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Jean François Chaix

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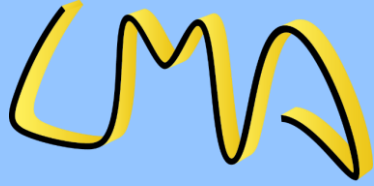
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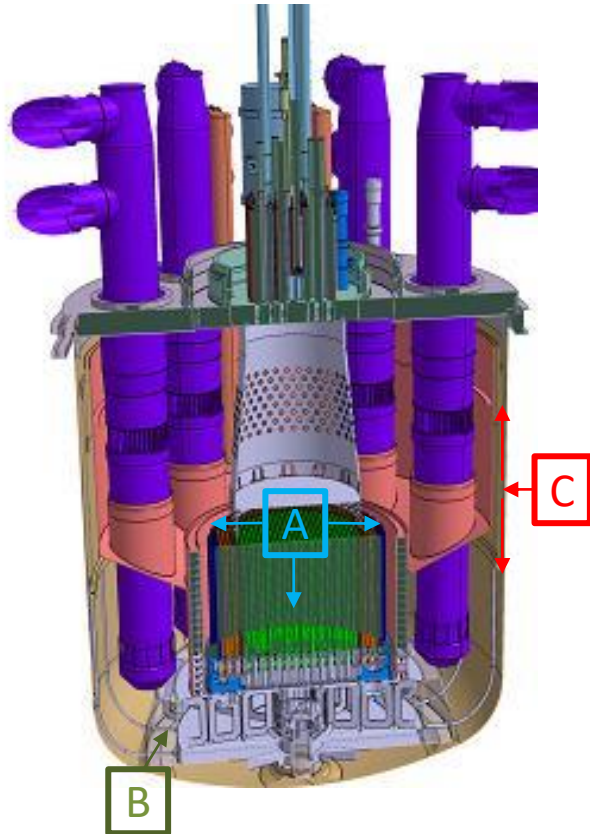
TIME REVERSAL METHOD APPLIED TO LEAKY LAMB WAVES IN AN IMMERSED LAYERED MEDIUM

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Industrial context



- Liquid sodium-cooled reactors (SFR-Na) - Generation IV

- Periodic inspection using ultrasonic waves (US)

- Internal inspection

 - (A) Immersion of a TUSHT sensor (wettability, resistance to sodium)

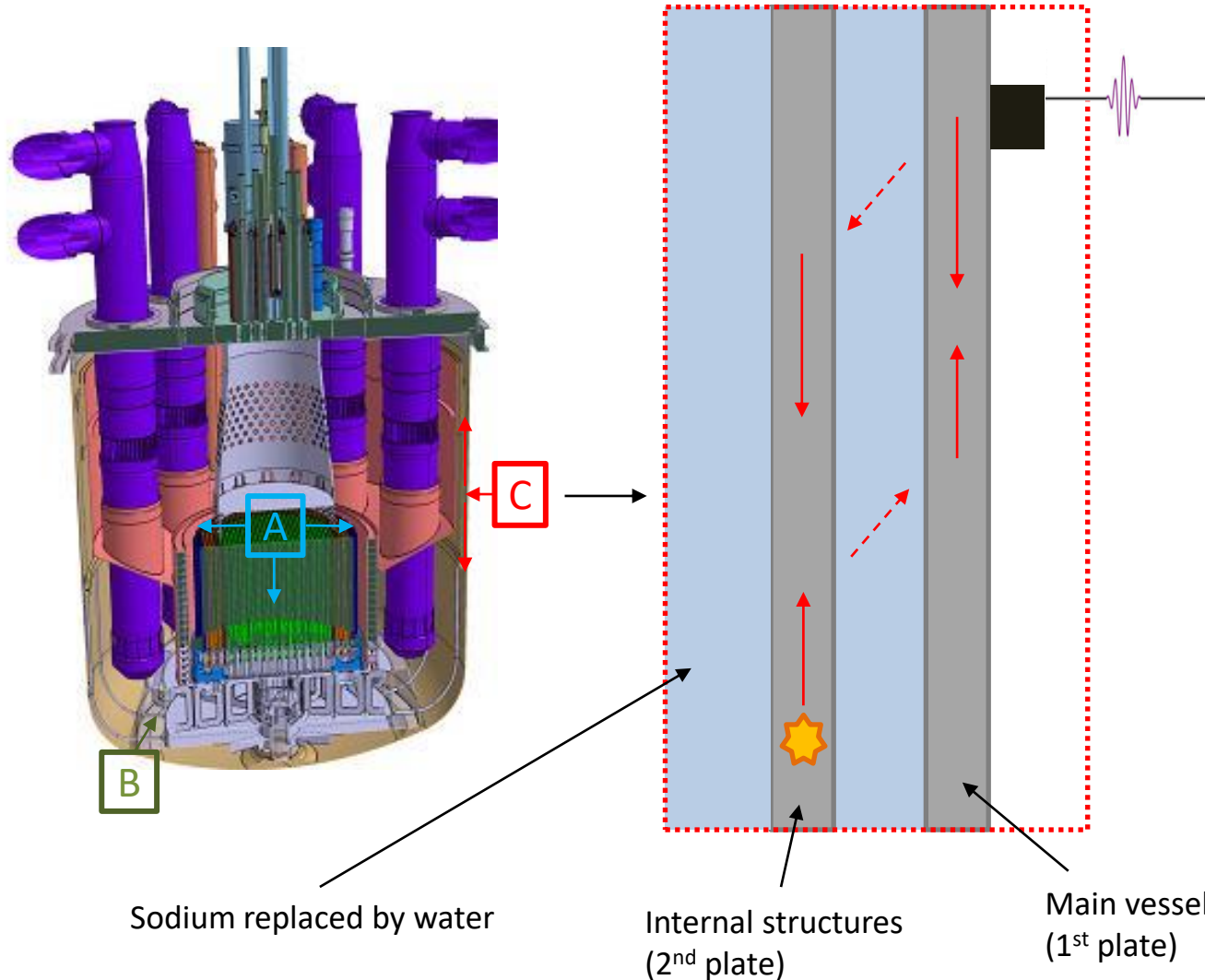
- External inspection

 - (B) Plate-supported guided waves

 - (C) Guided waves in the main tank and internal structures

➔ Problem statement of this work

Inspection configuration



- Generation of Lamb wave in the primary vessel
- Energy leakage from the fluid to the internal structure
- Interaction with a defect
- Energy leakage from the fluid to the primary tank
- Recording of the echo

Problem statement

Lamb waves

Propagation of leaky Lamb waves in an immersed multi-plate system

Time reversal

Application of topological energy to an immersed multi-plate system

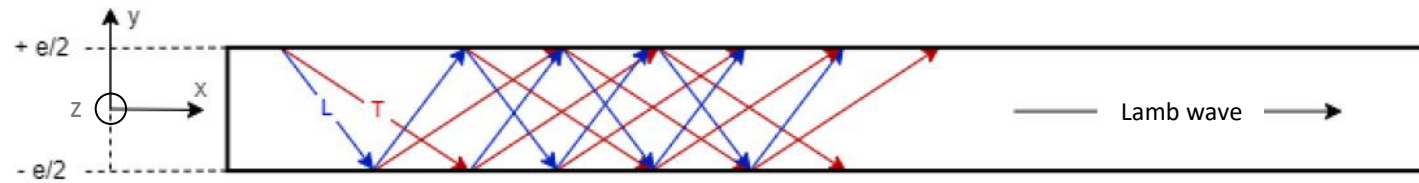


Detecting and locating potential defects in an immersed multi-plate system

- Identification of the damaged plate
- Defects: plate edge and notch

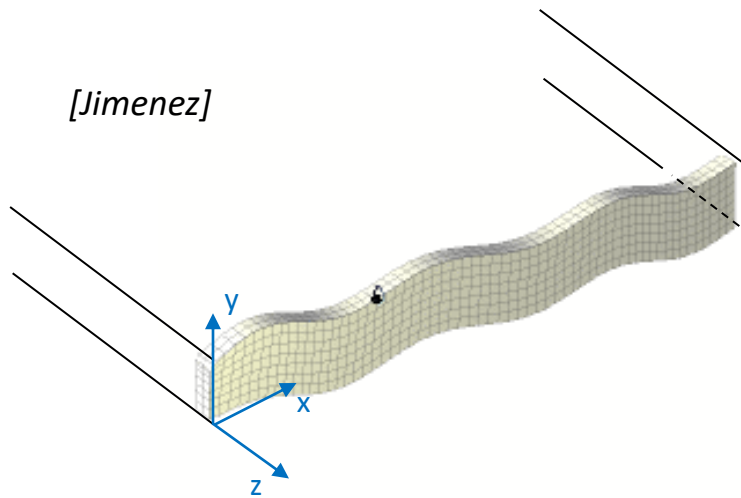
Lamb waves

Conversions between longitudinal and transverse waves

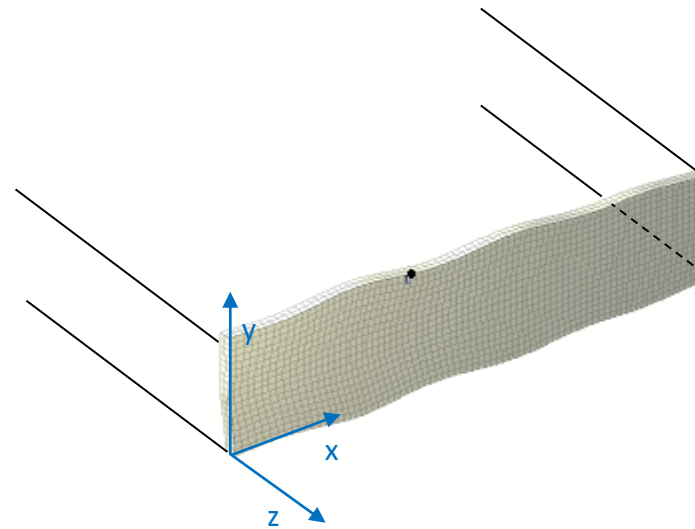


Two families of Lamb waves

[Jimenez]



