Lock-in Thermografie:
Prinzip und technische Anwendungen

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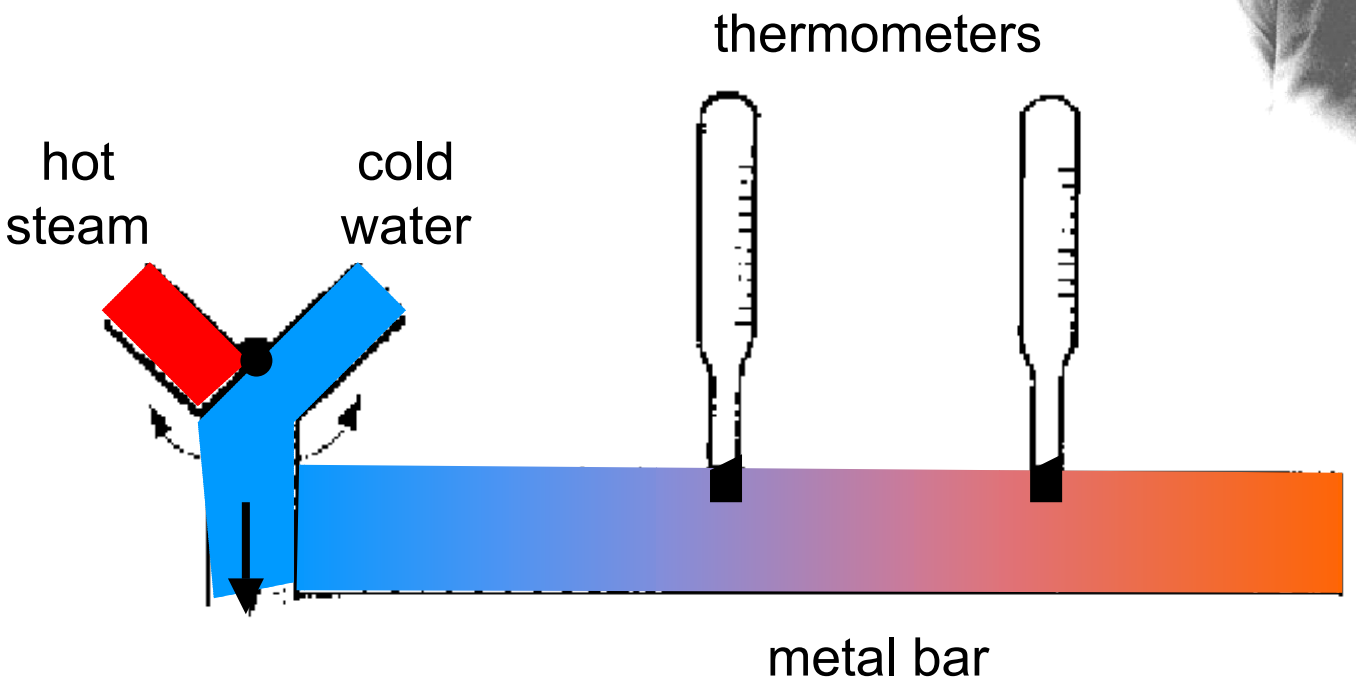
Lockin-Thermografie:

- Prinzip
- Technische Anwendungen
- Aktuelle Entwicklungen
- Zusammenfassung

Angstrom´s method: determine thermal diffusivity from phase shift across modulated heat flow

Phil. Mag. 25 (**1863**), S. 130-142

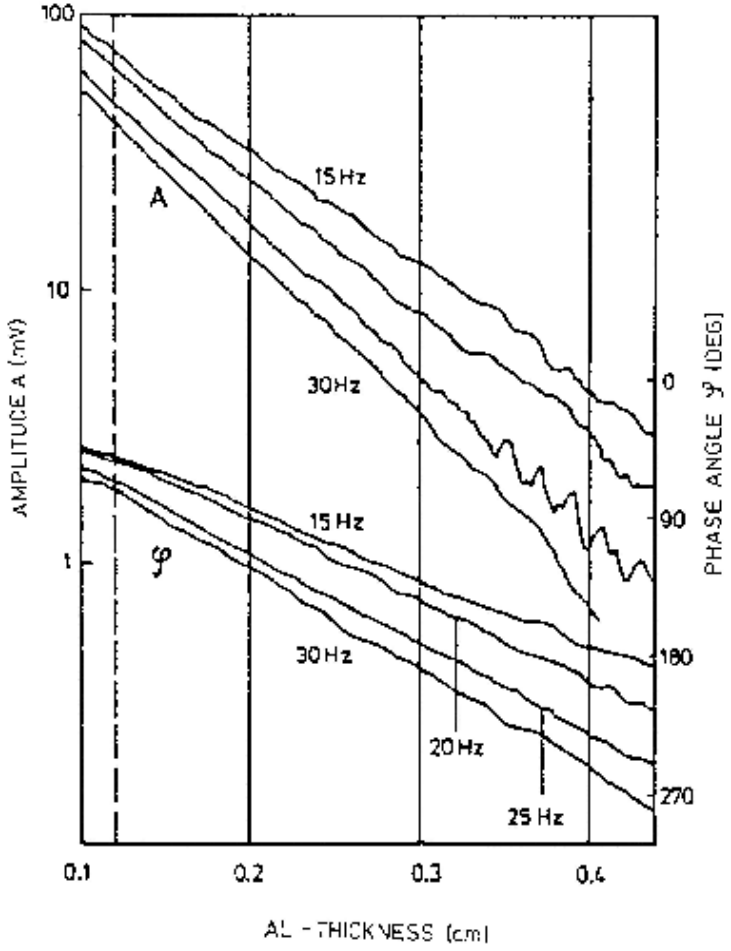


$$T(x,t) = T_0\, e^{-x/\mu} e^{i(\omega t - x/\mu)}$$

wobei

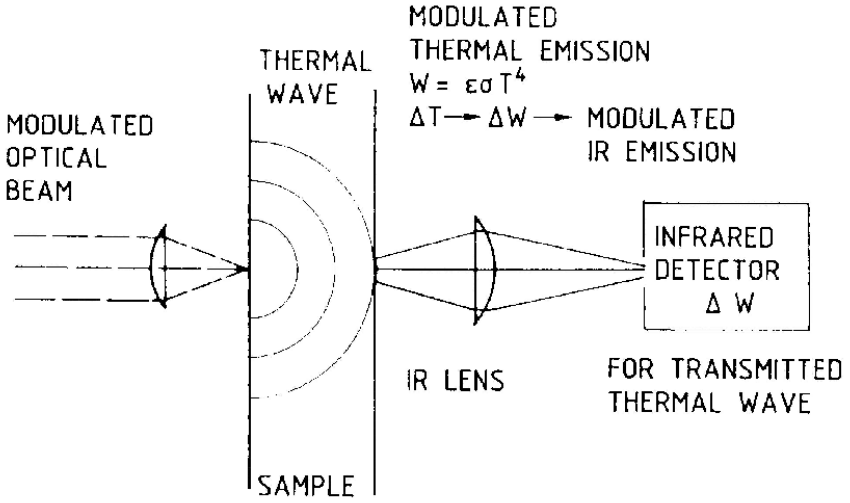
$$\mu = \sqrt{\frac{2\lambda}{\omega \rho c}}$$

„Thermische Eindringtiefe“



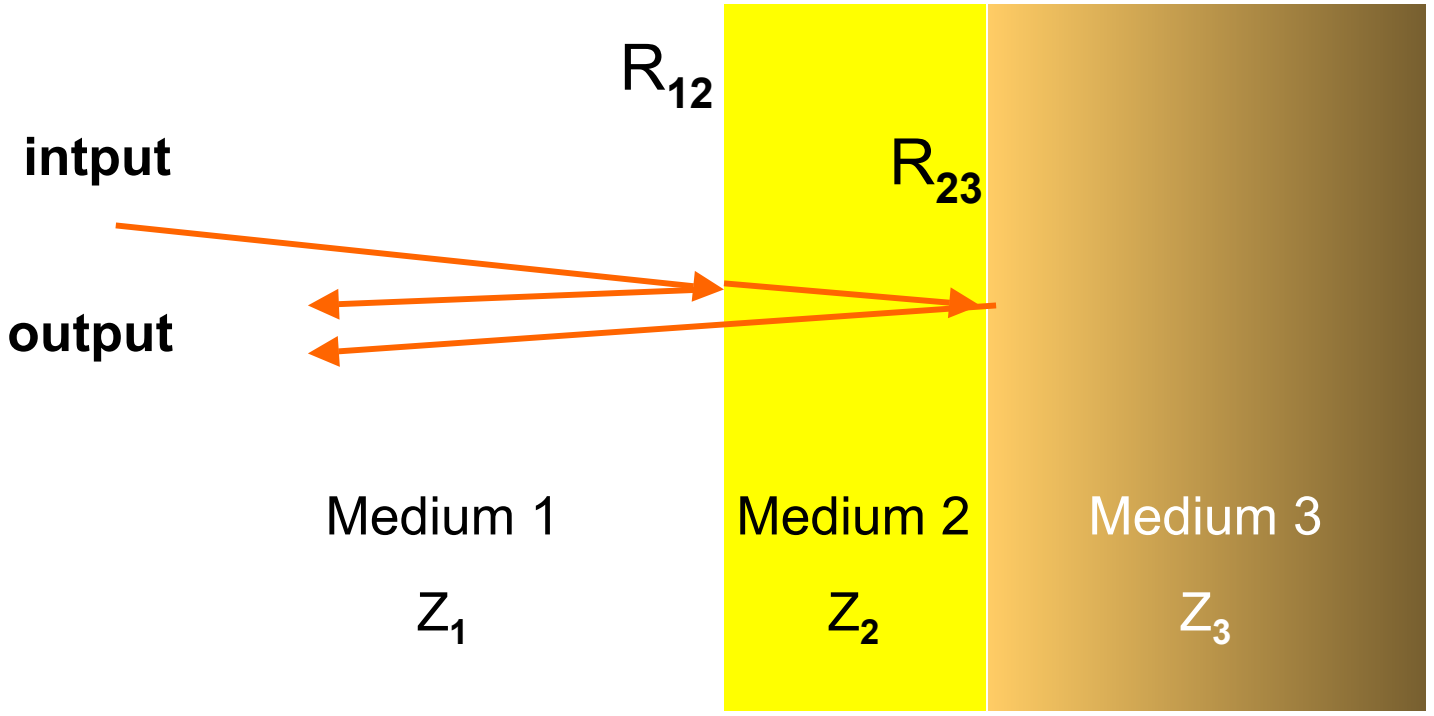
Photothermal transmission probing of wedged aluminium

G. Busse: Infrared Phys. 20 (1980) 429

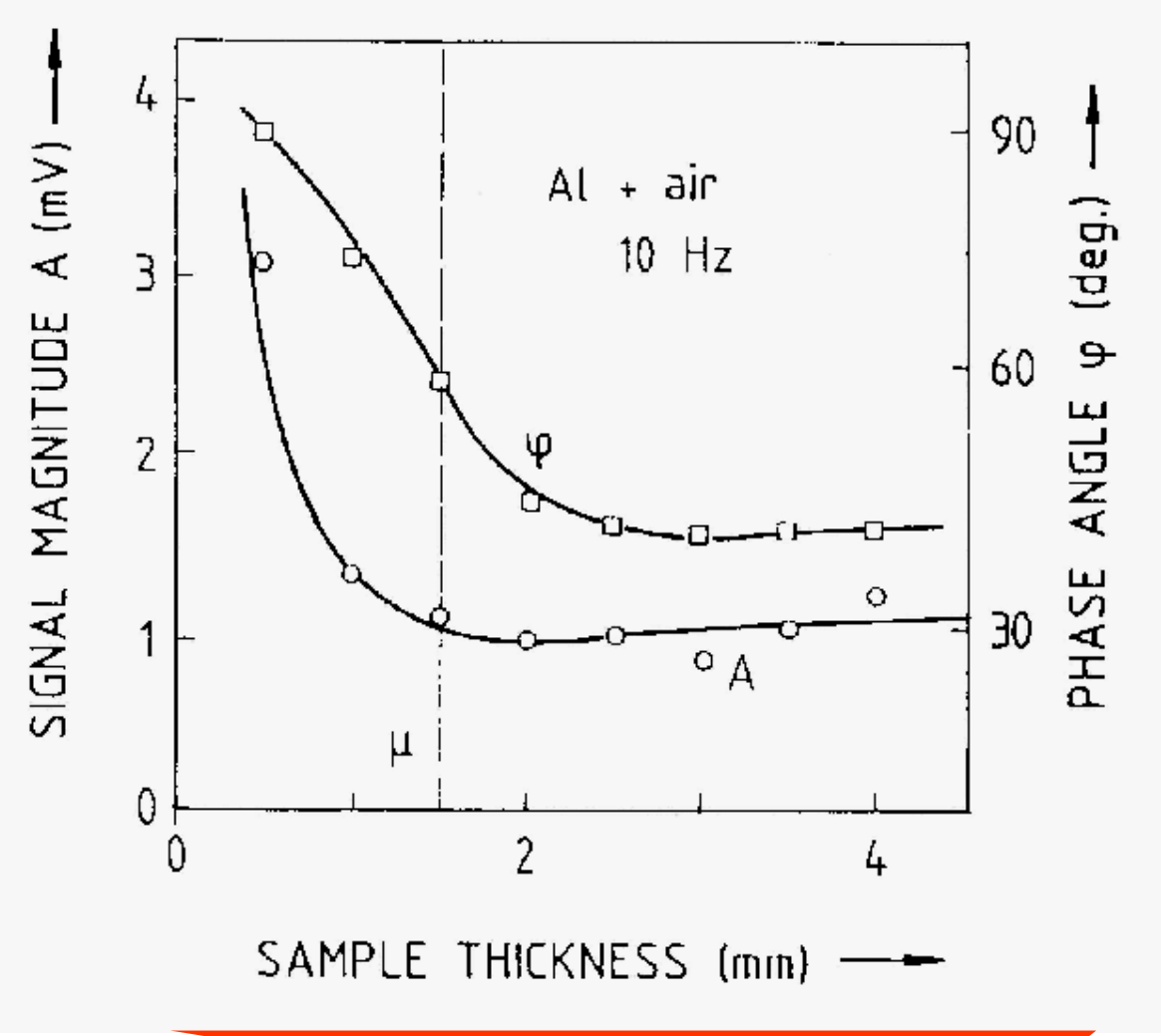


Thermal wave transmission for thickness measurement

Subsurface boundary probing using propagation time effects or interference (phase is normalised propagation time...)



