

12th ECNDT
Gothenburg-Sweden-2018



For its 10th anniversary, Academia NDT International invites you to attend the European Research Day (June 13th, Room E1)



Sicherheit in Technik und Chemie

ECNDT 2018, Gothenburg June 11th – 15th, 2018

CURRENT DEVELOPMENTS IN DIGITAL RADIOGRAPHY AND COMPUTED TOMOGRAPHY - FROM NM TO MACRO SCALE -

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-
- **Conversion of film radiography to digital radiography**
 - Repeat the success story of optical photography (1990 – 2000)
 - **Scatter radiography with single sided access**
 - New X-ray optics
 - Application for aerospace components
 - **Computed Tomography (CT) and Laminography**
 - Flaw detection
 - Dimensional Measurement
 - Selected applications
 - **Micro Radiography and μ CT**
 - 2D and 3D inspection in the nm scale
 - Phase contrast
 - Diffraction CT

FILM REPLACEMENT WITH DIGITAL DETECTORS

- THE DIGITAL REVOLUTION RT 2.0 -



Problems:

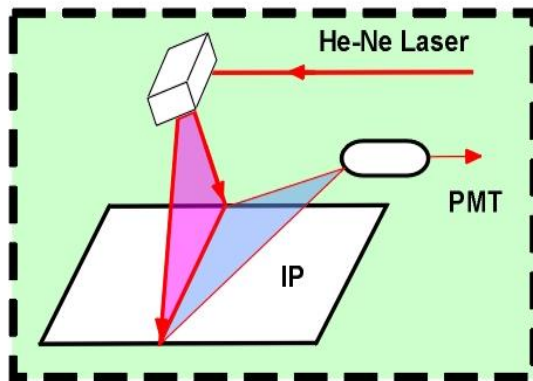
- Accessibility
- Time pressure
- Weather

Application areas

- Training
- Minimum image quality
- Minimum equipment spec required

Key Technologies for Film Replacement

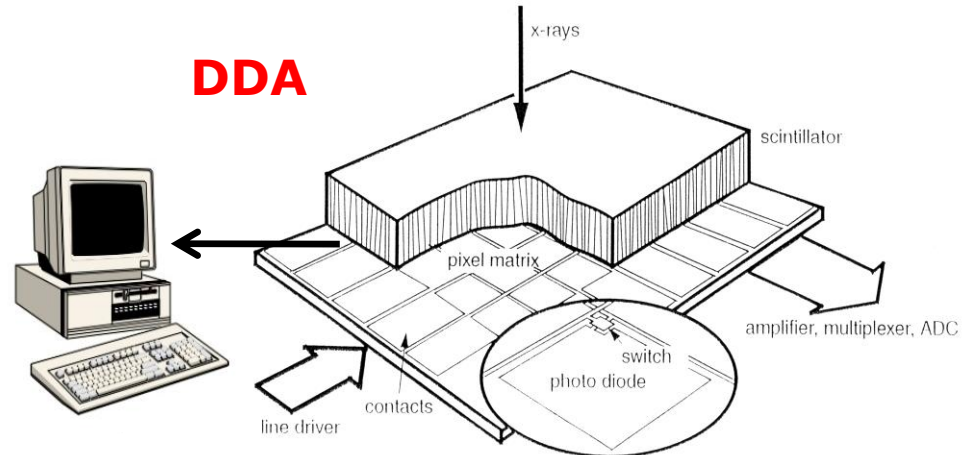
- **Computed Radiography (CR)** with storage phosphor imaging plates
- **Digital Detector Arrays (DDA)**



CR

→
Data Output

DDA



Film vs. DDA: Comparison with Reference IQI BAM 5; Reference Weld.



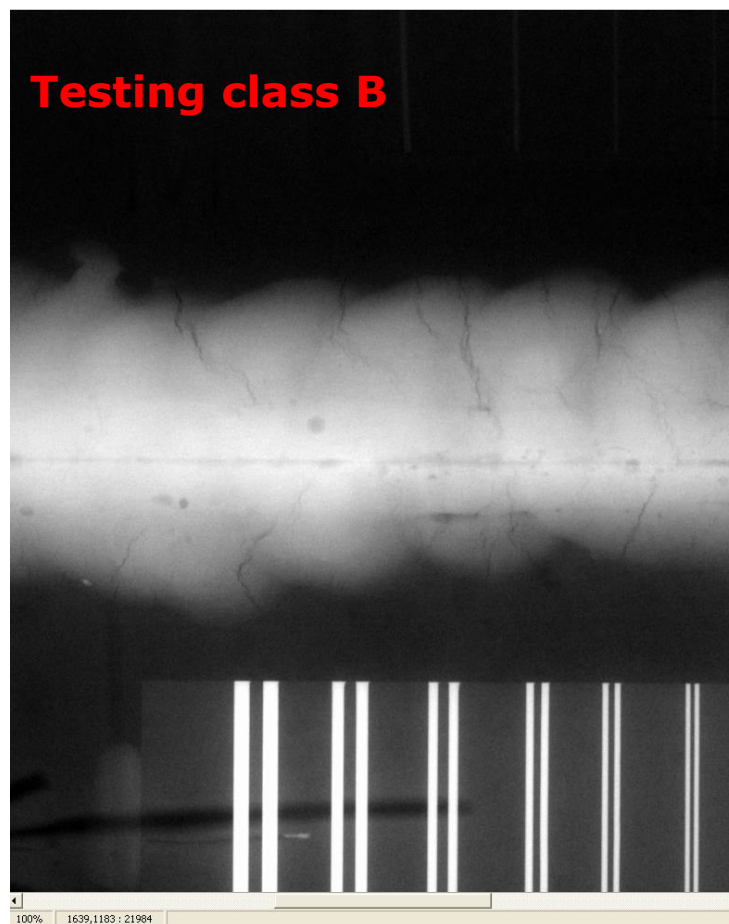
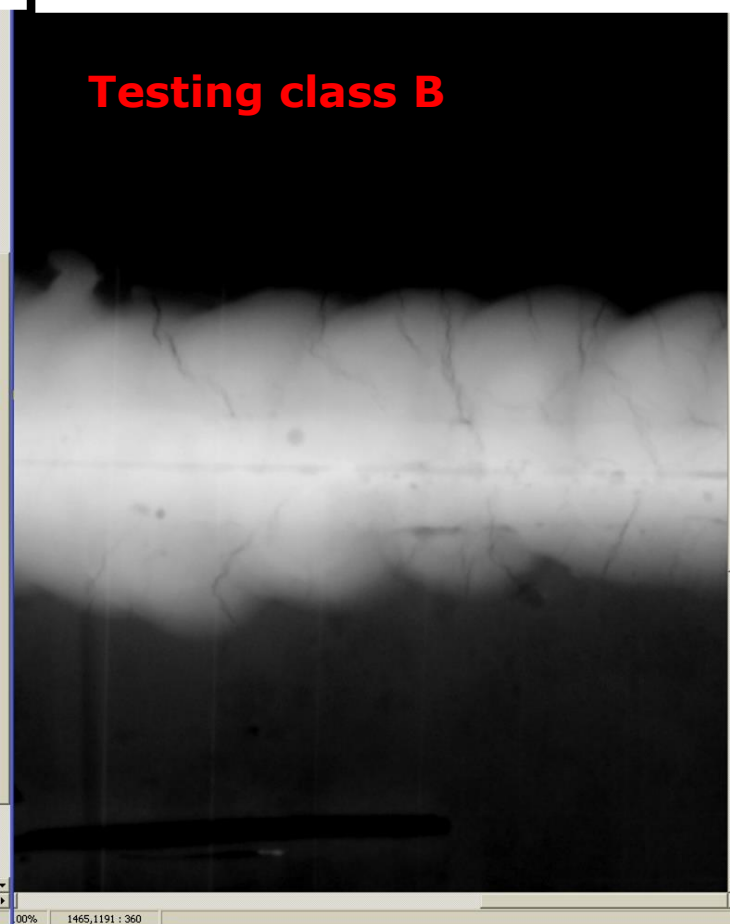
BAM 5 is a hand welded steel plate (St 35) 8 mm thick, the welding seam is max. 10 mm thick. It contains all types of welding flaws, especially nice cracks at the surface of the welding seam.

Film vs. DDA: Comparison for the *BAM 5* Weld.



BAM 5 (8mm St), D4 Film
50 μm Scan, D = 3,5 at 8 mm.
150 kV, 10 mA, 1.9 min, FFD 800 mm

CMOS Hamamatsu C 7942 CA
50 μm Pixel, 12 Bit, 0,47s /Frame
160 kV, 6,3 mA, 2 min, FFD 800 mm



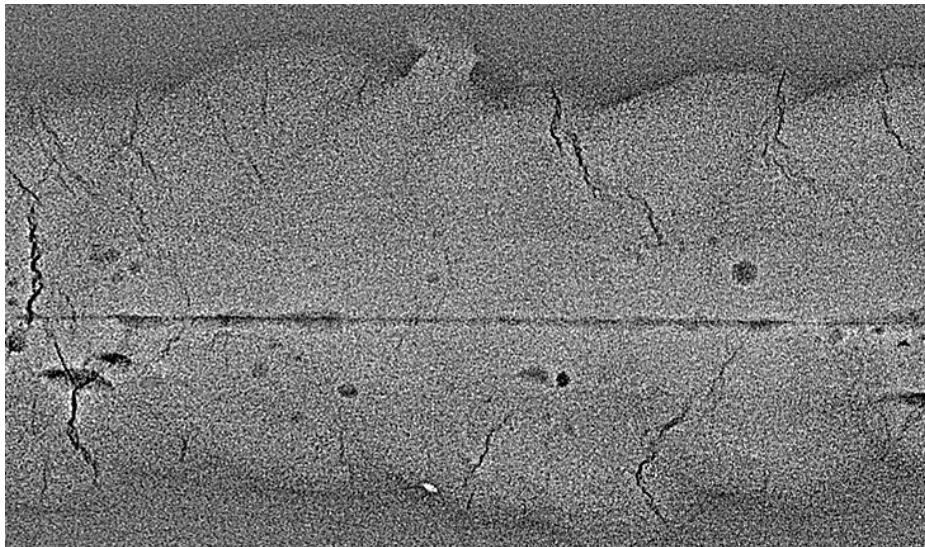
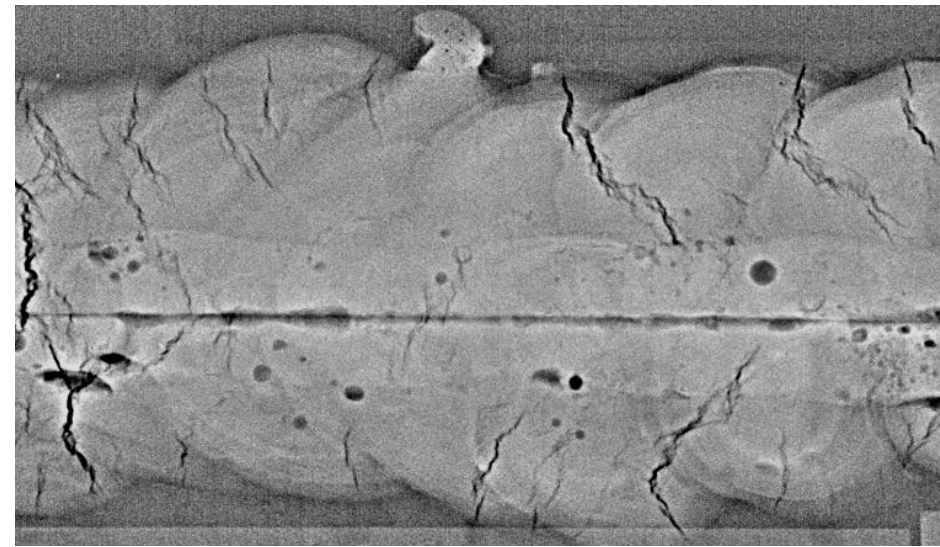
Film vs. DDA: Comparison for the *BAM 5* Weld.

