



HAL
open science

A 3D spectral finite element solution to simulate ultrasonic inspection of austenitic welds

Nicolas Leymarie, Alexandre Imperiale, Edouard Demaldent, Thibaud Fortuna

► To cite this version:

Nicolas Leymarie, Alexandre Imperiale, Edouard Demaldent, Thibaud Fortuna. A 3D spectral finite element solution to simulate ultrasonic inspection of austenitic welds. QNDE 2021 - 48th Annual Review of Progress in Quantitative Nondestructive Evaluation, Jun 2021, Virtual conference, United States. cea-04920054

HAL Id: cea-04920054

<https://cea.hal.science/cea-04920054v1>

Submitted on 29 Jan 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

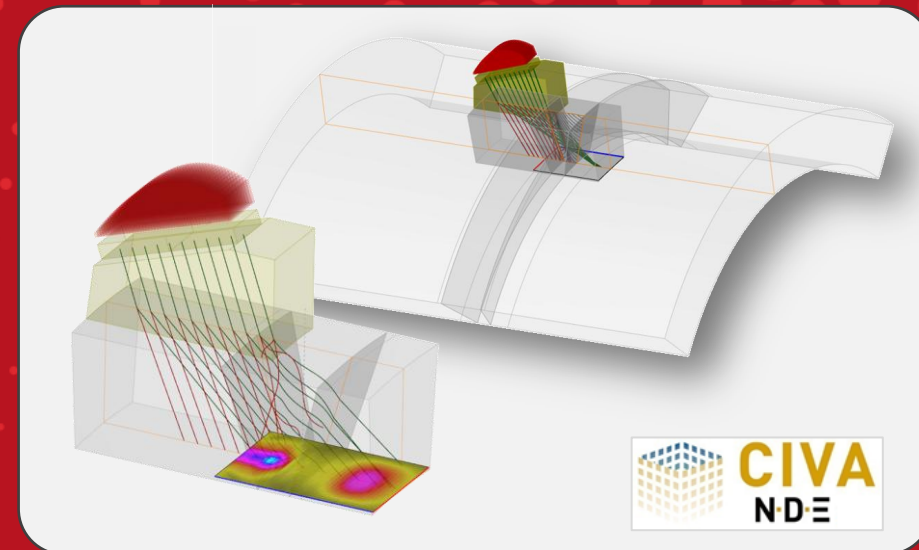


FROM RESEARCH TO INDUSTRY

A 3D spectral finite element solution to simulate ultrasonic inspection of austenitic welds

July 28-30, 2021 – Annual Review of Progress in Quantitative Nondestructive Evaluation

N. Leymarie, A. Impériale, T. Fortuna, E. Demaldent
Université Paris-Saclay, CEA, LIST, F-91120, Palaiseau, France



The ADVISE Project

► About the project

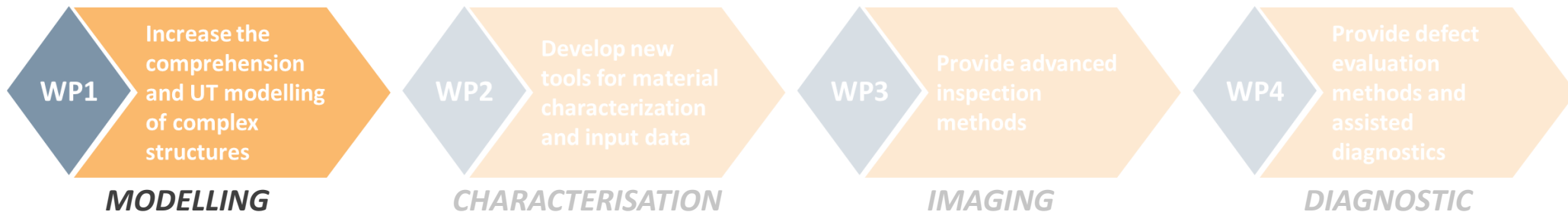
- Funded by the European Commission's EURATOM programme under the Horizon 2020 framework programme for Research and Innovation
- 13 partners
- Started in September 2017 and lasting 4 years

► Overall objective

- enhance the ultrasonic inspection of complex structures materials in order to **improve confidence and reliability**



<https://www.advise-h2020.eu/>

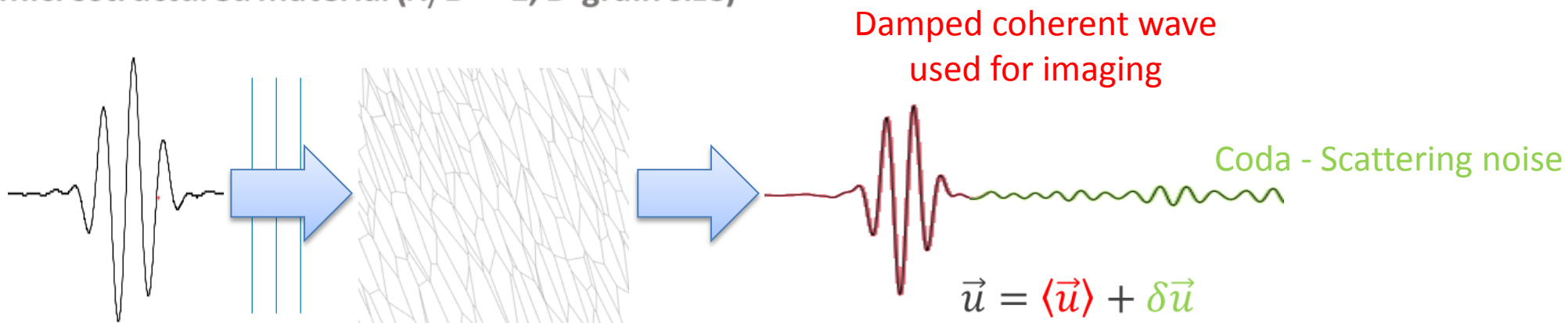


► Our goal in WP1:

- propose **UT modelling tools** well-adapted to parametric study for UT technique design and data analysis for complex microstructure materials in welds
 ⇒ *“seek a compromise between weld description accuracy and computational cost”*

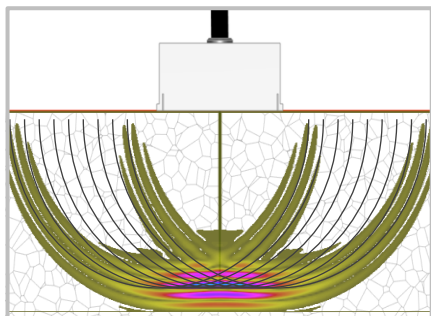
Macroscale modelling
 effective material consideration