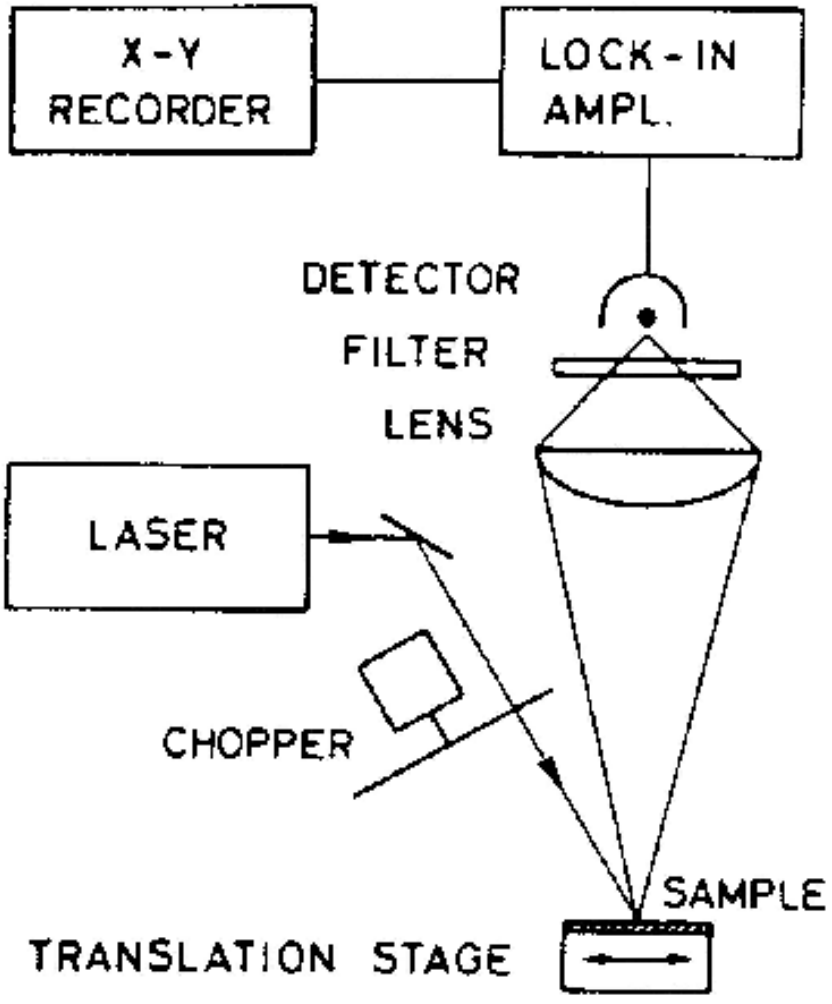
Z= thermal wave impedance



Amplitude and phase for thermal wave scan across wedged aluminium sample

G. Busse: Appl. Phys. Lett. 35 (1979) 759-760 and

A. Lehto, M. Jokinen, J. Jaarinen, T. Tiosanen, M. Luukkala: Electr. Lett. 17 (1981) 364

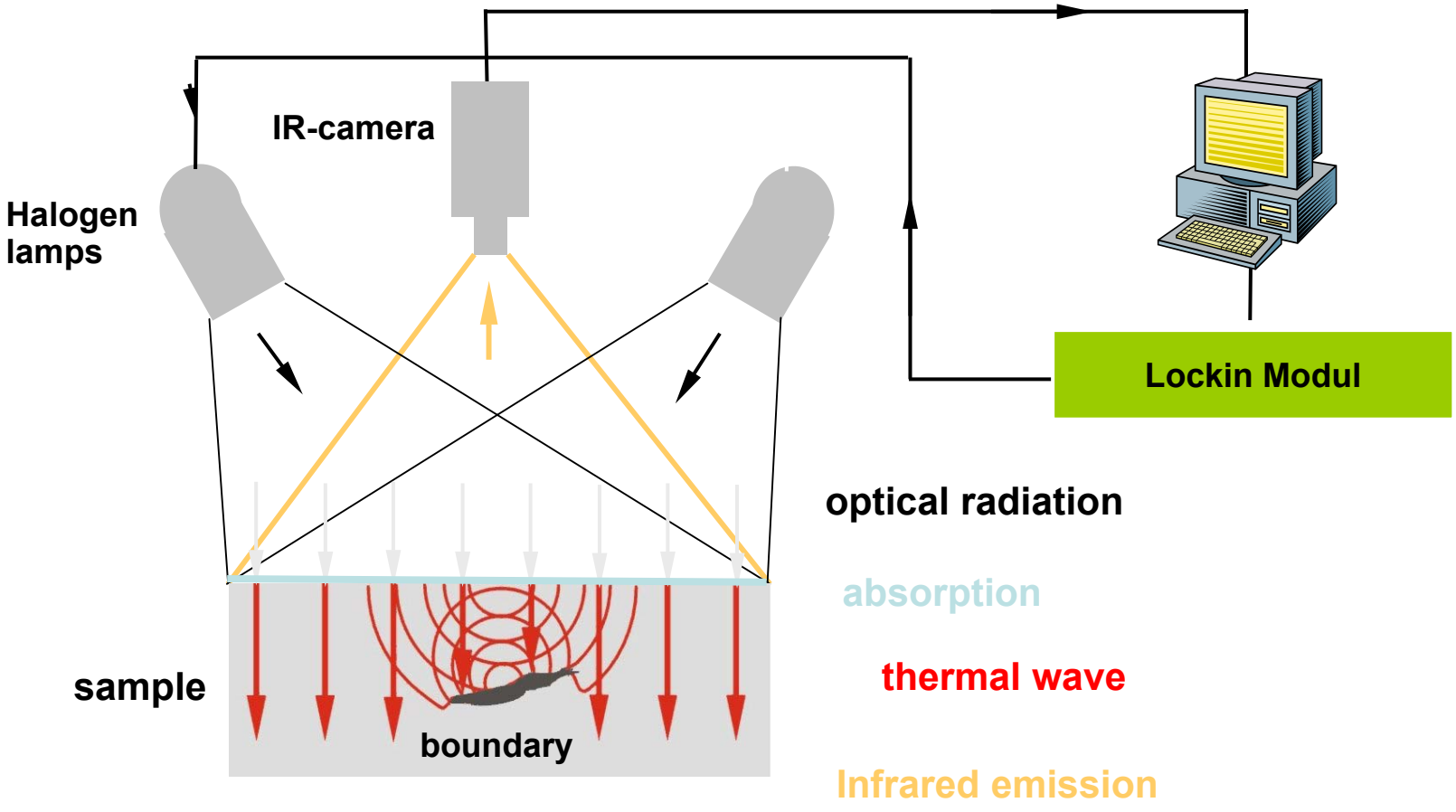


Photothermal radiometry:

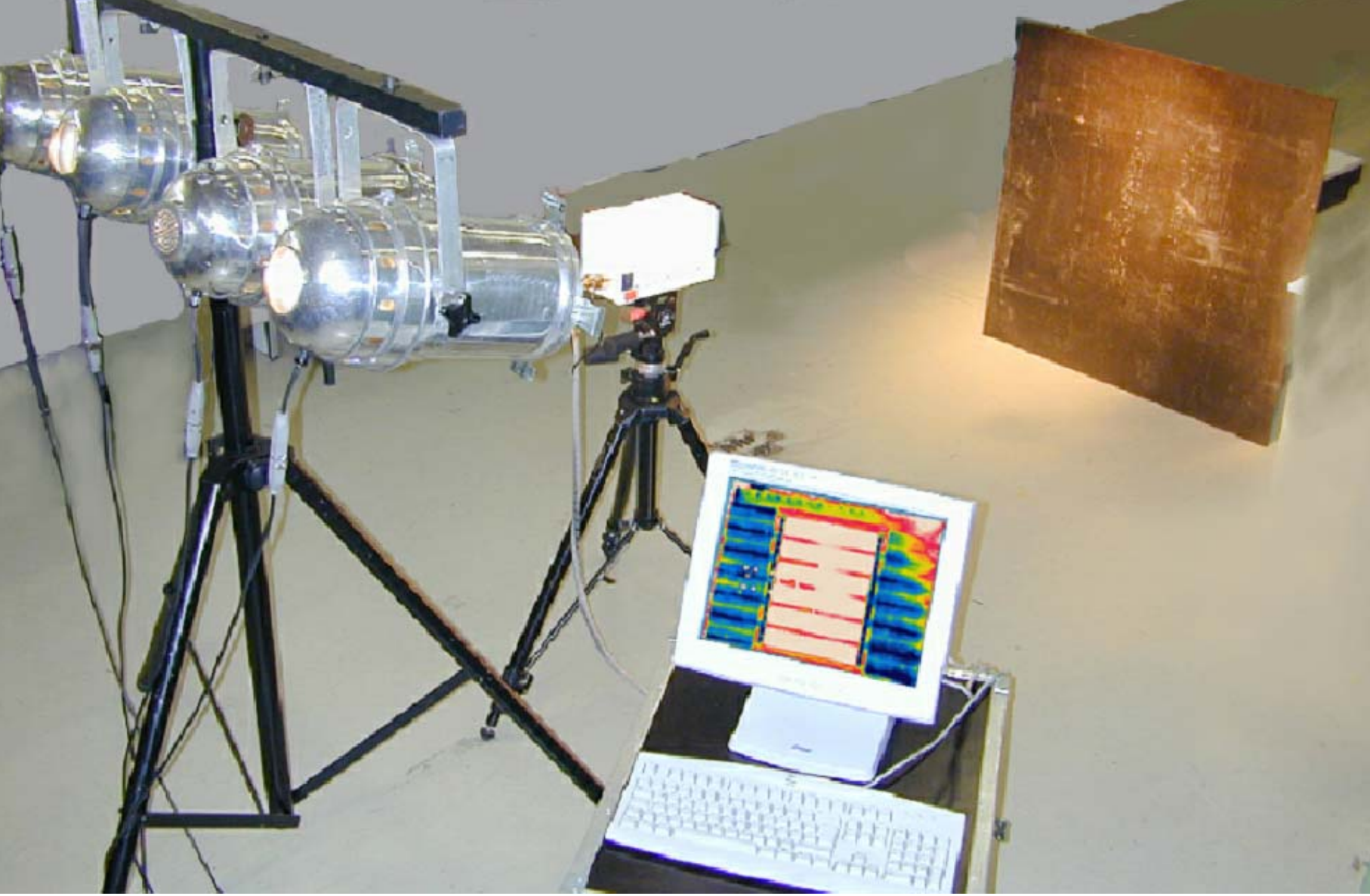
Local remote measurement of temperature modulation (amplitude and phase).

Imaging:
Point-by-point measurement one after each other.

P.-E. Nordal, S. O. Kanstad:
Phys. Scripta 20 (1979) p. 659-662



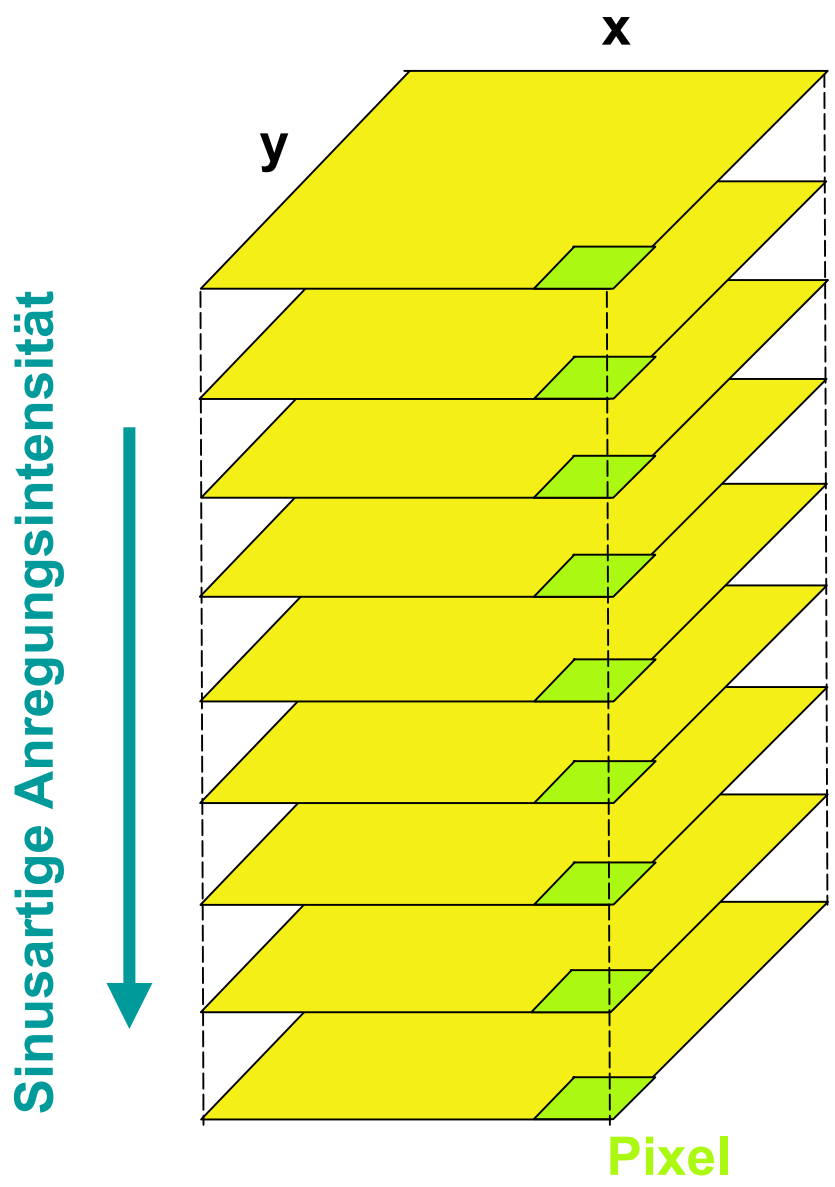
Principle of **O**ptical **L**ockin **T**hermography (**OLT**)



erstörungs-
ZfP
eie Prüfung

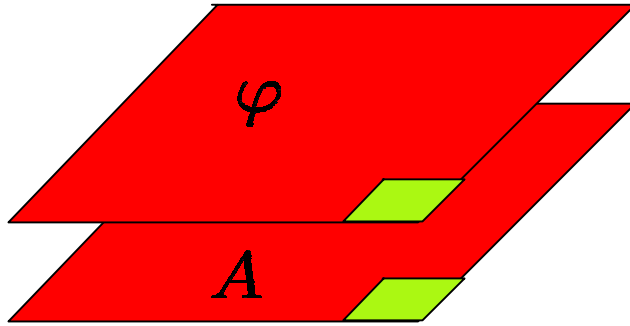
Optisch angeregte Lockin-Thermografie (OLT)

Universität
IKT
Stuttgart



Math.

