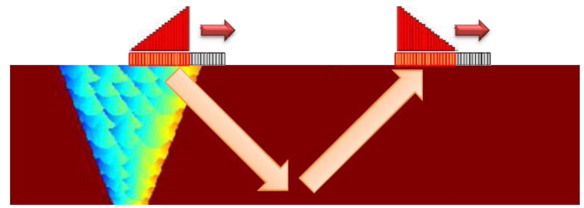

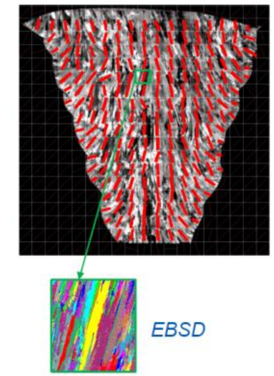

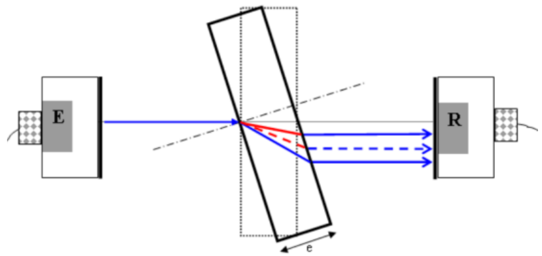

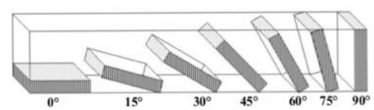

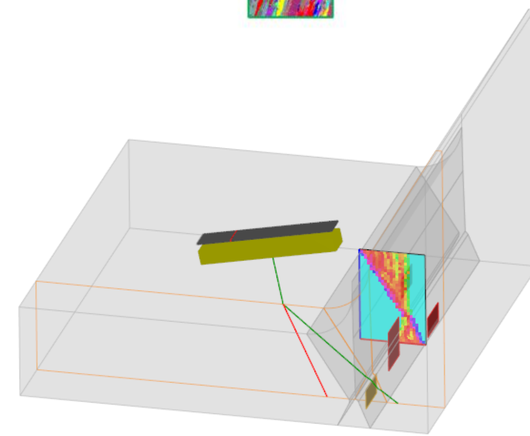

VALIDATION OF AN ULTRASONIC CHARACTERIZATION TECHNIQUE FOR ANISOTROPIC MATERIALS: COMPARISON OF EXPERIMENTS WITH BEAM PROPAGATION MODELLING

Michel Darmon[1], Bastien Clausse[2], Benoit Mascaro[3], Déborah Elbaz[2], Nicolas Leymarie[1], Philippe Guy[3], Souad Bannouf[2] and Sylvain Chatillon[1]

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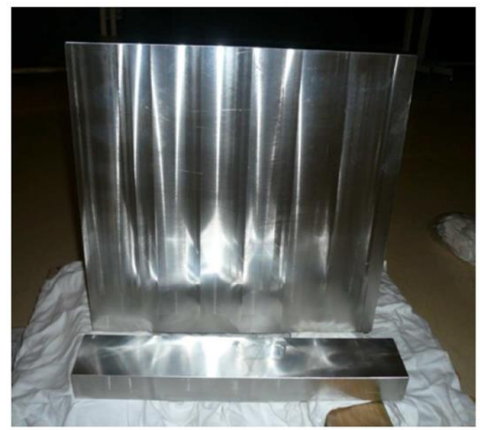
OUTLINE

- **Context and motivation**
- **UT Modelling in welded Structures**
  - Weld description for NDT simulation in CIVA
  - Estimation of the stiffness tensor for simulation inputs
- **Simulation of the experimental characterization procedure**
- **Validation results**
  - Isotropic material
  - Anisotropic materials
- **Conclusion and perspectives**

CONTEXT AND MOTIVATIONS

- **Industrial Issues in Ultrasonic Testing of Welded components**
  - Requirement to qualify welding inspection method

    ⇒ Evaluate the impact of welding structures on the detection performance and characterization of defects <u>without taking into account the effects of geometry</u>

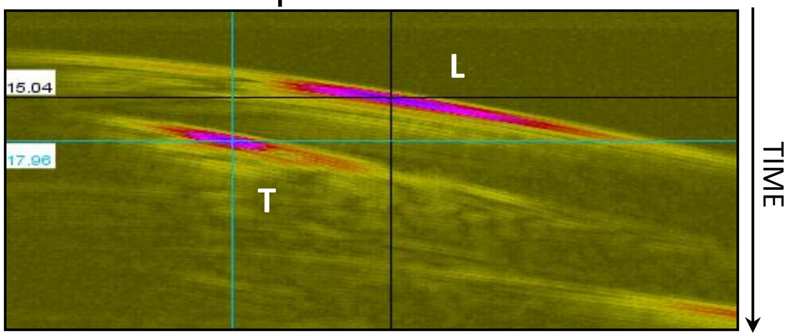


  - **Need a good knowledge of features useful to modeling tools**:
    - Analysis of the polycrystalline structure of the weld using macrographies
    - Reliable identification of the mechanical properties of the material

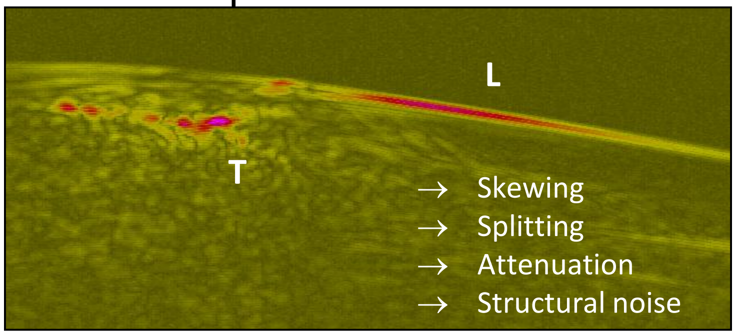
UT MODELLING IN WELDED STRUCTURES

- **Effects of welding structures on UT inspections**
  - Textured polycrystalline material: heterogeneous and anisotropic properties
    - Beam splitting and beam deviation
    - Anisotropic damping depending on grain geometry and grain texture

