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Ultrasonic imaging in liquid sodium: ImagiNa

2013-2014

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OVERVIEW

- Industrial context
- Surface Imaging
- Imaging of heterogeneous media: Adjoint method
- Perspective

INDUSTRIAL CONTEXT AND OBJECTIVE

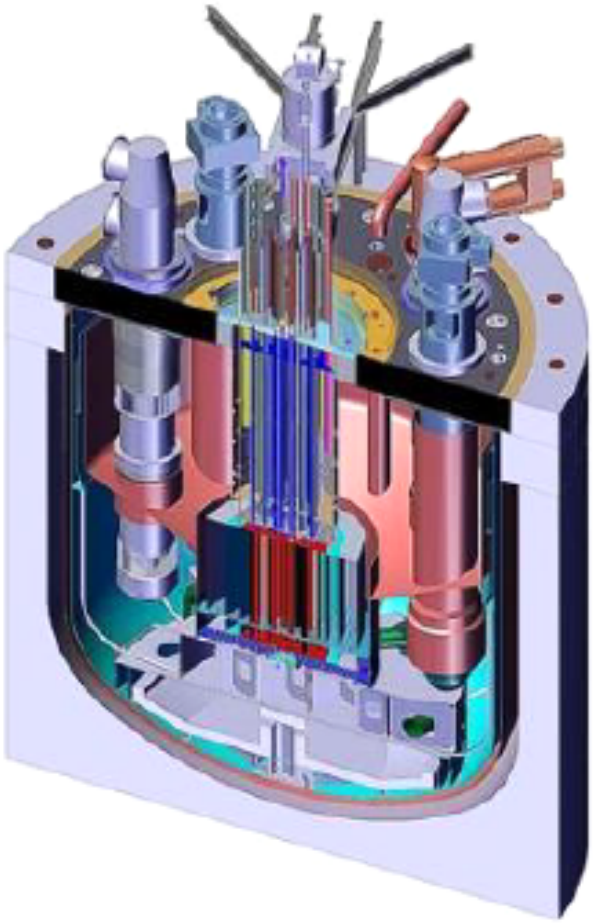
➔ CONTEXT : FAST NEUTRON REACTOR

1. Insure the safety of sodium cooled fast reactor

2. Check the integrity of immersed structures and assess component degradation.

➔ OBJECTIVE

Design an advanced ultrasound methodology for **under-sodium (opaque) imaging** (Reactor periodic inspection, 200°C).

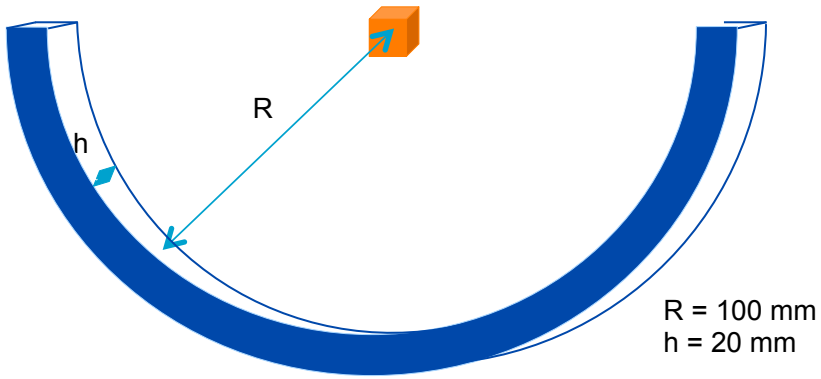


ASTRID reactor

SURFACE IMAGING

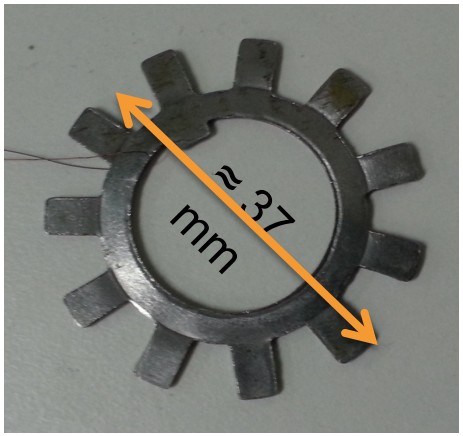
- **Goals**
  - Detection/characterization of small (lost) objects

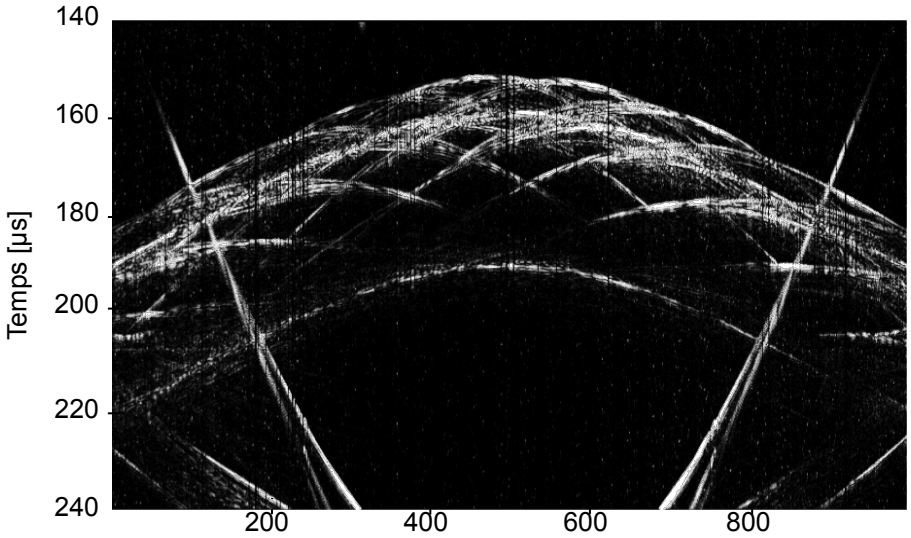
- **Tomographic approach (with/without prior information):**
  - Half ring antenna,
  - 1024 transducers
  - Central frequency 3 MHz

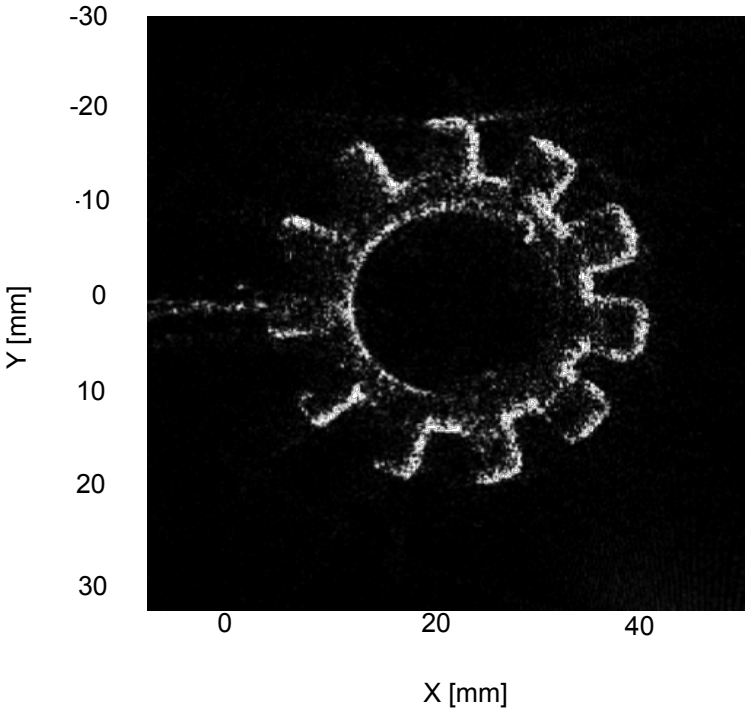


Synoptic of the experimental imaging system (in water)

