Special Interest Group Meeting : Quality Control for Additive Manufacturing
23rd – 24th January 2017


euspen

# Non-destructive volumetric control of additive manufactured parts: alternatives methods to X-ray tomography

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- **Assessment of the potential of…**
  - ✓ …density and percentage of lattice cell measurements…
  - ✓ …Eddy currents…
  - ✓ …ultrasound techniques…
  - ✓ …terahertz waves…

**…to characterize AM parts**

- **LNE projects on AM:**
  - ✓ PhD thesis: On line control using laser ultrasound
  - ✓ National project: Quality control on industrial AM parts
  - ✓ European project: Metrology for AM medical implants

## Assessment of the potential of density and percentage of lattice cell measurements to characterize AM parts:

- Archimedes' method
- Gas pycnometric method

## Assessment of the potential of density and percentage of lattice cell measurements to characterize AM parts:

- Archimedes' method
-

# Archimedes' method

**Equipment:**

**Balance: 400 g max, 0,1 mg resolution**

**Container: filled with liquid placed beneath the balance**

**Suspension device: immersed in the liquid and hung beneath the weighing pan.**

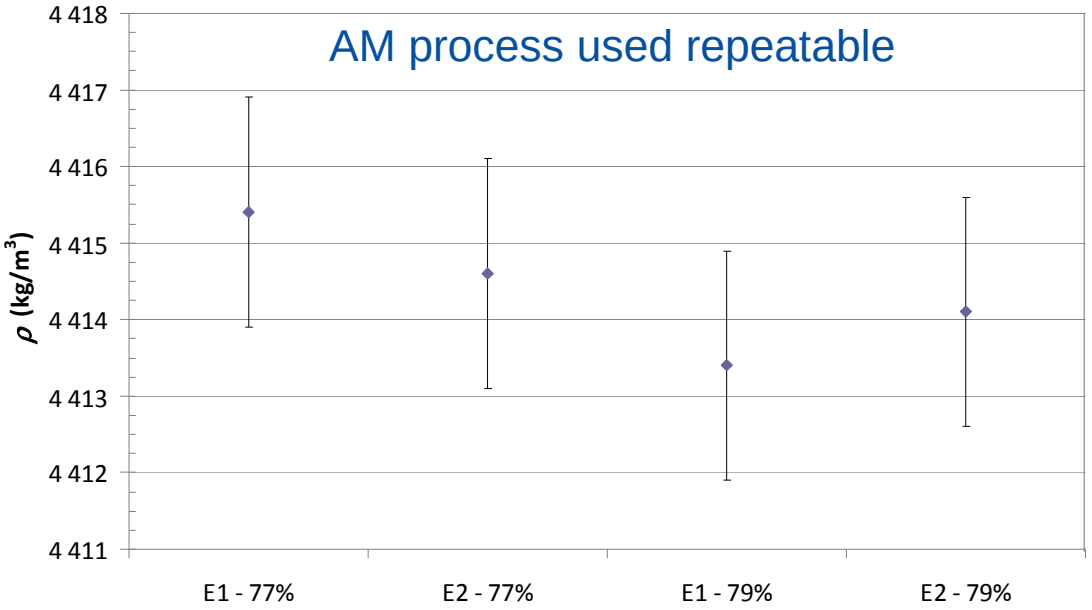
**Protocol**

1. Measurement of the apparent mass ($m_1$) in air
2. Measurement of the apparent mass ($m_2$) in twice –distilled water for dense parts or in absolute ethanol for lattice structures
3. Calculation of the density:

$$\rho = \frac{m_1}{m_1 - m_2}\left(\rho_{air} - \rho_{liquid}\right) + \rho_{liquid}$$

# Density and percentage of lattice cell measurements of dense structures

**Analysis of two different (77 % and 79% porosity) AM titanium lattice structure specimens**




**Measurements performed by E. Mahé and P. Jeanjacquot from LNE**

## Benefits of the method for AM:

- Density measurement
- Percentage of lattice cell measurement
- Compliance verification with part specifications
- Characterisation of lattice structures
- Material characterisation (internal porosity quantification)
- Part repeatability/reproducibility (part comparison)

**Limitation: long measurement**

## Assessment of the potential of density and percentage of lattice cell measurements to characterize AM parts:

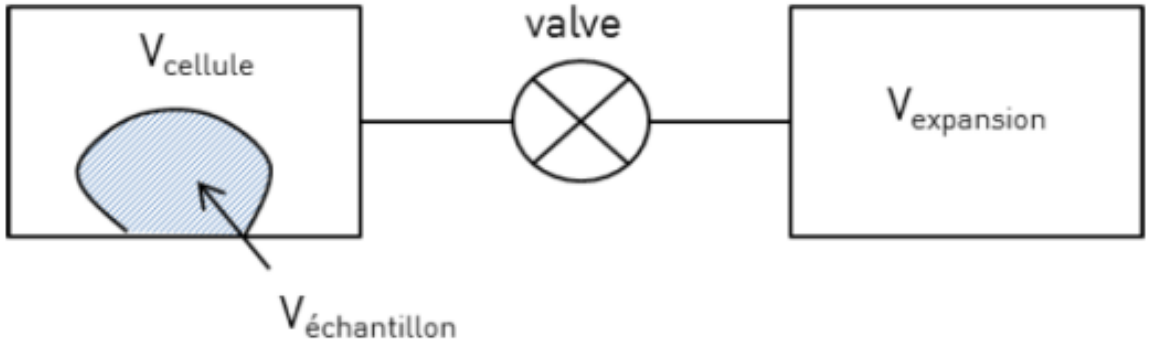
- 
- **Gas pycnometric method**

# Gas pycnometric method

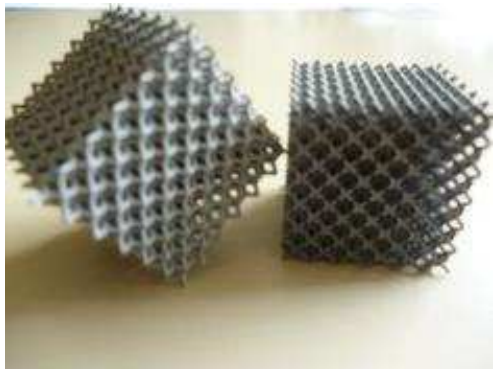
## Protocol

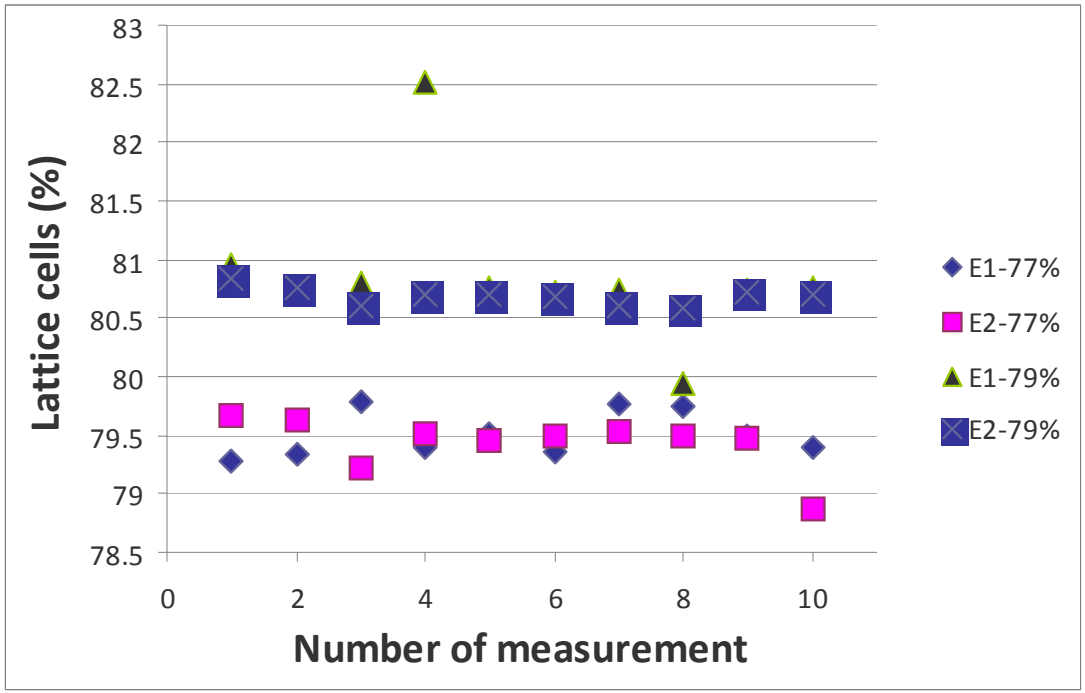
1. Measurement of the apparent mass (*m*) in air
2. Increase of the pression from $P_{atm}$ to $P_1$ in the cell where the sample is placed
3. Opening of the expansion cell until equilibrium
4. New measurement of the pression $P_2$ in the cell where the sample is placed
5. Density calculation:

$$\rho = \frac{m}{V_{cellule} - V_{expansion}\left(\frac{P_2 - P_{atm}}{P_2 - P_1}\right)}$$



# Density and percentage of lattice cell measurements of dense structures






**Measurements performed by Dr. C. Cayron from LNE**

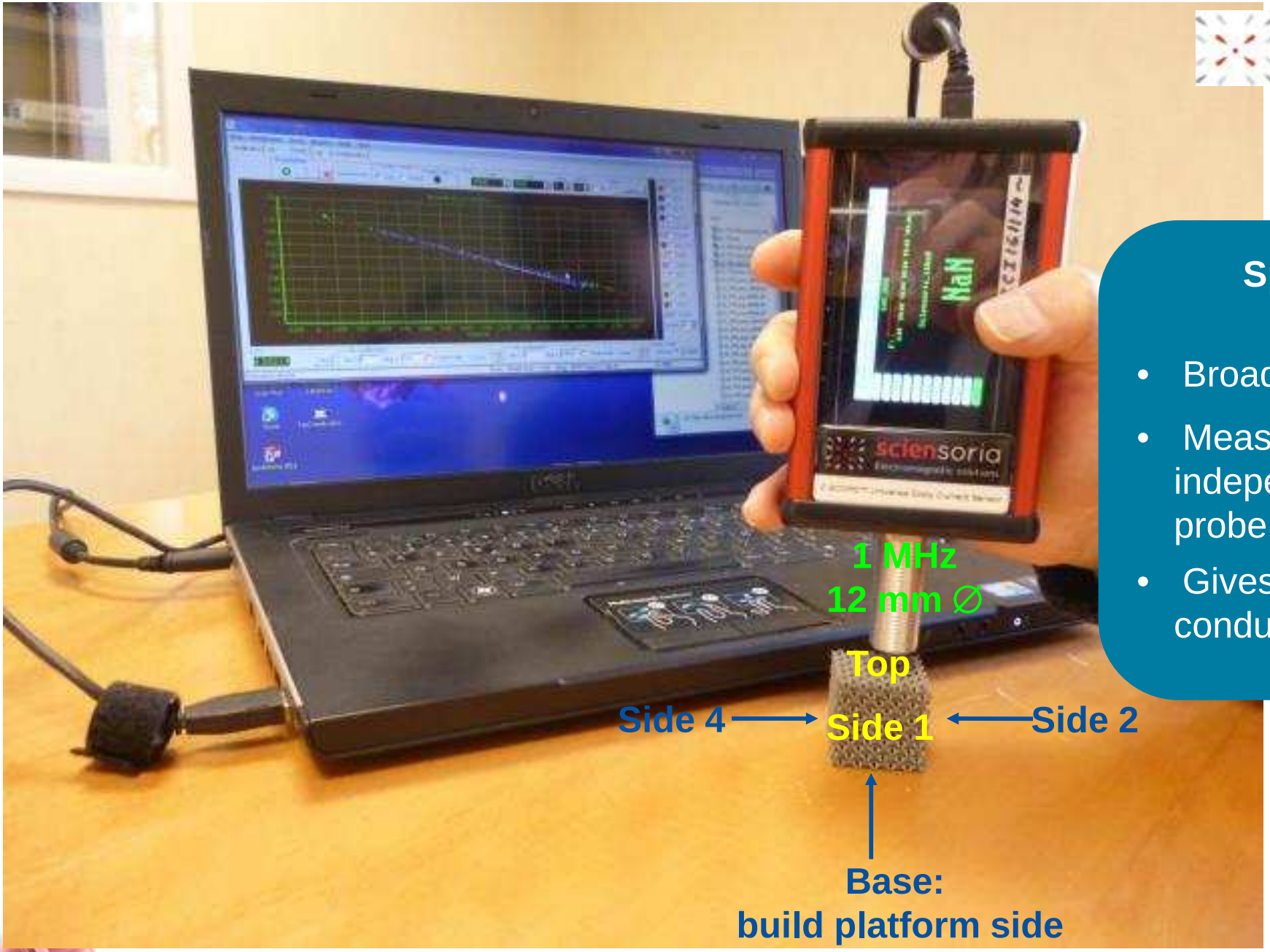
## Benefits of the method for AM:

- Density measurement
- Percentage of lattice cell measurement
- Compliance verification with part specifications
- Characterisation of lattice structures
- Material characterisation (internal porosity quantification)
- Part repeatability/reproducibility (part comparison)
- Fast measurement, convenient for routine control

**Limitation: less accurate than Archimedes' method**

# Assessment of the potential of Eddy currents to characterize AM parts

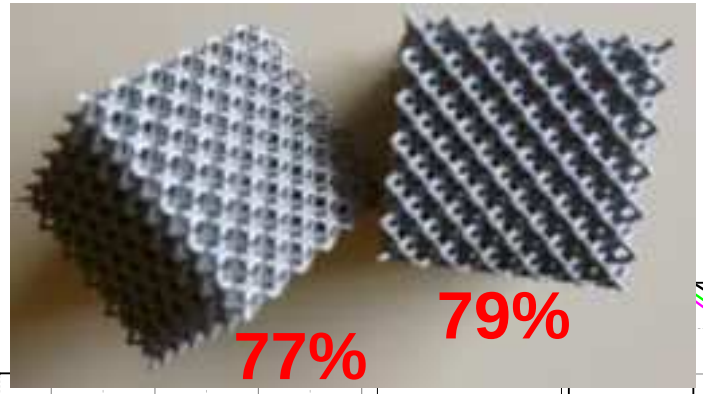
# Innovative Eddy current method

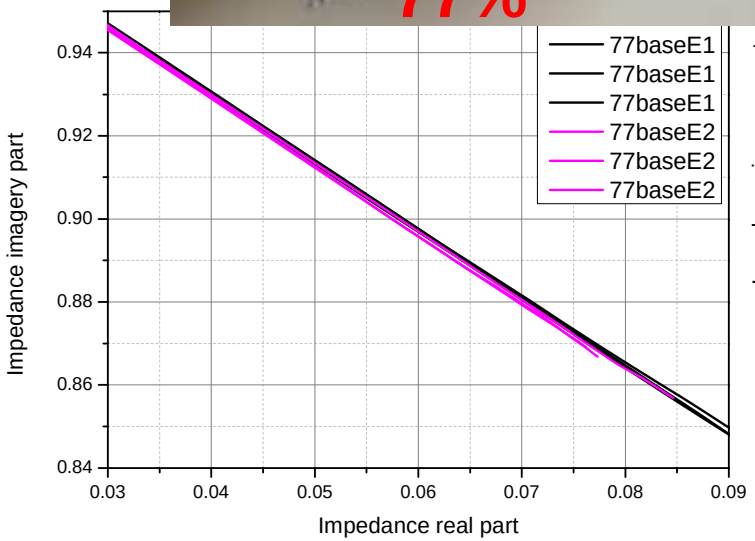



## Specificities

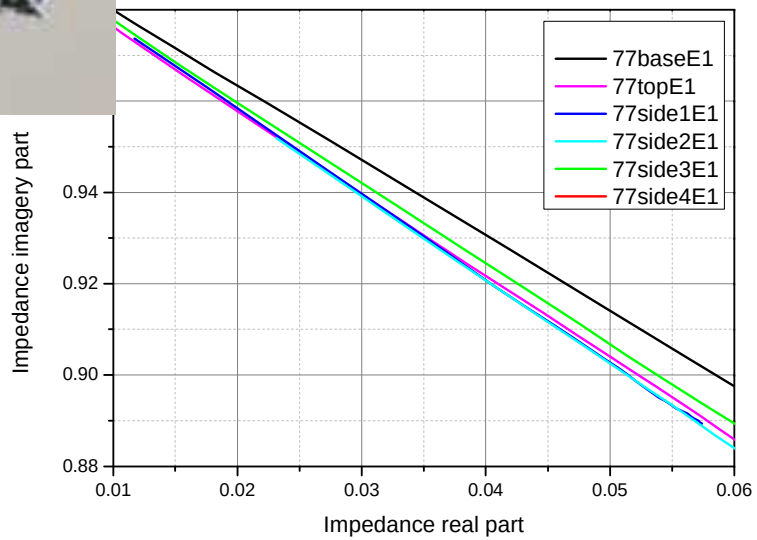
- Broadband system
- Measurements independent of the probe position
- Gives the electrical conductivity

# Electrical conductivity measurements of lattice structures

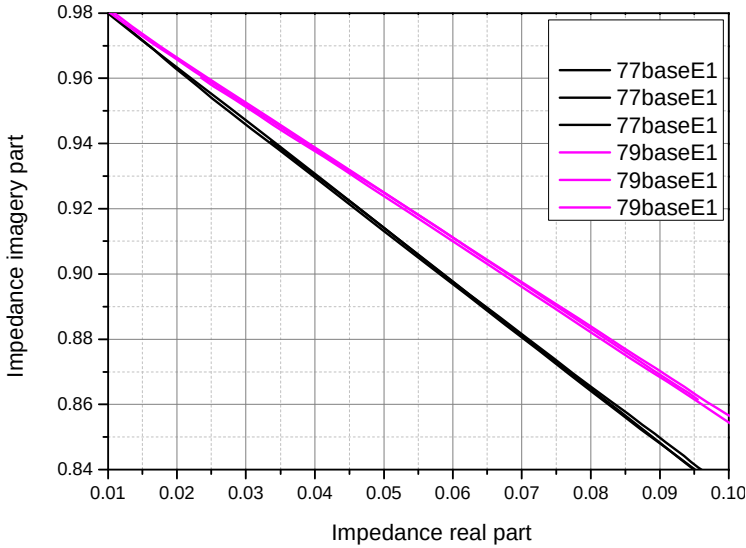



AM process used repeatable




Enables to differentiate 2 surface conditions




Enables to differentiate 2 lattice structures by their pore sizes

**Measurements performed by Dr. Minh-Quang LÊ from Sciensoria (sciensoria@gmail.com)**

## Benefits of the method for AM:

- **Electrical conductivity measurement**
- **Characterisation of lattice structures**
- **Part repeatability/reproducibility (part comparison)**
- **Fast measurement, convenient for routine control**
- **Complementary to ultrasound methods**

**Limitation: sub-surface characterisation**

**Assessment of the potential of ultrasound techniques to characterize AM parts:**

- **Resonant Ultrasound Spectroscopy (RUS)**
- **C-Scan high frequency ultrasound**

## Assessment of the potential of ultrasound techniques to characterize AM parts:

- Resonant Ultrasound Spectroscopy (RUS)
-

# Elasticity parameter measurement methods

**Destructive testing**
**High volum specimens**

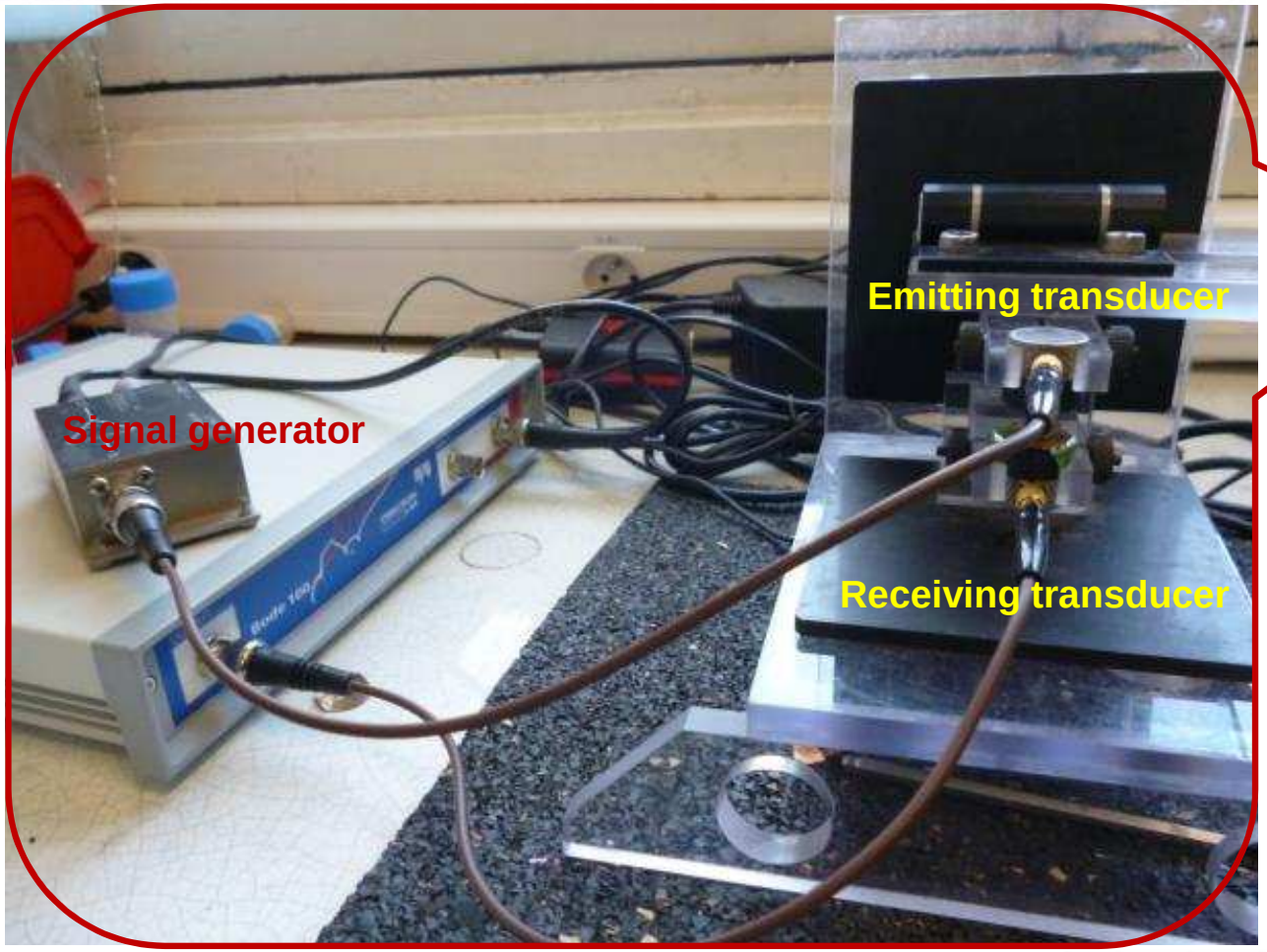
- **Traction tests** → **Stress strain curves** → **Isotropic elasticity** → **Young's modulus**, **Poisson's ratio**
- **Shear tests** → **Shear Modulus**

