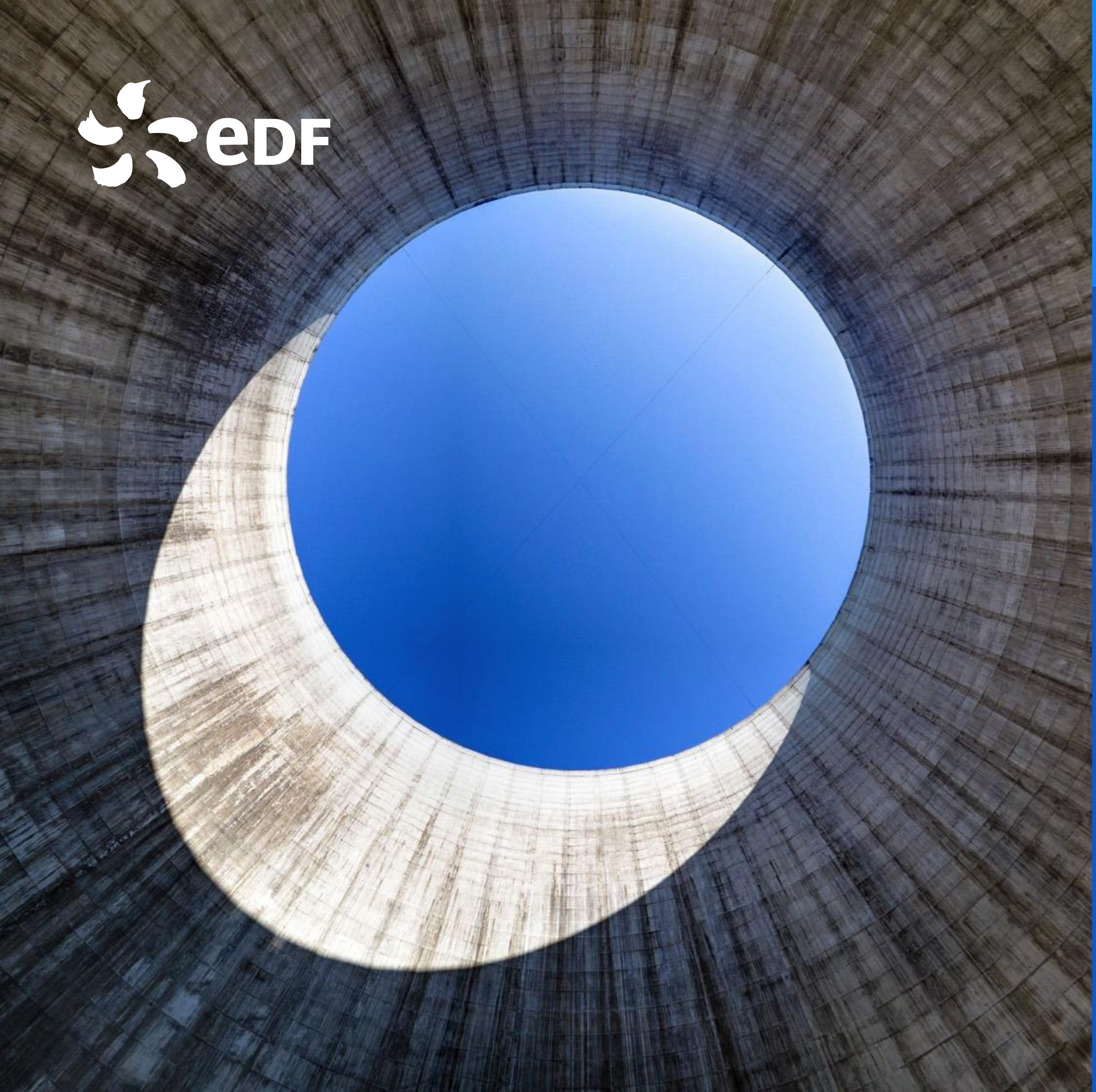


Kick-off workshop of the HIPOTHEC ANR project.

08/03/2024

Simulation of ultrasonic testing in metallic components

J. Dalphin

September 2019 | 2017-2019 | 2016-2017 | 2015-2016 | 2011-2014 | 2007-2011

Jérémy DALPHIN

jeremy.dalphin@edf.fr

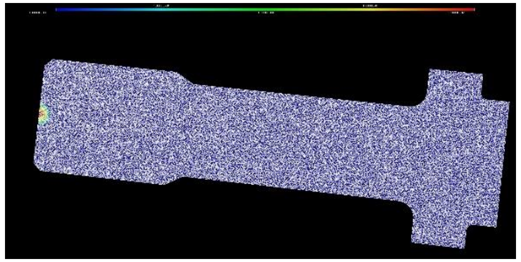
Research engineer

ERMES T6D group (D. Geoffroy)

- Mechanics of components
- Non-destructive testing (NDT)

Projects

- **Software for ultrasonic NDT**
- **Tools for Eddy-current NDT**
- Development in code_aster



Research engineer in Jussieu

INSTITUT DES SCIENCES DU CALCUL ET DES DONNÉES

SORBONNE UNIVERSITÉ

Computational quantum chemistry
P. Frey and B. Braïda

Maximal Probablity Domains

- Software development
- Adaptative mesh techniques
- Level-set method

Academical thesis in Nancy

Institut ÉLIE CARTAN

UNIVERSITÉ DE LORRAINE

Applied mathematics
A. Henrot and T. Takahashi

Studying the shape of vesicles

- Design optimization
- Tridimensional geometry
- Partial differential equations

Postdoctorate in Santiago, Chile

CMM Center for Mathematical Modeling

fcfm Ingeniería Matemática FACULTAD DE CIENCIAS FÍSICAS Y MATEMÁTICAS UNIVERSIDAD DE CHILE

A. Osses
Study of a copper converter

- Inverse problems
- Random incertainties
- Numerical simulations

2007-2011: Ecole des Mines de Nancy

MINES NANCY

UNIVERSITÉ DE LORRAINE

Mathematical engineering section
2009-2010: gap year

- CRIGEN (Saint Denis) GDF SUEZ
  L. Sinègre and N. Castellan
  Impact of CCCG on the gaz network

- BCAM (Bilbao, Spain) bcam basque center for applied mathematics
  Zuazua and R. Barros
  Optimal shape generating waves

Sommaire

1. Context
2. Workflow
3. Results

1

Context

It is a collaboration between different entities of EDF R&D:

- **ERMES** (J. Dalphin, *P. Thomas*) and
- **MMC** (P.-E. Lhuillier, A. Schumm, Y. Gelebart, S. Wentzel, and Z. Aghenzour)

for the **APEXIS** project financed by Direction Industrielle (**DI**).

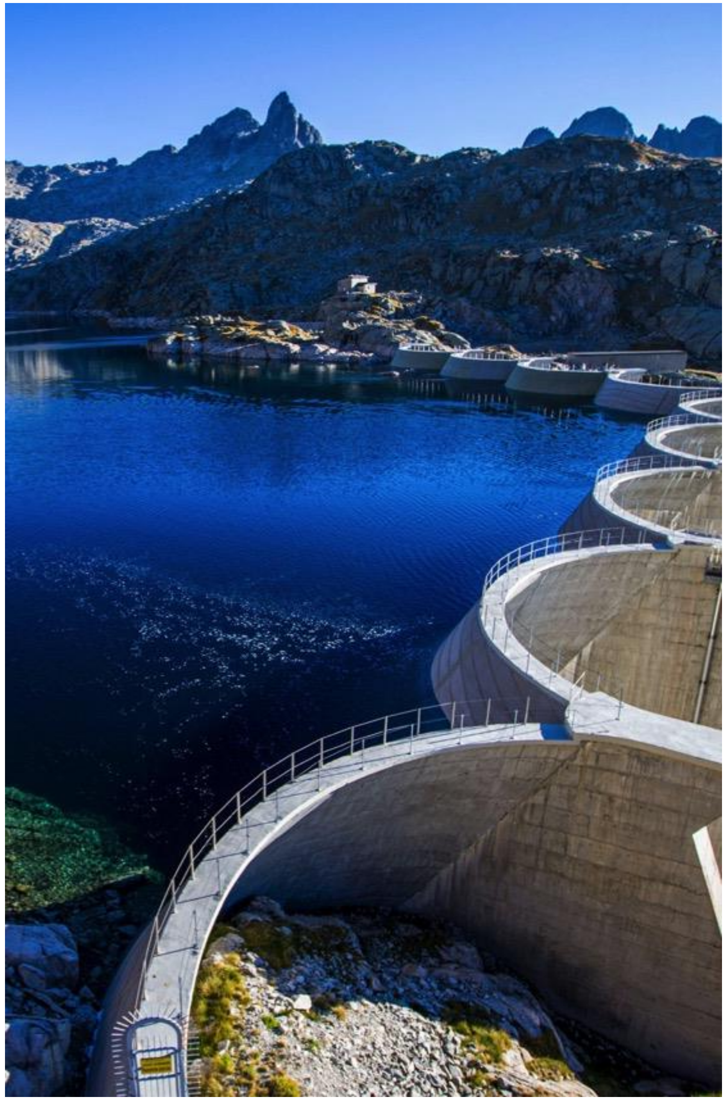
The set of techniques and processes giving informations about the health of a component or a structure, without resulting in any harmful alterations to their uses are gathered under two principal appelations: non-destructive testing (NDT) or non-destructive examinations.

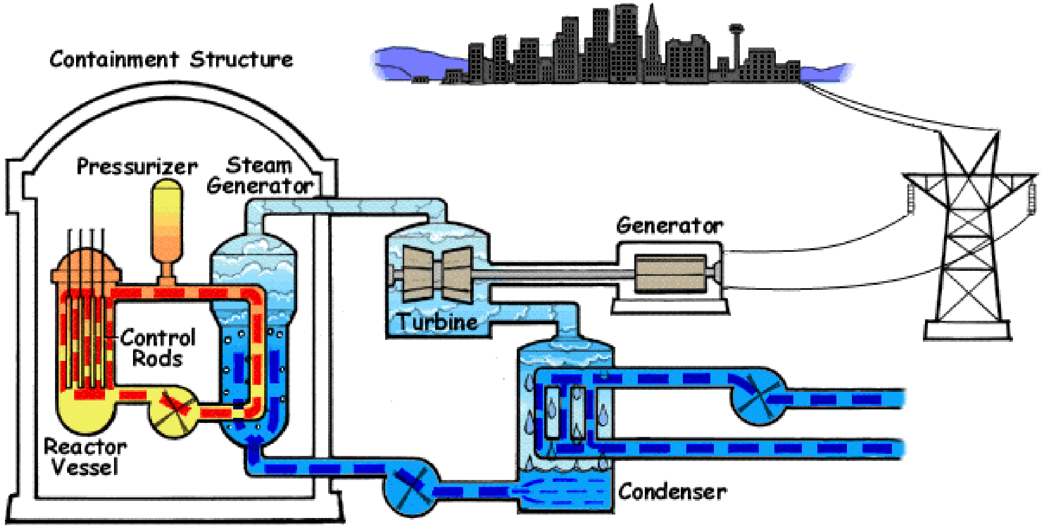
Created in 1967, the COFREND, Confédération Française pour les Essais Non Destructifs, is the reference entity in the domain of Certification and Qualification of agents in France for non-destructive testings and evaluations.