US field acquisition above base metal



US field acquisition above the weld bead



Difficult analysis of inspection results in welded areas

- Modelling approach used to simulate welding effects in UT inspection

$$\vec{u} = \langle \vec{u} \rangle + \delta \vec{u}$$

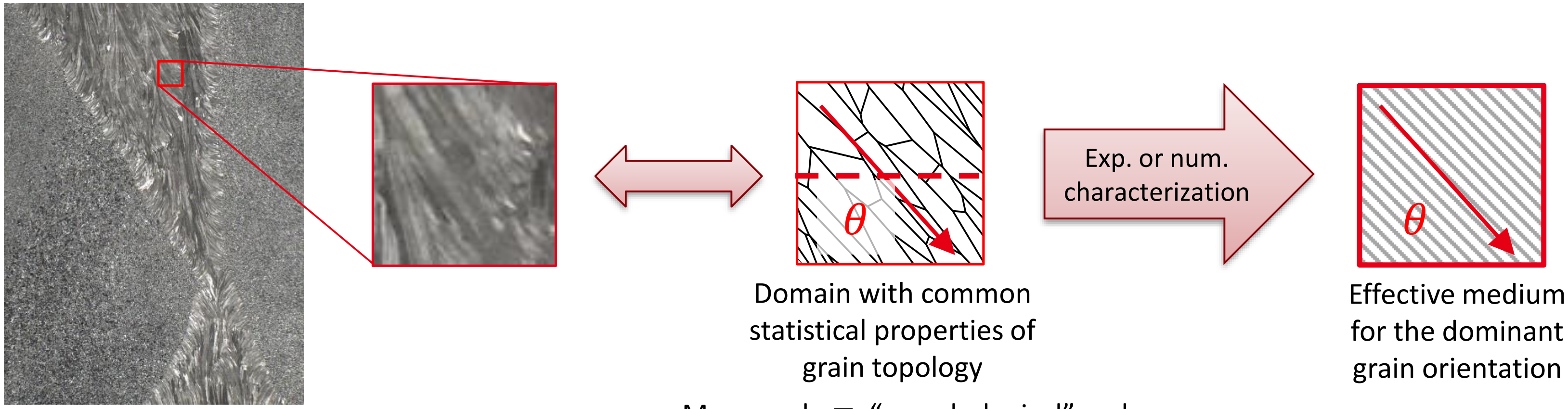
Structural noise

Coherent wavefield → *Effective medium ?*

UT MODELLING IN WELDED STRUCTURES – MACROSCALE APPROACH

- **Coherent wave field modelling in weld** $\langle \vec{u} \rangle$
  - Observation
    - Attenuation and anisotropy of the coherent wave
    - Correlated with grain orientations for microstructure with elongated grains
  - Modelling assumptions
    - Assume locally equivalent material properties defined by a stiffness tensor in a local coordinate system related to the elongated axis orientation of the grain (quasi-hexagonal symmetry)

$\Longrightarrow$ real C_{ij} with modal attenuation laws or complex frequency dependent C_{ij} (complex wavenumbers)

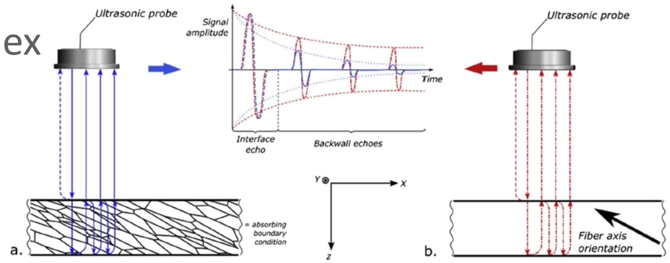


Macroscale ≡ "morphological" scale

ESTIMATION OF THE STIFFNESS TENSOR FOR SIMULATION INPUTS

- **Techniques for effective medium characterization**
  - Numerical characterisation
    - Semi-analytical integral methods using effective complex wavenumber calculation
    - Full numerical simulation with FE transient model

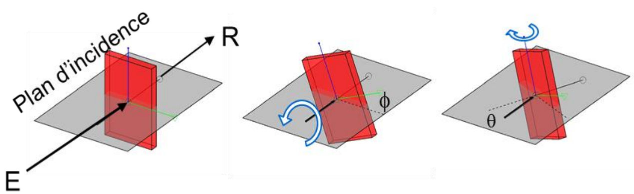
      ⇒ analysis of the coherent wavefronts using multiple backwall echoes



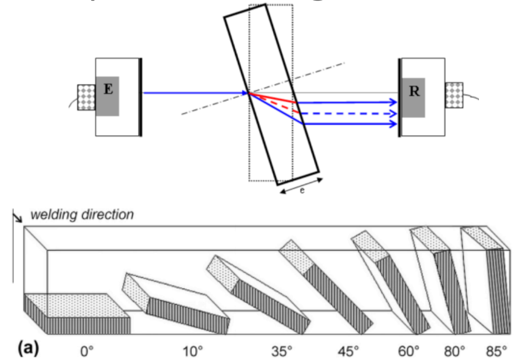
P.E. LHUILLIER et al. Ultrasonics, 2017

  - Experimental characterization
    - Measurement of wave velocities and attenuation of ultrasonic wave for different modes and wavefront directions
    - Characterization on different samples cut out from a special mock-up with homogeneous grain orientation

P. GUY, LVA experimental setup



P.A. BODIAN (Thèse INSA, 2011)
N. ALAOUI-ISMAILI (ANR MOSAICS, 2014)



M.A. PLOIX et al. Ultrasonics, 2014

WELD DESCRIPTION FOR NDT SIMULATION IN CIVA

- **Anisotropic elastic properties of the effective medium**
  - wave velocity variations with respect to wavefront direction

Density 7.915 $g.cm^{-3}$

Symmetry Orthotropic

Anisotropic matrix (GPa)

218	148	148	0	0	0
148	248	110	0	0	0
148	110	248	0	0	0
0	0	0	80	0	0
0	0	0	0	105	0
0	0	0	0	0	105

C_{IJ}

- **2 ways to define anisotropic damping properties**
  - 2D discrete damping data (versus Theta) to handle a 3D anisotropy of the wave attenuation
  - Stiffness tensor with imaginary part

$$\tilde{C}_{IJ} = C_{IJ} + \mathrm{i}\,\eta_{IJ}$$

Longitudinal wave attenuation

Attenuation law: Anisotrope attenuation Law

Reference axis: (•) X' ( ) Y' ( ) Z'

(•) Table ( ) Curve

Angle	Attenuation (dB)
0	0.037
15	0.036
30	0.048
45	0.075
60	0.115
75	0.168
90	0.235

Power of the attenuation rate: 0

Wave frequency: 1 MHz

Properties | Orientations | Attenuations / Noises | Visualization

Attenuation range: Global

Viscosity matrix (GPa)

7.28	3.76	3.12	0	0	0
3.76	8.12	2.37	0	0	0
3.12	2.37	4.74	0	0	0
0	0	0	0.19	0	0
0	0	0	0	10.78	0
0	0	0	0	0	11.27

