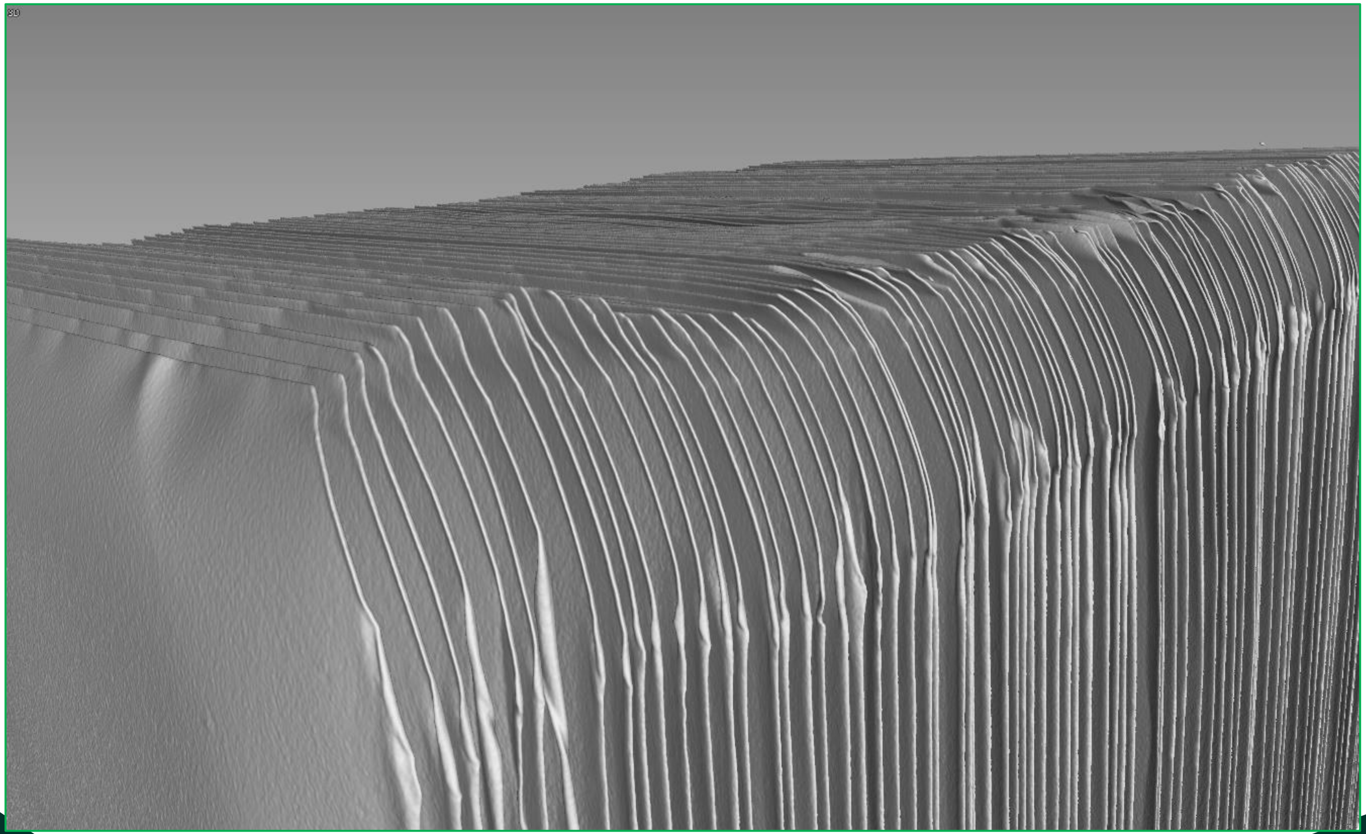


Waygate Technologies

GWL A.S.

Czech Republic

Applications Report 0056-21

May, 04 2021

Baker Hughes

Summary

Customer requirements

Samples: 4 batteries - LPF

Systems: Phoenix V|tome|x M300, V|tome|x L450

Inspection request:

- Overview scan with maximum resolution
- Region of interest CTs of stack/jelly roll for overhang area
- Scan housing for welding and porosity observation
- Show separators, connectors and other details

Application approach

- Overview CT on the Phoenix V|tome|x L450 for given samples with reasonable voxel resolution and best achievable contrast resolution
- Region of interest CTs on the Phoenix V|tome|x M300 with very high voxel resolution and best achievable contrast resolution to show welding quality, porosity, separators, connectors

Conclusions

- The Phoenix V|tome|x L450 X-Ray system is capable to achieve high contrast CT overview results for all delivered batteries. The reasonable voxel size is about 60-70 µm.
- The region of interest CTs on the Phoenix V|tome|x M300 show also very high quality for the contrast resolution, but at a much smaller voxel size for 2 different regions of each battery. By this the welding quality, porosity, separators and connectors can be well inspected.

Baker Hughes Digital Solutions GmbH,
CSC Wunstorf

Hanna Jacobs
Applikationsingenieur

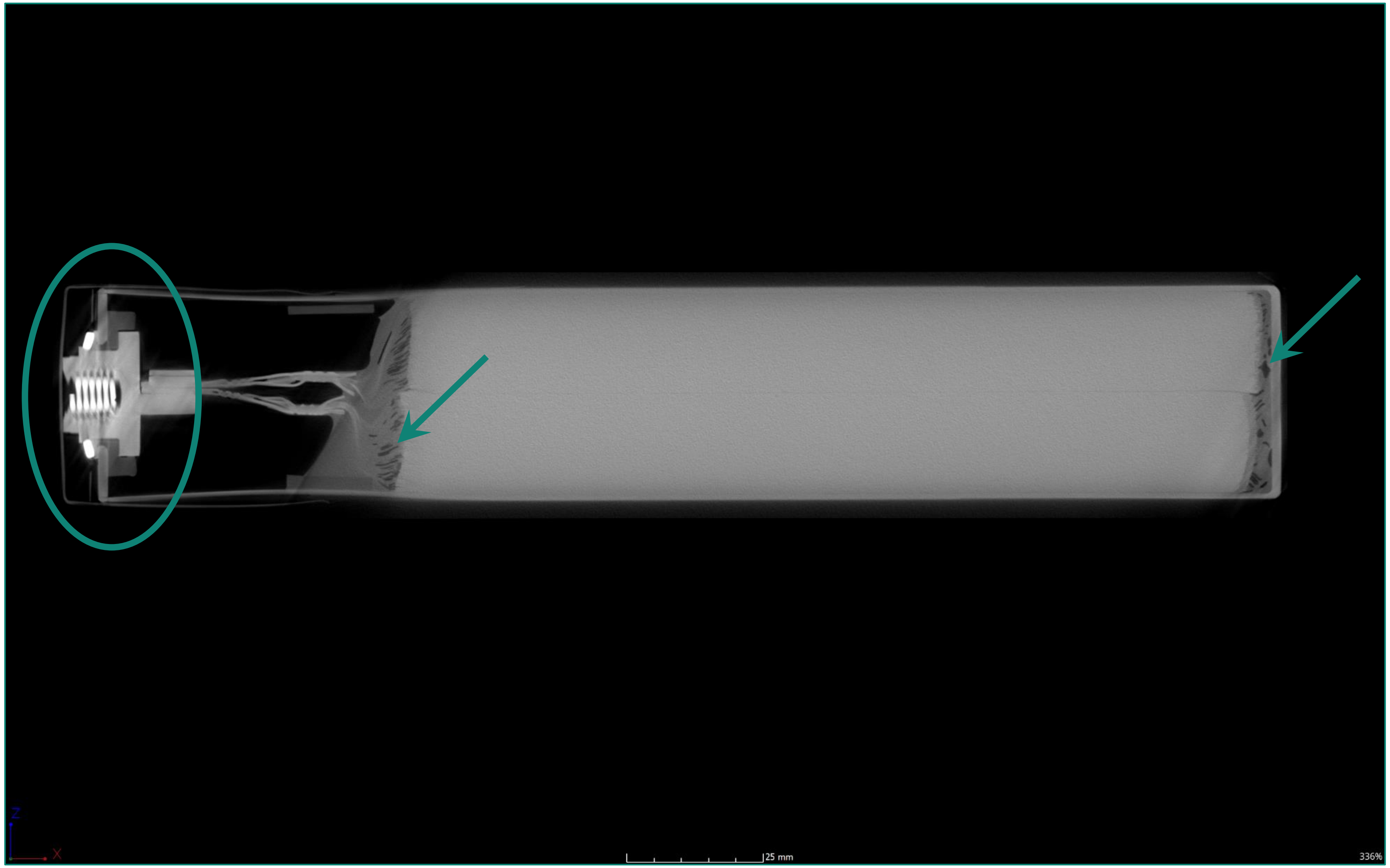
Dr. Tobias Neubrand
Technical Lead, Electronics

Waygate Technologies
a Baker Hughes business

Results

Adjacently some representative results are displayed.

Elerix 110Ah overview scan



Elerix 110Ah

CT X-Ray image

V|tome|x L450

450 kV / 1500 μA

Scan time 2.8 h

Voxel size 70 μm

Slice of side view through the cathode. Some pores are visible.

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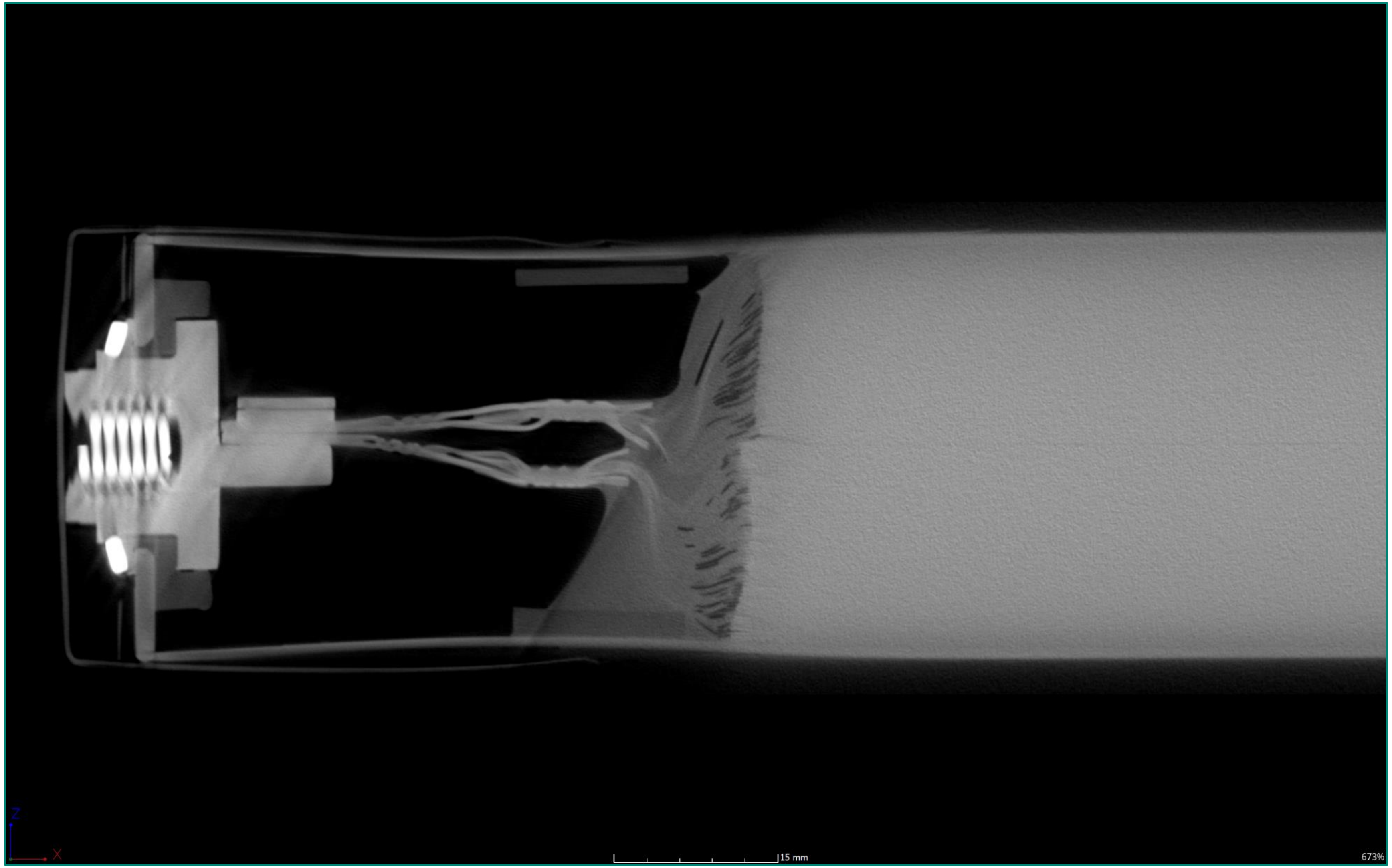
Elerix 110Ah overview scan



Elerix 110Ah

CT X-Ray image

V|tome|x L450

450 kV / 1500 µA

Scan time 2.8 h

Voxel size 70 µm

Higher magnification of the top part of the previous image. Even at this voxel size of 70 µm some small details can already be detected.

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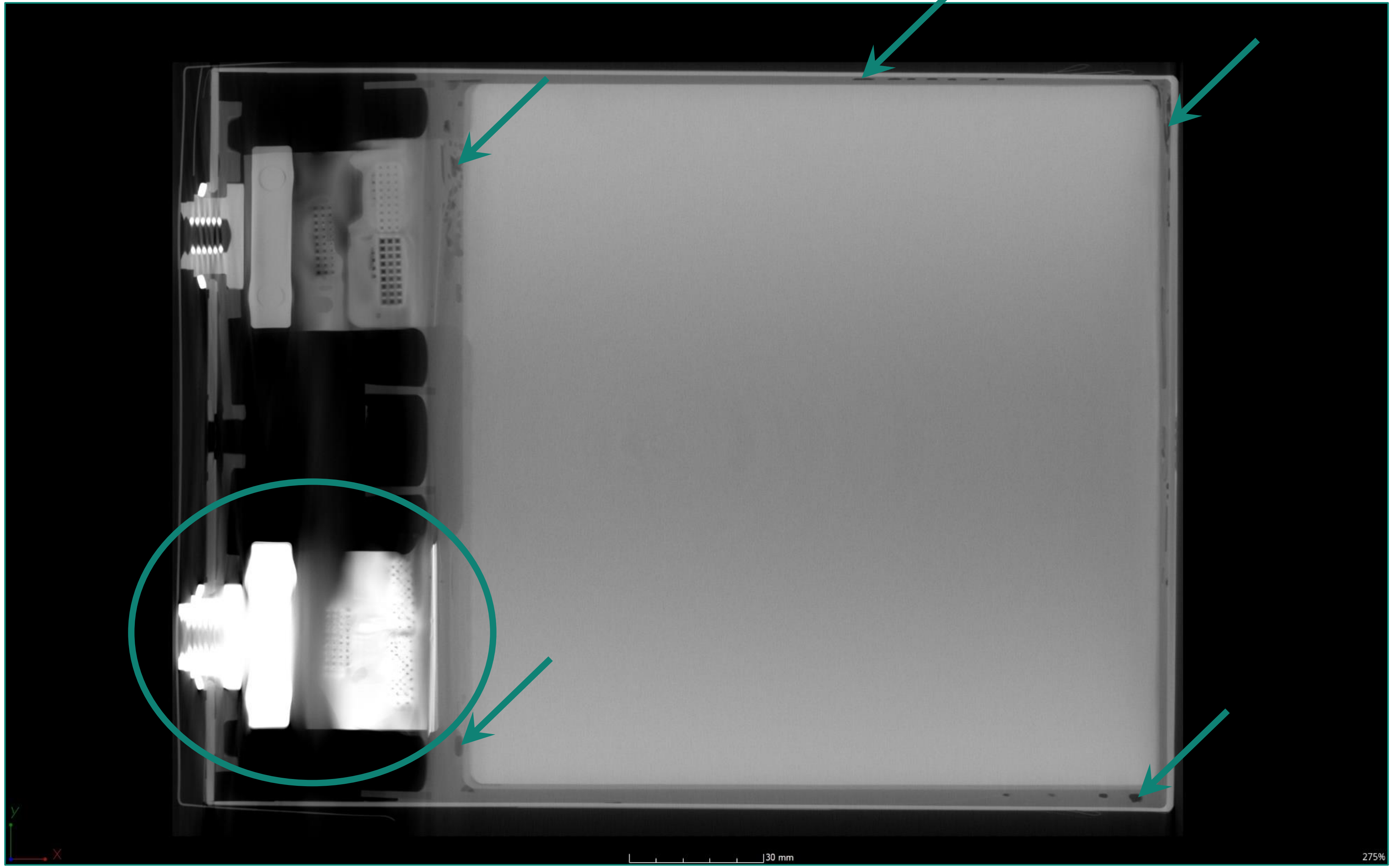
Elerix 110Ah overview scan



Elerix 110Ah

CT X-Ray image

V|tome|x L450

450 kV / 1500 µA

Scan time 2.8 h

Voxel size 70 µm

Slice of perpendicular view through anode (white because of a lot of copper) and cathode. Some pores can be identified.

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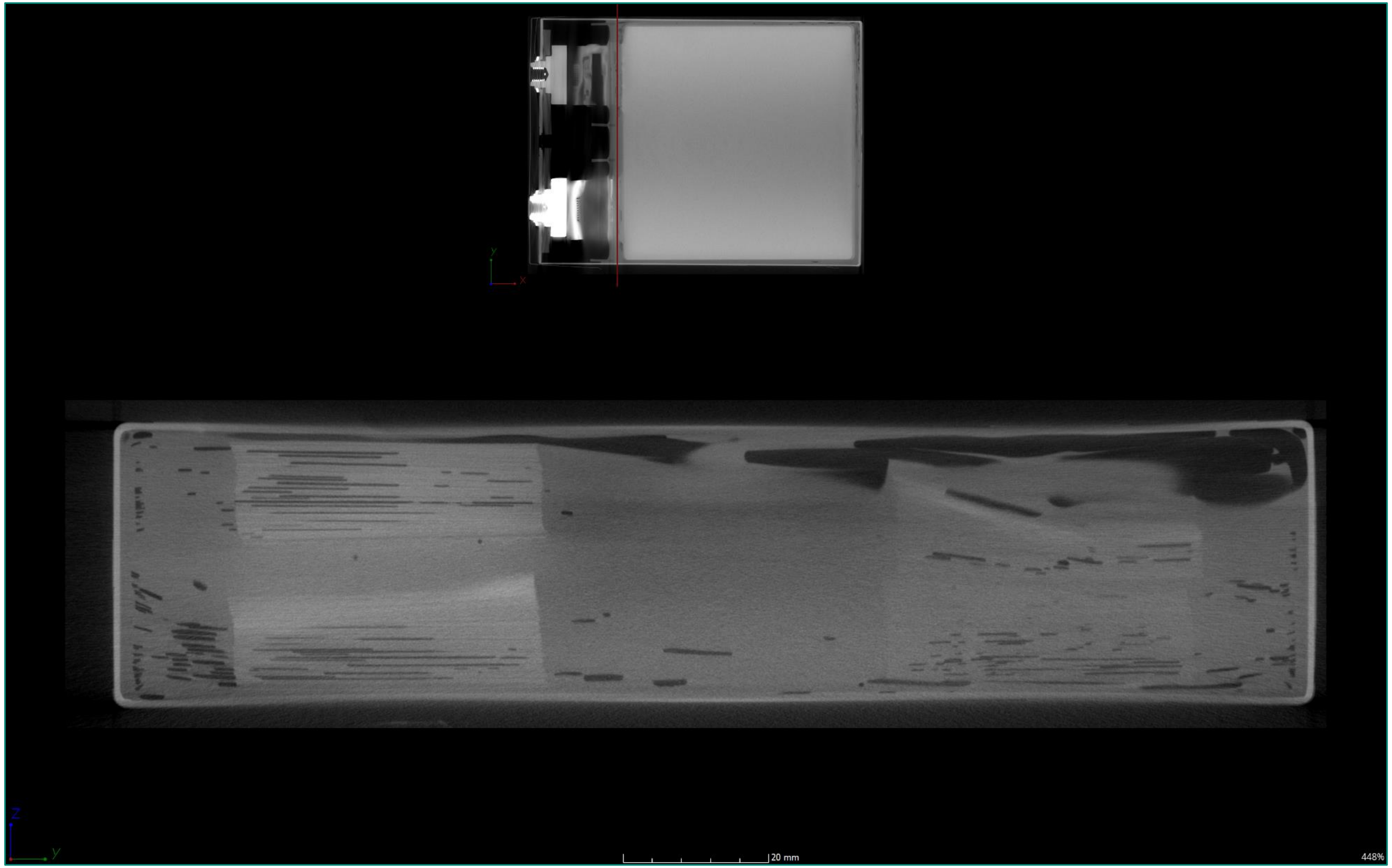
Elerix 110Ah overview scan



Elerix 110Ah

CT X-Ray image

V|tome|x L450

450 kV / 1500 µA

Scan time 2.8 h

Voxel size 70 µm

Slice view (along red line of small image above).

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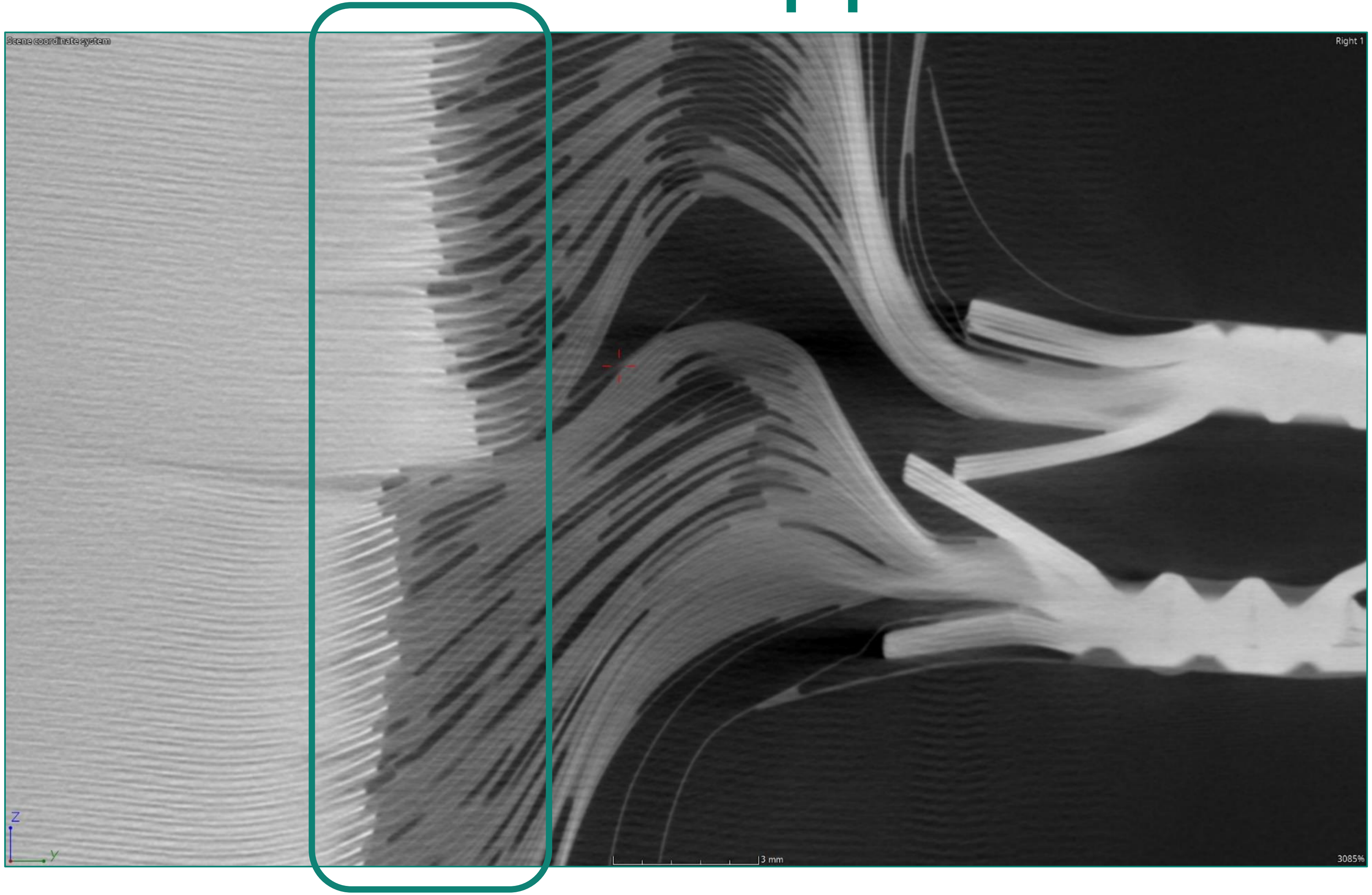
Elerix 110Ah scan of top part



Elerix 110Ah top part

CT X-Ray image

V|tome|x M300

260 kV / 110 μA

Scan time 2 h

Voxel size 22 μm (Resolution 2)

Higher magnification showing alignment of electrodes. – Red cross area is shown in next slide in perpendicular view.