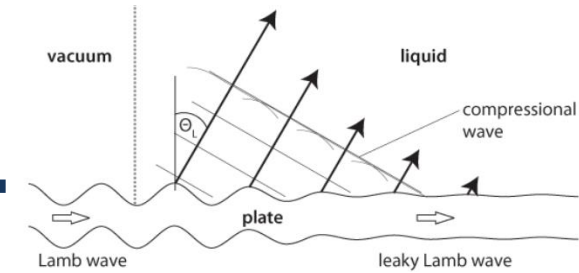
Antisymmetric modes



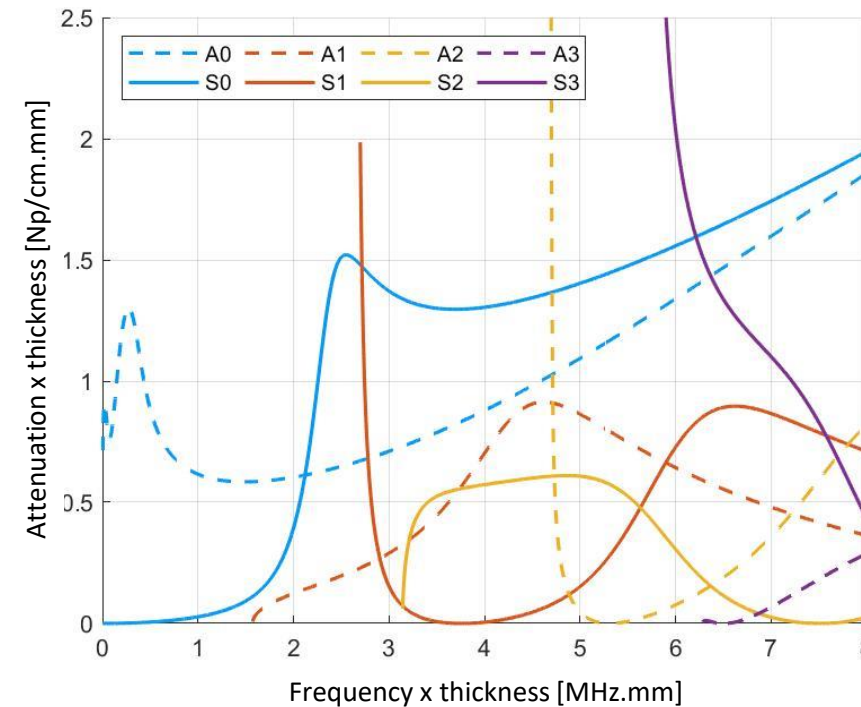
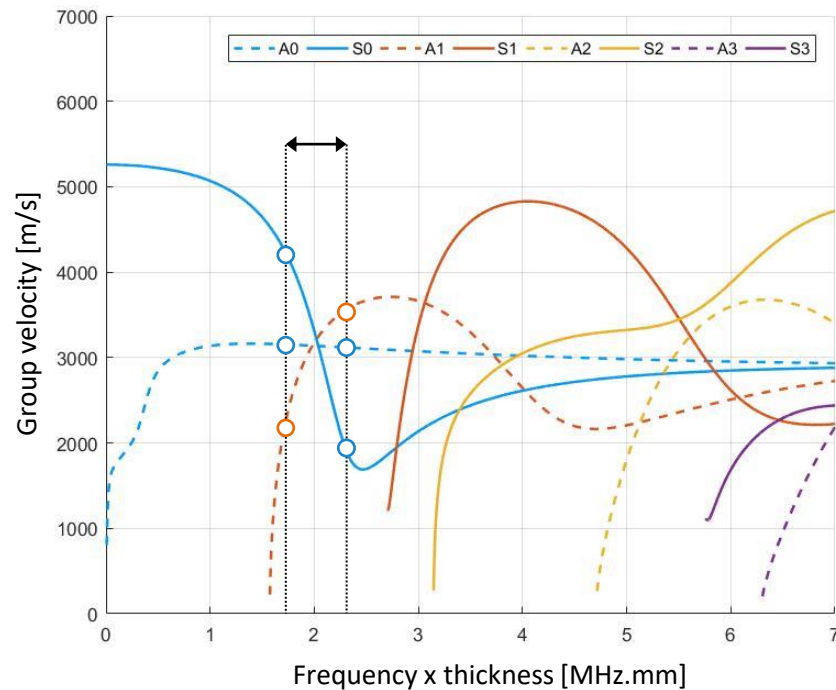
Symmetric modes

Each mode has a displacement profile that is either symmetric or antisymmetric in the thickness of the plate

Lamb waves characteristics



[Schmitt, 2013]



- Multimodal nature: multiple modes can coexist at the same frequency
- Dispersive nature: the group velocity of a mode varies over a frequency range

- Imaginary part of the solution of the dispersion equations
- Attenuation by re-emission into the surrounding fluid \Rightarrow Leaky Lamb Waves (LLW)

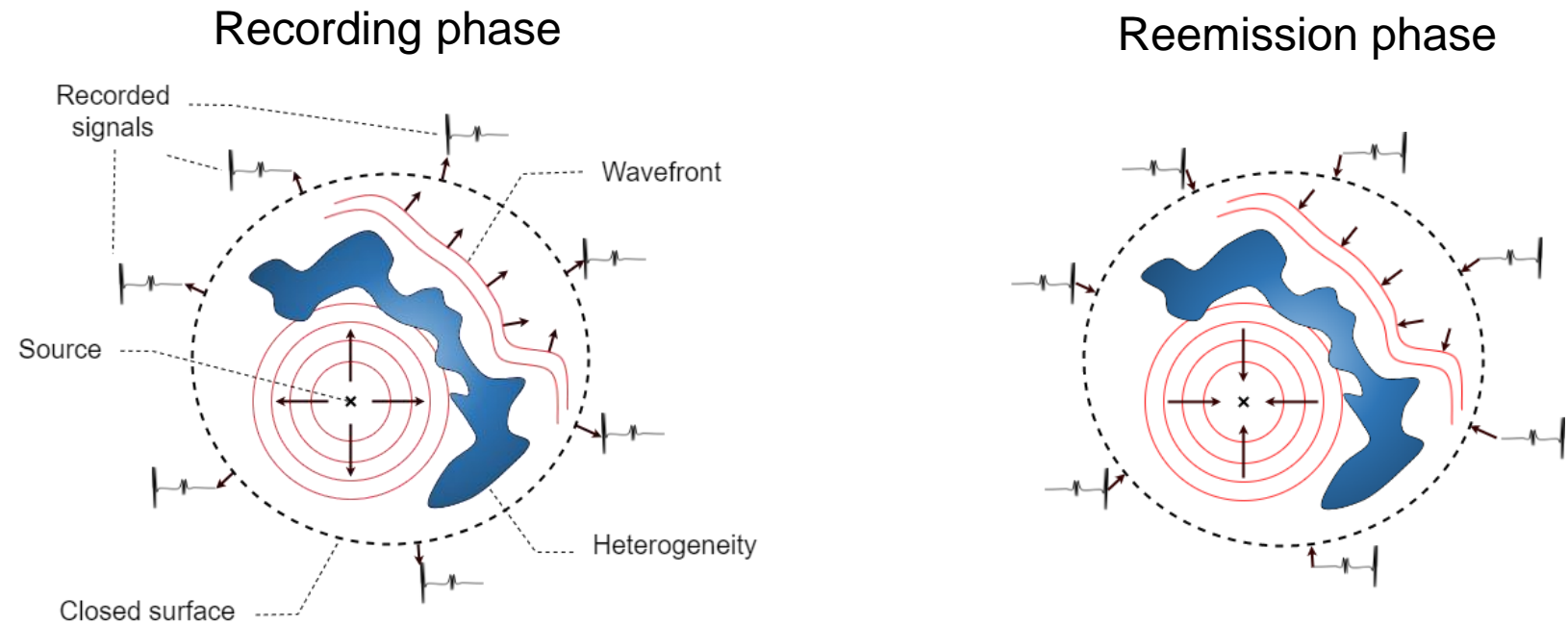
Time-reversal cavity

from [Fink, 1992]

In a non-dissipative homogeneous medium:

$$\mathbf{L} = \Delta - \frac{1}{c^2} \frac{\partial^2}{\partial t^2}$$

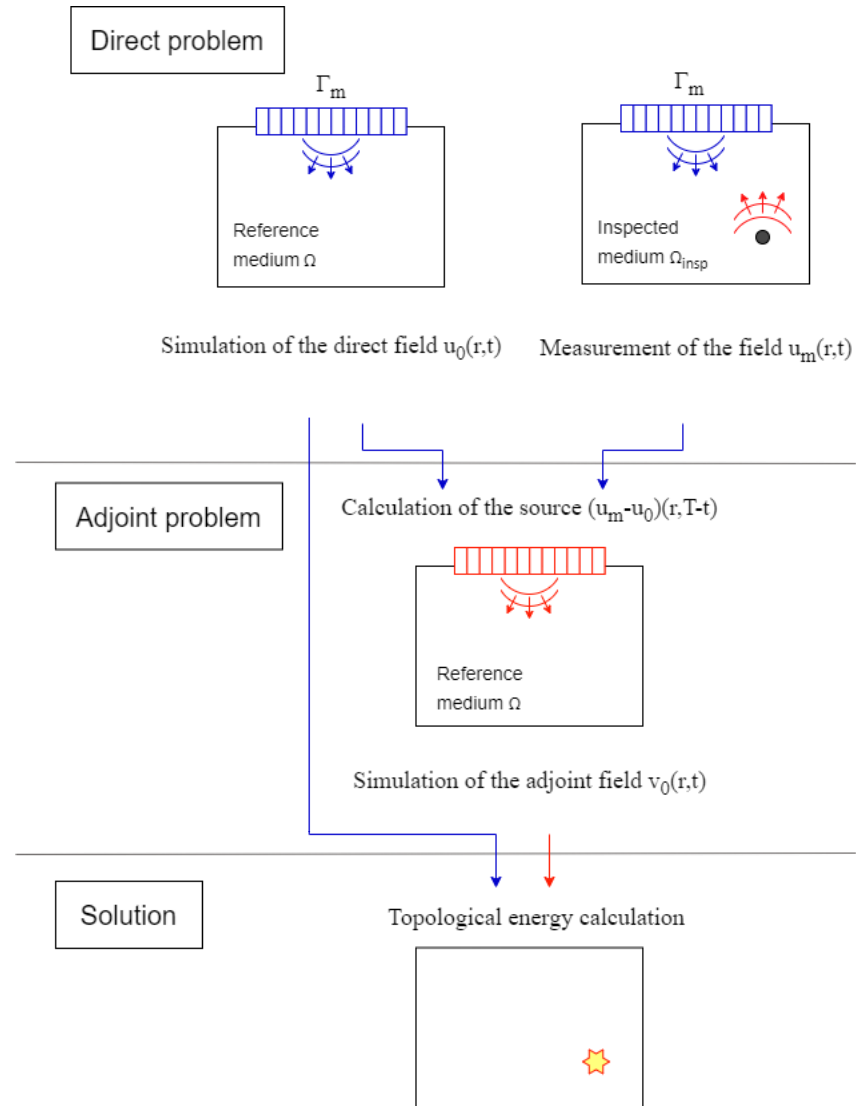
- Spatial reciprocity
- Temporal reciprocity
- Huygens-Fresnel principle



Limitations: Simultaneous knowledge of the field and its gradient, diffraction (focal spot), number of sensors ...

Topological energy: calculation steps

Inspired by [Dominguez, 2005]



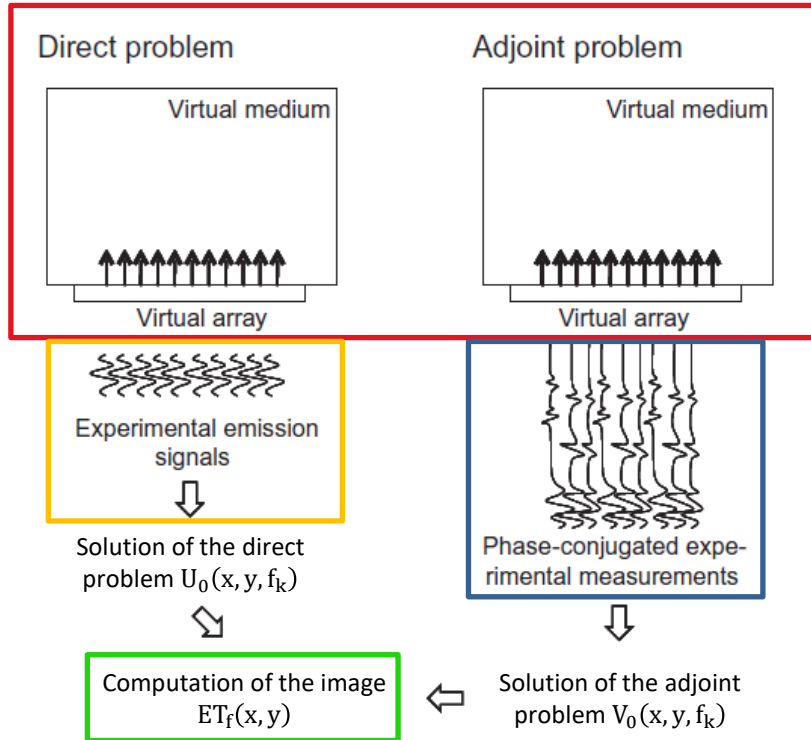
1. **Numerical resolution** of the **direct problem** in the reference medium:
 → Response of the medium in the equivalent healthy case
2. **Measurement** of the **direct problem** in the unknown medium:
 → Response of the inspected medium (reference medium + **acoustic signature of the defect**)
3. **Numerical resolution** of the **adjoint problem** in the reference medium, with the residual as the source term:
 → Backpropagation of the **residual**: refocusing at the location of the defect.
4. Calculation of topological energy:

$$ET(\vec{r}) = \int |u_0(\vec{r}, t)|^2 |v_0(\vec{r}, t)|^2 dt$$

Topological energy: frequential domain

[Rodriguez, 2012]

Same media



Direct field

$$U_0(x, y, f_k) = \sum_{i=1}^N H_i(x, y, f_k) S_j(f_k)$$

Adjoint field

$$V_0(x, y, f_k) = \sum_{i=1}^N H_i(x, y, f_k) R_j^*(f_k)$$

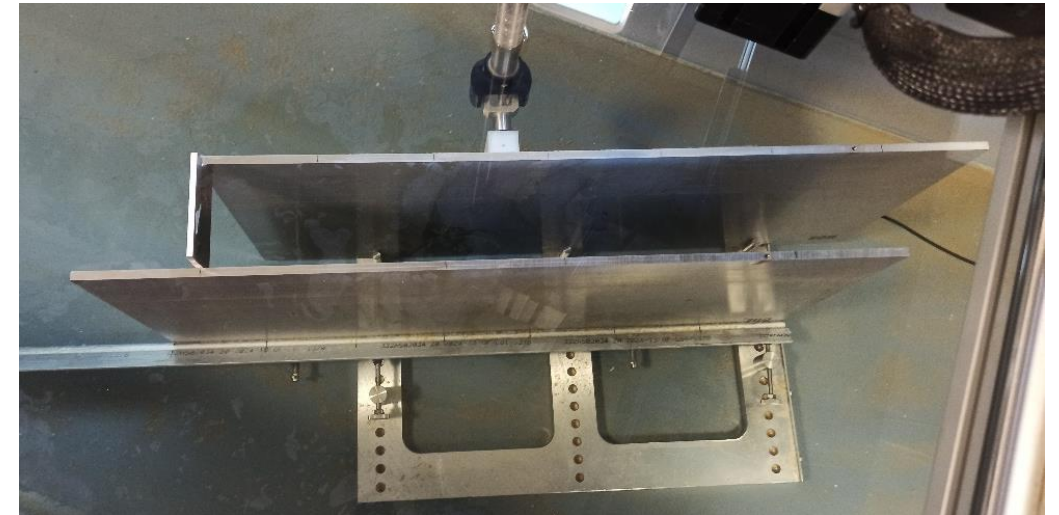
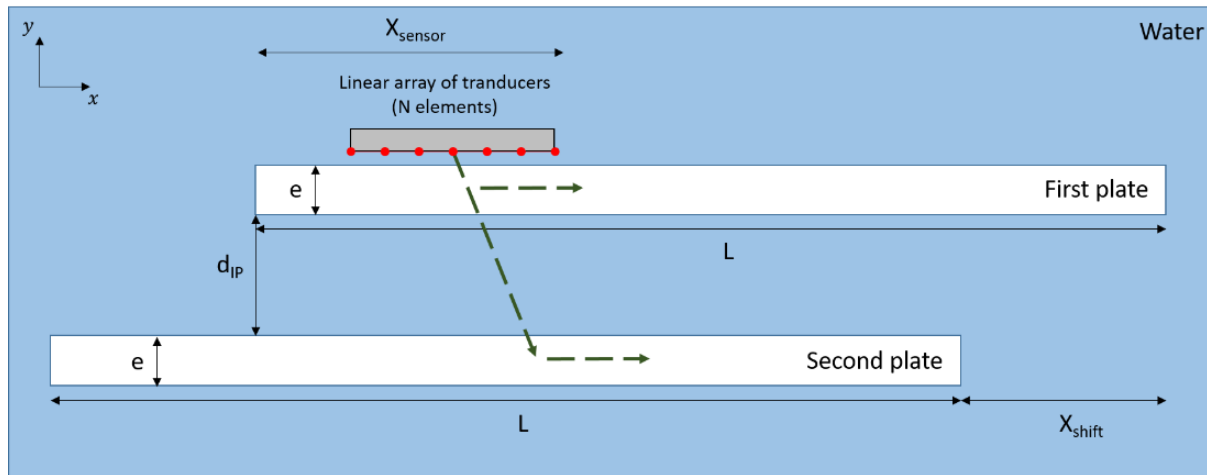
$$ET_f(x, y) = \left| \sum_{k=1}^N U_0(x, y, f_k) V_0(x, y, f_k) \right|$$

Protocols

Experimental protocol

Two plates of the same thickness ($e = 7,8 \text{ mm}$)

