# Spectral CT in the world of electronics: moving toward failure free devices

## Introduction

Printed circuit boards (PCBs) are at the heart of numerous advancements in electronic science and technology, and as such they are expected to work flawlessly and as designed. Errors, no matter how seemingly minor, cannot be tolerated because PCBs are used in many highly technological applications, such as those supporting aerospace, biotechnology, automotive, military and many more industries. There exist many PCB testing protocols, such as in-circuit testing or bare board testing; however, these tests may not detect performance issues that are outside of their testing ranges. So, these PCBs are most often subject to additional optical and internal validation. One technique for visualizing inside PCB materials is X-ray imaging, which can be used to build an understanding of the material's internal structure and any possible defects. Examples of defects that may occur are micro-cracks, component misalignment, voids and an excess of solder.

As PCBs become more densely populated, with hundreds of smaller components and multiple layers of material mixes, a single radiography approach has limitations. In this study, we will highlight the use of the full X-ray energy spectrum by using spectral radiography to discern the individual materials present. With this approach, components in a mixed or multi-layered electronic device become visible.

Conventional and spectral x-ray imaging is, of course, not limited to the analysis of PCBs. As an example, a multimodal conventional and spectral CT study was performed on a smart ring wearable electronic device. Wearable electronic devices are becoming increasingly popular and are packed with different sensors to measure temperature, heart rate, blood oxygen or movement. In addition, these devices need components such as batteries, antennas, or gyroscopes to monitor and transmit data about the person wearing them. Given the unconventional shape of some of these components, it is crucial to assess and understand the internal connections once they are fitted into the final device.

In this application note, we will demonstrate how in the fast-growing market of electronics, conventional micro-CT in combination with spectral CT help pave the way toward failure free electronic devices.

## Materials and methods

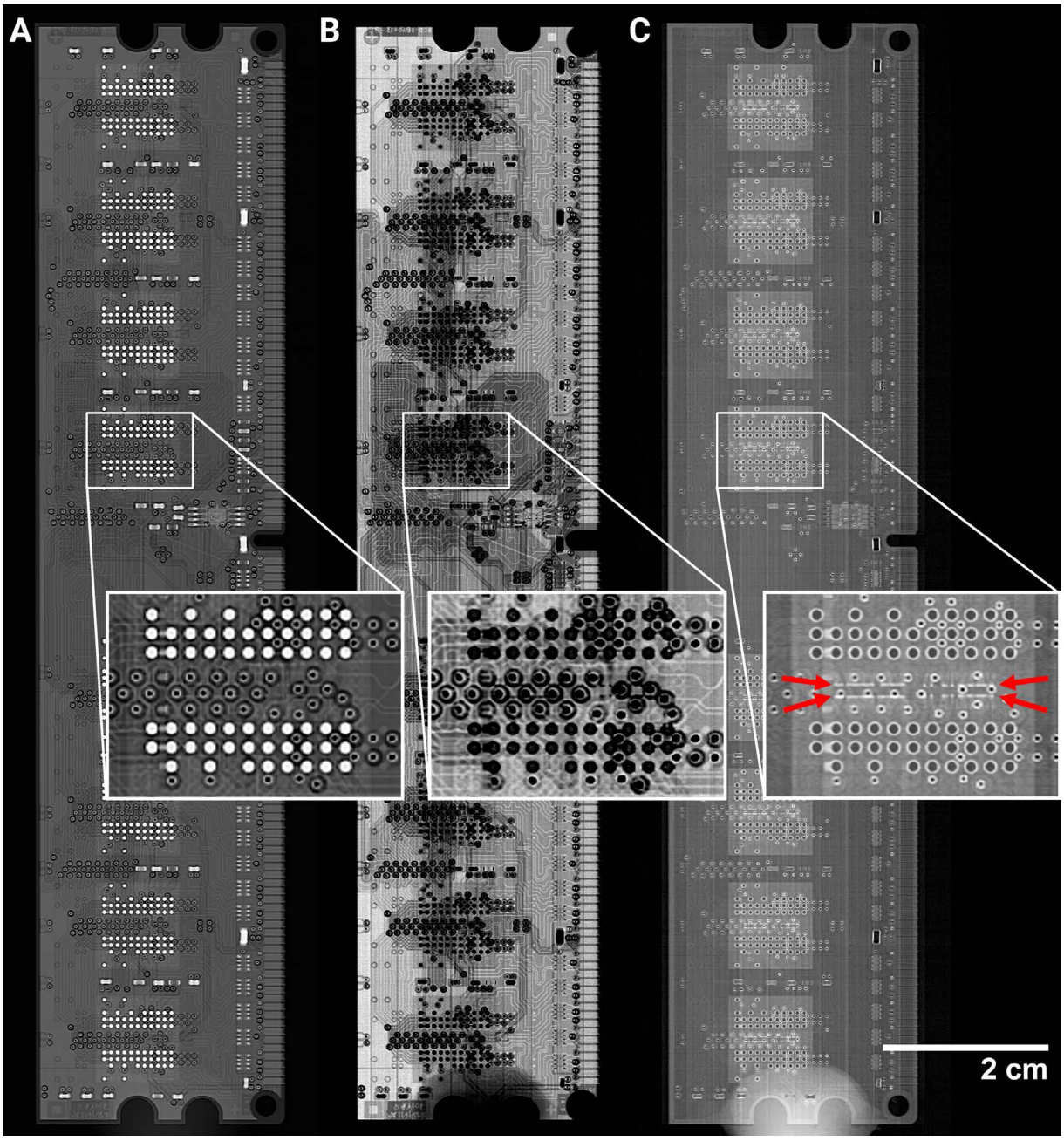
A dual In-Line Memory Module (DIMM), often referred to as a RAM stick or RAM module has a similar structure to a PCB and thus was chosen for demonstrating the capabilities of spectral radiography. The full sample was investigated at 160 kV accelerating voltage, 20 W target power and a resolution of 50 µm, resulting in an image of 760 x 2700 pixels. Due to the complexity of the DIMM, it is very hard to distinguish individual components in the sample, as overlapping components hinder the visibility of underlying structures. While micro-CT offers the possibility to investigate this in 3D, it is not always possible or desired due to the time required or other constraints. Using spectral radiography, it is possible to resolve each material layer separately without resorting to a full 3D CT scan. By harnessing the multi-energy information from a single spectral radiography acquisition, it is possible to distinguish the different materials in the x-ray path. An unlimited number of materials can be identified from this full spectral information, without pre-tuning the acquisition parameters which is often required in classical dual-energy approaches. In the case of the DIMM, the Cu signal and the polyimide board signal can be visualized separately.

