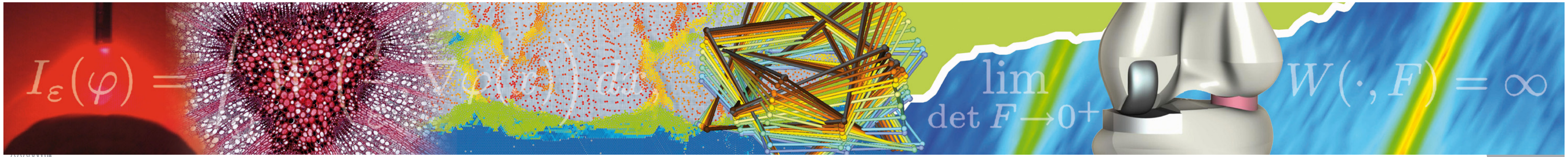

Thermodynamique des Processus Irréversibles
Quiberon, 16-22 sept. 2018

7ème école d'été de mécanique théorique

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

(2ème partie)

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LMGC, UMR 5508 CNRS-UM

LABORATOIRE DE MÉCANIQUE ET GÉNIE CIVIL - UM/CNRS

Programme

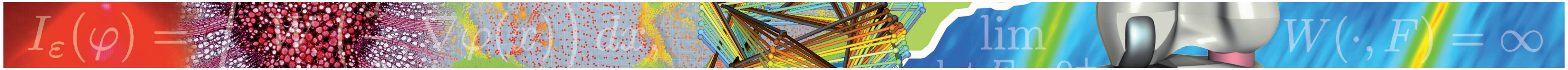
1 - Cadre thermomécanique et bilan d'énergie
(TPI-MSG)

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

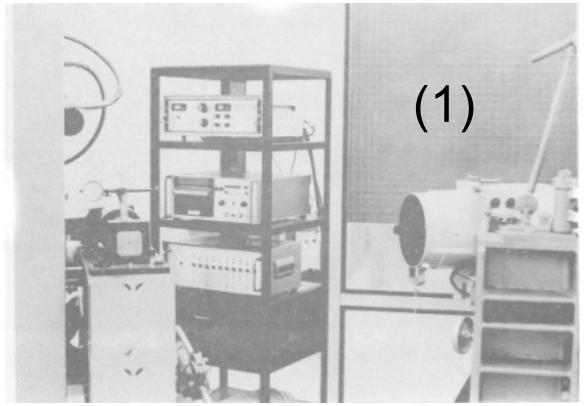
Observer les effets cinématiques, thermiques et calorimétriques accompagnant le processus de déformation.

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

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

DIC - Mechanics	IRT - Thermodynamics
- displacement fields	- temperature fields
- strain and strain rate,	- heat source (via the heat equation)
- kinetic energy rate	- intrinsic dissipation
- deformation energy rate	- coupling heat sources

Thermomécanique expérimentale



Très bref historique …

1805, Gough, caoutchouc naturel
…
1857, Joule, métaux vs. caoutchouc, µcalorimètre (a)
…
1900, Charbonnier & Galy Aché, métaux en compression + µcalorimètre
…
1933, Taylor & Quinney, 1933, métaux en torsion ➔ µcalorimètre
…
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

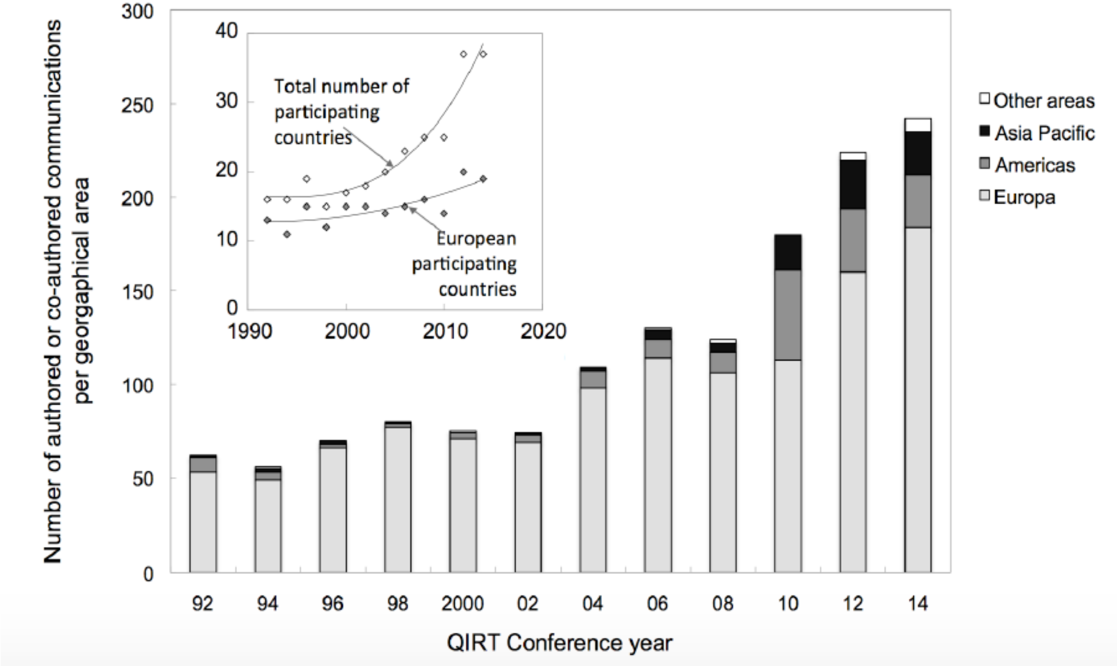
(a) (Joule, 1857) J.P. Joule, On some thermodynamic properties of solids, *Phil. Mag. 4th Ser.* **14**, p.227 (1857)

Très bref état des lieux …

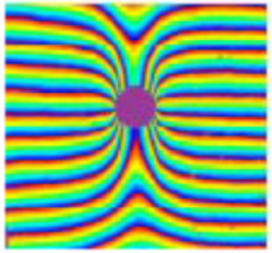
1992

QIRT

Quantitative InfraRed Thermography



2003-2014



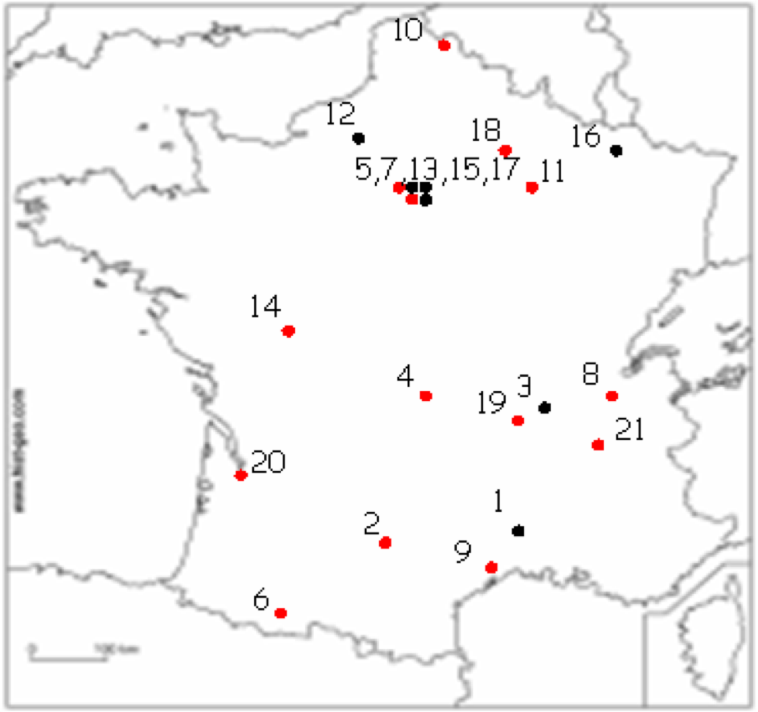
GDR CNRS 2519

MESURES DE CHAMPS

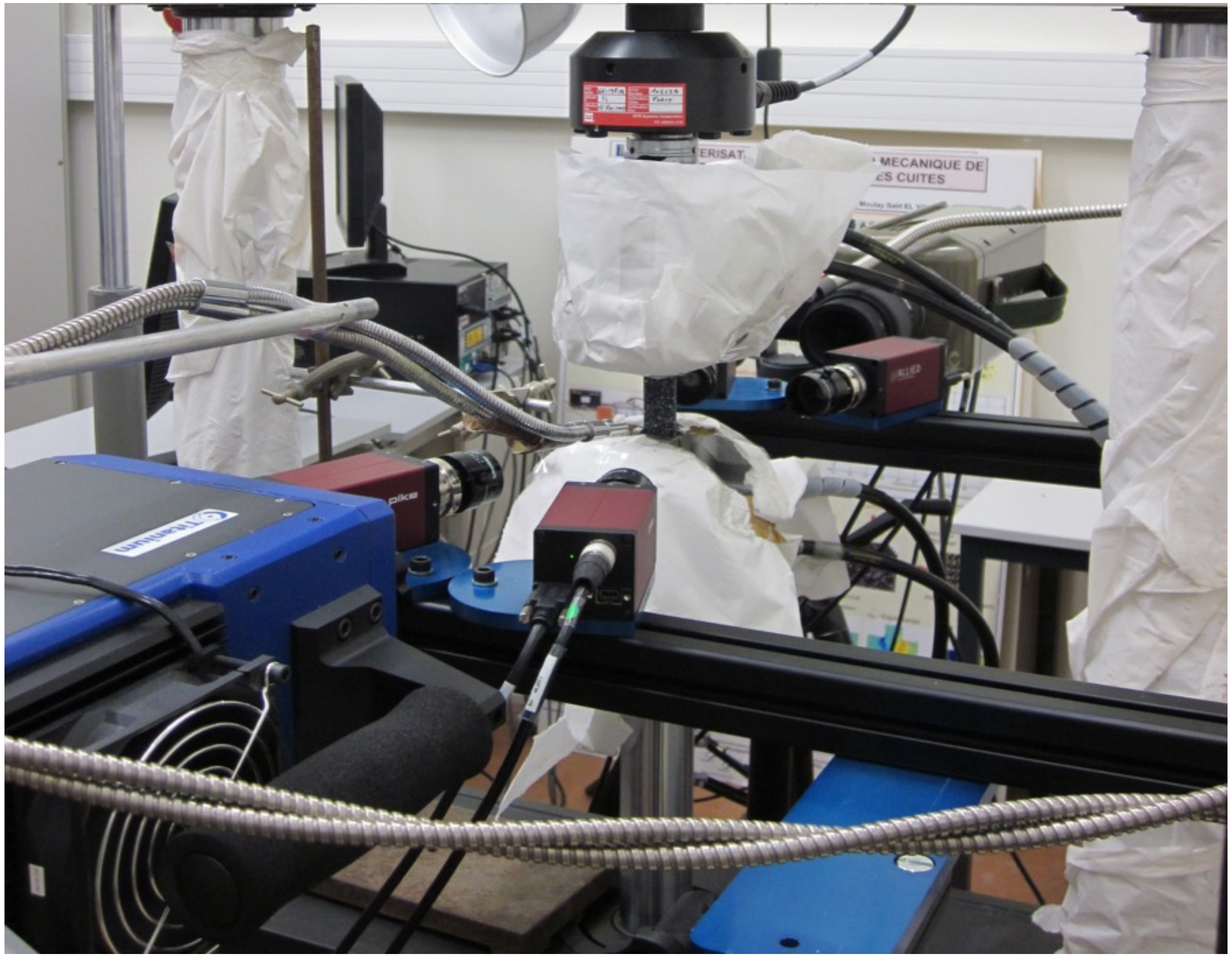
ET IDENTIFICATION EN

MECANIQUE DES SOLIDES

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

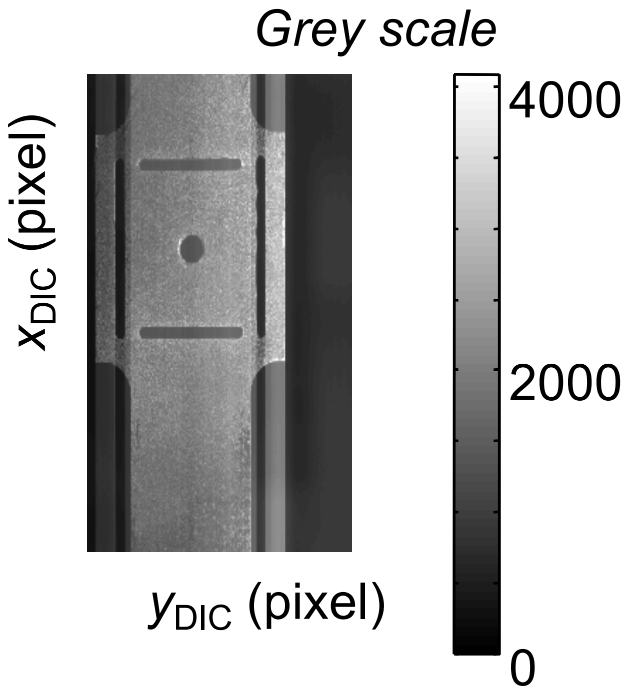
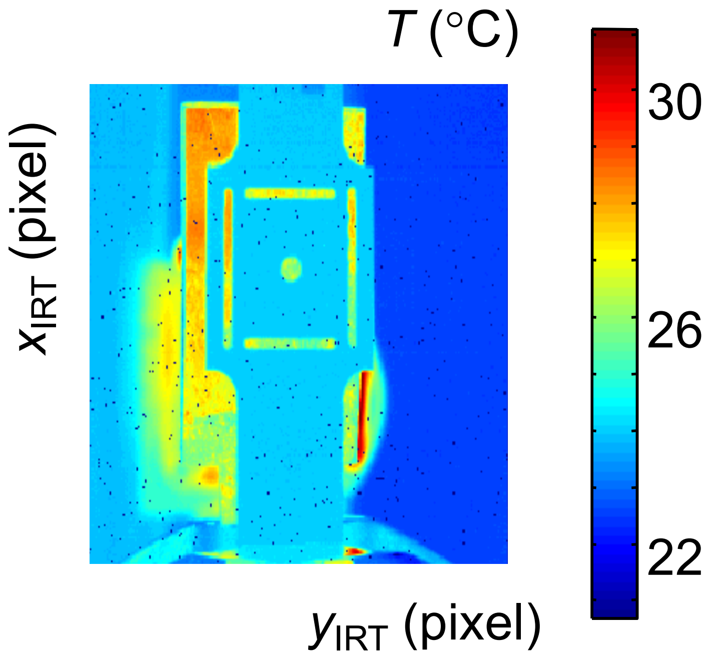


image infrarouge



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

t_{DIC} Synchrocam (*) t_{IRT}

(x_{DIC}, y_{DIC}) cible (x_{IRT}, y_{IRT})

Correspondance entre données cinématiques et thermiques

Quelques mots sur la DIC (2D)

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

Image 1

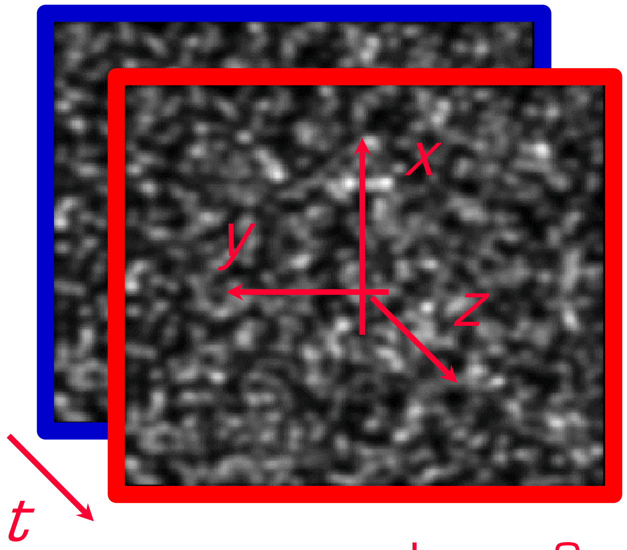
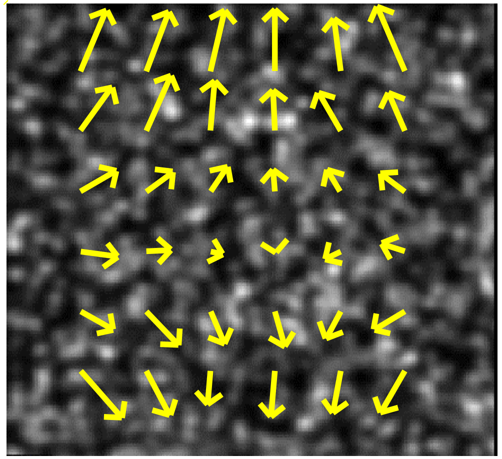


