 EXP-MECH : 2014
 QIRT : 2017



Thm analysis of a monotonous tensile test on steel

[AC et al., JoMMS, 2009] from slide #21 to #34

❖ Material - sample

- IF TI steel (Arcelor-Mittal)
- steel generally used in metal forming (deep drawing)

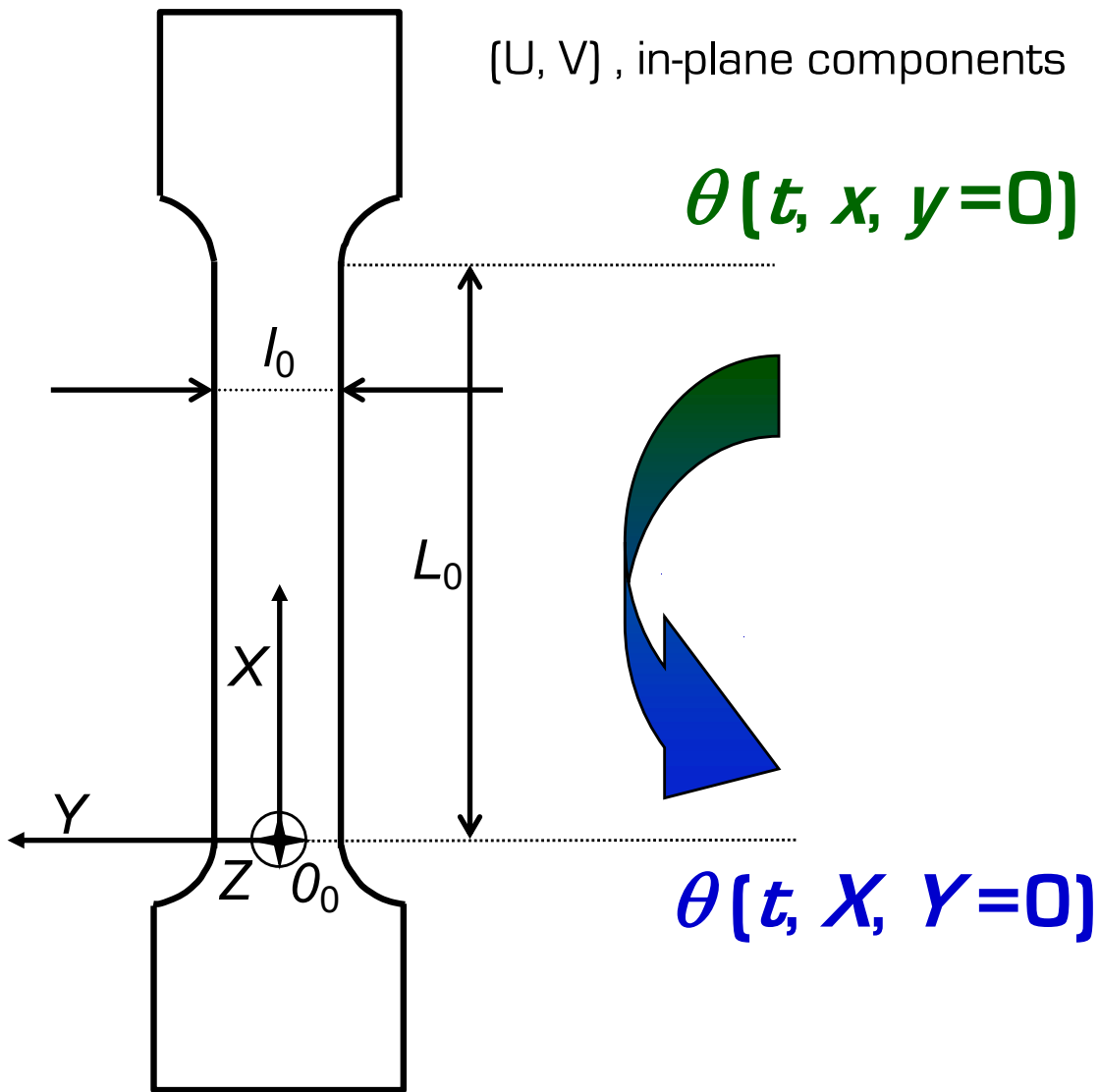
	C	Mn	P	S	Si	Al	N	Ti
% (w)	0.003	0.15	0.007	0.007	0.007	0.02	0.003	0.06

- $\rho = 7800 \text{ kg.m}^{-3}$, $C = 480 \text{ J.kg}^{-1}.\text{°C}^{-1}$, $k = 60 \text{ W.m}^{-1}.\text{°C}^{-1}$
- thin flat samples: $50 \times 12.5 \times 0.3 \text{ (mm}^3\text{)}$

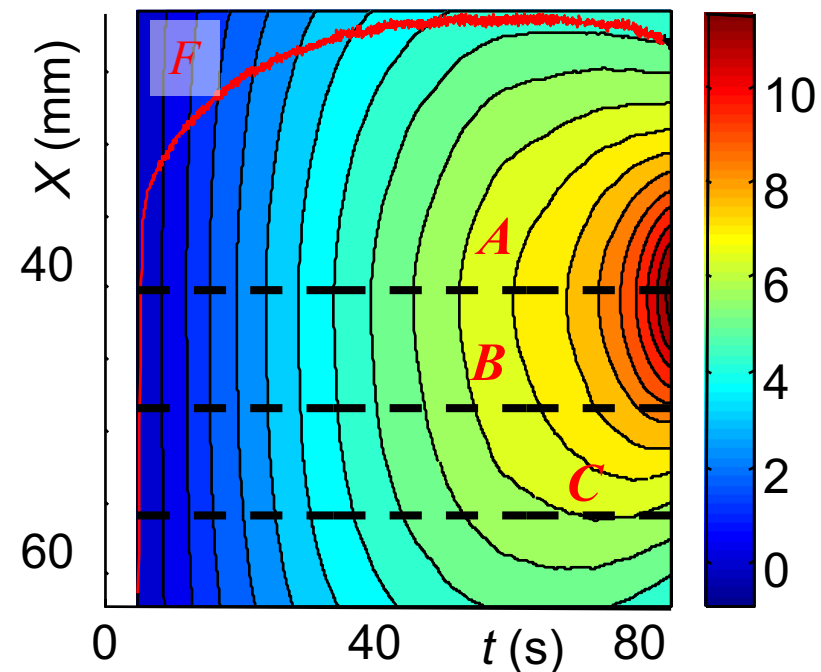
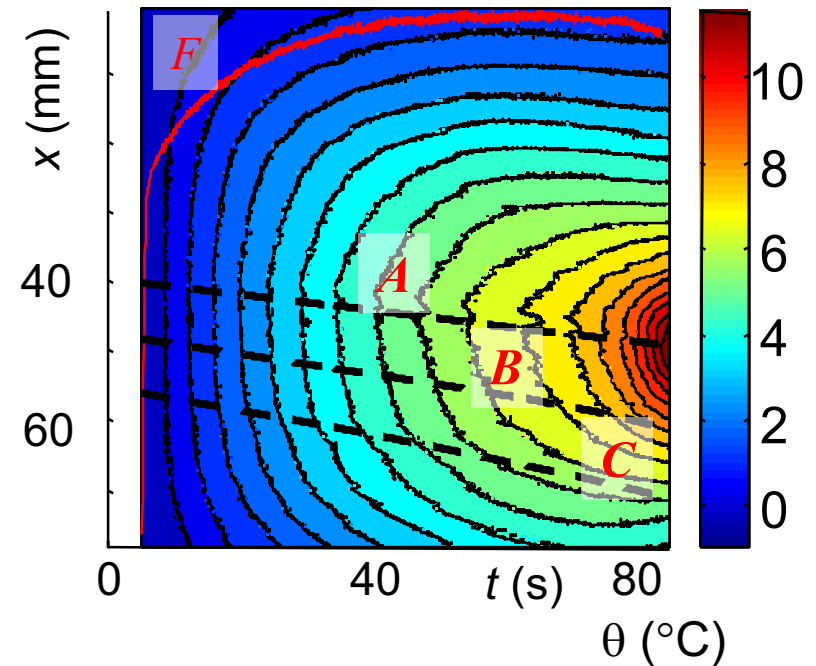
❖ Test

- quasi-static loading test
- displacement-controlled: $250 \mu\text{m s}^{-1}$ (5.10^{-3} s^{-1})
- room temperature: $T_0 = 300 \text{ K}$
- kinematic and thermal data processing : local least squares fitting