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Testing class B

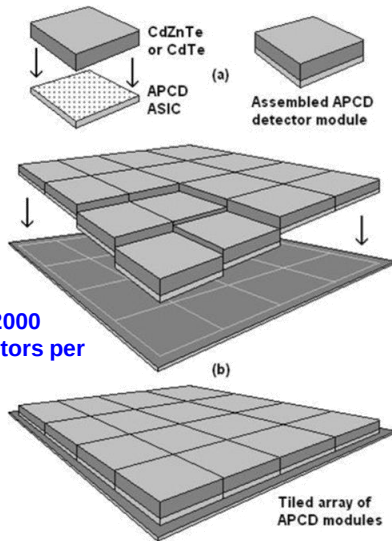
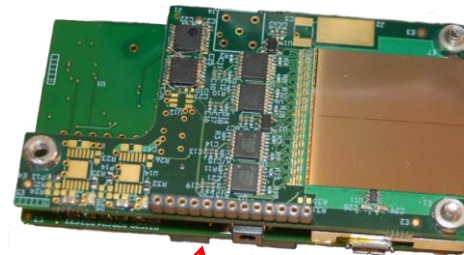
Digital-High pass filter (Extract Details) of Isee!



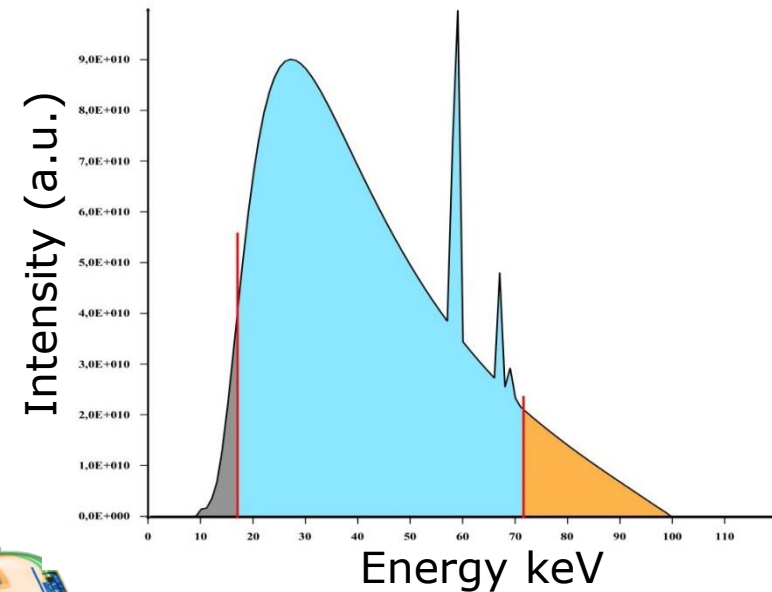
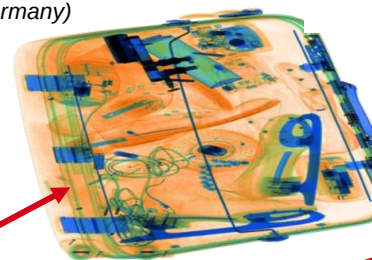
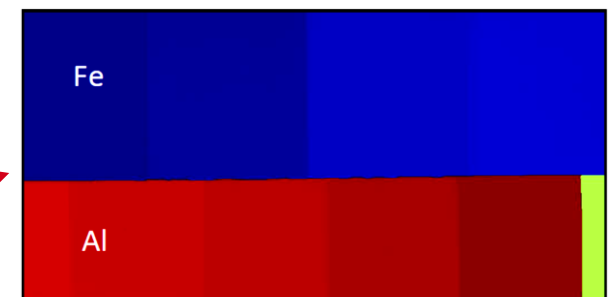
$\text{SNR}_{\text{norm}} \sim 83$
 $\text{SR}_b = 50 \mu\text{m}$, scanned

$\text{SNR}_{\text{norm}} \sim 550$
 $\text{SR}_b = 83 \mu\text{m}$

New Photon Counting and Energy Discriminating Digital Detector Arrays



"PDT 25" (XCounter/Ajat, Sweden/Finnland)
"WidePIX" (IEAP CTU in Prague, Czech)
"PILATUS" (PSI/SLS, Switzerland)
"XPAD" (CNRS, France)
"MEDIPIX" (CERN)
"LAD" (RAL, UK)
"MPEC" (Univ. Bonn, Germany)



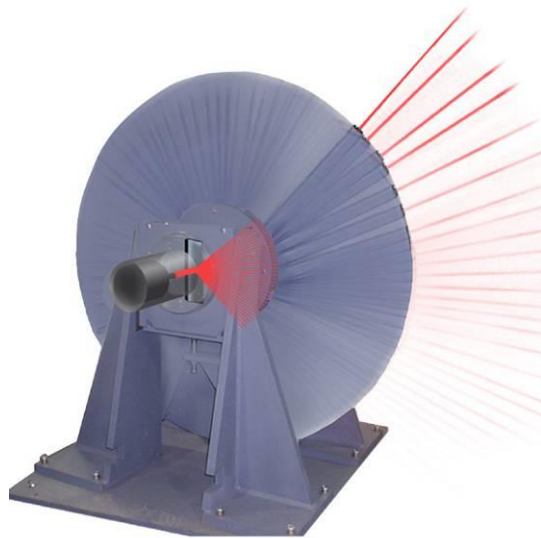
Radiograph of two step wedges

- Increase of the thickness dynamic
- "Color radiography" for material's discrimination

