NDT Applications of All-Electronic 3D Terahertz Imaging

Stefan BECKER[*], Andreas Keil[*], Heinrich Nolting[*]
[*]Becker Photonik GmbH, D-32457 Porta Westfalica, Germany

- Basics of All-Electronic 3D Terahertz Imaging
- Inspection of Fibre-Reinforced Plastic (FRP) Components
- Inspection of Foams and Sandwich Components
- Inspection of (Fibre-Reinforced) Ceramic Components
- Comparison with Established NDT Methods

3D Terahertz Imaging – A new method for Industrial Non Destructive Testing (NDT) !?

Strong competition by established methods:

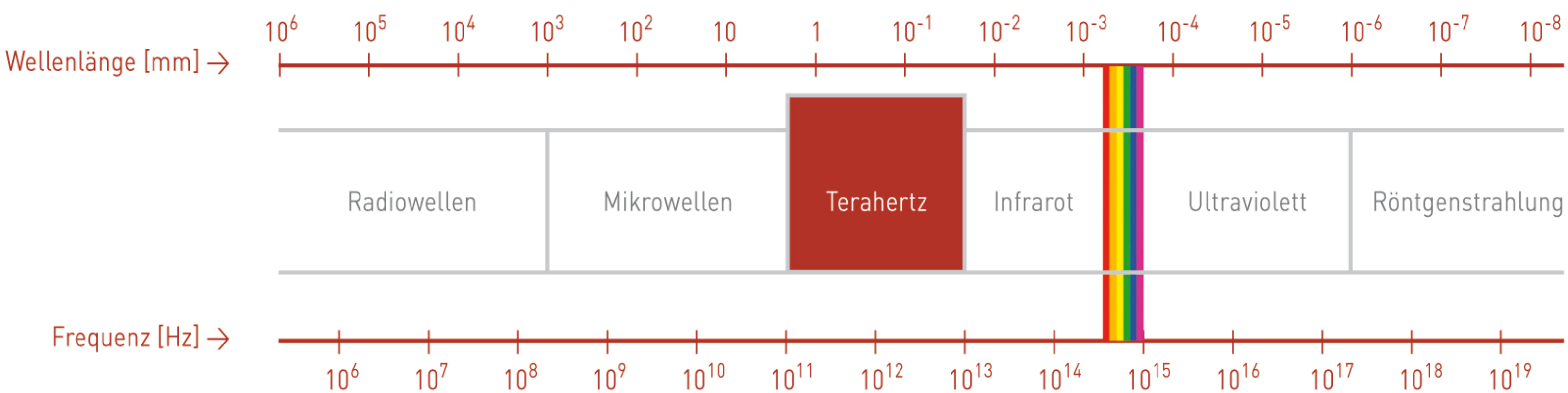
- X-ray: Industrial use since >100 years!
- Ultrasound: Industrial use since >50 years!
- Active Thermograhy: Industrial use since >20 years!

- 3D Terahertz Imaging: Industrial use since only >2 years!

Terahertz technology will only be commercially successful in NDT if there are applications where terahertz inspection is more efficient (cost, quality, speed) than with established methods.

What is Terahertz Radiation?

- Electromagnetic radiation in the frequency range 0.1 THz - 10 THz
- Corresponding wavelength range in vacuum is 3 mm – 0.03 mm
- For many years it was called the „terahertz gap“

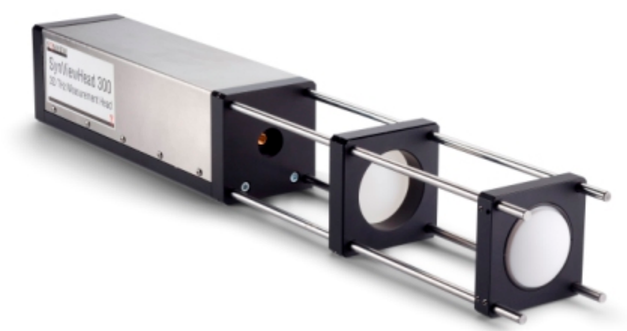


How can terahertz radiation be generated?

- Laser based systems *(not discussed further in this presentation)*
  - variable frequency
  - higher frequencies (> 1 THz) available

- **All-electronic systems**
  - Frequency multiplication of microwave radiation
  - compact + robust
  - fast (10 kHz)
  - SynView technology

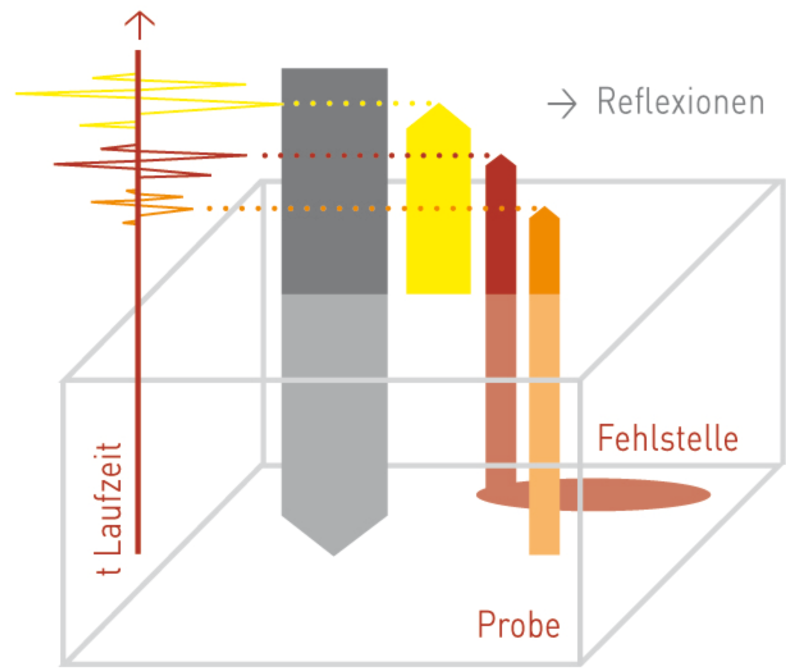
  (effective 1st July 2013 Becker Photonik GmbH acquired the technology from **SynView GmbH**)



beckerphotonik gmbh
messtechnik | dienstleistung | ausbildung

How does all-electronic terahertz imaging work?

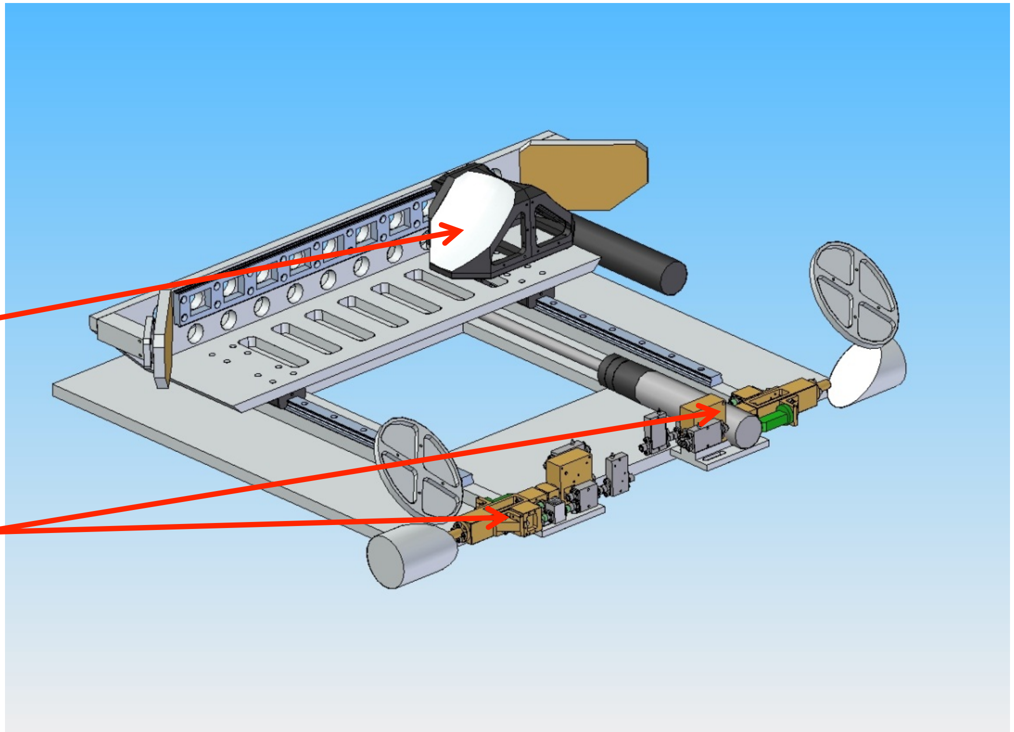
- Frequency modulated source (T_x) and coherent detector (R_x)
- „distance radar" in reflection: (T_x – R_x) ~ d (distance)
- All distance measurements for each x/y-position together give the **3D terahertz image**



beckerphotonik gmbh
messtechnik | dienstleistung | ausbildung

How does all-electronic terahertz imaging work?

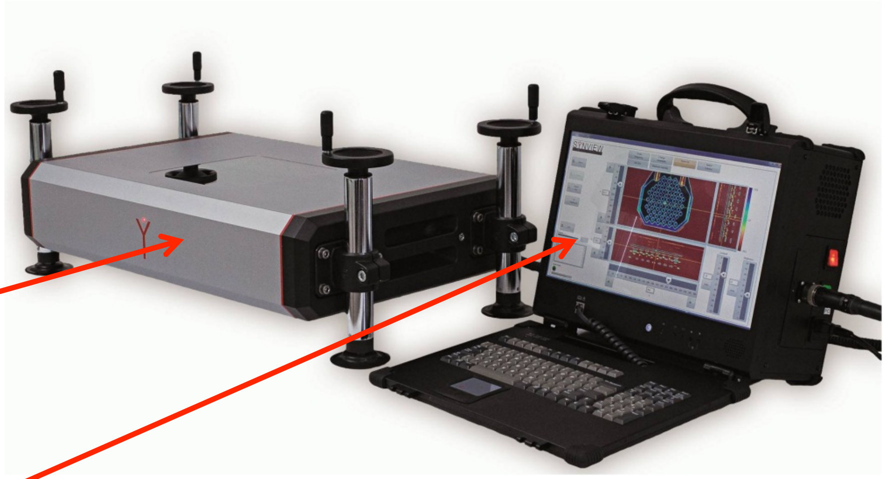
- Focussing optics for the terahertz radiation
- 2 sources and 2 detectors (100 GHz + 300 GHz) integrated
- The 3D terahertz image is generated by scanning line after line and the inspection time for a 200 mm x 300 mm area is less than 5 minutes (no preparation necessary)



SynViewCompact

How does all-electronic terahertz imaging work?

- One mobile scanning unit (approximately 20 kg weight) can be used in any orientation (horizontal, vertical, flipped)
- One mobile PC unit contains all necessary control boards



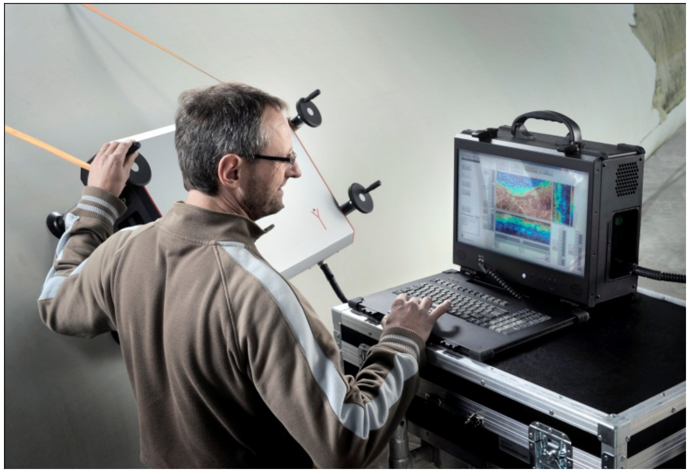
SynViewCompact

beckerphotonik gmbh
messtechnik | dienstleistung | ausbildung

How does all-electronic terahertz imaging work?

- One mobile scanning unit (approximately 20 kg weight) can be used in any orientation (horizontal, vertical, flipped)

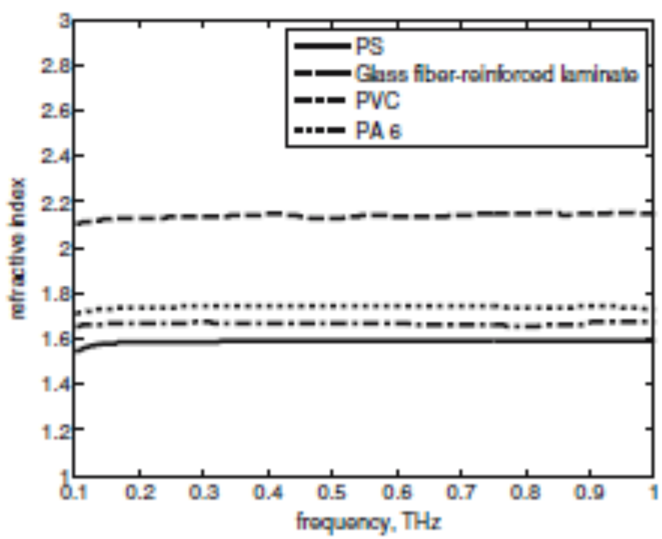
- One mobile PC unit contains all necessary control boards

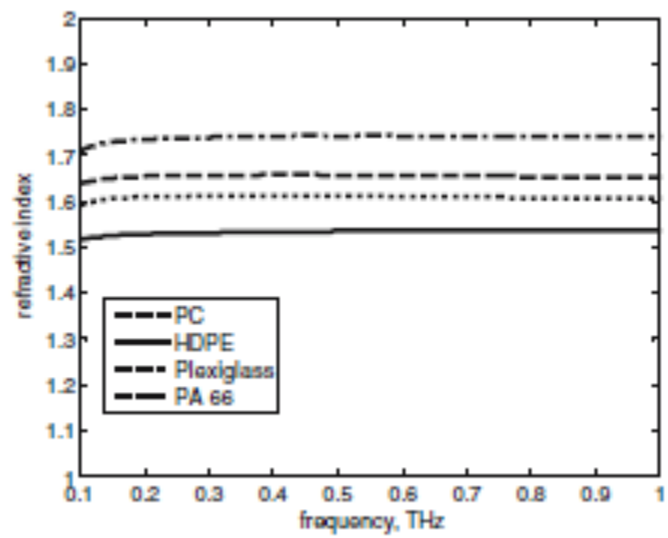


General characteristics

- Terahertz radiation is not ionizing, therefore a protection of operators is not necessary
- No contact medium necessary (electromagnetic radiation)
- Inspection in case of only single sided access is no problem (in reflection mode)!
- Portable technology which can be used to inspect large objects
- Lateral resolution at 0.3 THz is 1 mm in vacuum
- Fast data acquisition with up to 10 kHz acquisition rate
- Dielectric materials can be penetrated (glas fiber reinforced plastics, ceramics, Paper etc.)