- **Classical RUS** → **Free resonant frequencies** → **Anisotropic elasticity** → **Young's modulus**, **Poisson's ratio**, **Shear Modulus**, **Damping**

**Complex method**

RUS: Resonant Ultrasound Spectroscopy

# Innovative Resonant Ultrasound Spectroscopy (RUS) method



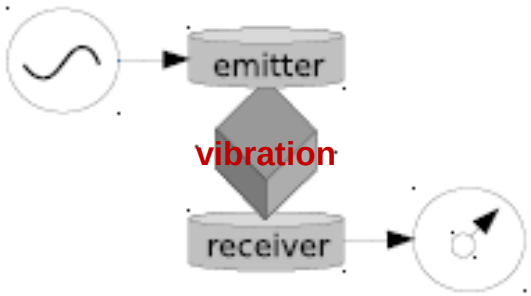

UMR-S 1146 / UMR 7371

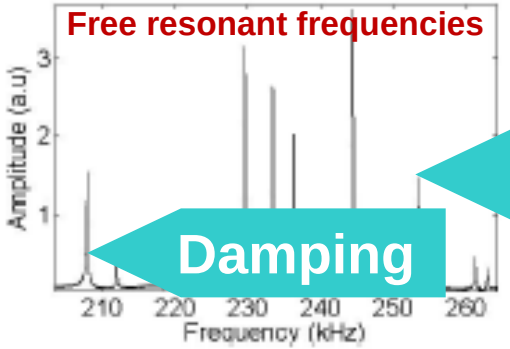
**Non-destructive testing**
**Low volum specimens**
**Easy to use method**

## Specificities

- Shear broadband (5kHz-1MHz) transducers (instead of longitudinal transducers)
- Automation of the determination of anisotropic elastic constants based on the resonance peaks (Bayesian inverse problem)

**US excitation with piezoceramic elements polarized in compression and suspended to copper thin films**



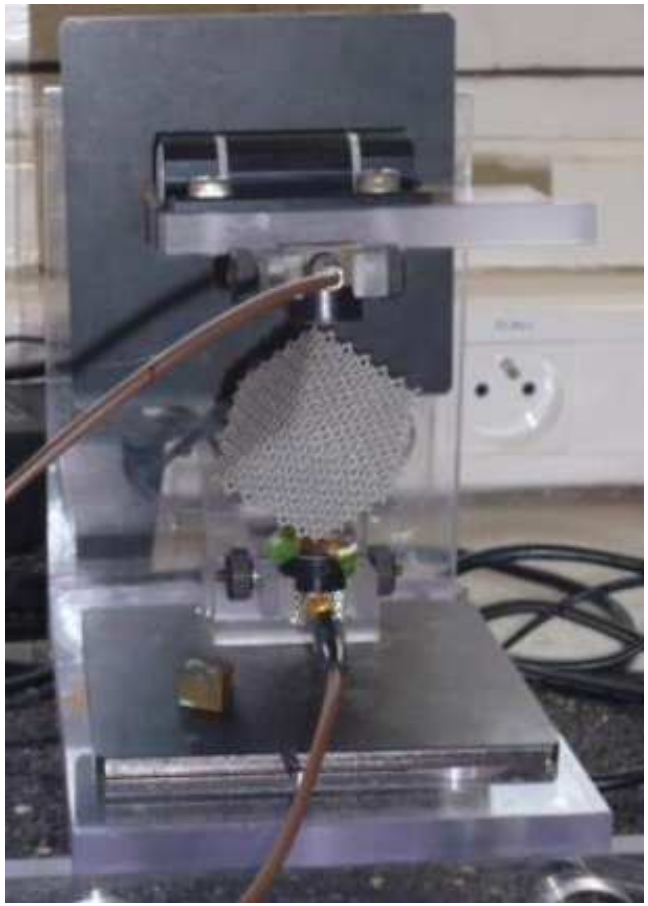



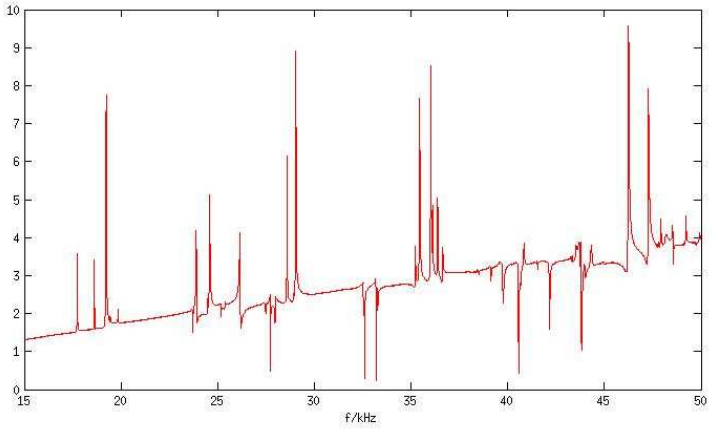

**Damping**

**Poisson's ratio**
**Young's modulus**
**Shear Modulus**

# Elasticity parameter measurements

## Comparison of pore sizes in lattice structures






| | Shear modulus (GPa) |
|---|---|
| E1 - 77% | 1.32 |
| E2 - 77% | 1.31 |
| E1 - 79% | 1.12 |
| E2 - 79% | 1.12 |

16% variation of the shear modulus between the two specimens

**LIB measurements (contact: pascal.dargent@upmc.fr)**

**Benefits of the method for AM:**

- **Elasticity parameter measurement**
- **Non-destructive mechanical characterisation (reusable part)**
- **Low volum speciment needed**
- **Part repeatability/reproducibility (part comparison)**
- **Easy to use for routine control**

## Assessment of the potential of ultrasound techniques to characterize AM parts:

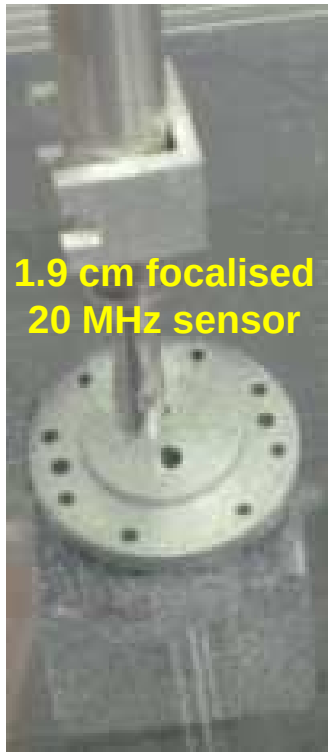
- 
- **C-Scan high frequency ultrasound**

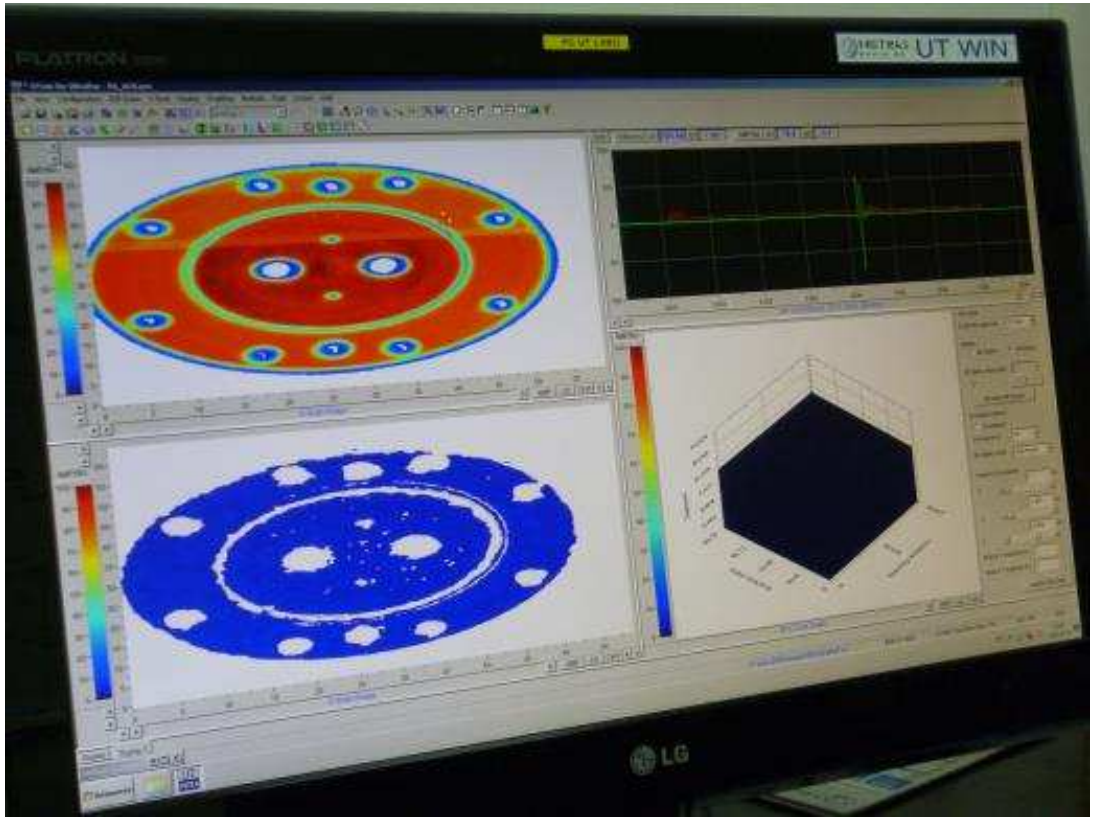
# C-Scan high frequency ultrasound set-up

**Specificities**

- Emission and reception card adapted to the sensor
- Adaptive system to the needs, applications and conditions

# C-Scan high frequency ultrasound measurements



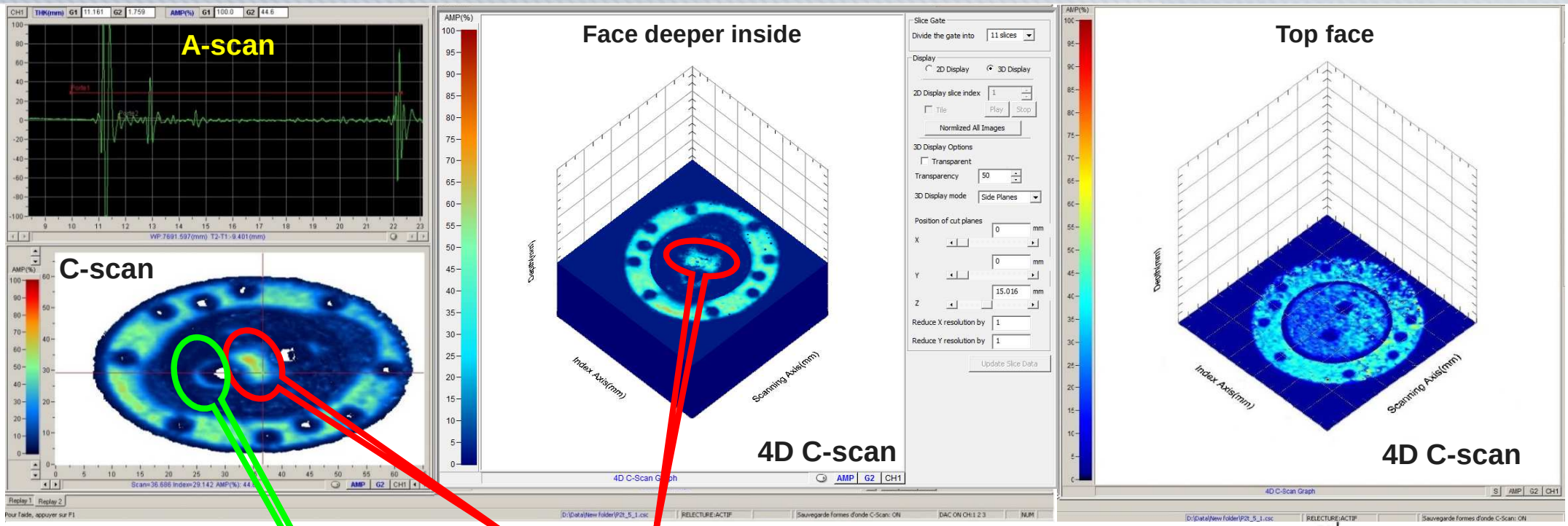






**AM Al 6061 parts**

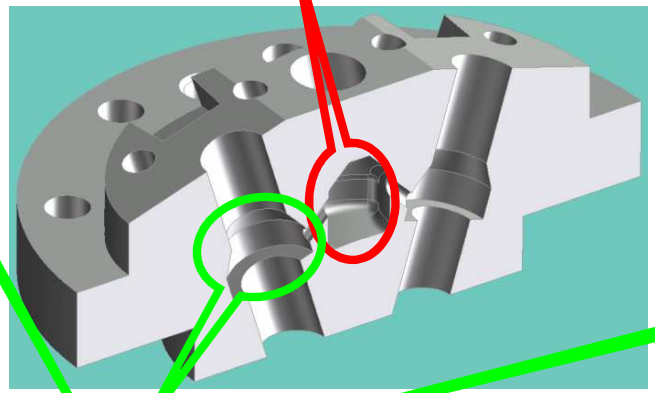
**Measurements performed by V. Prezza, P. Delvart and D. Marlot from Eurosonic-Mistras (dmarlot@mistrasgroup.eu)**