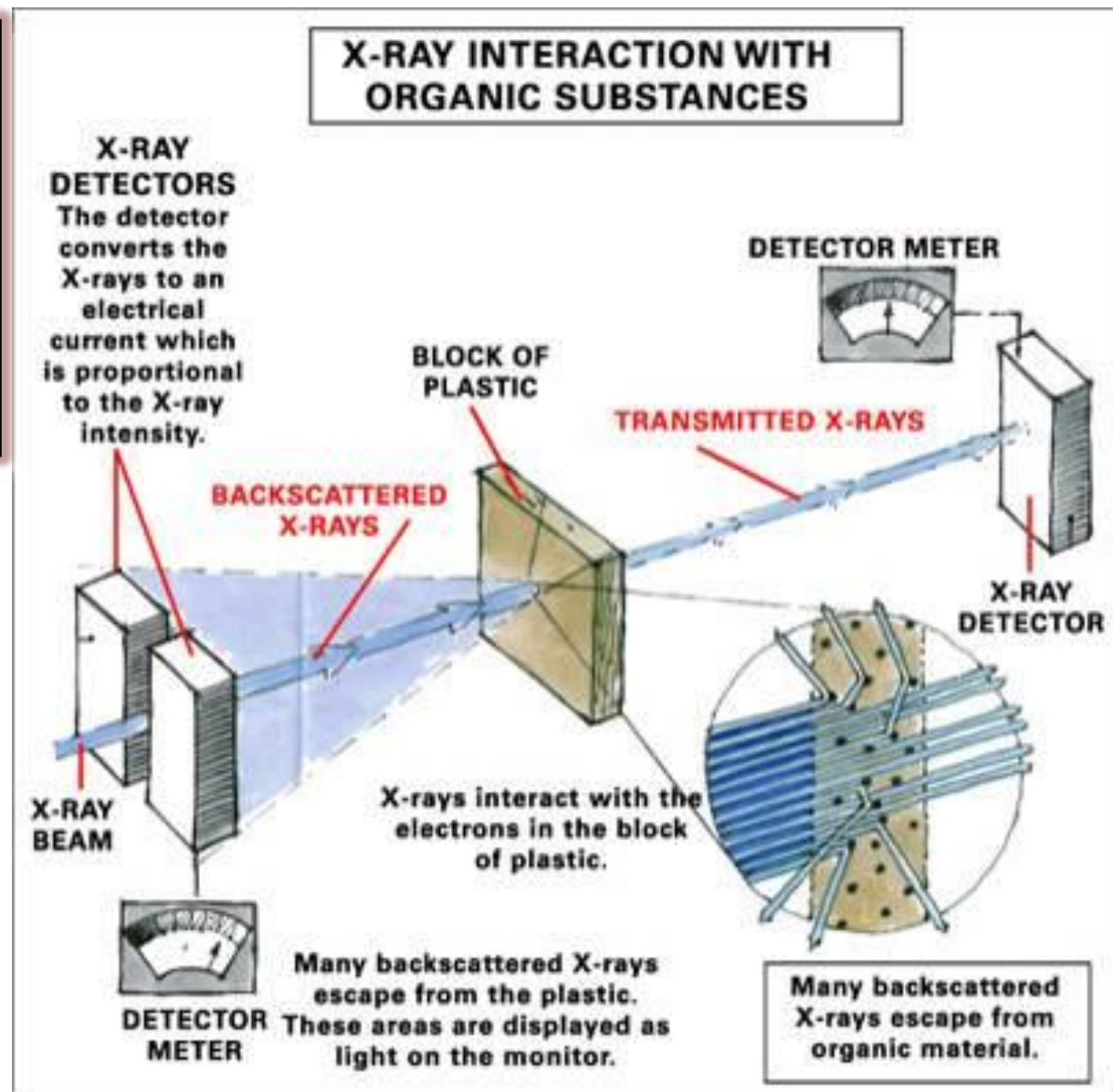
SCATTER IMAGING

- RADIOGRAPHY WITH SINGLE SIDED ACCESS -

X-Ray Back Scatter Technique with single sided access

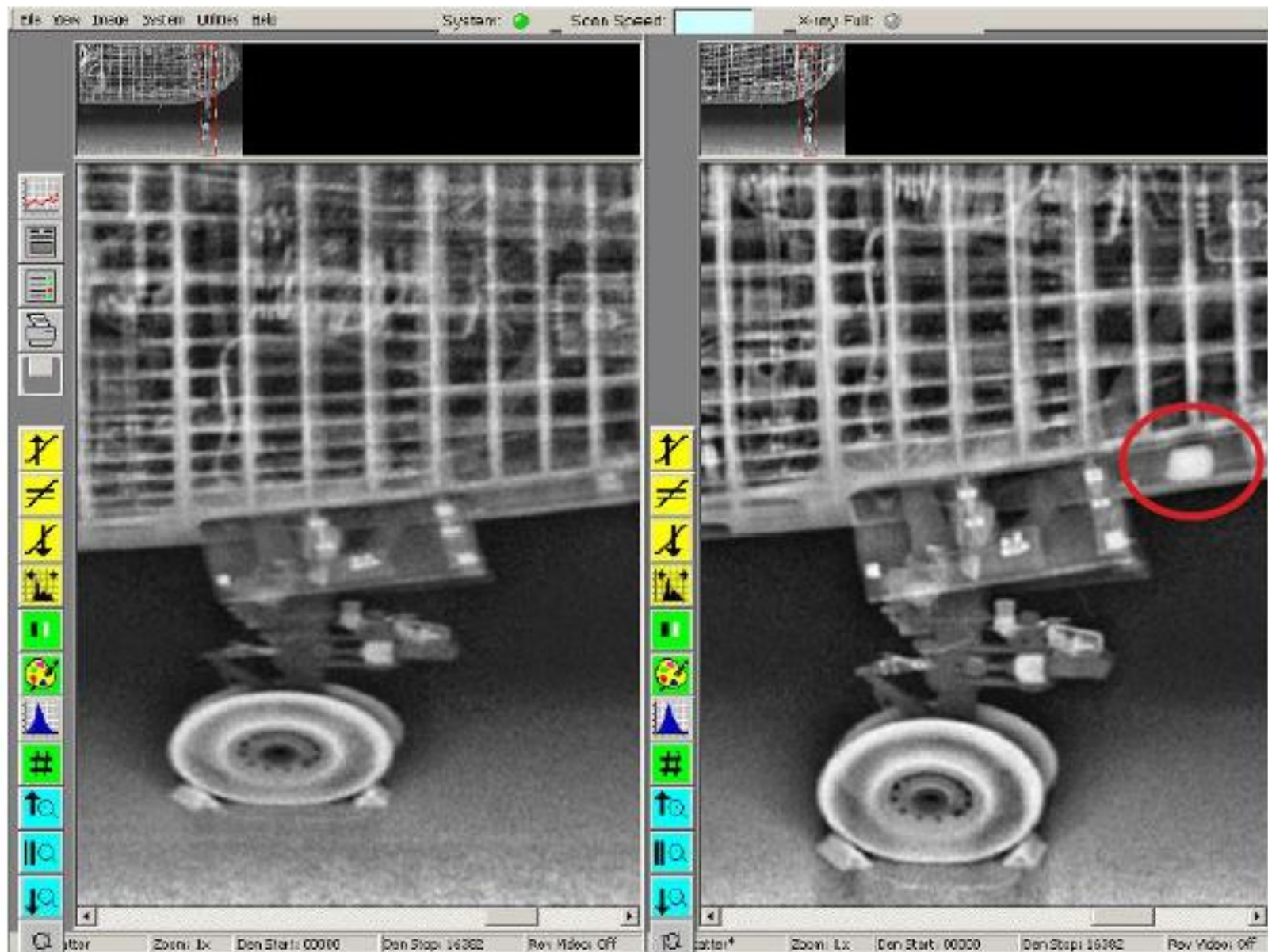


Flying Spot Technique

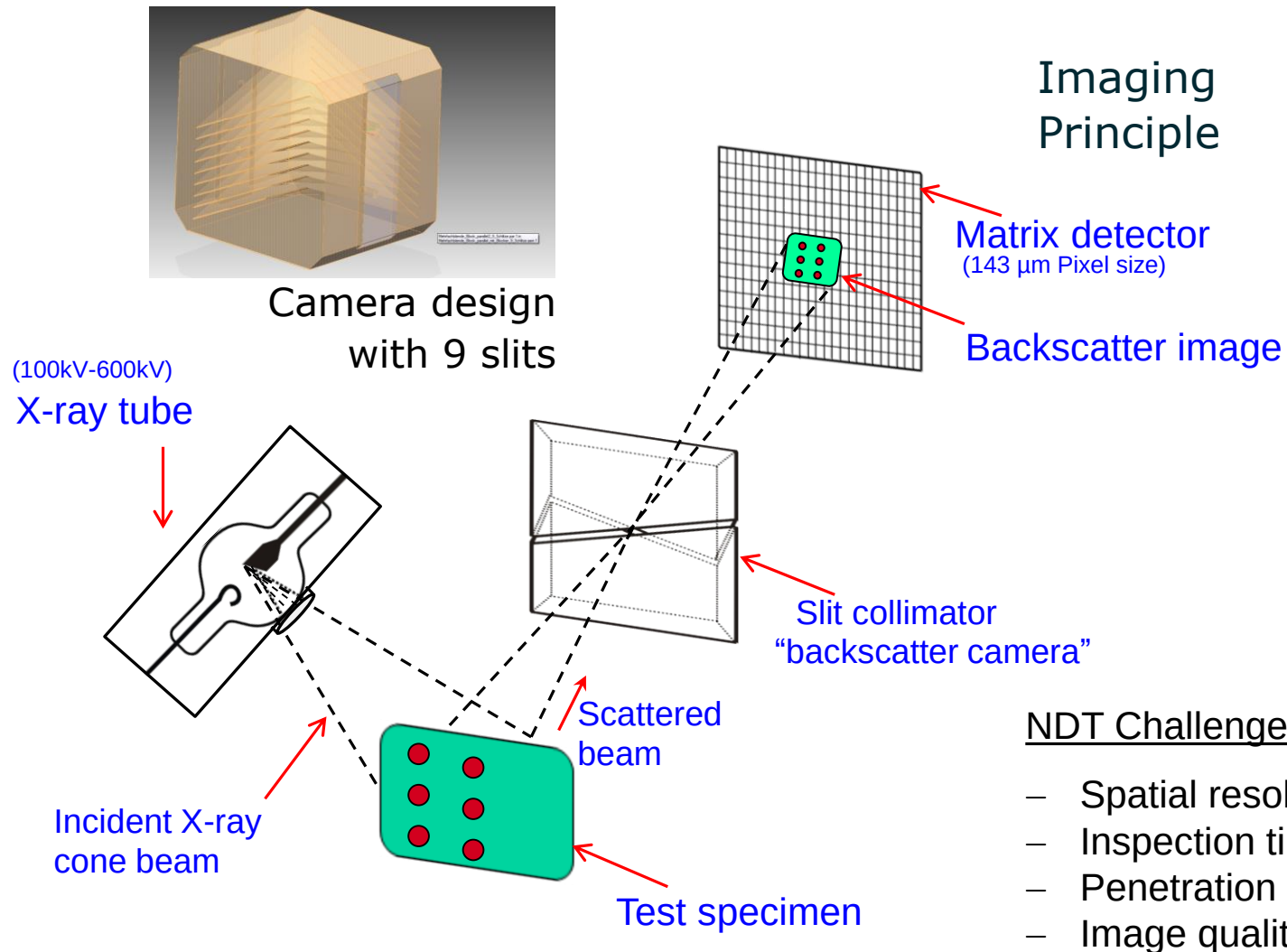


AS&E

Detected Threat in the Front Fuselage of an Aircraft



Slit Collimator Technique of BAM



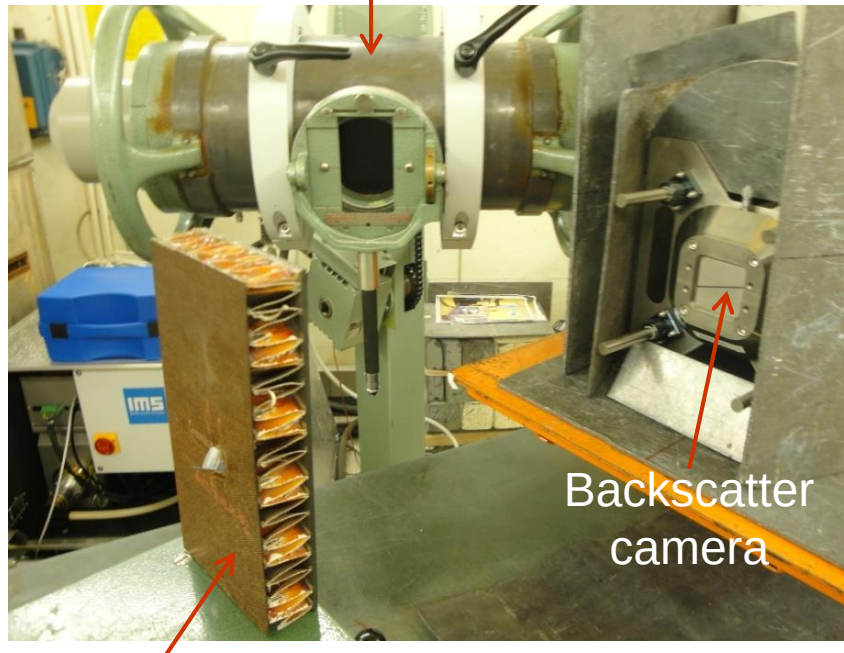
NDT Challenges

- Spatial resolution
- Inspection time
- Penetration depth
- Image quality

S. Kolkoori et al., NDT&E International, Vol.70, pp: 41-52, 2015, [doi:10.1016/j.ndteint.2014.09.008](https://doi.org/10.1016/j.ndteint.2014.09.008)

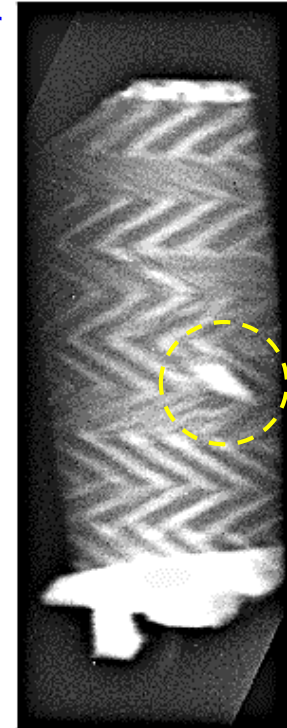
Experimental Results

X-ray tube 420kV
(GE ISOVOLT TitanE)



CFRP Sandwich plate
(10cm x 20cm x 3.3cm)

X-ray backscatter
image



Experimental parameters:

- 420 kV, 10mA, 3 min
- Slit width: 0.9 mm
- Source-object-distance (SDD): 61cm
- Object-slit-distance (SOD): 47 cm
- Slit-detector-distance: 22 cm

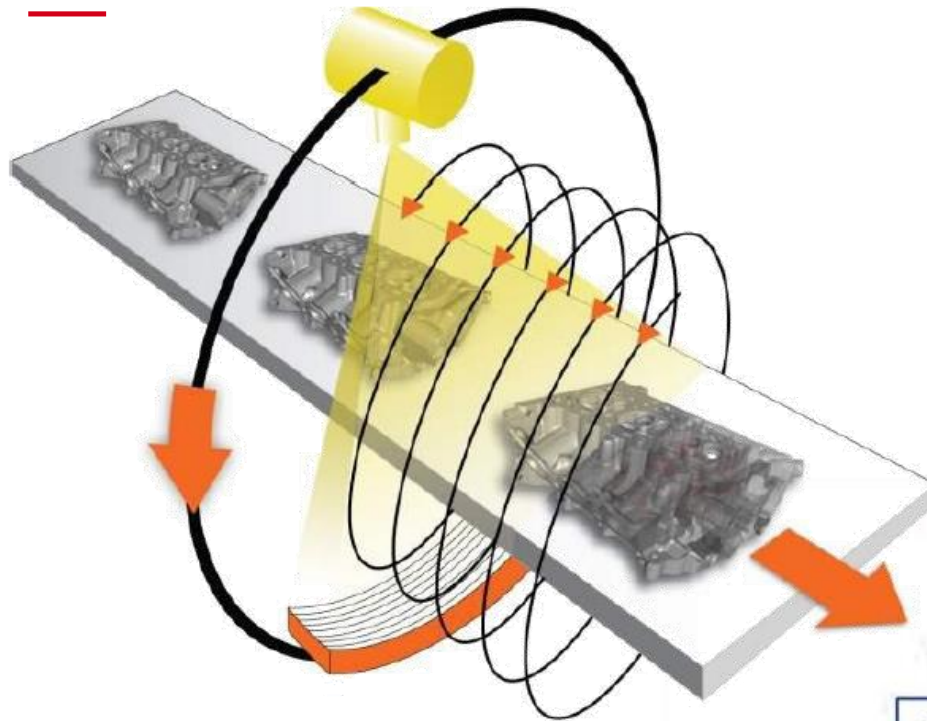
- Impact damage on the CFRP skin can be identified
- Water inclusions between CFRP skin and core materials can be detected
- Structural Integrity of the core-waviness can be imaged