Linear array : 16 sensors

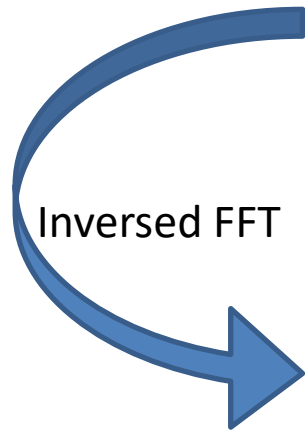


Numerical protocol

Frequential topological energy

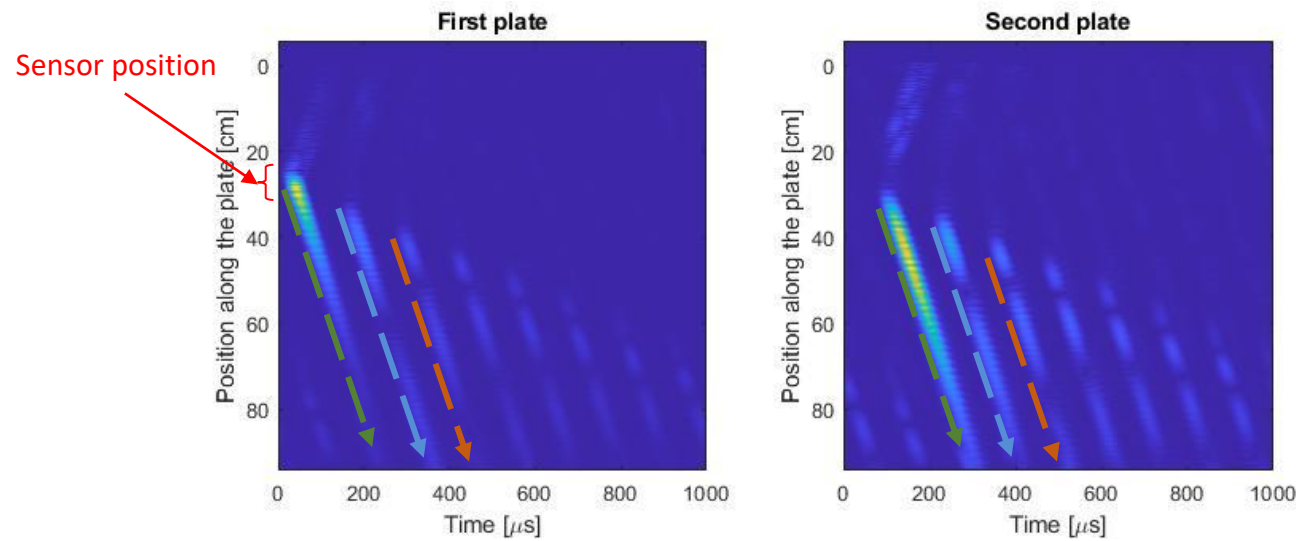
Radiation patterns calculated on the range $[1 \text{ kHz} ; 700 \text{ kHz}]$ with a step of 1 kHz in COMSOL Multiphysics®

Numerical direct problem

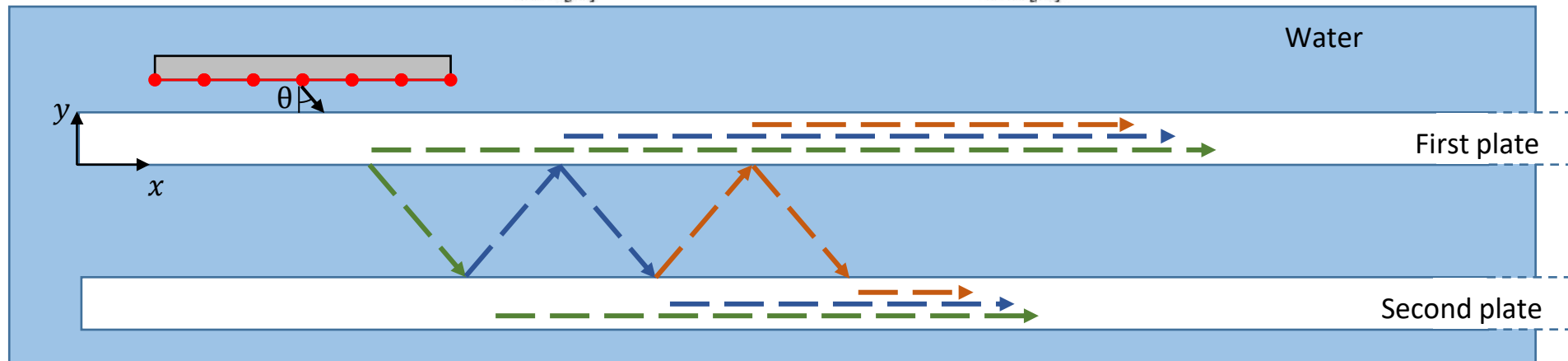


Direct field calculation:

$$U(x, y, f_k) = \sum_{i=1}^N H_i(x, y, f_k) S_j(f_k)$$



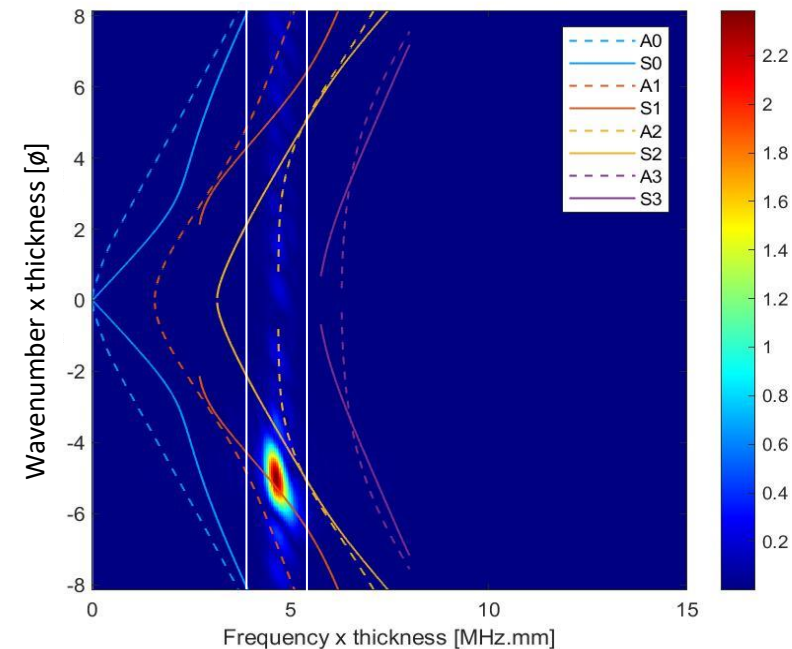
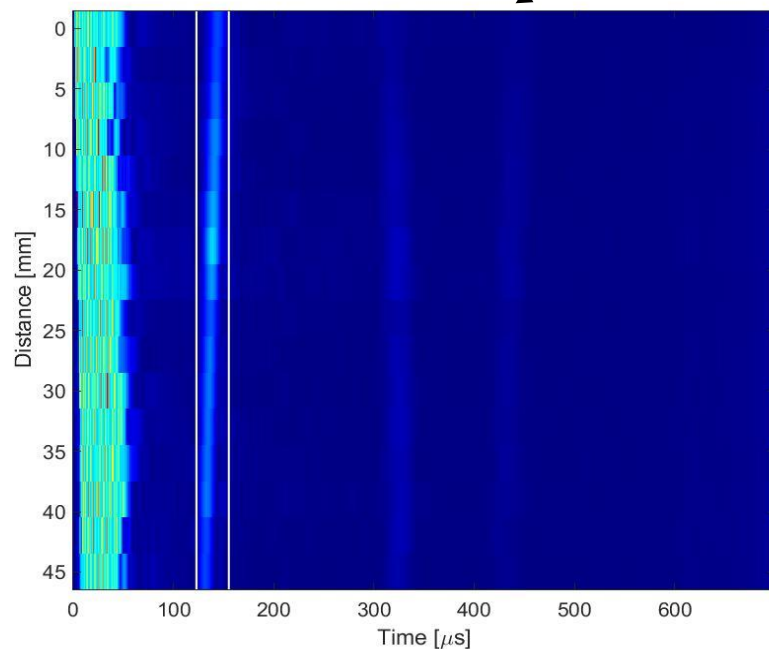
$f = 480$ kHz
 A1 mode ($\theta = 16,7^\circ$ - Snell's Law)



Analysis of the propagation: definition of the 3D-FFT

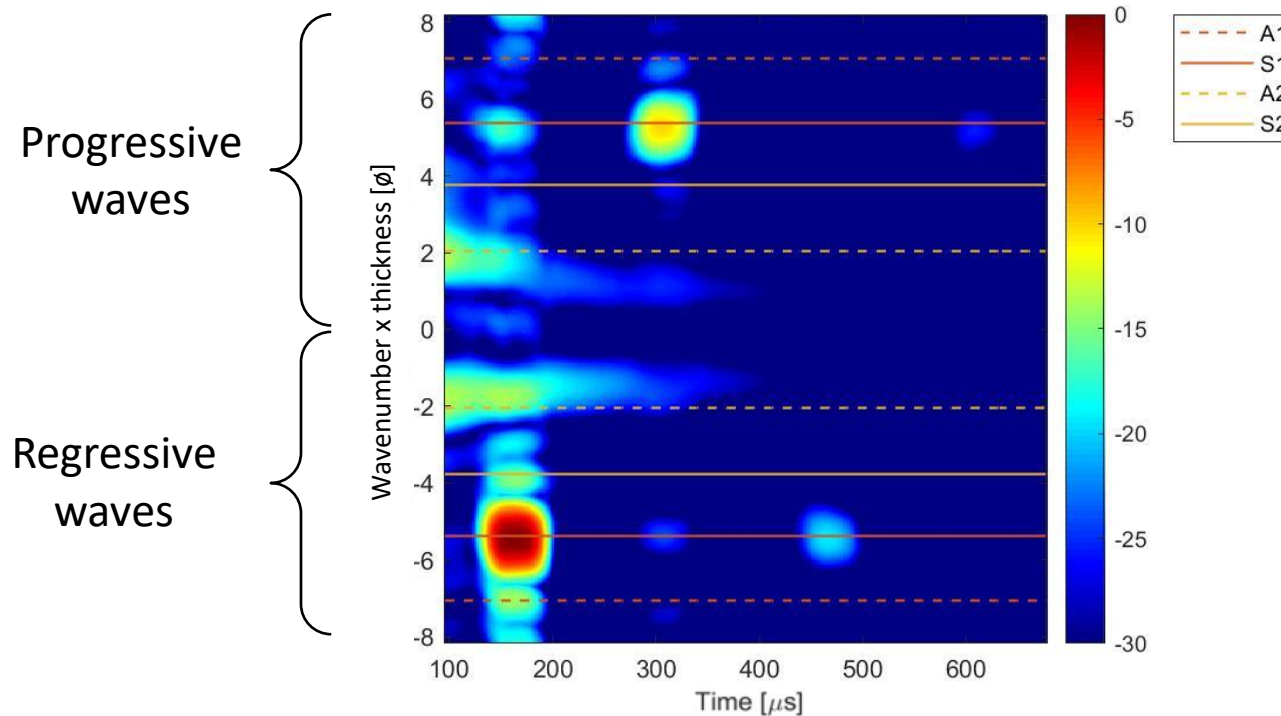
τ : the translation parameter of the weighting window

$$\text{FFT}_{3D}(u(x, t)) = \hat{U}(k, f, \tau) = \iint u(x, t) \underbrace{h^*(t - \tau)}_{\text{Weighting window function}} \underbrace{e^{-i(kx + 2\pi ft)}}_{\text{2D Fourier transform}} dx dt$$