# Volumetric ultrasound views for two different depths

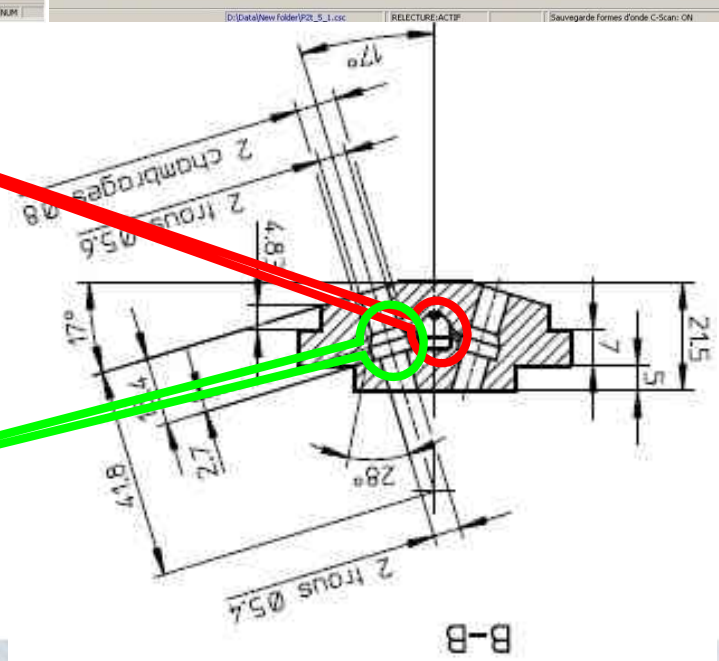



Internal cavity

Bottom,
relative to the scan



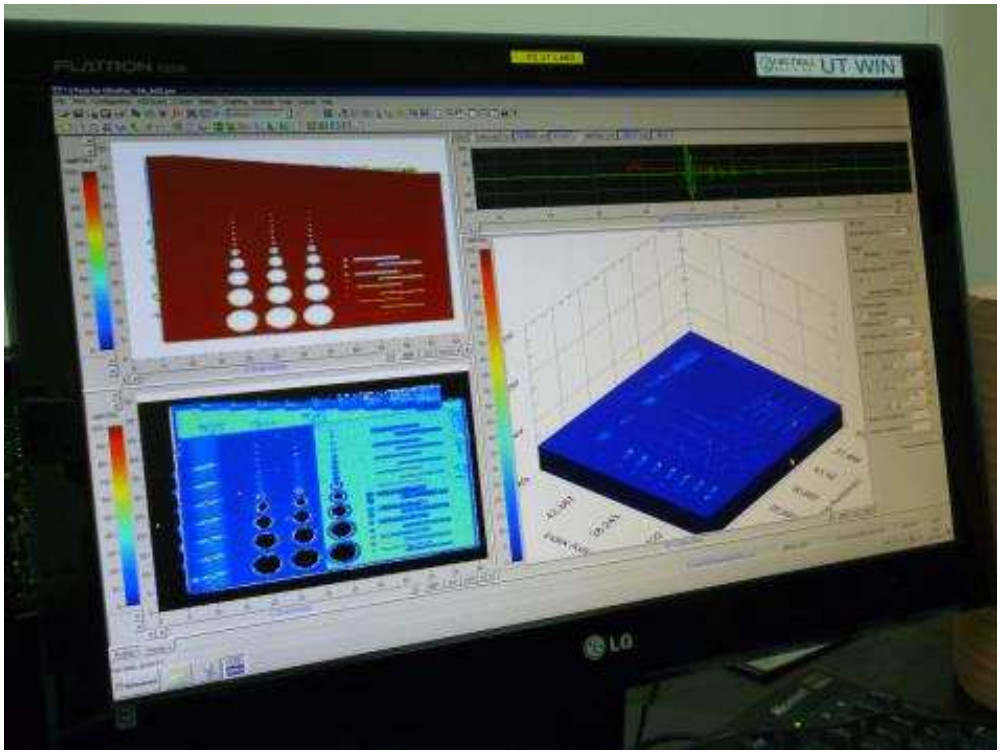
Internal cavity



Measurements performed by V. Prezza, P. Delvart and D. Marlot
from Eurosonic-Mistras (dmarlot@mistrasgroup.eu)

