Intelligente Batteriezellprüfung mit KI

Stand der Technik und die Rolle von KI in der inline 3D-CT Inspektion

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3. Fachtagung für Digitalisierung und KI in der ZfP
Wuppertal, 28. – 30.01.2026

Xnovo Technology
Overview

xnovotech
— a RAITH company —

Our Mission

Be a technology development and enablement company.
We deliver cutting edge imaging processing for complicated inspection tasks.

Commercialization & Go-to-Market

Since 2012 we reach our customers through partnerships and collaborations with OEMs in which we engage as a development partner and/or supplier.

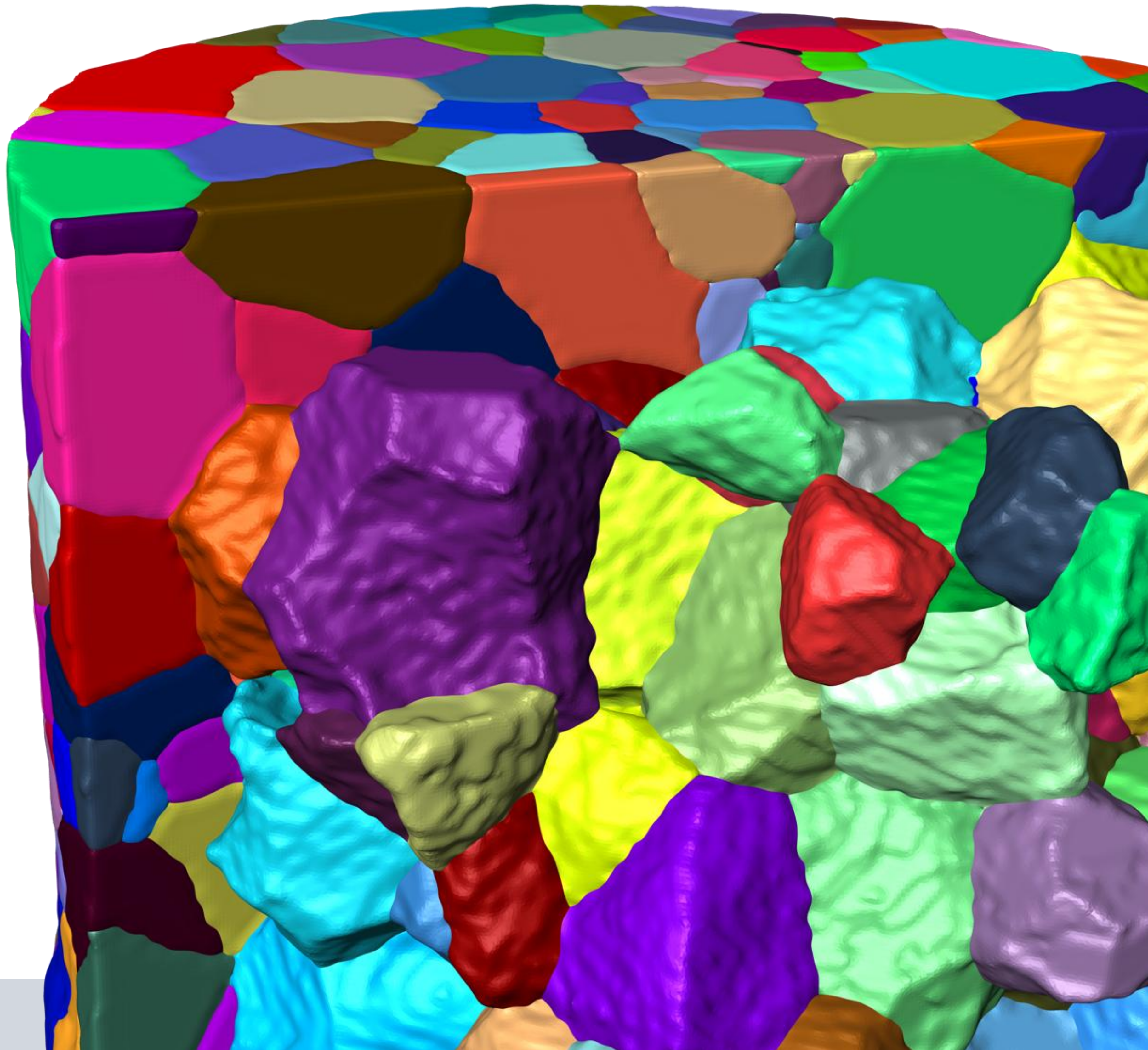
The International Xnovo Team

Comprised of 35+ scientists from various fields (physics, material science, engineering and computer science).

Company Location

We are located in the Hvide By (White City) district within the city of Køge approx. 25 minutes south-west of Copenhagen, DK.

Rendering of metal microstructure created and reconstructed by Xnovo LabDCT solution. Imaging modality: X-ray.



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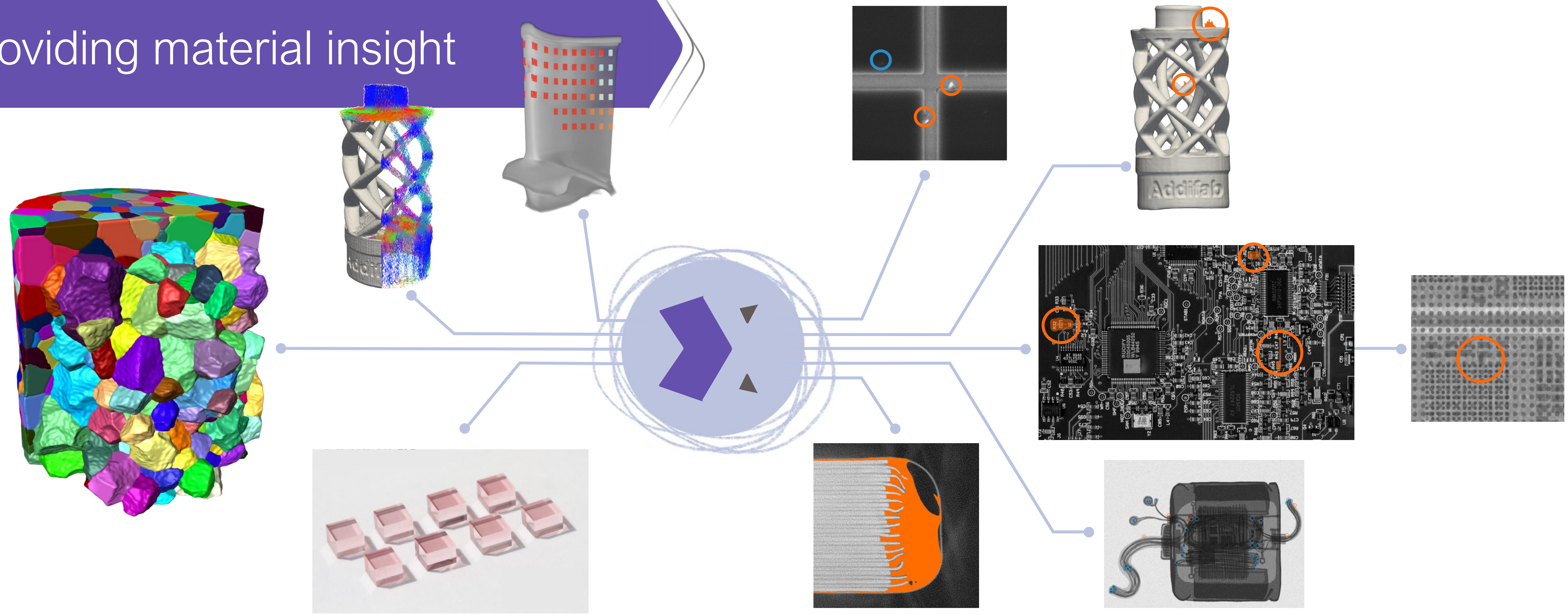
…providing material insight