Phenomenological aspect for UT inspection and effective material consideration

► NDT in microstructured material ($\lambda/D \gg 1$, D grain size)

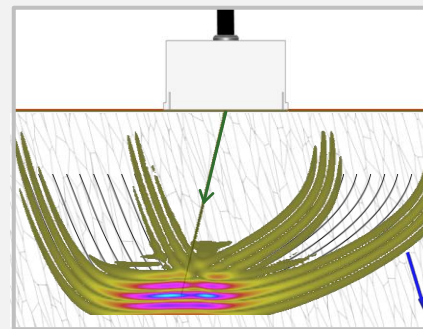
► Effective material properties for coherent wave propagation

- Equiaxed grain with random crystal orientations



⇒ isotropic damped material

- austenitic welds: **elongated grains** with preferential texture $\langle 100 \rangle$ around grain elongation axis



⇒ **anisotropic (quasi-hexagonal) damped material** whose symmetry axis is correlated with elongation axis

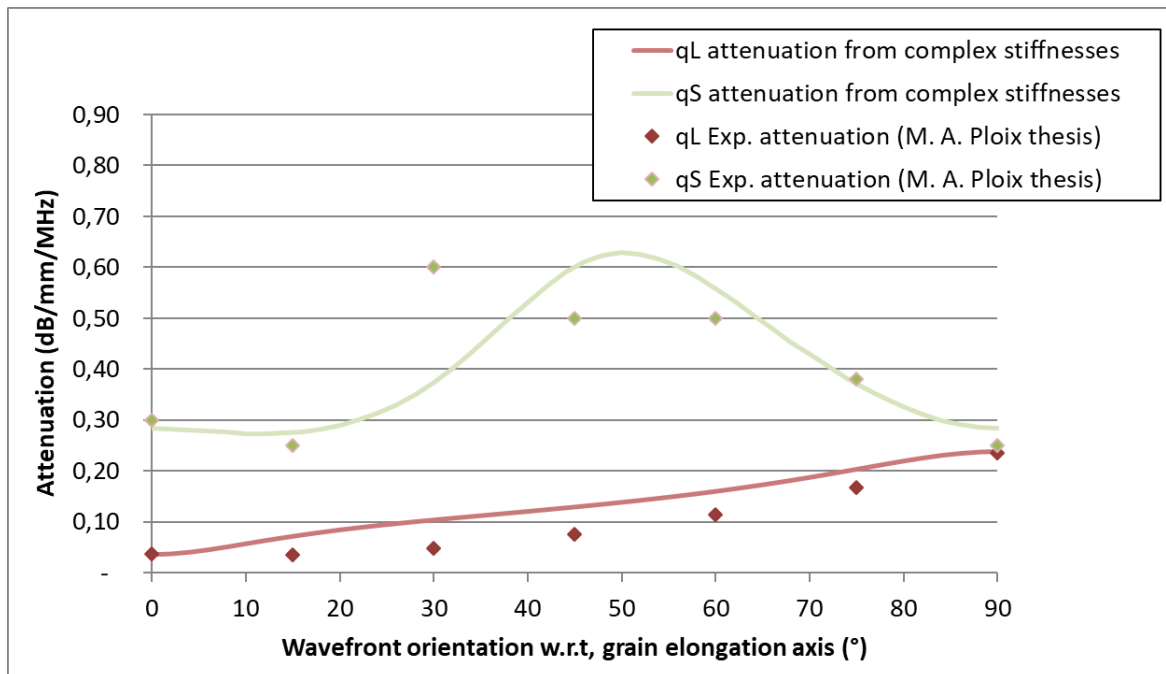


Inputs for weld material using macroscale approach

► Properties of the effective media

- Anisotropic viscoelastic constitutive law
- Definition of complex stiffnesses to fit wave velocities and attenuation variations w.r.t. wavefront directions

$$\Rightarrow C_{ij}(\omega_0) = C'_{ij}(\omega_0) + iC''_{ij}(\omega_0)$$

 C'_{ij}

220	135	135	0	0	0
135	245	110	0	0	0
135	110	245	0	0	0
0	0	0	80	0	0
0	0	0	0	110	0
0	0	0	0	0	110

 C''_{ij}

1.6	2	2	0	0	0
2	12	2.5	0	0	0
2	2.5	12	0	0	0
0	0	0	2.7	0	0
0	0	0	0	4.3	0
0	0	0	0	0	4.3

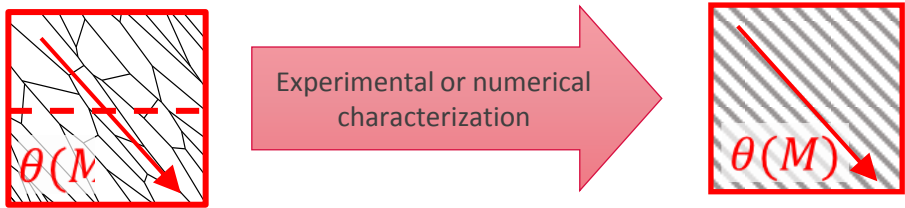
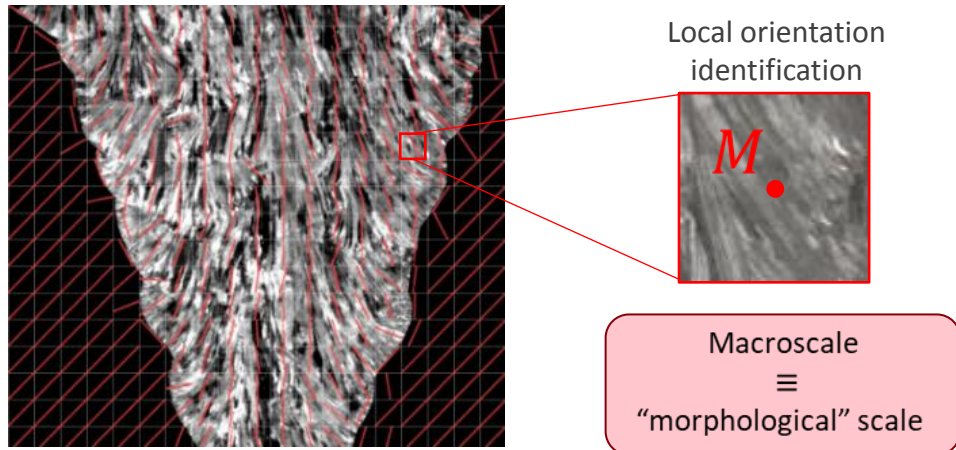
Typical values for the stiffnesses of an effective material consisting of a set of elongated grains mainly oriented along the 1 axis.



