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Simulation of ultrasonic inspection in a highly heterogeneous media: strategies and modelling tools applied to austenitic welds

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Edouard Demaldent

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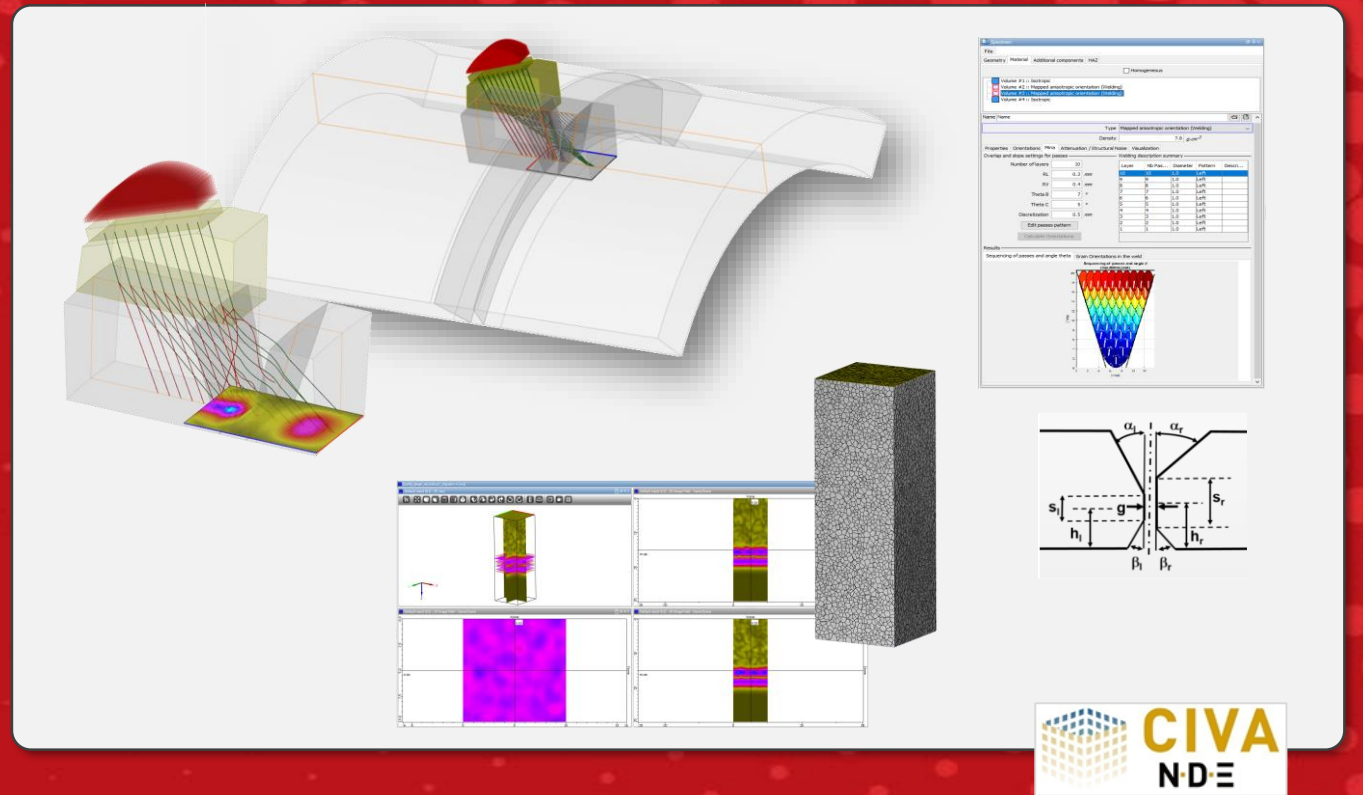


DE LA RECHERCHE À L'INDUSTRIE

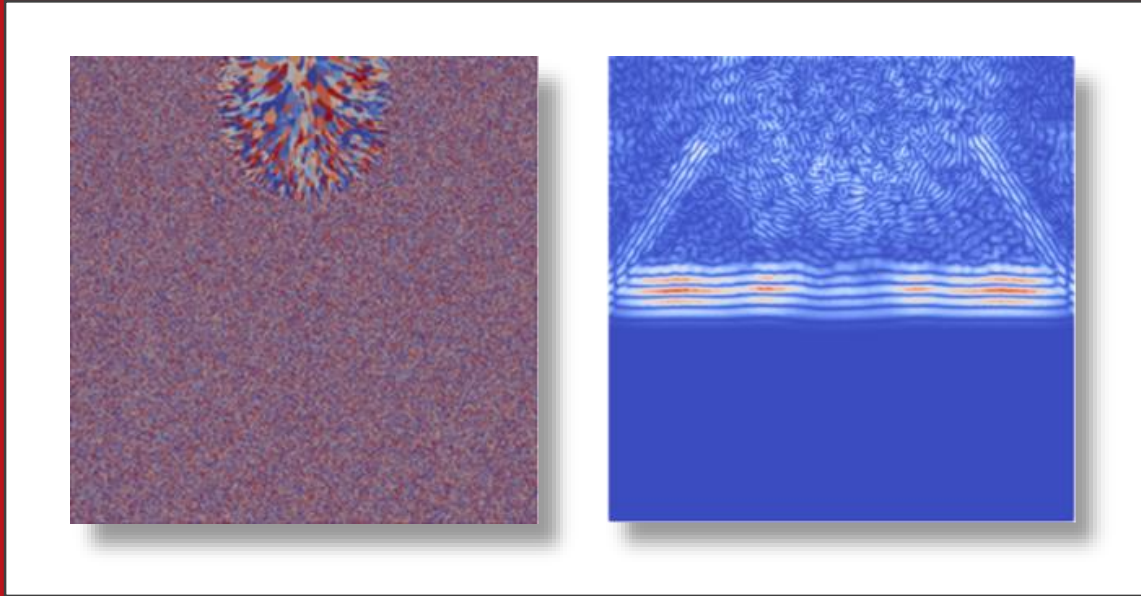
Simulation d'inspection ultrasonore en milieu fortement hétérogène : stratégies et outils de modélisation appliqués aux soudures austénitiques

Matériaux Fortement Hétérogènes, Journée Technique Régionale COFREND, 03 novembre 2022

N. LEYMARIE, A. IMPERIALE, V. DORVAL, T. FORTUNA, E. DEMALDENT



 **COFREND**[®]
Confédération Française pour les Essais Non Destructifs



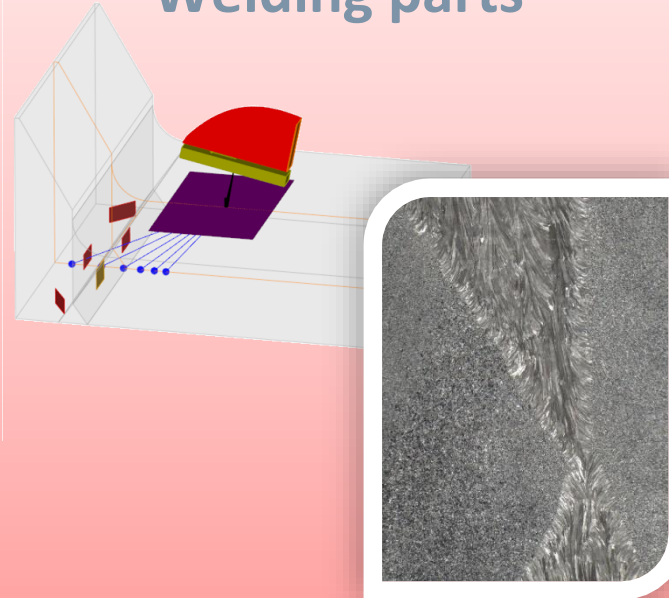
Phenomenological aspects

Wave propagation and interactions in heterogeneous materials and main issues for UT applications

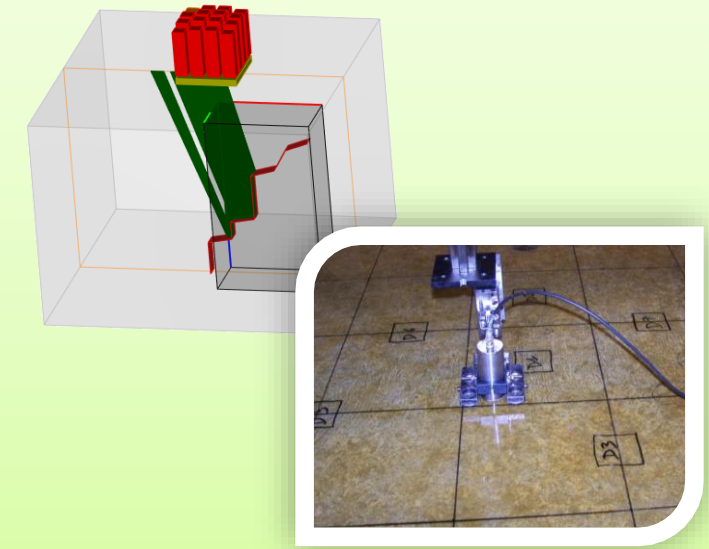
Cast steels (coarsened-grain structures)



Welding parts



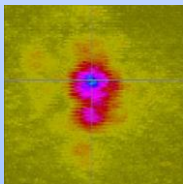
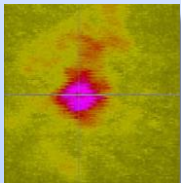
Concrete



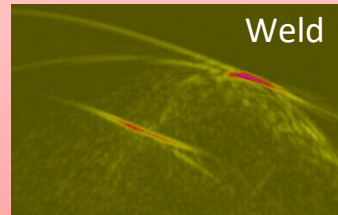
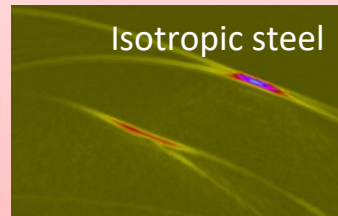
- **Heterogeneous materials** at the wavelength scale used for UT applications
- Various **geometrical characteristics** of the heterogeneities (sizes and shapes)
- With possibly **anisotropic properties** or **impedance variations**

Cast steels (coarsened-grain structures)

Fields for \neq pos.
on backwall

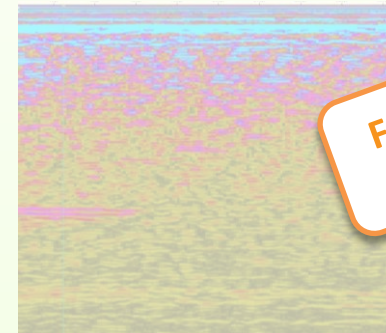


Welding parts



Concrete

Bscan acquisition



**Focus on polycrystal
applications**



- ⇒ Ultrasonic beam splitting and skewing and attenuation of the coherent wavefront
- ⇒ Structural noise in the echo responses

Performance loss in
defect detection
and sizing

Strong interest in UT simulation
to assist in interpretation and
inspection optimisation

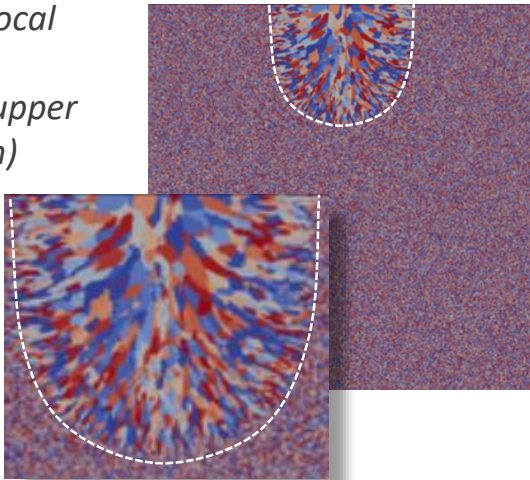
Wave interactions and scattering effects

► Main influencing parameters

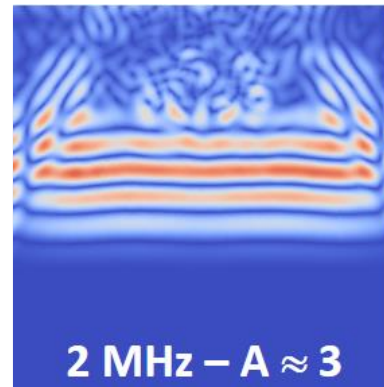
- **Frequency:** scattering effect depending on the grain size D relative to the main wavelength λ
- **Grain anisotropy:** scattering effect related to the impedance contrast between the grains associated with the single crystal anisotropy factor (Zener factor A)

$$A = \frac{2C_{44}}{C_{11} - C_{12}} \text{ for a cubic monocrystal property}$$

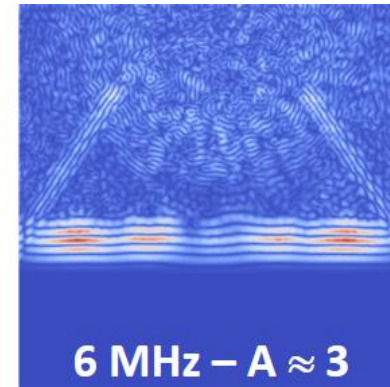
Example of the effect of a local weld deposit
(plane wave source at the upper interface - 2D FE simulation)



