Applications and Methods with High Energy CT Systems

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Abstract
The increase of Computed Tomography (CT) as an applicable method for non-destructive testing (NDT) and metrology awakes interest on expanding the application fields, on which CT was rarely applied in the past due to their requirements on the imaging system. Especially the classical X-ray generation techniques based on bipolar high voltage (HV) supplies restricted the application fields of CT to typical material penetration lengths of only a few cm of steel. Even with accelerator technology that offers a suitable way to overcome these restrictions only the 2D radioscopy technique found a widespread application.
Beside the generation and detection of photons in the MeV range itself, the achievable image quality is limited using standard detectors due to the dominating absorption effect of Compton scattering at high energies. Especially for CT reconstruction purposes these effects have to be considered on the development path from classical 2D radioscopy to 3D imaging. Most High Energy CT applications are therefore based on line detectors shielding scattered radiation to a maximum with an increase in imaging quality but with time consuming large volume scan capabilities.
In this contribution we present the High-Energy X-ray Imaging facility at the Fraunhofer Development Centre for X-ray Technology in Fürth with regards to the potential of the CT-system stage according to metrological and other application capabilities and to the conceptual tasks due to the construction and development of the CT system until now and for the future stages. Results of the investigation on achievable scan quality on different objects are presented compared to state of the art 450 kV X-ray systems.

Keywords: High energy Computed tomography, security, sea-freight inspection, XXL-CT

1. High Energy X-ray facility

1.1 X-ray chamber

The high energy application requires special shielding properties. Besides the high energy photons themselves where the dominant absorption effect is the Compton scattering resulting in the need of very thick walls, new effects compared to classical X-rays have to be considered to full-fill the safety requirements. The activation of irradiated matter and the production of ozone due to the interaction of accelerated electrons in air are typical high energy effects that can be limited to an acceptable level by limiting the energy to 9 MeV. Otherwise a significantly higher safety class has to be considered affecting the demands on safety.
The very large scale of the X-ray chamber with inner dimensions of 20 m x 20 m x 16 m and up to 3 m thick walls allowing for CT application on very large objects like complete cars or large structural components resulted in a challenging task for the engineering and construction of the chamber. To enable the construction of that large chamber in a sufficient time a patented method based on two precast concrete walls and a dense filler material was applied [1]. Compared to the classical method which uses armored concrete with X-ray absorbing additives no long settling times are needed and even locally variable absorption properties can be achieved by varying the filler material and its density.

