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Detection of grinding burns with NV center in diamond magnetometer

Diamond Quantum Sensors for Non-Destructive Testing

QUEST-IS'25

KWAN-TEK – Baptiste Vindolet (R&D engineer)

September 1st, 2025

baptiste.vindolet@kwan-tek.com

KWAN-TEK: Startup in quantum sensing

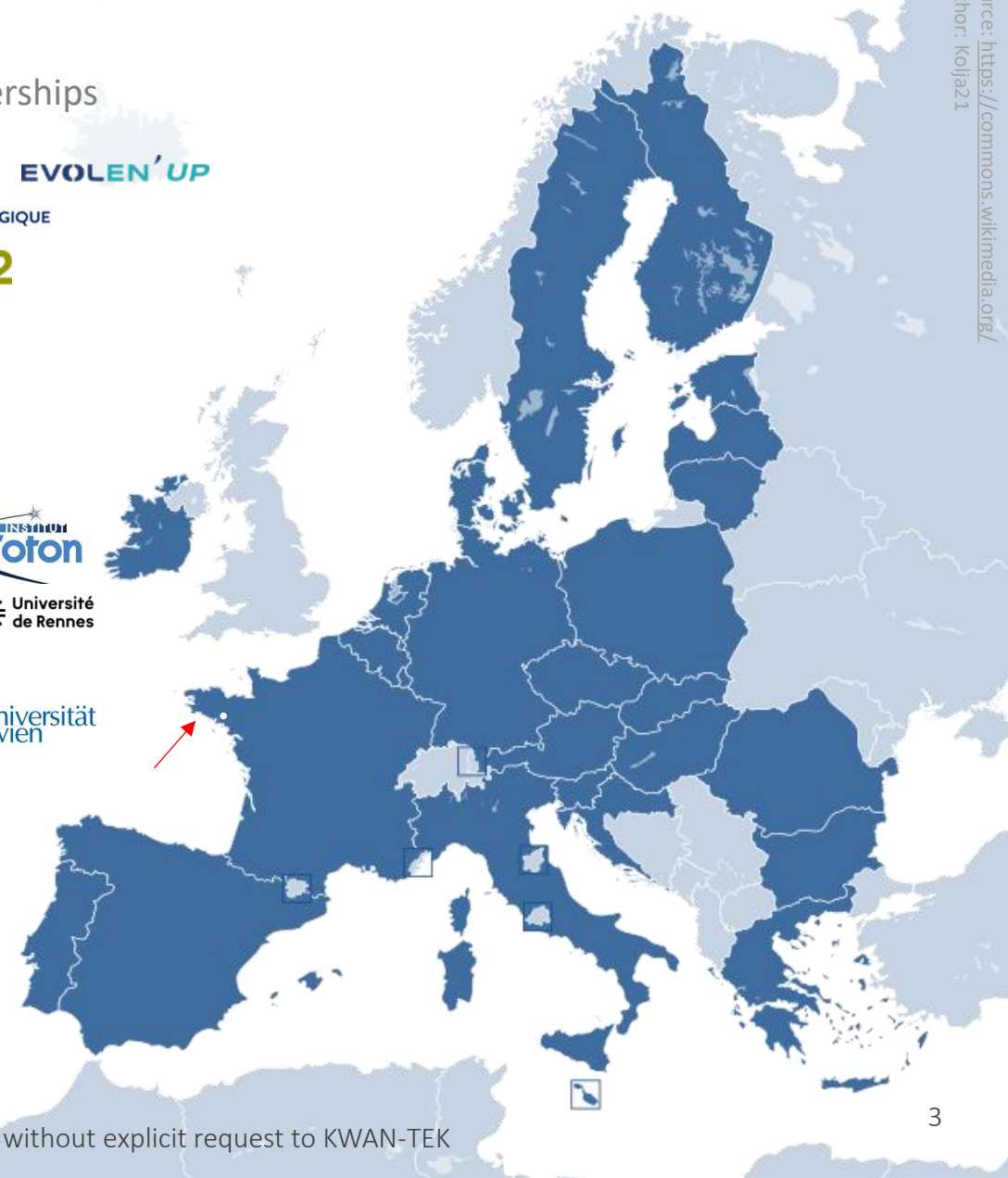
Leading metrology with diamond quantum sensors

- Founded in April 2023 (France)
- Team of 24 people (16 in R&D)
- 5 patents

Recognitions and partnerships

KWAN-TEK develops and commercial diamond quantum sensors for critical industrial applications.

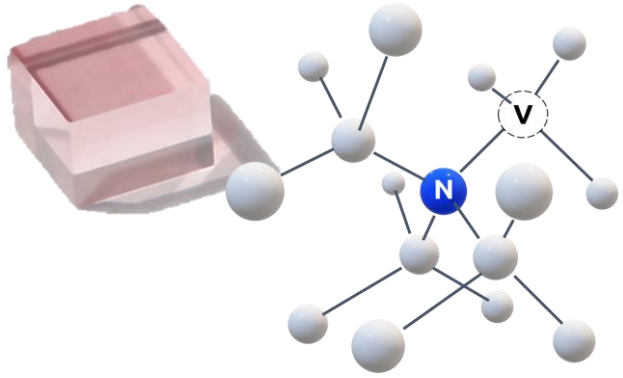
→ What can these sensors bring to the industry?



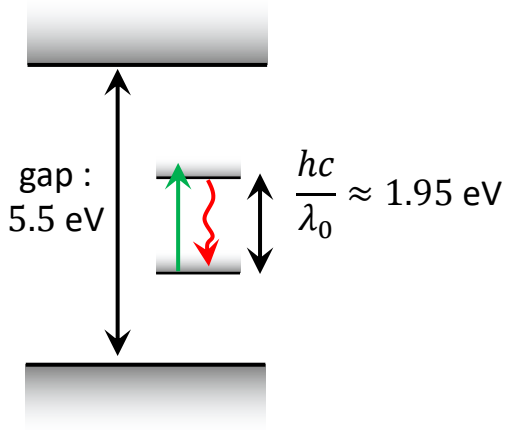
source: https://commons.wikimedia.org/
Author: Kolja21

The NV centre in diamond

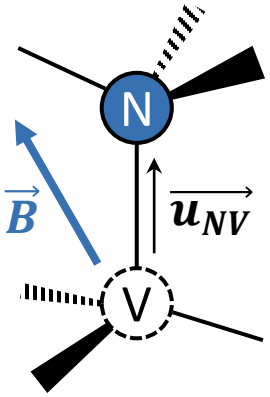
The NV centre is an atomic defect, perfectly photostable

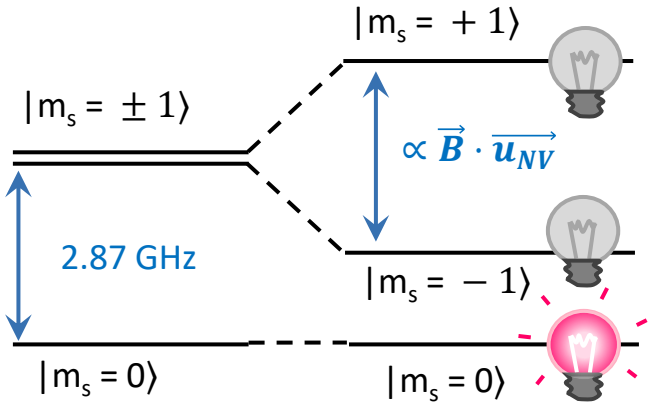


NV : Nitrogen Vacancy



Electronic spin S=1, optically addressed

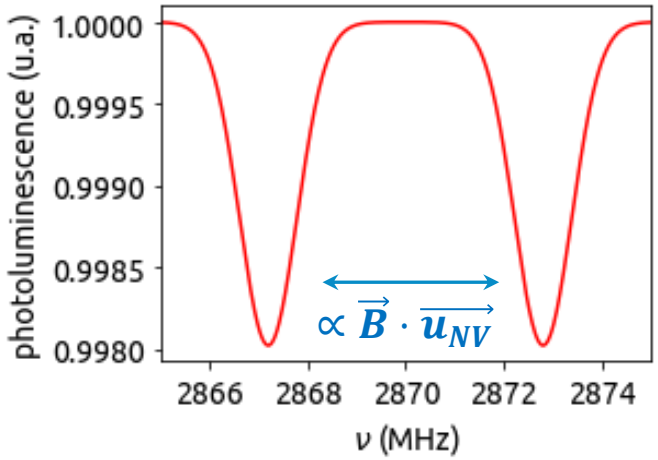




A bulk diamond is an excellent magnetometer

- High resolution, small size (10 ~ 100 µm)
- Vectorial (3 axes)
- Quantitative and absolute (no calibration)
- High sensitivity (≤ nT/√Hz → 10 pT/√Hz*)
- Robust

Optically detected magnetic resonance (ODMR)

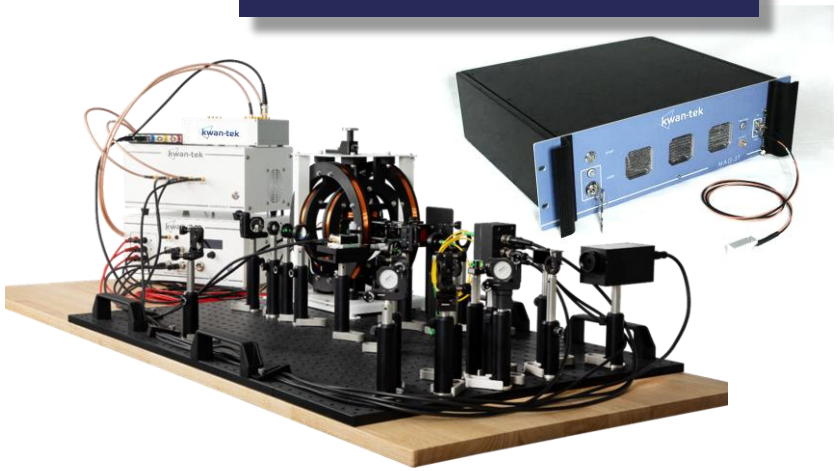


*See for example J. F. Barry, et al. "Optical magnetic detection of single-neuron action potentials using quantum defects in diamond," PNAS (2016).