Tomographic reconstruction : lock washer



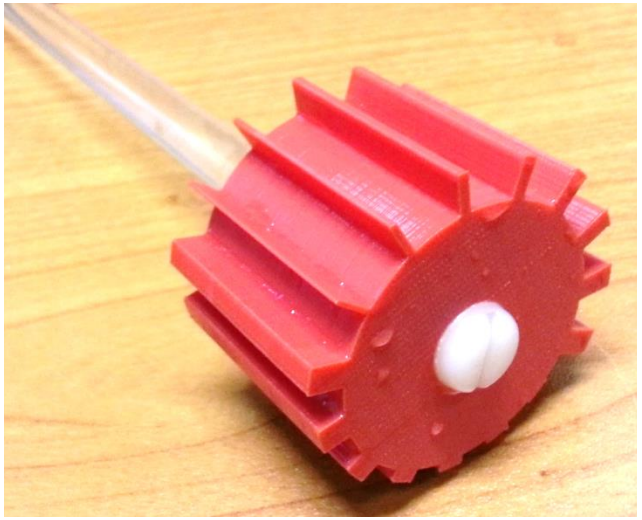


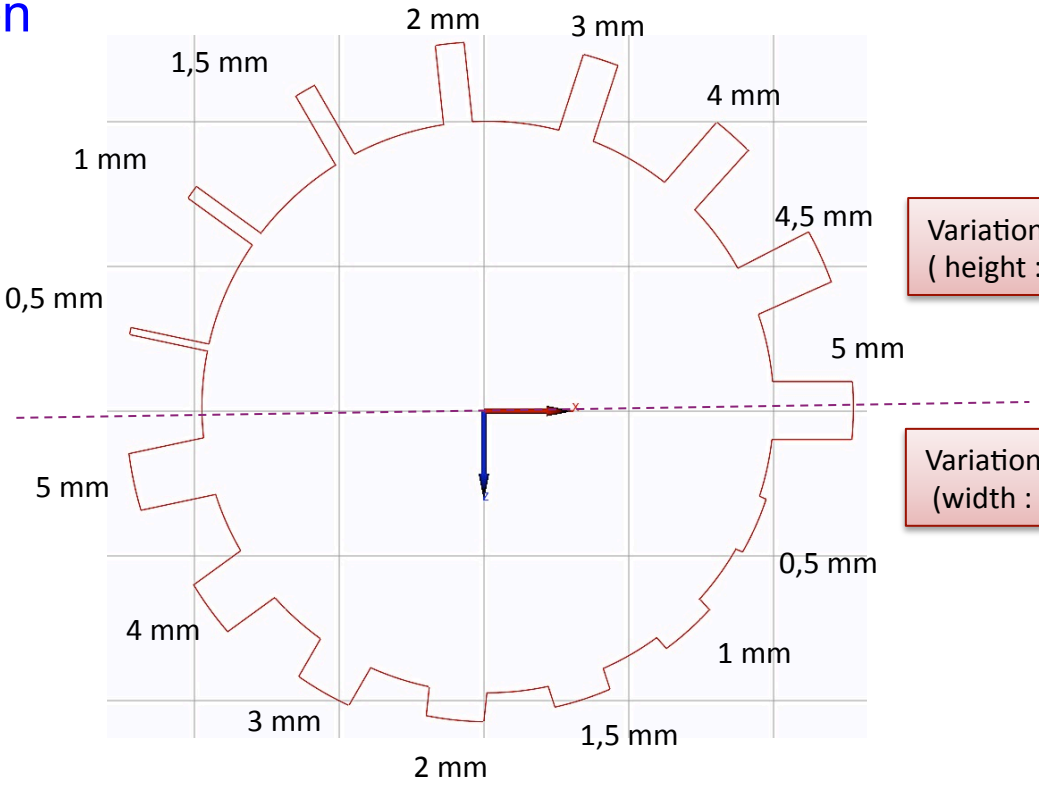


Lock washe reconstructed image

Acoustic labeling (barcode)

Fuel assembly identification





Variation of the **width** (height : 5 mm)

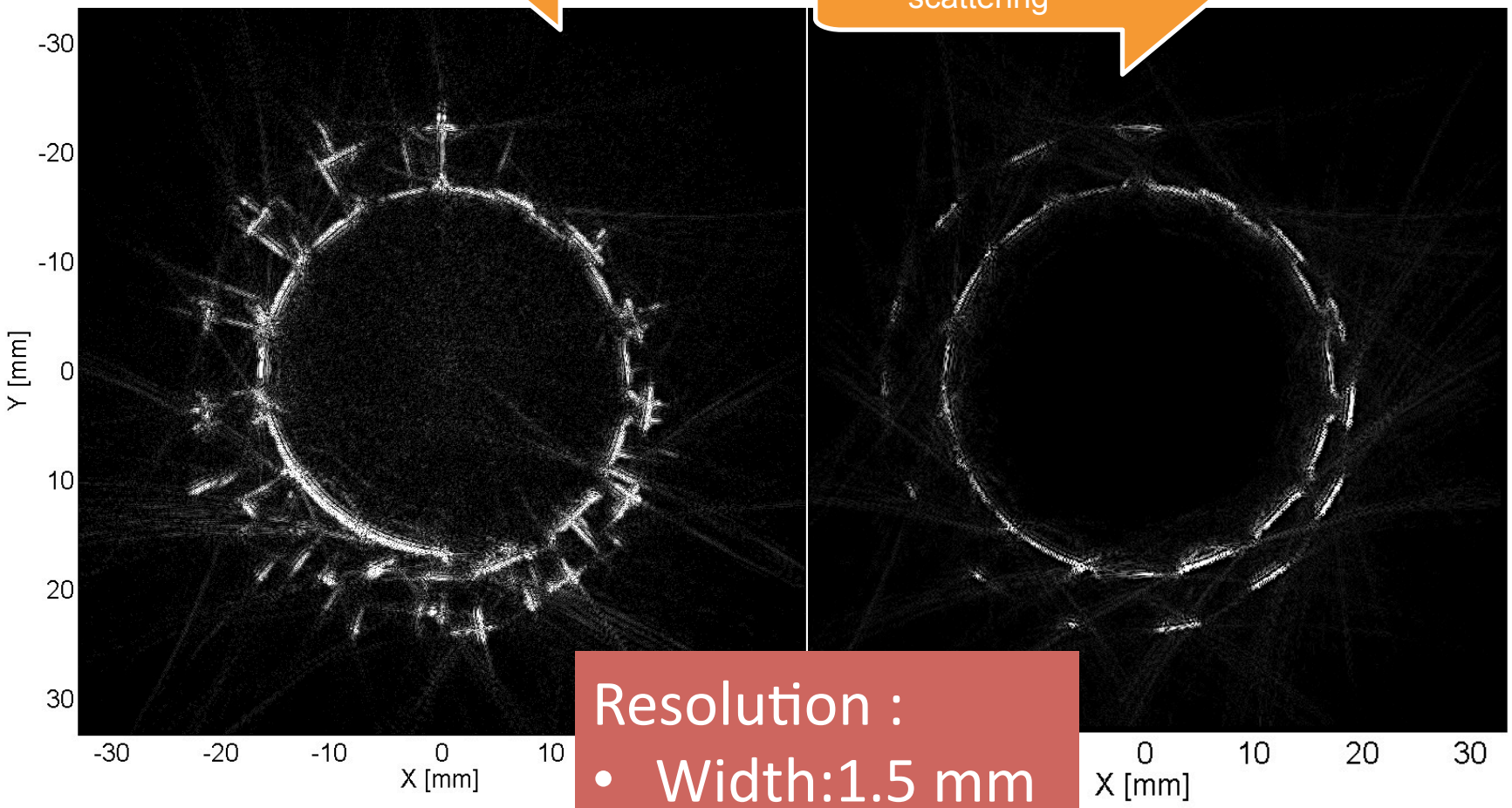
Variation of the **height** (width : 5 mm)