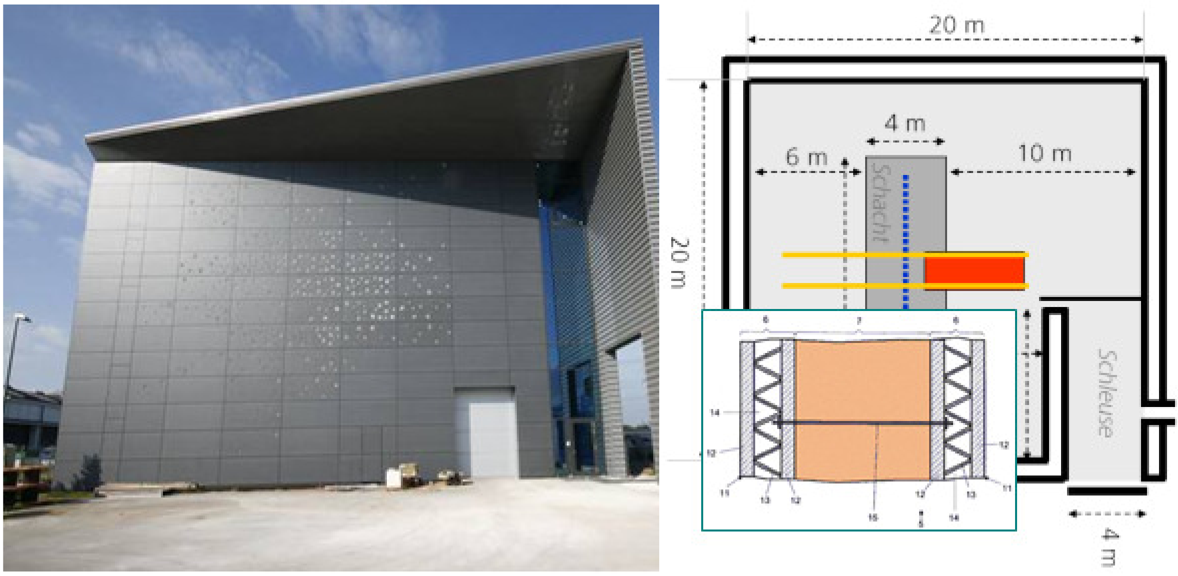

Figure 1: High Energy X-ray facility (left). Schematic drawing of the X-ray chamber with double layered walls and dimensions (right).

1.2 High Energy source LINAC

At the Fraunhofer EZRT a Siemens Linear Accelerator (SILAC) has been installed providing photon energies from 4 – 9 MeV at up to 1 kW of average power. Unlike classical X-ray sources the initial electrons emitted from an electron gun are accelerated by a HF-modulation produced by a magnetron through a cascade of cavities leading to a stepwise acceleration of

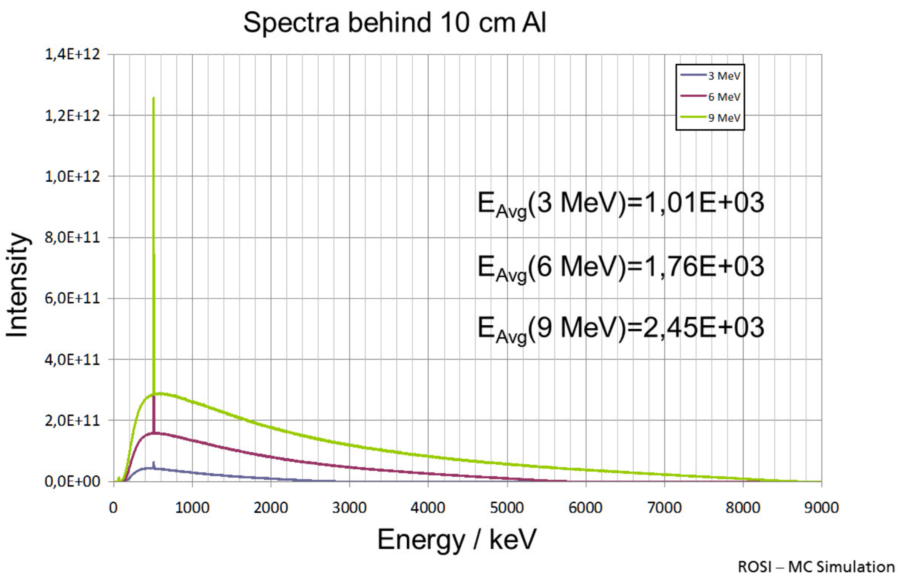

Figure 2: High-Energy X-ray spectra at 3, 6 and 9 MVp. The average energy remains in the region between 1 and 2.4 MeV.

the electrons to a certain level. The X-ray production is based on a tungsten anode leading to the typical "Bremsstrahlung" spectrum with a maximum energy of up to 9 MeV that is pre-defined by the physical length of the accelerator (compare **Fehler! Verweisquelle konnte nicht gefunden werden.**). Due to the oscillation property of the acceleration process the X-ray beam appears pulsed which has to be considered in the detection process.