The spectrum also can be filtered for K-edges. Since these absorption edges are unique for any given element, it is possible to identify the materials used in the sample. The lower detection limit for K-edges is just below 20 keV, meaning that the K-edge detection method can be used for materials containing molybdenum or heavier elements.

Also in this study, we analyzed a 2.5 cm diameter smart ring wearable device which features electronics and a battery pack on the inside. A conventional micro-CT scan of the complete sample was performed with a voxel size of 13 µm and acceleration voltage of 180 kV using the TESCAN UniTOM XL SPECTRAL. In a second step, a full spectral CT scan was performed by sliding the TESCAN PolyDET II detector into the field of view. The detector counts every photon that reaches its surface after interacting with the sample. At the same time, the energy of each of those photons is measured, resulting in a spectrum between 20 and 160 keV. This allows analysis of how photons of different energies interact with the different materials in the sample. All of this information is captured in one single CT scan. By analyzing the spectrum with spectral CT, it is possible to get an absolute identification of the main atomic number in a given area of the sample using K-edge detection, even without having compositional information prior to scanning. The spectral CT scan of the smart ring was performed with a voxel size of 40 µm and the acquisition time was 12.4 hours. The conventional CT scans were reconstructed using Panthera™ software for 3D visualization and analysis, as well as VGSTUDIO MAX (Volume Graphics) for 3D rendering.

For spectral CT scans, the TESCAN PolyDET II detector was used, and reconstruction, visualization, and analysis were performed using the TESCAN Spectral SuiteTM. AcquilaTM was used for acquisition of both spectral and conventional CT scans.

Based on the information of both the conventional overview and the spectral CT scans of the smart ring, specific regions of interest were identified from the reconstructed volume. With Panthera™ it is possible to mark regions of interest directly on the reconstructed slices. The coordinates of these volumes of interest (VOIs) can then loaded in the acquisition software AcquilaTM. Subsequently batch scanning was performed on the VOIs using a voxel size of 4.5 µm. The five high resolution VOI scans were correlated with the overview volume by using the shared coordinate systems.