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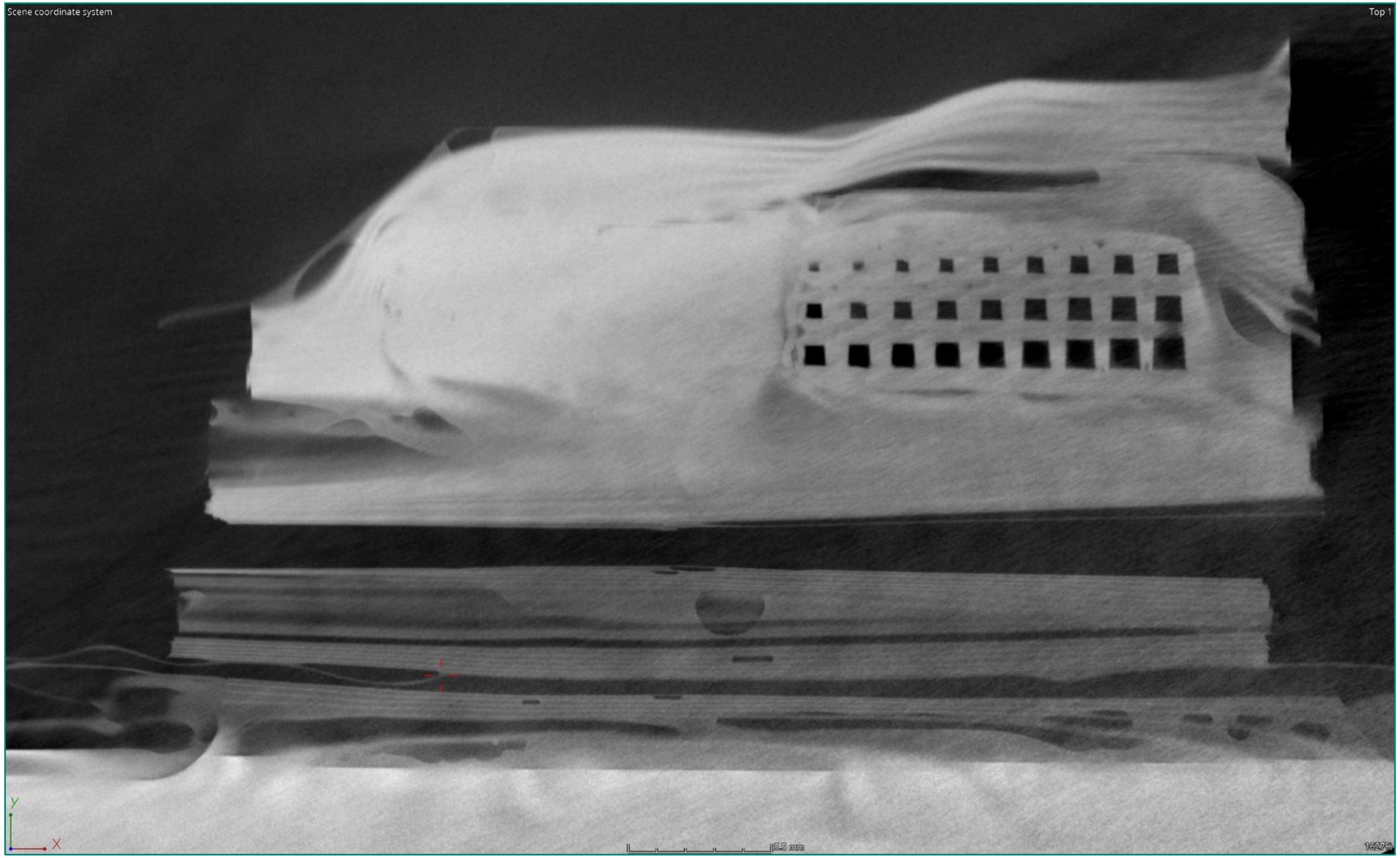
Elerix 110Ah scan of top part



Elerix 110Ah top part

CT X-Ray image

V|tome|x M300

260 kV / 110 µA

Scan time 2 h

Voxel size 22 µm

Red cross area from previous slide in perpendicular view.

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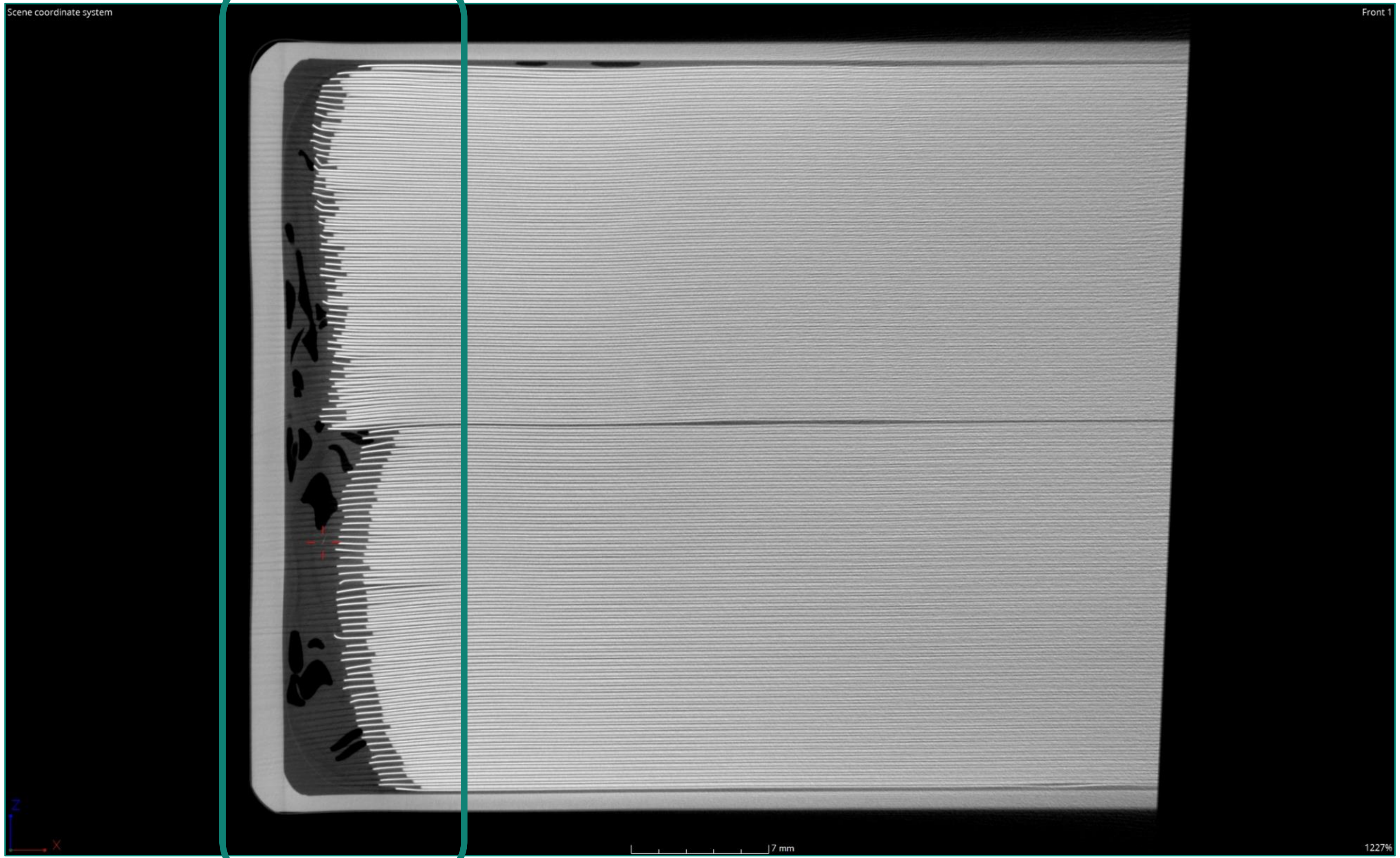
Elerix 110Ah scan of bottom part



Elerix 110Ah bottom part

CT X-Ray image

V|tome|x M300

260 kV / 110 µA

Scan time 2 h

Voxel size 19 µm (Resolution 2)

Alignment of electrodes at the bottom. – Red cross again in next slide.

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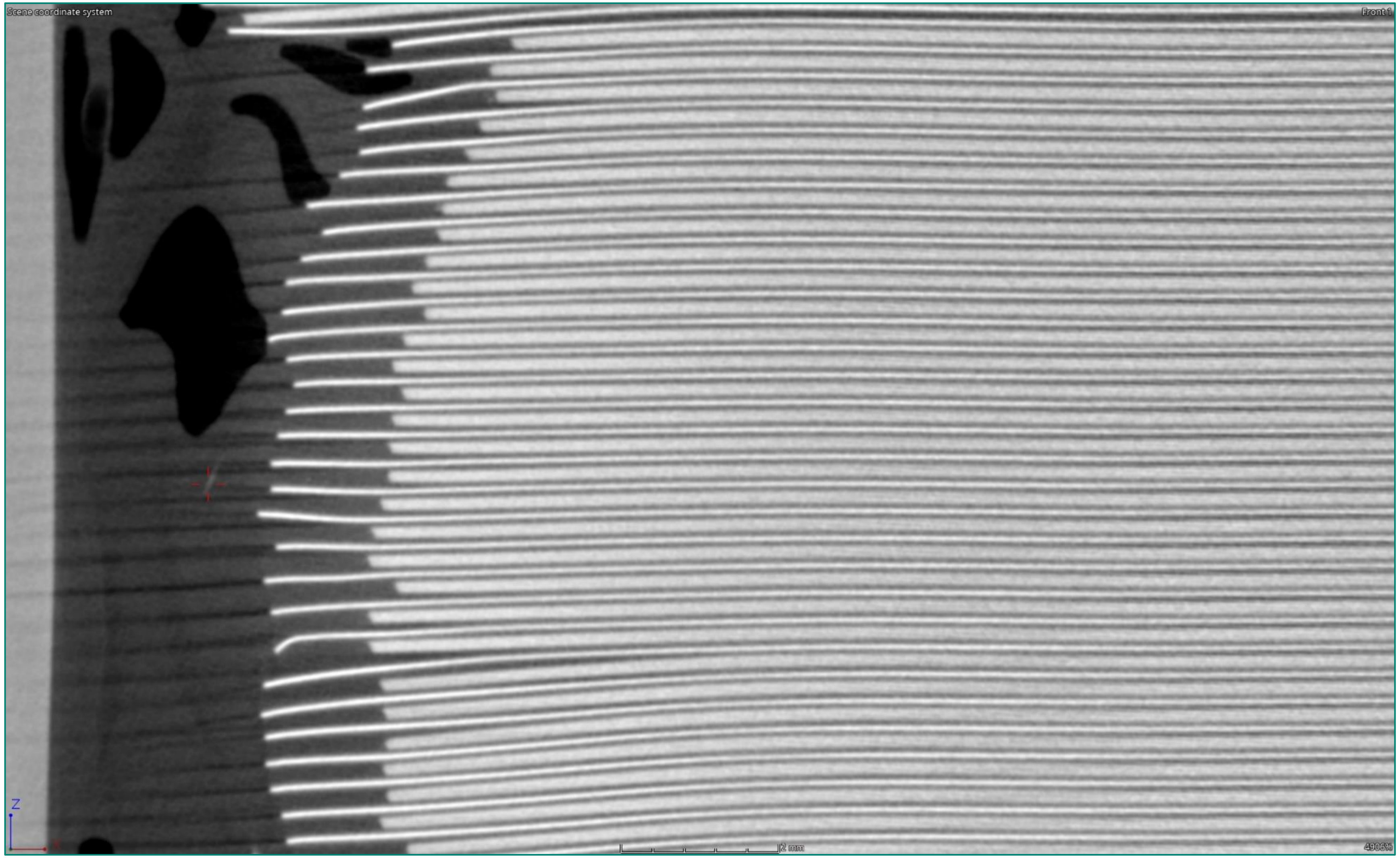
Elerix 110Ah scan of bottom part



Elerix 110Ah bottom part

CT X-Ray image

V|tome|x M300

260 kV / 110 µA

Scan time 2 h

Voxel size 19 µm

Higher magnification of red cross area of the previous image. Alignment of anodes and cathodes is presented.

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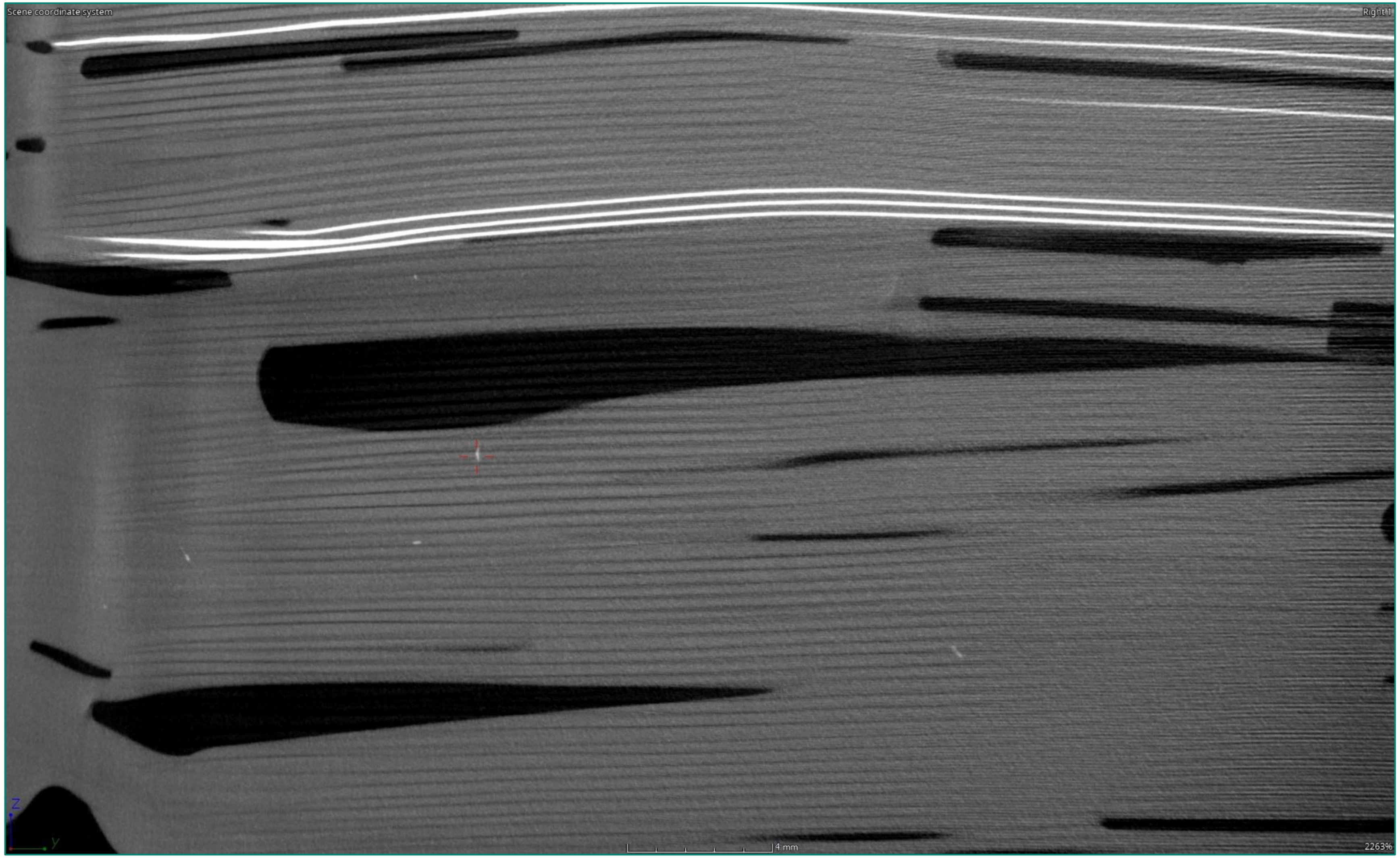
Elerix 110Ah scan of bottom part



Elerix 110Ah bottom part

CT X-Ray image

V|tome|x M300

260 kV / 110 µA

Scan time 2 h

Voxel size 19 µm

Perpendicular view of the previous image.

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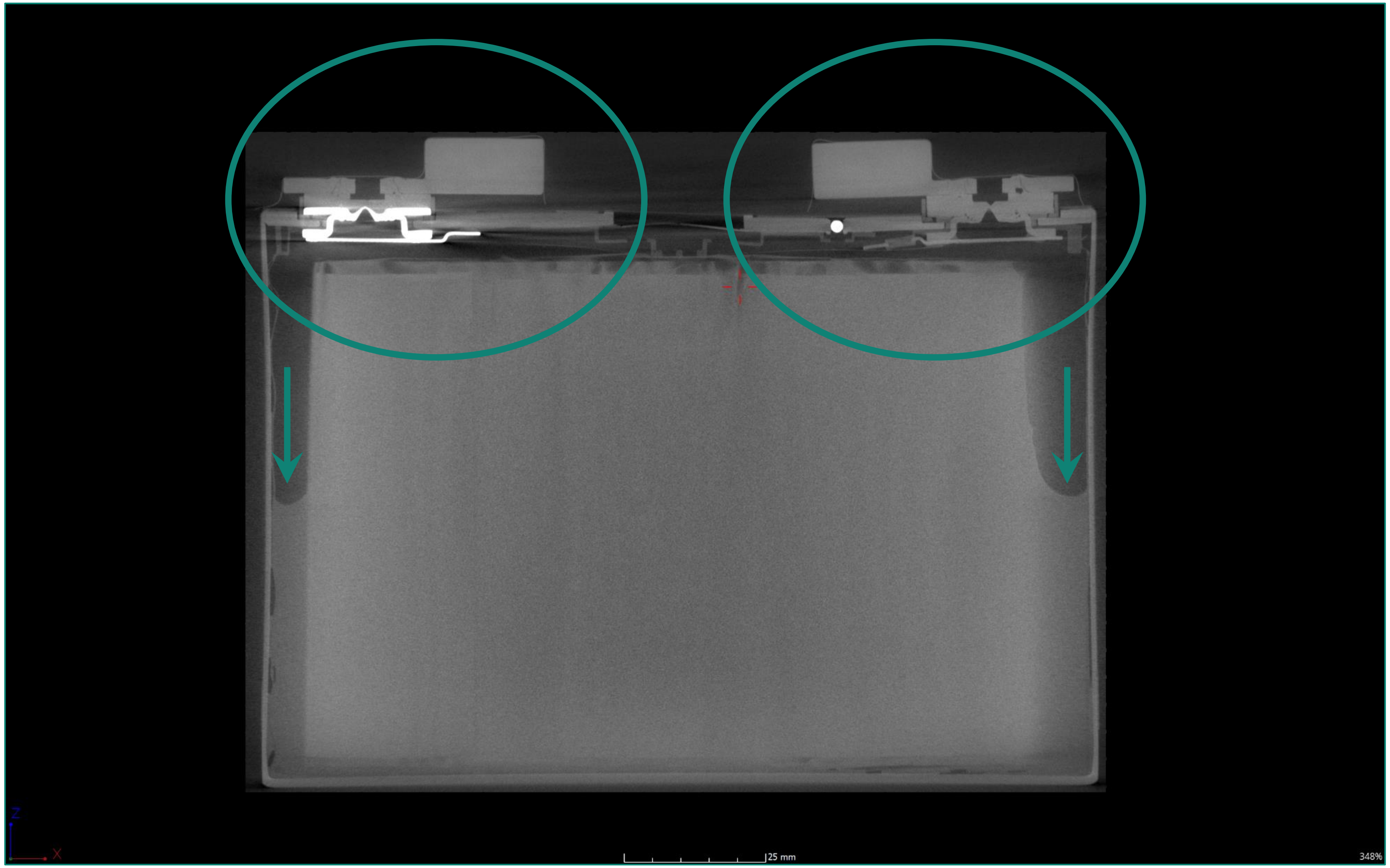
Elerix 135Ah overview scan



Elerix 135Ah

CT X-Ray image

V|tome|x L450

450 kV / 1500 µA

Scan time 2.8 h

Voxel size 65 µm

Slice view. Poles and isolation can be controlled (left anode, right cathode). Arrows: Filling height of electrolyte can be clearly seen.

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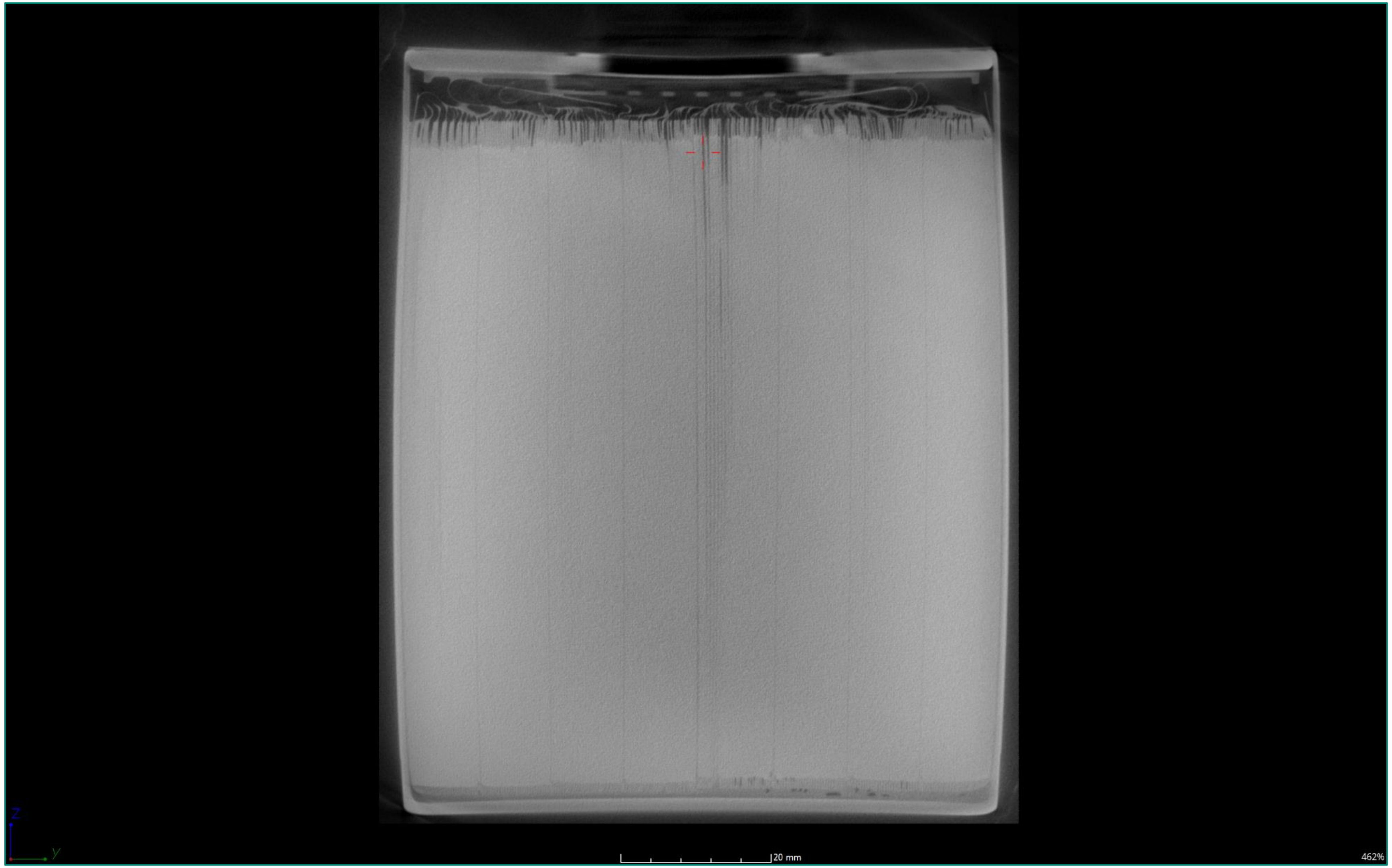
Elerix 135Ah overview scan



Elerix 135Ah

CT X-Ray image

V|tome|x L450

450 kV / 1500 µA

Scan time 2.8 h

Voxel size 65 µm

Slice view. Red cross of previous page in perpendicular view

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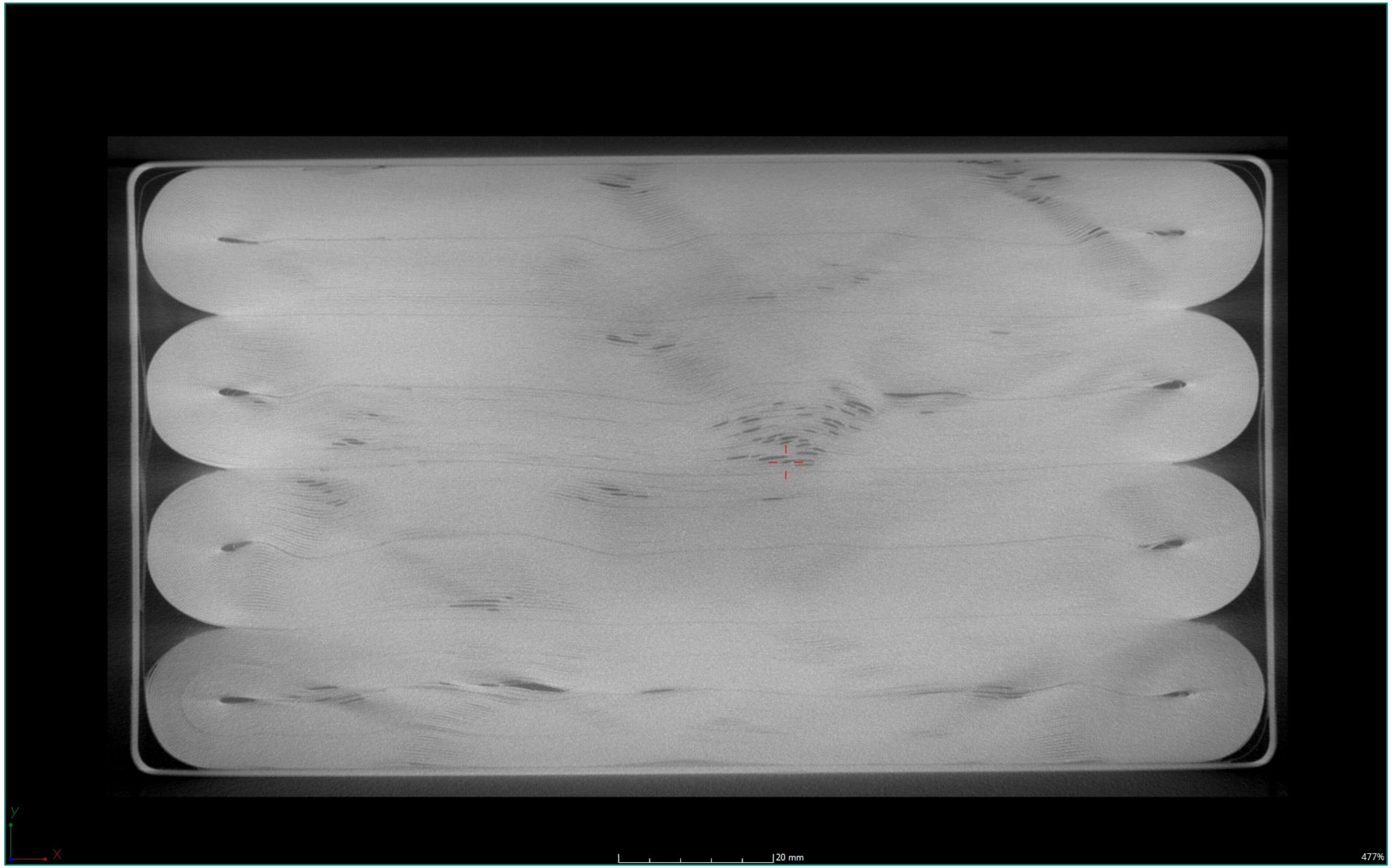
Elerix 135Ah overview scan



Elerix 135Ah

CT X-Ray image

V|tome|x L450

450 kV / 1500 µA

Scan time 2.8 h

Voxel size 65 µm

Cross section through all 4 jelly rolls.