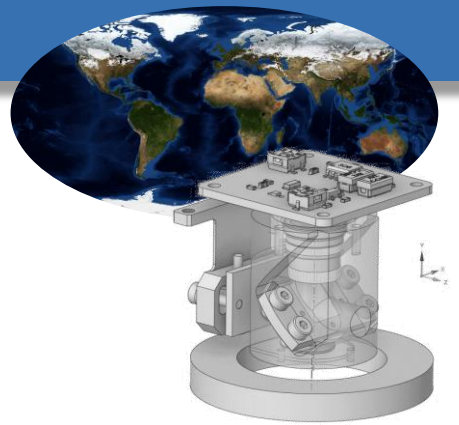
Development of new applications with NV magnetometers

The NV centre is an excellent magnetometer: unique combination of resolution – accuracy – integration

Education & scientific instrumentation



Navigation & detection

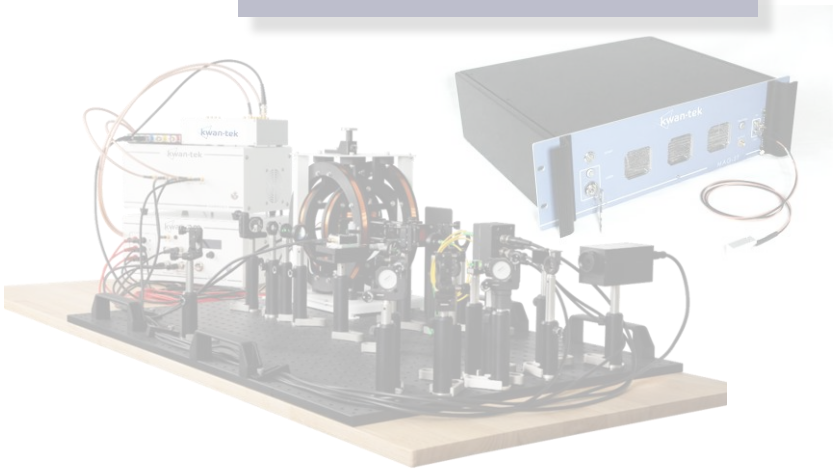


Non destructive testing

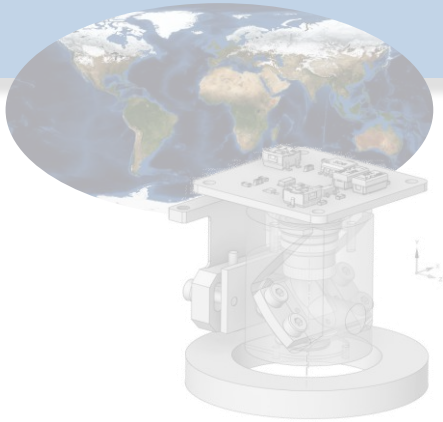
Development of new applications with NV magnetometers

The NV centre is an excellent magnetometer: unique combination of resolution – accuracy – integration

Education & scientific instrumentation



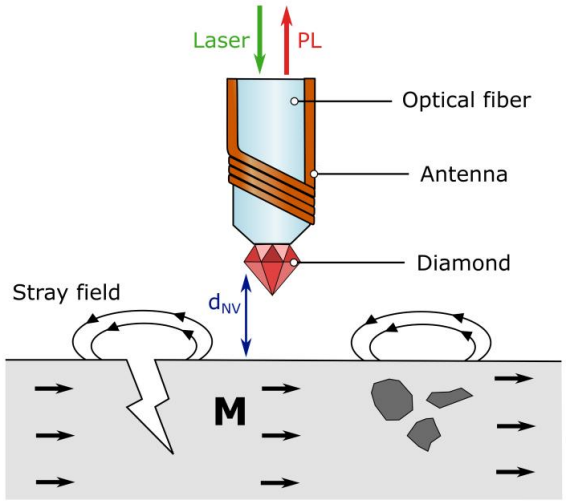
Navigation & détection

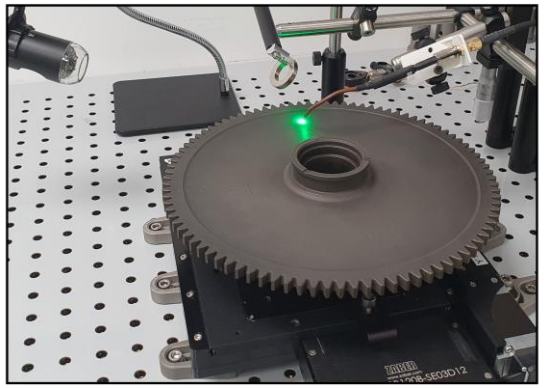


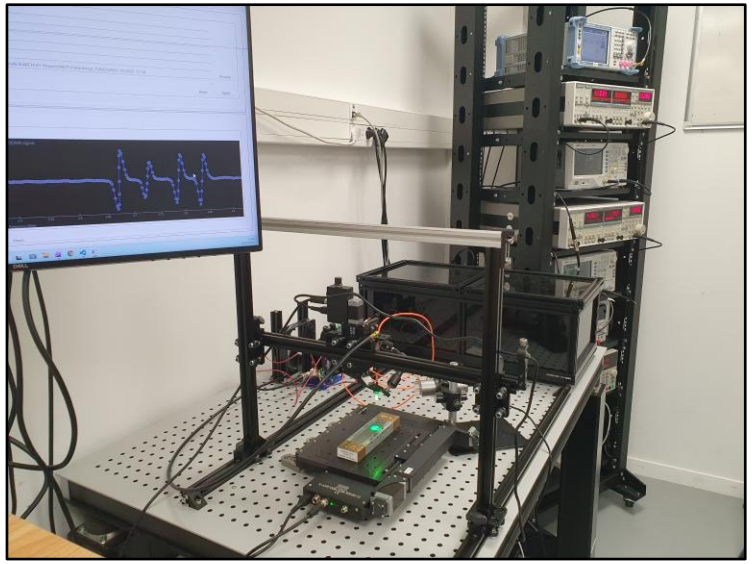
Non destructive testing

Many techniques already make use of the magnetic field for NDT

R&D set-up - Experimental implementation

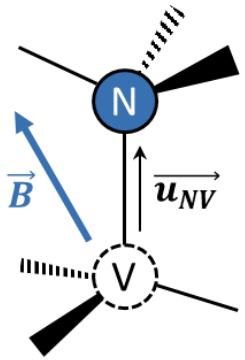




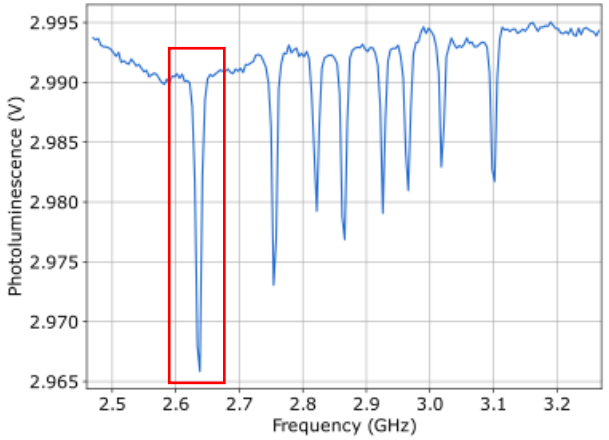


Defects (cracks, stresses, corrosion, phase change ...) in ferromagnetic samples give rise to leakage fields.

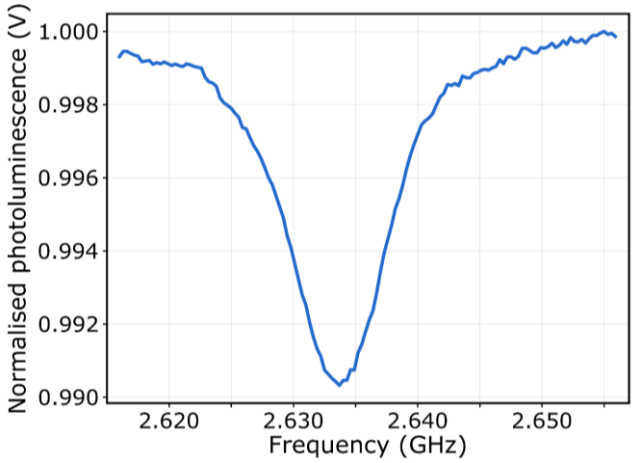
We map the magnetic field → Track the position of ODMR lines on each pixel.



ODMR spectrum



Zoom on 1 resonance



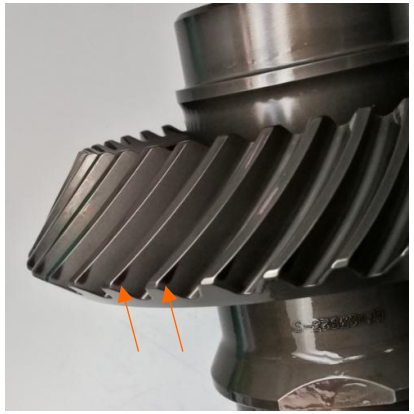
Micro-wave modulation

NDT case #1

Grinding burns in steel

Detection of grinding burns in steel

Study with **Safran Transmission System** (France).