▲ **Figure 1: A)** Conventional radiograph of the DIMM. **B)** Radiograph only showing the Cu signal. **C**) Spectral radiograph with Cu signal subtracted, revealing connections not visible in the other images.

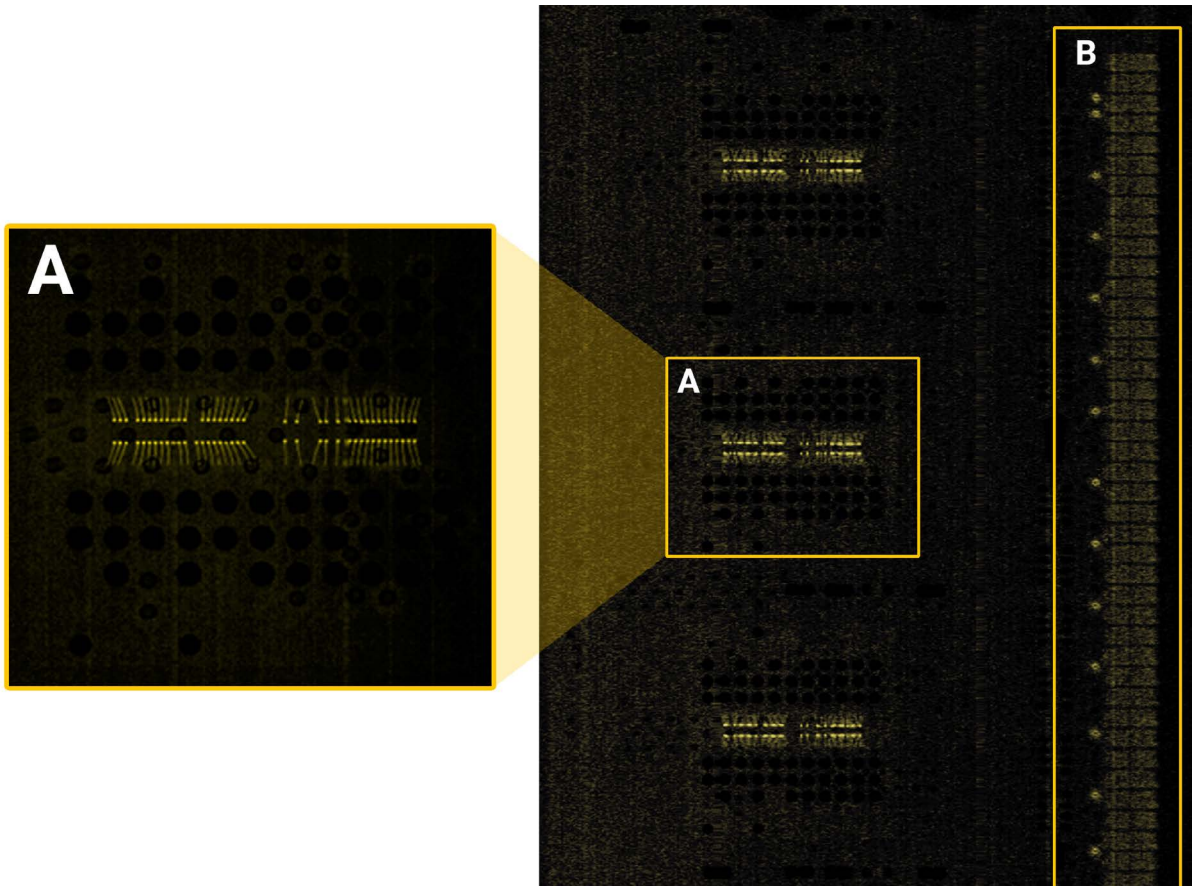
## Results and discussion

### DIMM radiographs

Figure 1A shows the results of conventional radiography performed on the DIMM showing the combination of all material interactions in the sample. As stated in the materials and methods section, the brightest regions in the image may indicate either very high atomic numbers such as you would see for solder material, or a combination of several layers of materials with lower atomic numbers. The darkest areas in the image are composed of a relatively thin layer of low atomic number material. This is the polyimide board itself.

In Figure 1B, the signal of the PCB's polyimide board is subtracted from the radiograph, leaving only the Cu tracks visible in the image. This provides more distinct information on connections between components and makes it possible to observe features that were otherwise hidden in the conventional radiograph. When subtracting the Cu signal from the radiograph, features that were otherwise overshadowed by the Cu signal become visible, as shown in Figure 1C.