Inputs for weld material using macroscale approach

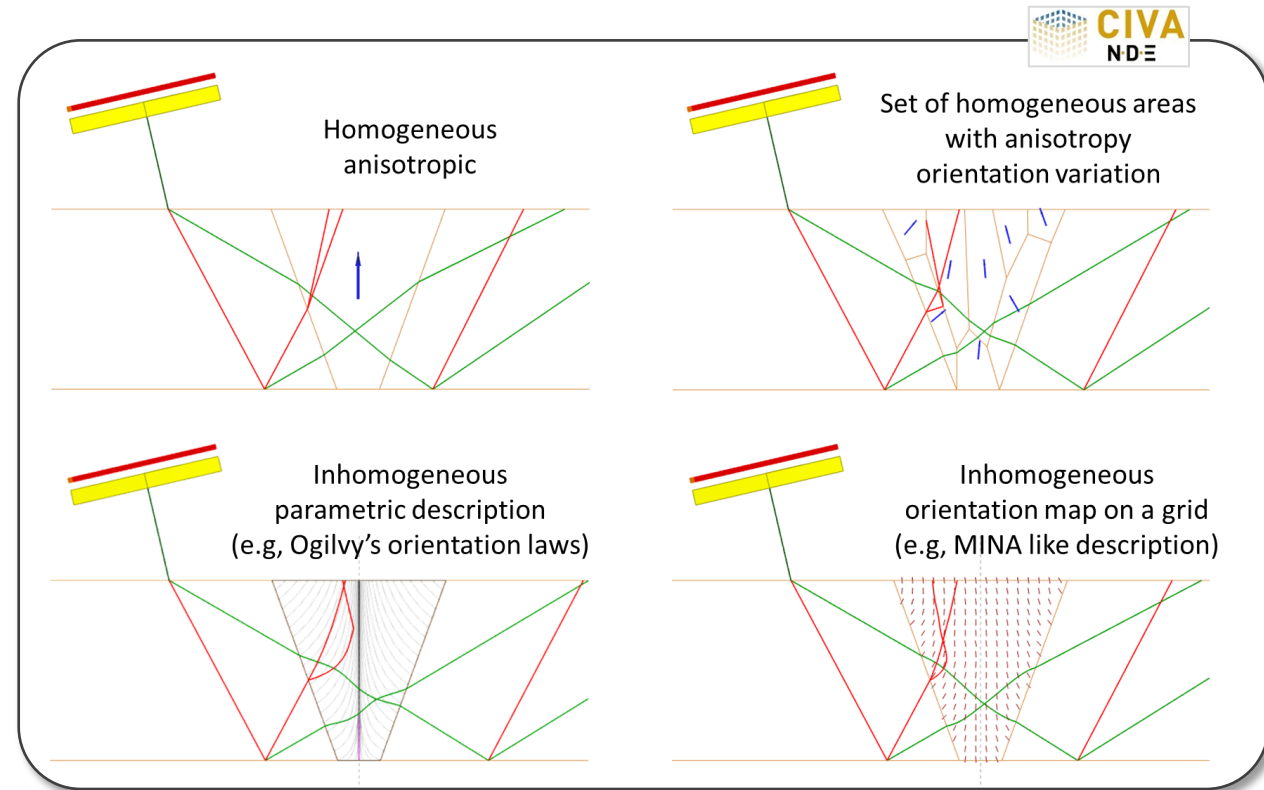
► Grain orientation mapping in the bevel

- Local definition of the main elongation axis



Domain with common statistical properties of grain topology

Effective media for the dominant grain orientation



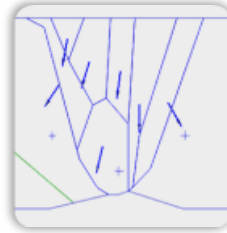
A complementary solution to ray models in order to provide reference results



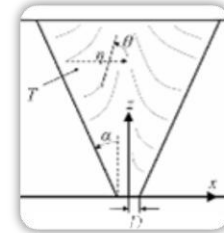
UT inspection
simulation

Macroscale modelling

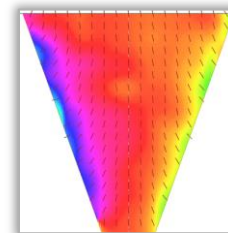
numerical tools based on
effective material consideration
(ray model, FEM)



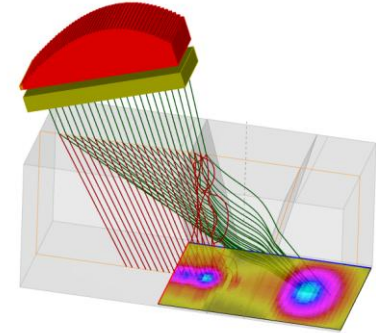
Piecewise



Parametric



Mapping



Dedicated simulation tools for NDT on welds

UT performance estimation -
variation analysis - imaging

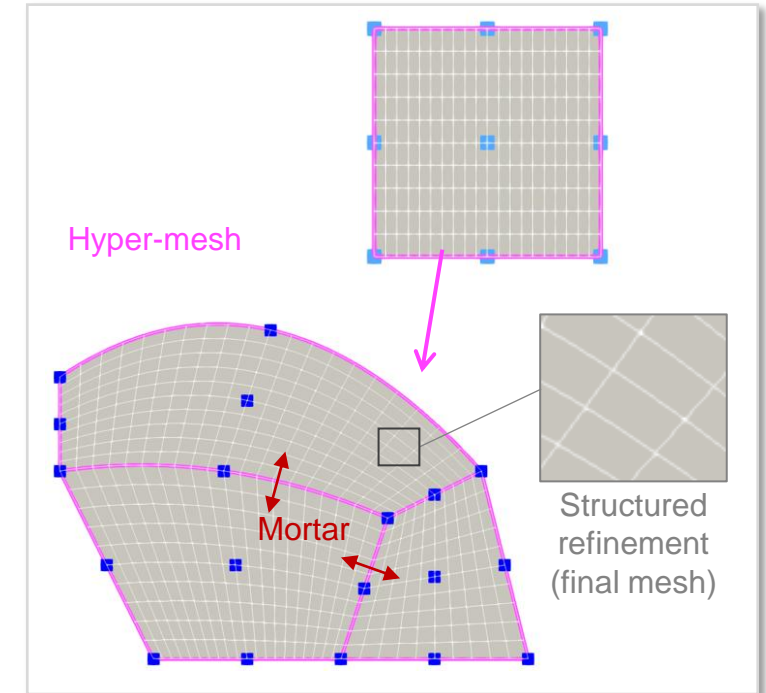
► Motivation:

- Efficient ray model but limitations on various cases (caustics, surface wave, diffraction...)
 - In practice difficult to anticipate these issues
- ⇒ **Need 2D/3D FEM simulation as references**



A dedicated Spectral Finite Element Method (SFEM)

- ▶ **High-order mass-lumped FEM:**
 - full explicit time-transient solver with diagonal mass matrix
- ▶ **Parametric hyper mesh structure of the UT scene:**
 - domain decomposition into macro-elements (MEs) containing material and geometrical inputs
- ▶ **Mortar element method used for MEs interactions**
- ▶ **Each ME carries a structured refinement w.r.t. λ**
- ▶ **Optimal data structure for parallelization and memory load**



[A. Imperiale et al., Int. J. Numer. Methods Eng., 2019](#)
DOI: 10.1002/nme.6080

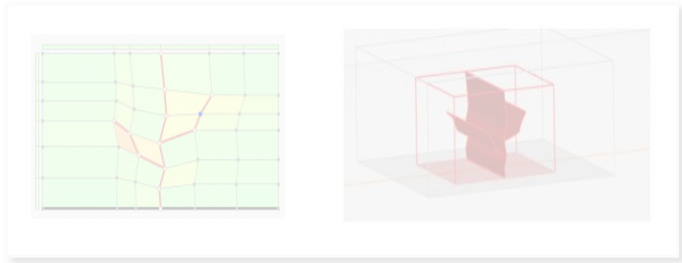


Objective: to enable macroscale FE simulations for 3D cases on PC for realistic configuration sizes

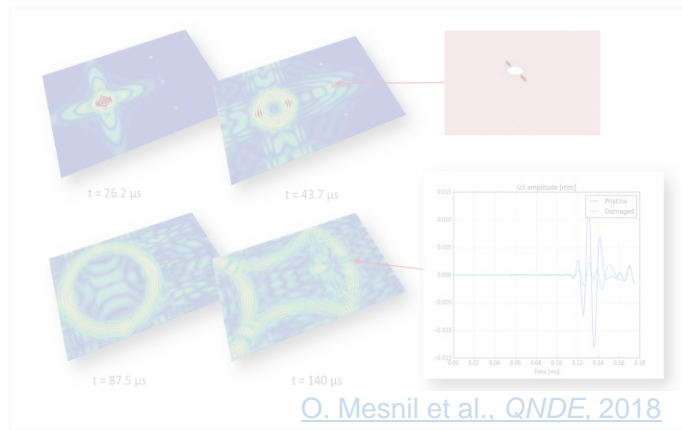


Features already using SFEM code in CIVA

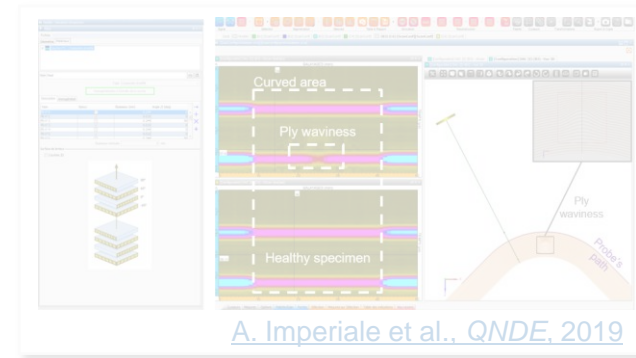
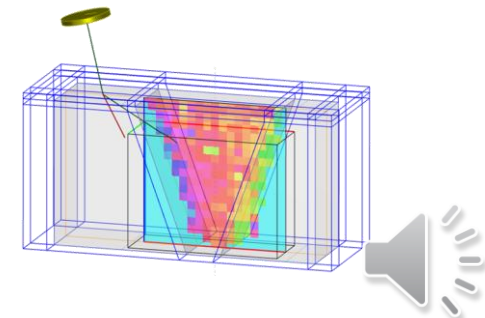
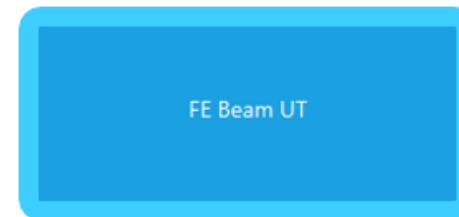
► FE Grid Defect (CIVA 2020) – UT inspection



► CIVA SHM (CIVA 2020 SP3)



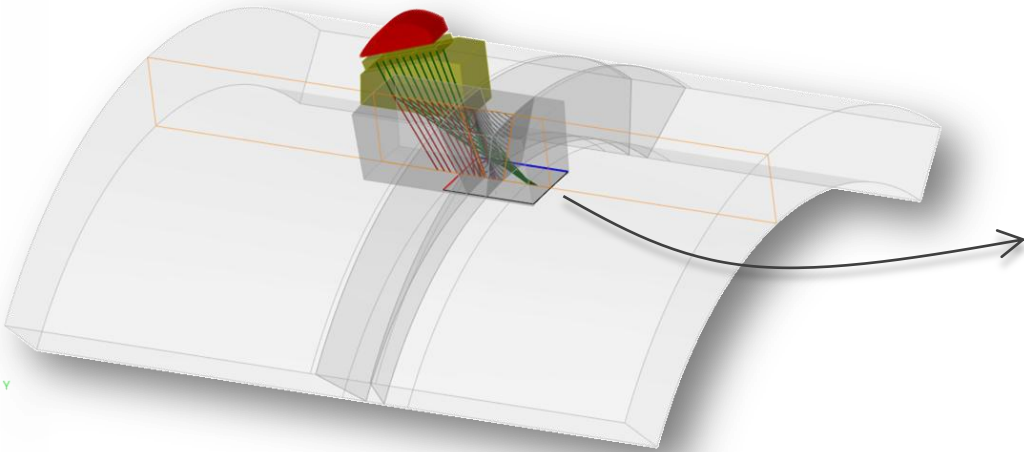
► Composite inspection (dev only)