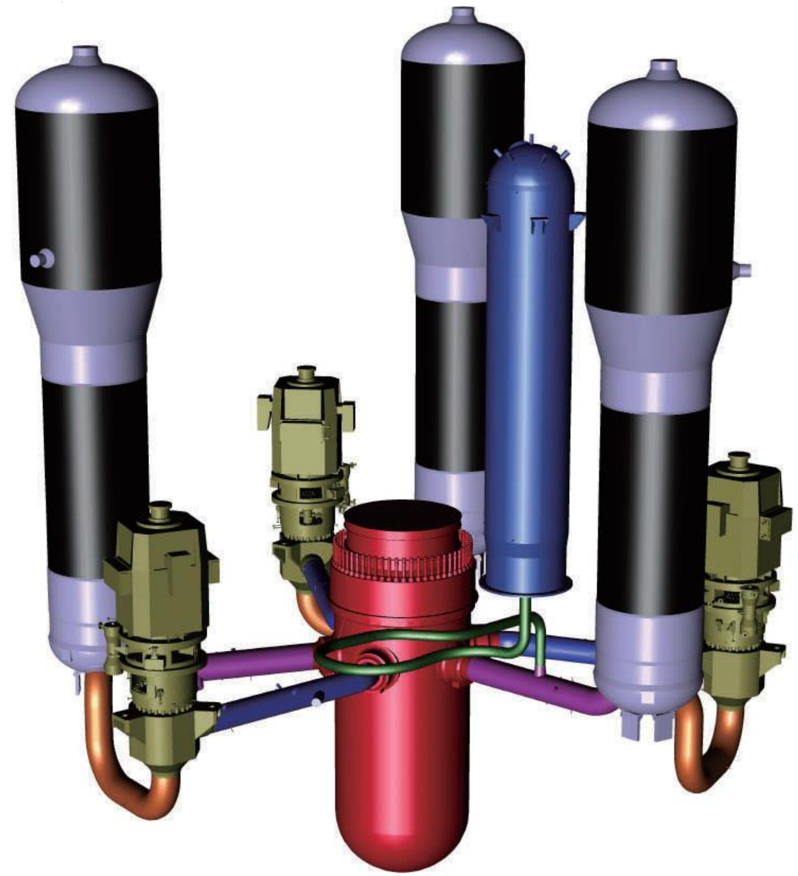
The object of NDT is to **determine with reliability** and at the appropriate scale of observations the presence and the nature of defects in components.

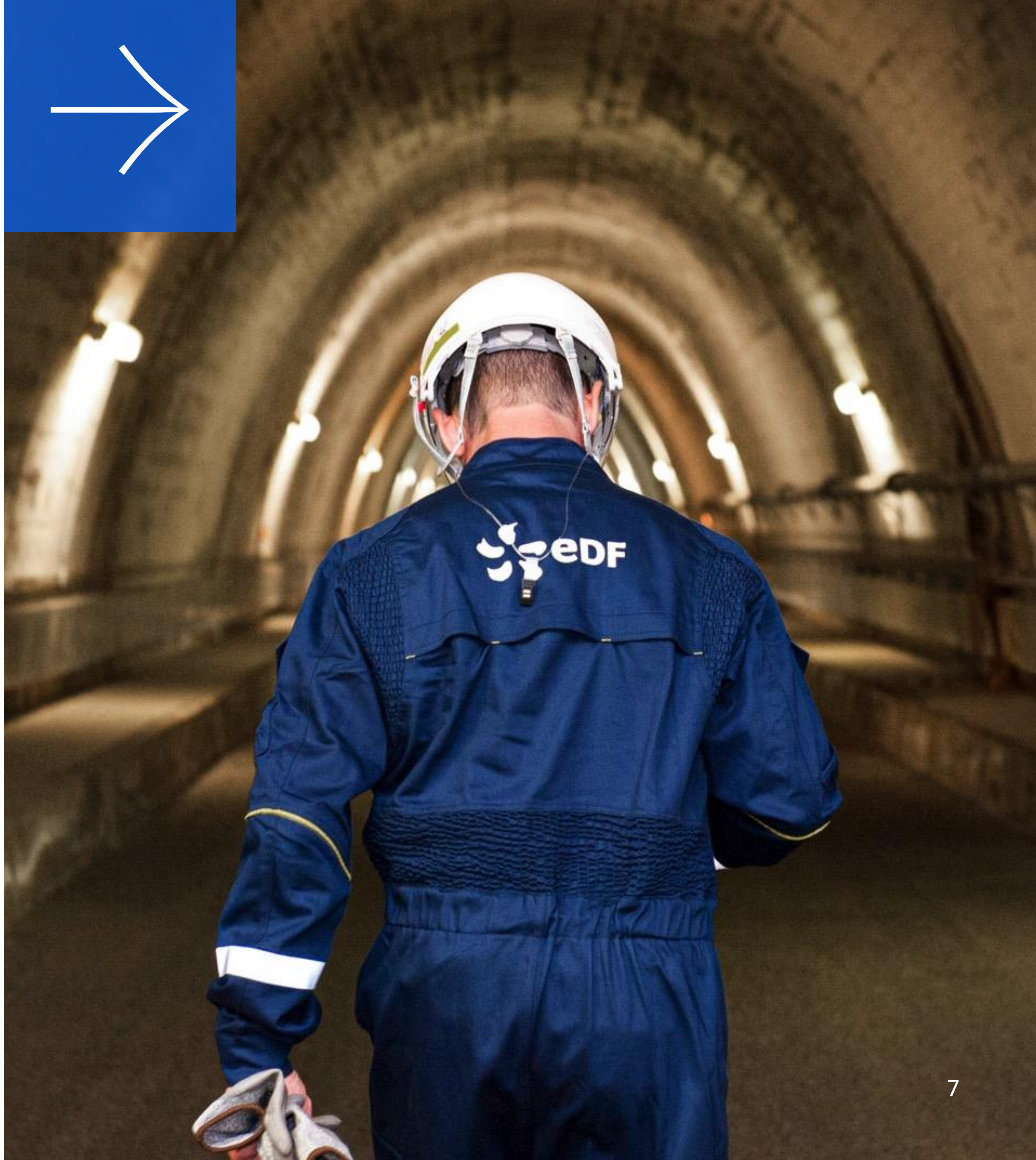
In the specific context of EDF SA: NDT are the main techniques the operator disposes to **guarantee the components integrity**, in addition to the design and manufacturing ones.

This requirement of detecting defects as soon as they represent a **security threat** of components integrity of pressurized water **nuclear reactor is enforced by law** (arrêté du 10/11/1999). It is one of the main purposes of the operator.




Containment Structure
Pressurizer
Steam Generator
Generator
Turbine
Control Rods
Reactor Vessel
Condenser

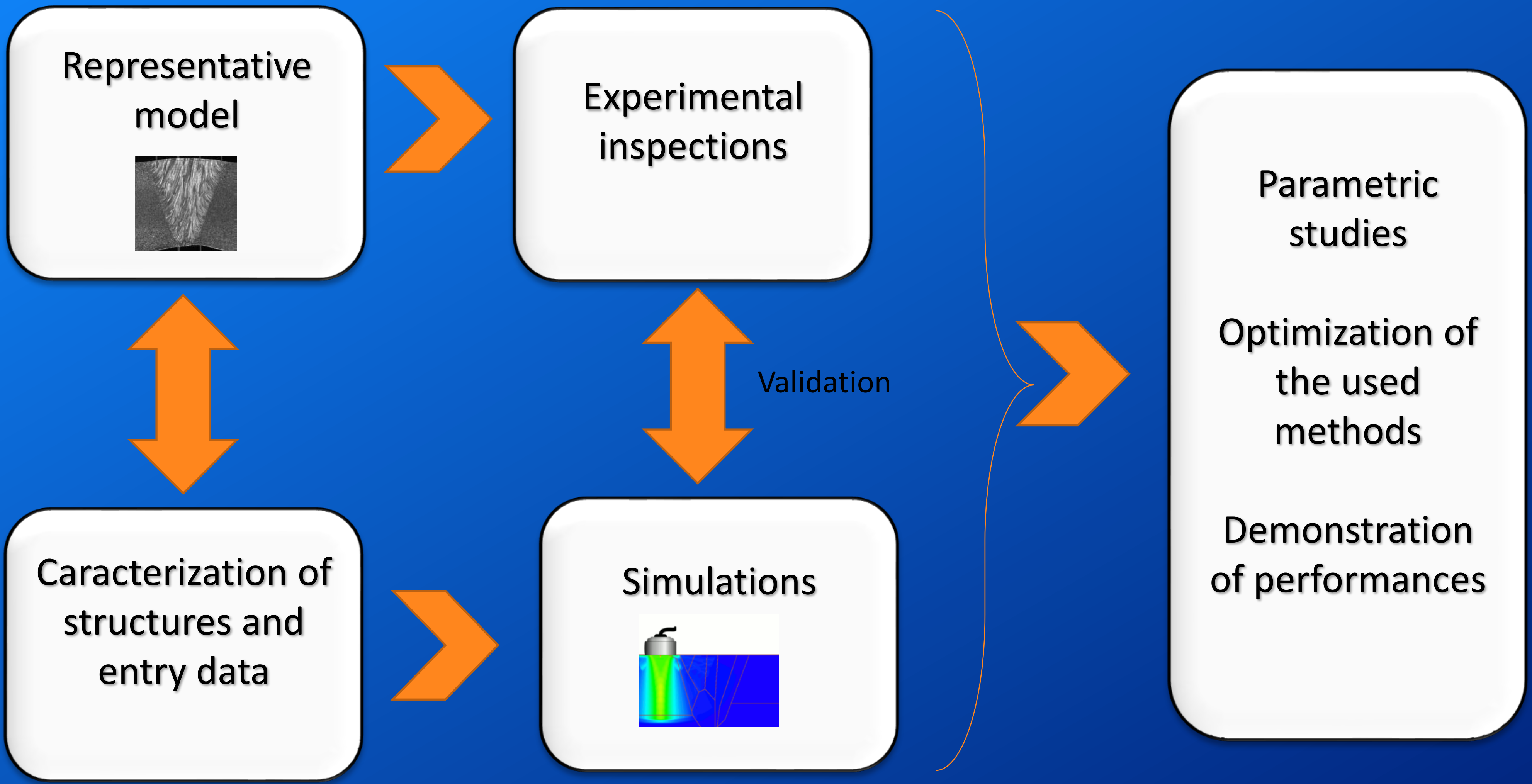



eDF

In the field of **metallic components** they are three main types of NDT:

- Eddy-currents
- Ultrasounds
- *Radioagraphy* (≲ 2027)

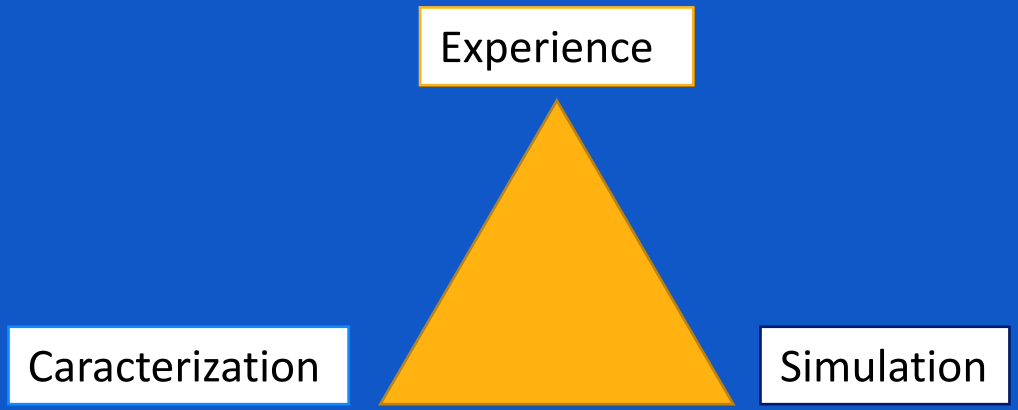
The methodology of the ultrasonic NDT laboratory



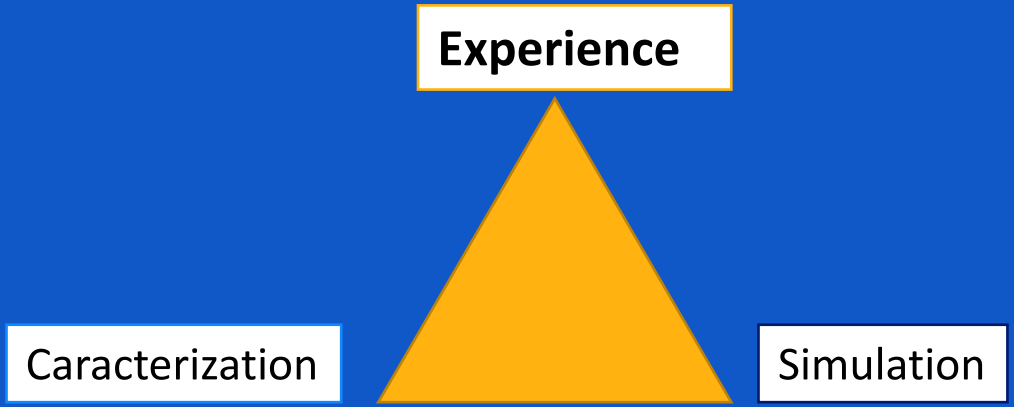
The methodology of the ultrasonic NDT laboratory