Using K-edge detection on the radiograph, absorption edges for barium (capacitors), tin (solder bumps) and gold (connectors and wire bonds) could be identified. While the capacitors and solder bumps are quite easily distinguished from other features in the sample when viewing conventional radiographs, the gold connectors and coatings really stand-out in spectral radiographs. Although gold is expected to be a high attenuating material, the small dimensions of the wire bonds compared to other components in the DIMM and the extremely thin gold coating on the connectors makes it almost indistinguishable in a conventional radiograph. Figure 2 shows the K-edge filtered images for the gold absorption edge at 80.7 keV, revealing the gold in the IC wire bonds found at various locations on the DIMM and at the gold-plated contacts that connect the DIMM to the motherboard of a PC. At these contacts, gold is used as a very thin connective coating to prevent the nickel lying underneath from oxidizing. Figure 2A shows a higher resolution, more detailed radiograph which improves visualization of the small wire bonds.



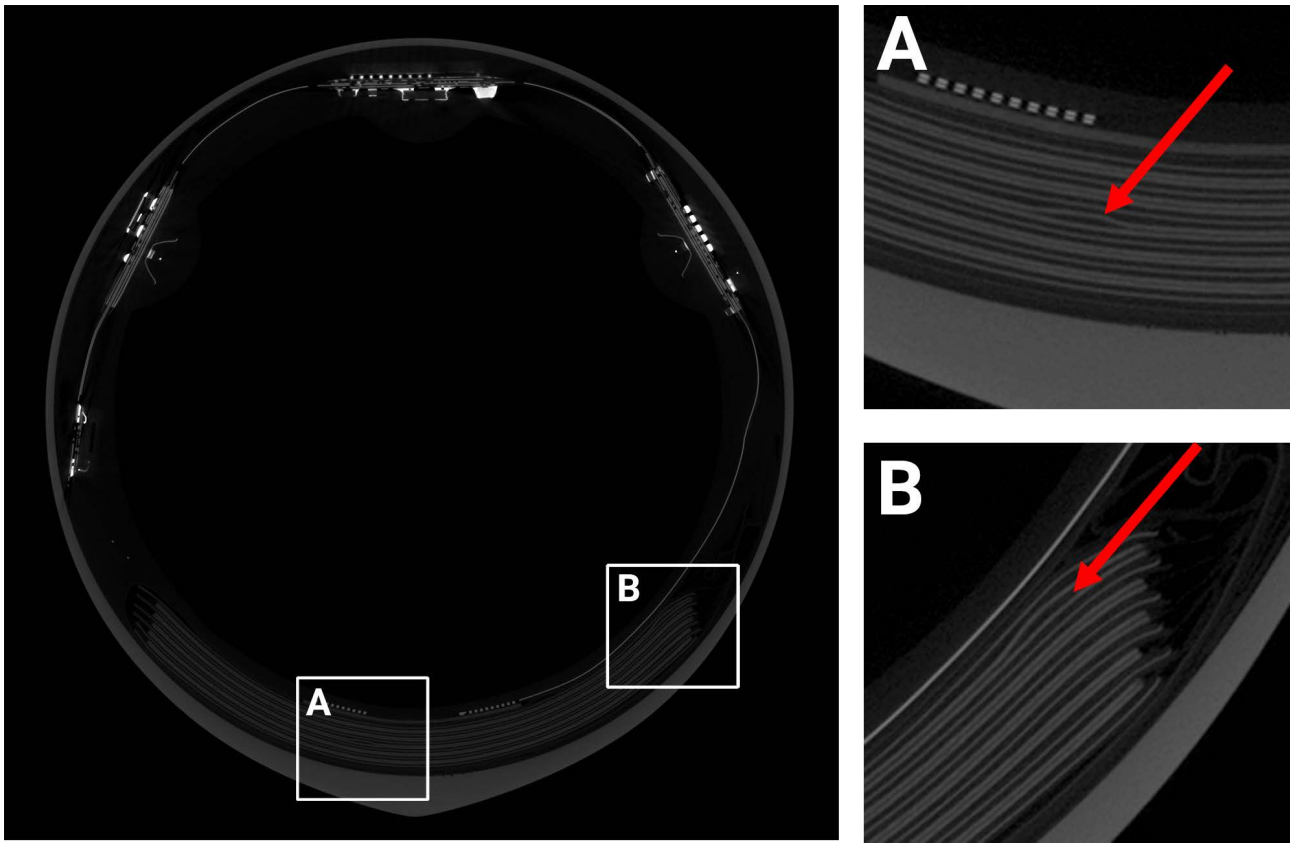

▲ **Figure 2:** K-edge filtered image showing only the gold signal on the DIMM. The gold is present in wire bonds **(A)** and on the connectors **(B)**.

