

2022-05-25

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# **NON-DESTRUCTIVE TESTING IN CIVIL ENGINEERING: WHY AND WHAT AND HOW**

PD Dr. rer. nat. Ernst Niederleithinger

# Questions to be answered

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- What is special in the civil engineering industry and about concrete?
- Why is there a need for NDT in CE and why is it so difficult?
- State of the art in NDT-CE and the way ahead?
- NDT-CE @ BAM?
- Why are we thinking about muon tomography?

## Federal Institute for Materials Research and Testing

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1. Governmental research institute, founded 1871 in Berlin, Germany
2. About 1800 employees
3. Mission: safety in technology and chemistry
4. Departments on NDT and civil engineering



## BAM 8.2

### NDT-CE Methods

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- Ultrasound (echo, transmission, monitoring)
- Radar (echo, transmission)
- Embedded sensors (RFID, ultrasonic)
- Laser-induced breakdown spectroscopy LIBS
- *Covermeter, Impact Echo, rebound hammer, ...*

*In other divisions:*

- Fiber-optical sensors
  - IR Thermography
  - Radiography, CT
  - Potential mapping
  - Optical methods
- 



## BAM 8.2

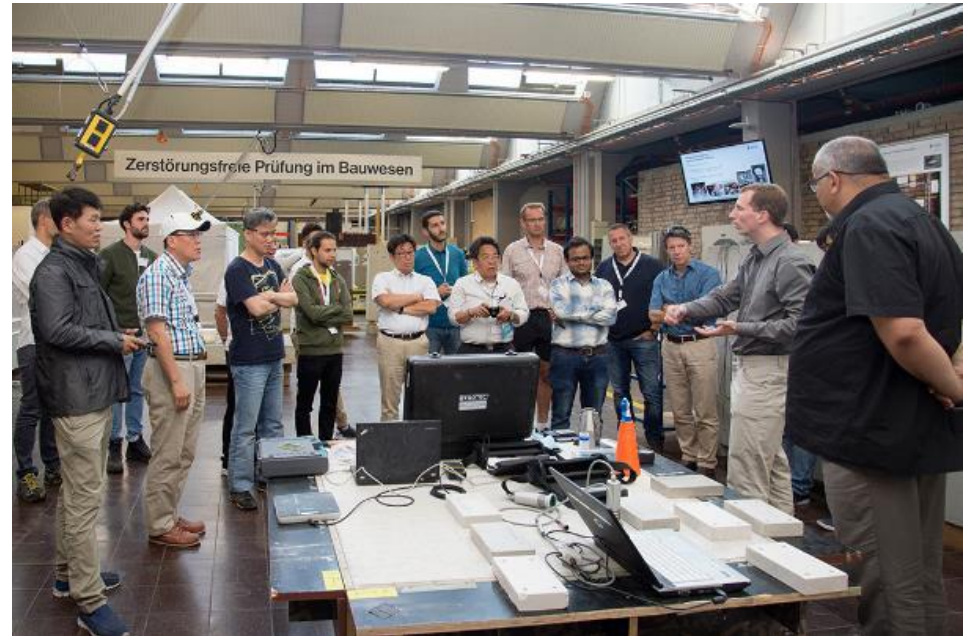
### NDT-CE application areas

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- Quality assurance
- Condition assessment
- Structural health monitoring

for

- Road, railway and waterway infrastructure
- Buildings, basements and foundations
- Nuclear and other energy related structure
- New construction materials and methods



# What is special in the civil engineering industry?

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- Mostly unique constructions
- Sites very large, objects huge
- Very limited automation and serialization
- Low grade and low speed of innovation (currently changing)
- NDT: mostly low level of standardization and application (changing as well)



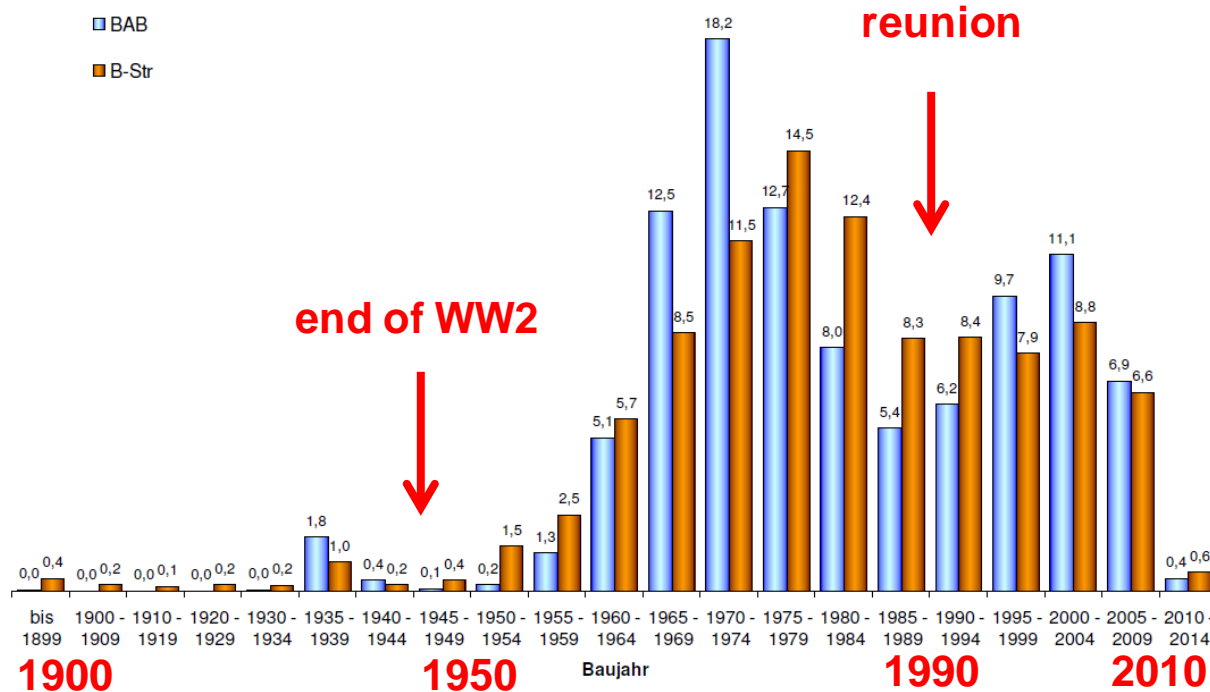
# Bridges can be beautiful

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Credits: pixabay

# But they are ageing objects



## Age structure of bridges under federal administration in Germany



# Under loads they have not been designed for

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Credits: dpa/A3390 Kay Nietfeld

# Will fail at some time

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Credits: BZ Berlin/DAVIDS

# Hard to inspect

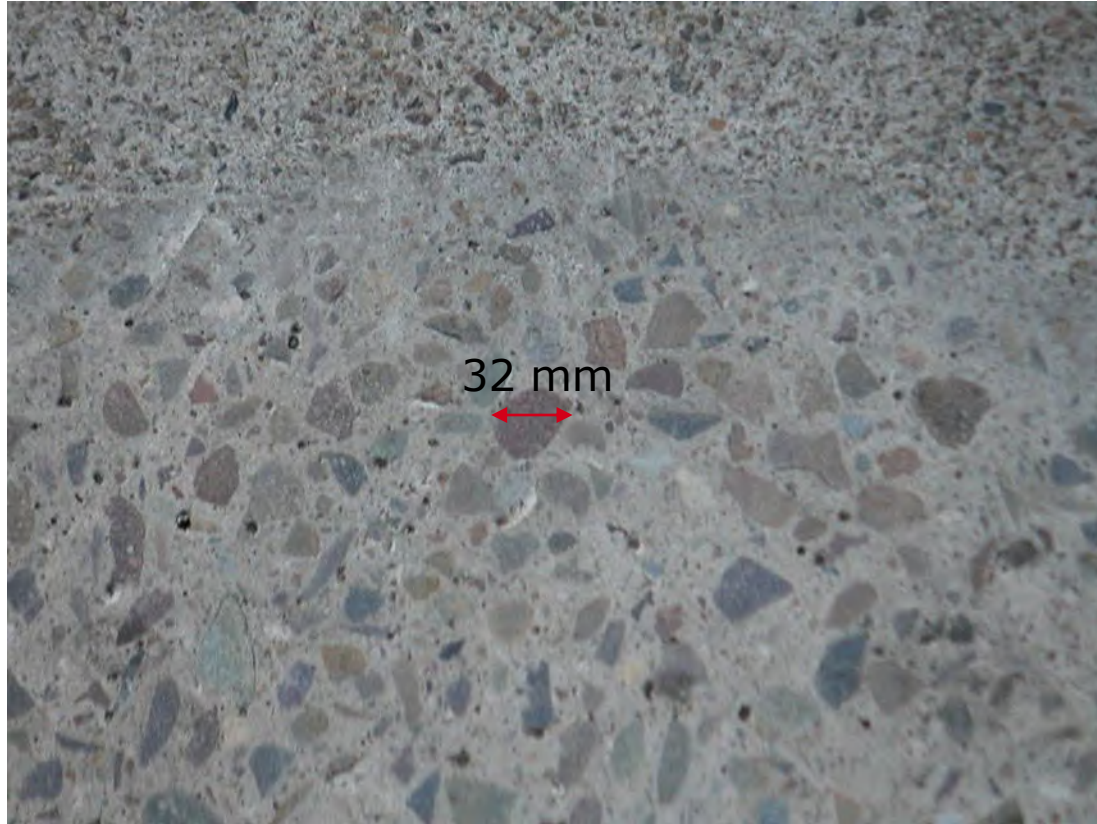
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Credits: Autobahn GmbH

# Concrete

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## 1. Concrete:

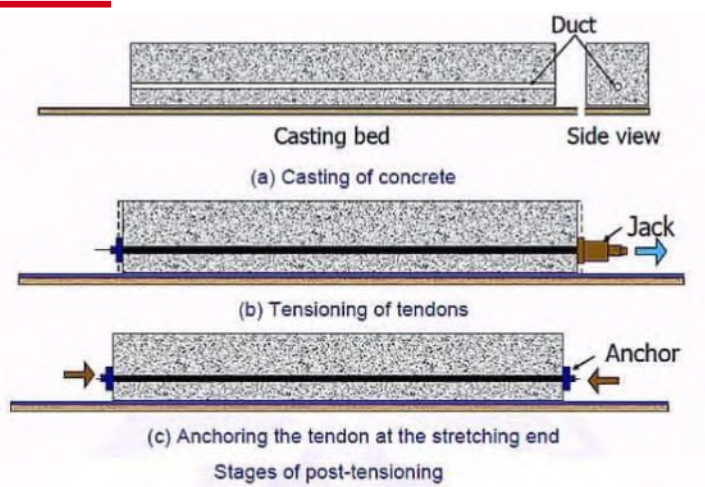
- High Compression strength 10 – 100 MPa
- Can be poured in almost any form
- Tensile strength only 10-15 %
- Prone to cracking

## 2. Steel reinforcement:

- High tensile strength
- Flexible
- Corrosion
- Heavy
- Expensive



# Pre- and posttensioning



# Concrete



# Concrete

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# Concrete





# Concrete



**Still, you can make wonderful and useful things out of concrete!**



# Bridge inspection

- Visual, tap test
- Arms distance
- Every few years

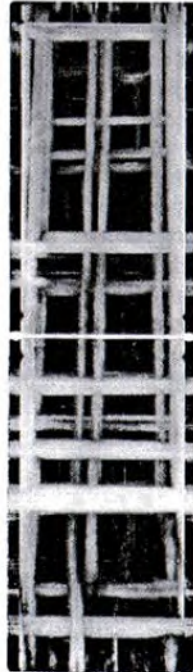
In case of damage;