SURFACE IMAGING

Acoustic labeling

Raw data

Suppression of multiple scattering



Resolution :

- Width:1.5 mm
- Height: 0.5 mm

SURFACE IMAGING

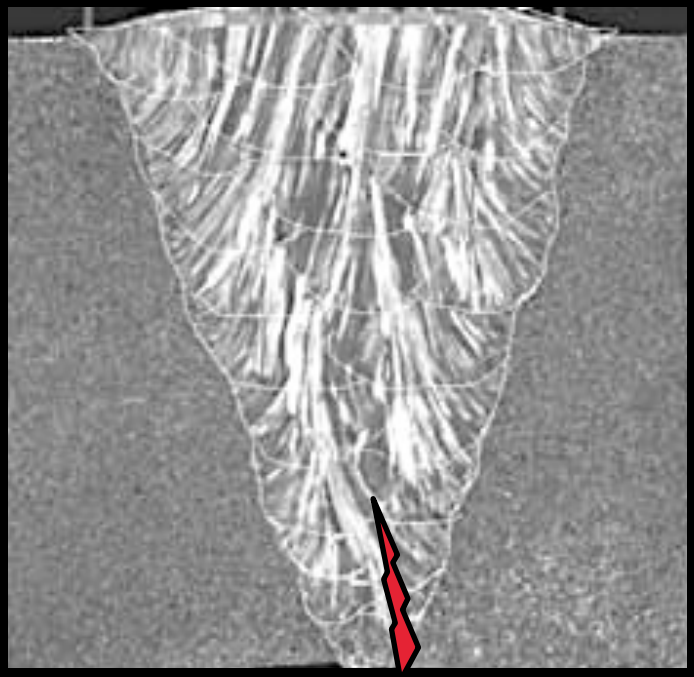
Summary:

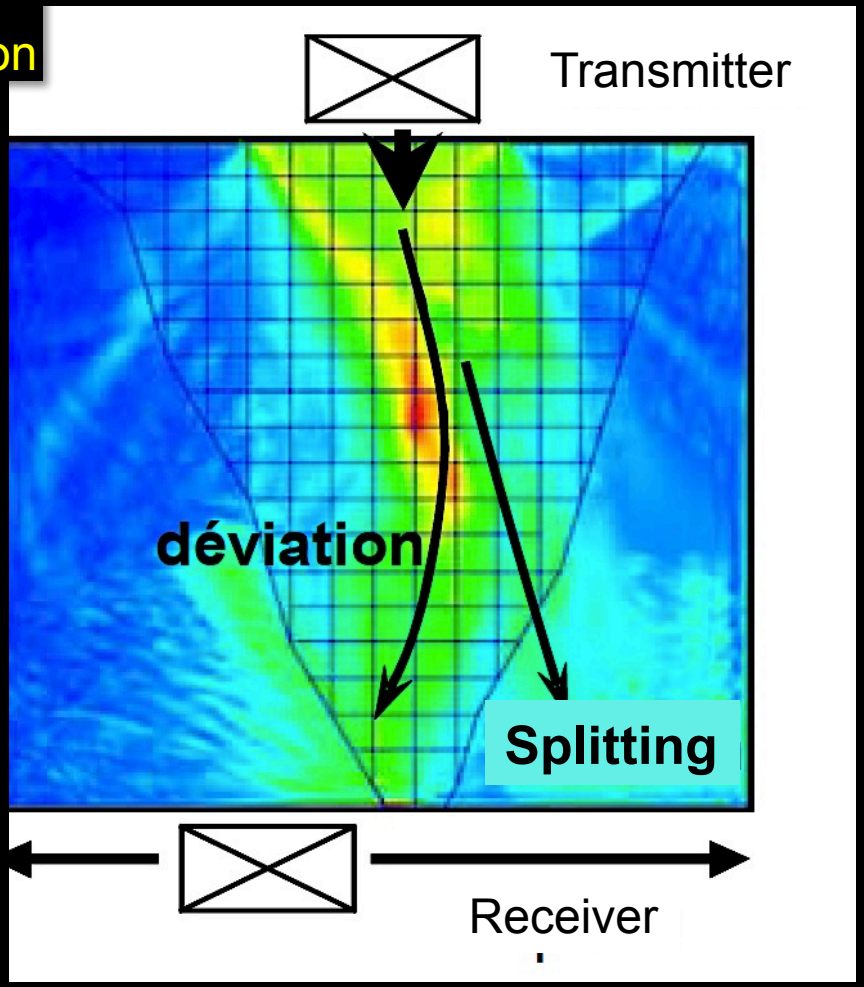
- Satisfactory tomographic image quality
- Possibility to introduce *prior* information

- **Limitation**: *homogeneous* host medium

Ultrasounds propagation:

Influence of welding passes on grain orientation





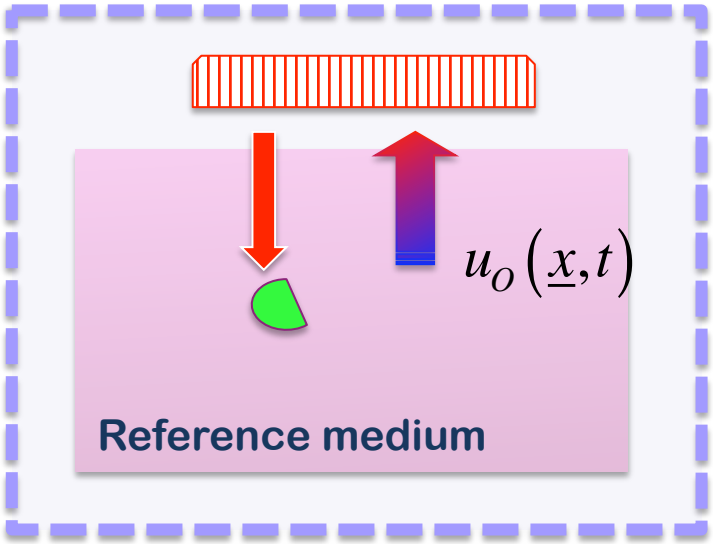
Chassignole, Thesis 2000
Ploix 2006, Apfel Ultrasonics 2005
Becache, Joly, Tsoka, JCA 2001
Ye, IJPVP 2012

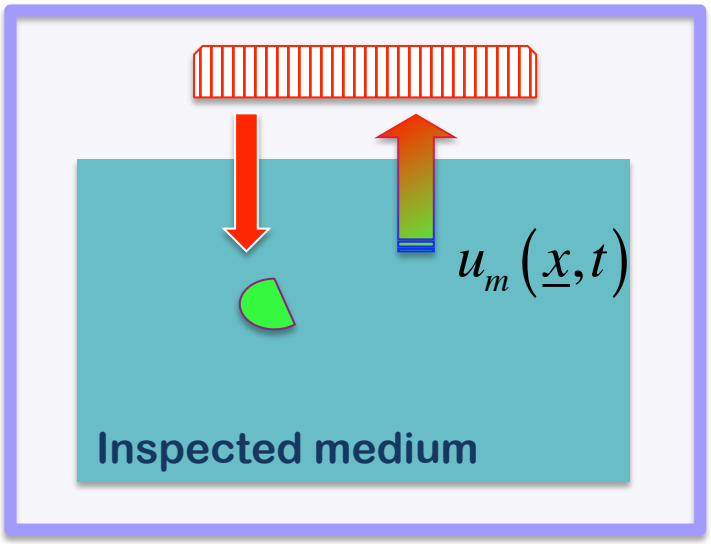
ADJOINT METHOD

Issue : in depth imaging of heterogeneous media (**strong contrast**)

Minimization

$$E_Q = \frac{1}{2}\int_0^T \int_{\Gamma_m} (u_0 - u_m)^2 \, dx \, dt$$





Iterative process

ADJOINT METHOD : ELASTODYNAMICS

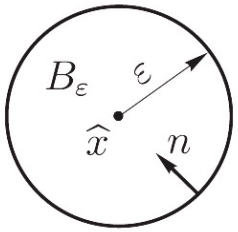
Wave equation : $\dfrac{\partial^2 u}{\partial t^2} - \dfrac{\operatorname{div}\sigma(u)}{\rho} = F$, Hooke's law : $\underline{\sigma_2}(u) = \underline{C_4}\ \underline{\varepsilon_2}(u)$

$$E_Q = \frac{1}{2}\int_0^T \int_{\Gamma_m} (u_0 - u_m)^2\, dx\, dt, \qquad \delta E_Q = \frac{1}{2}\int_0^T \int_{\Gamma_m} \nabla_u E_Q \,.\, f(x)\, dx\, dt$$

Quadratic error from reference — **Differential of E_Q**

Boundary conditions	*f(x)*	$\nabla_u E_Q$
2D Dirichlet	$\dfrac{2\pi}{\log(\epsilon)}$	$\int_0^T \dfrac{2\mu(\mu+\eta)}{2\mu+\eta} u_0 v_0\, dt$
2D Neumann	$\pi\epsilon^2$	$\int_0^T \left(\dfrac{(\mu+\eta)}{2\mu\eta} [4\mu\sigma(u_0) : \varepsilon(v_0) + (\eta - 2\mu)\, \mathrm{tr}\sigma(u_0).\mathrm{tr}\varepsilon - \rho\partial_t u_0 . \partial_t v_0] \right) dt$

Garreau, SIAM JCO 2001, ECCOMAS 2004



ADJOINT METHOD

Theoretically :
Functional gradient

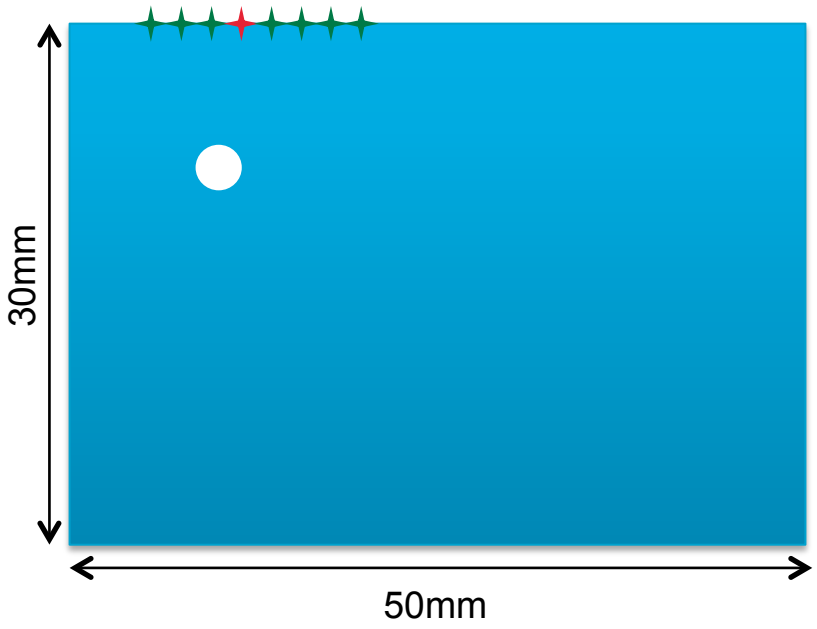
$$\nabla_u E_Q \approx \int_0^T u_0(x,t) v_0(x,t) dt$$