# C-Scan high frequency ultrasound measurements

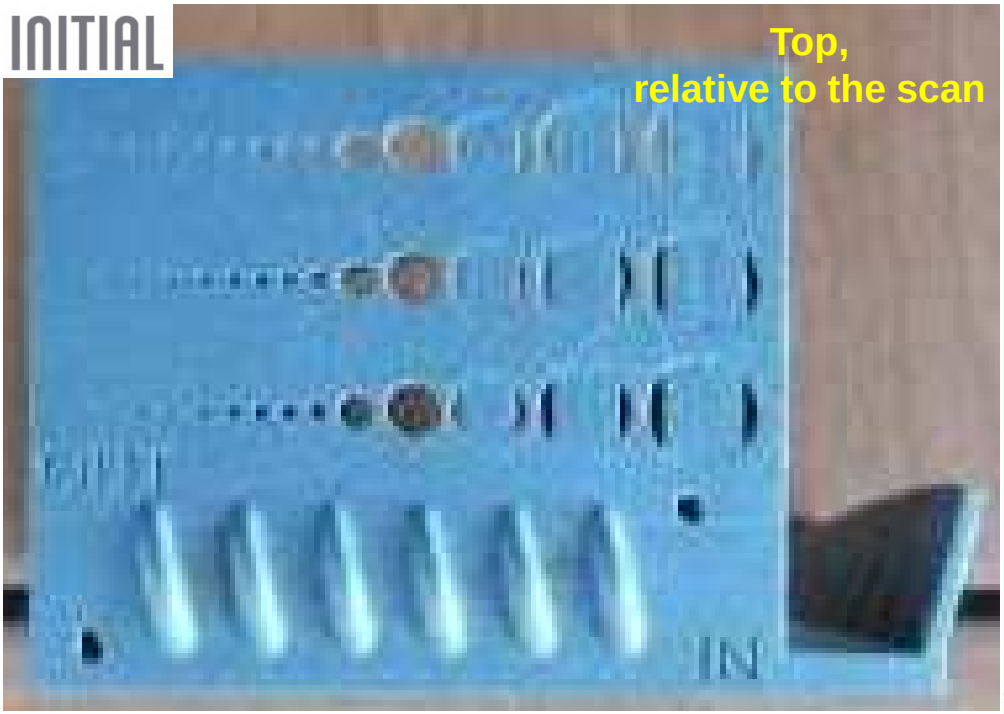

**AM Al 6061 parts**

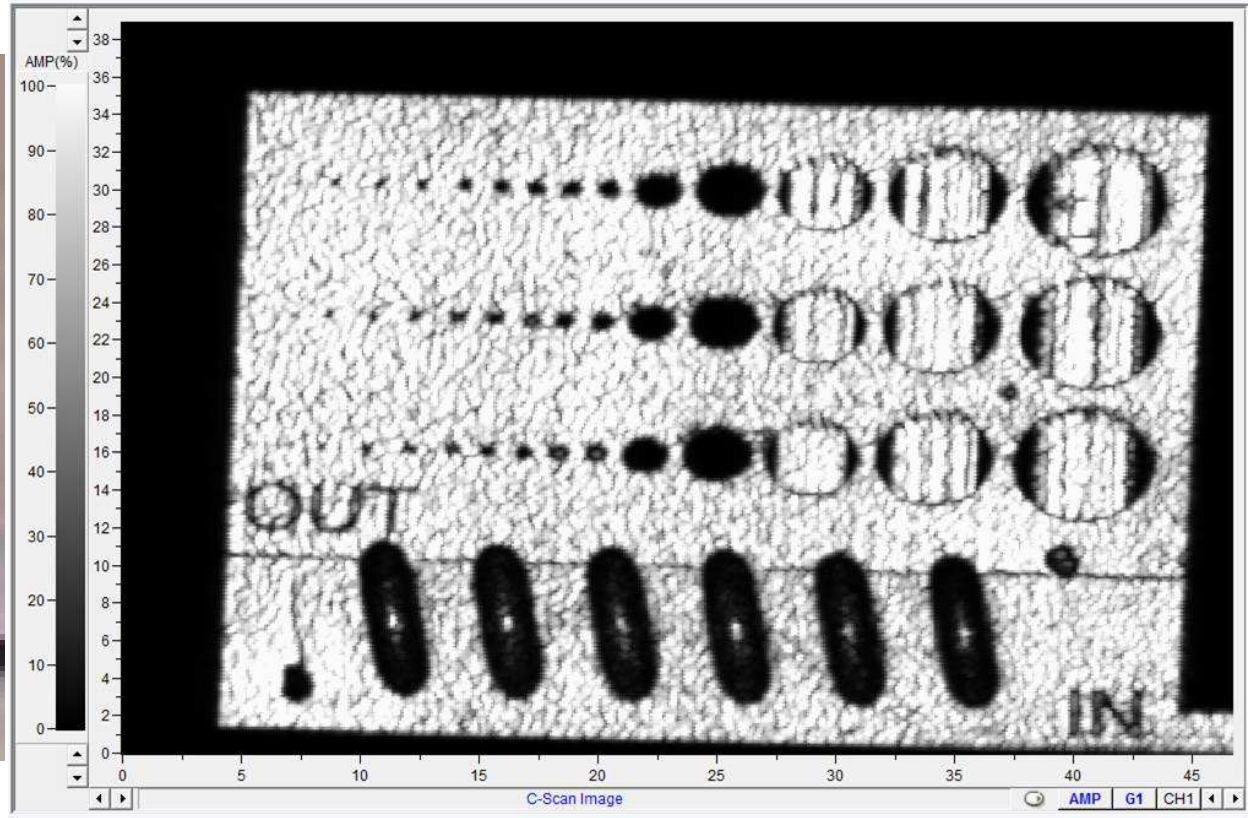



**1.9 cm focalised 20 MHz sensor**

**Measurements performed by V. Prezza, P. Delvart and D. Marlot from Eurosonic-Mistras (dmarlot@mistrasgroup.eu)**

## Surface measurements

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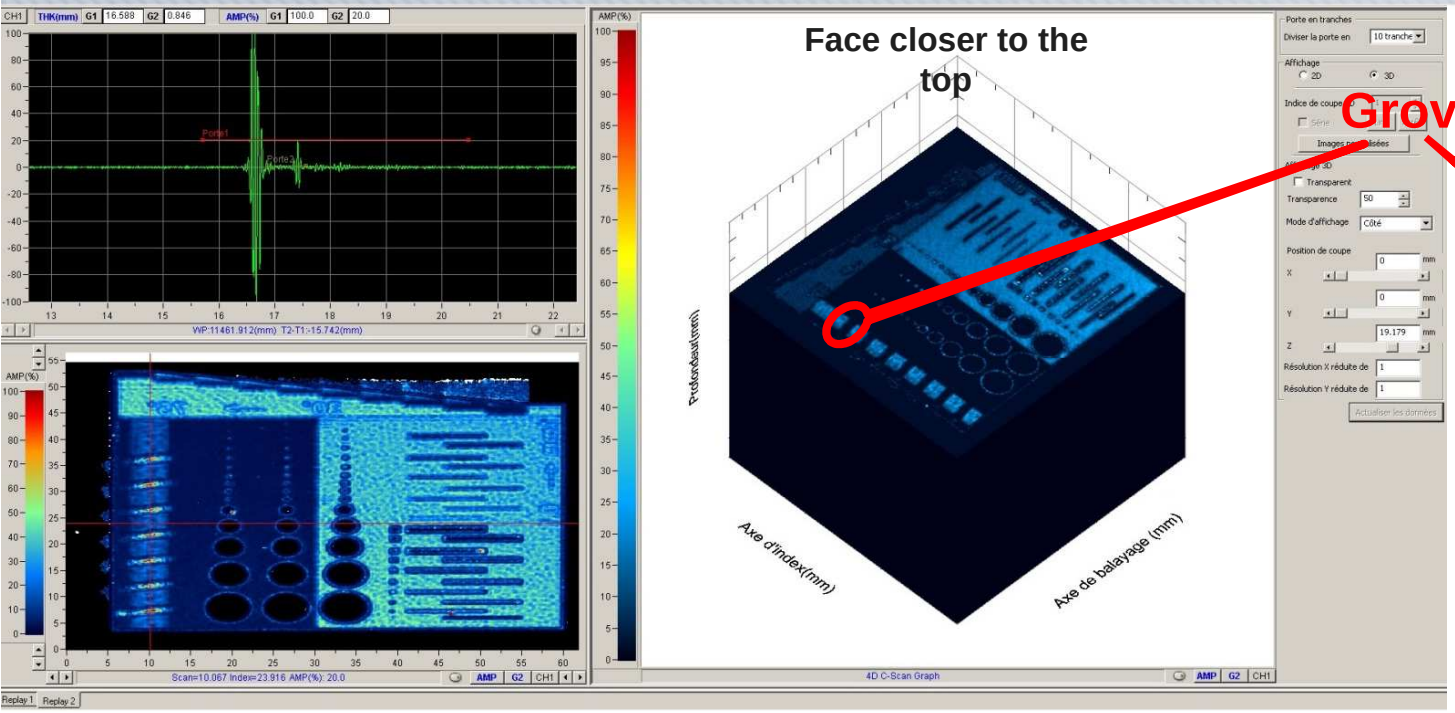
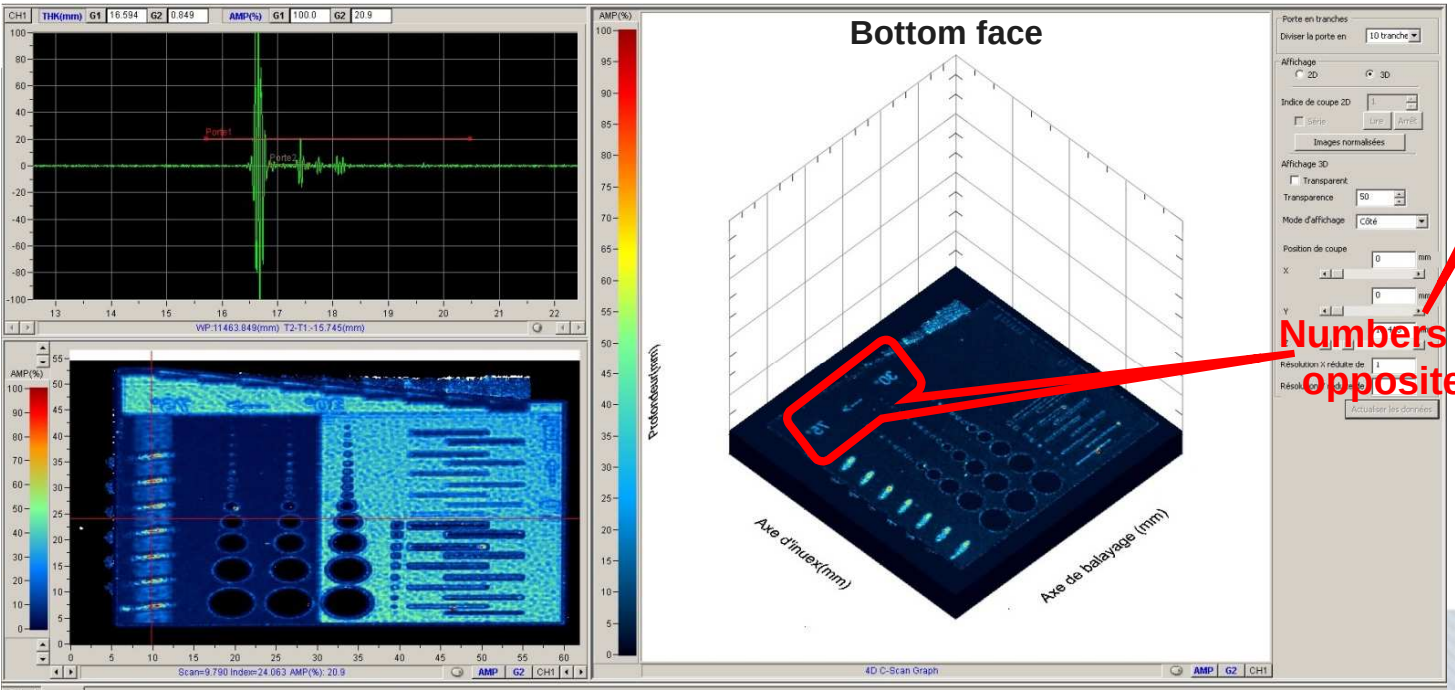
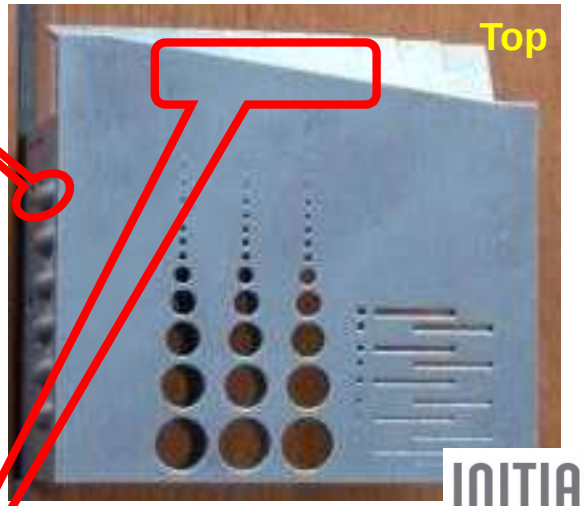
# Volumetric ultrasound views for two different depths




Grove



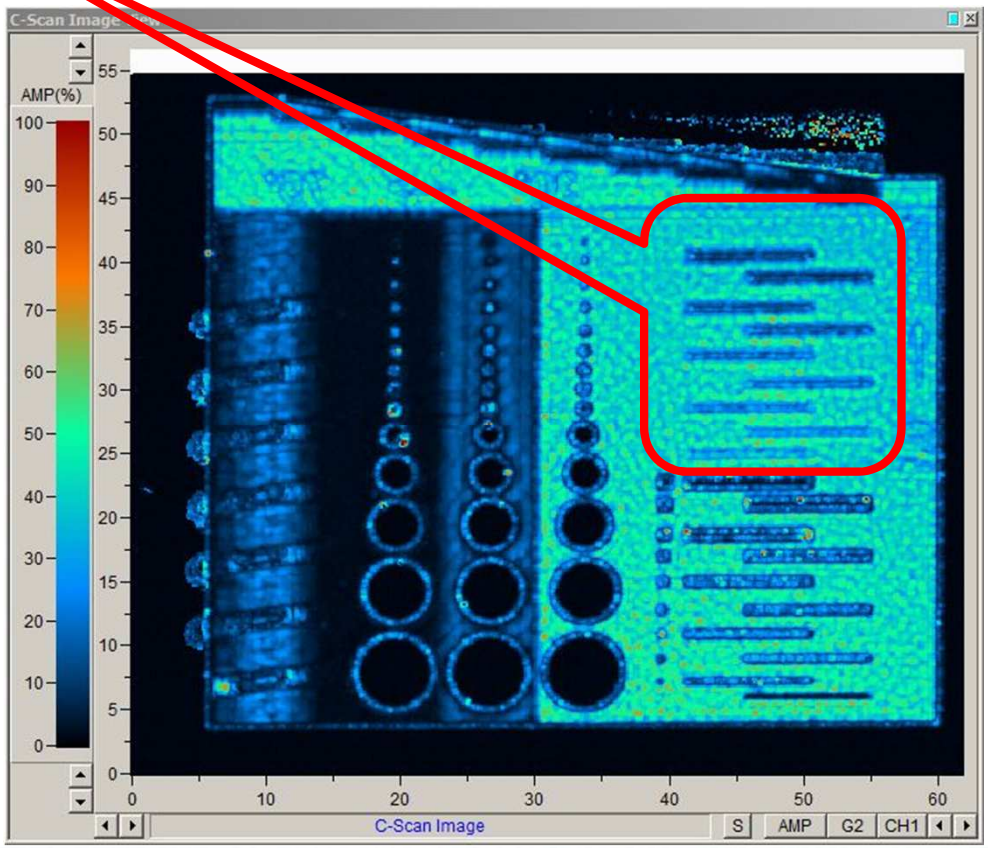

Numbers on the opposite face


Measurements performed by V. Prezza, P. Delvart and D. Marlot from Eurosonic-Mistras (dmarlot@mistrasgroup.eu)