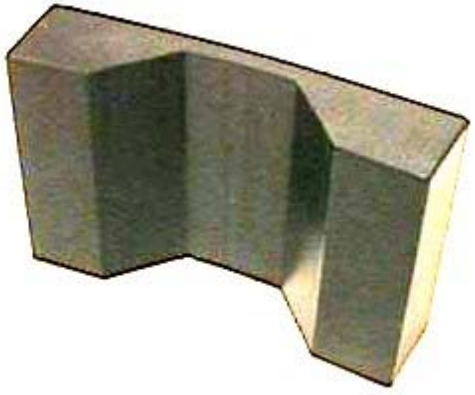
DFT

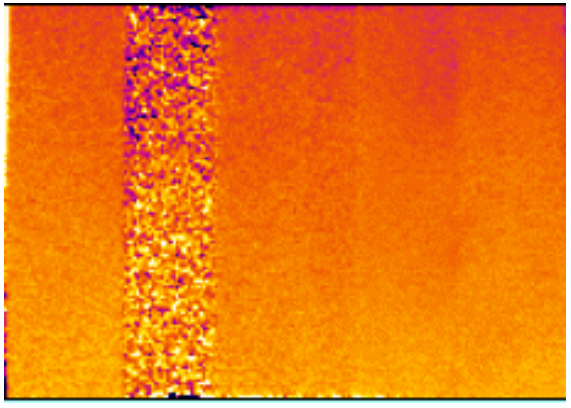


Ergebnisbilder:
Amplitude und Phase
bei Anregungsfrequenz

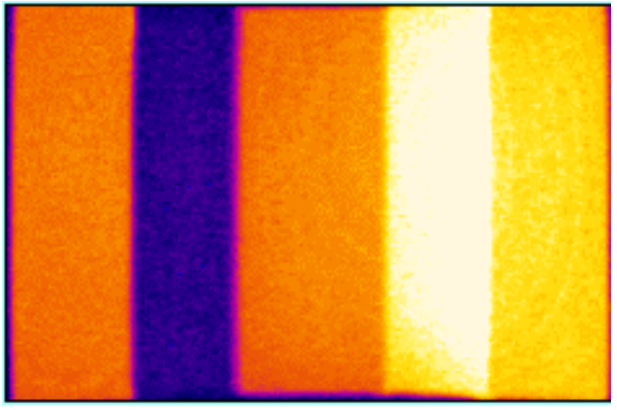
Kontrastmechanismus:
Lokale Temperaturleitfähigkeit
und Geometrie.

Advantage of phase angle image: Not sensitive to topography and inhomogeneous illumination





Phase image



Amplitude image

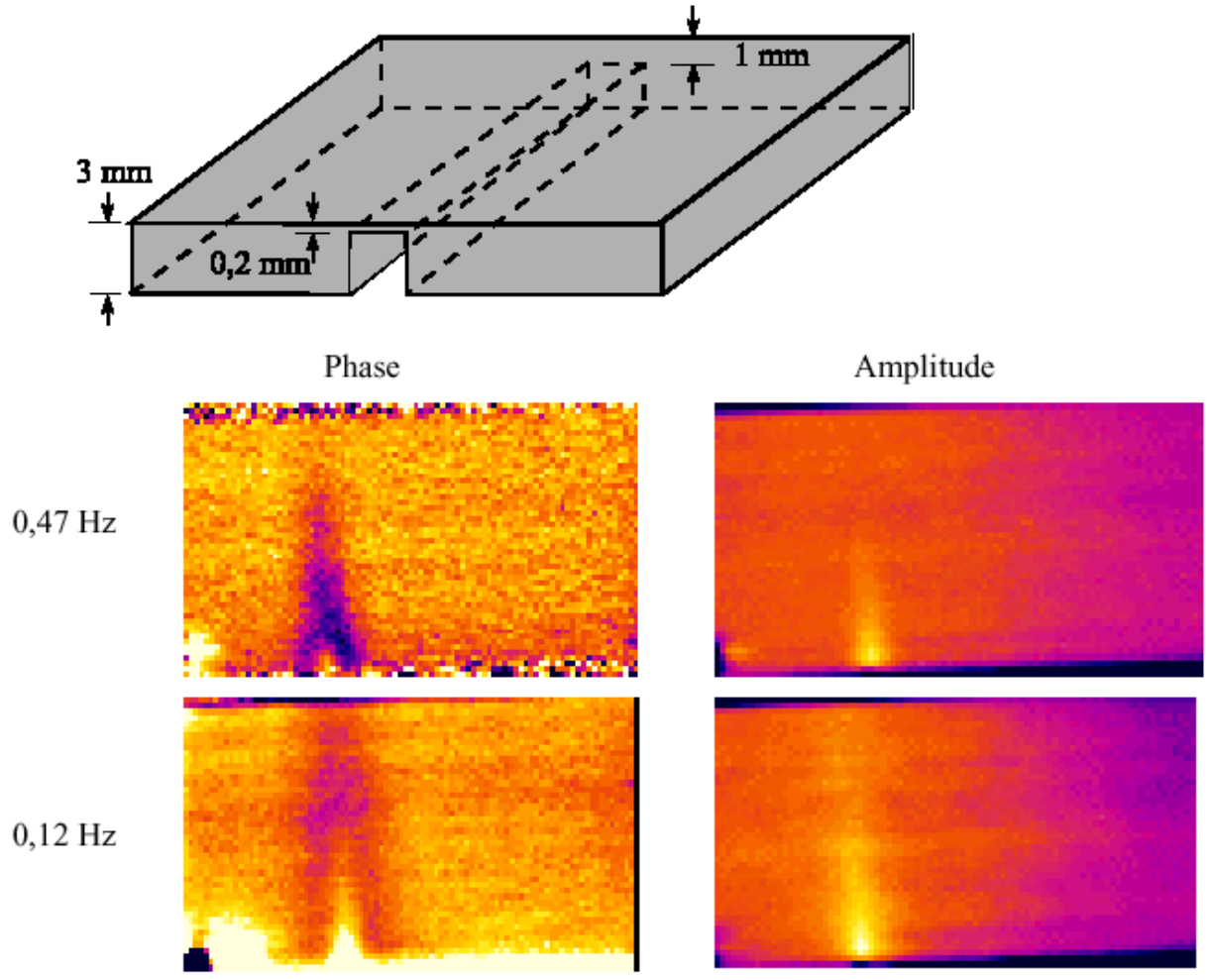


Fig 3: Inclined slot milled into rear surface of a carbon fiber reinforced polymer (CFRP) plate. Images obtained on front surface with OLT using phase and amplitude at two modulation frequencies /13, 14/.

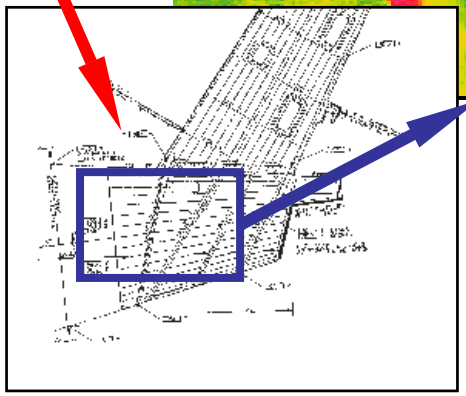
Lockin-Thermografie:

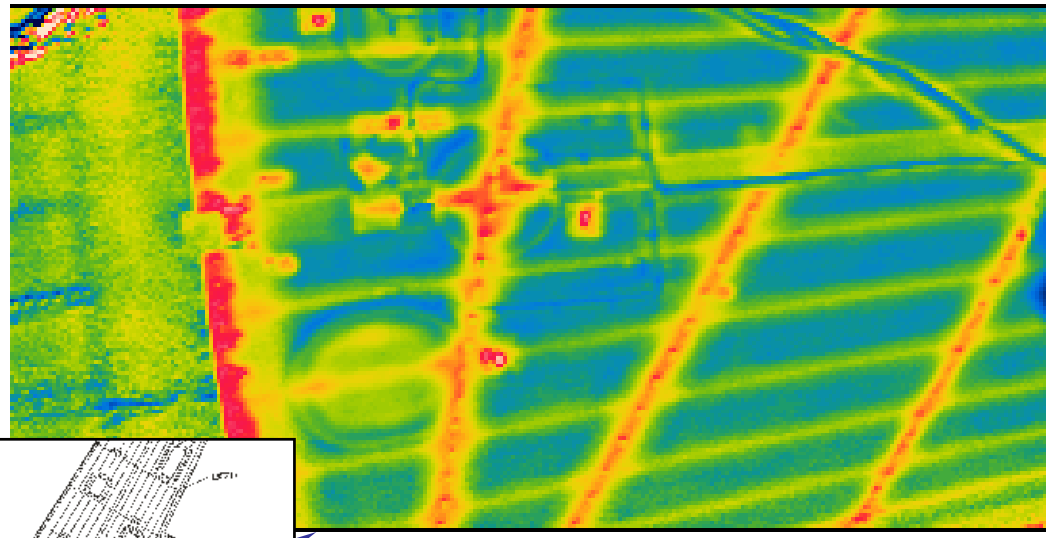
- Prinzip
- Technische Anwendungen

  (Anregung durch Licht oder Ultraschall)
- Aktuelle Entwicklungen
- Zusammenfassung

Do 328: ZFP des Heckbereichs

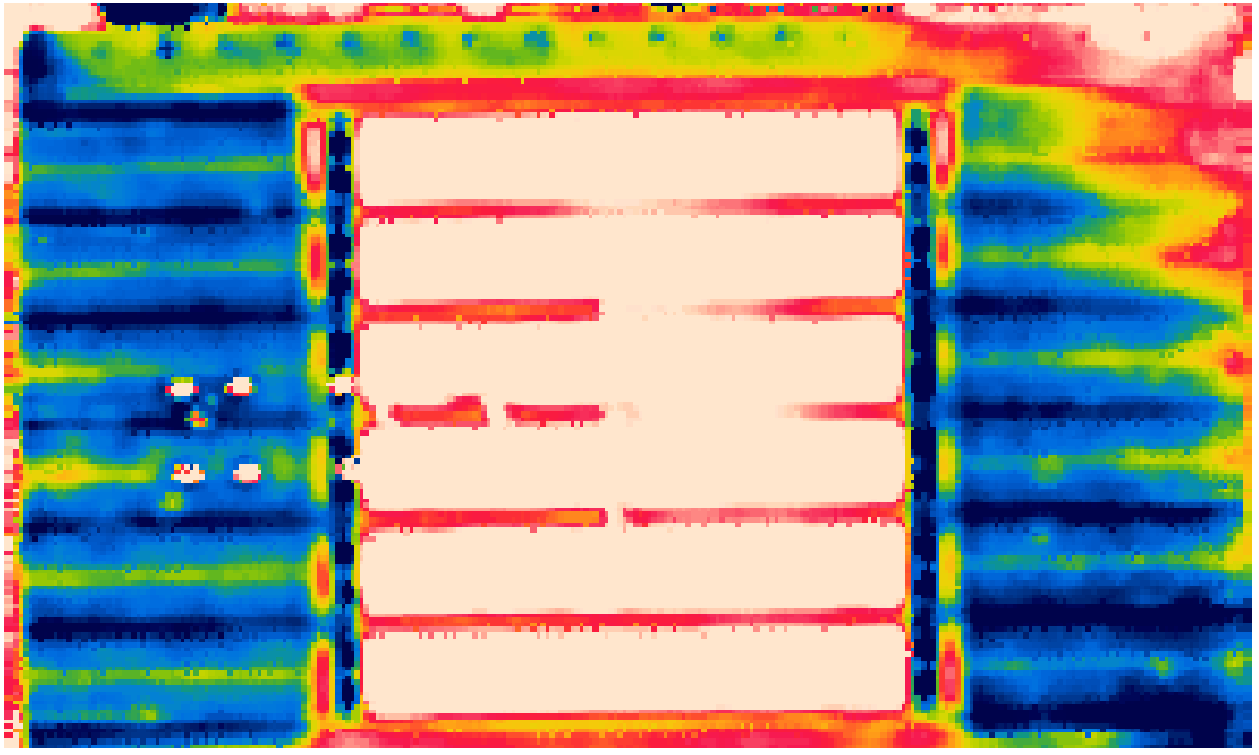
Durchführung der Messung...