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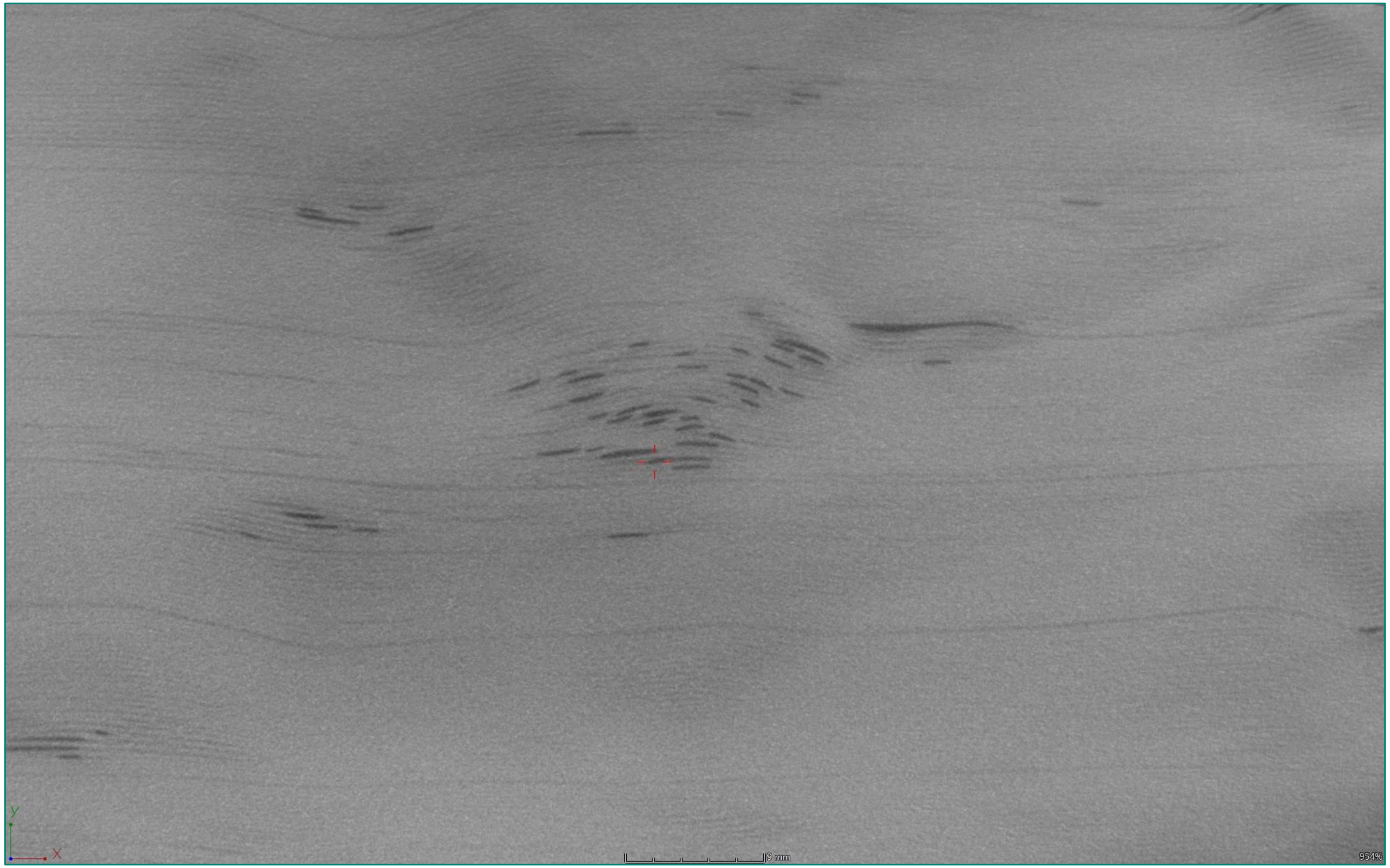
Elerix 135Ah overview scan



Elerix 135Ah

CT X-Ray image

V|tome|x L450

450 kV / 1500 µA

Scan time 2.8 h

Voxel size 65 µm

Higher magnification of the previous image (red cross area).

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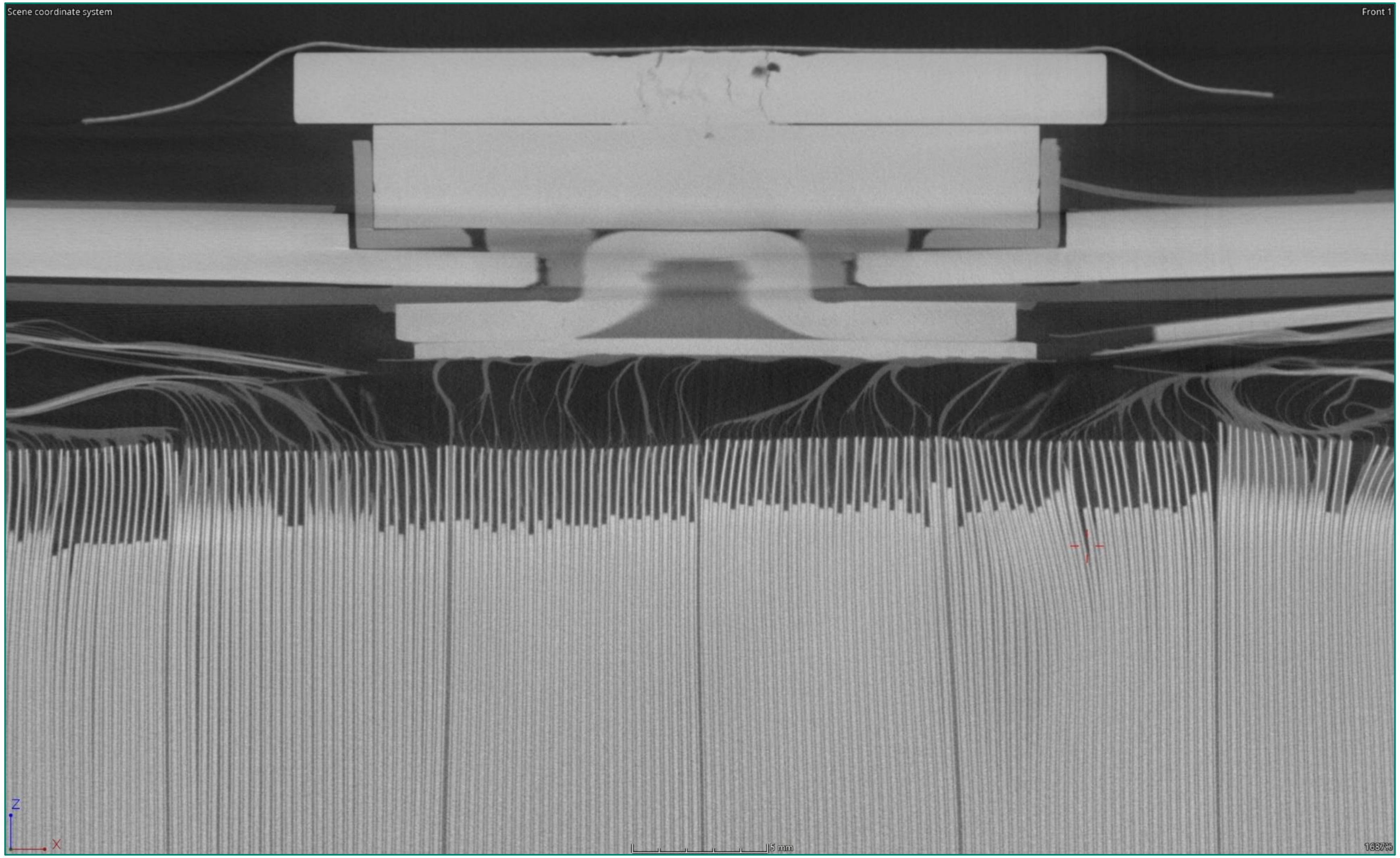
Elerix 135Ah scan of top part



Elerix 135Ah top part

CT X-Ray image

V|tome|x M300

260 kV / 110 µA

Scan time 2 h

Voxel size 19 µm (Resolution 2)

Slice view. Pole and overhang area. – Red cross on next page in perpendicular view.

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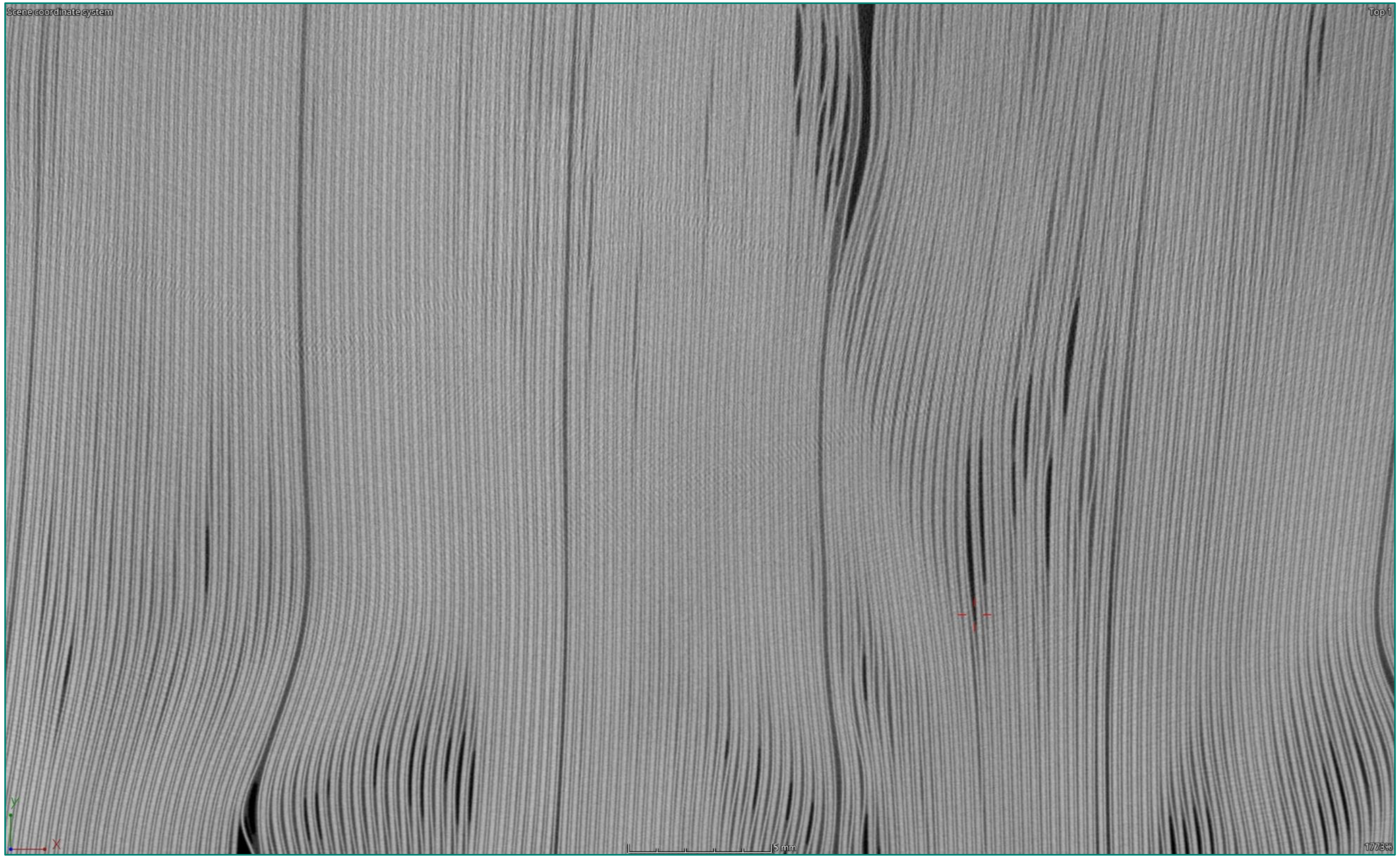
Elerix 135Ah scan of top part



Elerix 135Ah top part

CT X-Ray image

V|tome|x M300

260 kV / 110 µA

Scan time 2 h

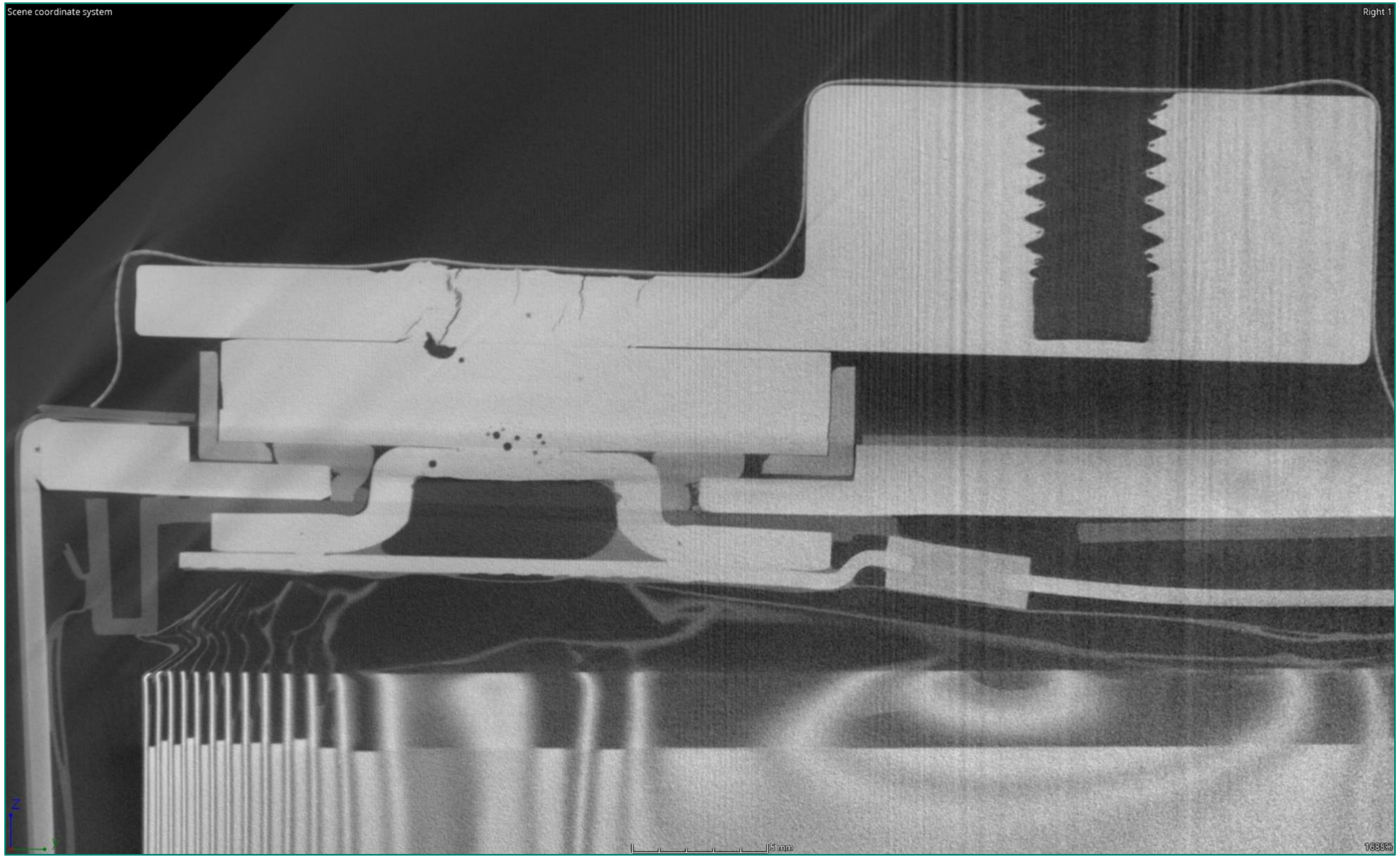
Voxel size 19 µm

Cross section through the jelly rolls.

Waygate Technologies

a Baker Hughes business

Elerix 135Ah scan of top part



Elerix 135Ah top part

CT X-Ray image

V|tome|x M300

260 kV / 110 µA

Scan time 2 h

Voxel size 19 µm

Slice view. Cathode area and a part of the housing are detected.

Waygate Technologies
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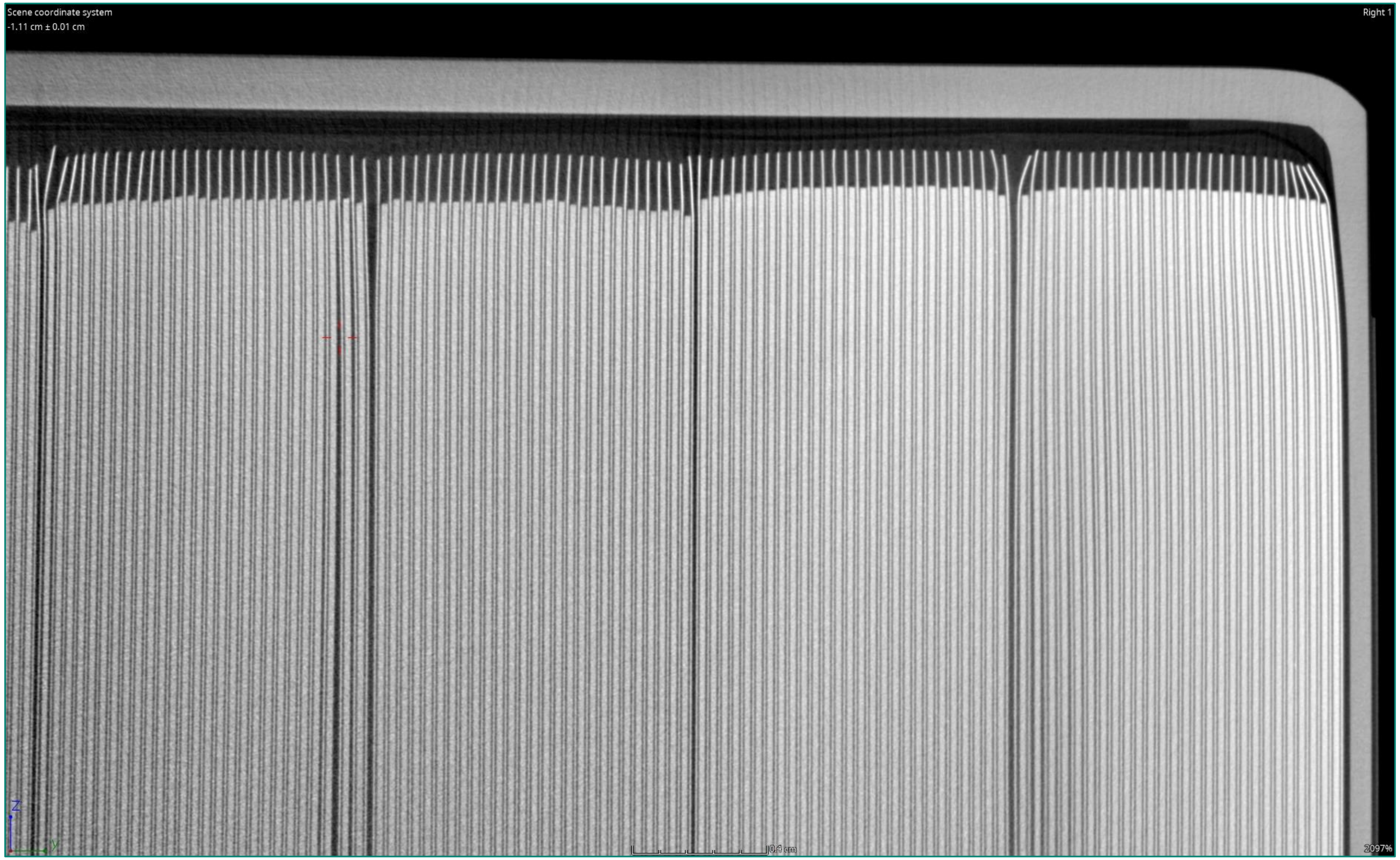
Elerix 135Ah scan of bottom part



Elerix 135Ah bottom part

CT X-Ray image

V|tome|x M300

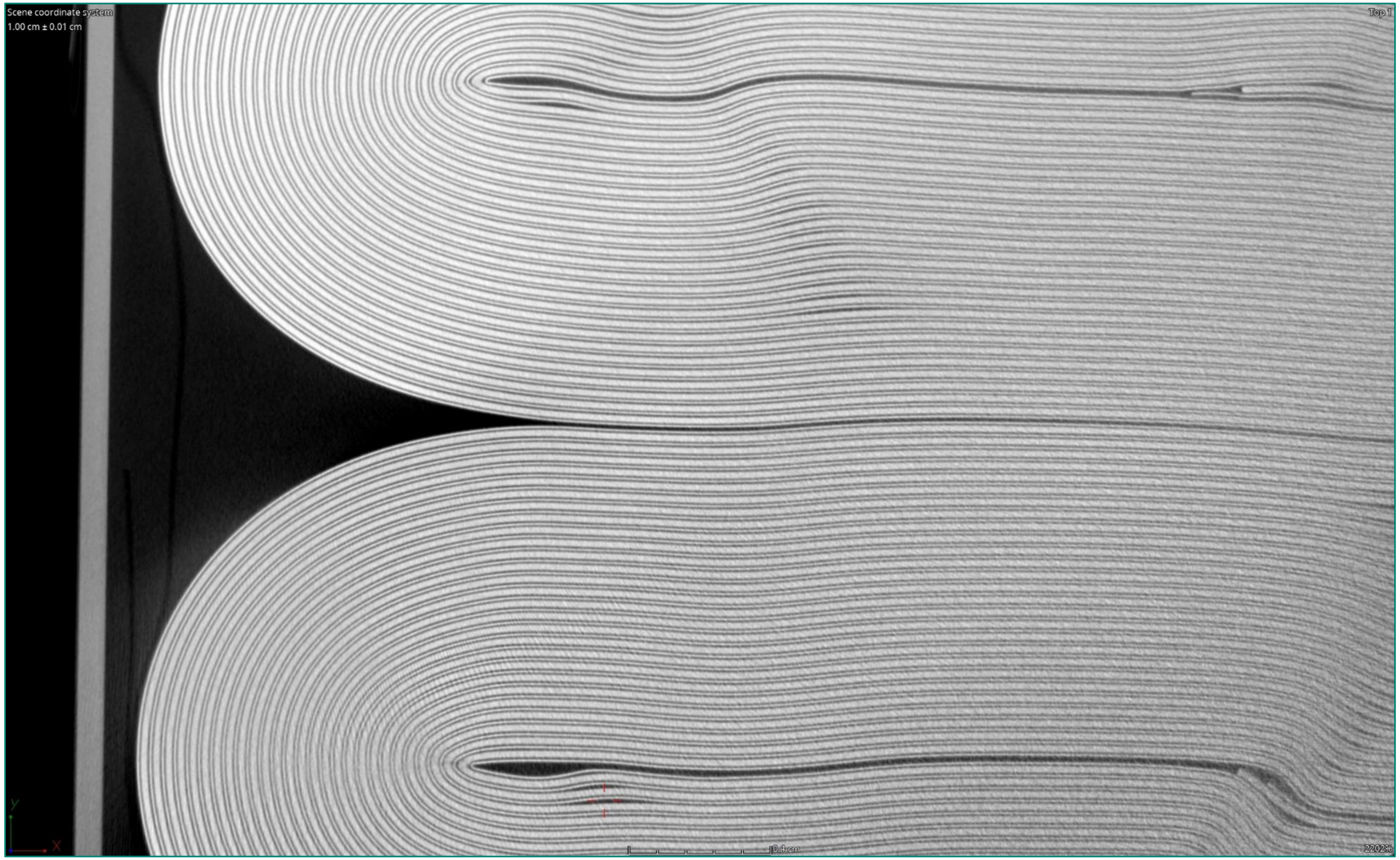
260 kV / 110 µA

Scan time 2 h

Voxel size 20 µm (Resolution 2)

Overhang area at medium magnification. - Red cross on next page in perpendicular view.