## Smart ring

While radiographs are sometimes sufficient for analyzing flat samples such as the DIMM described above, more complex electronic devices such as the smart ring need a 3D approach. The initial conventional CT scan of the wearable device gives a clear overview of its different components(Figure 3).

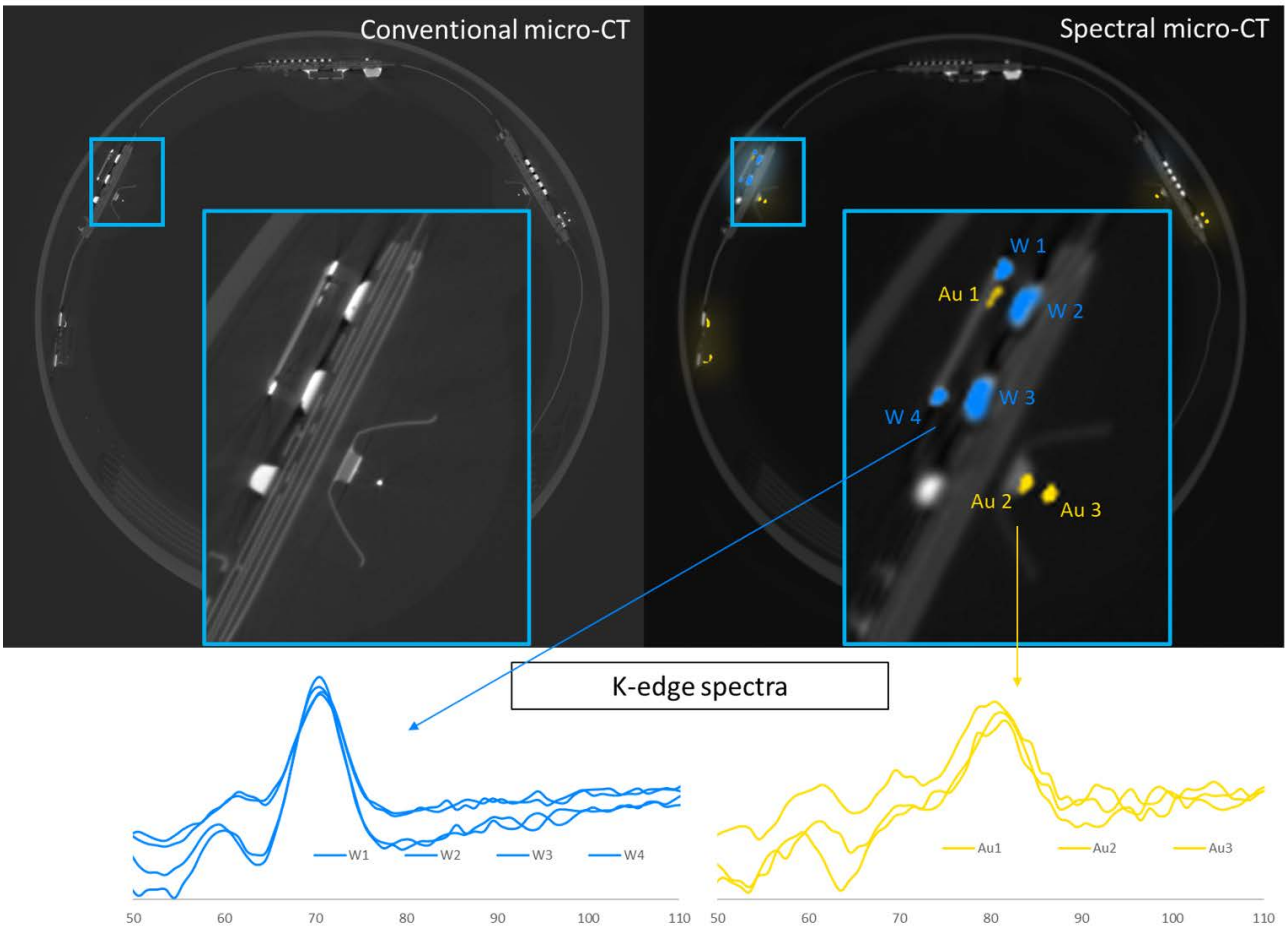
This overview scan, at a resolution of 13 µm, exposes the location of the different areas of interest in the sample, including components like the battery, sensors, antennas, etc., but also possible defects inside these components. For example, Figure 4 shows the location of delamination defects inside the battery of the smart ring.