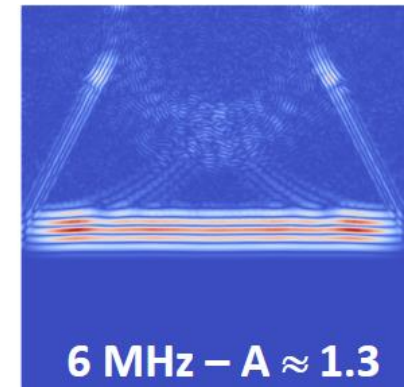
Basse freq. – contraste moyen



Haute freq. – contraste moyen



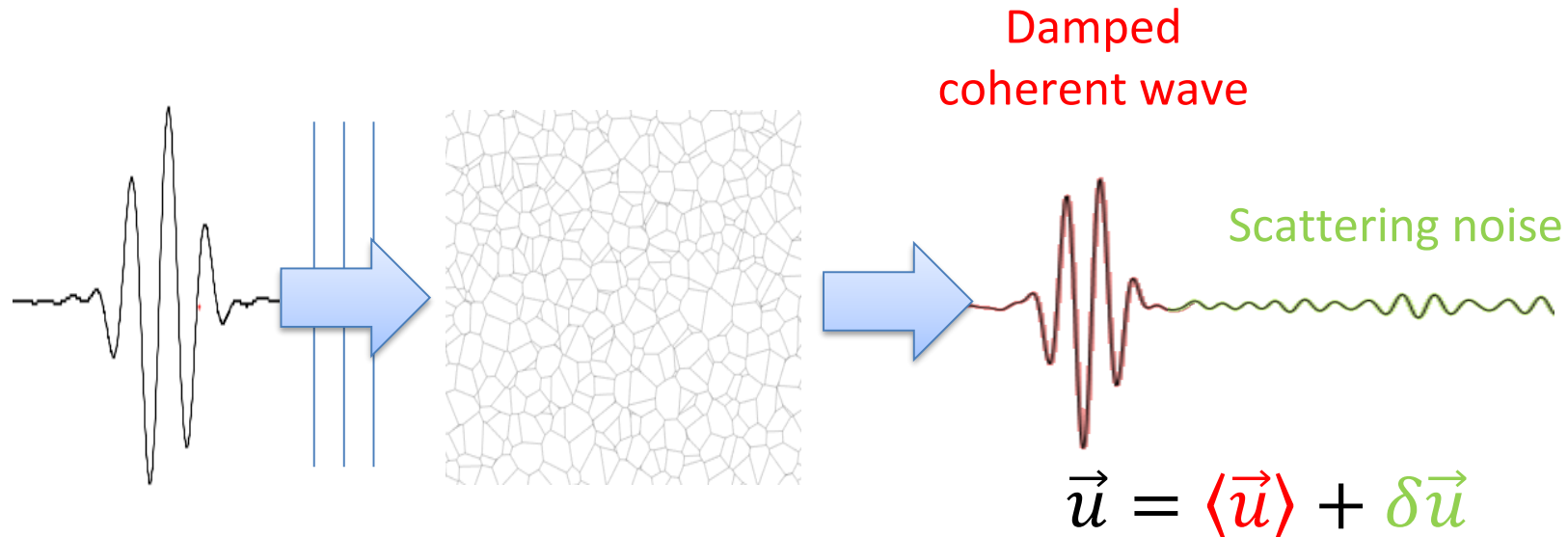
Haute freq. – faible contraste



Phenomenological observations for UT inspection in the Rayleigh regime

► Coherent wave and structural noise

- If $\lambda \gg D$, we keep a coherent wavefront to perform UT imaging in depth
 - Damped coherent plane wave - “average field” $\langle \vec{u} \rangle$
 - Added scattering effects - coda $\delta \vec{u}$

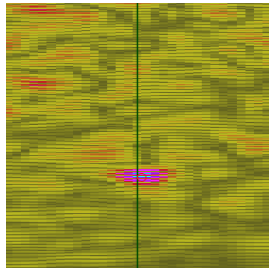


Pragmatic philosophy for UT simulation

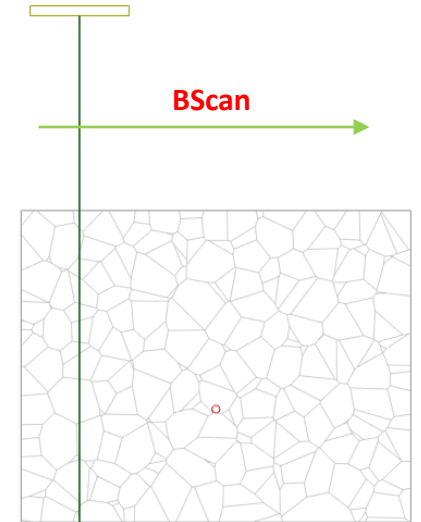
► Example of simulation: LO-Bscan of a SDH flaw in a microstructured material

- calculation considering microstructured material

Grain-scale
simulation

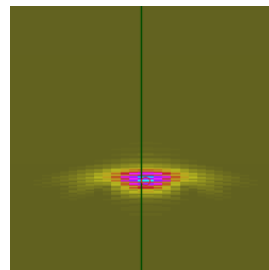


Global response without approximation (reference solution)
deterministic according to the provided description
HIGH 3D COMPUTATIONAL COST ! ⇒ reference solutions only

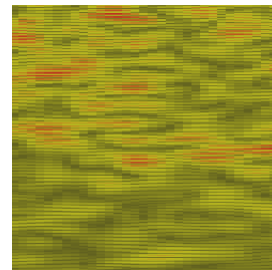


- calculation considering an effective material

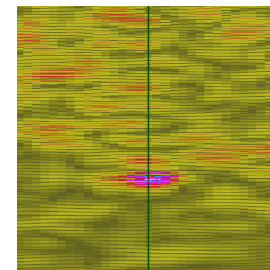
Macroscale
simulation



*SDH response
in an effective damping medium*
**LOWER COMPUTATIONAL
COST !**



*Backscattering noise
(if necessary)*
*Random solution according to
a distribution of scatterers*



Equivalent response using effective media
dedicated to intensive parametric studies
(in an idealistic point of view)

UT Microscale modelling

Effective material characterization
structural noise model
calibration

UT Macroscale modelling

effective material (anisotropy,
damping), bevel geometry, grain
orientation map...

Dedicated simulation tools for NDT on welds

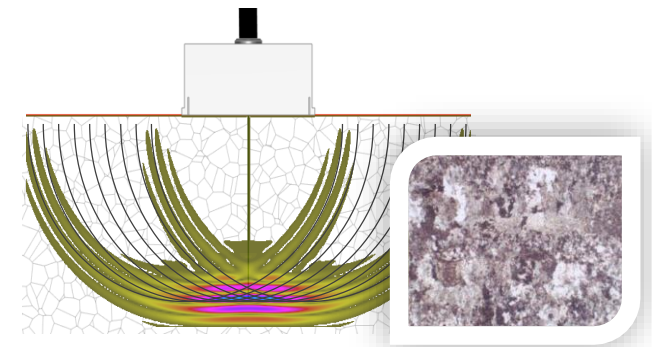
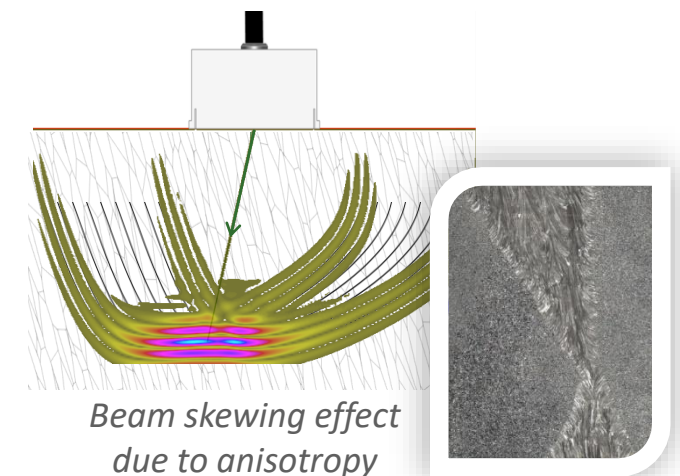
UT performance estimation -
variation analysis - imaging

From microscale properties to macroscale description

Effective material concept and a practical approach to UT simulation in application to welded parts

Grain-scale properties and modelling of the coherent wavefront propagation

► Equiaxed grain with random crystal orientations

⇒ Effective material for UT: isotropic damped material► Columnar grain structure with preferential texture $\langle 100 \rangle$ around grain elongation axis⇒ Effective material for UT: anisotropic (quasi-hexagonal) damped material whose symmetry axis is correlated with the elongation axis

Modelling strategy applied to the weld material including grain orientation variations

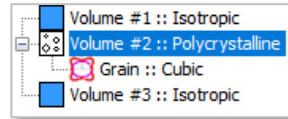
Microscale modelling

description of the microstructure
at the grain-scale

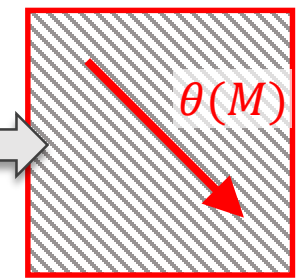
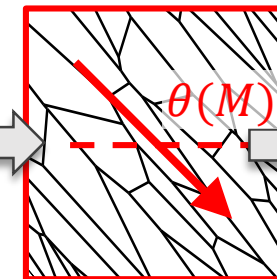
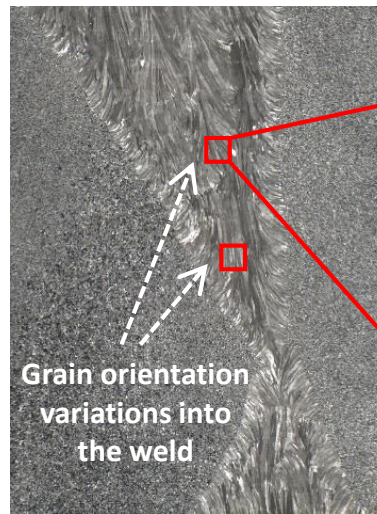
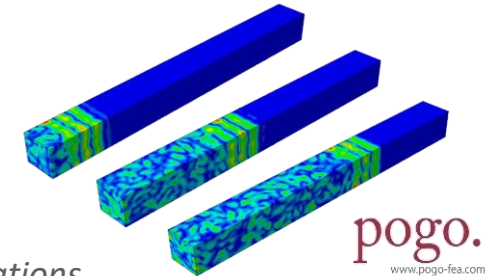
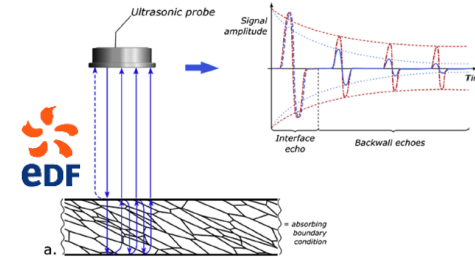
Effective material qualification
Structural noise calibration

Macroscale modelling

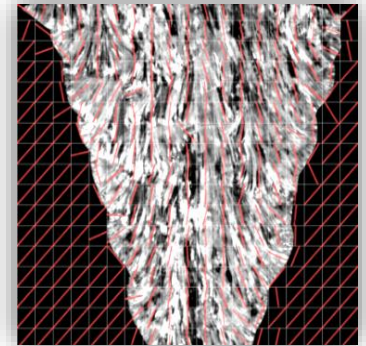
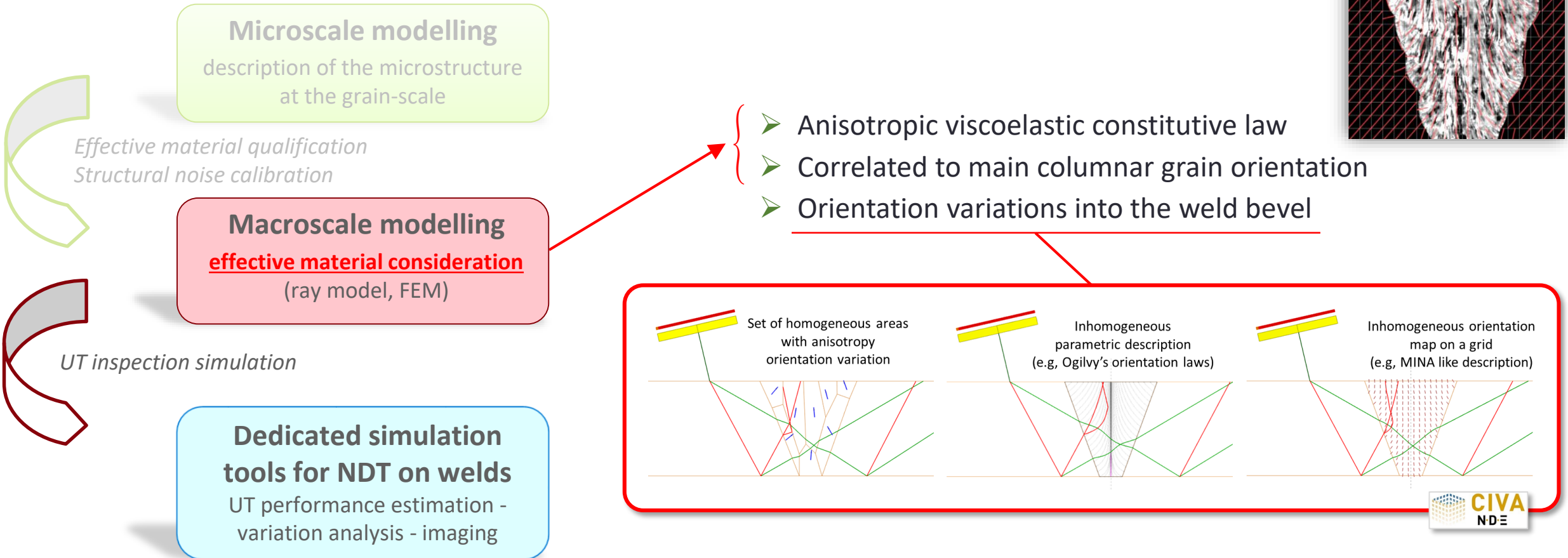
effective material consideration
(ray model, FEM)