Noise

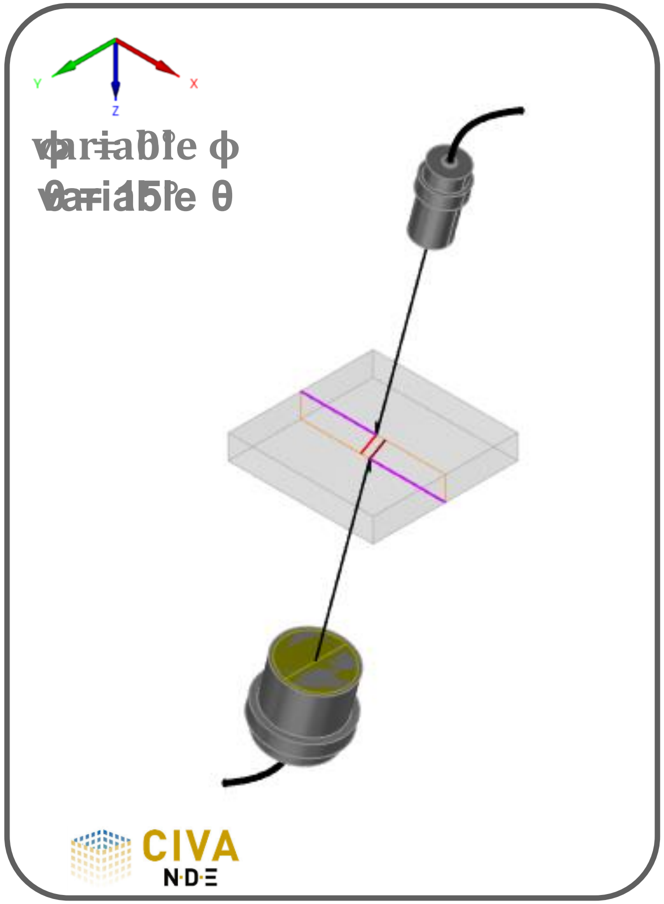
η_{IJ}

OBJECTIVES OF THE STUDY

- **Objective**
  - Validate the UT characterization technique used to determine effective stiffness tensor
    - Properties evaluation is performed using plane wave assumptions
    - Phase velocity and attenuation are estimated for a set of incident angles and plane inspection

- **Mean**
  - Simulate with CIVA the complete experimental setup using the viscoelastic stiffnesses given by the inversion process
    - Compare simulated and experimental signals (modal time-of-flight and amplitude)
    - Analyse anisotropic behaviour w.r.t. inspection plane variation
    - Study the effects of radiated beams by limited sources especially for large incidence angles

- **CIVA simulation of the transmitted field**
  - Inputs of the complex Cij coefficients obtained from experimental inversion process
  - Definition of the crystallographic orientation in Bunge convention (in case of anisotropic material)
  - Importation of the design of experiments in CIVA parametric study with θ and ϕ incidence variations
  - Optimization of water path and velocity in CIVA simulation to calibrate the reference signal compared to experiments

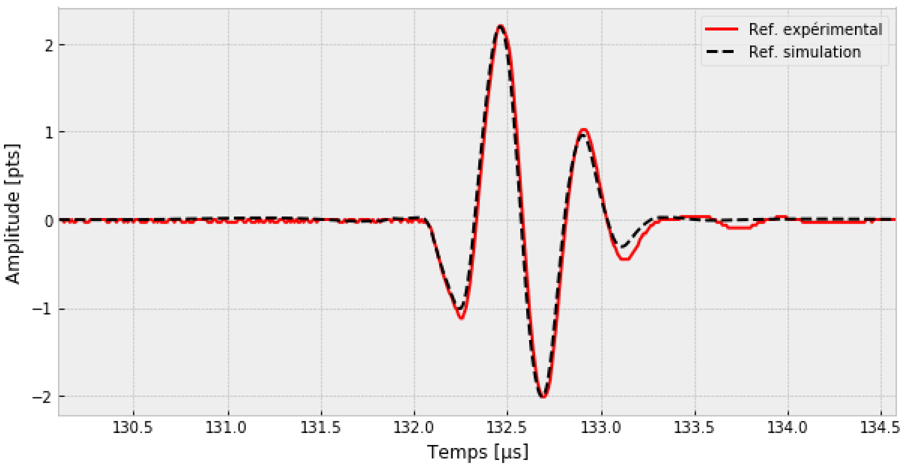


REFERENCE SIGNAL CALIBRATION

EXTENDE CIVA

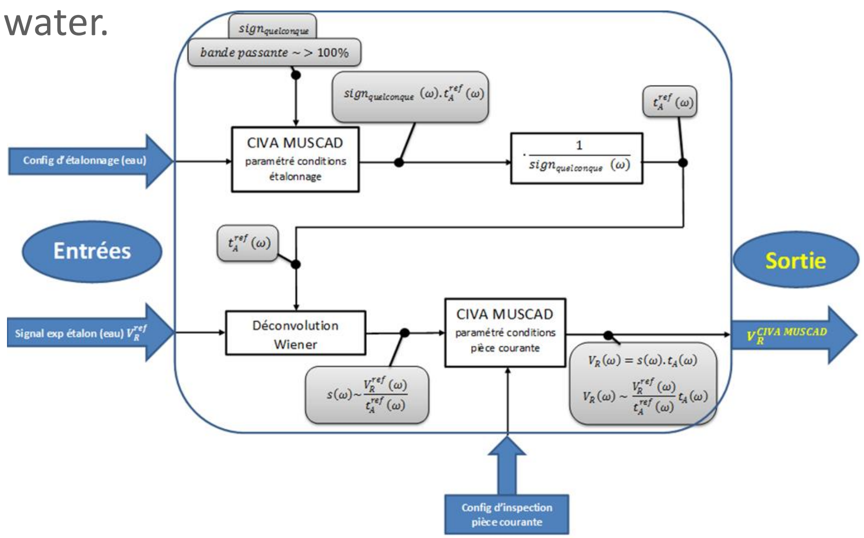
Simulation calibration: definition of the reference signal

- The reference signal embeds the modelling of probes responses and emission/reception electronics.
- Once it is calibrated in water with experiments, inspection simulations in case of tested samples are performed with this reference signal unchanged.