- Detailed examination
- NDT, sampling
- Re-assessment

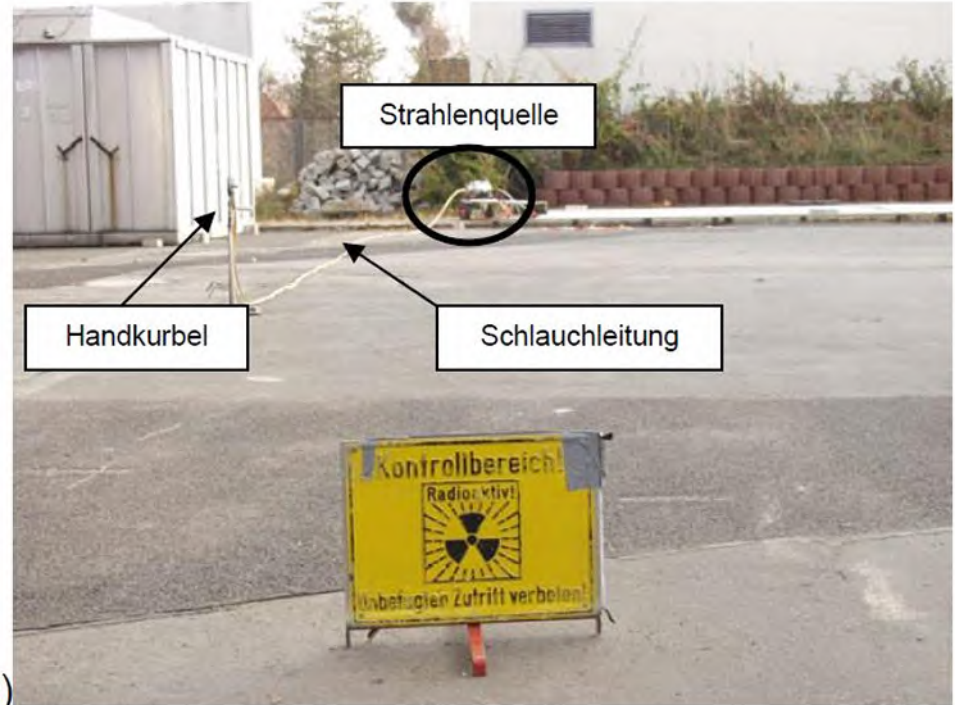


# How to inspect the interior? X-ray?

- It works!
- Due to regulations, hardly ever applied these days

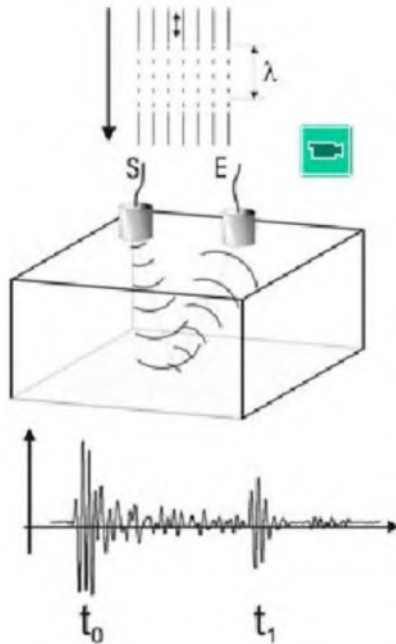


(b)



# State of the art in NDT-CE and the way ahead: Inspection of structures

1995



2015

# State of the art in NDT-CE and the way ahead: Inspection of structures

2021

Radar



Proceq GP8800, AR, Cloud data storage

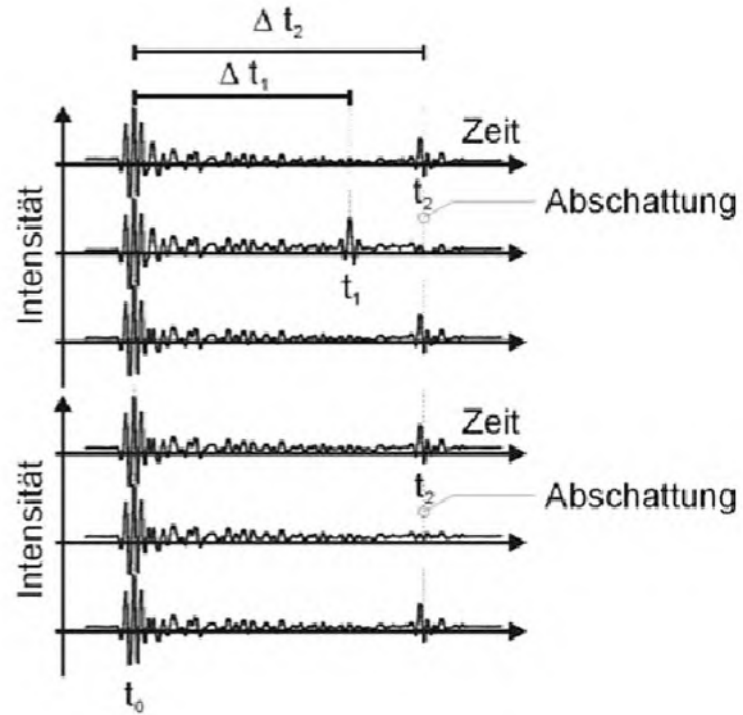
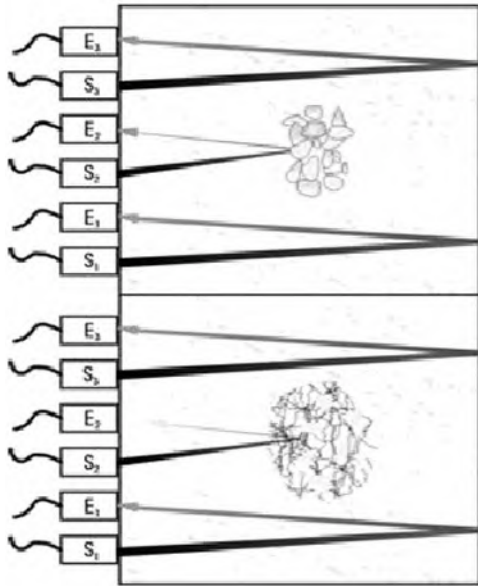
Ultrasound



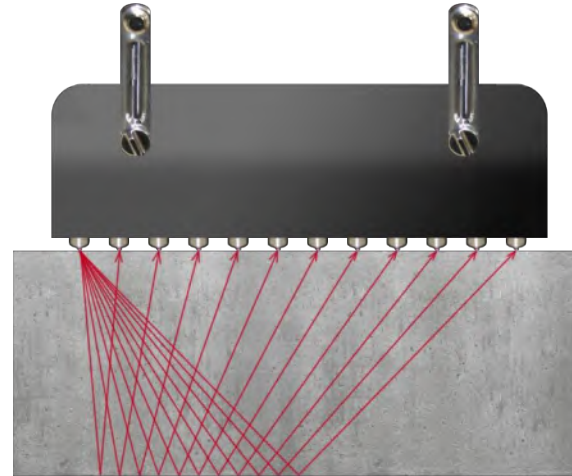
ACS International, Mira 3D, FMC/TFM



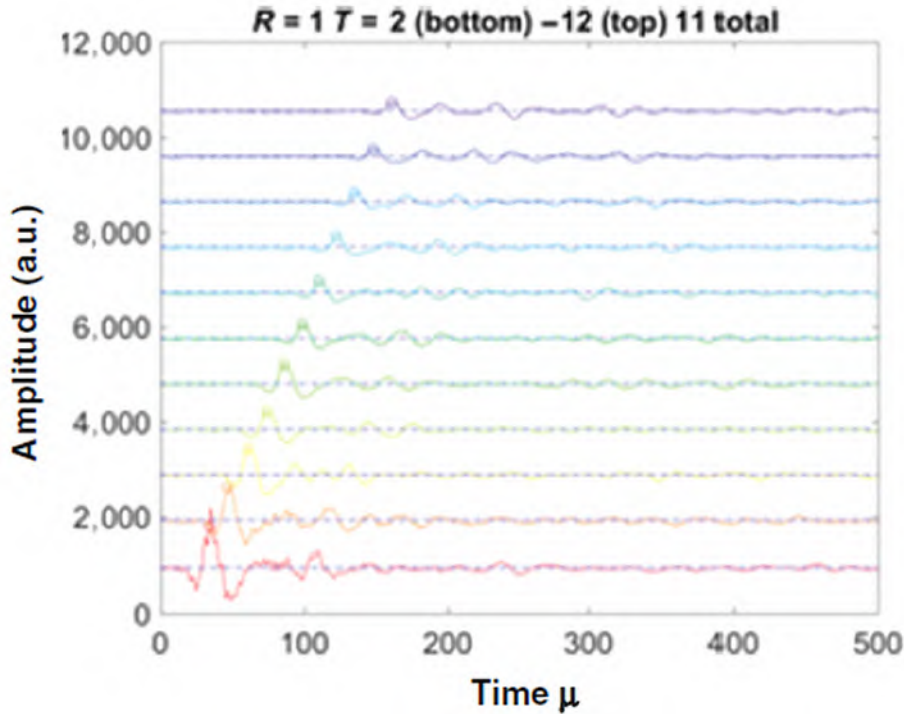
# Ultrasonics: detection of flaws



# Ultrasonics: SAFT



ACS A1040 Mira

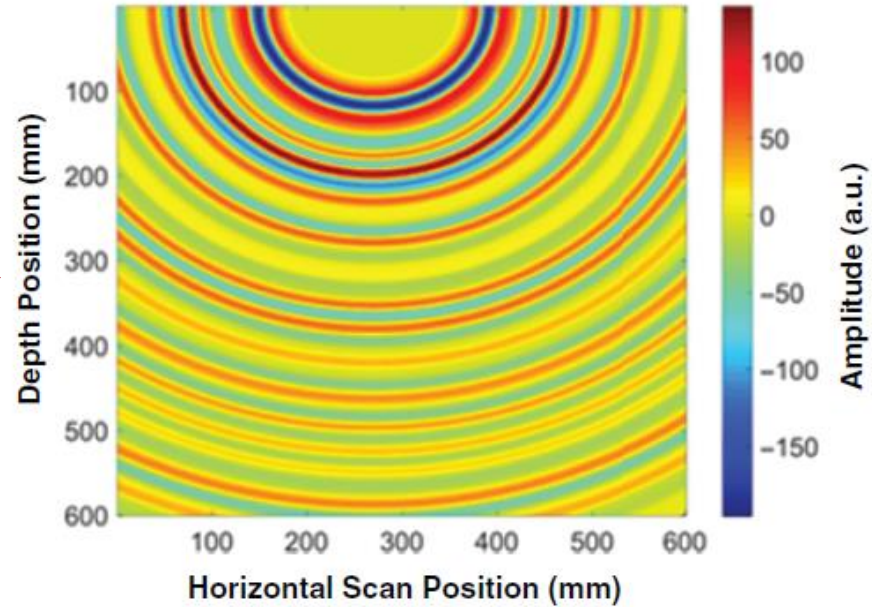
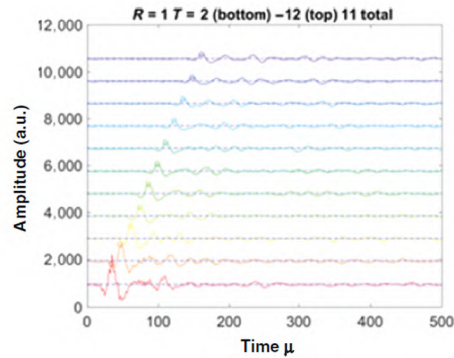


## Comparison of Ultrasonic Imaging Techniques for Full-Scale Reinforced Concrete

Hajin Choi, James Bittner, and John S. Popovics

*Transportation Research Record: Journal of the Transportation Research Board, No. 2592*, Transportation Research Board, Washington, D.C., 2016, pp. 126–135.  
DOI: 10.3141/2592-14

# Ultrasonics: SAFT

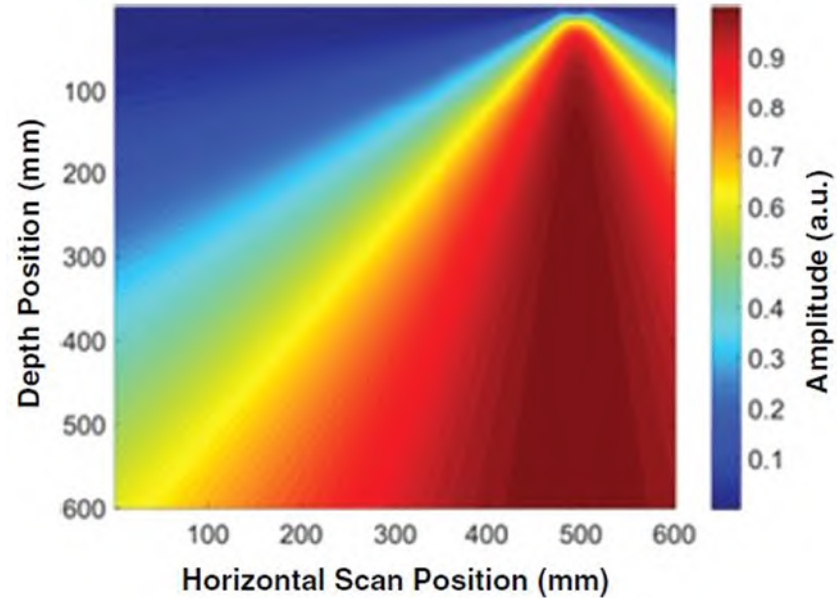


Spatially average of a specific T-R combination

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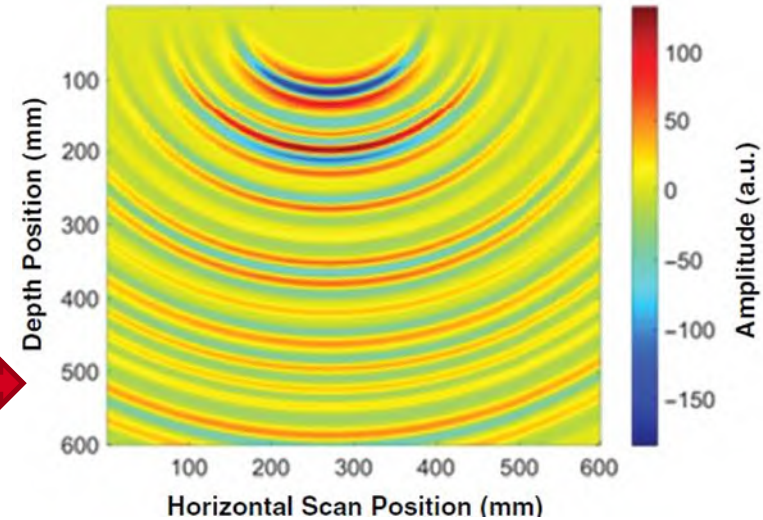
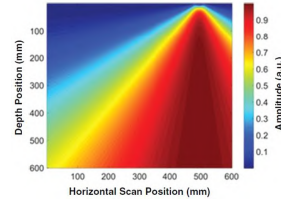
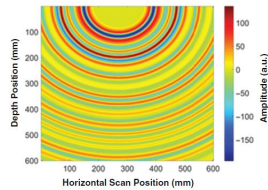
$$A = \frac{Z_s}{\sqrt{X_{\text{receiver}}^2 + Z_s^2}} \times \frac{Z_s}{\sqrt{X_{\text{transmitter}}^2 + Z_s^2}}$$