# C-Scan high frequency ultrasound measurements


## Volumetric measurements

**Groves on the opposite side**


**Bottom, relative to the scan**

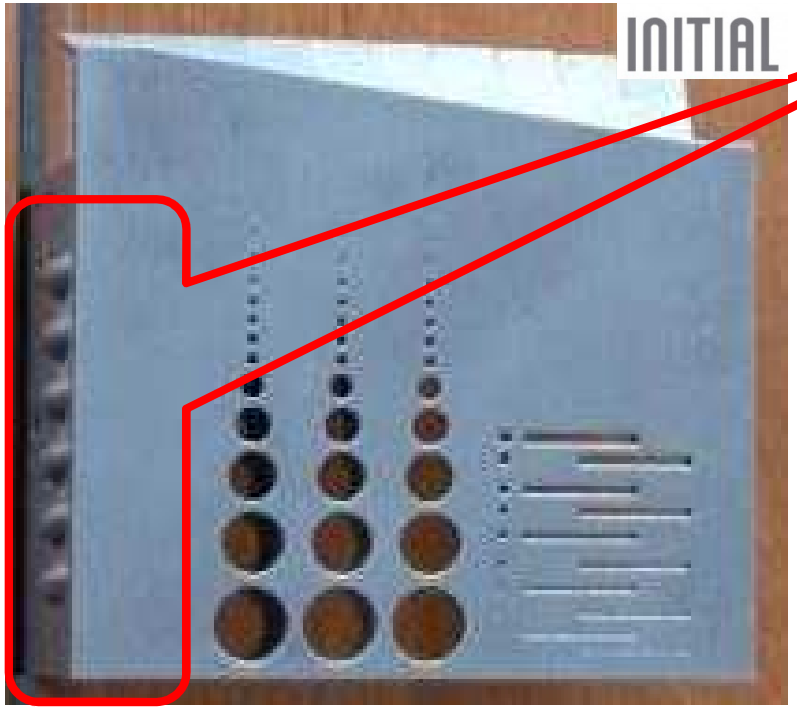
**Top, relative to the scan**

**Measurements performed by V. Prezza, P. Delvart and D. Marlot from Eurosonic-Mistras (dmarlot@mistrasgroup.eu)**

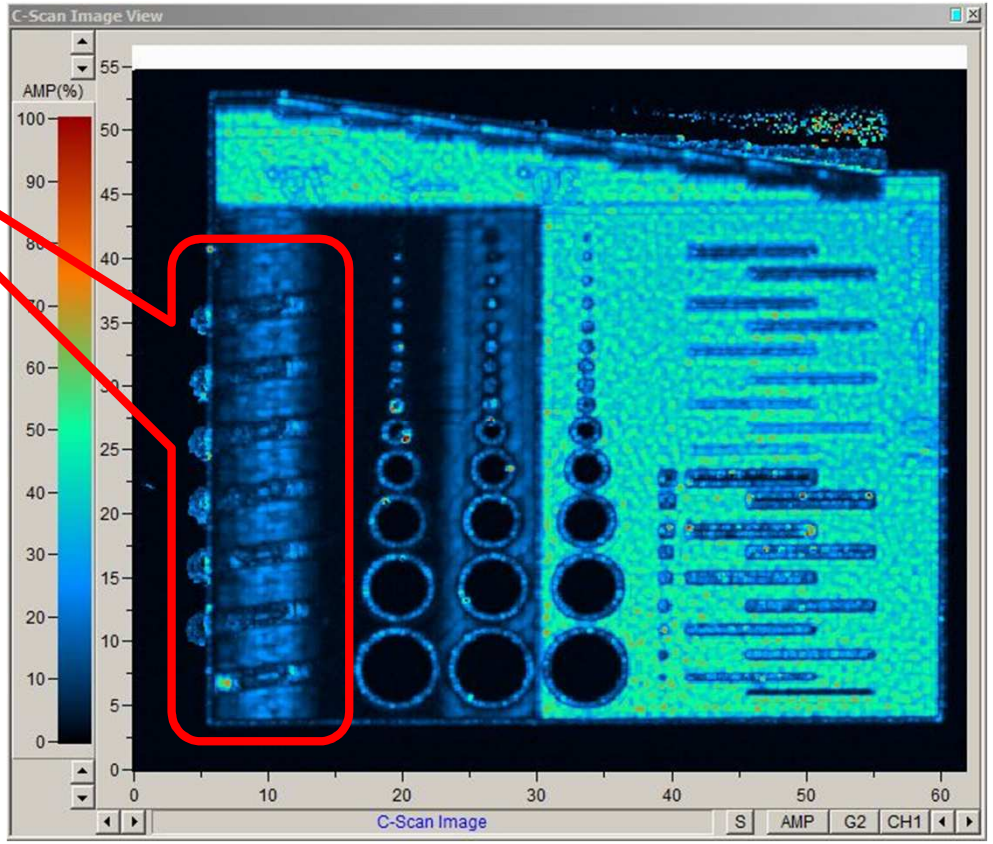
# C-Scan high frequency ultrasound measurements

## Volumetric measurements

**Spirals inside the hollow cylinder**




**Top, relative to the scan**




**Measurements performed by V. Prezza, P. Delvart and D. Marlot from Eurosonic-Mistras (dmarlot@mistrasgroup.eu)**

### Benefits of the method for AM:

- Dimensional measurement
- Non-destructive control
- 3D images of external and internal structures
- Compliance verification with part specifications
- Faster than X-ray tomography (XCT)

**Limitations:**

- ✓ Not suitable for complex geometry parts
- ✓ Less accurate than XCT

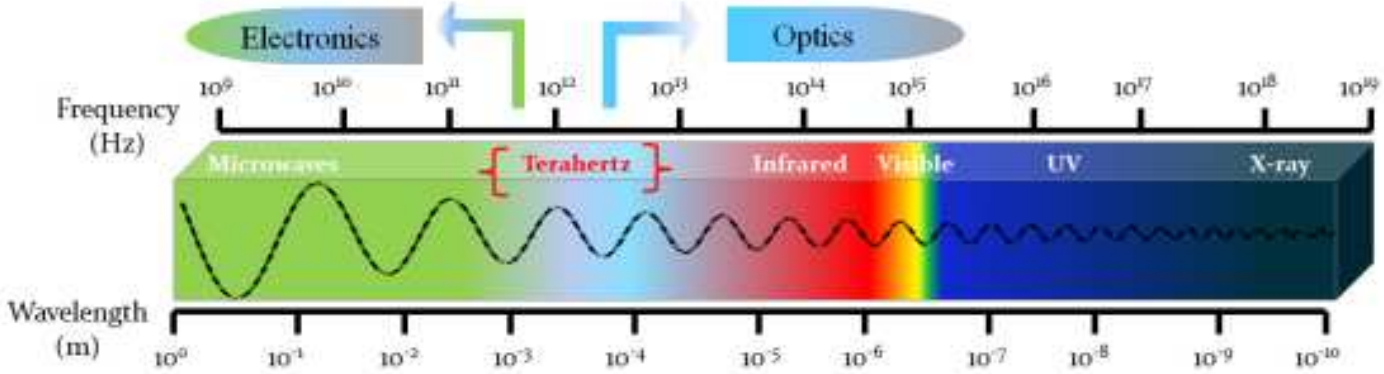
**Assessment of the potential of terahertz waves to characterize AM parts:**

- **Terahertz spectrometry**
- **Terahertz tomography**

## Assessment of the potential of terahertz waves to characterize AM parts:

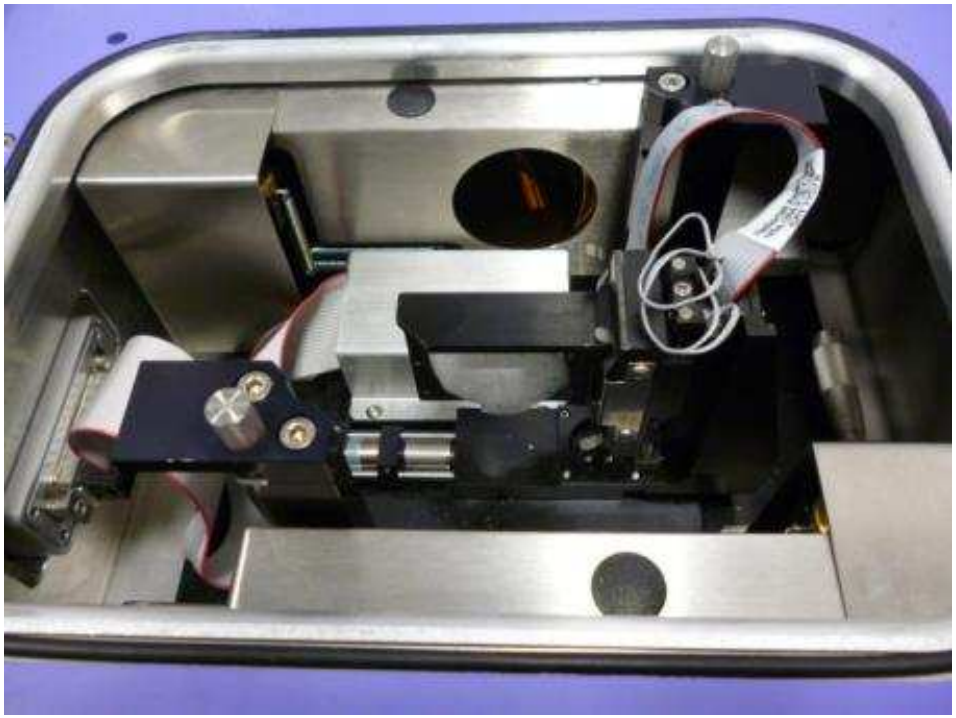
- Terahertz spectrometry
-

# Terahertz spectrometer





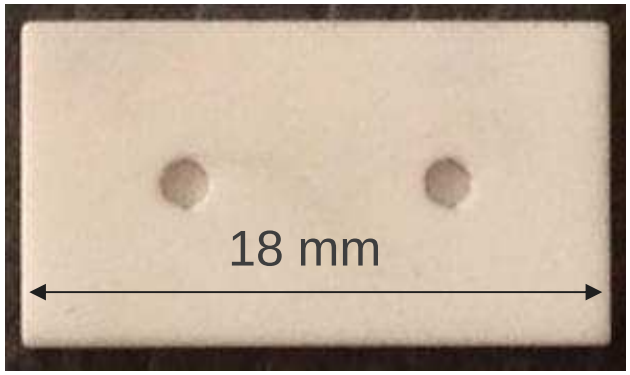
Terahertz spectrometer TPS3000 from TeraView

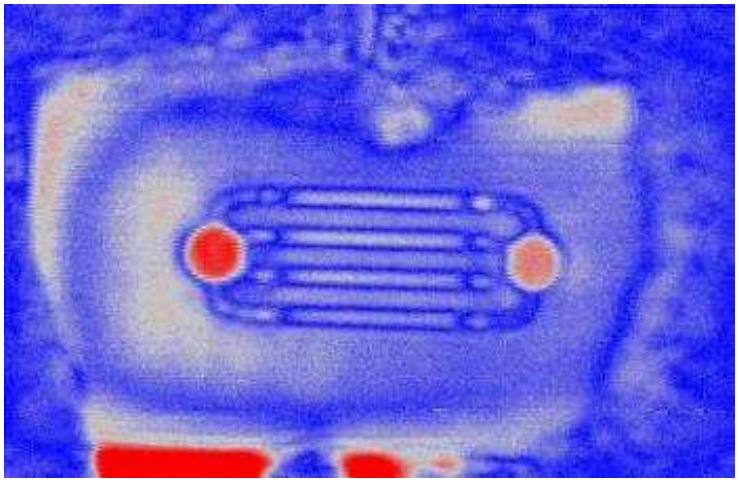


TPS3000 experimental setup for transmission measurement

# Terahertz spectrometer measurements

AM zirconium part for microfluidic applications



Terahertz spectrometer image

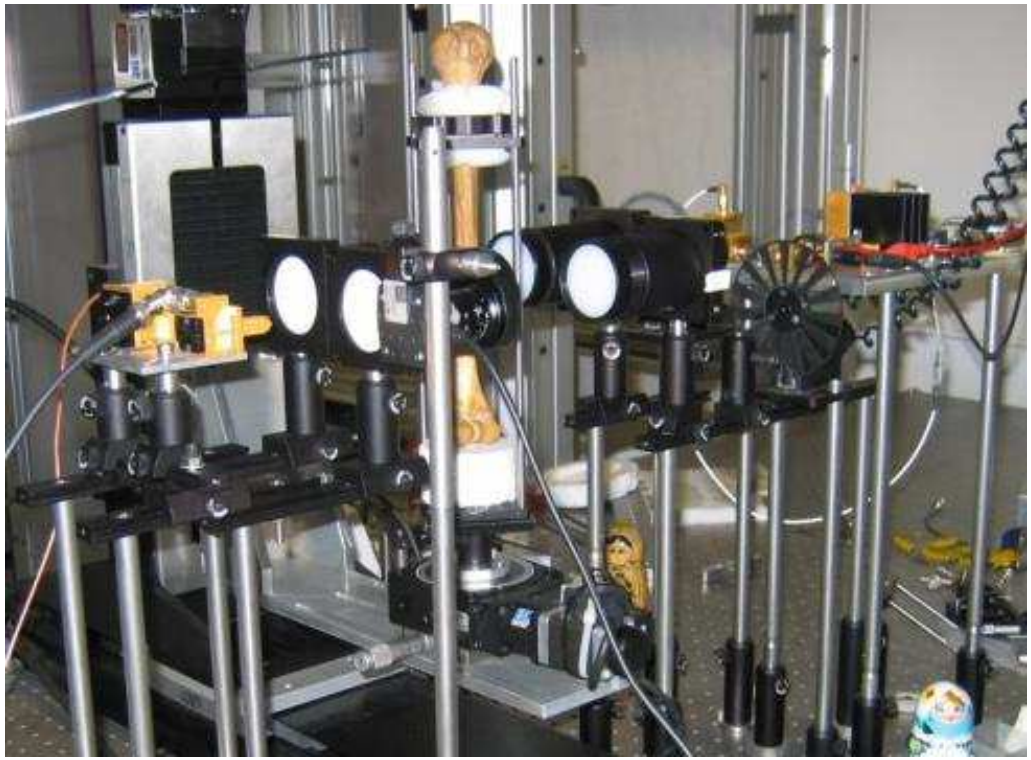
Optical image after sectioning of the part