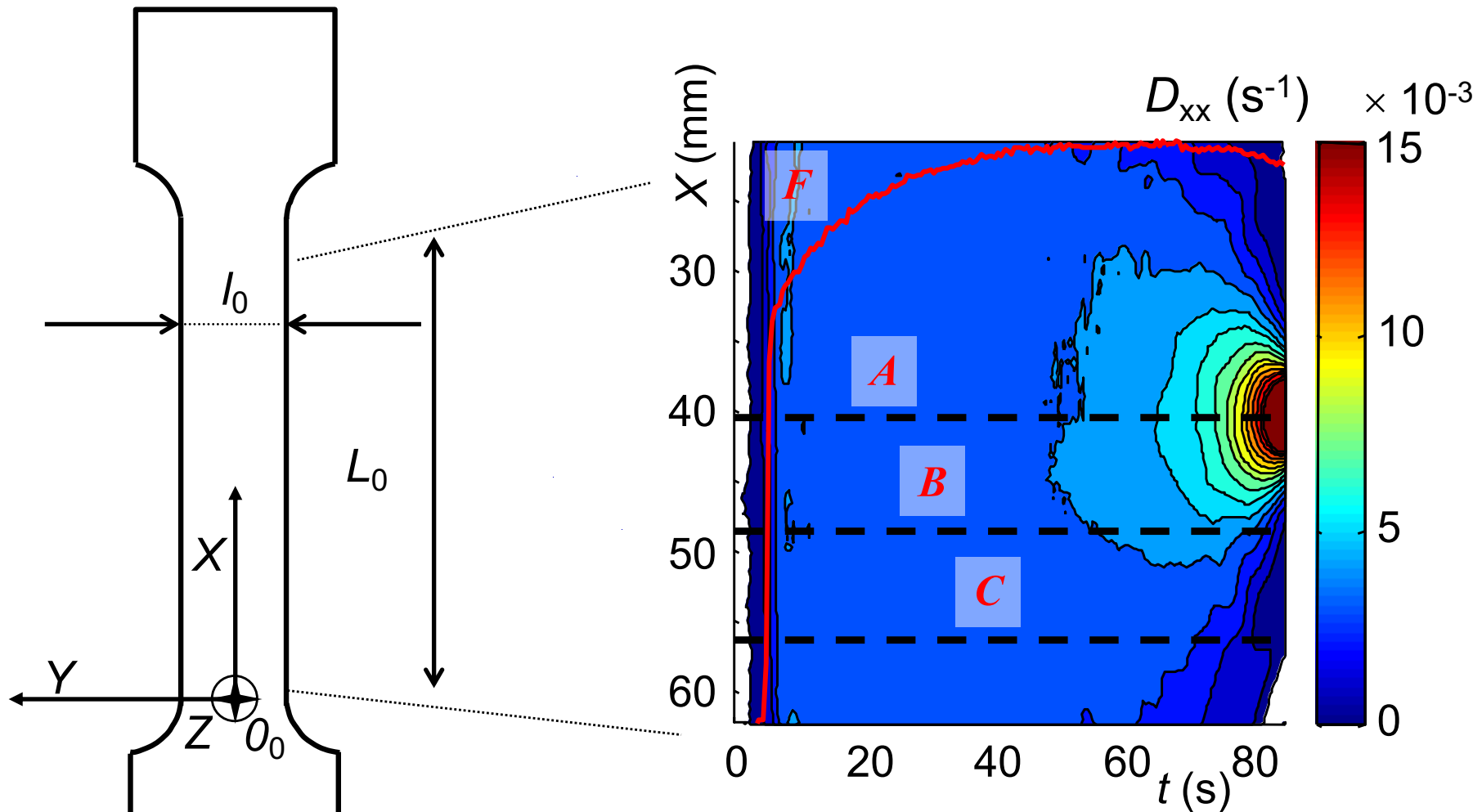
Thermoprofiles



*A, B, C, 3 material surface elements
Progressive concentration of level curves*



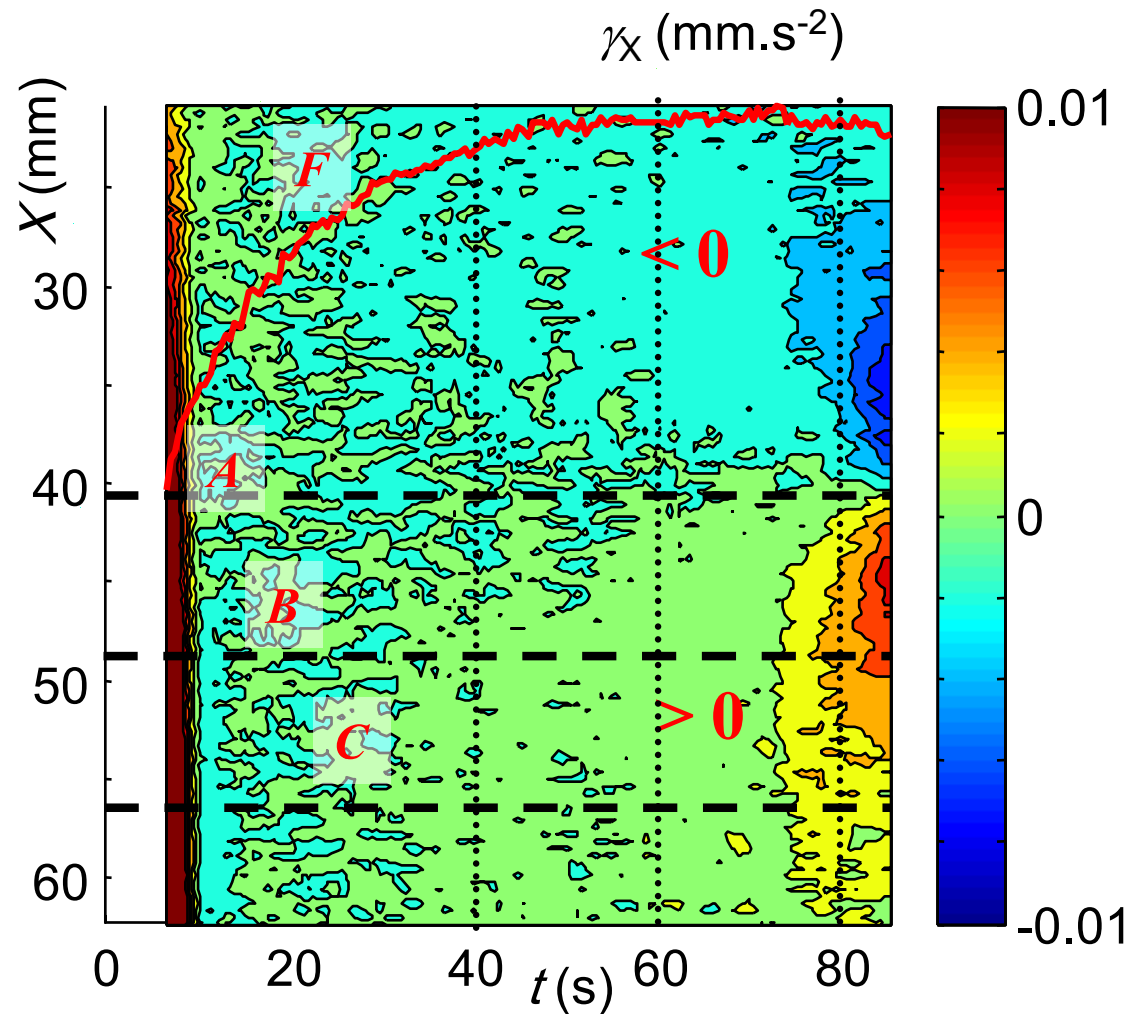
Strain rate profile $D_{xx}(t, X, Y=0)$



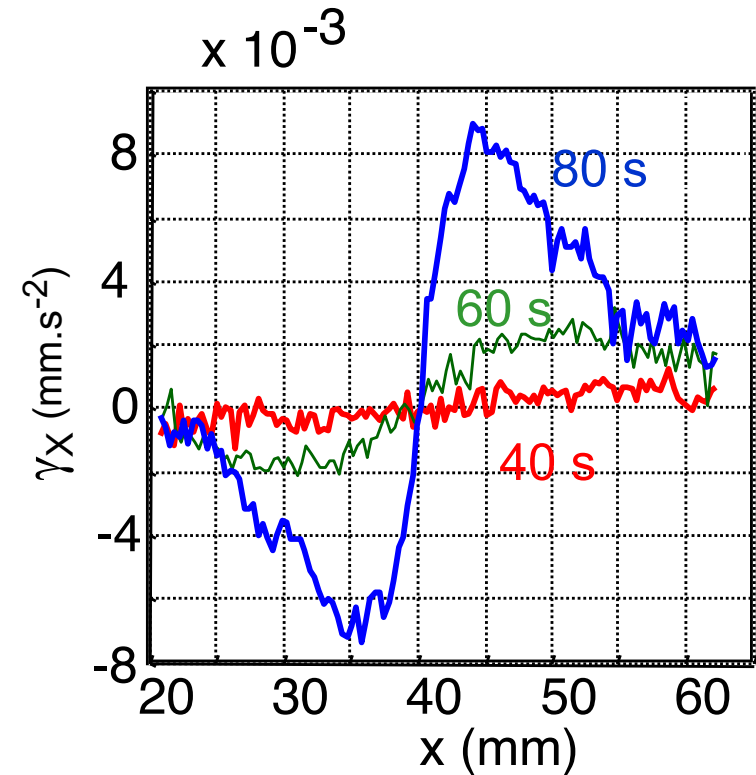
$v_0 = 250 \mu\text{m s}^{-1}$
 $\dot{\varepsilon}_c = v_0 / L_0$
 $= 5 \cdot 10^{-3} \text{ s}^{-1}$

Sample / structure
Early progressive development of localization
Progressive transition (diffuse/localized)

Acceleration field



Aziz? مكتوب, again?



Acceleration remains small [$< 10^{-4} \text{ m.s}^{-2}$]; quasi-static process
Fracture zone = zero acceleration with change of sign
Gradual transition between localized necking and fracture

$$I_\varepsilon(\varphi) = \int \nabla \varphi(t) \cdot d\mathbf{x}$$

$$\lim_{F \rightarrow \infty} W(\cdot, F) = \infty$$

Stress I: computation

$$\begin{cases} \frac{\partial \sigma_{xx}(x, y, t)}{\partial x} + \frac{\partial \sigma_{xy}(x, y, t)}{\partial y} = 0 \\ \frac{\partial \sigma_{xy}(x, y, t)}{\partial x} + \frac{\partial \sigma_{yy}(x, y, t)}{\partial y} = 0 \end{cases}$$

$$\sigma_{xx}(x, t) = \frac{f(t)}{S_0} \exp(\varepsilon_{xx}(x, t))$$

$$\sigma_{xy}(x, y, t) = -\sigma_{xx}(x, t) \frac{\partial \varepsilon_{xx}(x, t)}{\partial x} y$$

$$\sigma_{yy}(x, y, t) = \frac{\partial}{\partial x} \left(\frac{\sigma_{xx}(x, t)}{2} \frac{\partial \varepsilon_{xx}}{\partial x} \right) \cdot \left(\frac{l(x, t)^2}{4} - y^2 \right)$$

quasi-static process (!)

plane stress (?)

uniform distribution (?)

ε_{xx} y-independent (!)