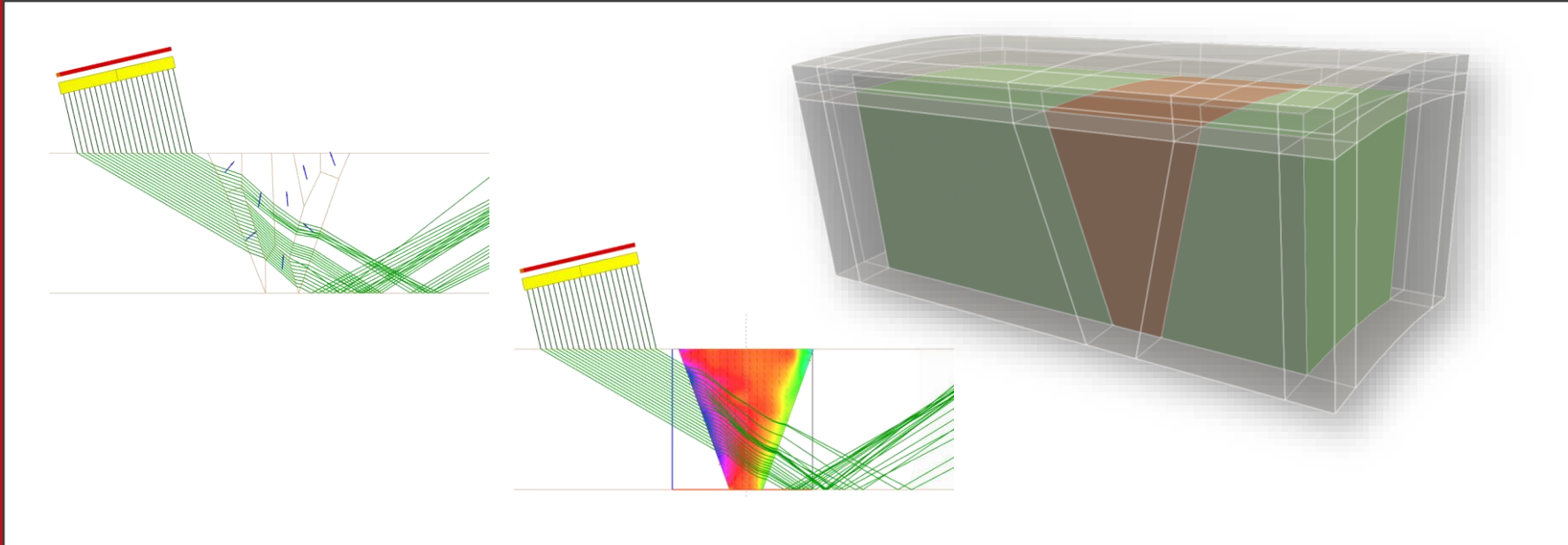


Approx. integral for
homogenization



Modelling strategy applied to the weld material in CIVA





Ultrasonic models for macroscale simulation in CIVA

Ray-based models and FEM hybrid approaches in CIVA

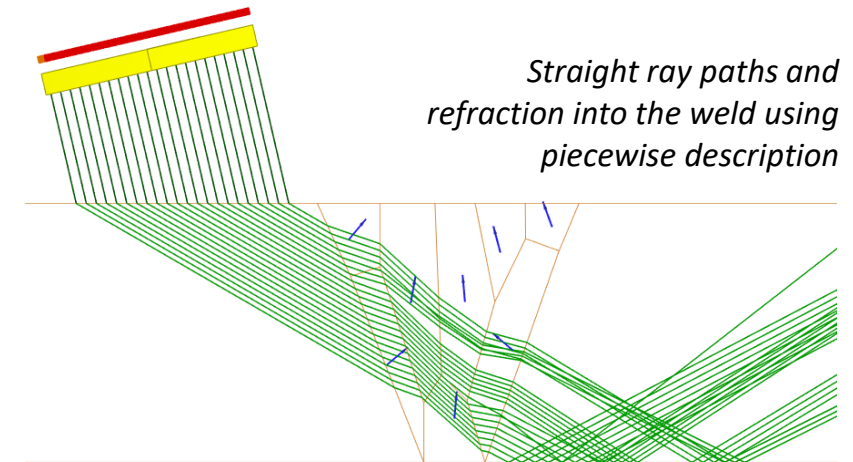
Ray-based HF models in CIVA for welding structures

► Homogeneous anisotropic weld parts descriptions

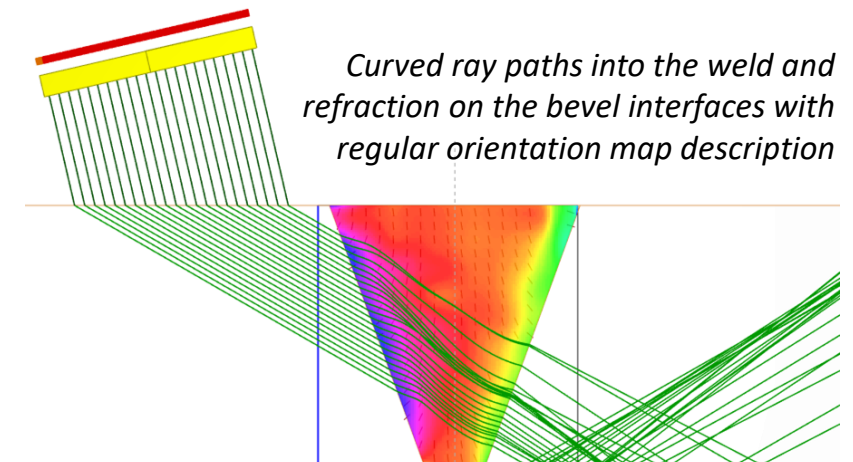
- + Efficient straight ray model (historically used in CIVA)
- + Good results if domain size $\gg \lambda$ and weak contrast between domains
- Unrealistic artefacts and wave mode conversions due to fictive interfaces
- Excessive approximation for some weld descriptions

► Inhomogeneous anisotropic weld descriptions

- + Interface removal reduces ray artefacts in the weld
- + Well-adapted for TFM imaging techniques
- Regularisation of map descriptions with a smoothed procedure causing sometimes unrepresentative data
- Increase in computational time (iterative procedure for ray prop.)



N. Gengembre, 2000



A. Gardahaut, 2013

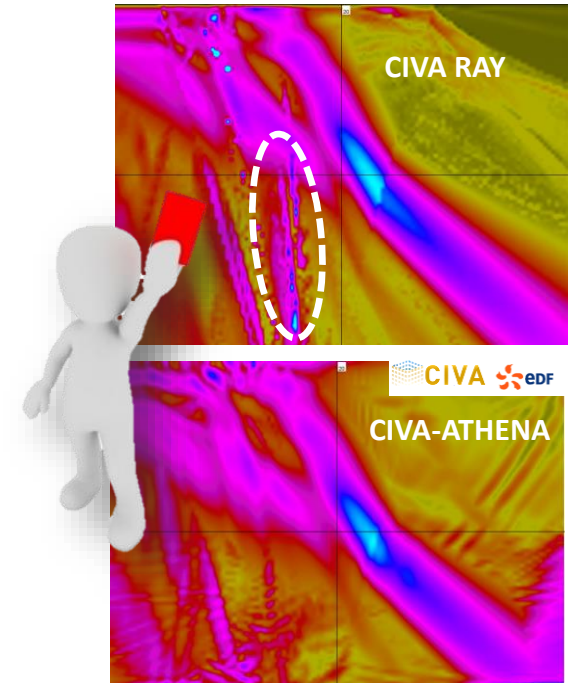
Needs for FEM to complement HF models in CIVA

► Main advantages of ray models (HF) ...

- Fast modal ToF computations (useful for TFM imaging)
- High efficiency to compute radiated ultrasonic field (e.g. in a local ROI of potential defects)

► ... and drawbacks

- Amplitude estimations can be locally wrong (caustics, shadowing or tunnelling effects)
- Neglected edge diffractions and surface waves



Need to develop efficient FEM solutions to check ray model approximations and propose reference solutions

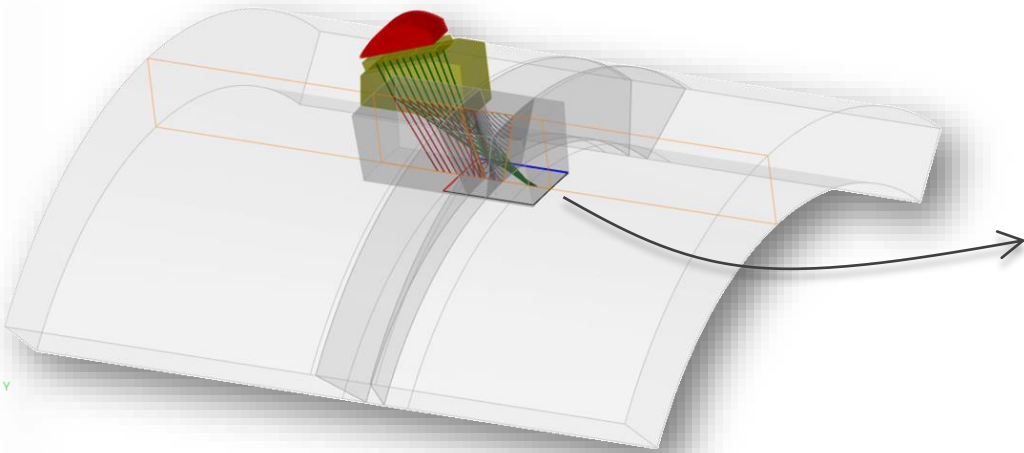


FE Beam UT

Principle of the FE BEAM solution in the framework of the ADVISE project

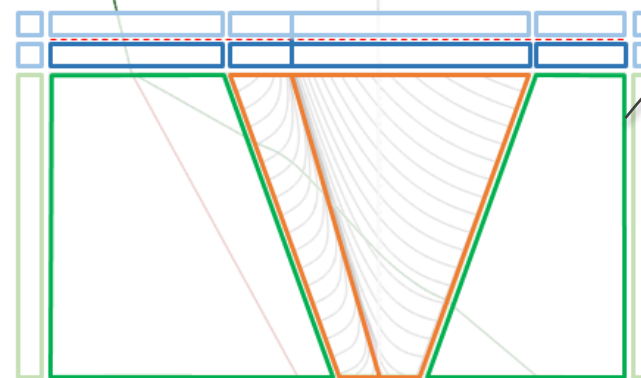
- ▶ Ray-based calculation of the source field in the coupling above the specimen
- ▶ Automated build-up of the high-order SFEM hexahedron mesh

Ray tracing pre-treatment to adjust the region of interest



Straight or V-shaped weld chamfer
Plane or cylindrical extrusion
Cartesian observation grid

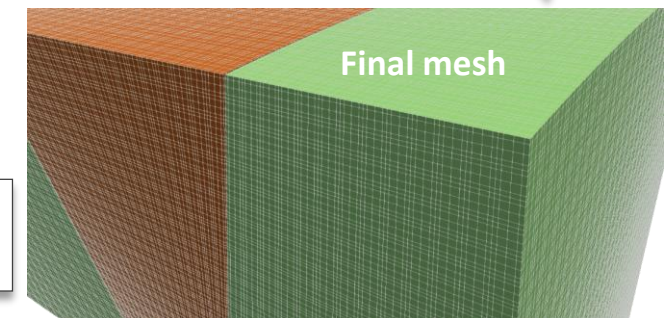
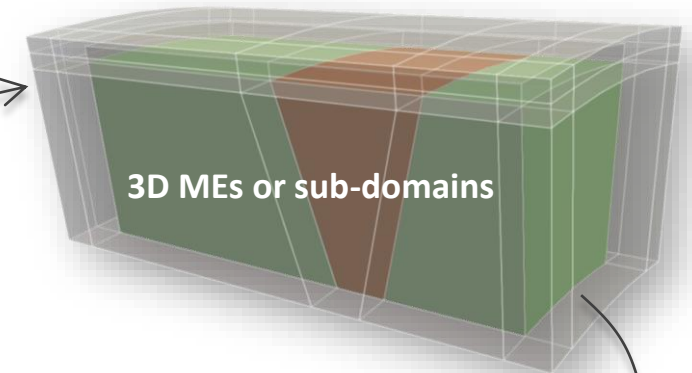
Radiated source field computed by ray model applied as a boundary condition



---	COUPLING INTERFACE
■	ME ISOTROPIC ACOUSTIC
■	ME ISOTROPIC ELASTIC
■	ME ANISOTROPIC ELASTIC
■	ME PML ELASTIC
■	ME PML ACOUSTIC