Elerix 135Ah scan of bottom part



Elerix 135Ah bottom part

CT X-Ray image

V|tome|x M300

260 kV / 110 µA

Scan time 2 h

Voxel size 20 µm

Red cross from previous slide in perpendicular view. The alignment of the anodes and cathodes in the jelly rolls is presented.

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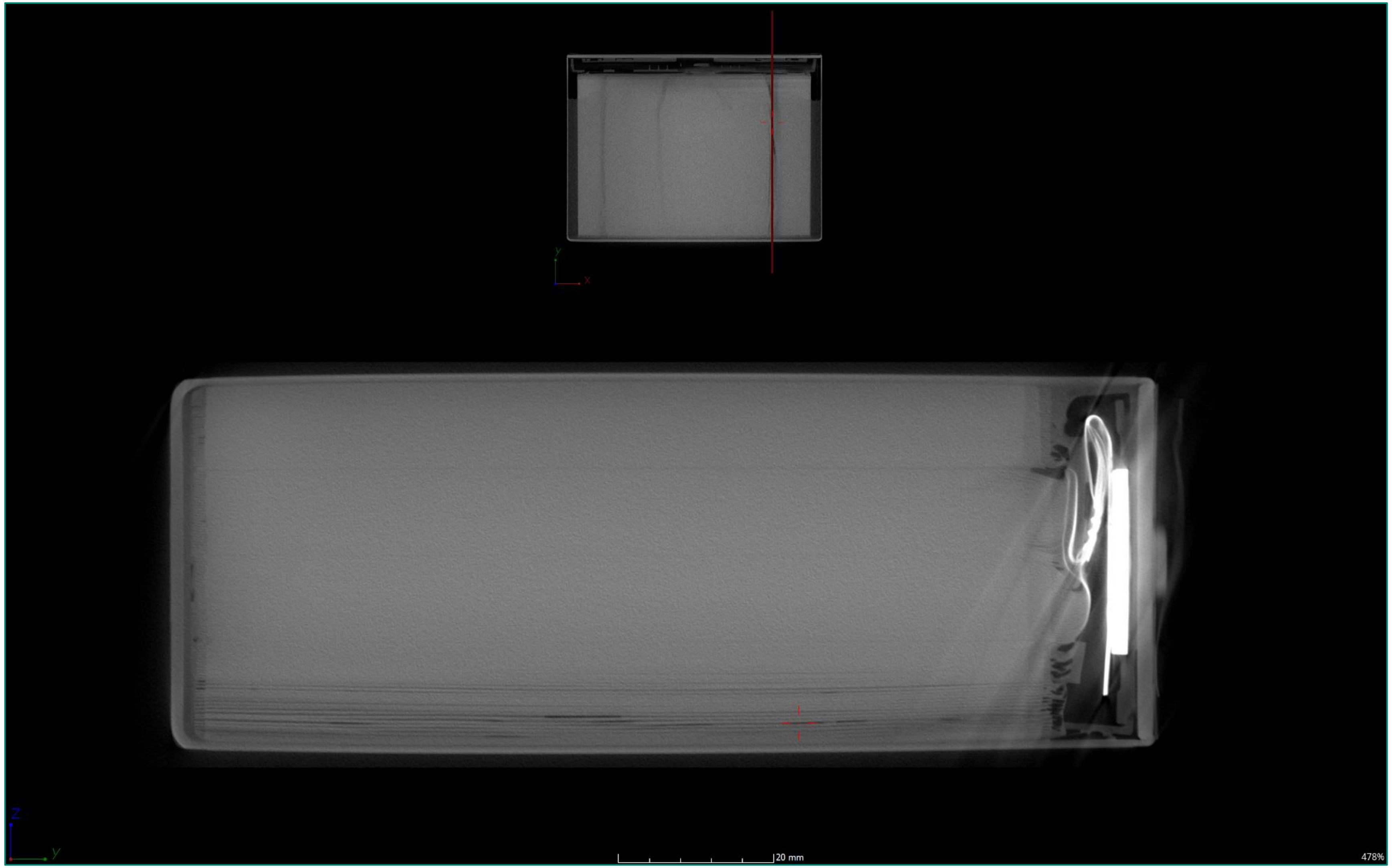
Elerix 100Ah overview scan



Elerix 100Ah

CT X-Ray image

V|tome|x L450

450 kV / 1500 µA

Scan time 2.8 h

Voxel size 65 µm

Slice view through anode (along red line of small image above).

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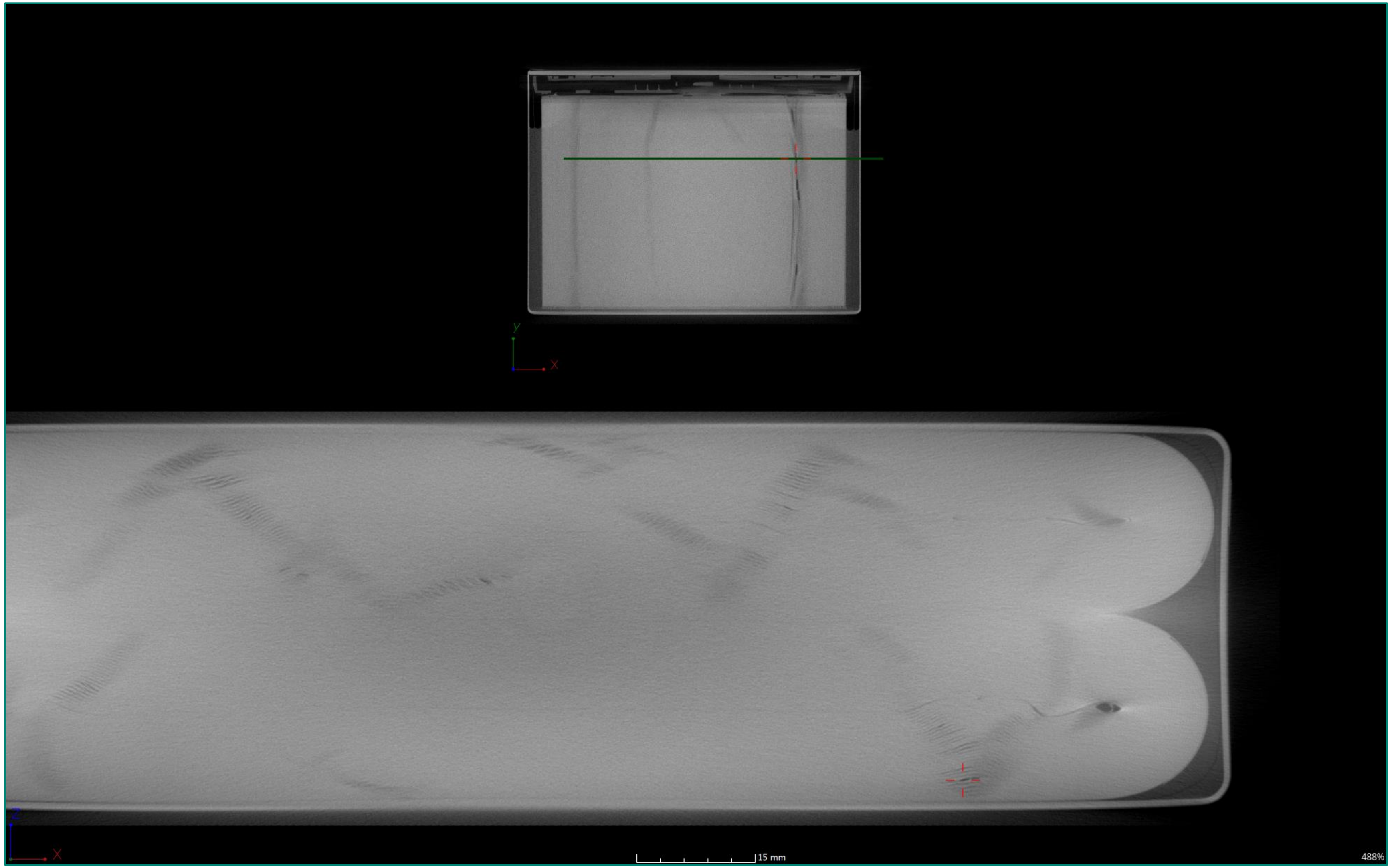
Elerix 100Ah overview scan



Elerix 100Ah

CT X-Ray image

V|tome|x L450

450 kV / 1500 µA

Scan time 2.8 h

Voxel size 65 µm

Slice view (along green line of small image above). – Cross section through jelly rolls.

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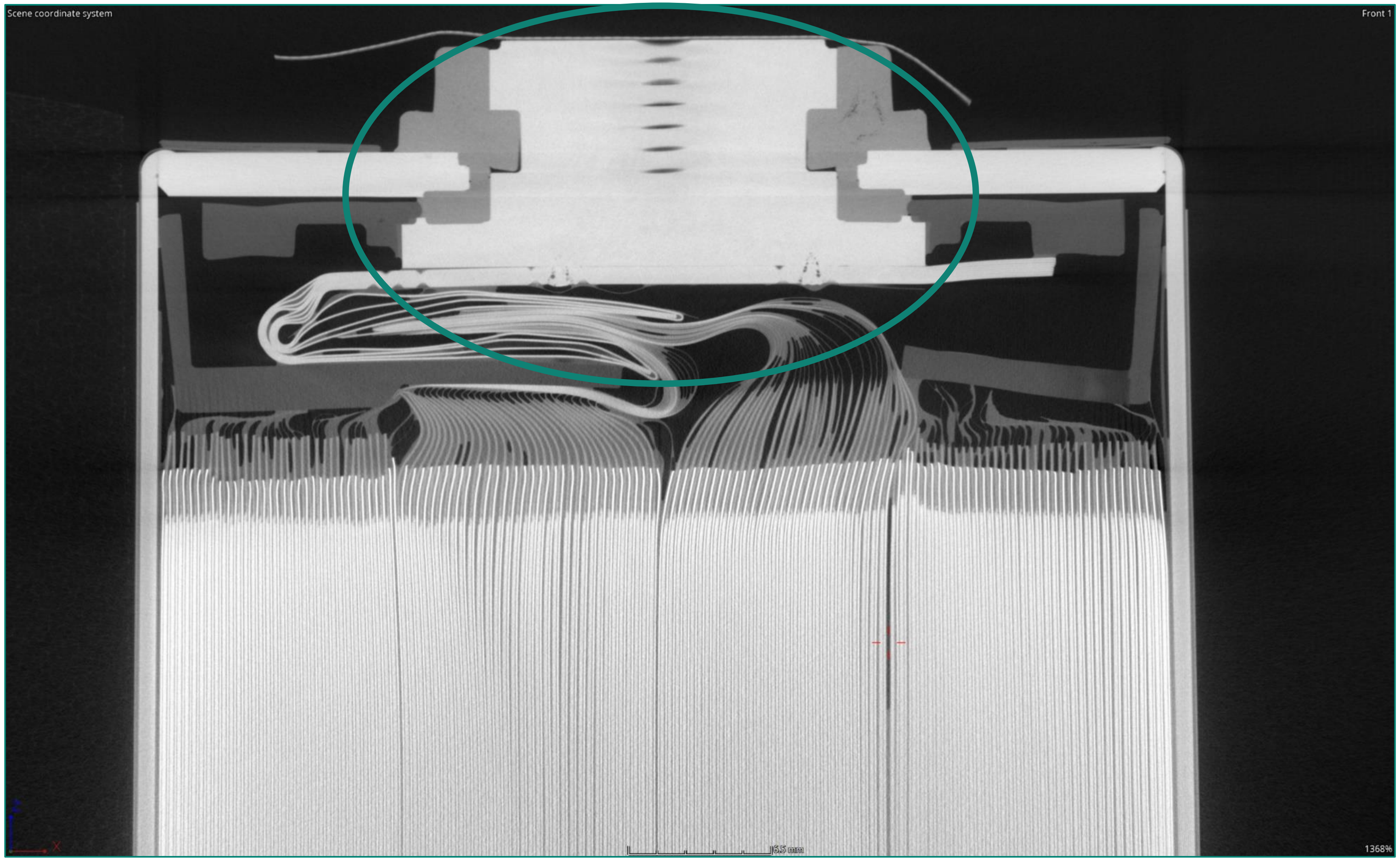
Elerix 100Ah scan of top part



Elerix 100Ah top part

CT X-Ray image

V|tome|x M300

260 kV / 110 µA

Scan time 2 h

Voxel size 20 µm (Resolution 2)

Slice view. Cathode and its welding. - Red cross on next slide perpendicular.

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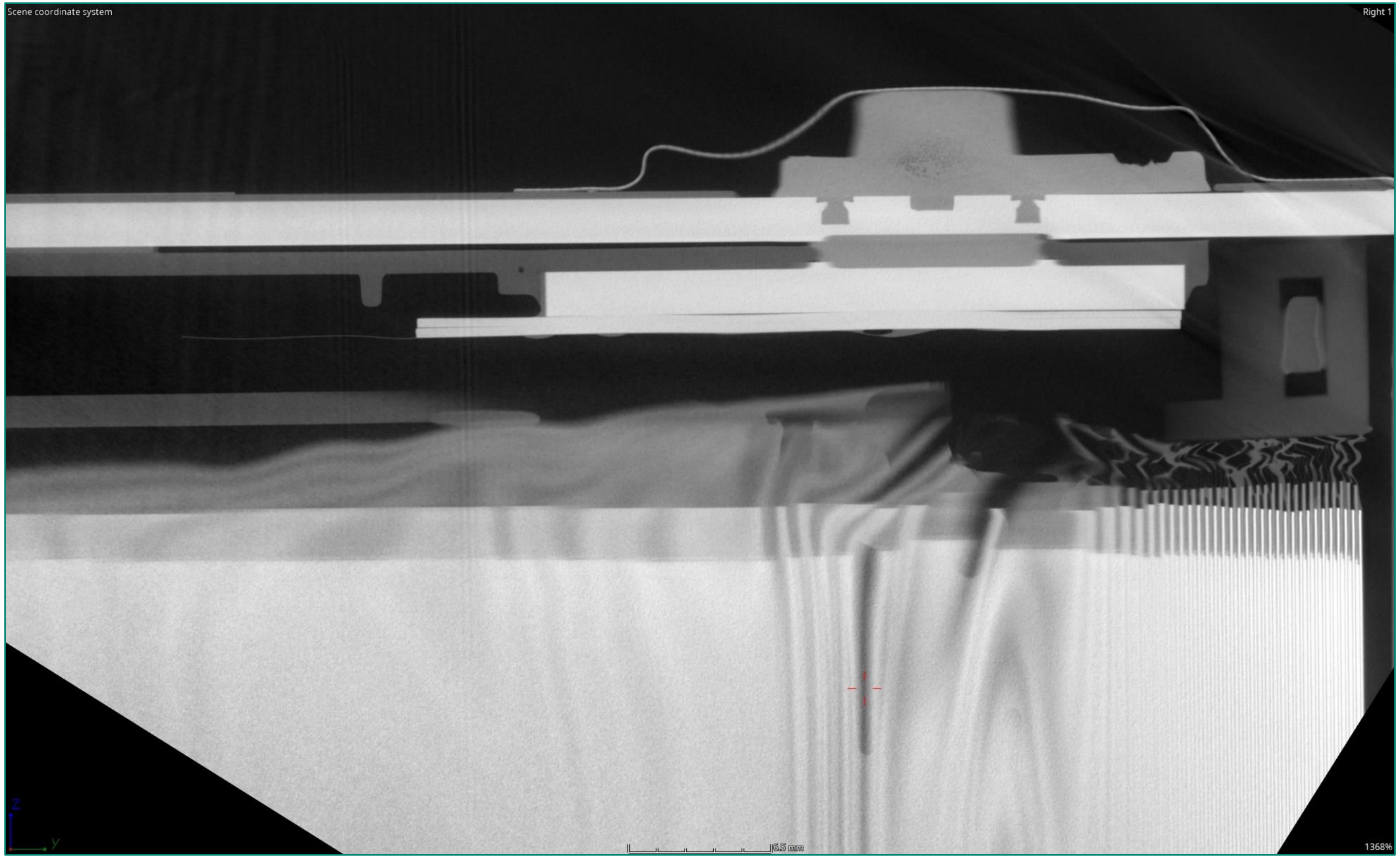
Elerix 100Ah scan of top part



Elerix 100Ah top part

CT X-Ray image

V|tome|x M300

260 kV / 110 µA

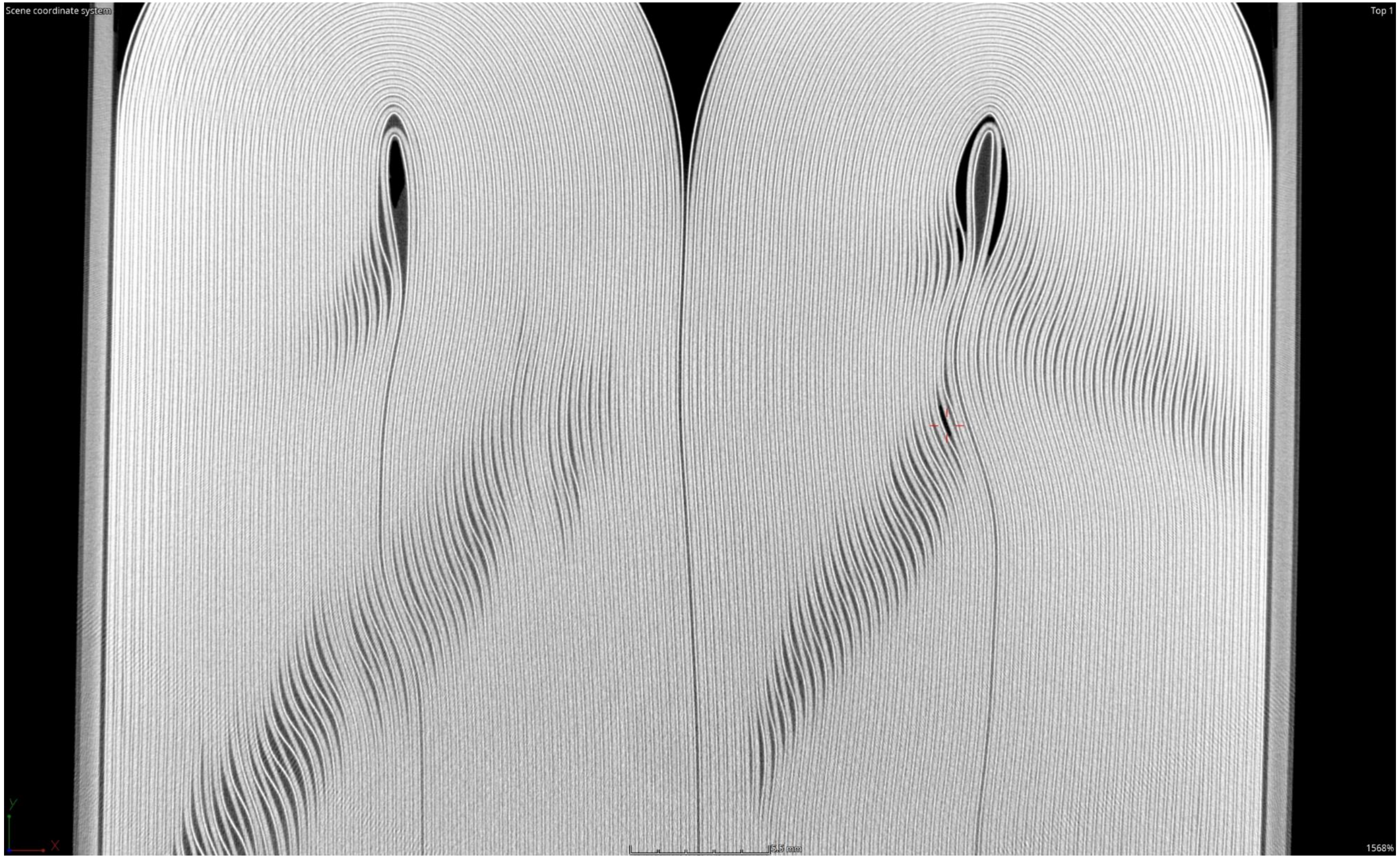
Scan time 2 h

Voxel size 20 µm

Slice view. Red cross of previous slide in perpendicular view.

Waygate Technologies
a Baker Hughes business

Elerix 100Ah scan of top part



Elerix 100Ah top part

CT X-Ray image

V|tome|x M300

260 kV / 110 μA

Scan time 2 h

Voxel size 20 μm

Slice view. Red cross shows details of slice 25 again. Alignment of cathodes and anodes in jelly rolls.

Waygate Technologies
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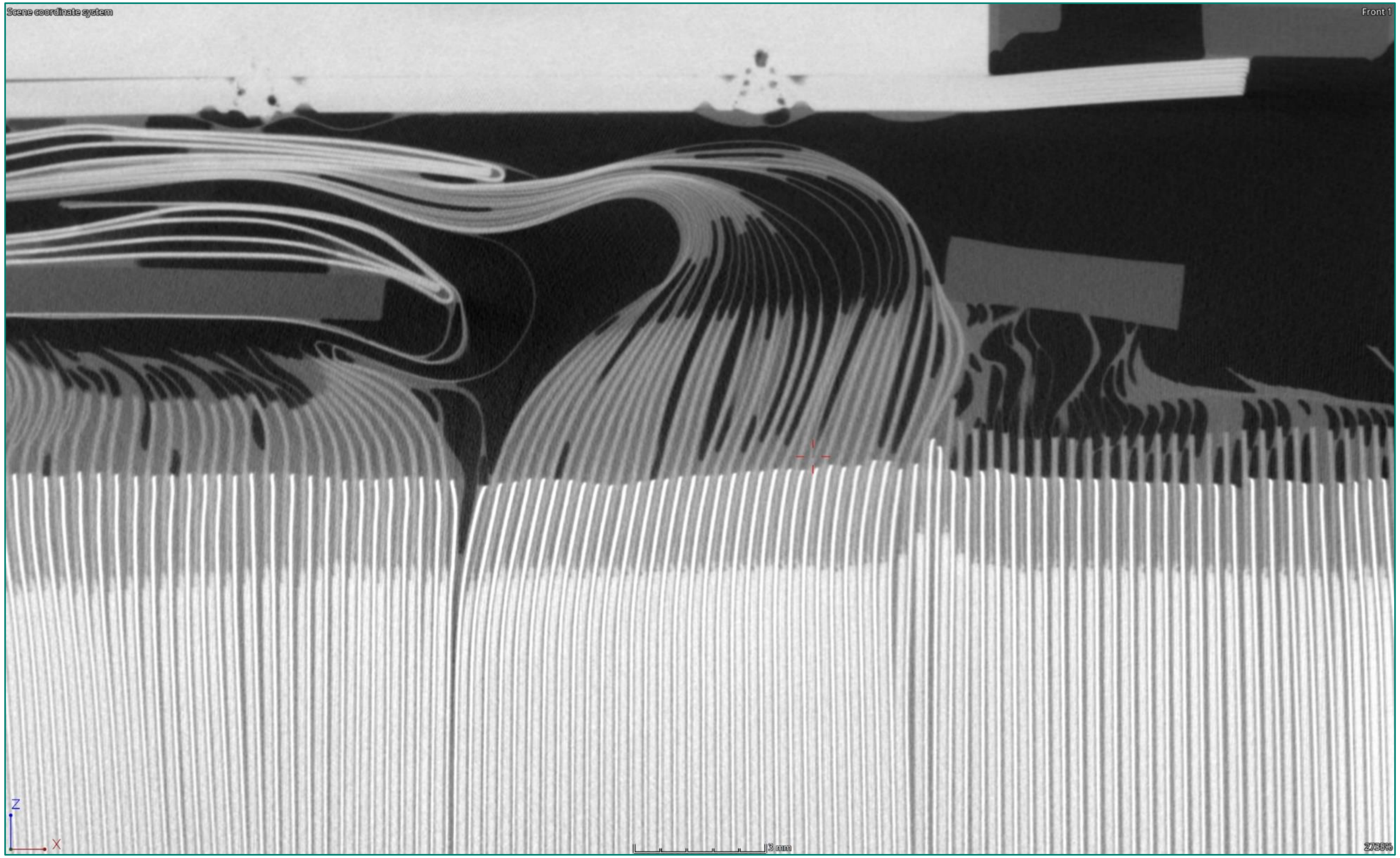
Elerix 100Ah scan of top part



Elerix 100Ah top part

CT X-Ray image

V|tome|x M300

260 kV / 110 µA

Scan time 2 h

Voxel size 20 µm

Slice view in cathode area. Welding quality can be inspected. – Red cross highlights cross section of next page in overhang area.