Characteristics regarding plastics





→ refractive index of plastics in the range 0.1 THz - 1.0 THz is typically n = 1,5 - 2

Quelle:

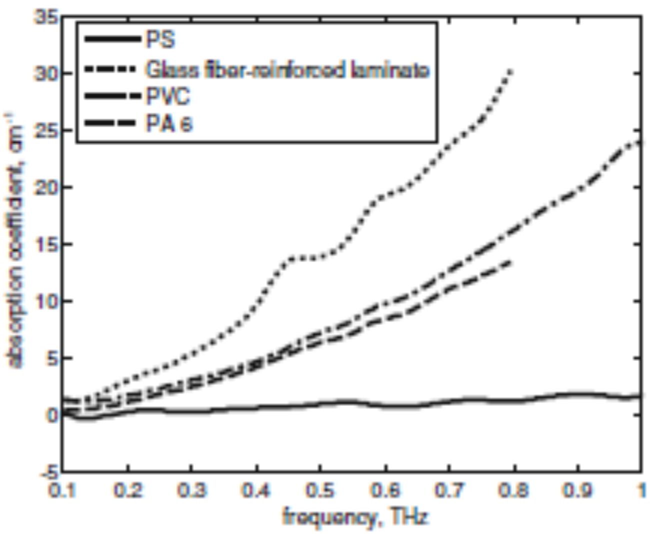
Int J Infrared Milli Waves (2007) 28:363–371
DOI 10.1007/s10762-007-9217-9

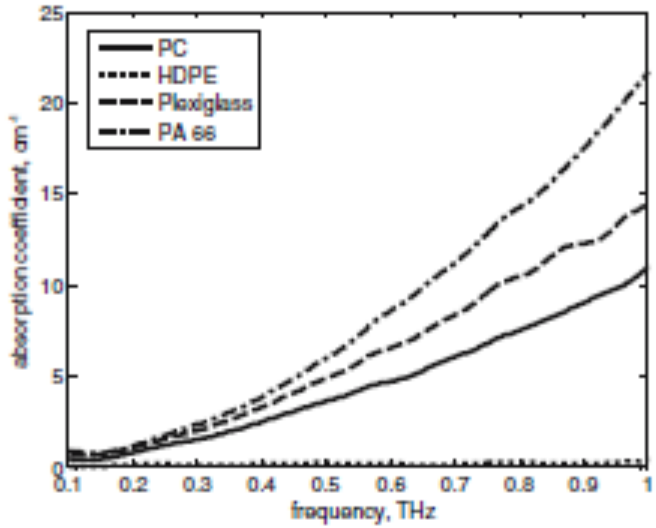
Properties of Building and Plastic Materials in the THz Range

R. Piesiewicz · C. Jansen · S. Wietzke · D. Mittleman · M. Koch · T. Kürner

beckerphotonik gmbh
messtechnik | dienstleistung | ausbildung

Characteristics regarding plastics





→ absorption of plastics increases ≈ 1-2 orders of magnitude in the range 0.1 THz - 1.0 THz
→ Penetration is up to 100 mm

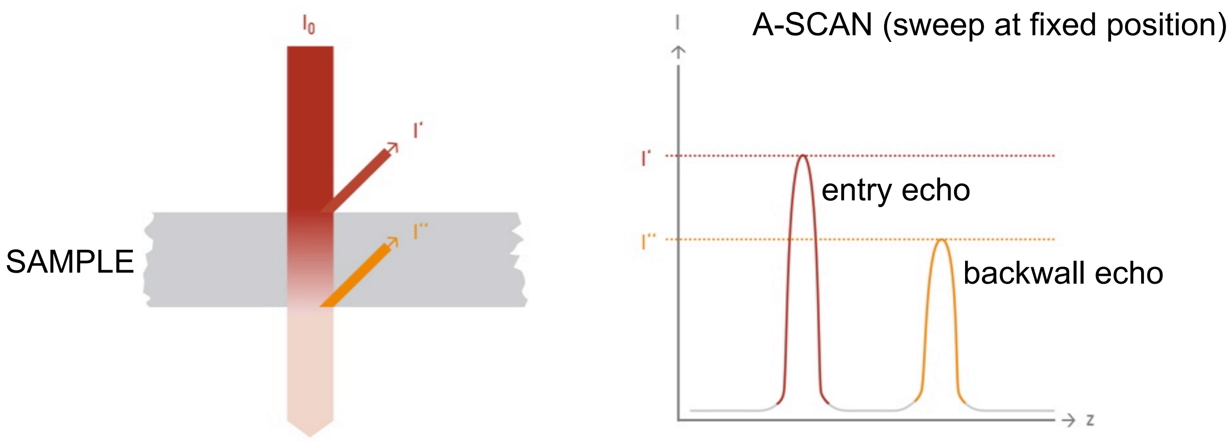
Quelle:

Int J Infrared Milli Waves (2007) 28:363–371
DOI 10.1007/s10762-007-9217-9

Properties of Building and Plastic Materials in the THz Range

R. Piesiewicz · C. Jansen · S. Wietzke · D. Mittleman · M. Koch · T. Kürner

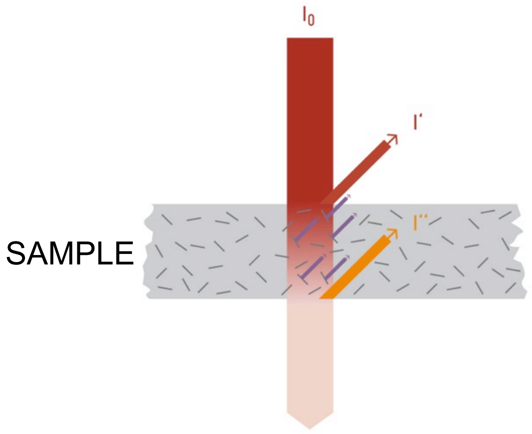
(1) Interpretation of Test Results: Homogeneous Plate

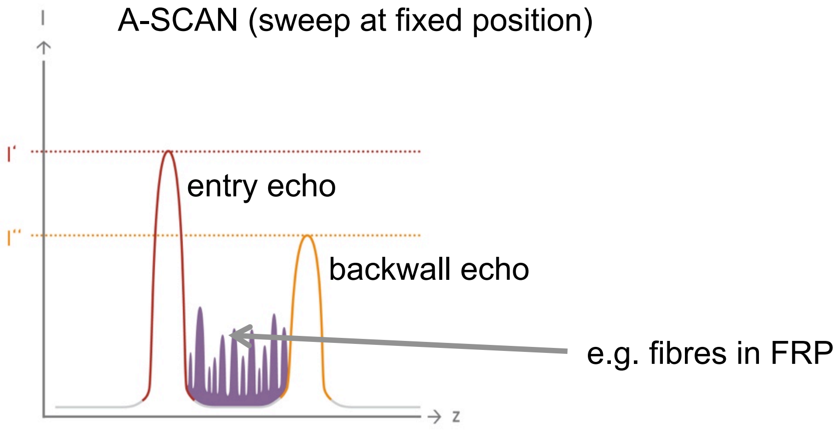


→ intensity of entry echo depends on surface reflectivity

→ intensity of backwall echo depends also on signal damping in material

(2) Interpretation of Test Results: Inhomogeneous Plate

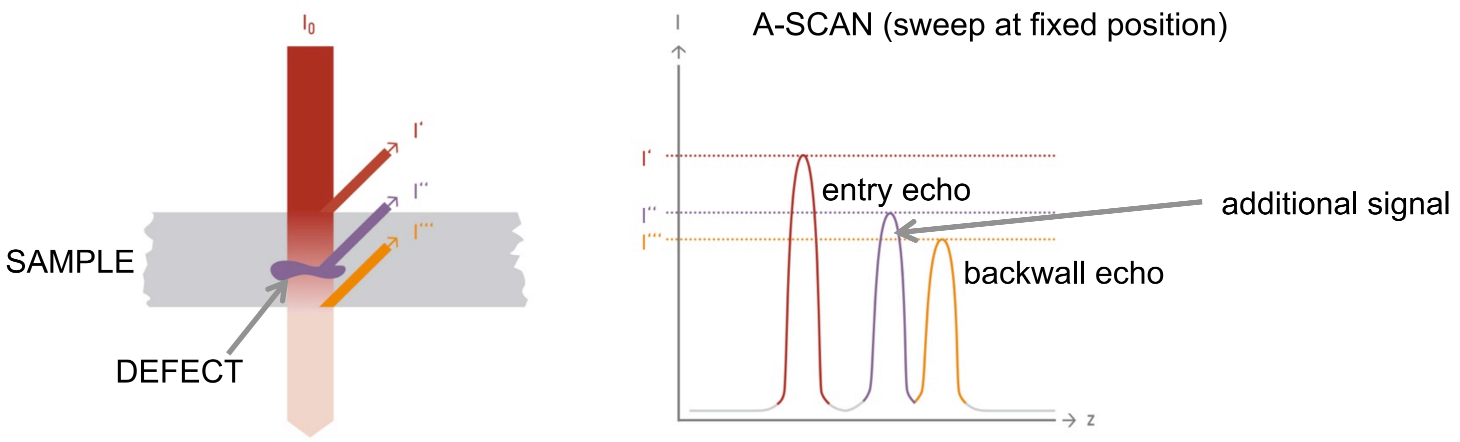




→ **additional signals due to e.g. fibres in FRP**

→ **increased signal damping in material due to e.g. fibres in FRP**

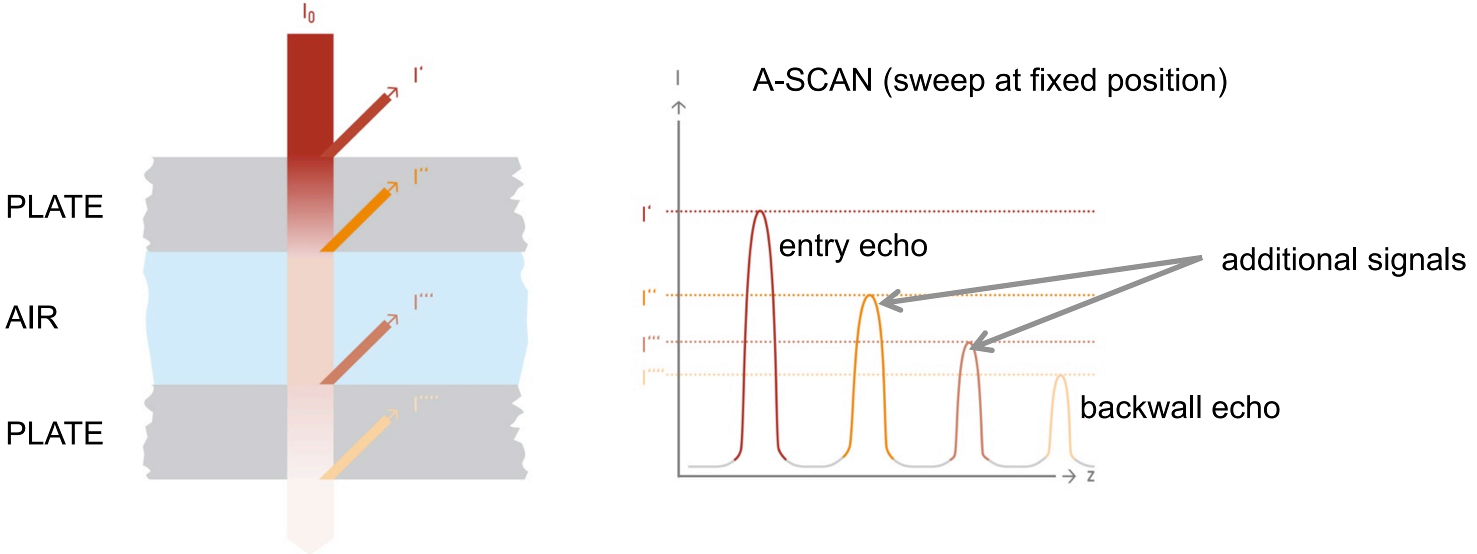
(3) Interpretation of Test Results: Homogeneous Plate + Defect



→ **additional signal due to defect**

→ **increased signal damping due to defect**

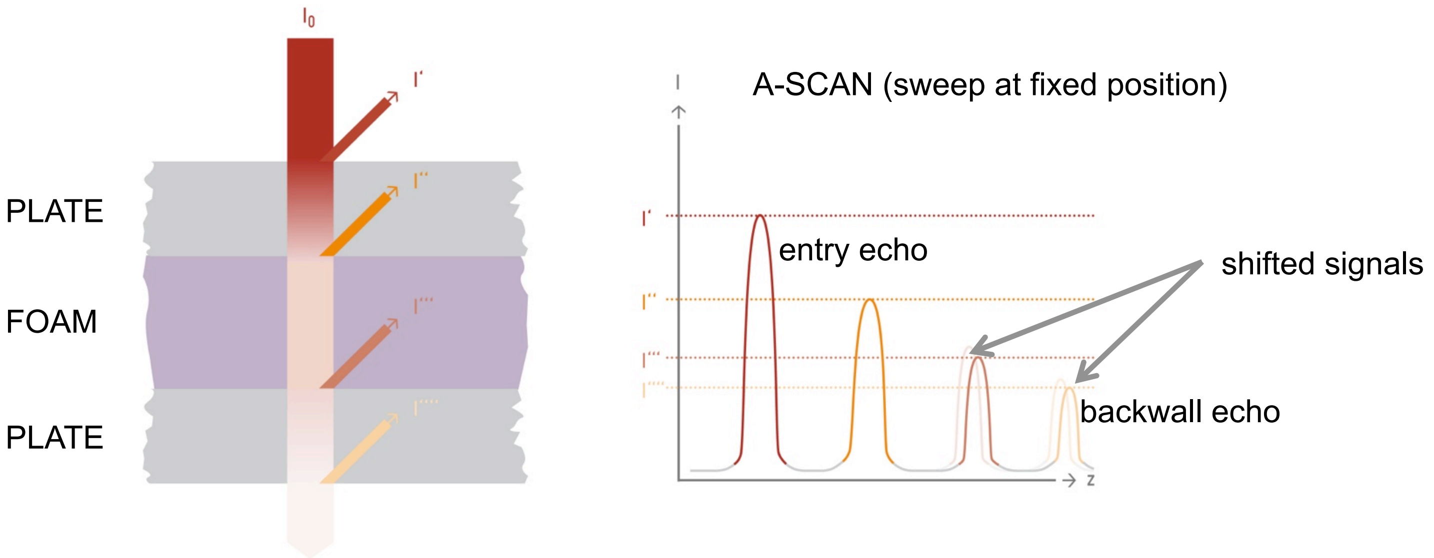
(4) Interpretation of Test Results: Hollow Component



→ **2 additional signals due to 2 more interfaces**

→ **increased signal damping due to additional interfaces**

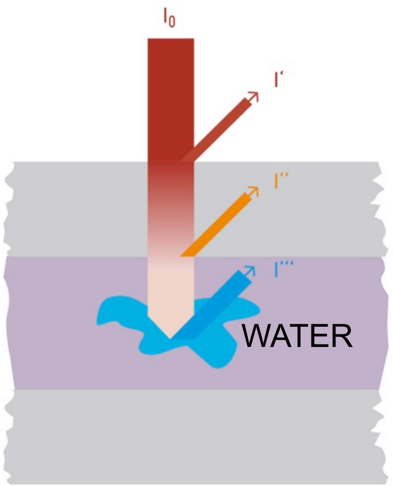
(5) Interpretation of Test Results: Sandwich Component

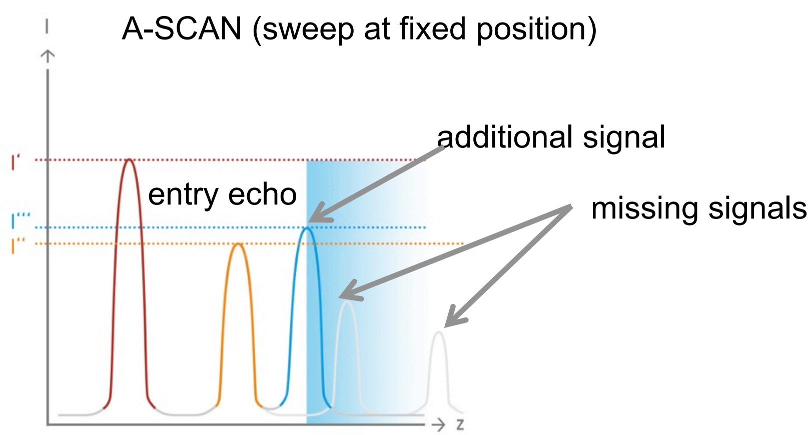


→ 2 (slightly) shifted signals due to increased refractive index of foam

→ (slightly) increased signal damping due to foam

(6) Interpretation of Test Results: Sandwich Component + Humidity



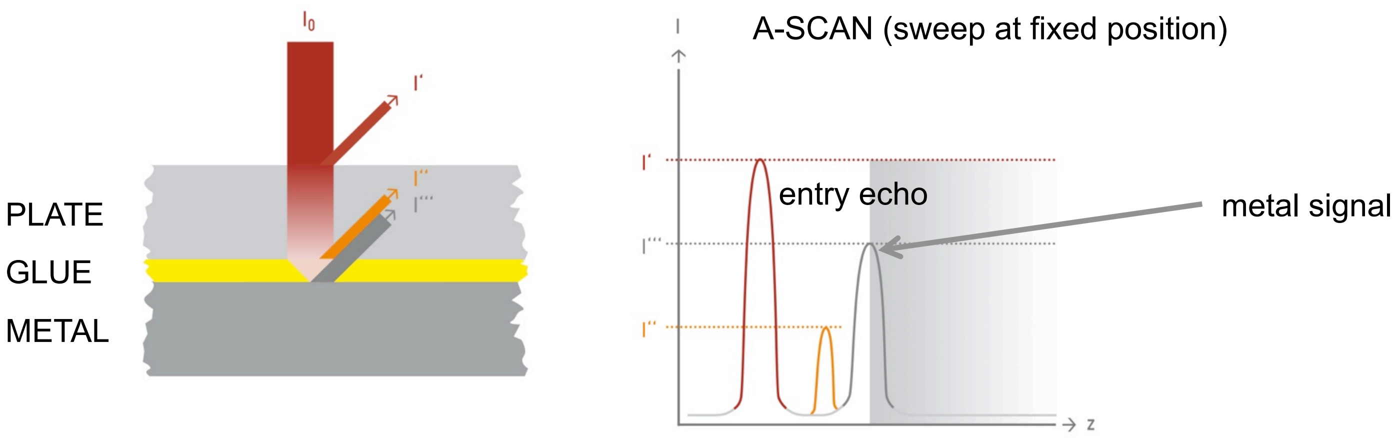


→ **1 additional signal due to reflection of water**

→ **2 missing signals due to absorption/reflection of water**

→ **no signals beyond the „water signal"**

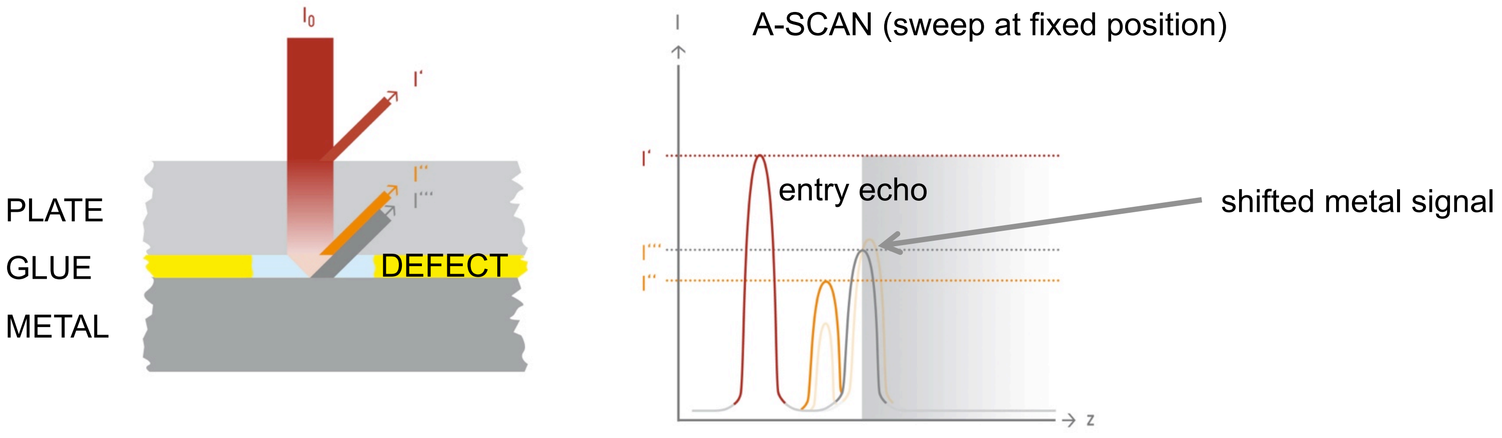
(7) Interpretation of Test Results: Metal Substrate