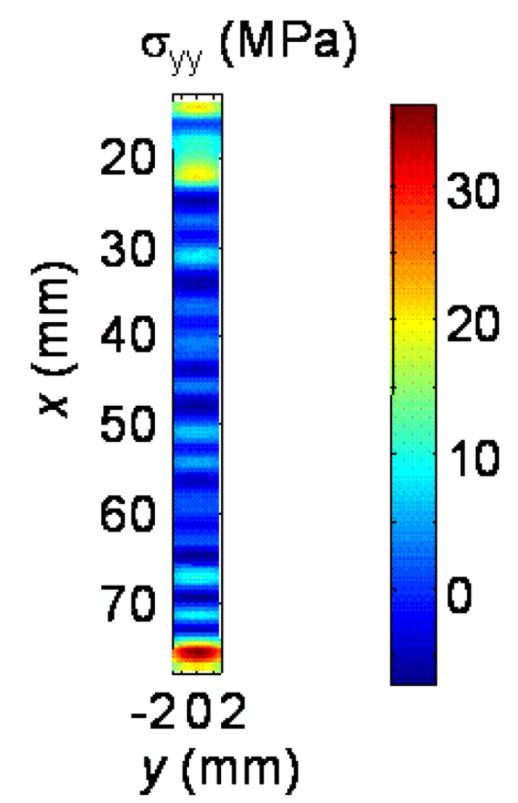
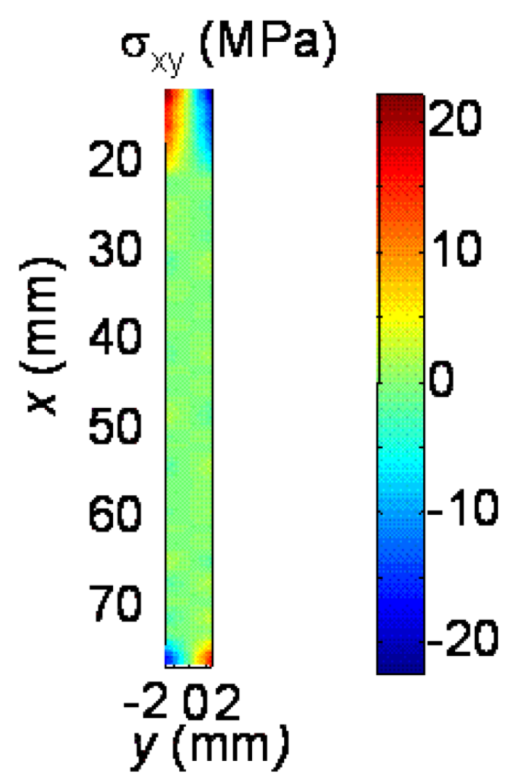
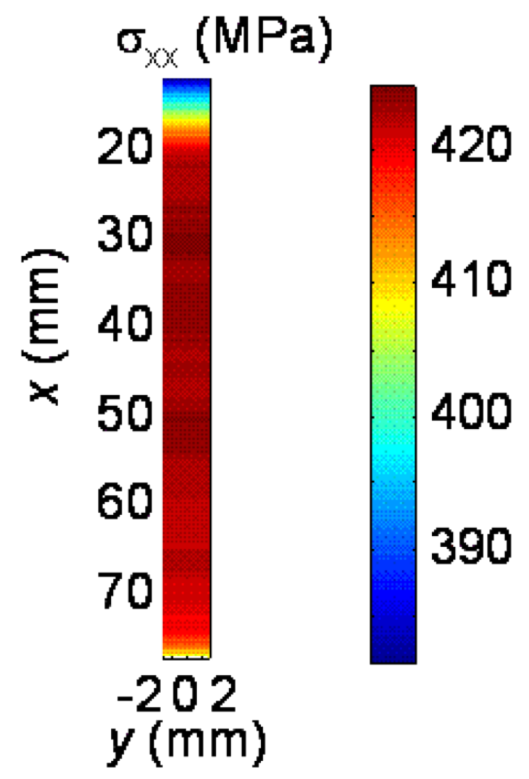
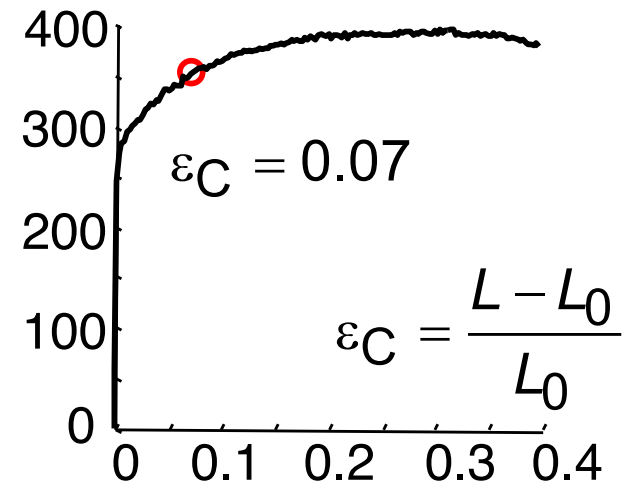
$\varepsilon_{yy}(x, y, t) \approx \varepsilon_{yy}(x, -y, t)$ (!)

no overall shear force (?)

lateral surfaces: free
of normal stresses (!)

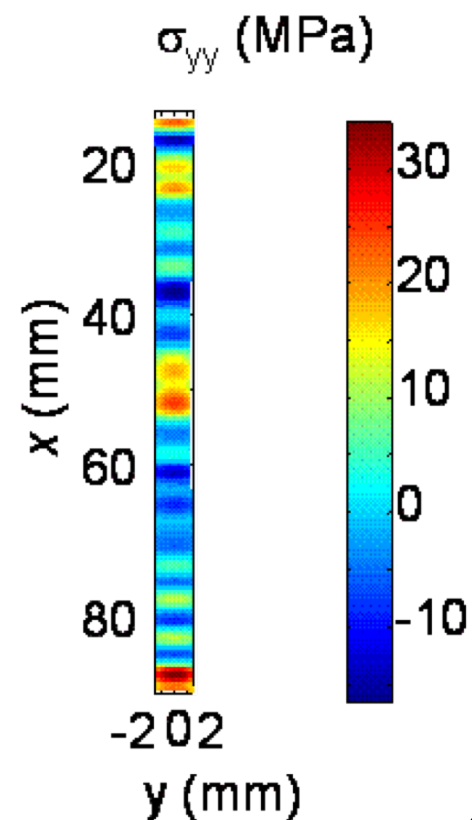
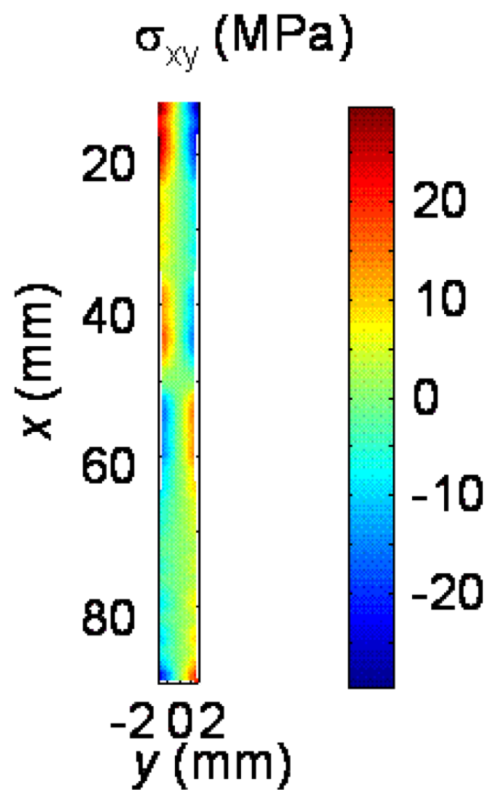
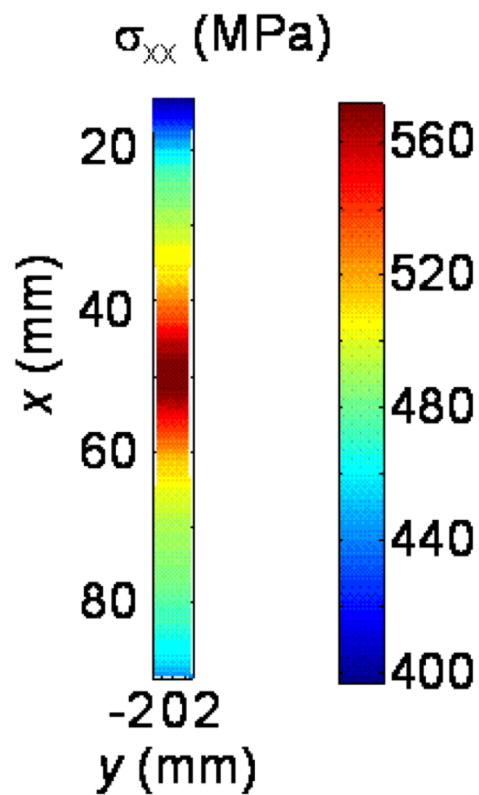
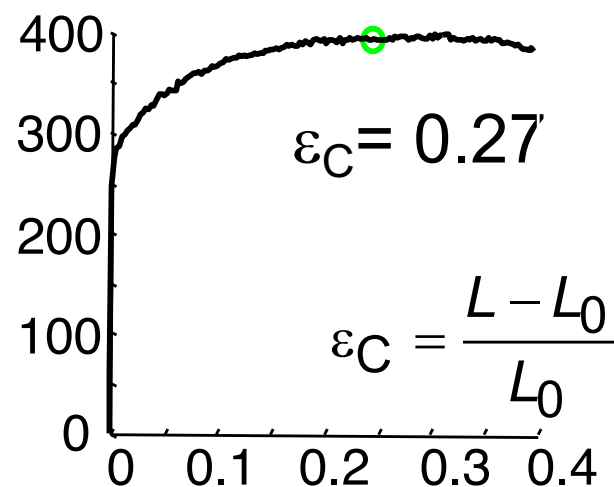
Stress II : patterns