Computed Tomography in Production Processes

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COMPUTED TOMOGRAPHY RT 3.0

Flaw detection and Measurement of Dimensions of Engine Blocks for Cars

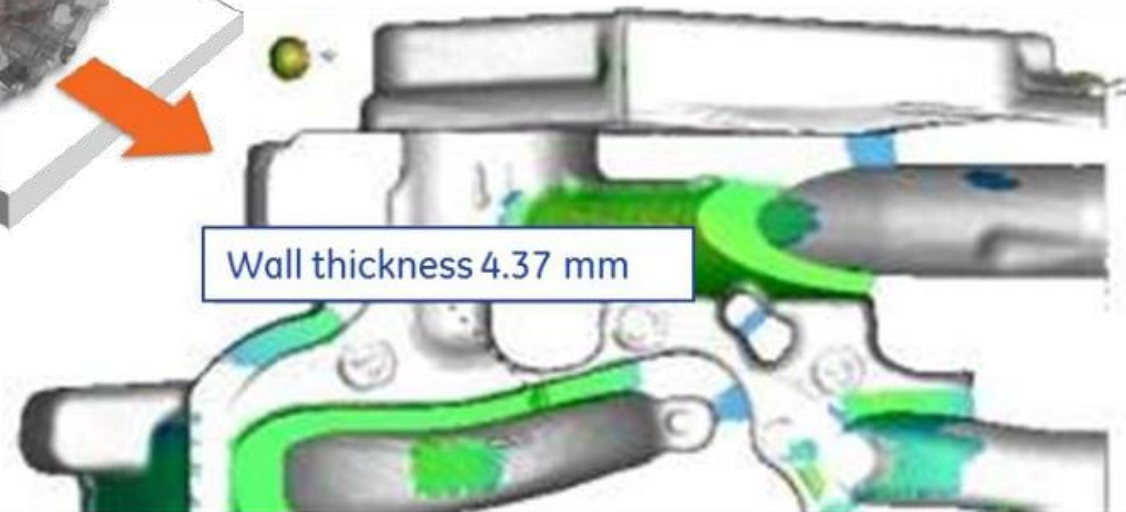


Inspection for flaws and dimensional accuracy of engine blocks with

➤ **Spiral CT,**

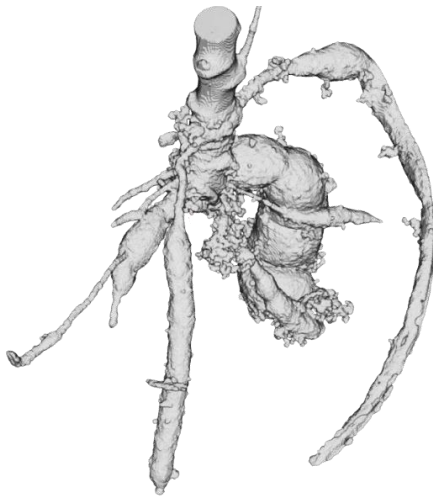
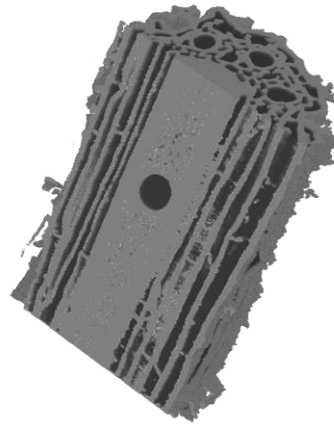
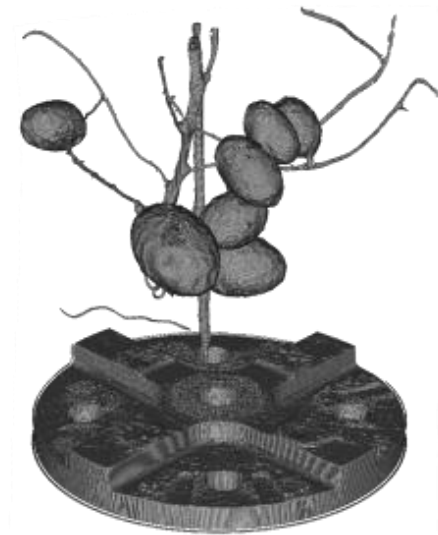
- Rotating high power X-ray tube,
- Rotating multi line detector

At-line inspection with spiral CT



GE S&IT, Volkswagen
Oliver BRUNKE, Ferdinand HANSEN, Ingo STUKE,
Franz Friedrich BUTZ

Monitoring of Plant Grows by Computed Tomography - Agricultural Engineering -



CT of roots of growing plants under soil

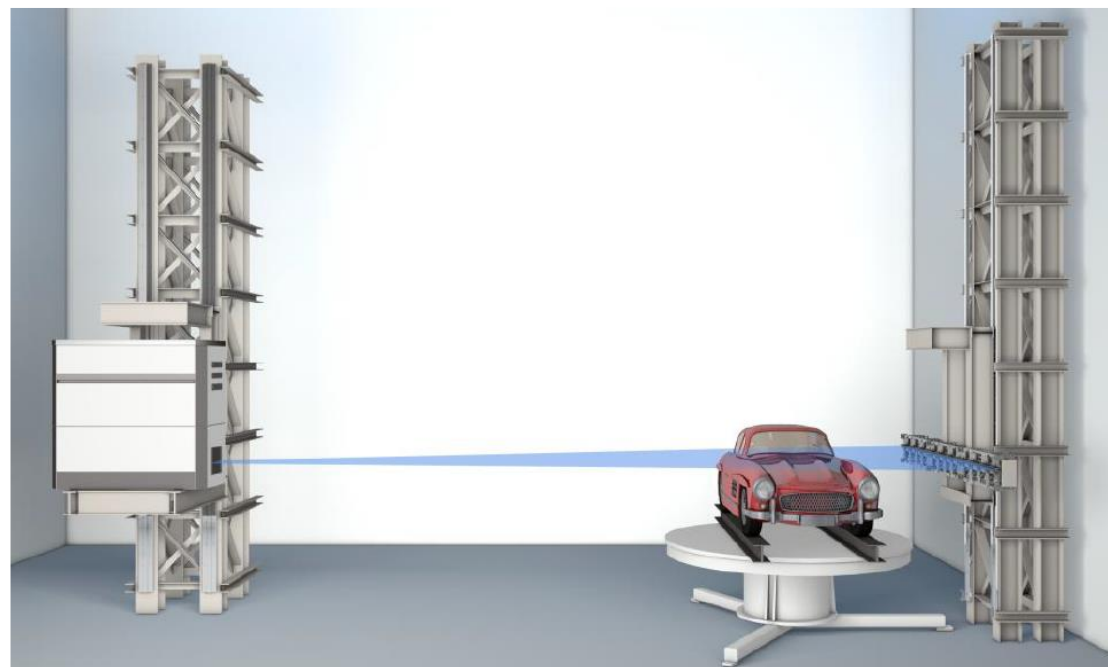
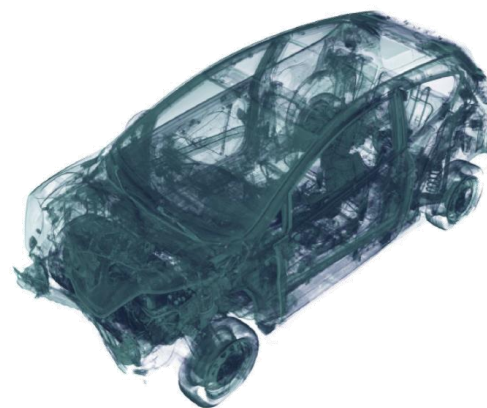
- Capillary tube inside the stem or trunk, fruits and organs.
- In all cases the soil which covers the complex structures was virtually removed

High Energy Computed Tomography

XXL – Computed Tomography

at EZRT (Center for X-Ray Technologies), FhG, Germany

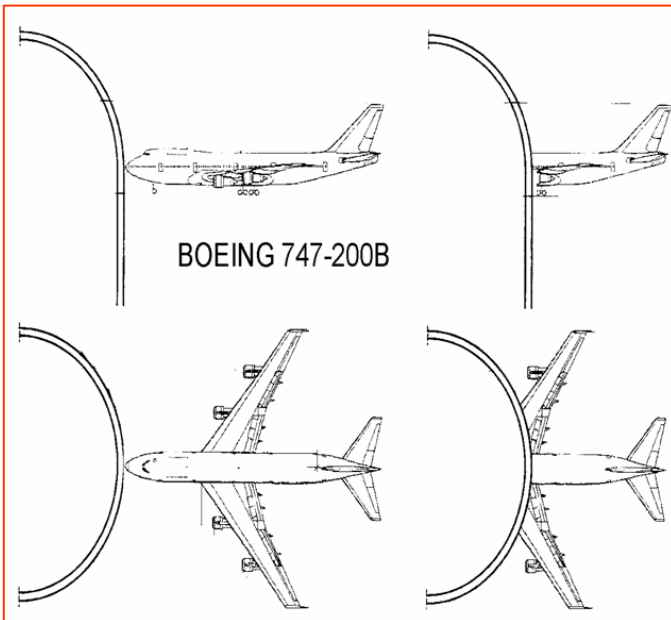
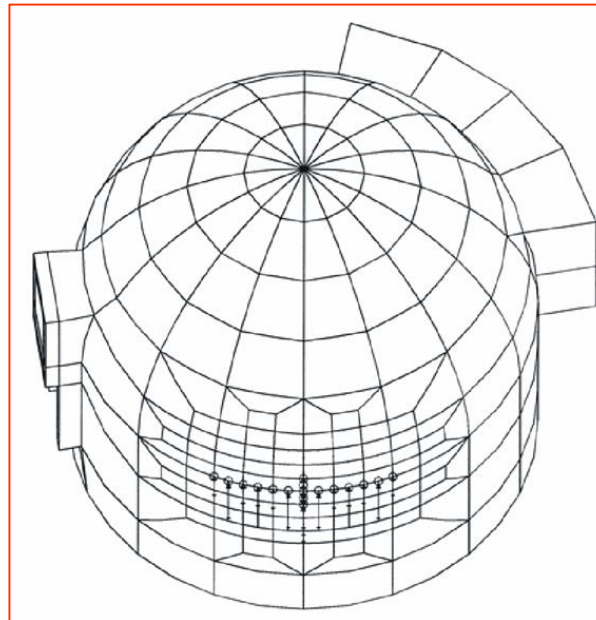
- CT of complete cars with an AoI of $4 \times 4 \times 4 \text{ m}^3$
- Source: LINAC 9 MeV
- Scanning line detector of 4 m with pixel size of $400 \mu\text{m}$.