„Apodization“ of a specific T-R combination

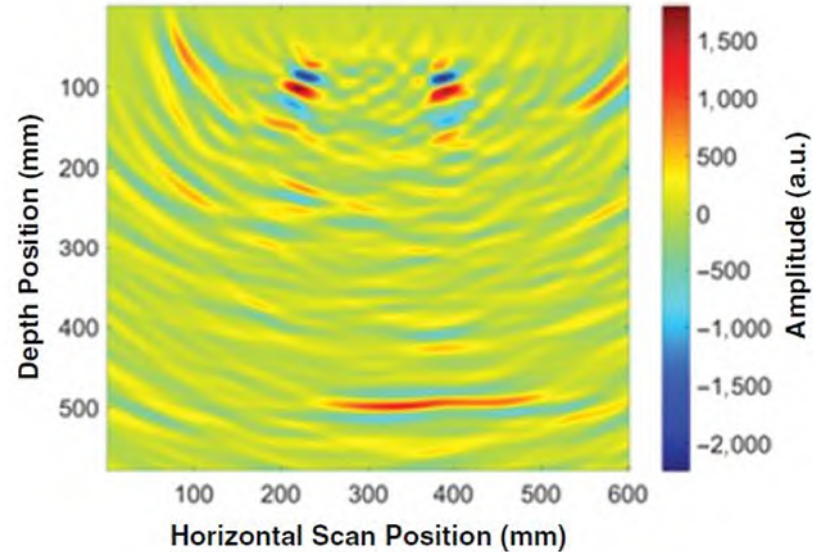
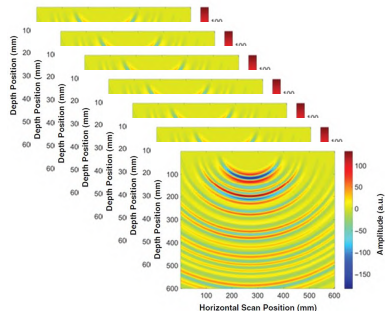
# Ultrasonics: SAFT

$$f(x, z) = \int_{t_0}^{t_1} \text{Apodization}(Z_s, X_{\text{transmitter}}, X_{\text{receiver}}) \times \text{Signals}(t, X_{\text{transmitter}}, X_{\text{receiver}}) dt$$



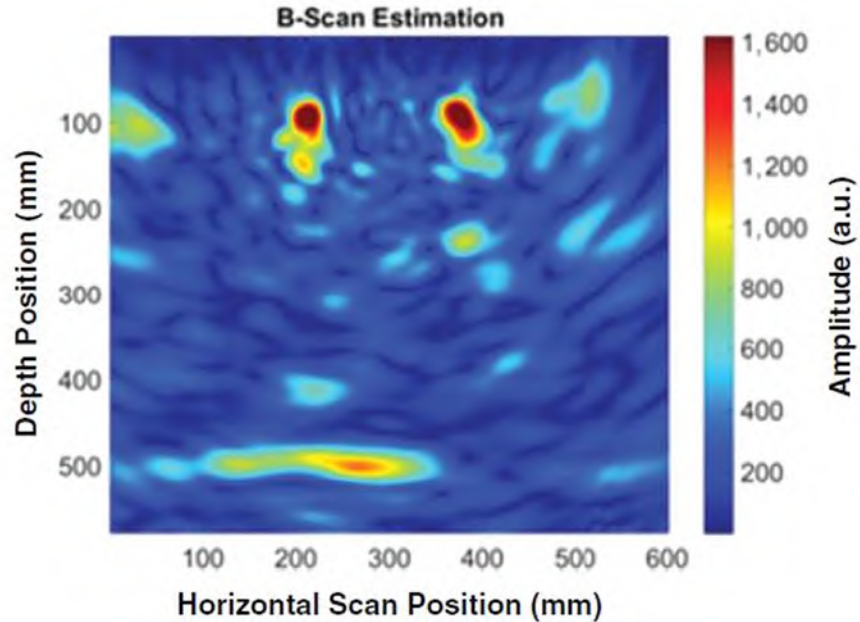
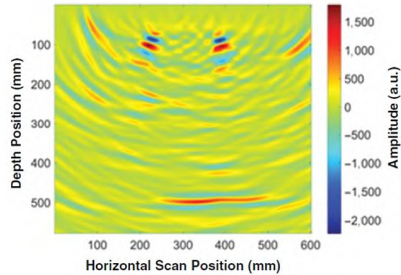
„Apodization“ of a specific T-R combination

$$f(x, z) = \sum_{N_{\text{Pairs}}} \int_{t_0}^{t_1} \text{Apodization}(Z_s, X_{\text{transmitter}}, X_{\text{receiver}}) \times \text{Signals}(t, X_{\text{transmitter}}, X_{\text{receiver}}) dt$$



Summation for all T-R combinations

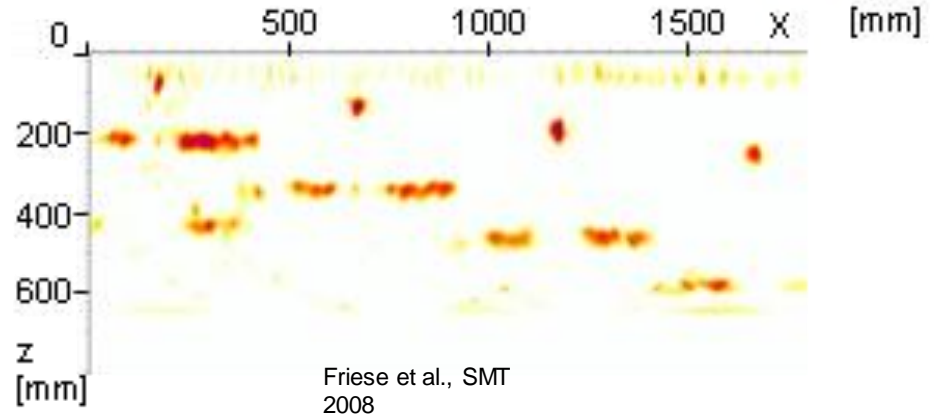
# Ultrasonics: SAFT



Hilbert transform

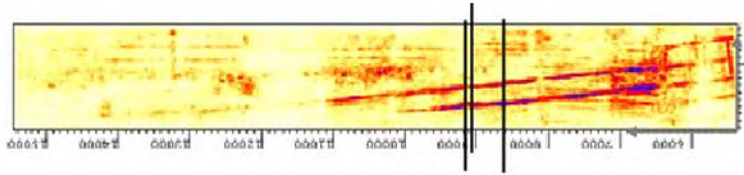


## SAFT imaging



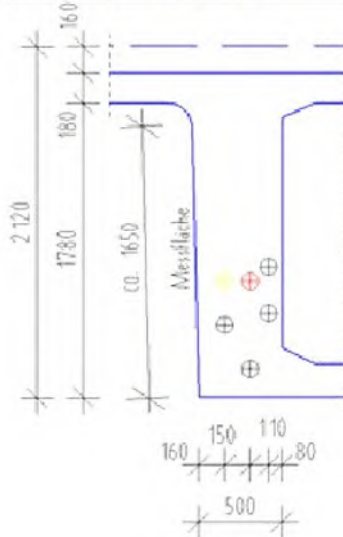
- ▶ Synthetic aperture focusing technique
- ▶ Family of methods
- ▶ Constant and multi-offset data
- ▶ Direct reflections only
- ▶ Phase evaluation possible (Krause et al., SF&R 2008)

Main contributors to SAFT:  
Langenberg, Mayer,  
Marklein,  
University of Kassel

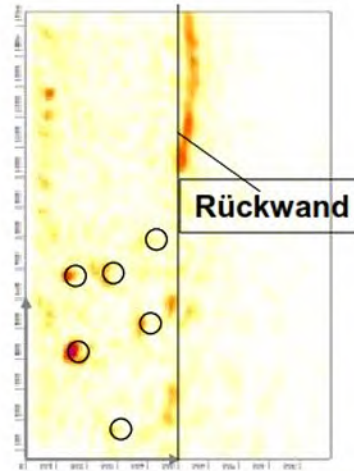


SAFT-C-Projektion  
Messtiefe 9 – 17 cm

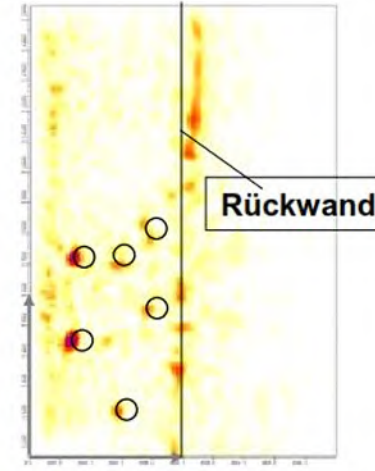
Steg-Querschnitt  
x = 916 cm



SAFT-B-Bild  
x = 905 cm



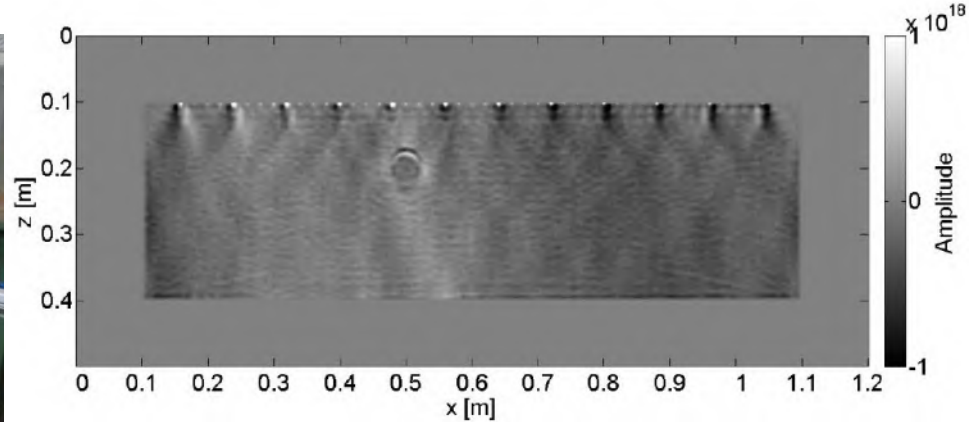
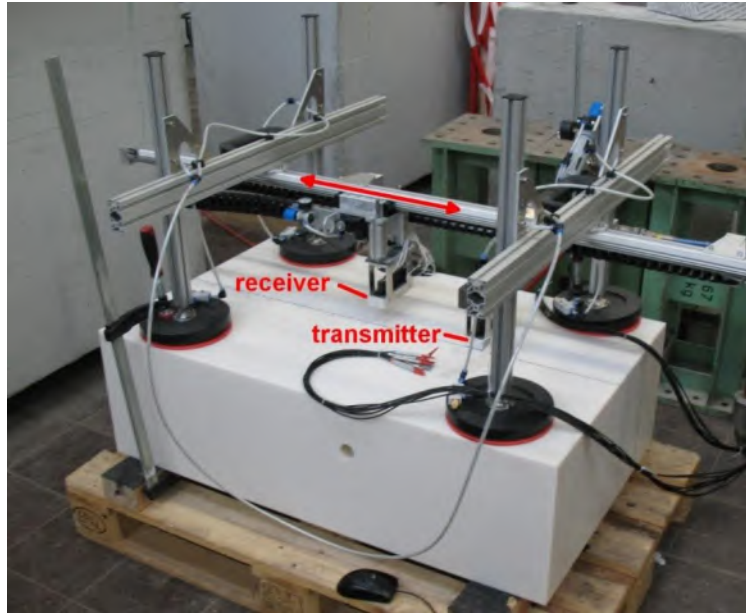
SAFT-B-Bild  
x = 861 cm



Ergebnisse: D. Streicher, M. Krause, BAM

# We are working on improvements

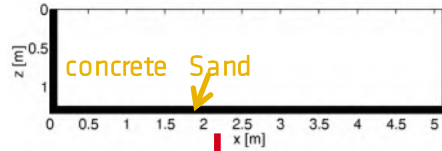
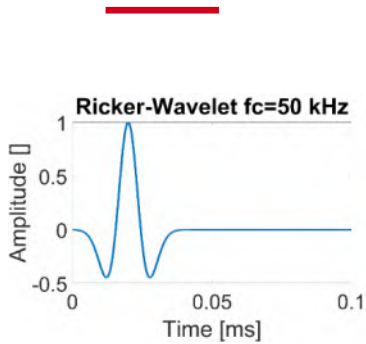
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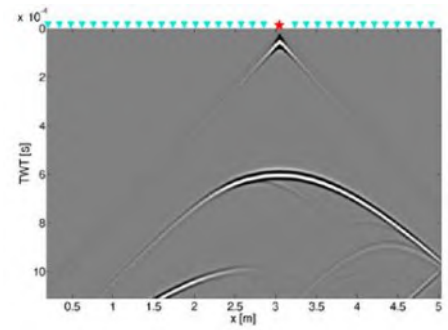
Reverse Time Migration,  
e.g. Grohmann et al. 2015, 2022 (in prep.)