Image 2

intercorrelation

interpolation



(u_x, u_y)
in-plane components

(u_x, u_y)
+ det $F = 1$
+ *depthwize uniform strain field*

$= u_z$
out-of-plane components

fitting

derivation

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

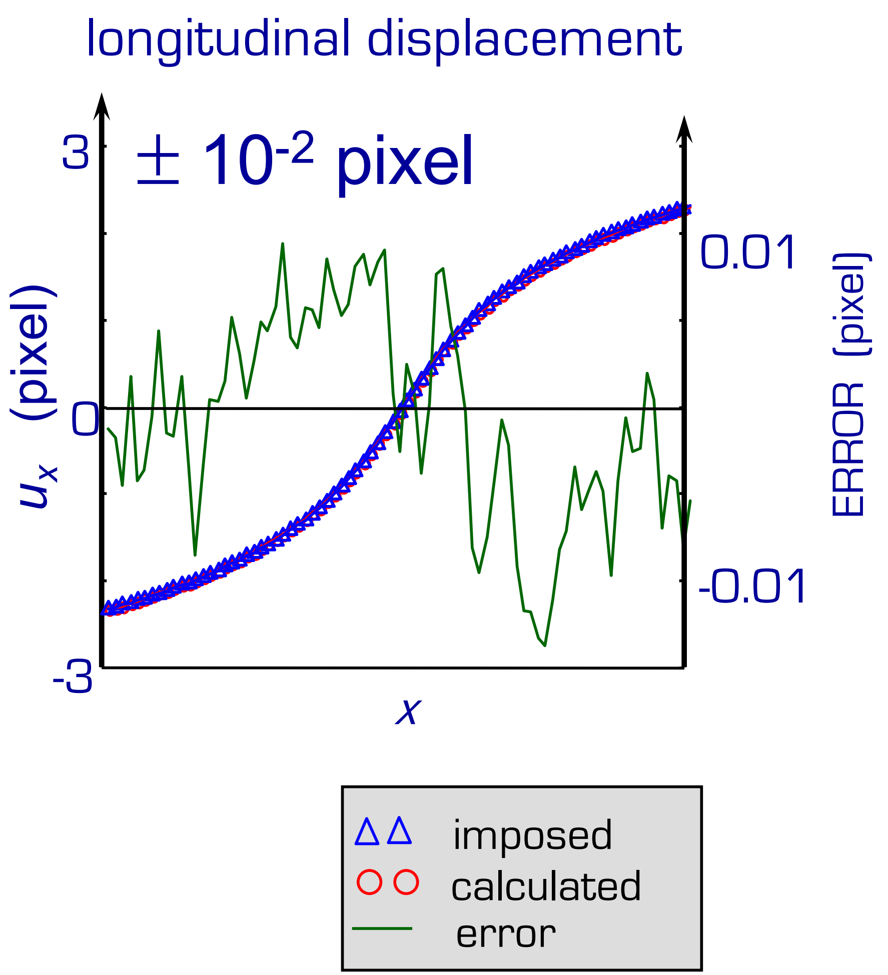
displacement gradient tensor

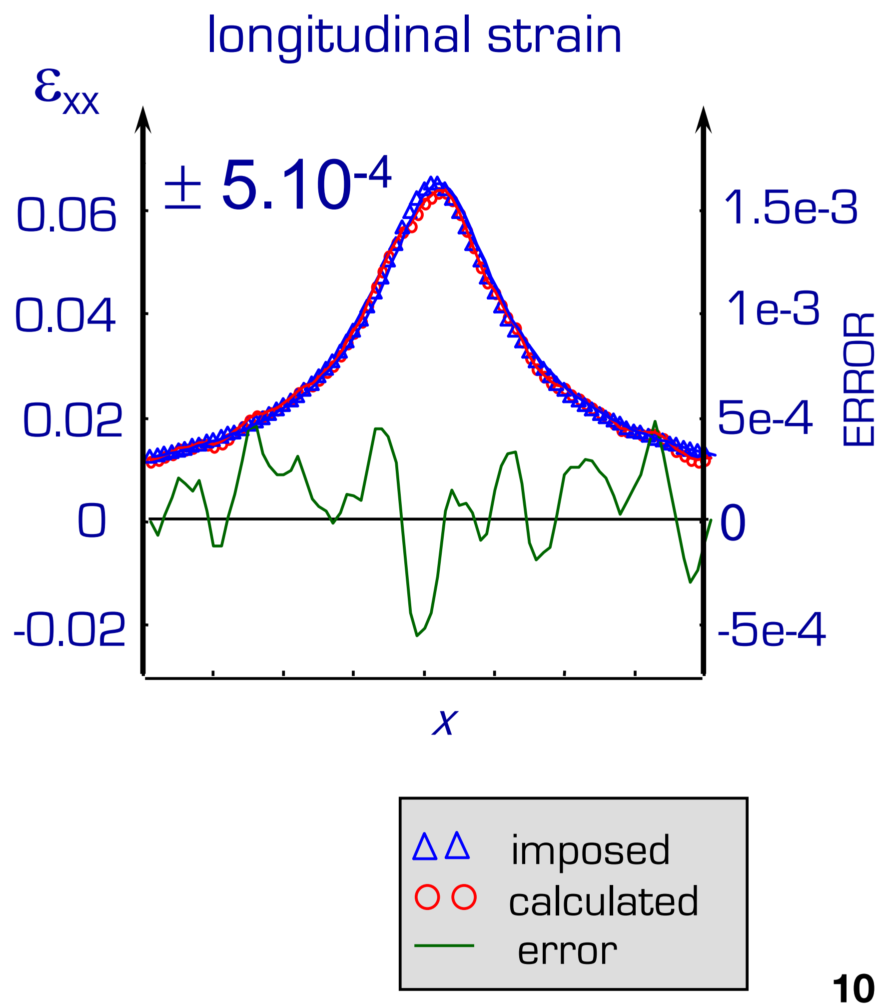
DIC (2) : précision des mesures cinématiques

Utilisation d'images de granularité « artificielles »

Champ de déplacements donné

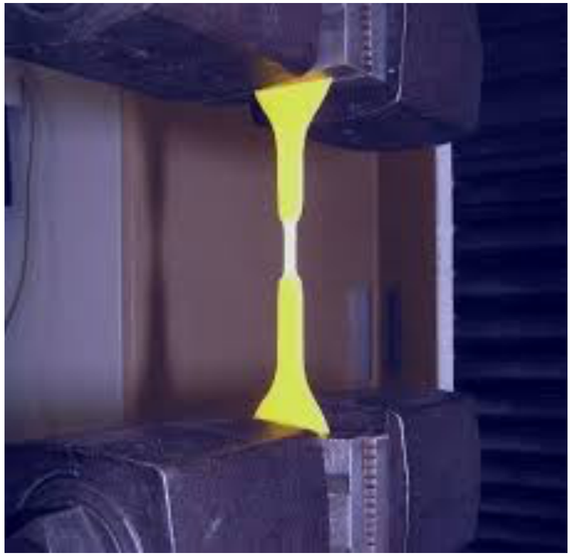
[Bornert et al., Assessment of Digital Image Correlation Measurement Errors: Methodology and Results, Exp. Mech., 2009] - Prix SEM 2011.



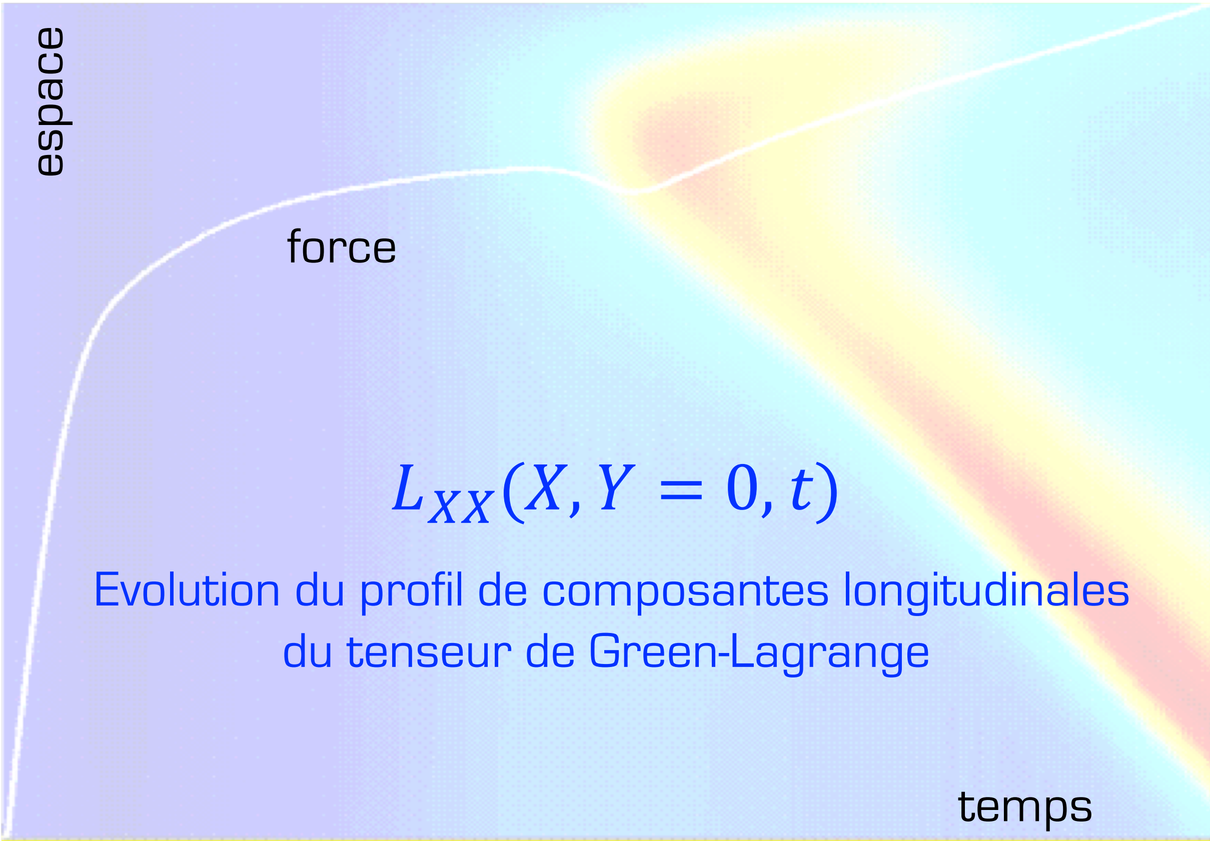


Un exemple de champ 1D au cours du temps

PA11 : thermoplastique semi-cristallin
propagation de lèvres de striction



Allongement de la zone « strictionnée »

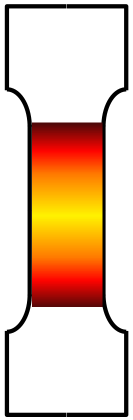


[Muracciole et al., Strain (2008)]

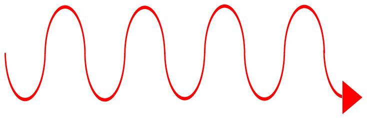
Un minimum de radiométrie IR

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

cible rayonnante

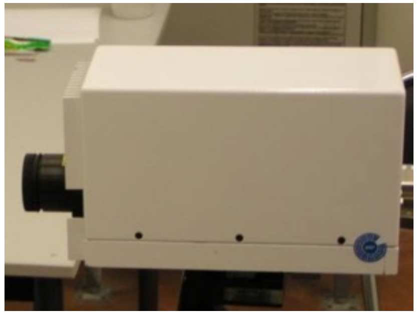


atmosphère



rayonnement I.R.

détecteur IR



Δ_λ=3-5 µm / 4-8 µm / 8-12 µm

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 (W.m^{-2})

… pour une bande passante donnée

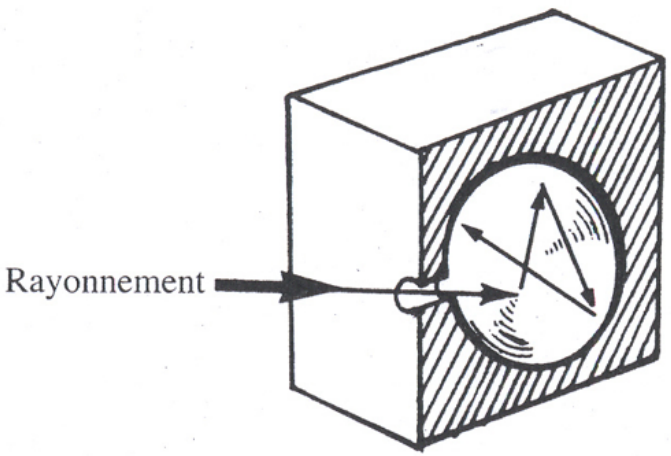
$$R = \int_{\Delta_\lambda} \frac{\partial R(\lambda, T)}{\partial \lambda} d\lambda$$

émittance spectrale varie avec *T* !

Une situation sympa ...

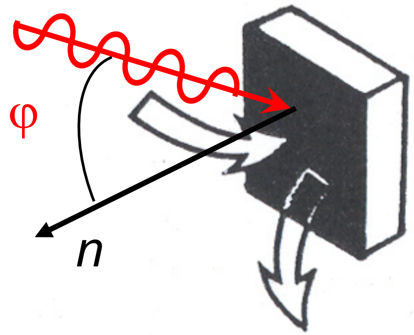
- Cible : corps noir capable d'absorber tout rayonnement incident, $\forall\ \varphi$, $\forall\ \lambda$,
  (i.e. pas de réflexion, pas de transmission)

cavité presque totalement fermée



[G. Gaussorgues, TEC & DOC, 99]

revêtement absorbant parfait (*)



(*) peinture noir mat ...
Pub.: 3M velvet coating

- Atmosphère : petite distance, air sec, transparent aux IR, transmission parfaite.
  (i.e. ce qui est émis par la cible, est reçu par le détecteur)

… où s' appliquent directement les lois du rayonnement

- Loi de Planck

$$\frac{\partial R_{cn}(\lambda, T)}{\partial \lambda} = \frac{2\pi h c^2 \lambda^{-5}}{\exp(\frac{hc}{\lambda k T}) - 1}$$

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

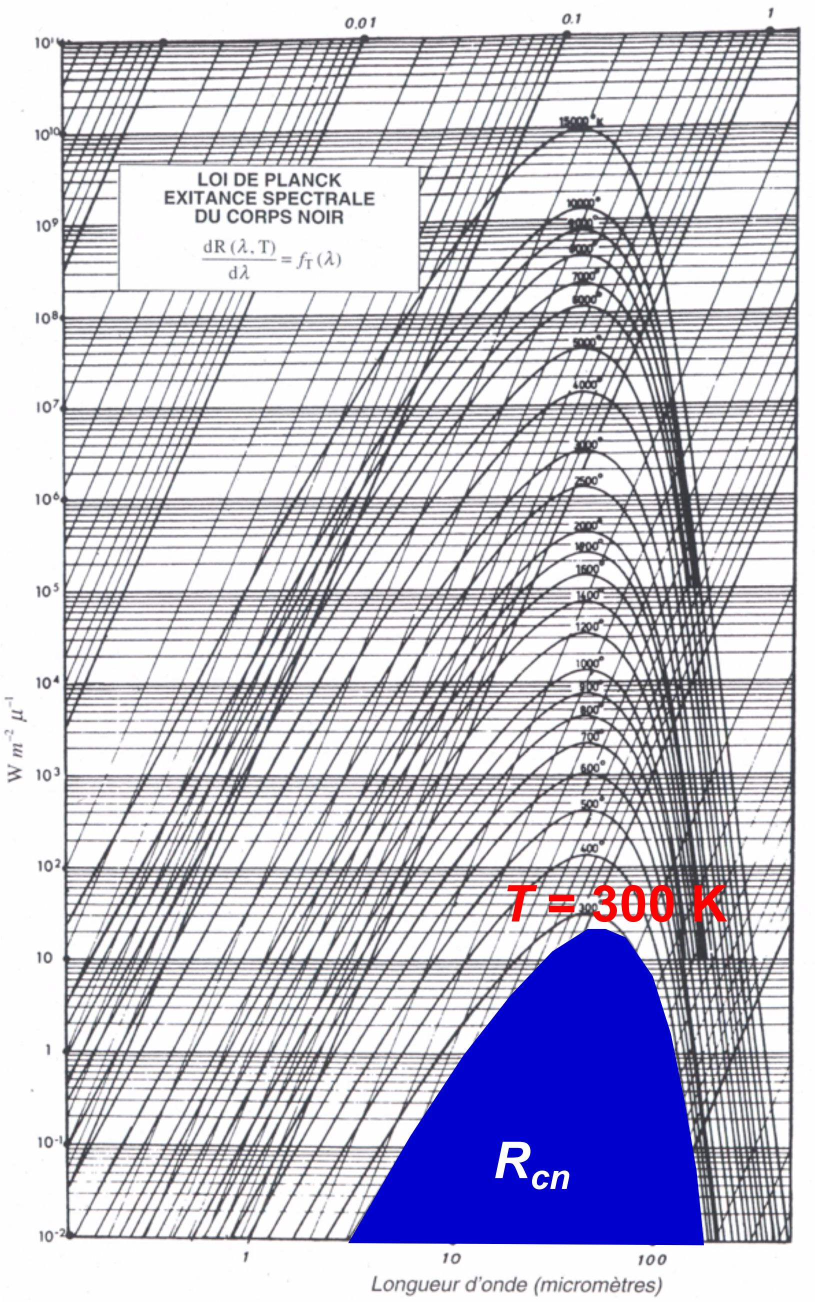
- Loi de Stefan-Boltzmann

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

σ_s : constante de Stephan

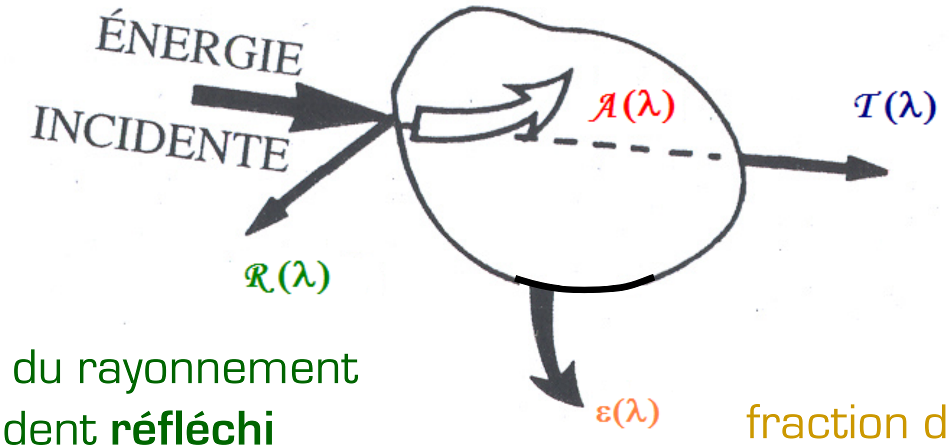
$$\sigma_s = \frac{2\pi^5 k^4}{15 c^2 h^3} = 5{,}67\,10^{-8}\, W.m^{-2}.K^{-4}$$