Pioneering novel imaging methods

- Crystallographic Imaging
- Fiber-composite Characterization

Re-thinking image analysis

- AIA – Automated Image Analysis

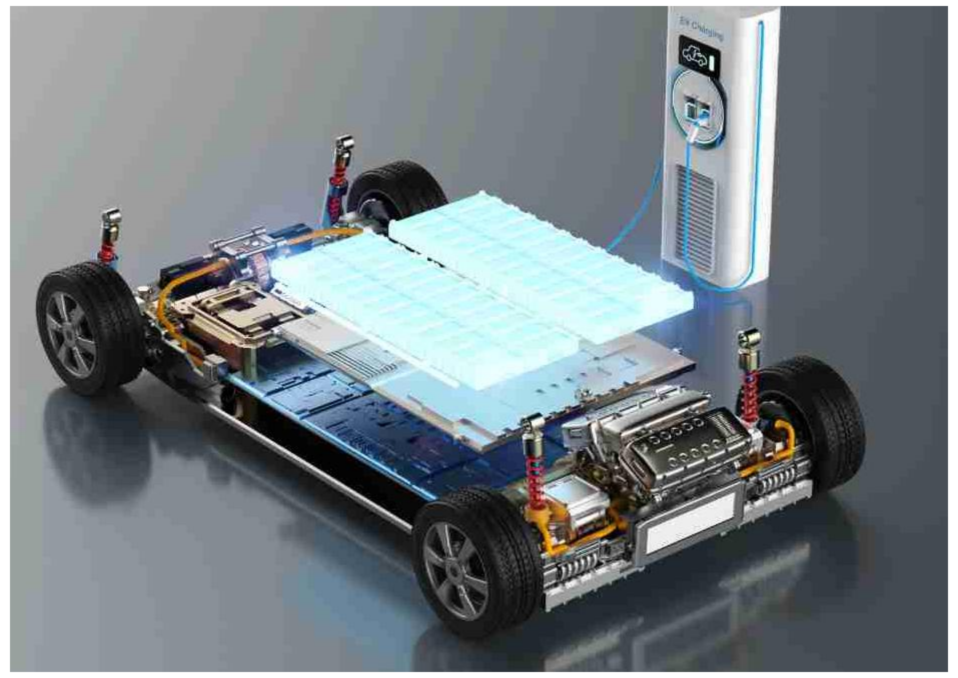
Usage of Li-ion Batteries

Lithium-ion batteries

- Li-ion batteries are characterized by higher specific energy (energy per mass), higher energy density (energy per volume) and energy efficiency (ratio between useful output and input in terms of energy) than other types of rechargeable batteries.
- They are expected to have a longer cycle life and calendar life as well.

Areas of usage

- E-Mobility (electric vehicles, bikes
- Electronic devices (laptops, smartphones, cameras, headphones, …)
- Drones
- Robots
- Energy storage systems
- …