**IMS measurements (contact: patrick.mounaix@u-bordeaux.fr)**

## Assessment of the potential of terahertz waves to characterize AM parts:

- 
- **Terahertz tomography**

# Terahertz tomography measurements

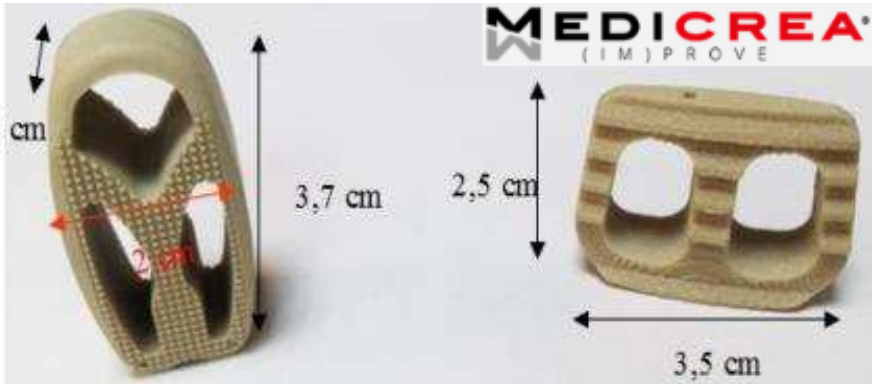


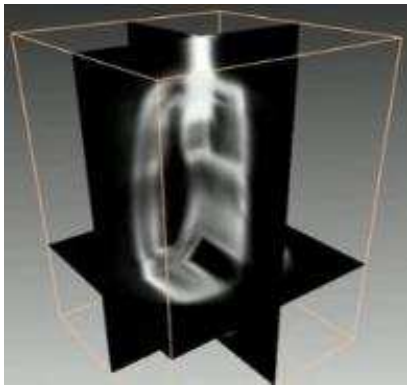
IMS terahertz tomograph

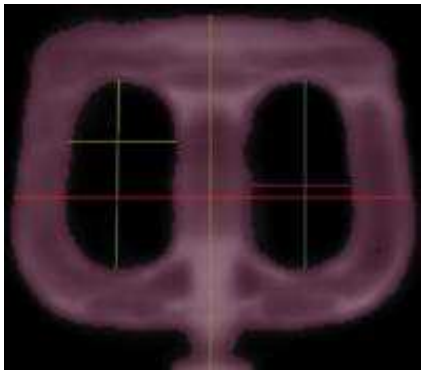
- **Set-up:**
  - ✓ **THz source**
  - ✓ **Chopper modulating the terahertz beam**
  - ✓ **Polytetrafluoroethylene lens focusing the beam on the DUT**
  - ✓ **DUT**
  - ✓ **Polytetrafluoroethylene lens recollimating the beam on the detector**
  - ✓ **Detector**
  - ✓ **Lock-in amplifier**
- **THz source:** **Gunn diode**
  - ✓ **coupled to a horn-shaped antenna**
  - ✓ **frequency tripled**
  - ✓ **power and frequency: 12 mW at 287 GHz**
  - ✓ **beam size: 1.33 mm**
- **Chopper:** **kilohertz range**
- **Detector:** **Schottky diode**
  - ✓ **one monopixel**

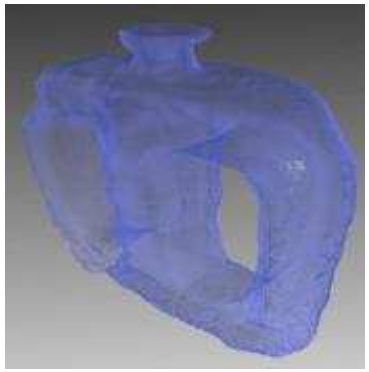
# Terahertz tomography measurements

AM spinal implants in peek

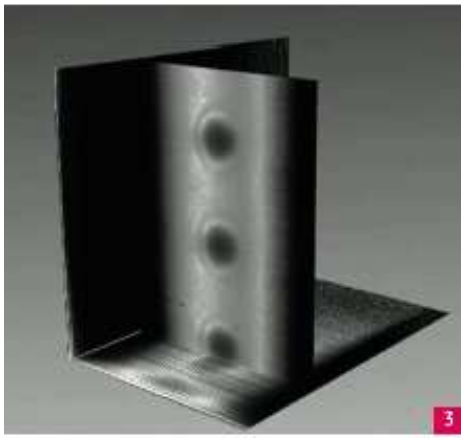






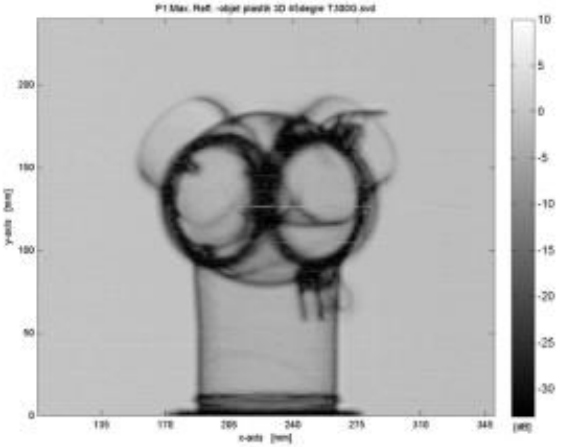
AM ceramic part

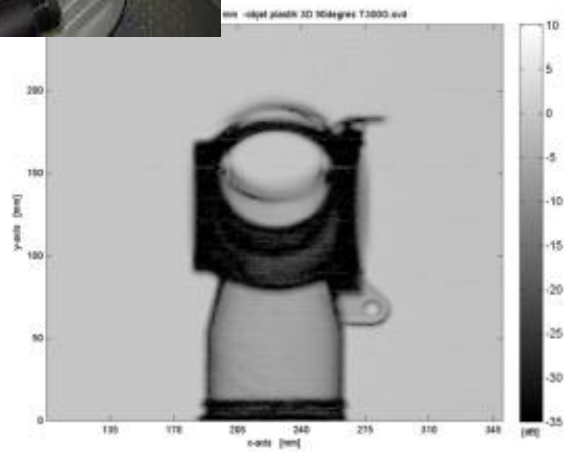


**IMS measurements (contact: patrick.mounaix@u-bordeaux.fr)**

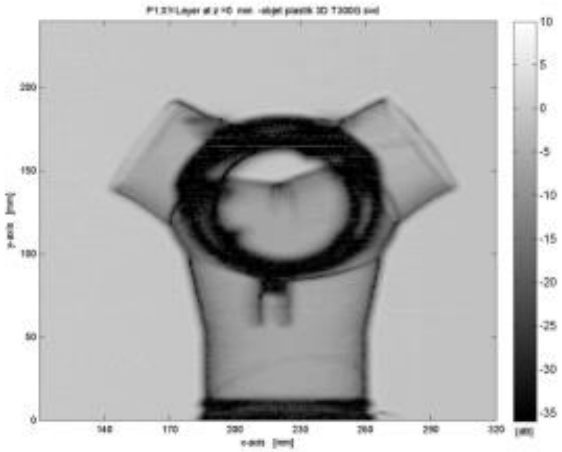
# Terahertz tomography measurements

IMS terahertz tomograph





AM polymer part



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**Limitations:**

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- ✓ **Less accurate than XCT**

- **Assessment of the potential of…**
  - ✓ …density and percentage of lattice cell measurements…
  - ✓ …Eddy currents…
  - ✓ …ultrasound techniques…
  - ✓ …terahertz waves…

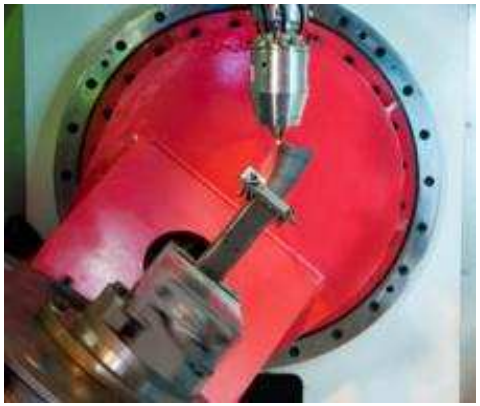
**…to characterize AM parts**

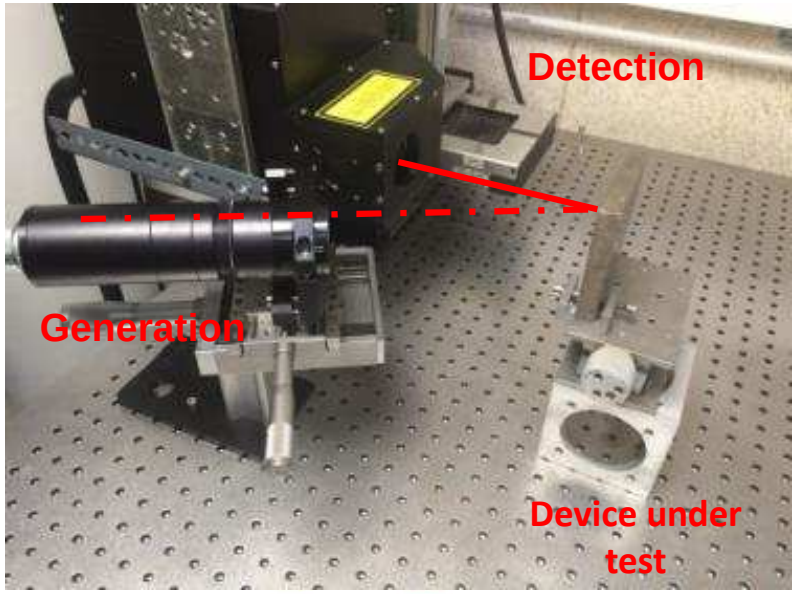
- **LNE projects on AM:**
  - ✓ PhD thesis: On line control using laser ultrasound
  - ✓ National project: Quality control on industrial AM parts
  - ✓ European project: Metrology for AM medical implants

