AGENCE NATIONALE DE LA RECHERCHE ANR

3D modelling of utrasonic testing of austenitic welds

MOSAICS project

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Outline

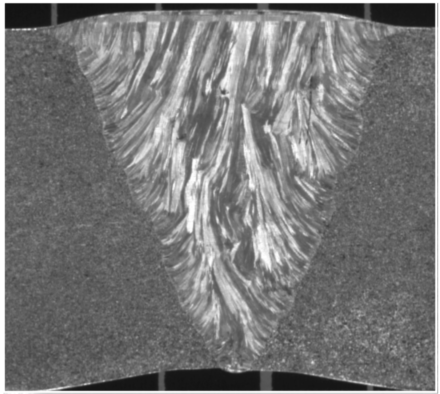
- Context
- Objectives and tasks of MOSAICS project
- Half-time project overview:
  - Material Characterization
  - Ultrasonic experimental tests
  - Code development, validation and exploitation

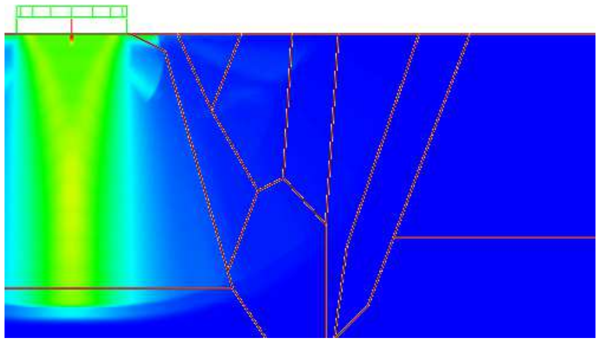
Context

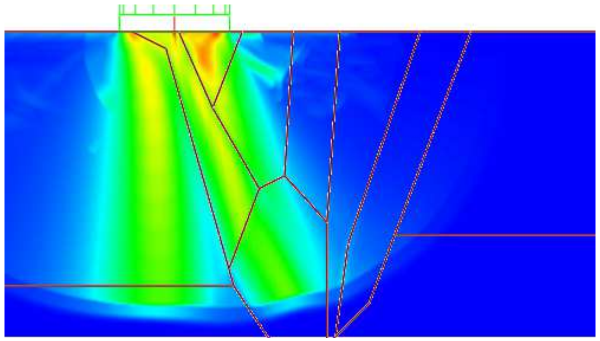
- **Austenitic welds of primary circuit of EDF PWR plants and DCNS structures are subject to thermal and mechanical stresses:**
  - **In-service flaws**
- **Regulatory requirements:**
  - **In-depth inspection of components ⇒ UT techniques: flaw detection and sizing**
  - **Process qualification**

- **But limitations for the UT inspection of austenitic welds:**
  - **Anisotropic, heterogeneous and coarse grain structures highly disturbing UT propagation:**

Beam deviation, division and attenuation



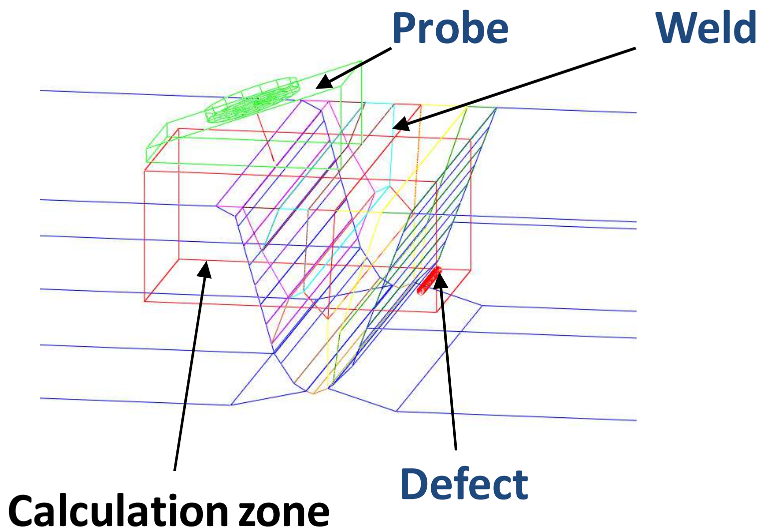




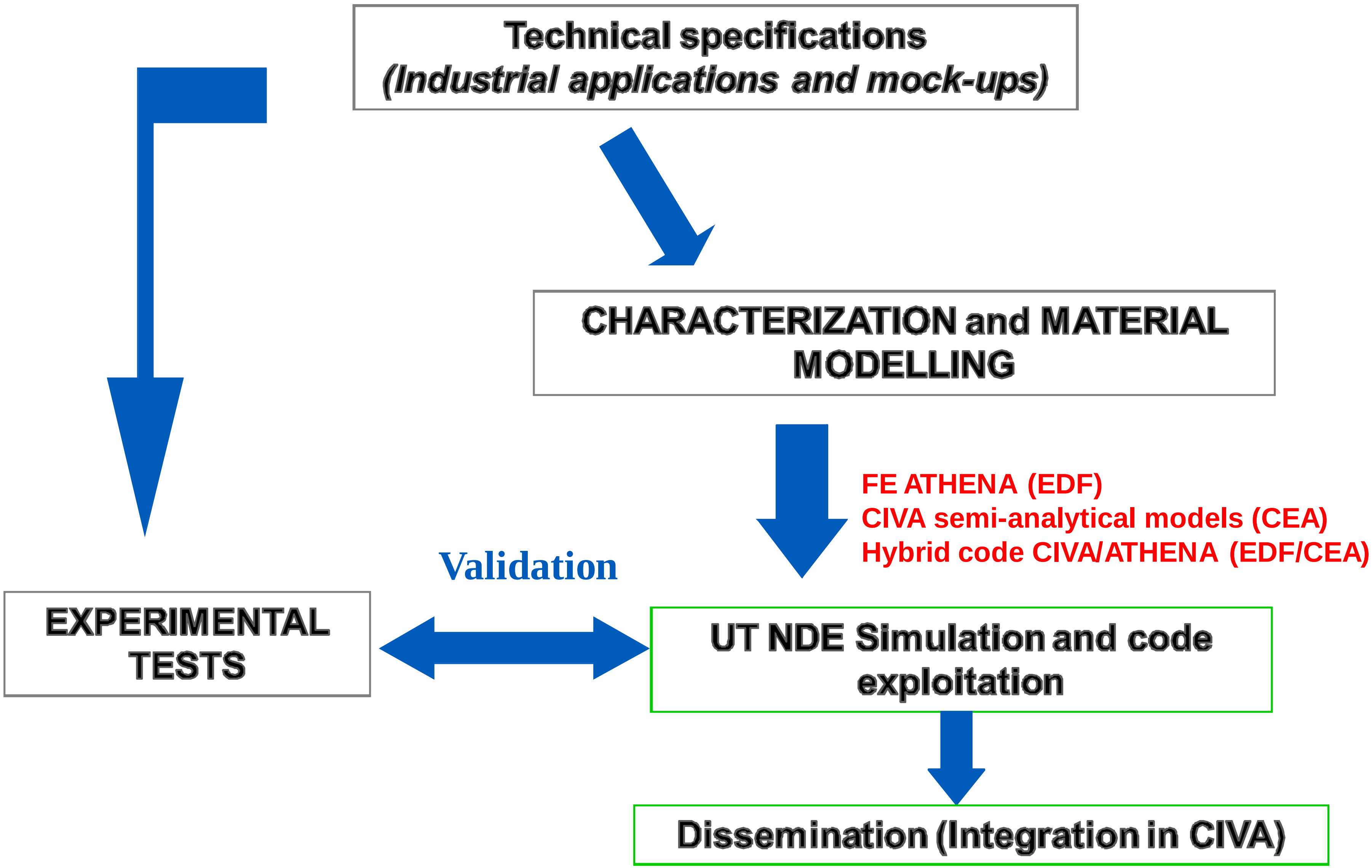
MOSAICS Project (supported by French National Research Agency)

- **UT simulation: process development and qualification:**
  - **Parametrical studies for performance demonstration**
- **BUT current code limitations:**
  - **Semi-analytical models (CIVA) : not adapted to highly heterogeneous structures (current ray theory not valid)**
  - **Finite element code (ATHENA) : 2D version**

- ***MOSAICS project : Development and validation of numerical tools used for ultrasonic testing of austenitic welds in 3D configurations***
- ***Duration : Nov. 2011 to jan. 2015***



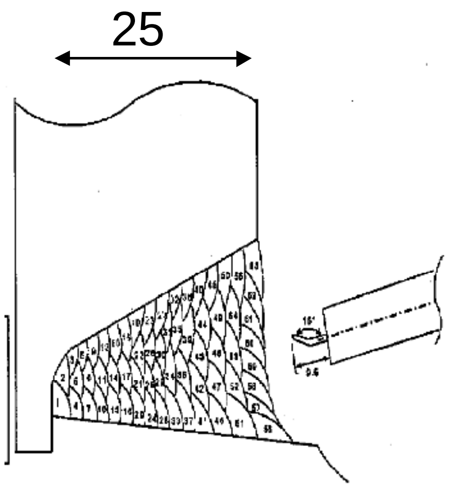
MOSAICS technical tasks



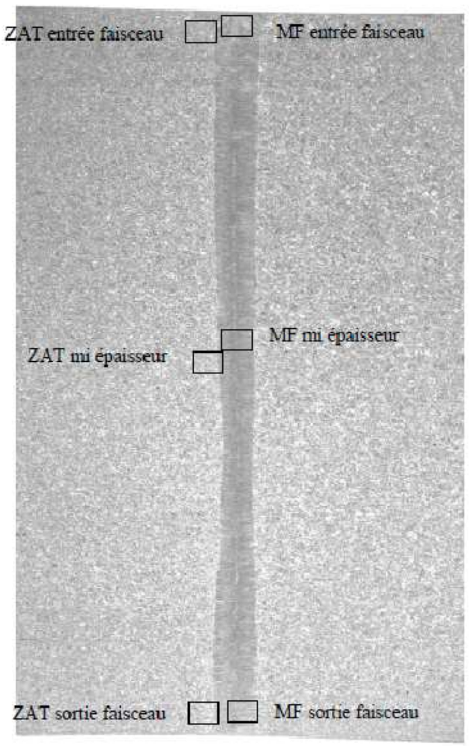
Technical specifications

- **Modelling input data (weld description)**
- **Industrial applications and mock-ups:**