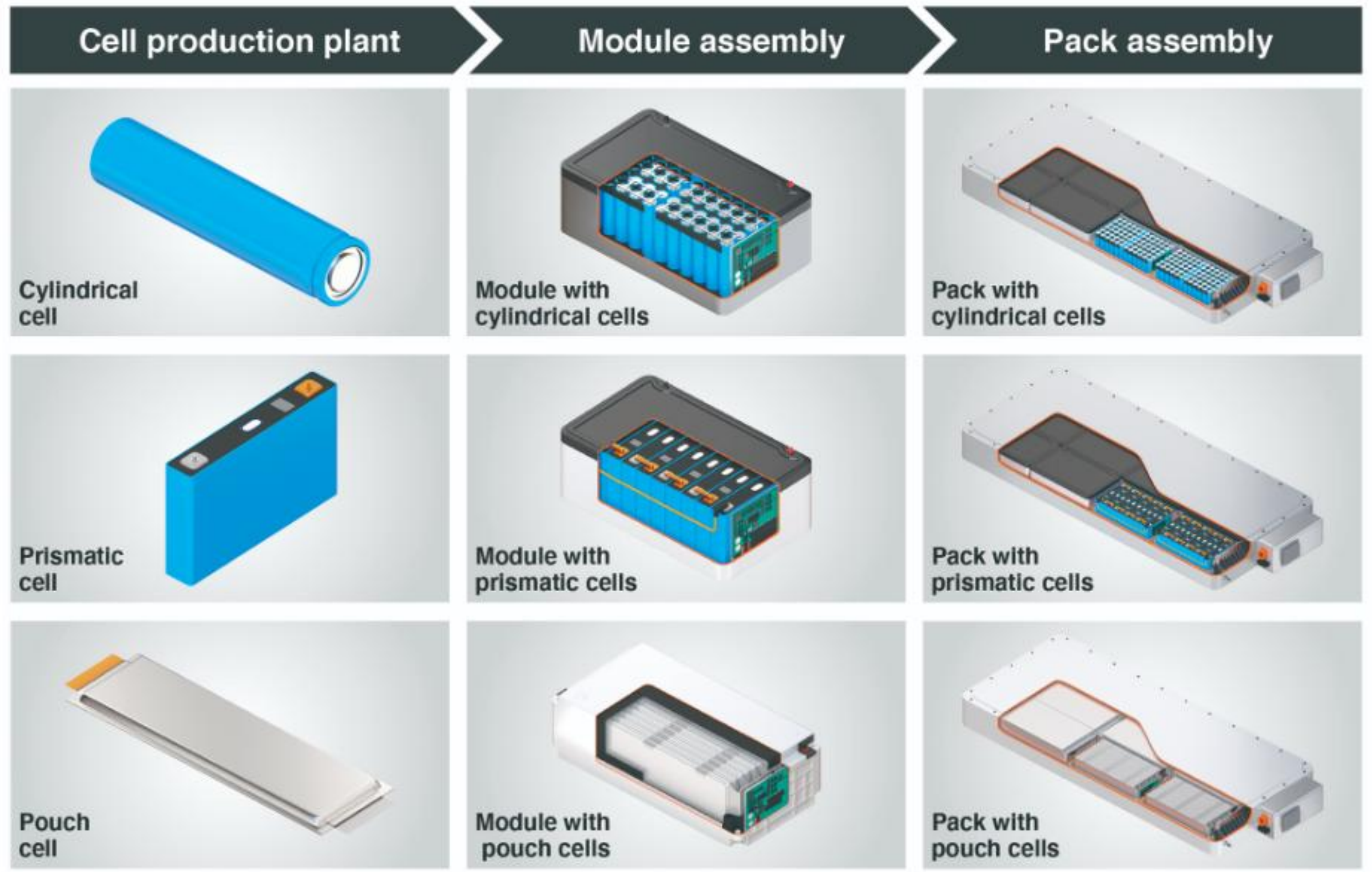


Very big, important and fast-growing market!

Problem Statement of EV Battery Inspection

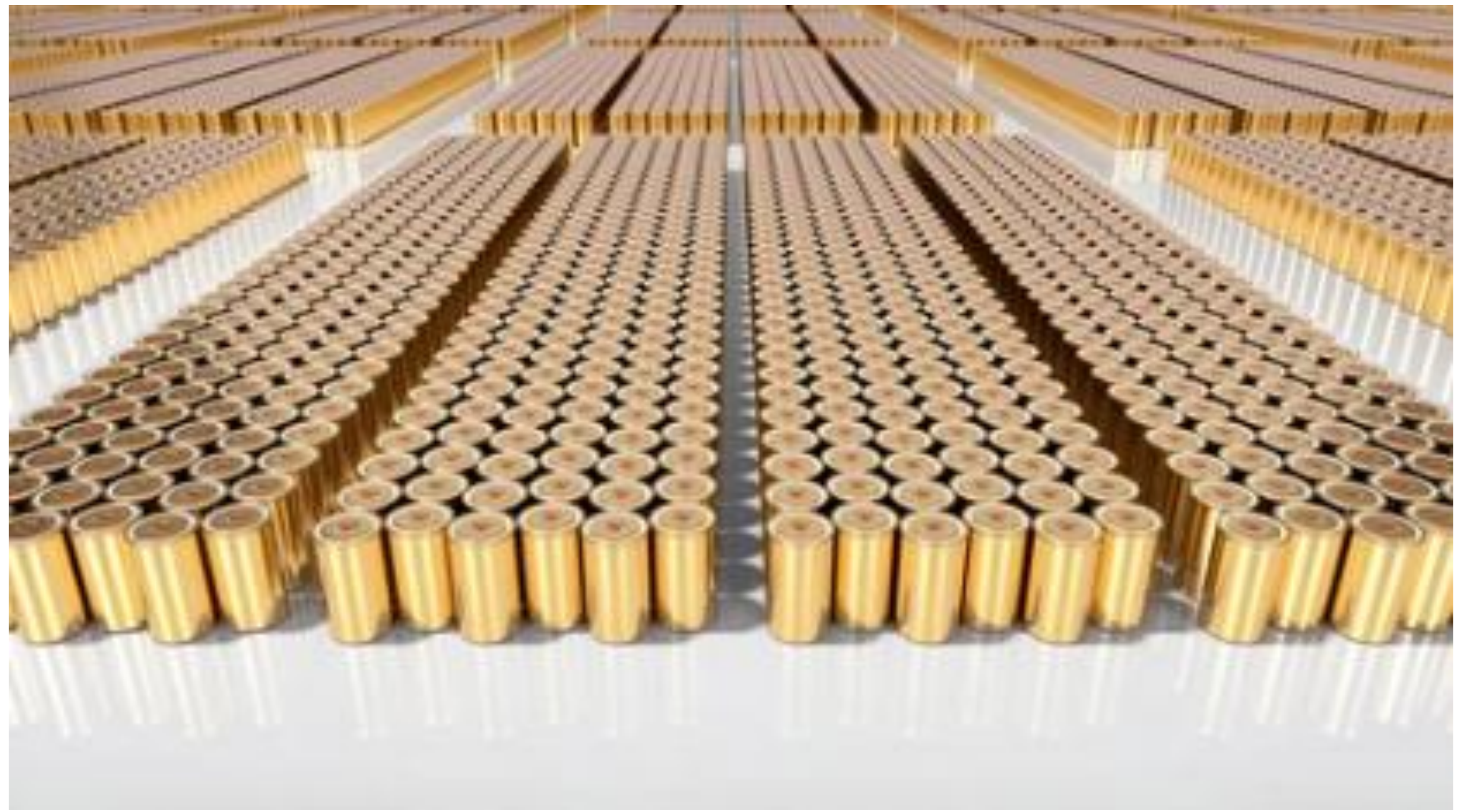
Task Description

- An average Gigafactory today produces battery cells with a capacity of 38 GW/year, which corresponds to the production of ~70 battery cells per second.
- Producing cells with a capacity of 1 kWh needs an energy effort of 30 to 60 kWh.
- Nowadays best scrap rates are slightly below 5%, but up to 90% (!!!) during ramp-up (>1 year), which commercially and ecologically is a disaster and urgently needs to be enhanced.



CT Inspection

- 3D-CT is the only NDT method that allows a complete inspection of a battery cell including anode/cathode overhang and stacking quality analysis, as well as delamination and inclusion detection.
- Detection of small metallic inclusions is the most difficult and critical part of battery inspection.
- Especially very small and low contrast metallic inclusions, such as small Al particles, are extremely difficult to be detected in noisy inline CT data.