# Reverse Time Migration (RTM)

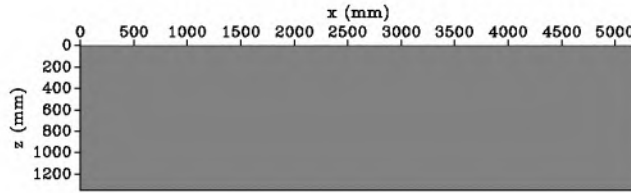
## 1. Velocity model



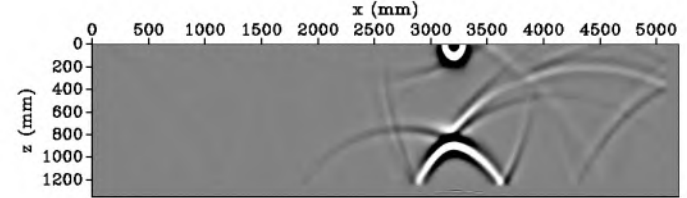
Recorded data  
(real/synthetic)



## 2. Forward simulation source field

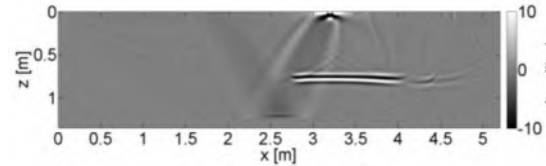


## 3. Reverse simulation of receiver field

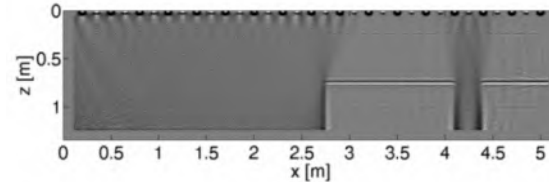


## 4. Imaging condition (e. g. cross correlation)

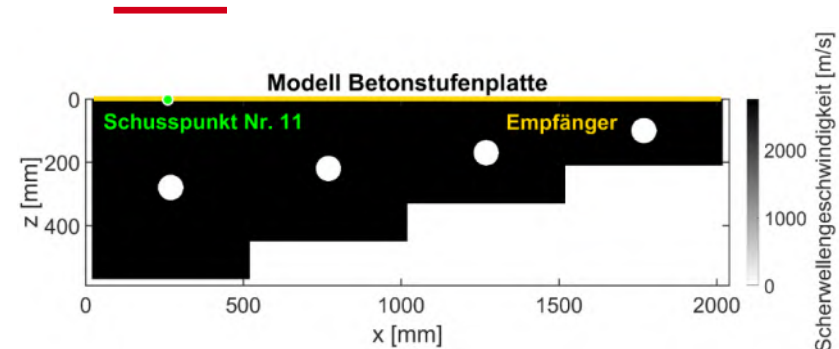
$$I(x, z) = \int_0^T W_S(x, z, t) \cdot W_R(x, z, t) dt$$



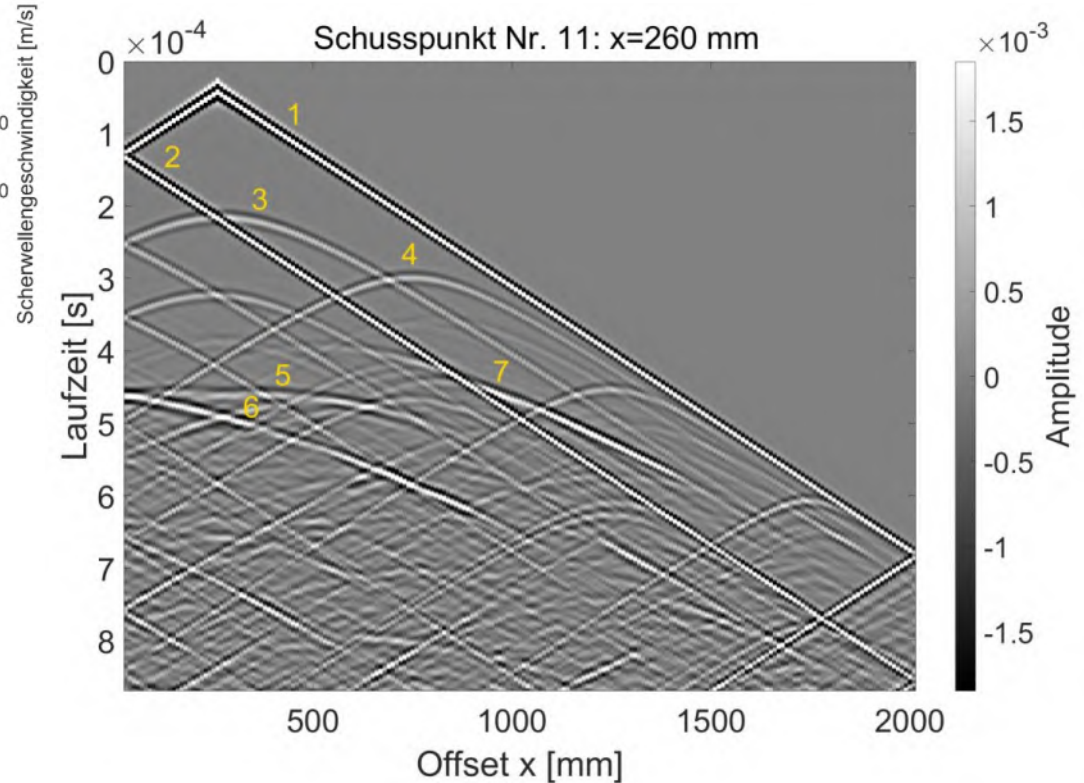
## 5. Stacking cross correlation for all shot records



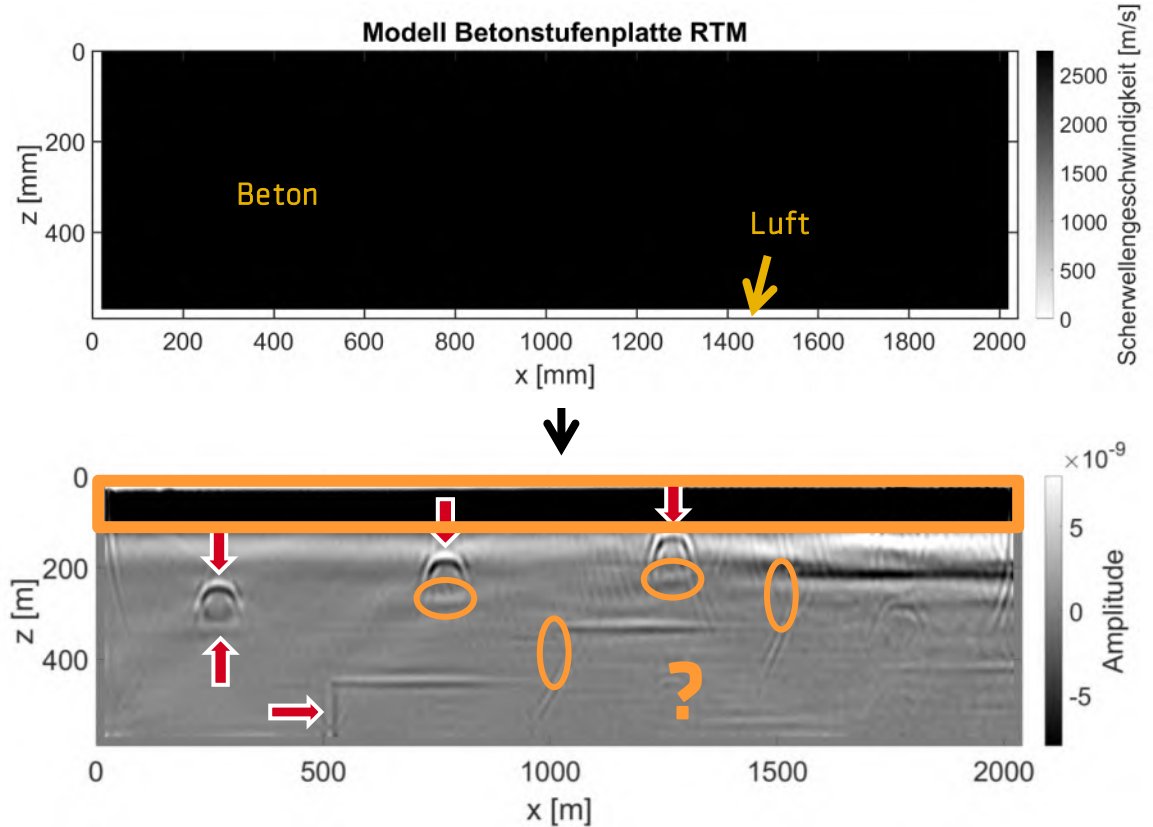
# Synthetic example (SH-elastic)



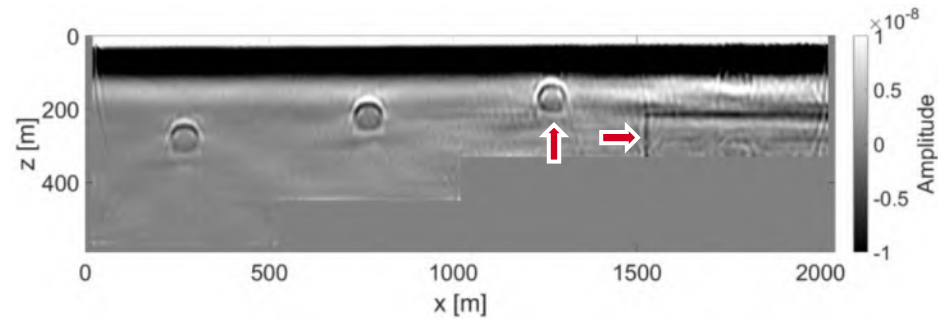
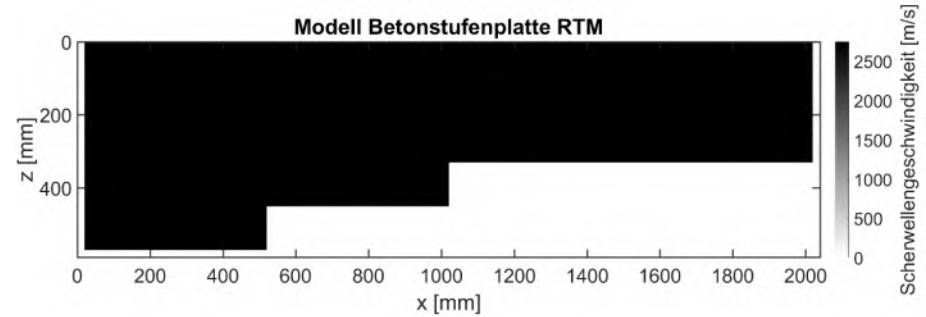
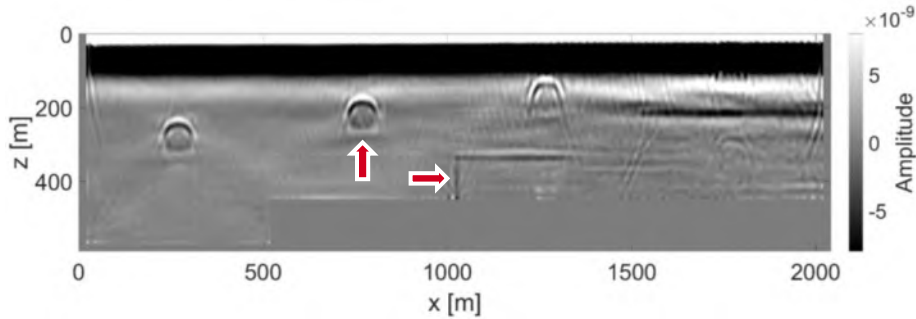
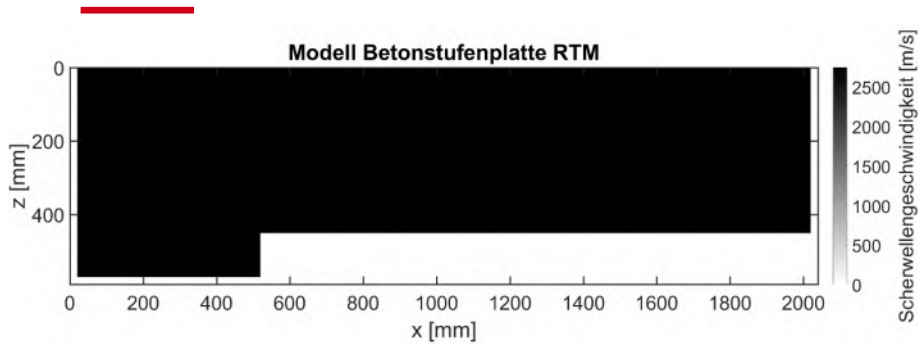
	waves
1	Direct wave
2	Reflection of direct wave (left)
3	Reflection duct 1
4	Reflection duct 2
5	Reflection from bottom
6	Diffraction from lower left corner
7	Diffraction/reflection from first step