→ **additional signal due to layer of glue**

→ **no signals beyond the „metal signal“**

(8) Interpretation of Test Results: Metal Substrate + Defect

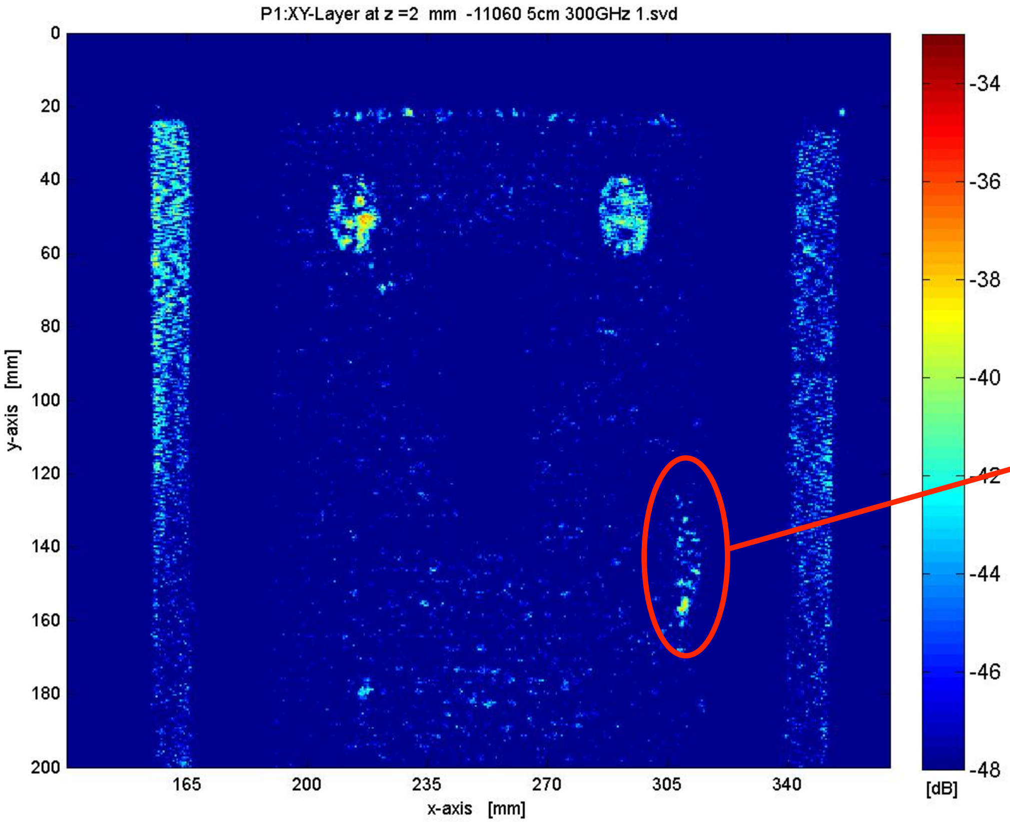


→ **increased signal due to defect in glue**

→ **no signals beyond the „metal signal“**

beckerphotonik gmbh
messtechnik | dienstleistung | ausbildung

SMC component

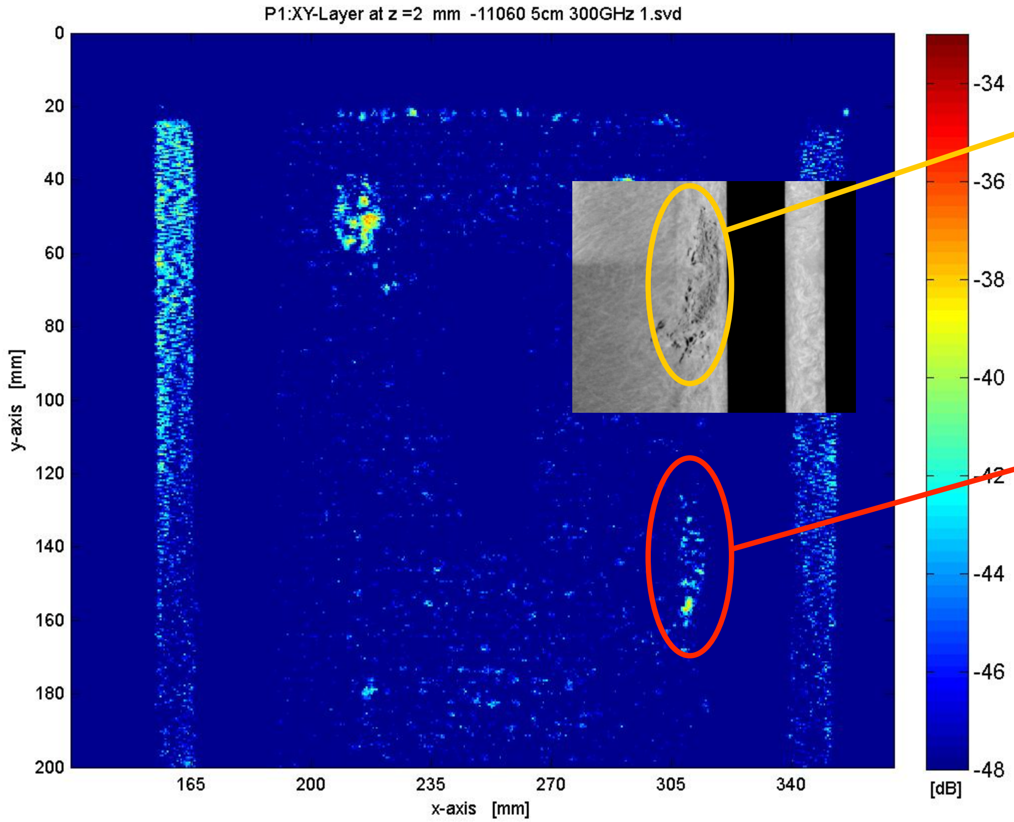


- **0.3 THz C-Scan**
- 200 mm x 200 mm Scan
- Material 14 mm thick
- Layer appr. 4 mm underneath the surface

- **Reflection** signal (area appr. 10 mm x 40 mm)
- All other signals are related to the geometry of the sample

beckerphotonik gmbh
messtechnik | dienstleistung | ausbildung

SMC component

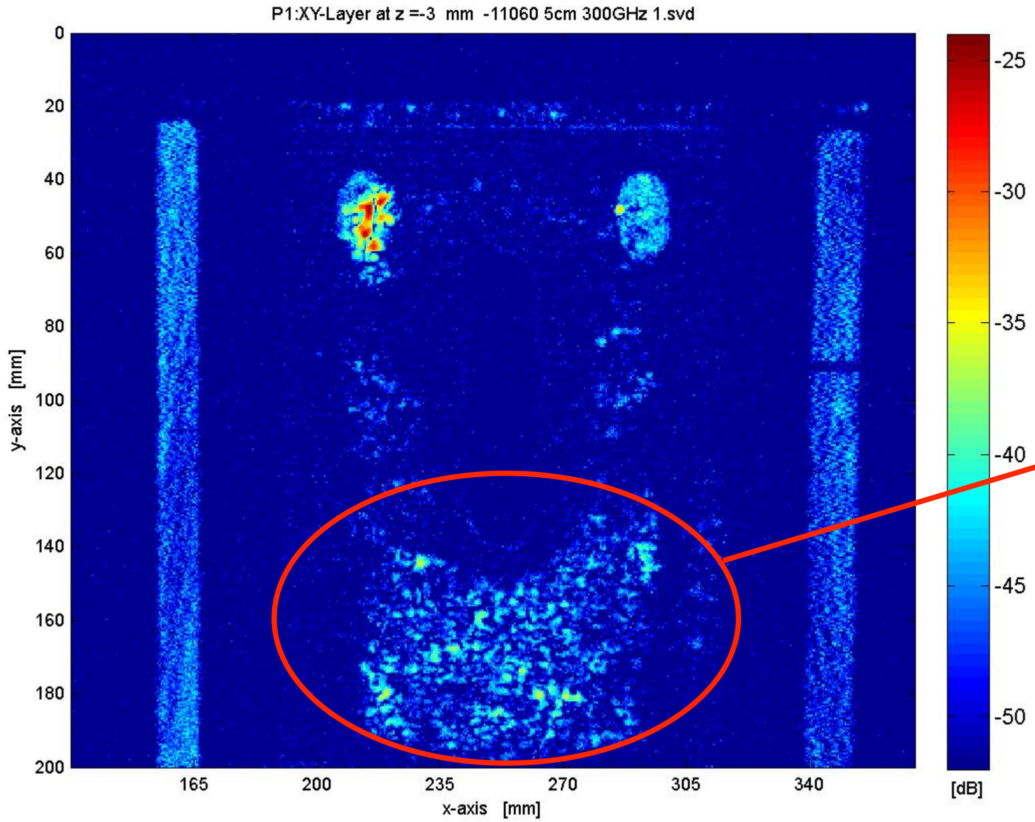


- **Comparison with X-ray CT**
- Position identical with cluster of pores
- Layer appr. 4 mm underneath the surface

- **Reflection** signal (area appr. 10 mm x 40 mm)
- All other signals are related to the geometry of the sample

beckerphotonik gmbh
messtechnik | dienstleistung | ausbildung

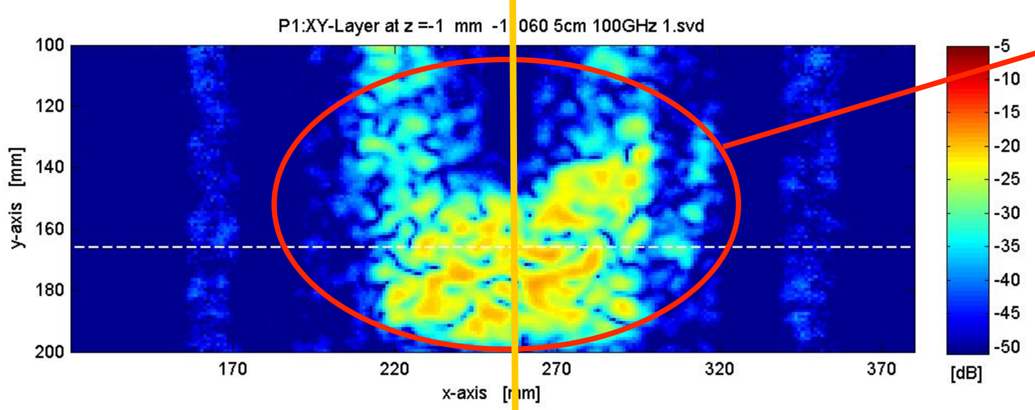
SMC component



- **0.3 THz C-Scan**
- 200 mm x 200 mm Scan
- Material 14 mm thick
- Layer appr. 7 mm underneath the surface

- **Reflection** signal (area appr. 60 mm x 80 mm)
- All other signals are related to the geometry of the sample

- SMC component

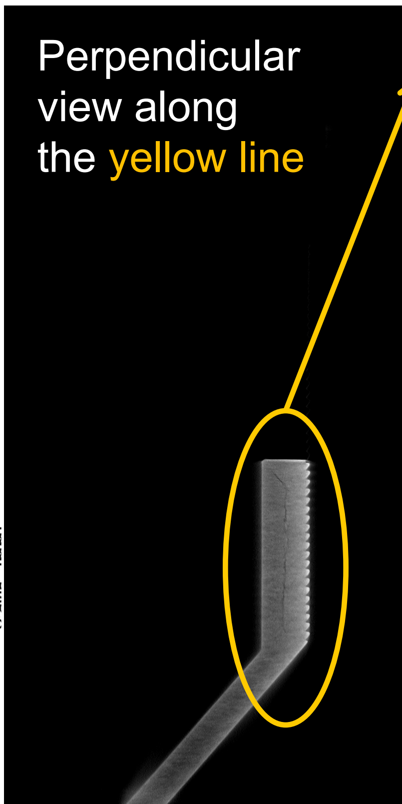


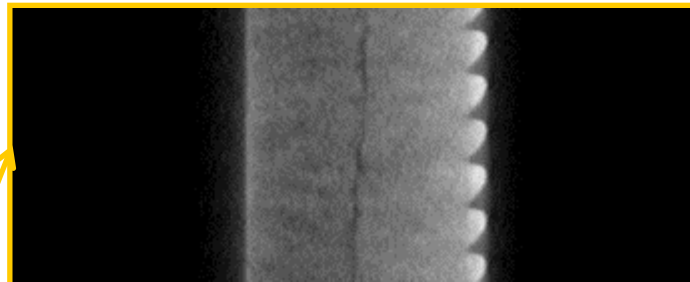
- **0.1 THz C-Scan**
- 200 mm x 200 mm Scan
- Material 14 mm thick
- Layer appr. 7 mm underneath the surface

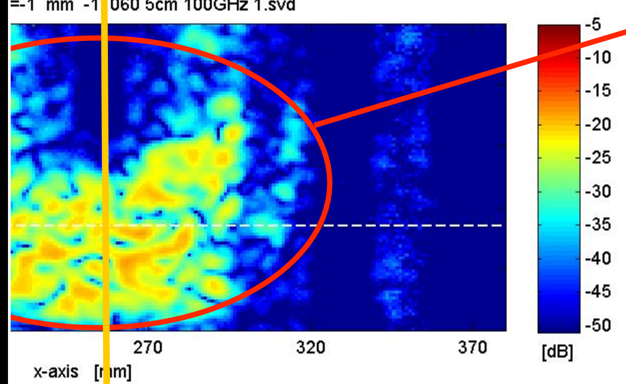
- **Reflection** signal (area appr. 60 mm x 80 mm)
- All other signals are related to the geometry of the sample

Inspection of FRP Components

- SMC component



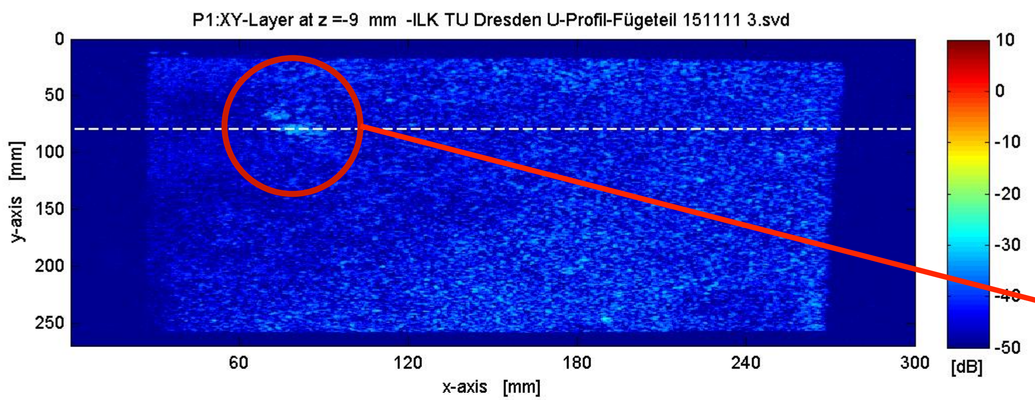


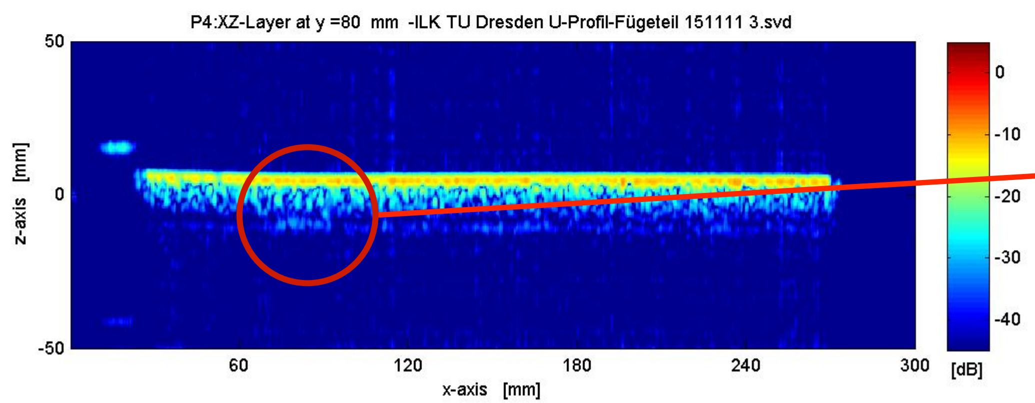


- **Comparison with X-ray CT**
- (perpendicular view)
- Large area crack appr. 7 mm underneath the surface

