



THERMISCHE TOMOGRAFIE

DER 3D-BLICK INS BAUTEILINNERE

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FH OÖ Forschungs & Entwicklungs GmbH, Wels, Austria



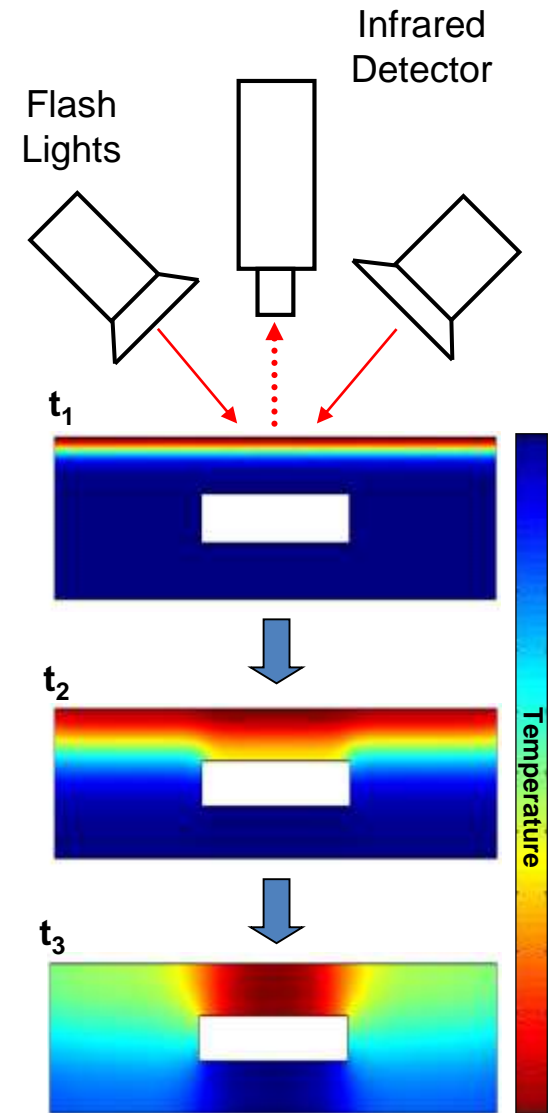
www.thermo-ndt.com

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UNIVERSITY
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ACTIVE THERMOGRAPHY



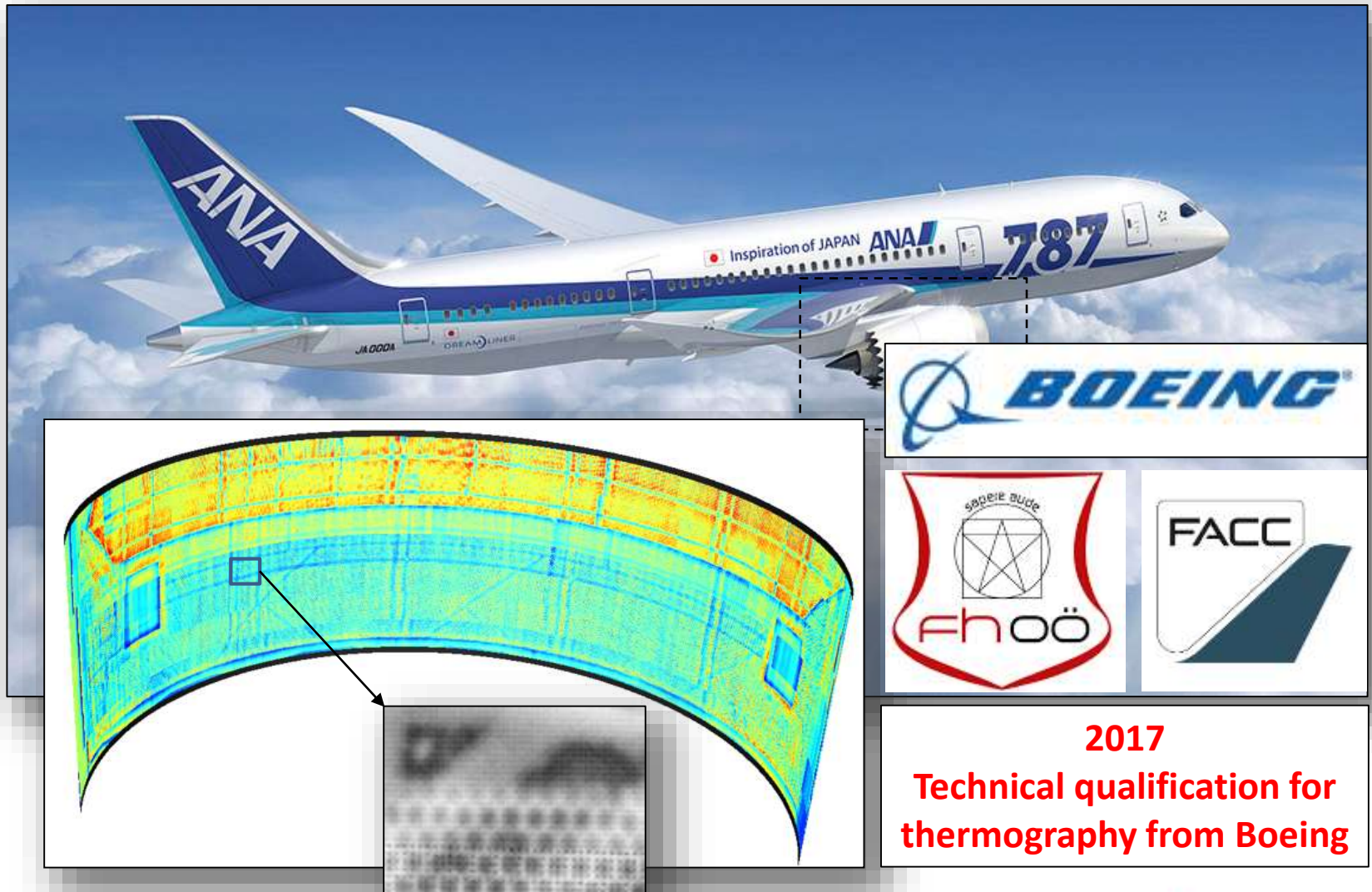
APPLICATIONS in AEROSPACE INDUSTRY



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VIRTUAL WAVE CONCEPT

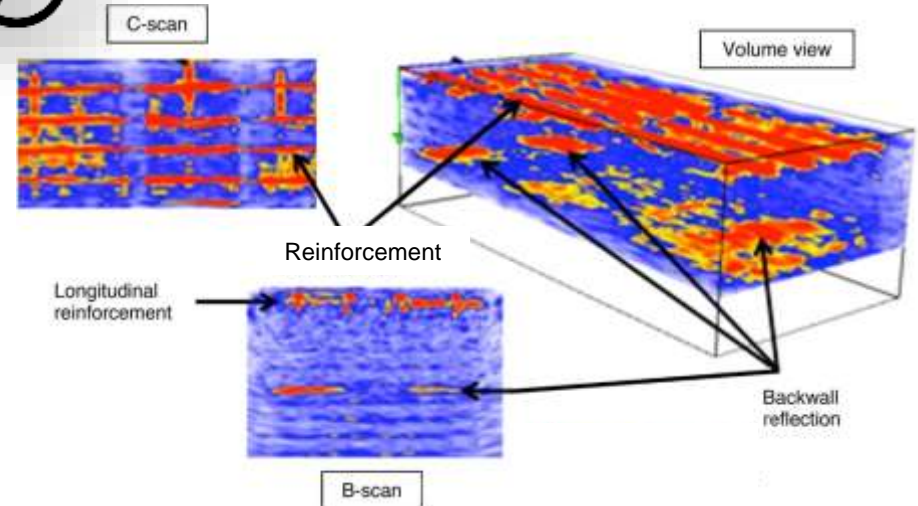
2D Thermographic Imaging



... more than
1 Million
detector
elements



3D Ultrasonic Imaging



~100 detector
elements

VIRTUAL WAVE CONCEPT

Step 1: Calculation of the virtual wave field ⁽¹⁾

Heat conduction equation

$$\left(\nabla^2 - \frac{1}{\alpha} \frac{\partial}{\partial t} \right) T(\mathbf{r}, t) = \underbrace{-\frac{1}{\alpha} T_0(\mathbf{r}) \delta(t)}_{\text{source term}}$$

Virtual temperature wave equation

$$\left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) T_{\text{virt}}(\mathbf{r}, t) = \underbrace{-\frac{1}{c^2} \frac{\partial}{\partial t} T_0(\mathbf{r}) \delta(t)}_{\text{source term}}$$