1.3 Interaction of high energy X-rays

Contrary to lower X-ray energies (< 450 keV) the Photoelectric Effect is nearly insignificant at high energies above 1 MeV as shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**. For low dense as for high dense materials the Compton scattering is the most dominant absorption effect leading to a high linearity of signal independent of any material combination. Due to this physical property of X-ray photons above 1 MeV the imaging quality of the radiographs is mainly related to the density and penetration length inside the object. The resulting reconstruction gains high signal homogeneity and much lower beam hardening artifacts compared to lower X-ray energy even in regions with mixed materials. The low energy level mentioned in this contribution corresponds to the conventional X-ray sources in the field of ndt with up to 450 keV. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows two CT cross-sections acquired at low energy (left) and at high energy (right) of a CFRP panel with iron inlays for assembly purpose. The influence of the higher non-linearity of absorption in the low energy scan is clearly visible at the level of the cylindrical inlays. The grey value in the afflicted area is not corresponding to the real material, contrary to the high energy scan shown right.

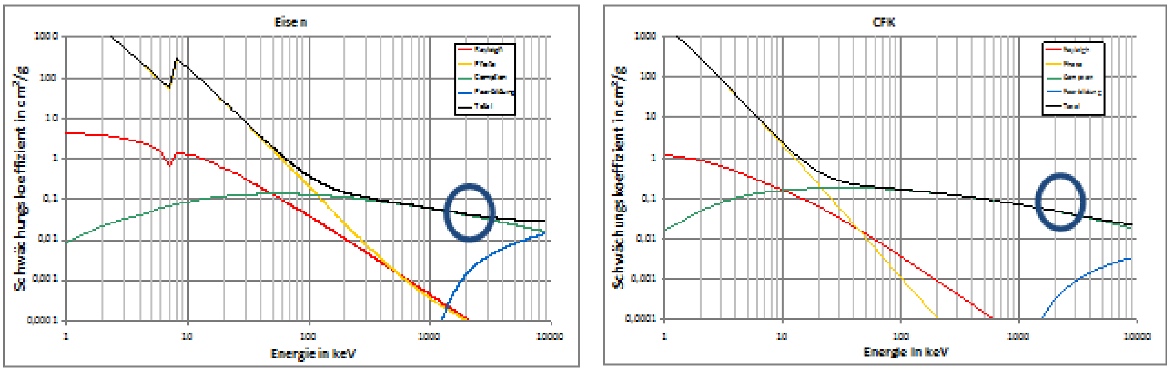

Figure 3: Absorption mechanisms dependent on X-ray energy for different materials. Left: Iron (Fe), Right: CFRP. The marked position represents the average energy of the high energy X-ray spectrum produced by 9 MeV SILAC source.

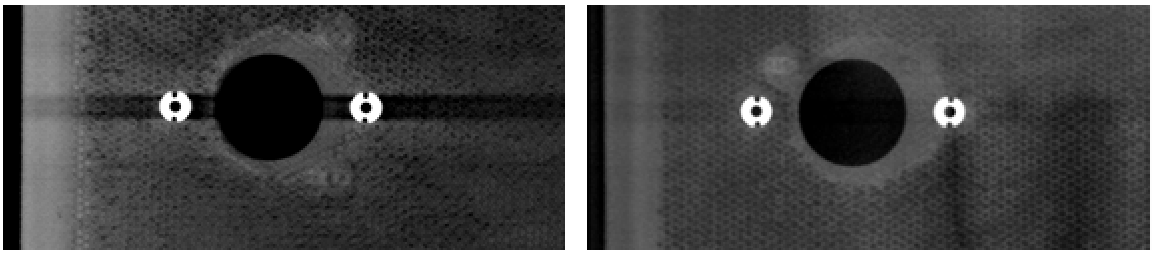

Figure 4: Comparison of a low energy scan at 450 keV(left) to a high energy scan at 9 MeV(right). The iron inlays caused metal artifacts due to the predominant photo effect with radiation of 450 keV. These artifacts do not occur in the high energy scan.