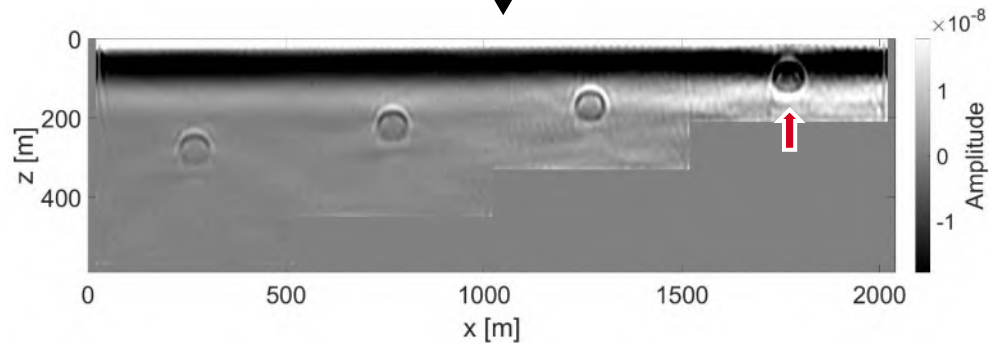
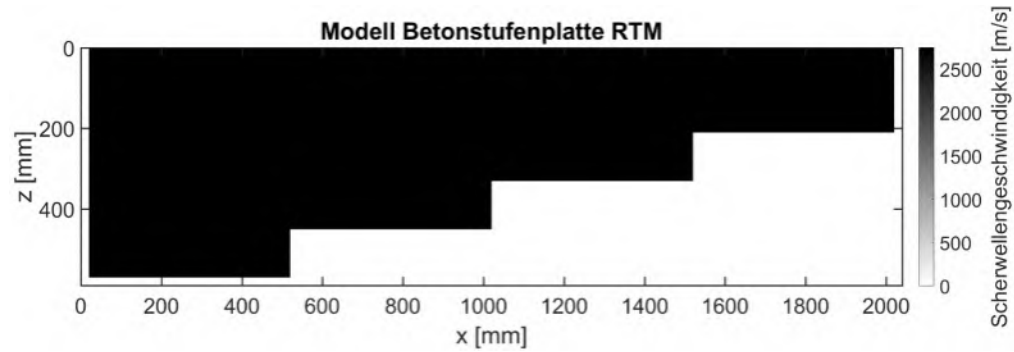


# Rectangular velocity model

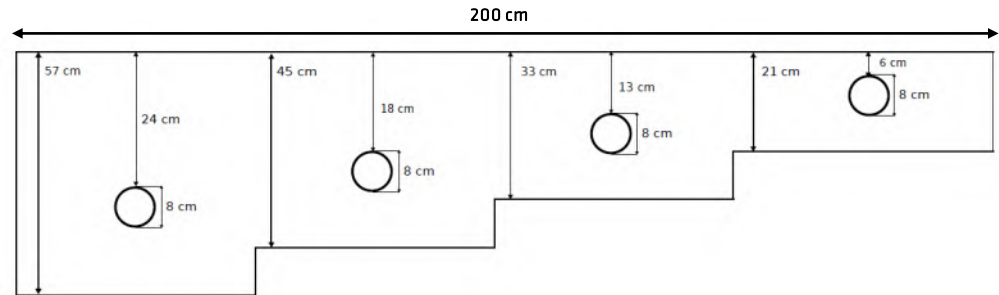


# Stepwise improvement of velocity model



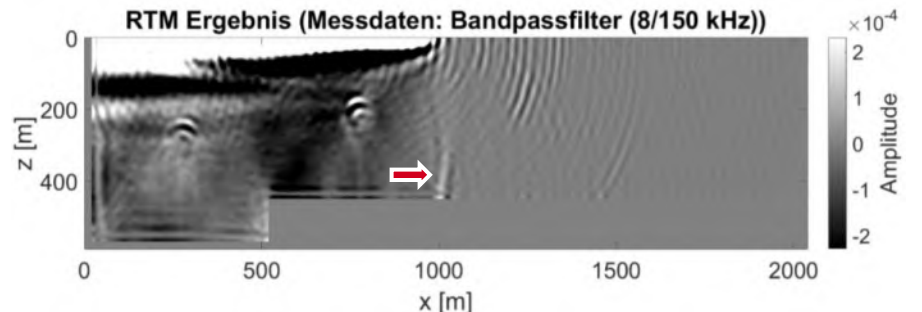
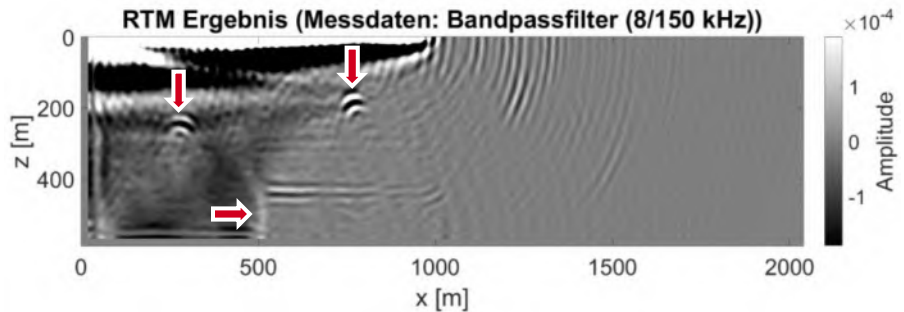
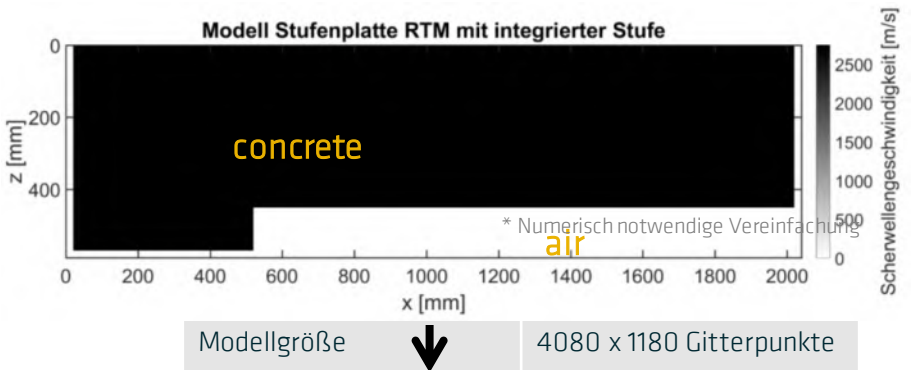
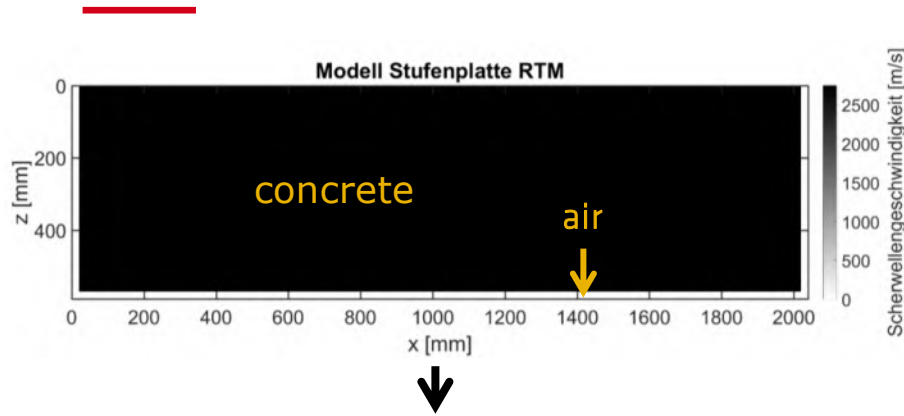






Parameters	
Sources	44 (dist. 20 mm)
Anzahl der Empfängerpositionen	86 (distance 10 mm)
Frequency [kHz]	50
Recording time [s]	0.0025

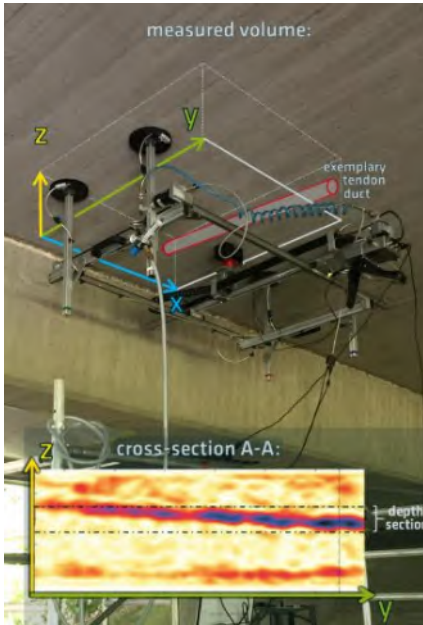




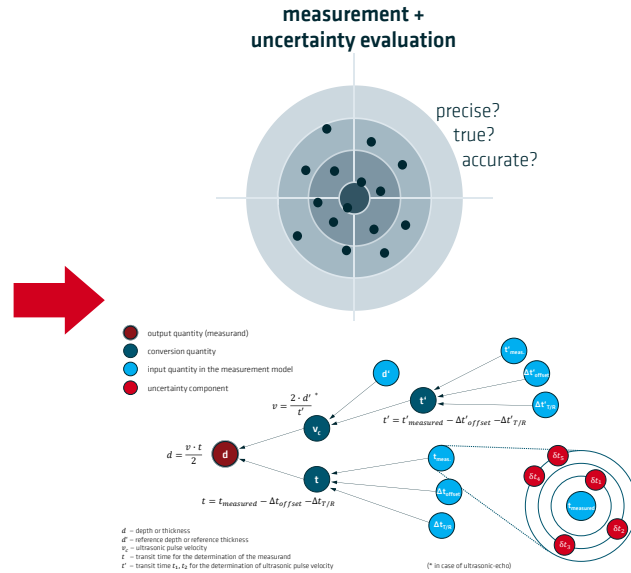
# How to use the results „ZfPStatik“

(Stefan Maack & Stefan Küttenbaum)

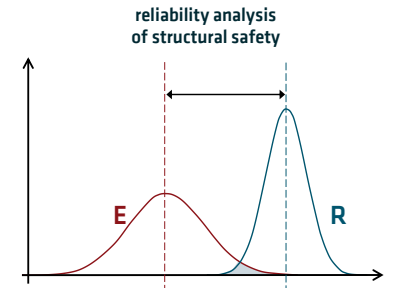
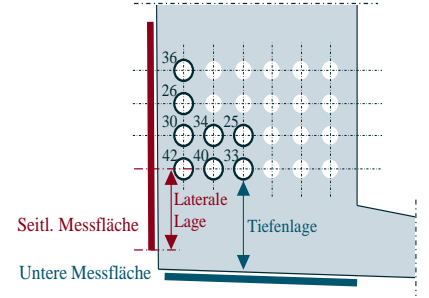
## Measurement on site



## Evaluation using nach GUM



## Load capacity calculation



Küttenbaum, S.; Maack, S.; Taffe, A.: Structural safety referring to ultrasound on concrete bridges. In: Beton- und Stahlbetonbau 113 (2018) 4, S. 7-13.