▲ **Figure 3:** Renders of the smart ring, acquired using conventional CT at a voxel size of 13 µm, visualized using different opacity settings.




▲ **Figure 4:** Horizontal cross section through the conventional CT scan of the smart ring. The battery shows delamination defects at different locations.

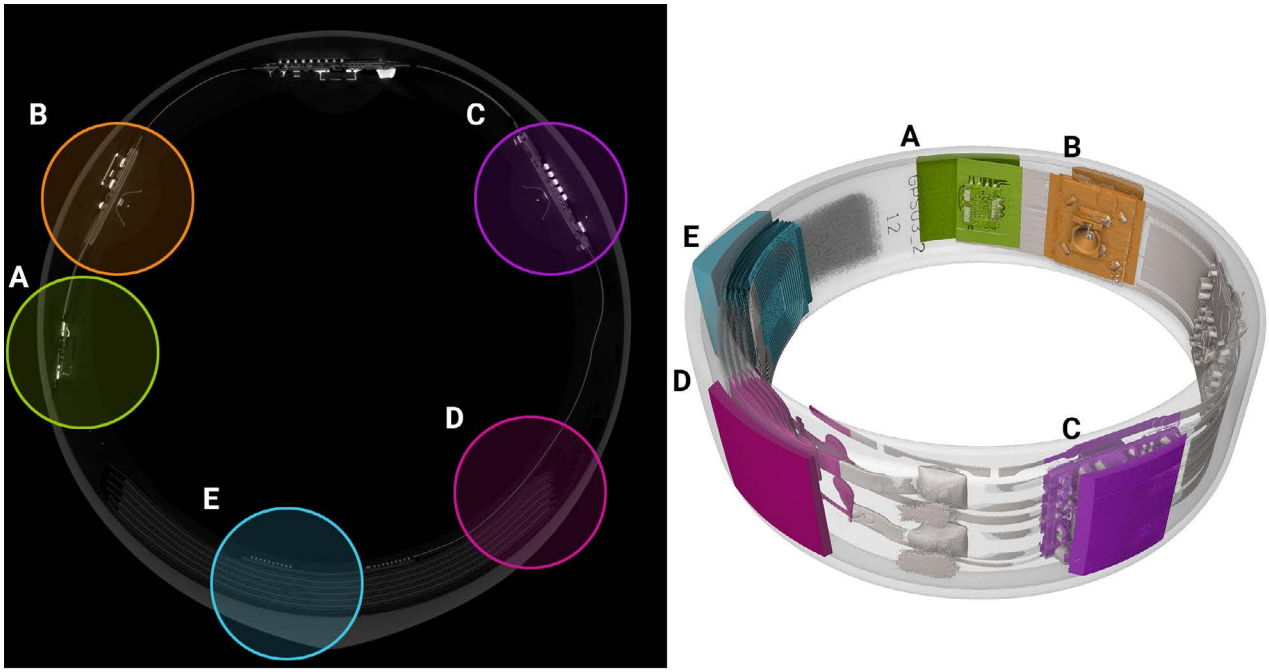
To identify other areas of interest, conventional micro-CT was complemented with spectral CT. The spectral detector was moved into the field of view to acquire a full spectrum 3D volume. This volume holds complete spectral information in every voxel of the dataset, meaning the volume can be seen as a combination of 140 monochromatic tomograms between 20 and 160 kV. Figure 5 shows a comparison of a conventional CT slice (left) and a spectral CT slice (right) through the central part of the ring. Using K-edge detection, areas that hold high-Z elements, such as gold or tungsten can be identified automatically and mapped in the 3D spectral volume. The insert in Figure 5 show locations inside the infrared LED of the heart rate sensor where K-edges at 69.5 and 80.7 keV are observed, indicating the presence of tungsten and gold respectively.