$$\sigma_C = \frac{F}{S_0} \text{ (MPa)}$$

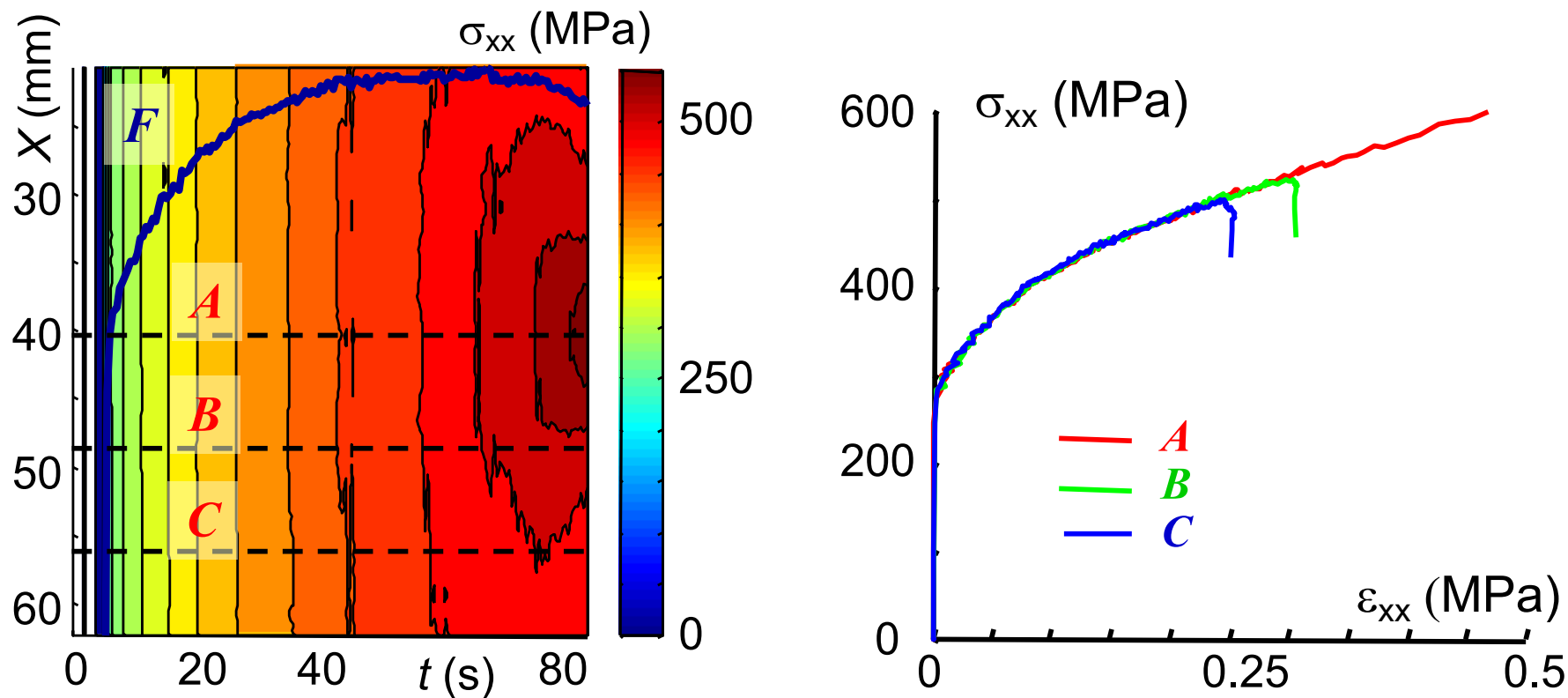


Stress III: patterns

$$\sigma_C = \frac{F}{S_0} \text{ (MPa)}$$

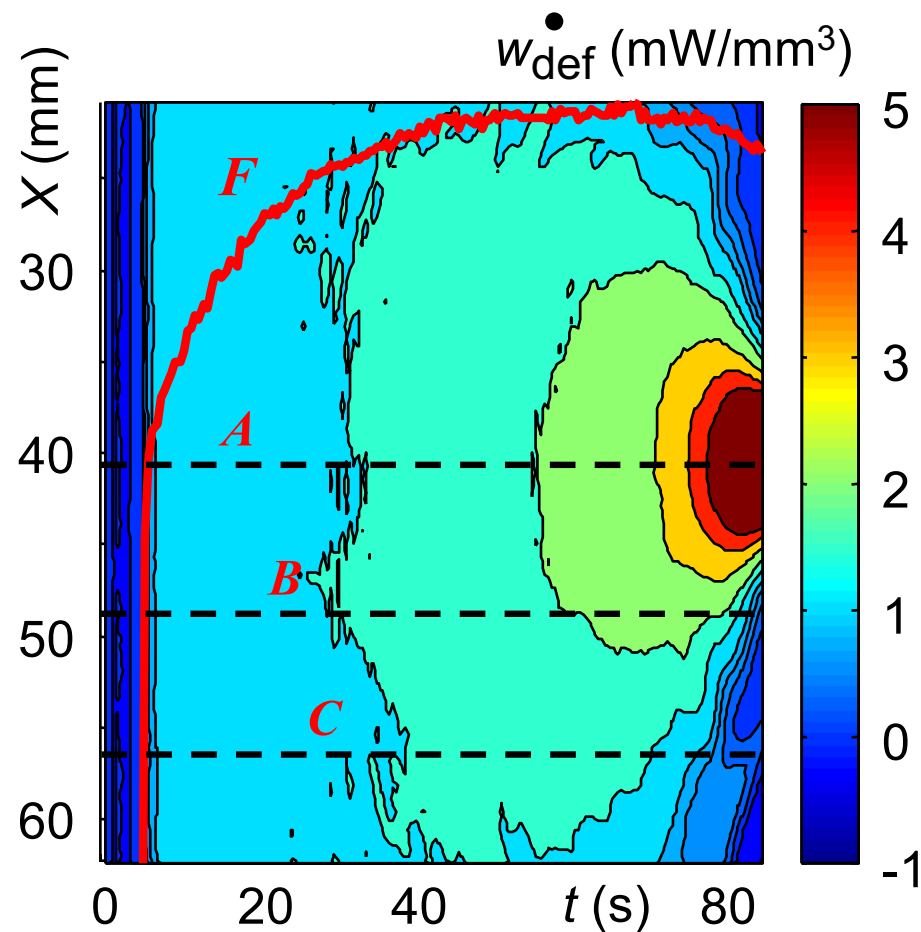
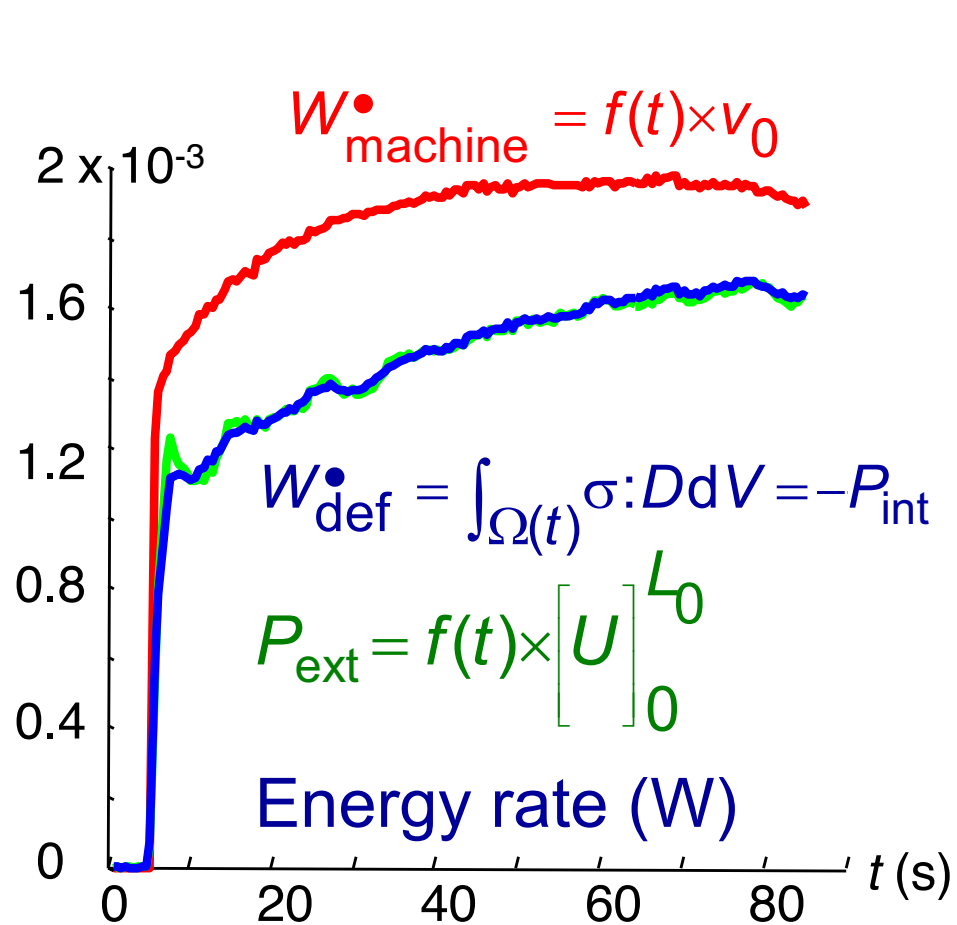


Stress III : tensile stress – stress vs strain



Sample softening = strain hardening within localization zone + elastic unloading outside this zone

Deformation energy rate



quasi-static process $\Rightarrow P_{\text{ext}} + P_{\text{int}} = 0$

elastic loading: finite stiffness of the testing machine

plastic deformation of the connection zones of the sample

Volume heat rate

$$\rho C \left(\frac{\partial \theta}{\partial t} + v_x \frac{\partial \theta}{\partial x} + v_y \frac{\partial \theta}{\partial y} + \frac{\theta}{\tau_{th}} \right) - k \left(\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} \right) = \dot{w}_h$$

1 - Time derivative: $\dot{\theta}(t,x,y) = \frac{\partial \theta}{\partial t} + v_x \frac{\partial \theta}{\partial x} + v_y \frac{\partial \theta}{\partial y} = \frac{\partial \theta(t,X,Y)}{\partial t}$

1a 1b

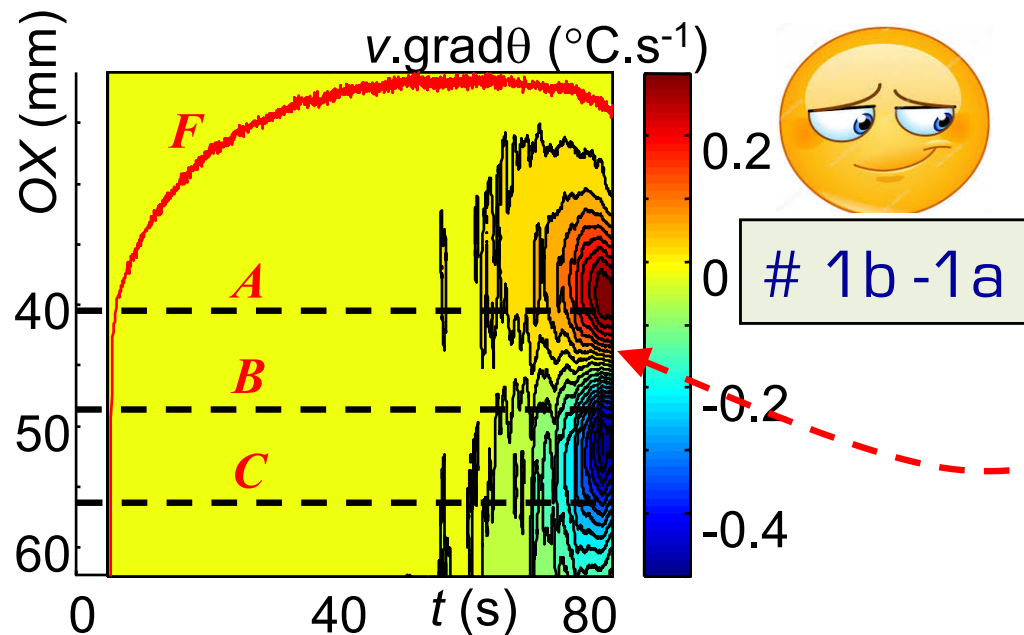
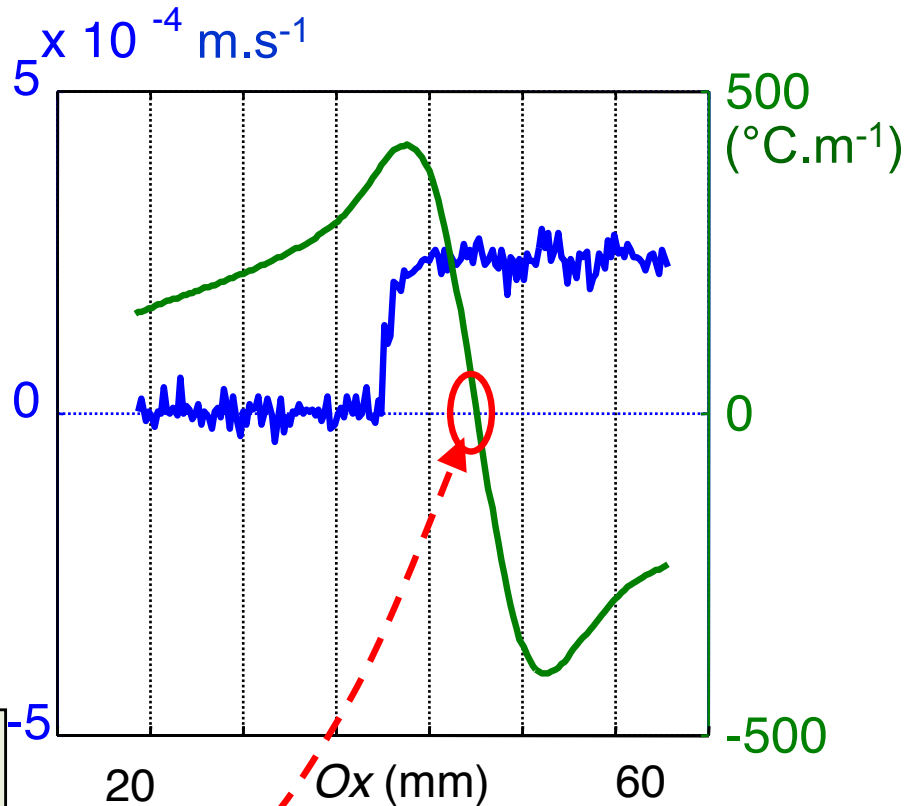
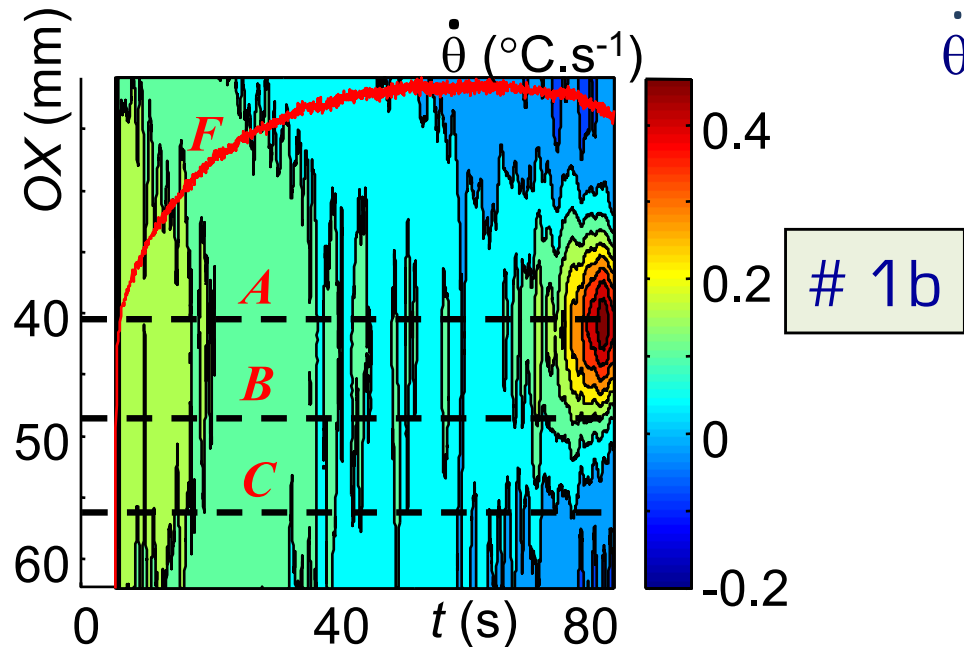
2 - Out of plane heat losses: linear heat losses - $\tau_{th} = \frac{\rho C}{2h} \left(\frac{el}{e+l} \right)$