Physical Boundary Conditions require System Optimizations

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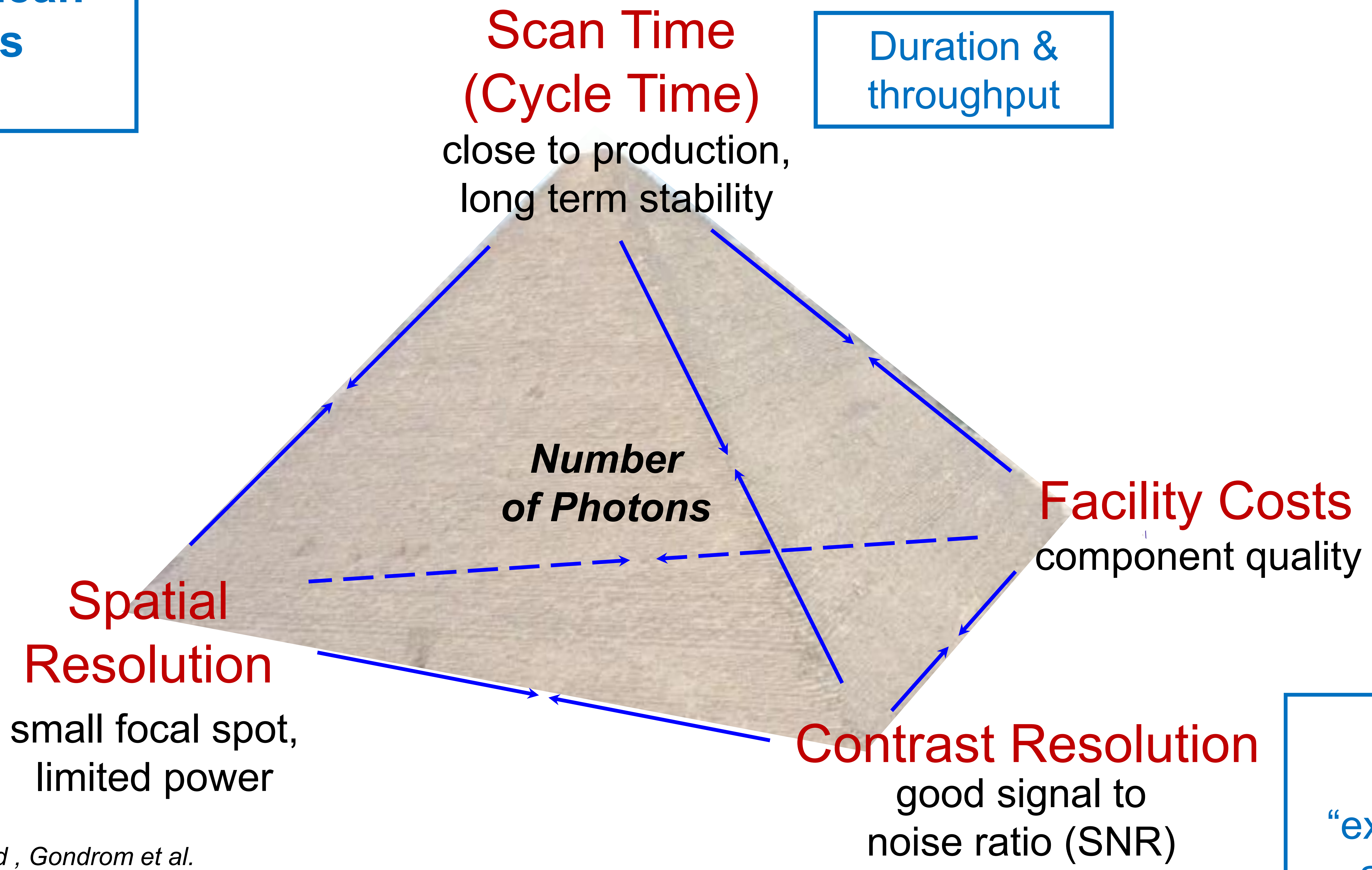
What does this mean for the analysis software?



Duration & throughput

Number of available CPUs and GPUs (workstations, racks, cooling, network, …)

Highest resolution results in huge data sizes for data transfer, analysis and storage

Limited contrast requires more "expensive" AI based analysis methods

**X-Ray testing Pyramid , Gondrom et al. World Congress on Nondestructive Testing, Montreal, 2004*

Typical Inspection Demands in eMobility

Inclusion detection

Small Fe, Cu and Al inclusions shell be reliably detected in fast at-line 3D-CT scans

- Typical cycle time: 15 s – 120 s (quite high noise level)
- With special HW cycle times ~4 s are reachable
- Reasonable voxel size: 12 - 50 µm
- Typical volume sizes: 8 to 64 GB

Typical demands:

- Inclusions with 4 voxels size must be detected with a neglectable slip rate. This means inclusions with a size of 3 voxels must be reliably detected!
- Pseudo defect rate: less than 1 pseudo detection in 50 to 100 battery cells
- Inclusions inside and outside of the jelly roll

Additional features and requests

- Fully automated surveil of scan quality
- Geometrical measurements
- Anode/cathode overhang analysis
- Delamination detection
- Determining start and end points of cathodes and anodes
- Inspection of welding zones of the electrical connection of the current conductors