# On line control using laser ultrasound

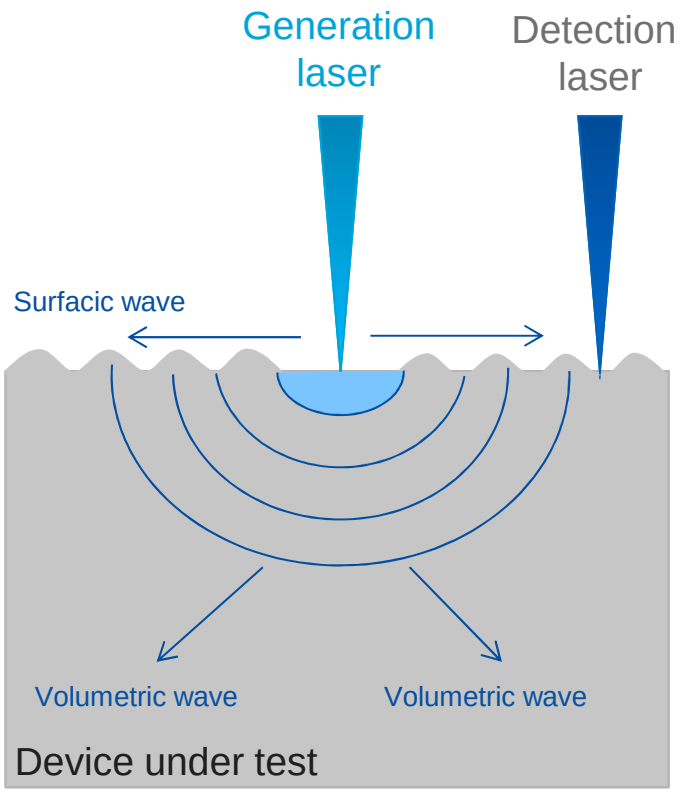
# (2016-2018)

# On line control using laser ultrasound

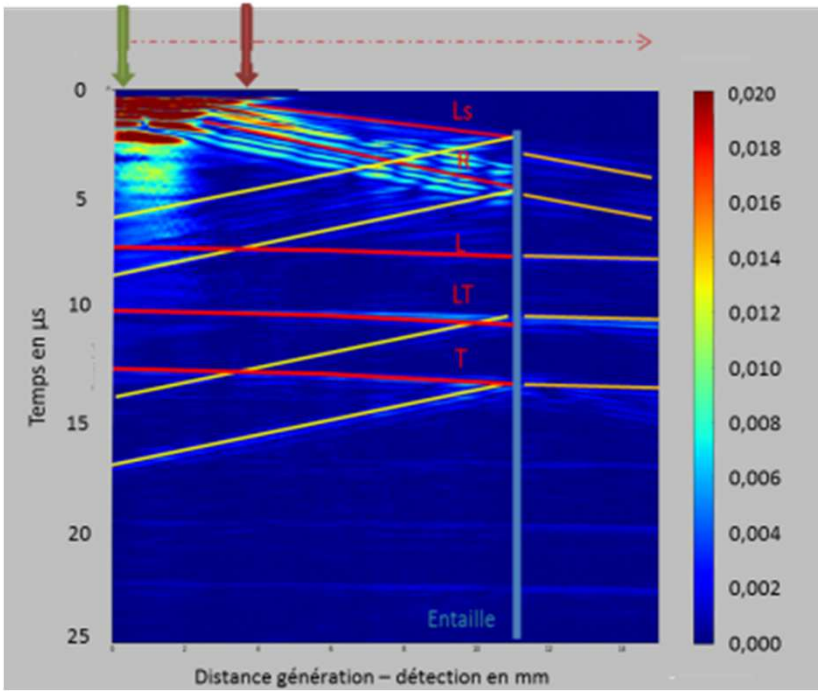





Célia Millon
PhD student
CEA/LNE




Surfacic waves: *Rayleigh waves, surfacic longitudinal waves*
Volumetric waves : *longitudinal waves, transverse waves*




matériaux : acier ferritique, épaisseur 20 mm
entaille : profondeur 2,5 mm, largeur 0,3 mm dans

« I AM SURE » project with Airbus Group, DCNS, Thales, LNE, CEA-List, Cetim, VLM, Polyshape and AFPR

# National project:

# Quality control on industrial AM parts

# ("I AM SURE", 2016-2018)

✓ Metrological characterisation and validation of X-ray tomographs for dimensional measurements of the industrial AM parts;

✓ Supervising the PhD thesis : On line control using laser ultrasound;

✓ Metrological characterisation and validation of the AM machines.

# European project:

# Metrology for AM medical implants

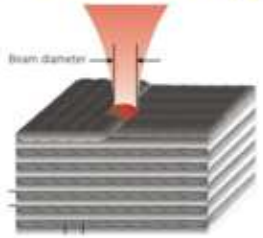
# ("MetAMMI", 2016-2018)

**Objective: Provide dedicated and qualified metrology tools as well as good practise protocols for a safe use of AM implants and guides in the medical sector:**

- ✓ Non-destructive volumetric methods for FAI: XCT and alternative methods;
- ✓ Routine controls for mass production;
- ✓ Good practice guides/Measurement protocols

SRT h04, 227.8 MM, 1876 k€ MetAMMI

## Metrology for additively manufactured medical implants





Lattice structures

### Motivations

The ageing population ⇒ Need for more patient specific health care system.

### Solutions

**Additive manufacturing:**

*on demand, customised and complex geometry implants and guides.*

⇒ New manufactured technology in highly critical applications: health
↳ Measurement tools, procedures, good practices and standards for high quality
↳ Guarantee of reliability to notified bodies
↳ Facilitation of acceptance in the medical sector.

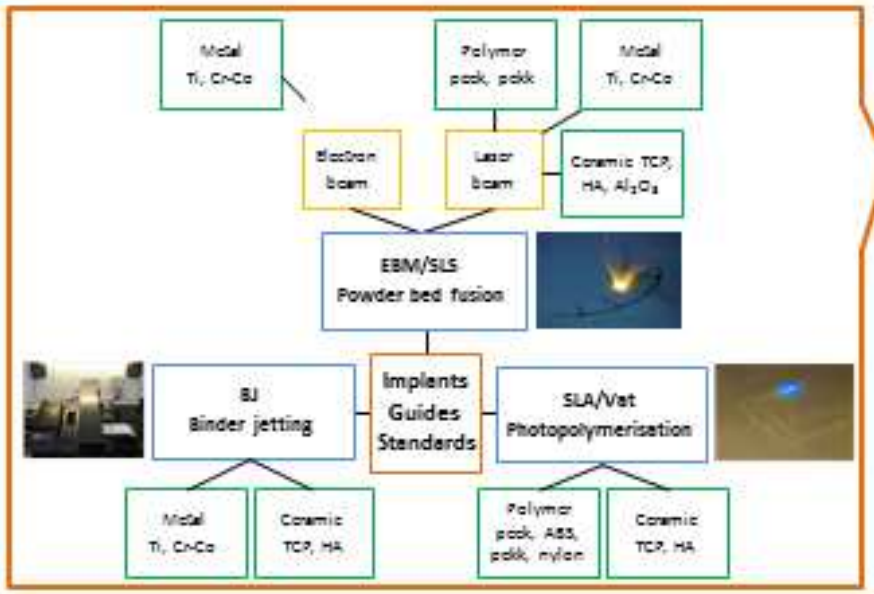
+

⇒ Manufacture of very complex geometry parts of high surface roughness
↳ Need for new non-destructive control methods
↳ Qualification and traceability of these methods.

### Overall objective and Metrology challenges

Provide dedicated and qualified metrology tools as well as good practise protocols for a safe use of additive manufacturing implants and guides in the medical sector.

# Euramet project coordinate by LNE

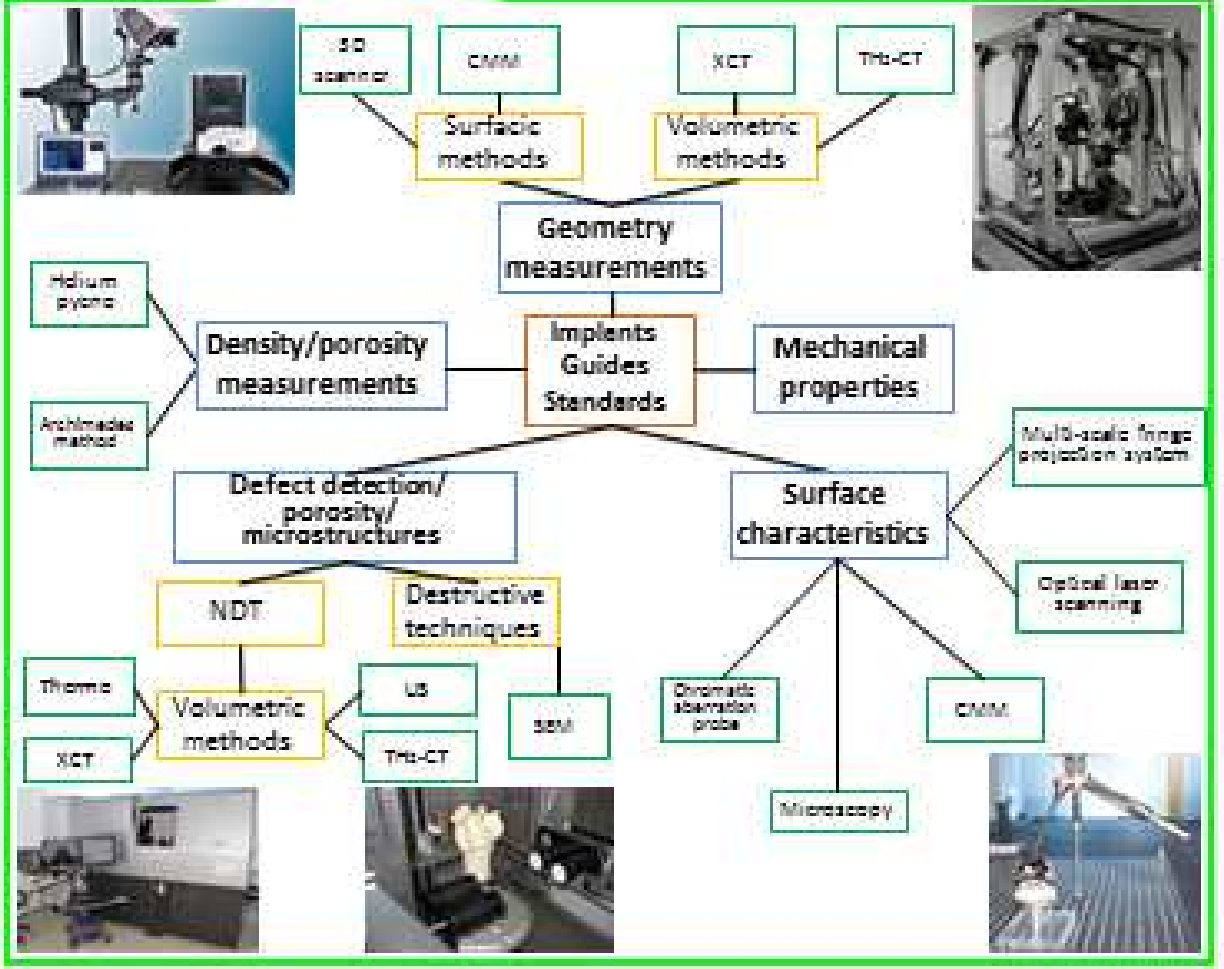



**WP1: Realisation of AM implants and guides, and traceable standards**

Aim: Providing implants, guides and standards to be characterized throughout the project.

**WP2: Characterisation of AM implants and guides, and traceable standards using non-destructive and destructive techniques**

Aim: Full implant, guide and standard characterisation.




LNE · DTU Technical University of Denmark · NSAI National Metrology Laboratory · VTT · BAM · DFM Danish National Metrology Institute · PTB · Aalto University

DANISH TECHNOLOGICAL INSTITUTE · ims · FAU · LITHOZ · Klinikum Braunschweig · UNIVERSITY OF UPPER AUSTRIA · The University of Nottingham

MEDICREA · BEGO · PRAXIS AM SANDE · XILLOC

# Thank you for your attention

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