Automated build-up of the SFEM domain decomposition method

CONFORMAL MESH
4TH ORDER ELEMENTS
2 OR 3 ELEMENTS / λ_T

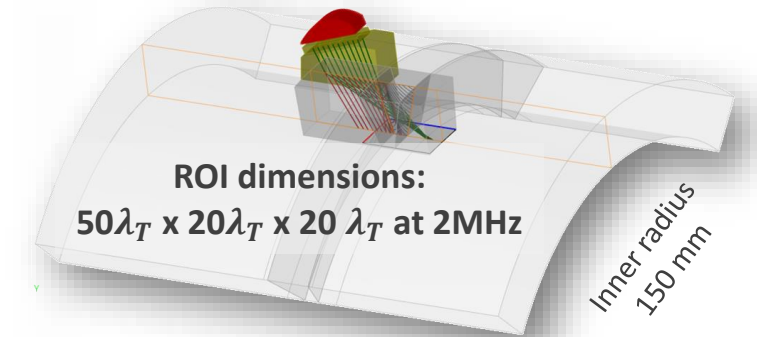
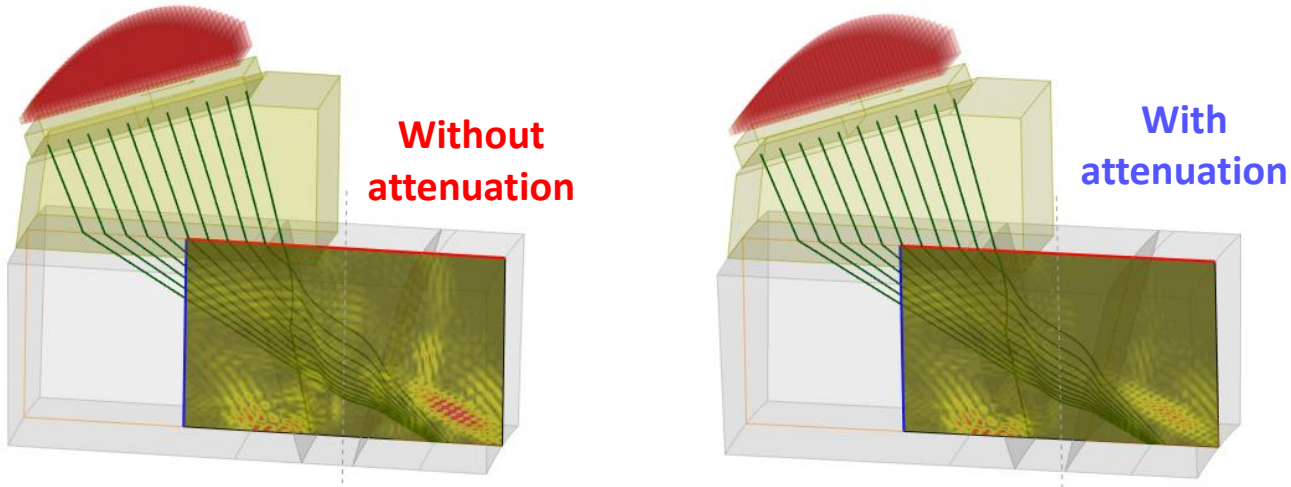




FE Beam UT

PoC using FEM technique allowing 3D field computation with high performances

- ▶ A SFEM kernel accounting for both anisotropy and energy loss effects of the coherent wave propagating in the weld



Workstation using Intel® Xeon® W-2155 Processor (13.75M Cache, 3.30 GHz)

- ▶ Optimal calculation costs

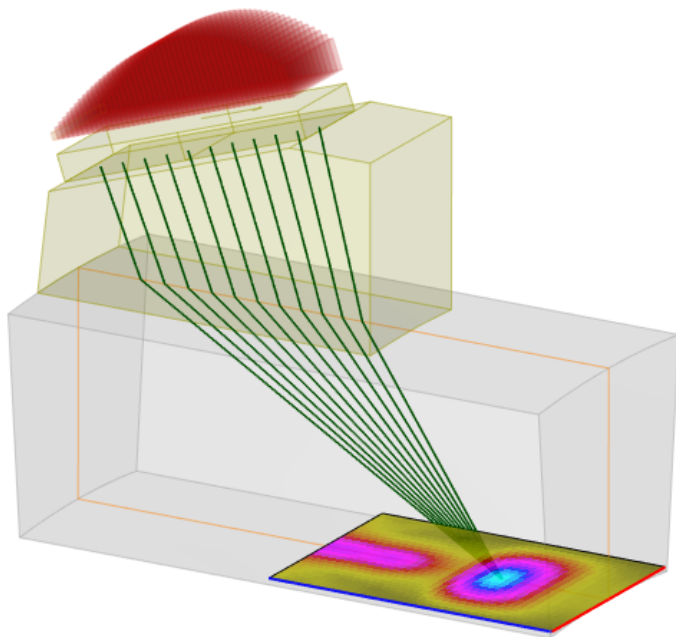
- Low memory load (< 6 GB in more complex 3D case with 30M of points)
- Very efficient in 2D (feasible ML database)
- Acceptable computation time in 3D for reference

20 μ s at 2MHz	Time step and # of iterations	Computation Time	
		3D	2D
Isotropic	1.2e-2 μ s 1650 it.	\approx 25 min	< 3s
Weld (no damping)	4e-3 μ s 5000 it.	\approx 75 min	< 10s
Weld (with damping)	4e-3 μ s 5000 it.	\approx 85 min	< 10s

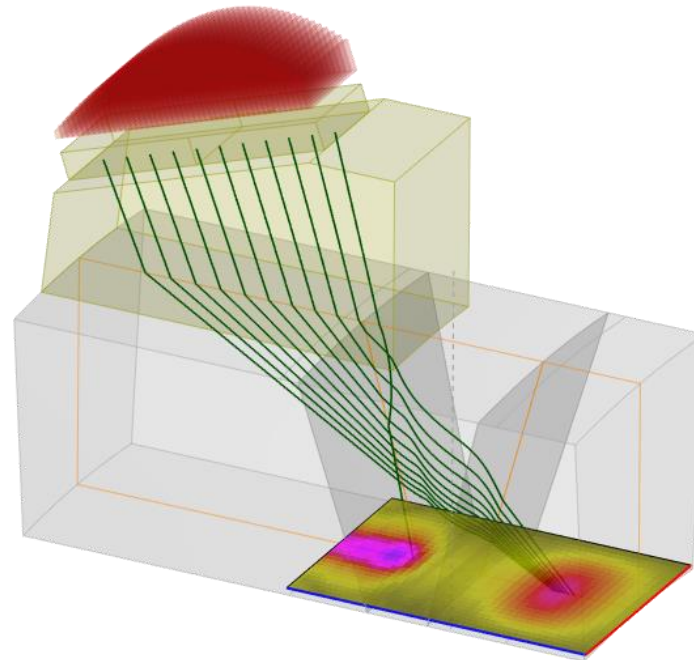
3D field computation on the backwall of a cylindrical welding component

► PA probe with focusing law on the backwall

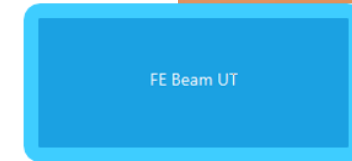
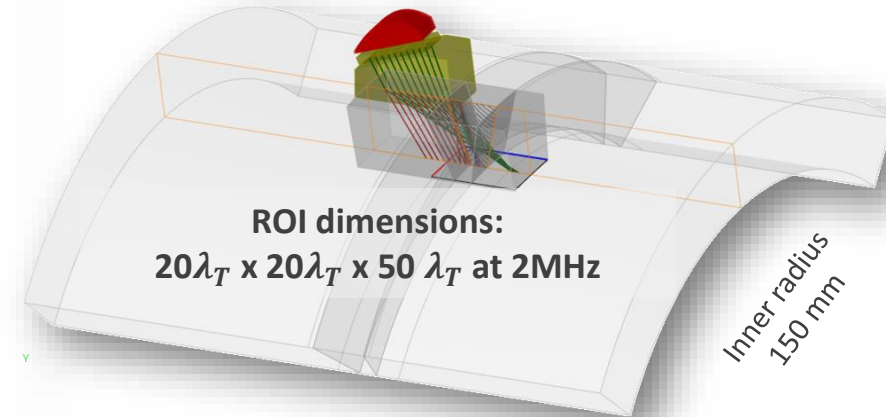
- 2MHz wedge probe (nominal L45) – linear 48 elements – point focusing law
- Ogilvy description using anisotropic damped material properties
- Simulated time for wave propagation to the bottom: 20 μ s



Point focusing law computation considering an isotropic metal



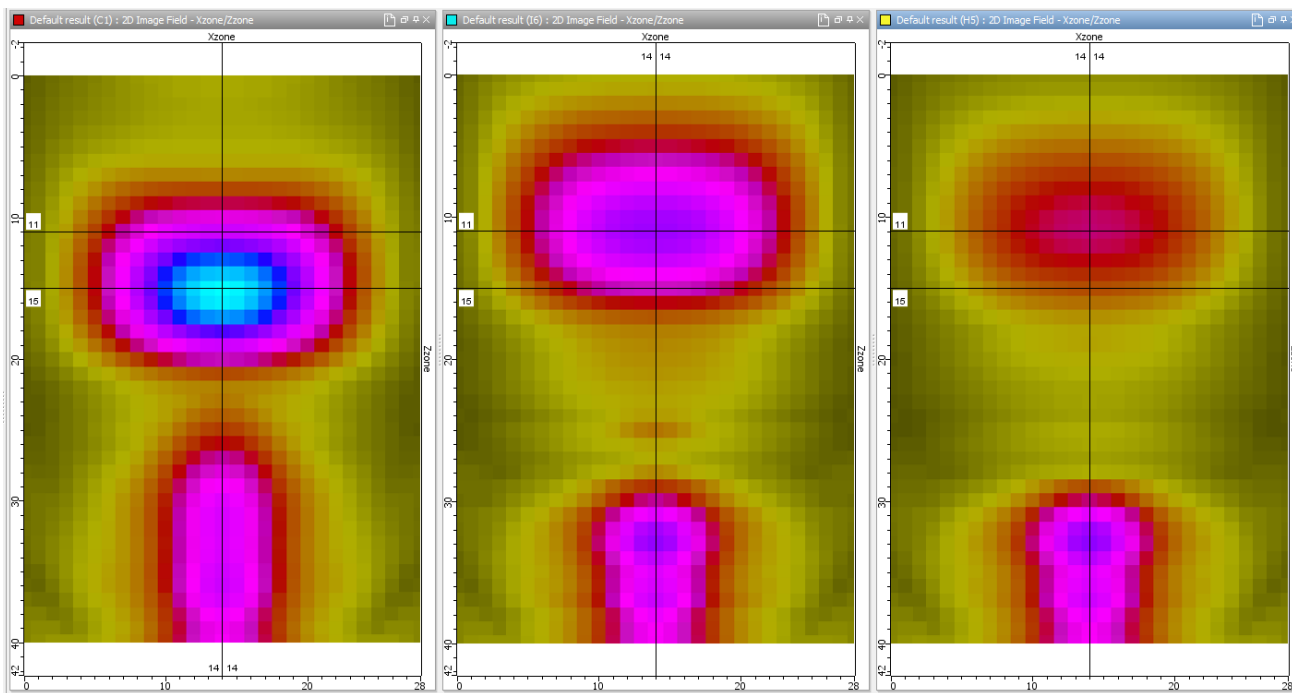
Superposed SFEM results with ray tracing analysis



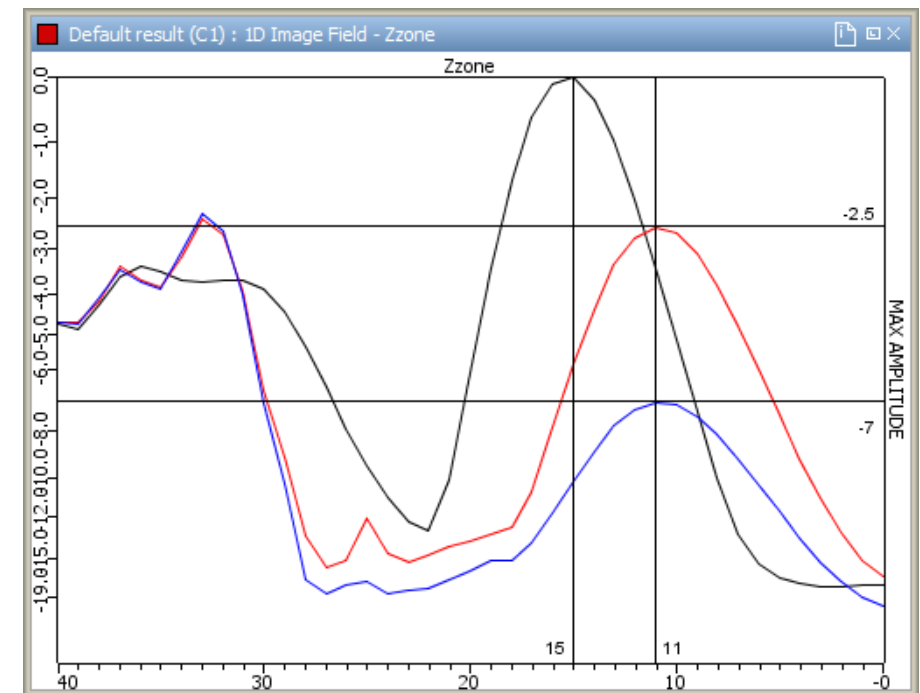
3D field computation on the backwall of a cylindrical welding component