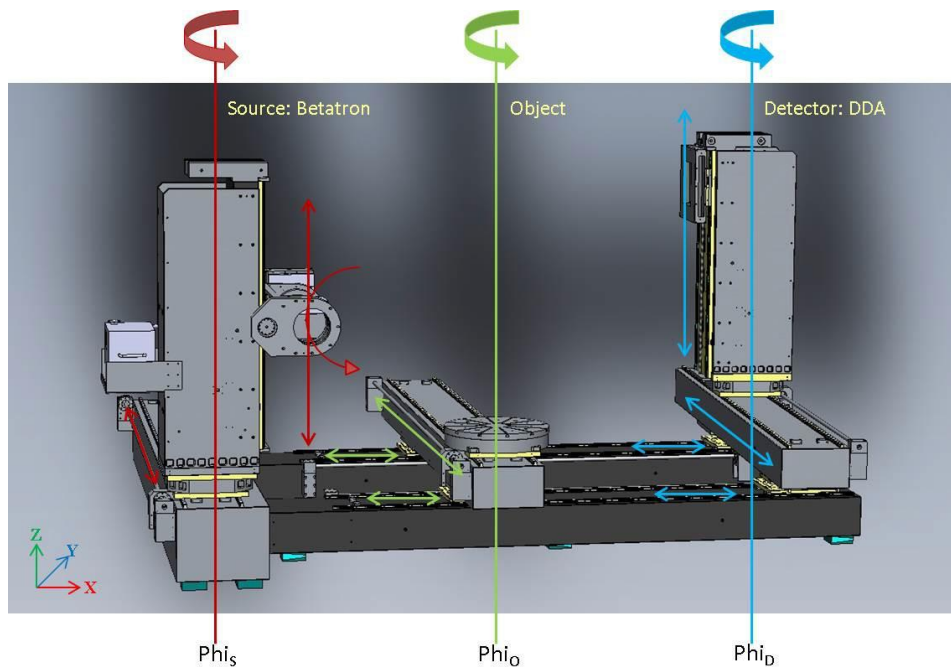


CT of cars after crash tests

- Evaluation of damages before and after crash
- Segmentation of damages at different parts
- Effective evaluation

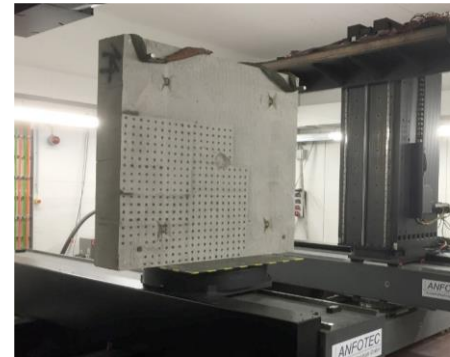
- **After Sept. 11th, 2001:** Evaluation of critical infrastructure required
- Measurement of materials properties with large testing machines. (e.g. Servo-Hydraulic 1000 kN Impact-Test device) and numeric Modelling
- > **New evaluation** of critical infrastructure





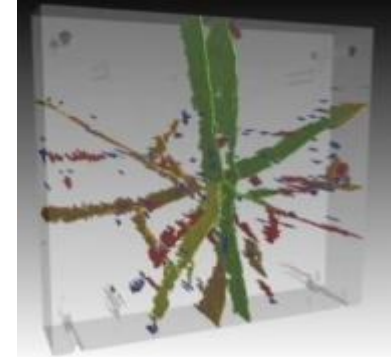
Computed Laminography at BAM, Germany

- CT of large objects with scanning DDA of $2 \times 2 \times 2 \text{ m}^3$
- 13 axis on granite support
- Source: Betatron 7.5 MeV
- Scanning area DDA of 40 cm with pixel size of $200 \mu\text{m}$.



Concrete block

- Size: $1,5 \times 1,5 \times 0,3 \text{ m}^3$
- Weight: 1700 kg



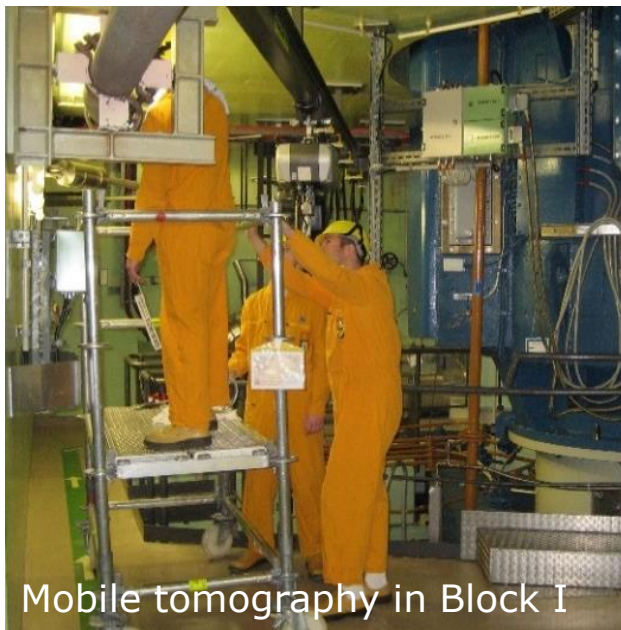
CT concrete blocks after heavy impact

- Evaluation of damages and after impact
- Segmentation of crack fields
- Evaluation in comparison to fracture mechanical modelling

Computed Tomography in Field

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COMPUTED TOMOGRAPHY MOBILE APPLICATIONS IN NUCLEAR POWER INDUSTRY



Mobile tomography in Block I



NPP Neckarwestheim, Germany



Mounting of scanner at pipe

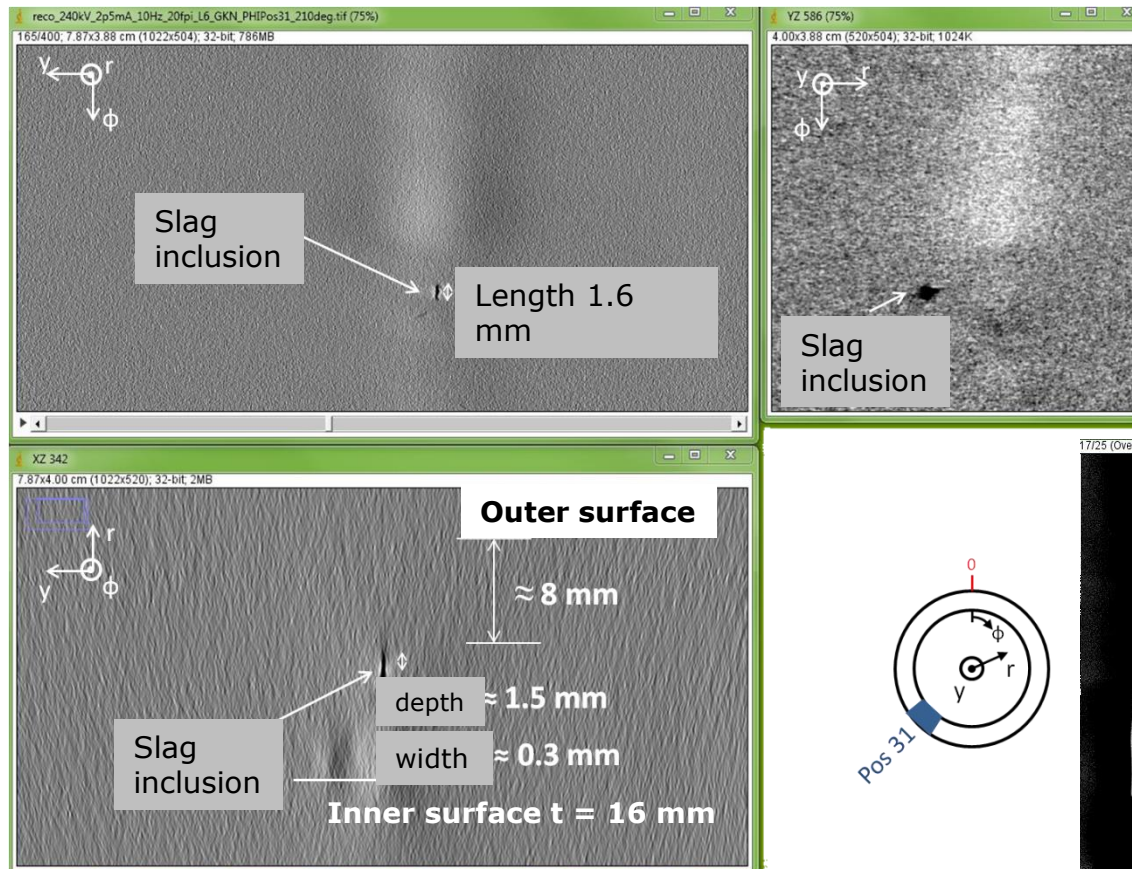
Mobile CT in Nuclear Power Plants and in Aircraft Industry

➤ *Planar-Tomography for analysis and better evaluation*



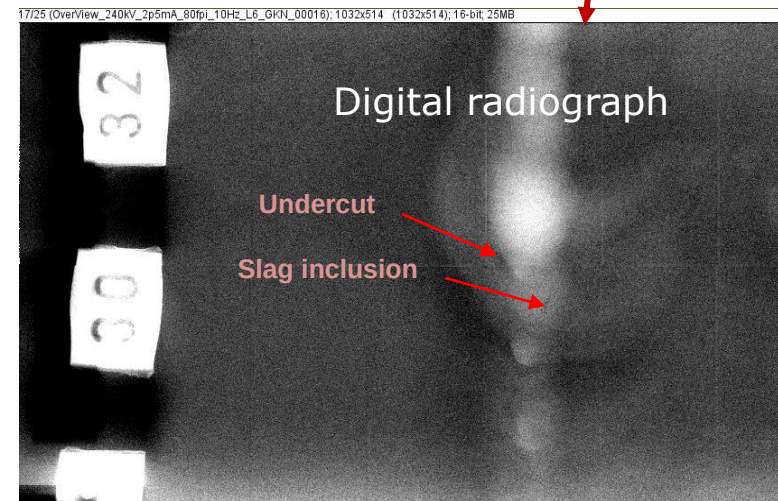
Field Test in a Nuclear Power Station

Test of TomoWELD-Scanner in NPP at secondary circuit pipe, Block I



Evaluation in three views permits the evaluation by different standards

KTA 3211.4 in service inspection
ISO 5817 cross section evaluation
DIN 25435-7: 2015 RT-practice



Indications permissible and in agreement with indications found after manufacturing

COMPUTED TOMOGRAPHY MOBILE APPLICATIONS IN AEROSPACE INDUSTRY

Laminographic Inspection of Large Carbon Fibre Composite Aircraft-Structures at Airbus

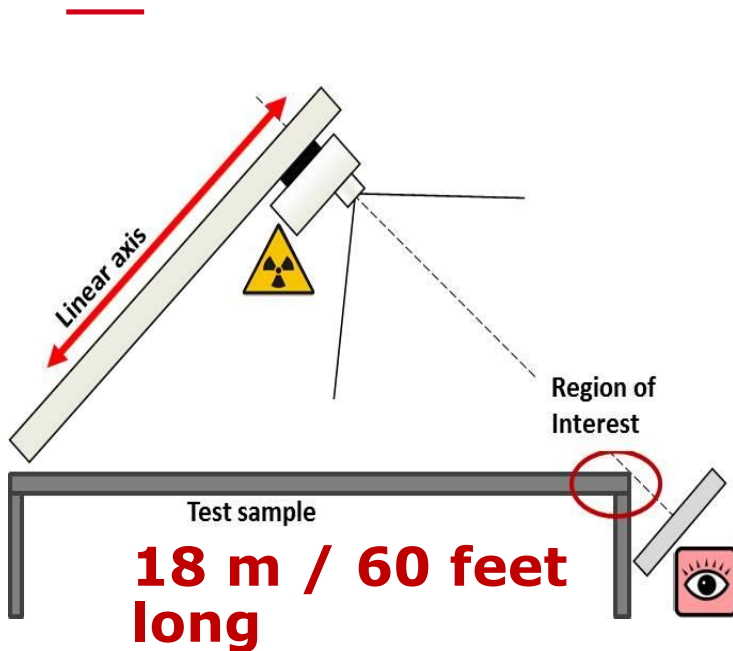
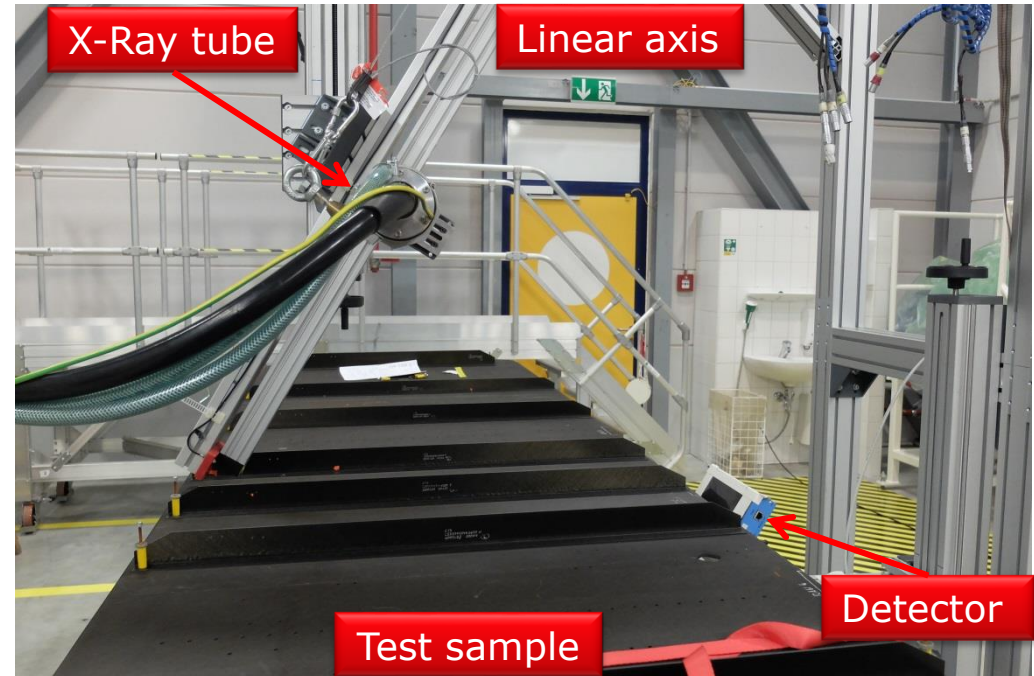
WCNDT 2016