- **Reflection** signal (area appr. 60 mm x 80 mm)
- All other signals are related to the geometry of the sample

U-profile (FRP), bonding left



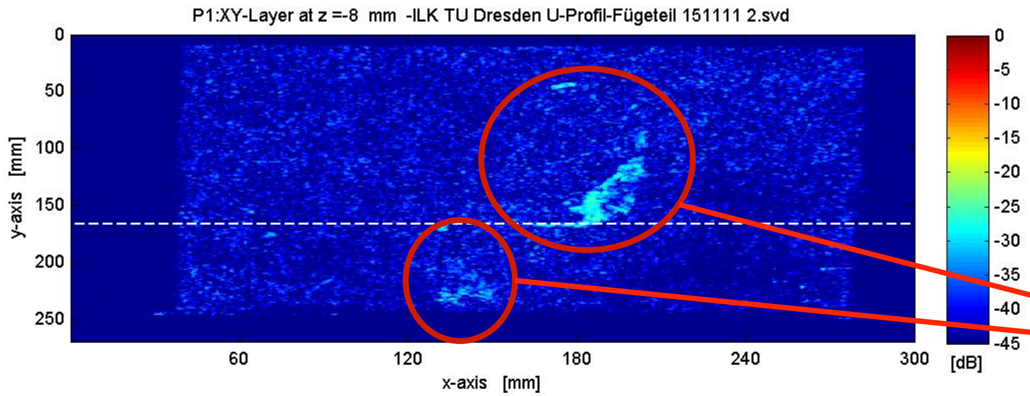


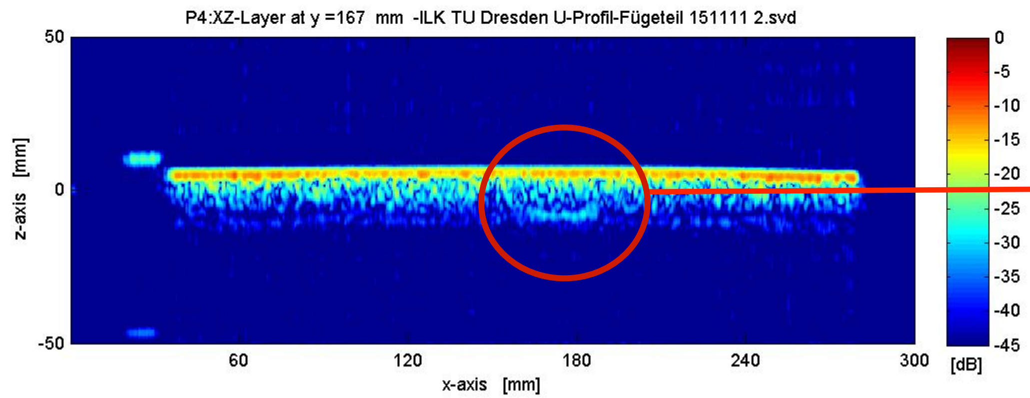
- **0.3 THz C-Scan**
- 300 mm x 270 mm Scan
- Material 12 mm thick
- Bonding area 6 mm underneath the surface
- **Small pore area**

- **B-Scan (z)**
- Position (y-axis) see image above

beckerphotonik gmbh
messtechnik | dienstleistung | ausbildung

U-profile (FRP), bonding right



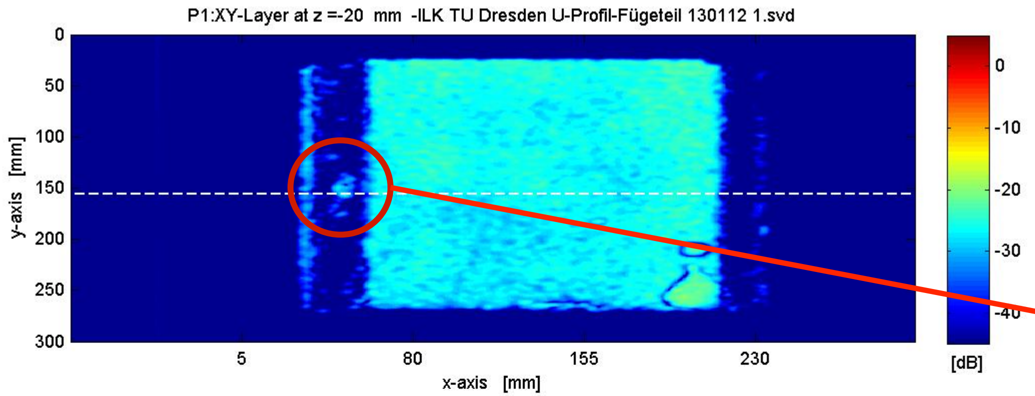


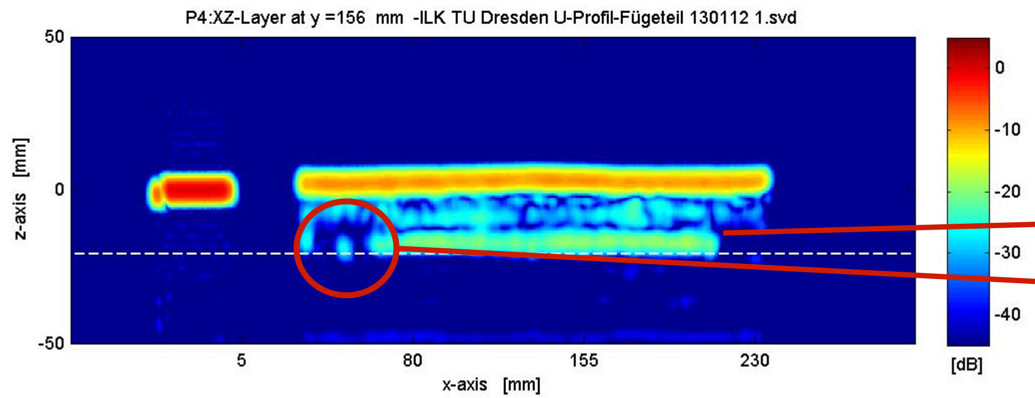
- **0.3 THz C-Scan**
- 300 mm x 270 mm Scan
- Material 12 mm thick
- Bonding area 6 mm underneath the surface
- **Large Pore areas**

- **B-Scan (z)**
- Position (y-axis) see image above

beckerphotonik gmbh
messtechnik | dienstleistung | ausbildung

U-profile (FRP), bonding top

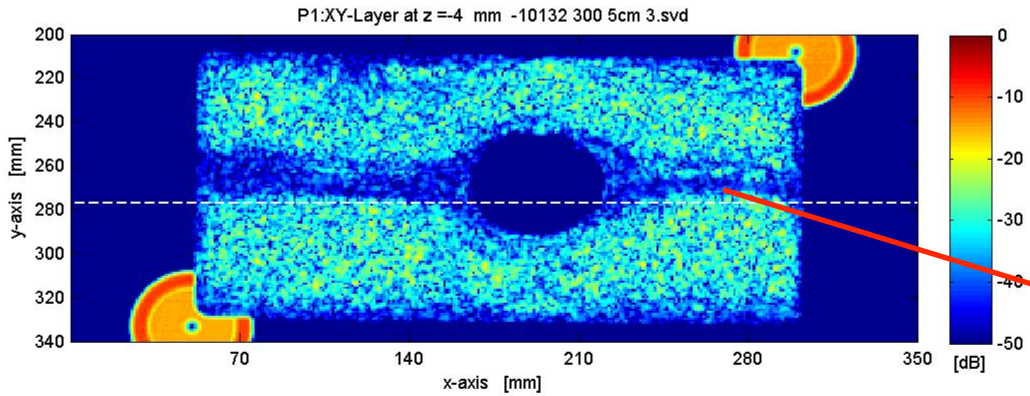


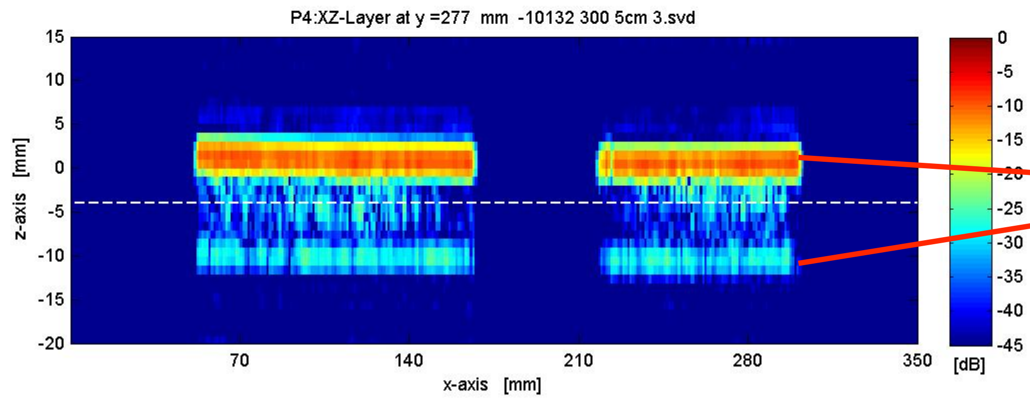


- **0.1 THz C-Scan**
- 300 mm x 300 mm Scan
- Material 12 mm thick
- Bonding area 13 mm underneath the surface
- **Pore in the bonding area**

- **B-Scan (z)**
- Backwall echo
- Pore

SMC-Plate

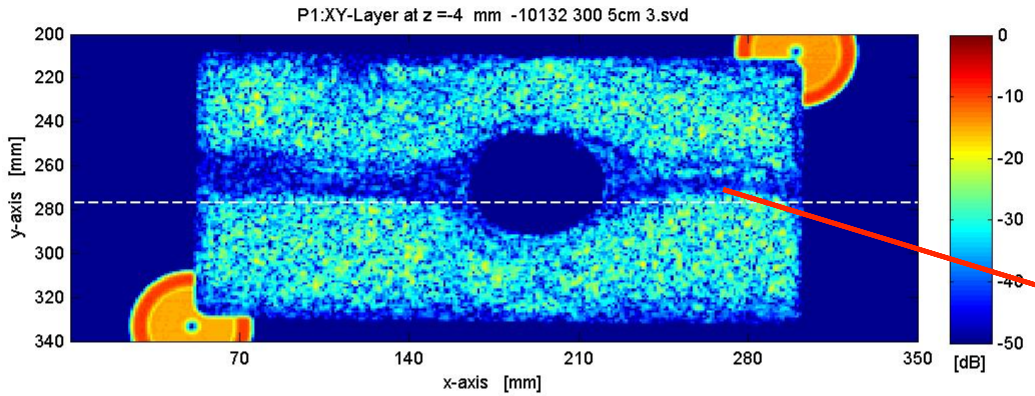


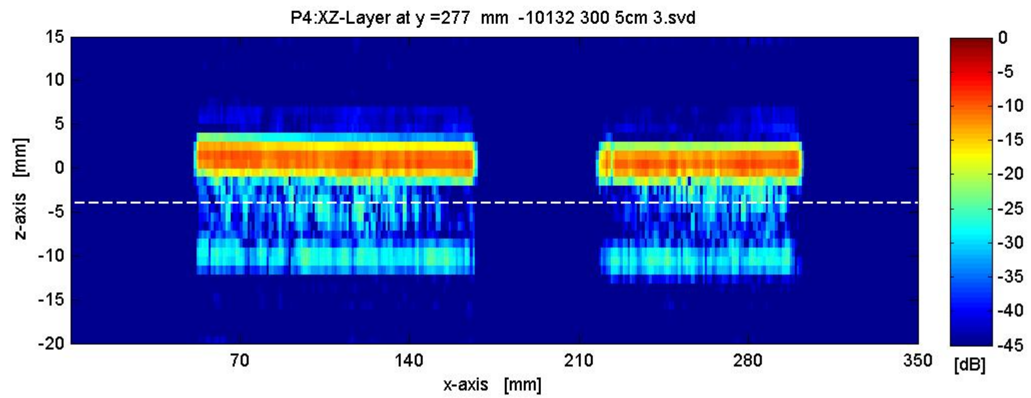


- **0.3 THz C-Scan**
- 350 mm x 140 mm Scan
- Material 6 mm thick
- Layer appr. 3 mm underneath the surface
- Area with decreased reflection signal

- **B-Scan (z)**
- Entry and backwall echo

- SMC-Plate



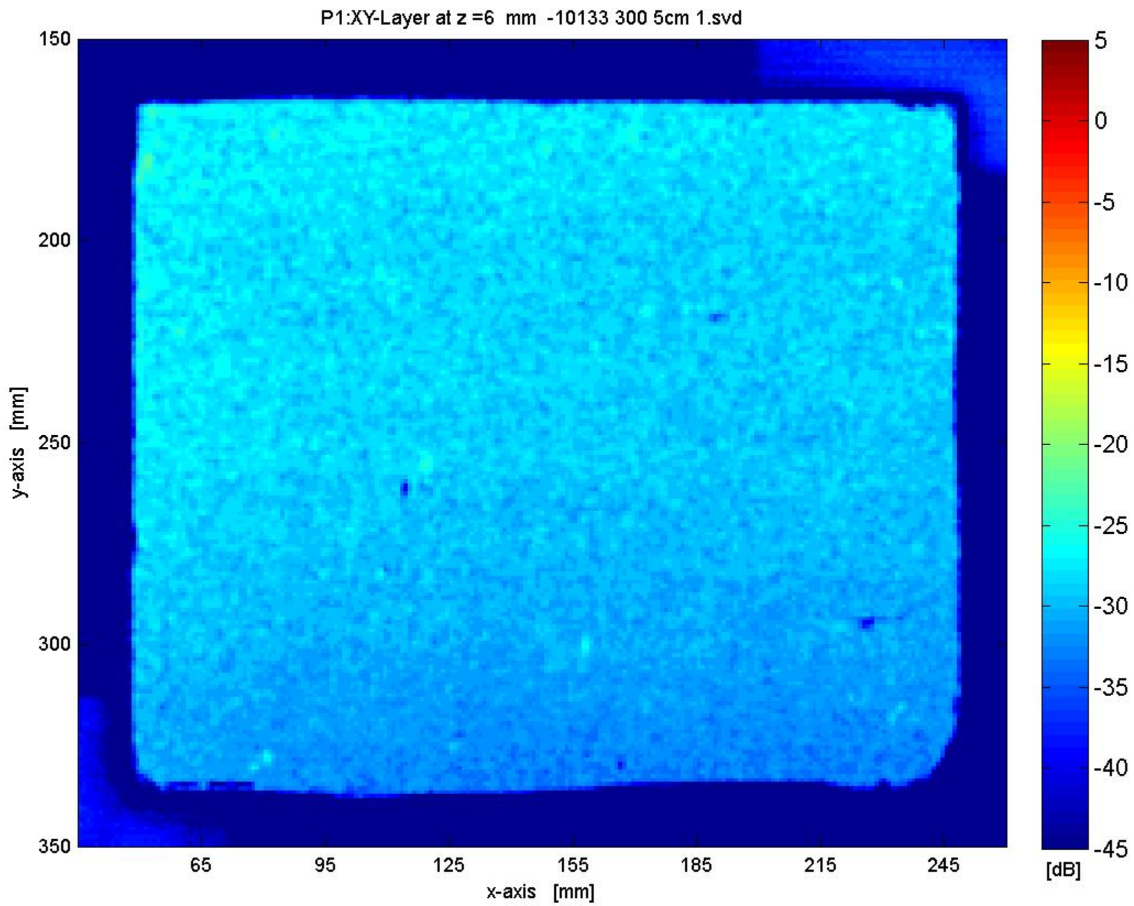


- **0.3 THz C-Scan**
- 350 mm x 140 mm Scan
- Material 6 mm thick
- Layer appr. 3 mm underneath the surface
- Area with decreased reflection signal