3 - In plane heat losses by conduction - 2D Laplacian

Particular time derivative

$$\dot{\theta}(t,x,y) = \frac{\partial \theta}{\partial t} + v_x \frac{\partial \theta}{\partial x} + v_y \frac{\partial \theta}{\partial y} = \frac{\partial \theta(t, X, Y)}{\partial t}$$

1a
1b

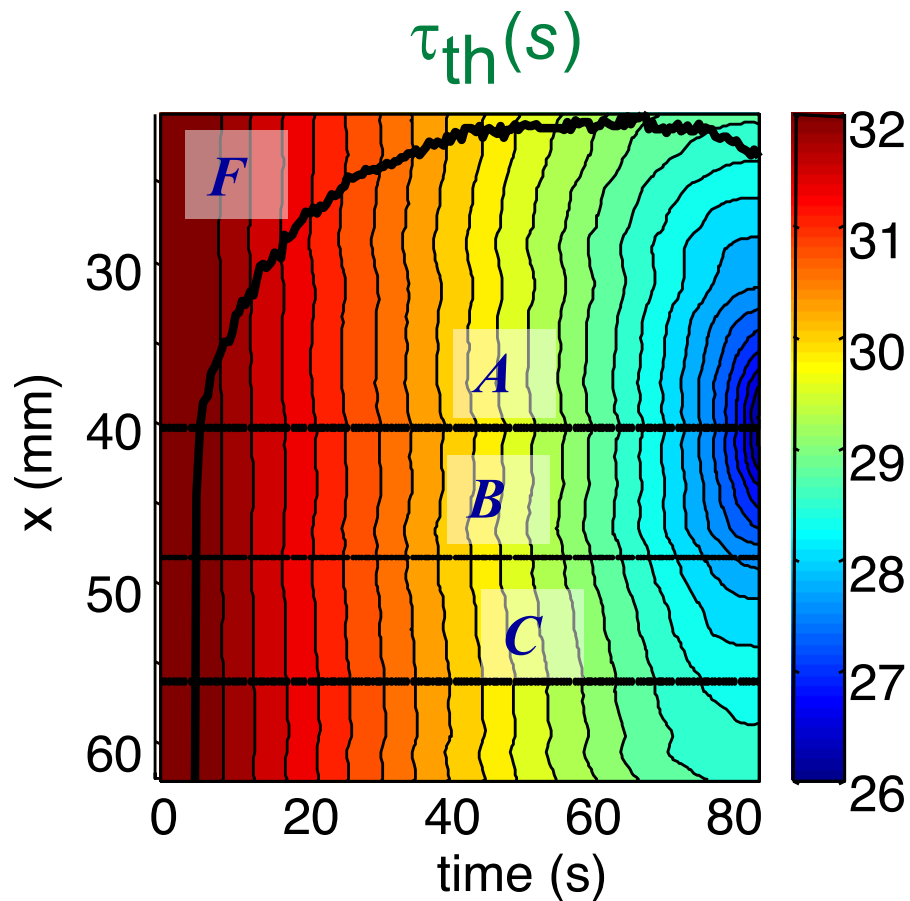


Convective terms are not negligible!

Out of plane heat losses – time “constant”