► Quantification of weld material properties

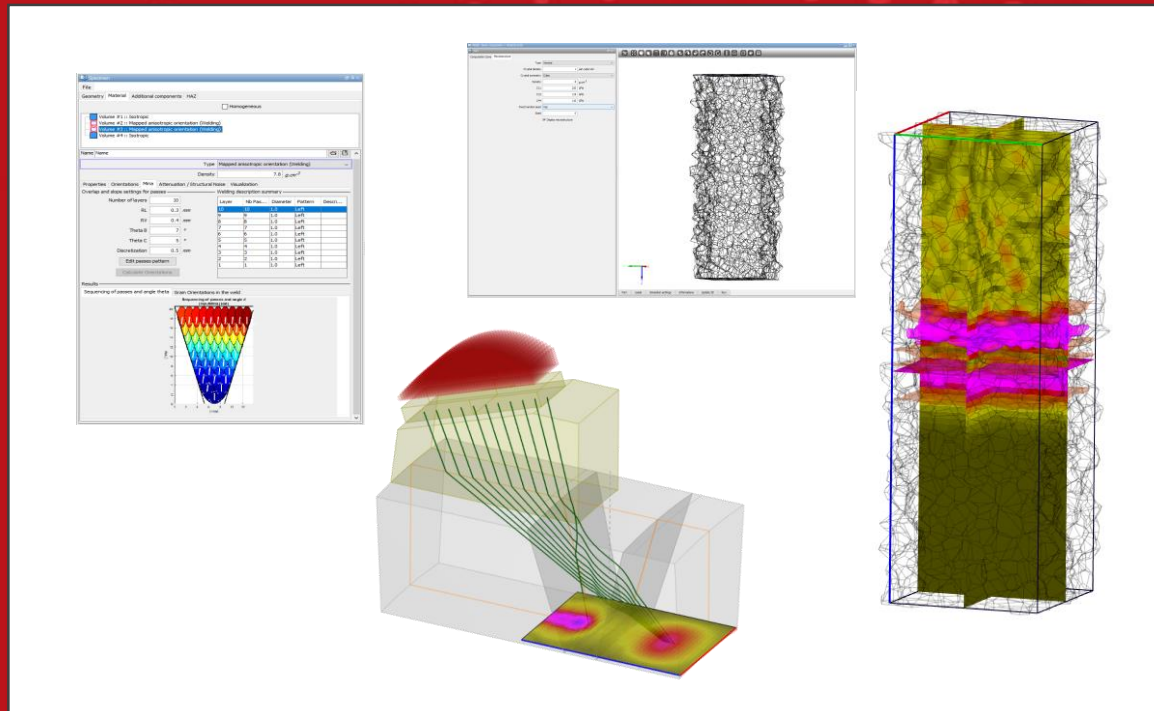
- Beam deviation
- Beam damping



Isotropic

Anisotropic
(no attenuation)Anisotropic
(with attenuation)

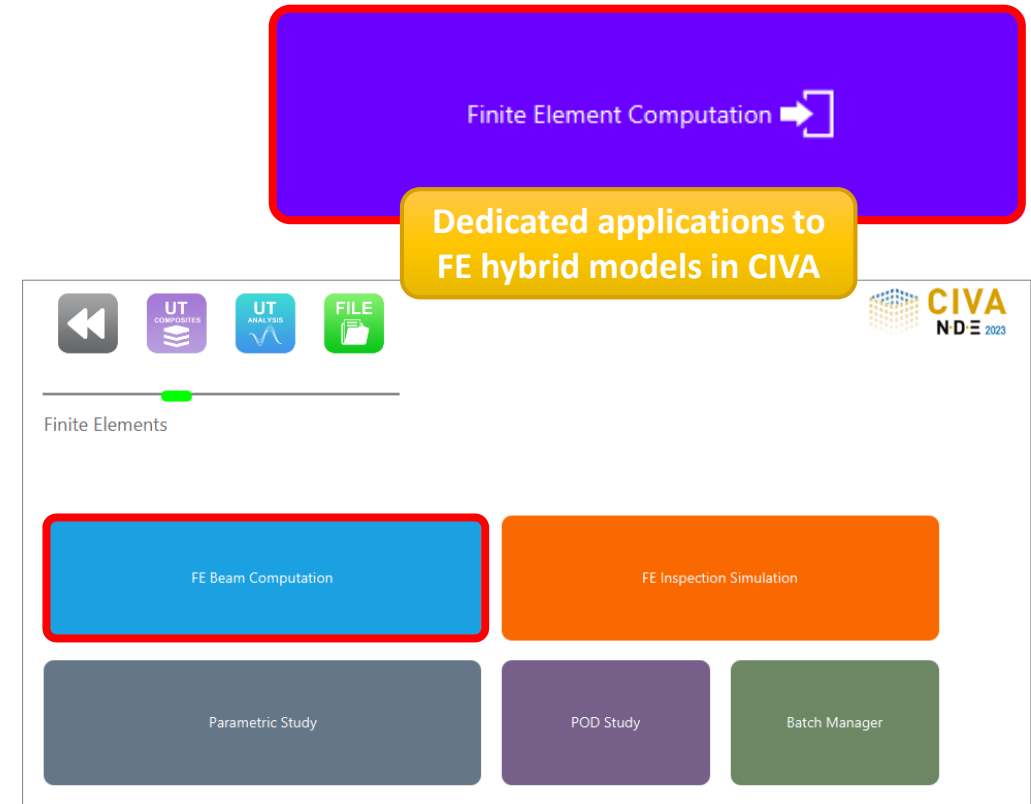
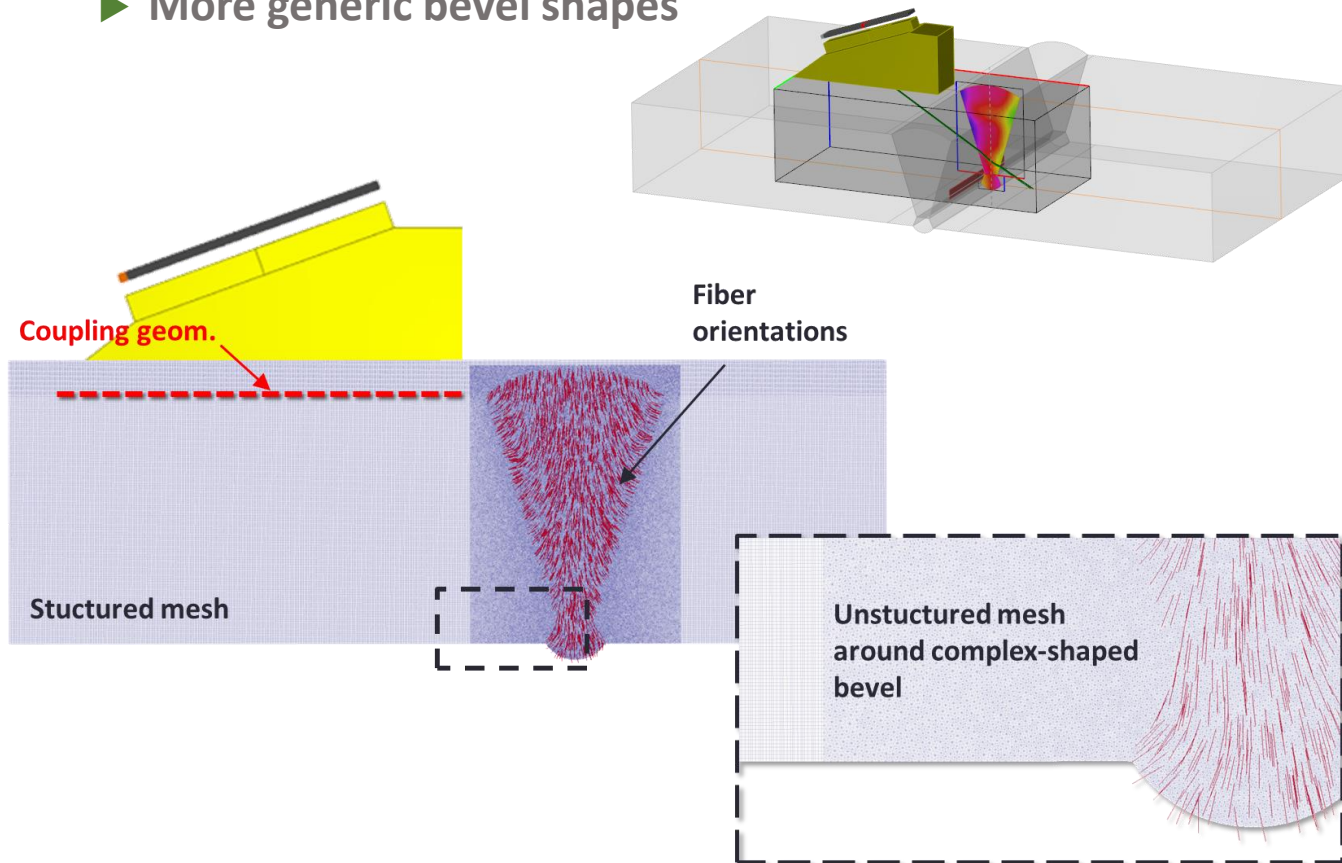
Extraction of the max. fields in the inspection plane



Prospects and related R&D activities

Improvement of the FE Beam computation tool

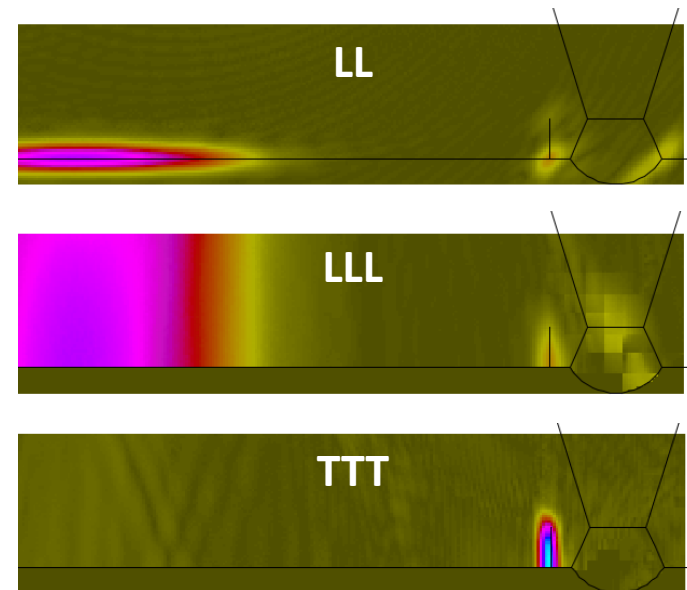
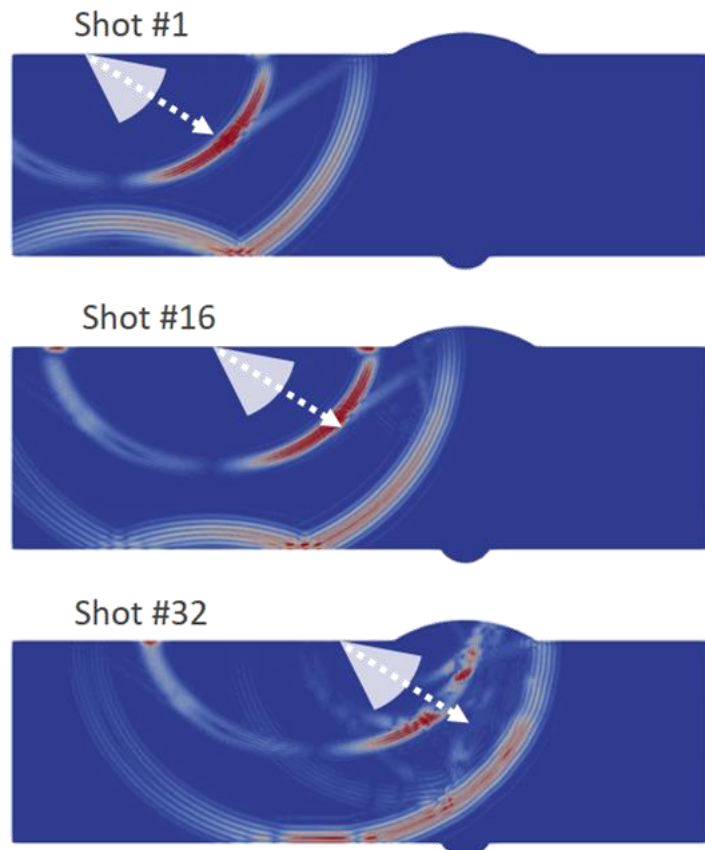
- ▶ New probe types
- ▶ More generic bevel shapes



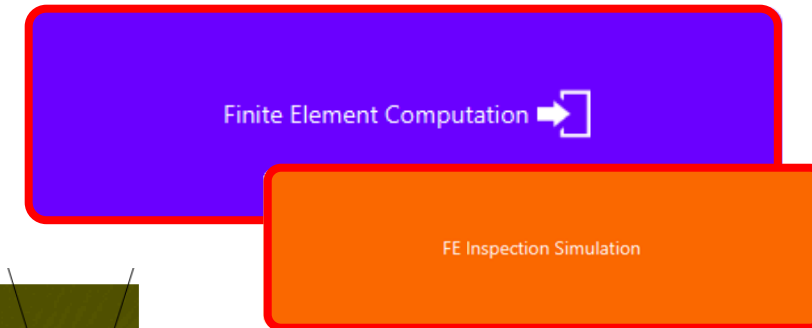
New FE INSPECTION module (echoes for UT imaging)