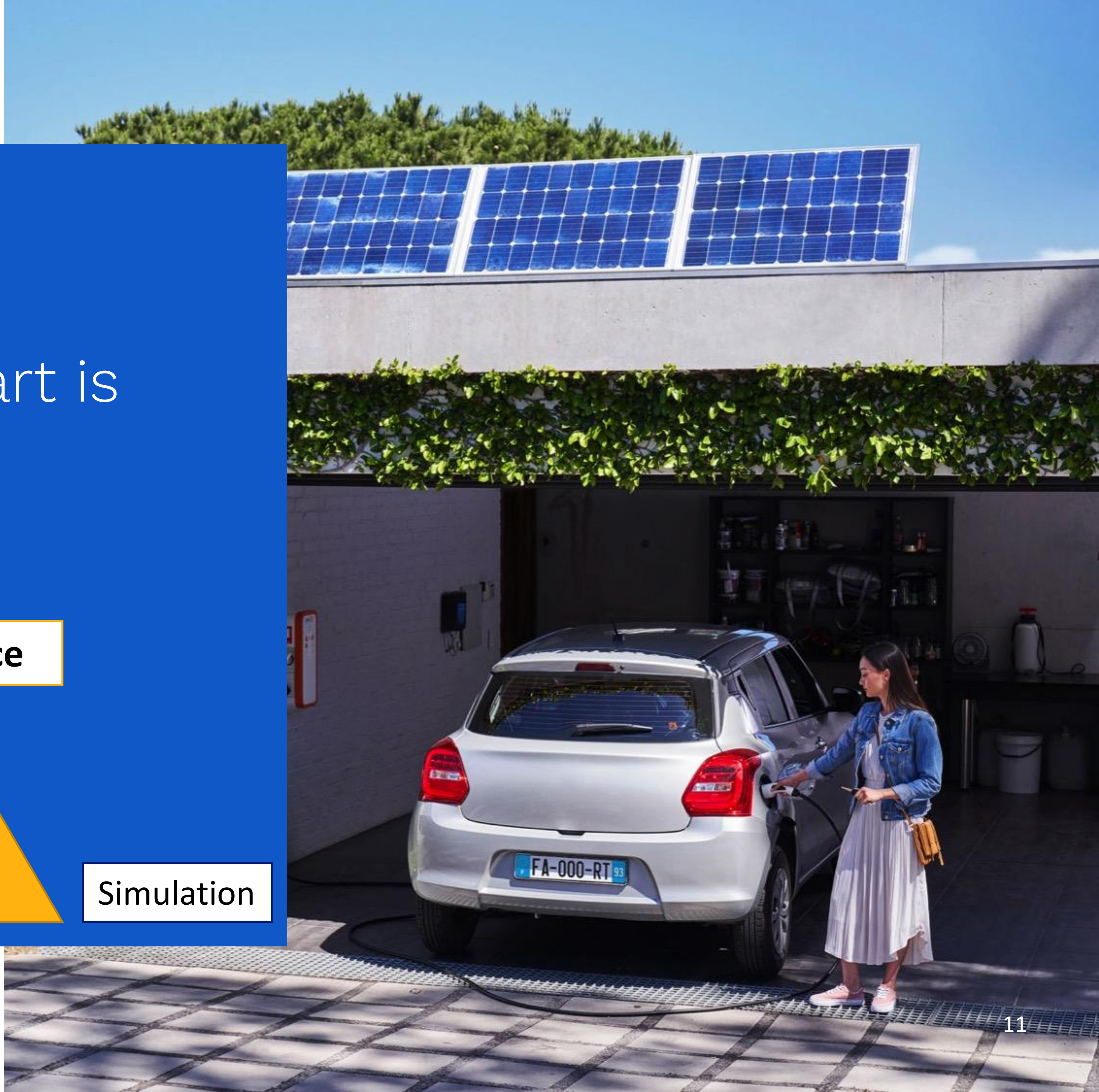
Fundamental expertise of the ultrasonic NDT laboratory:

→ link between the metallurgic structure of components and their controlability by ultrasounds.



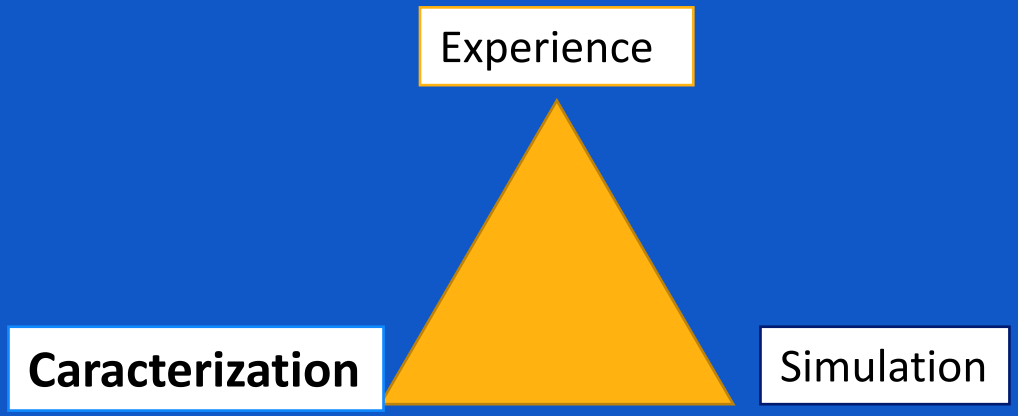
→ Sorry, this part is confidential



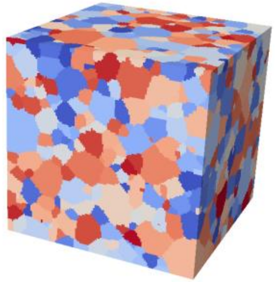


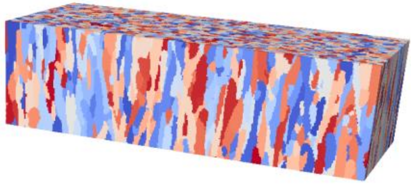
General methodology - Caracterization

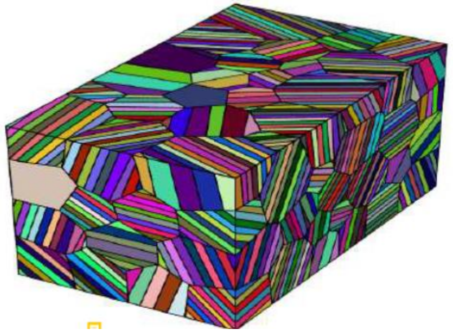
→ Give reliable entry data for the simulation codes

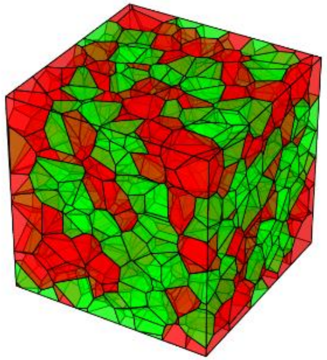


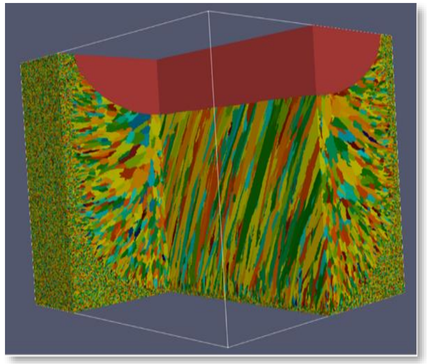
1. The tools for the characterization of materials