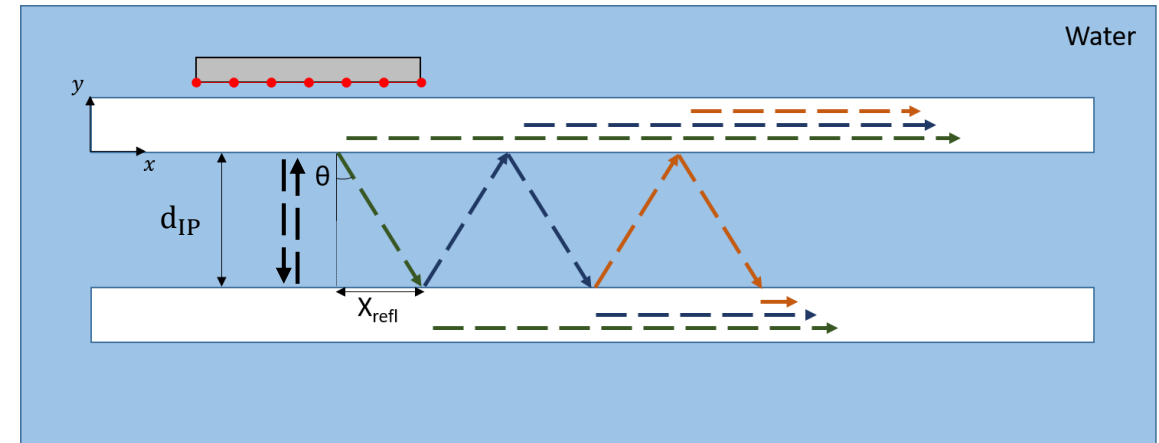
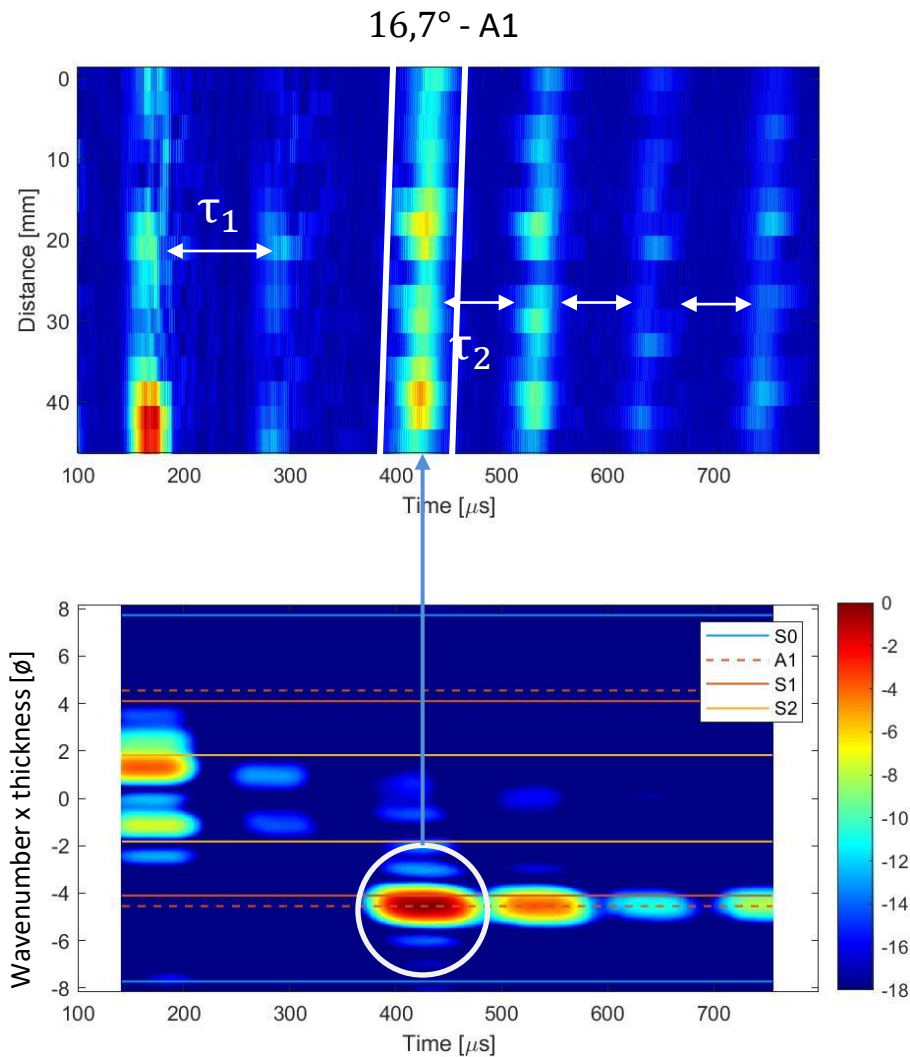
Analysis of the propagation: exploitation of the 3D-FFT

By averaging over the working frequencies for each time step τ :



→ The 3D-FFT allows for the selection and temporal isolation of Lamb modes

Measured direct problem



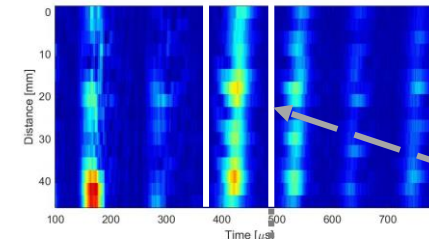
τ_1 : time of flight between the two plates (normal direction to the surface)

τ_2 : time difference of flight between two successive wave packets

→ The most energetic regressive wave packet is isolated and backpropagated

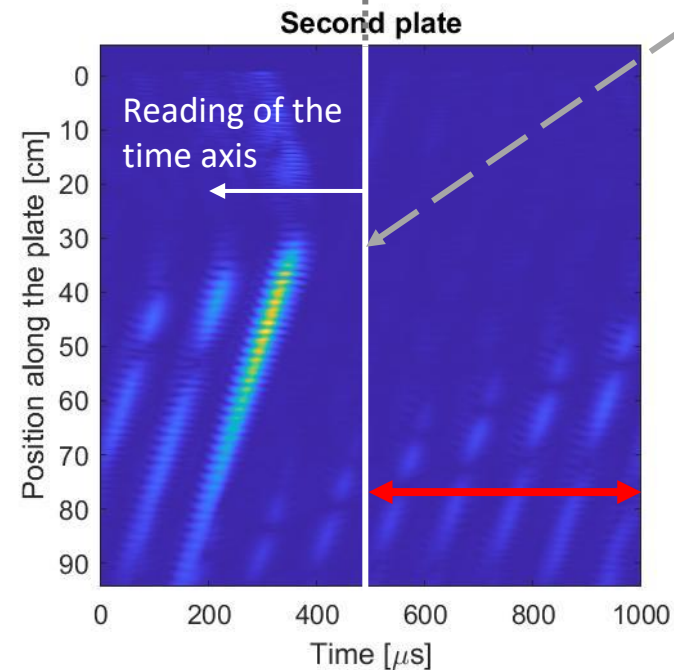
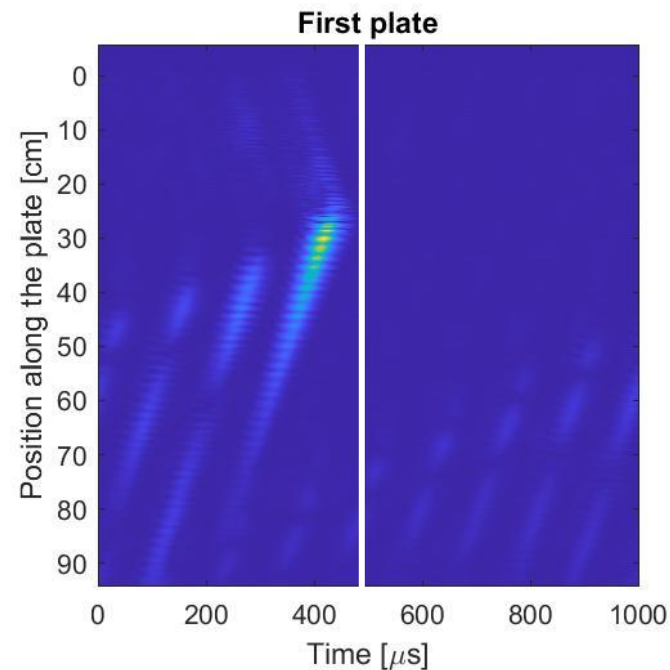
Adjoint problem

Adjoint field calculation:
$$V(x, y, f_k) = \sum_{i=1}^N H_i(x, y, f_k) R_j^*(f_k)$$