- **Interpretation: Fibre orientation is different in the weld line area!**

Inspection of Foams and Sandwich Components

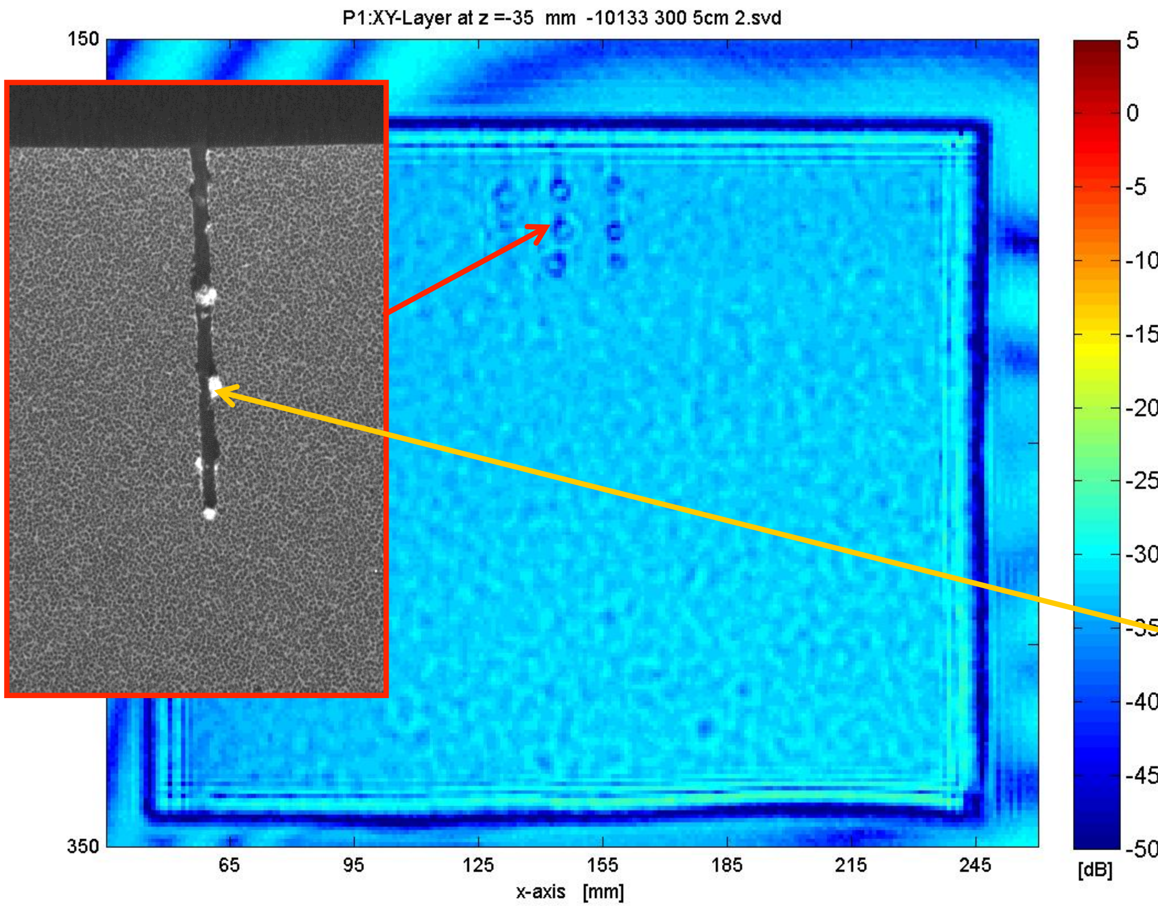
PU-Foam



- **0.1 THz C-Scan**
- 220 mm x 200 mm Scan
- Material 40 mm thick
- Layer at position of first (of totally 3) drilling holes

- **No metal substrat**
- All 3 drilling holes (Ø 2 mm) are not visible

- PU-Foam

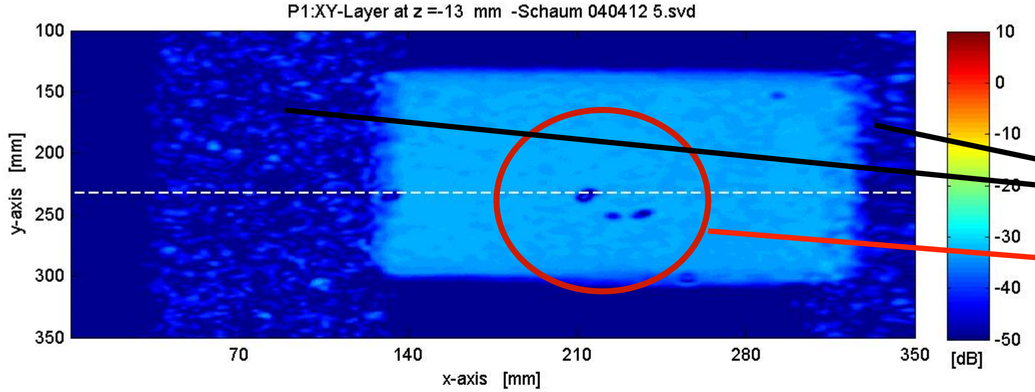


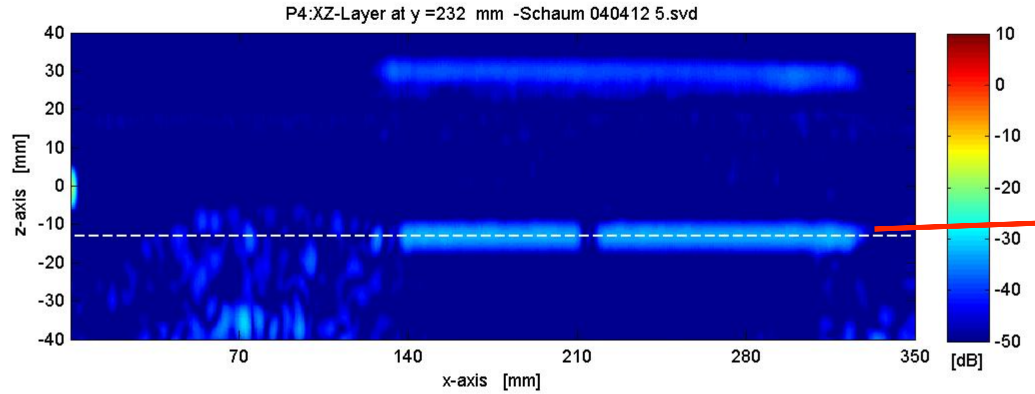
- **0.1 THz C-Scan**
- 220 mm x 200 mm Scan
- Material 40 mm thick
- Layer at metal substrate surface position

- **„back wall echo“**
- All 3 drilling holes (Ø 2 mm) are clearly visible
- X-ray CT image of one of the drilling holes

Inspection of Foams and Sandwich Components

- 40 mm foam

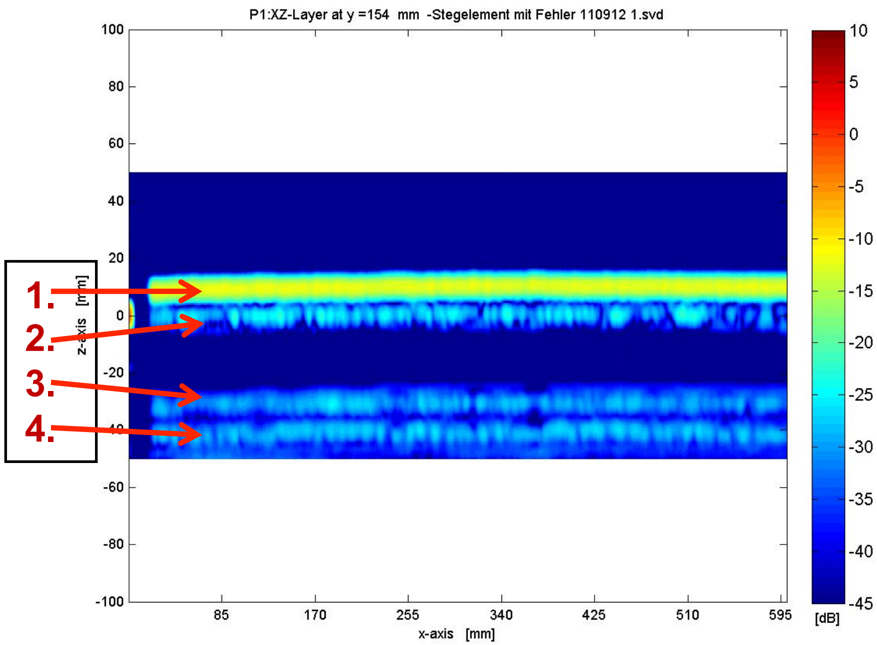


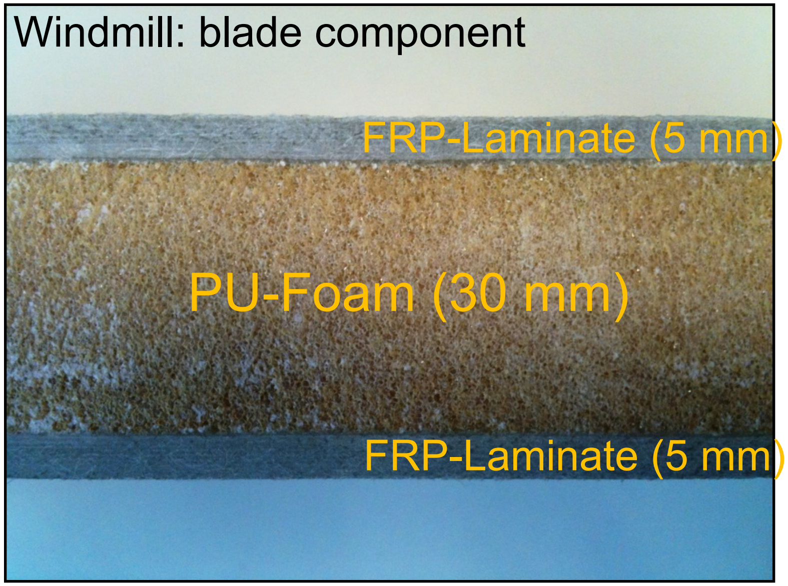


- **0.1 THz C-Scan**
- 350 mm x 250 mm Scan
- Material 40 mm thick
- Sample carrier
- **Several defects visible in back wall echo signal**

- **Tiefenprofil (z)**
- Back wall echo

- **B-Scan** (100 GHz), measurement from top side

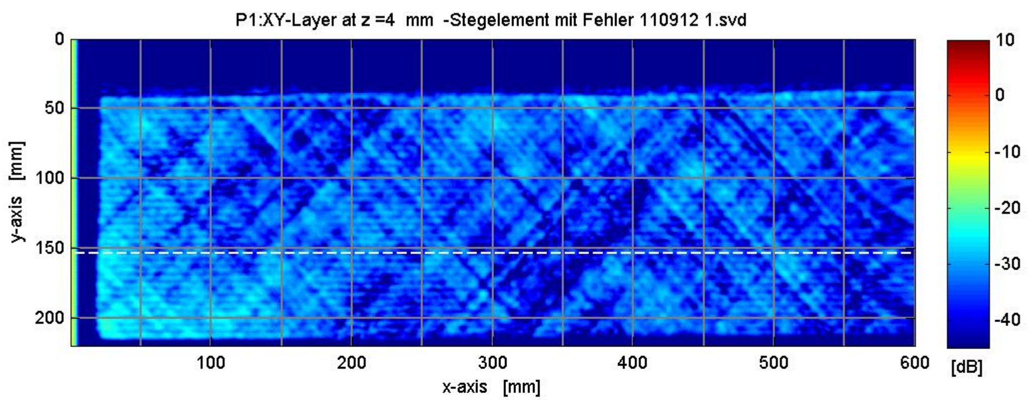


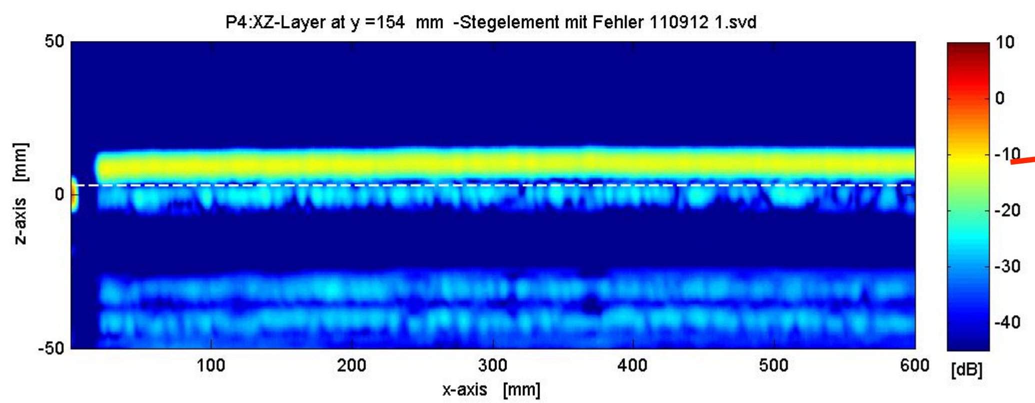


Signals of 4 interfaces:
1. Air – FRP
2. FRP - Foam
3. Foam - FRP
4. FRP - Air

Inspection of Foams and Sandwich Components

- **C-Scan** (100 GHz), measurement from top side



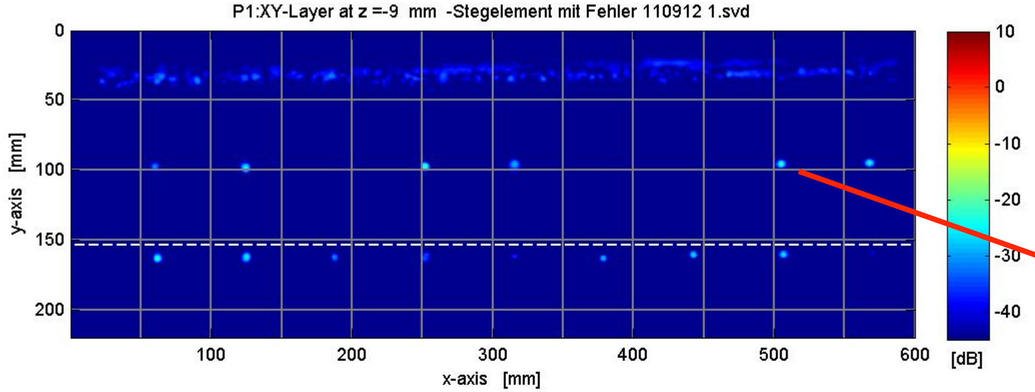


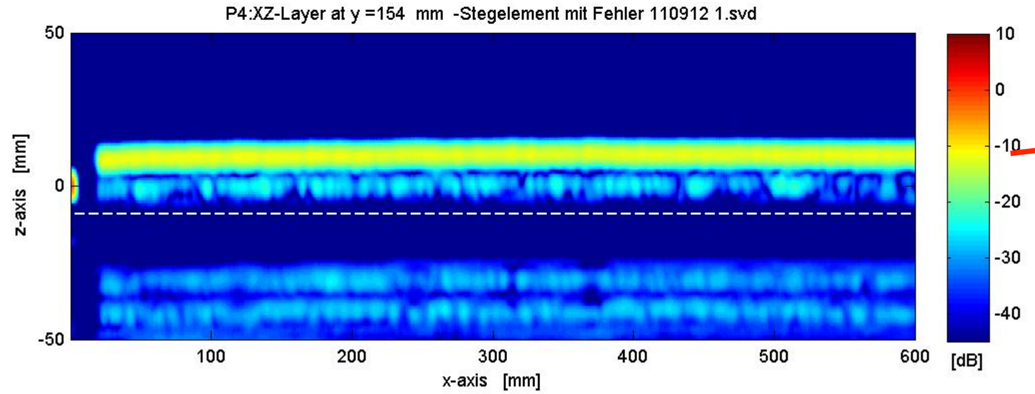
- Windmill: blade component
- 600 mm x 250 mm Scan
- Layer appr. **3 mm** underneath the surface (within the first FRP-Plate)
- Fibre orientations are visible