...und nach 30 s das Ergebnis: Das Phasenwinkelbild zeigt die hinter der Außenhaut verborgenen Strukturen

OLT for detection of stringer disbond after application of excessive mechanical load



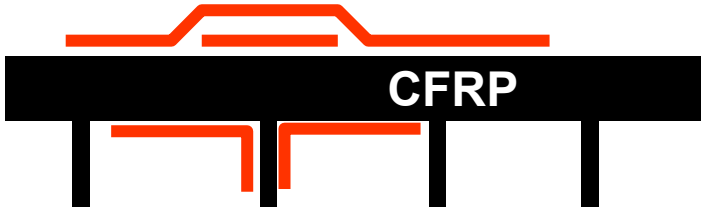
$$\mu = \sqrt{\frac{2\lambda}{\omega \rho c}}$$

Modulationsfrequenz

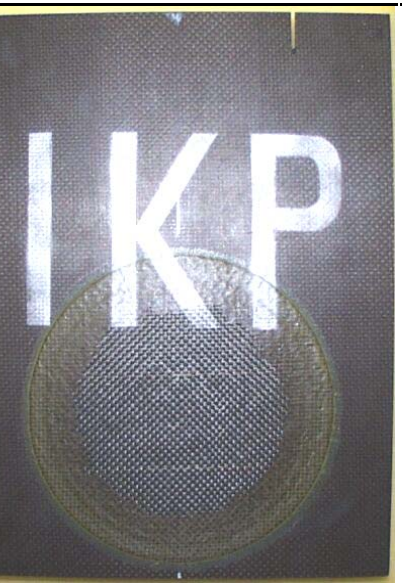
Optisch angeregte Lockin-Thermografie :

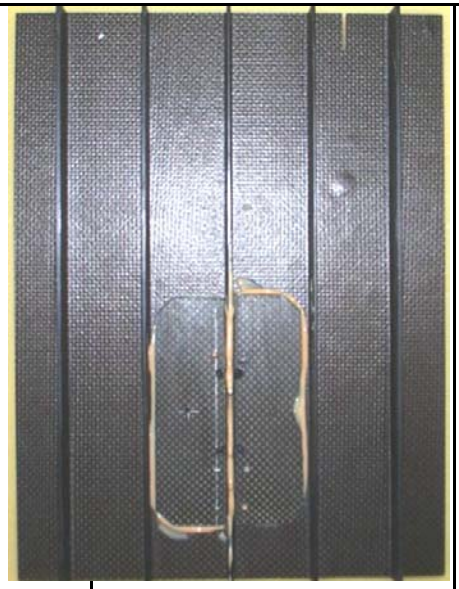
Bilder der lokalen Temperaturleitfähigkeit, tiefengewichtet. Beitrag bis zur frequenzabhängigen thermischen Eindringtiefe.

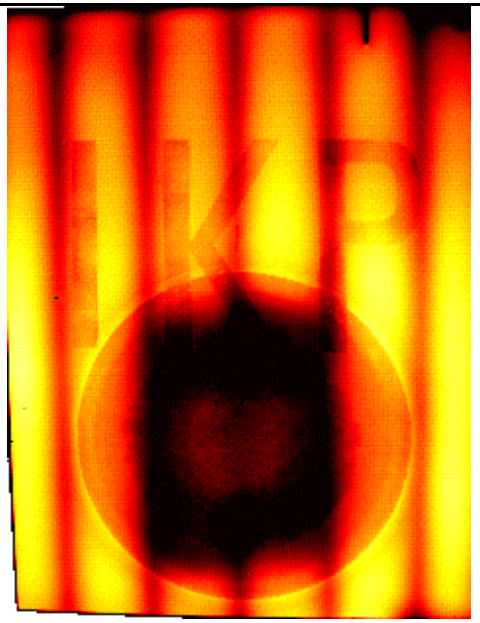
Thermische Tiefenprofile.

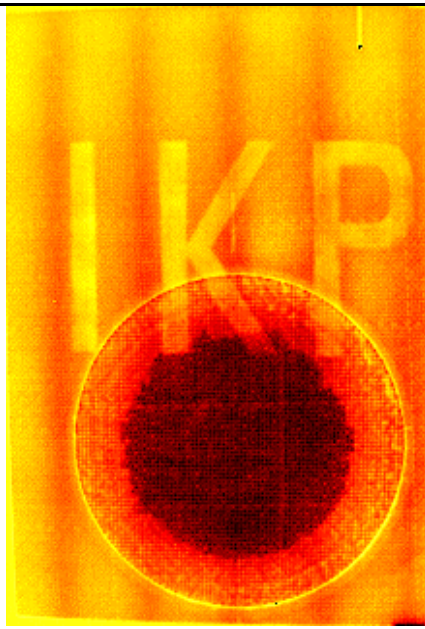


Patches of repair



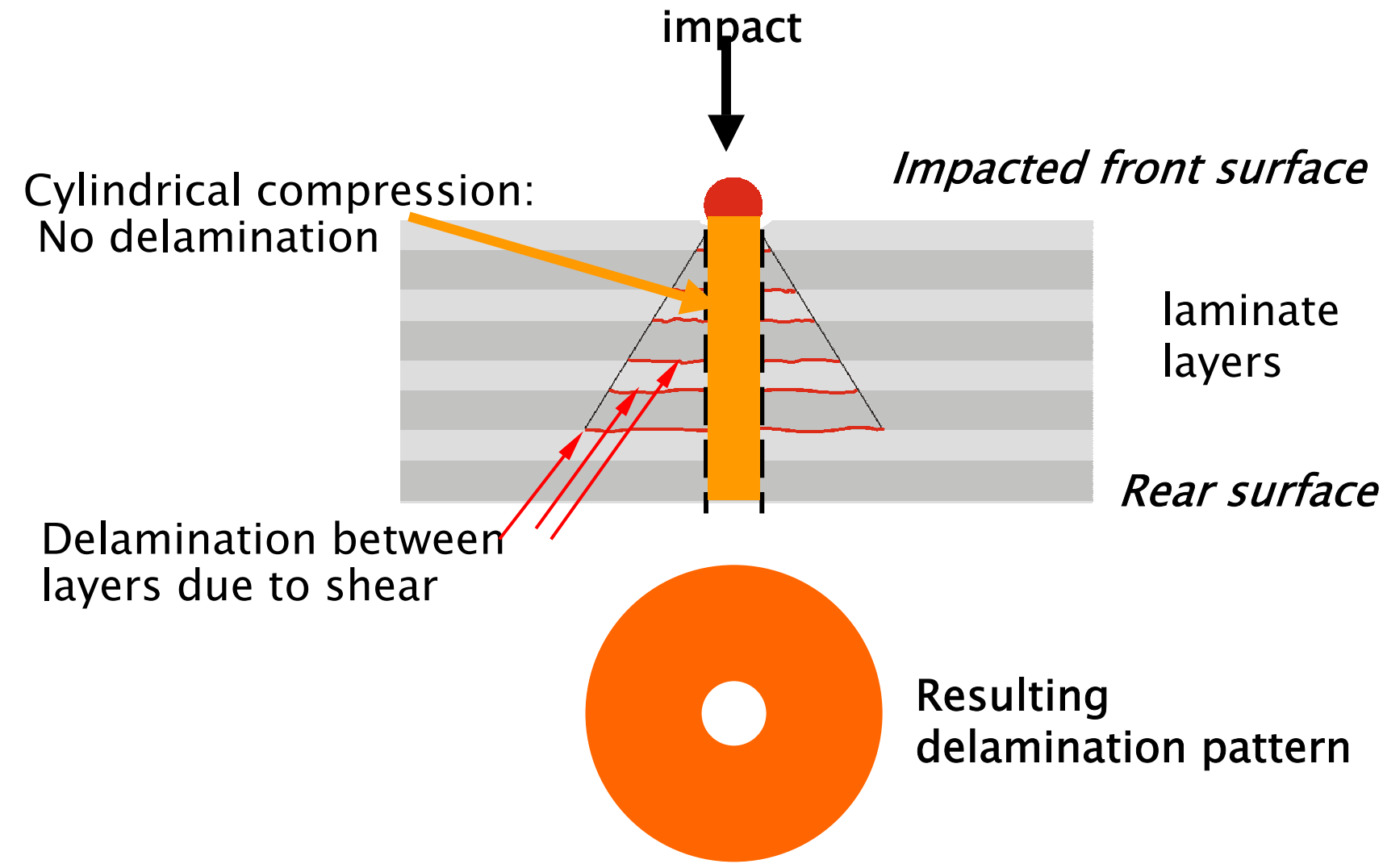






a: photo (front side) | *b: photo (rear side)* | *c: Phase angle 0.02 Hz* | *d: Phase angle 1.1 Hz*

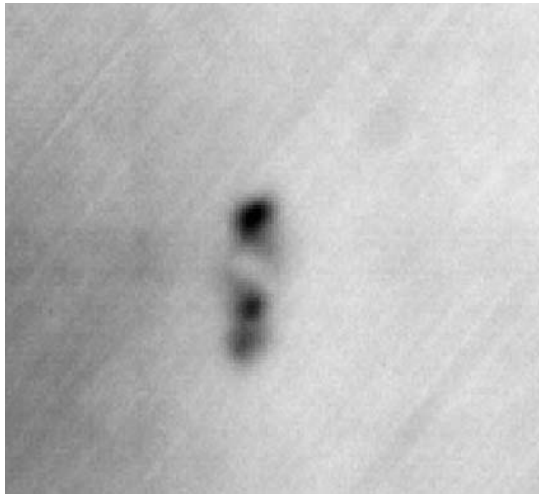
OLT on front side of CFRP-sample with stringers on rear surface (sample courtesy of DLR Stuttgart)



Cone-shaped damage in impacted laminate

Impactschaden in CFK– tiefenaufgelöste Darstellung von der Impactseite aus (“Thermische Tomographie”)

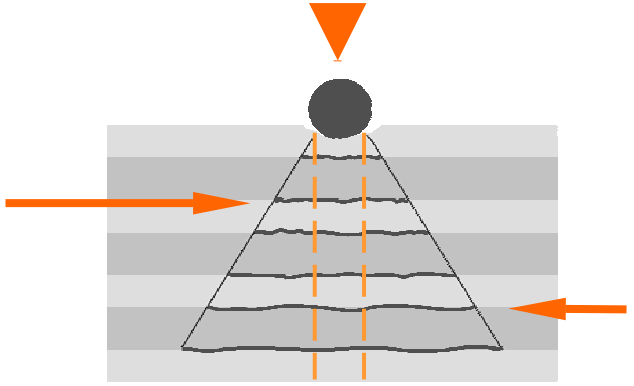
oberer Querschnitt



Phase bei 0,3 Hz

Impactseite

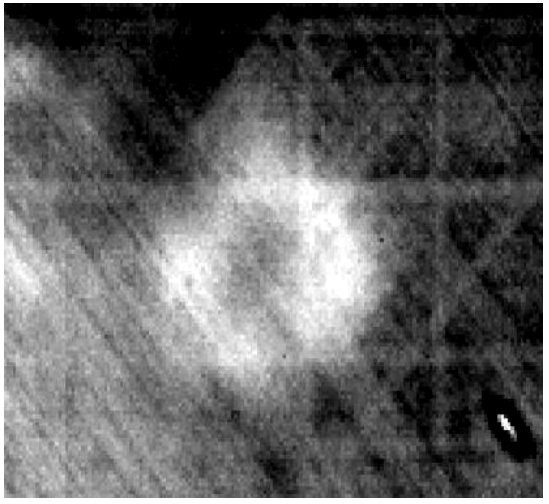
0,4 J



Delamination

Rückseite

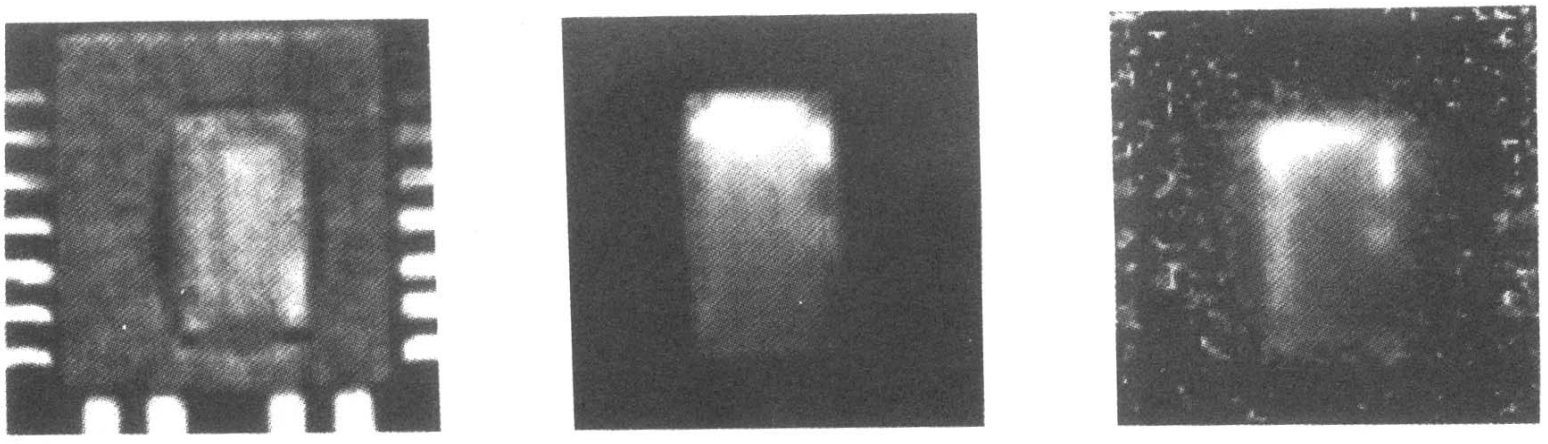
tieferer Querschnitt



Phase bei 0,1 Hz

Lockin Thermografie

mit interner Heizung



(a) (b) (c)

Fig. 8 Inspection of integrated circuit with thermography a) as well as magnitude b) and phase c) of lockin thermography with current modulation at 1.87 Hz.