Time T at which time reversal is performed

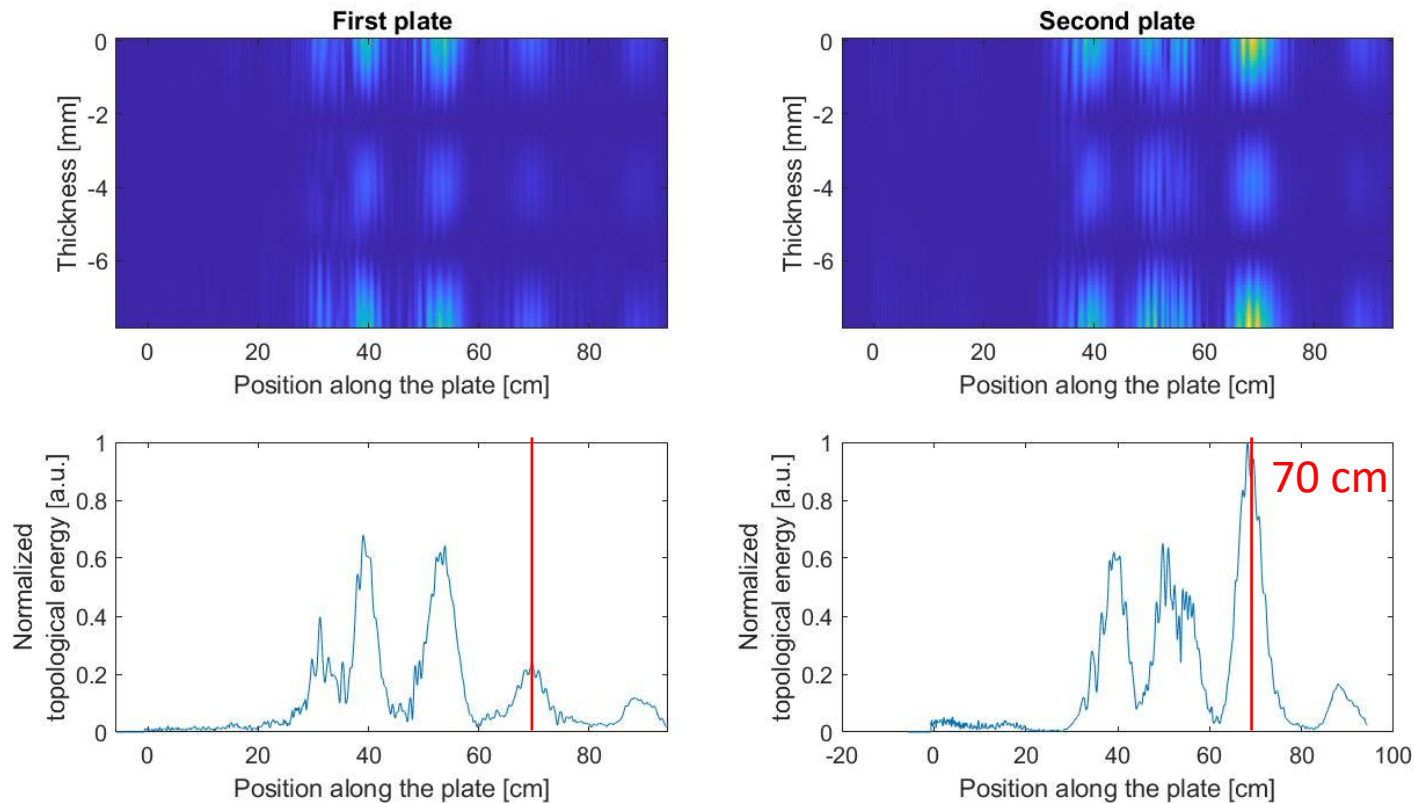
Inversed FFT



No physical meaning
(causality of signals)

Calculation of the topological energy

Knowing the direct and adjoint fields, the topological energy can be calculated and represented in both plates:

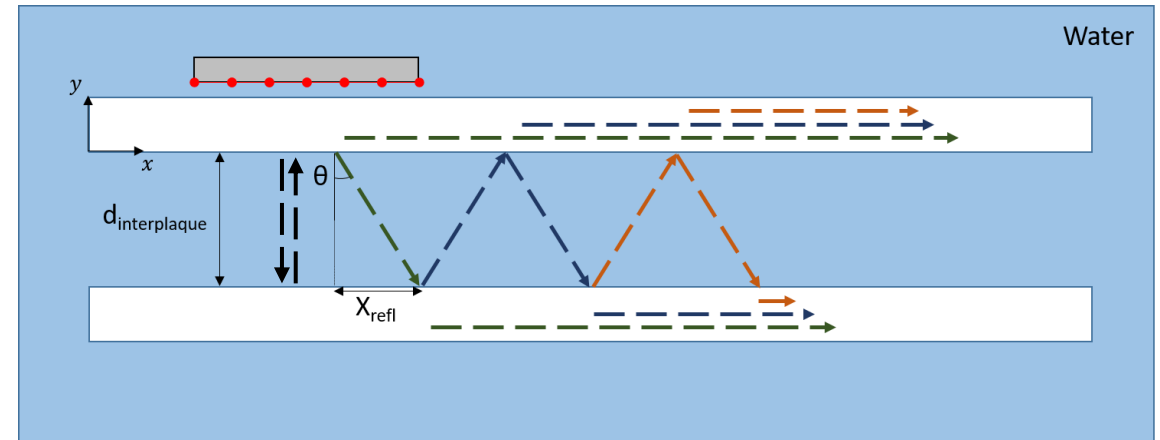
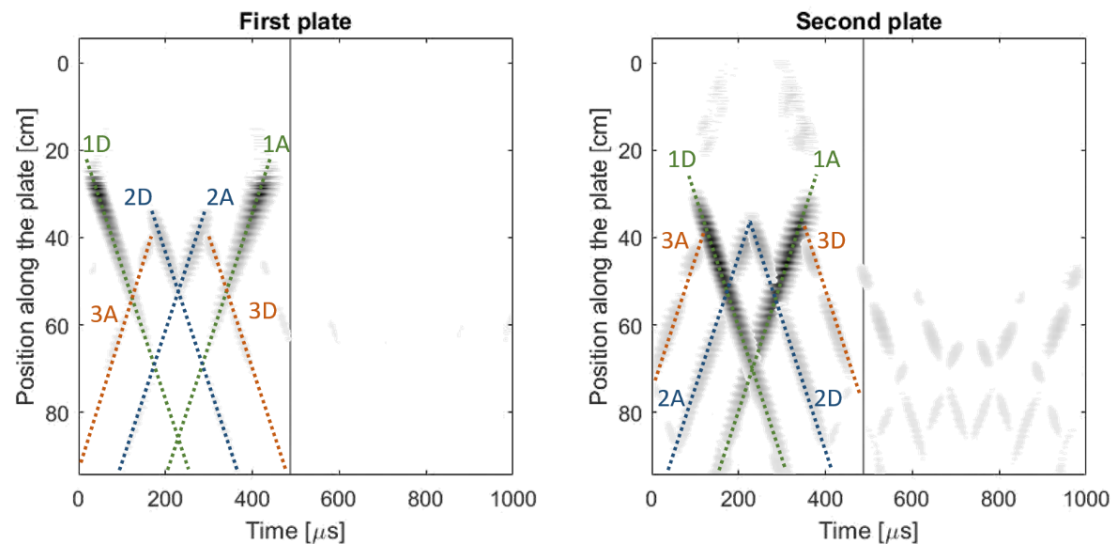


Maximum of topological energy
= edge of the second plate

Local maxima are observed and do not correspond to known defect positions

Topological spots (1)

Superposition of the direct and adjoint problems $\Leftrightarrow ET(\vec{r}) = \int |u_0(\vec{r}, t)|^2 |v_0(\vec{r}, t)|^2 dt$



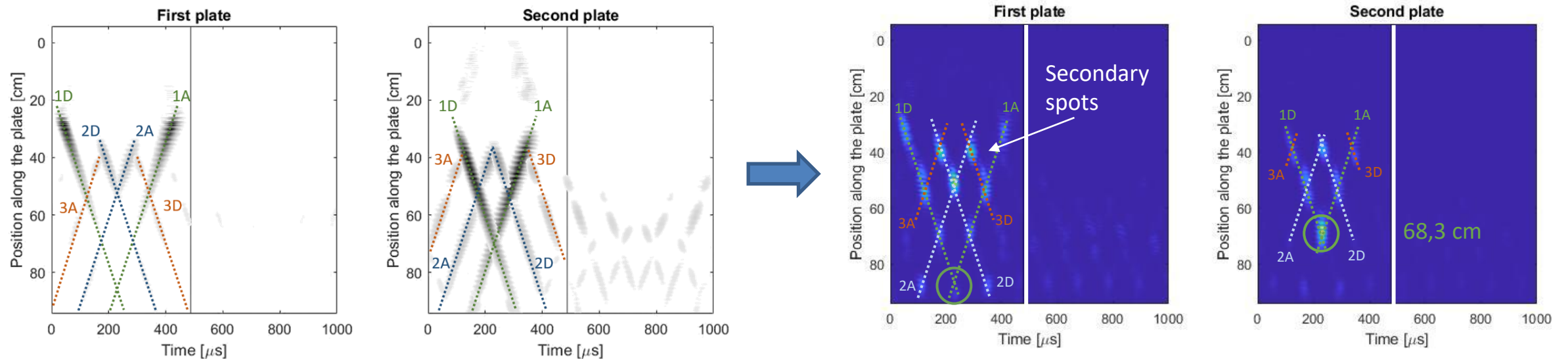
Examples:

Trajectory 2D: 2nd wave packet - direct problem ⋯

Trajectory 1A: 1st wave packet - adjoint problem. ⋯

Topological spots (2)

The topological energy resulting from the **correlation** of the two fields (direct and adjoint): representation in **spots**