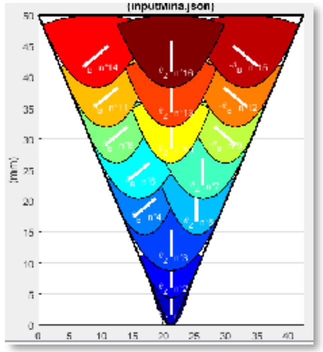












EBSD

Virtual micro-structures

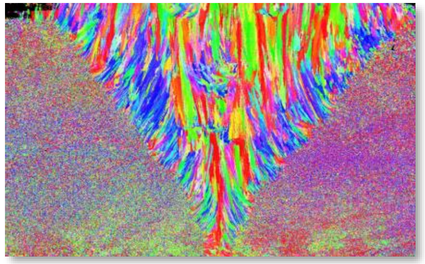
Metallography

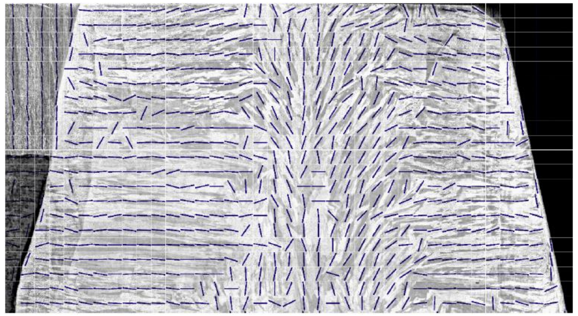
NDT laboratory Les Renardières

Weld Models

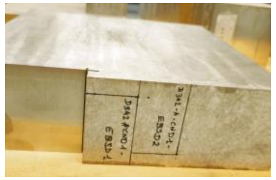
Elastic propreties

Ultrasonic properties



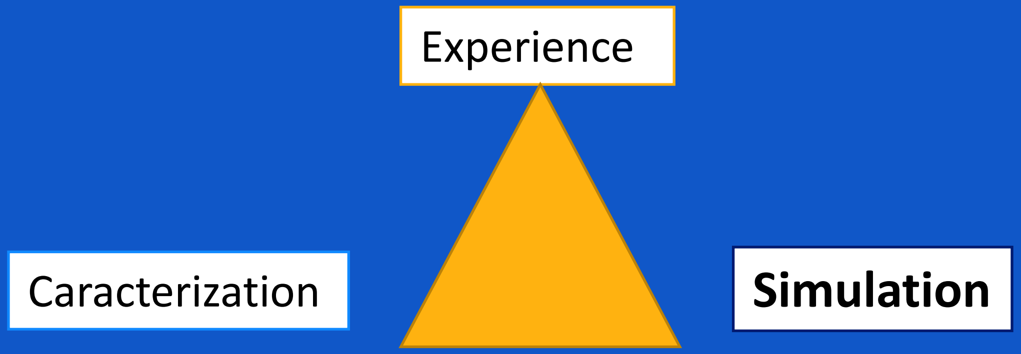


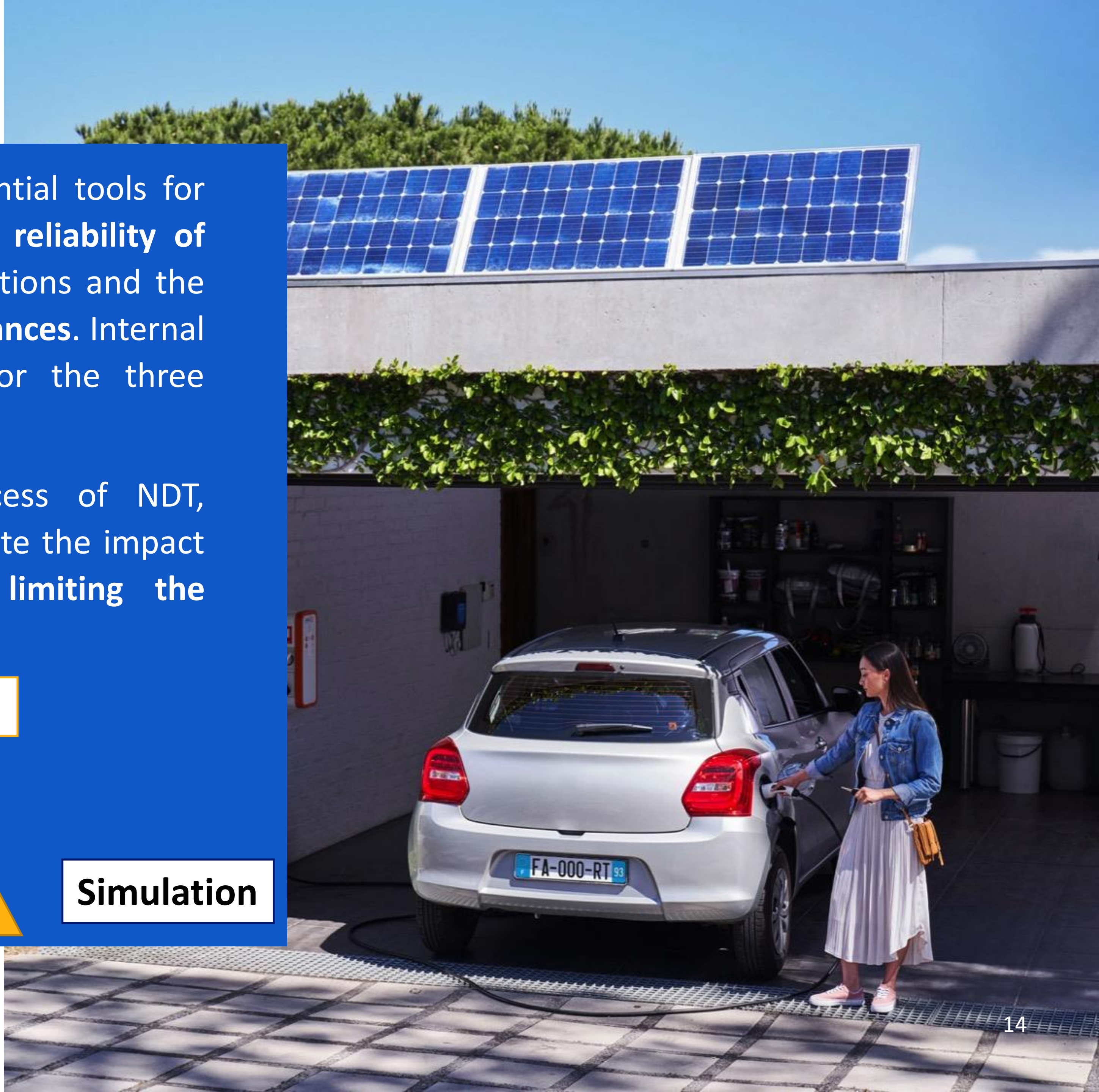
233	139	139			
	233	139			
		233			
			106		
				106	
					66



General methodology - Simulation

- Simulation codes are essential tools for engineers to enhance the **reliability of diagnostics** for NDT inspections and the **demonstration of performances**. Internal softwares are available for the three types of NDT at EDF R&D
- In the qualification process of NDT, simulations allow to evaluate the impact of influent parameters, **limiting the number of experiments**.



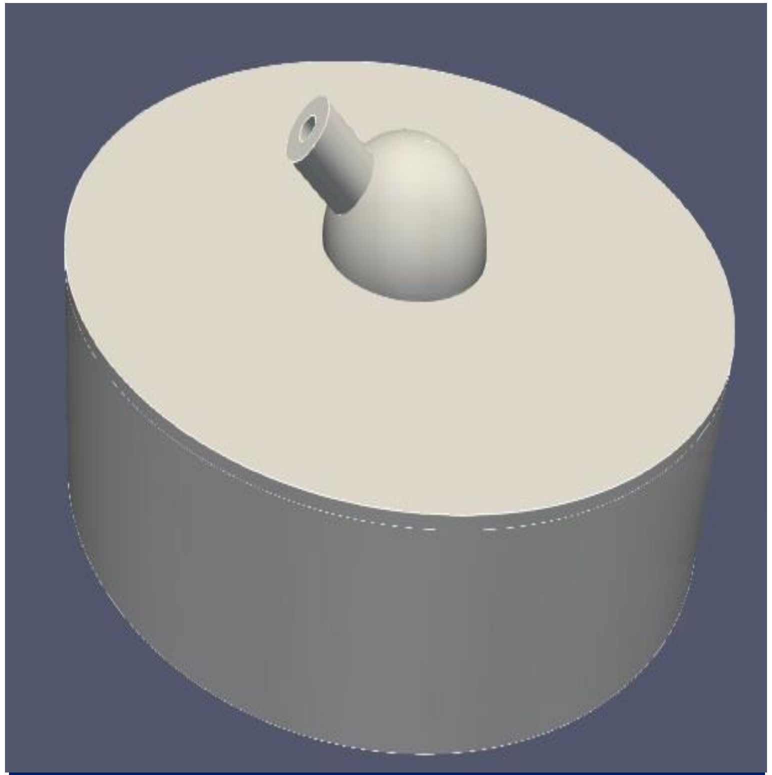


- → Detection of **realistic defects** by numerical simulations.
- → Propagation of 3D ultrasonic waves in an **elastic media**.
- → Remplace ATHENA3D by a industrial tools to help engineers to make decision.
- → Be compatible with the already-existing tools of **pre-** and **post-processing treatements.**

- Treat arbitrary geometry with potential complex defects.
- Elastodynamics in heterogeneous anisotropic media.
- Performance et reliability greater than ATHENA3D.
- Easy code maintenance and ergonomy of use for engineers.
- Compatibily with MILENA, SALOME and PARAVIS.

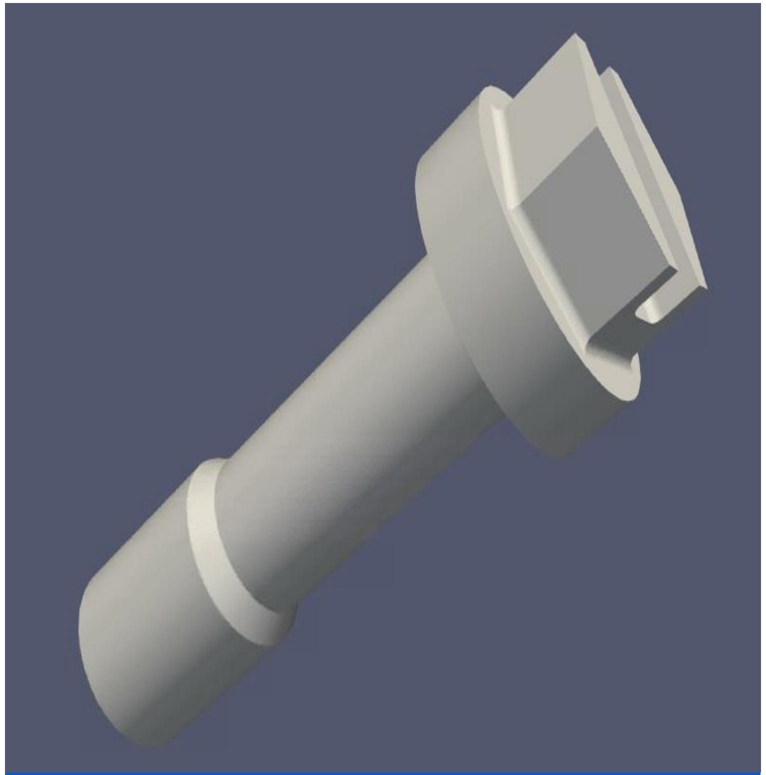
Desired specifications with respect to the new solver called A3D-CND.

2020



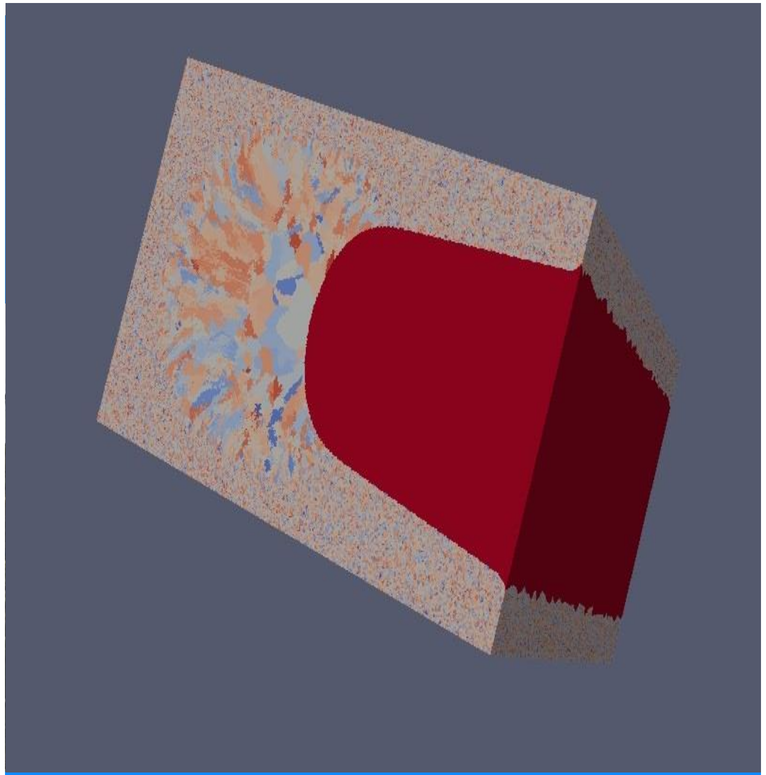
Comparison of performances between a Fortran short code (P. Thomas) et code_aster on a PFC.

2021



First successfull connection between A3D-CND (written in C) and MILENA (C++) on a isotropic screw of the nuclear pressure vessel.

2022



Simulation over granular microstructures highly anisotropic and heterogeneous like a numerical real three-pass weld (NEMESIS).

2

Workflow

Strong physical and numerical constraints:

- **Simplify** methods as much as one can;
- Gain **time** in software development.

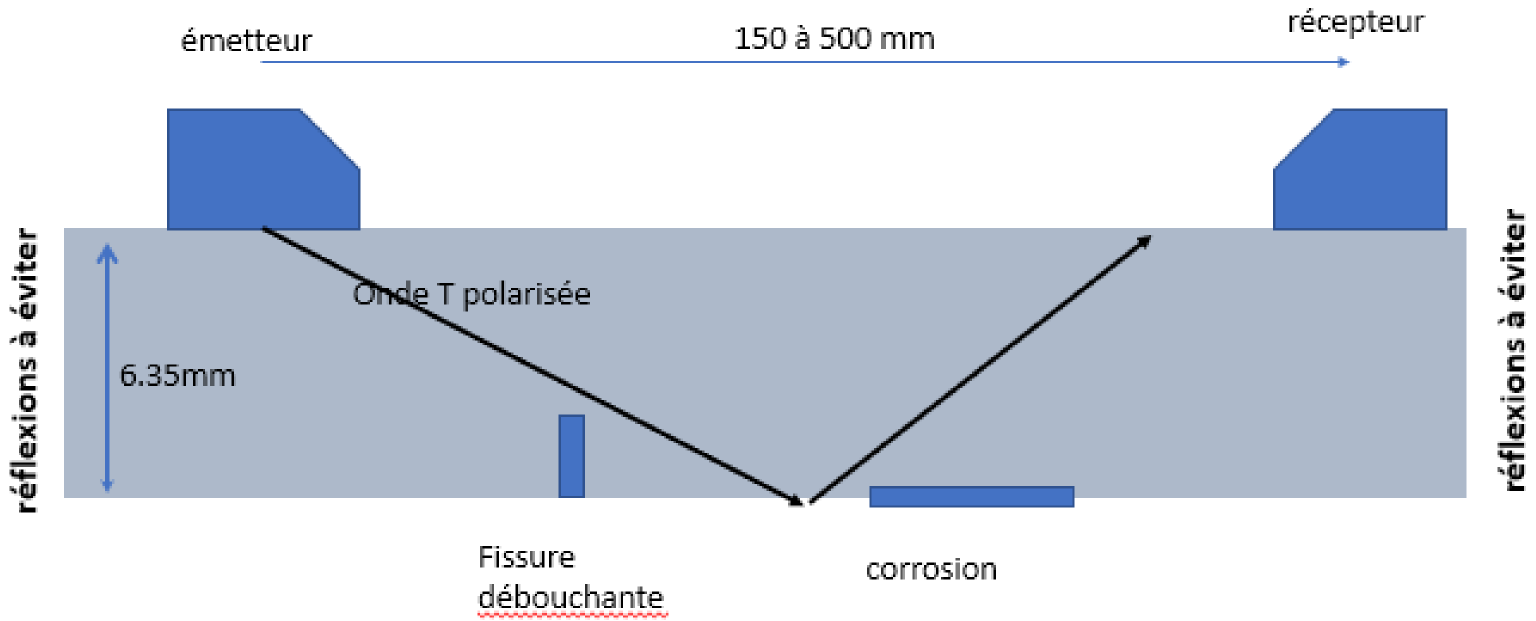
2.0 Typical workflow of an ultrasonic inspection