► FE BEAM UT (available in the CIVA project version, planned 2022 for commercial release)
FE solution for 3D field computation in welds

Weld-oriented hybrid technique coupling ray model and SFEM

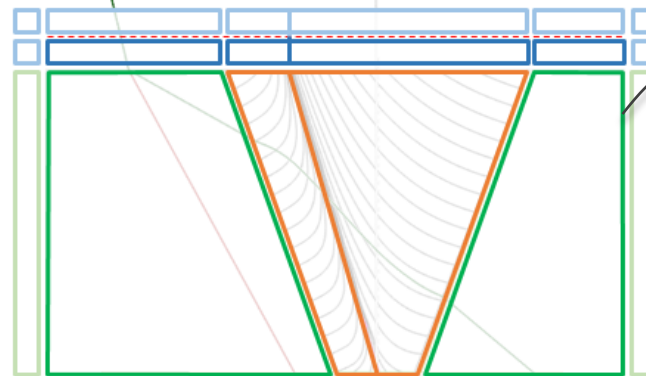
- ▶ Ray-based calculation of the source field in the coupling above the specimen
- ▶ Automated build-up of the high-order SFEM hexahedron mesh

Ray tracing pre-treatment to adjust the region of interest



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

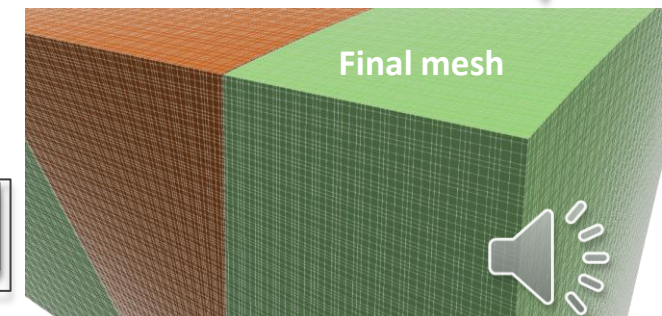
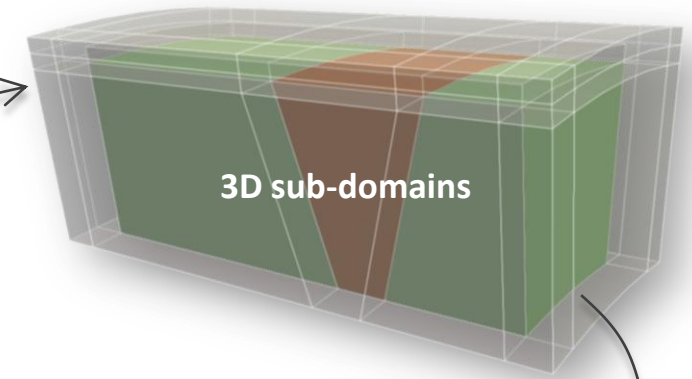
Radiated source field computed by ray model applied as a boundary condition



---	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



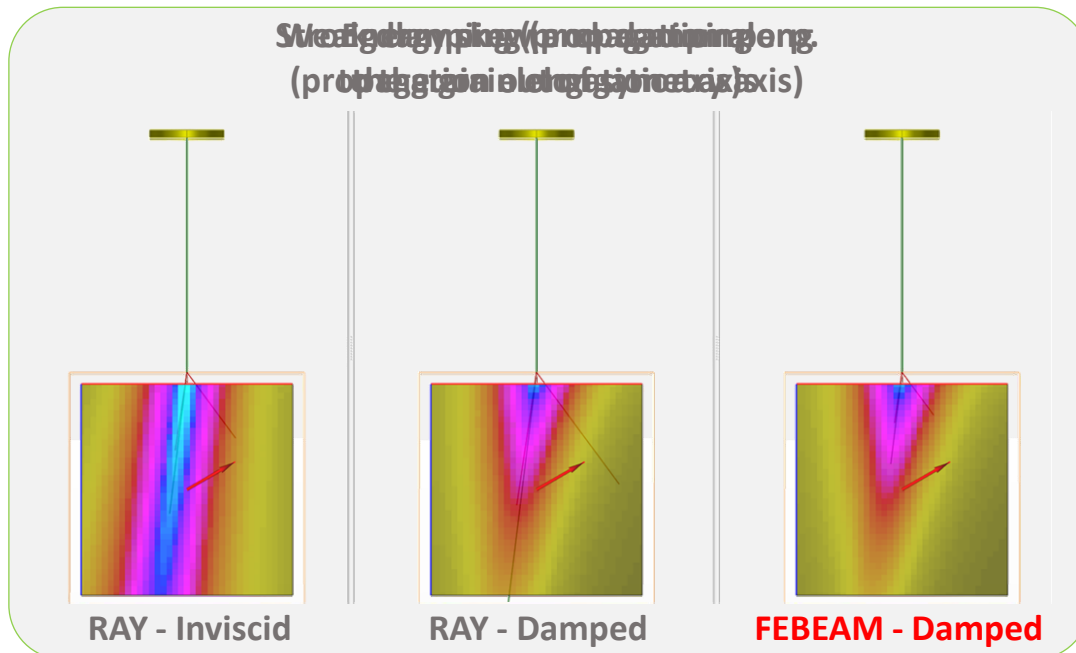
A FEM code including anisotropic damping effects of the weld material

- ▶ Consideration of coherent wave energy losses from scattering by the microstructure: anisotropic viscoelastic constitutive law
- ▶ Different schemes proposed:
 - Maxwell (constant attenuation w.r.t. frequency)
 - Zener (linear attenuation w.r.t. frequency)
 - Kelvin-Voigt (quadratic attenuation w.r.t. frequency)

	CFL vs h	CFL vs Q_*	Nb. of stiffnesses	Memory cost
Inviscid	$O(h)$	$O(1)$	1	$3 \times N_h$
Kelvin-Voigt	$O(h^2)$	$O(Q_*)$	2	$3 \times N_h$
Maxwell	$O(h)$	$O\left((I + Q_*^{-2})^{-\frac{1}{2}}\right)$	1	$3 \times N_h + 2 \times N'_h$
Zener	$O(h)$	$O\left((I + Q_*^{-1})^{-\frac{1}{2}}\right)$	2	$3 \times N_h + 2 \times N'_h$

TABLE 1 Qualitative comparison of fully discrete explicit viscoelastic propagators

[A. Imperiale et al., Int. J. Numer. Methods Eng., 2020](#)
DOI: 10.1002/nme.6359