Practically :
Topological energy

$$E_T \approx \int_0^T \|u_0(x,t)\|^2 . \|v_0(x,t)\|^2 dt$$

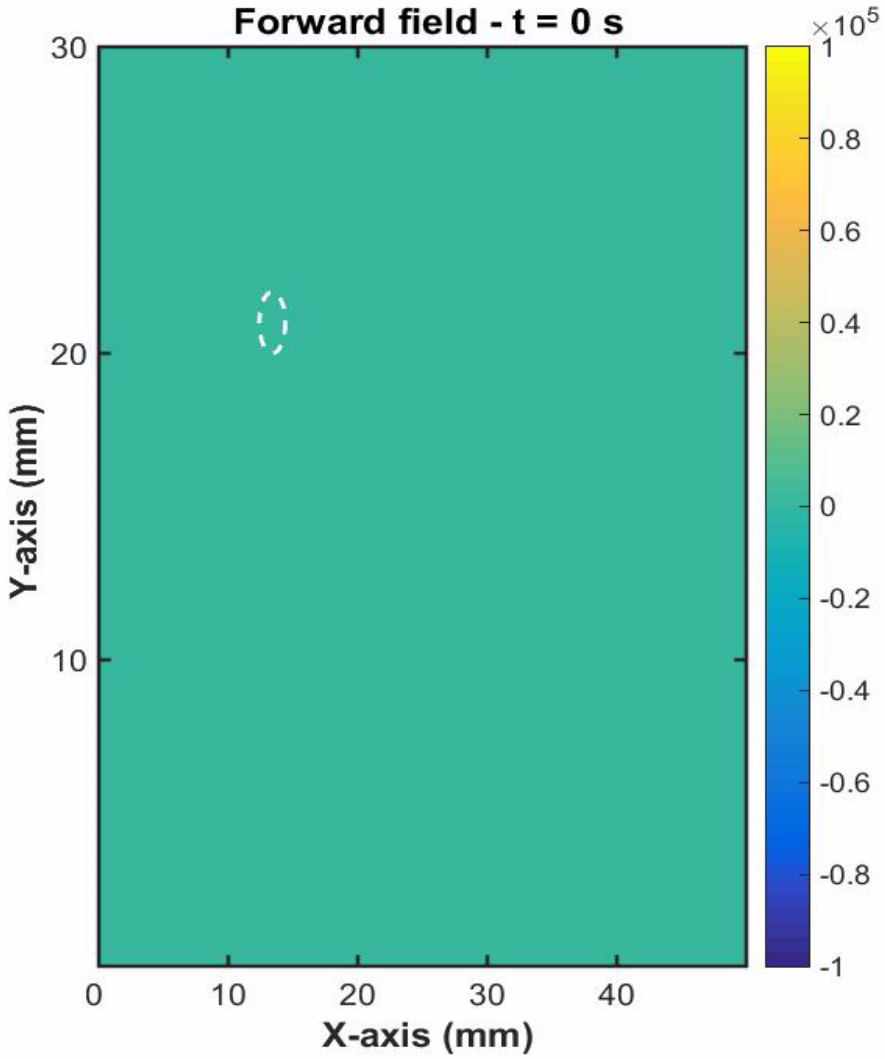
Dominguez, Thesis 2000

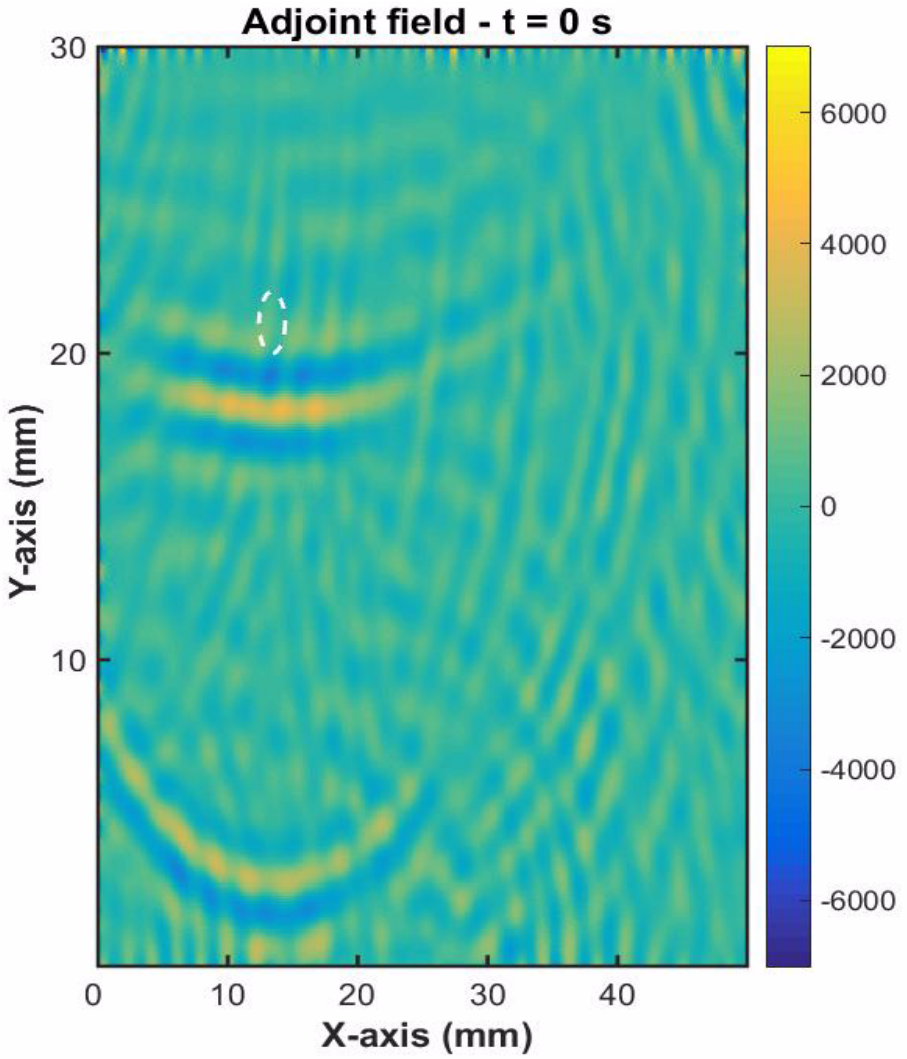
Simulation configuration



- Stainless steel slab
- Cylindrical incident wave,
- Wavelength: 0.15 mm (2 MHz)
- Defect Air : $\emptyset = 1\ \mathrm{mm}$
- Boundary condition: Dirichlet condition
  - ➢ Total wave reflection with a phase shift.