[G. Gaussorgues]



Cible et environnement quelconques …
… ça se complique un peu !

fraction du rayonnement
incident **absorbée**



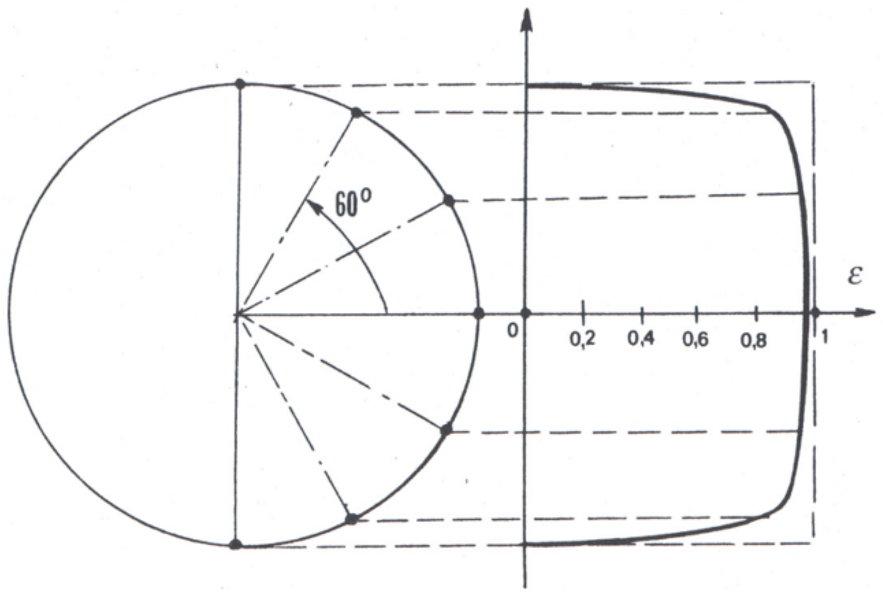
fraction du rayonnement
incident **transmis**

fraction du rayonnement
incident **réfléchi**

fraction du rayonnement
incident **ré-émis**

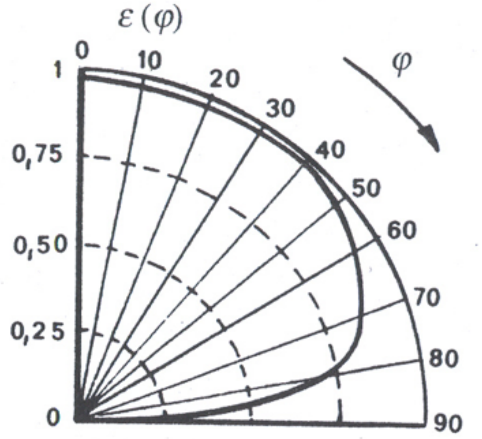
- conservation de l'énergie ……….. $\mathcal{A}(\lambda) + \mathcal{R}(\lambda) + \mathcal{T}(\lambda) = 1$
- équilibre « thermodynamique » … $\mathcal{A}(\lambda) = \varepsilon(\lambda)$

Rôle de l'incidence du rayonnement



émissivité : fonction de l'incidence

ε : émissivité



φ : angle observation

émissivité de l'eau à λ=10 μm

Jusqu'à 45-50 degré, corps lambertiens … ∂ε/∂φ ≈ 0
Risque faibles : éprouvettes planes ⊥ 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)

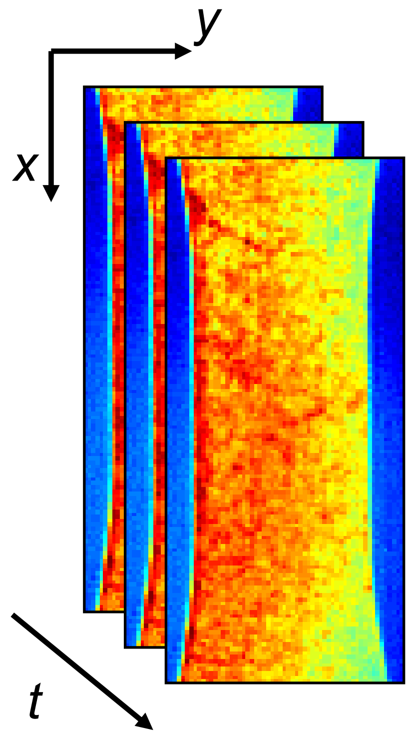
Image : 320×240 pixels

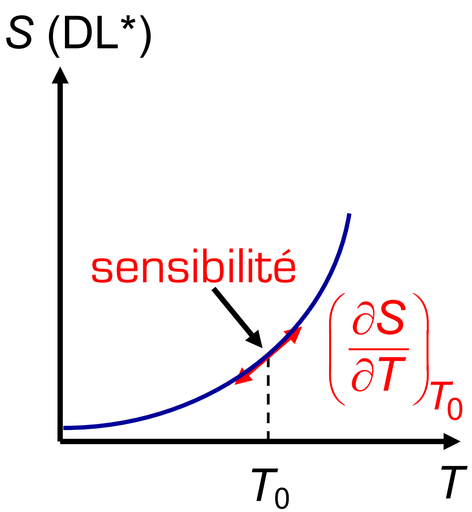
Codage : 14 bits

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.

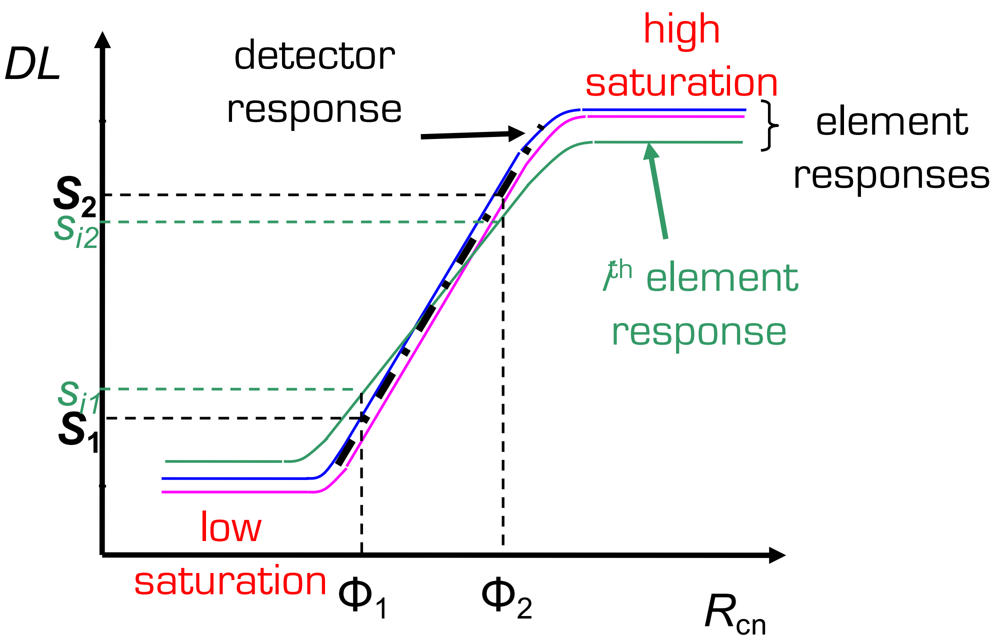
Etalonnage : constructeur

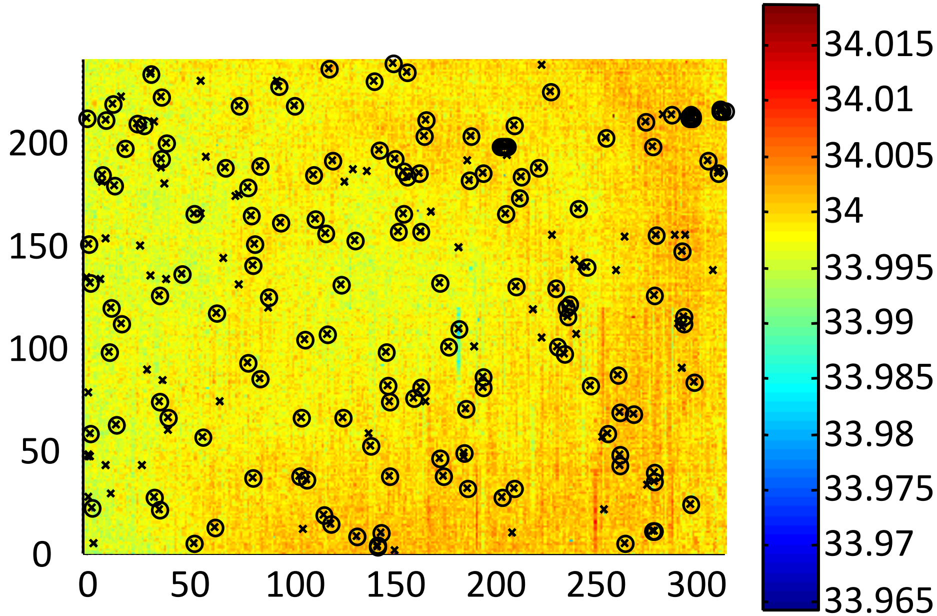
- 2 scènes thermiques uniformes (Φ_1 et Φ_2)

    feuille blanche + main ...

- 50 % de la dynamique des capteurs (partie linéaire)
- opérations NUC et BPR

$s_i = a_i \phi + b_i$ a_i = gain b_i = offset





Nb pixels défectueux = 255, soit 0.29%
T_{cn} = 34 ° C

Etalonnage : laboratoire

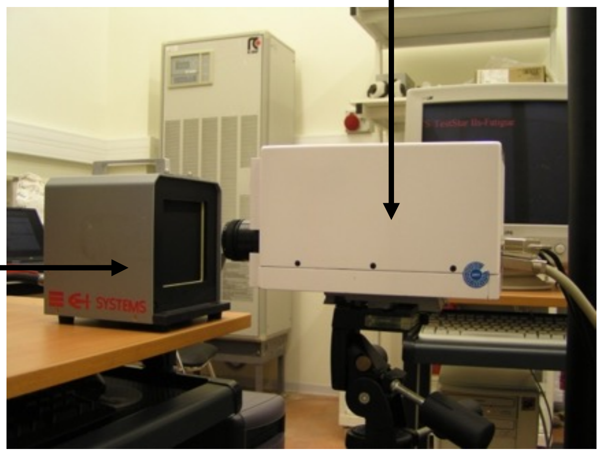
Calibration pixel à pixel [Honorat et al., QIRT 2005]

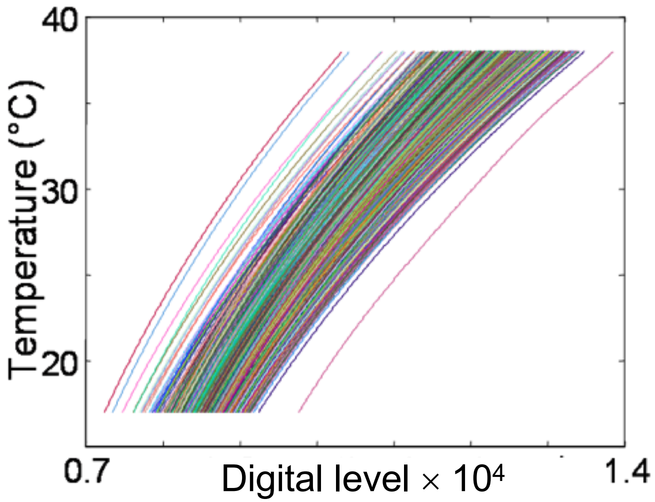
- nécessité d'1 corps noir plan (20 mK) + 30 k€ (+ 40-120 k€ de caméra !)
- stabilité thermique de la caméra (4-5 h) et de la salle d'essai …
- étalonnage pixel à pixel (polynôme de degré 5)
- précision 20 mK et plus de remplacement de «bad pixel»
- à refaire dès que l'on modifie un paramètre (temps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

$$T(i,j) = \sum_{p=0}^{p=P} a_p(i,j)\,DL(i,j)^p$$

Caméra IR

Corps noir





Estimation des sources de chaleur

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

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

1980-90

- *Estimation directe de sources en utilisant des données discrètes et bruitées*
  - Le traitement d'image a évolué avec les performances des caméras

- *Estimation d'opérateur aux dérivées partielles*

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

  camera à matrice de détecteur
  - outils de Fourier, filtrage convolutif, prolongement périodique (2000)
  - lissage local par moindres carrés (2004)
  - POD: préfiltrage dez 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

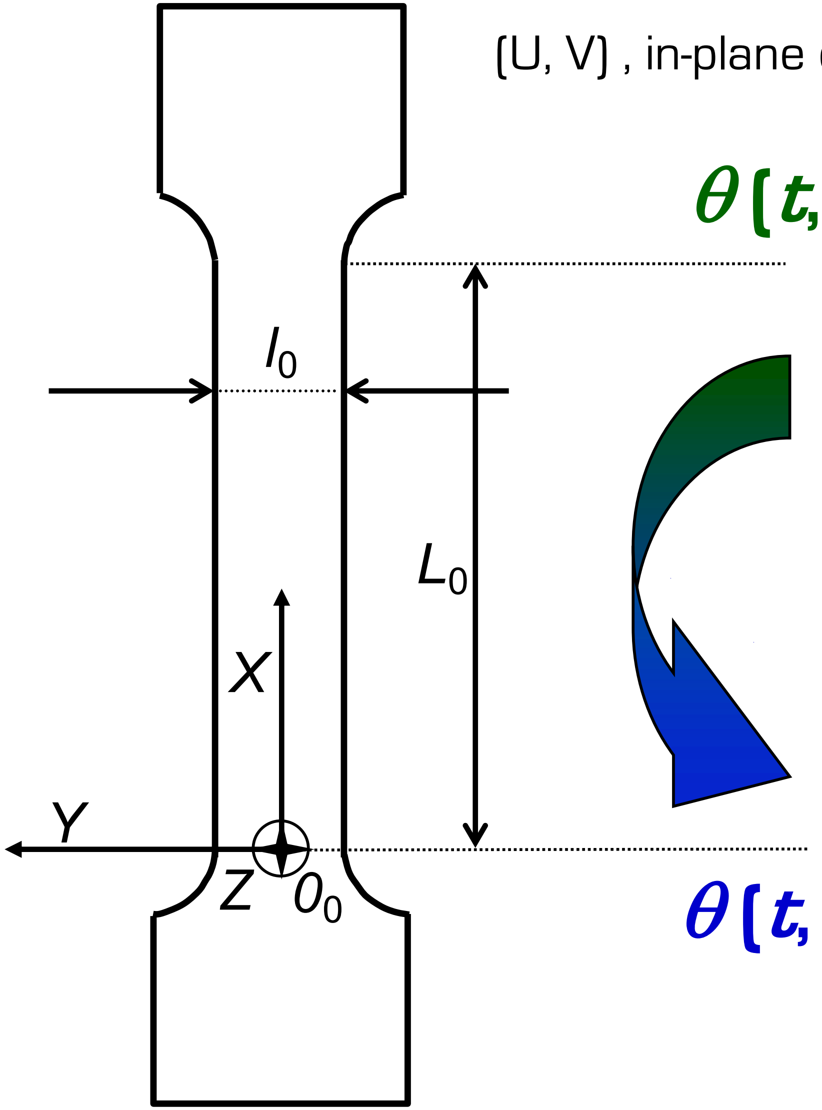
- ρ =7800 kg.m^{-3}, C =480 J.kg^{-1}.°C^{-1}, k =60 W.m^{-1}.°C^{-1}
- thin flat samples: 50 × 12.5 × 0.3 (mm^3)