Beside this linearity benefits, the scattering resulting from the Compton Effect decreases the image quality especially in terms of cone beam CT. Due to the uncollimated X-ray beam the amount of scattered radiation leads to a reduction of the contrast and signal to noise ratio (SNR). Thus fan beam scan geometry vertically collimated to a minimum is preferable for high energy X-ray imaging, especially for applications at low resulting signals like massive iron parts shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

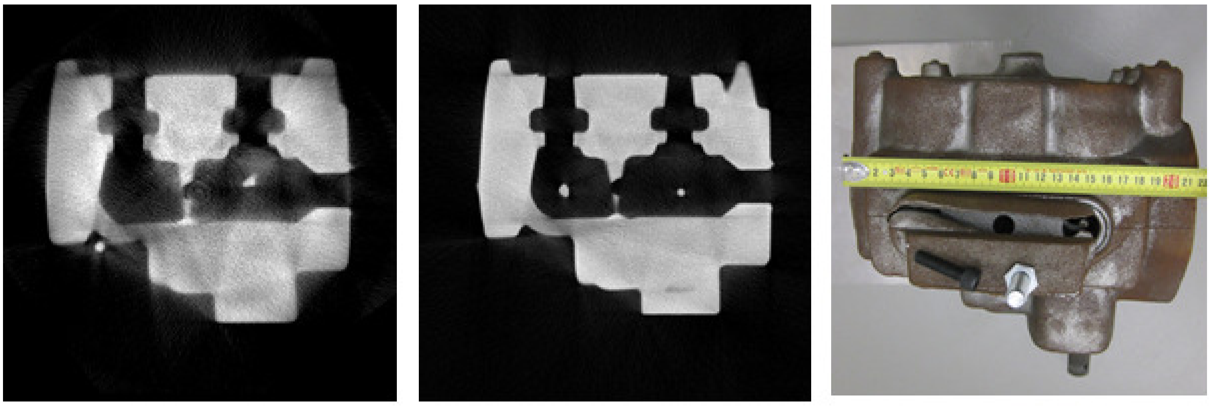

Figure 5: Comparison of a cone beam scan using a Flat Panel Detector (left) and a fan beam scan using a linear detector array (center) at 9 MeV. Photograph of the original iron casting part (right).

2. XXL-CT project

2.1 Realized system stages

In the beginning of 2011 after the final construction and SILAC installation process the first evaluation stage has been set up [2]. This phase was aimed to investigate the high energy X-ray physics and its capabilities for new industrial CT applications. For this purposes a first setup based on standard Flat Panel Detectors (FPDs) has been realized providing CT capability for highly dense objects. Large scale objects were measured with a Perkin Elmer RID 1640 with a pixel pitch of 400 µm. For smaller objects a new XRD 820 AO has been used providing a higher resolution (200 µm).