Oliver BULINGER¹, Ulf SCHNARS¹, Daniel SCHULTING¹,
Bernhard REDMER², Martin TSCHAIKNER², Uwe EWERT²

¹ Airbus Operations GmbH,

² Bundesanstalt für Materialforschung
und -prüfung, Berlin, Germany

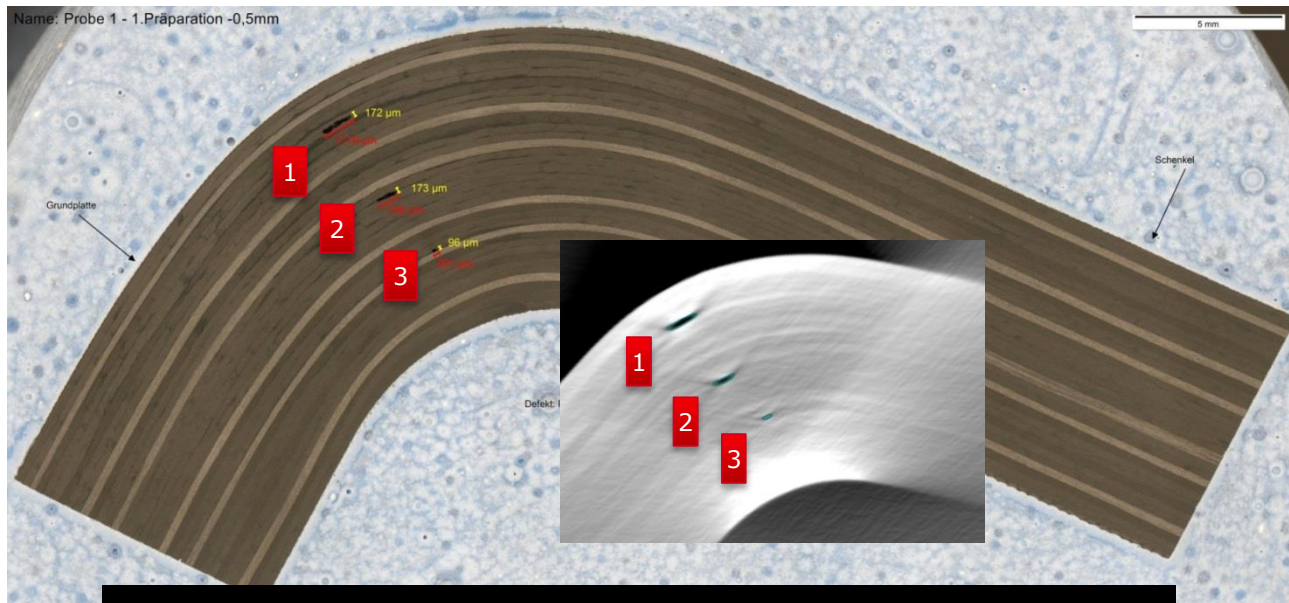
Laminographic 3D Imaging of Large CFRP Aircraft Parts



Main characteristic of laminography for this application:

- Able to inspect 20mm of CFRP in radius area
- Smallest detected defect: ca. 0,2-0,3 mm defect length

Comparison between Micro- Cross Sectioning and Laminogram



No.	Microcut Length	Microcut Depth	Planar-CT Length	Planar-CT Depth
1	1,119	1,396	1,31	1,38
2	0,749	4,428	0,88	4,36
3	0,201	6,73	0,35	6,53

Computed Tomography in Research

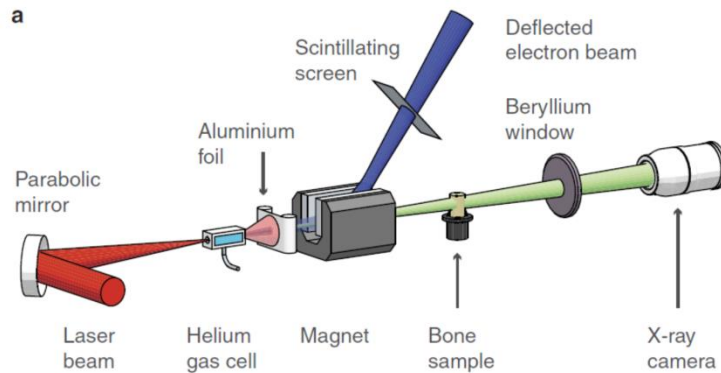
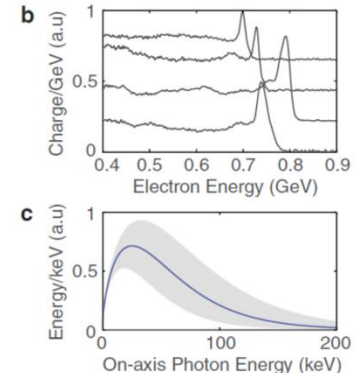
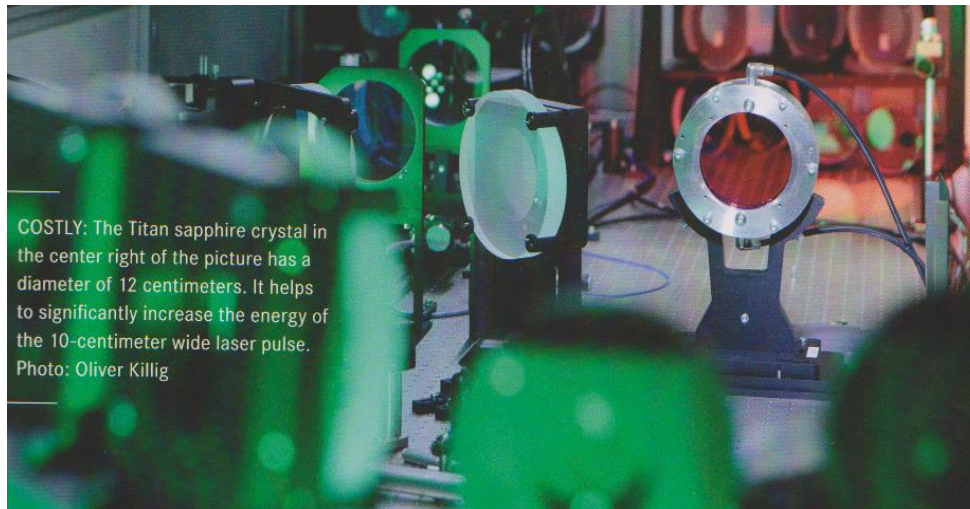
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MICRO RADIOGRAPHY AND CT

μ Focus X-Ray Generation by Laser Wakefield Acceleration of Electrons in a Plasma

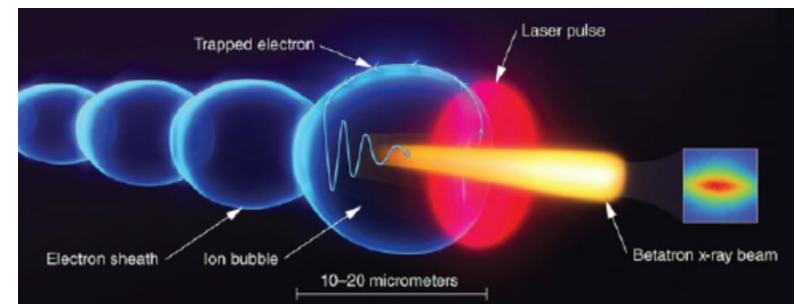
Principle: from Nature 2015
DOI:10.1038/srep123244

Laser: 30 fs Ti:Sa at 800 nm
40 J, Petawatt power range
HZDR "DRACO", over 2 rooms:



X-ray generation:

in He plasma by non-linear electron acceleration, potential for 50 μ m focus and MeV monochromatic energy

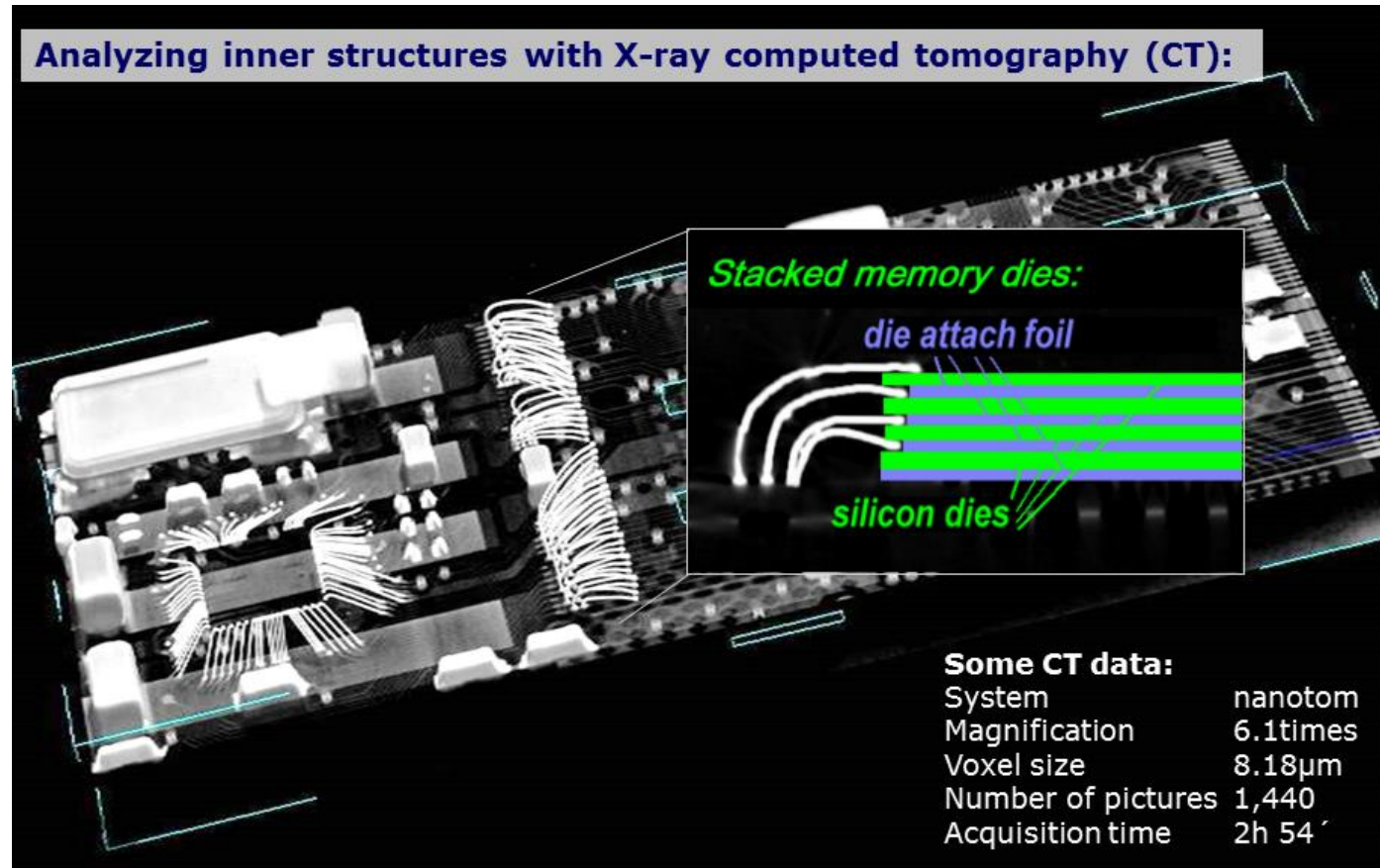


Micro CT of Electronic Components

Micro CT of electronic components

(USB drive)

The **mechanical integrity** is tested after impact, moisture and thermal exposition.