Example of reference signal in case of Inconel 1581A1 (CU5) experiment

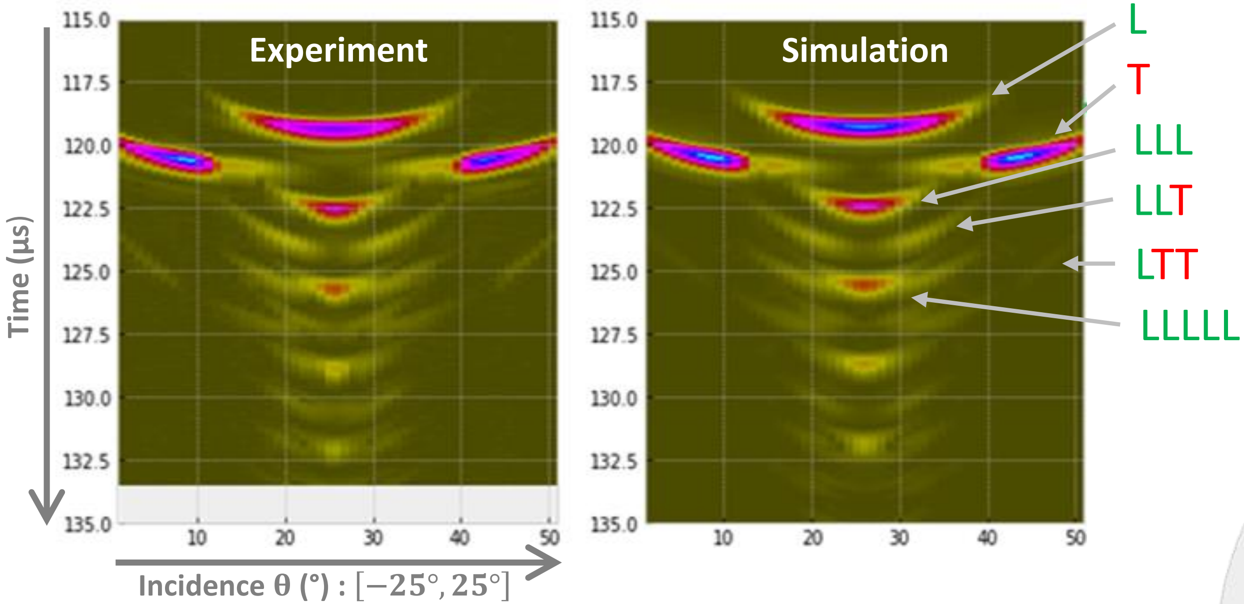
1. CIVA simulation of the reference inspection setup without sample (in water) with arbitrary input signal.
2. Deconvolution of the obtained output signal with the input signal : acoustic/elastic impulse response (IR) in water.
3. Input signal of inspection simulation with the tested sample : deconvolution of the experimental signal in water by the IR in water.



CARNOT CEA LIST
université PARIS-SACLAY

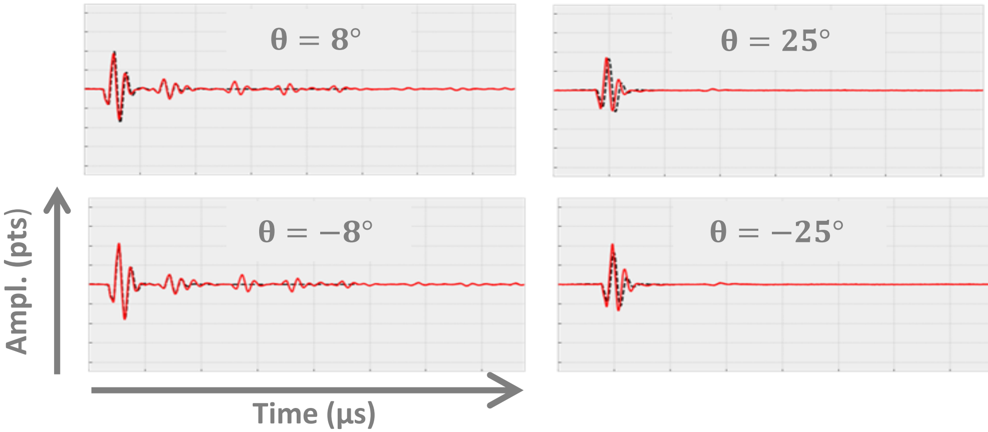
RESULTS IN ISOTROPIC NON-ATTENUATED MATERIAL

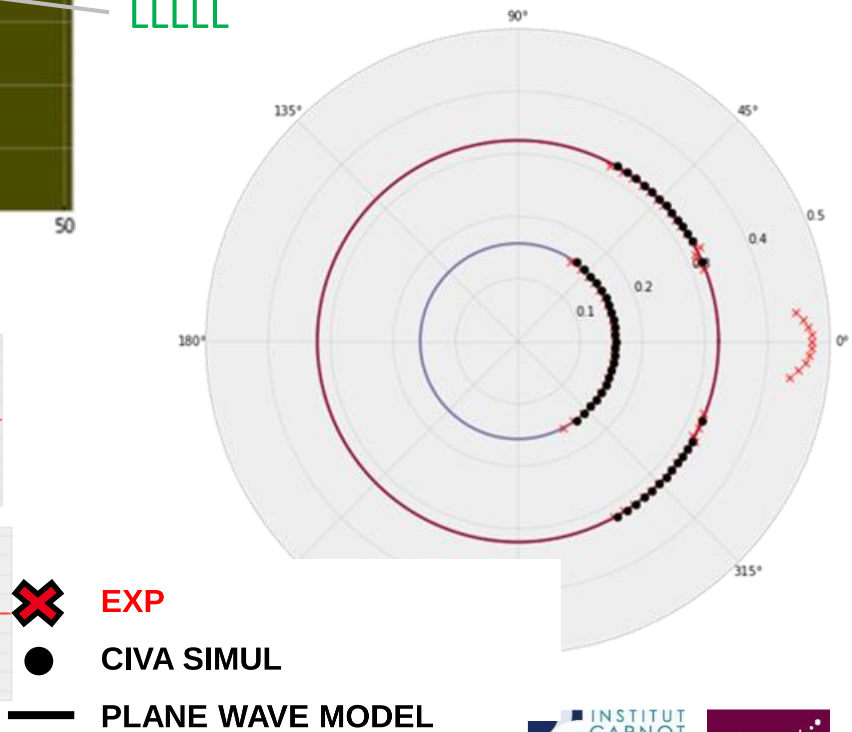
- Validation with <u>Aluminum</u> material : results with incidence $\phi = 0$



<u>3 types of images</u>:

- Amax(time, θ, ϕ=cst.)
- A(time, θ=cst., ϕ=cst.)
- Slowness curves





RESULTS IN ANISOTROPIC ATTENUATED MATERIAL

- **CIVA material inputs and parameters in variation**

Re(C_{ij})

Propriétés | Atténuation / Bruit de structure | Visualisation

Type de symétrie: Orthotrope

Tenseur des rigidités (GPa) - propriétés élastiques

244	123	144	0	0	0
123	245	140	0	0	0
144	140	243	0	0	0
0	0	0	106	0	0
0	0	0	0	113	0
0	0	0	0	0	78

Im(C_{ij})

Propriétés | Atténuation / Bruit de structure | Visualisation

Attenuation type: Globale

Matrice de viscosité (GPa)