❖ Test

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

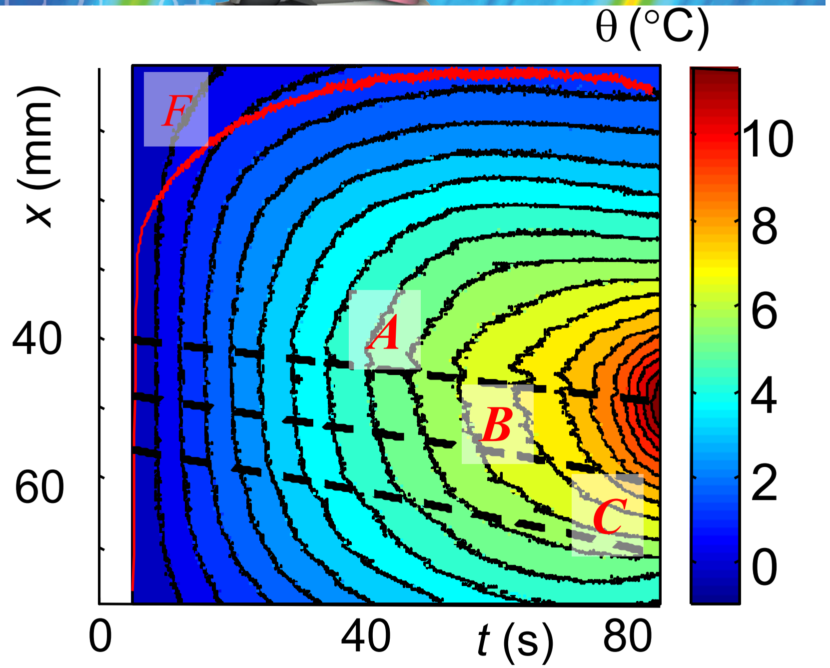
Thermoprofiles

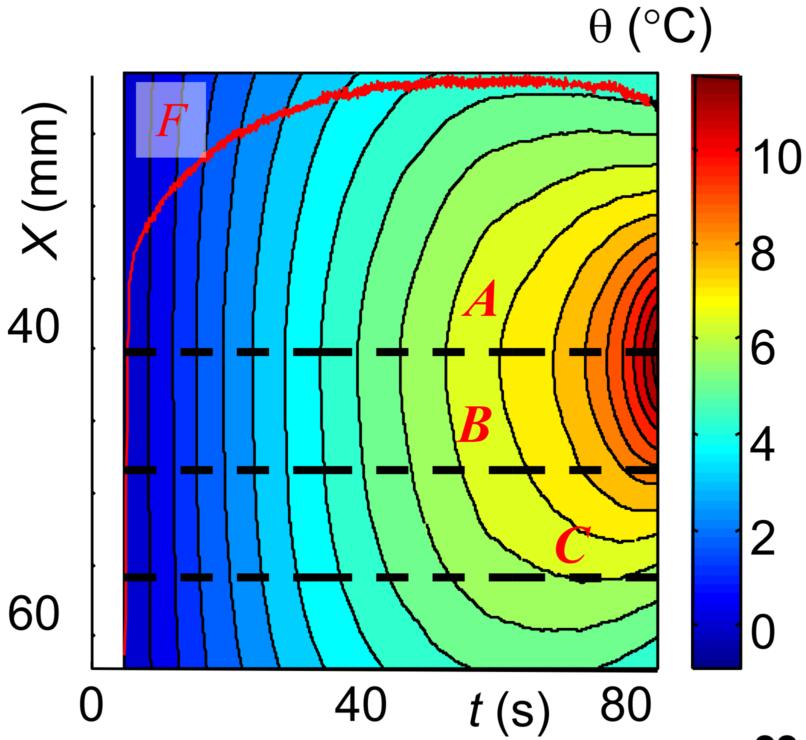
(U, V) , in-plane components



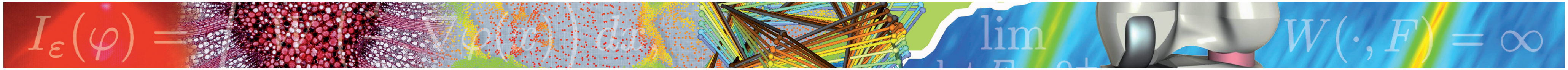
$\theta\,(t,\ x,\ y=0)$

$\theta\,(t,\ X,\ Y=0)$

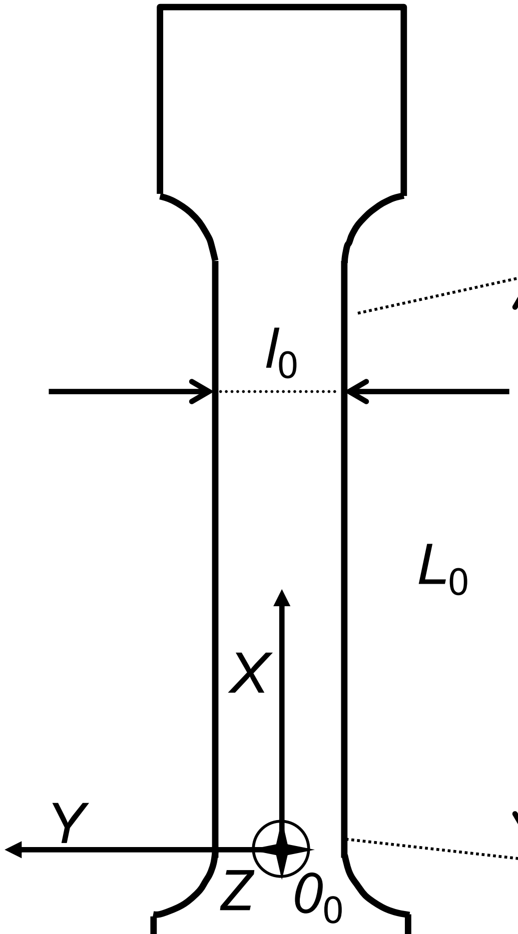




A, B, C, 3 material surface elements
Progressive concentration of level curves



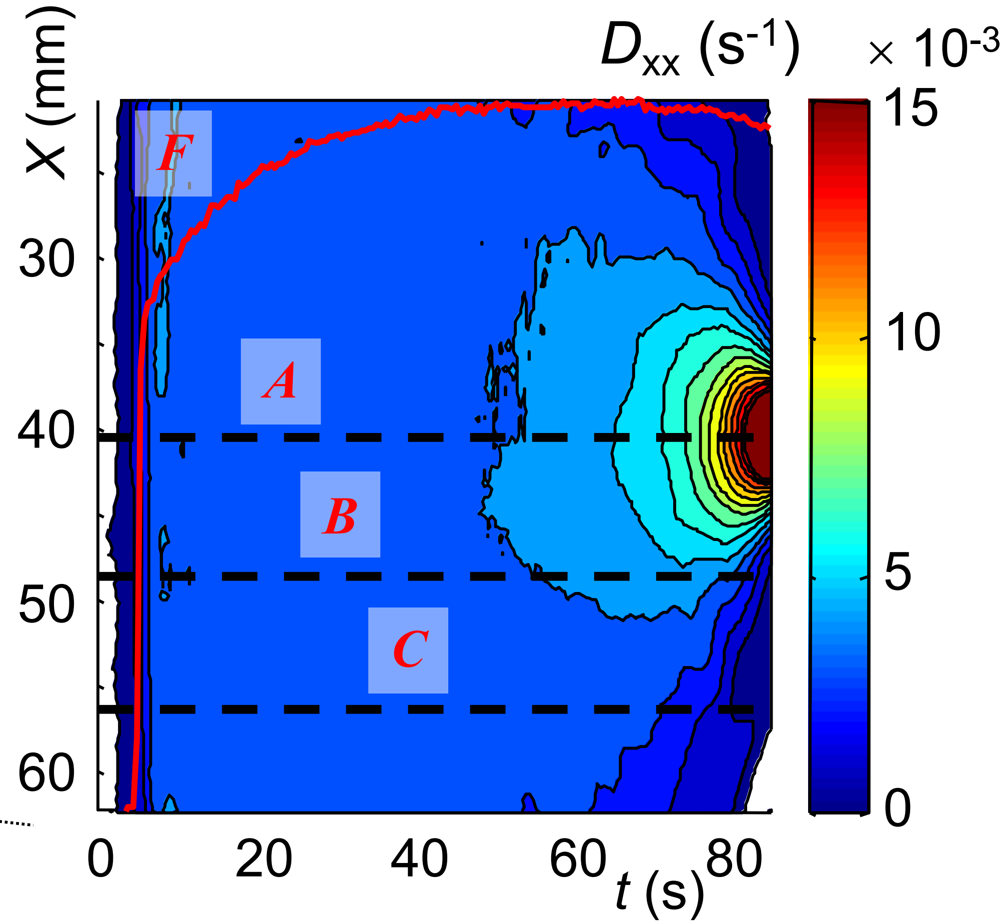
Strain rate profile $D_{xx}(t, X, Y=0)$



$v_0 = 250\ \mu\text{m s}^{-1}$

$\dot{\varepsilon}_c = v_0 / L_0$

$= 5.10^{-3}\ \text{s}^{-1}$

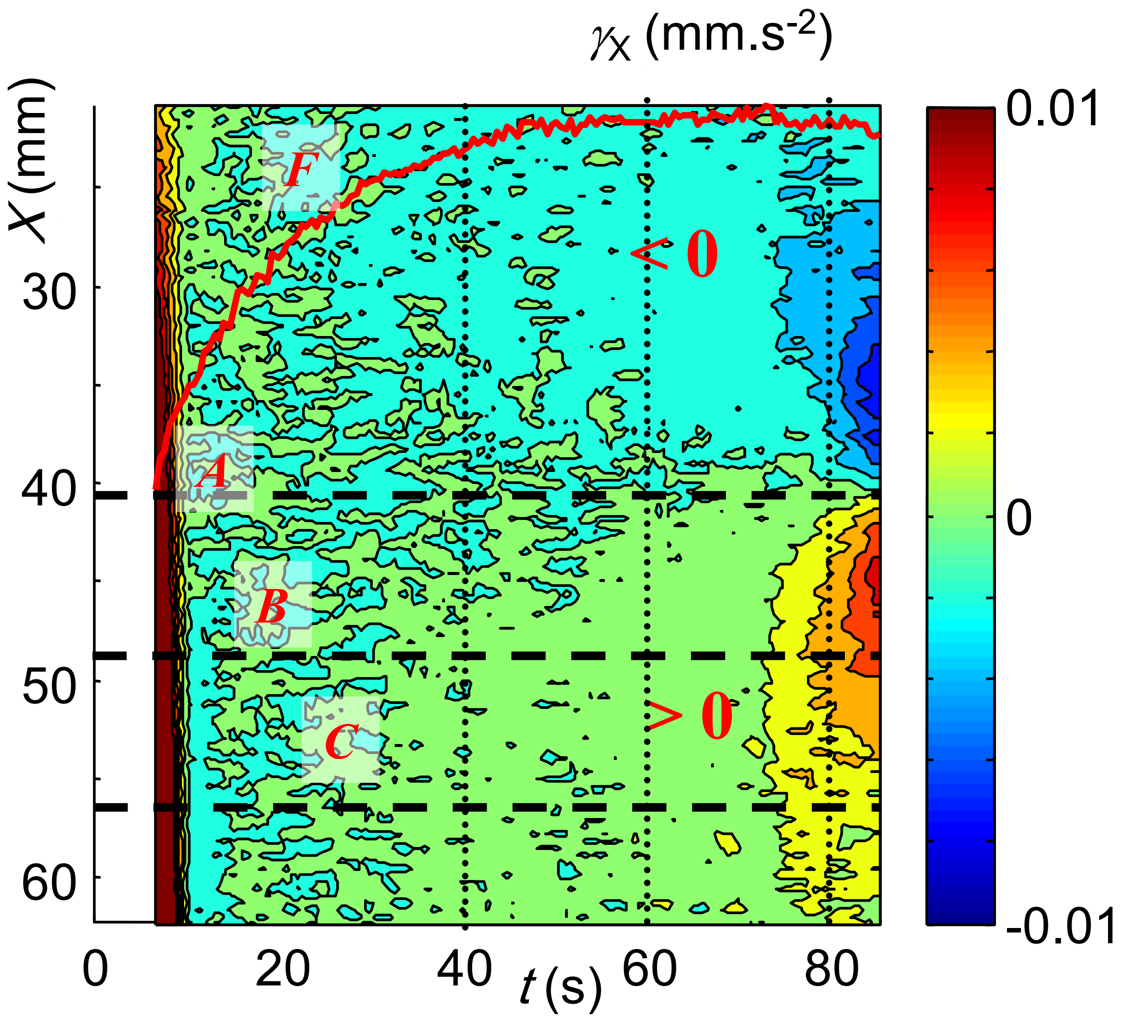


Sample / structure

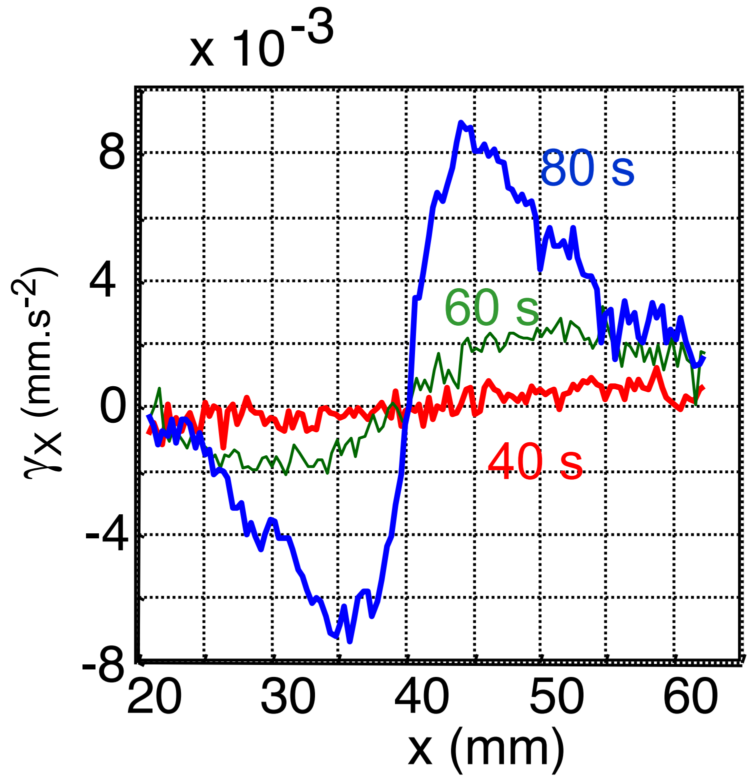
Early progressive development of localization

Progressive transition (diffuse/localized)

Acceleration field



Aziz? مكتوب, again?



Acceleration remains small [$<10^{-4}$ m.s^{-2}]; quasi-static process

Fracture zone = zero acceleration with change of sign

Gradual transition between localized necking and fracture

Stress I: computation

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

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

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

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

quasi-static process [!]

plane stress [?]

uniform distribution [?]

ε_{xx} y-independent [!]

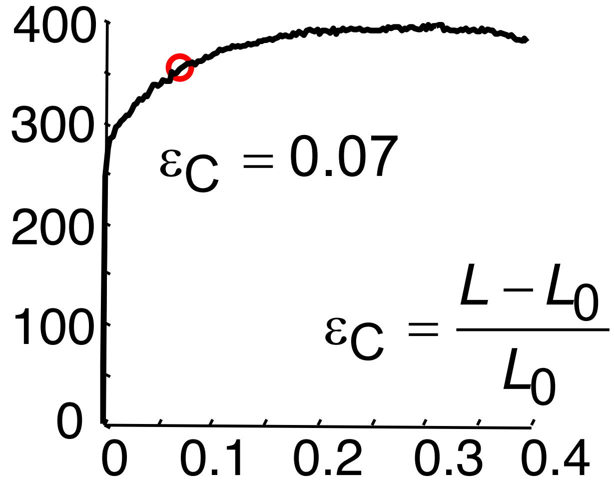
$\varepsilon_{yy}(x,y,t) \approx \varepsilon_{yy}(x,-y,t)$ [!]

no overall shear force [?]