Gearwheel of 16NiCrMo13 steel

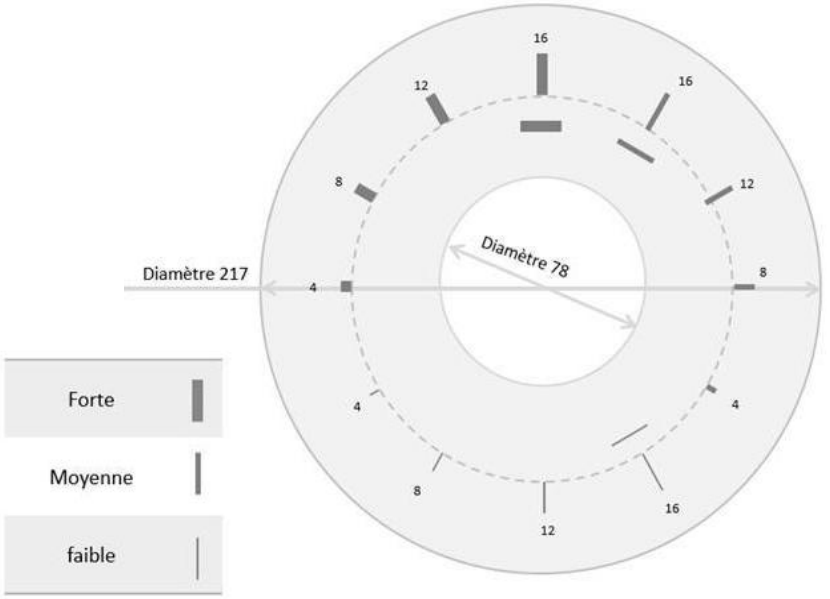
Goal:

First validate NV magnetometry on a well-understood NDE use case.

During the machining of steels, grinding burns can appear on the surface, due to local heating.

Sample:

Gear with 3 grinding burns intensities.

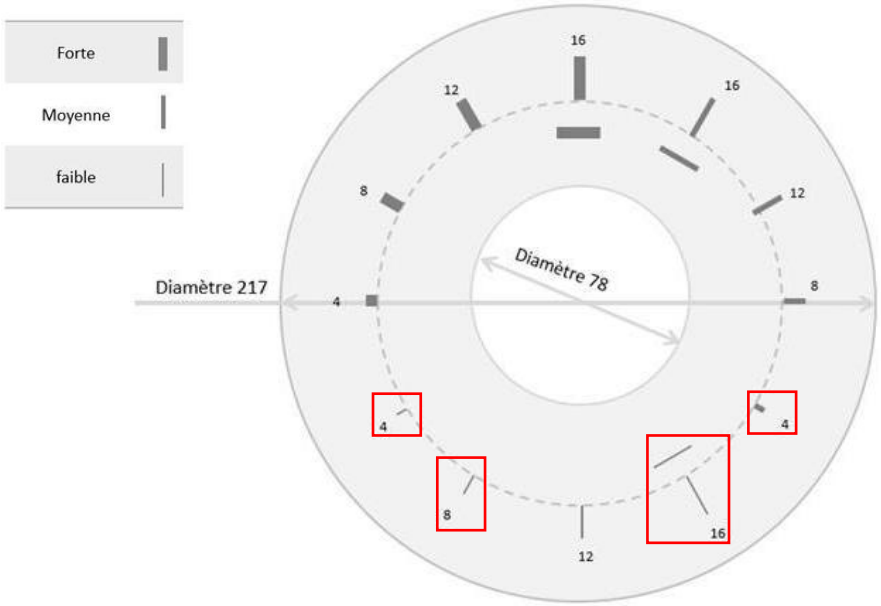


The burns were revealed by nital etching prior to NV measurements.

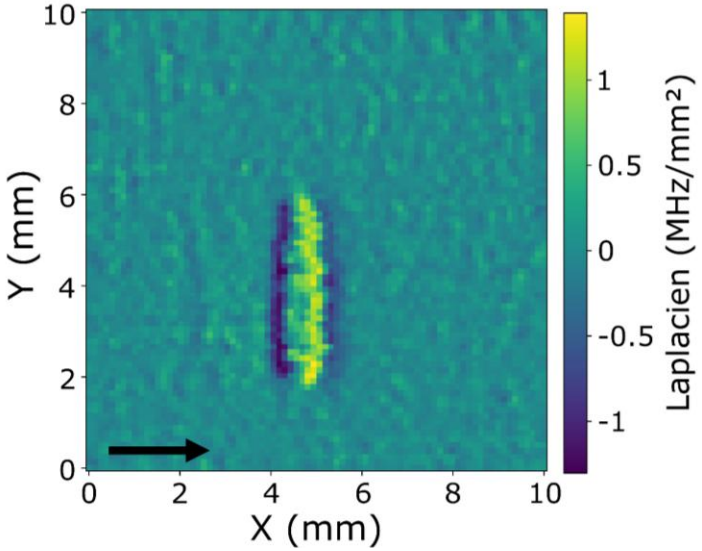
Determining the detection level

→ Weak intensity: hardly detected visually

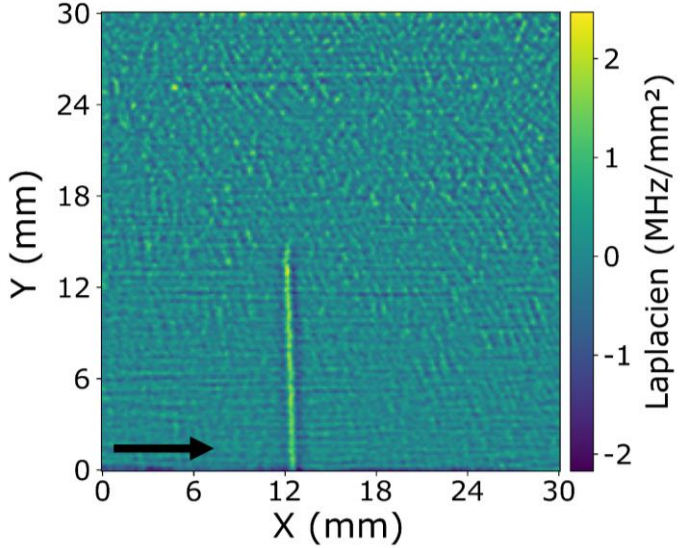
(4 mm long and 500 µm wide)



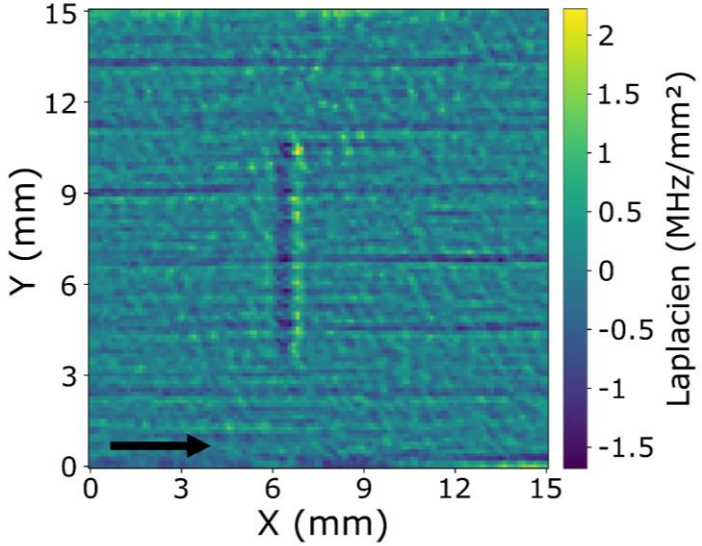
Medium intensity – 4 mm length



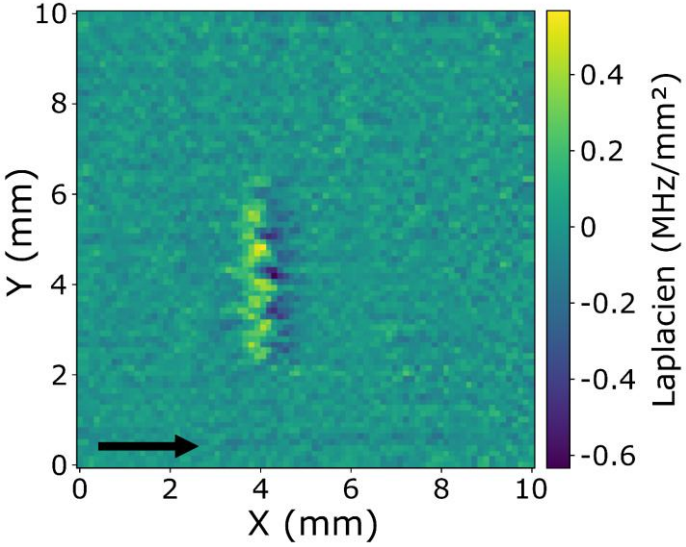
Weak intensity – 16 mm length



Weak intensity – 8 mm length



Weak intensity – 4 mm length



→ **High sensitivity and high resolution.**

NDT case #2

Martensite in stainless steel

Detection of martensite in stainless steel

Study with **CETIM** and **ELyTMaX** (France, Japan).

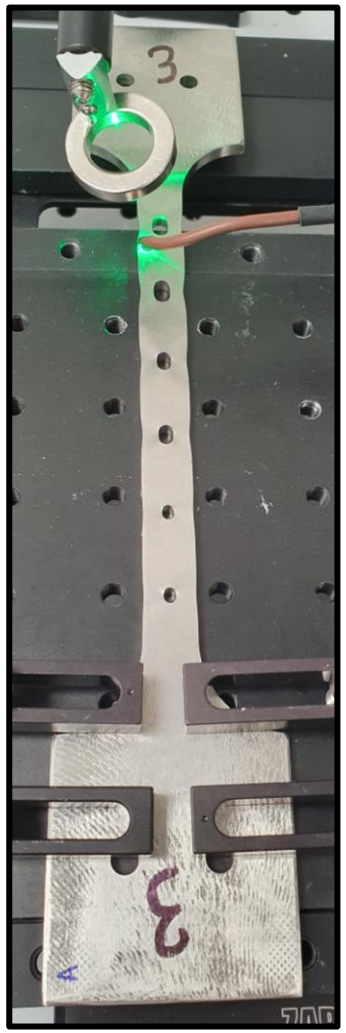
Goal:

Detect ferromagnetic **martensitic** phases in stainless steel (316L) used for hydrogen transportation and storage. Martensite can lead to **embrittlement**, which is one of the major challenges in scaling up hydrogen installations.