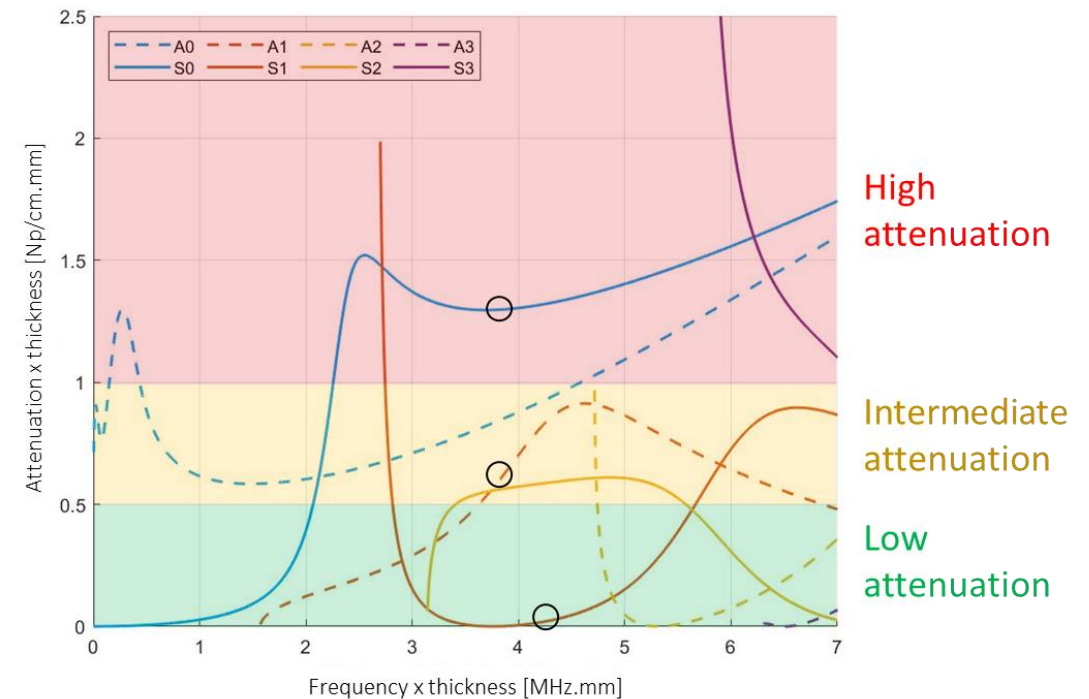
The wave packet selected as the residue: 1st trajectory of the direct problem (1D)

Backpropagation of the residue: 1st trajectory of the adjoint problem (1A)

→ Intersections 1D/1A (2 solutions)

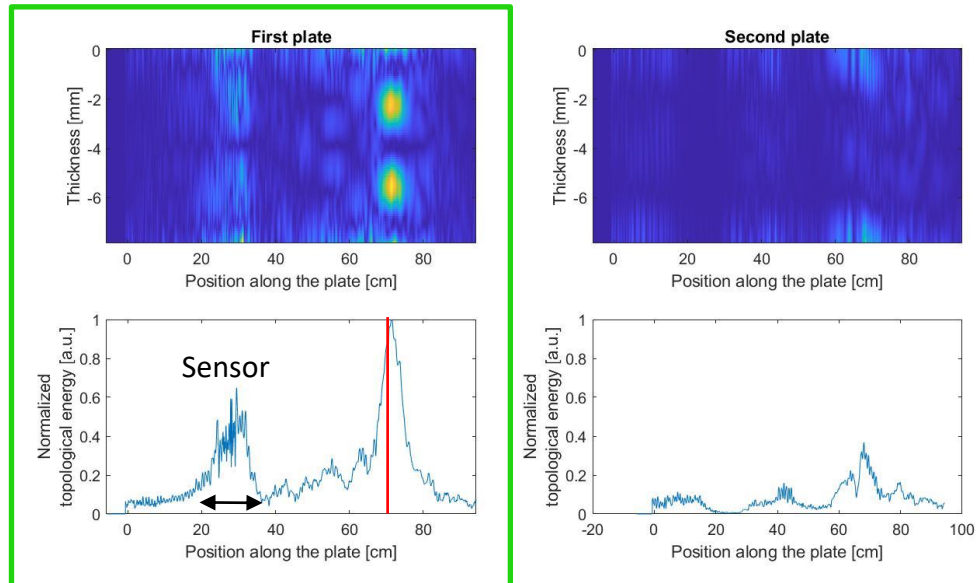
Influence of the attenuation of the generated mode

- High attenuation: S0 mode at $f = 480$ kHz
- Intermediate attenuation: A1 mode at $f = 480$ kHz
- Low attenuation: S1 mode at $f = 550$ kHz

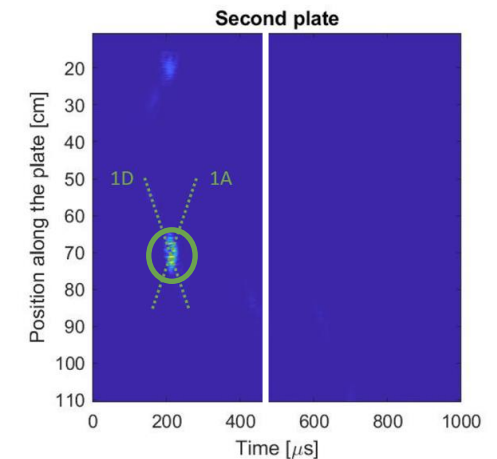
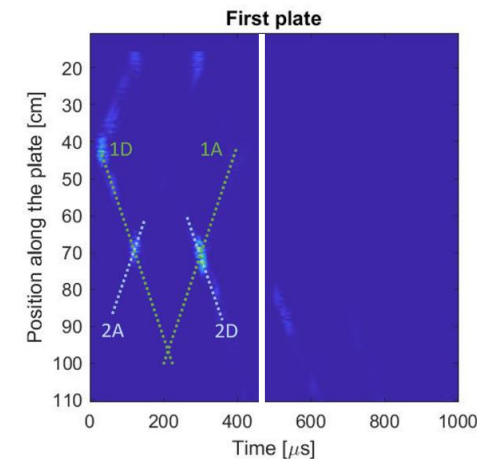
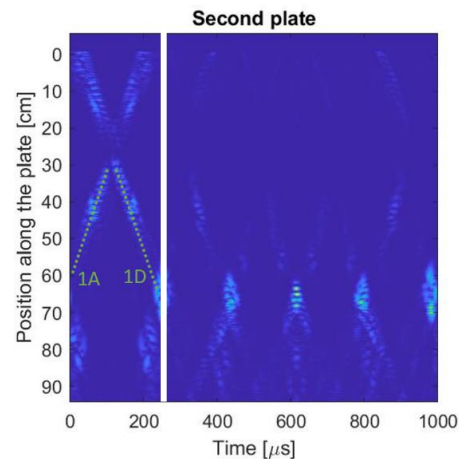
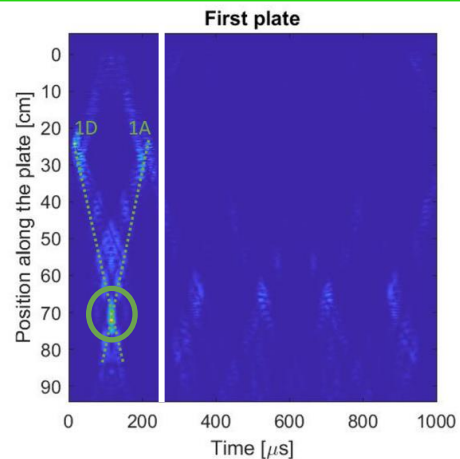
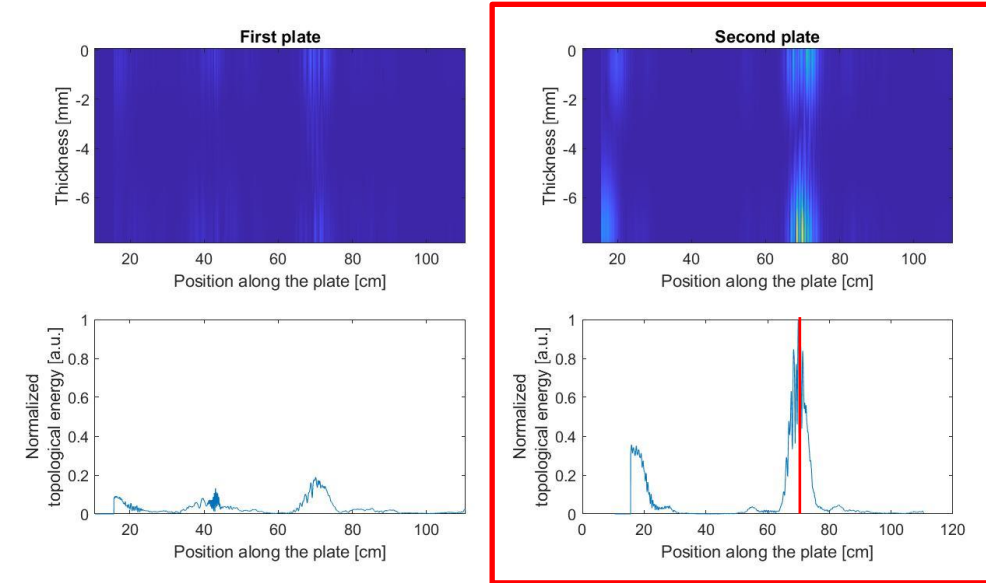


Influence of the attenuation of the generated mode (1)