WU, D., RANTALA, J.; KARPEN, W.; ZENZINGER, G.; SCHÖNBACH, B.; RIPPEL, W.; STEEGMÜLLER, R.; DIENER, L.; BUSSE, G.: Applications of lockin-thermography methods. D.O. Thompson u. D.E. Chimenti (Hrsg.): Review of Progress in Quantitative Nondestructive Evaluation, Plenum Press, New York (1996) 15, S. 511-519

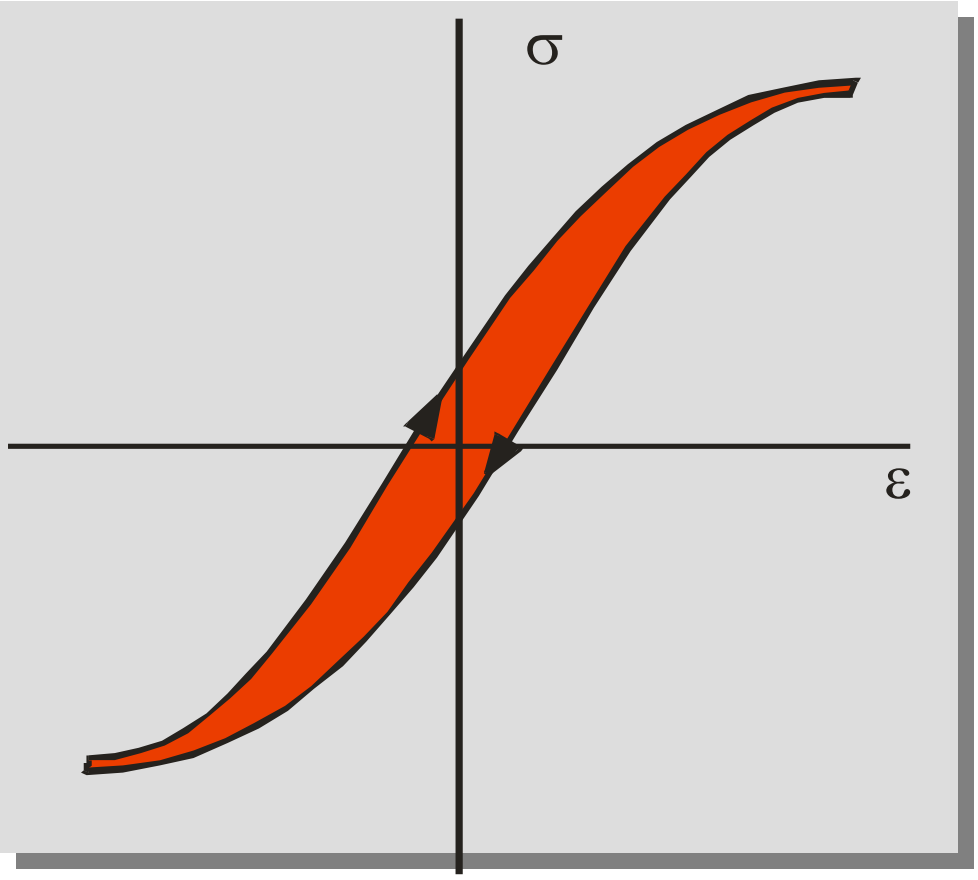
Stress / strain diagram

Increase in temperature due to

hysteresis effect

(mechanical friction)

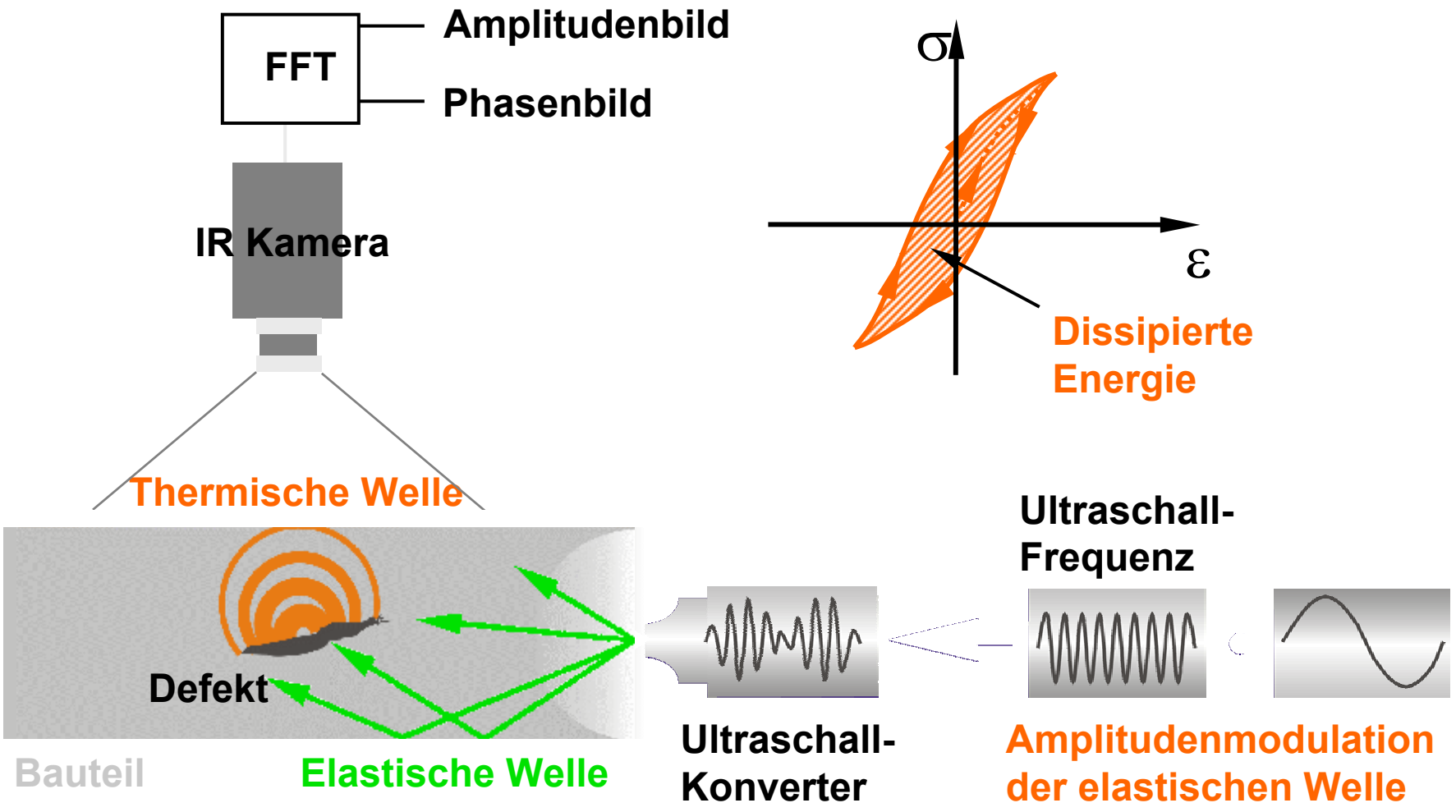
…internal heat source driven by elastic waves



Lockin-Thermografie:

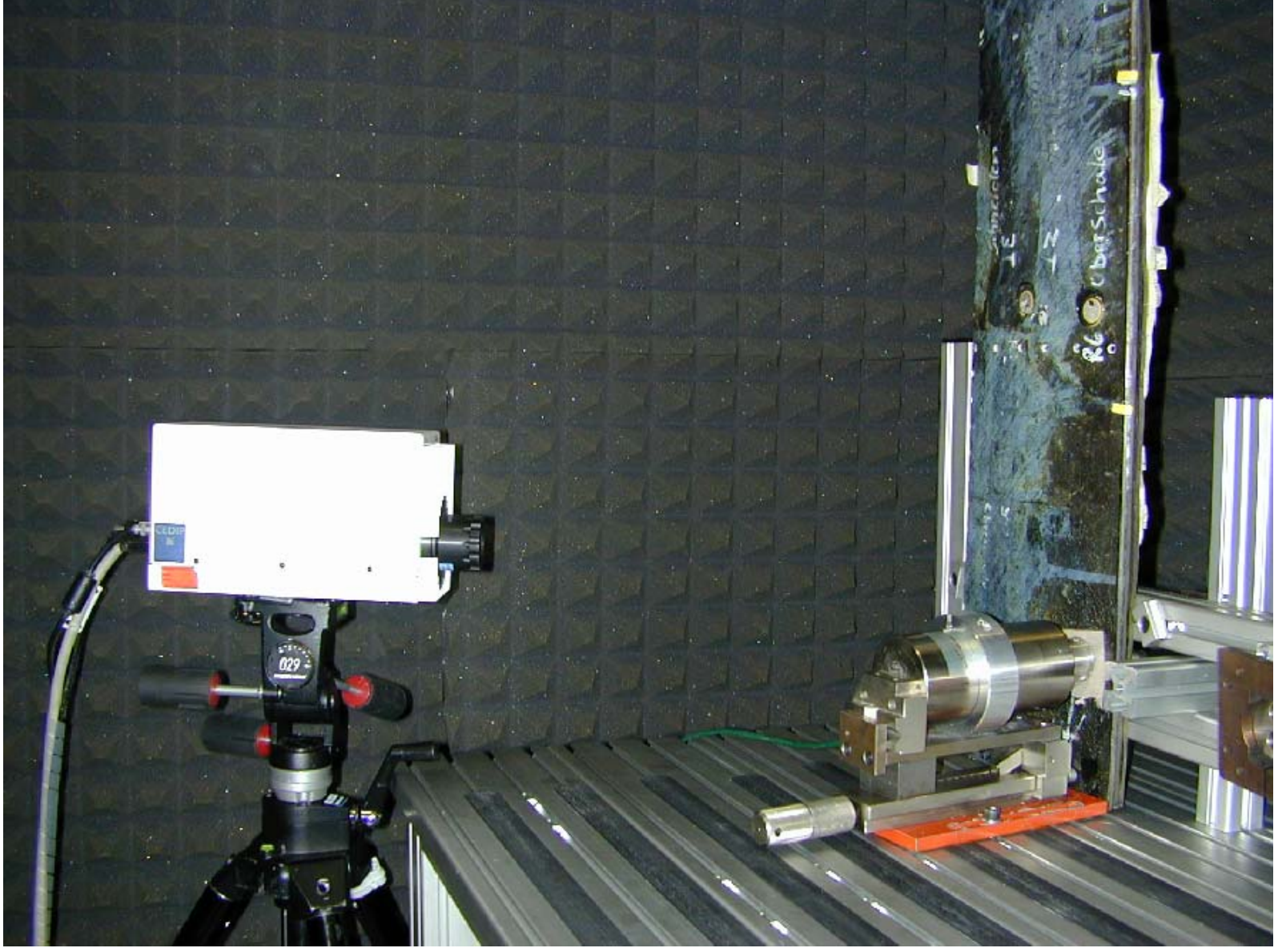
- Prinzip
- Technische Anwendungen

  (Anregung durch Licht oder Ultraschall)
- Aktuelle Entwicklungen



Lock-in Thermografie mit elastischen Wellen

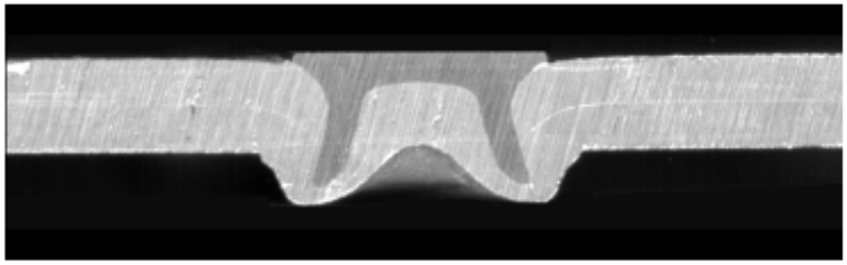
(U.I.T. Patent IKT 1992)

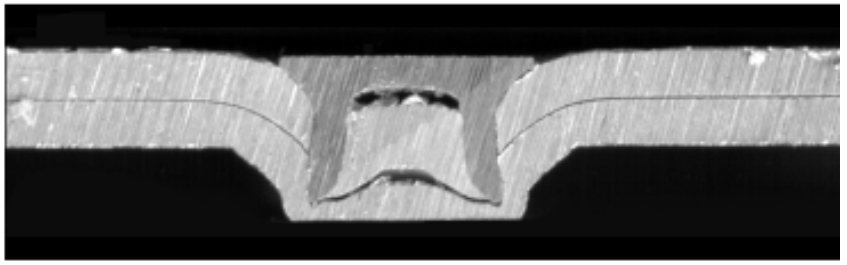

Oberschale

Ultraschallangeregte Lockin-Thermografie (ULT):

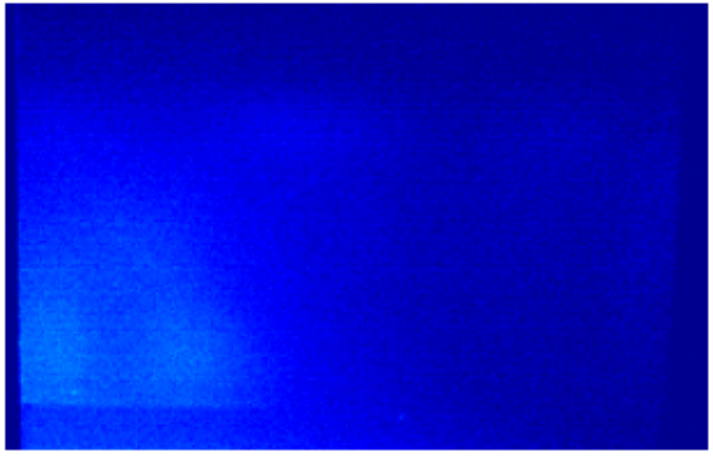
Defektselektive Abbildung des lokalen mechanischen Verlustwinkels,
z.B. nicht-kraftschlüssiger Bereiche,
Niet- und Kleb- und Schraubverbindungen.