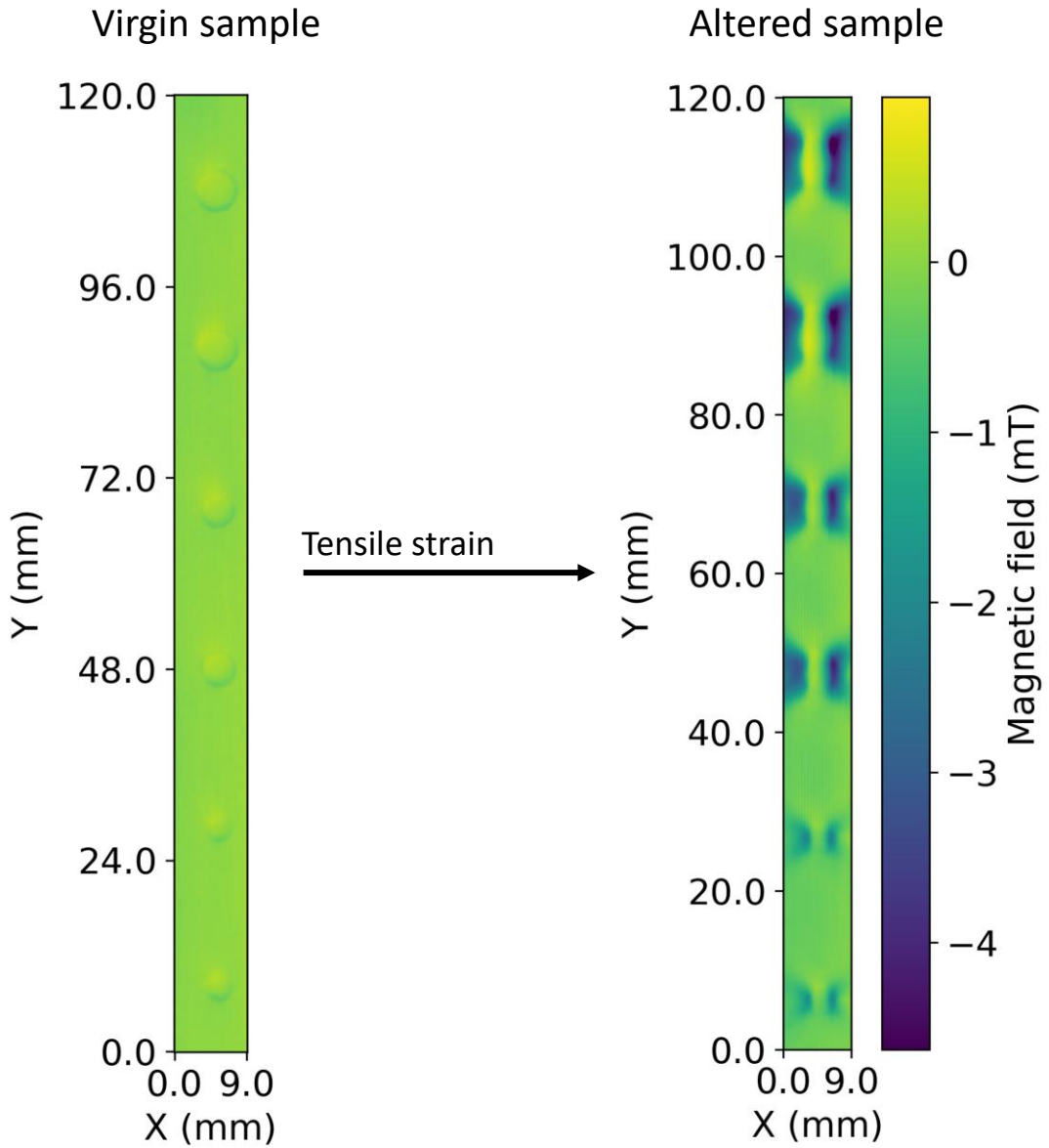
Sample:

Traction test piece with holes to locally increase constraints.

Hydrogen storage tanks, CETIM

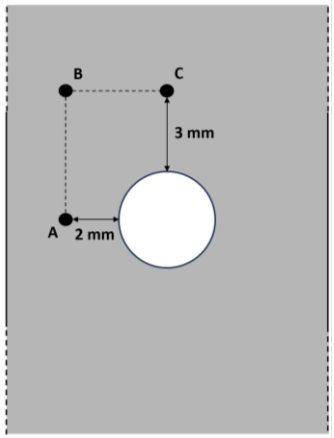


Lift-off distance = 200 µm

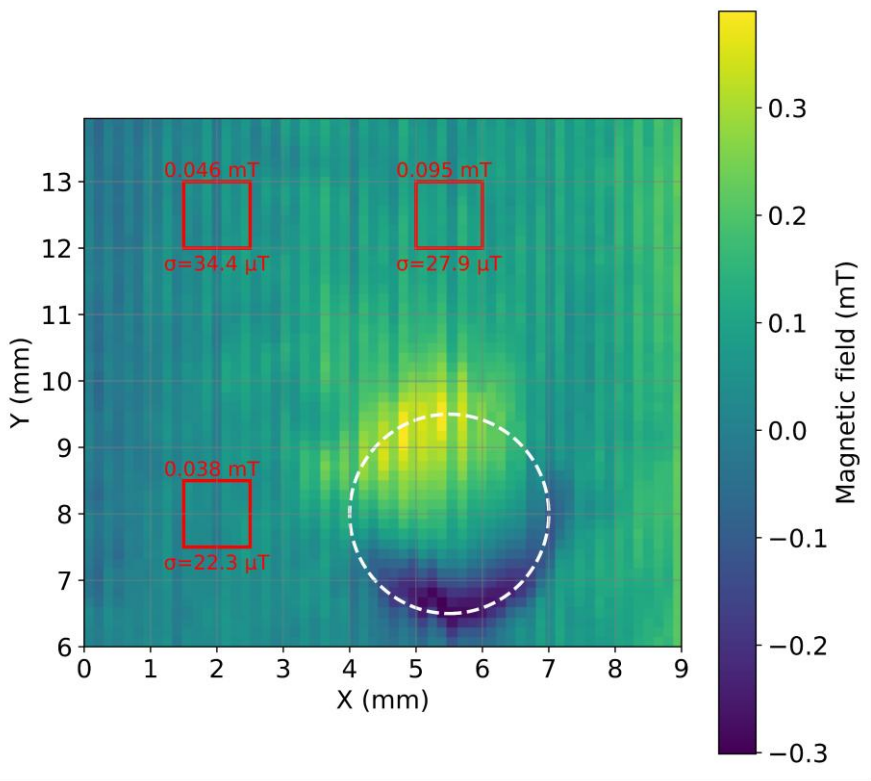


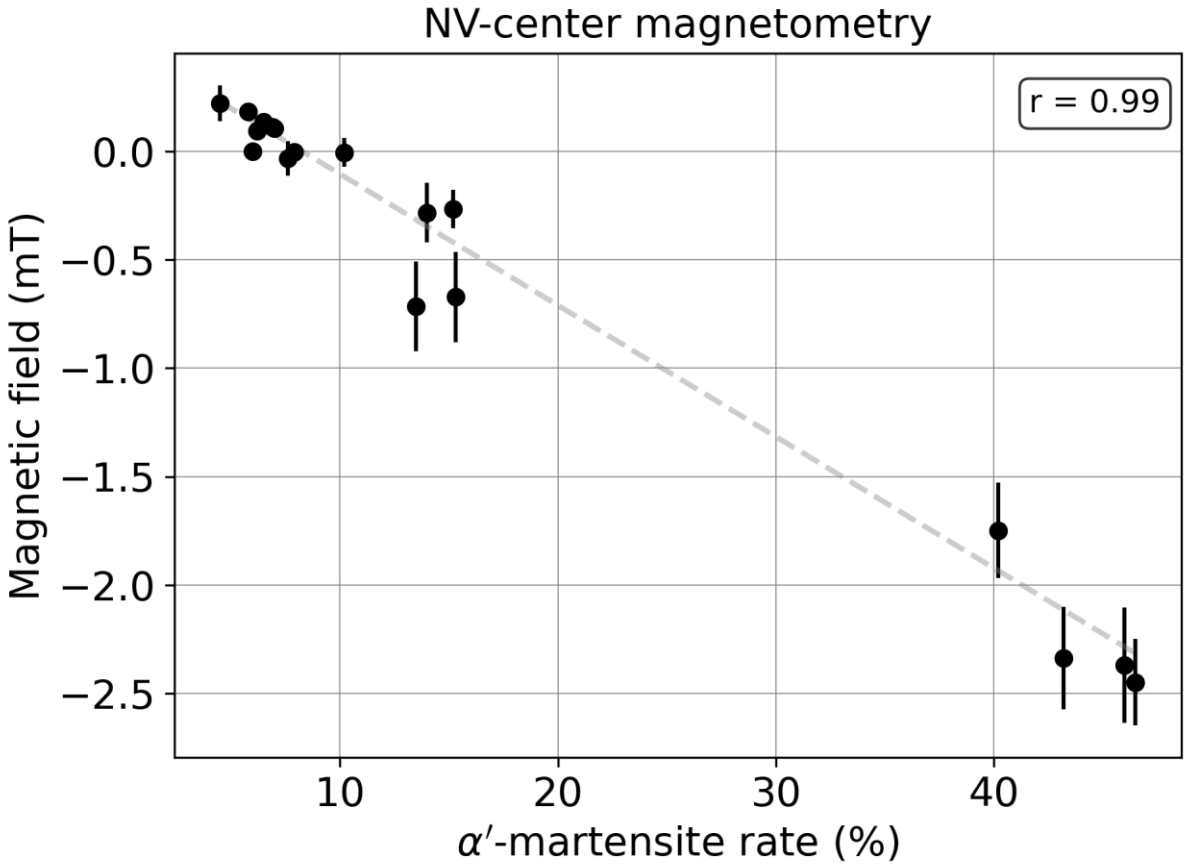
Detection of martensite in austenitic steel