DCNS applications

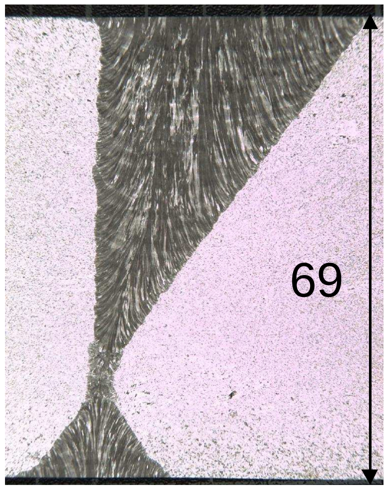


GTAW weld Horizontal-vertical position –26BN steel

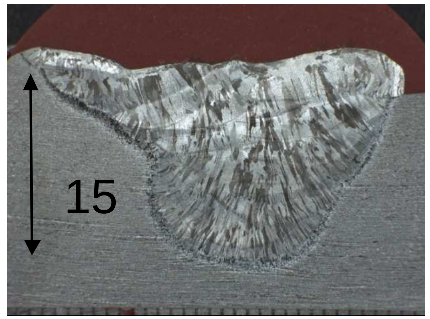


Electron beam weld

EDF Applications



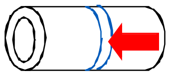
CVCS nozzle– 316L steel – SMAW

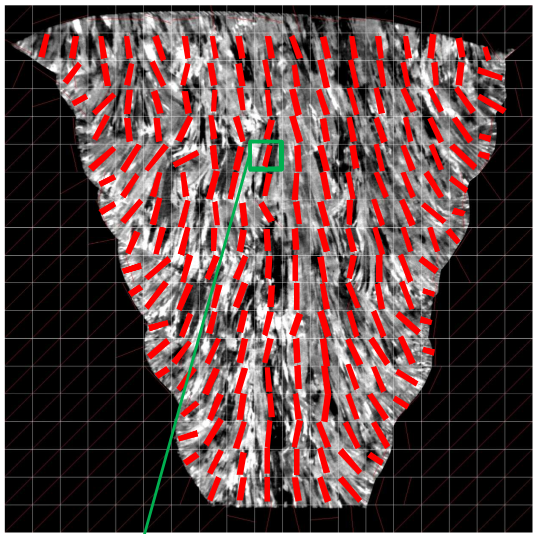


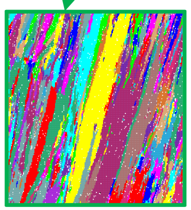
Weld repair – alloy 82 – GTAW

Metallurgical weld characterization

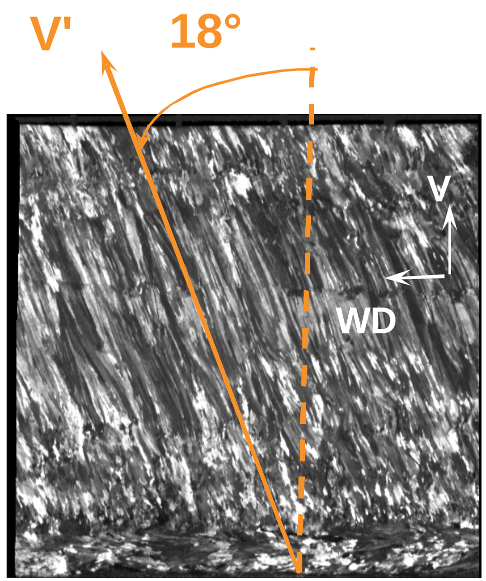
- Up-vertical position: 3D modelling
- Weld description (grain orientation mapping) :
  - Image processing on macrography
  - Crystallographic analyses (X-Ray diffraction and EBSD)
  - Description files compatible with modelling codes