- ▶ Use the same principle to simulated radiated beam into the part
- ▶ Echo response using the reciprocity principle

FMC simulations

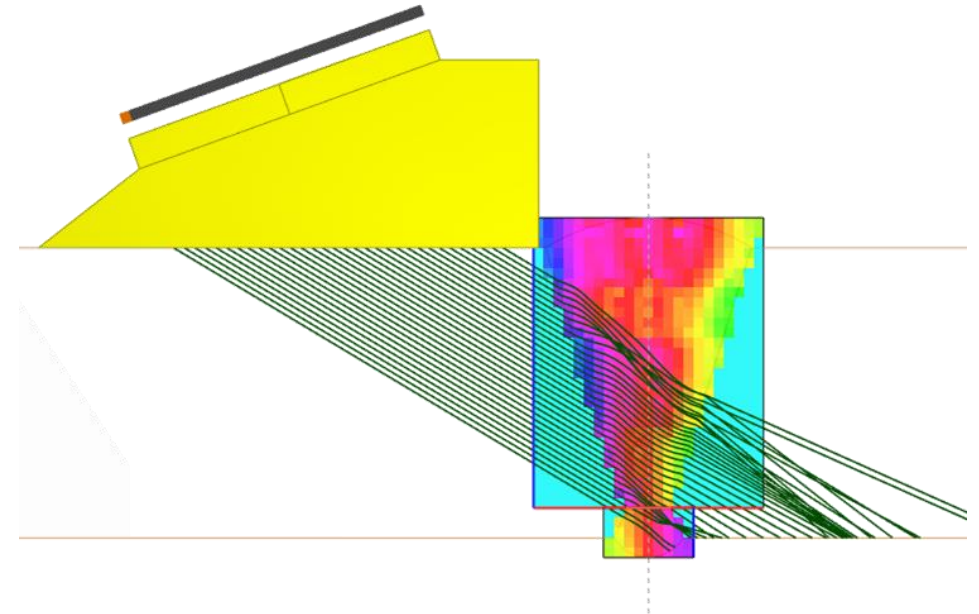
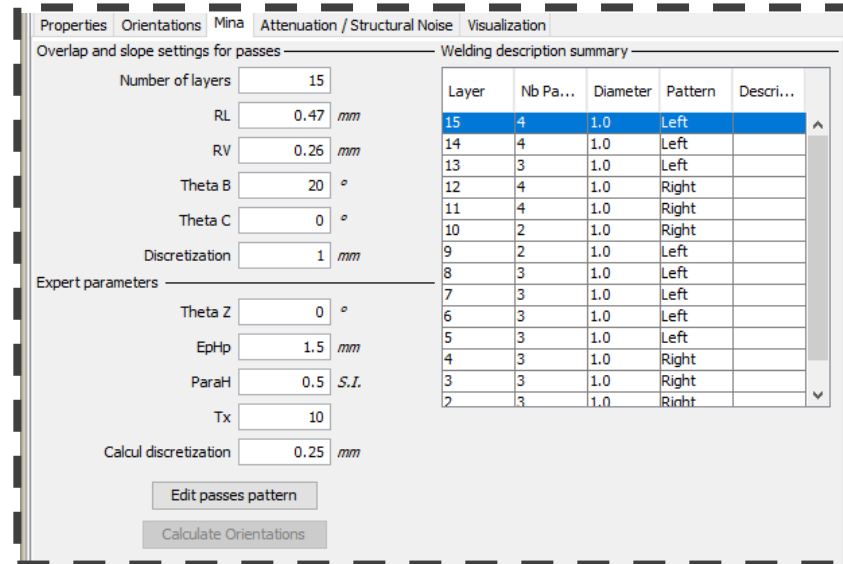
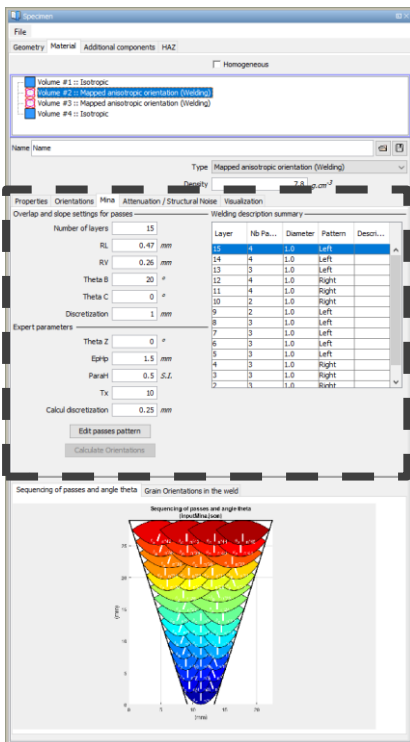


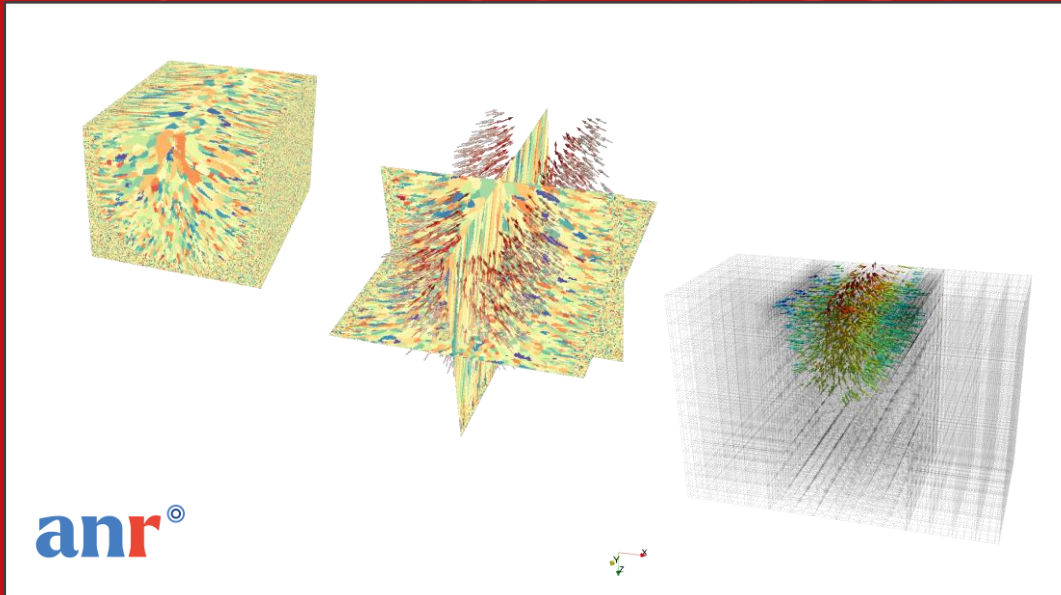
TFM imaging from FMC simulation using FEM



Grain orientation maps using the MINA2D solution

- Generation of grain orientation maps from the use of information recorded in the welding notebook





Project developed in the framework of the **NEMESIS project** supported by the **ANR french agency**



<https://anr.fr/Projet-ANR-17-CE08-0036>

Methodology for the exploitation of virtual microstructures and comparison of modelling strategies - focus on the results of the ANR NEMESIS project

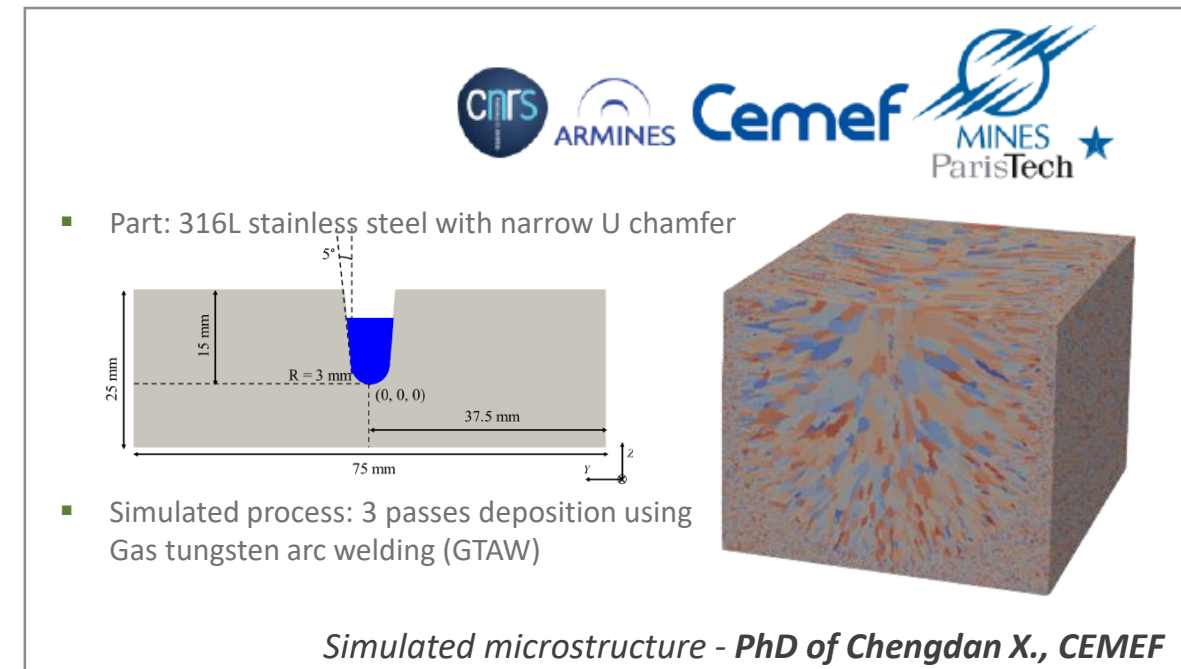
Solidification and grain growth modelling using Cellular Automate Finite Element (CAFE)

► CAFE simulation principles:

- Fixed FE domain (regular lattice of cubic cells)
- Each cell has internal variables
 - a state index (e.g., gas, liquid, solid)
 - other parameters (e.g., Euler angles)
- Rules applied to change the state index and parameters of the cells to mimic transformation from gas to metal
 - nucleation of crystals from the melt
 - growth of crystals in the melt
 - melting of solid...
- For more details see references of the CEMEF team:
 - *Gandin Ch.-A., Rappaz M. Acta materialia 45 (1997)*
 - *Chengdan X., et al. Materialia 21 (2022).*

► Type of provided data for UT simulations

⇒ Vtk grid data of Euler's angles in the Bunge convention



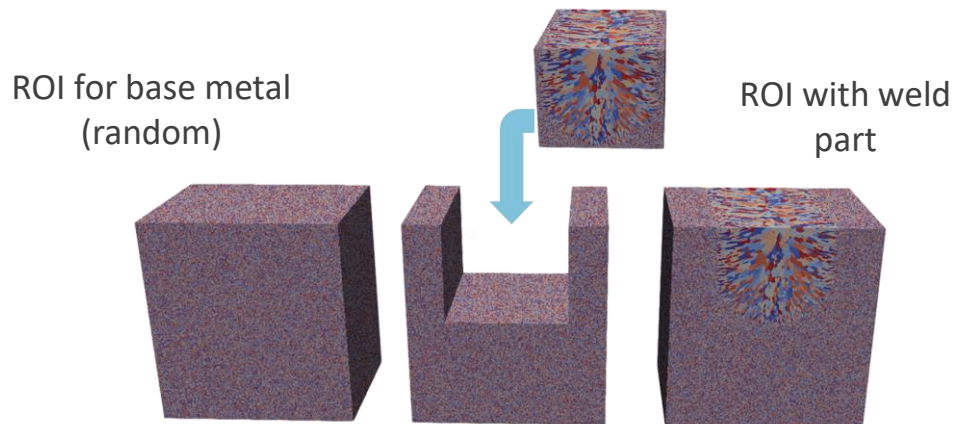
Comparisons of UT beam field simulation for the two modelling approaches