→ Comparison with X-ray diffraction measurements :



XRD measurement points

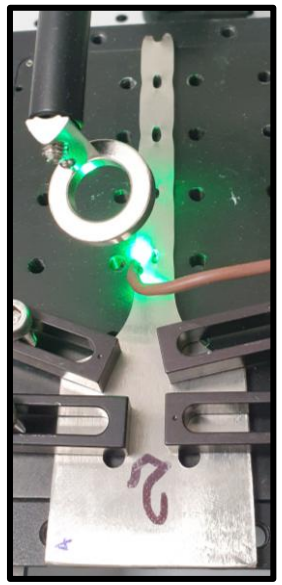


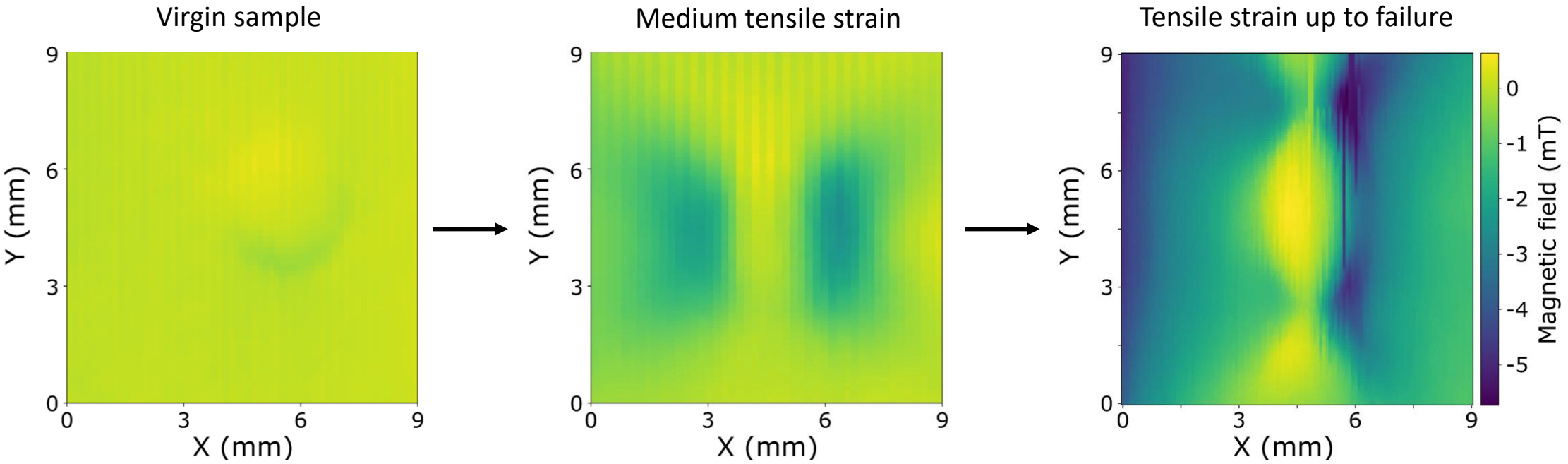


Perfect correlation between NV magnetic measurements and martensite rate measurements by X-ray diffraction → NV magnetometry enables the detection of the martensite phase.

Detection of martensite in austenitic steel

→ Zoom on the smallest hole:





The larger the traction, the stronger the magnetic response → Attributed to martensite creation, confirmed by X-ray diffraction.

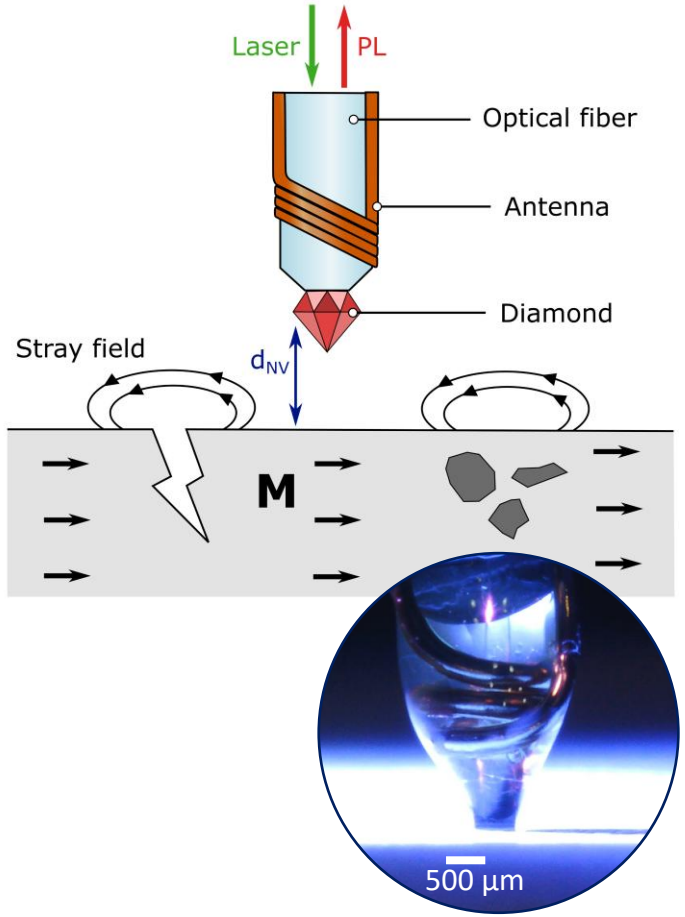
→ High resolution, quantitative sensing.

NDT case #3

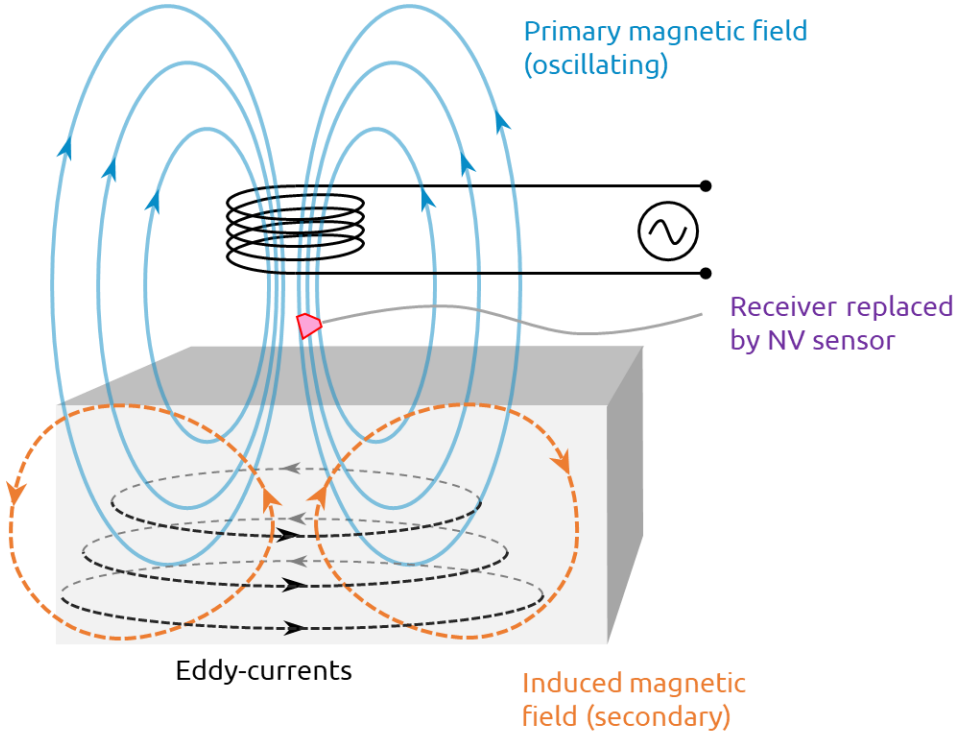
Cracks in stainless steel, using eddy currents

NV magnetometry

Stray field measurements



Eddy currents measurements



- Implement AC sensing with eddy current testing:
  - Local magnetic excitation.
  - Study non magnetic materials (nickel-based, austenitic steel).

Cracks in stainless steel (304L)

Example of use cases: Storage of hydrogen or Liquefied Natural Gas in stainless steel tanks.

LNG tankers

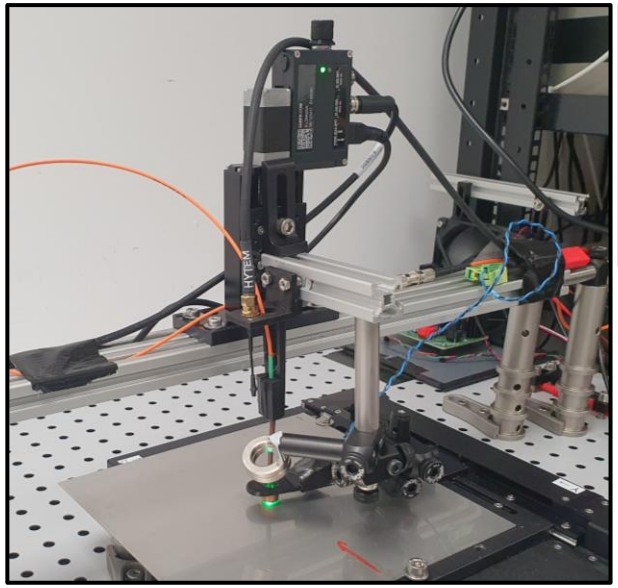
Goal:

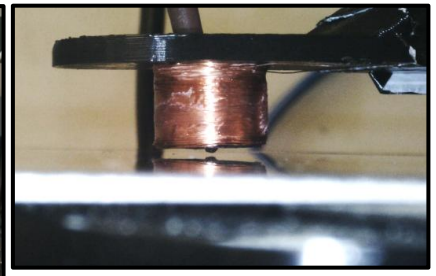
- ❑ Validate eddy current measurements with NV magnetometry.
- ❑ Detect micrometric non-surface-breaking defects.