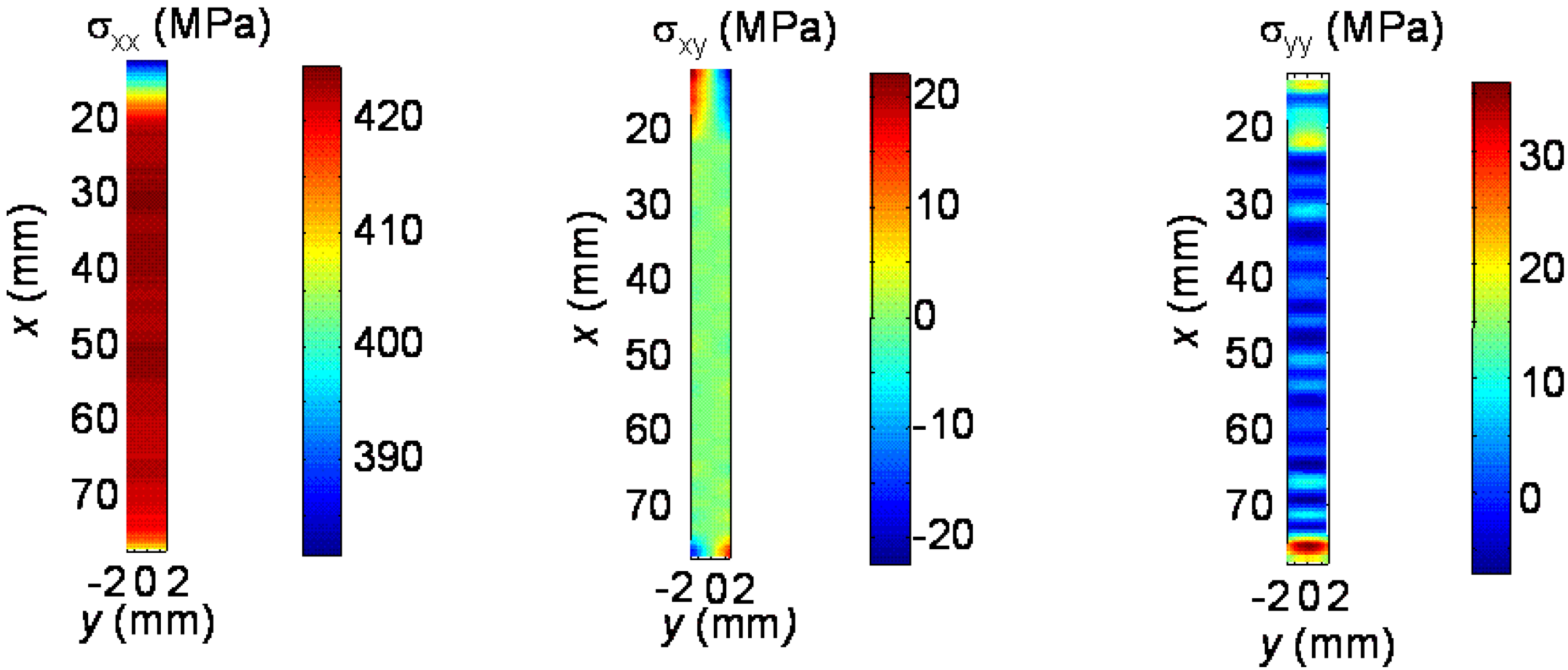
lateral surfaces: free of normal stresses [!]

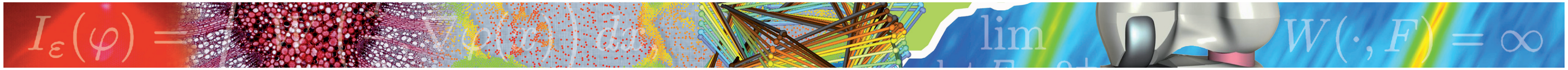
Stress II : patterns

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



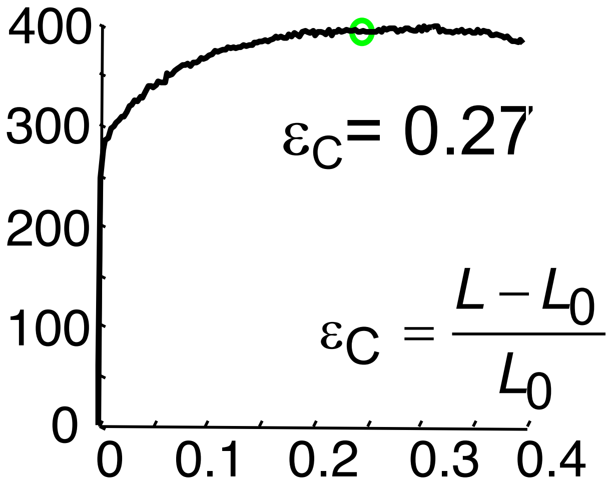
$$\varepsilon_C = \frac{L - L_0}{L_0}$$



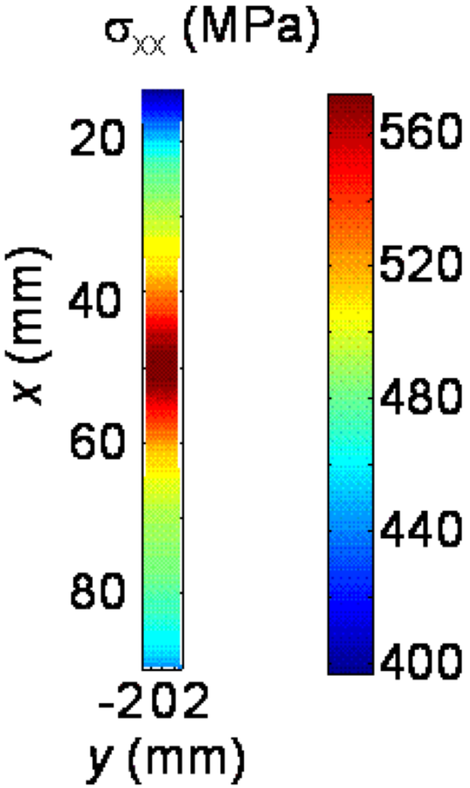


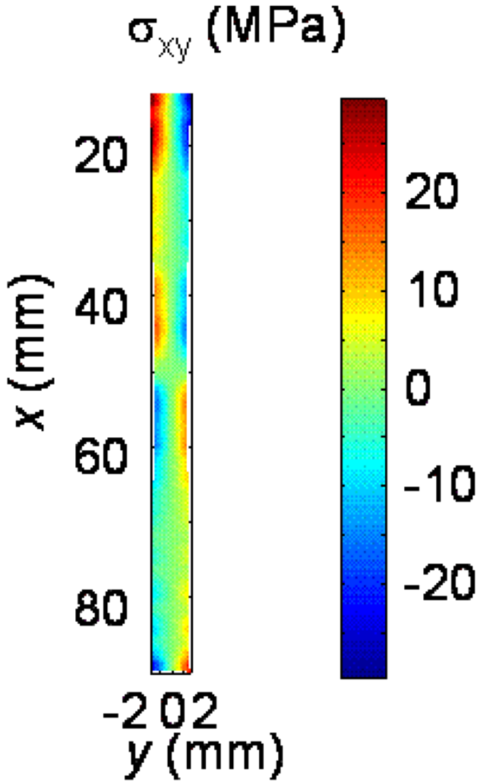
Stress III: patterns

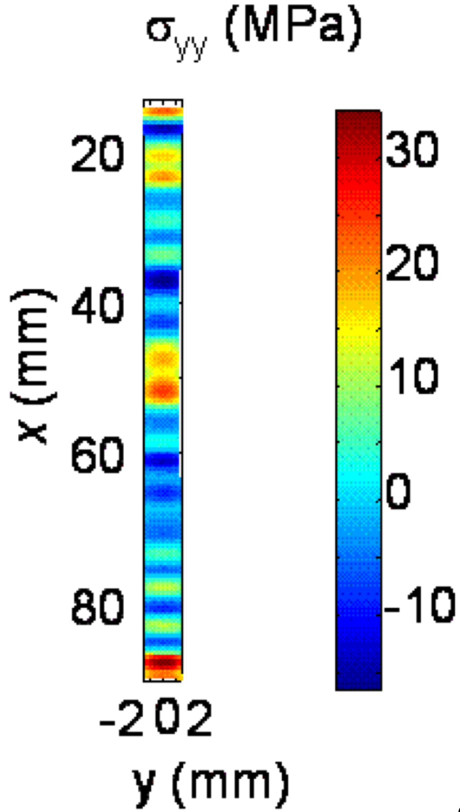
$$\sigma_C = \frac{F}{S_0}(\mathrm{MPa})$$



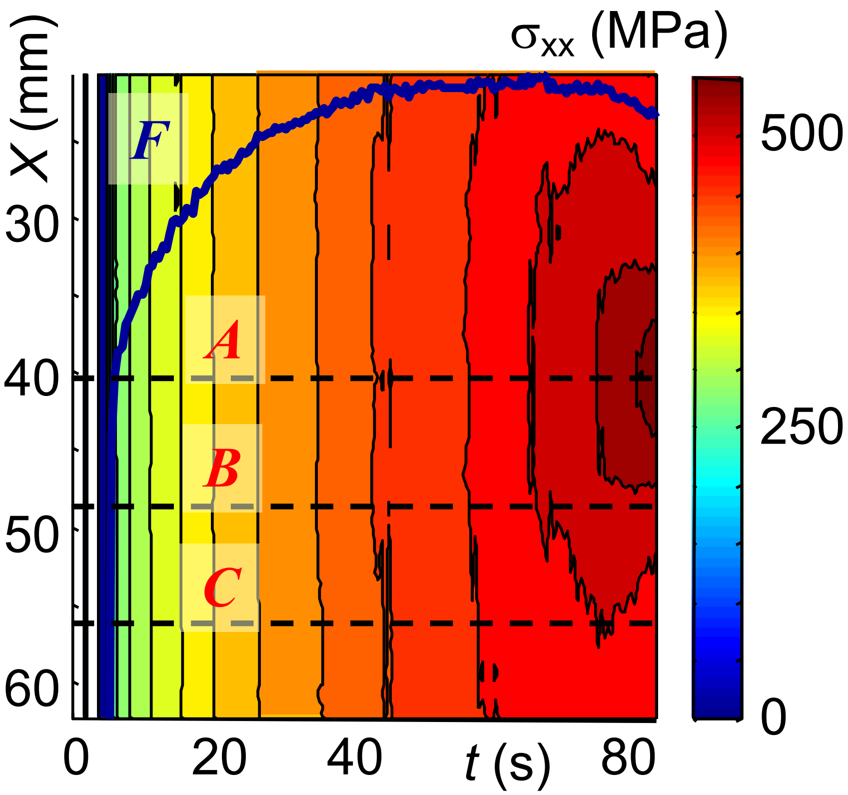
$$\varepsilon_C = \frac{L - L_0}{L_0}$$

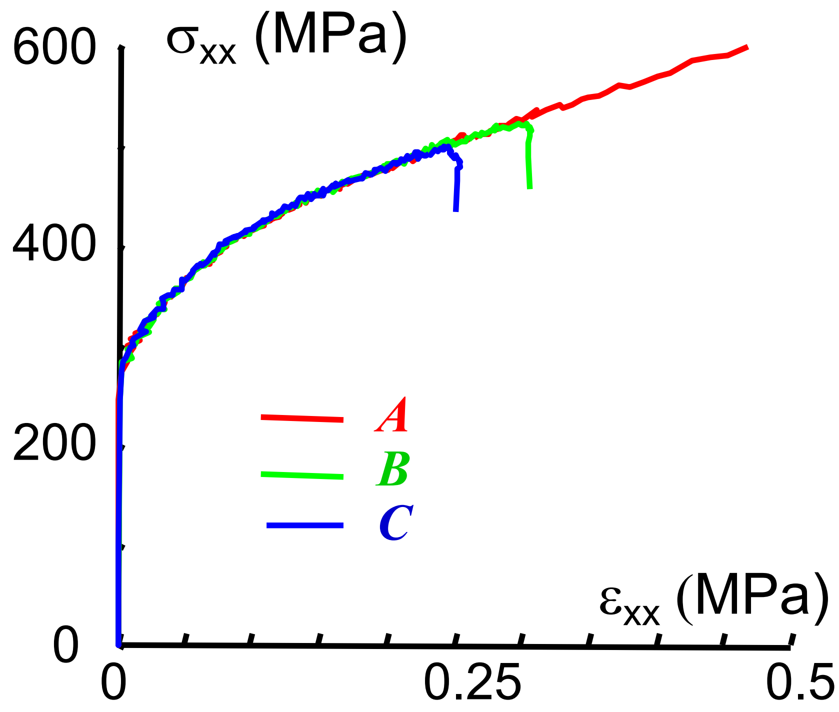






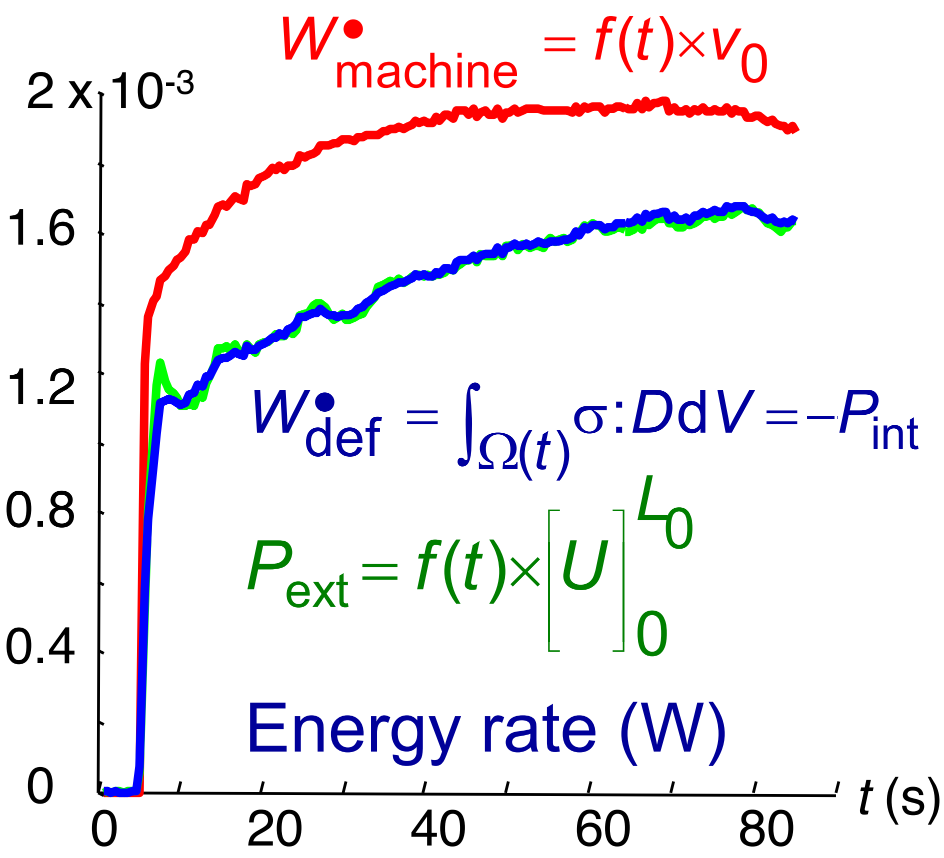
Stress III : tensile stress – stress vs strain

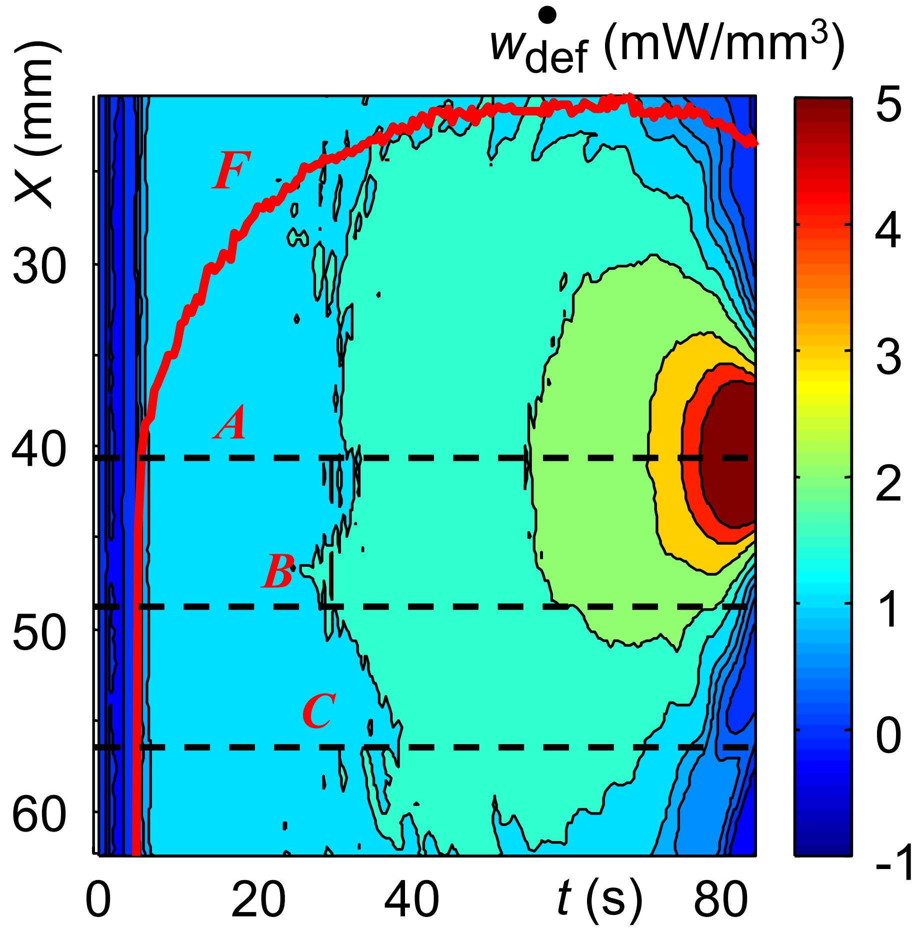




Sample softening = strain hardening within localization zone + elastic unloading outside this zone