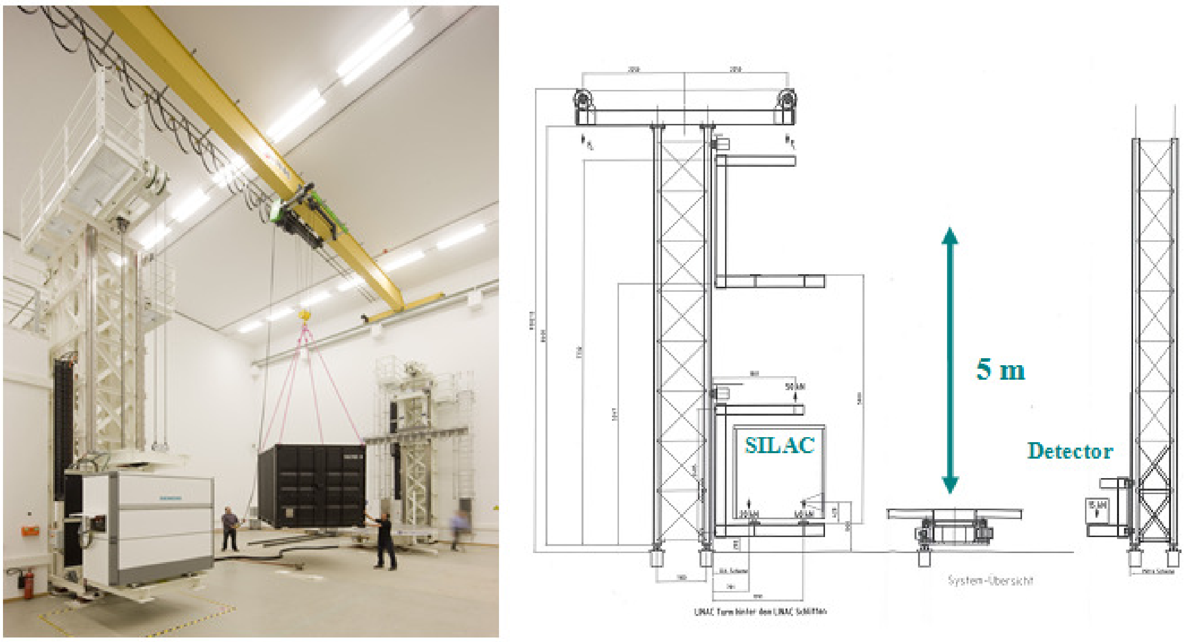

Figure 6: Photograph of the realized scanner Stage 1 (left). Drawing of the stage 1 setup with the SILAC (3 t) and the detector (1 t) providing a scan area of 3.2 x 5 m (right).

Due to the limited field of view of commonly available FPDs and the strong influence of scattering on image quality at high photon energies line detectors have been installed with different characteristics. The development stage 1 is currently equipped with a 4 m long line detector array with 10.000 pixels optimized for high energy photons. It provides CT capability based on a rotating specimen stage taking up to 10 t of weight capturing a cylindrical volume of a diameter of 3.2 m and a height of up to 5 m. Due to the large field of view and a relatively small X-ray fan-beam source a large source detector distance of approx. 8 m have been applied. The high requirements on precision of the manipulation system for a scan volume of that size were challenging for the manufacturer's engineering team. The full operation of stage 1 started in the beginning of 2013.

2.2 Future system stage 2

The final development stage 2 is aimed to result in a rotating gantry system allowing for long objects like e.g. cars or sea-fright containers to be scanned in their native orientation. For this purpose the imaging system will be rotated vertically around the specimen.

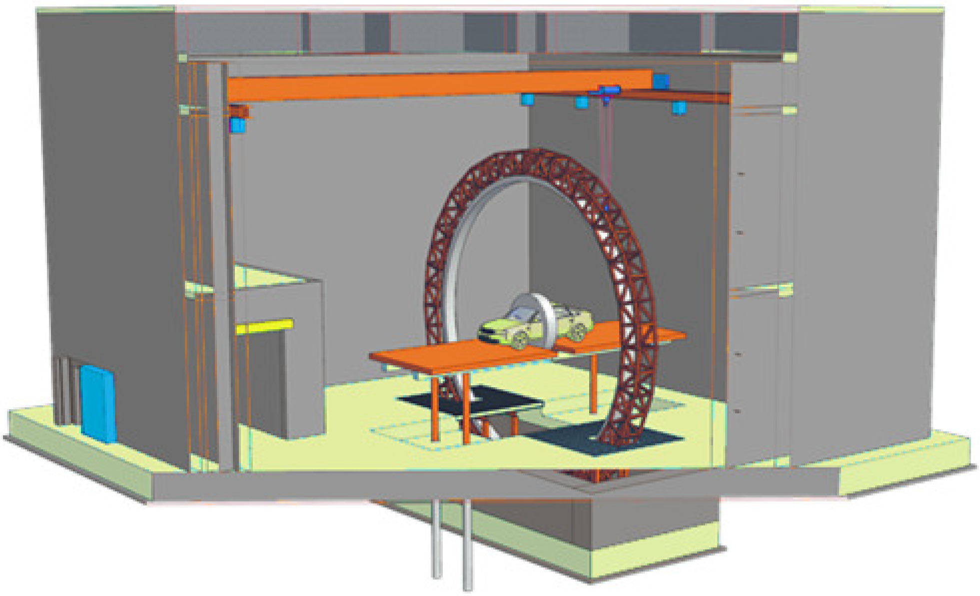

Figure 7: 3D drawing of the final development stage planned for the CT-scan of long objects in their native orientation.