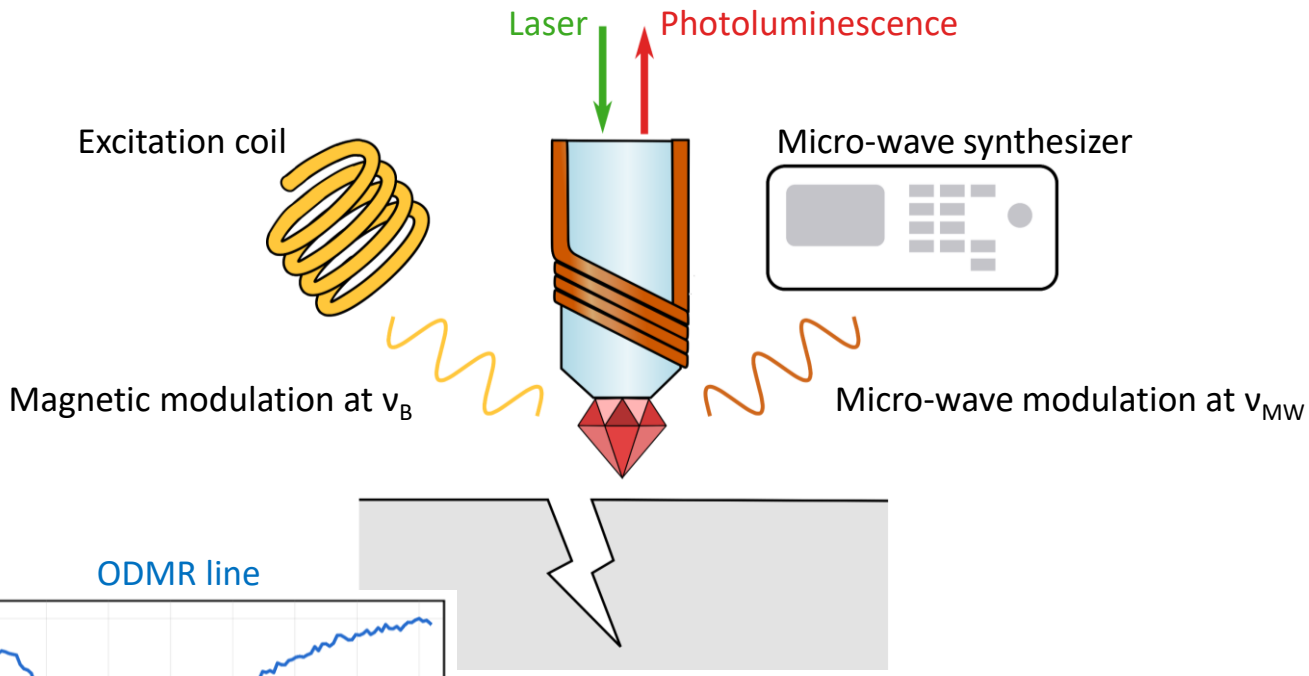
Sample:

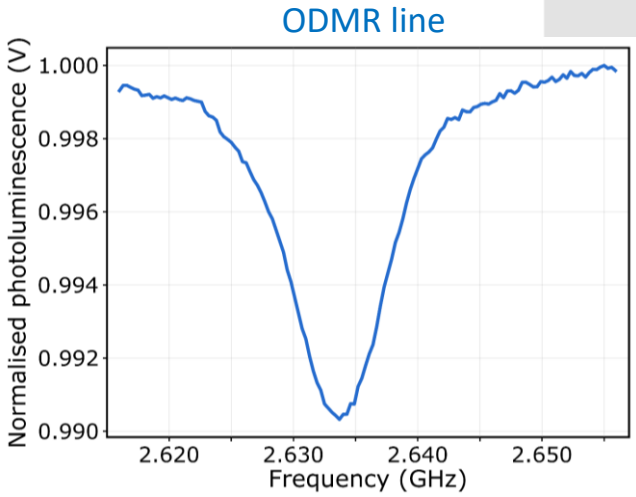
1.5 mm stainless steel plate with cracks.

Cracks dimensions: L = 2 mm, width = 100 µm, depth = 300 µm

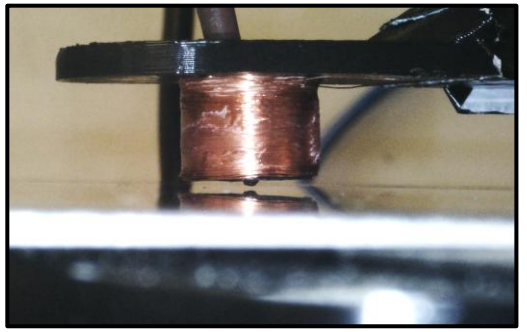




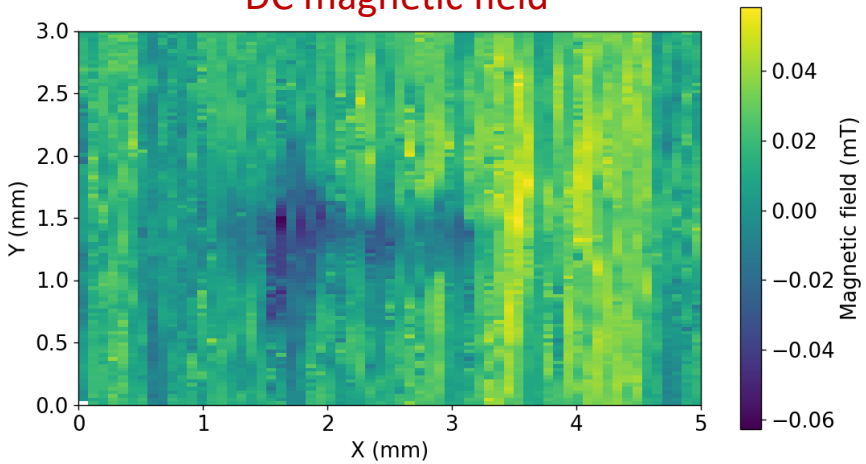




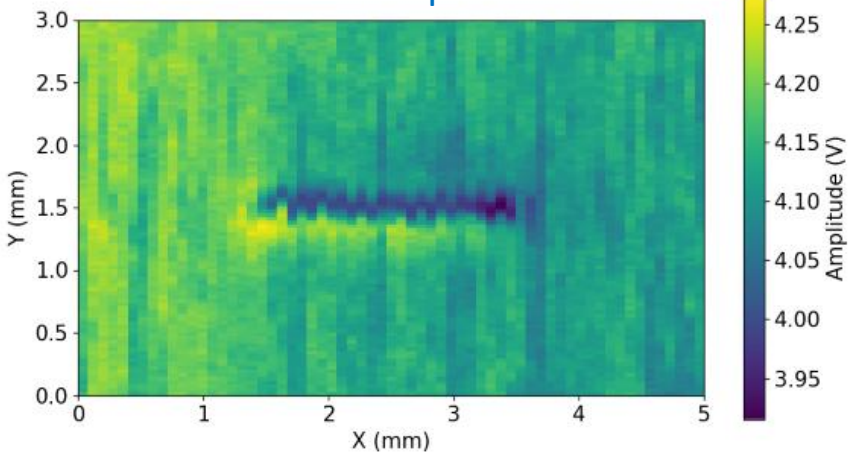
Cracks in stainless steel (304L)



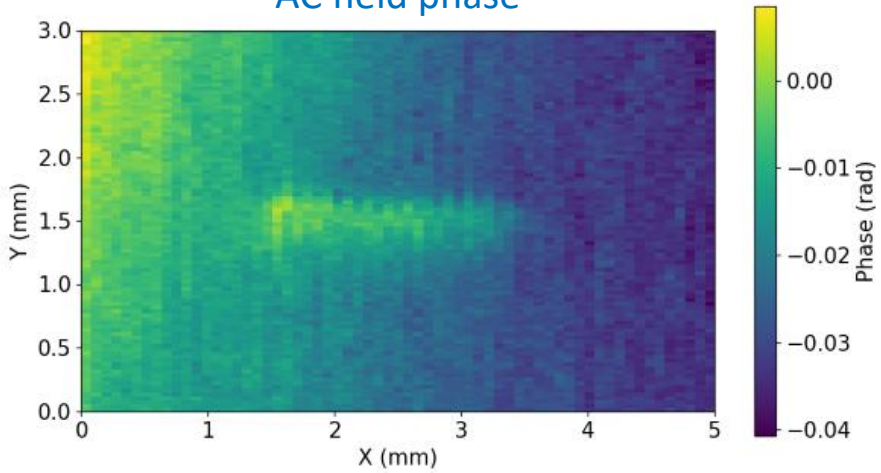
DC magnetic field



AC field amplitude



AC field phase



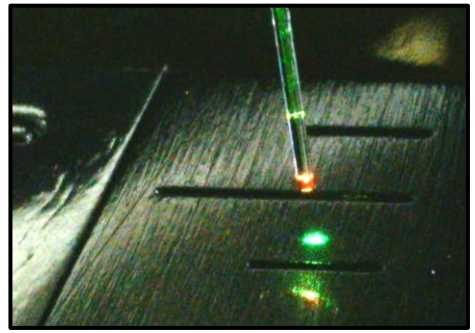
Goal:

→ **Versatile: one sensor, multiple readouts**

- ✓ Validate eddy current measurements with NV magnetometry.
- ✓ Detect micrometric non-surface-breaking defects → Done through thickness up to **2.7 mm** in stainless steel.