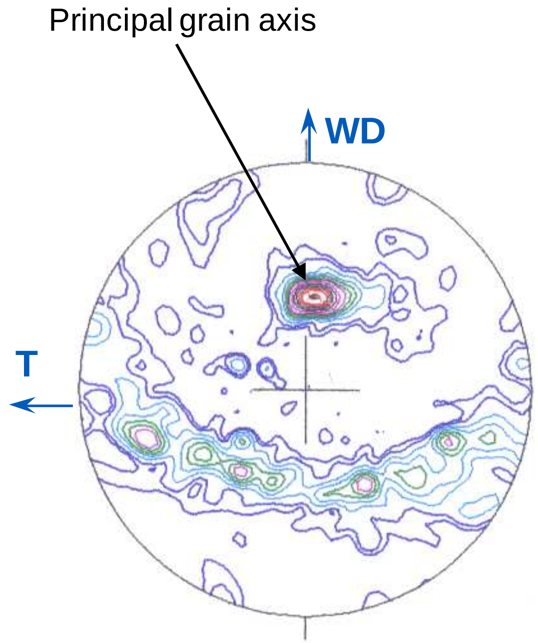






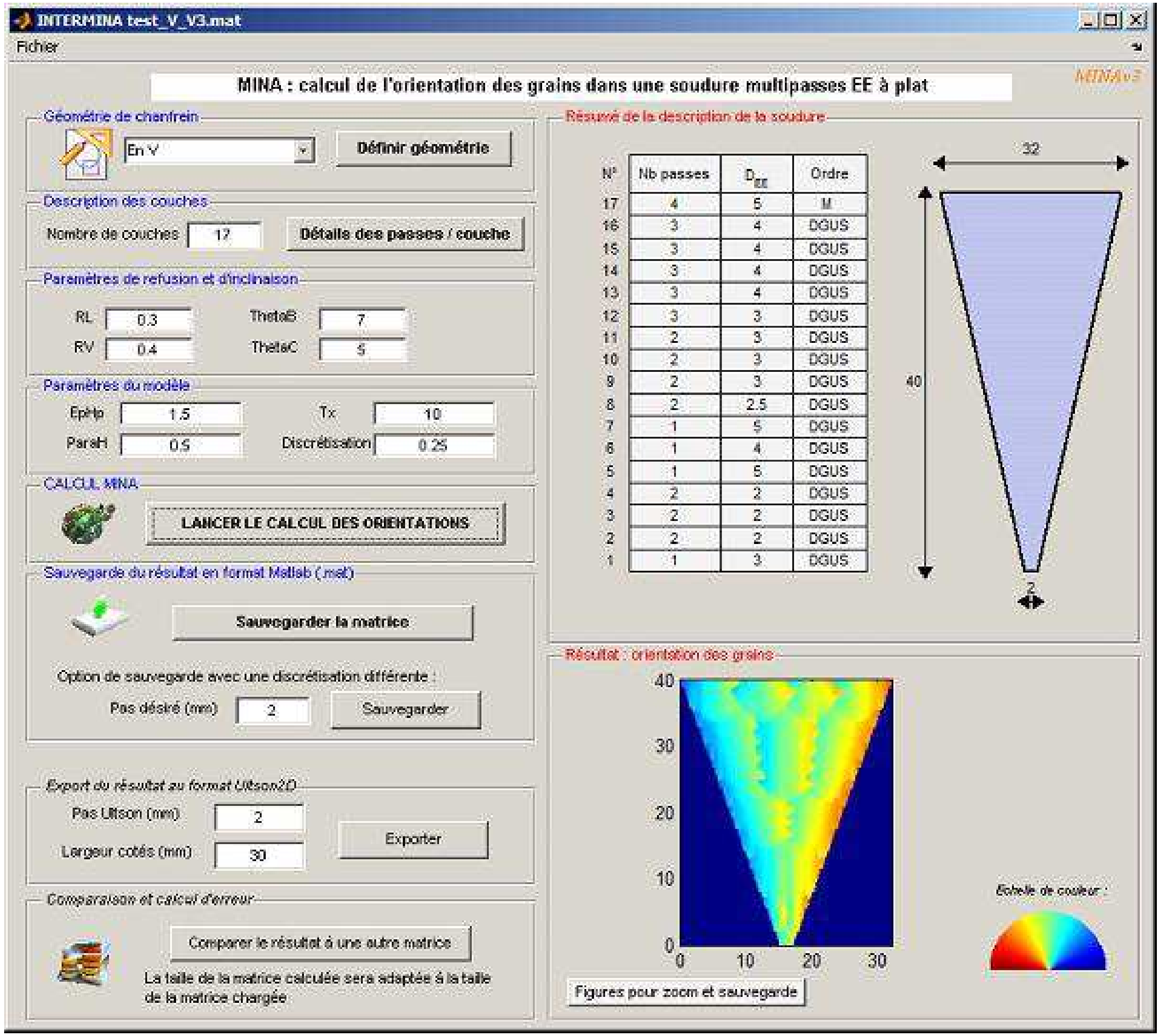
EBSD





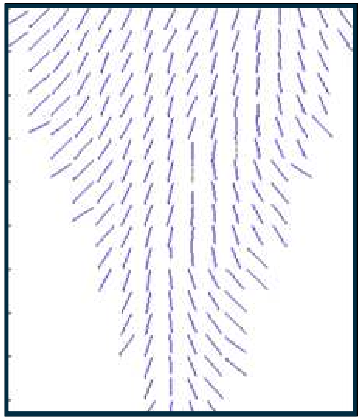
X-ray diffraction

MINA Model



2D configurations SMAW

Adaptation to GTAW in progress



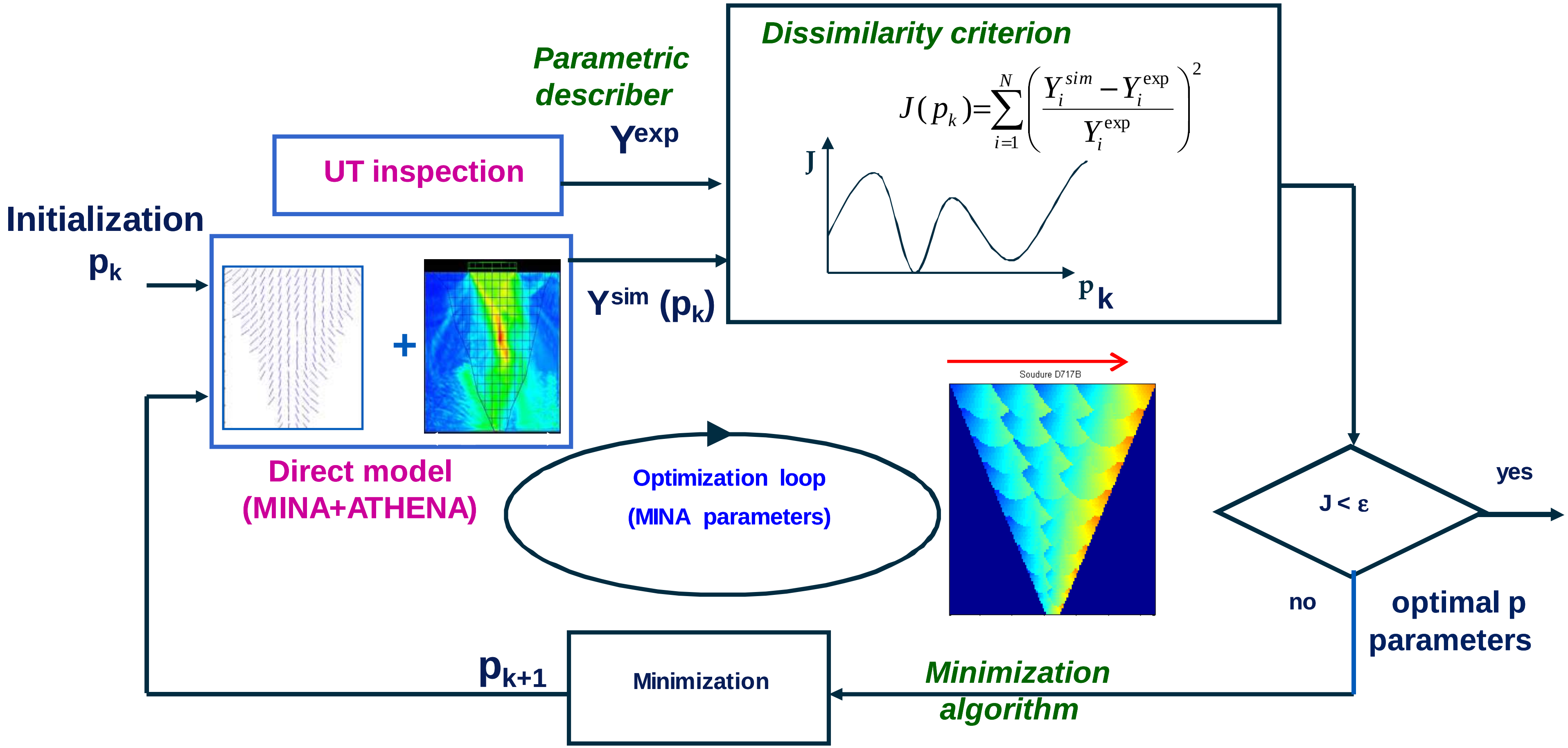
Meshing 2x2 mm^2

J. Moysan et al, IJVPV, 2003
A. Apfel et al, Ultrasonics, 2005

Inversion process for weld characterization

- **Objective: weld characterization of unknown structure**
- Previous work: process validation on numerical results in transmission mode
- MOSAICS :
  - **Experimental data in tandem mode**
  - **Inversion on passes order**

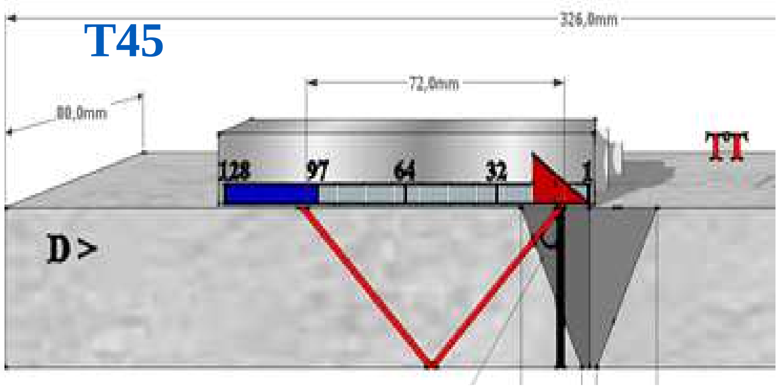
C. Gueudre et al, QNDE, 2010

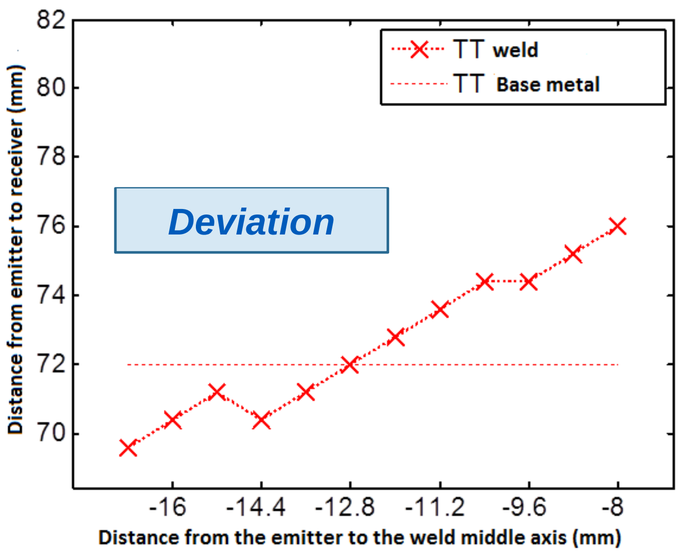


Inversion process for weld characterization

- Work progress: research of accurate parametric describer(s) by experimental and modelling studies
- First conclusion: T45 highly sensitive to passes order and structure dissymmetry

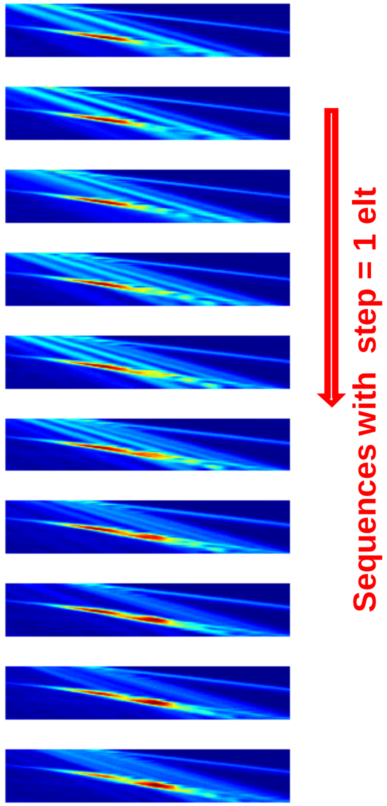
Experiment



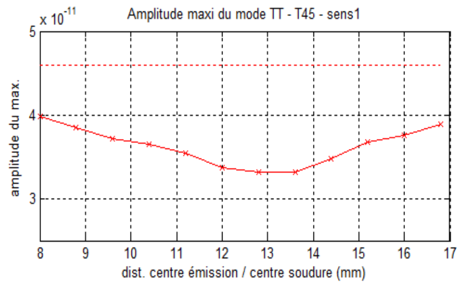


ATHENA modelling

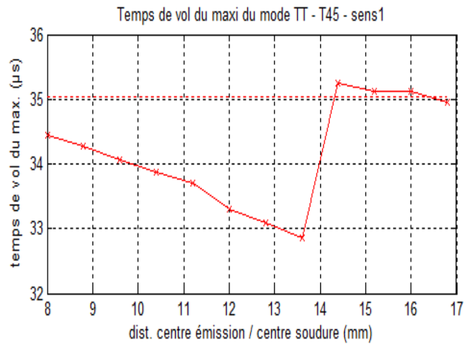
Direction 1



Amplitude ?

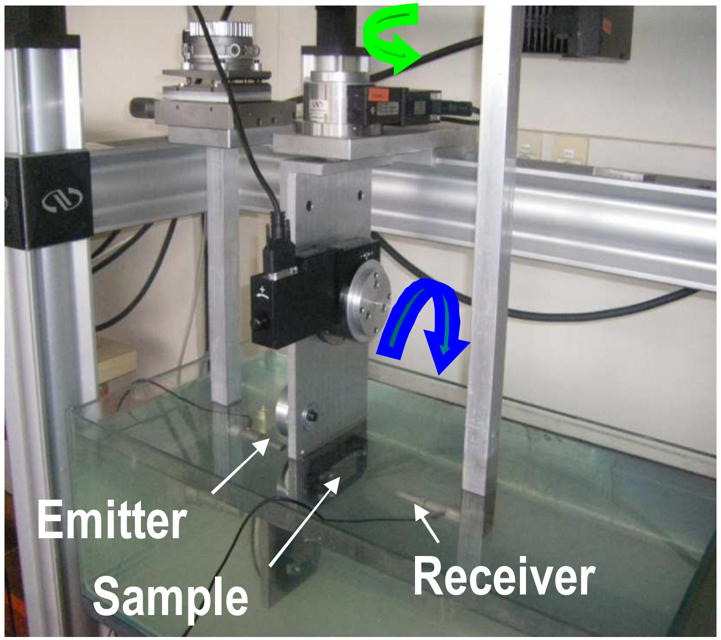


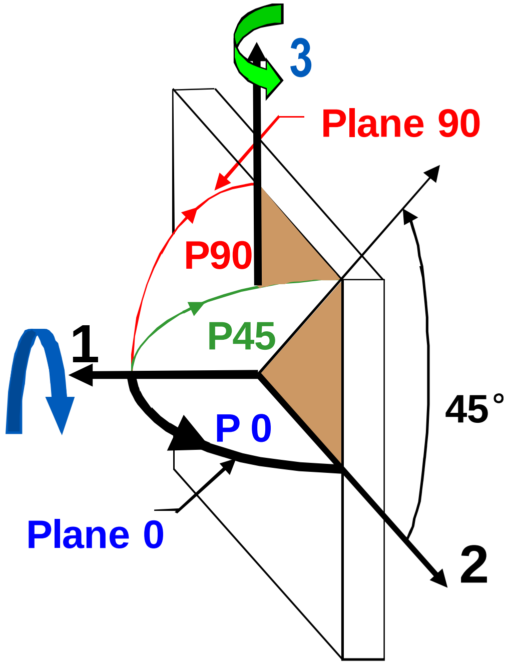
Time of flight ?