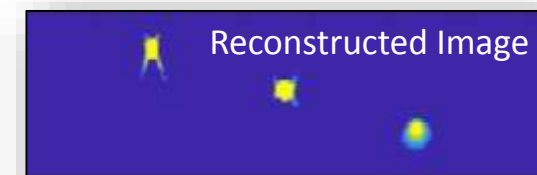
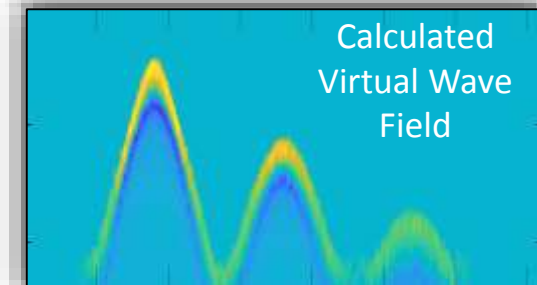
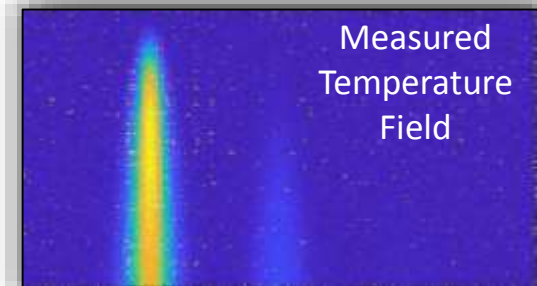
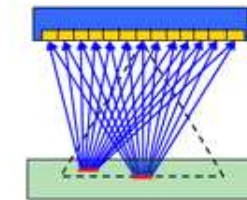
Transformation: $\int_{-\infty}^{\infty} K(t, t') T_{\text{virt}}(\mathbf{r}, t') dt' = T(\mathbf{r}, t)$

with: $K(t, t') \equiv \frac{c}{\sqrt{\pi \alpha t}} \exp\left(-\frac{c^2 t'^2}{4 \alpha t}\right)$ for $t > 0$

Fredholm
Integral 1st
kind

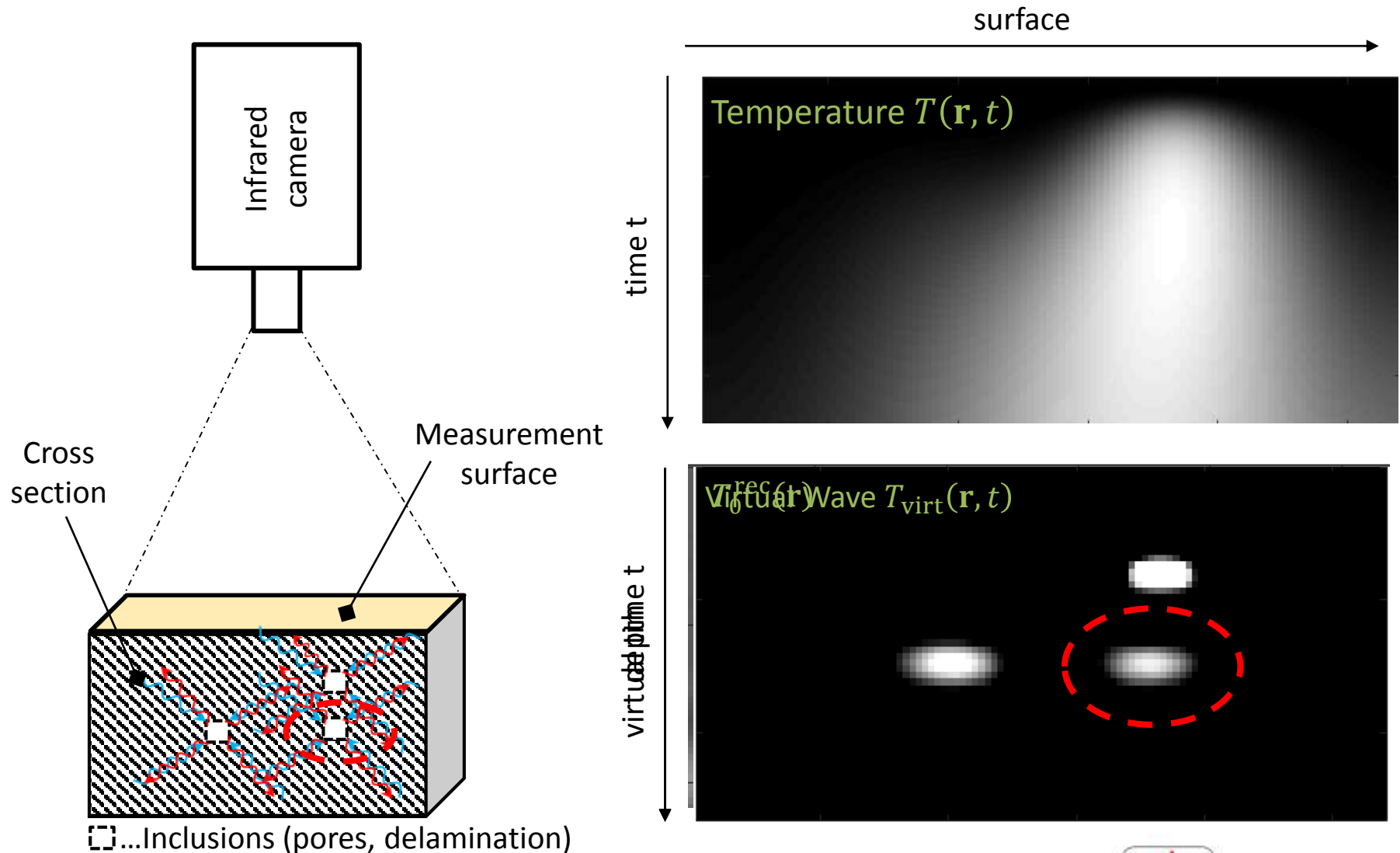
Step 2: Ultrasound image reconstruction methods

- **F-SAFT** (Frequency domain synthetic aperture focusing technique)
- **Time Reversal Techniques**



¹ Burgholzer P, Thor M, Gruber J, Mayr G. *J Appl Phys* **121**, 105102 (2017)

VIRTUAL WAVE CONCEPT

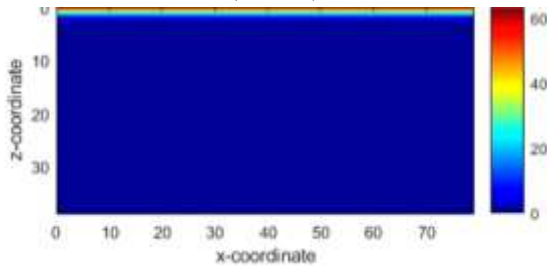


1D VIRTUAL WAVE FIELD

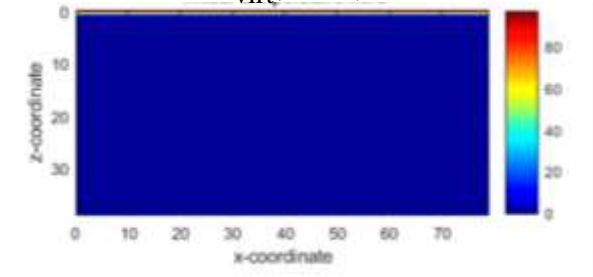
Active Thermography
(Optical excitation)



Temperature Field
 $T(x, z, t)$



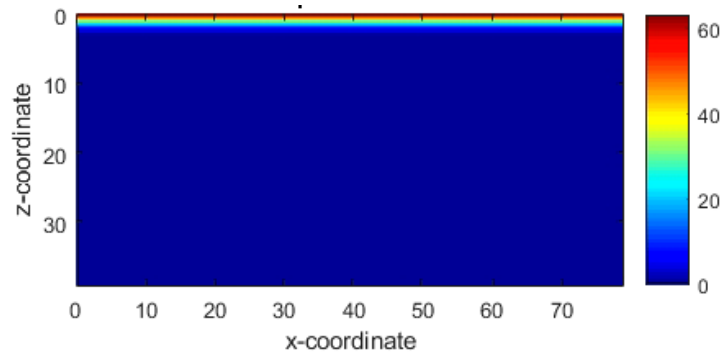
Virtual Wave Field
 $T_{\text{virt}}(x, z, t)$