- ▶ Cross-validation with ray-based computation using Maxwell scheme with calibration procedure at the main frequency

- Validation in homogenous cases for various grain orientations (10 – 2MHz)
- Very good agreement for simulating anisotropic damping and beam deviation

→ = main grain orientations

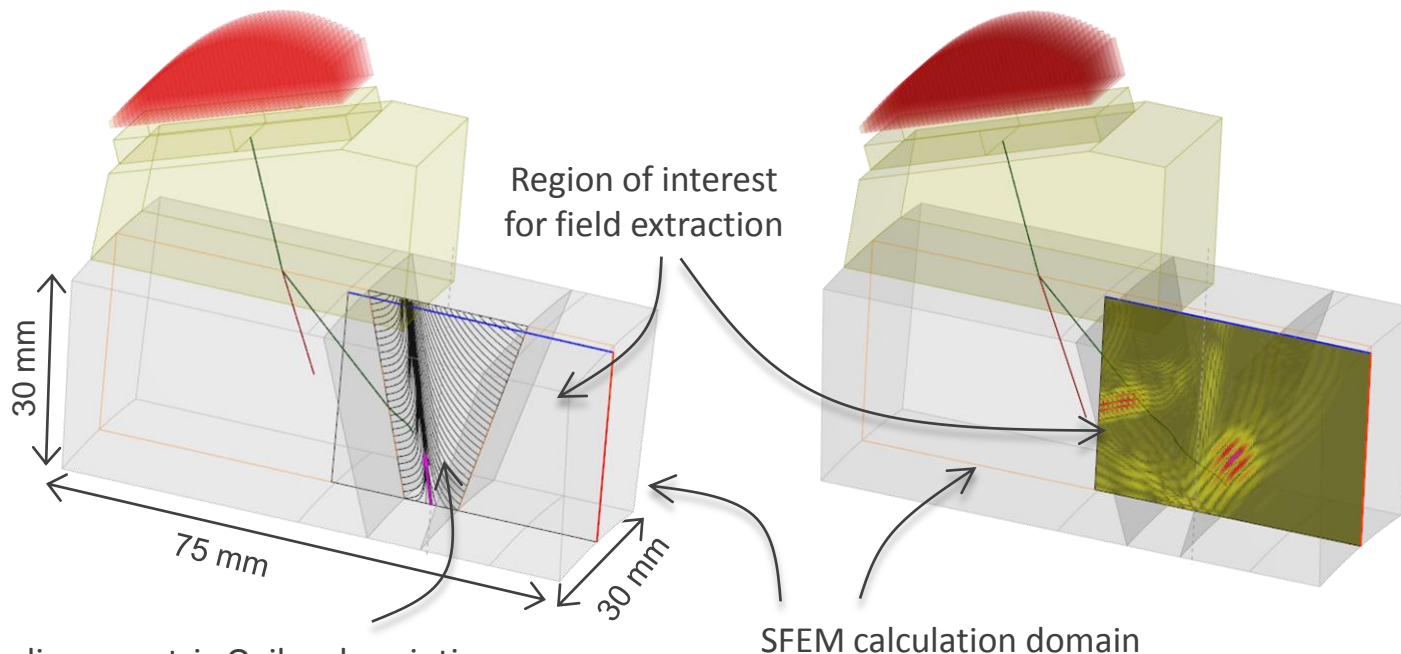


Other advantages

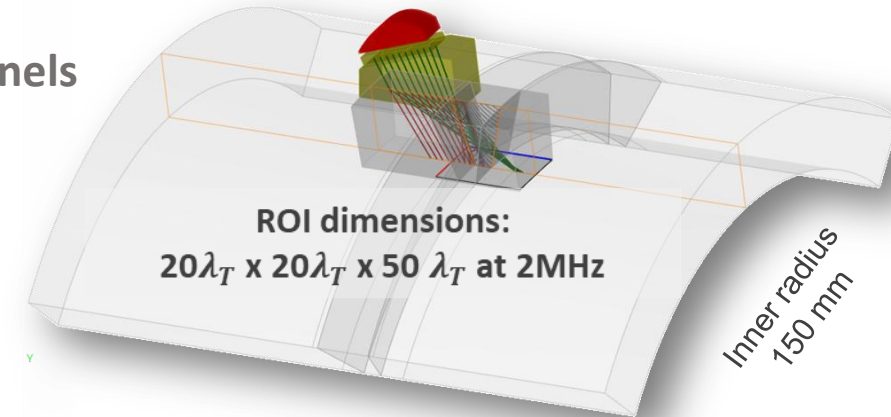
► Applicable to the main probe classes handled in CIVA

- immersion and wedge contact probes (rectangular, circular or elliptical shapes and focus settings)
- single element or any phased array patterns (linear, matrix, dual probe...)

► Field extraction in a 2D or 3D region of interest using CIVA analysis panels



e.g. dissymmetric Ogilvy description
& anisotropic damped properties



► Macroscale description with low-memory requirements

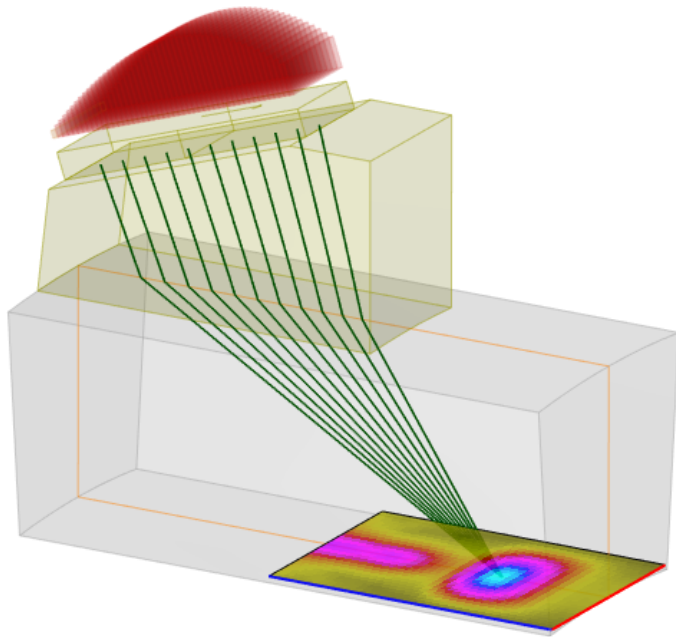
- e.g. for the current use case at 2MHz
 - Homogeneous Isotropic < 1 GB
 - Heterogeneous anisotropic < 6 GB