Waygate Technologies

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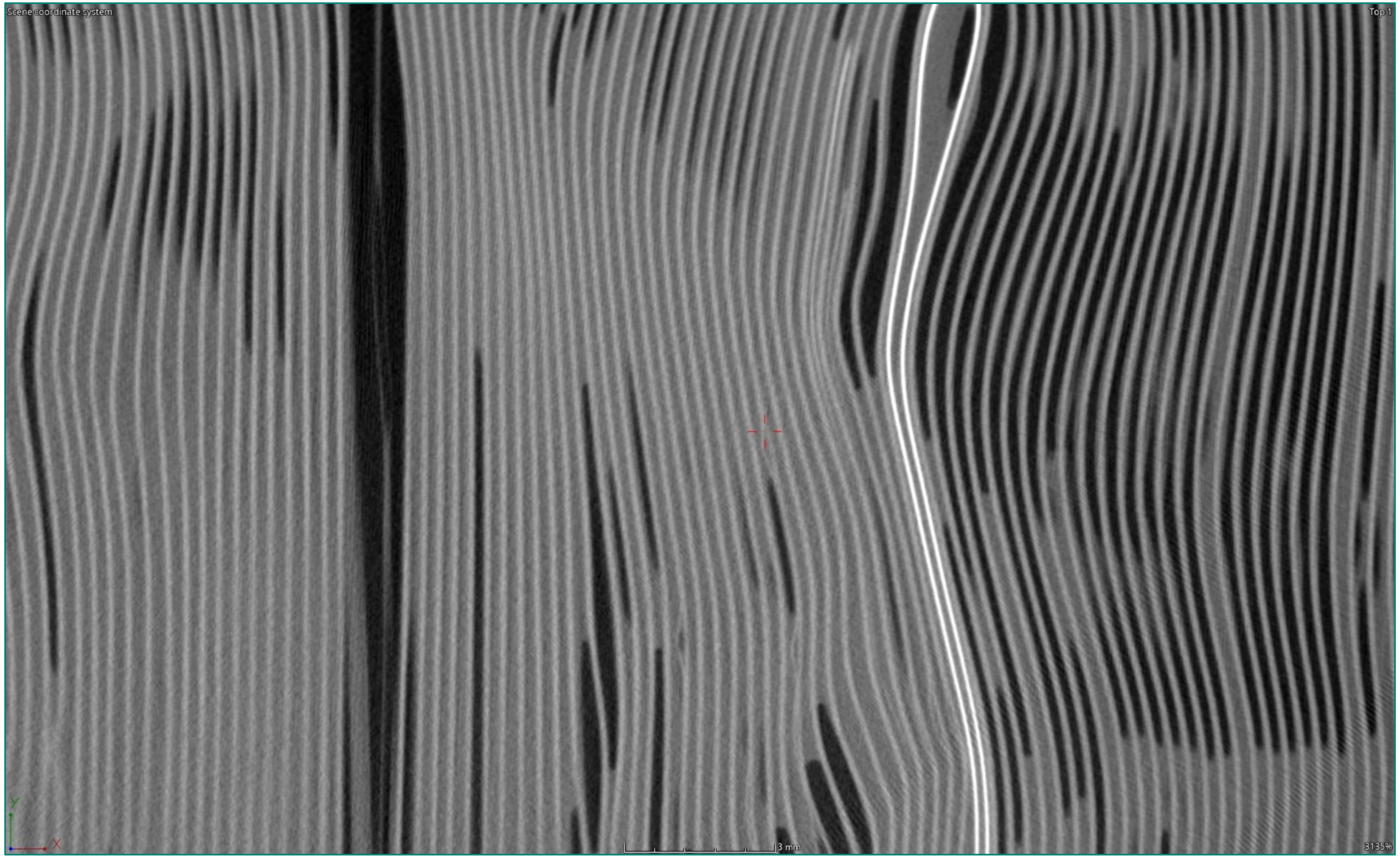
Elerix 100Ah scan of top part



Elerix 100Ah top part

CT X-Ray image

V|tome|x M300

260 kV / 110 µA

Scan time 2 h

Voxel size 20 µm

Red cross highlights cross section of overhang area of previous page in a perpendicular view.

Waygate Technologies
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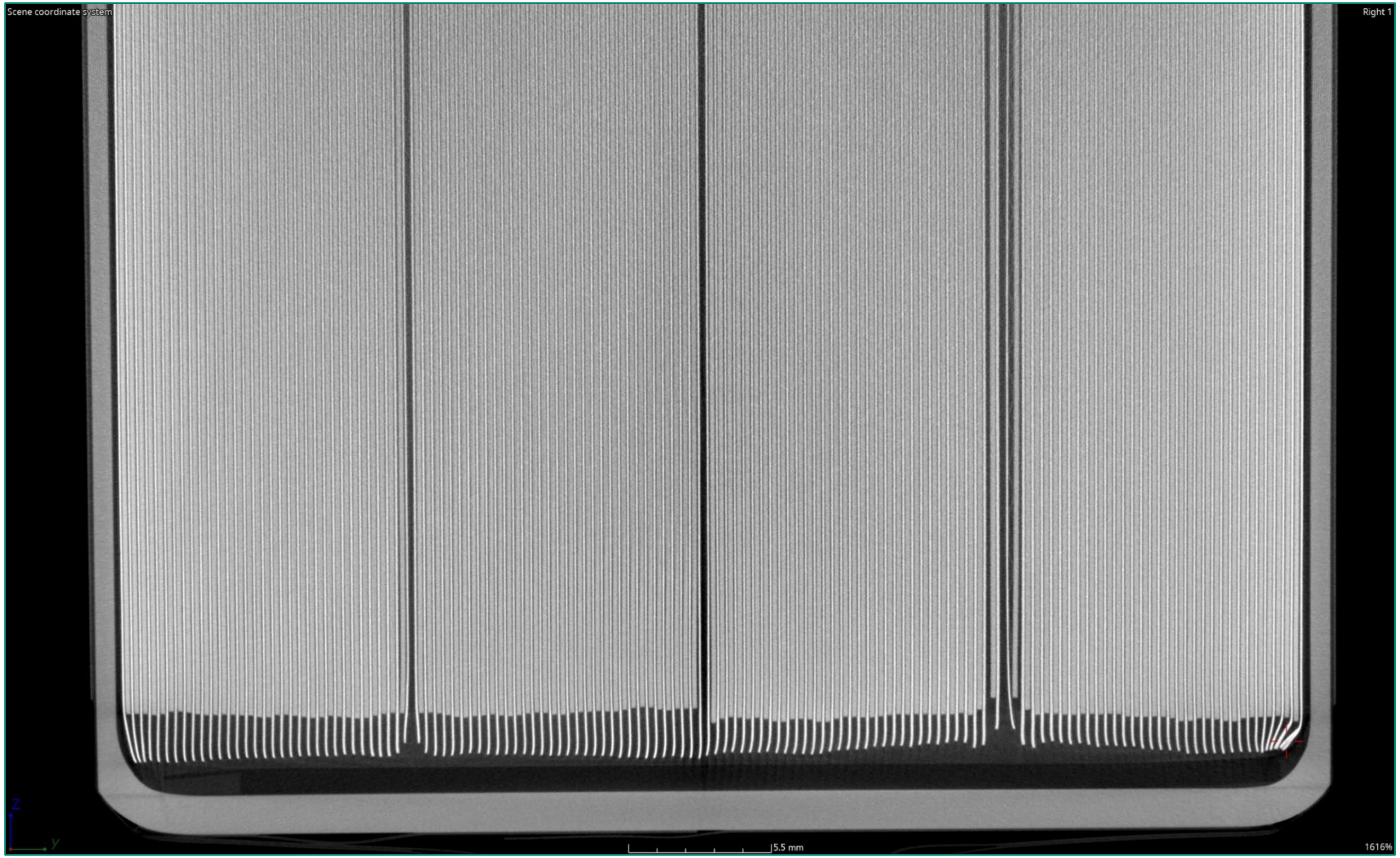
Elerix 100Ah scan of bottom part



Elerix 100Ah bottom part

CT X-Ray image

V|tome|x M300

260 kV / 110 μA

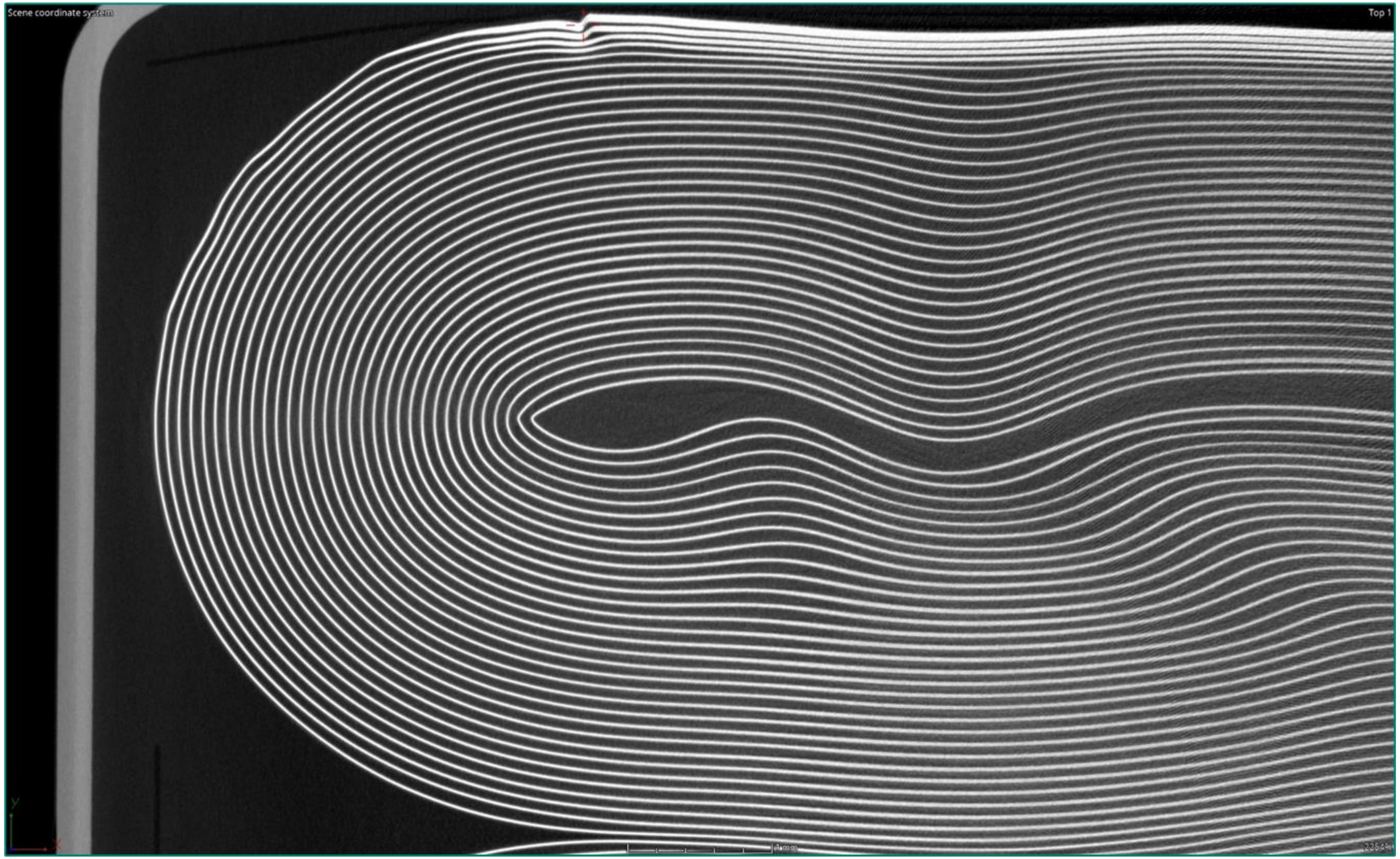
Scan time 2 h

Voxel size 17 μm (Resolution 2)

Red cross indicates cross section of next slide.

Waygate Technologies
a Baker Hughes business

Elerix 100Ah scan of bottom part



Elerix 100Ah bottom part

CT X-Ray image

V|tome|x M300

260 kV / 110 µA

Scan time 2 h

Voxel size 17 µm

Red cross area of previous slide (perpendicular) showing alignment quality.

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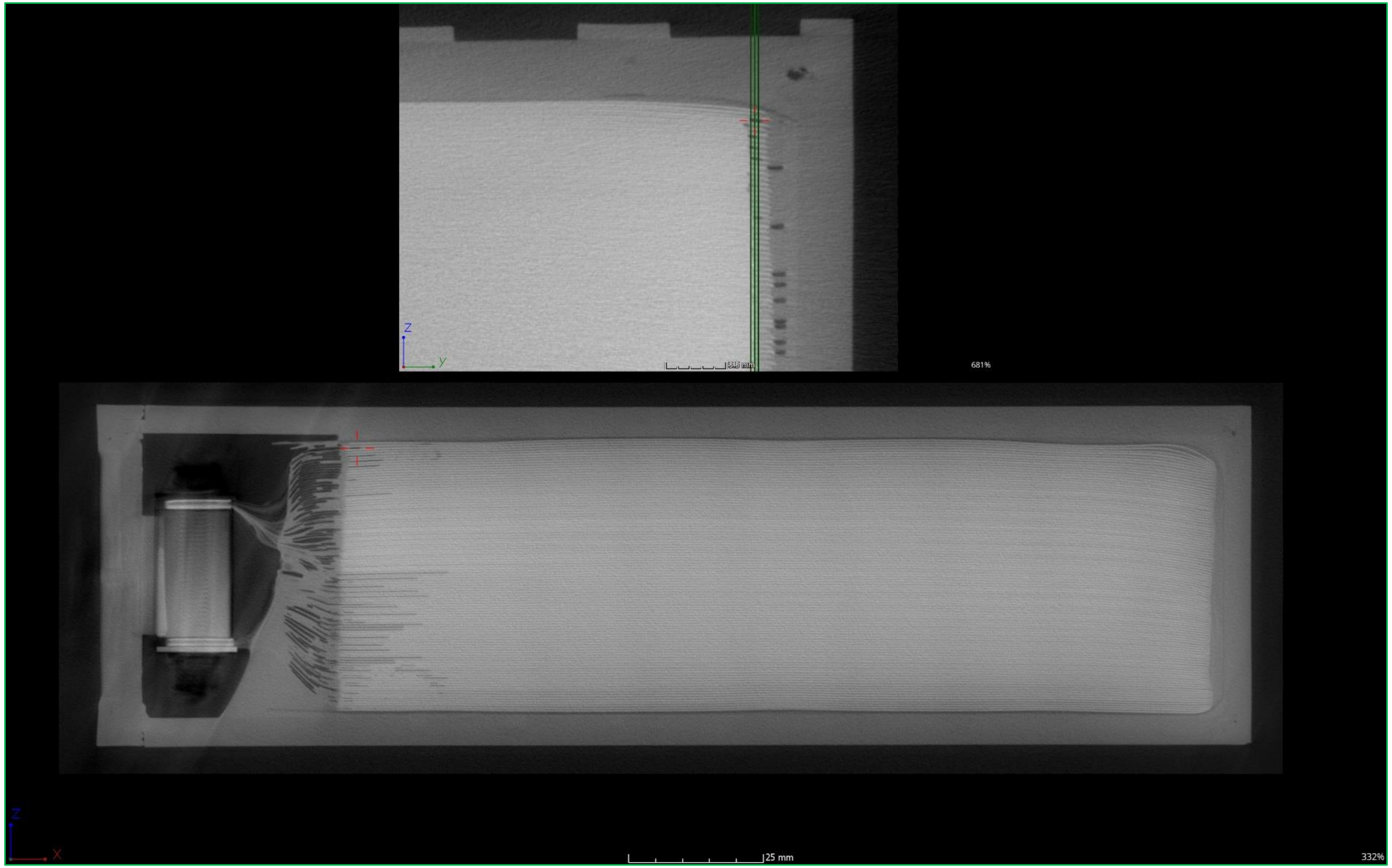
Winston 100Ah overview scan



Winston 100Ah

CT X-Ray image

V|tome|x L450

450 kV / 1500 µA

Scan time 130 min

Voxel size 70 µm

Two overview slice views. Red cross presents always the same "point" in the slice views.

Waygate Technologies
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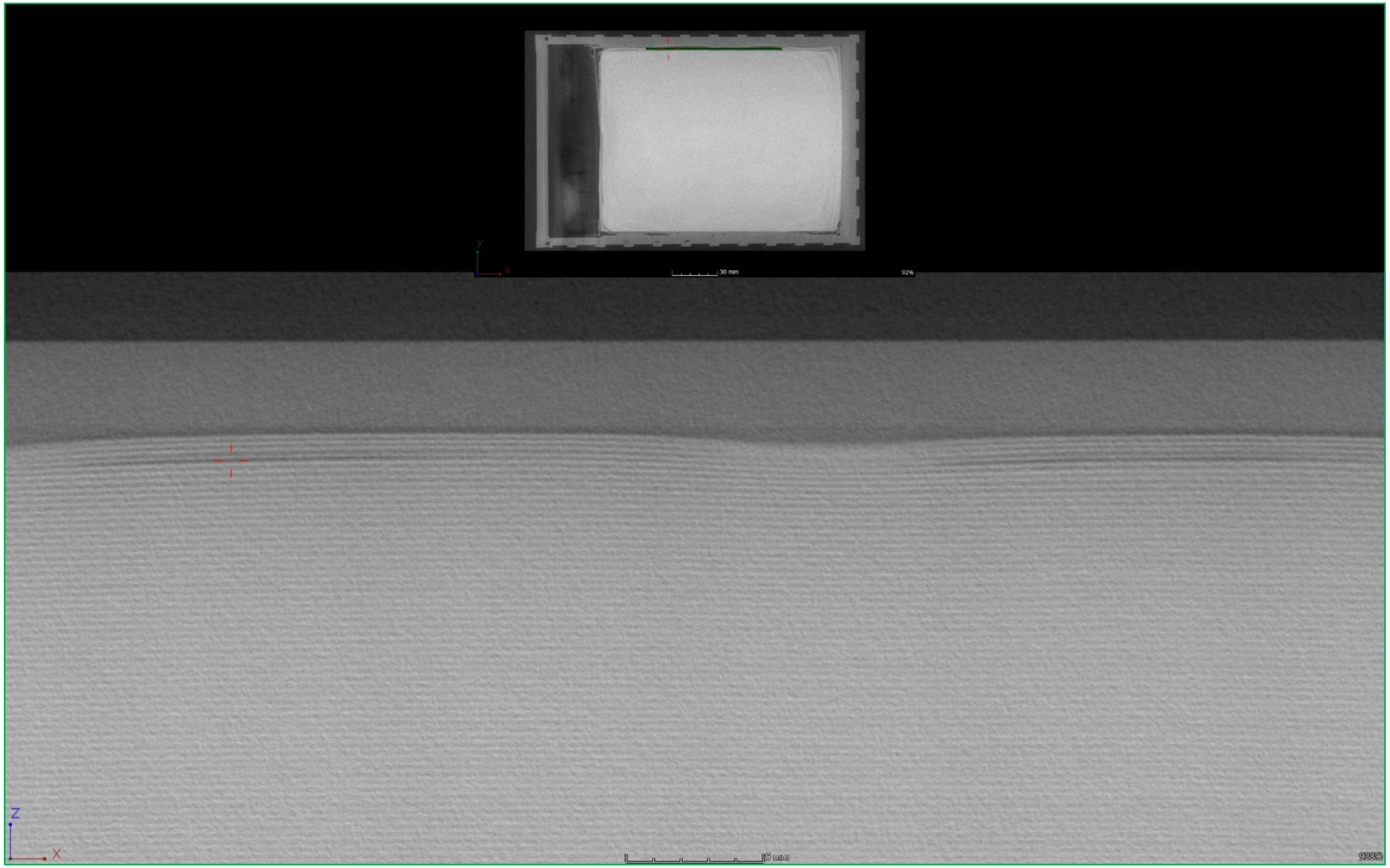
Winston 100Ah overview scan



Winston 100Ah

CT X-Ray image

V|tome|x L450

450 kV / 1500 µA

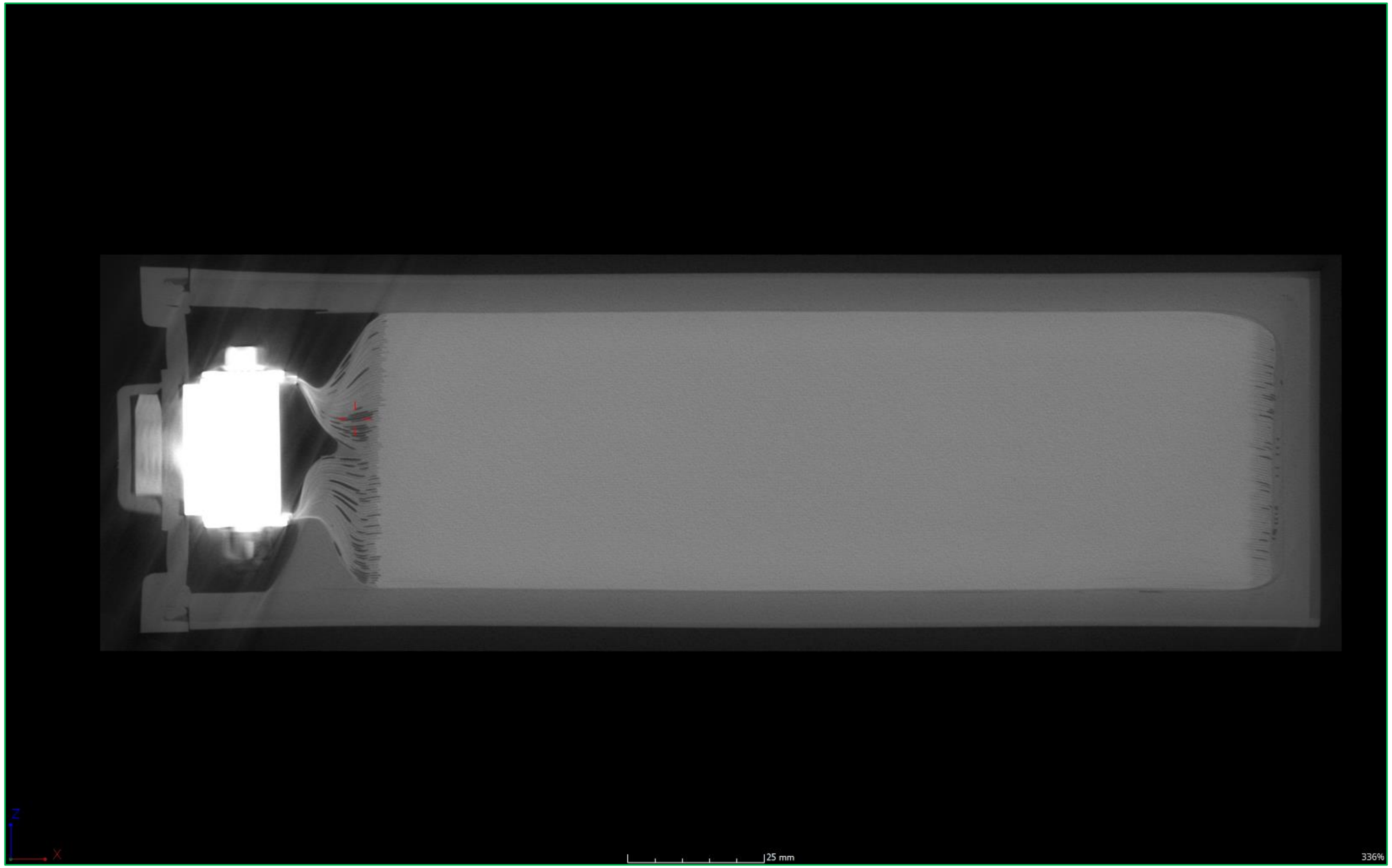
Scan time 130 min

Voxel size 70 µm

Slice view (along green line of small image above). – Alignment of cathodes and anodes is visible.

Waygate Technologies
a Baker Hughes business

Winston 100Ah overview scan



Winston 100Ah

CT X-Ray image

V|tome|x L450

450 kV / 1500 µA

Scan time 130 min

Voxel size 70 µm

Slice view of anode (copper, white) area. Red cross in area is shown on next slide in cross section.