Deformation energy rate





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

elastic loading: finite stiffness of the testing machine

plastic deformation of the connection zones of the sample

Volume heat rate

$$\rho C\left(\underbrace{\frac{\partial\theta}{\partial t}+v_x\frac{\partial\theta}{\partial x}+v_y\frac{\partial\theta}{\partial y}}_{1}+\underbrace{\frac{\theta}{\tau_{th}}}_{2}\right)-k\left(\underbrace{\frac{\partial^2\theta}{\partial x^2}+\frac{\partial^2\theta}{\partial y^2}}_{3}\right)=\dot{w}_h$$

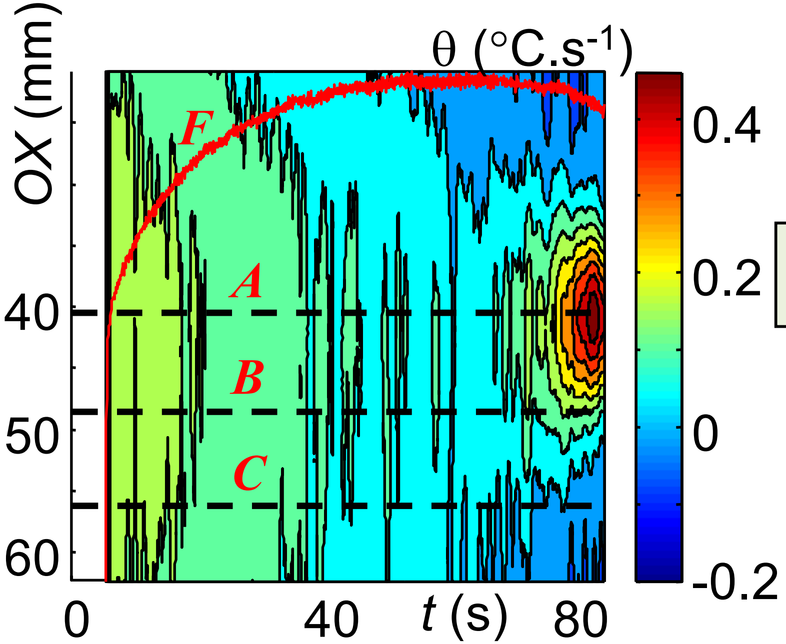
1 – Time derivative: $\dot{\theta}(t,x,y)=\underbrace{\frac{\partial\theta}{\partial t}+v_x\frac{\partial\theta}{\partial x}+v_y\frac{\partial\theta}{\partial y}}_{1a}=\underbrace{\frac{\partial\theta(t,X,Y)}{\partial t}}_{1b}$

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

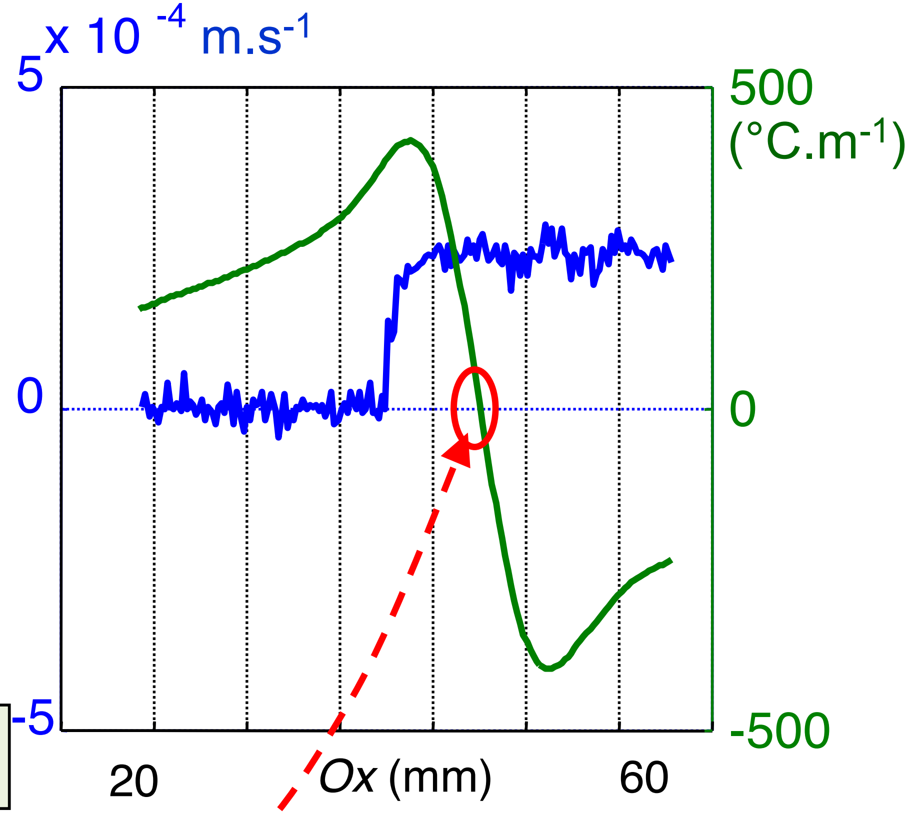
3 – In plane heat losses by conduction – 2D Laplacian

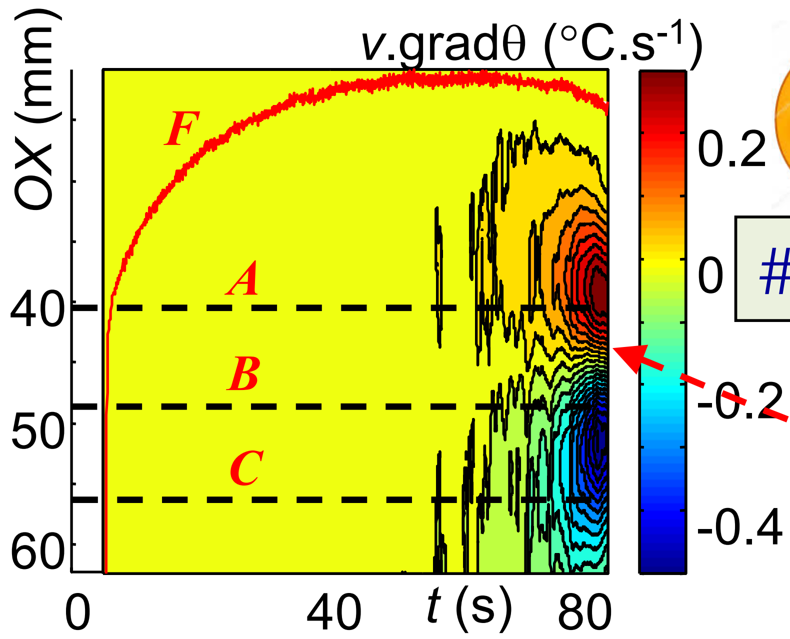
Particular time derivative

$$\dot{\theta}(t,x,y) = \underset{1a}{\frac{\partial\theta}{\partial t}} + v_x\frac{\partial\theta}{\partial x} + v_y\frac{\partial\theta}{\partial y} = \underset{1b}{\frac{\partial\theta(t,X,Y)}{\partial t}}$$



1b





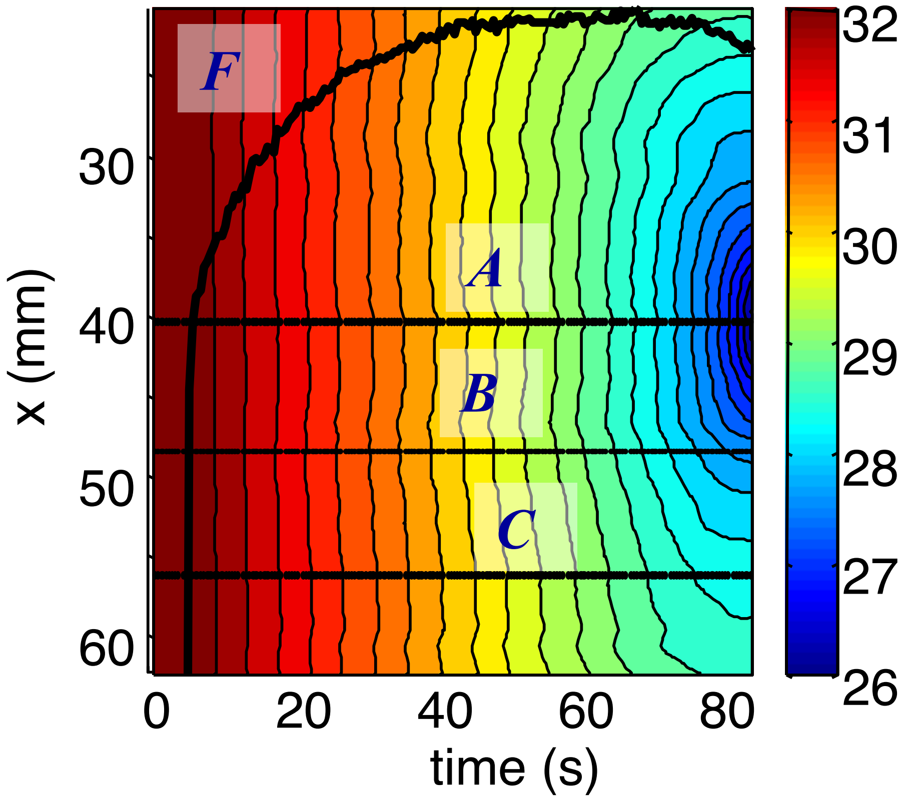
1b -1a

Convective terms are not negligible !

Out of plane heat losses – time "constant"

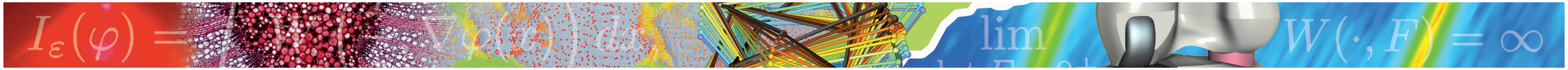
θ/τ_{th}

$\tau_{th}(s)$



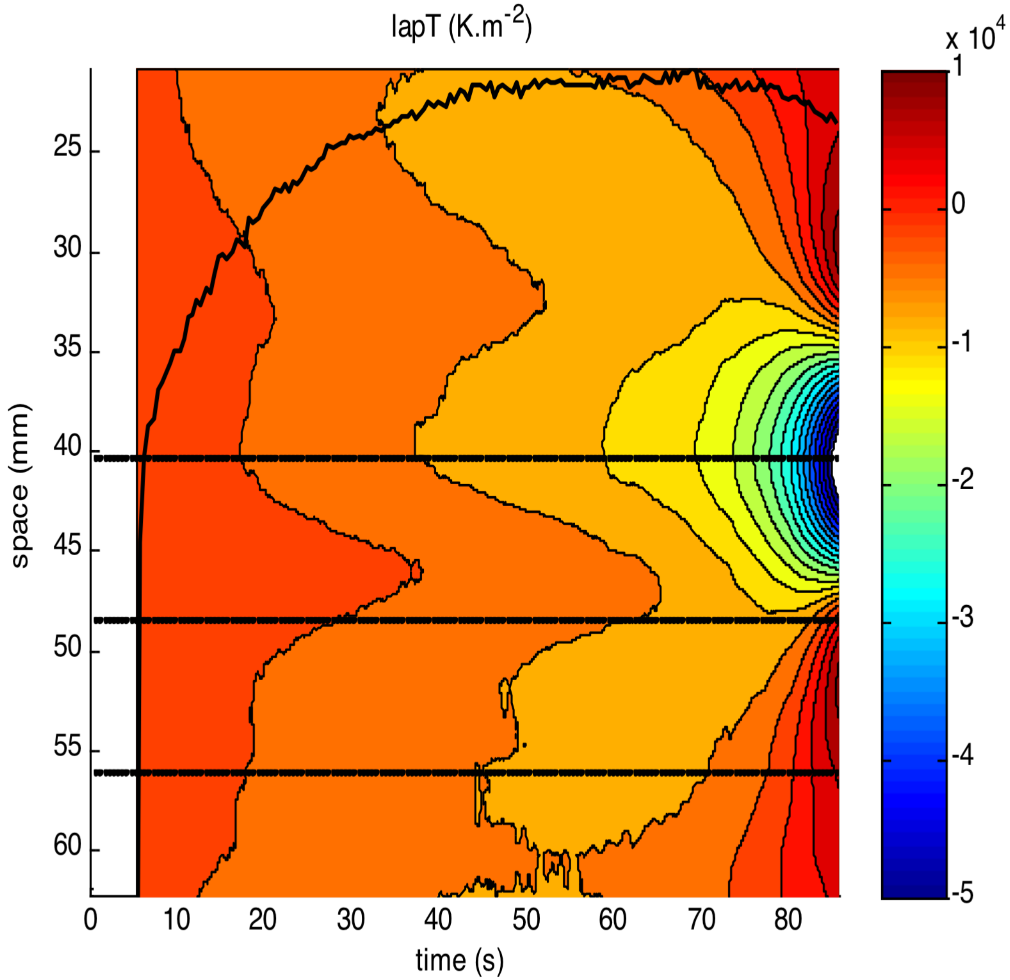
 # 2

Significant geometrical effects induced by necking

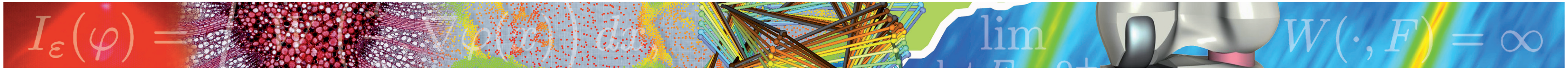


Laplacian assessment

$\Delta_{xy}\theta$

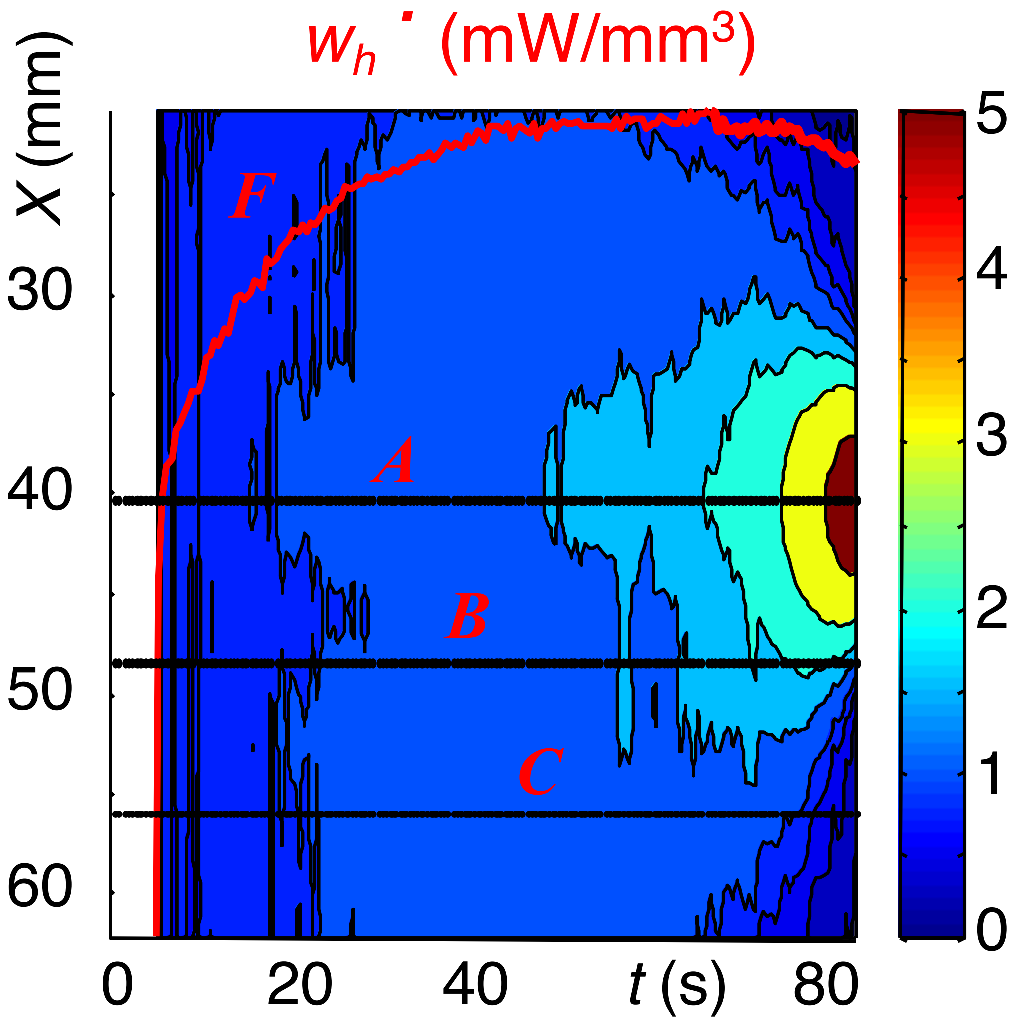


Significant geometrical effects induced by necking



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)