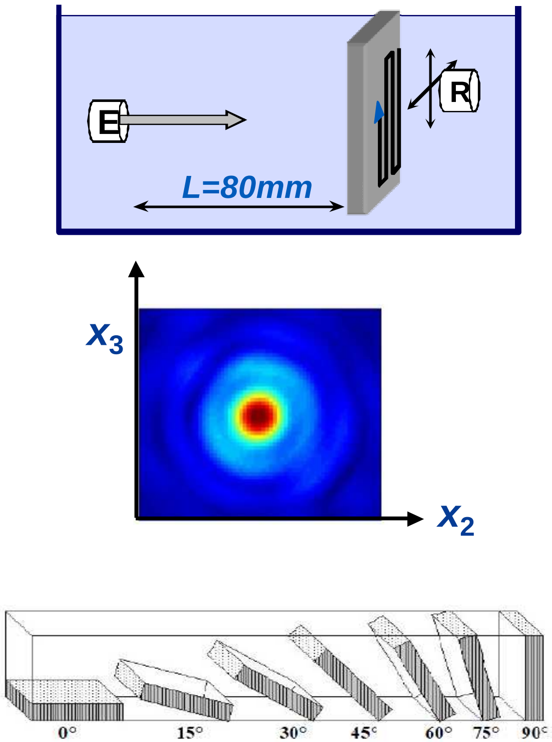


Ultrasonic characterization of weld properties

- Ultrasonic technique in transmission mode
- Homogeneous sample machined in welding molds (316L steel and alloy 182)
- Phase velocity measurements in various planes and directions of propagation ⇒ elastic properties and Euler angles
- Transmitted beam mapping: attenuation measurement at different frequencies (normal incidence) ⇒ 2D attenuation model
- **Longitudinal and shear wave attenuation measurements in any direction ?**
- **3D attenuation model ?**

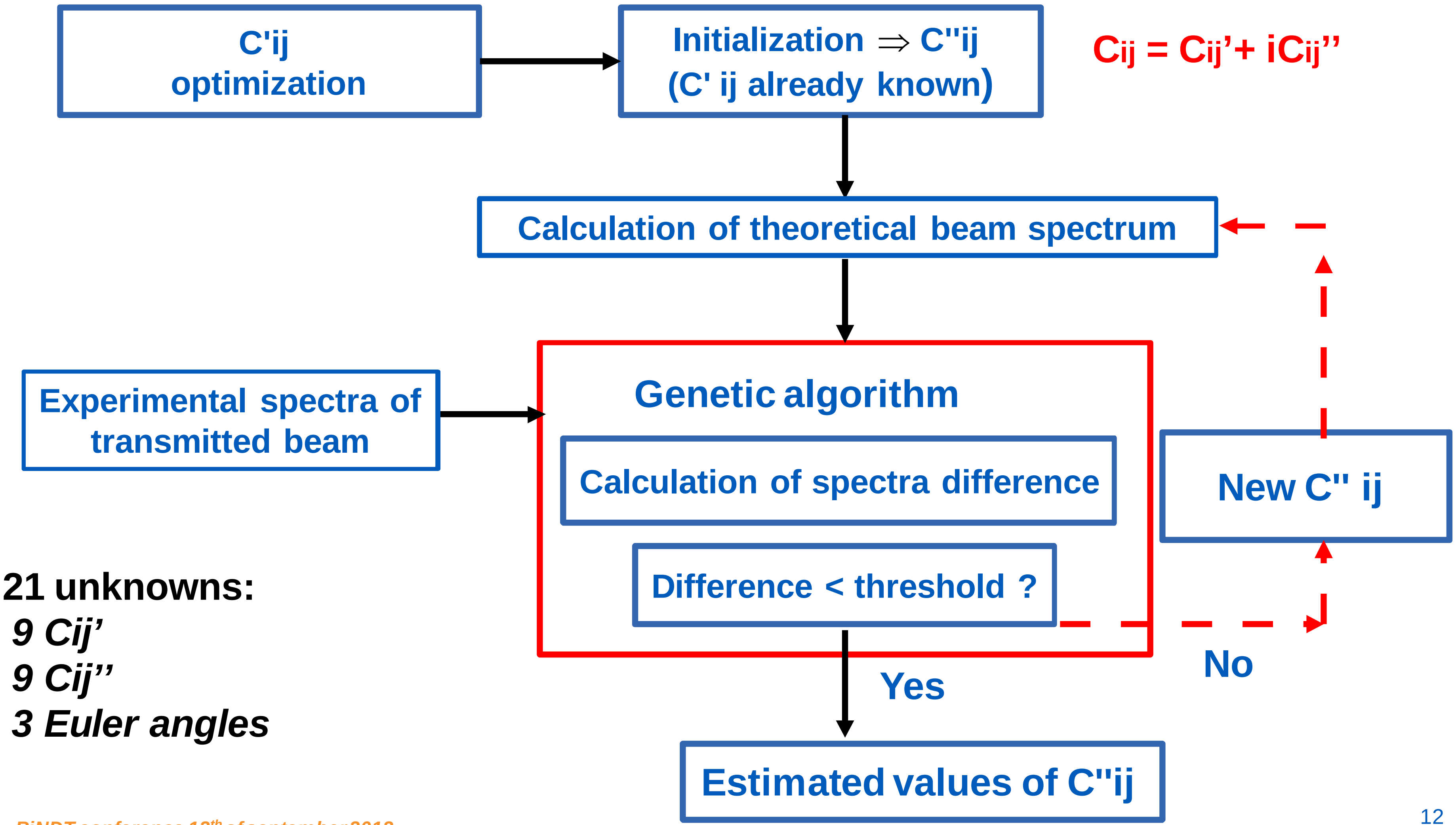






Attenuation measurement: new strategy

- Inverse problem resolution based on comparison between experimental and theoretical frequency spectra of the transmitted beam



21 unknowns:

9 Cij'

9 Cij''

3 Euler angles

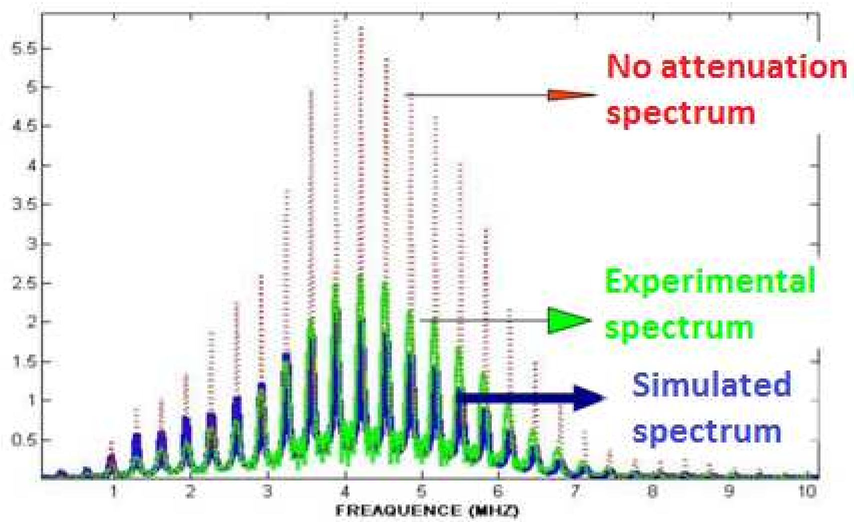
Attenuation measurement: first results

- Alloy 182 weld

	C_{11}	C_{22}	C_{33}	C_{12}	C_{13}	C_{23}	C_{44}	C_{55}	C_{66}	φ (°)	θ (°)	ψ (°)
C' (GPa)	233	243	247	134	146	114	80	104	110	8	26	0
C'' (GPa)	2.54	3.01	0.22	1.09	0.9	1.24	1.96	1.04	2.13	/	/	/

N. Alaoui Ismaili et al, QNDE, 2013

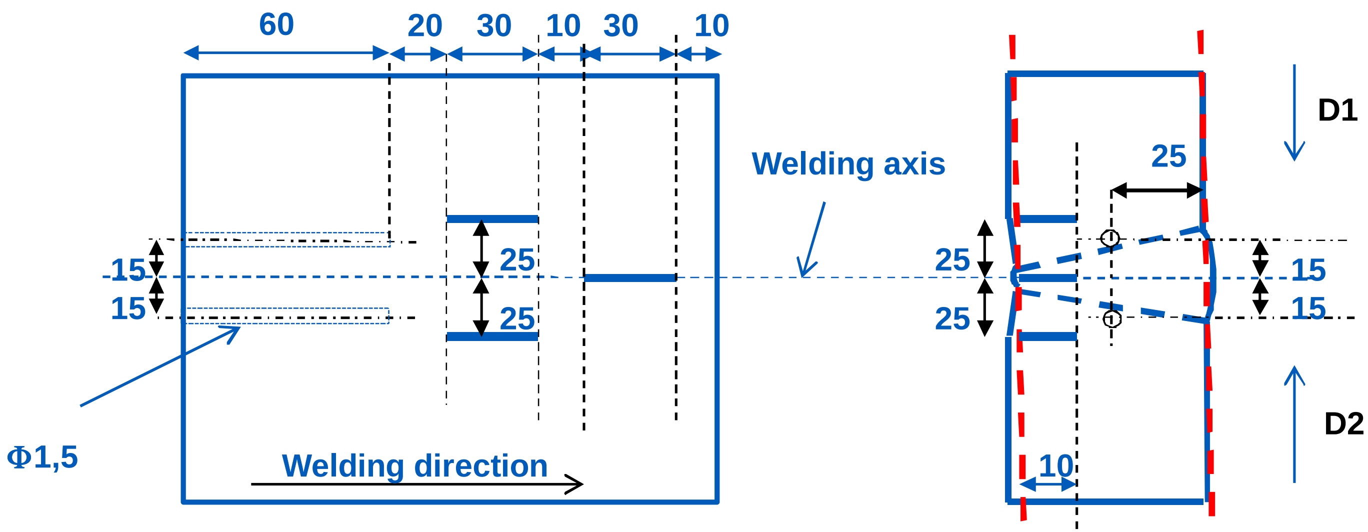
f = 3 MHz



- Prospects:
  - Cij" variation with frequency
  - Global optimization of 21 unknowns