Low attenuation = detection in the 1st plate

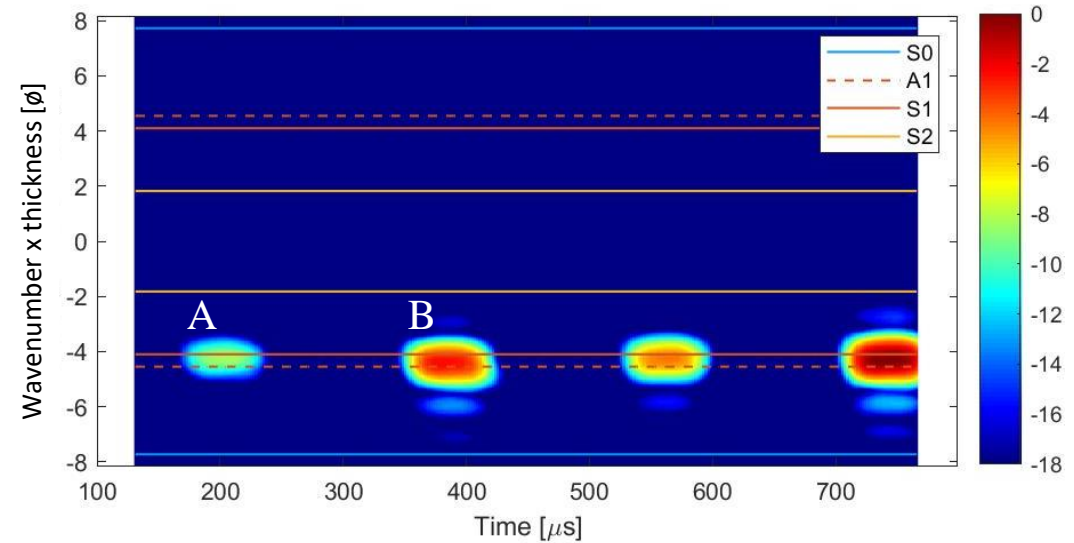
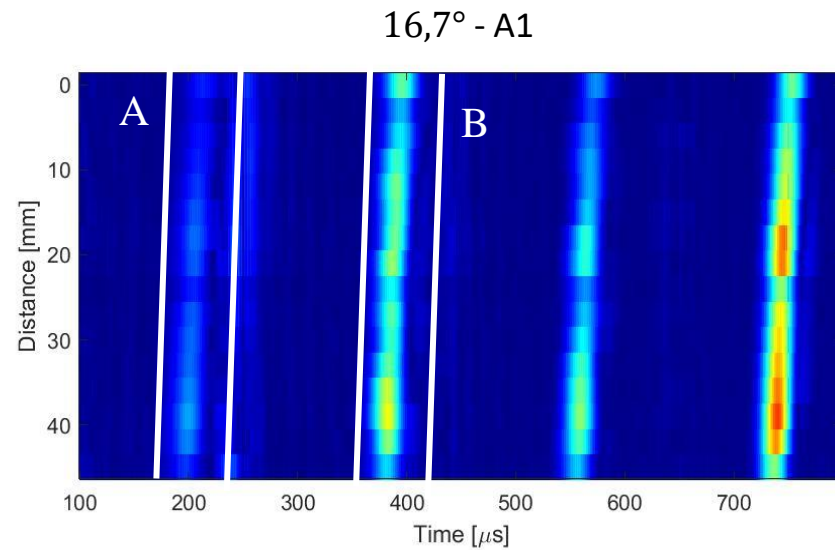


High attenuation = detection in the 2nd plate



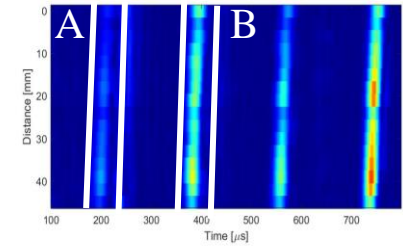
Influence of the attenuation of the generated mode (2)

Intermediate attenuation

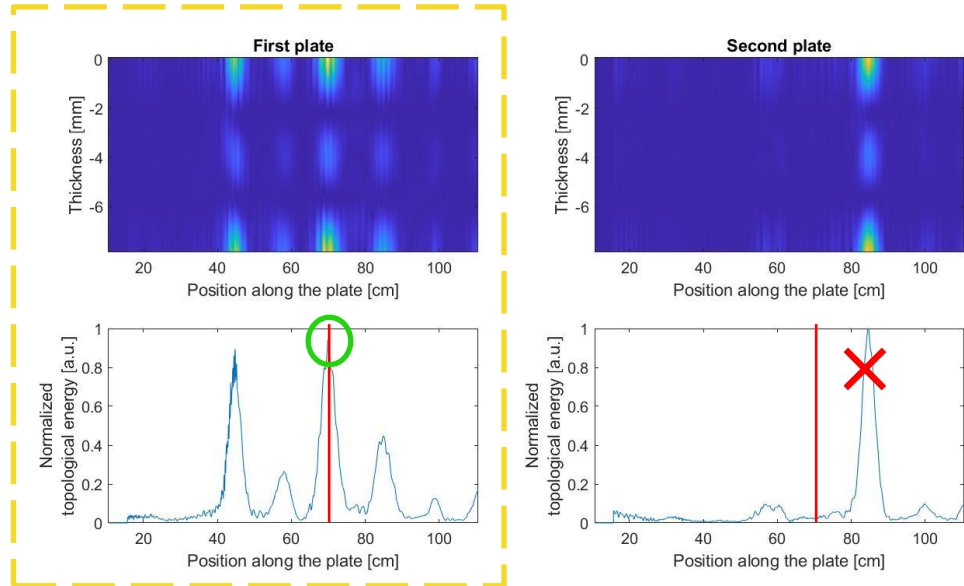


→ The two wave packets A and B are isolated and backpropagated independently

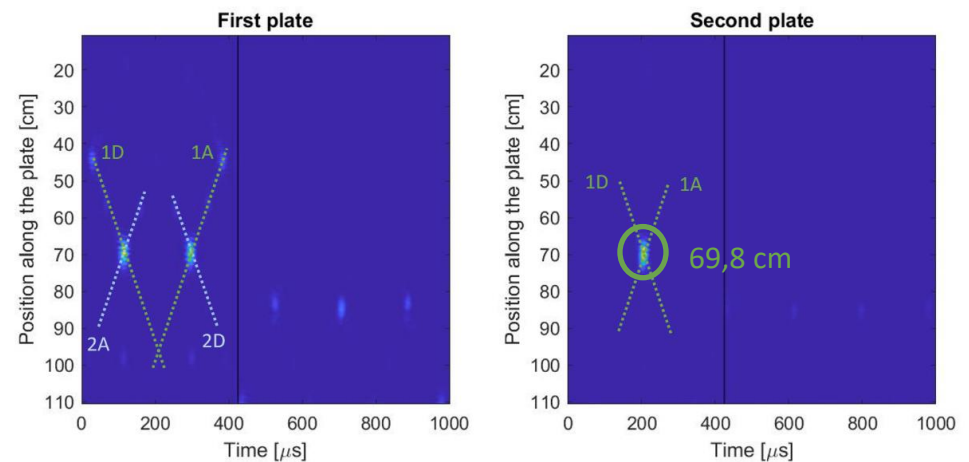
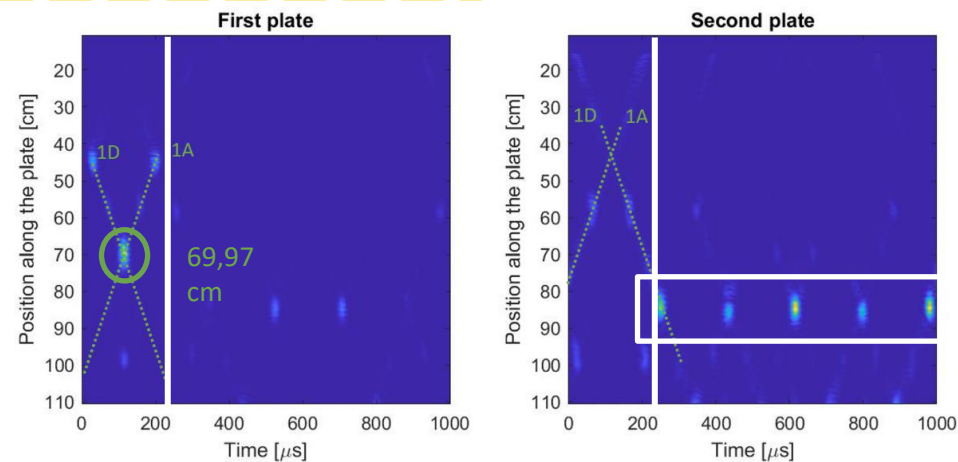
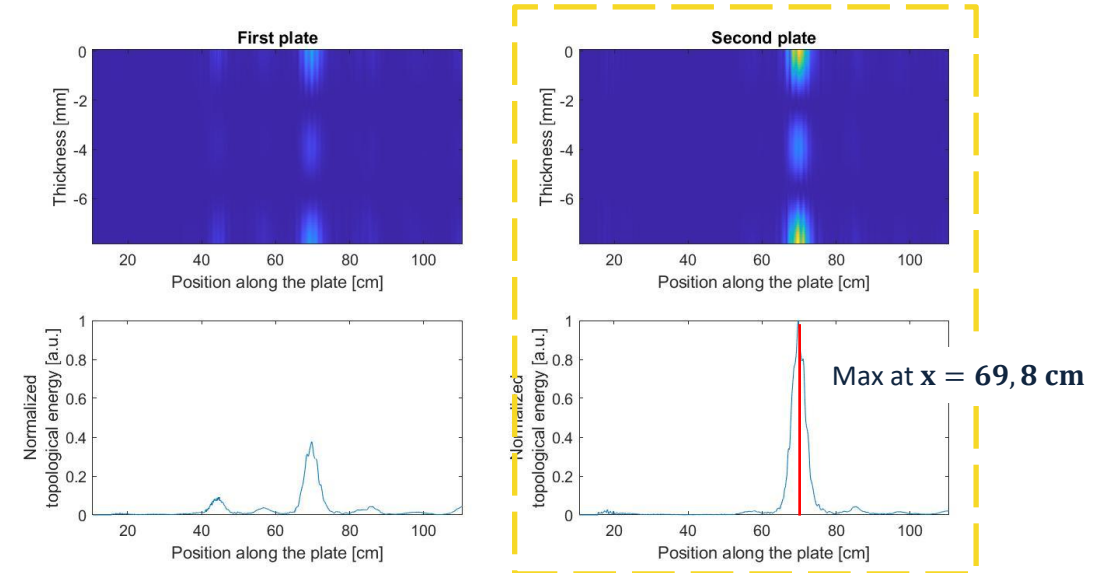
Influence of the attenuation of the generated mode (3)



Intermediate attenuation (Wave packet A)



Intermediate attenuation (Wave packet B)



Conclusions & perspectives

- We can **locate** a defect in the second plate hidden by the first one
- The concept of **topological spots** has been introduced
- The study of topological spots allowed **discrimination of the main image** of the detected defect among the secondary images
- The influence of attenuation has been discussed

Perspectives :

- **Potential for more complex systems (3 plates, different thickness..)**
- Identification of defect nature and dimensioning
→ Study of Lamb waves mode **conversion**



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THANKS FOR YOUR ATTENTION
ANY QUESTION ?

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