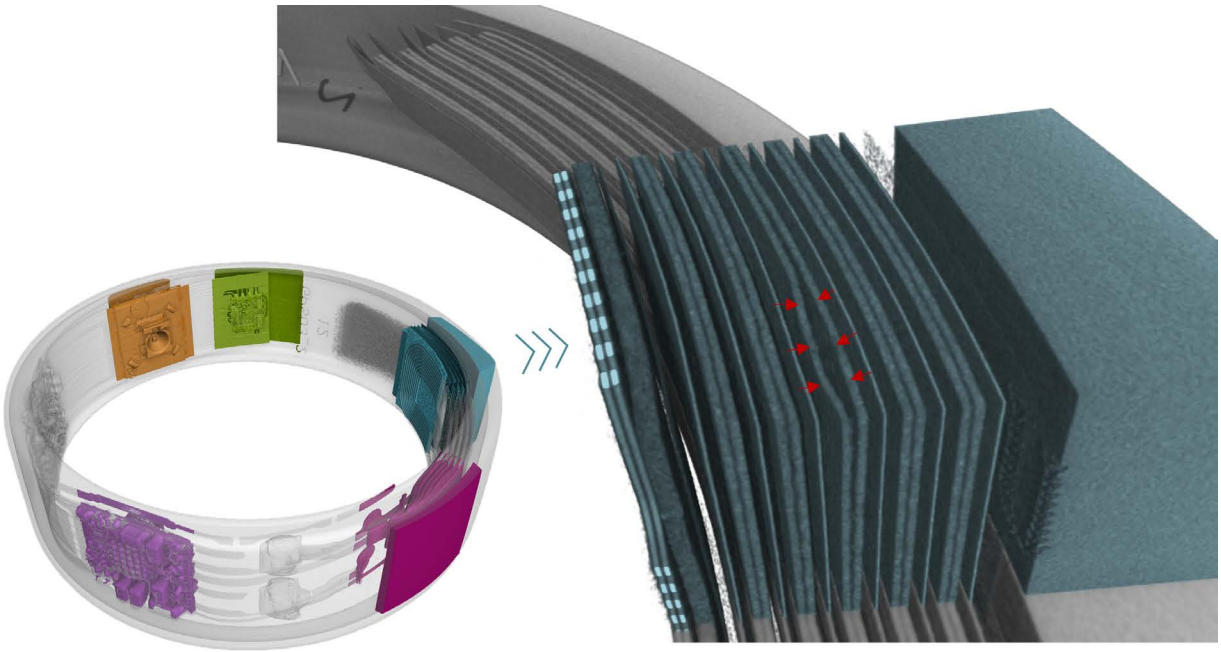

▲ **Figure 5:** Conventional **(left)** and spectral **(right)** CT slice through the center of the smart ring. Peaks at 69.5 and 80.7 keV indicate the presence of tungsten and gold.

Panthera™ was used to analyze both the conventional CT and spectral CT overview scans, and areas of interest were identified for scanning at higher resolution to resolve additional detail. Using the conventional CT scan, volumes of interest were selected for the two defects in the battery. The spectral CT scan was used to select VOI locations where gold is present: the two infrared LEDs from the heart rate sensor and the gyroscope. These locations are shown on a horizontal slice and on a 3D render in Figure 6.

The resulting high-quality scan of each region, at 4.5 µm voxel size, can be used to study various components at high resolution using conventional CT. In case of the battery pack, VOI scanning provides a detailed image of the delamination in the battery. This provides critical information about the degradation of batteries, which is especially important for wearable devices that are in close contact with the human body, as battery failure could lead to physical injury. Figure 7 shows a detailed view of one of the delamination defects in the battery pack of the smart ring.