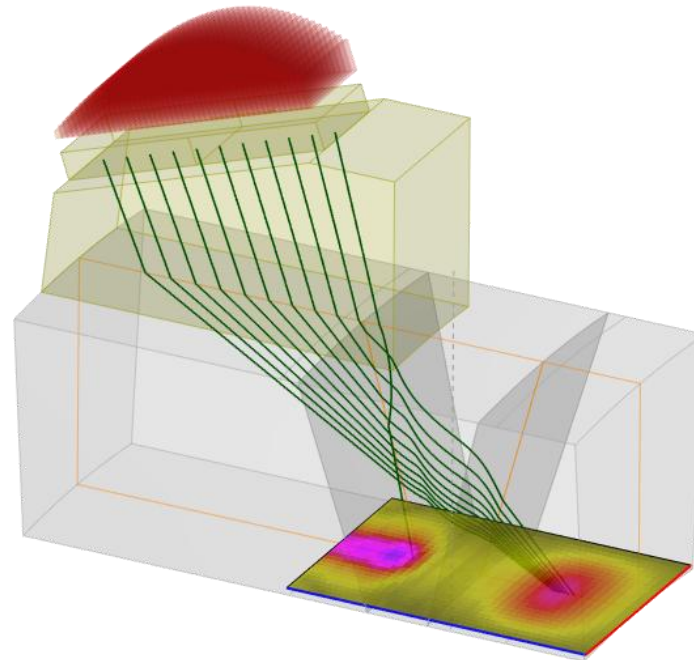
3D field computation on the backwall of a cylindrical welding component

► PA probe with focusing law on the backwall

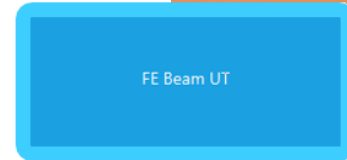
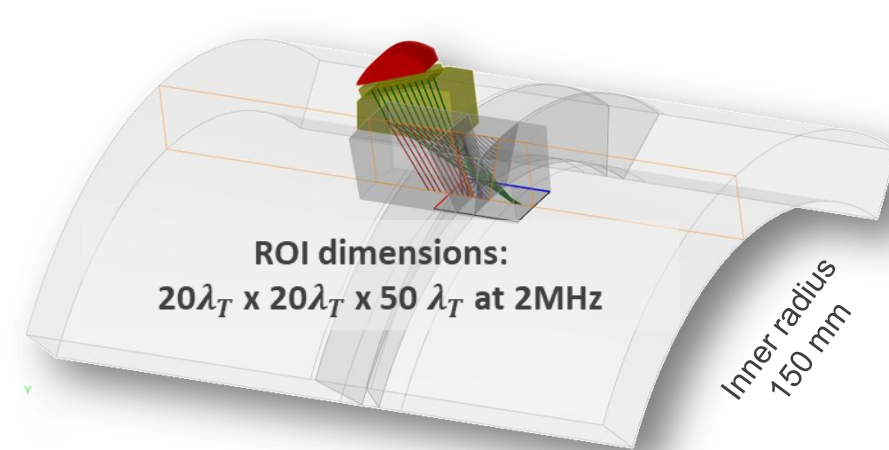
- 2MHz wedge probe (nominal L45) – linear 48 elements – point focusing law
- Ogilvy description using anisotropic damped material properties
- Simulated time for wave propagation to the bottom: 20 μ s



Point focusing law computation considering an isotropic metal



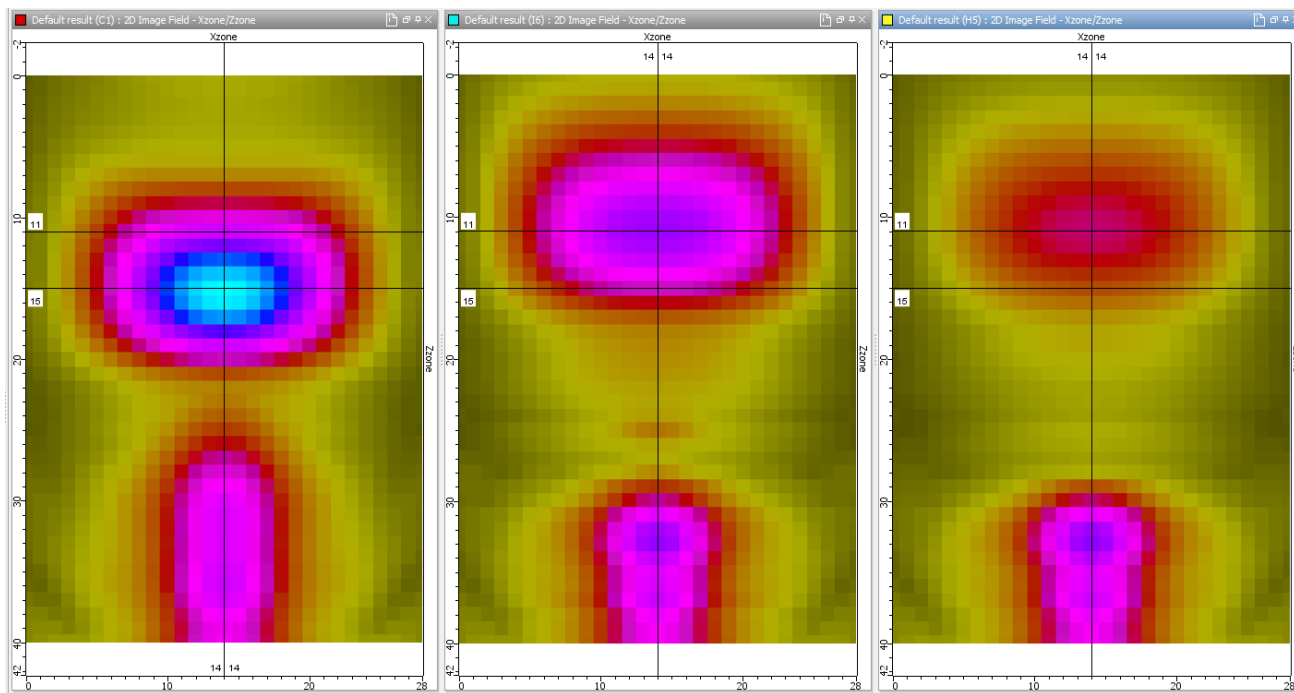
Superposed SFEM results with ray tracing analysis