PHASE 0 (preparation): machining or generation of the component to inspect

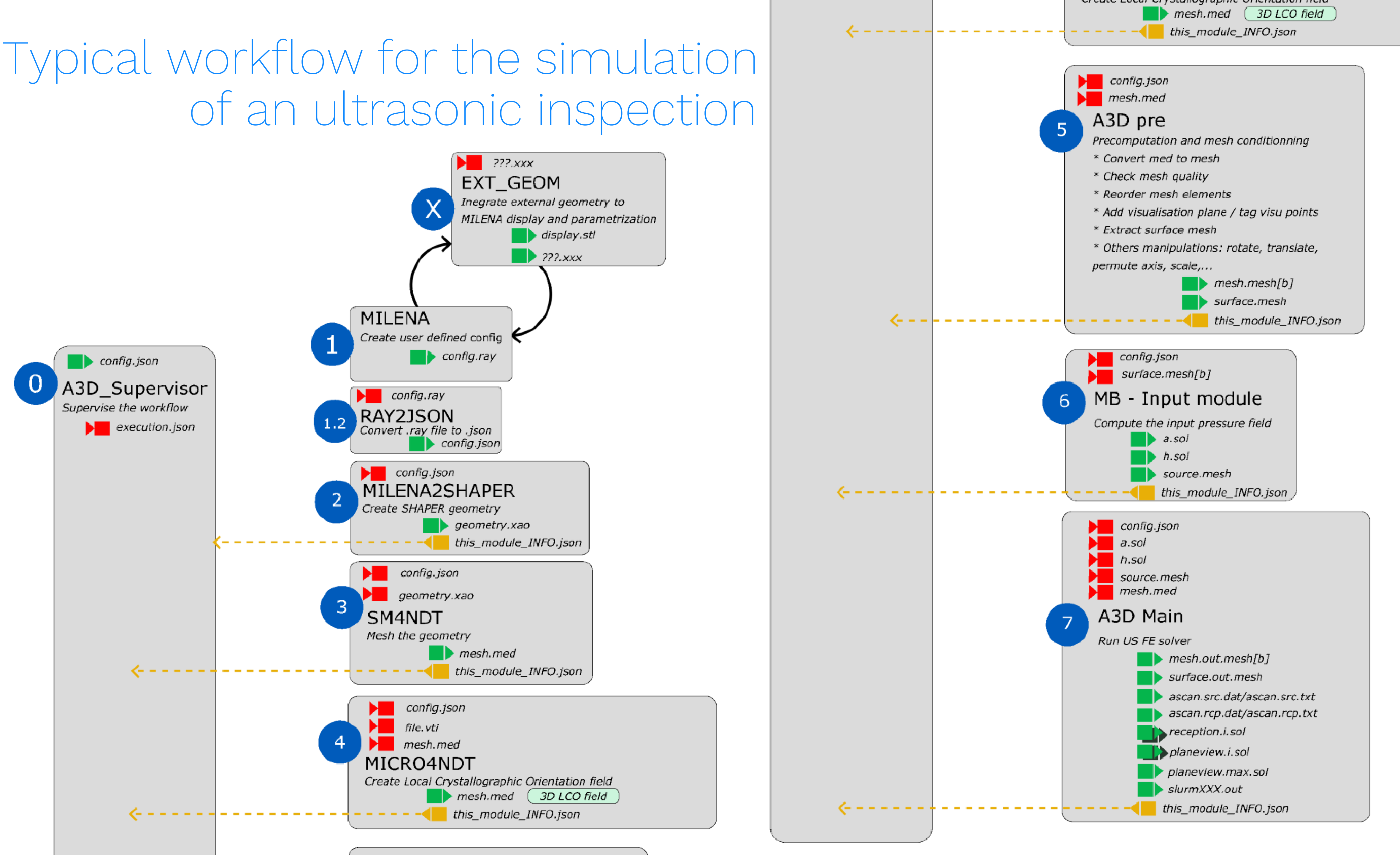
PHASE 1 (emission): creation of an ultrasonic signal and propagating it up to the boundary of the object to inspect

PHASE 2 (inspection): propagate the signal inside the material with complex properties and arbitrary geometry

PHASE 3 (reception): recording the part of the signal that will propagate up to the sensors (A-Scan).



2.0 Typical workflow for the simulation of an ultrasonic inspection

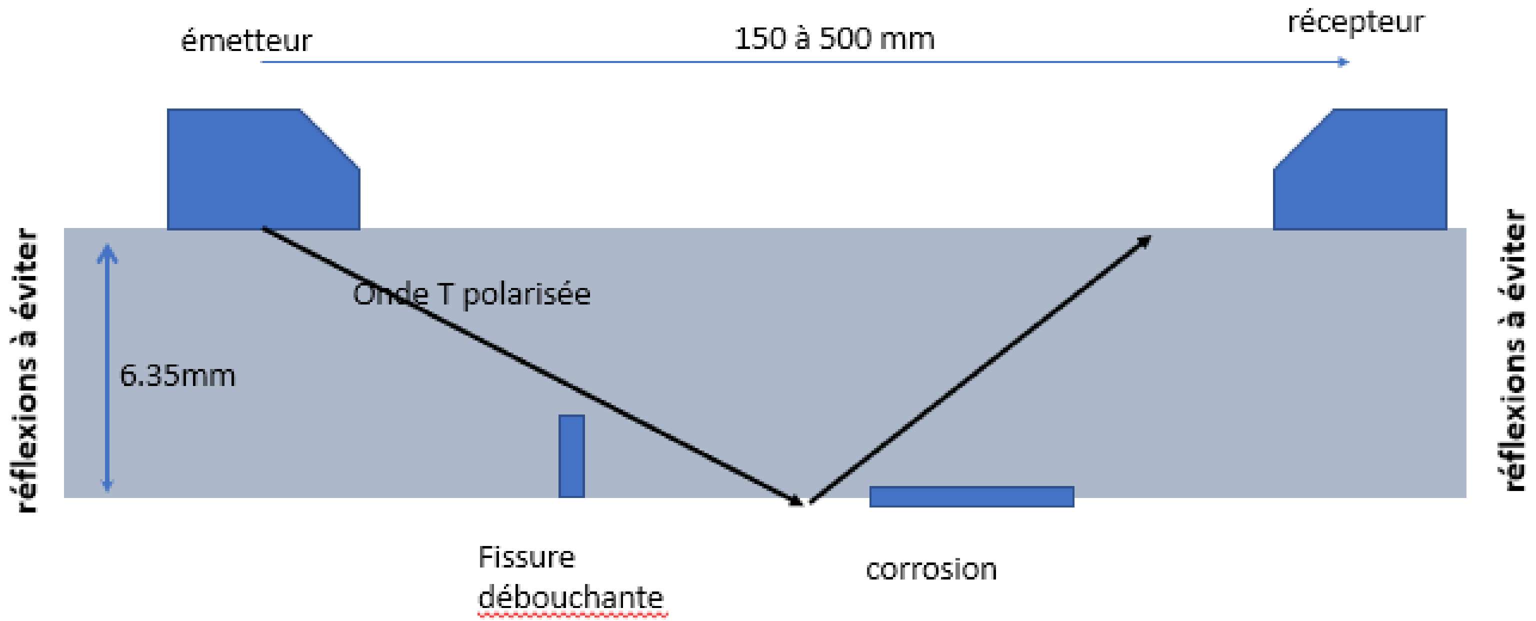


2.1 The physical constraint

The **size** of the defect one aims to detect **determine** the minimal **frequency** of the incident wave sent by the emission sensor:

- frequency_minimal = speed_waveP_steel / 2 size_defect.

Example: A **defect of 1 mm** imposes a central **frequency of 6 MHz** (with 50% bandwidth) for the emission sensor.



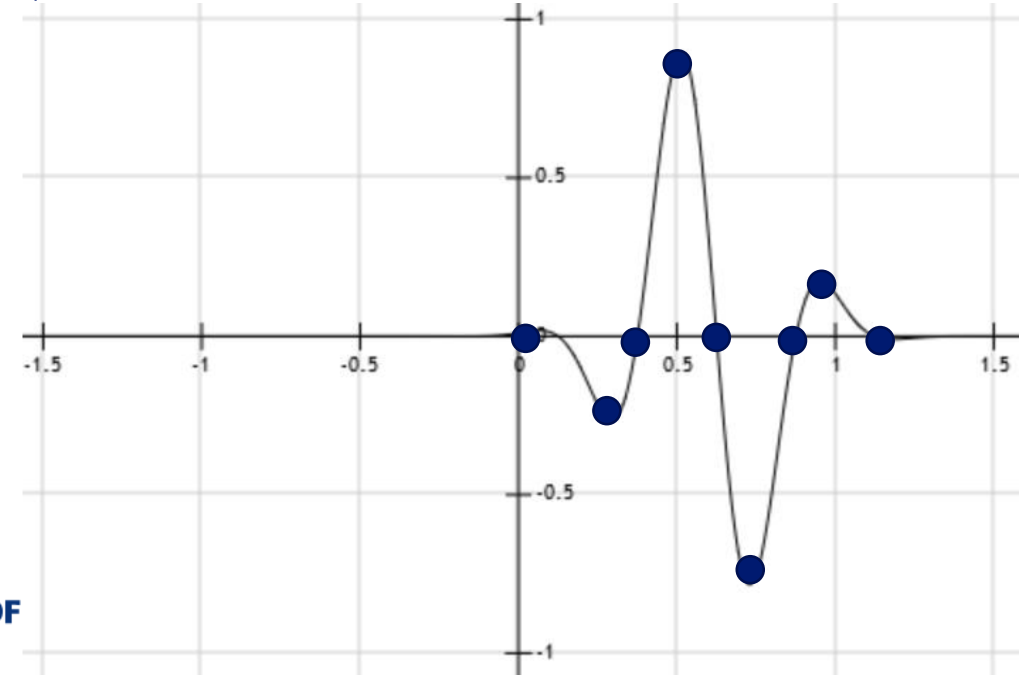
2.2 The spatial numerical discretization constraint

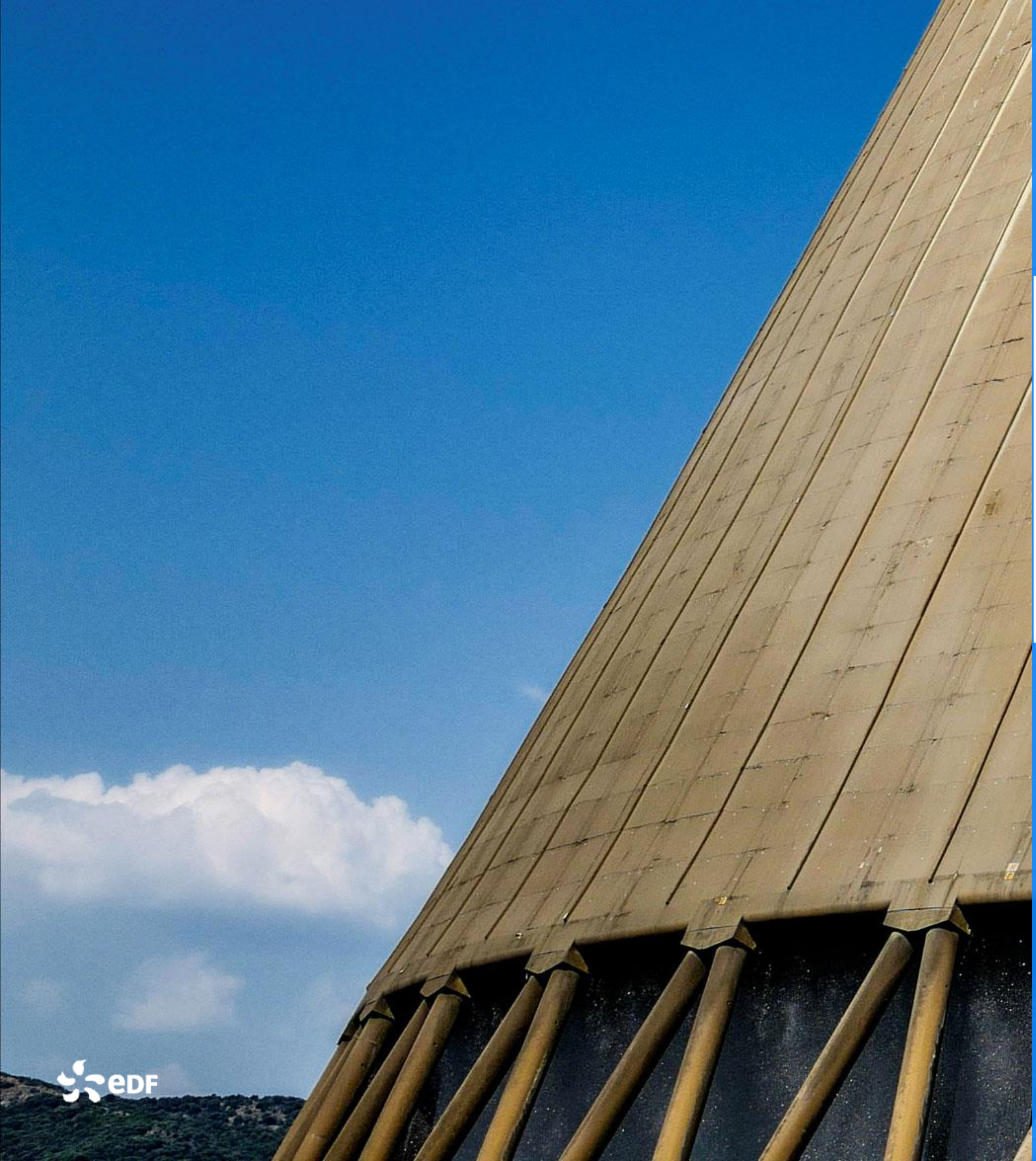
Spatial discretization must correctly approximate the incident waves.