Grain-scale simulation

- ▶ Simulation using low-order FEM on regular grid
- ▶ Consider the unique monocrystal properties
 - austenite cubic material with a Zener's factor

$$A = \frac{2C_{44}}{C_{11} - C_{12}} = 3,28$$

C_{11} (GPa)	C_{12} (GPa)	C_{44} (GPa)	ρ (g.cm ⁻³)
206	133	120	7.9

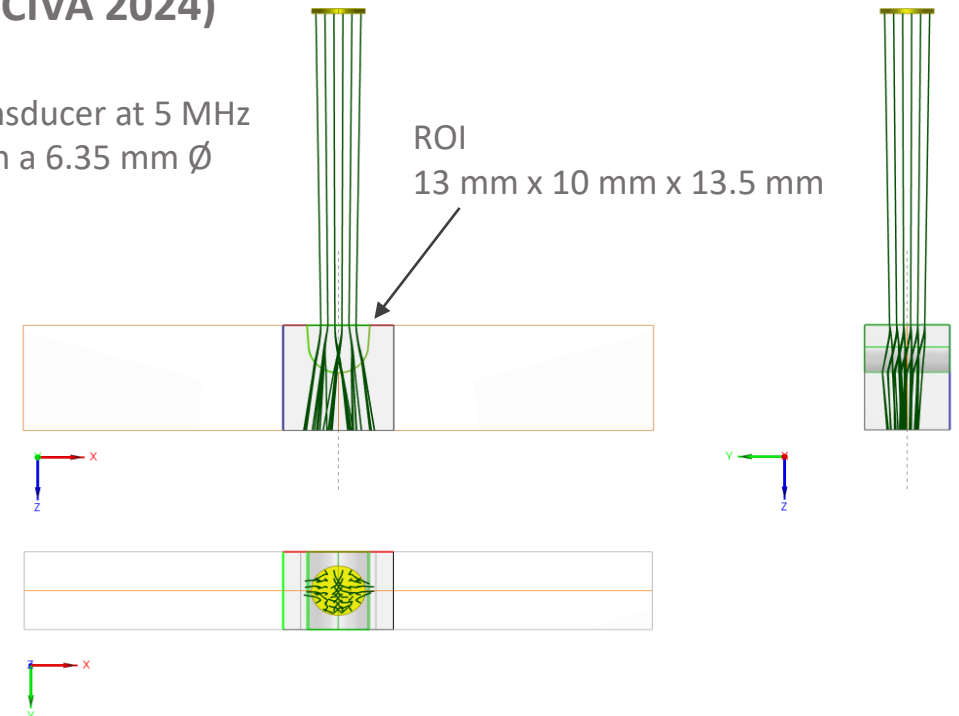


Macroscale simulation

- ▶ Simulations using either the CIVA ray model or a high-order FEM, (FE BEAM in-house solution, CIVA 2024)

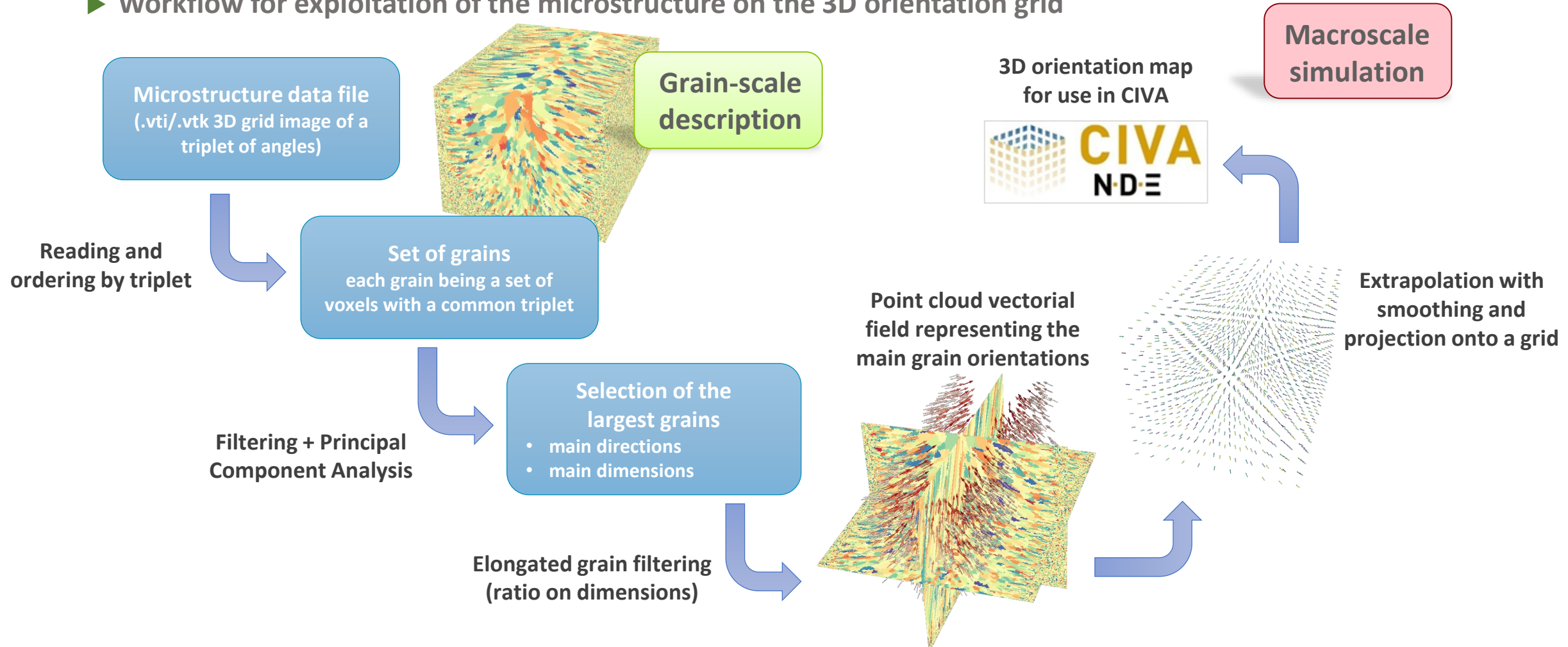
transducer at 5 MHz
with a 6.35 mm \varnothing

ROI
13 mm x 10 mm x 13.5 mm



Extraction of grain orientation from CAFE data for macroscale descriptions

► Workflow for exploitation of the microstructure on the 3D orientation grid



Microscale 3D calculation results

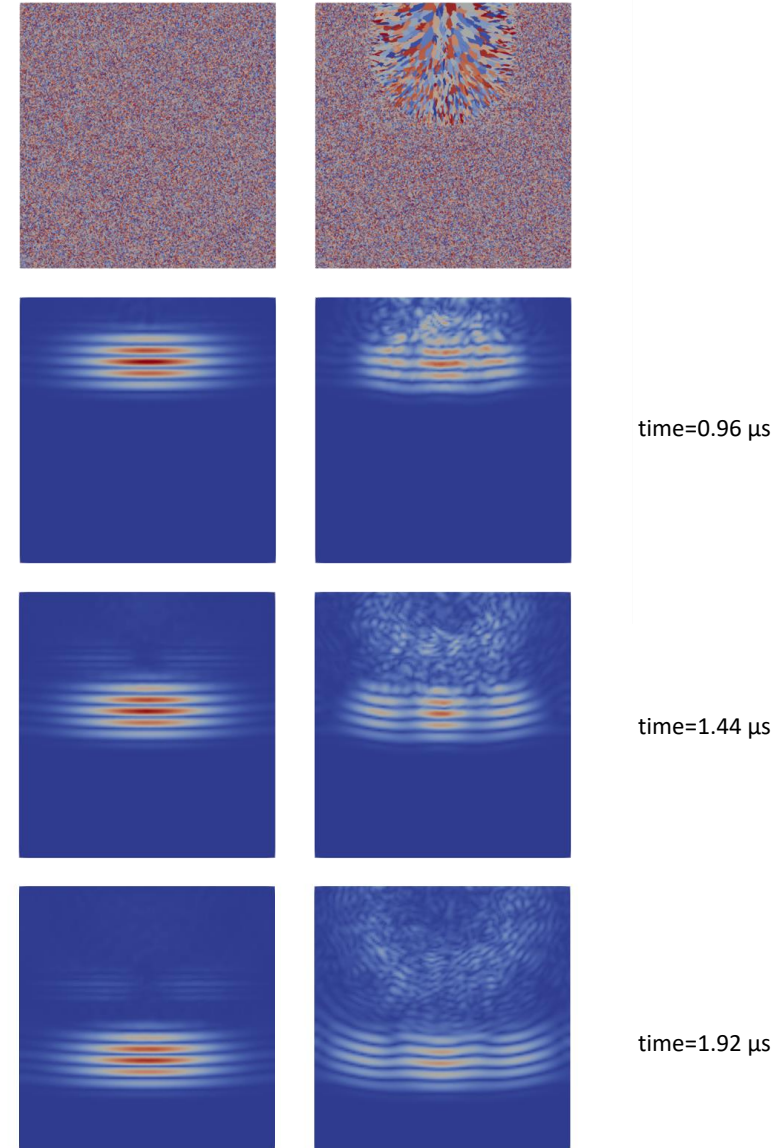
► Main characteristics :

- Source term: plane wave with Gaussian support in space, Hanning in time (central frequency 5MHz)
- Modelling time: 3 μs to reach the bottom of the part
- Scheme step size in time: $5\text{e-}4 \mu\text{s}$ i.e. 6000 iterations
- Computation time $\sim 3\text{h}$ - workstation Intel® Xeon® W-2155 Processor (13.75M Cache, 3.30 GHz); # of Cores 10 (# of Threads 20)

► Comparison of UT beam propagation with and without weld part (XZ-plane)

- Observation of the behaviour in the XZ plane (central cutting plane $y = 5 \text{ mm}$)
 - **Disturbed beam** compared to base metal calculation
 - **Beam splitting** into three parts
 - **Significant energy loss** along the natural focal axis of the beam
 - Observation of structural noise

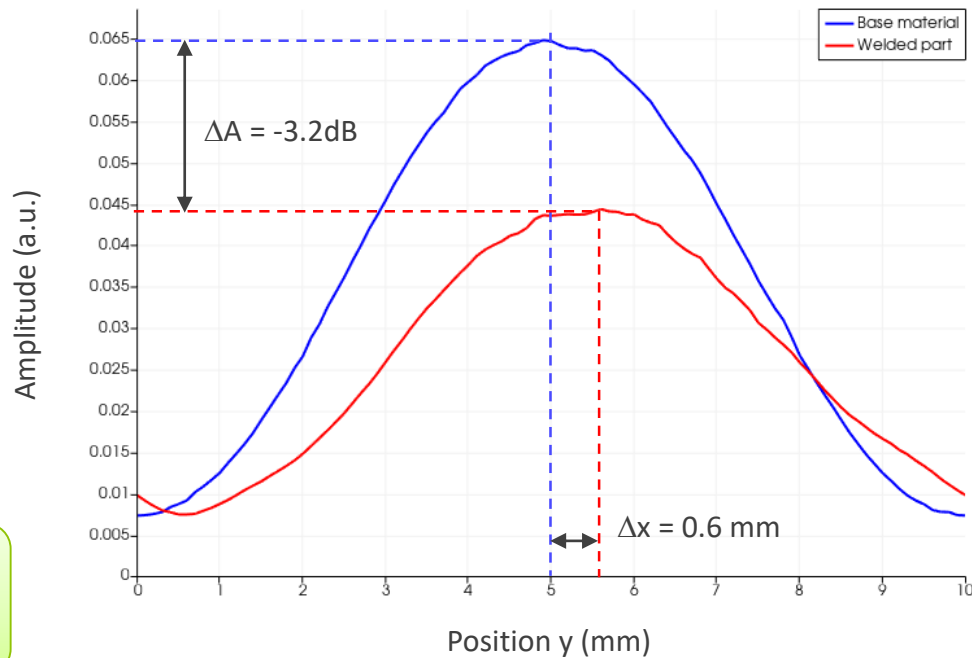
Grain-scale
simulation



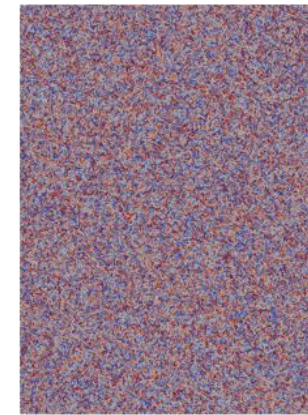
Microscale 3D calculation results

► Comparison of UT beam propagation with and without weld part (YZ-plane)

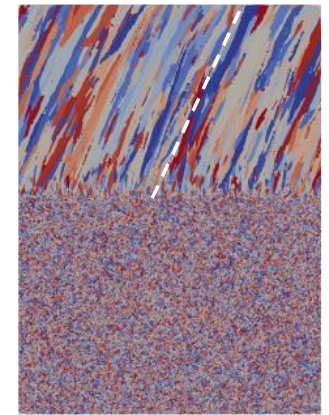
- Observation of the behaviour in the YZ plane (central cutting plane $x = 6.5$ mm)
 - Beam deflection out of control plane (0.6 mm at $z=8.8$ mm)
 - Estimated energy loss of about 3.2dB compared to base metal



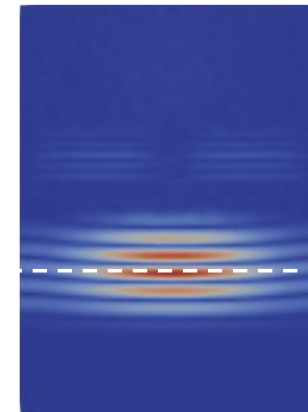
Grain-scale simulation



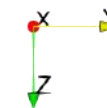
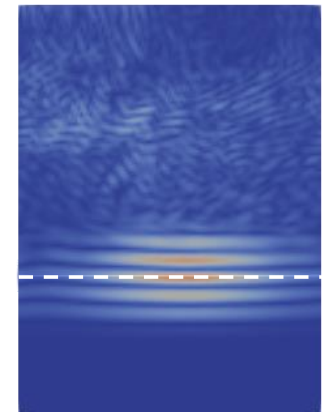
Grain slope in YZ-plane
--> Y deposit axe of weld passes