# How to use the results „ZfPStatik“

(Stefan Maack & Stefan Küttenbaum)

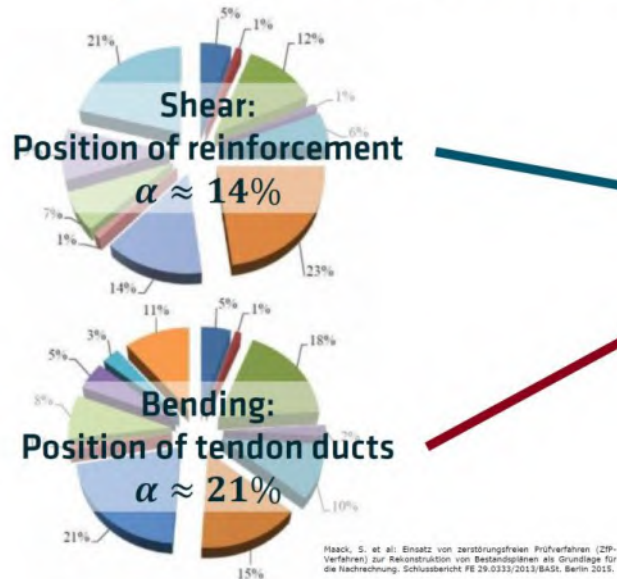


# How to use the results „ZfPStatik“

(Stefan Maack & Stefan Küttenbaum)

## 1 Preinvestigation

Sensitivity analysis vs. measurement methods



# How to use the results „ZfPStatik“



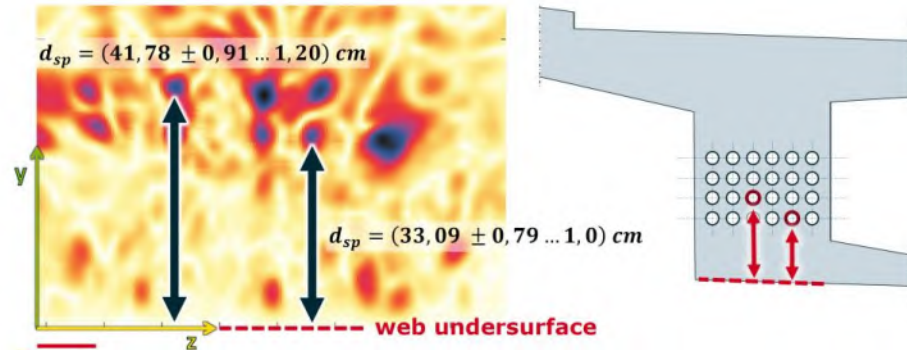
# How to use the results „ZfPStatik“

(Stefan Maack & Stefan Küttenbaum)

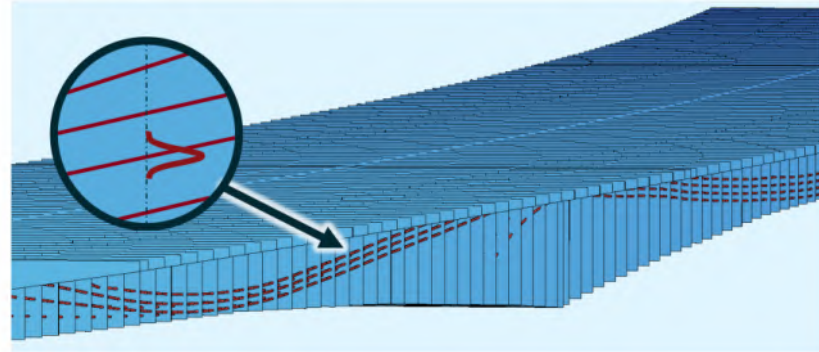
## ③ Model update based on measurements

Position of longitudinal tendon ducts

> 95% level of confidence & normal distribution



## ④ Reassessment using probabilistic methods

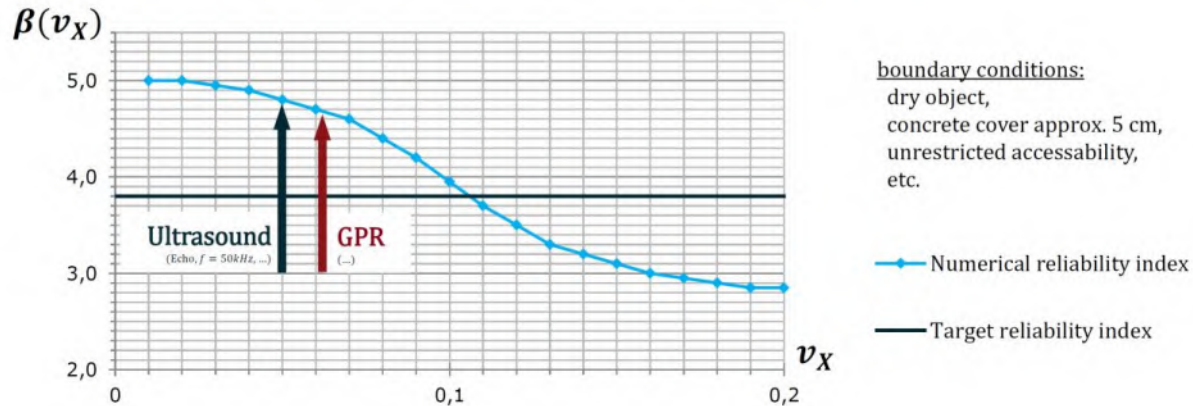


# How to use the results „ZfPStatik“

(Stefan Maack & Stefan Küttenbaum)

## 4 Reassessment using probabilistic methods

- > Combined vertical position of longitudinal tendon ducts
- > Exemplary bending proof (cross-section: midspan)





# Current challenges for NDT-CE

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Task 1: Look deeper

Task 2: Look where we can't look at yet

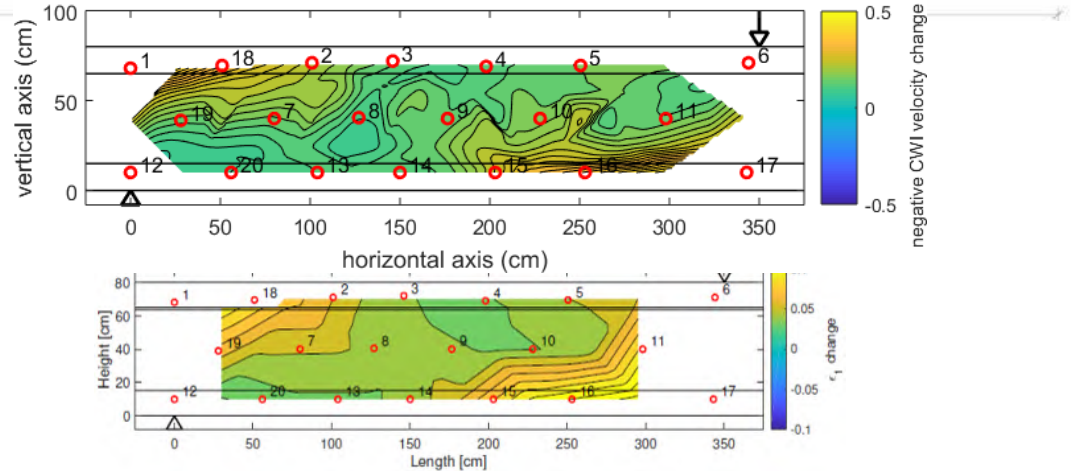
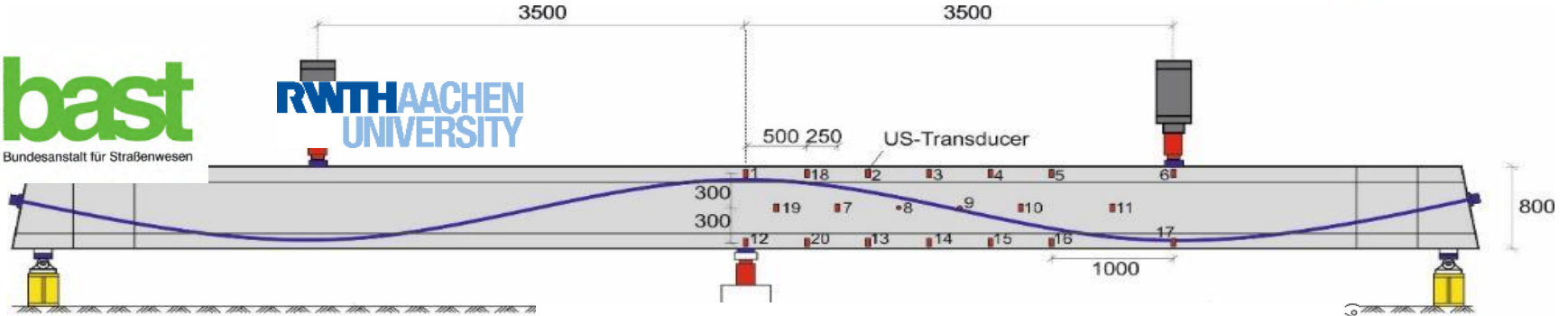
Task 3: Reveal more details

Task 4: Reliability, accuracy

Task 5: Combine data

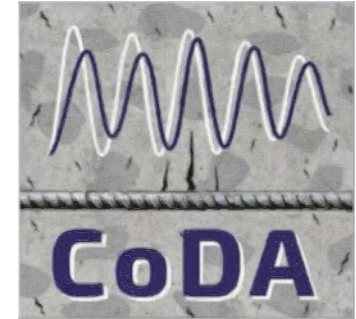
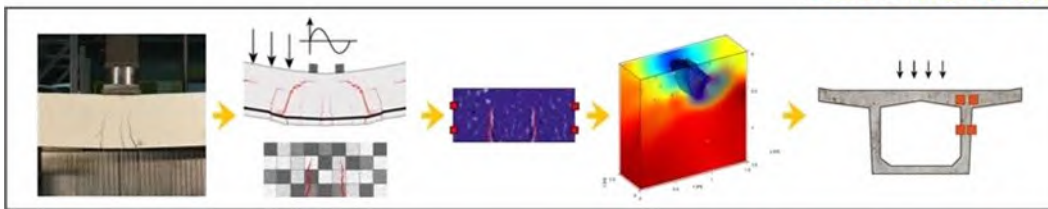
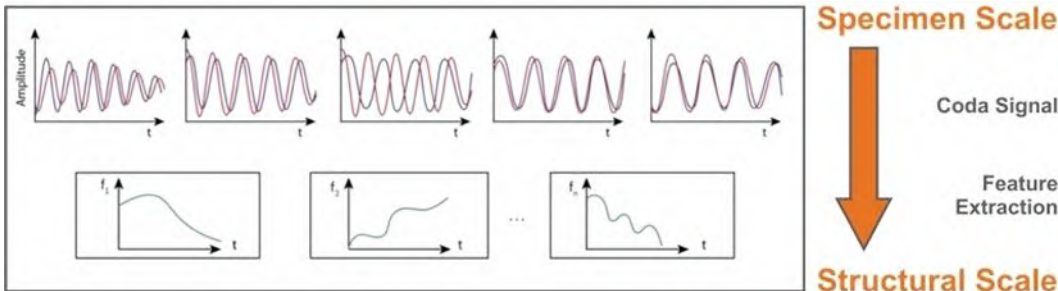
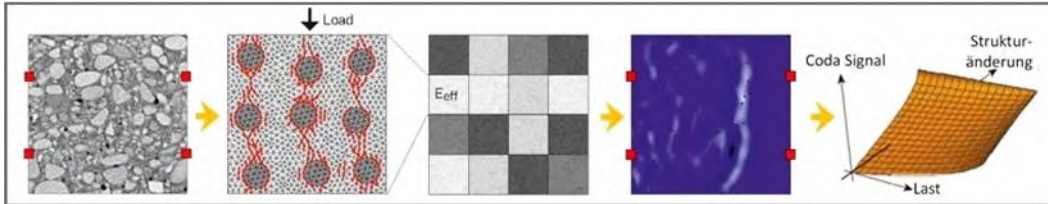
# Where is the connection to SPIN?

## Example 1: Ultrasonic monitoring of bridge girder



# Where is the connection to SPIN?

## Example 2: Ultrasonic monitoring of bridges



Concrete Damage

Funded by



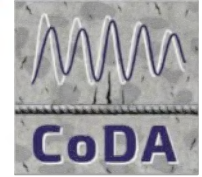
Deutsche Forschungsgemeinschaft

German Research Foundation

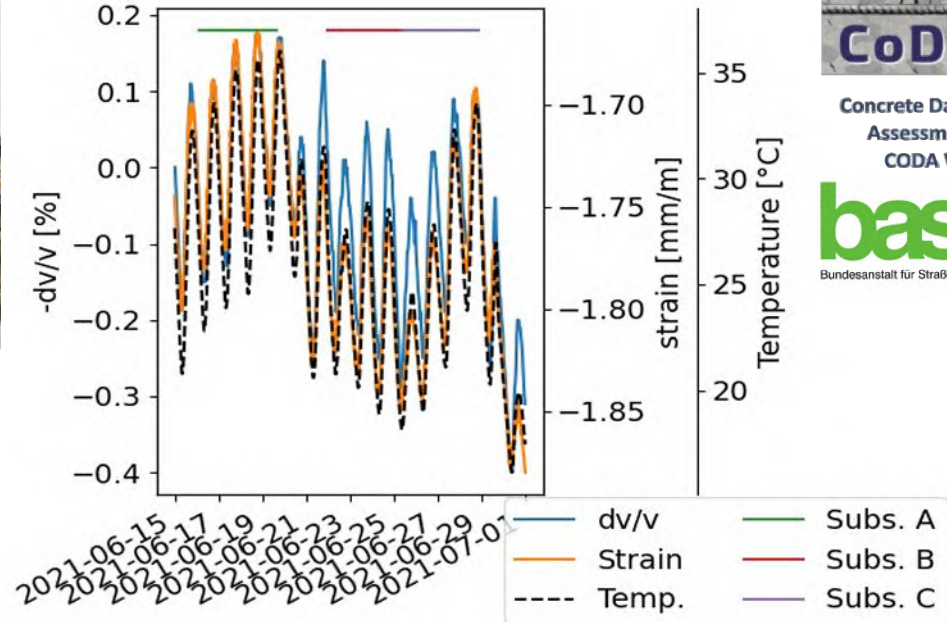
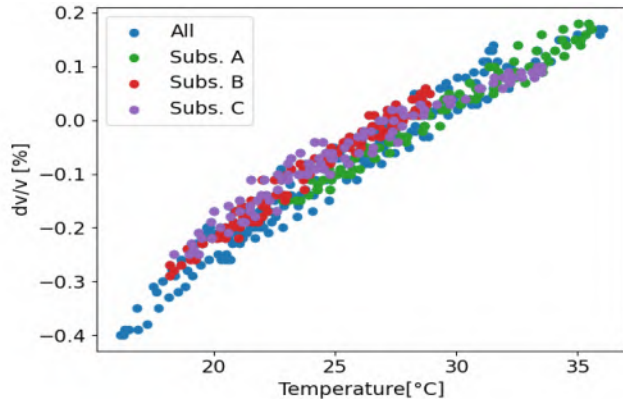