1D VIRTUAL WAVE FIELD

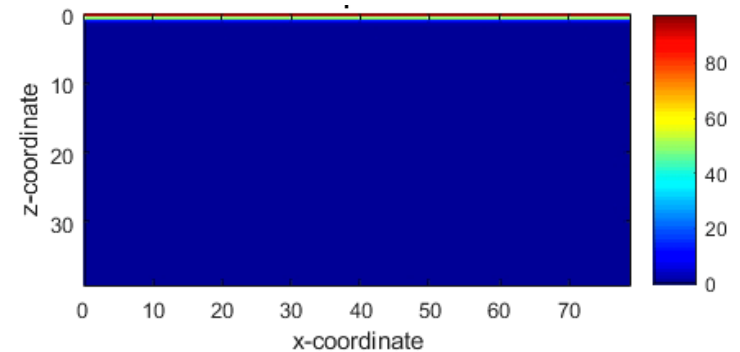
Temperature Field 1D

$$T(x, z, t)$$

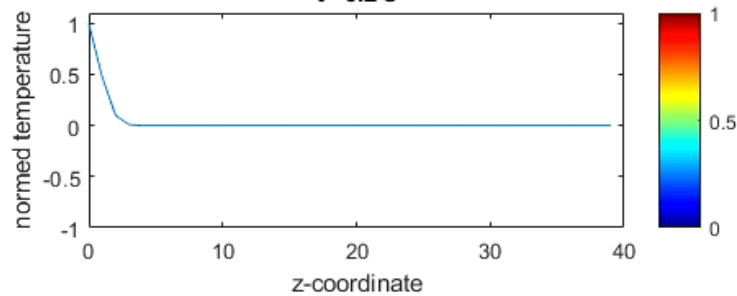


Virtual Wave Field 1D

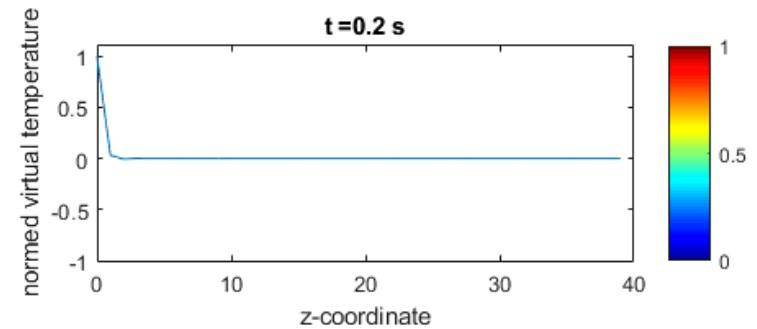
$$T_{\text{virt}}(x, z, t)$$



$t = 0.2 \text{ s}$



$t = 0.2 \text{ s}$



INFRARED DETECTORS

Josef Ressel Zentrum, FH OÖ Campus Wels



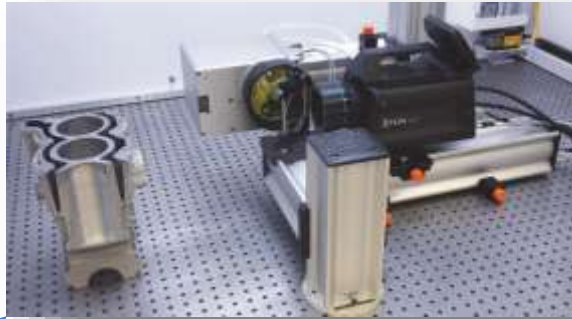
	High-Resolution IR quantum detector	Standard IR quantum detector	Microbolometer IR detector	High-Speed IR quantum detector
Device	FLIR X8400 sc	IRCAM Equus 81k M Pro	FLIR PM 695	FLIR X6900 sc
Detector type	Indium Antimonide (InSb)	Indium Antimonide (InSb)	uncooled microbolometer	Indium Antimonide (InSb)
Resolution	1280 x 1024 pixels	320 x 256 pixels	320 x 240 pixels	640 x 512 pixels
Minimal pixel size	~ 5 μm	~ 40 μm	~ 80 μm	-
Sprectral range	3 to 5 μm	3 to 5 μm	7.5 to 13 μm	3 to 5 μm
Image frequency (fullframe)	106 Hz	386 Hz	50 Hz	1004 Hz

THERMAL EXCITATION SOURCES

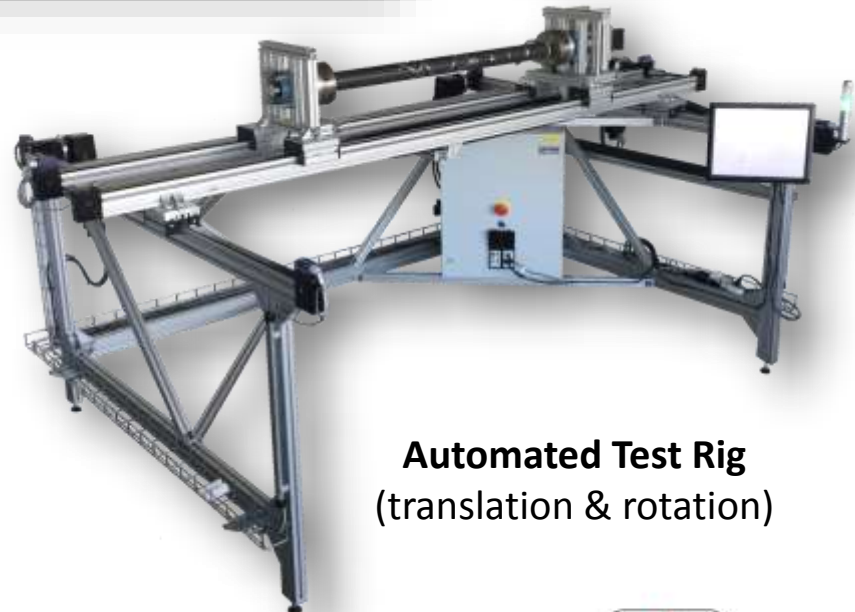
Laser Test System
(250 W)



Galvano-Scanner
(2D)



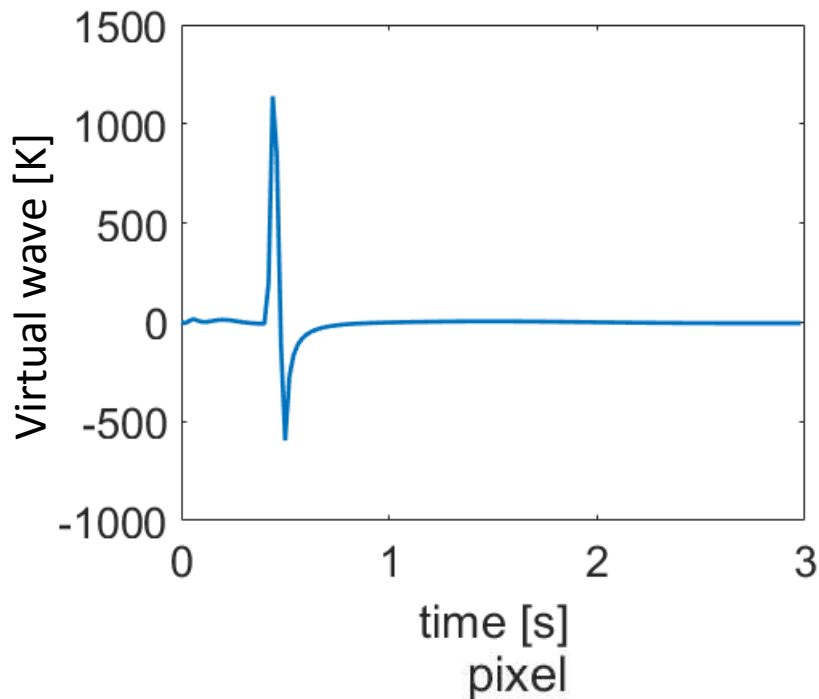
Flash Lights
(12 000 Ws)