The **frequency** of the incident wave **determine** the **maximal edge length** possible inside the mesh:

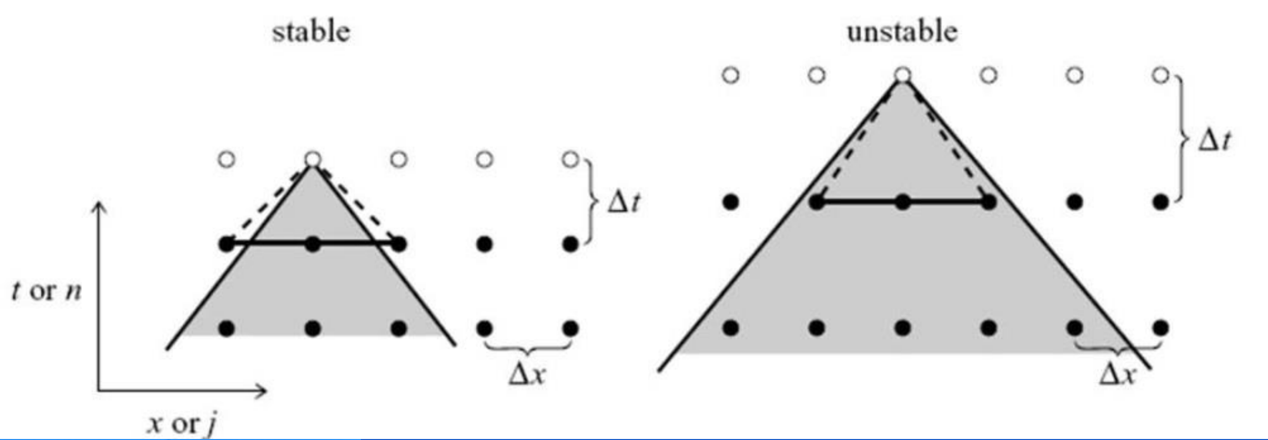
- Length_max = speed_wave / 12 frequency_max

<u>Example:</u> 60 micrometers maximum for 6 MHz.





2.3 The time discretization numerical constraint

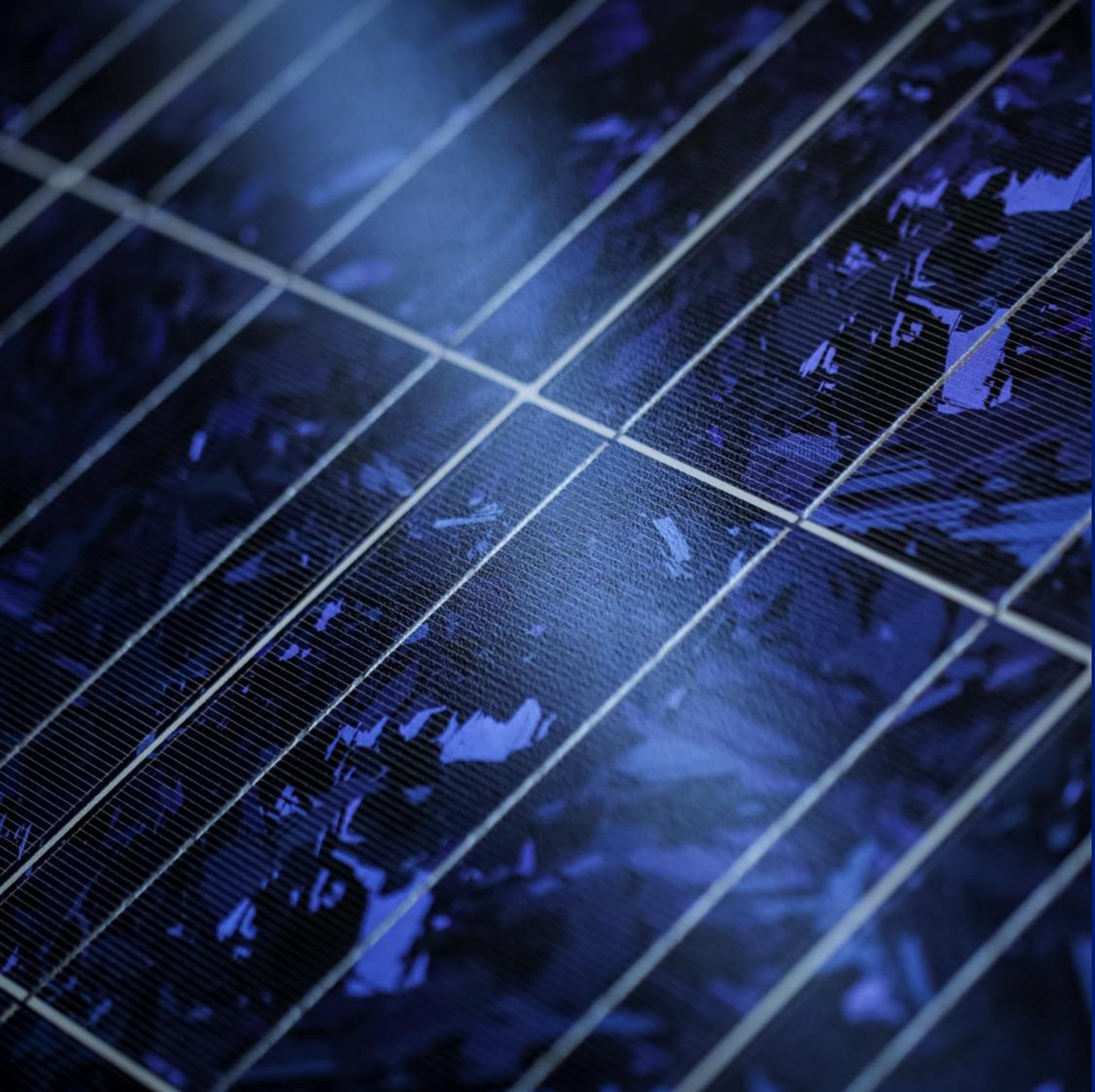


<u>Condition CFL (Courant-Friedrich-Levy):</u> roughly speaking, the time necessary for any physical wave to travel over one tetrahedra in the worst case cannot be lower than the numerical time step.

The **minimal edge length** possible inside the mesh **determine** the maximal **time step**:

- Time_step_max = 0.5 length_min / speed_waveP_steel.

<u>Example:</u> 2 ns for 10 micrometers.



Engineer: can you simulate on a (10cm)x(10cm)x(5cm) grid the propagation of an incident wave of 5MHz?

Numerician: yes, but that implies a space discretization step of 50 micrometers, hence a mesh of 24 billions of tetraedra (and 4 billions of nodes) for 5000 iterations of 8 ns.

About the number of tetraedra:

- Coarse mesh: 400 millions
- Usual mesh: **1 milliard**
- Fine mesh: 10 milliards

Software development choice:

- Re-**implementation** ex-nihilo
- A solution using code_aster

Bet made on the solver A3D-CND:

- **P1** –finite element for space discretization, **explicit** Euler scheme for the time discretization
- Parallelization with **OpenMP** of the time loop.

$$\begin{cases} U_{m+1} = U_m + \Delta t\, \dot{U}_m \\ \dot{U}_{m+1} = \dot{U}_m + \Delta t\, M^{-1} \left[G_{m+1} \; + \; F_{m+1} \; - \; K\, U_{m+1} \right]. \end{cases}$$

$$\nabla \cdot \boldsymbol{\sigma} + \mathbf{f} = \rho \ddot{\mathbf{u}},$$

$$\varepsilon = \frac{1}{2} \left[\nabla \mathbf{u} + (\nabla \mathbf{u})^T \right],$$

$$\boldsymbol{\sigma} = C : \varepsilon,$$

$$\boldsymbol{\sigma} \cdot \mathbf{n} = \mathbf{g};$$

$$\mathbf{u}(\bullet, 0) = 0 \quad \text{and} \quad \dot{\mathbf{u}}(\bullet, 0) = 0,$$

3

Results

Two typical studies are considered for qualitative results:

- Simulate for a potentially little defect (7 MHz) on a complex geometry (crew) with homogeneous **isotropic** material.
- Simulate for potentially **coarser defects** (2 MHz) on granular objects (weld) with simple geometry but highly **heterogeneous** and/or **anisotropic** material.

3.1 Results obtained for a crew in 2021

≠

Mesh of a screw with specifications (23,8mm)x(23,8mm)x(69,55mm):

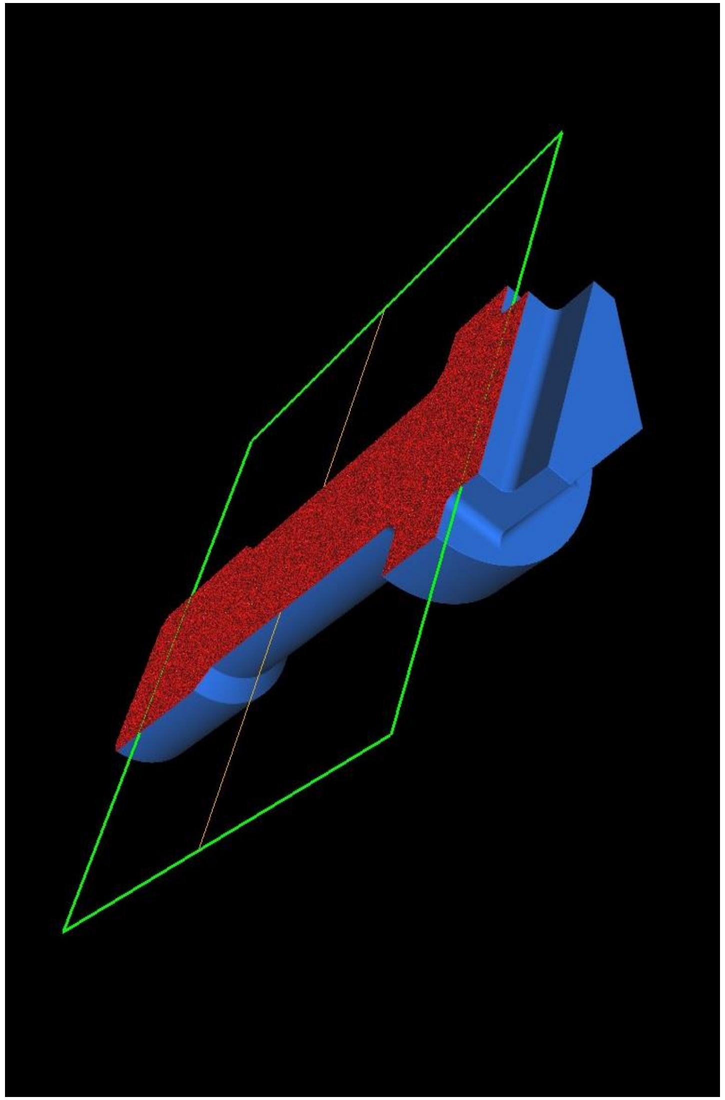
- Nb nodes (= nb dof) ~ 40 millions
- Nb tetra ~ 225 millions
- Nb coef ≠0 matrix ~ 570 millions