- **B-Scan**
- Position see dotted line above

Inspection of Foams and Sandwich Components

- **C-Scan** (100 GHz), measurement from top side



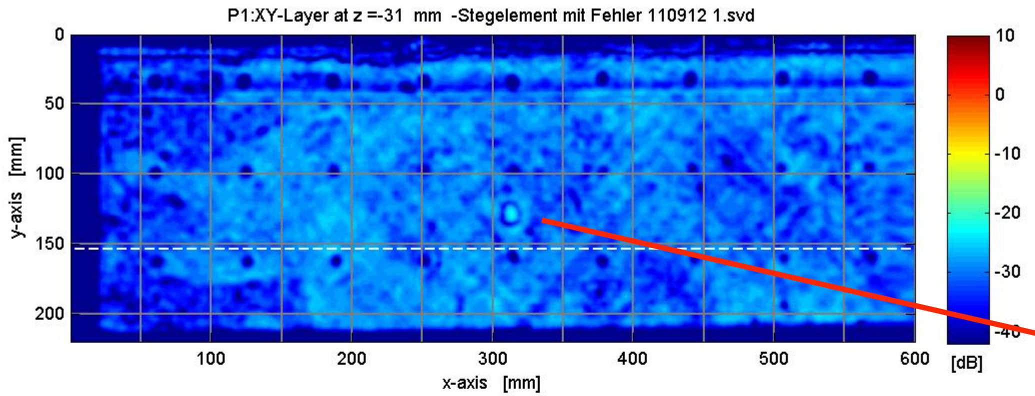


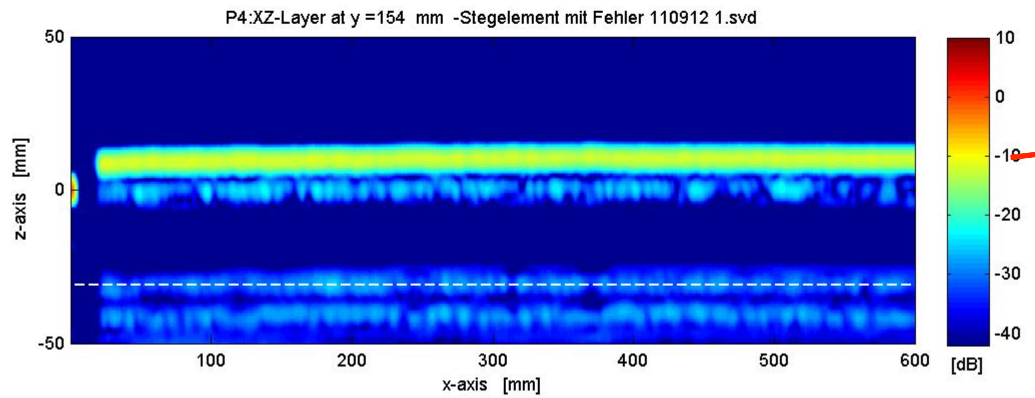
- Windmill: blade component
- 600 mm x 250 mm Scan
- Layer appr. **10 mm** underneath the surface (foam)
- Spots generated by distance pieces

- **B-Scan**
- Position see dotted line above

Inspection of Foams and Sandwich Components

C-Scan (100 GHz), measurement from top side



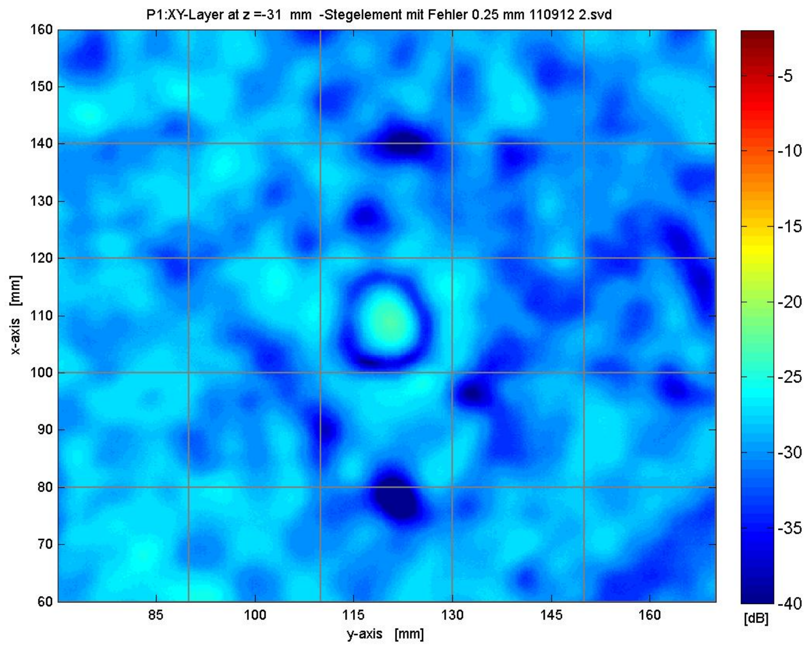


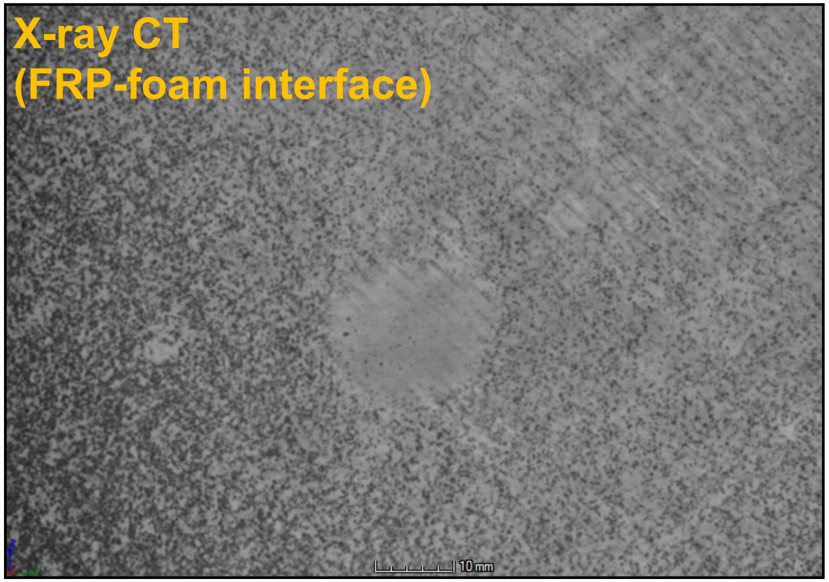
- Windmill: blade component
- 600 mm x 250 mm Scan
- Layer appr. **35 mm** underneath the surface (interface foam-FRP)
- Wetting defect: Ø appr. 20 mm

- **B-Scan**
- Position see dotted line above

beckerphotonik gmbh
messtechnik | dienstleistung | ausbildung

- **C-Scan** (100 GHz), measurement from top side





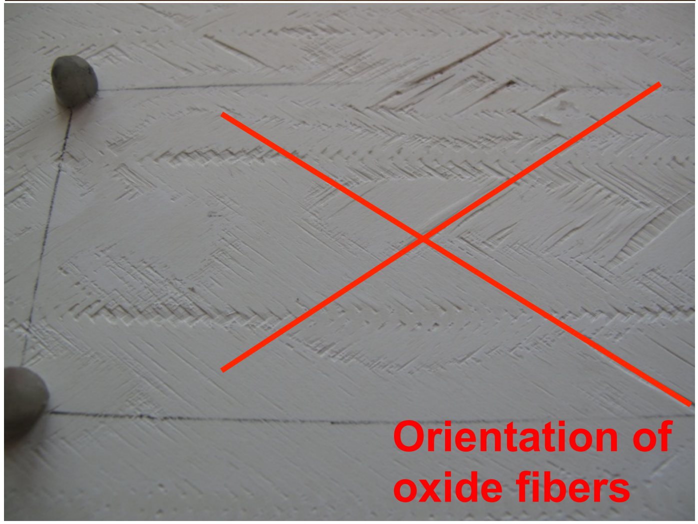
Defect magnified

A comparison with the result of a high resolution CT shows an identical position and size of the defect.

WHIPOX™: Wound highly porous oxide composite (DLR Cologne)

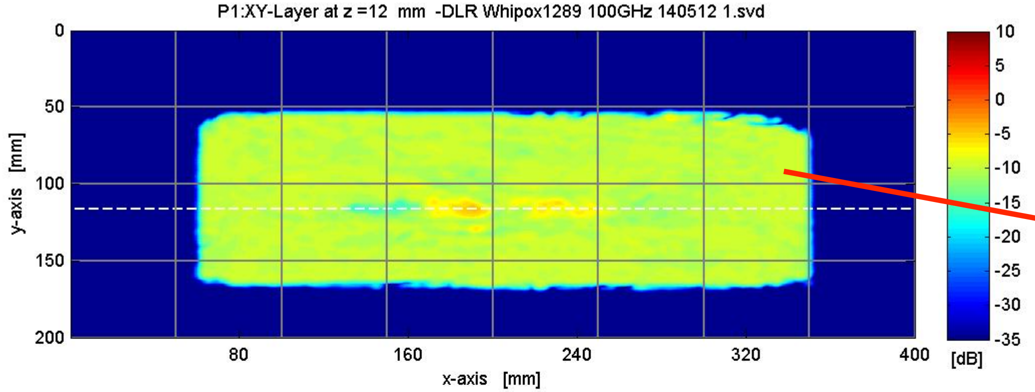
Stefan BECKER[*], Thomas ULLMANN[**], Gerd BUSSE[***]
[*]Becker Photonik GmbH, Portastrasse 73, D-32457 Porta Westfalica, Germany
[**] German Aerospace Center (DLR), Institute of Structures and Design, Pfaffenwaldring 38-40, D-70569 Stuttgart, Germany
[***] University of Stuttgart, IKT, Pfaffenwaldring 32, D-70569 Stuttgart, Germany

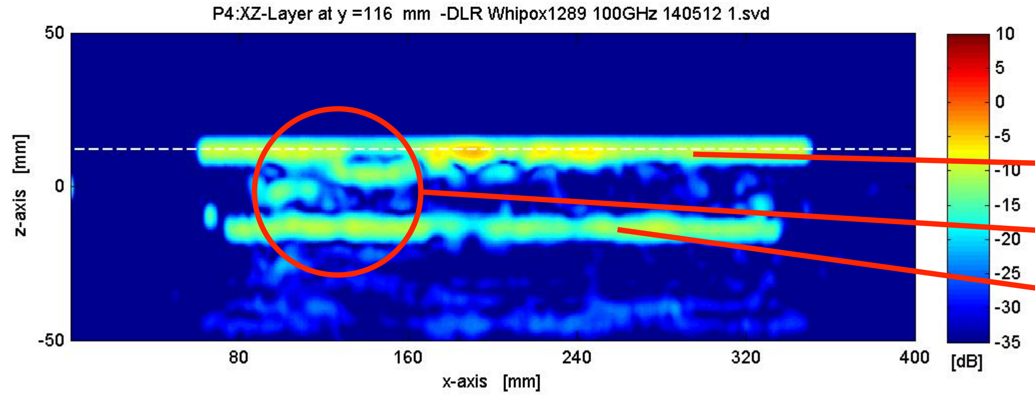
- Innovative all-oxide fiber-reinforced ceramic matrix composite for high-temperature applications.Transparency for radio signals.
- Panels as part of the TPS system of the SHEFEX II reentry vehicle
- e. g. burning chambers of turbines will be designed with new highly damage-tolerant and corrosion-resistant high-temperature ceramic matrix composites.



Inspection of (FR) Ceramic Components

- **C-Scan** (100 GHz)



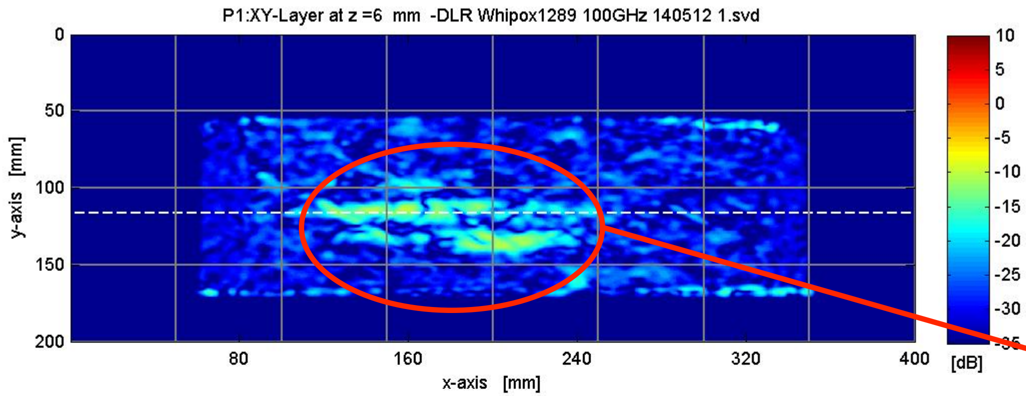


- **WHIPOX™** sample W1289
- 10 mm thick
- 400 mm x 200 mm Scan
- Upper surface signal
- Variation due to surface structure

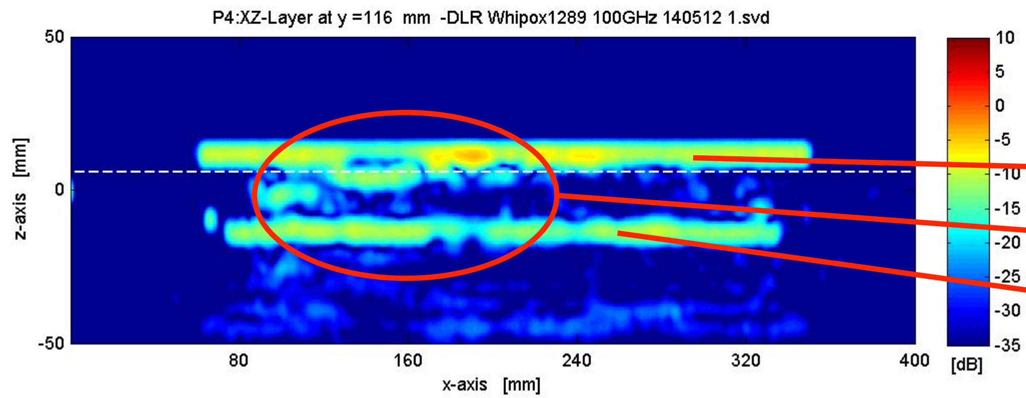
- **B-Scan**
- Upper surface
- Internal defects
- Backside surface

Inspection of (FR) Ceramic Components

C-Scan (100 GHz)

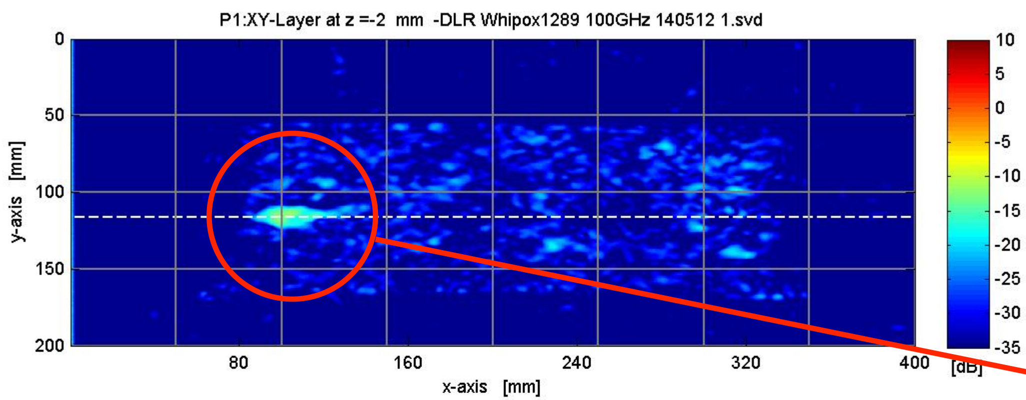


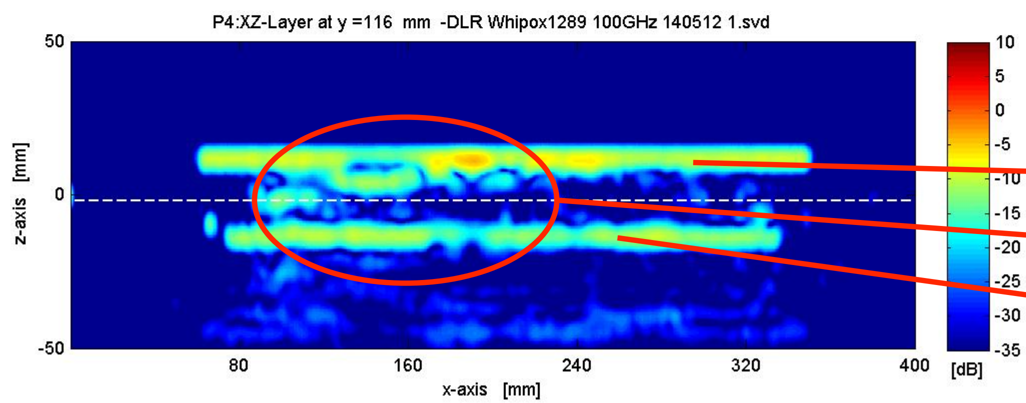
- **WHIPOX™** sample W1289
- 10 mm thick
- 400 mm x 200 mm Scan
- Layer appr. 2.5 mm below the upper surface
- Defect area



- **B-Scan**
- Upper surface
- Internal defects
- Backside surface

C-Scan (100 GHz)