# Where is the connection to SPIN?

## Example 2: Ultrasonic monitoring of bridges

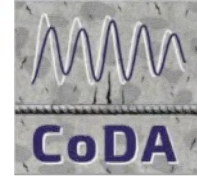


Concrete Damage  
Assessment by  
CODA Waves

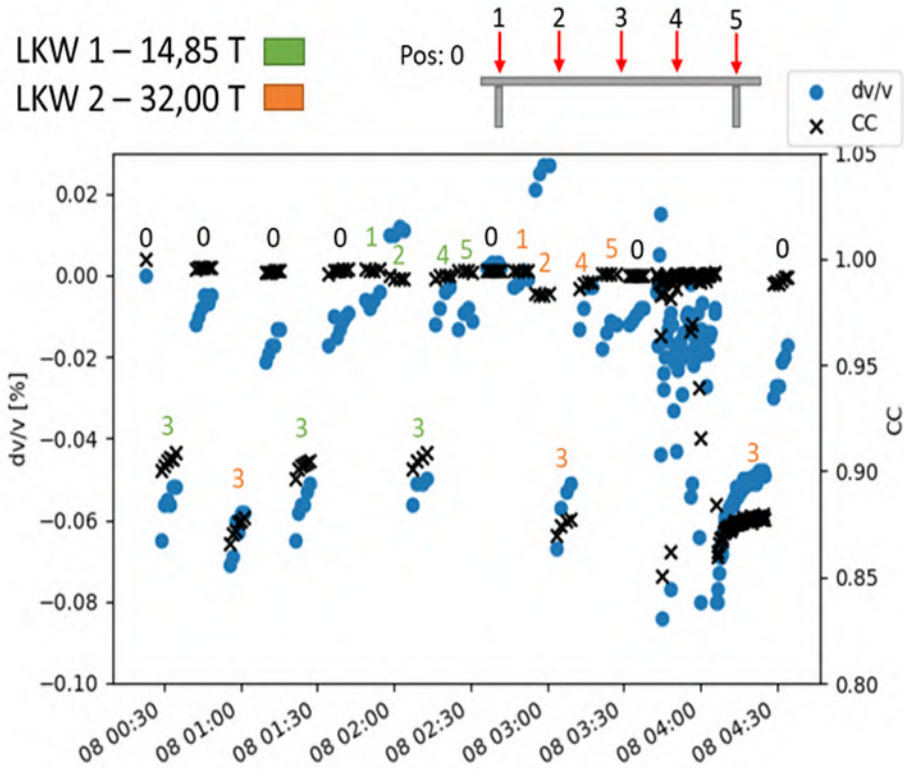


# Where is the connection to SPIN?

## Example 2: Ultrasonic monitoring of bridges

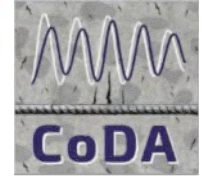


Concrete Damage  
Assessment by  
CODA Waves

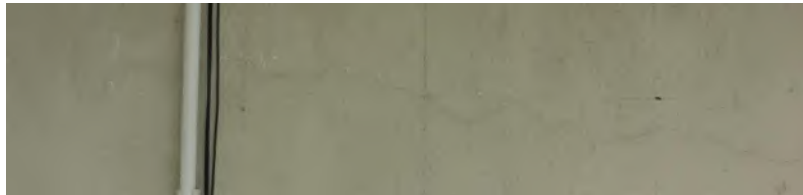
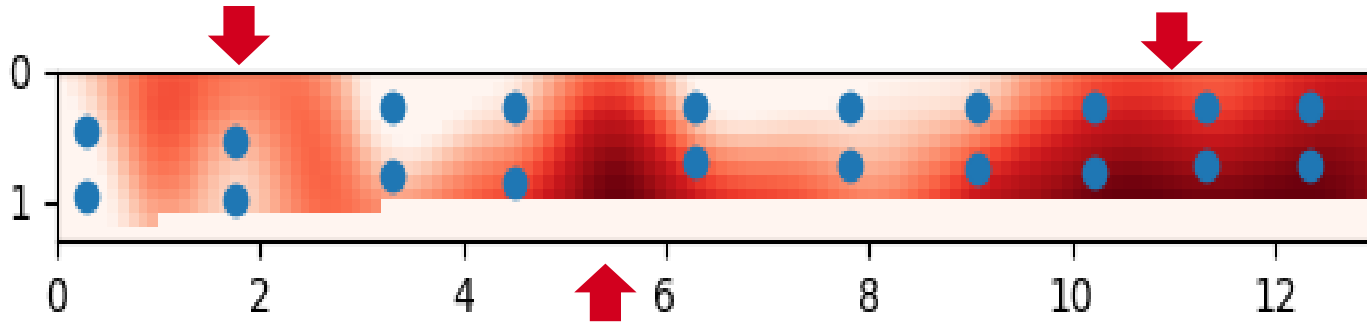
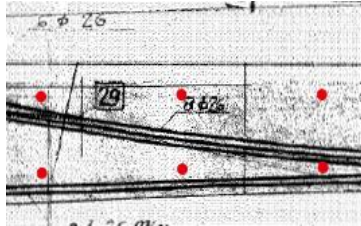


# Where is the connection to SPIN?

## Example 2: Ultrasonic monitoring of bridges



Concrete Damage  
Assessment by  
CODA Waves

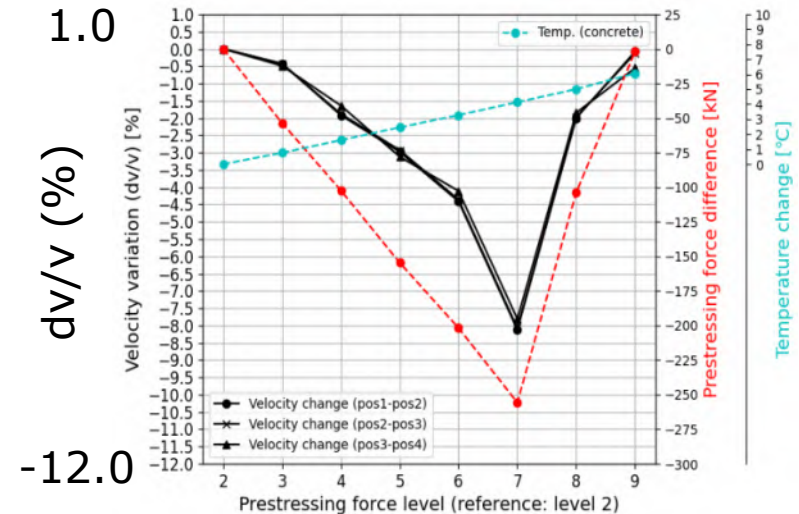
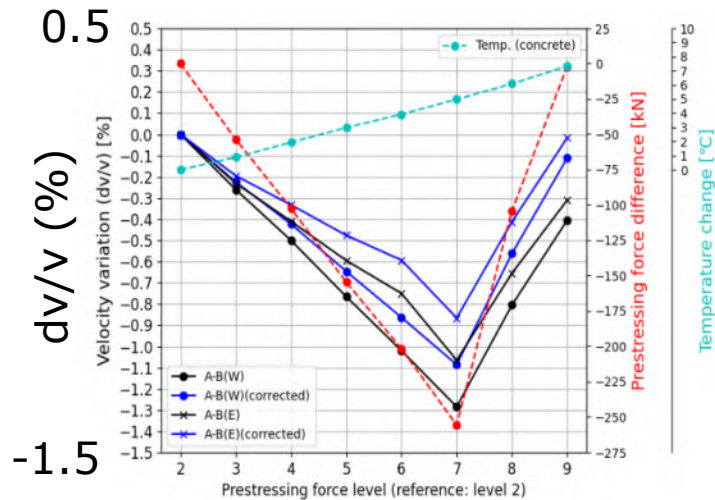


Decorrelation imaging (diffusive):  
Scattering cross section  
(Epple et al., in prep.)

# Where is the connection to SPIN?

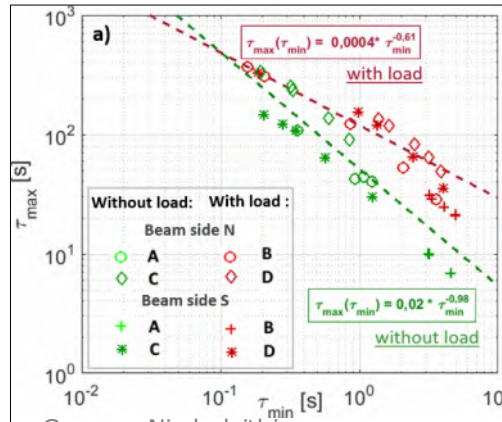
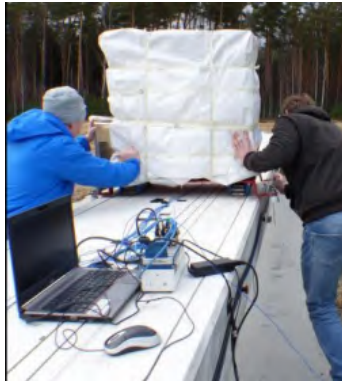
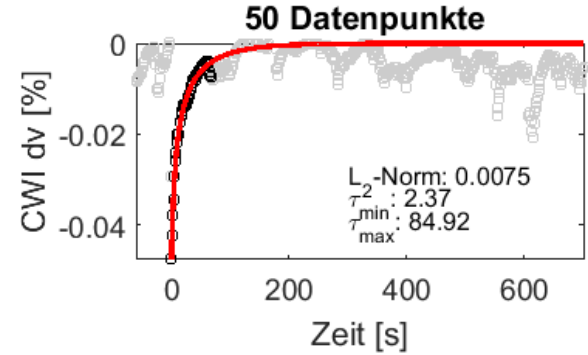
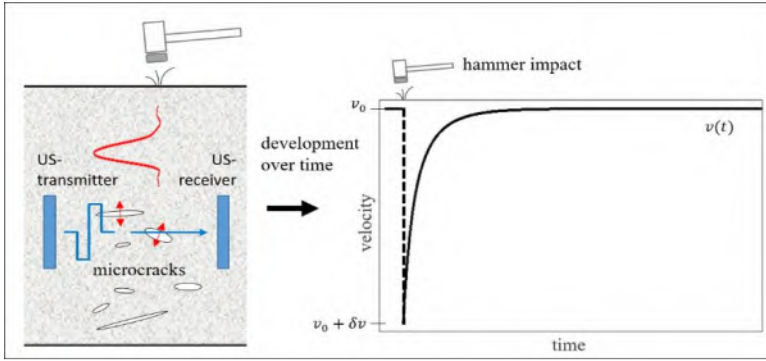
## Example 4: Loss of prestress in BLEIB bridge model

Chun et al., submitted to JONE



# Where is the connection to SPIN?

## Example 5: Nonlinear ultrasound



Gassenmeier et al., 2016  
 Snieder et al., 2016  
 Berschat, M. sc. thesis 2018

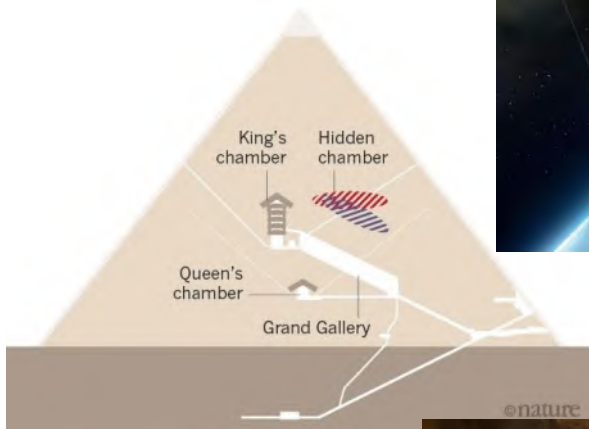




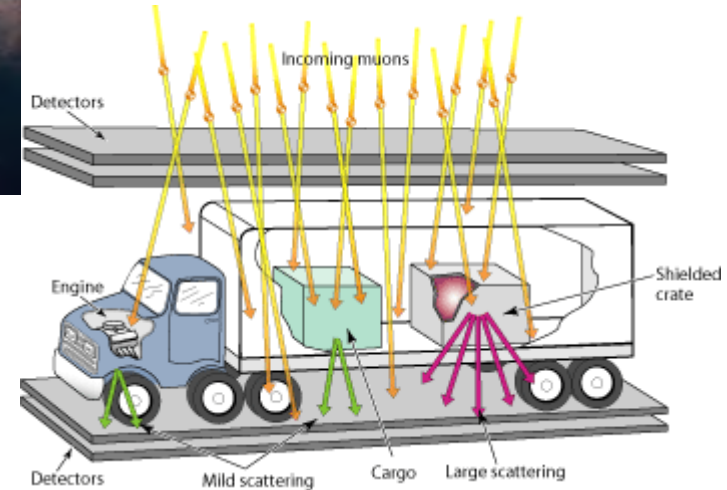
Courtesy of BAM NDT department  
Division 8.3 Radiography