3. Scan capabilities

3.1 Large scale radioscopy

The huge size of the scanner and the relatively high resolution of 0.4 mm provide unique capabilities for radioscopic imaging of fully assembled objects like complete motorcycles or even heavy construction machines. Due to the simple 2D imaging technique and the collimated fan beam the quality of the scans is all over excellent, without disturbing artifacts. Even in regions of high absorption like within the balance weight of the digger shown in **Fehler! Verweisquelle konnte nicht gefunden werden.** signal still remains. The scanning times for high quality radioscopy imaging are in the region of 10 minutes for 1.5 m of height.

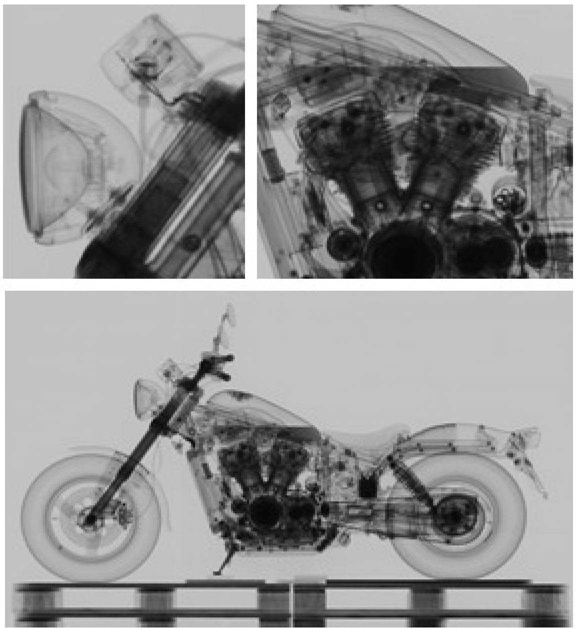

Figure 8: Radioscopy of large machines. Digger with approx. 3 t weight (left), Motorcycle with low fuel (right). Even in the regions of high absorbing materials details of the interior are recognizable.

3.2 Large scale computed tomography

The high energy above 1 MeV provides unique imaging capability for the inspection of multi-material objects. In **Fehler! Verweisquelle konnte nicht gefunden werden.** a cross section of a traditional television tube is shown, scanned with 3000 rotation angles. The high absorbing lead-glass based tube doesn't affect the image quality of the low absorbing surrounding material. Even within a 20 ft steel sea-fright container shown in **Fehler! Verweisquelle konnte nicht gefunden werden.** the plastic surrounding is visible in the cross-section as low absorbing materials like charcoal. Due to the task of a relatively short scan time the scan was performed with just 400 angles resulting in a approx. scan time of 4 h for 1.5 m scan height.