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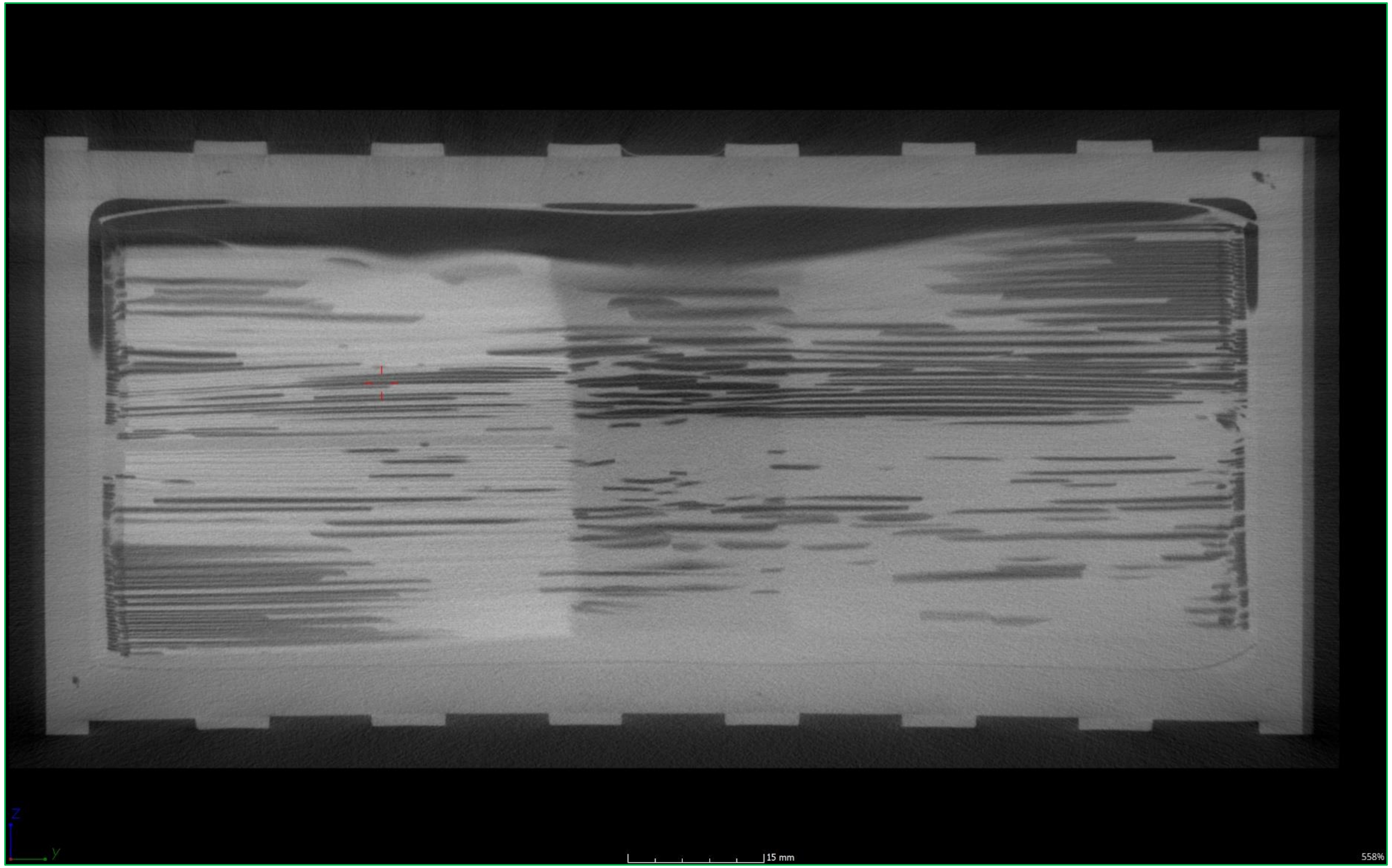
Winston 100Ah overview scan



Winston 100Ah

CT X-Ray image

V|tome|x L450

450 kV / 1500 µA

Scan time 130 min

Voxel size 70 µm

Slice view. Red cross in the region of the overhang area which was presented on previous slide.

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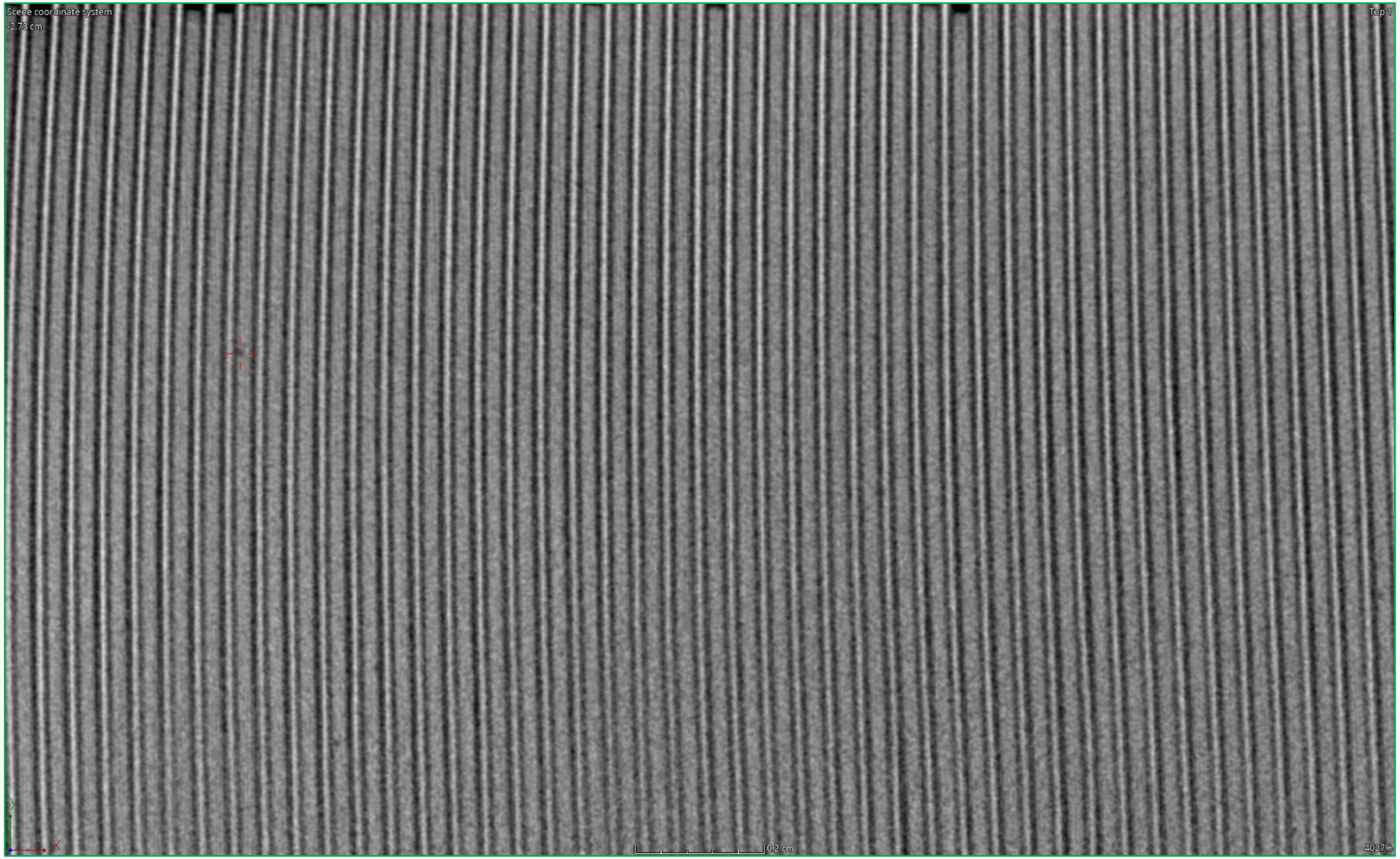
Winston 100Ah scan of top part



Winston 100Ah top part

CT X-Ray image

V|tome|x M300

260 kV / 110 µA

Scan time 2 h

Voxel size 20 µm (Resolution 2)

Slice view. Alignment of cathodes and anodes.

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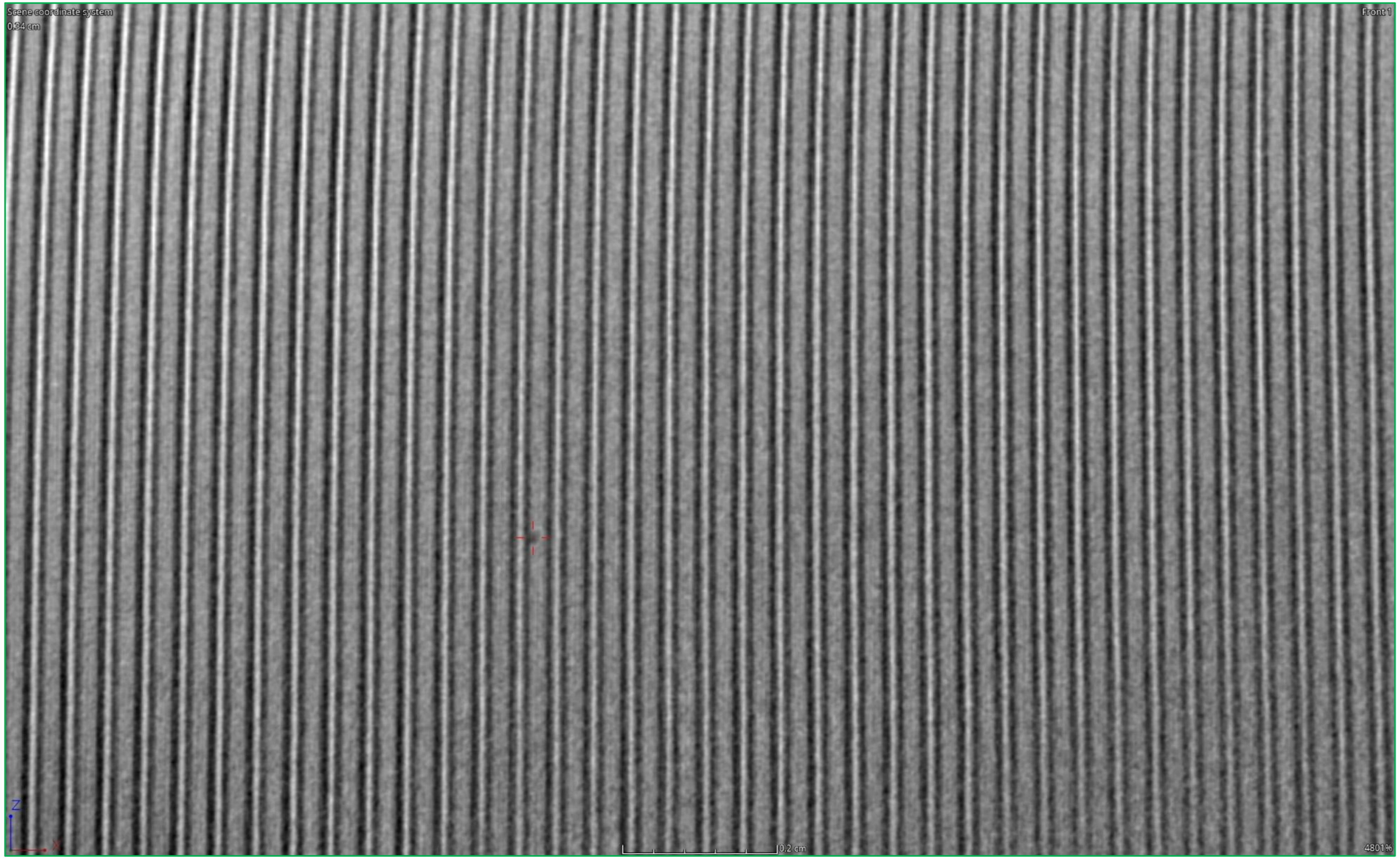
Winston 100Ah scan of top part



Winston 100Ah top part

CT X-Ray image

V|tome|x M300

260 kV / 110 µA

Scan time 2 h

Voxel size 20 µm

Slice view. Higher magnification of previous image.

Waygate Technologies
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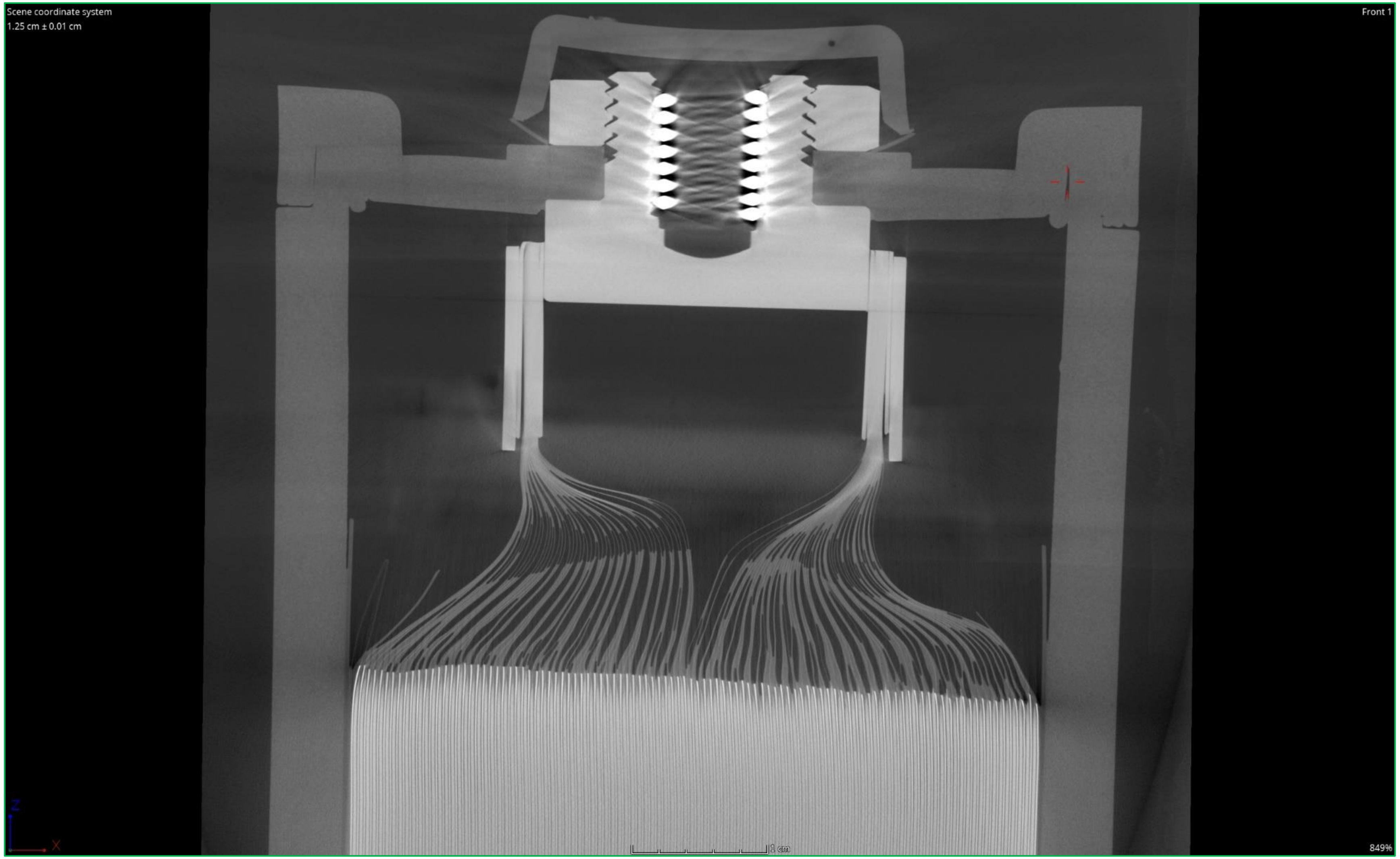
Winston 100Ah scan of top part



Winston 100Ah top part

CT X-Ray image

V|tome|x M300

260 kV / 110 µA

Scan time 2 h

Voxel size 20 µm

Slice view of cathode, overhang area and a part of the housing.

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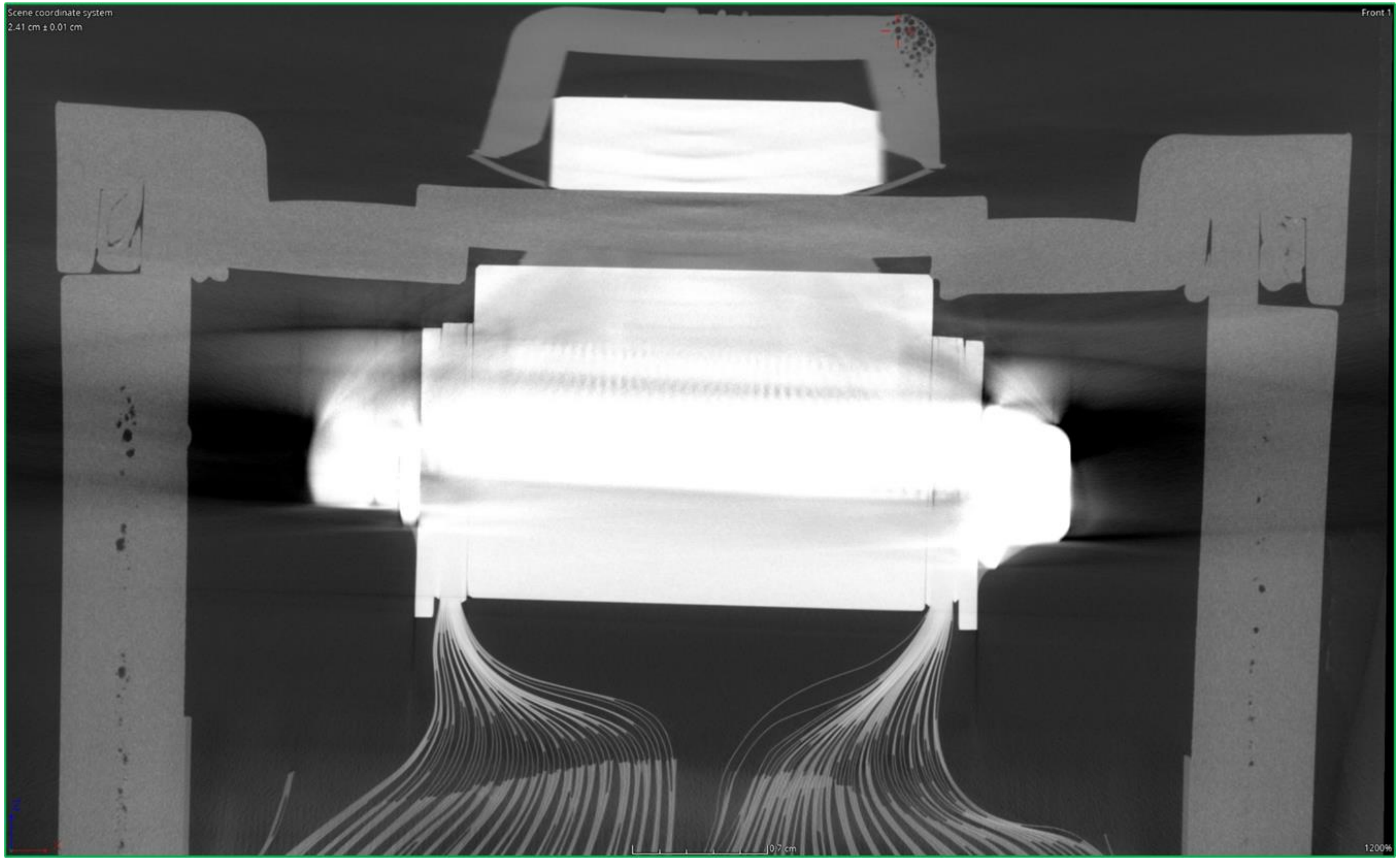
Winston 100Ah scan of top part



Winston 100Ah top part

CT X-Ray image

V|tome|x M300

260 kV / 110 µA

Scan time 2 h

Voxel size 20 µm

Slice view of anode and a part of the housing.

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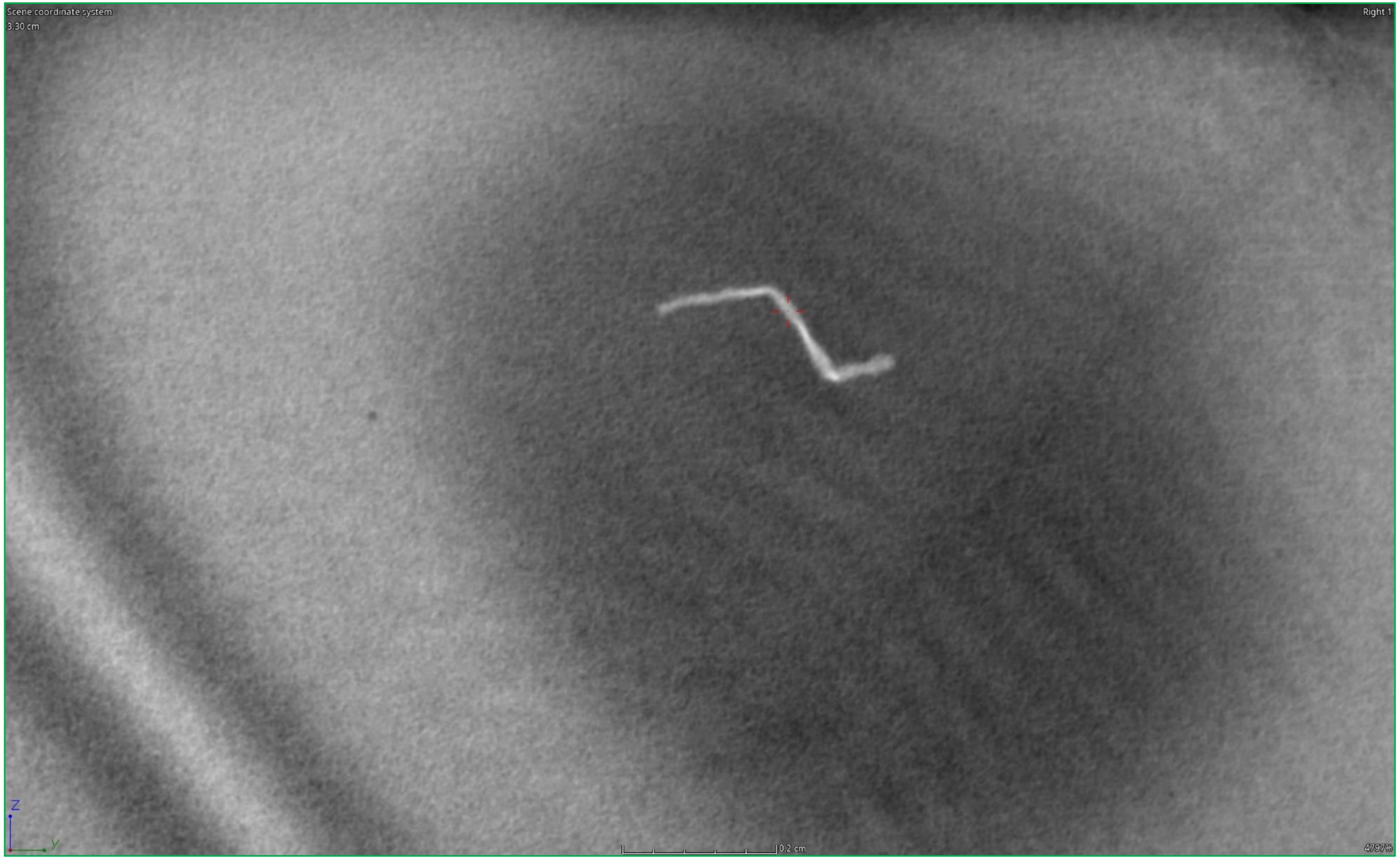
Winston 100Ah scan of top part



Winston 100Ah top part

CT X-Ray image

V|tome|x M300

260 kV / 110 µA

Scan time 2 h

Voxel size 20 µm

Slice view. Red cross indicates very high magnification of a small metal part.