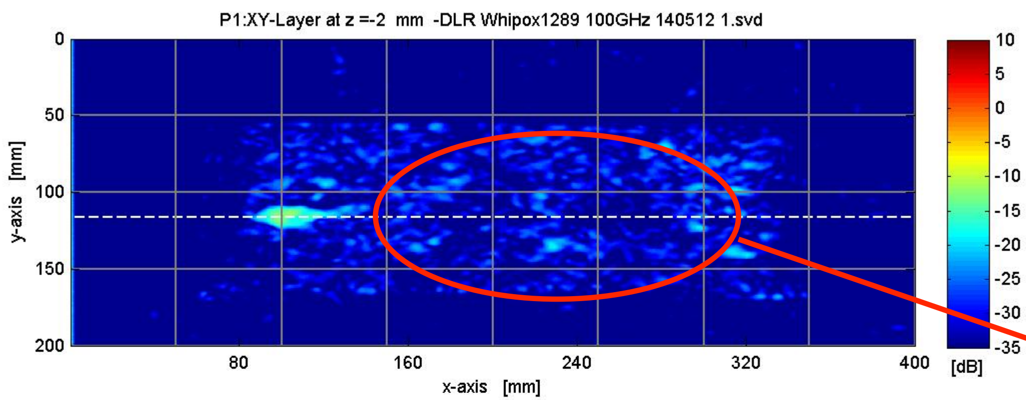


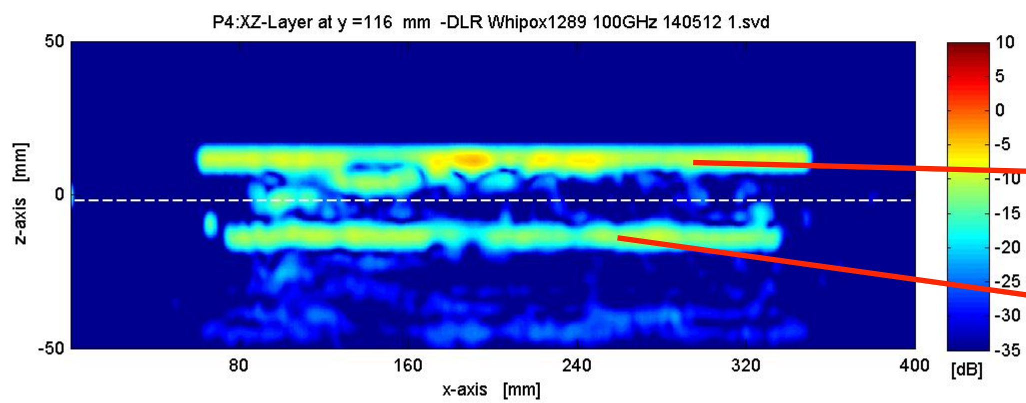
- **WHIPOX™** sample W1289
- 10 mm thick
- 400 mm x 200 mm Scan
- Layer appr. 5.5 mm below the upper surface
- Defect area

- **B-Scan**
- Upper surface
- Internal defects
- Backside surface

Inspection of (FR) Ceramic Components

C-Scan (100 GHz)



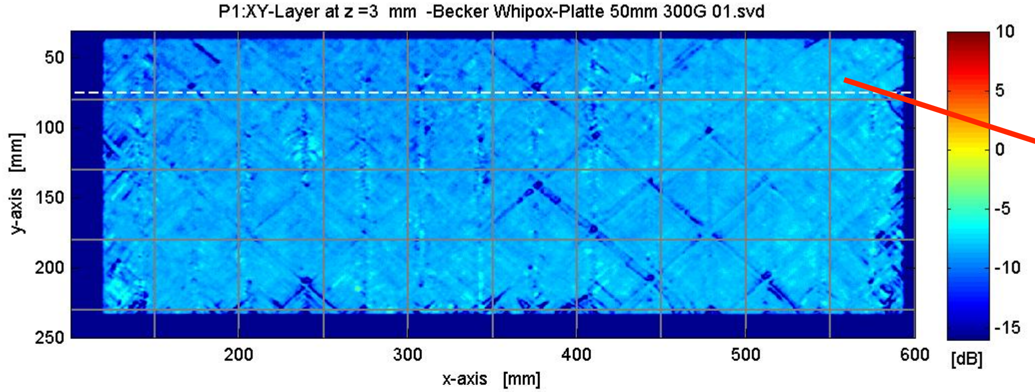


- **WHIPOX™** sample W1289
- 10 mm thick
- 400 mm x 200 mm Scan
- Layer appr. 5.5 mm below the upper surface
- Inherent porosity

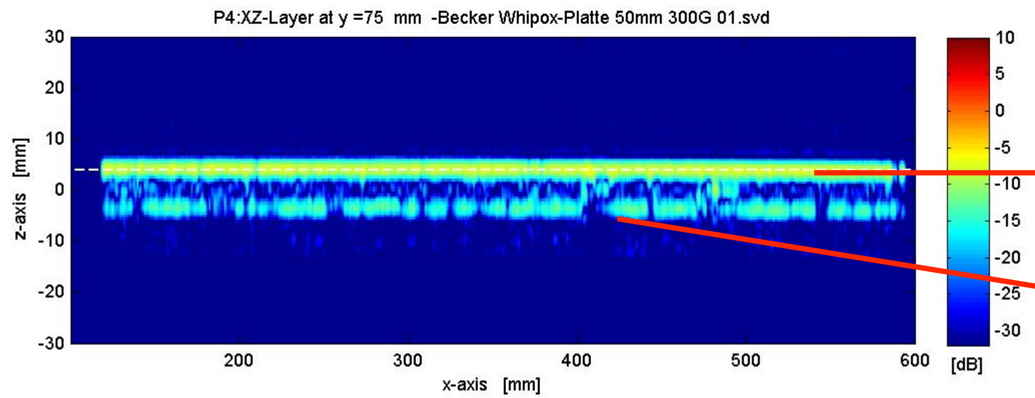
- **B-Scan**
- Upper surface
- Internal defects
- Backside surface

Inspection of (FR) Ceramic Components

C-Scan (300 GHz)



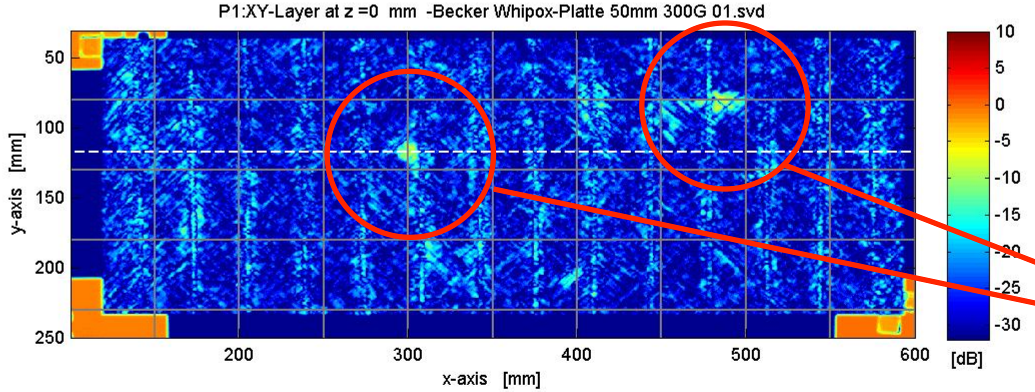
- **WHIPOX™** sample W1233
- 3 mm thick
- 600 mm x 250 mm Scan
- Upper surface signal
- Fiber orientation clearly visible

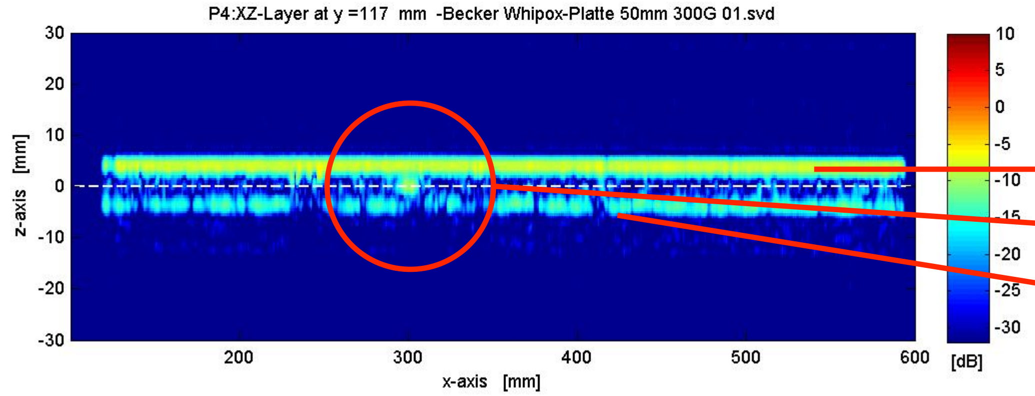


- **B-Scan**
- Upper surface
- Backside surface

Inspection of (FR) Ceramic Components

C-Scan (300 GHz)



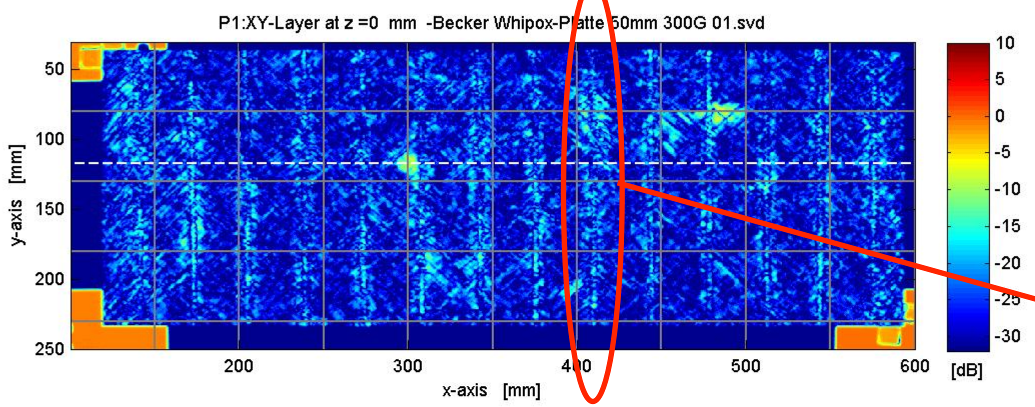


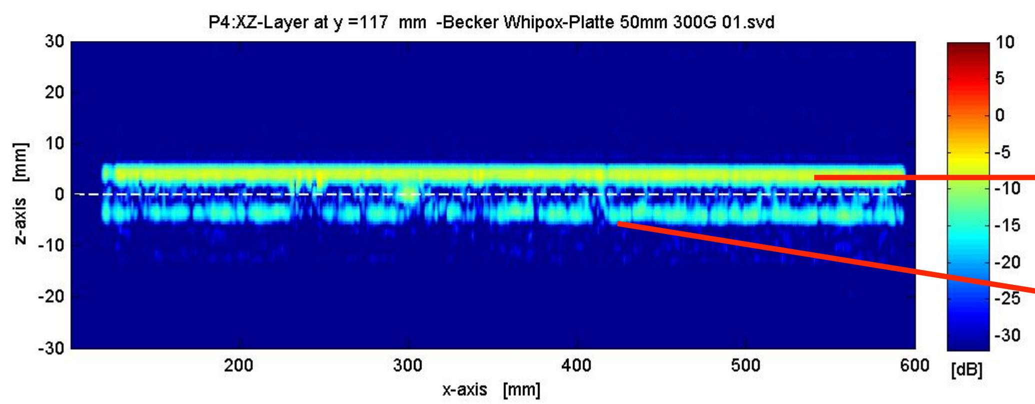
- **WHIPOX™** sample W1233
- 3 mm thick
- 600 mm x 250 mm Scan
- Layer appr. 1.5 mm below upper surface
- Small defects (porosity)

- **B-Scan**
- Upper surface
- Internal defects
- Backside surface

Inspection of (FR) Ceramic Components

- **C-Scan** (300 GHz)





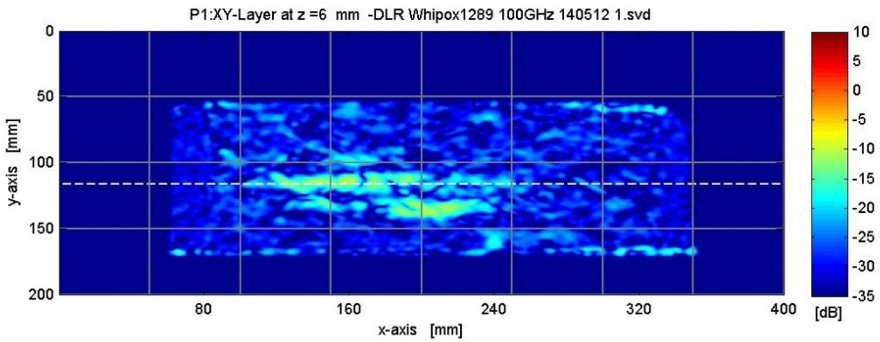
- **WHIPOX™** sample W1233
- 3 mm thick
- 600 mm x 250 mm Scan
- Layer appr. 1.5 mm below upper surface
- Minor porosity at fiber cross-over pos.

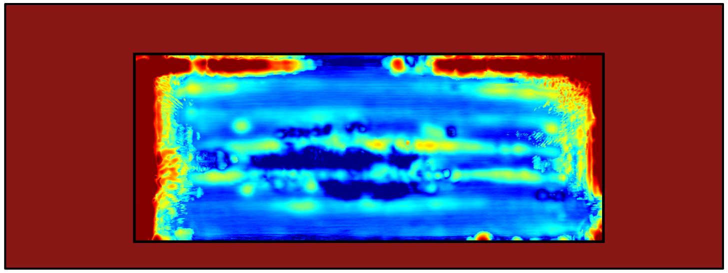
- **B-Scan**
- Upper surface
- Backside surface

Inspection of (FR) Ceramic Components

- **Terahertz C-Scan** (100 GHz) of sample W1289 (10 mm thick), layer 2.5 mm below surface

Ultrasound
(air-coupled, transmission)





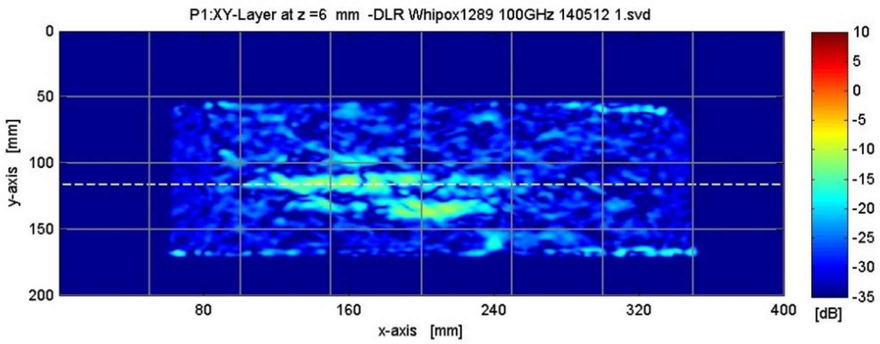
DELAMINATION AREA

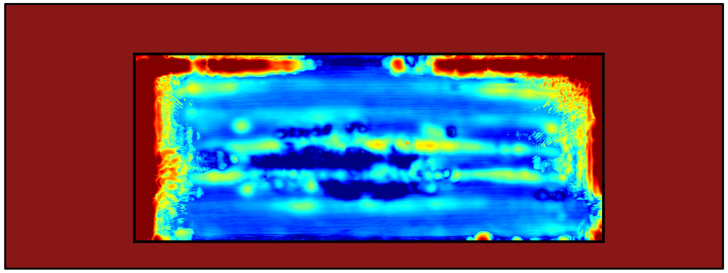
A comparison with air-coupled ultrasound performed in transmission and also X-ray CT data shows a delamination area identical in position in size.

Inspection of (FR) Ceramic Components

- **Terahertz C-Scan** (100 GHz) of sample W1289 (10 mm thick), layer 2.5 mm below surface

Ultrasound
(air-coupled, transmission)





DESTRUCTIVE TESTING

Defects as shown above are significantly decreasing the mechanical stability.

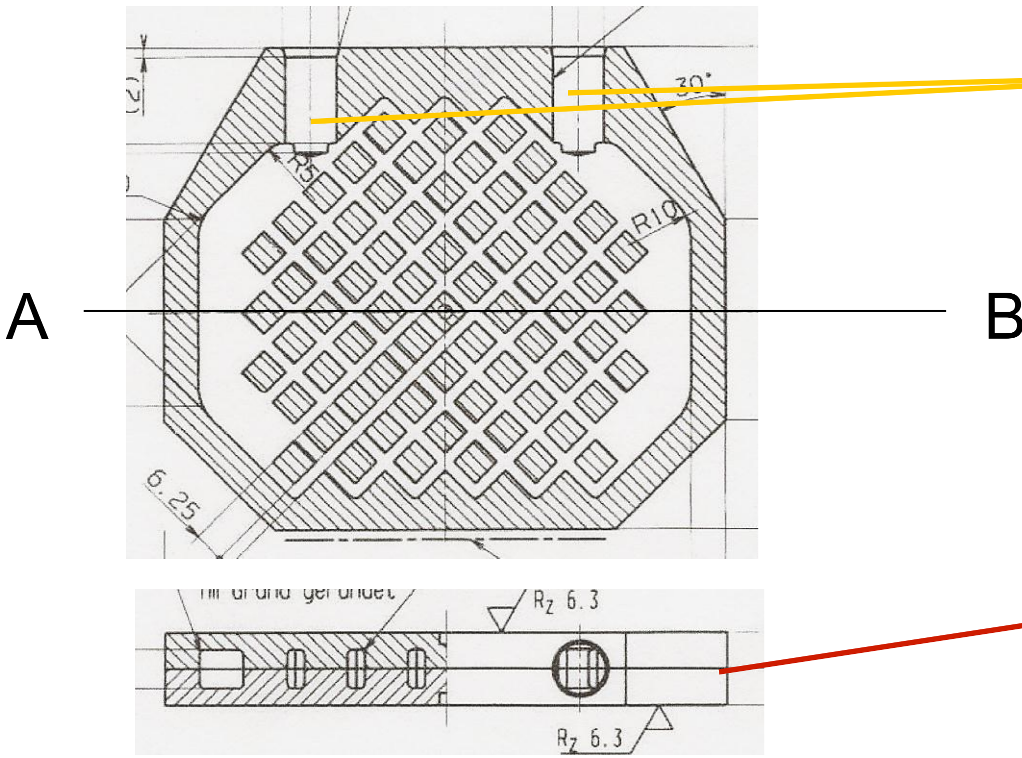
EFFECTIVE INSPECTION METHOD

The generated 3D terahertz results clearly demonstrate the capability of the new method to efficiently detect the relevant defects in WHIPOX™.