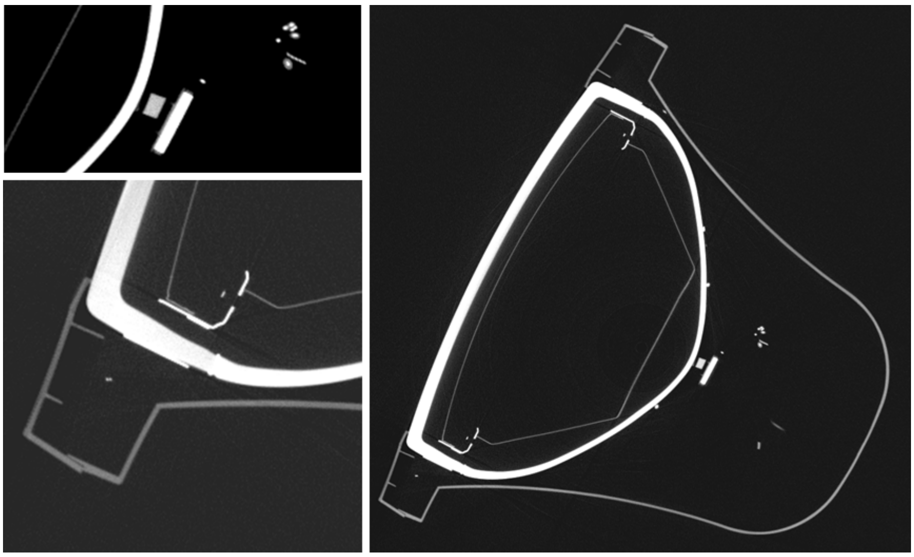

Figure 9: Cross-section of a television tube scanned with 9 MeV. The tube made of lead-glass gives a good contrast to the remaining materials in the TV. Differently than with lower energy scans, image quality is not affected by the high-absorbing material.

The standard Feldkamp reconstruction applied leads to streak artifacts due to the undersampled angular scan range. Nevertheless, finest details and low contrasts are visible showing potential for further development of reconstruction in terms of less angular steps and shorter scan time at high quality.

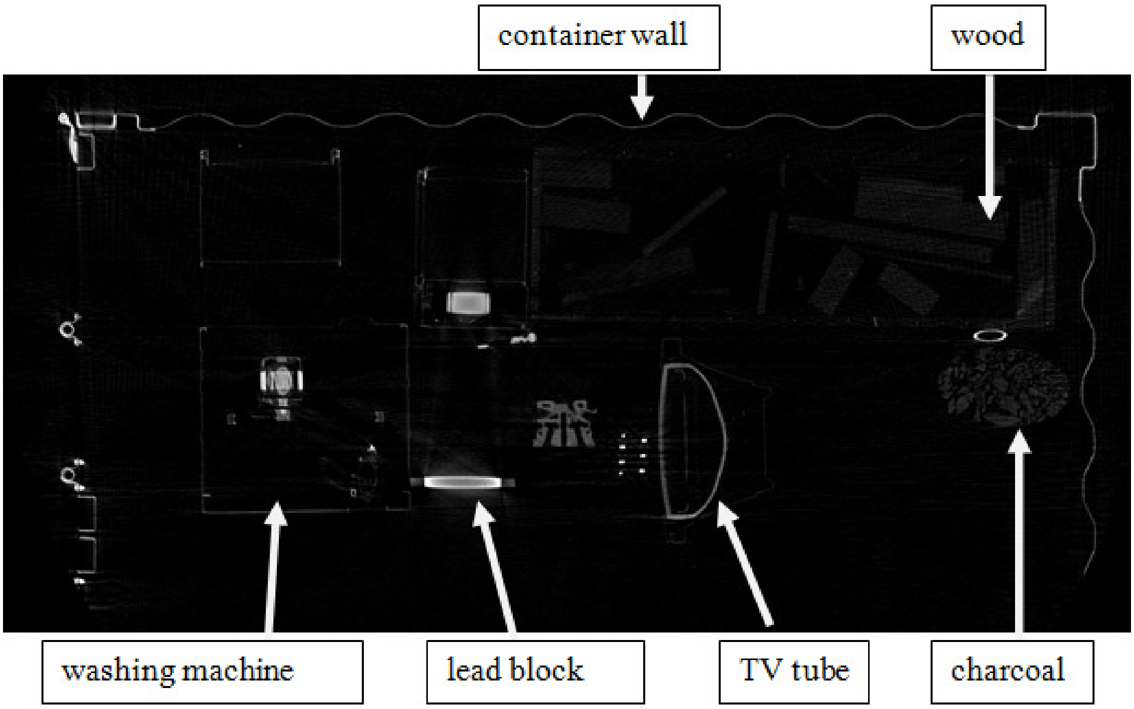

Figure 10: Feldkamp reconstructed cross section of a loaded 20 ft sea-fright cargo container with differently absorbing materials.