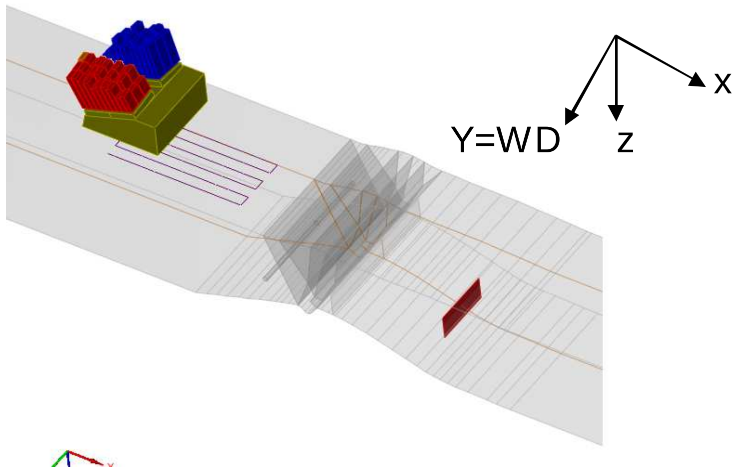
UT experiment

- Calibrated flaws (Side drilled holes, notches) machined in welded mock-ups



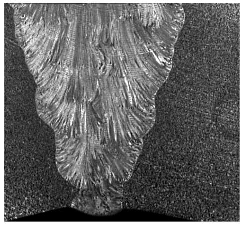
Up-vertical position SMAW weld

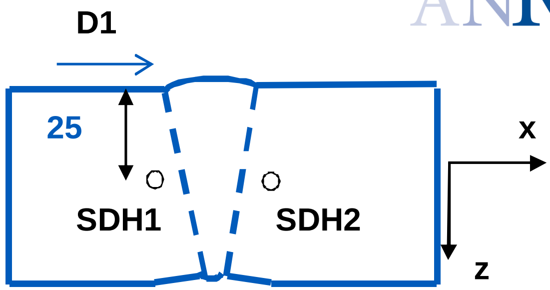
- Inspections in automatic mode:
  - Standard single-element probes and TRL phased arrays
  - Longitudinal waves
  - Two directions of inspection
  - Influential parameters:
    - ***Beam angle***
    - ***Beam focusing***
    - ***Frequency***



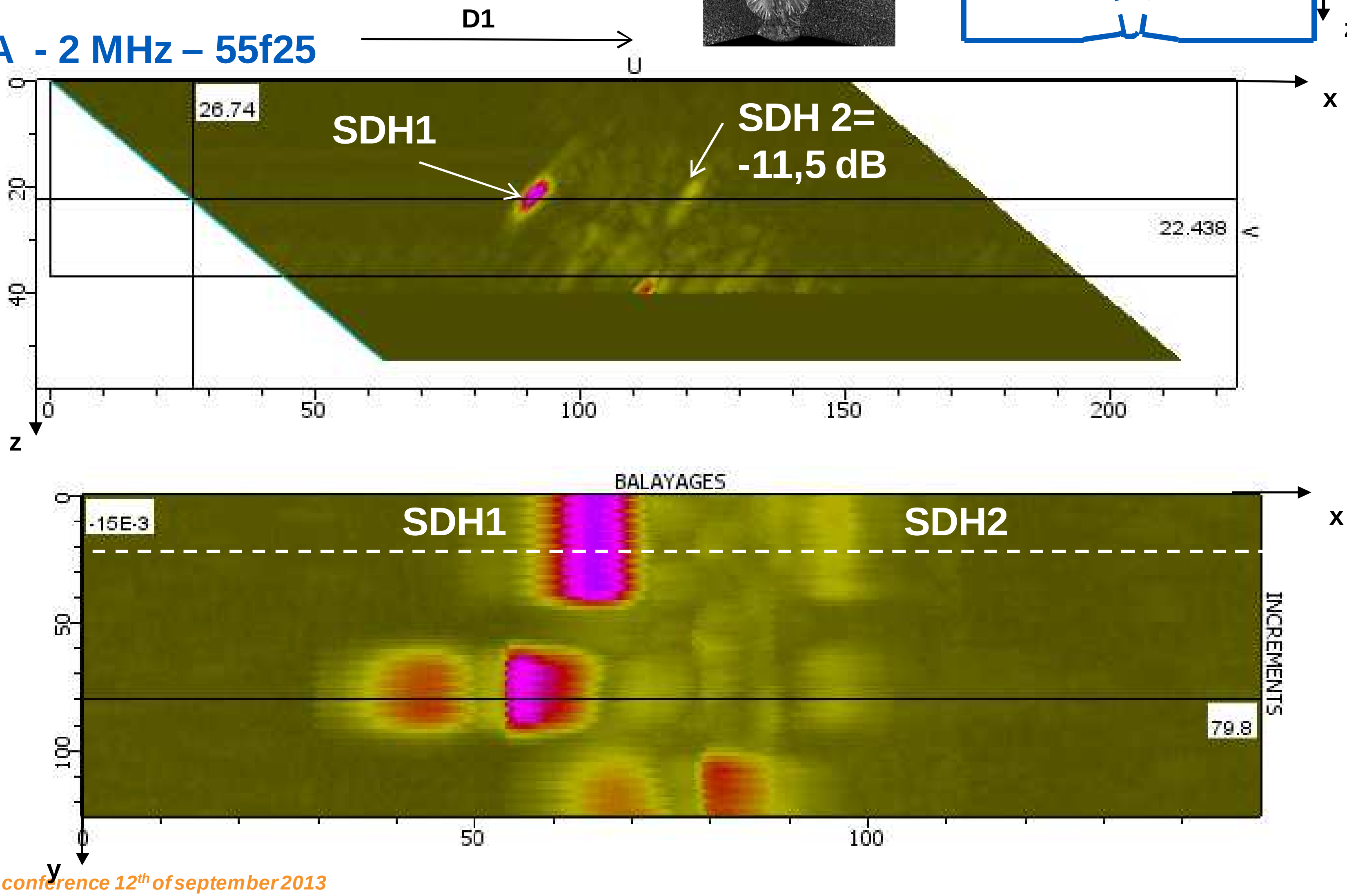
Results: SDH

High attenuation due to the weld structure



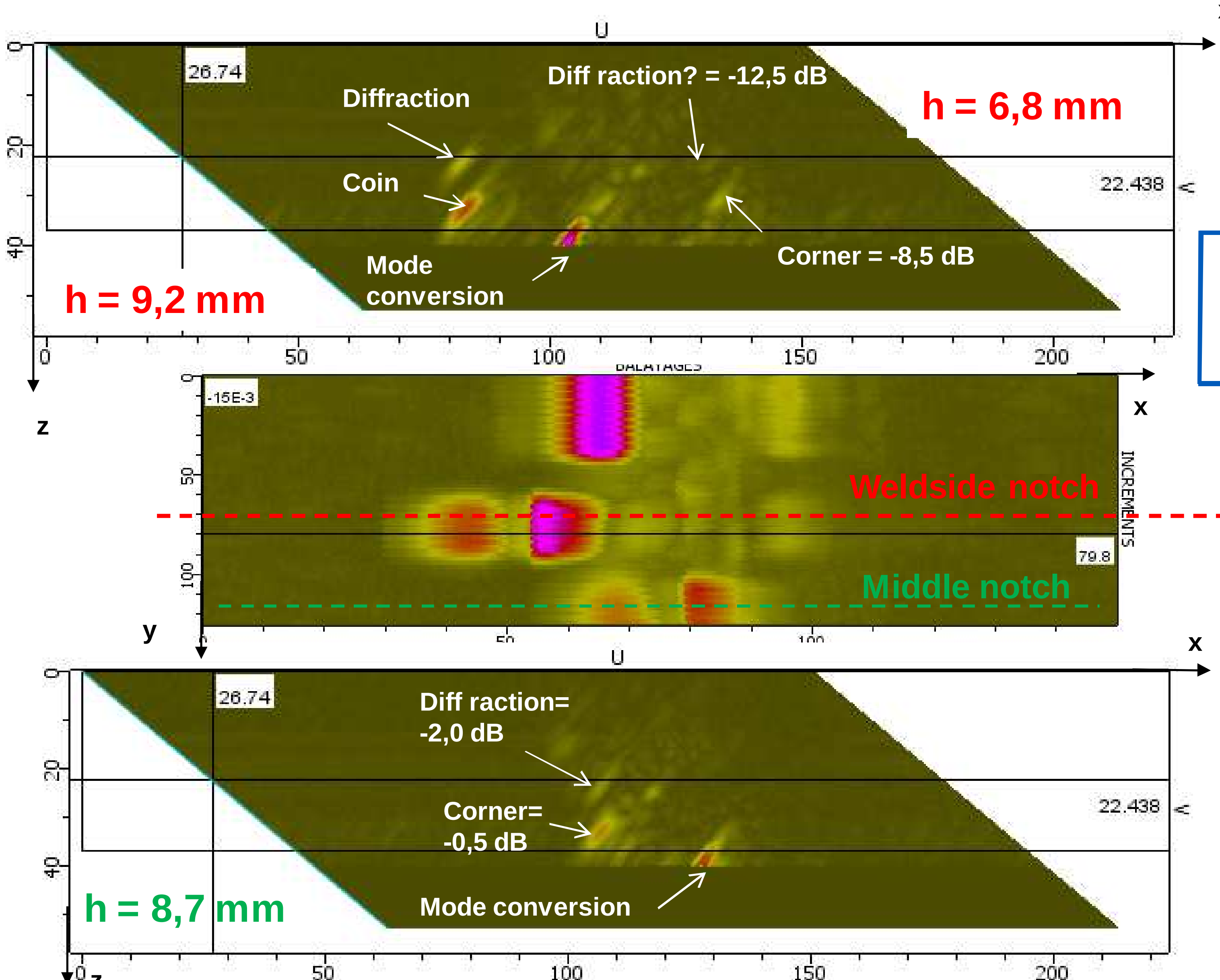


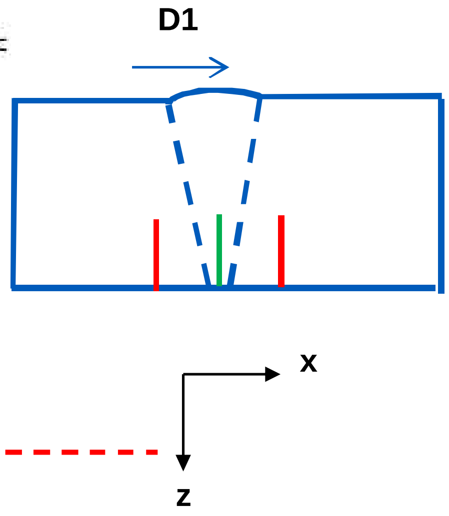
TRLPA - 2 MHz – 55f25



Results: notches

TRLPA - 2 MHz – 55f25



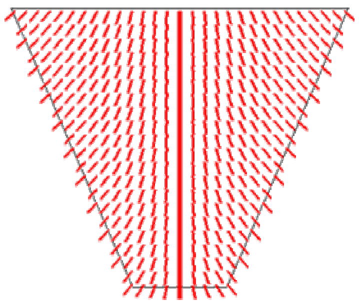


Weldside notch:

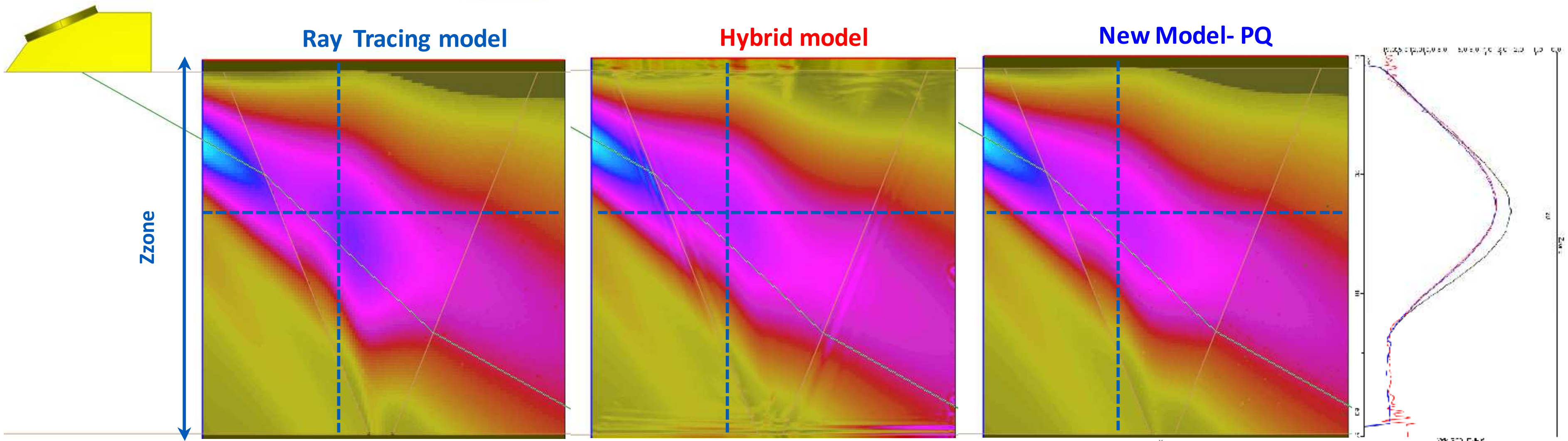
- high attenuation
- sizing error
- spurious echo

UT modelling: CIVA

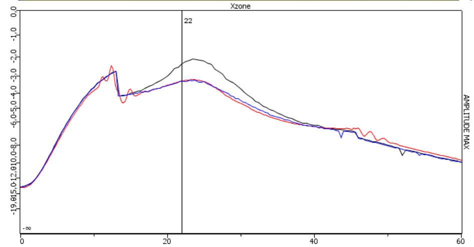
- **Current model : limitation when λ ≈ anisotropic domain size**
- **Solution: smoothly inhomogeneous weld description**
  - From macrography, analytical model or MINA model
- **Dynamic (paraxial) Ray Tracing model (DRT) :**
  - Implementation of paraxial quantities in semi-analytical models (pencil method)



N. Leymarie et al, BINDT, 2013



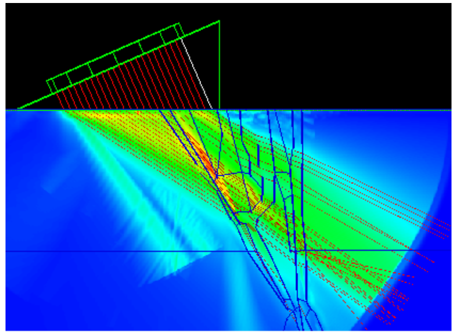
Xzone

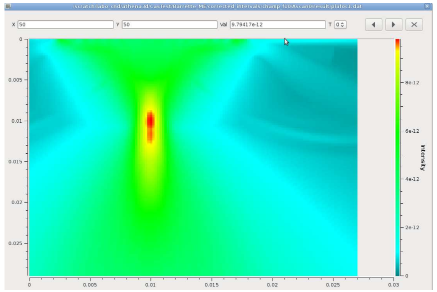


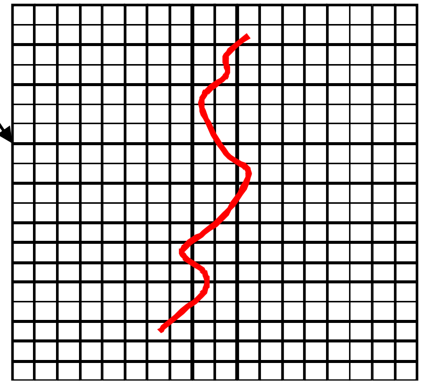
Modelling results with inhomogeneous weld description

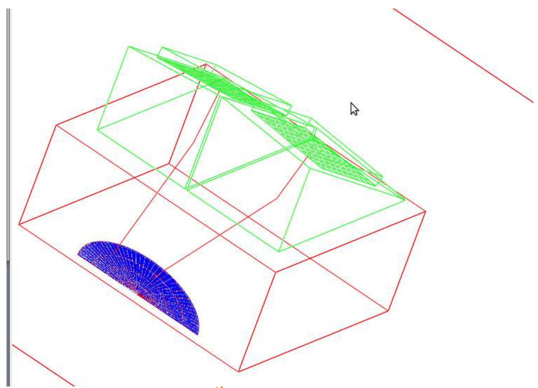
FE code ATHENA

- Quasi-explicit scheme and regular mesh **: good numerical performances**
- Beam propagation in anisotropic and heterogeneous media
- Beam to flaw interaction (fictitious domain method)
- 2D version
  - Various probe types (TOFD, phased arrays,…)
  - Coupled with CIVAv11 (2012)
  - Attenuation model
  - GUI
- 3D needs :
  - **3D probe (TRL PA)**
  - **3D flaw (elliptical)**
  - **3D anisotropy**

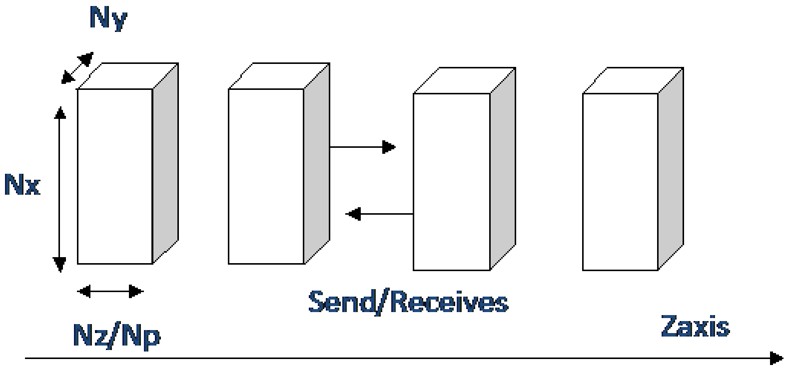






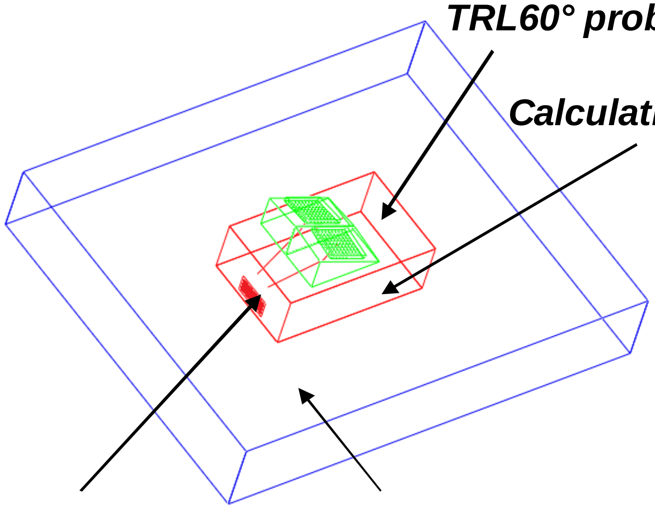


Parallelization of 3D version

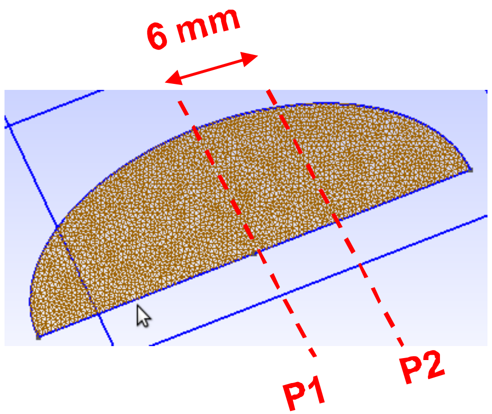


ATHENA 3D: validation in isotropic and homogeneous medium

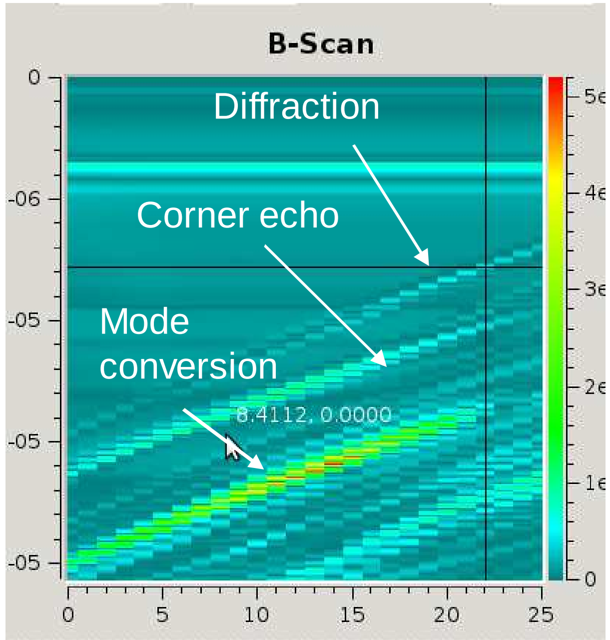
C. Rose et al, 10th AFPAC



10*20 mm
depth = 30 mm



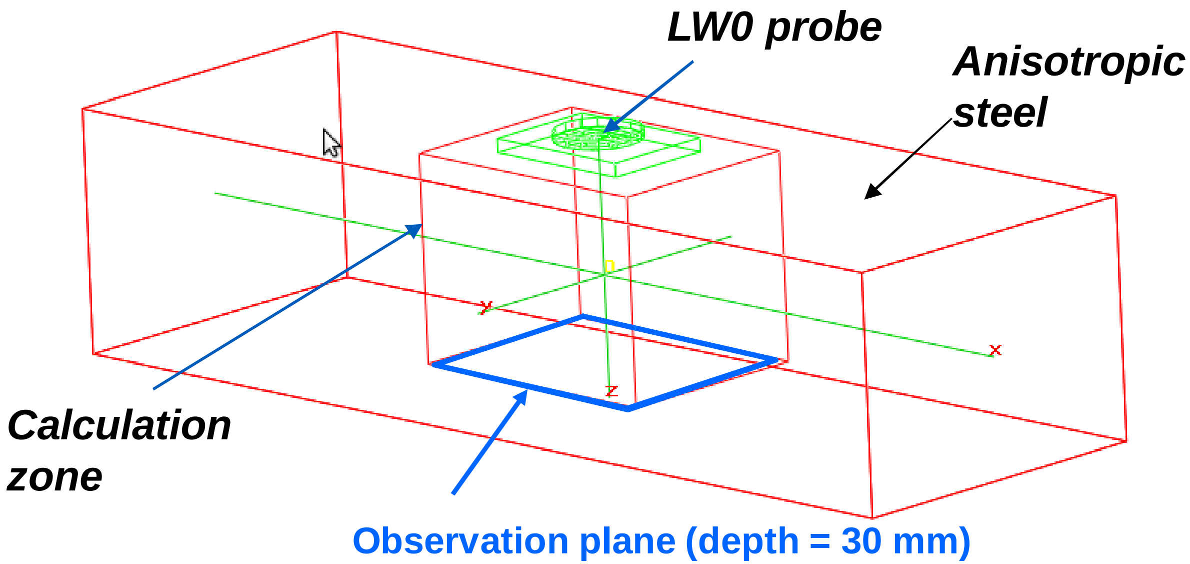
Flaw meshing (GMSH)