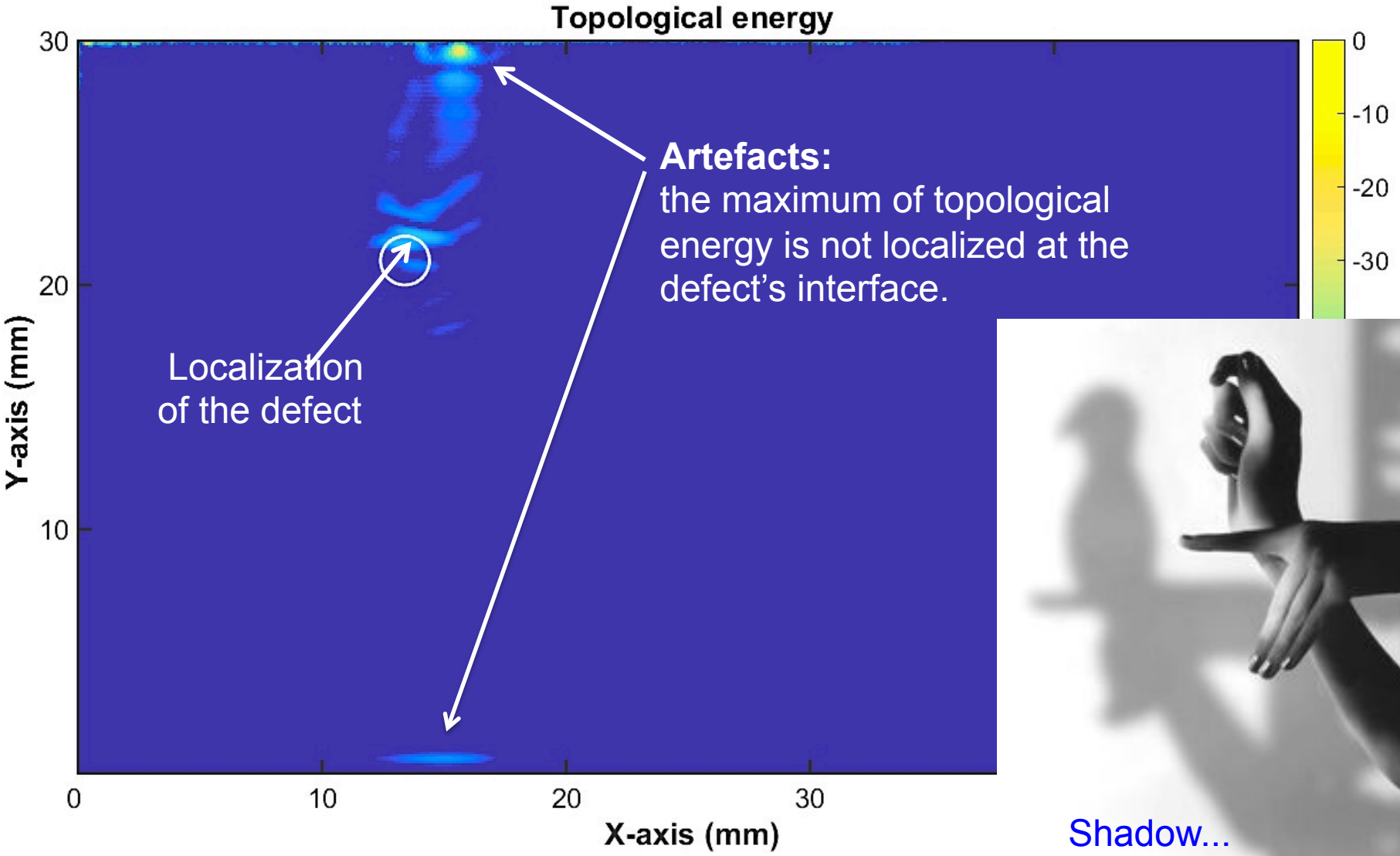
ADJOINT METHOD





BACKPROPAGATION: DIRICHLET BOUNDARY CONDITIONS

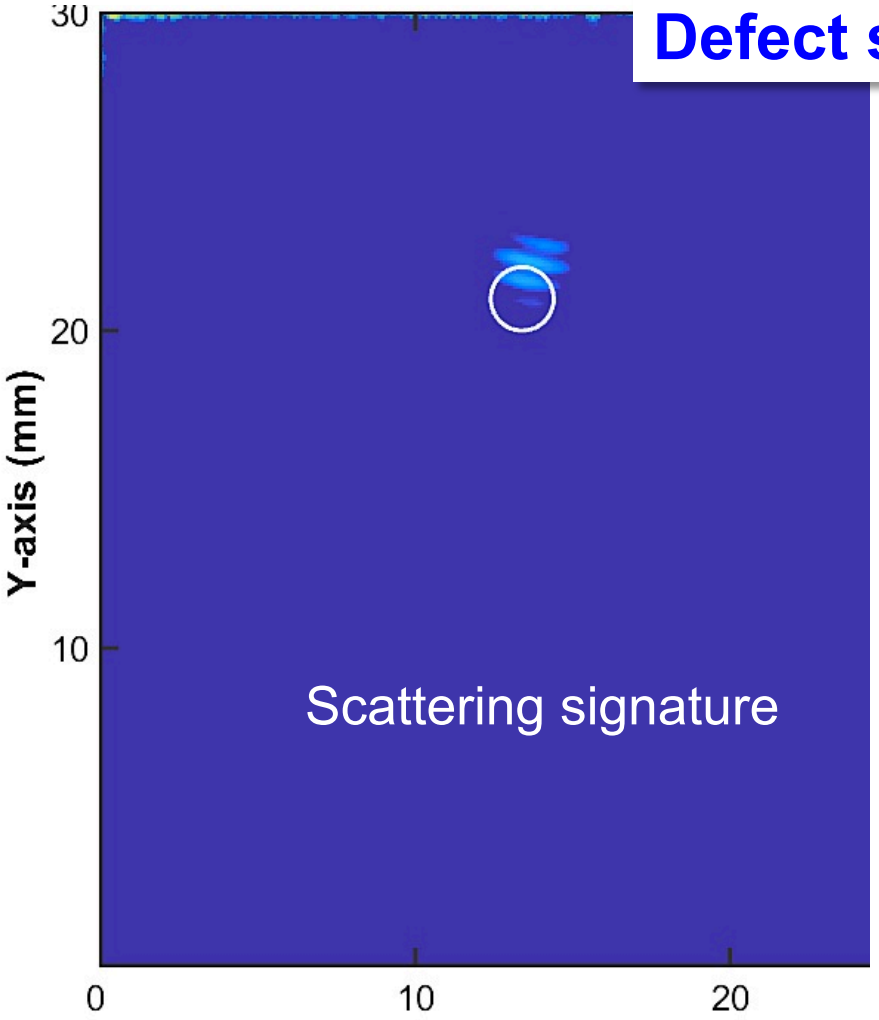
ADJOINT METHOD

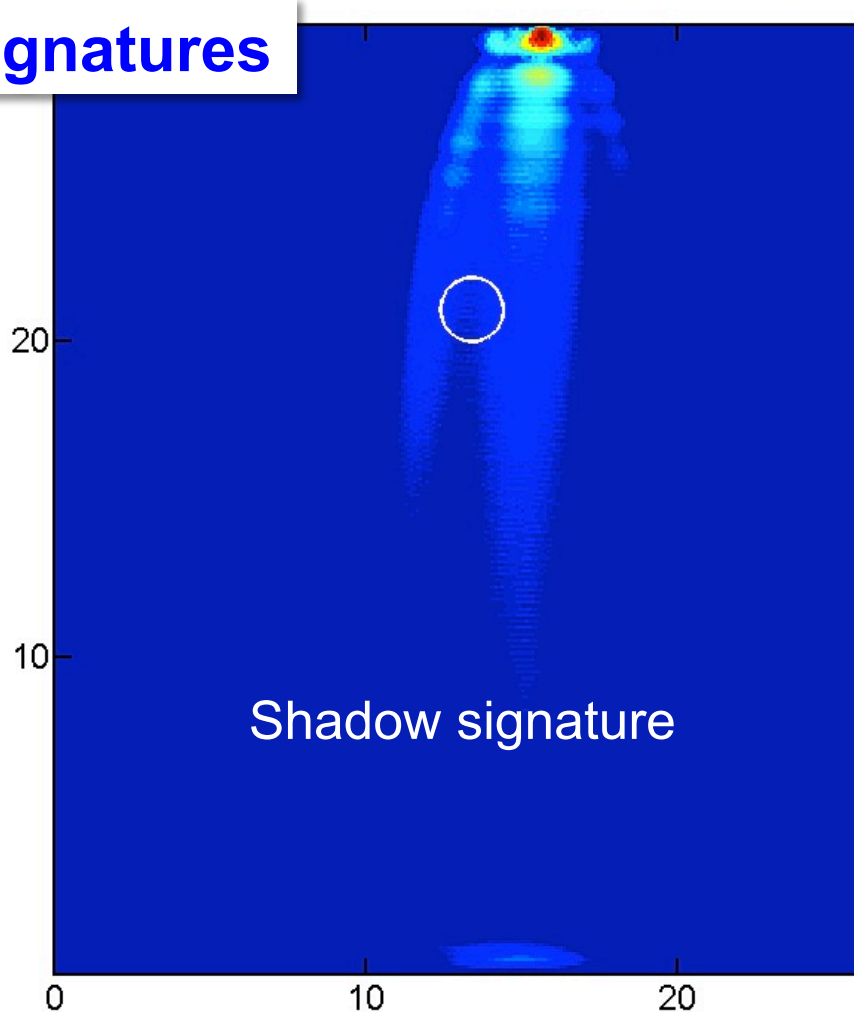


Shadow...