9.4	0.75	2.65	0	0	0
0.75	4.6	2.8	0	0	0
2.65	2.8	2.25	0	0	0
0	0	0	2.35	0	0
0	0	0	0	0.2	0
0	0	0	0	0	0.55

Complex stiffness tensor for Inconel 1581A1 from experimental inversion

Type de convention: ○ CIVA ○ ROE ● BUNGE

θ_1 (/Z) -9.75 deg

θ_2 (/X) 28.33 deg

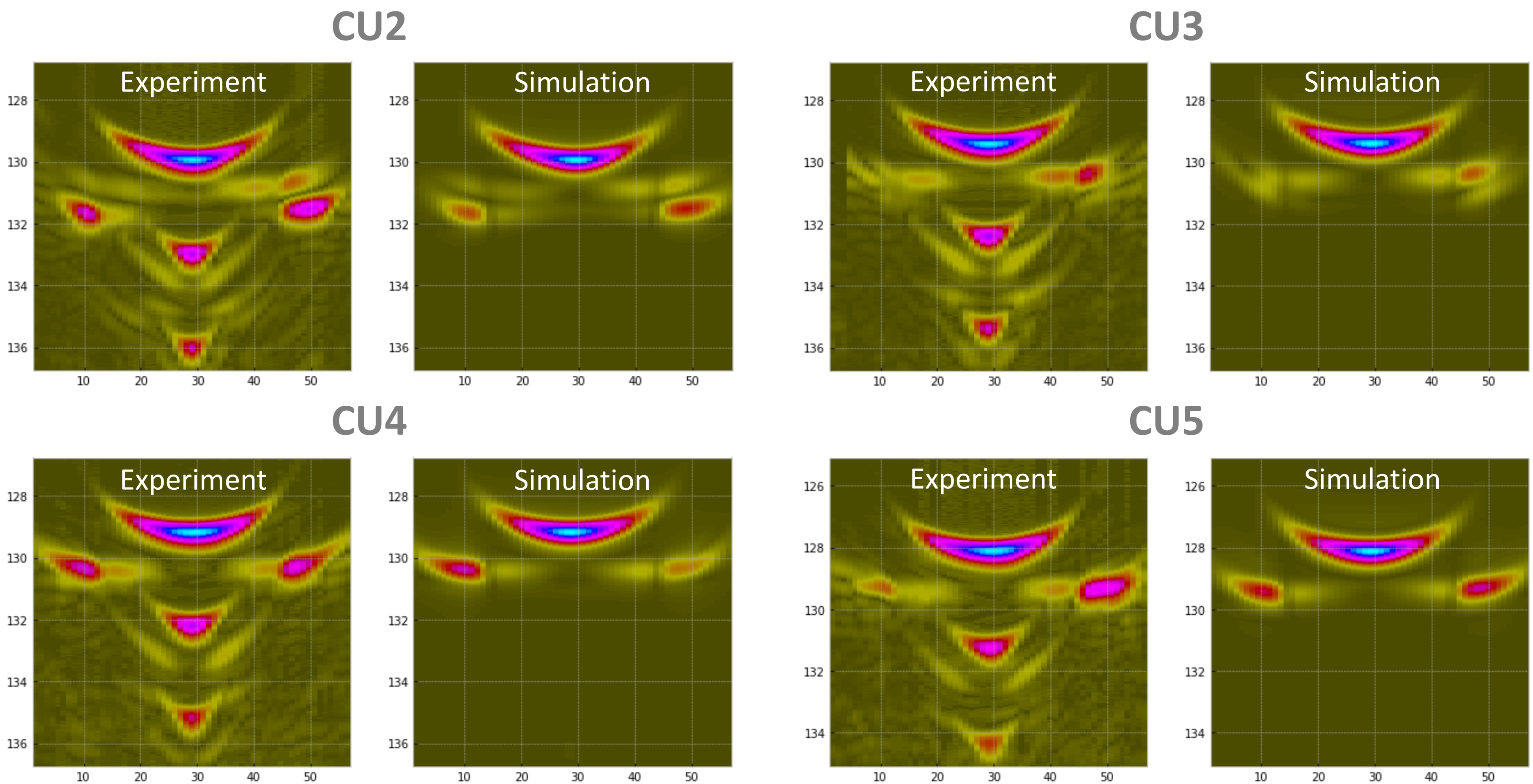
θ_3 (/Z) 13.94 deg

	CU2	CU3	CU4	CU5
$\theta_1(/Z)$	-9.75°	-6.6°	-4.44°	-4.86°
$\theta_2(/X')$	28.33°	41.0°	56.7°	73.19°
$\theta_3(/Z'')$	13.94°	7.44°	-1.85°	3.5°