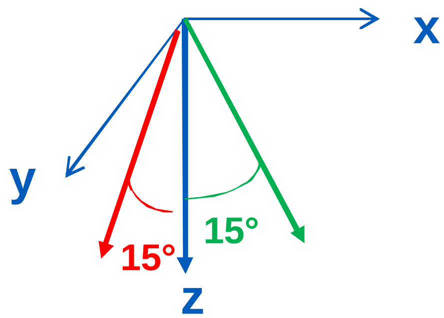


Reference = SDH 1 mm-radius

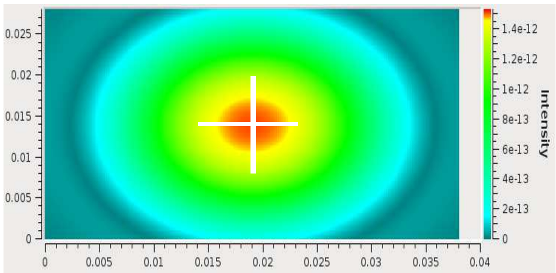
	Diffraction (dB)		
	Rectangular	½ elliptical – P1	½ elliptical – P2
ATHENA 3D	-9.0	-12.0	-17.5
Experiment	-8.0	-12.0	-16.5

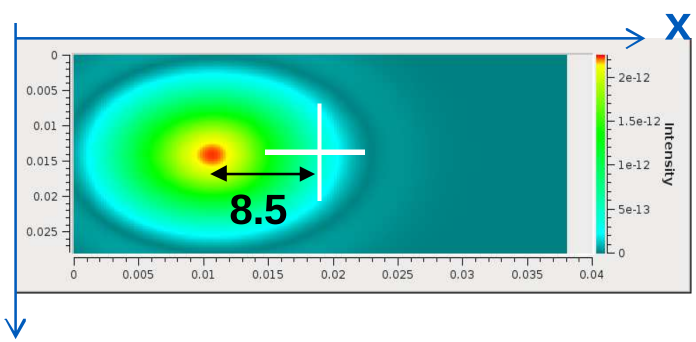
ATHENA 3D: validation in anisotropic and homogeneous medium

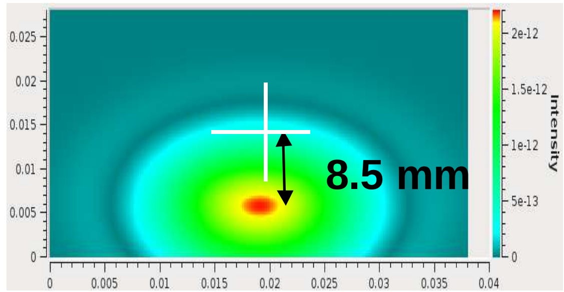




Orientation of fiber axis:
Case 1: parallel to z
Case 2: 15° rotation around y
Case 3: 15° rotation around x





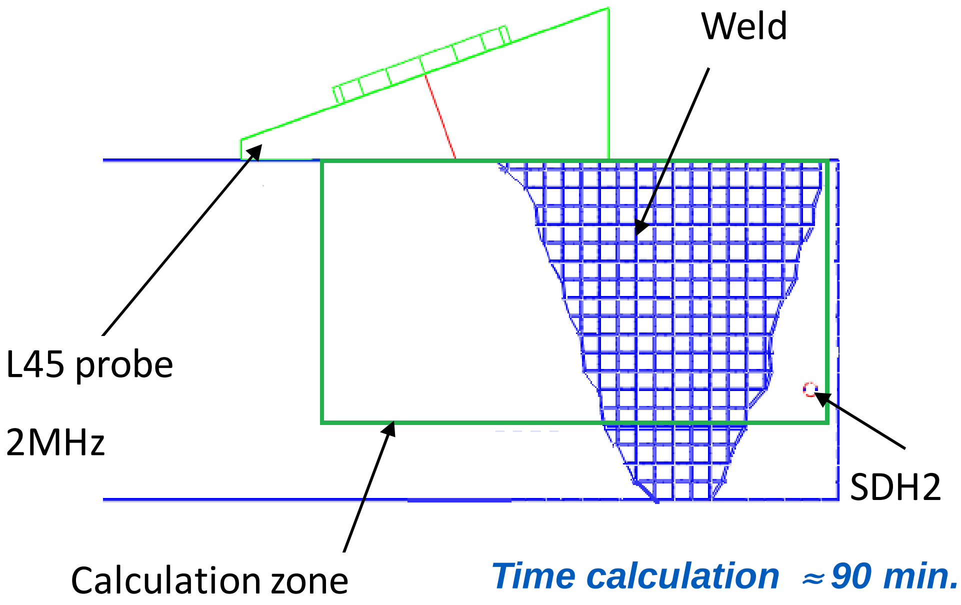


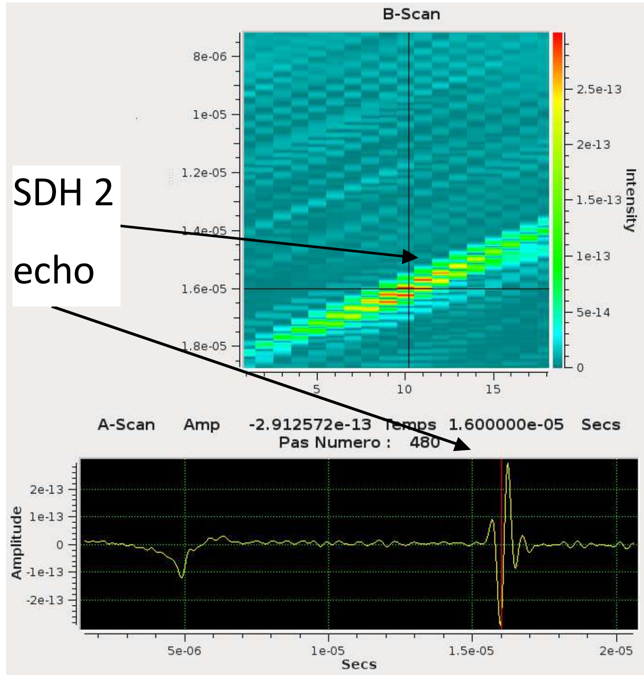
Case 1: No beam deviation **Case 2: deviation on x** **Case 3: deviation on y**

In agreement with theory of ultrasonic propagation in such medium

ATHENA 3D: first validation in welded structure

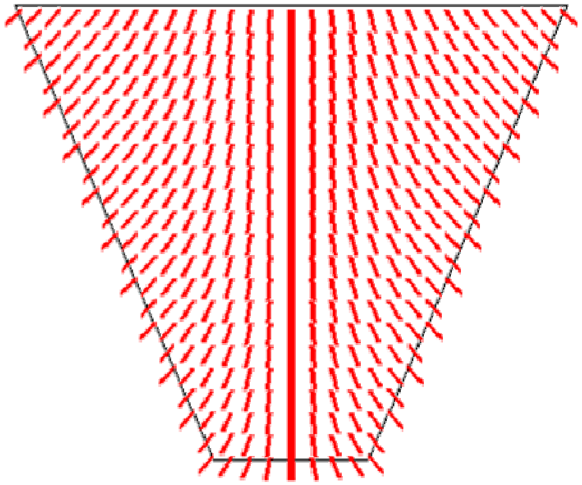
- **Up-vertical weld and SDH**

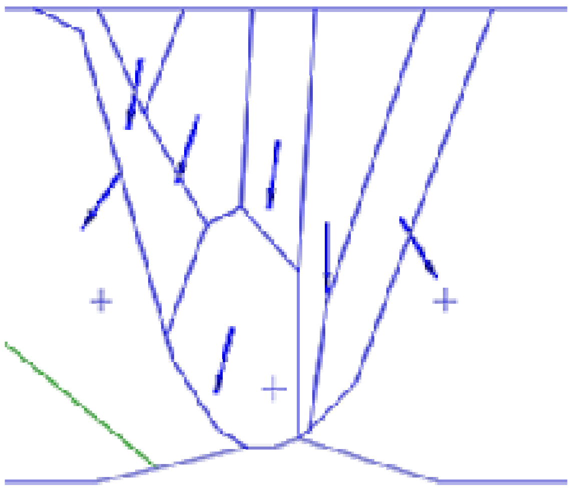


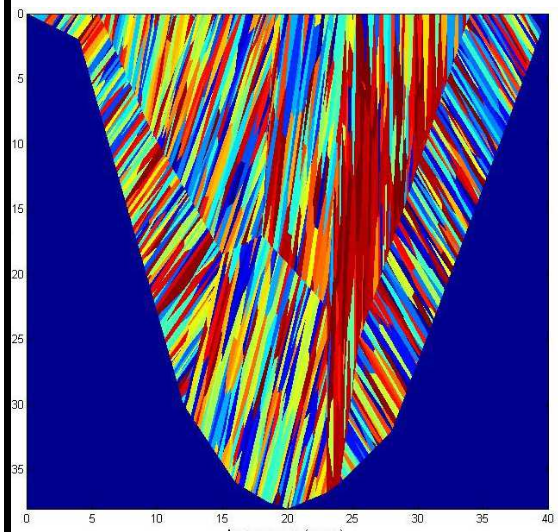


- **SDH2 – SDH1 = - 9 dB (beam division and distortion, scattering at each domain interface)**
- **Experiment = -11.5 dB :**
  - Influence of weld description ?
  - Influence of uncertainties on input data (material, probe…)?