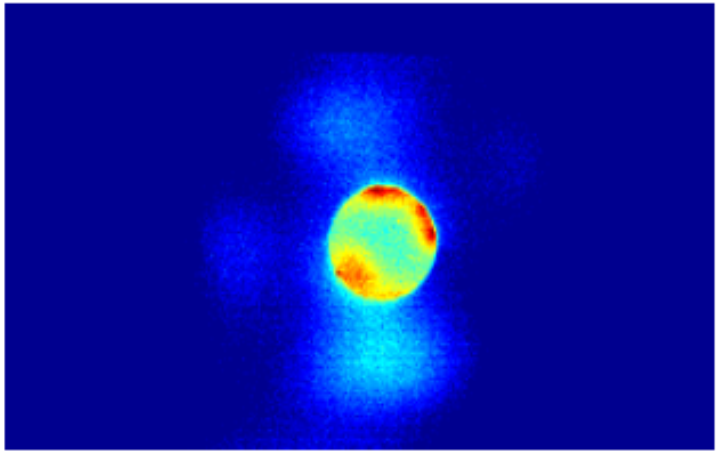
Cross Section…

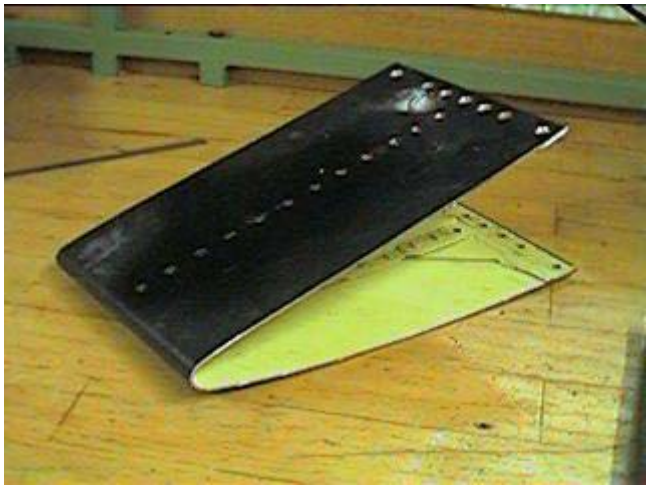




… and ULT phase image at 0.54 Hz

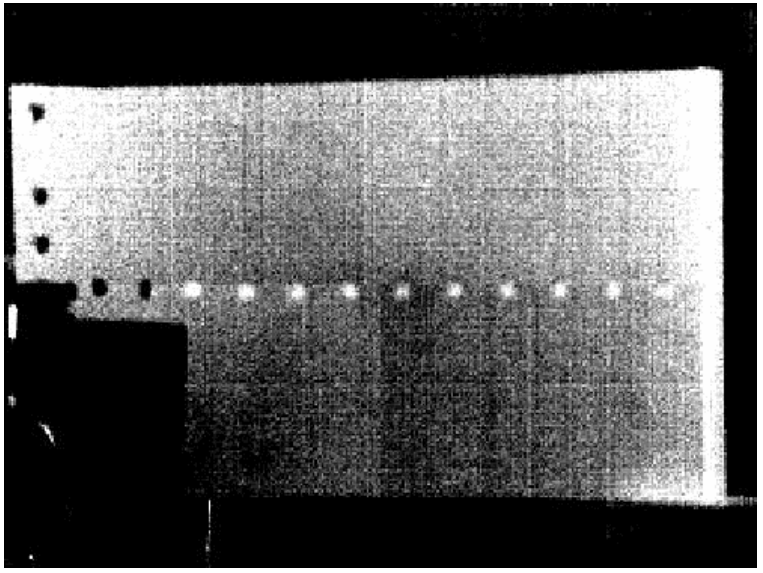






riveted aluminium
structure of aircraft

one primary thermography image



Fourier phase image at 0.18 Hz

Difference between the two techniques:

Optical lock-in thermography (OLT)
…responds to thermal features:
provides images e.g. of all boundaries.

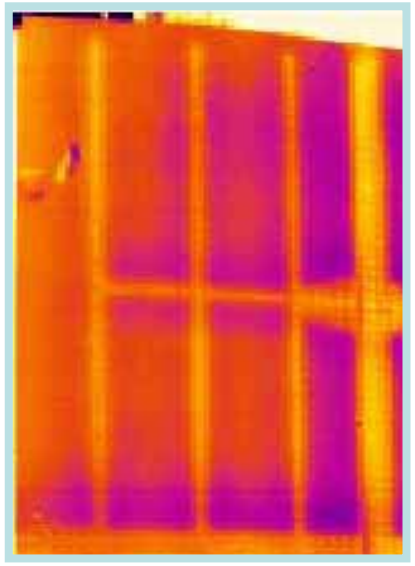
Ultrasound lock-in thermography (ULT)
…responds to local heat generation
due to mechanical losses:
provides images e.g. of local hysteresis
or friction in cracks…it is defect-selective!

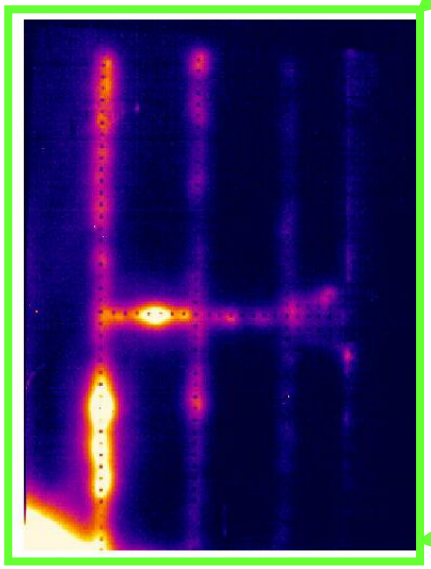
Lockin thermography:

Excitation with ultrasound

as compared to

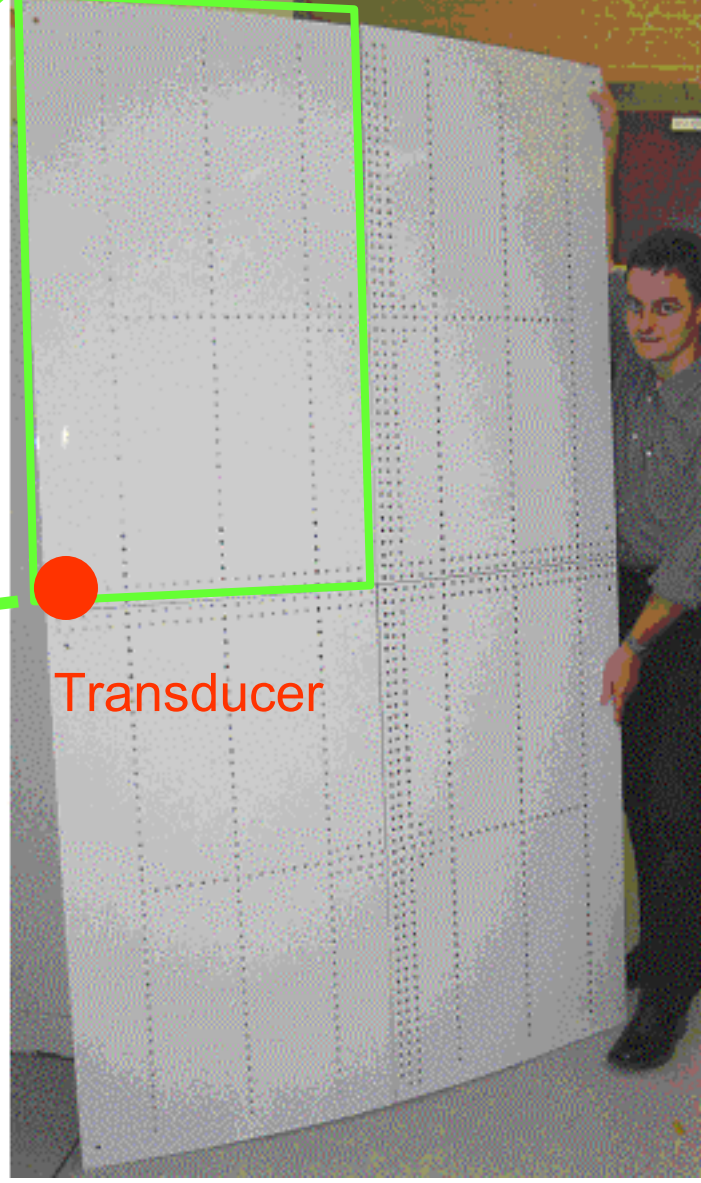
optical excitation





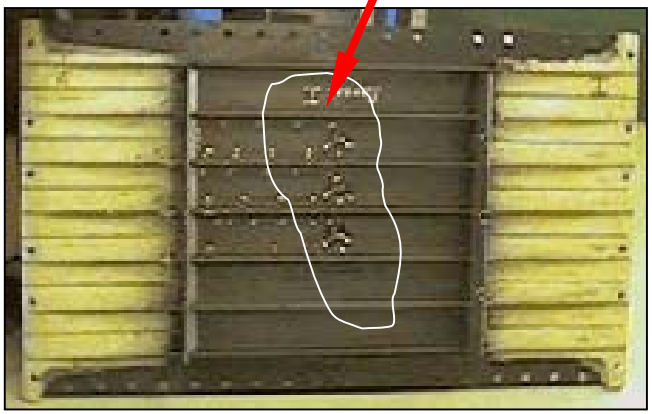
OLT **ULT**

Phase angle images



ZFP mit OLT and ULT an der ebenen Vorderseite

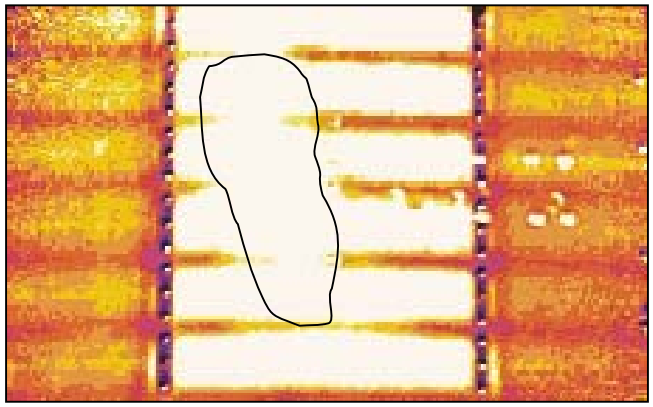
Bereich der Stringerablösung



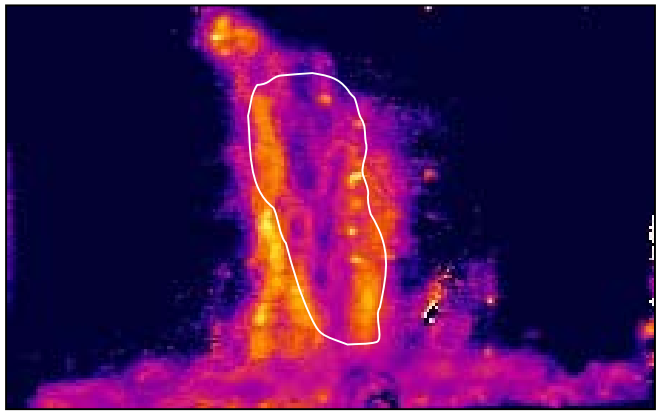
0.7 m

1 m

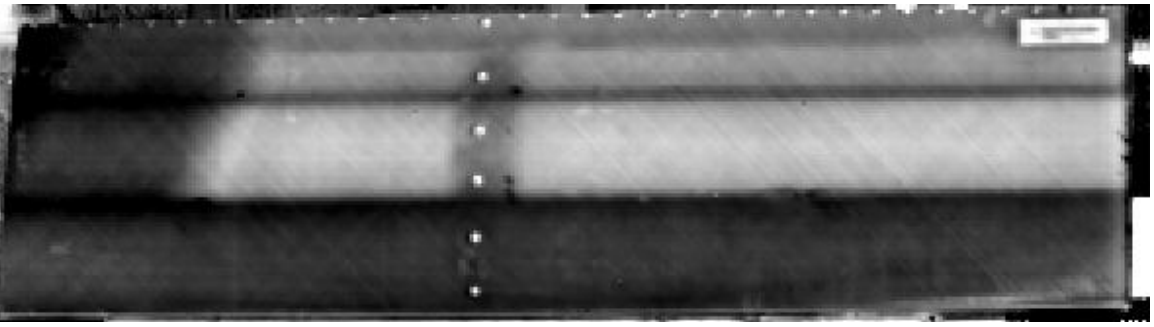
Optisches Bild der Rückseite



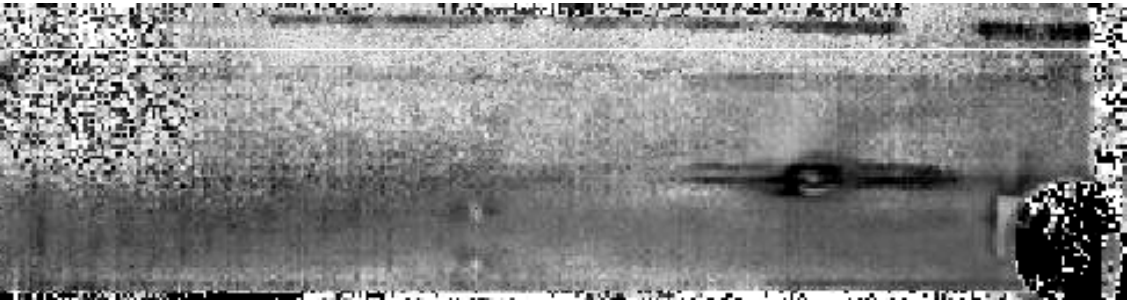
OLT **Phasenbild bei 0,0015 Hz zeigt <u>alle</u> verborgenen Grenzflächen**



ULT **Phasenbild bei 0,02 Hz, Ultraschall-Leistung 1600 W**



Optisch angeregte Lockin Thermografie
Phase bei 0,03 Hz



Ultraschallangeregte Lockin Thermografie
frequenzmodulierter Ultraschal
15...25 kHz
Phase bei 0,05 Hz

Lockin-Thermografie:

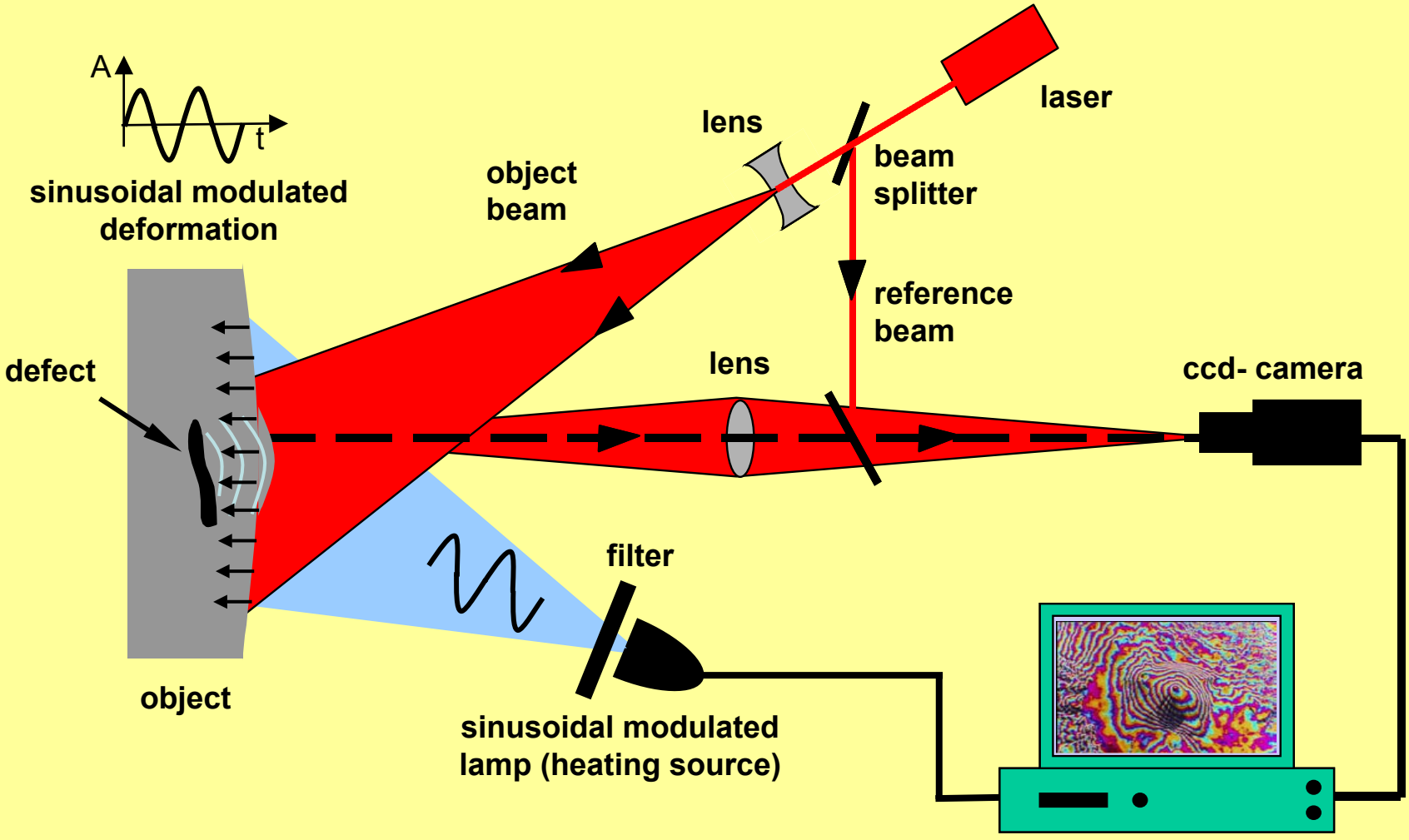
- Prinzip
- Technische Anwendungen

  (Anregung durch Licht oder Ultraschall)
- Aktuelle Entwicklungen
- Zusammenfassung

Aktuelle Entwicklungen

1. Nicht-thermischer Nachweis thermischer Wellen über die thermische Expansion: Lockin-Interferometrie.

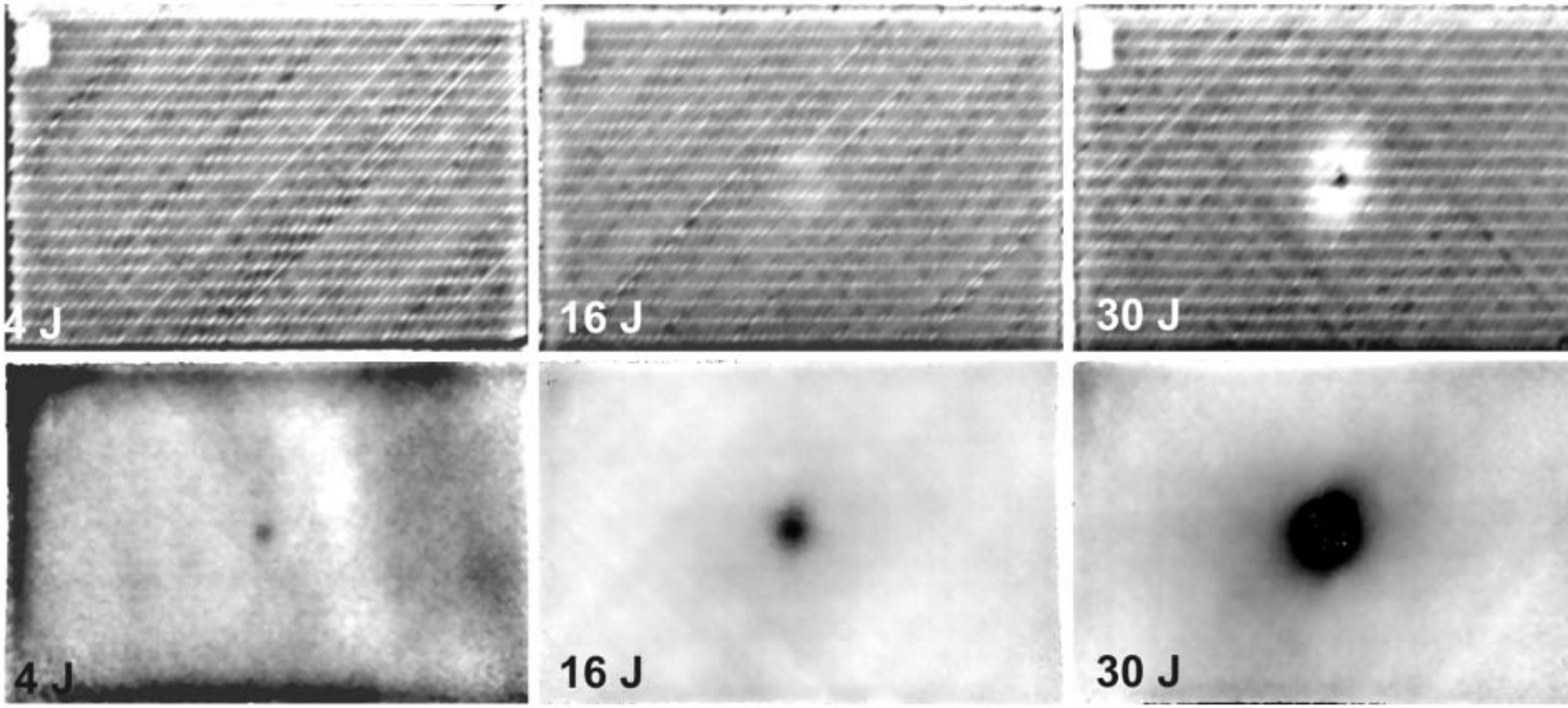
2. Data Fusion zur Merkmalsextraktion.



out-of-plane component

hasenbilder der **Einschlagseite** bei 0,1 Hz:

Optisch angeregte Lockin-Thermografie (OLT)

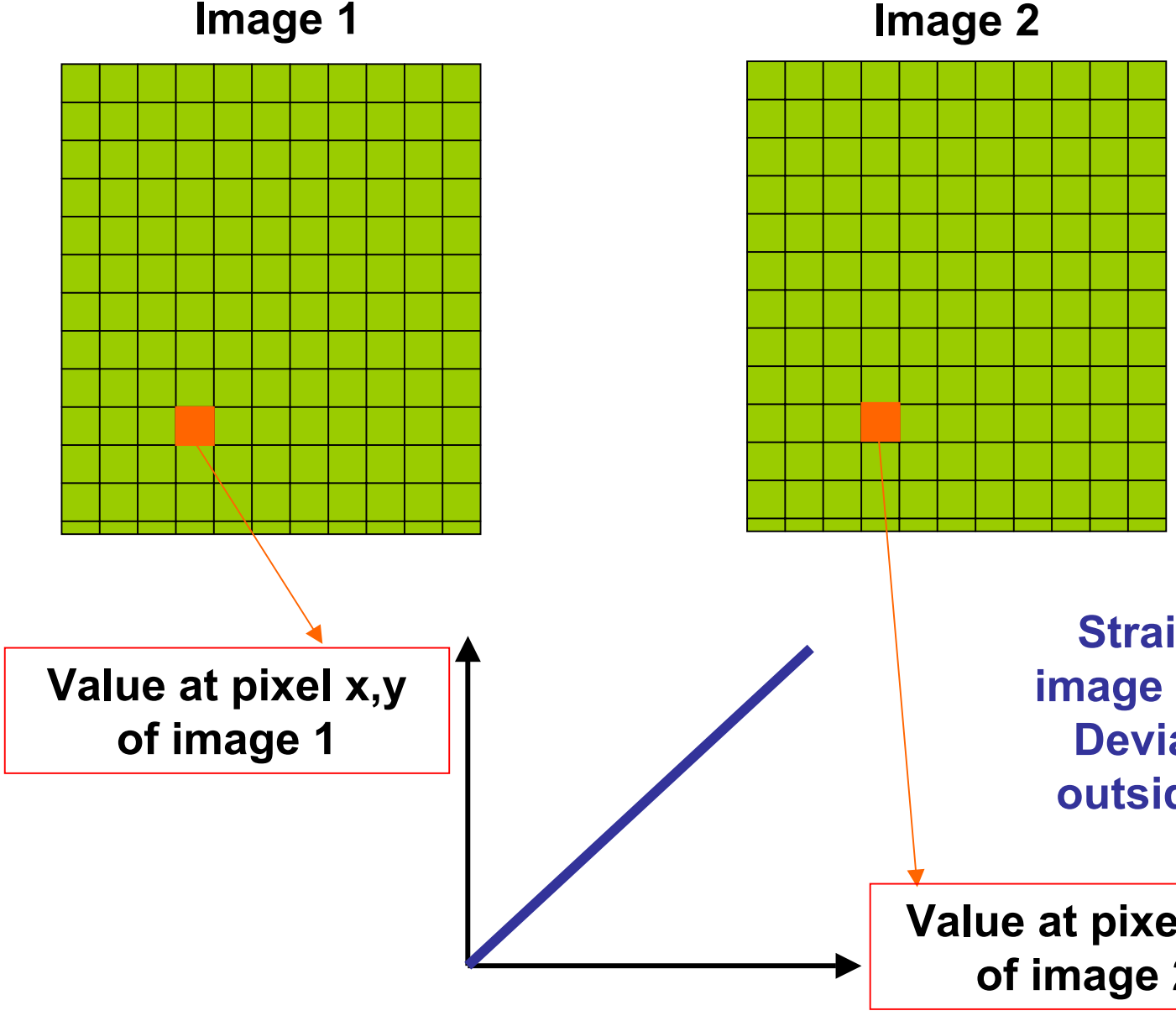


Optisch angeregte Lockin-ESPI (OLI)

Aktuelle Entwicklungen

1. Nicht-thermischer Nachweis thermischer Wellen über die thermische Expansion: Lockin-Interferometrie.

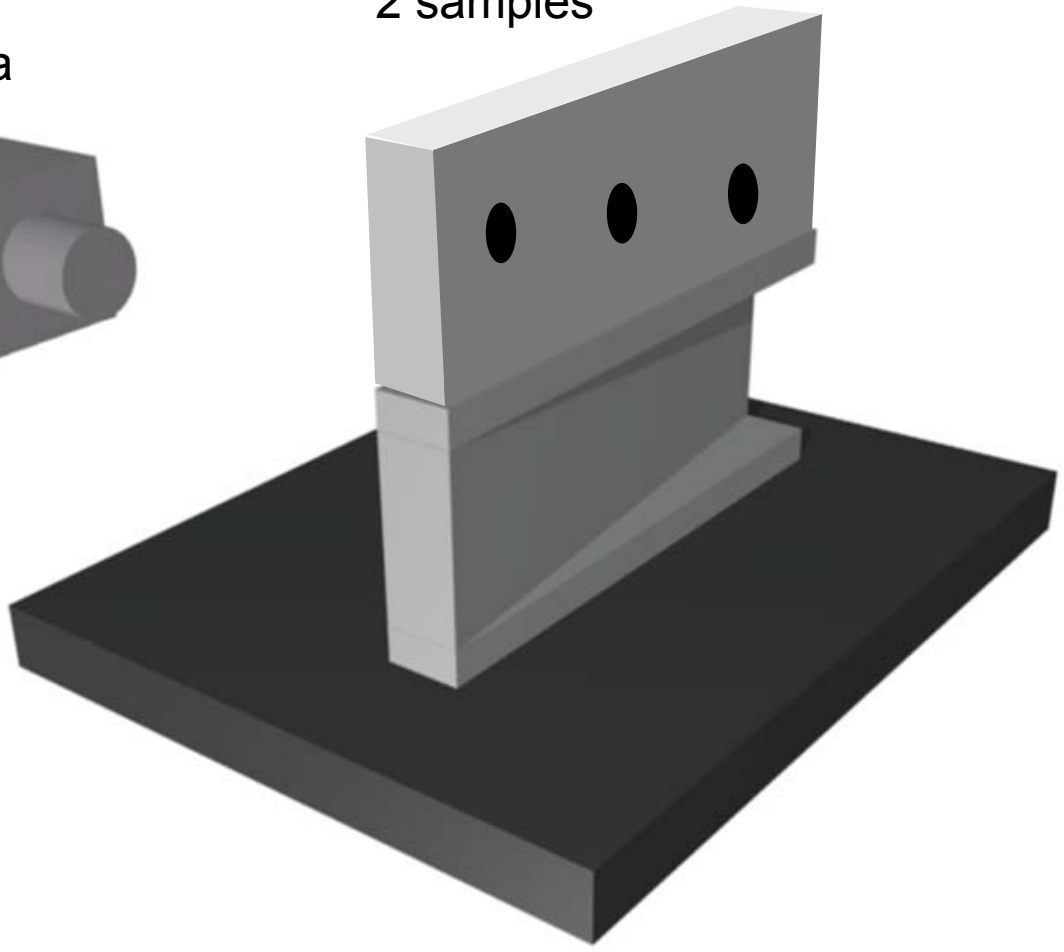
2. Data Fusion zur Merkmalsextraktion.