$$\theta/\tau_{th}$$

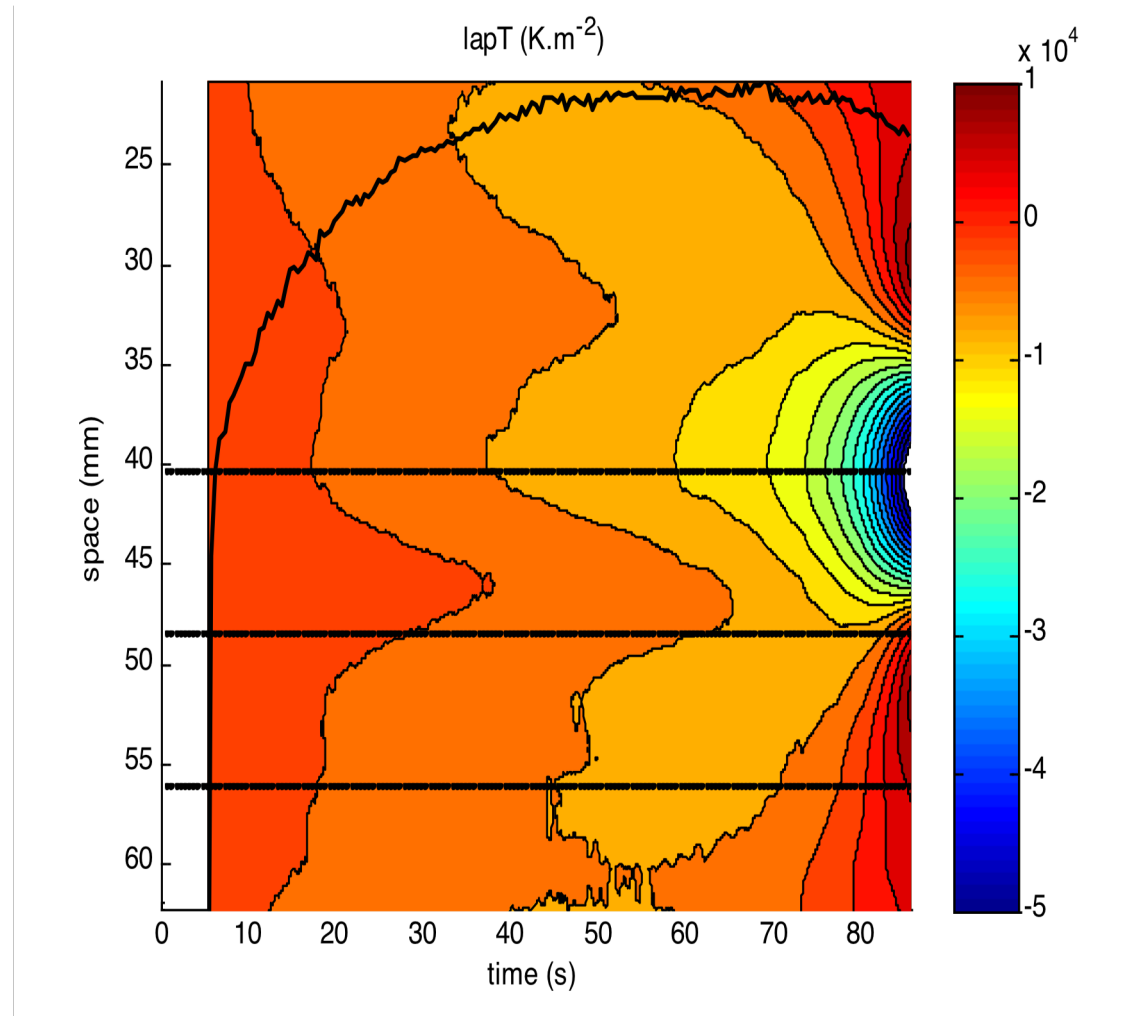


Significant geometrical effects induced by necking

Laplacian assessment



$$\Delta_{xy} \theta$$

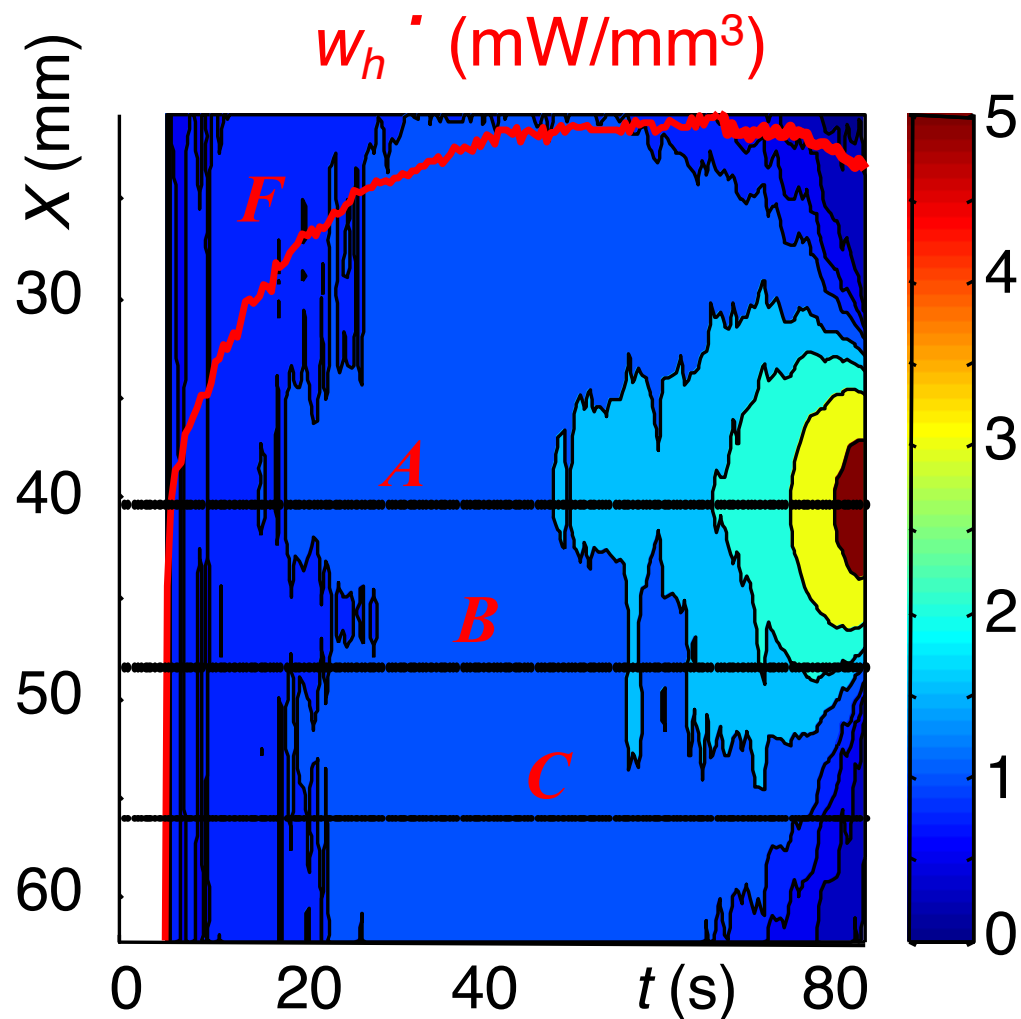


Significant geometrical effects induced by necking

Overall heat source



Qualitatively !



Quantitatively ?!

- ρ, C, k, τ_{th}
- SNR
- data processing
- POD ?!

gradual concentration of level curves

Proper Orthogonal Decomposition ... some words

- Applications** : réduction de model, turbulence, compression de données, ...
 Hotelling [1933], Karhunen [1946], Loève [1955]
- Intérêts** : Approcher un système de grande dimension, par un autre, de dimension significativement plus petite
 Déterminer une base de modes propres orthogonaux représentatifs des “réalisations les plus probables”

Images thermiques :

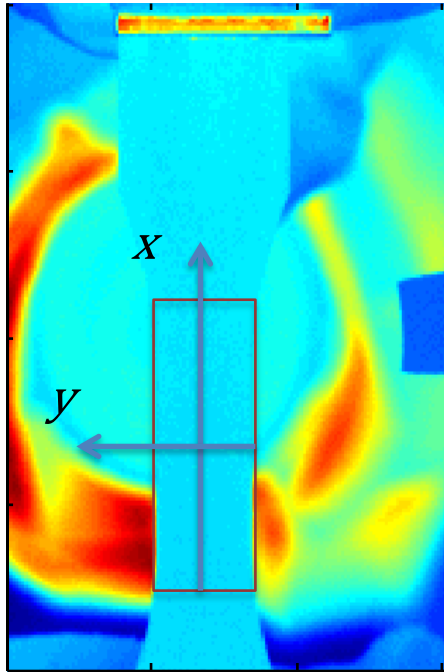
$$\vartheta(x_i, y_j, t_k) \simeq \sum_{p=1}^P a_p(t_k) \Phi_p(x_i, y_j)$$

où les composantes $\Phi_p(x_i, y_j)$ sont les modes propres orthogonaux (POM), “vecteurs” propres de la matrice des “clichés” [“snapshots”].

$$A = \Theta \Theta^T$$

$$A \tilde{\Phi}_p = \omega_p \tilde{\Phi}_p$$

Benchmark test : a penalizing case



- 2D heat diffusion problem (averaged over the thickness)

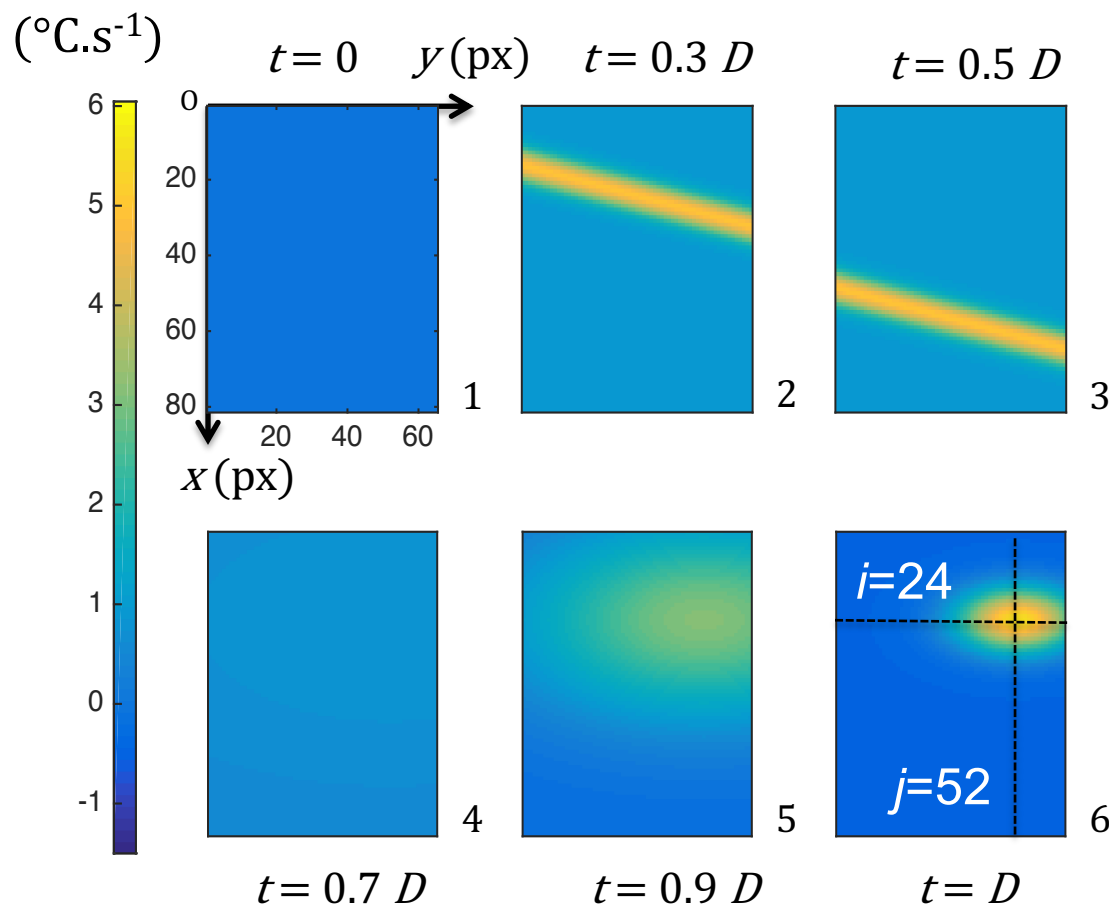
$$\begin{cases} \rho C \left(\frac{\partial \bar{\vartheta}_i(x, y, t)}{\partial t} + \frac{\bar{\vartheta}_i(x, y, t)}{\tau_{th}^{2D}} \right) - k_c \left(\frac{\partial^2 \bar{\vartheta}_i(x, y, t)}{\partial x^2} + \frac{\partial^2 \bar{\vartheta}_i(x, y, t)}{\partial y^2} \right) = \bar{s}^h(x, y, t), \\ \frac{\partial \bar{\vartheta}_i}{\partial x} \left(\pm \frac{L}{2}, y, t \right) = \mp \lambda_x \bar{\vartheta}_{i \pm \frac{L}{2}} \left(\pm \frac{L}{2}, y, t \right), \quad \frac{\partial \bar{\vartheta}_i}{\partial y} \left(x, \pm \frac{l}{2}, t \right) = \mp \lambda_y \bar{\vartheta}_{i \pm \frac{l}{2}} \left(x, \pm \frac{l}{2}, t \right) \\ \bar{\vartheta}_i(x, y, 0) = 0 \end{cases}$$

- Domain : $-L/2 \leq x \leq L/2, -l/2 \leq y \leq l/2, 0 \leq t \leq D$

- Material of high thermal diffusivity (pure copper : $10^{-4} \text{ m}^2/\text{s}$)
- High longitudinal heat exchange coefficient ($\lambda_x = 170 \text{ W/m/K}$)
- Noise superimposition (rnd / $\delta\theta = 70 \text{ mK}$)
- Complex heat source distribution ...

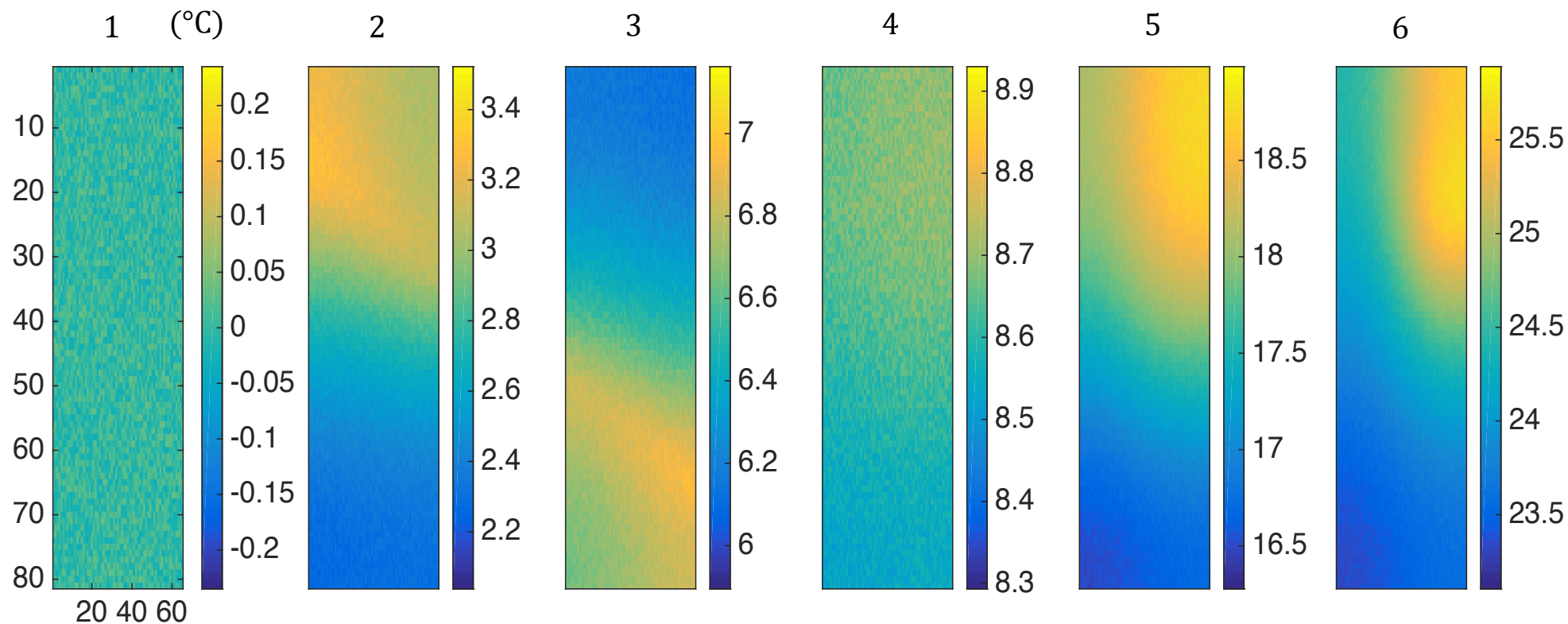
Heat source fields

- $0 \leq t \leq D$ $\bar{s}^{the} = s_0^{the} \sin(2\pi f_L t)$ cyclique coupling source
- $0.1 D \leq t \leq 0.6 D$ $\bar{s}_L^{dis} = s_L^0 \exp(-a_L [x - p_L y - v_L(t - t_L^0)]^2)$ Lüders' band
- $0.6 D \leq t \leq D$ $\bar{s}_N^{dis} = s_N^0 \tilde{t}^2 \exp(-a_N r^2(x, y) / [1 - \alpha_N \tilde{t}])$ localization