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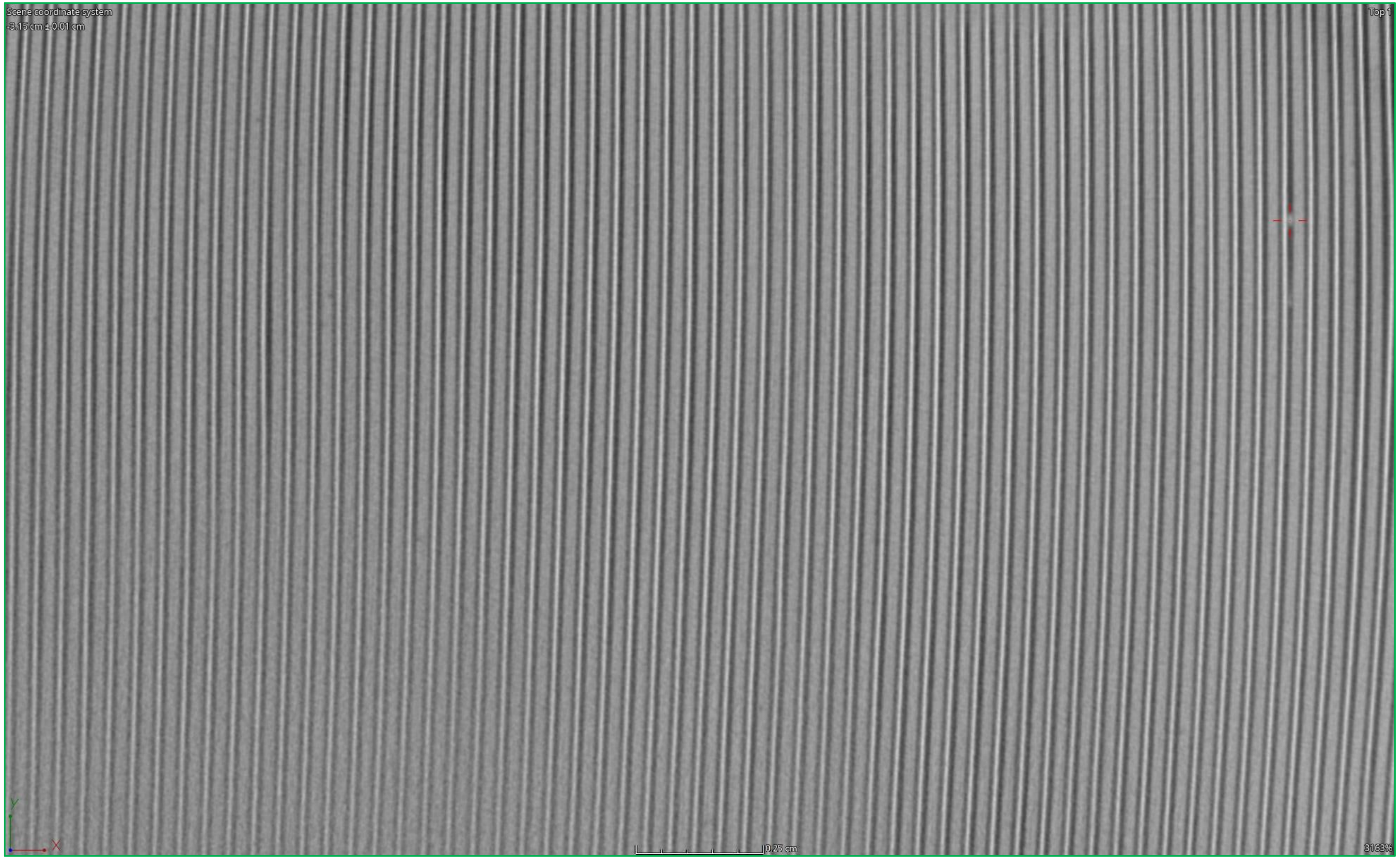
Winston 100Ah scan of top part



Winston 100Ah top part

CT X-Ray image

V|tome|x M300

260 kV / 110 µA

Scan time 2 h

Voxel size 20 µm

Lower magnification of alignment of cathodes and anodes.

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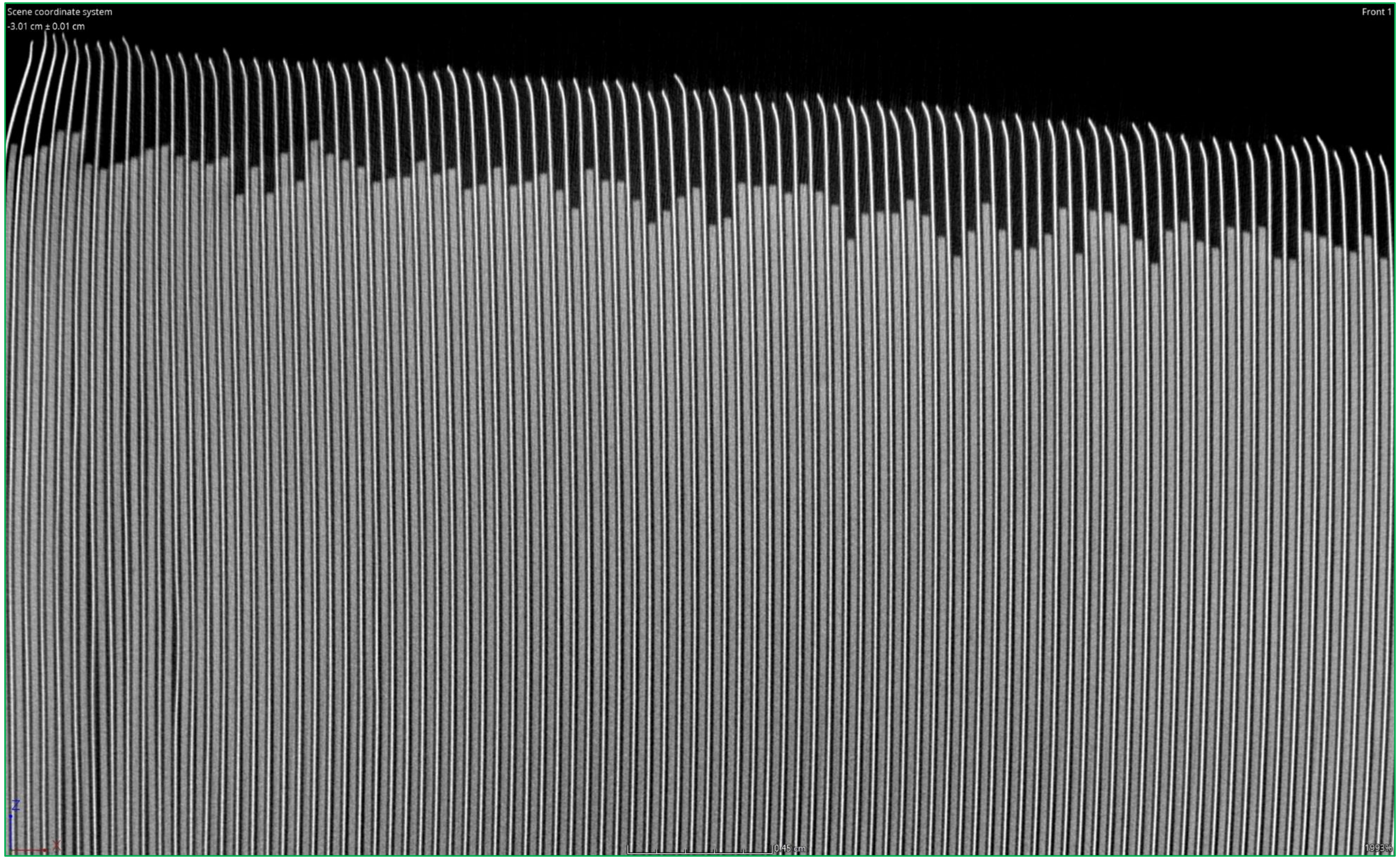
Winston 100Ah scan of bottom part



Winston 100Ah bottom part

CT X-Ray image

V|tome|x M300

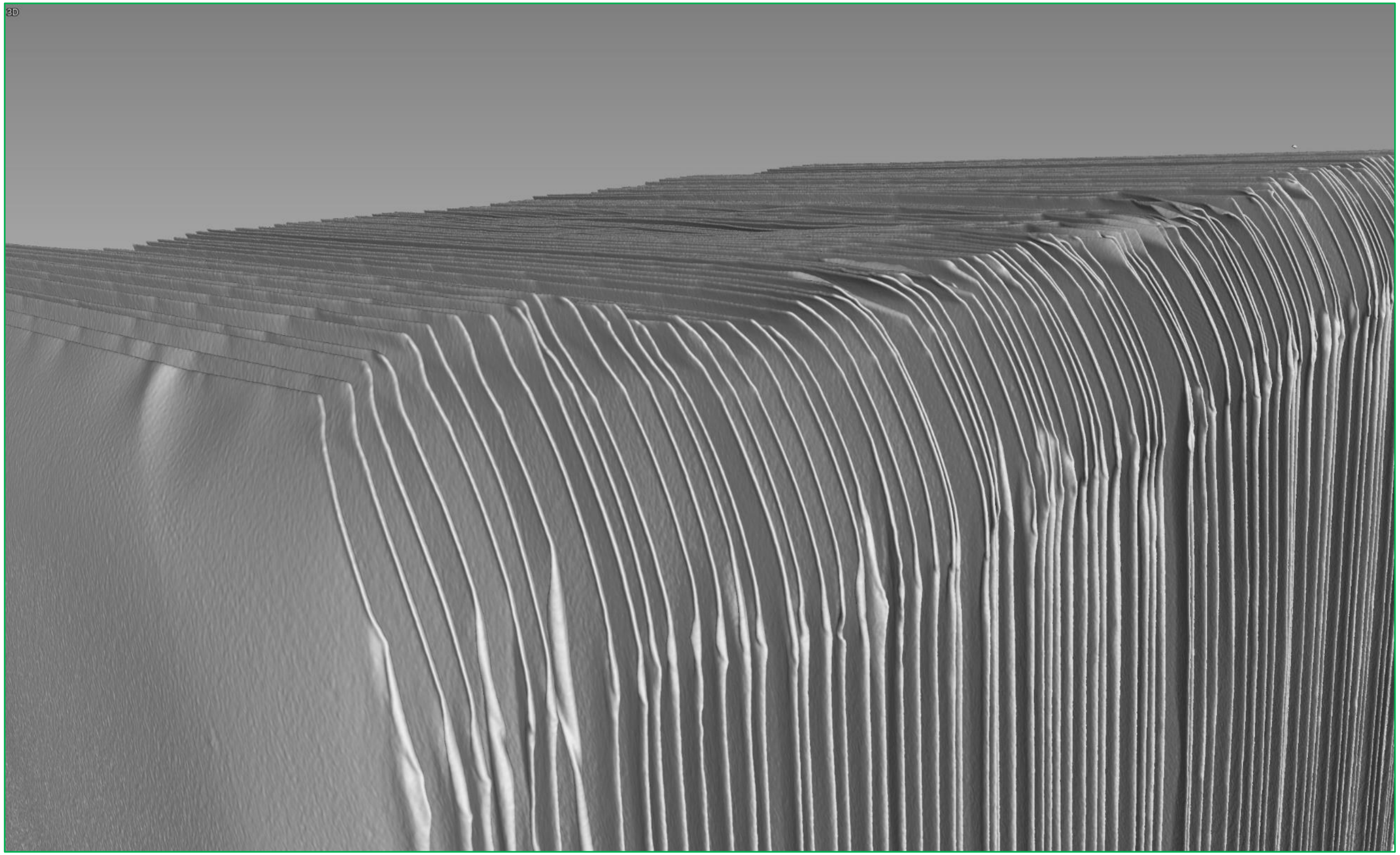
260 kV / 110 µA

Scan time 2 h

Voxel size 17 µm (Resolution 2)

Presentation of overhang at medium magnification.

Winston 100Ah scan of bottom part



Winston 100Ah bottom part

CT X-Ray image

V|tome|x M300

260 kV / 110 µA

Scan time 2 h

Voxel size 17 µm

3D view of electrodes stack.

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a Baker Hughes business

Scan Parameters

In this section you find the scan parameters for the scans.

Scan Parameters: CT Scans with V|tome|x L450

System	Phoenix V|tome|x L450
Acq./rec. software:	datos|x 2.9
Voxel size:	65-70 µm
Tube parameters: voltage, filter	450 kV / 1.0 mm Brass, 4.5 mm Sn
Tube current / target power:	1500 µA / 675 W
Focal spot size:	400 µm (calculated)
Exposure time (Average / Skip):	1000 ms (4/1), Winston 1000 ms (2/1)
No of images / total scan time:	2000 / 2.8 h (Winston 130 min)
Reconstruction time:	Less than 1 min

Waygate Technologies
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Scan Parameters: CT Scans with V|tome|x M300

System	Phoenix V|tome|x M300
Acq./rec. software:	datos|x 2.9
Voxel size:	17-22 µm
Tube parameters: voltage, filter	260 kV / 0.5 mm Cu
Tube current / target power:	110 µA / 28.6 W
Focal spot size:	28.6 µm (calculated)
Exposure time (Average / Skip):	500 ms (6/1)
No of images / total scan time:	2000/ 2 h
Reconstruction time:	Less than 1 min

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Recommended Solution

Adjacently we recommend an optimized technical solution including X-ray system and software as well as required options and accessories.

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V|tome|x L450

- 450 kV / 1500 W
bipolar minifocus X-ray tube
- Fast CT acquisition and brilliant images by next generation highly sensitive Dynamic 41|100 detector with 100 µm pixel pitch for detection of 2x smaller defects and inspection of larger objects at higher resolution (optional Dynamic 41|200) .

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V|tome|x M300

- 300 kV / 500 W Open directional microfocus X-ray tube
- Temperature stabilized GE Dynamic 41|200 detector with superior image quality, 16” x 16”, 200 µm pixel size, 2036 x 2036 pixels extremely high dynamic range > 10000:1
- Optional high-resolution 180 kV nano CT®
- Optional GE Dynamic 41|100 detector, 16 MP, 100 µm Pixel Size.
- Optional high-flux|target
- Optional fully automated robot
- Optional scatter|correct technology to perform cone beam CT scans with the quality level of up to 100 times slower fan beam CT

Glossary

On the following slides you find a glossary and some illustrations for the main technical terms in X-ray inspection and CT systems.

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Terminology: X-ray tubes

tube voltage U_{Acc}	Acceleration voltage for the elctron in the X-ray tube	
tube current I_{tube}	electric current of the electron beam in the tube	
hp tube	high power tube- standard sealed X-ray tube focal spot 200 μm .. 1000 μm	
microfocus tube	an X-ray tube with focal spot < 100 μm	
nanofocus tube	an X-ray tube with focal spot < 1 μm	Waygate
open X-ray tube	an X-tay tube with a permanentely pumped housing, can be opened to replace wear-out part	
sealed X-ray tube	an X-tay tube with a sealed housing, maintenance free	
focal spot size F, φ	diameter of the focal spot, i.e. the X-ray source	ASTM E1000

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Terminology: CT Systems

Voxel	element of a tomographic volume	ASTM E1316
Voxel size Δv	Length,width heigt of a voxel $\Delta v = \frac{\Delta p}{v}$	ASTM E1441
FDD	Focus-Detector-Distance	
FOD	Focus-Object-Distance	
Cone beam CT	CT using a DDA, also 3D CT	ASTM E1441
Fan beam CT	CT using a LDA, also 2D CT	ASTM E1441

Terminology: CT Systems

roi|scan	a CT scan only of a part of the sample diameter	
sector|scan	a CT scan of only a sectiobof the sample diameter in an incomplete rotation	Waygate
helix|scan	scan with helix shaped trajectory (see image),free from Feldkamp artefact	
fast|scan	scan under contious rotation – saved manipulation time	Waygate
x-offset	scan with rotation off center to increase field of view	
virtual detector	the detector moves in x-direction to increase field of view	
multi|bhc	software to correct multiple beam hardening artefacts	Waygate
scatter|correct	physical apparatus to remove scatter effects from a scan	Waygate

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Terminology: Detectors

DDA	Digital Detector Array	ASTM E1441
LDA	Linear Detector Array	ASTM E1441
Pixel	smallest element of a DDA or LDA	ASTM E1316
Pixel pitch Δp	distance of pixels in X- or Y direction; raster size	ASTM E1316
Scintillator	layer in front of the diodes to convert X-ray to visible light	
Diodes	actuals light sensitive elemnts of the DDA/LDA	
Spider Diagram	standardised diagram to specify detectors	ASTM E2597
SR_b	basic Spatial Resolution	ASTM E2597

Terminology: Image Quality

v, M	geometric magnification $v = \frac{FDD}{FOD}$	ASTM E1000
U_g	geom. unsharpness $U_g = \varphi \left(\frac{FDD}{FOD} - 1\right) = \varphi(v-1)$	
SR_b	Basic spatial resolution of a DDA or LDA	ASTM E2597
SR_b^{image}	Spatial basic resolution in the image (Object Scale)	ASTM E2002
U_T	Total unsharpness	ASTM E1000, E 2002
SNR	Signal-to-Noise Ratio	ASTM E1441
CNR	Contrast-to-Noise Ratio	ASTM E1441
$MTF_{10\%}$	Measure for the resolution of a CT system	ASTM E1414, E1695
CDF	Measure for the detectability of features through noise	ASTM E1414, E1695

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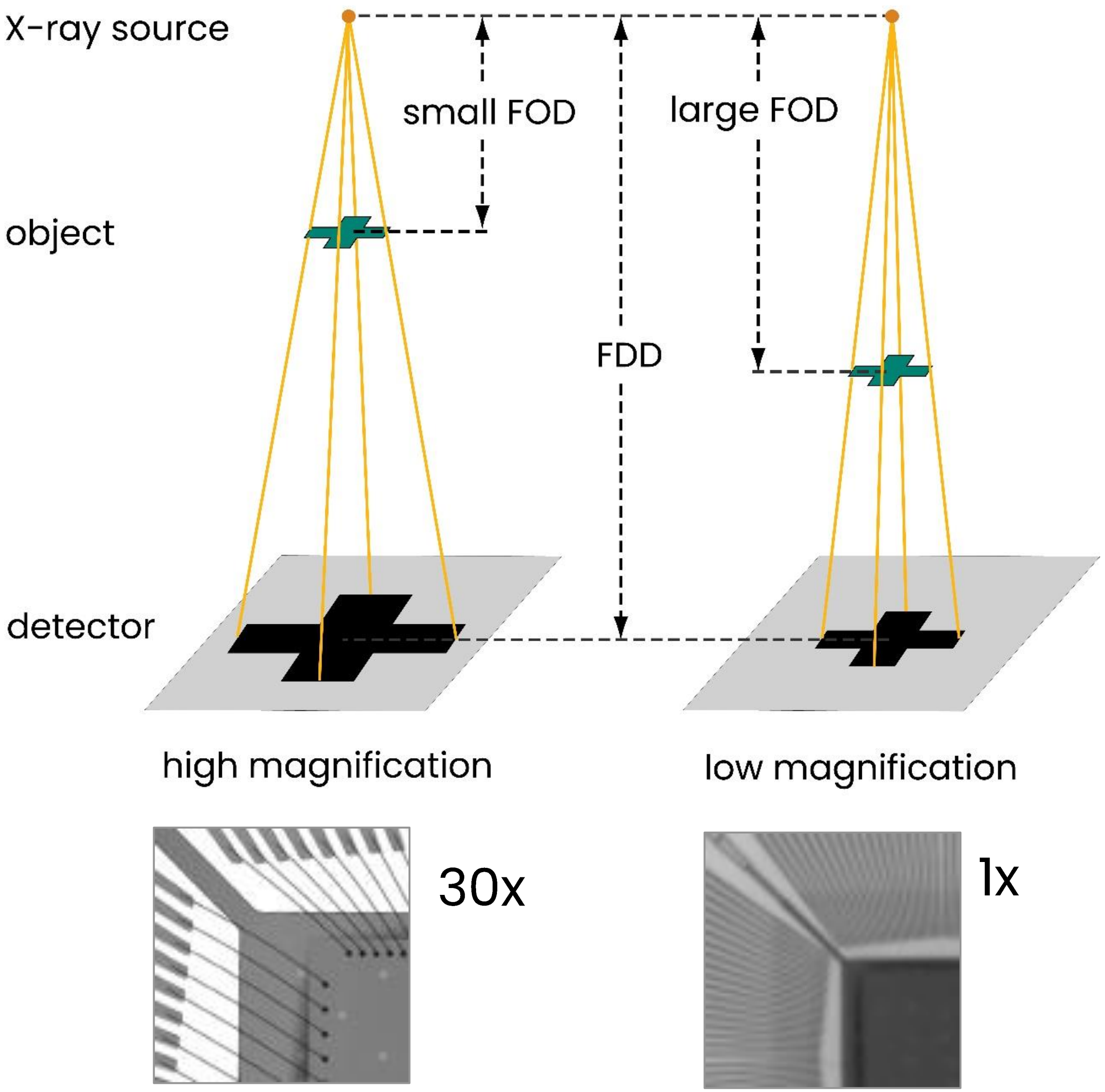
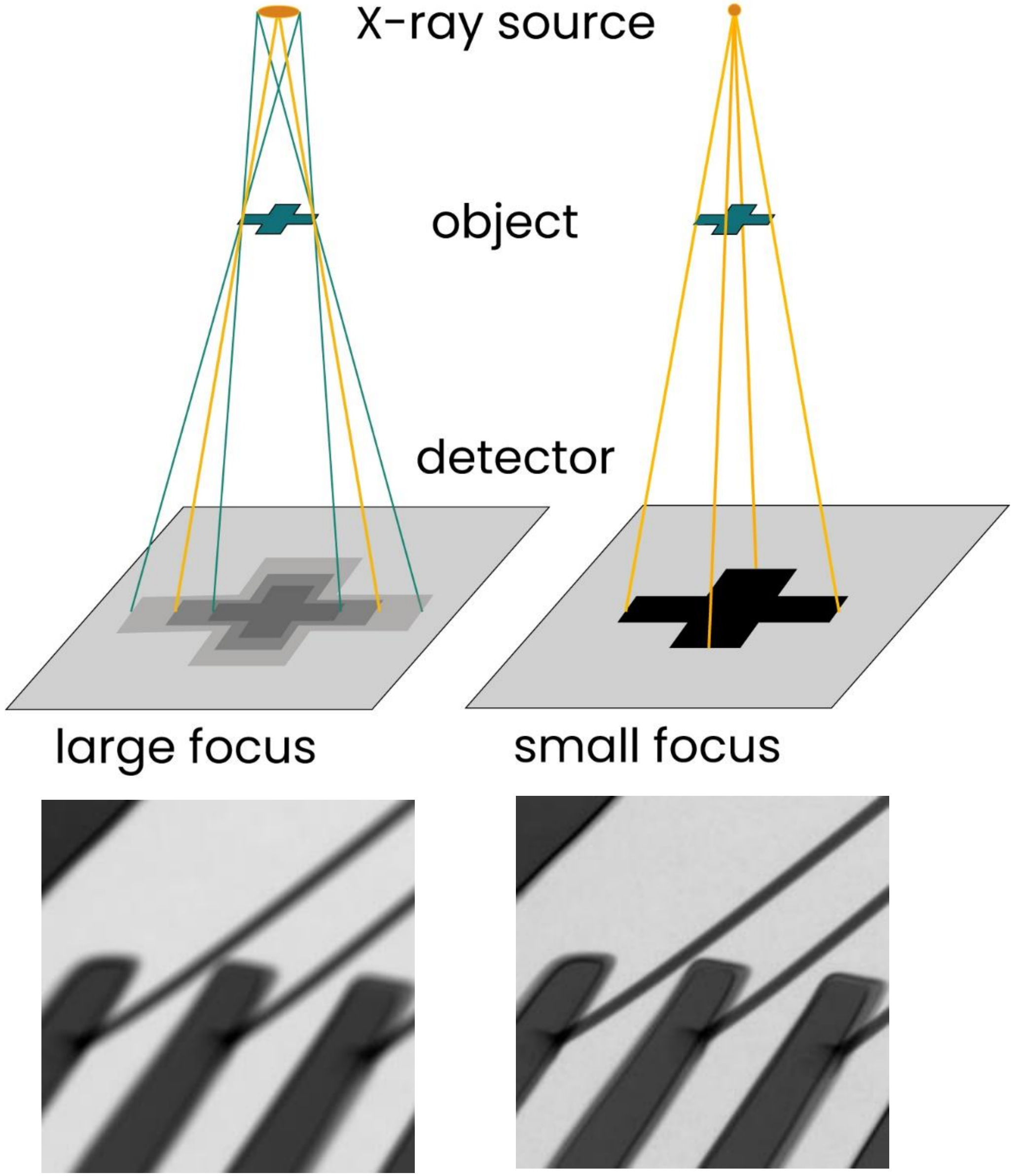
Why magnification?



The geometric magnification is needed to compensate the large pixel pitch of the detectors (100 to 200 µm)

An object feature must be magnified so that its image covers severals pixels to be clearly detectable.

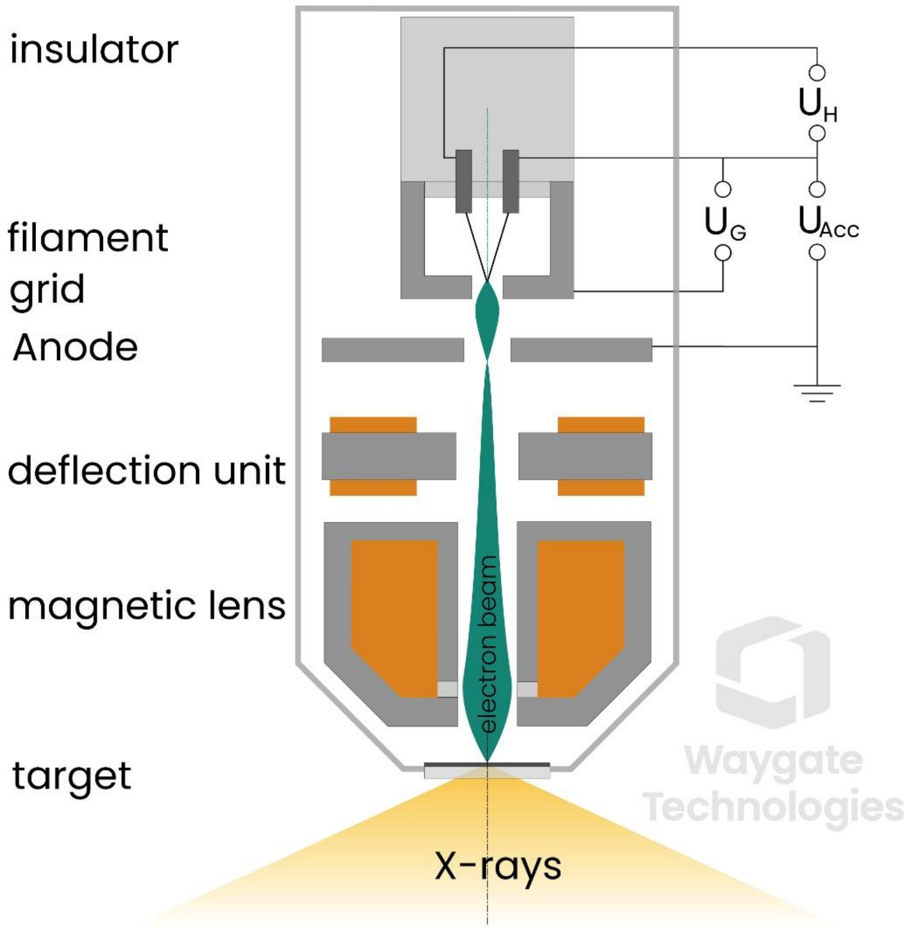
Why microfocus….?