Influence of weld description







Smoothly inhomogeneous

Macroscopic anisotropic and homogeneous domains

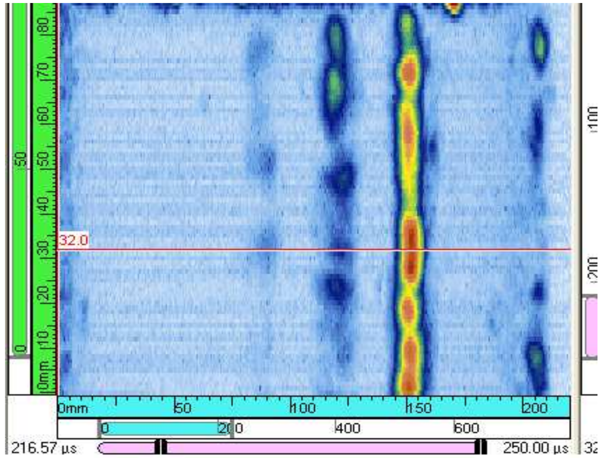
Grain-scale modelling (Voronoï tesselations)

+ 3D attenuation model

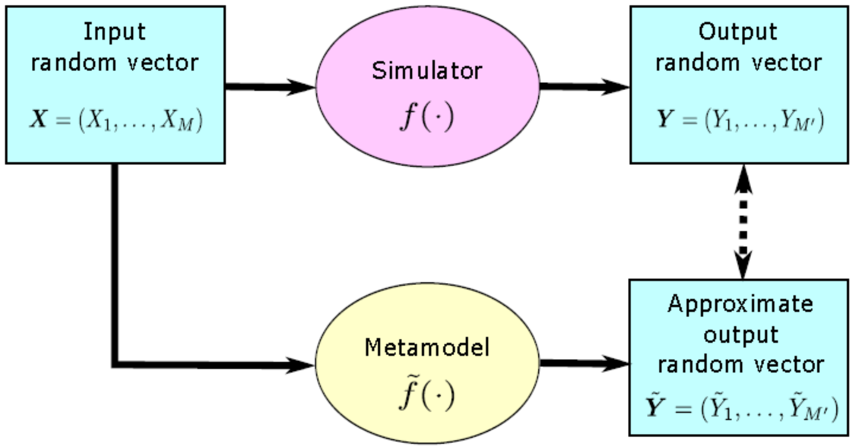
Sensitivity analysis with ATHENA2D: principle

- Variation of the flaw echo amplitude along the welding direction or between two welds : influence of uncertainties on material input data ?

⇒ **Sensitivity analysis**



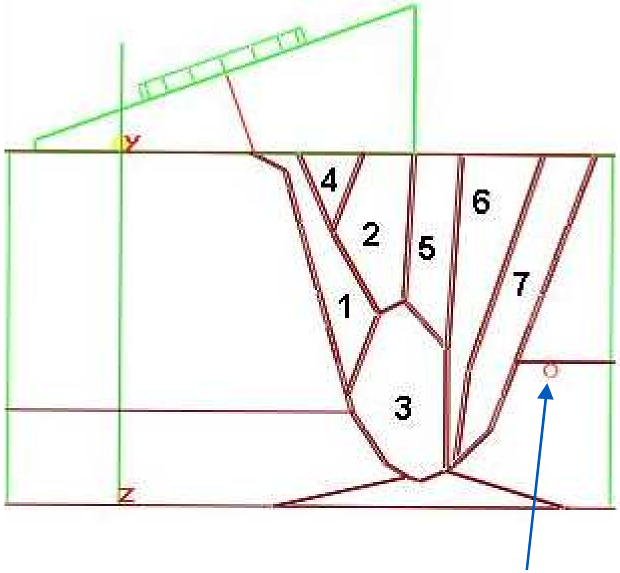
Quantification of Uncertainties → **ATHENA modelling coupled with OpenTurns tool (Meta-model)** → **Uncertainty propagation – variation of system response**; **Sensitivity analysis: influential parameters**



F. Rupin et al, QNDE, 2012

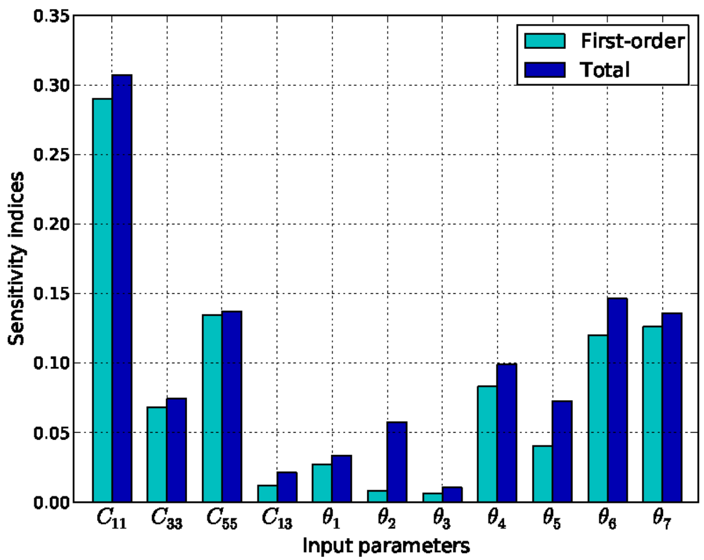
Sensitivity analysis with ATHENA2D: results

Horizontal position welding



SDH

- Bscan with 18 probe positions (LW45° - 2 MHz)
- 11 material parameters : 7 orientations + 4 elastic constants
- Attenuation model
- 2000 calculations
- Results :
  - **Amplitude variation = 15 %**
  - **Sensitivity analysis**

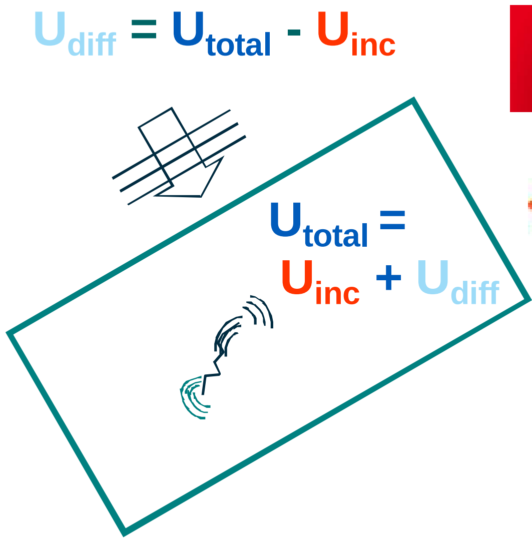


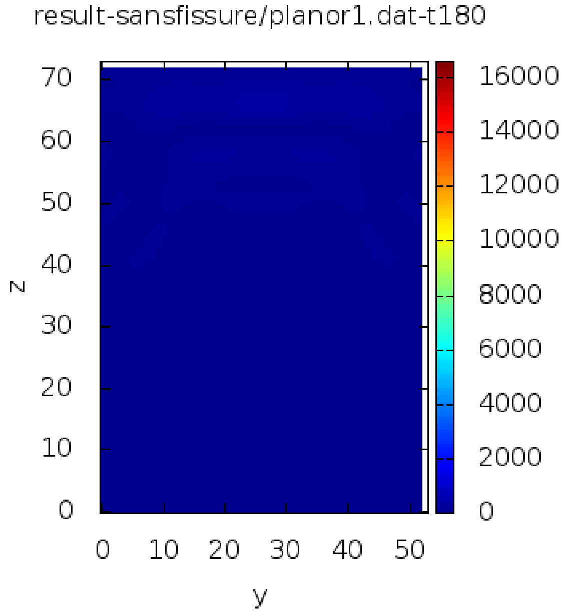
Influential parameters (Sobol Indices)

- **Prospects :**
  - Plane defects
  - Uncertainties on attenuation
  - MINA model
  - New applications

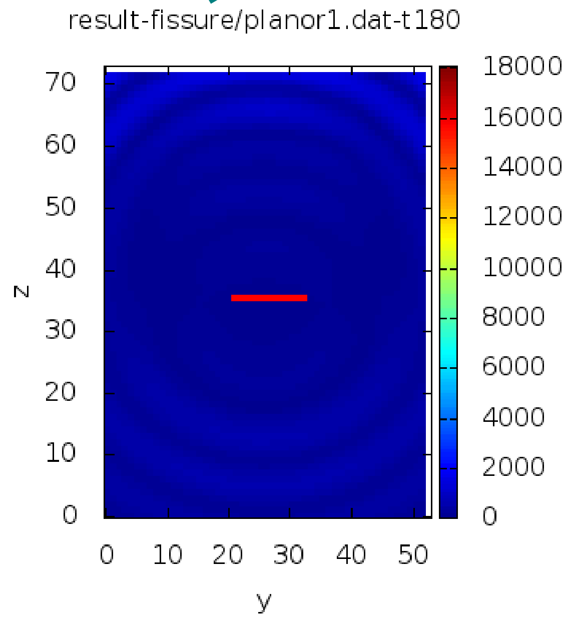
Hybrid CIVA/ATHENA : 3D version

- Previous work (MOHYCAN project) : 2D version
- MOSAICS :
  - **3D version with optimized model (reduction of FE box)**
  - **Calculation on HPC clusters**
  - **Validation on isotropic medium**
  - **Adaptation to anisotropic and heterogeneous media**





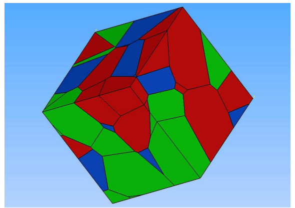
Without flaw



With flaw

Conclusion and prospects

- Metallurgical characterization realized on various welded mock-ups
- Inversion process for unknown structure to be developed and validated
- Experimental database for code validation
- Simulation:
  - **Specific developments on CIVA and ATHENA codes to take into account complex 3D configurations (material, probe, geometry, flaw)**
  - **First validation for « 2.5D » extruded weld : to be continued**
  - **Code adaptation for real 3D anisotropic and heterogeneous structures**



  - **Implementation of a 3D attenuation model based on ultrasonic characterization**

$$\frac{\partial \sigma}{\partial t} + D\sigma = C\varepsilon(v) \Longrightarrow \overline{C} = i\omega(i\omega + D)^{-1}C$$

  - **3D Hybrid model : validation on isotropic media and adaptation to weld configuration**