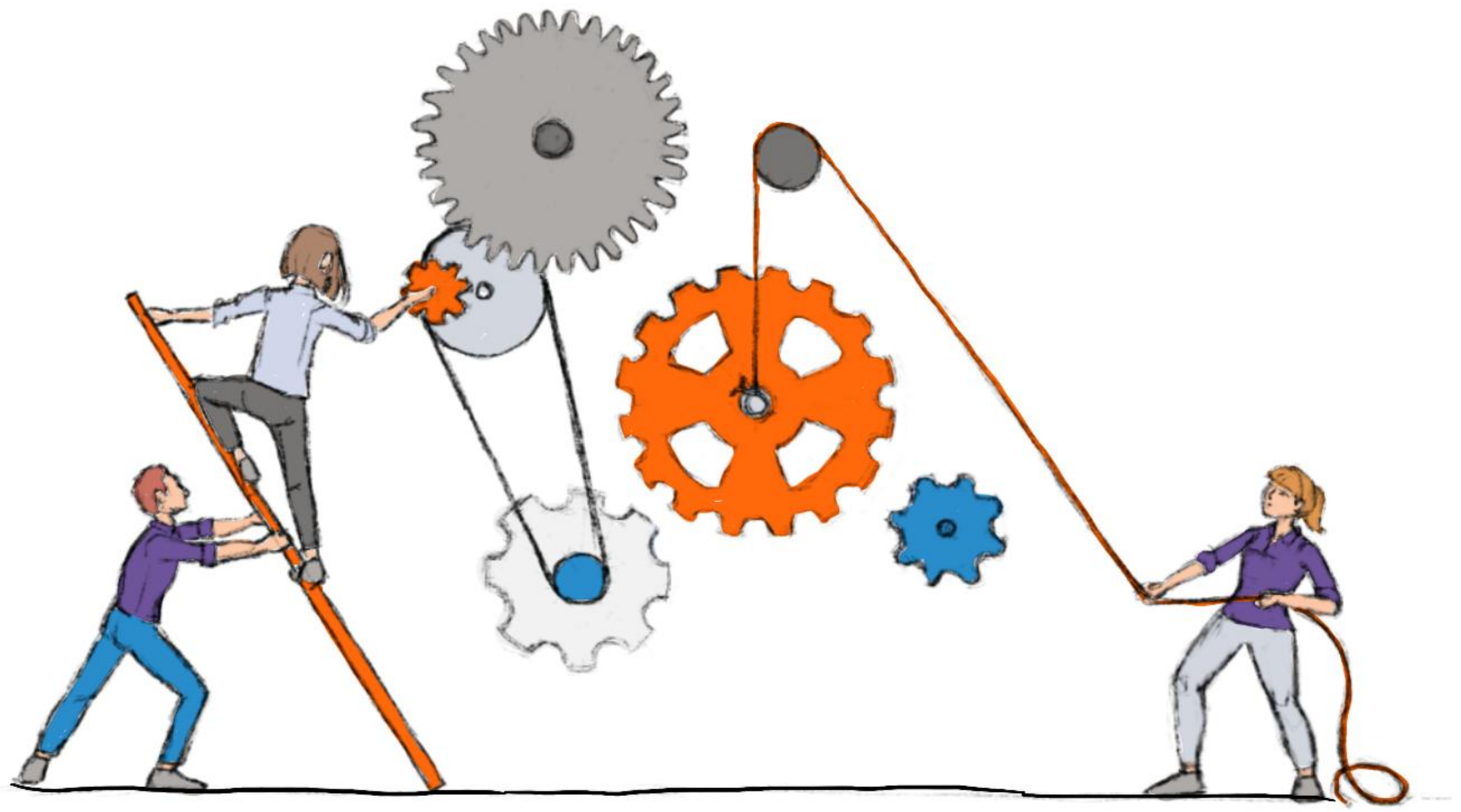
Available Generic Inspection Software

- Available generic SW packages only provide limited analysis capabilities such as simple thresholding, ML or deep-learning.

- AI based image processing may have the drawback of potentially being costly; on top training can be very time-consuming and unpractical, especially if common deep learning methods are used.
  So, AI methods have to be chosen carefully.

- Analytical methods deliver deterministic results, but standard thresholding, even local adaptive methods, will not be able to deal with occurring limited contrast resolution.

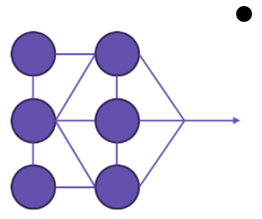
- There is no standard solution on the market which fulfills all demands!



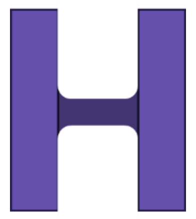
Comparison of AI-based Inclusion Detection

Common Architectures

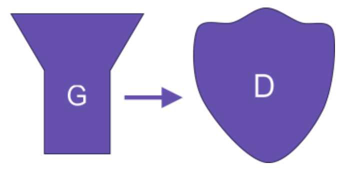
- **U-Net**
  - ✅ Can return very precise voxel-level segmentations of the defects
  - ❌ **Demands costly voxel-perfects masks** for every defect type and it's blind to unseen anomalies



- **Classification CNN**
  - ✅ Good at learning discriminative features when defect samples are abundant.
  - ✅ Requires less labeled defects and will flag any **untrained and unseen variation.**



- **Autoencoder / VAE / BAE**
  - ✅ Learns a compact, unsupervised representation of the volume i.e. doesn't require labeled data
  - ❌ Attempt to reconstruct the volume from a latent space which typically involve volume downscaling. **Small defects will likely be averaged out into noise making reliable thresholding highly impractical.**