The size of the focal spot or source causes a penumbra (half-shadow) or geometric unsharpness around the object points that compromises the resolution of the system.

By microfocus and nanofocus tubes we make the source small enough to minimize this effect.

How do microfocus ...?



Electrons are emitted from the filament heated by the heating voltage U_H and accelerated by the potential difference U_{Acc} (generator).

They propagate trough a hole in the anode.

Then they drift in field-free space.

The beam is aligned by deflection units and focused by a magnetic lens on to a spot on the target, the focal spot which is the actual X-ray source.

The current is controlled by the grid electrode voltage U_G.

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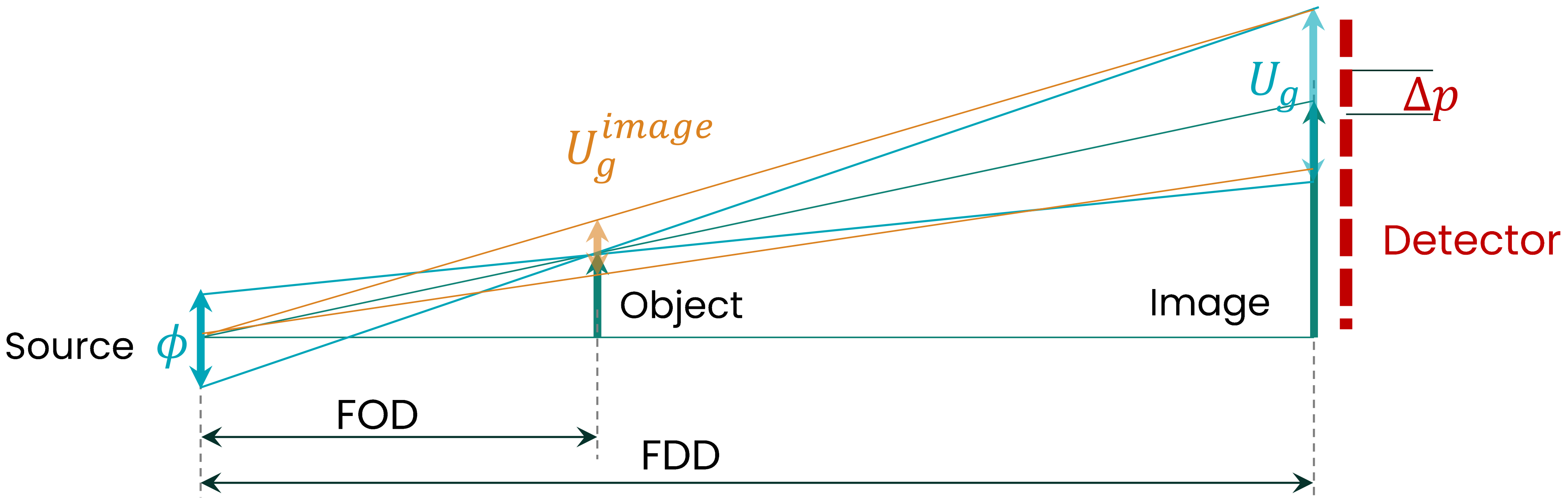
How to calculate total unsharpness?



The detector SR_b and the geometric unsharpness U_g both contribute to total unsharpness U_T

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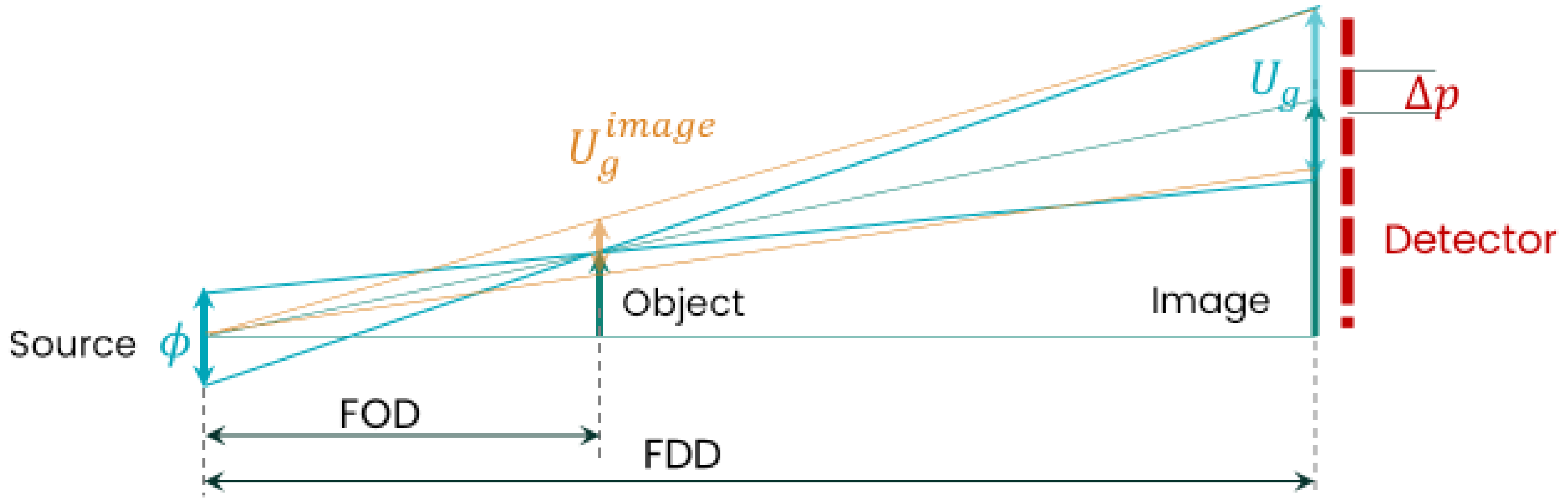
The Formula from ISO 17636-2 (adapted)

$$U_T^{image} = \frac{1}{v} \cdot \sqrt[2]{U_g^2 + U_{det}^2}$$

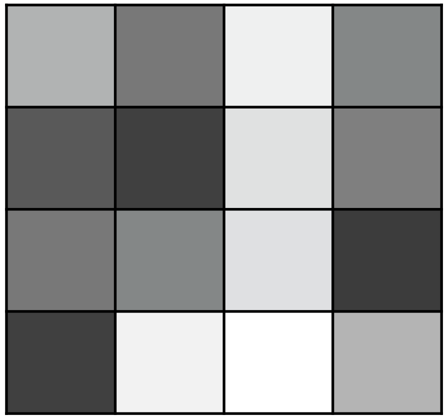
$$U_T^{image} = \frac{1}{v} \cdot \sqrt[2]{\left((v-1)\varphi\right)^2 + (2 \cdot SR_b)^2}$$

Tube Detector



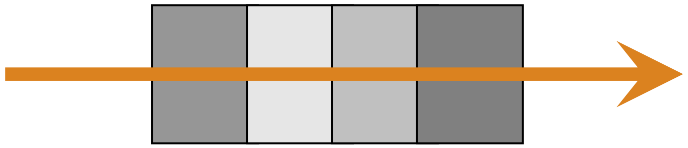
X-ray image and tomogram

An X-ray image is a 2D matrix of image element, the pixels.
Each pixel holds a pixel value which correspond to the received dose.



So each pixel contains information about the matter which was in the paths of the beams that hit this pixel:

I_0



$$I(x,y) = I_0 e^{\int -\mu(x,y,z)ds}$$

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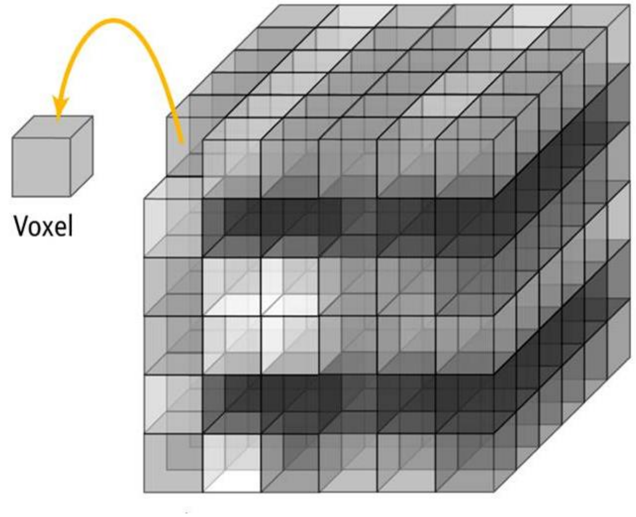
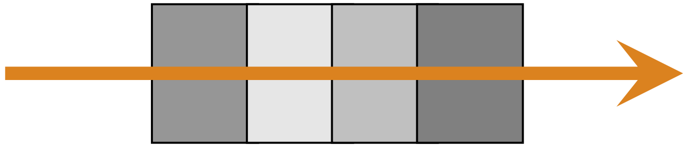
X-ray image and tomogram

An tomogram is a 3D matrix of image element, the voxels. Each voxel holds a voxel value which correspond to the average attenuation coefficient $\mu(x, y, z)$ in the corresponding object area.



So there must be a way to retrieve this from X-ray images in which all the μ are mixed.

I_0 

$$I(x, y) = I_0 e^{\int -\mu(x,y,z) ds}$$

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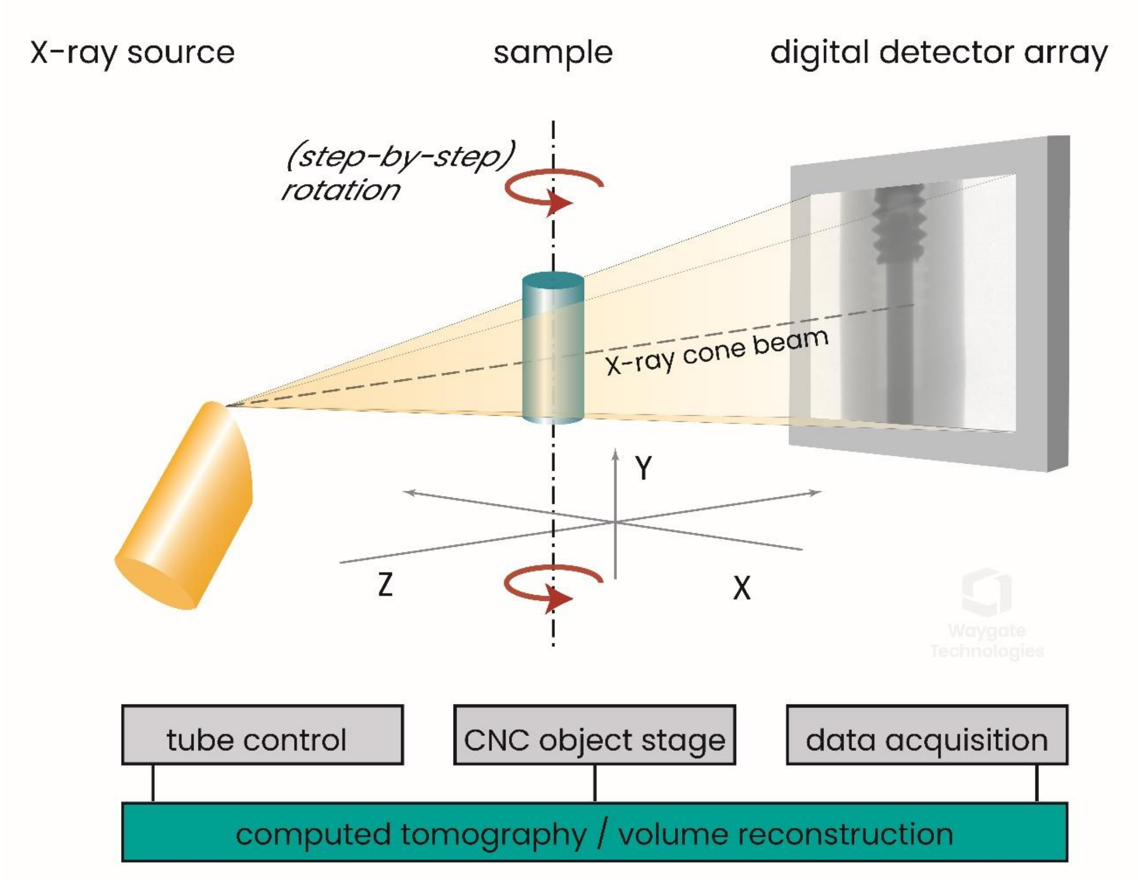
CT Acquisition



Cone Beam CT

The sample is irratiated by a cone shaped X-ray beam to create a radiographs.

While rotating the sample continously or step-by-step by 360° many radiographs (so called projections) are recorded and stored.

Using this set of projections and the geomety data of the apparatus the 3D volume is reconstructed numerically.

The CT system automatically controls the acquisition process and log all relevant data.

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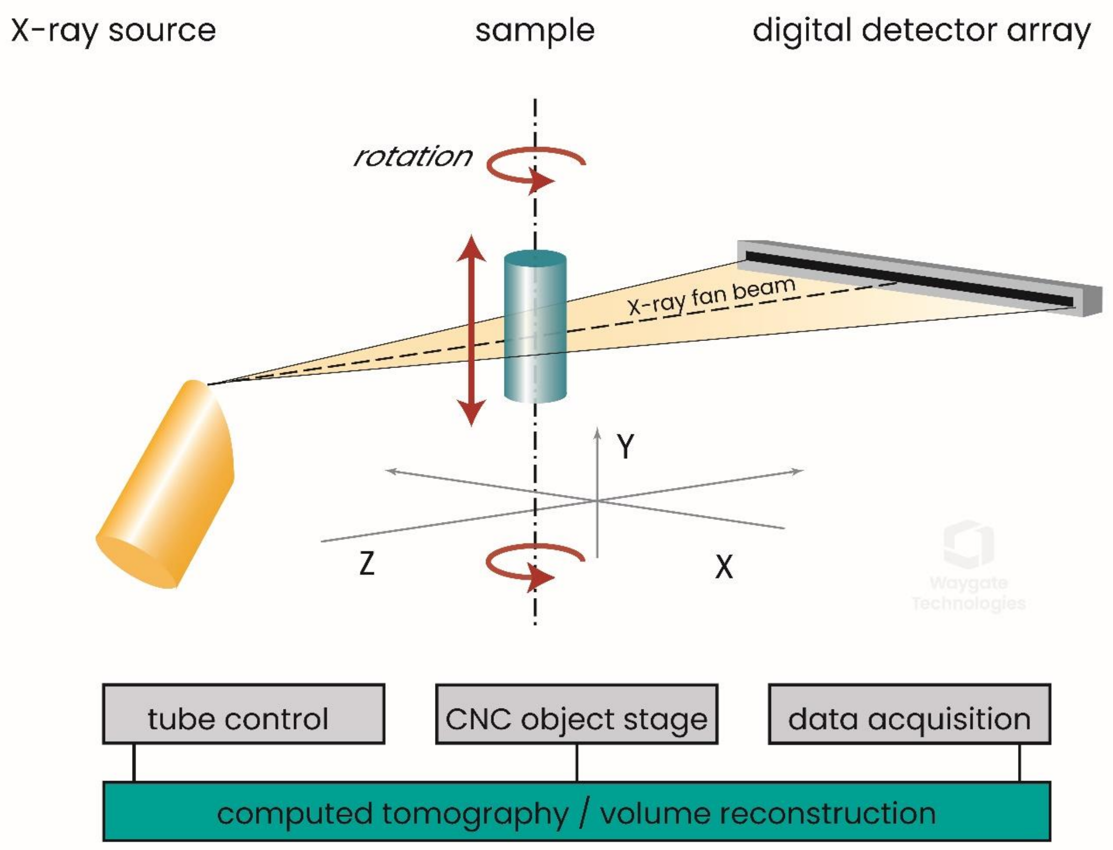
CT Acquisition



Fan Beam CT

The sample is irratiated by fans haped X-ray beam to create a line image.

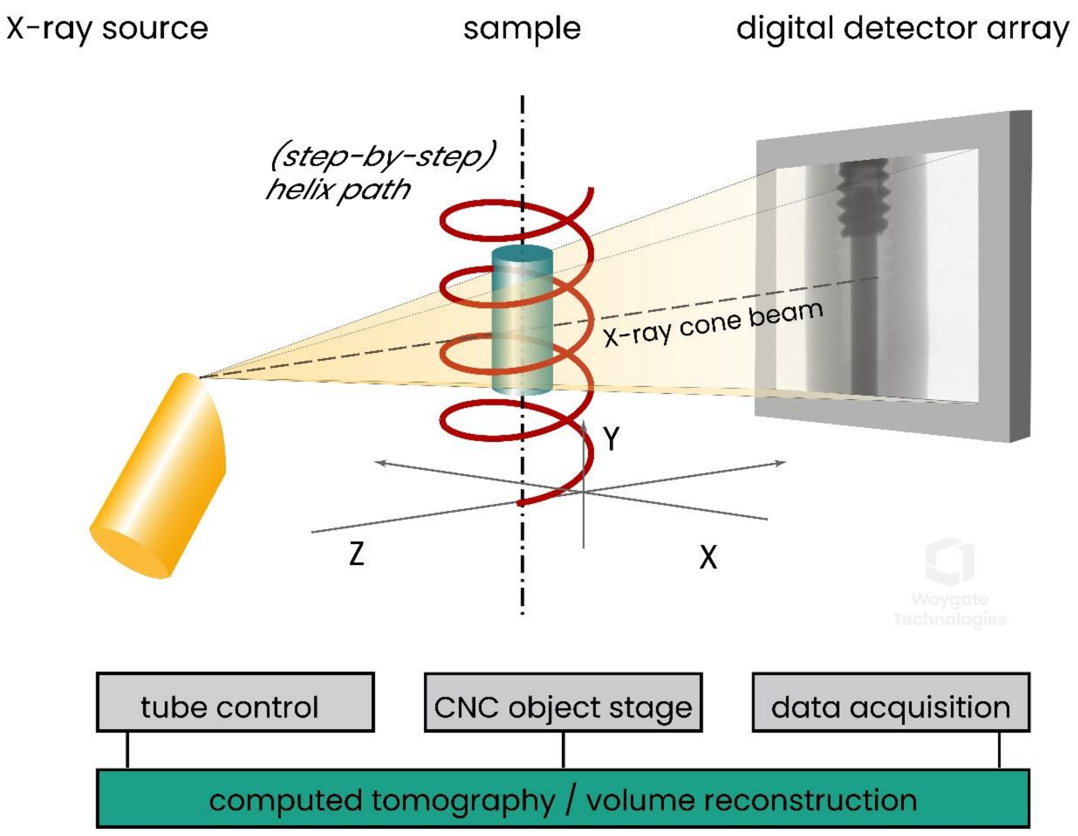
While rotating the sample by 360° many of these images (so called projections) are recorded and stored.

Using this set of projections and the geomety data of the apparatus a slice image is reconstructed numerically.

To scan the sample in different height the sample may moved in z direction with respect to tube and detector

The CT system automatically controls the acquisition process and log all relevant data.

CT Acquisition



Helix CT

The sample is irratiated by fans haped X-ray beam to create a line image.

While rotating the sample on a helix path many of these images (so called projections) are recorded and stored.

Using this set of projections and the geomety data of the apparatus a slice image is reconstructed numerically.

This kind of CT avoids image artifacts typical for cone beam CT.

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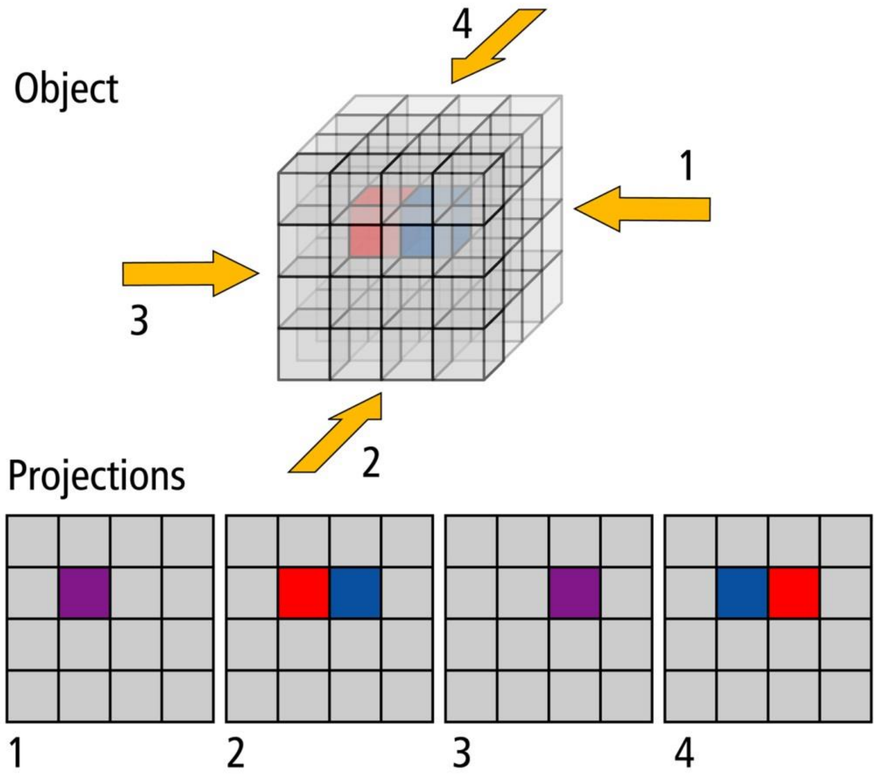
How do we retrieve the 3D data?



Let's try something different:

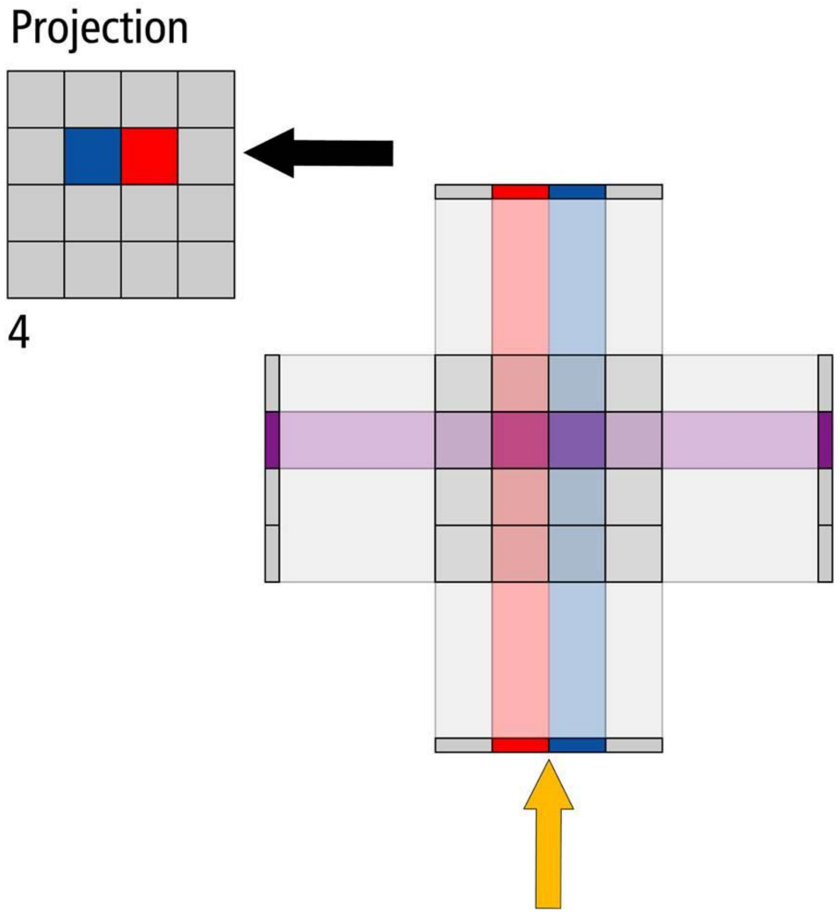
Model of acquisition

4 x 4 x 4 voxels

Are projected to four 4x4 pixel images

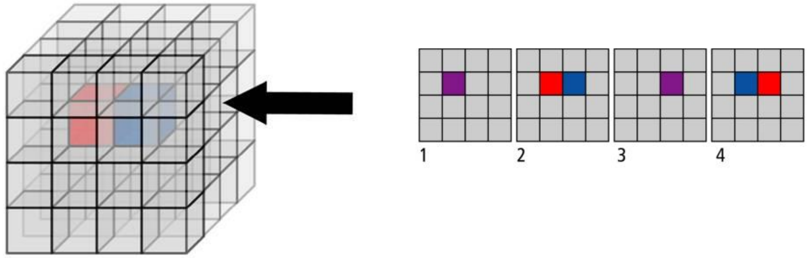
Obviously , the four projections contain information on the position an colour of the blue and red feature

How do we retrieve the 3D data?



Reconstruction of slice #2

Superposition of all back-projections



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