s^{the}		$(s^{dis})_L$		$(s^{dis})_N$	
s_0^{the}	1	s_L^0	4	s_N^0	6
f_L	0.05	a_L	$3e^{-3}$	a_N	$6.25e^{-6}$
		p_L	0.25	a_N	10^{-4}
		t_L^0	120		

Noisy temperature fields



$$\bar{\vartheta}_r = \bar{\vartheta}_i + N_g$$

- Peak-to-peak signal noise $N_g = 70$ mK
- Regularizing effect of heat diffusion

Lifting of the heat diffusion problem

$\bar{\vartheta}_r$ ↴

$$\bar{\vartheta}_s + \bar{\vartheta}_\ell = \bar{\vartheta}_i + N_g = \bar{\vartheta}_r$$

$$\left\{ \begin{array}{l} \rho C \left(\frac{\partial \bar{\vartheta}_\ell(x, y, t)}{\partial t} + \frac{\bar{\vartheta}_\ell(x, y, t)}{\tau_{th}^{2D}} \right) - k_c \left(\frac{\partial^2 \bar{\vartheta}_\ell(x, y, t)}{\partial x^2} + \frac{\partial^2 \bar{\vartheta}_\ell(x, y, t)}{\partial y^2} \right) = 0 \\ \bar{\vartheta}_\ell \left(\pm \frac{L}{2}, y, t \right) = \bar{\vartheta}_r \left(\pm \frac{L}{2}, y, t \right), \quad \bar{\vartheta}_\ell \left(x, \pm \frac{l}{2}, t \right) = \bar{\vartheta}_r \left(x, \pm \frac{l}{2}, t \right), \\ \bar{\vartheta}_\ell(x, y, 0) = 0, \end{array} \right.$$

↴ $\bar{\vartheta}_\ell$ →

$$\bar{\vartheta}_s = \bar{\vartheta}_r - \bar{\vartheta}_\ell$$

$$\left\{ \begin{array}{l} \rho C \left(\frac{\partial \bar{\vartheta}_s(x, y, t)}{\partial t} + \frac{\bar{\vartheta}_s(x, y, t)}{\tau_{th}^{2D}} \right) - k_c \left(\frac{\partial^2 \bar{\vartheta}_s(x, y, t)}{\partial x^2} + \frac{\partial^2 \bar{\vartheta}_s(x, y, t)}{\partial y^2} \right) = \bar{s}^h(x, y, t), \\ \bar{\vartheta}_s \left(\pm \frac{L}{2}, y, t \right) = 0, \quad \bar{\vartheta}_s \left(x, \pm \frac{l}{2}, t \right) = 0, \\ \bar{\vartheta}_s(x, y, 0) = 0, \end{array} \right.$$

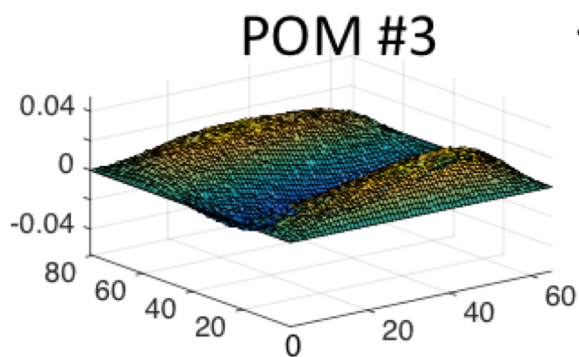
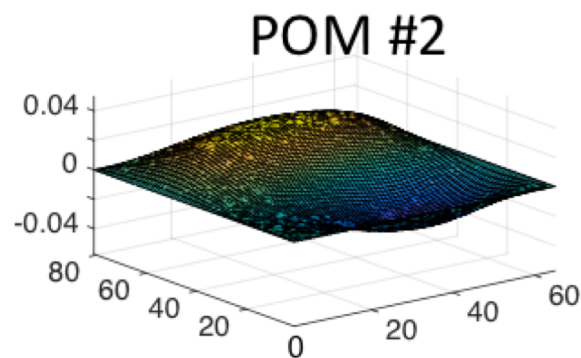
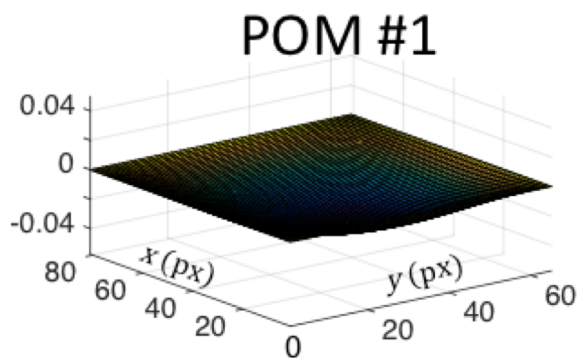
↴

POD of $\bar{\vartheta}_s$ data

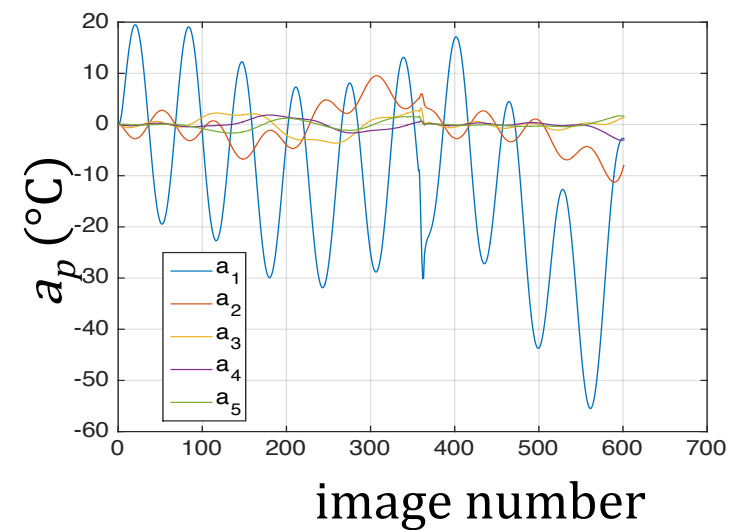
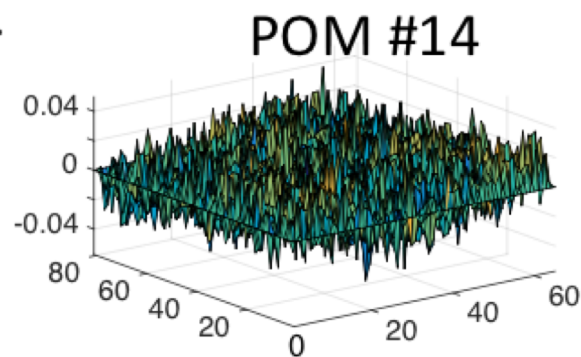
First POMs and components

$$A\tilde{\Phi}_p = \omega_p \tilde{\Phi}_p$$

$$\vartheta_{POD}(x_i, y_j, t_k) \approx \sum_{p=1}^P a_p(t_k) \Phi_p(x_i, y_j)$$

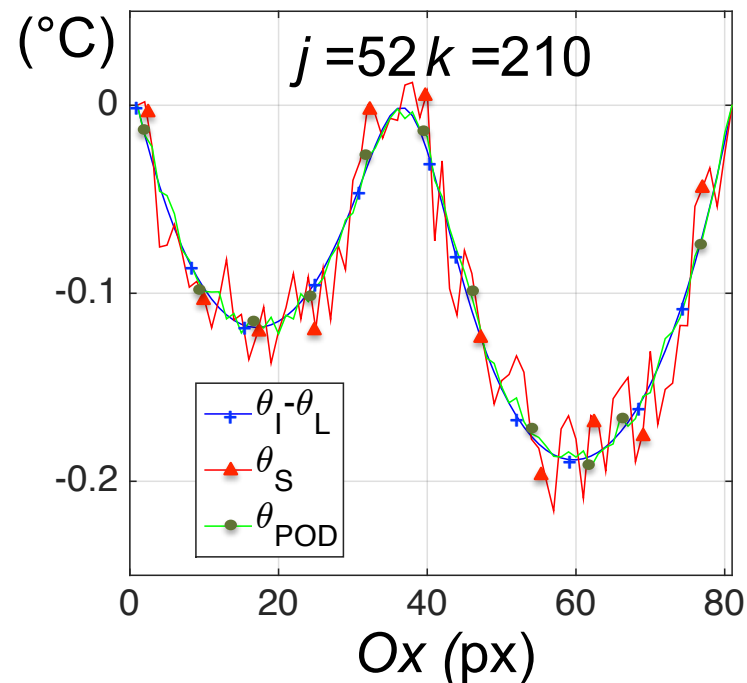
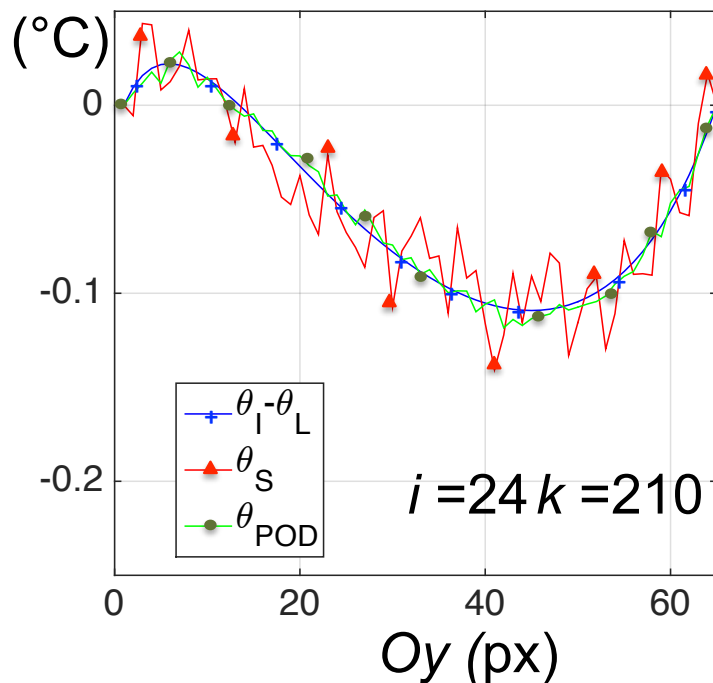


...