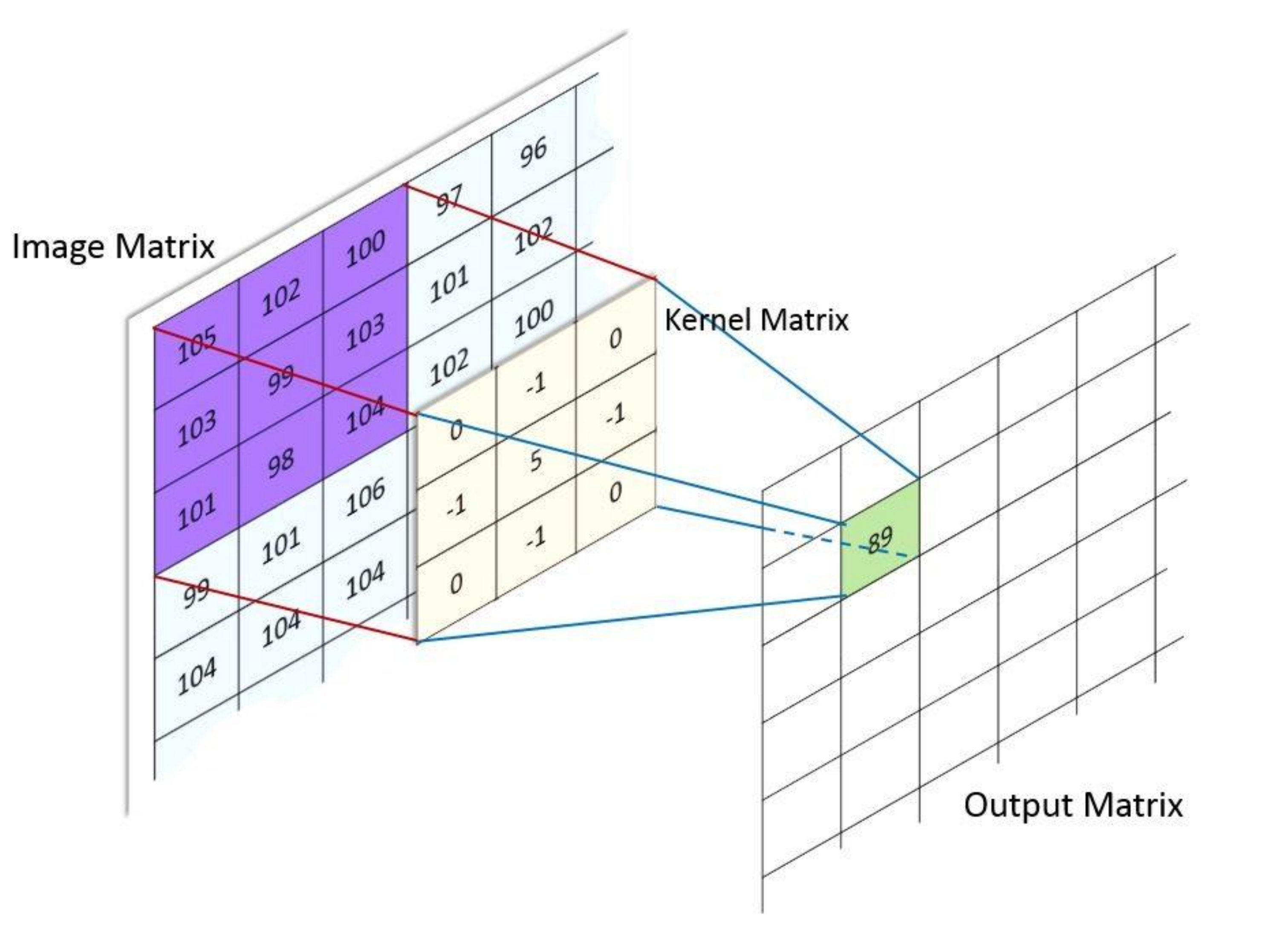


- **GANs**
  - ✅ Can generate high-fidelity volumes and highlight anomalies by its discriminator
  - ❌ **Prone to train instability** and "mode collapse". Very **expensive in 3D.**