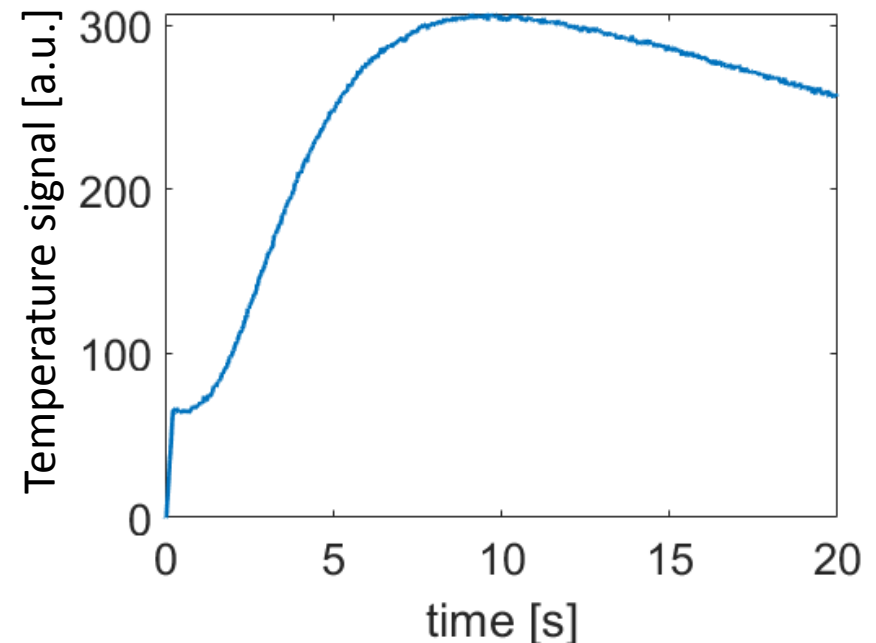
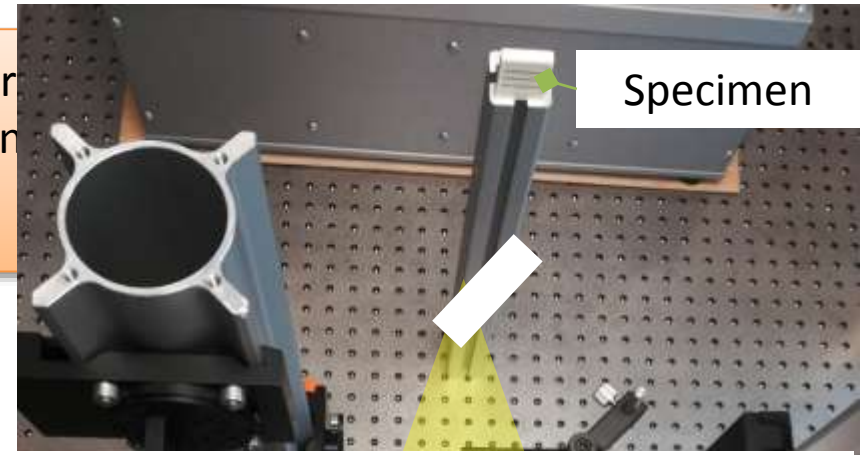
Automated Test Rig
(translation & rotation)

LASER-EXCITED THERMOGRAPHY

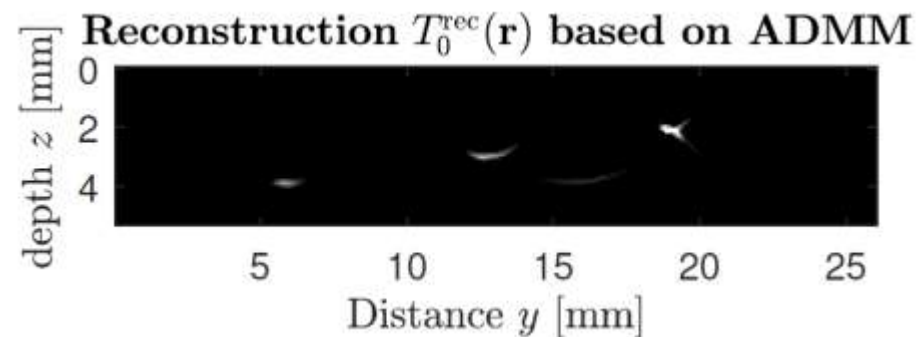
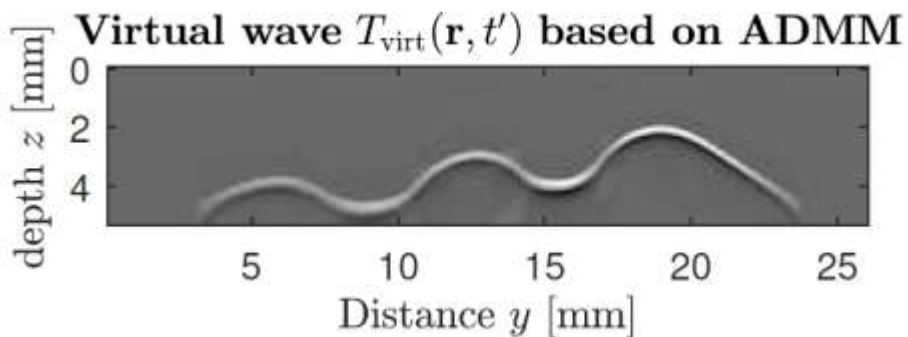
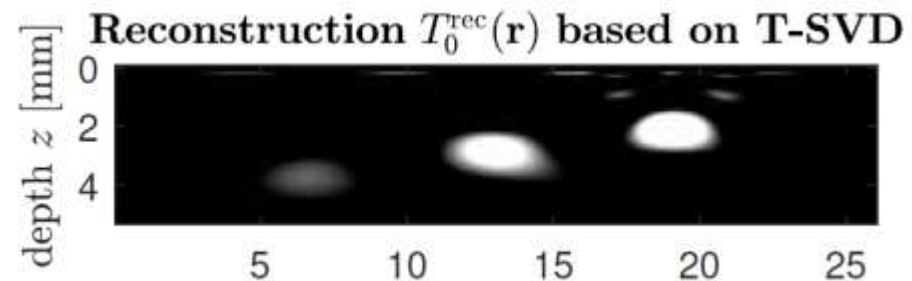
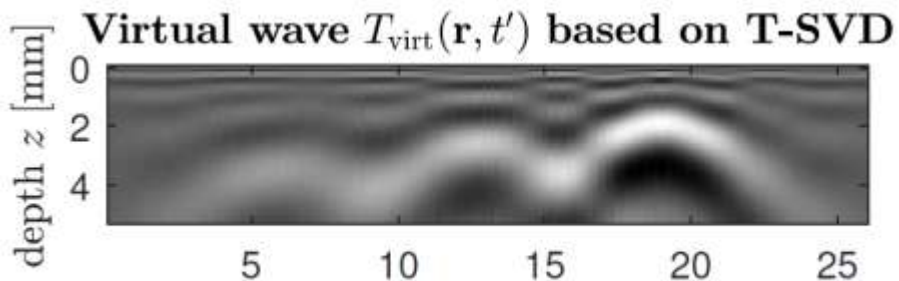
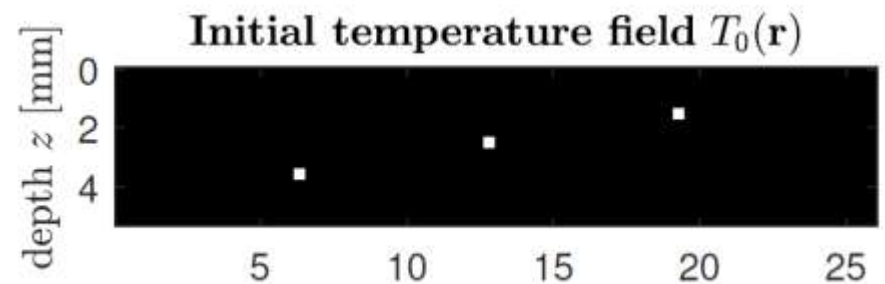
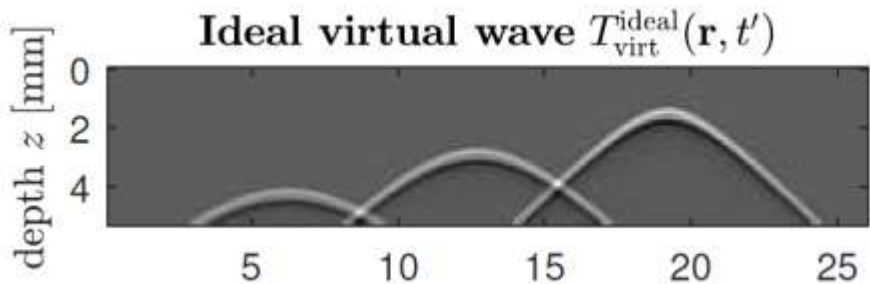
Thermographic A-Scan
(TIME OF FLIGHT - TOF)