Conclusions

Advantages of NV for NDT



Reliable and efficient

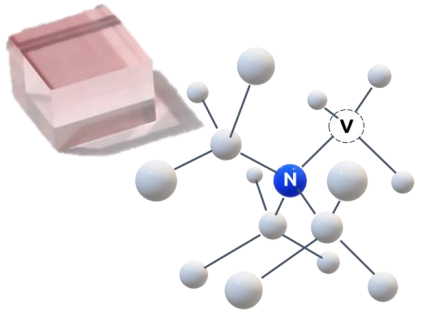
- High sensitivity (< nT/√Hz)
- High resolution (< 10 µm achievable)
- Quantitative, vectorial and no calibration
- Digital measurement

Easy implementation

- Small probe (sub-mm) with no electronics for difficult geometries
- Ready-to-use (no coupling fluid, no preparation)
- Detection through paints and coatings
- Diamond robustness (T°, radiation)

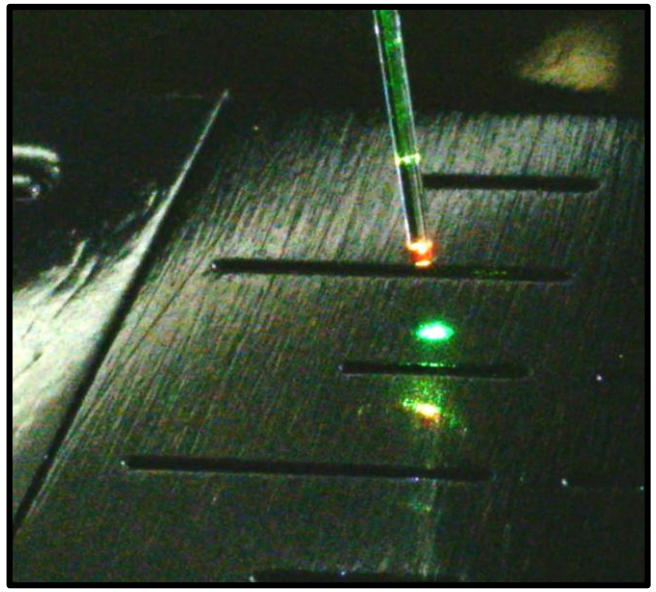
→ Advantages that make sense especially for critical defects and harsh environments.

Conclusion – what can quantum sensors bring to the industry?



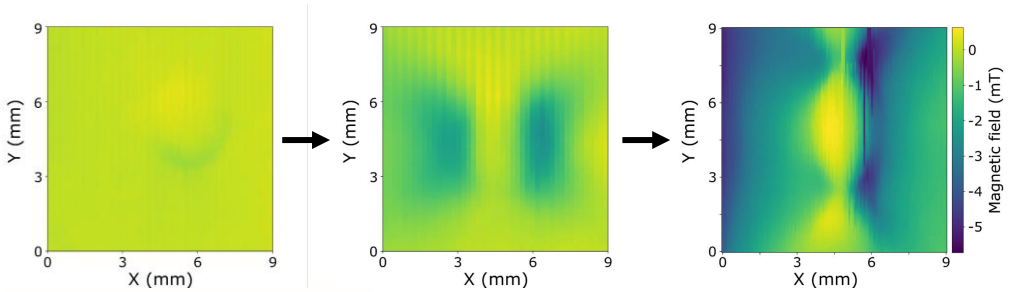
Diamond quantum sensors push back the limits of classical sensors:

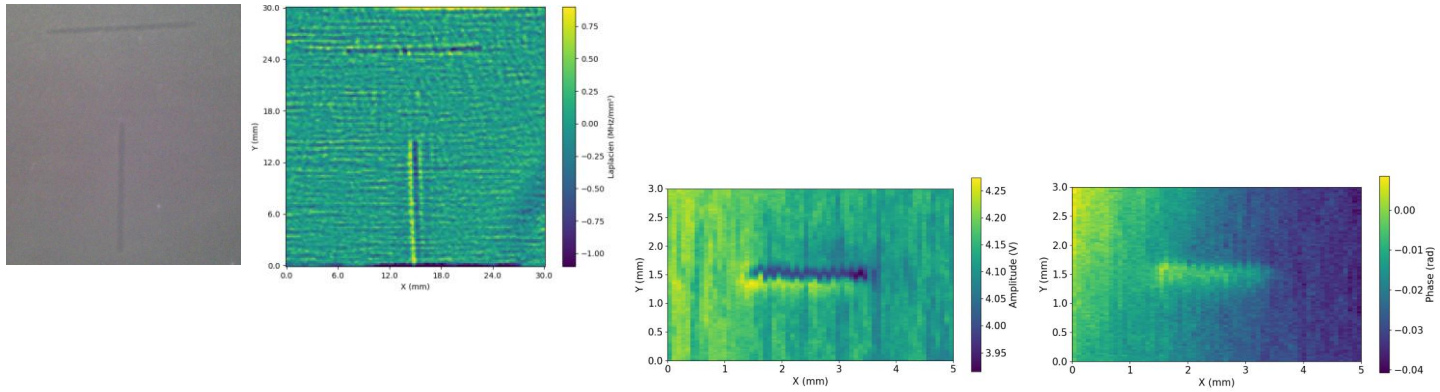
→ This opens new perspectives for applications, with an identified interest in the aeronautics, metallurgy and energy sectors (welding inspection, embrittlement characterization, non-surface breaking micrometric defects etc.).



We think that diamond sensors can improve existing magnetic-based NDT techniques (MFL, EC …) on critical defects and environments.

More sensitive, more efficient, not more complicated.





Thank you

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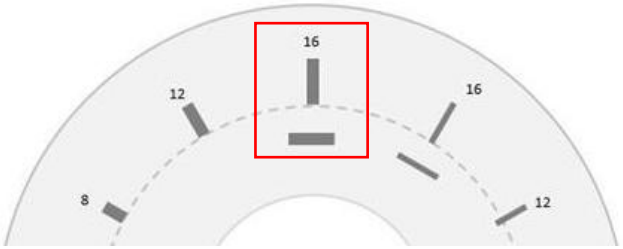
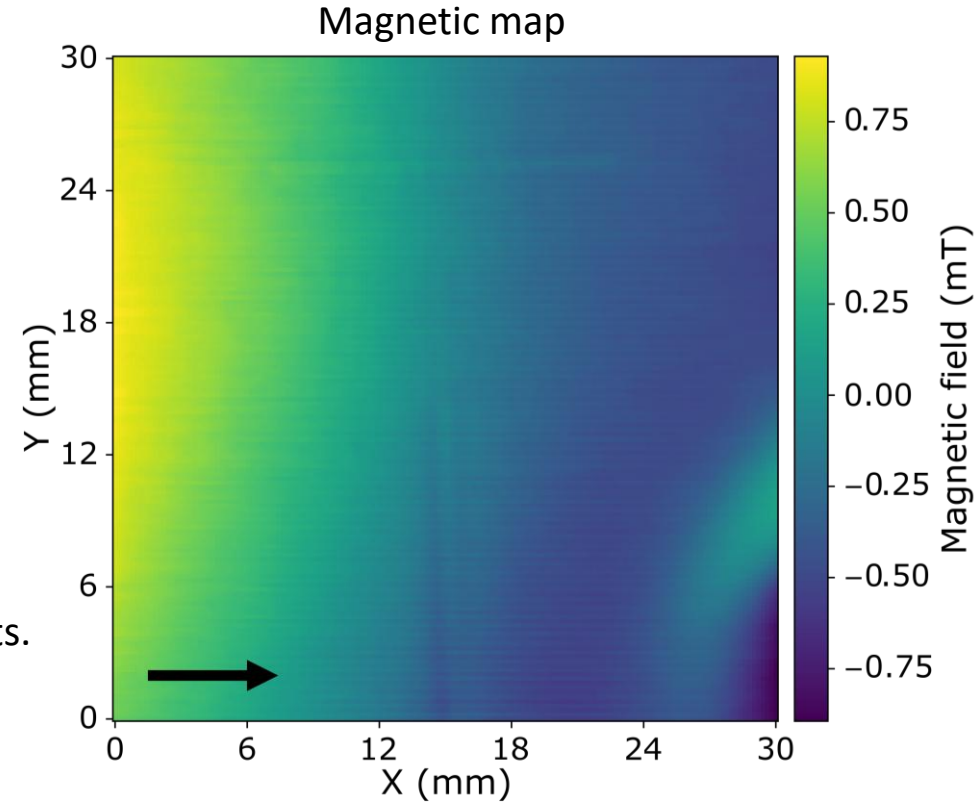
contact@kwan-tek.com

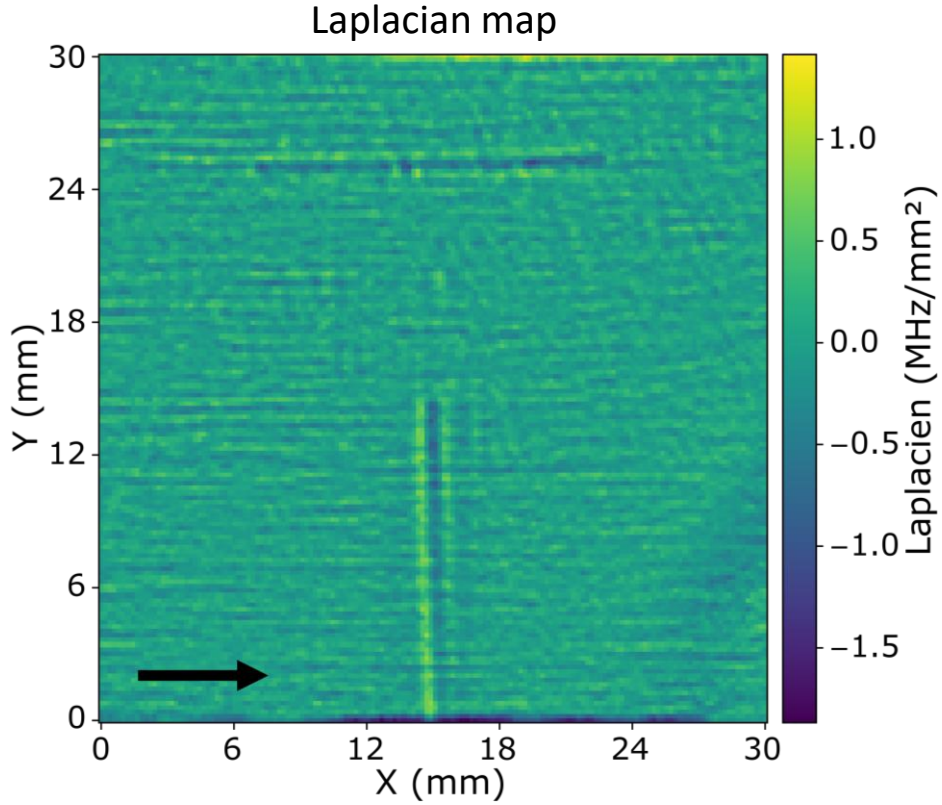
First results on intense burns

→ Development & validate the principle:

The burns were revealed by nital etching prior to NV measurements.