Inspection of (FR) Ceramic Components

beckerphotonik gmbh
messtechnik | dienstleistung | ausbildung

- Design of the cooling unit

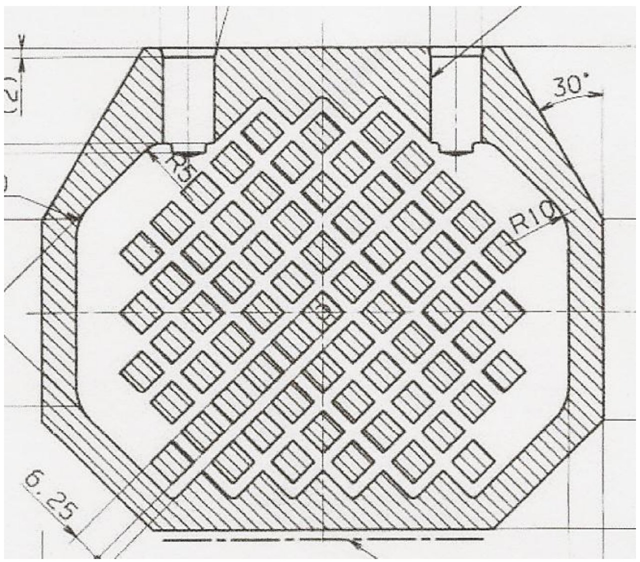


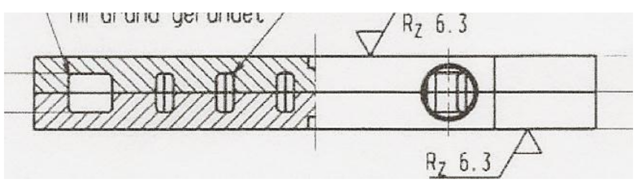
- **Top view**
- 115 mm x 100 mm
- In- and outlet
- Internal structure to improve the cooling efficiency

- **Cross section A-B**
- Thickness 15 mm
- 2 halfs are soldered together

Inspection of (FR) Ceramic Components

- Design of the cooling unit



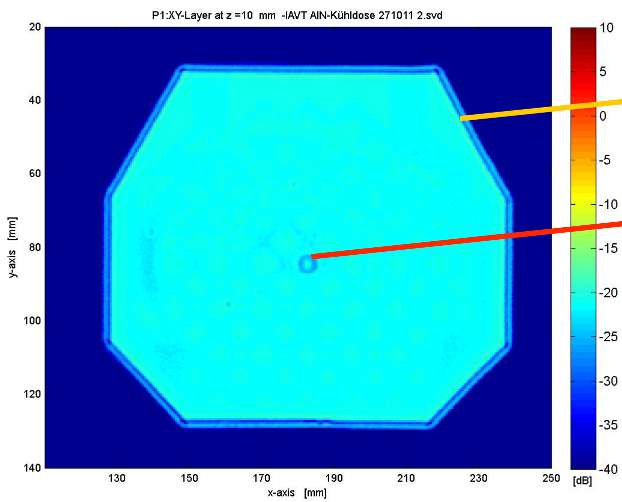


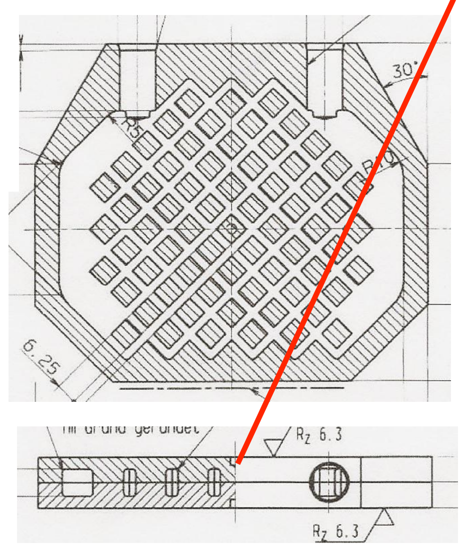
- **Material**
- AIN: Aluminiumnitrid
- Density: 3,26 g/cm³
- Refractive index: 2,9
- Thermal conductivity: 180-220 W/mK
- Melting point: 2150°C

Inspection of (FR) Ceramic Components

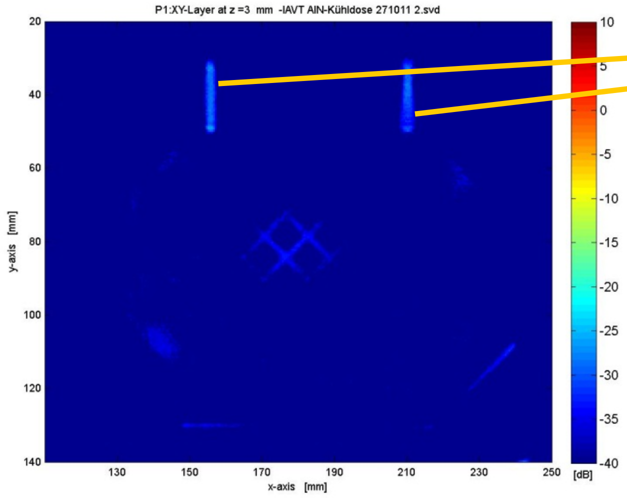
C-Scan, Layer: entry echo

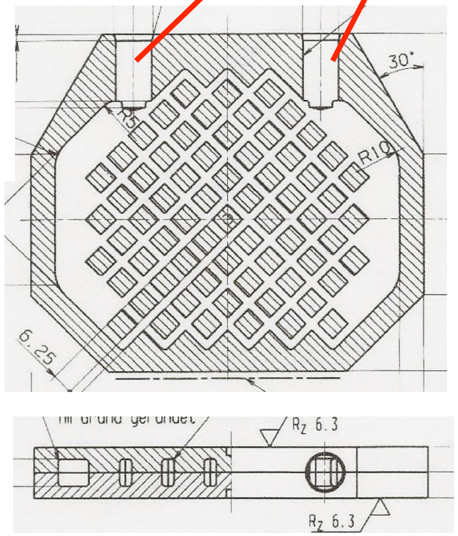
- **0.3 THz C-Scan**
- Layer: Entry echo
- Surface structure, Diameter 3 mm





- C-Scan, Layer: In- and Outlet

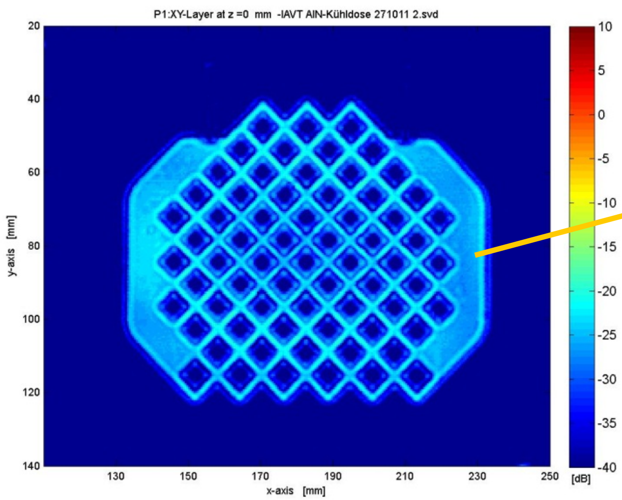


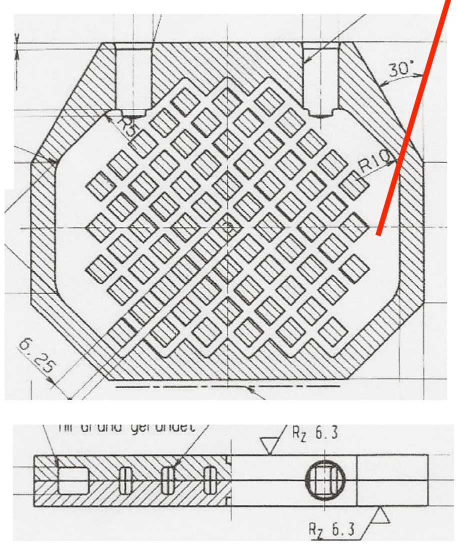


- **0.3 THz C-Scan**
- In- and outlet
- Diameter is not completely visible!

Inspection of (FR) Ceramic Components

- C-Scan, Layer: Internal upper surface

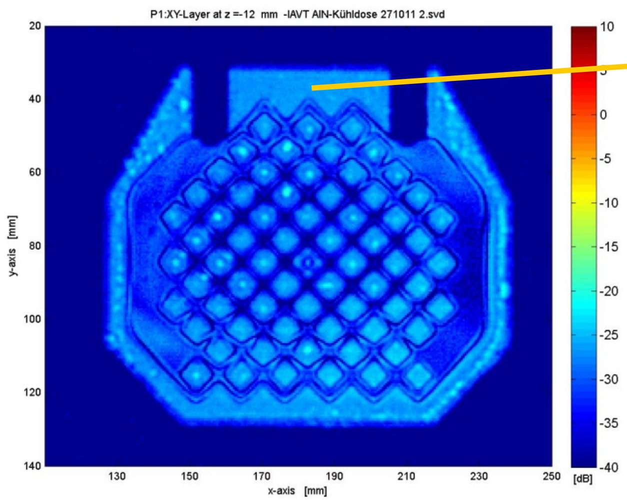


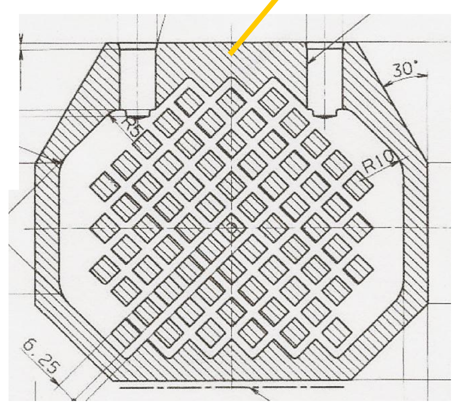


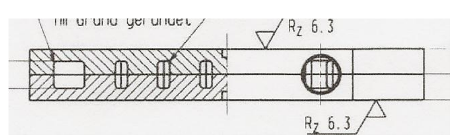
- **0.3 THz C-Scan**
- Internal upper surface

Inspection of (FR) Ceramic Components

C-Scan, Layer: Soldering



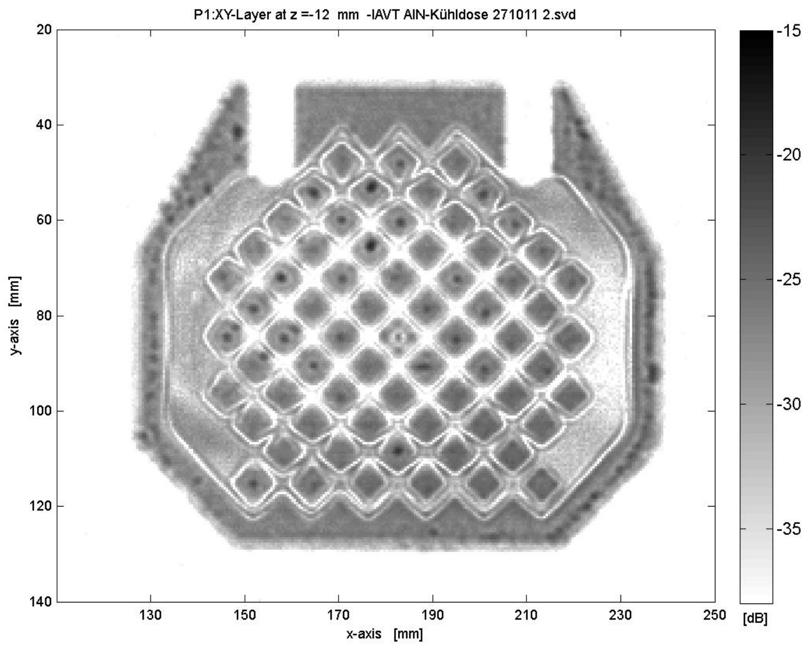


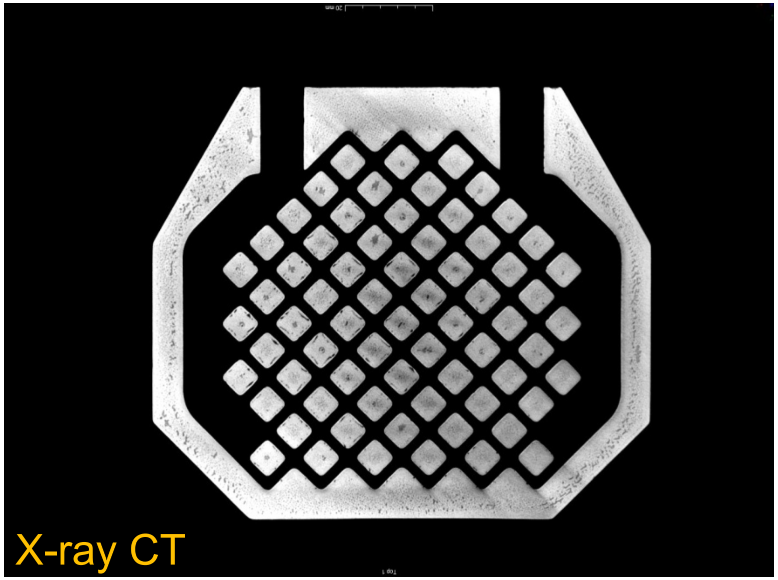


- **0.3 THz C-Scan**
- Soldering level
- Pores in the solder are clearly visible!

Inspection of (FR) Ceramic Components

- C-Scan, Layer: Soldering, Comparison with X-ray CT





Keeping in mind the resolution difference the results are in very good agreement!

3D Terahertz Imaging -
Comparison with Ultrasound

PLUS:

- Easy handling and non-contact (no preparation of samples)
- Inspection of foams, porous materials, hollow samples and sandwich samples

NEUTRAL:

- Lateral resolution compareable

MINUS:

- Can only be used for dielectric materials (metals and CRP reflect terahertz radiation, water absorbes and reflects)

3D Terahertz Imaging -
Comparison with Active Thermography

PLUS:

- Better penetration
- Inspection of foams, porous materials, hollow samples and sandwich samples

NEUTRAL:

- Lateral resolution compareable

MINUS:

- Can only be used for dielectric materials (metals and CRP reflect terahertz radiation, water absorbes and reflects)

3D Terahertz Imaging - Comparison with Radiography

PLUS:

- Easy handling, no protection necessary
- Access from only one side necessary
- 3D information!

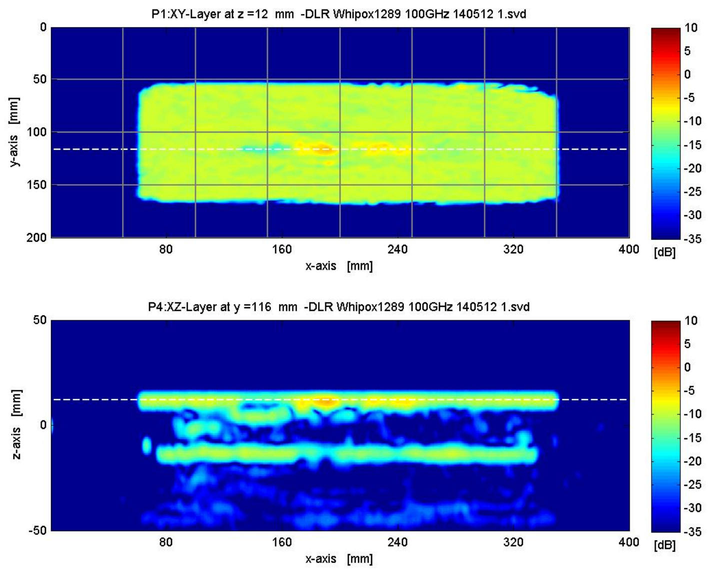
MINUS:

- Lower resolution
- Can only be used for dielectric materials (metals and CRP reflect terahertz radiation, water absorbes and reflects)

3D Terahertz Imaging -
Comparison with X-ray CT

PLUS:
- Easy handling, no protection necessary
- Access from only one side necessary
- Even components with size >1m can be inspected

MINUS:
- Resolution for components < 0.5 m significantly lower
- Can only be used for dielectric materials (metals and CRP reflect terahertz radiation, water absorbes and reflects)



Thank you for your attention!

Contact Details

Becker Photonik GmbH
Dr. Stefan Becker
Portastrasse 73
D-32457 Porta Westfalica
Fon: +49.571.88918865
stefan.becker@becker-photonik.de
www.becker-photonik.de