Bunge angles for each cut

RESULTS IN ANISOTROPIC ATTENUATED MATERIAL

- Validation with Inconel 1581A1 material : 5 different sample cuts

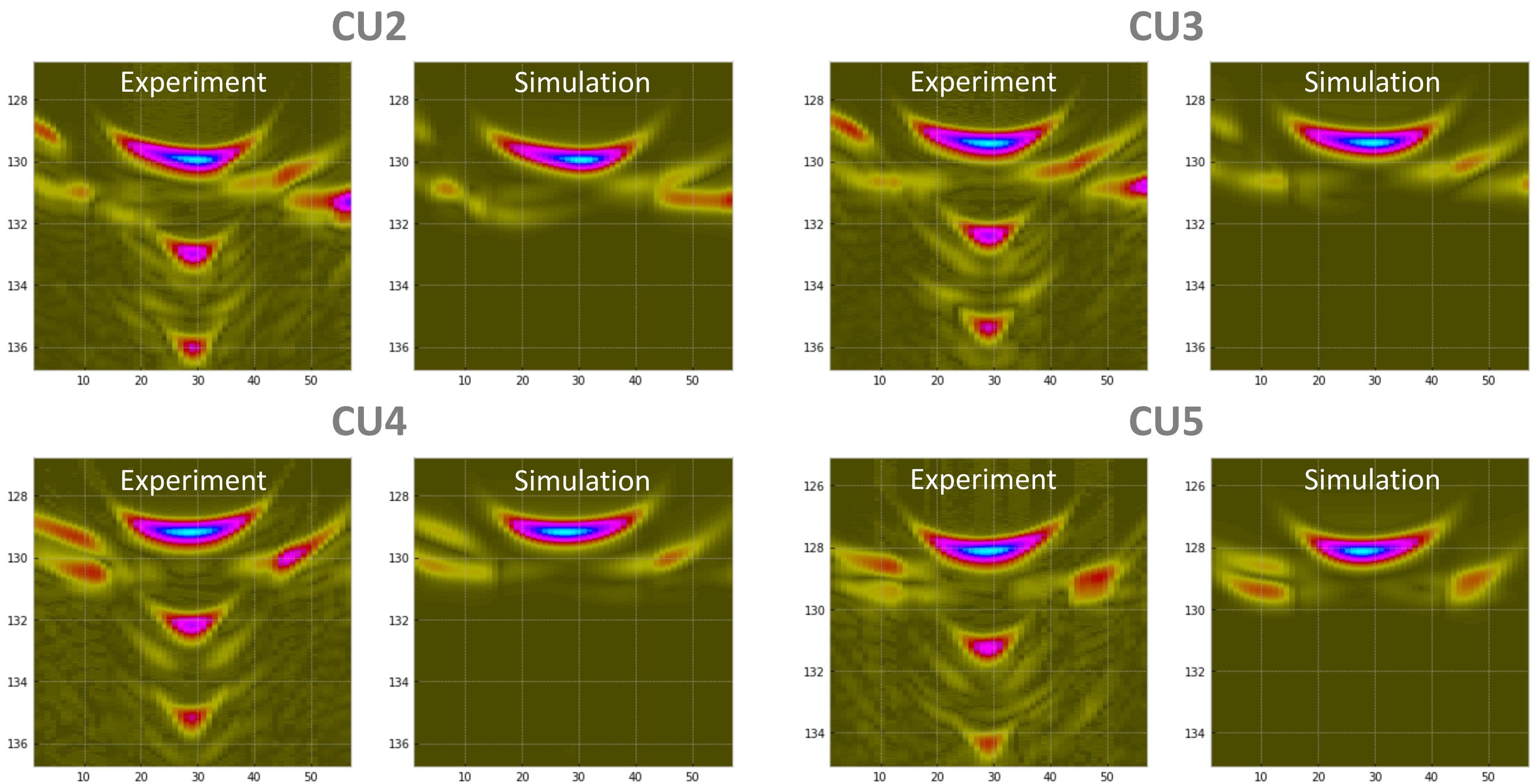


Amax(time, θ, ϕ =-90°)
Accounting for sample attenuation

$$\phi = -90°$$

RESULTS IN ANISOTROPIC ATTENUATED MATERIAL

- Validation with Inconel 1581A1 material : 5 different sample cuts



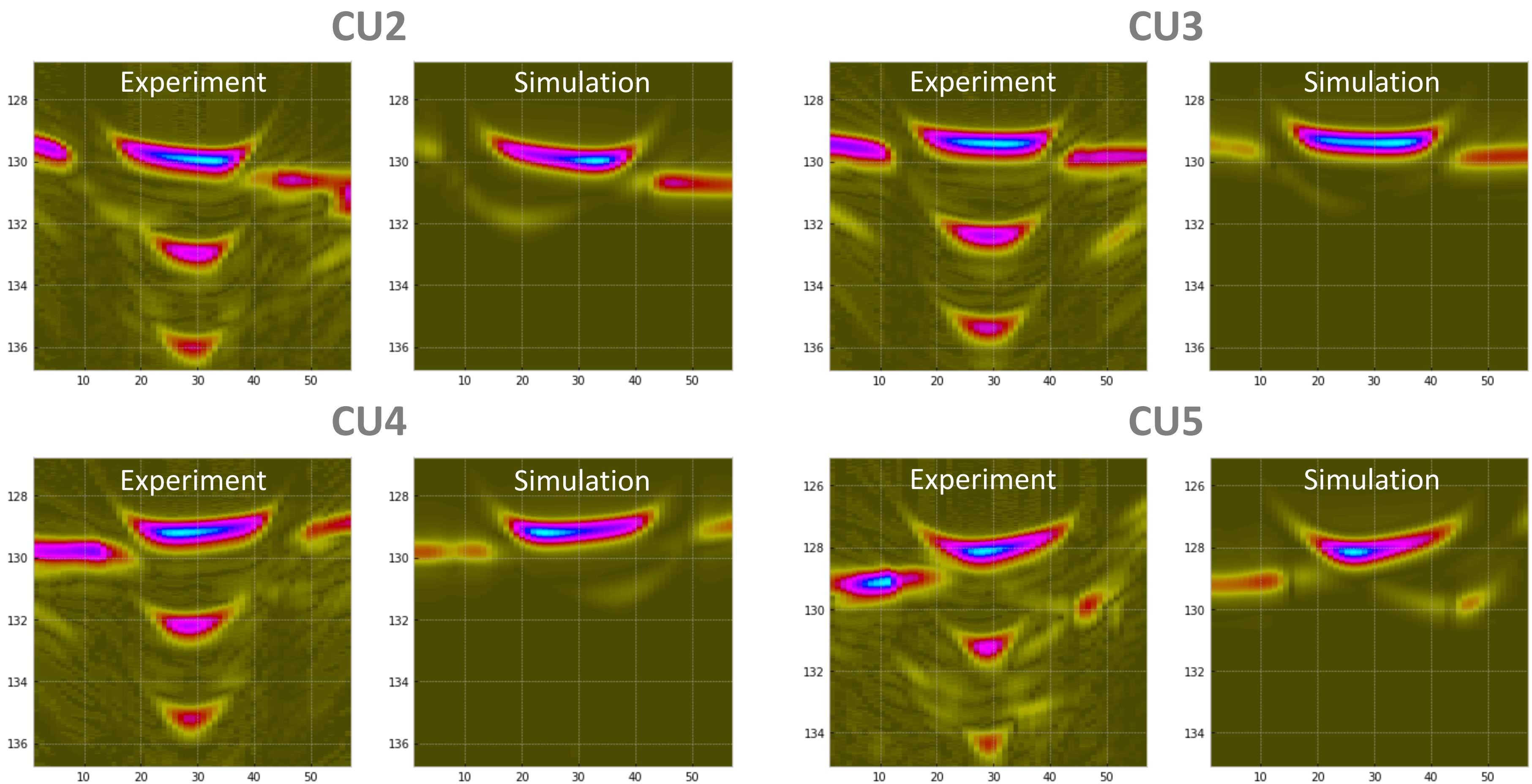
Amax(time, θ, ϕ =-60°)

Accounting for sample attenuation

$$\phi = -60°$$

RESULTS IN ANISOTROPIC ATTENUATED MATERIAL

- **Validation with <u>Inconel 1581A1</u> material : 5 different sample cuts**



Amax(time, θ, ϕ =0°)