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

► Quantification of weld material properties

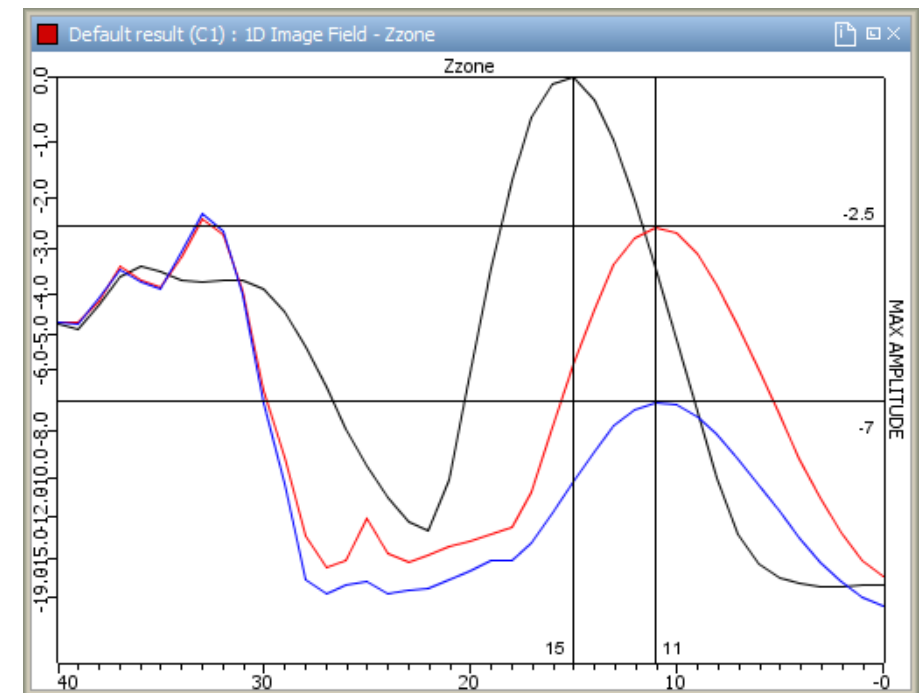
- Beam deviation
- Beam damping



Isotropic

Anisotropic
(no attenuation)

Anisotropic
(with attenuation)



Extraction of the max. fields in the inspection plane



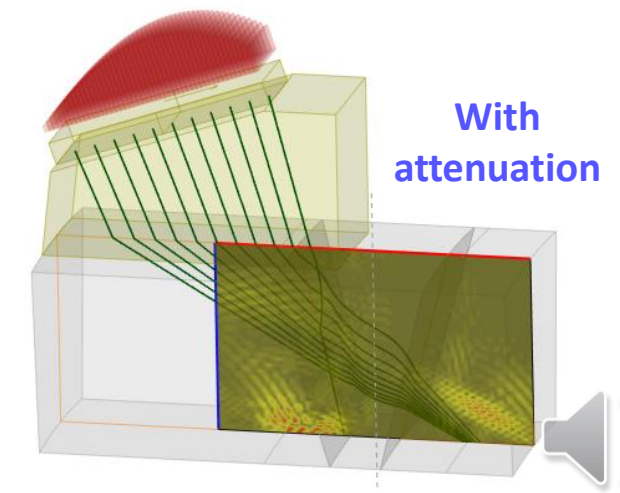
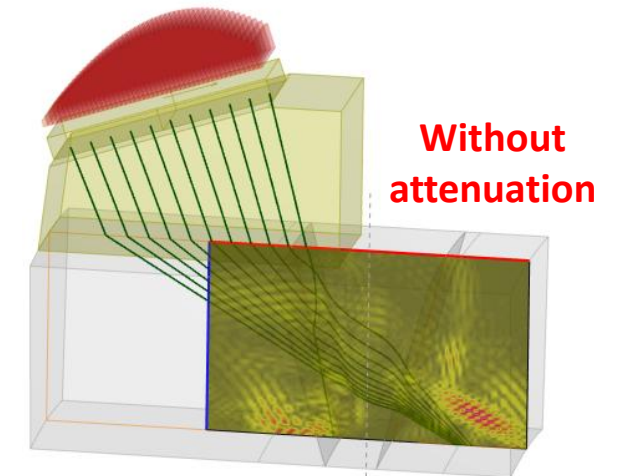
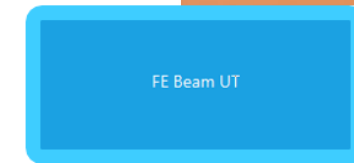
3D field computation on the backwall of a cylindrical welding component

► Performances obtained on

- Single workstation using Intel® Xeon® W-2155 Processor (13.75M Cache, 3.30 GHz)
- # of Cores 10 (# of Threads 20)



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





FE Beam UT

Summary of the present work

► An hybrid ray/SFEM technique

- Ray model used for radiated beam definition at the surface of the sample
- SFEM used for wave propagation into the whole sample reduced to a ROI

► Simulation tool fully integrated into the CIVA platform environment

► A complementary FEM solution to ray-based simulations in weld

- Provide FE reference solution
- Very efficient in 2D allowing intensive parametric studies
- Low memory and computational cost in 3D (several GB and of the order of a few hours)

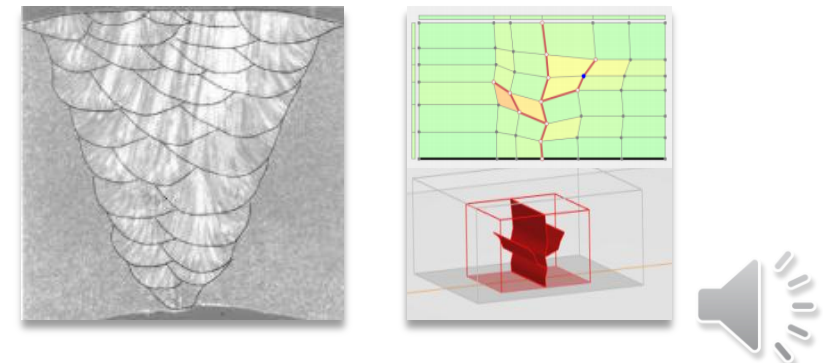
Next challenges within the FEM in welds

► Geometric distortion and variation of the weld bevel

► Taking into account the geometry of the passes according to a MINA technical description

► Introduction of a 3D flaw-area and propose echo response synthesis

► Adding structural noise in the FEM propagator





Thank you for your attention

Please feel free to send any questions and more details after this short presentation!

nicolas.leymarie@cea.fr