Besides the imaging of complex objects with critical material combinations or cargo scanning another focus of research is the field of NDT in terms of metrology. In order to achieve reliable results and accurate dimensions the quality of the scan has to be enhanced by a longer scan time. Figure 11 shows a variance analysis between CAD and CT data of a whole rear body of a car. The deviations are color coded to visualize the aberrations easily. Due to transportation and long term storage of the part at the facility especially at the edges larger aberrations appeared. Beside the dimensional measurement different types of steel and other materials can be distinguished precisely in the 3D volume. Even the different types of connections like welds and rivet joints can be analyzed at a resolution of 400 microns.

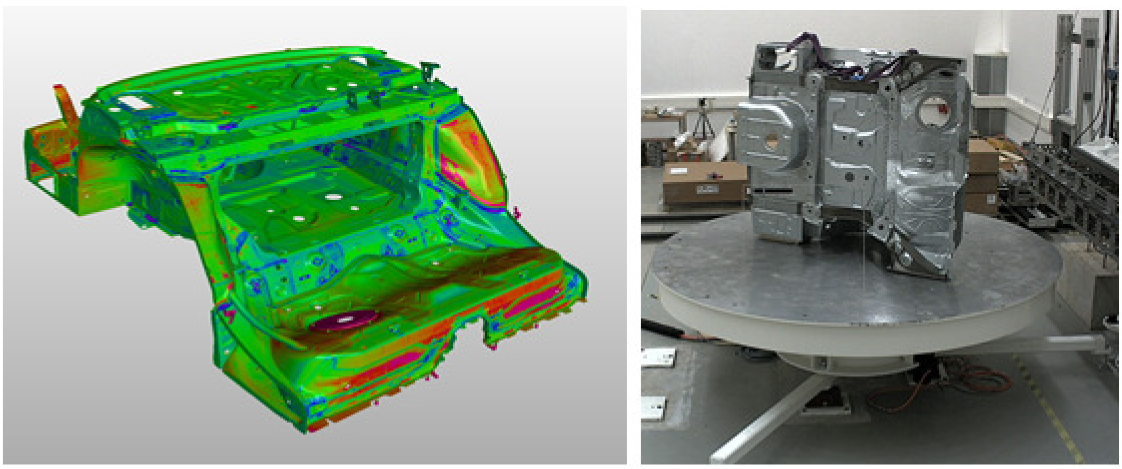

Figure 11: Body rear end of a car. The image quality of the scan allows for a metrological analysis, such as a variance analysis (left). A photograph of the object can be seen on the right.

4. Summary and conclusion

Until today the high energy X-ray inspection is just applied on high specialized tasks e.g. radiographic weld inspection. With the newest results of the XXL-CT facility at Fraunhofer EZRT the potential of that type of inspection is demonstrated. The results proof that the high energy X-ray and especially CT is not only suitable for high dense materials but also for low absorbing structures like large CFRP panels commonly used in the aircraft industry. The well-established rule by thumb high kV low contrast cannot persist in the high energy application due to the overwhelming domination of Compton Effect as absorption mechanism. On the other hand a high optimization of the imaging system for different tasks is required in order to achieve adequate results. The Fraunhofer EZRT research is open to the large variety of applications, focussing mainly on the minimization of scattered radiation influence and minimization of scan time by reducing the angular steps reconstruction**.** Unlike conventional radiation with energies up to 450 keV, apart from pure radiation shielding further effects such as activation and ozone production have to be considered.

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