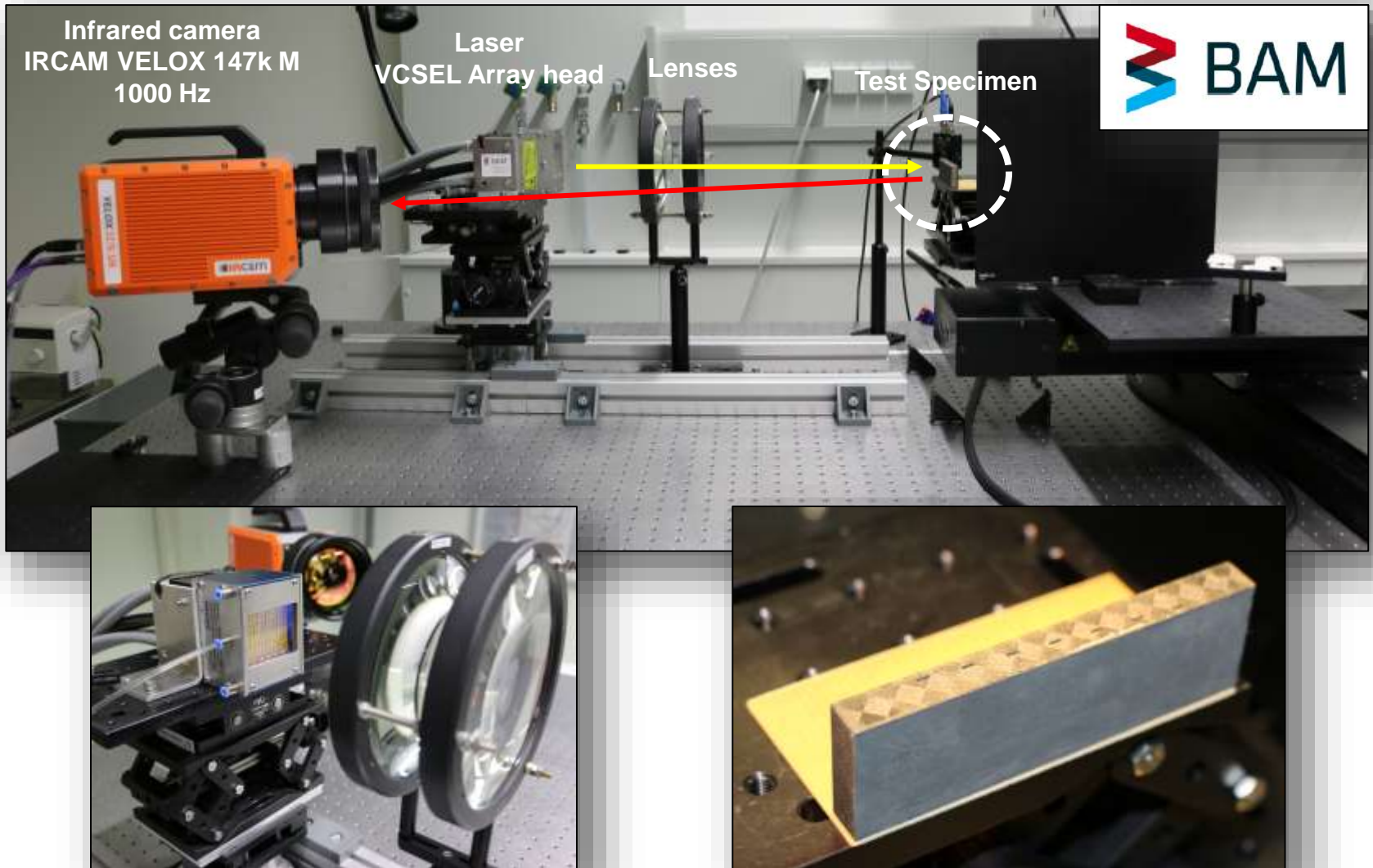
Transfer
Function
 \hat{K}



LASER-EXCITED THERMOGRAPHY

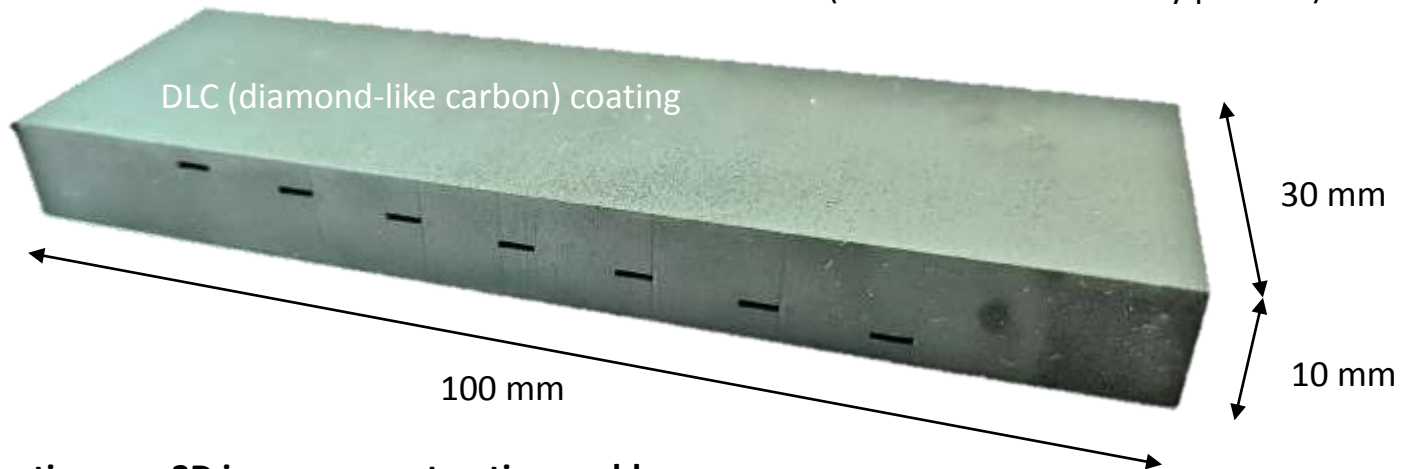


BREAKING THE DETECTION LIMIT

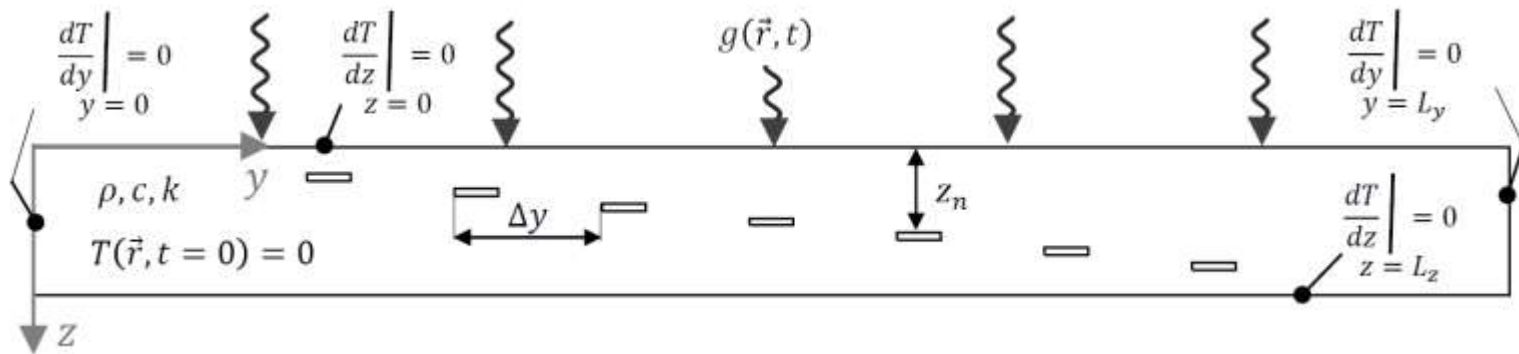


BREAKING THE DETECTION LIMIT

Test specimen manufactured with metal 3D printing
(cobalt-chromium alloy powder)



Realization as a 2D image reconstruction problem:

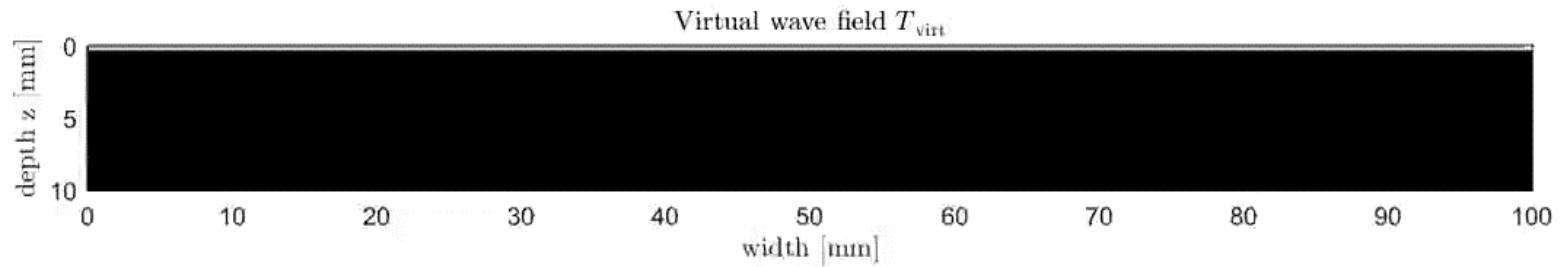


BREAKING THE DETECTION LIMIT



Exact solution of the Virtual Wave Field:

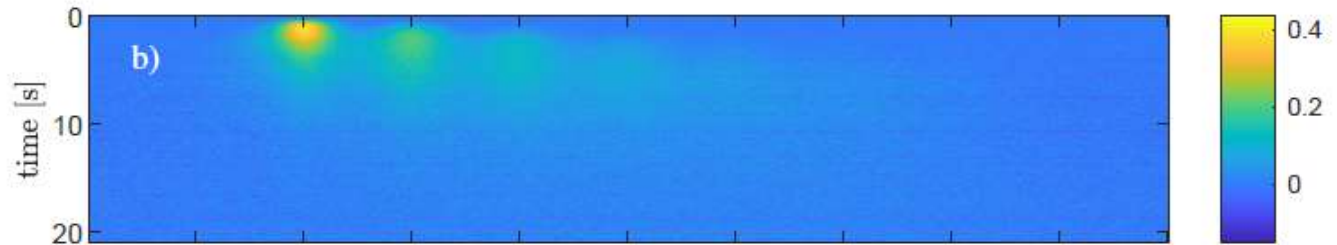
$T_{\text{virt}}^{\text{exact}}$



BREAKING THE DETECTION LIMIT



Temperature field
 T



Virtual wave field
 T_{virt}

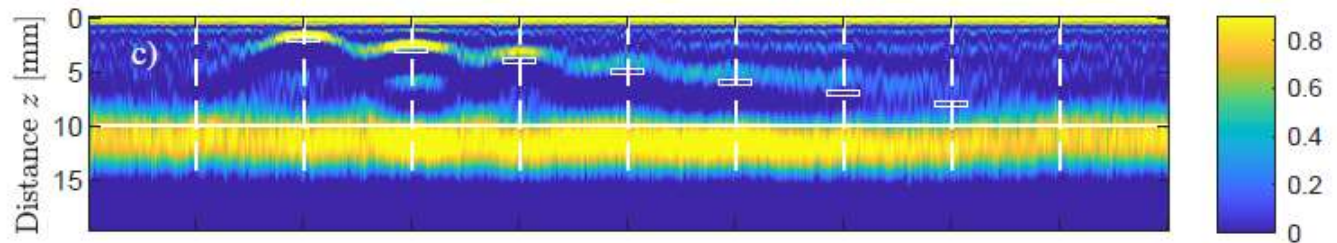
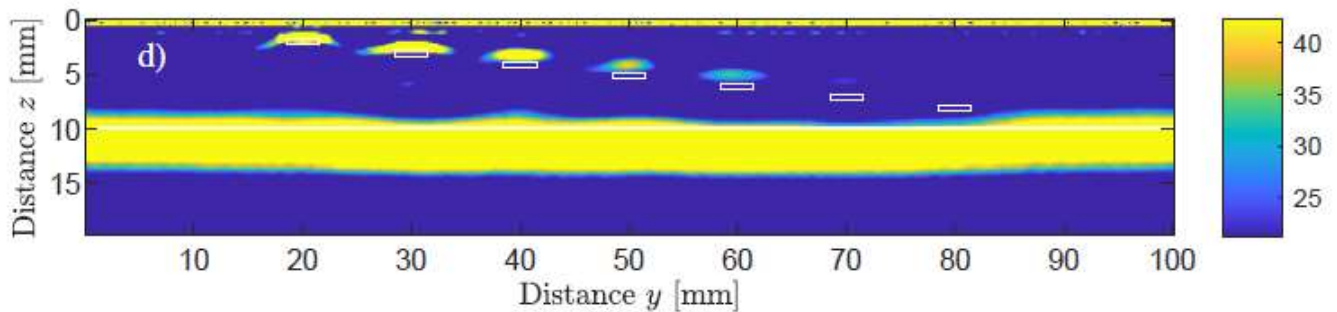


Image
reconstruction
 T_0



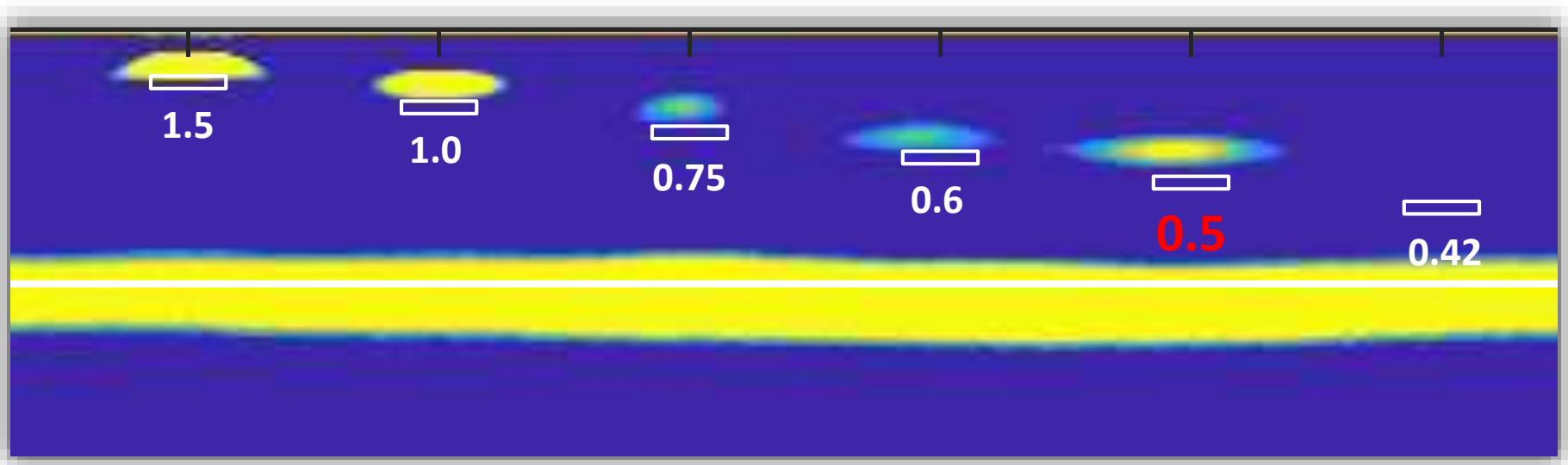
BREAKING THE DETECTION LIMIT

The Thermographic Rule of Thumb for Defect Detection:

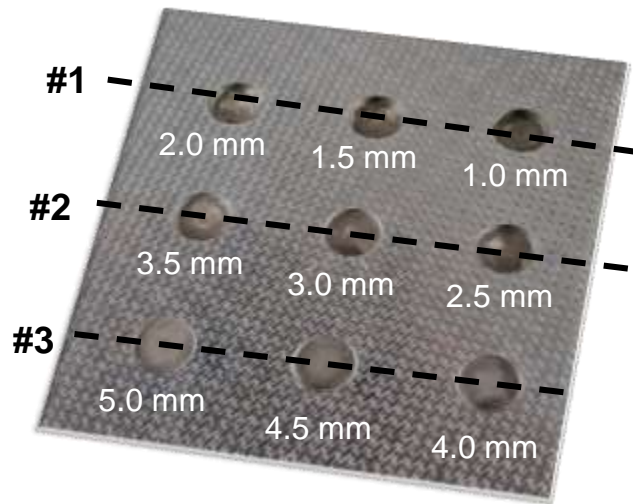
DEFECT ASPECT RATIO HAS TO BE GREATER THAN 2

ADMM, F-SAFT and laser excitation:

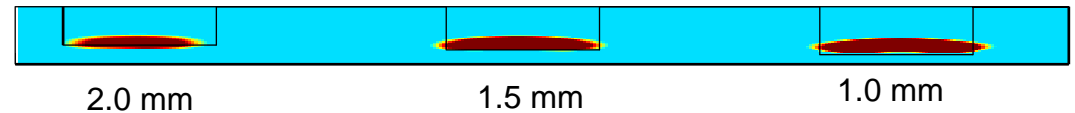
DEFECT ASPECT RATIO WITH 0.5 CAN BE DETECTED!