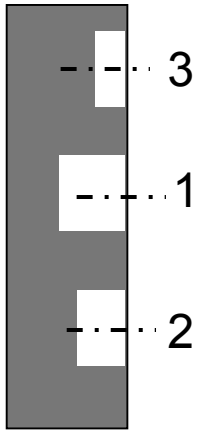


Scatter plot for image correlation

IR-camera

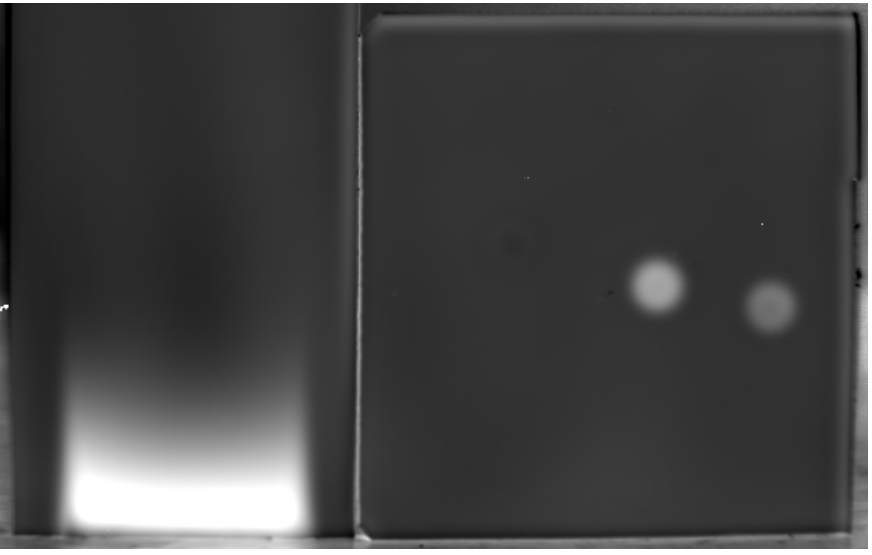
2 samples



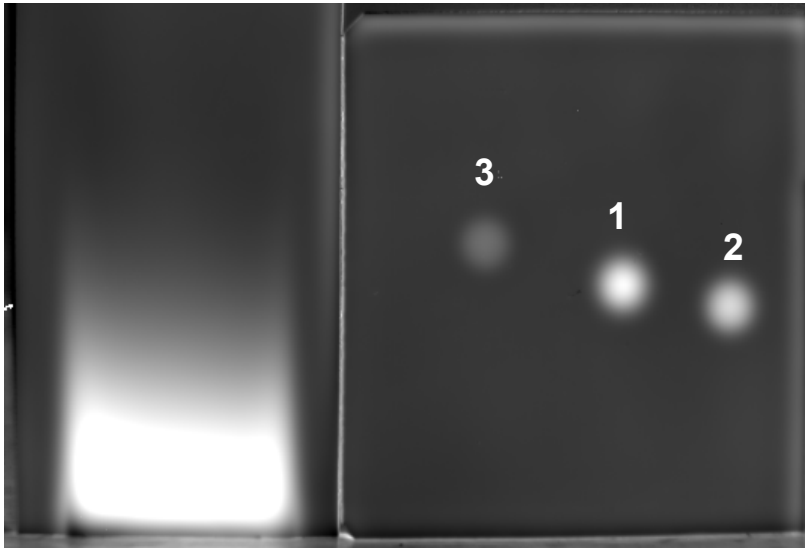


Edge effects around hole

Combined samples for data fusion

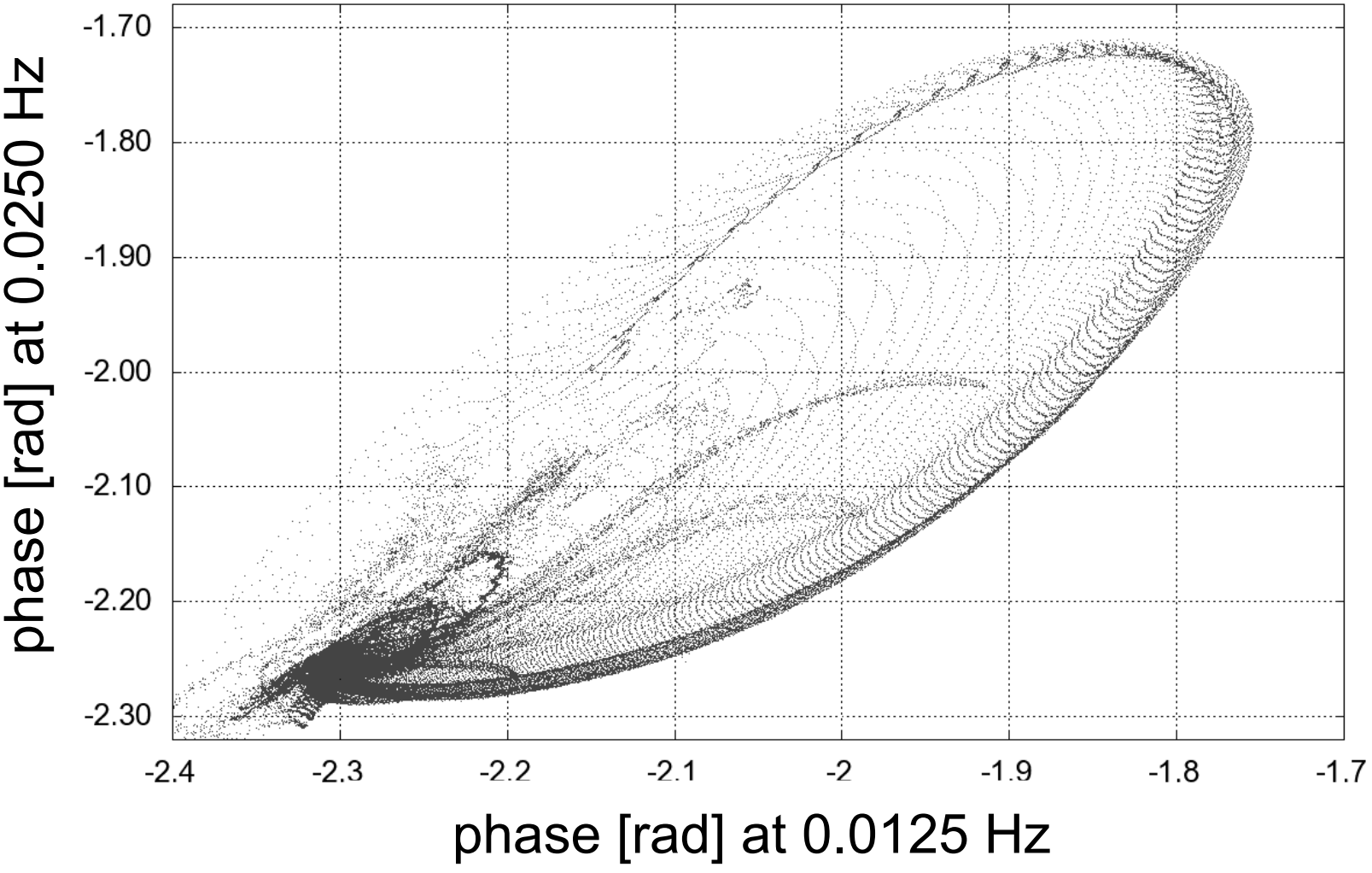


Phase image at 0.0250 Hz

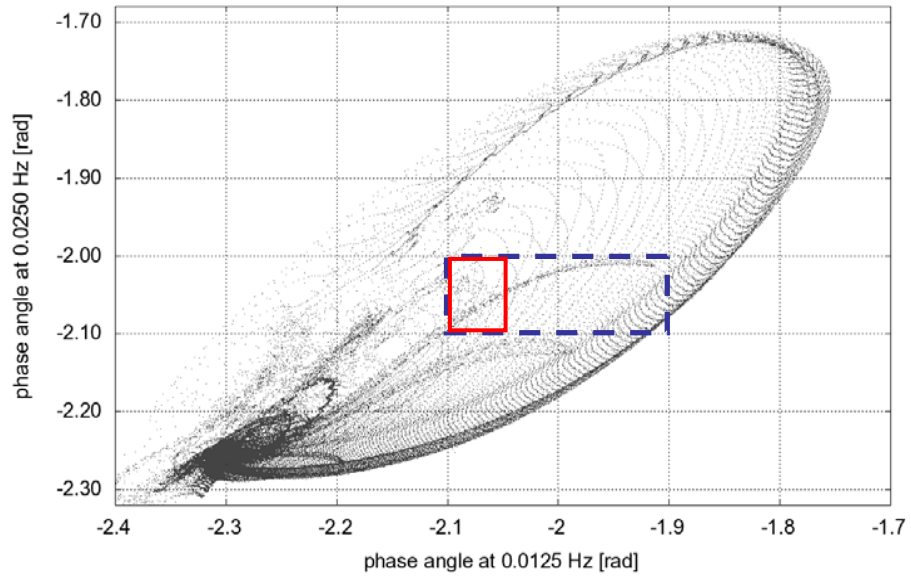


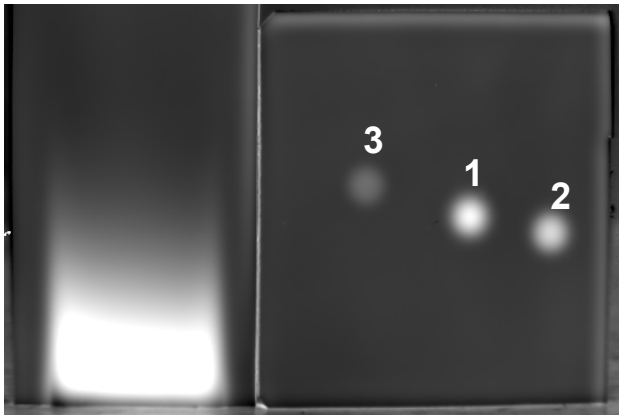
Phase image at 0.0125 Hz

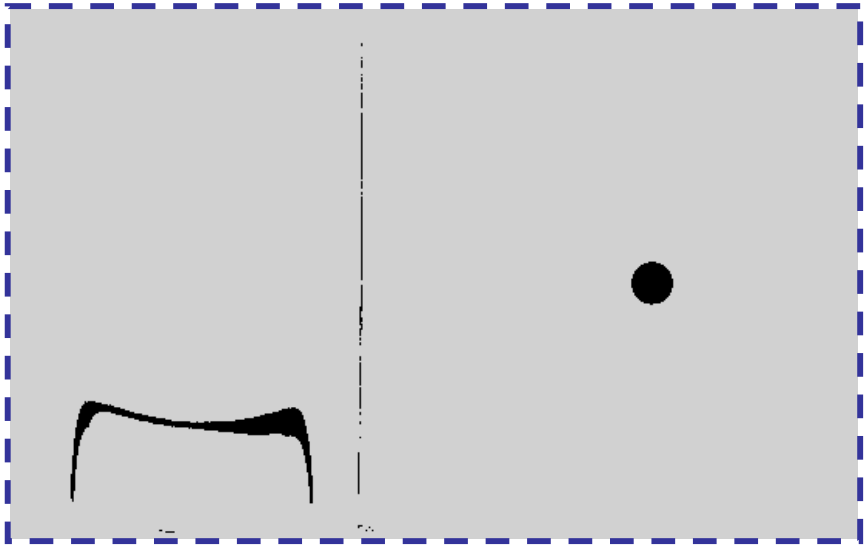
Phase images of whole scenery



Scatter plot of whole scenery







Tracing features back by filtering in the scatter plot

erstörungs-
ZfP
eie Prüfung

Universität
IKT
Stuttgart

Lockin-Thermografie:

- Prinzip
- Technische Anwendungen

  (Anregung durch Licht oder Ultraschall)
- Aktuelle Entwicklungen
- Zusammenfassung

Lockin-Thermografie:

Bildstapelanalyse: lokale Fouriertransformation an jedem Pixel entlang der Zeitachse.

- Robustes Phasenbild
- Abbildung thermischer Grenzflächen und Enthaftungen
- Tiefenreichweite über Modulationsfrequenz einstellbar. Grenze trotzdem etwa 8 mm in CFK.

ZFP an CFK

- **Fügefehler: Stringerablösung**
- **Delamination**
- **Impakterkennung von außen**
- **Reparaturqualität**
- **Harznester oder Harzmangel**

Worin liegt die Attraktivität neuer ZfP-Verfahren?

Schnell
(für 100%-Prüfung)

Berührungslos
(auch an nassen oder entfernten Oberflächen)

Bildgebend
(anschaulich)

Defektselektiv
(hohe Erkennungswahrscheinlichkeit)

Merkmalsextraktion durch Filteruzng im Scatter Plot

Die Ergebnisse wären nicht möglich gewesen ohne

- **die engagierte Forschungsarbeit des Stuttgarter interdisziplinären Teams (Gastwissenschaftler, Doktoranden, Diplomanden, Studenten, …)**
- **Gute Zusammenarbeit mit Luftfahrt-Nachbarn und Industriepartnern (Realprobleme statt Laborproben)**
- **finanzielle Unterstützung durch DFG (Normalverfahren, SFB 381, SPP 1123).**

Herzlichen Dank !!

Fragen?

Gerd Busse

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