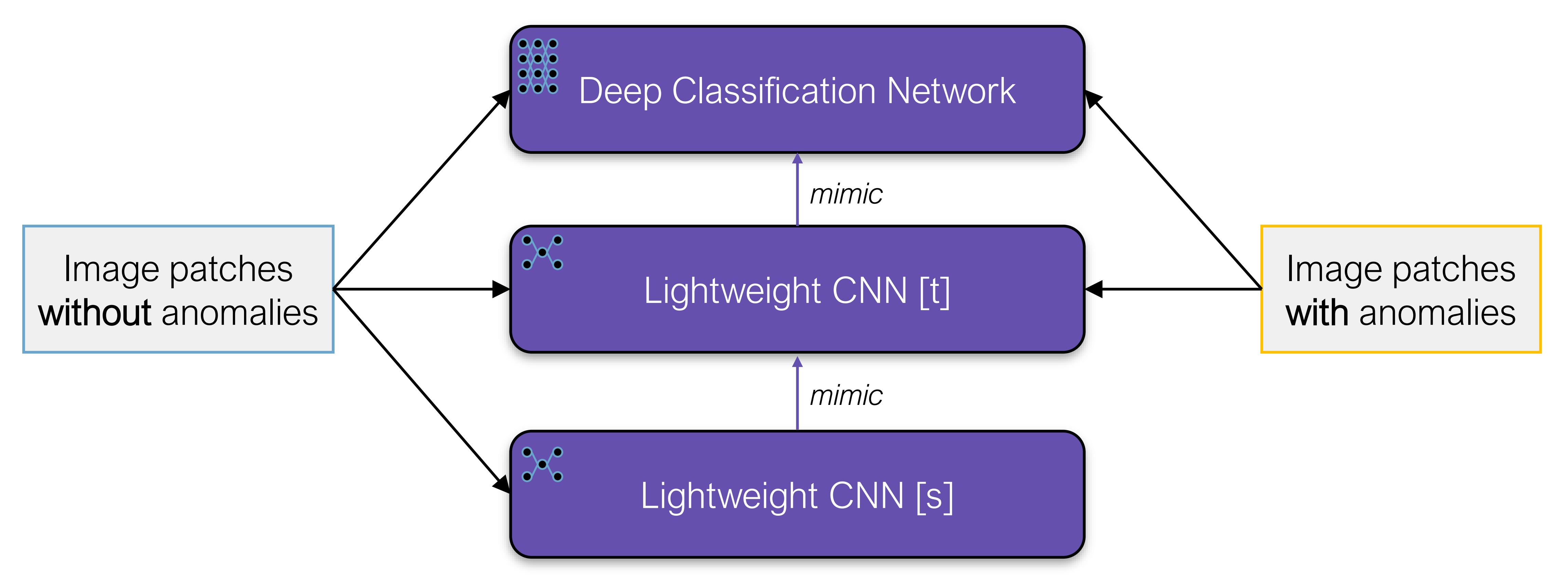
Xnovo Anomaly Detection Network

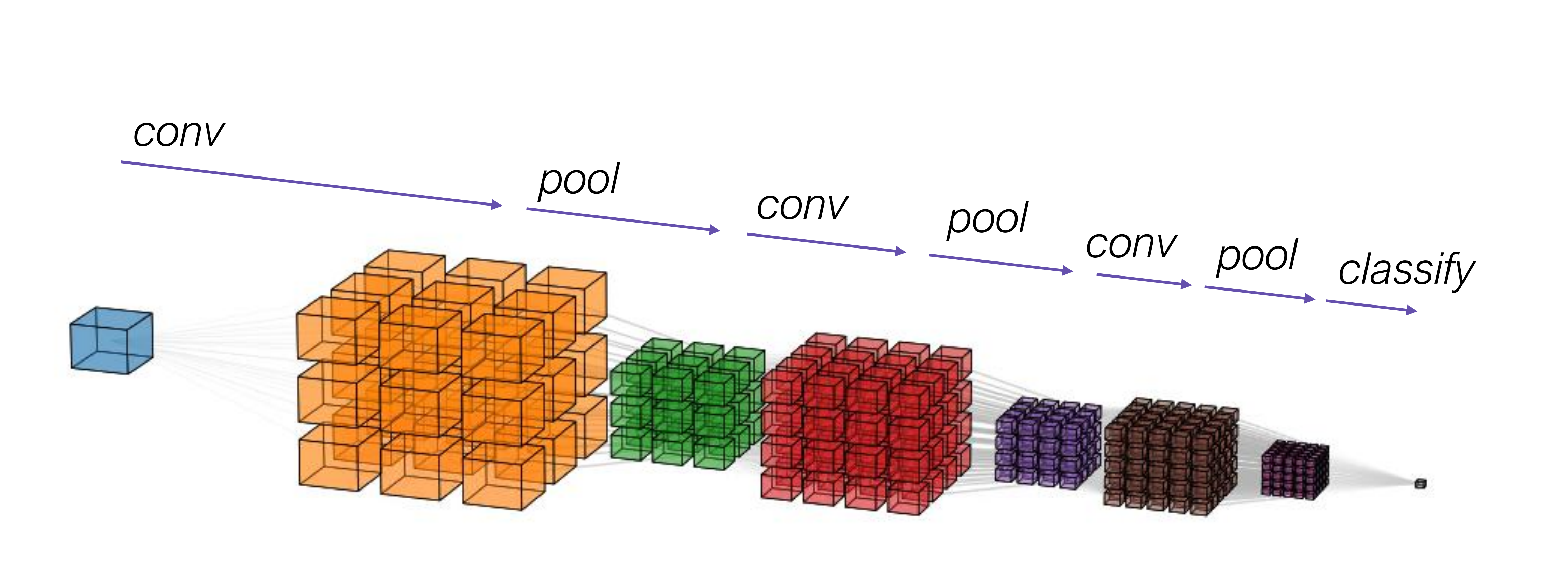
- ✅ Utilizes a well parametrized balance between different **competing networks**.
- ✅ **Requires fewer defect annotations** than a CNN.
- ✅ **Is able to detect small defects** via full-resolution patch comparison using fast dense feature extraction.
- ✅ **Is more tolerant to imperfect masks/labels** (unlike U-Net) and adapts to new fault types.
- ✅ **Requires only rough estimate of the defect's length-scales/sizes**
- ✅ More **stable training** convergence than GANs or VAEs, with minimal overfitting.
- ✅ Scales and **generalizes well to unseen fault** types
- ✅ Produces residual maps that can be directly segmented and measured in 3D volumes
- ❌ Cannot classify defects by type (iron vs aluminum vs copper…)

Multi-Stage-Approach



- 3 complementary detection methods for robustness.
- Could be individually used on different regions for an even faster throughput.





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Disclaimer

Data courtesy of BMW

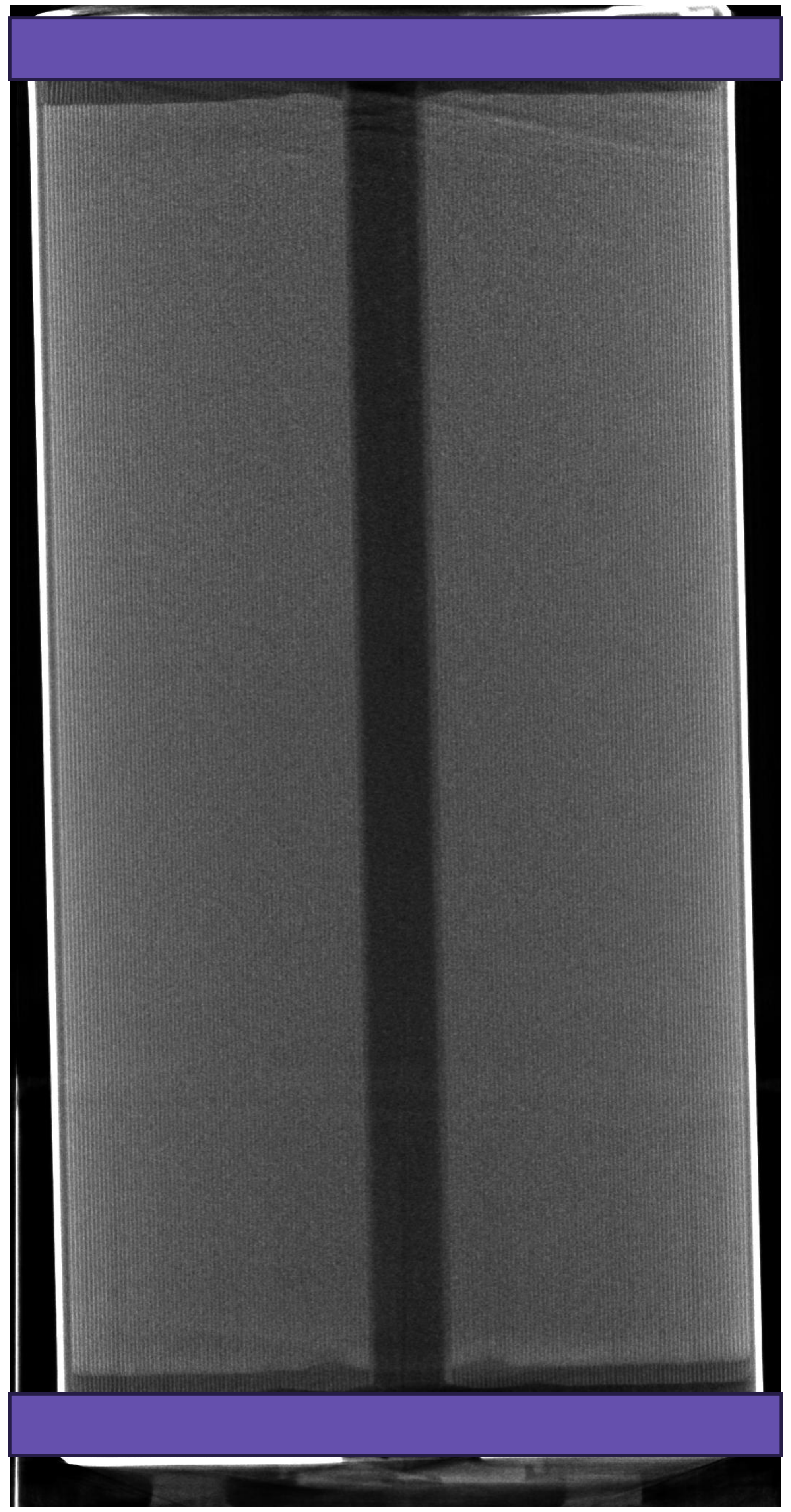
- The following 3D CT scans of battery cells with inclusions have been provided by BMW.
- All cells have been carfully produced with artificial test inclusions and are no samples out of serial production!
- Due to this, a well know ground truth for validation of image processing was available.
- Confidential functional areas will be hidden in the presented images.