Length of edges in the mesh:

- Minimal = 26 micrometers
- Mean = 84 micrometers
- Maximal = 153 micrometers

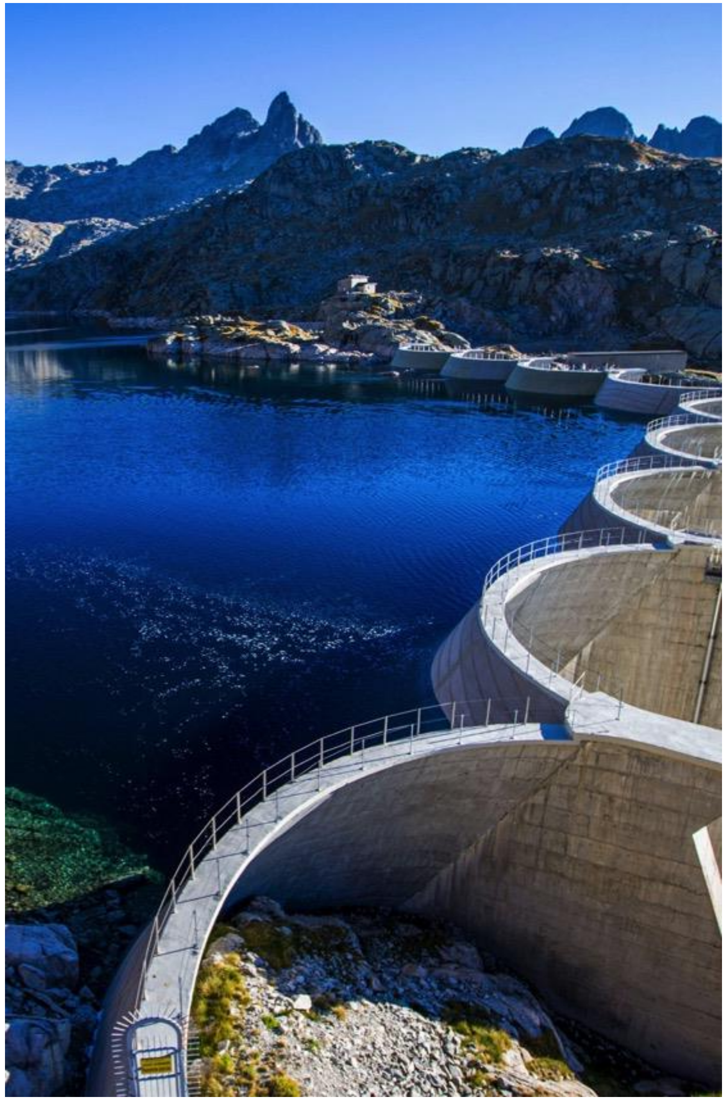
Numerical constraints:

- Central frequency < 4,2 MHz
- Time step < 4,4 ns
- Defect size ~ 1 mm

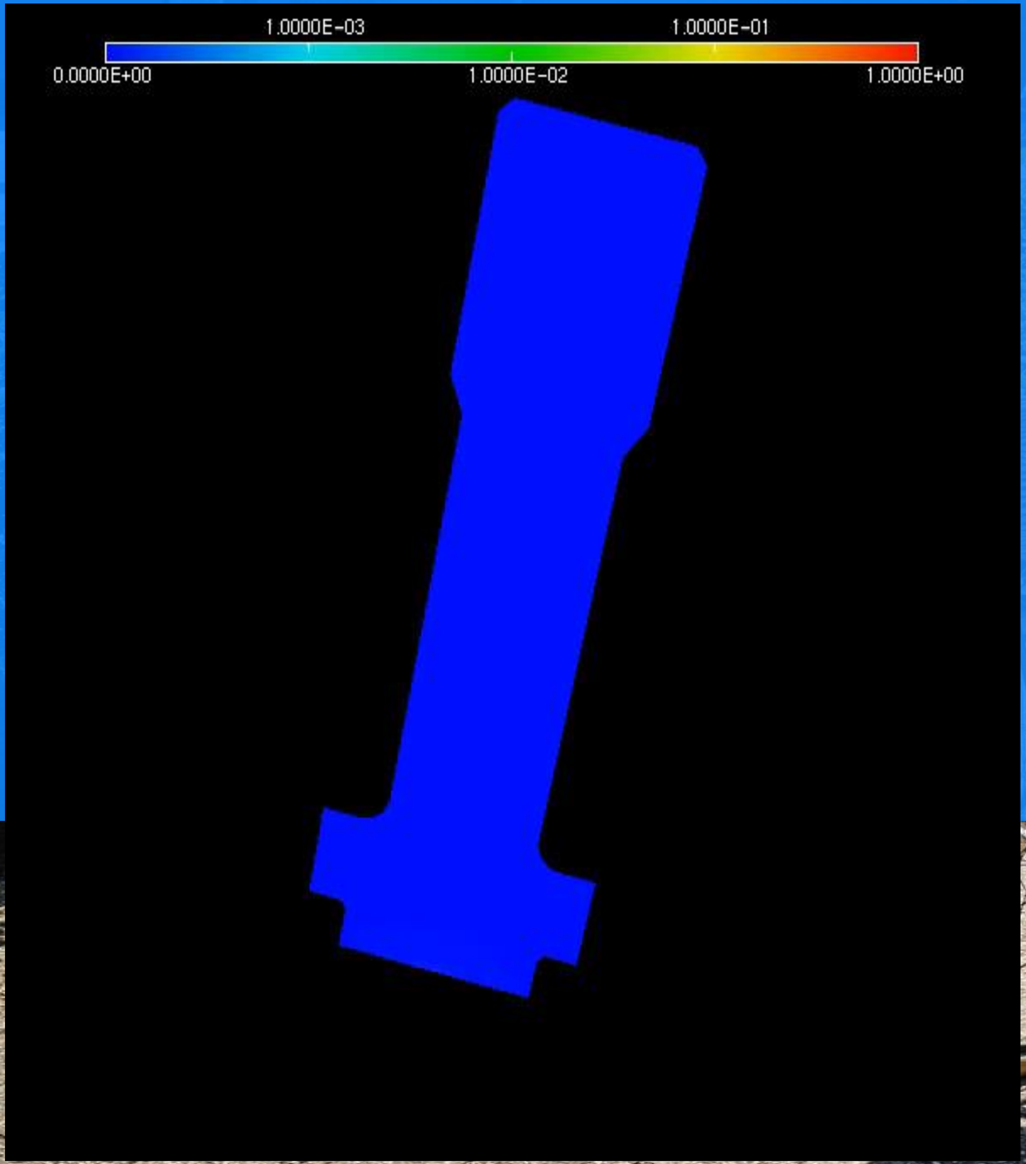


- Central frequency used for the emission: 4 MHz
- Source used: punctual and inclinated
- Sampling frequency: 500 MHz

- RAM used : 60 GB
- Standard node (cn) onthe old cluster with 28 cpus
- Computational time: 2h53 = 27 min (initialization) + 4 000 iter x 2,19 sec



Norm of the velocity inside a plane cut of the screw



3.2 Results obtained for a three-pass weld in 2022

≠

Mesh of an anisotropic heterogeneous grid (14mm)x(10mm)x(10mm):

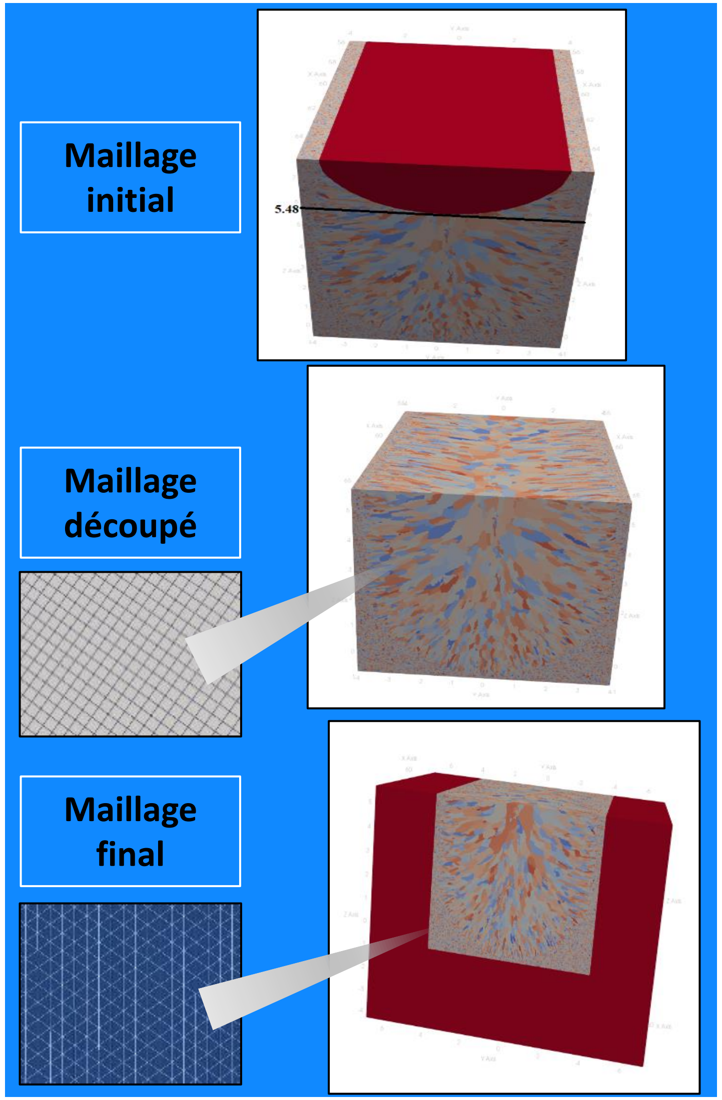
- Nb nodes (=nb dof) ~ 175 millions
- Nb tetra ~ 1 billion
- Nb coef ≠0 matrix ~ 2.5 billions

Length of edges in the mesh:

- Minimal=20 micrometers
- Mean=26 micrometers
- Maximal=35 micrometers

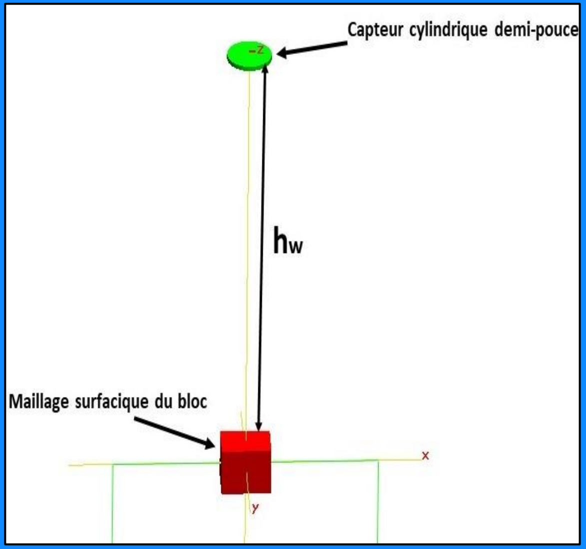
Numerical constraints:

- Source frequency < 4.8 MHz
- Time step < 3,3 ns
- Taille défaut ~ 1 mm



- Different frequencies used for a sensor in immersion
- Time of the simulation: 6,4 µs
- Sampling frequency: 625 MHz

- RAM used : 340 GB
- Big memory node (bm) on the new cluster with 24 cpus
- Computation time: 5h30 (4 000 iterations)