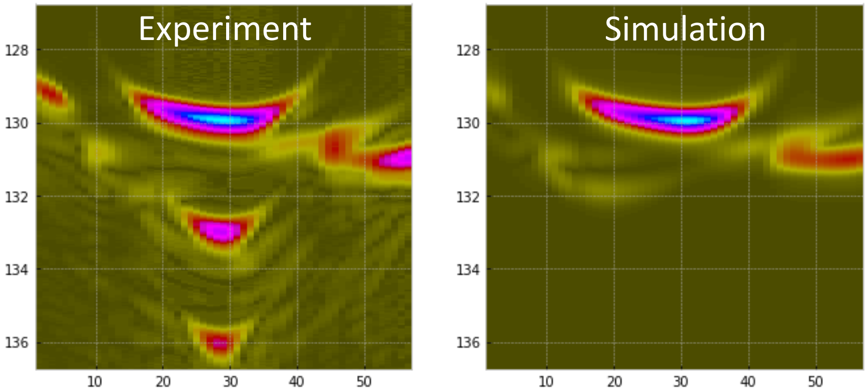
Accounting for sample attenuation

$$\phi = 0°$$

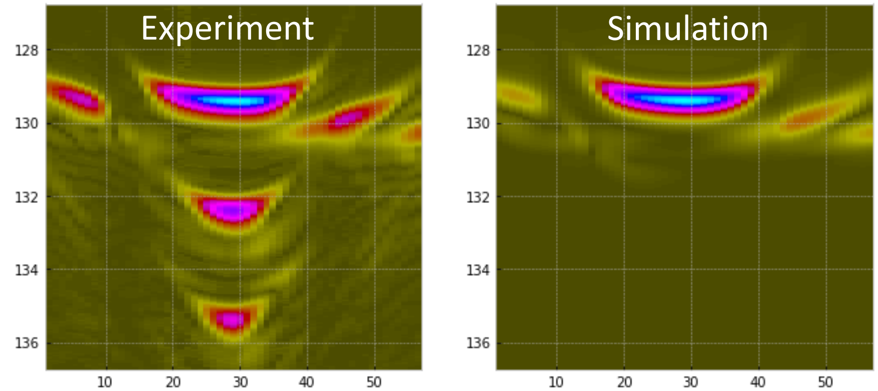
RESULTS IN ANISOTROPIC ATTENUATED MATERIAL