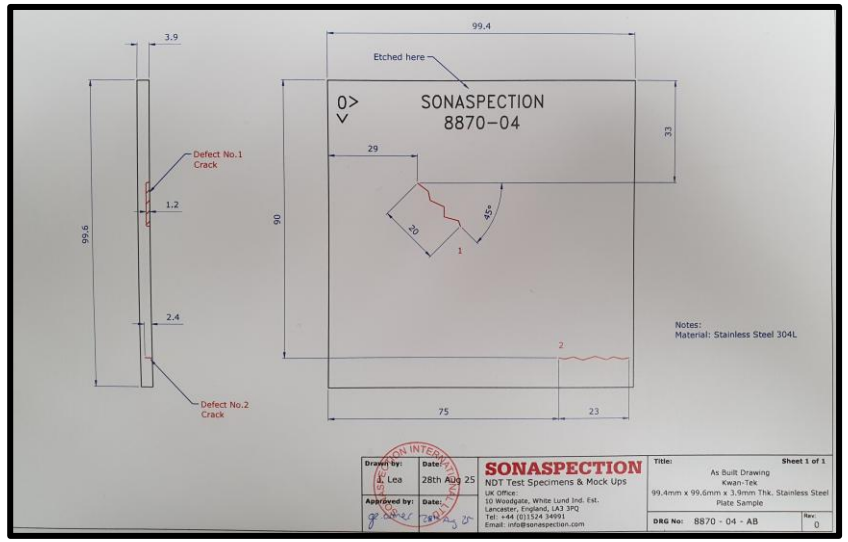
Goals of the project:

✓ Validate that NV can detect grinding burns

❑ Determine the detection levels

Non-surface-breaking defects in stainless steel (304L)

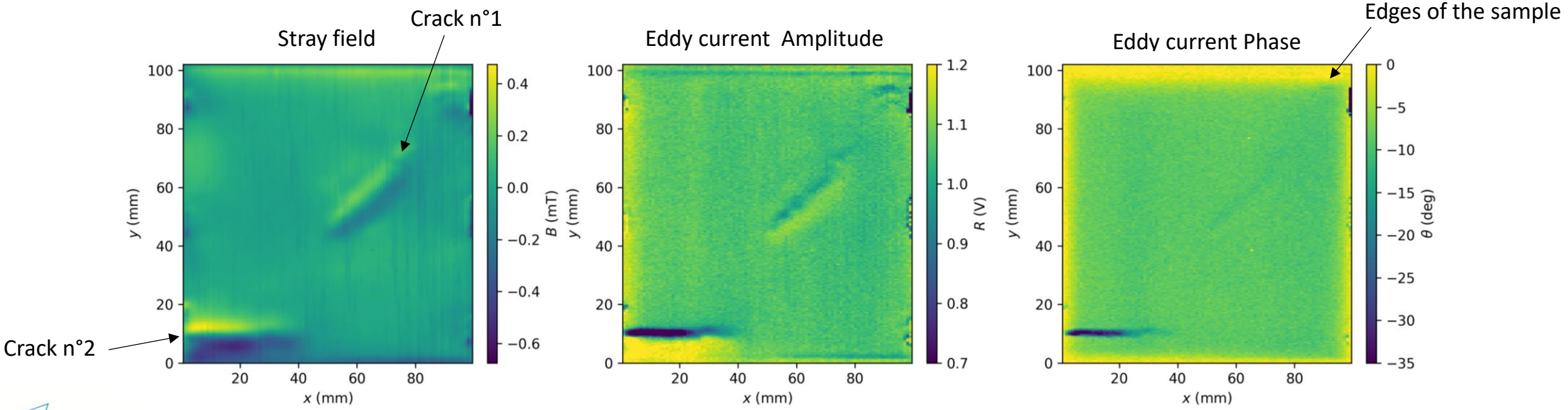
Sample detail (provided by Sonaspection, Lancaster)



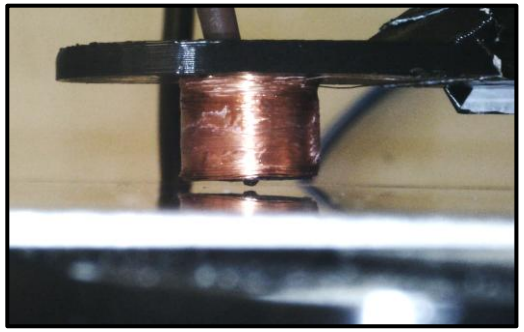
3.9 mm stainless steel plate with typical cracks defects for nuclear applications.

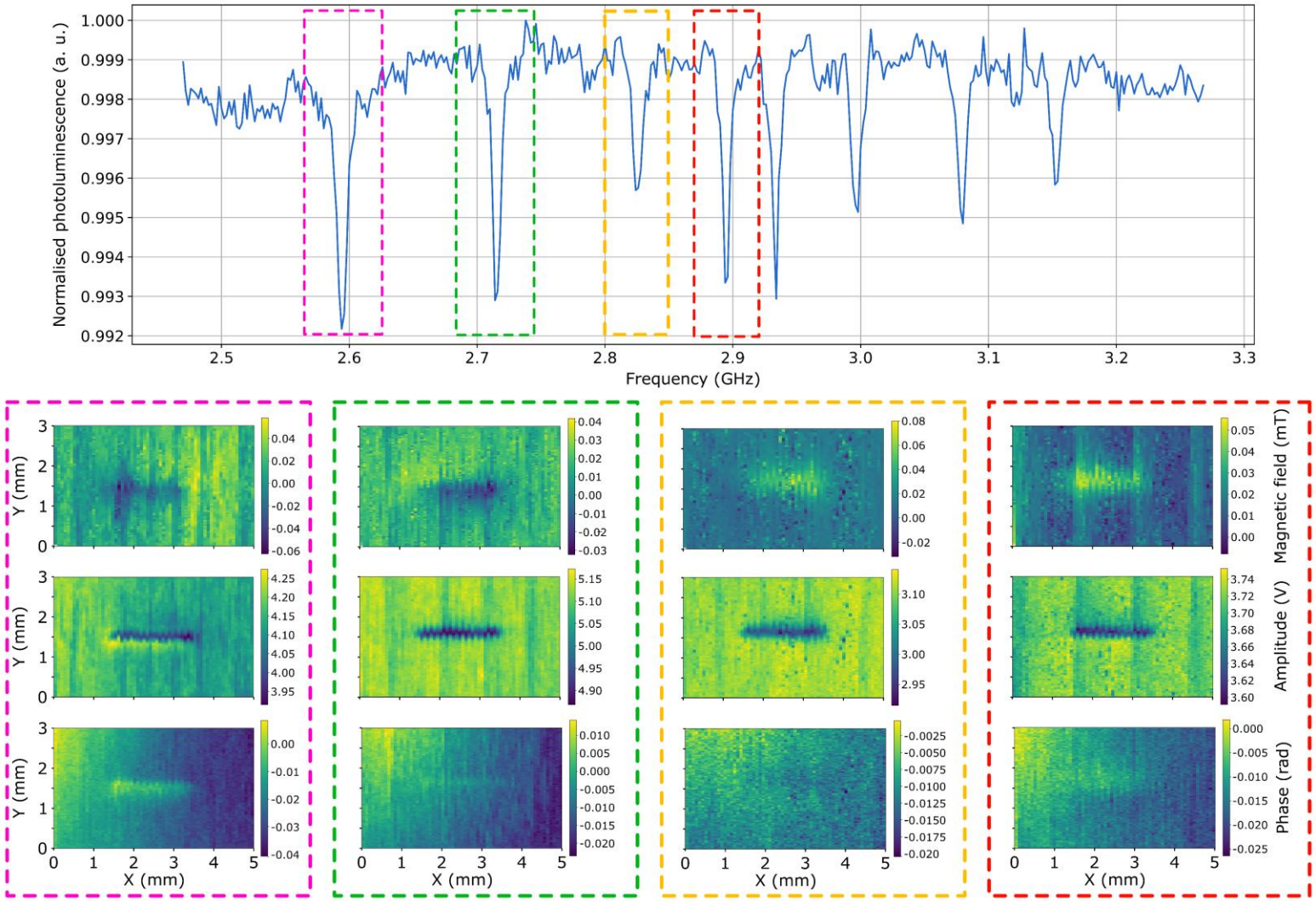
Cracks dimensions: L = 20 mm, depth = 1.2 and 2.4 mm

→ We were able to detect **micrometric non-surface-breaking cracks** through thickness up to **2.7 mm** (maximum sample thickness).



Cracks in stainless steel (304L)





→ Versatile: one sensor, multiple complementary readouts and vectorial measurement