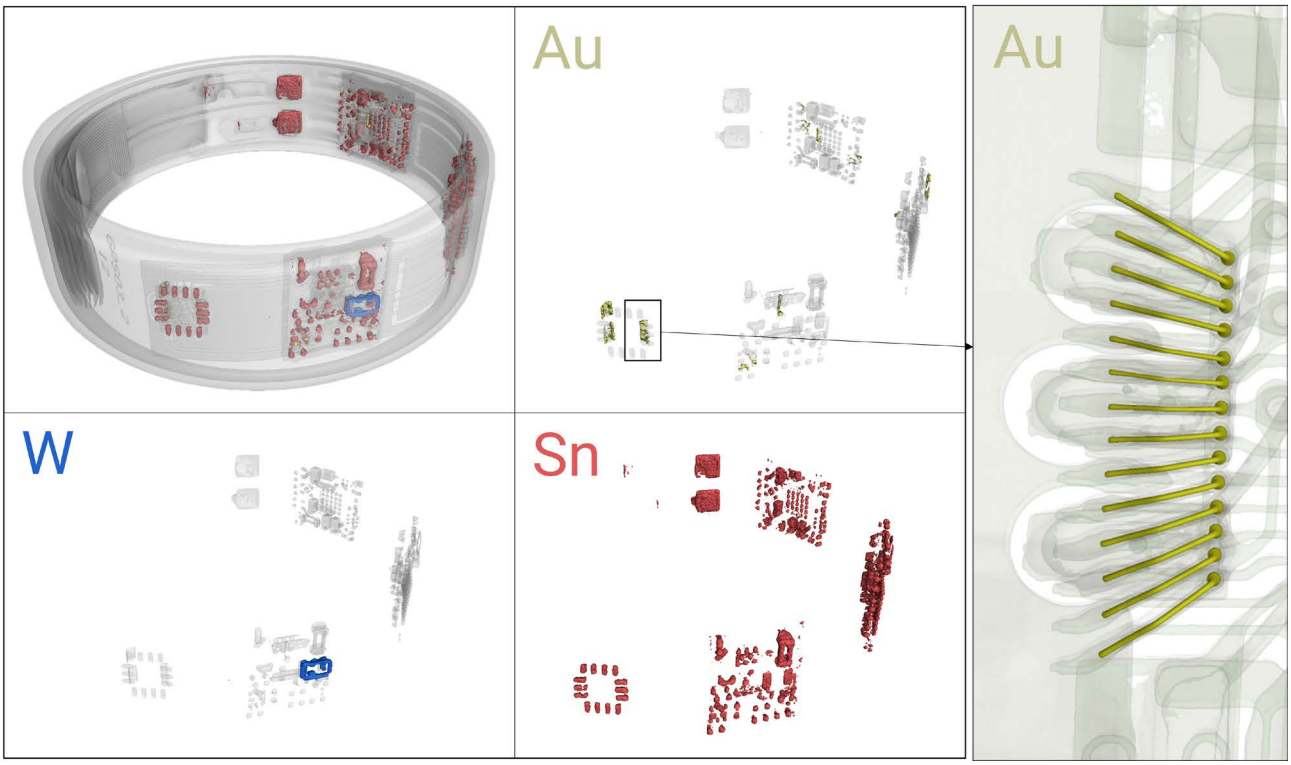



▲ **Figure 6:** Location of the volumes of interest for detailed CT scanning: gyroscope **(A),** infrared LED **(B,C),** battery defects **(D,E).**



▲ **Figure 7:** Detailed view of battery lamination by VOI scanning on the smart ring.

Using the other volume of interest scans, signals of gold, tungsten or even tin retrieved from the spectral CT scan can be correlated to high quality structural information. On the high-resolution VOI scans, the exact origin of the various K-edge signals can be pinpointed for an accurate image of the sample's true structure. Figure 8 shows the locations of the various K-edge signals and highlights the location of one of the gold signal origins. The gyroscope contains a series of three of small gold connections, which are clearly resolved on the VOI scan. The smart ring contains only one component made from tungsten and as the image shows, most of the soldering material is tin.




▲ **Figure 8: Left:** Location of Au, Sn and W in the smart ring sample. **Right:** detail of the VOI scan of the gyroscope showing the gold connectors used in this component.

## Conclusions and outlook

The combination of conventional CT and radiography with their spectral counterparts is a powerful way to gain insights into electronic components. Where CT can be seen as the gold standard for non-destructive 3D characterization, spectral CT makes it possible to actually identify gold. By harnessing the multi-energy information from a single spectral radiography acquisition, it is possible to discern within a radiograph the presence of different materials in the x-ray path. An unlimited number of materials can be distinguished from the full spectral information, even without pre-tuning the acquisition parameters as is often required in classical dual-energy approaches. The spectral information allows us to select regions of interest that are eligible to further investigation with high resolution CT imaging closing the failure analysis track and eventually leading to failure free devices.

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