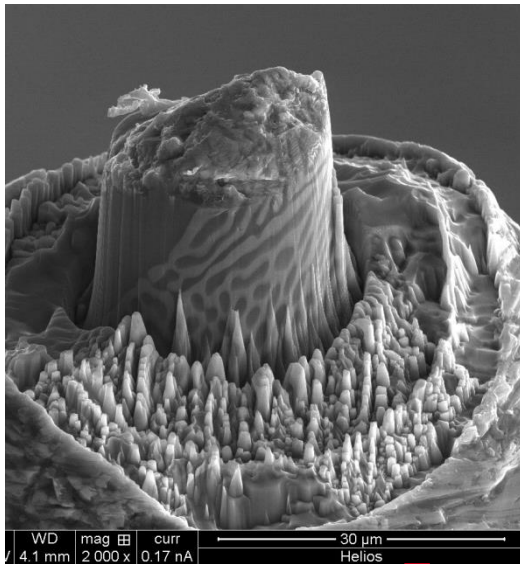


J. Gluch, M. Löffler, N. Meyendorf, M. Oppermann, M. Röllig, P. Sättler, K.-J. Wolter, E. Zschech, "Multi-scale Radiographic Applications in Microelectronic Industry", QNDE 2015, 26.-31.07.2015, Minneapolis (USA)

Application: Material analysis by Nano-CT, XRM-II

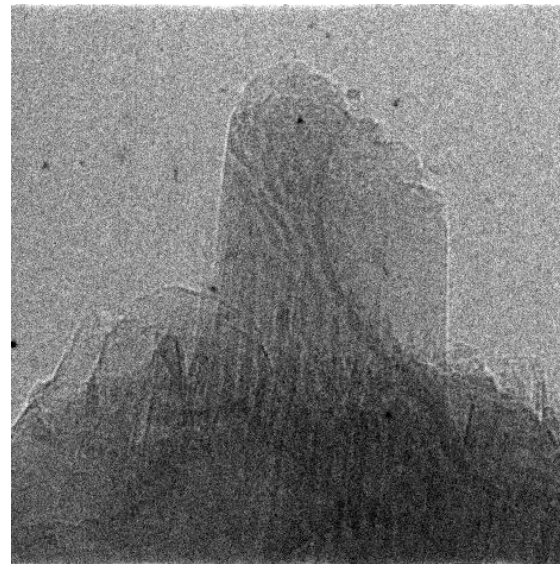
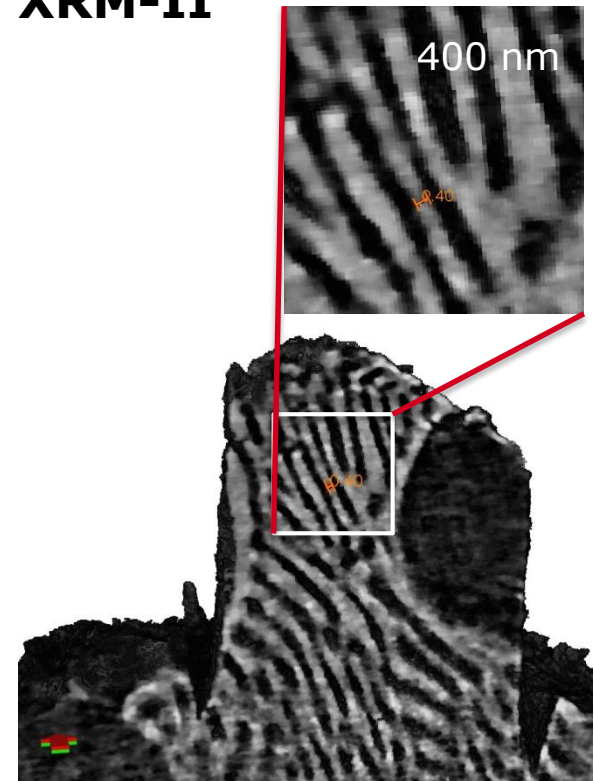
REM image

Preparation by focused ion beam



XRM II Nano image

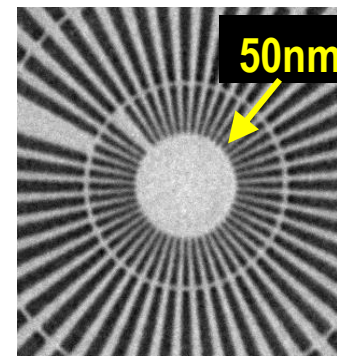
Recording of 200 projections



Example of a 24 μm AlCu29 alloy

3D reconstruction and visualization
of microstructures (eutectic
lamellas)

Nano Radiography and CT



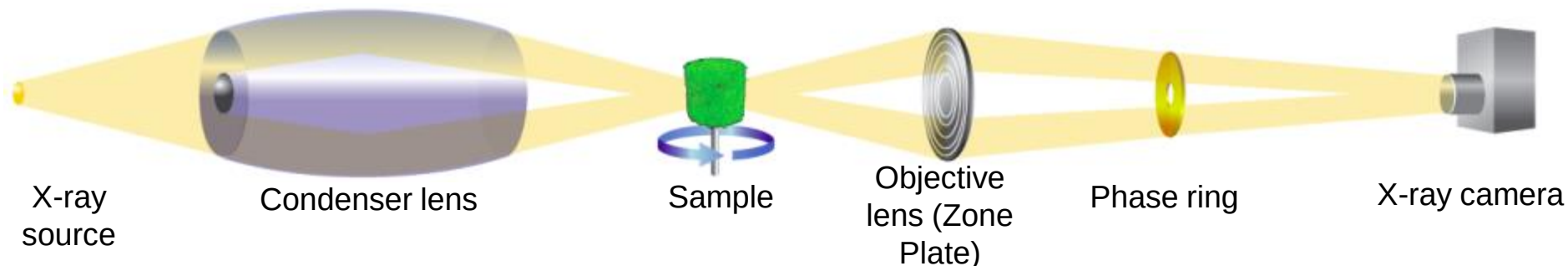
Nano Radiography and CT

- Can be achieved by combination of nano focus tubes and X-ray lenses and/or zone plates.
- Reports are available indicating an achieved **resolution of 30 nm**.
- The **sample preparation** for CT is a challenge.

Carl Zeiss X-ray Microscopy, Inc.

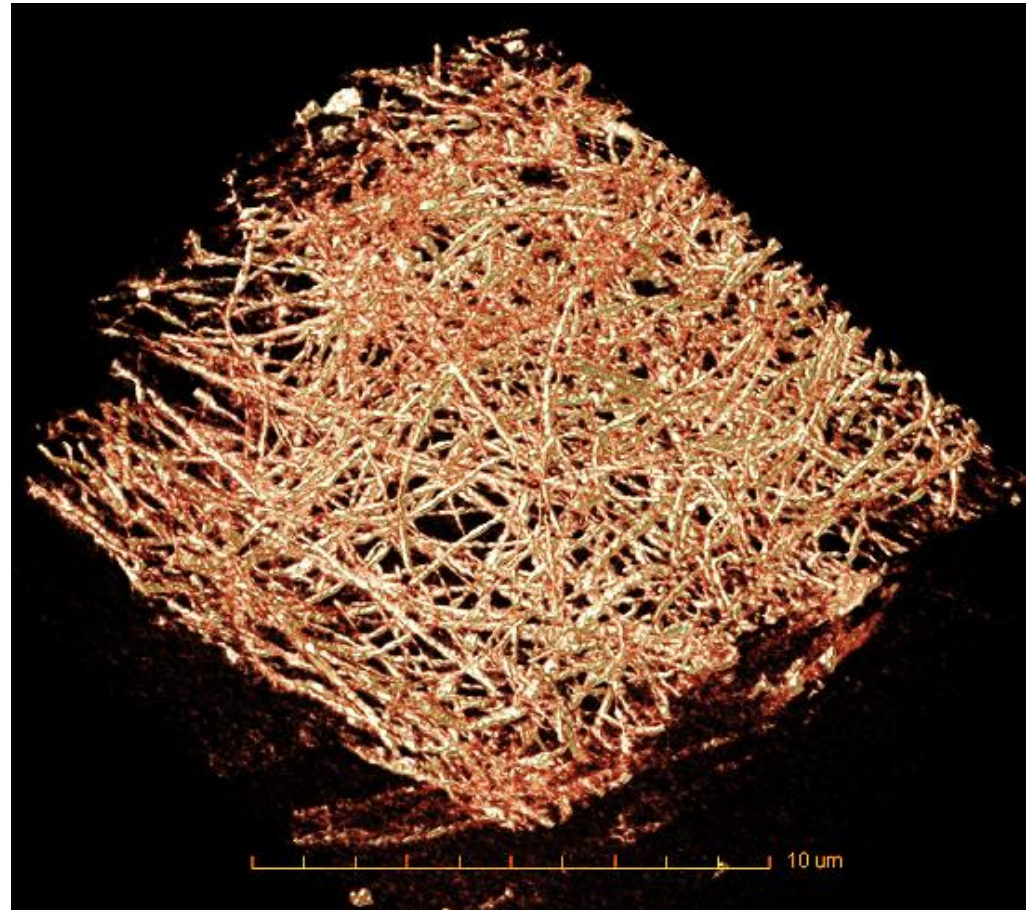
- **Xradia 810 Ultra: 5.4 keV**
- **Xradia 800 Ultra: 8.0 keV**

Mode	Mag	2D Res	Voxel	Field of View
Large Field of View	200X	150 nm	64 nm	65 μm x 65 μm
High Resolution	800X	50 nm	16 nm	16 μm x 16 μm