# Muon imaging

## Cosmic insight into concrete

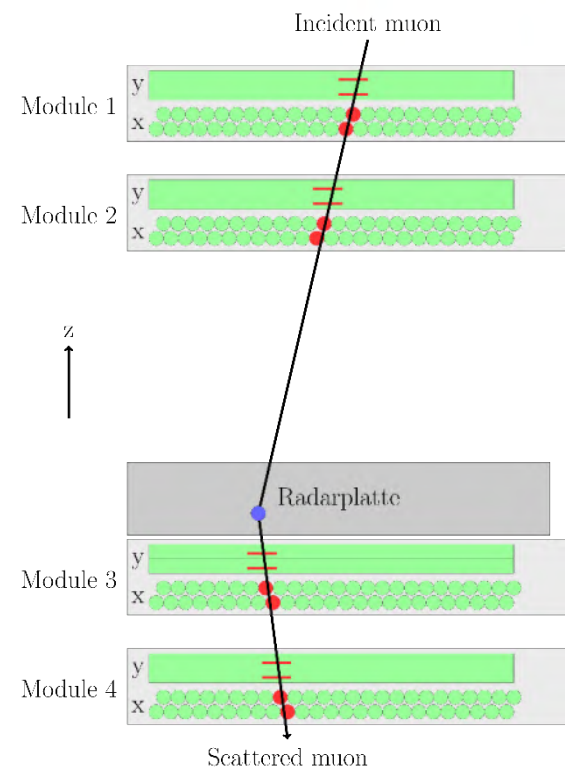
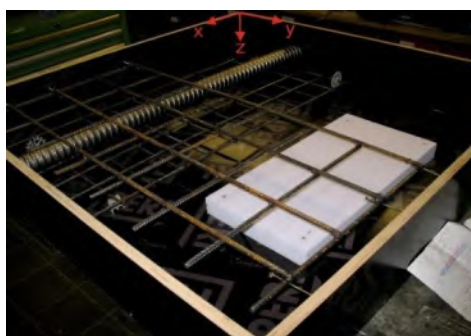
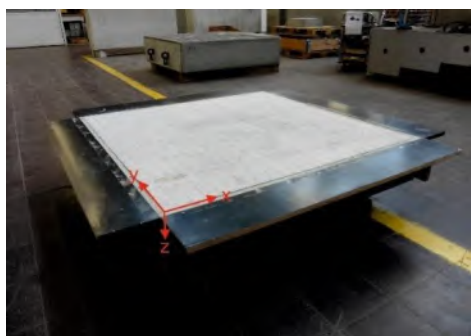


Locating voids  
Nature  
[10.1038/nature.2017.22939](https://doi.org/10.1038/nature.2017.22939)



Checking for contraband  
DOE/office of science

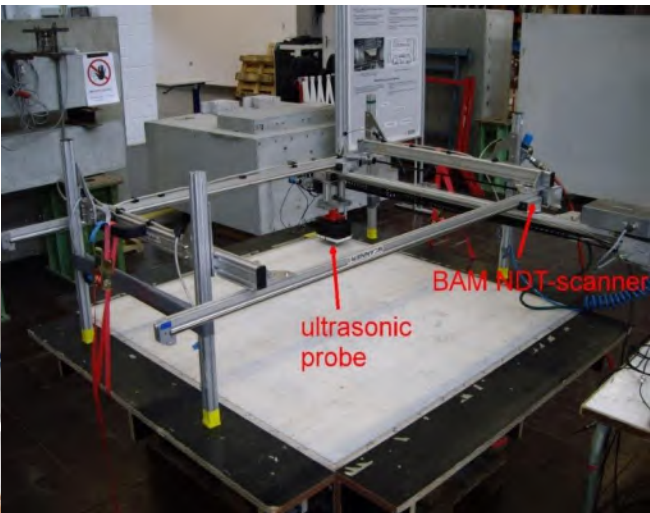
# Muon imaging Cosmic insight into concrete



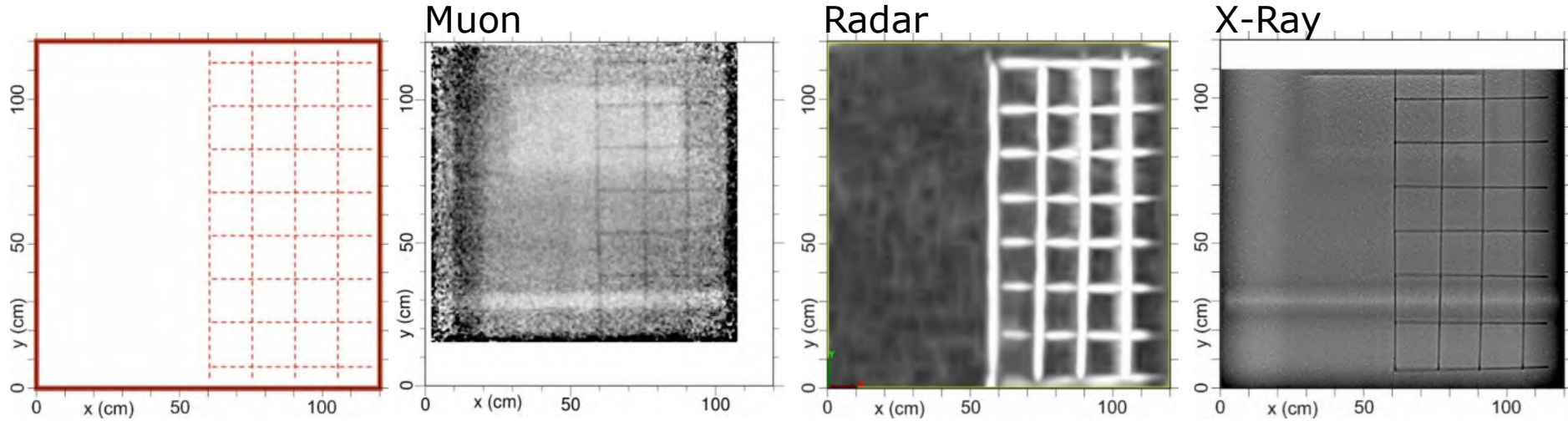
Niederleithinger et al., JONE, 2021

# Muon imaging Cosmic insight into concrete

Reference: Radar, X-Ray, *Ultrasound*



# Muon imaging Cosmic insight into concrete



Niederleithinger et al., JONE, 2021

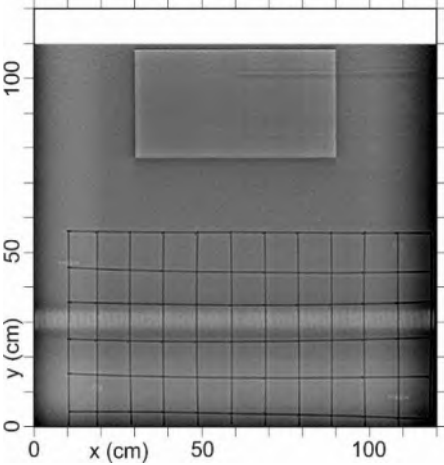
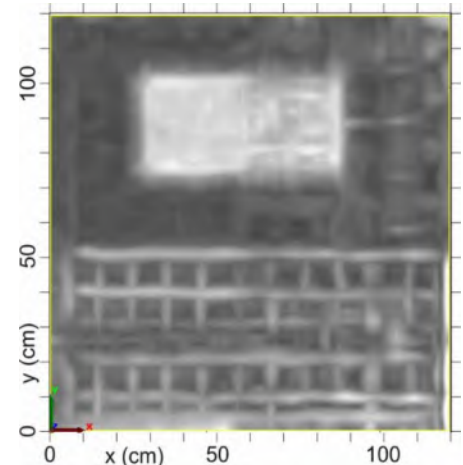
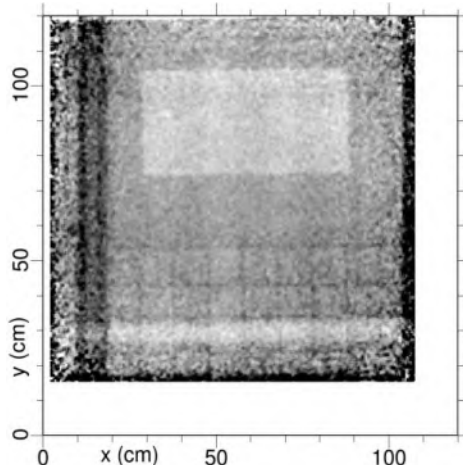
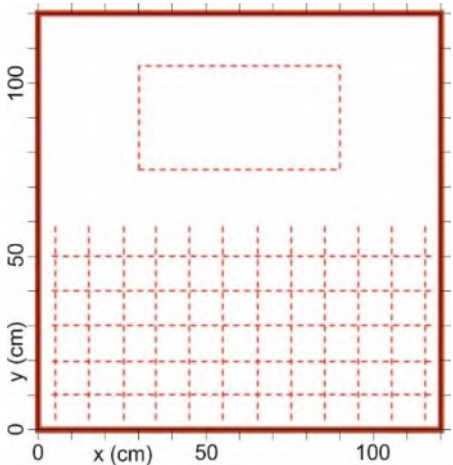
# Muon imaging

## Cosmic insight into concrete

Muon

Radar

X-Ray



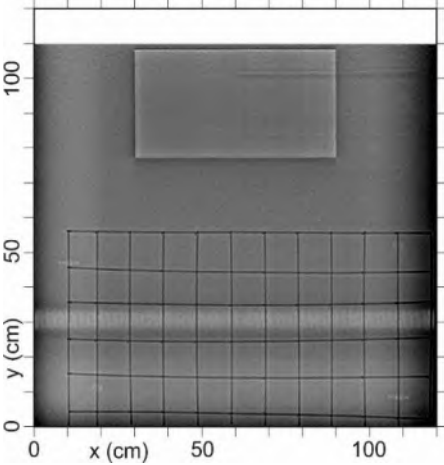
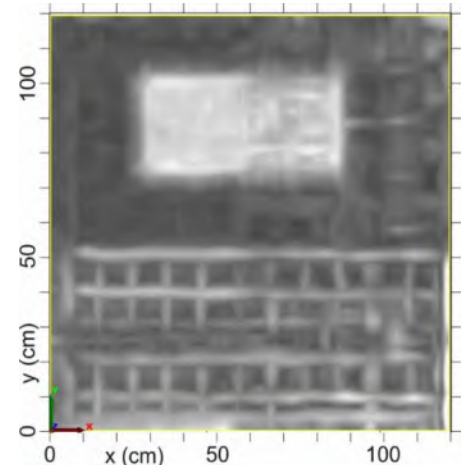
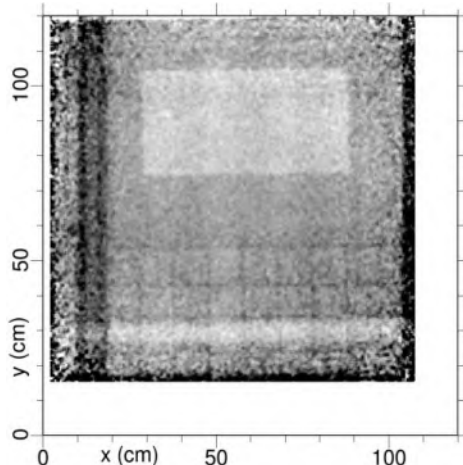
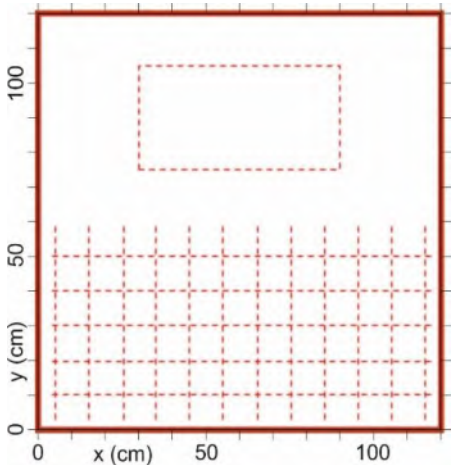
Niederleithinger et al., JONE, 2021

# Muon imaging Cosmic insight into concrete

Muon

Radar

X-Ray



Niederleithinger et al., JONE, 2021