SUMMARY: DEFECT SIGNATURES

Defect signatures

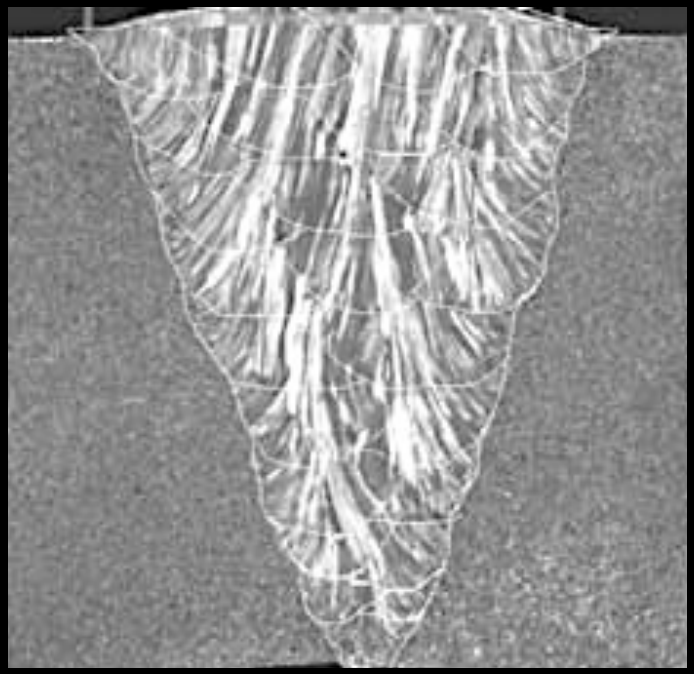


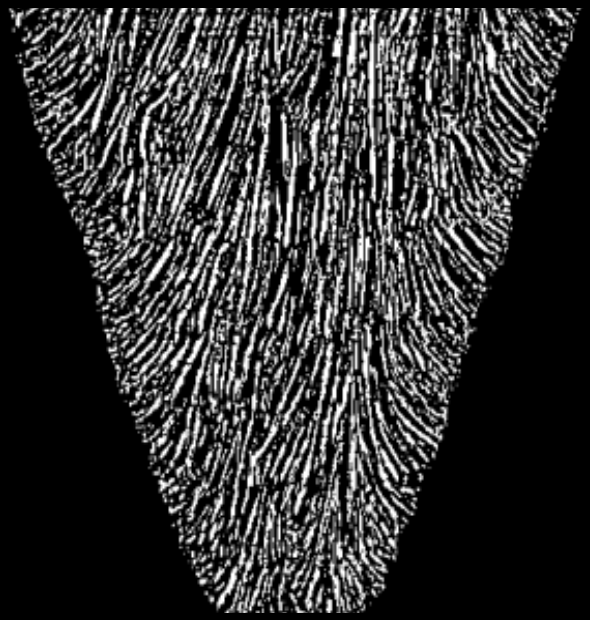


ANALYSE RADIOGRAPHIQUE – SOUDURE D717B

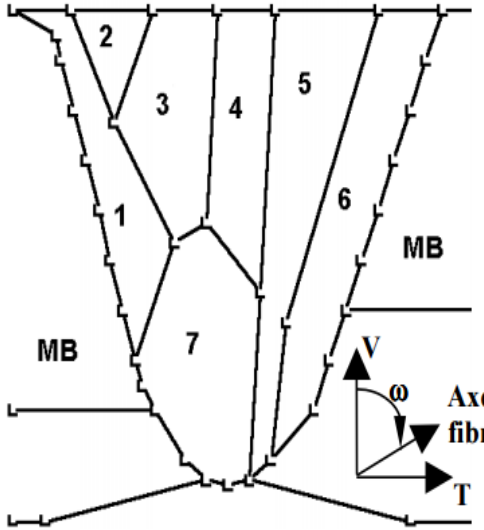
Ultrasounds propagation:

Influence of welding passes on grain orientation

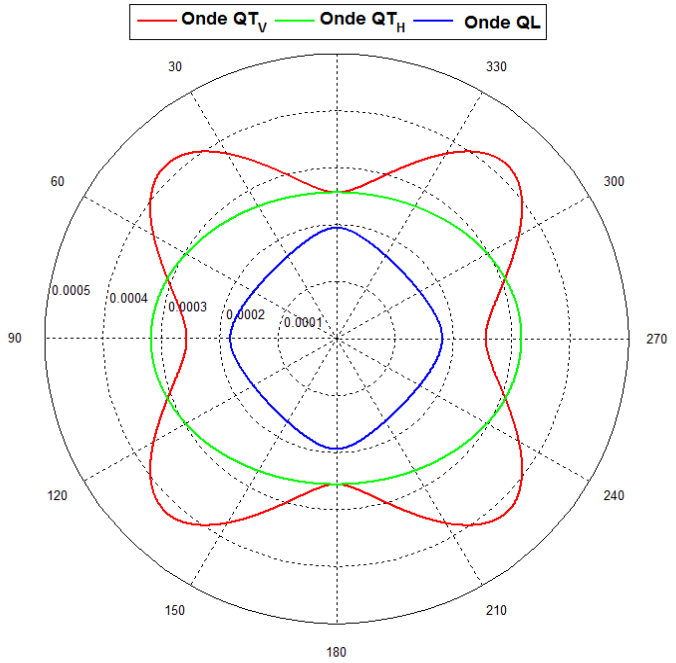


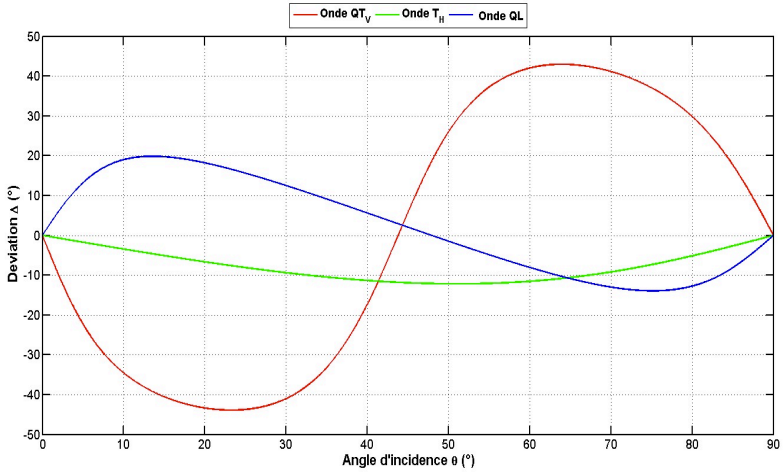


PROPAGATION ULTRASONORE



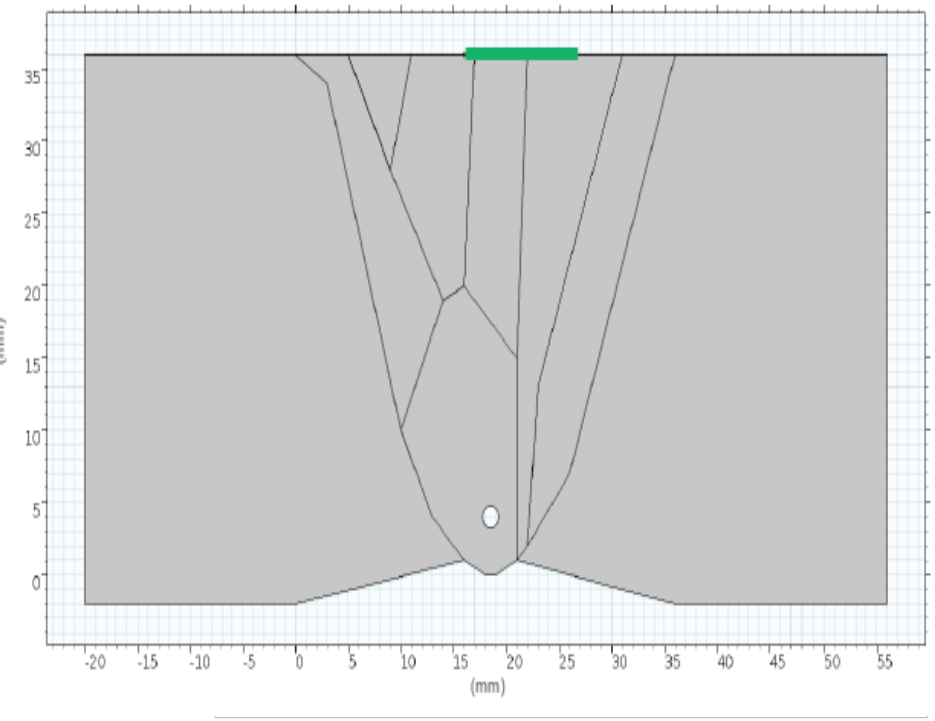
Domaines orthotropes	ω (°)
1	35
2	11
3	18
4	8
5	0
6	-31
7	14
Domaines isotropes	
MB	/

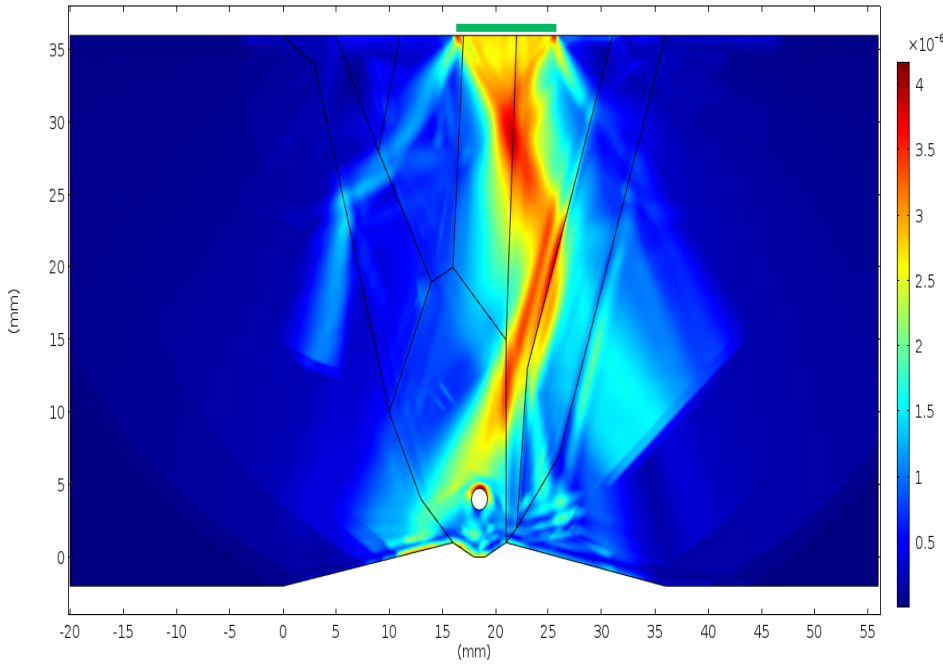




$$c = \begin{vmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12} & c_{11} & c_{13} & 0 & 0 & 0 \\ c_{13} & c_{13} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{c_{11}-c_{12}}{2} \end{vmatrix}$$

PROPAGATION ULTRASONORE – SOUDURE D717B





Domaine de calcul et zones quasi-homogènes ; maxima d'amplitude de l'onde US.

Résultat de simulation COMSOL.

ESSAIS EXPÉRIMENTAUX EN SODIUM

Banc VENUS d'essais en sodium liquide à 200°C, opérationnel 2016

CONCLUSION

- **Surface imaging**
  - Homogeneous reference medium : tomographic reconstruction.
  - Prior knowledge of the object: Fitting of scattering signature
- **Adjoint method: solution to heterogeneous medium imaging**
  - Separation of defect's signatures
    - Diffraction: localization of the proximal defect boundary.
    - Shadow: information relative to energy loss (scattering, viscosity)
  - **Specificities :** Localization vs Probability of detection

- **Perspective:**
  - **Normalization (Energy map).**
  - **Consideration for defect detection/characterization.**
  - **Experimental evaluation**

Thank you for your attention

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