$f_{cen}\ (MHz)$	$h_w\ (mm)$
2	90
5	160
7.5	250

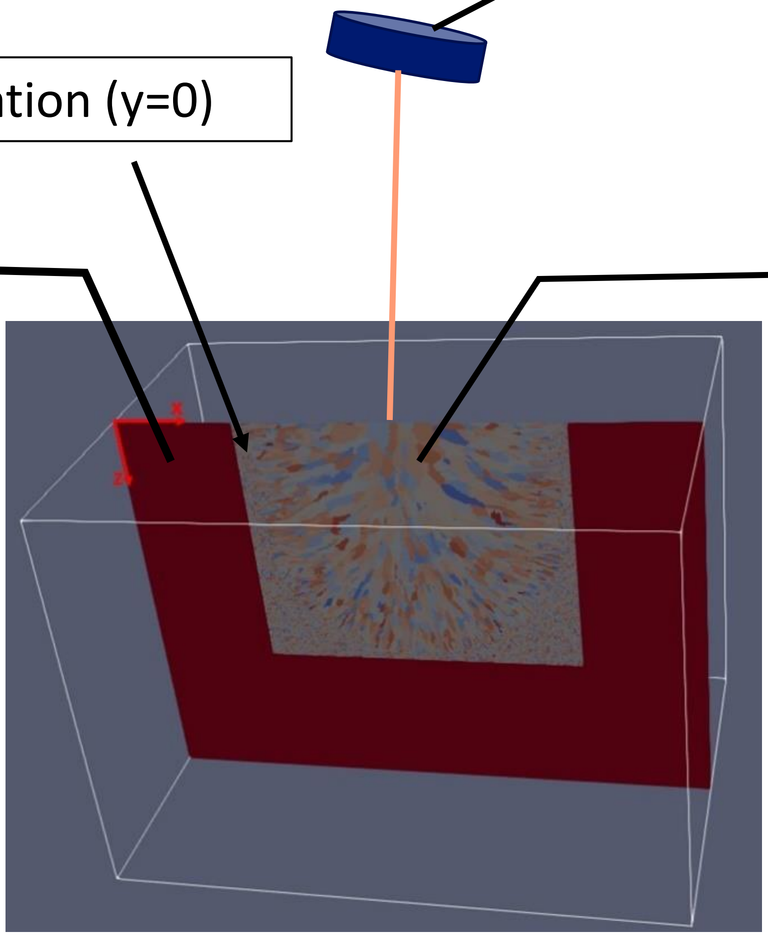
Configuration of the NEMESIS simulation

US sensor
Type : cylindrical
Incidence : normal (i=0°)
Coupling media : immersion in water
Dimension :12,7 mm (demi-inch)

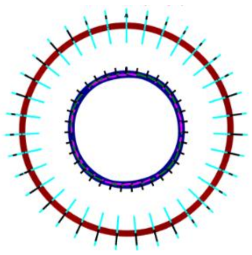
Vizualization plane (Oxz) of equation (y=0)

Homogeneous isotropic zone
Material = ferritic steel

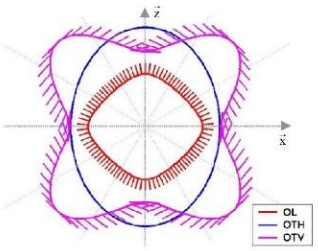
CAFE zone
Material = Austenite (single crystal)



268	107	107			
	268	107			
		268			
			80		
				80	
					80



rho = 7700, V_L= 5900, V_T = 3230

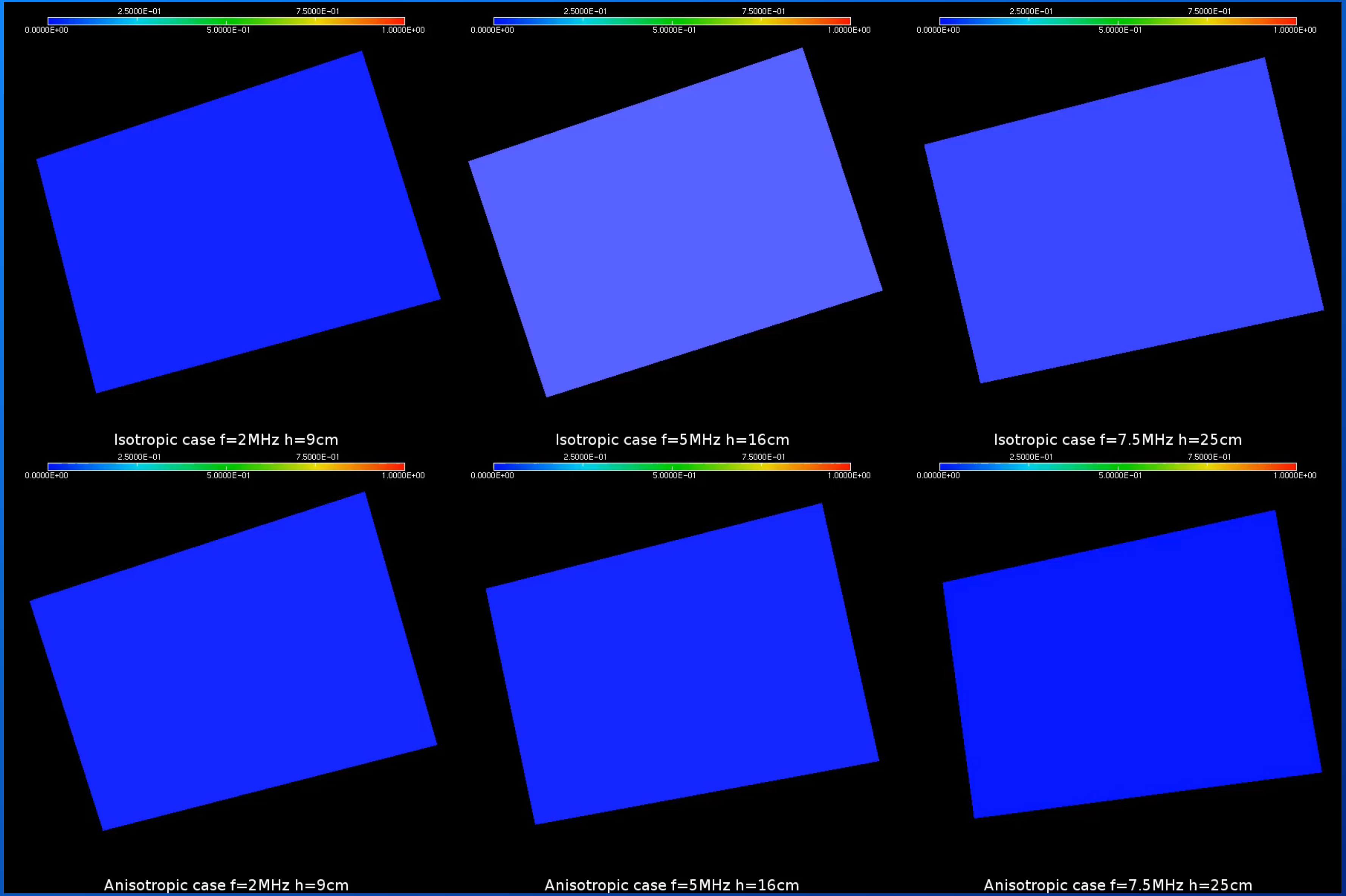


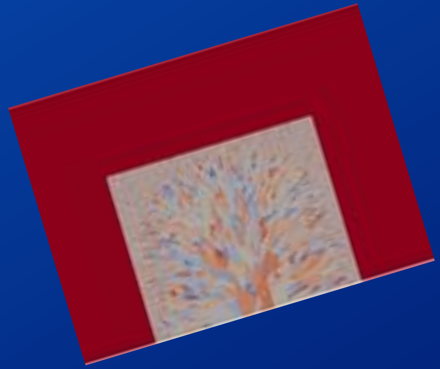
206	133	133			
	206	133			
		206			
			119		
				119	
					119

rho = 7925, V_{Lmax} = 6184, V_{Tmin} = 2292

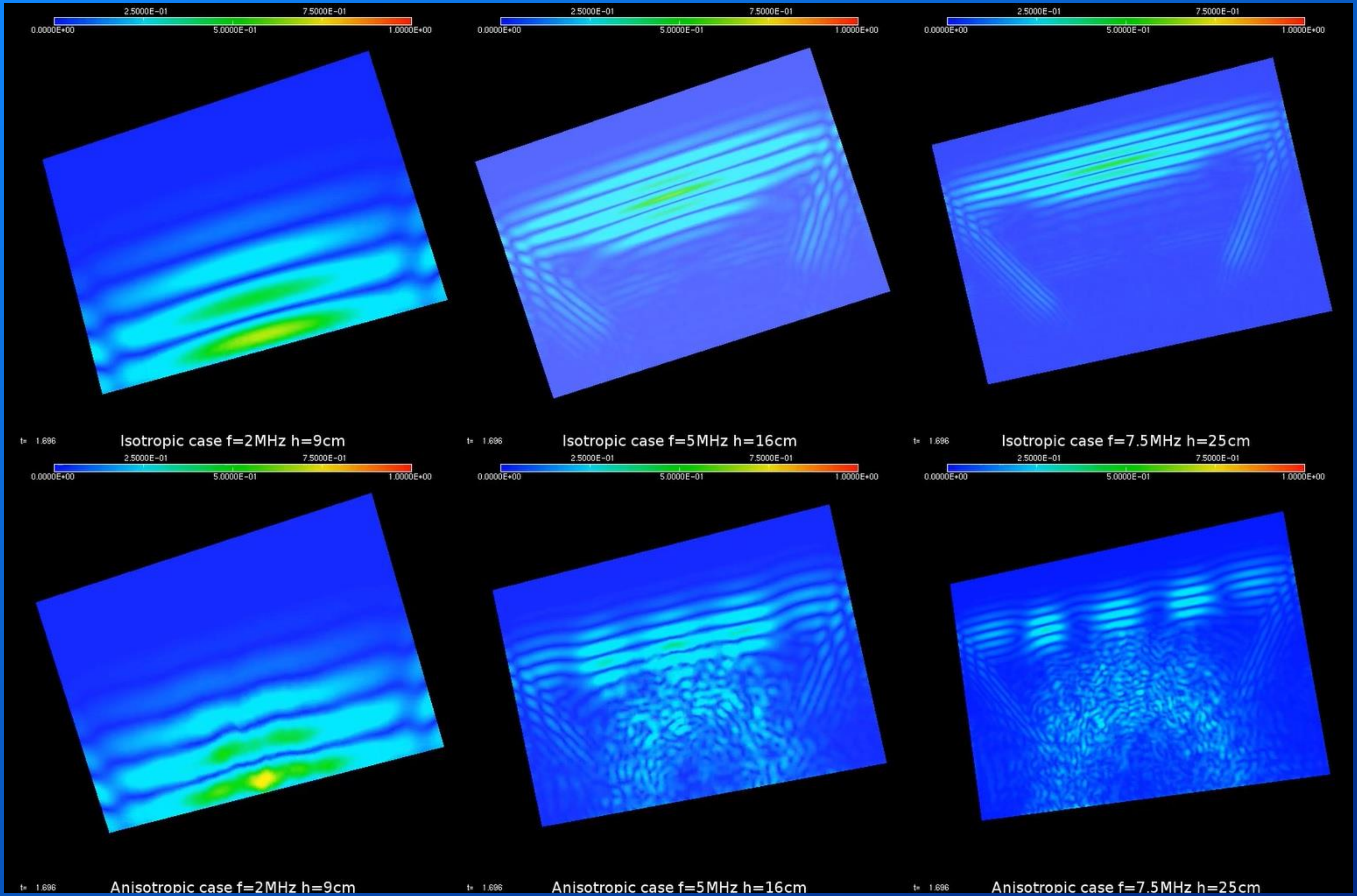
+ 3 Euler angles for each grain (x 3 000 000 grains)

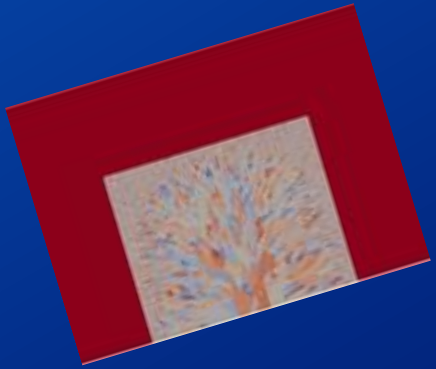
Norm of the velocity in the visualization plane for different frequencies





Norm of the velocity in the visualization plane for different frequencies at t=1,7μs





Merci