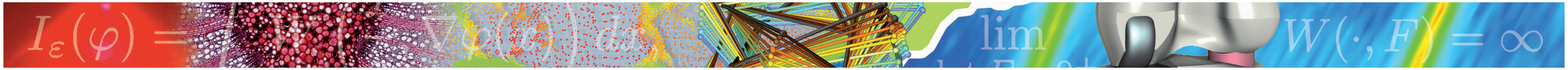
- Intérêts : Approcher un système de grande dimension par un autre de taille de dimension significativement plus petite
  Déterminer une base de modes propres orthogonaux représentatifs des “réalisations les plus probables”

- Images thermiques :

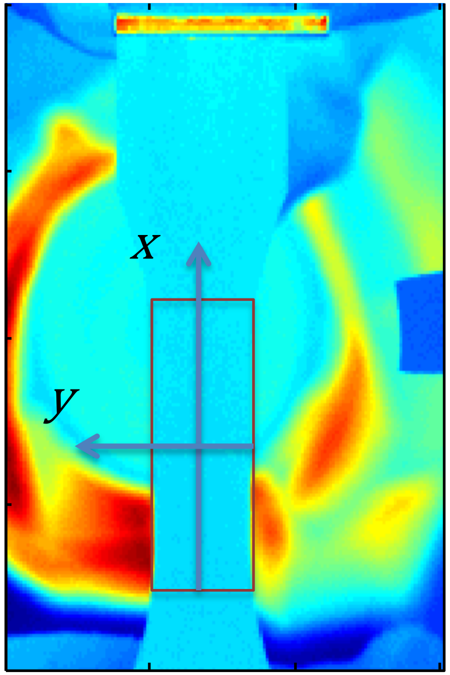
$$\boxed{\vartheta(x_i, y_j, t_k) \simeq \sum_{p=1}^{P} a_p(t_k)\, \Phi_p(x_i, y_j)}$$

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

$$A = \Theta\, \Theta^T \qquad \boxed{A\Phi_p = \omega_p \Phi_p}$$



Benchmark test : a penalizing case



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

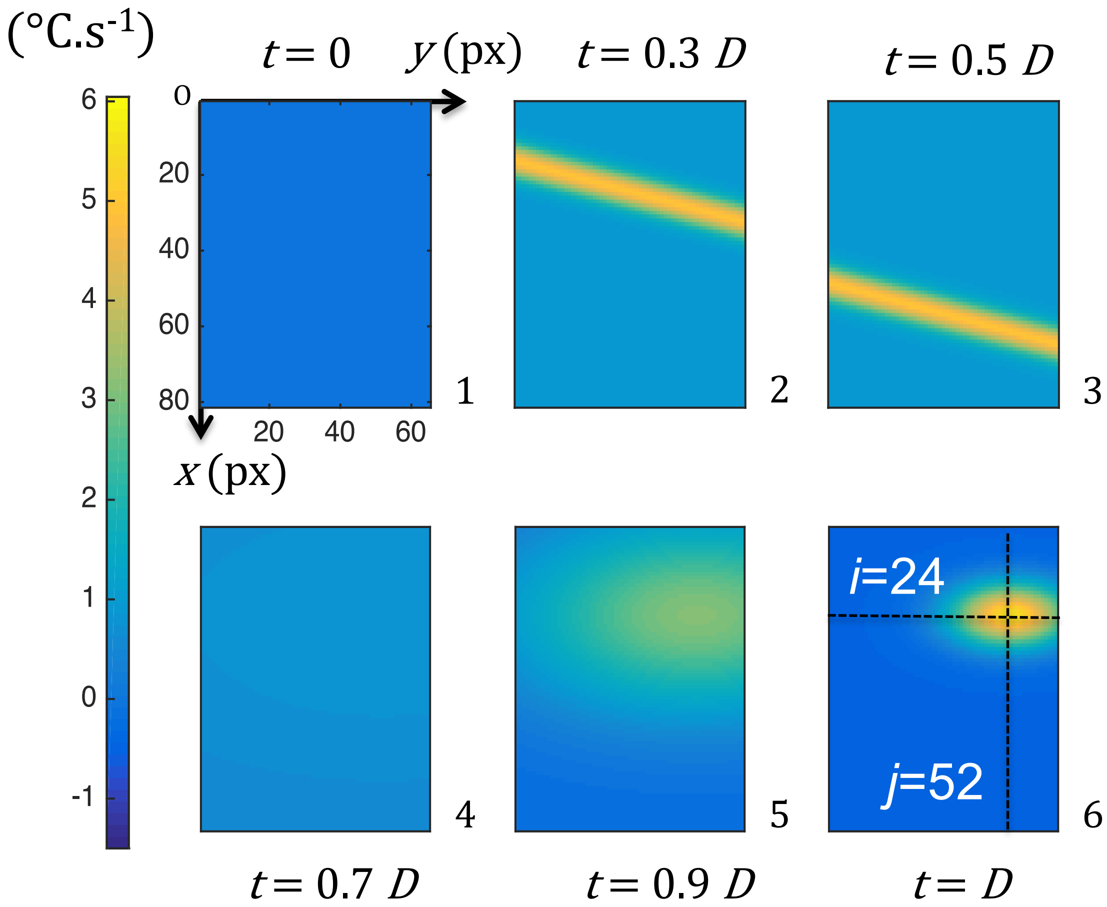
$$\begin{cases} \rho C\left(\dfrac{\partial \bar{\vartheta}_i(x,y,t)}{\partial t}+\dfrac{\bar{\vartheta}_i(x,y,t)}{\tau_{th}^{2D}}\right)-k_c\left(\dfrac{\partial^2 \bar{\vartheta}_i(x,y,t)}{\partial x^2}+\dfrac{\partial^2 \bar{\vartheta}_i(x,y,t)}{\partial y^2}\right)=\bar{s}^h(x,y,t), \\ \dfrac{\partial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

- 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} m^2/s)
- High longitudinal heat exchange coefficient (λ_x=170 W/m/K)
- Noise superimposition (rnd / $\delta\theta$=70 mK)
- Complex heat source distribution ...

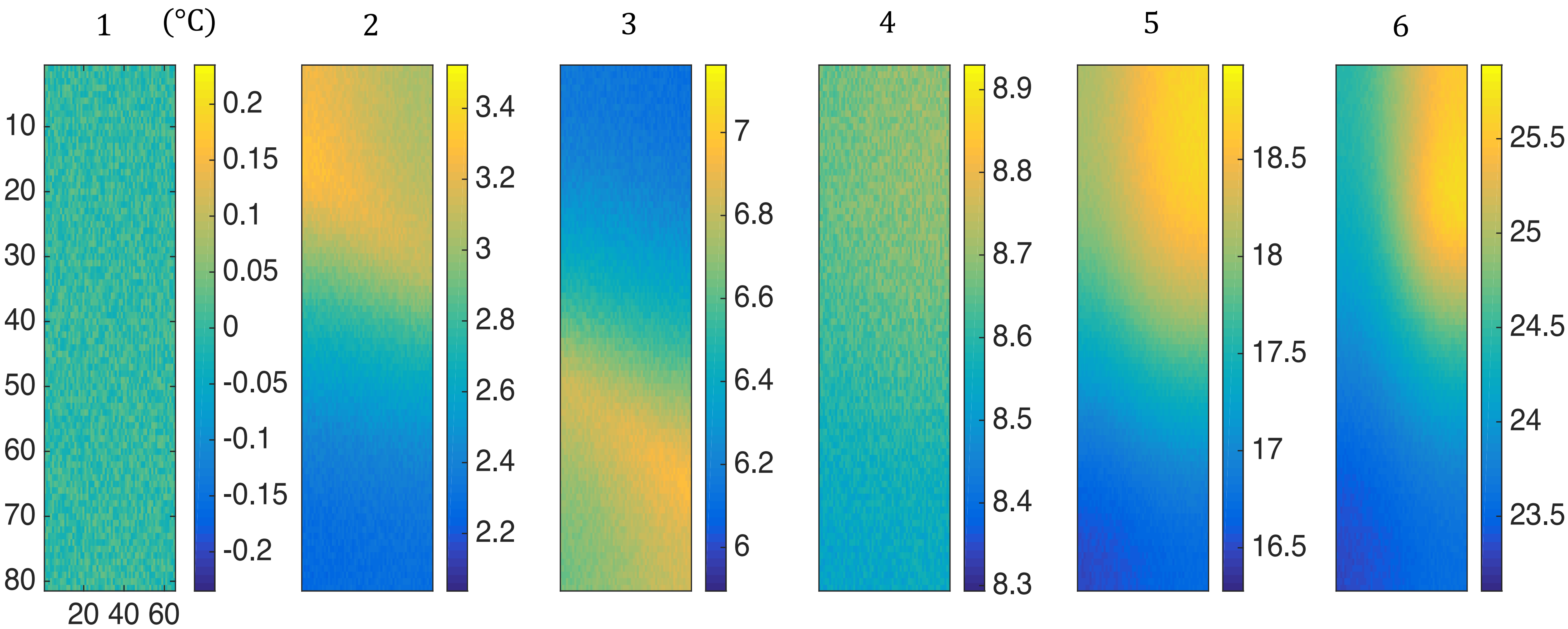
Heat source fields

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

$\bar{\vartheta}_r$

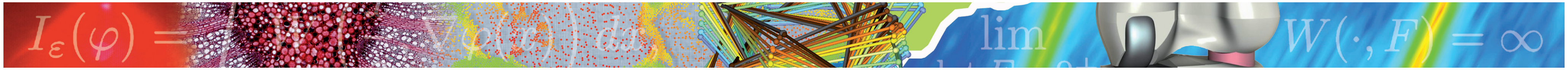
$$\bar{\vartheta}_s + \bar{\vartheta}_\ell = \bar{\vartheta}_i + N_g = \bar{\vartheta}_r$$

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

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

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

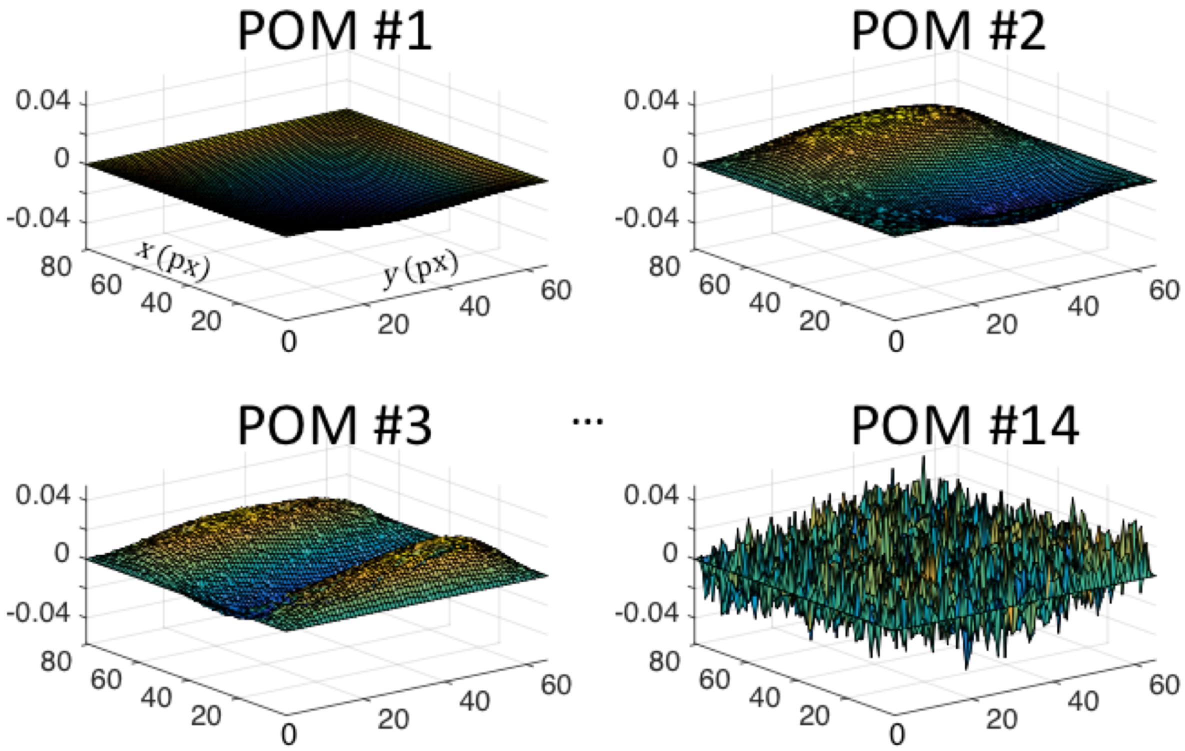
POD of $\bar{\vartheta}_s$ data

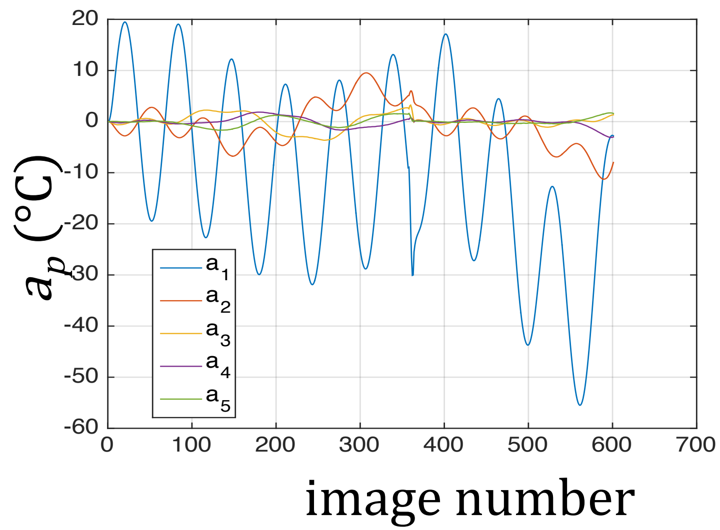


First POMs and components

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

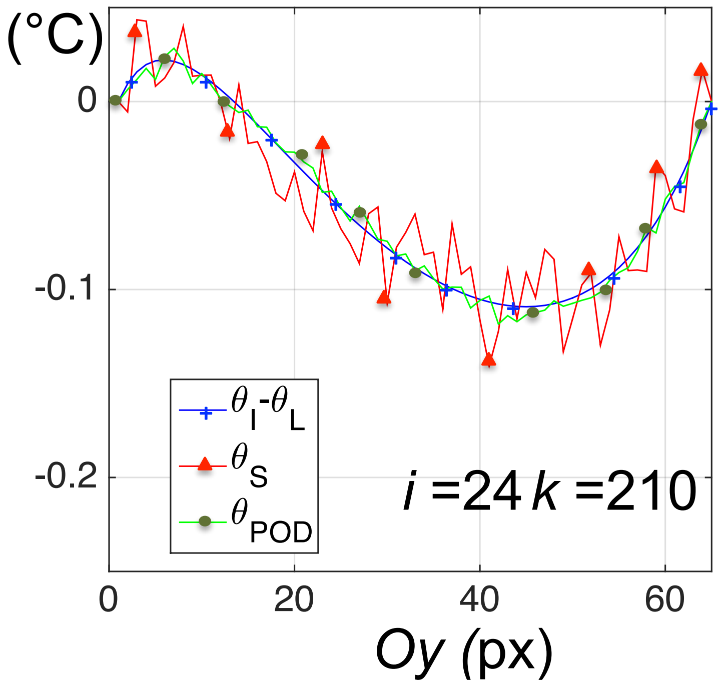
$$\boxed{\underset{POD}{\vartheta}(x_i, y_j, t_k) \simeq \sum_{p=1}^{P} a_p(t_k)\, \Phi_p(x_i, y_j)}$$