- Validation with <u>Inconel 1581A1</u> material : 5 different sample cuts

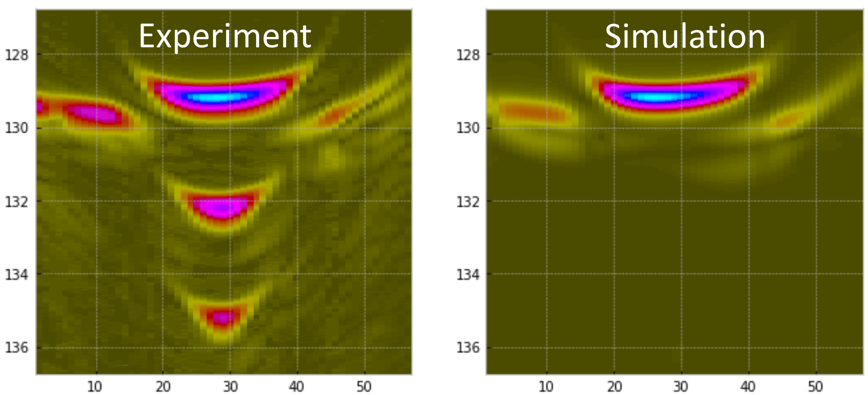
CU2



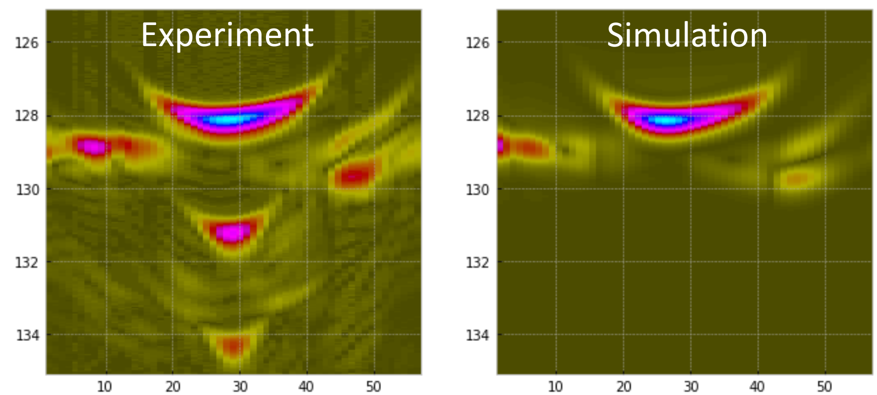
CU3



CU4



CU5



Amax(time, θ, ϕ =30°)
Accounting for sample attenuation

$\phi = +30°$

RESULTS IN ANISOTROPIC ATTENUATED MATERIAL

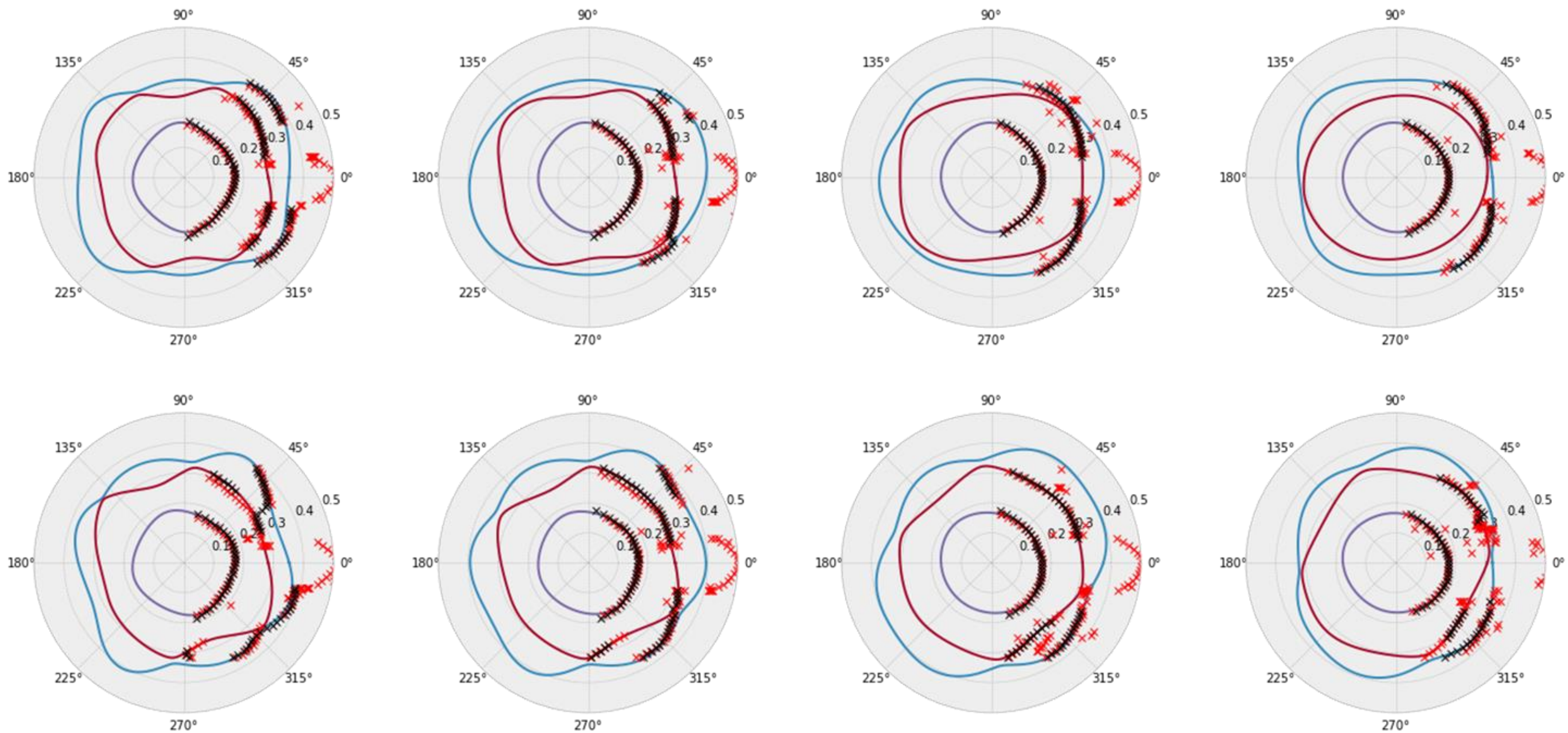
EXTENDE CIVA

- Validation with <u>Inconel 1581A1</u> material : 5 different sample cuts

CU2 | CU3 | CU4 | CU5

$\phi = -90°$

$\phi = -60°$



Slowness curves
Accounting for sample attenuation

EXP
CIVA SIMUL
PLANE WAVE MODEL

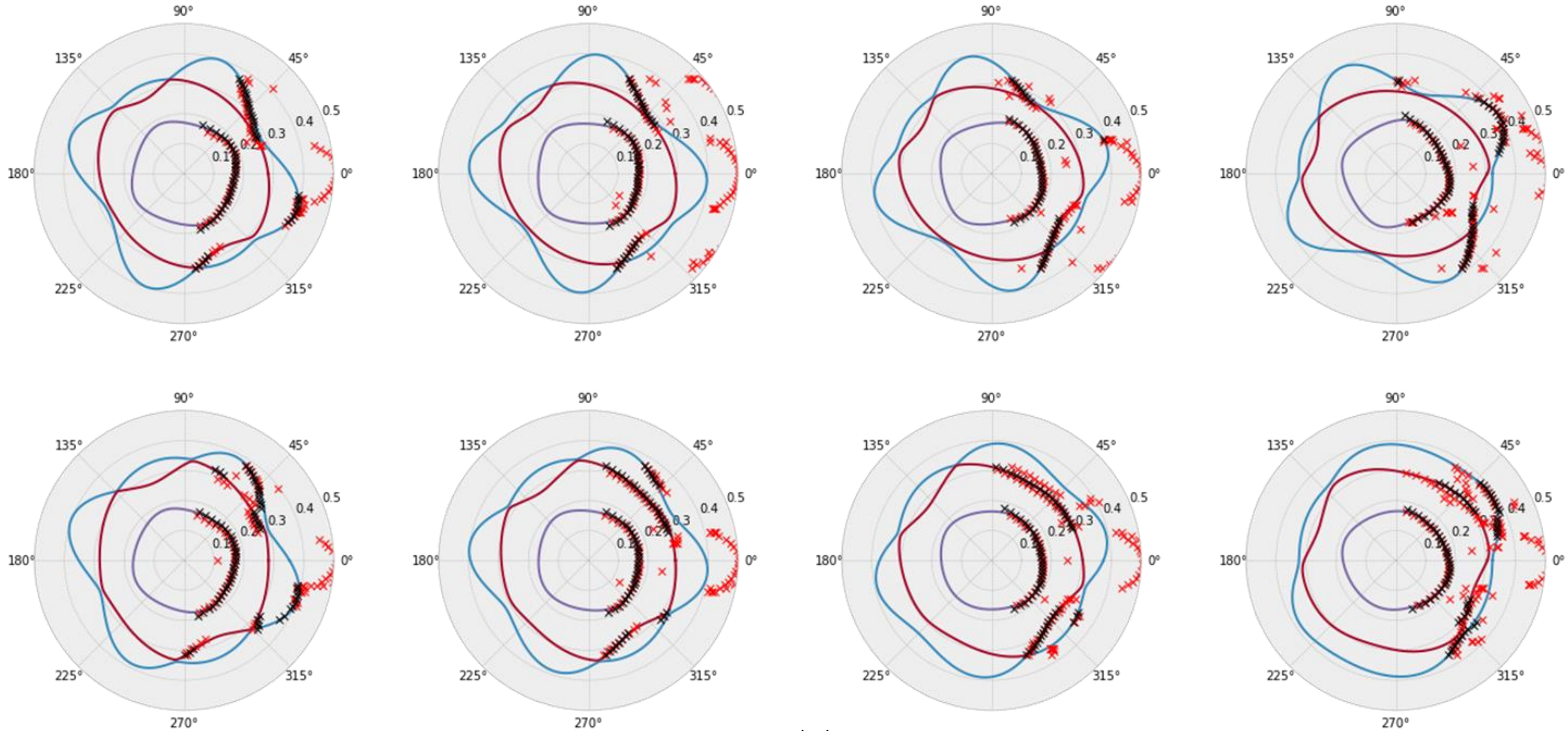
RESULTS IN ANISOTROPIC ATTENUATED MATERIAL

- **Validation with Inconel 1581A1 material : 5 different sample cuts**

CU2 **CU3** **CU4** **CU5**

φ = 0°

φ = +30°



Slowness curves

Accounting for sample attenuation

EXP

CIVA SIMUL

PLANE WAVE MODEL

CONCLUSION AND PERSPECTIVES

- **Objective**
  - Validate the UT characterization technique used to determine effective stiffness tensor
- **Mean**
  - Development of a simulation tool to reproduce the experimental set-up of anisotropic material characterization procedure
- **Results**
  - Good agreement between experimental and simulated data
    - Modal time-of-flight and amplitude are well predicted
    - Variations due to anisotropy are well reproduced for all the sample cuts
- **Perspectives**
  - Estimation of the effects of probe aperture on plane wave approximation
  - Sensitivity analysis of the identification procedure using simulated synthetic data obtained with varying stiffness properties

Thank you for your attention

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