Examples of thermo-profile

- number of POMs = 14
- $Ng = 0.07 \times [\text{rnd}_{ij} - 0.5]$



- reduction of the noise amplitude
- curvature preservation

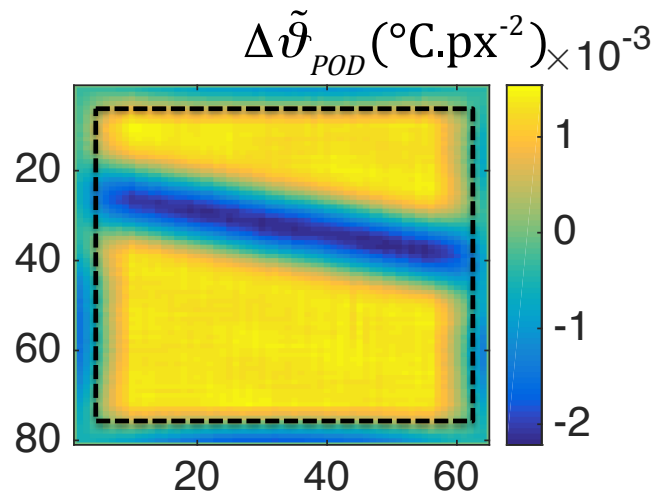
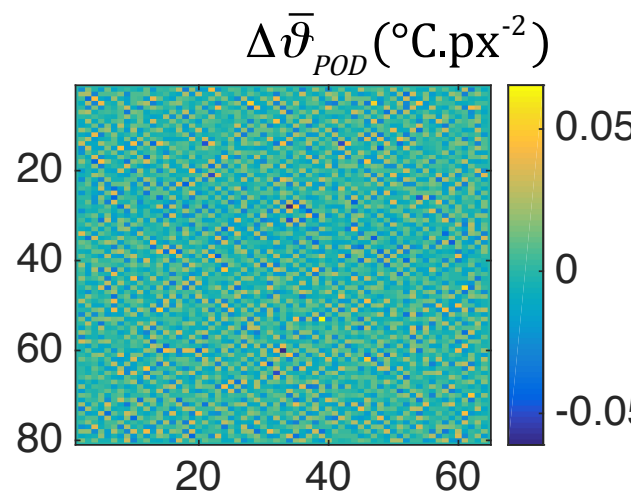
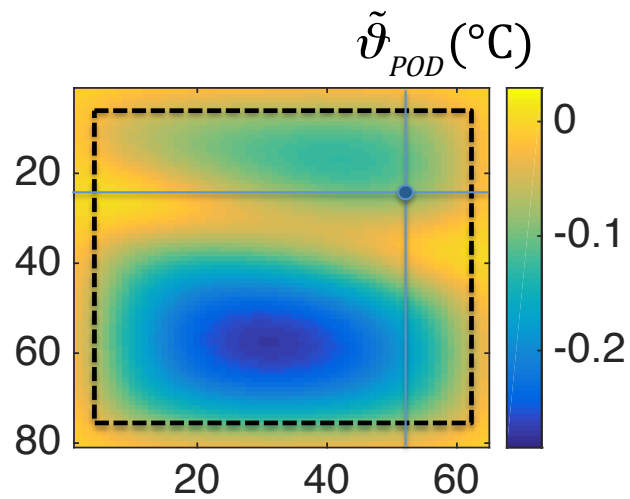
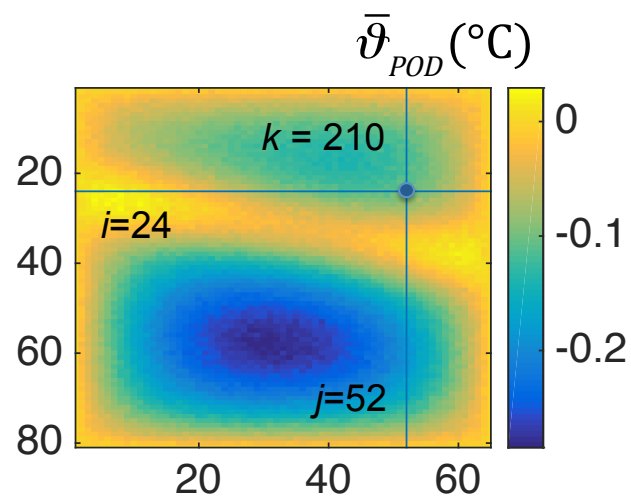
Estimations du laplacien de la température

● direct computation using a finite difference method

● «slight» 2D convolutive filtering prior to a finite difference computation

Remember !

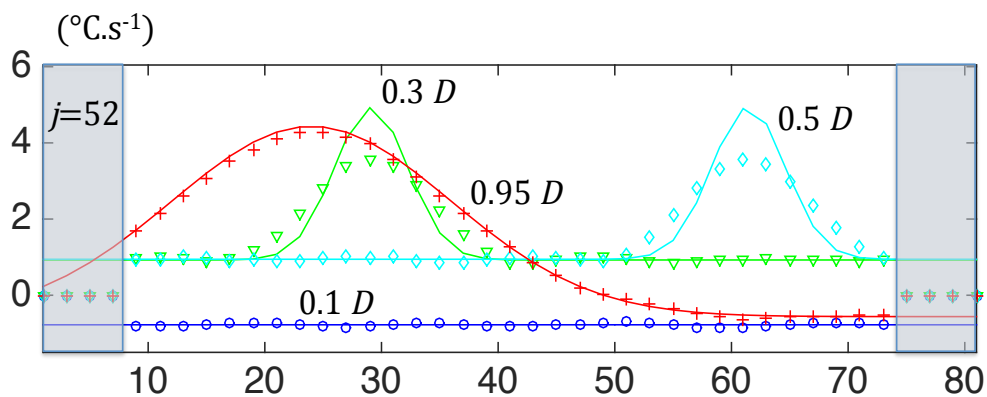
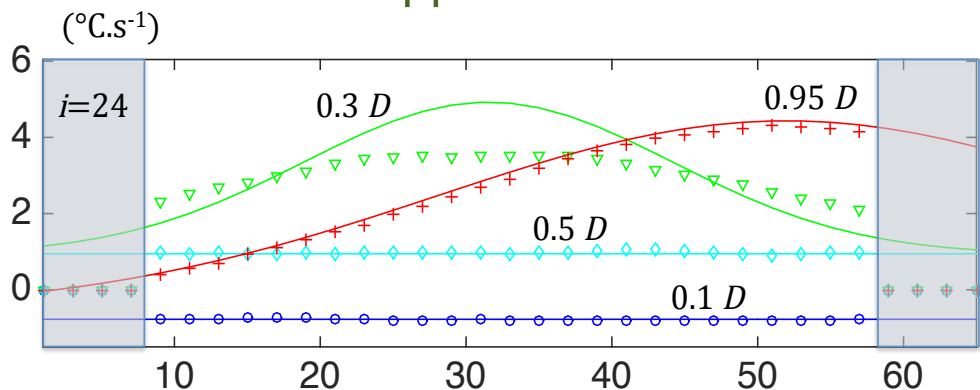
- High diffusivity
- Poor SNR
- Complex HS Distribution



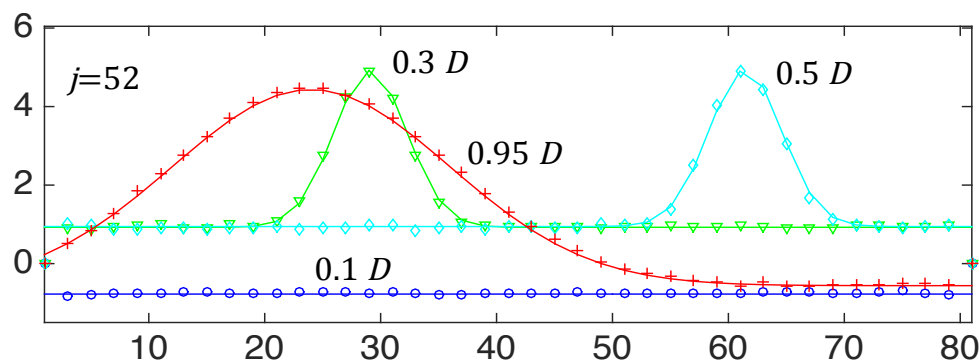
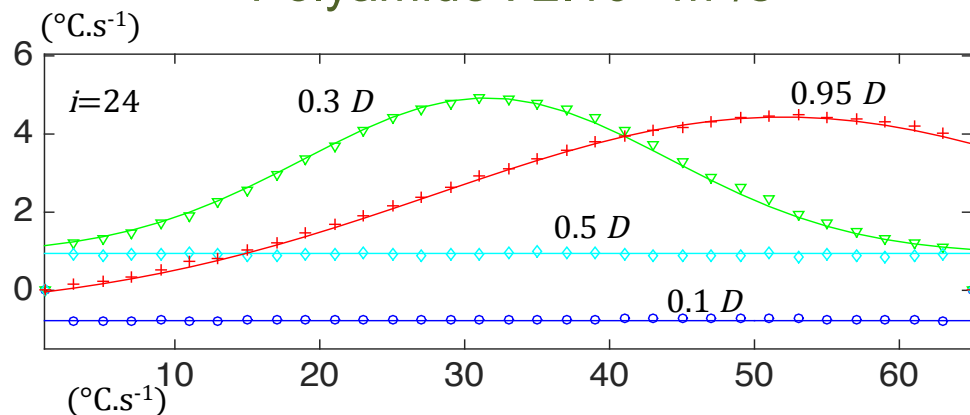
Heat source profiles

continuous lines : given sources ; symbols : reconstructed sources

Copper : $10^{-4} \text{ m}^2/\text{s}$



Polyamide : $2 \cdot 10^{-7} \text{ m}^2/\text{s}$



● High diffusivity : Slight spreading of HS concentration due to filtering!

● Low diffusivity : POD directly used. Direct estimates using FD!

$$I_\varepsilon(\varphi) = \int \sqrt{\varphi(t)} \, dt$$

LSQ vs. POD (PA6.6)

Fatigue test on short glass fiber reinforced PA 6.6
 $R_s = 0.1$, $f_L = 10$ Hz
 Mean dissipation per cycle

LSQ vs. POD : low mismatch!
 $|\delta s| \leq 10^{-2} \text{ } ^\circ\text{C.s}^{-1}$

JACKPOT : CPU times !
 POD/LSQ $\approx 10^{-3}$!
 Data : 60 Go

3 months \rightarrow 1 hour
 PC: Intel Core i7 2.5 GHz processor
 RAM: 16 GB