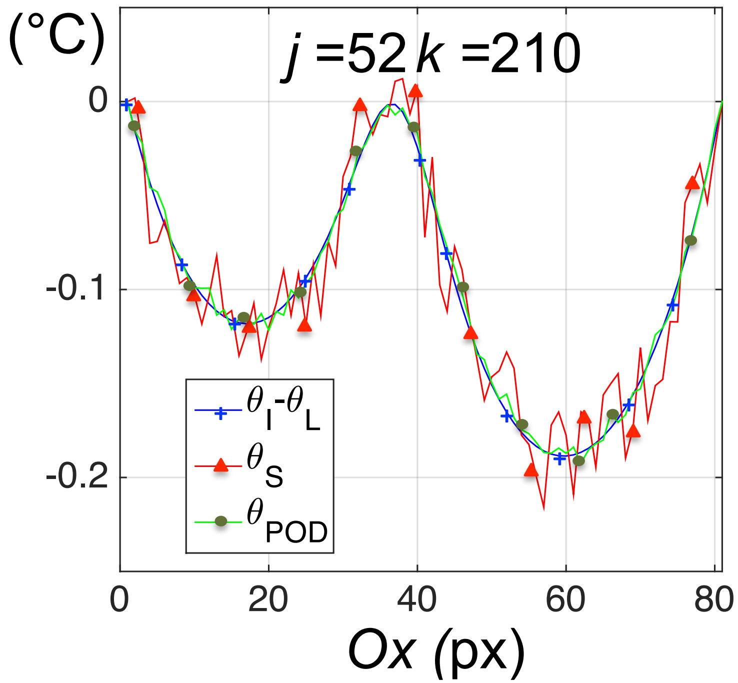




Examples of thermo-profile

- number of POMs = 14
- Ng = 0.07 × (rnd$_{ij}$-0.5)

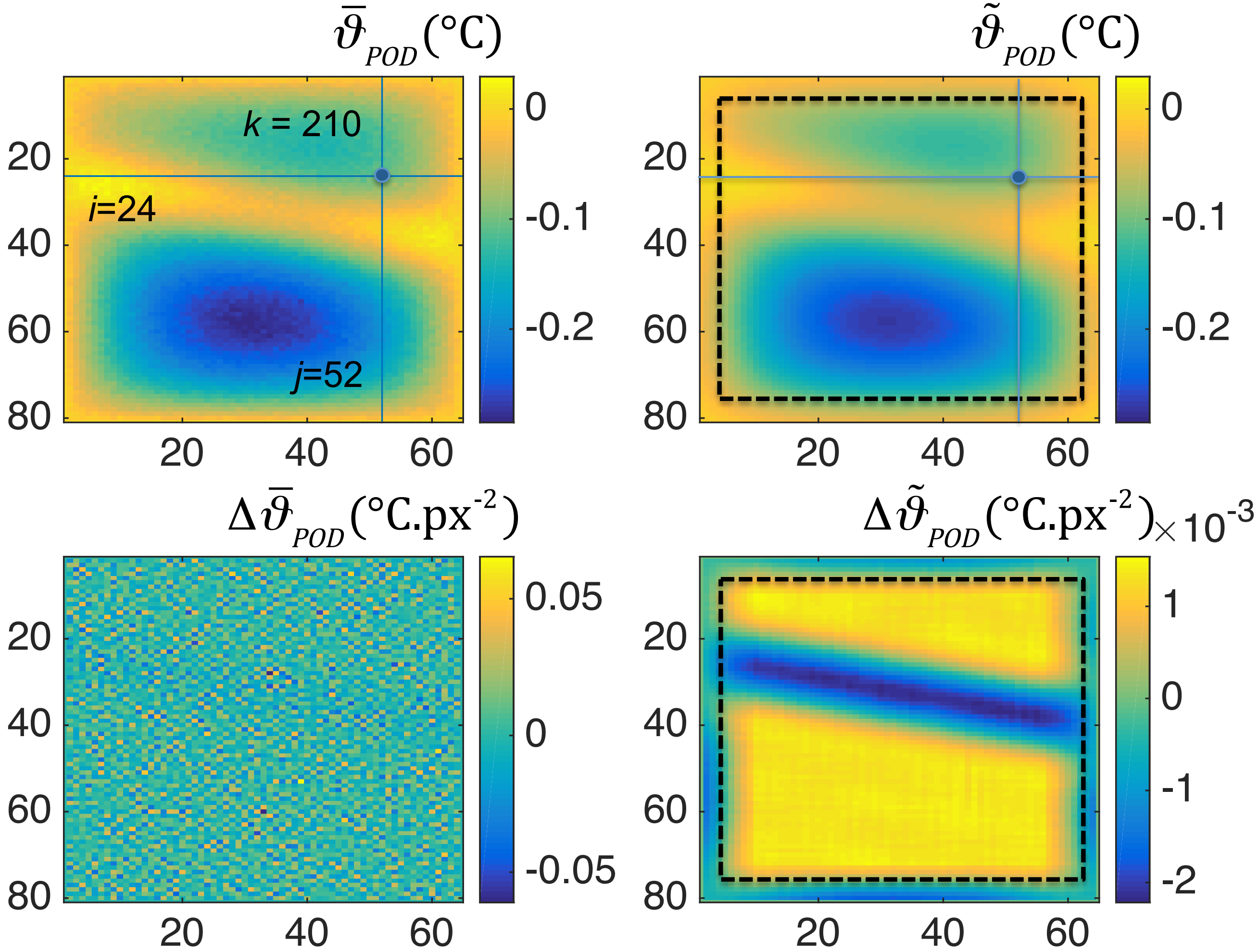




- reduction of the noise amplitude
- curvature preservation

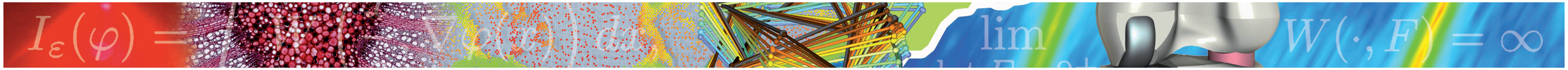
Estimations du laplacien de la température

- direct computation using a finite difference method
- «slight» 2D convolutive filtering prior to a finite difference computation



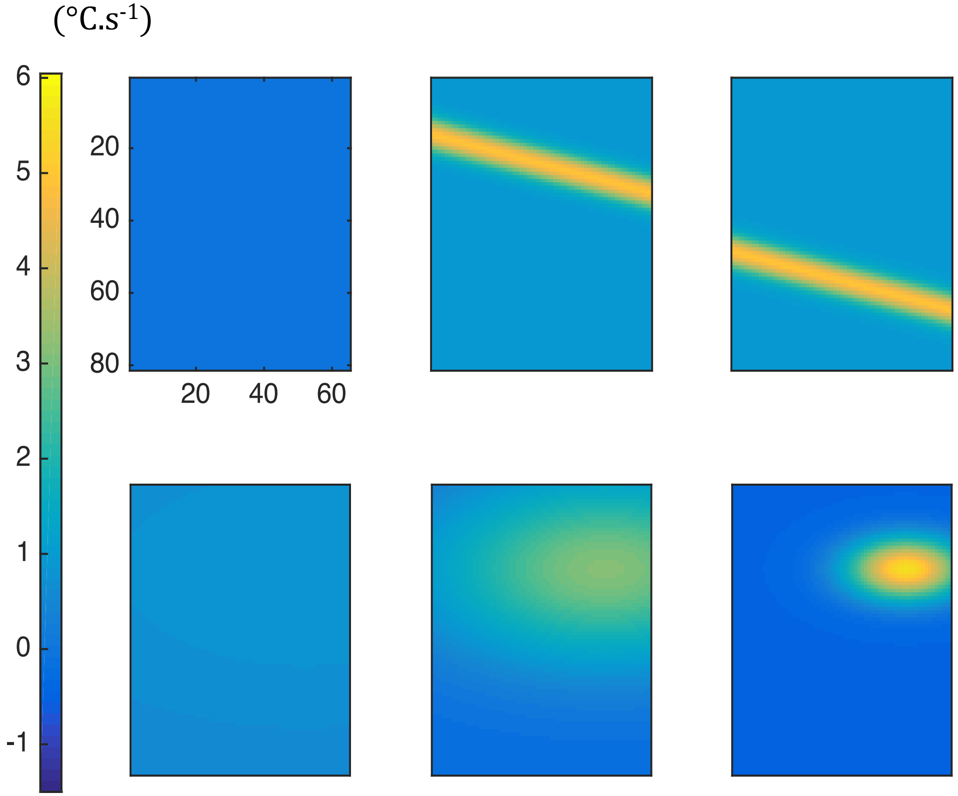
Remember !

- High diffusivity
- Poor SNR
- Complex HS Distribution

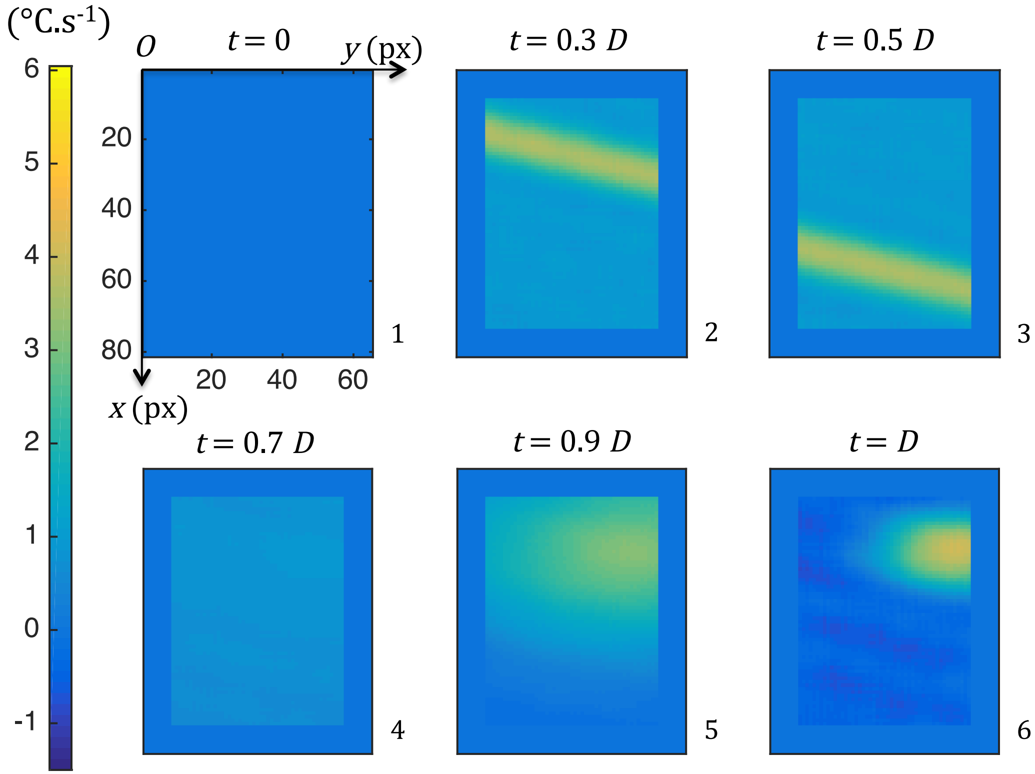


Heat source fields

given



reconstructed

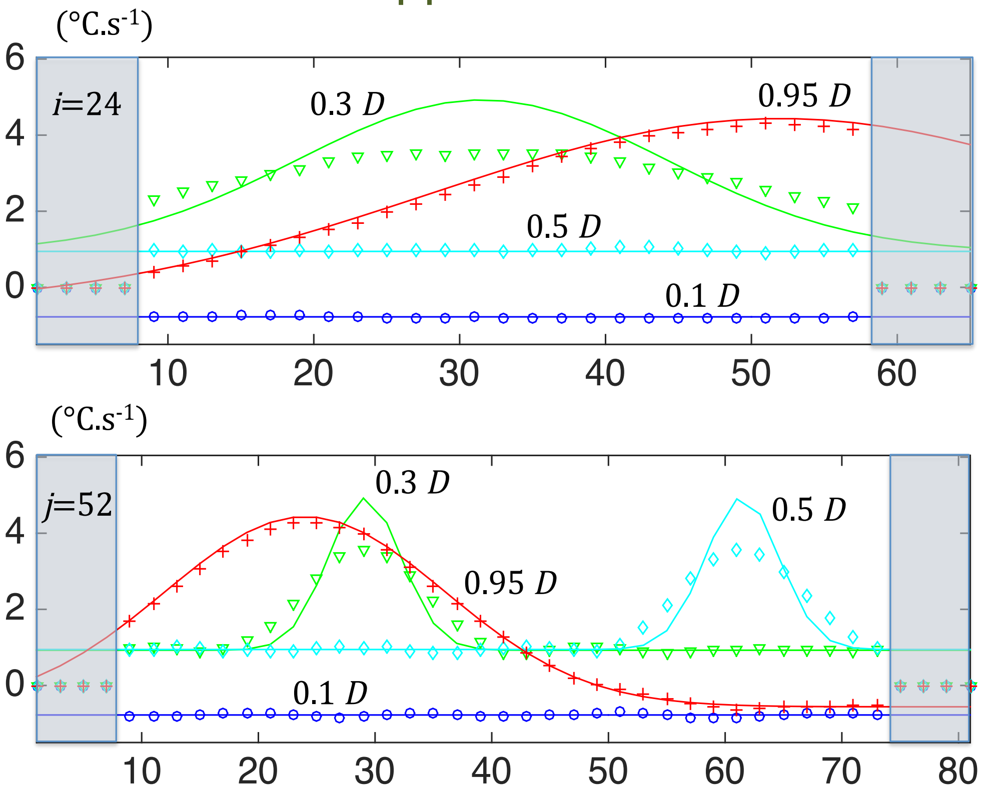


- filtering induces a slight crushing of thermoprofiles
- and thus a spreading of sources
- loss of part of the HS field due to zero-padding

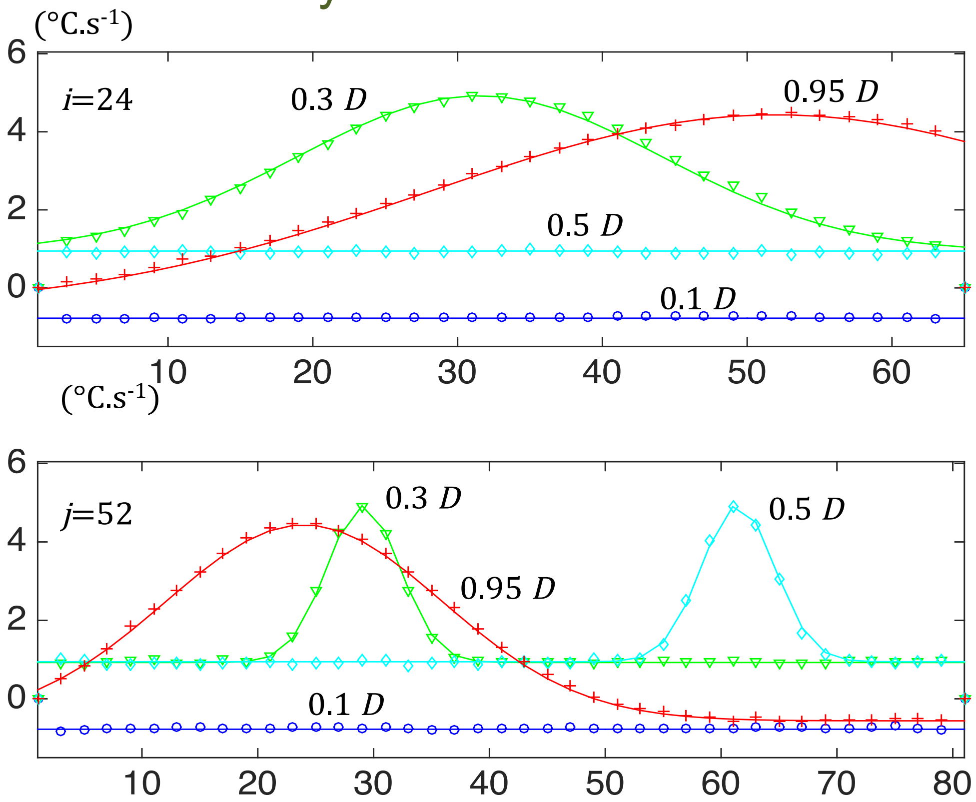
Heat source profiles

continuous lines : given sources ; symbols : reconstructed sources

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



Polyamide : 2.10^{-7} m^2/s



- High diffusivity : Slight spreading of HS concentration due to filtering!
- Low diffusivity : POD directly used. Direct estimates using FD!

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!
  $|\delta s| \leq 10^{-2}$ °C.s^{-1}

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

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