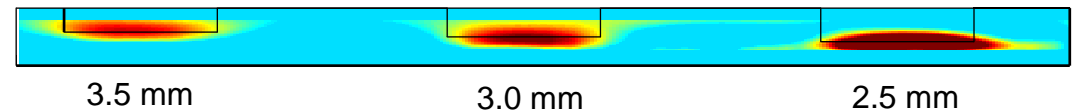
APPLICATION FOR COMPOSITES



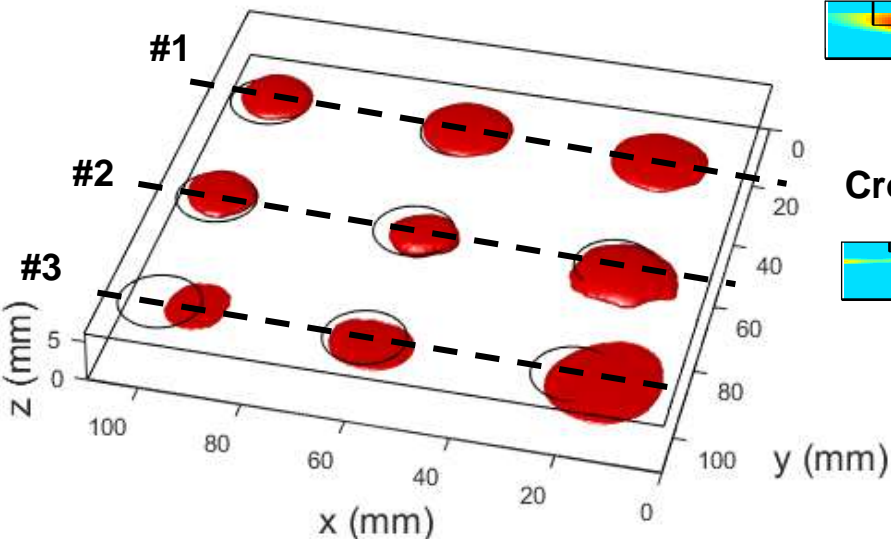
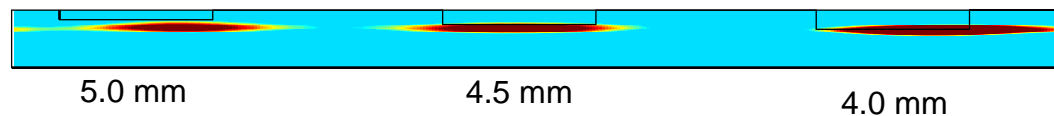
Cross-Section #1



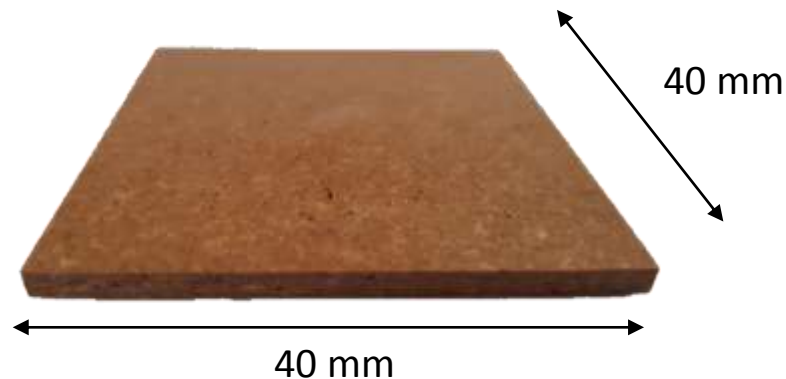
Cross-Section #2



Cross-Section #3



APPLICATION FOR COMPOSITES



Test Specimen

Wood Plastic Composite (WPC)

Thermal Diffusivity:

$$\alpha = 2 \cdot 10^{-7} \text{ m}^2/\text{s}$$

Thickness:

$$L = 3.3 \text{ mm}$$

Experimental Setup

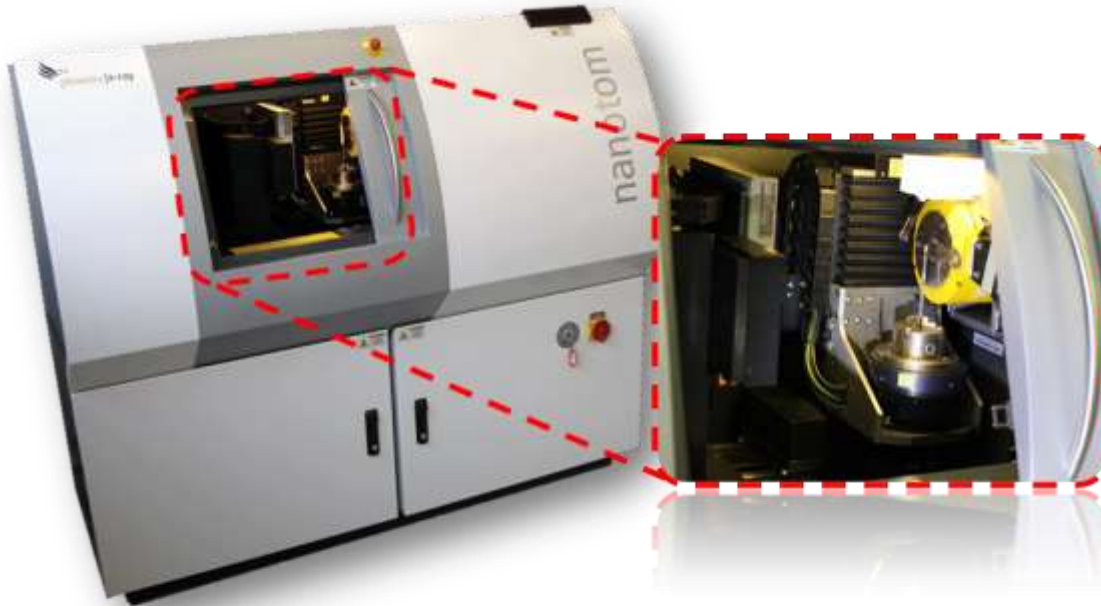
IR - camera:

FLIR X8400sc (1280x1064)

Flash lights:

Bläsing G6000Z

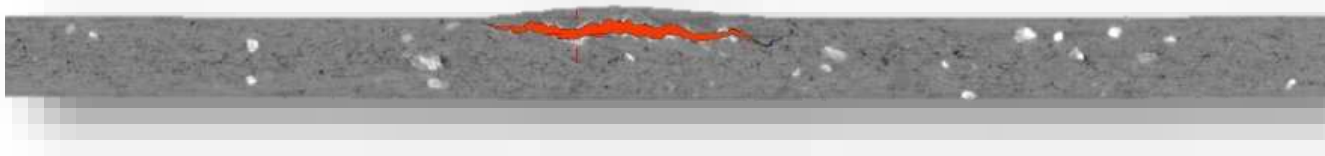
APPLICATION FOR COMPOSITES



3D Image reconstruction
with experimental data

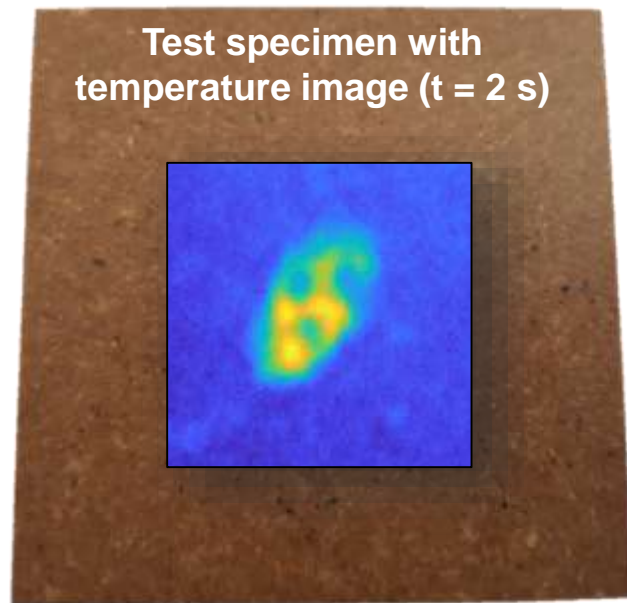


Cross section of crack

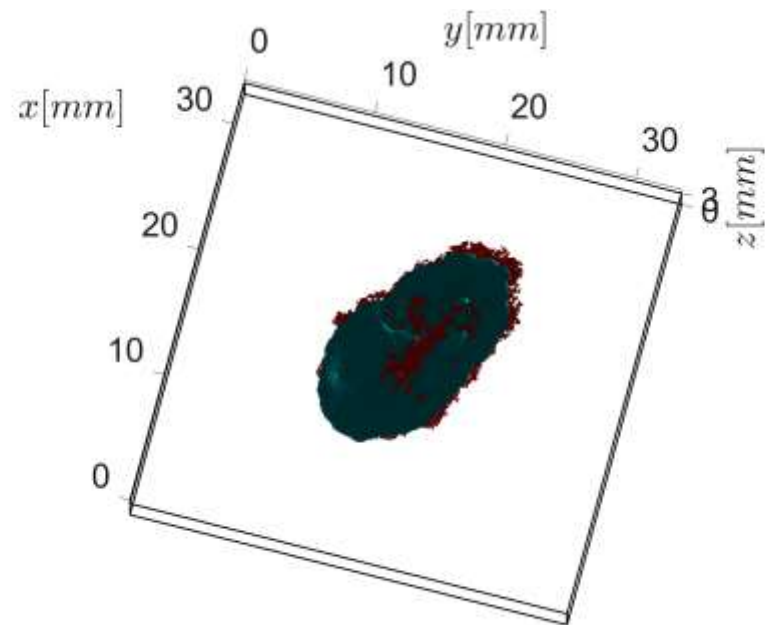


APPLICATION FOR COMPOSITES

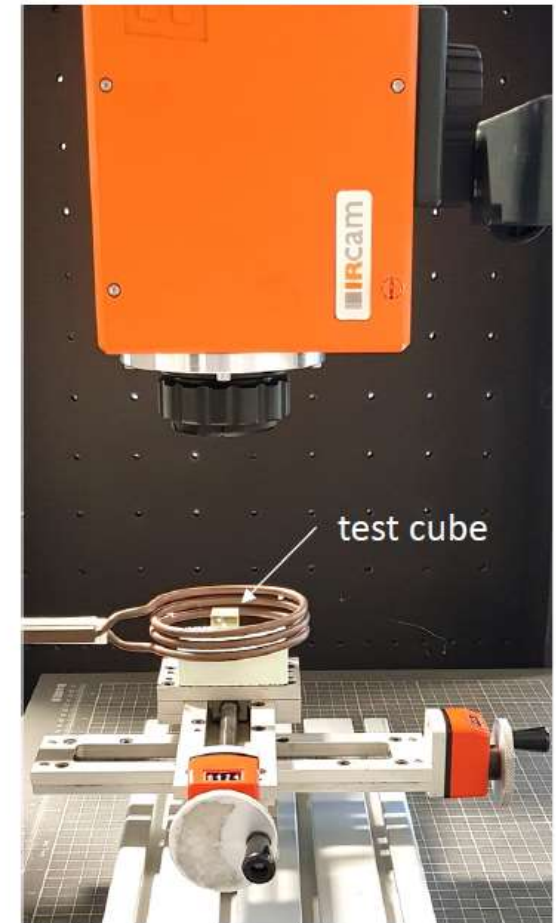
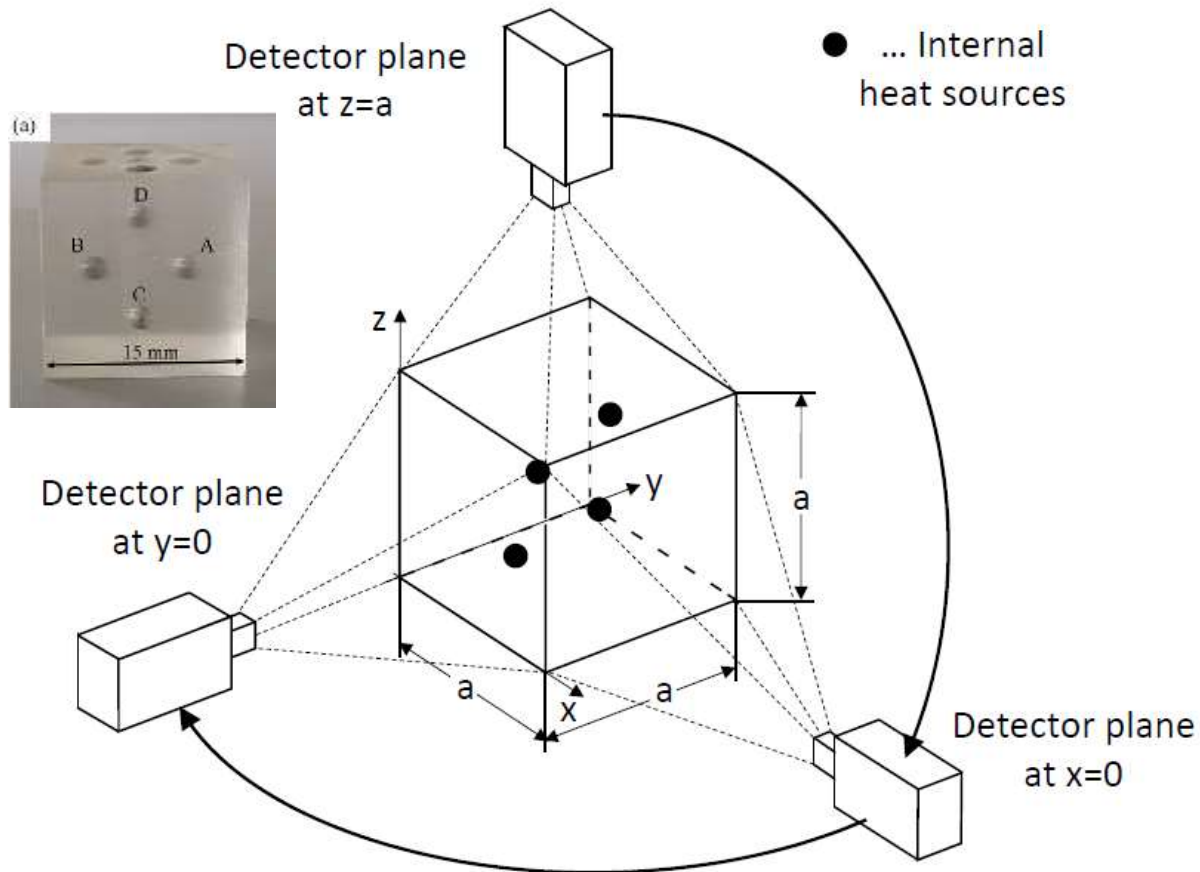
2D Thermographic measurement of the surface temperature



3D Reconstruction of the internal structure with the virtual wave concept

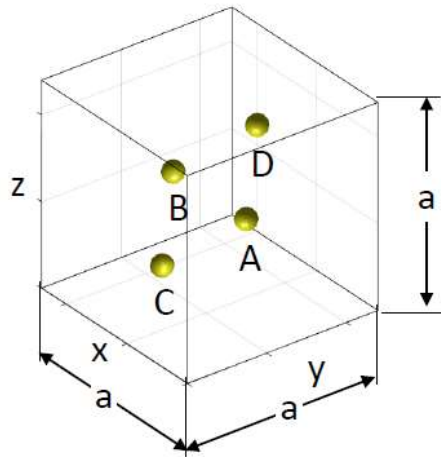


3D THERMO-TOMOGRAPHY

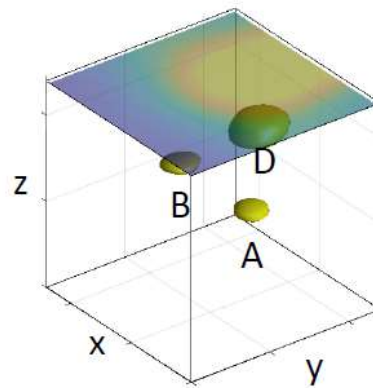


3D THERMO-TOMOGRAPHY

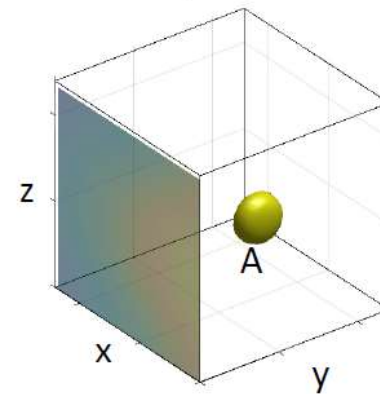
Initial temperature distribution



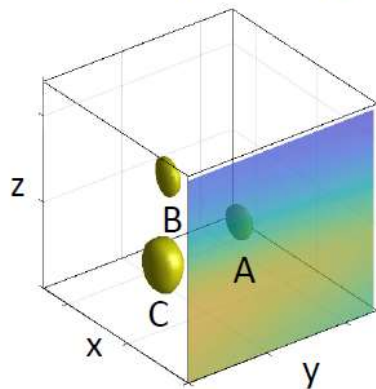
Detector plane at $z=a$



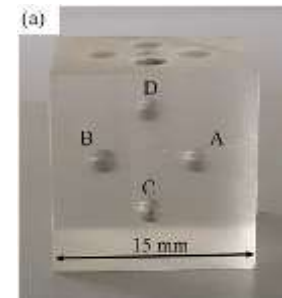
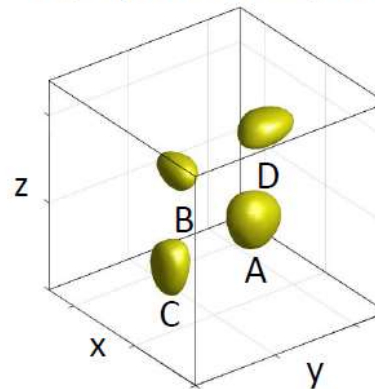
Detector plane at $x=0$



Detector plane at $y=0$



Superposition of planes



CONCLUSION

- Virtual wave concept allows the application of **ultrasonic imaging methods** for active **thermography data**
- For the calculation of the **virtual wave field** from multidimensional thermographic measurement only a **1D reconstruction** is necessary
- A **combination of multiple image reconstructions** from different detection planes (front or back side) is possible to improve the resolution

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