Polymer fibers in a
desalination
membrane, imaged
in phase contrast

Sample:
Industrial Technology
Research Institute, Taiwan

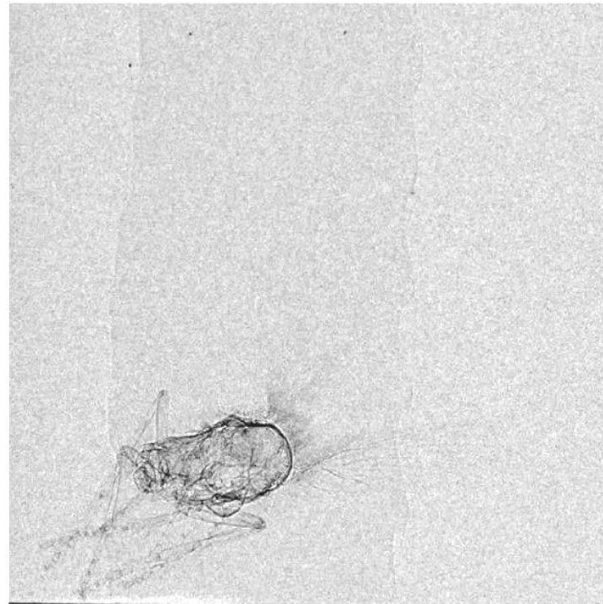
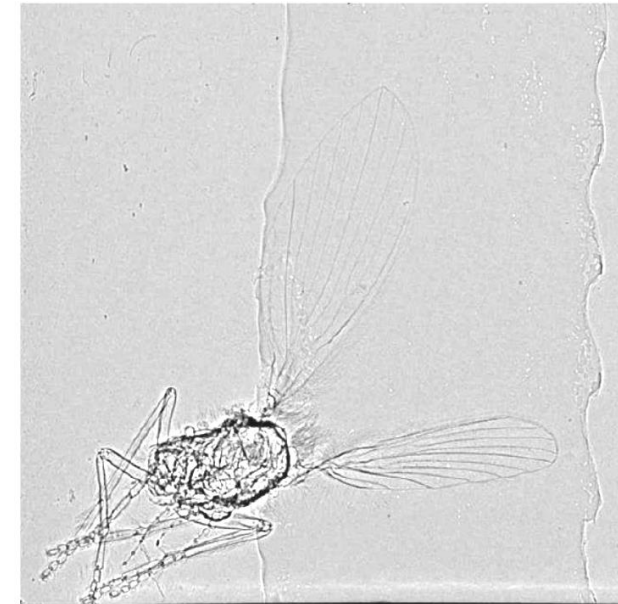


Phase contrast radiography at synchrotron

- Enhances the interface contrast generated by external (and internal) boundaries
- In the lab scale, it is performed with rather small focal spot size and high detector resolution and large sample-detector distances

Example: Phase contrast radiography at synchrotron

Radiographs of a common fruit fly (*drosophila melanogaster*), at two different sample-detector distances of 40 mm (left) and 1755 mm (right).

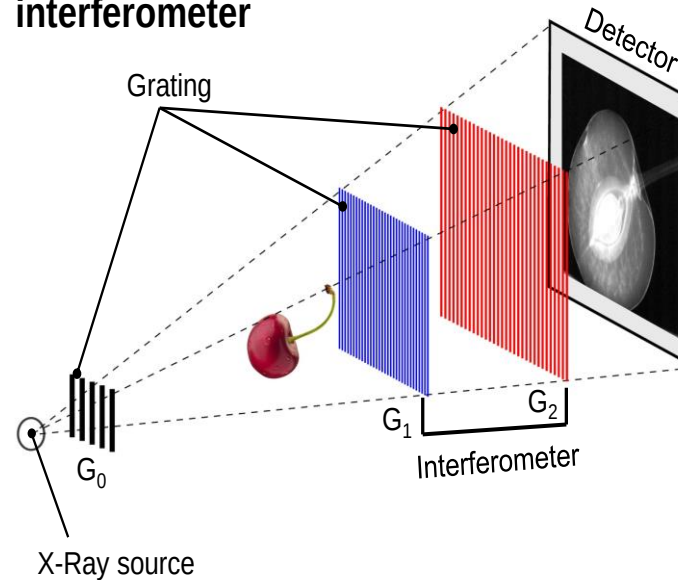


A. Kupsch, B. Müller, M. Hentschel, A. Lange, V. Trappe, R. Laquai, Y. Shashev, S. Evsevlev, G. Bruno, "Progress Survey of X-Ray Refraction Imaging Techniques", 19th World Conference on Non-Destructive Testing (WCNDT 2016), 13-17 June 2016 in Munich,

The Talbot-Lau interferometer

- consists of three X-ray transmission gratings (G_0 , G_1 and G_2)
- a digital X-ray detector
- an X-ray source with a large focal spot.
- Dark field images (DFI) provide enhanced contrast of fine details as cracks and surfaces of internal structures similar to synchrotron phase contrast.
- The technique is in competition with the lens or Fresnel phase plate based nm radiography

Talbot-Lau grating interferometer



J. Kastner, BAM Workshop, 2016, adaptiert von: V. Revol et al. / Conf. on Industrial Computed Tomography (2014) 45-51

V. Revol, C. Kottler, R. Kaufmann, I. Jerjen, T. Lüthi et al., AIP Conf. Proc. 1236, 221 (2010); doi: 10.1063/1.3426117, <http://dx.doi.org/10.1063/1.3426117>.

Talbot Lau Images

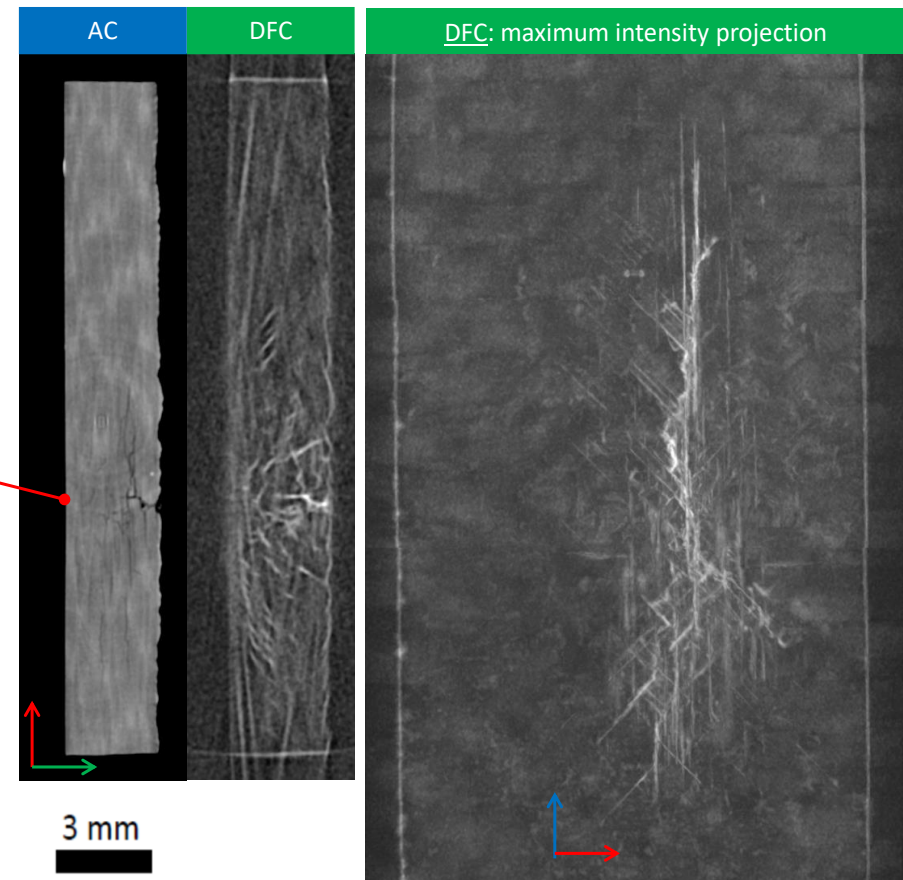
TLGI-XCT: Impact CFRP 10 J

Fiber reinforced polymer after impact test

- Measured with Talbot-Lau interferometer
- consists of three X-ray
- The absorption image provides good information about the coarse crack structure.
- The dark field image resolves fine cracks which are open even below the pixel size limit.

Sascha SENCK, Dietmar SALABERGER, Christian GUSENBAUER, Bernhard PLANK, Guruprasad RAO, Johann KASTNER, University of Applied Sciences Upper Austria, Wels, Austria, WCNDT, Munich, 2016, Germany.

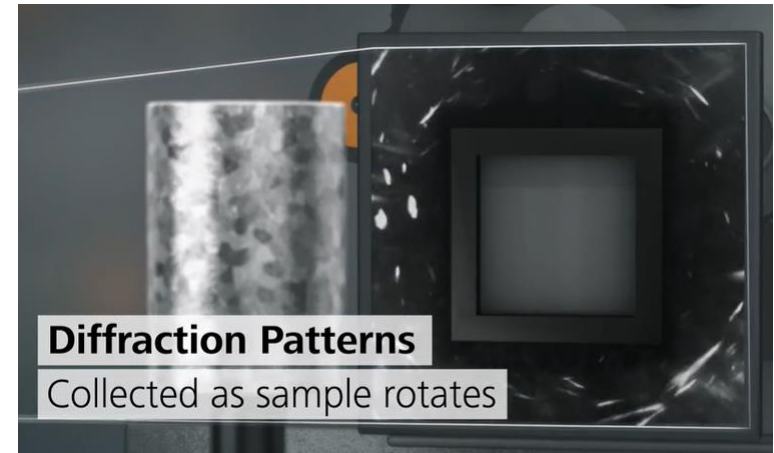
35 kV, Al 0.25 mm, (22.8 μm)³, 720 proj.



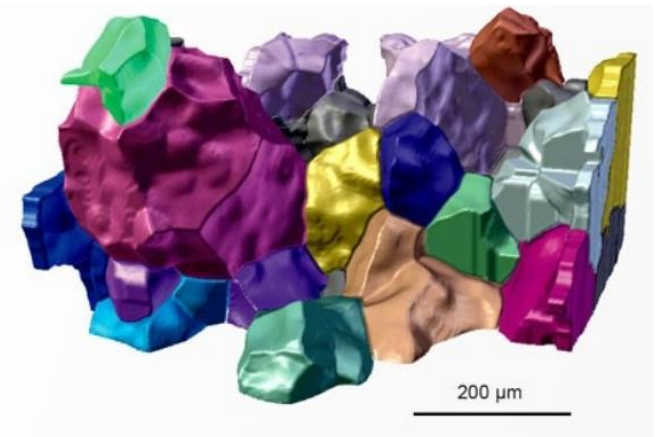
Diffraction Contrast Tomography

<https://zeiss.wistia.com/medias/76fk3rx90o>

- Combination of micro CT (submicron) and spatially resolved crystal structure analysis
- Suitable for CT of poly crystalline objects, as metals and alloys
- Visualization of 3D crystallographic grain orientation
- Investigations for materials science



3D grain mapping



**ZEISS Xradia 520 Versa –
Röntgen-Imaging im
Submikrometerbereich**

- Replacement of film radiography by digital techniques (RT 2.0) in NDT requires careful selection of suitable digital detectors.
- DDAs provide after careful calibration a significantly higher contrast sensitivity than film radiography and computed radiography.
- Scatter and back scatter radiography with different optics are applied for inspection of CFRP with single sided access.
- Computed tomography is entering serial production for flaw detection and dimensional measurements.
- Mobile laminography is applied successfully for non destructive sectioning of welded pipes and CFRP structures of airplanes and provides the dimensions and shape of the indications.
- Computed Tomography can be applied for testing of microstructures and large objects as complete cars.
- Microstructure images can be enhanced by phase contrast, Talbot Lau dark field contrast and diffraction contrast tomography.

I would like to thank the following researchers of BAM for their contributions and valuable discussions:

- B. Redmer
- U. Zscherpel
- G.-R. Jaenisch
- C. Bellon
- D. Schumacher
- A. Kupsch
- F. Wieder
- S. Kolkoori
- N. Wrobel
- S. Hohendorf
- M. Grunwald

ERD, June 13th, 2018

END Questions



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