$z=8.8$ mm



$z=8.9$ mm



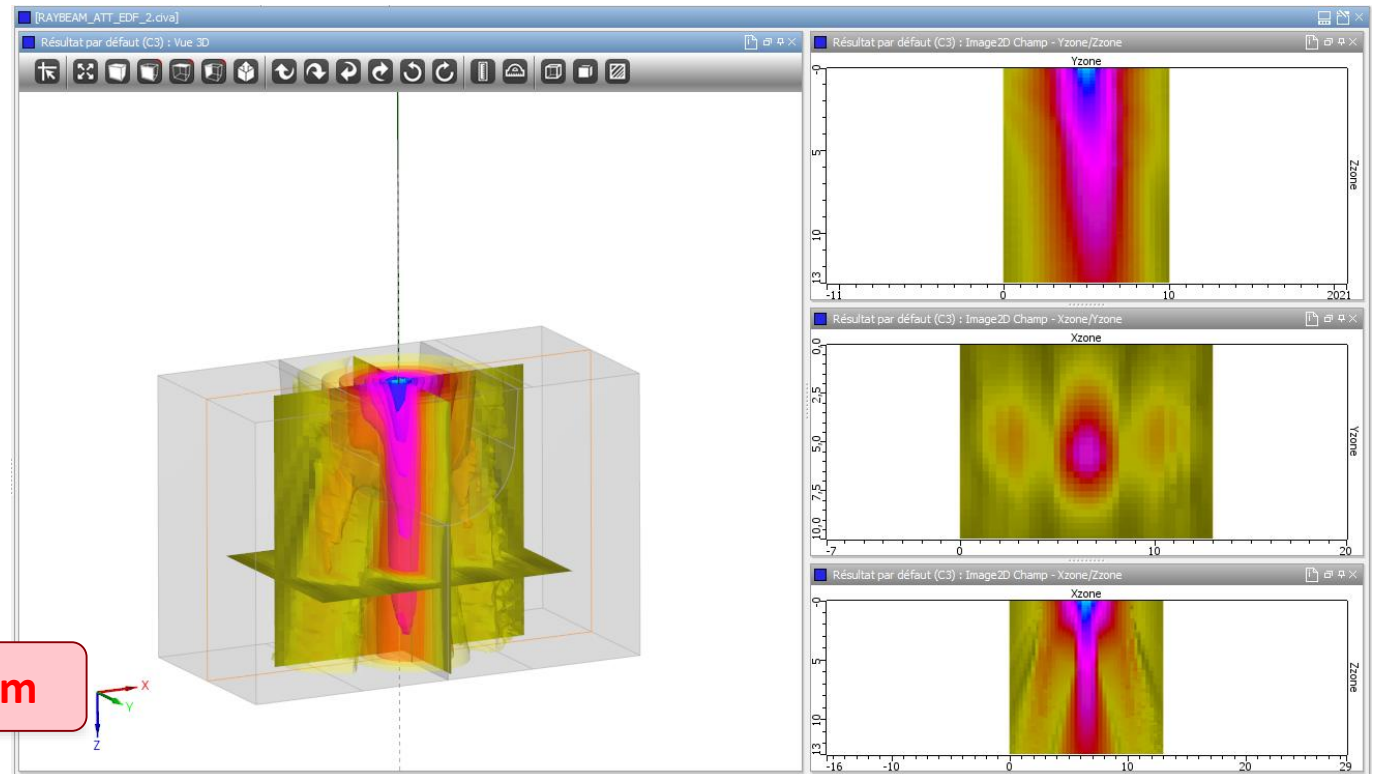
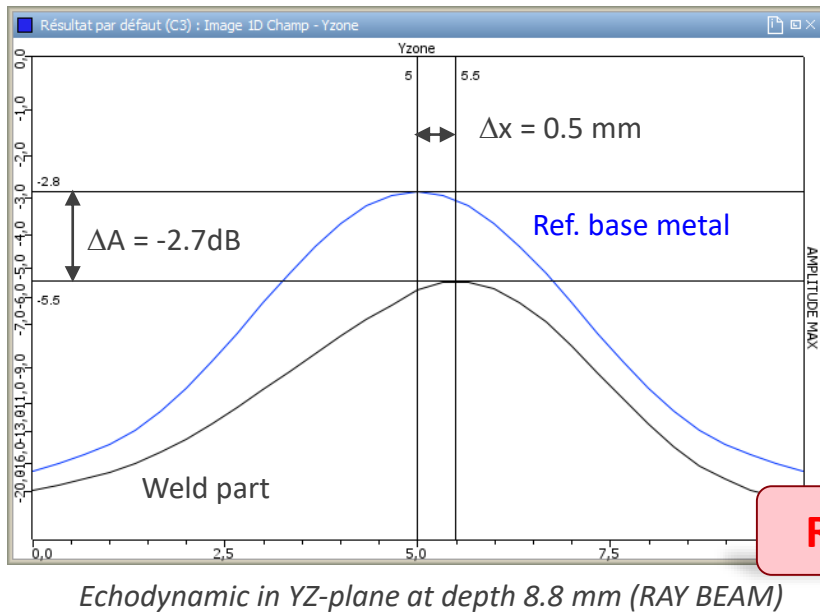
time=1.92 μ s

Macroscale
simulation

Macroscale calculation result using CIVA Ray Beam model

► Modelling of the ultrasound beam propagation (macroscale description using 3D orientation map)

- Characteristics consistent with those observed with the microscale simulation
 - Beam splitting in 3 (XZ plane) with numerical artefacts (chamfer edge diffraction)
 - Energy skewing (YZ plane)
 - Amplitude drop of 2.7dB
 - ⇒ underestimated attenuation ?

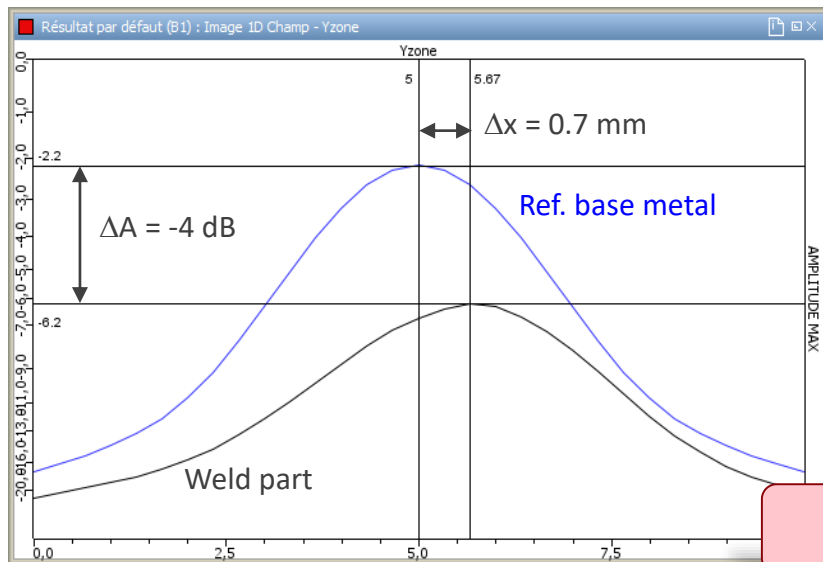


Macroscale
simulation

Macroscale calculation result using CIVA FE Beam model

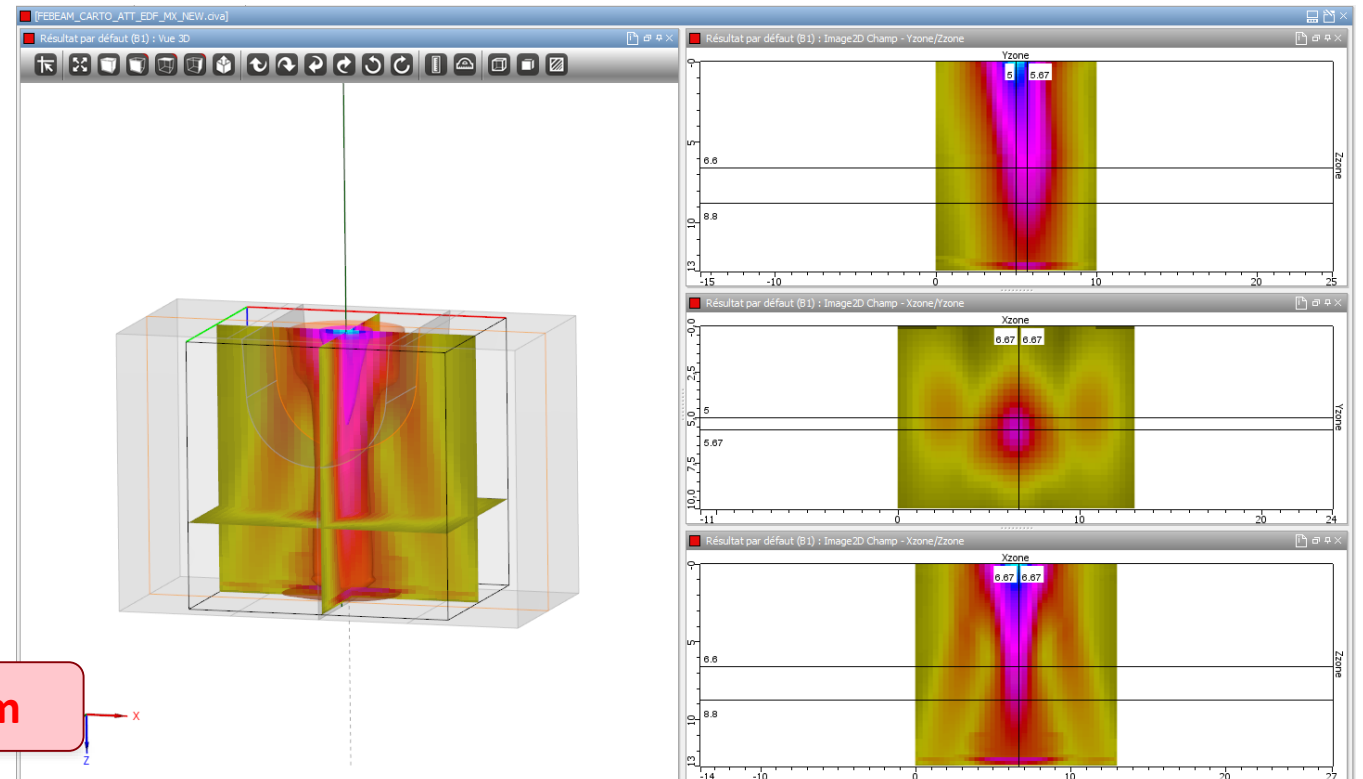
► Modelling of the ultrasound beam propagation (macroscale description using 3D orientation map)

- Characteristics consistent with those observed with the microscale simulation
 - Beam splitting in 3 (XZ plane) without numerical artefacts (soft diffraction)
 - Similar energy deflection (YZ plane)
 - Amplitude loss of 4dB
 - ⇒ Slight overestimated attenuation



Echodynamic in YZ-plane at depth 8.8 mm (FE BEAM)

FE Beam



Research projects - From micro to macro data

► Macro data to determine effective medium properties

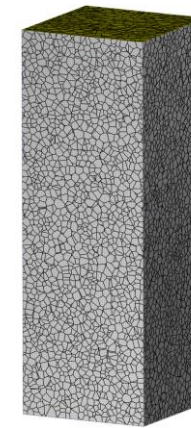
- CIVA plugin using low order FE computation with REV microstructures defined on regular grids (EDF collab.)
 - loading of uniform plane wave on Top interface
 - periodic boundary consideration (Left, Right, Front, Back sides) and to **identify coherent wavefront properties** (mean behaviour)

⇒ construction of **material and noise databases** for CIVA macroscale simulations

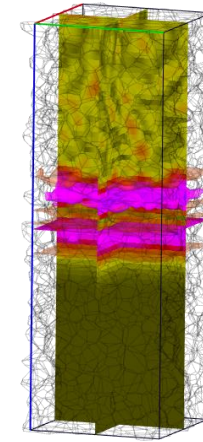
► Macro data on a set of possibilities for orientation variations into the bevel

- **IWELD project** to propose ML on weld map orientation from a range of welding process parameters

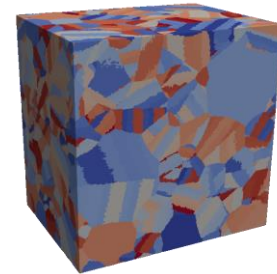
⇒ construction of **orientation map databases** for CIVA macroscale simulations



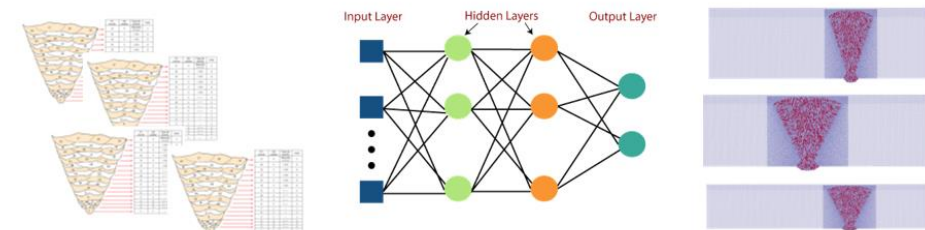
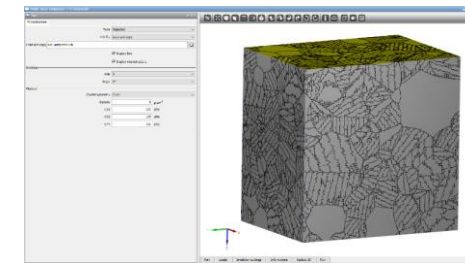
Equiaxed grain



Austenoferritic steel
(PhD, A. AGHENZOUR)



Built-in Vtk import





Thank you for your interest

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