Smart Battery Cell Inspection

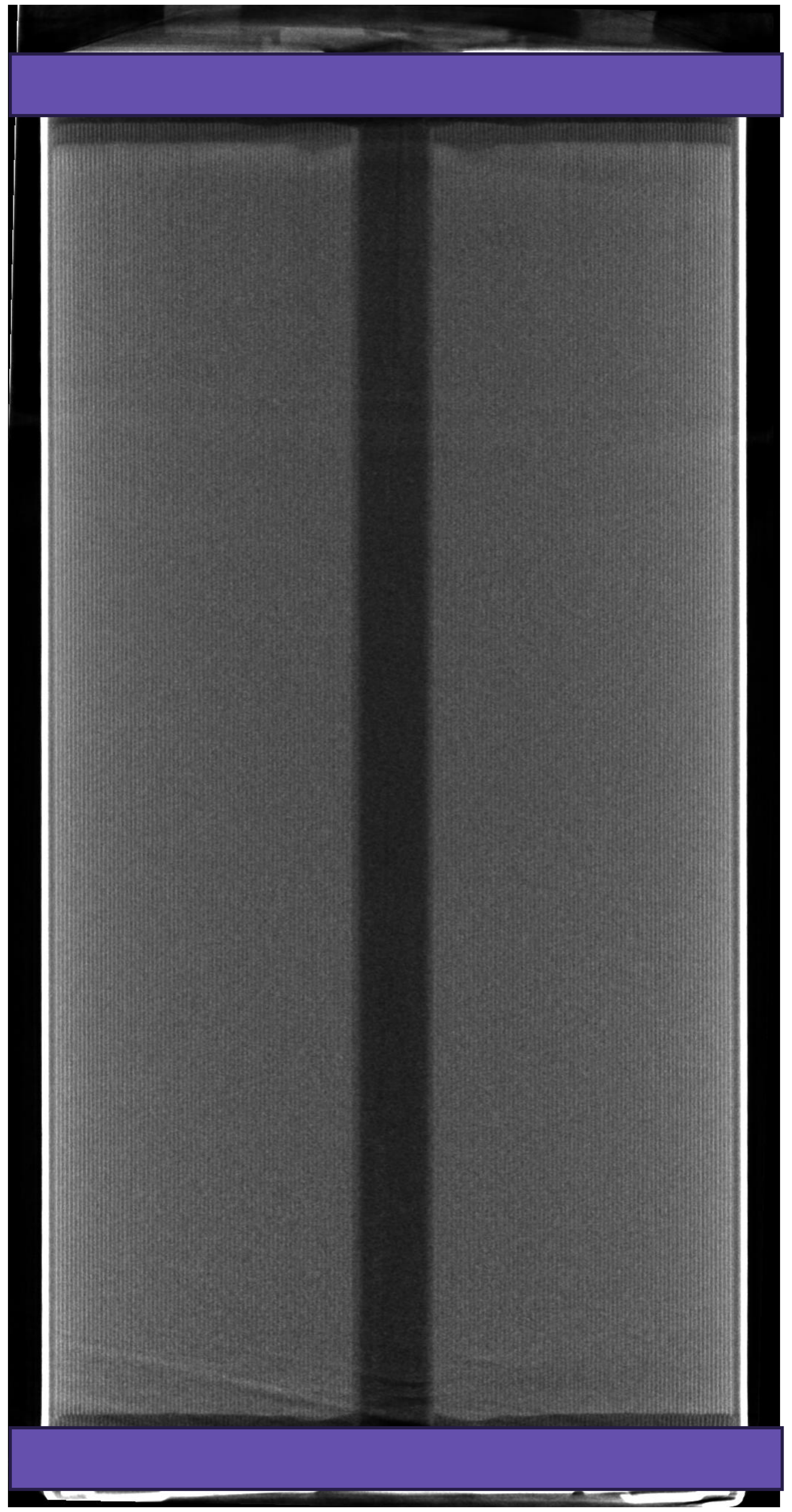
Pre-Processing

Volume Alignment & Battery Housing Segmentation

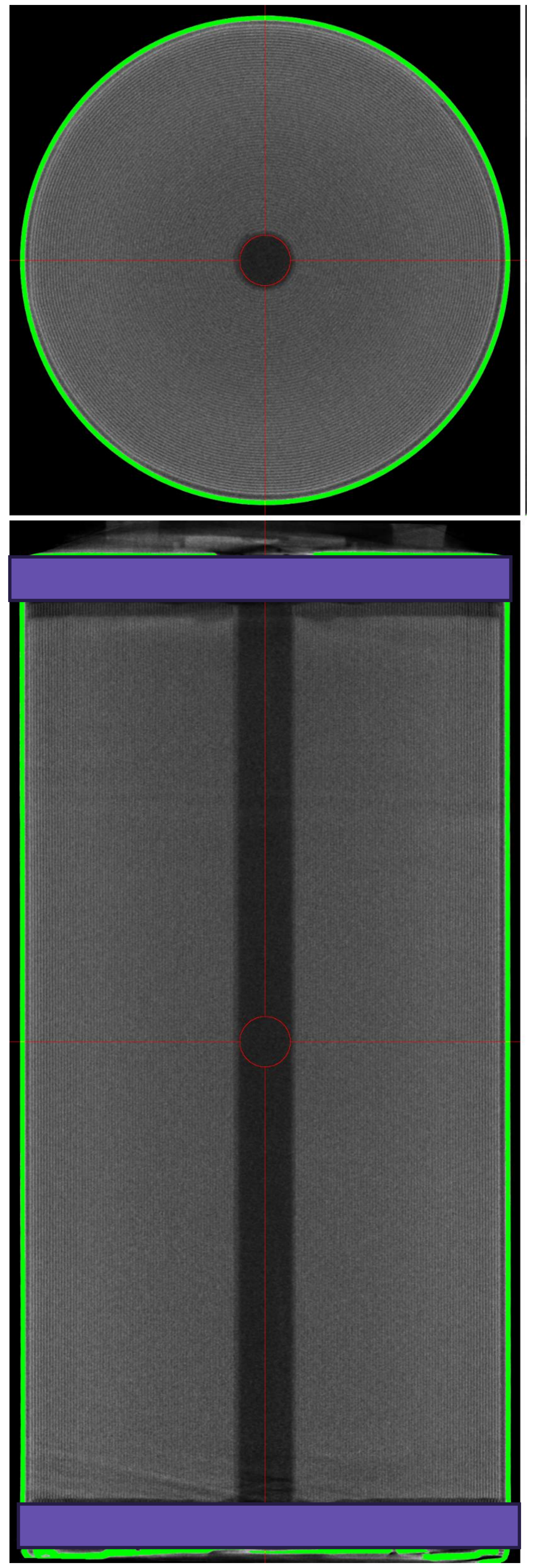
Dataset before alignment



Dataset after alignment



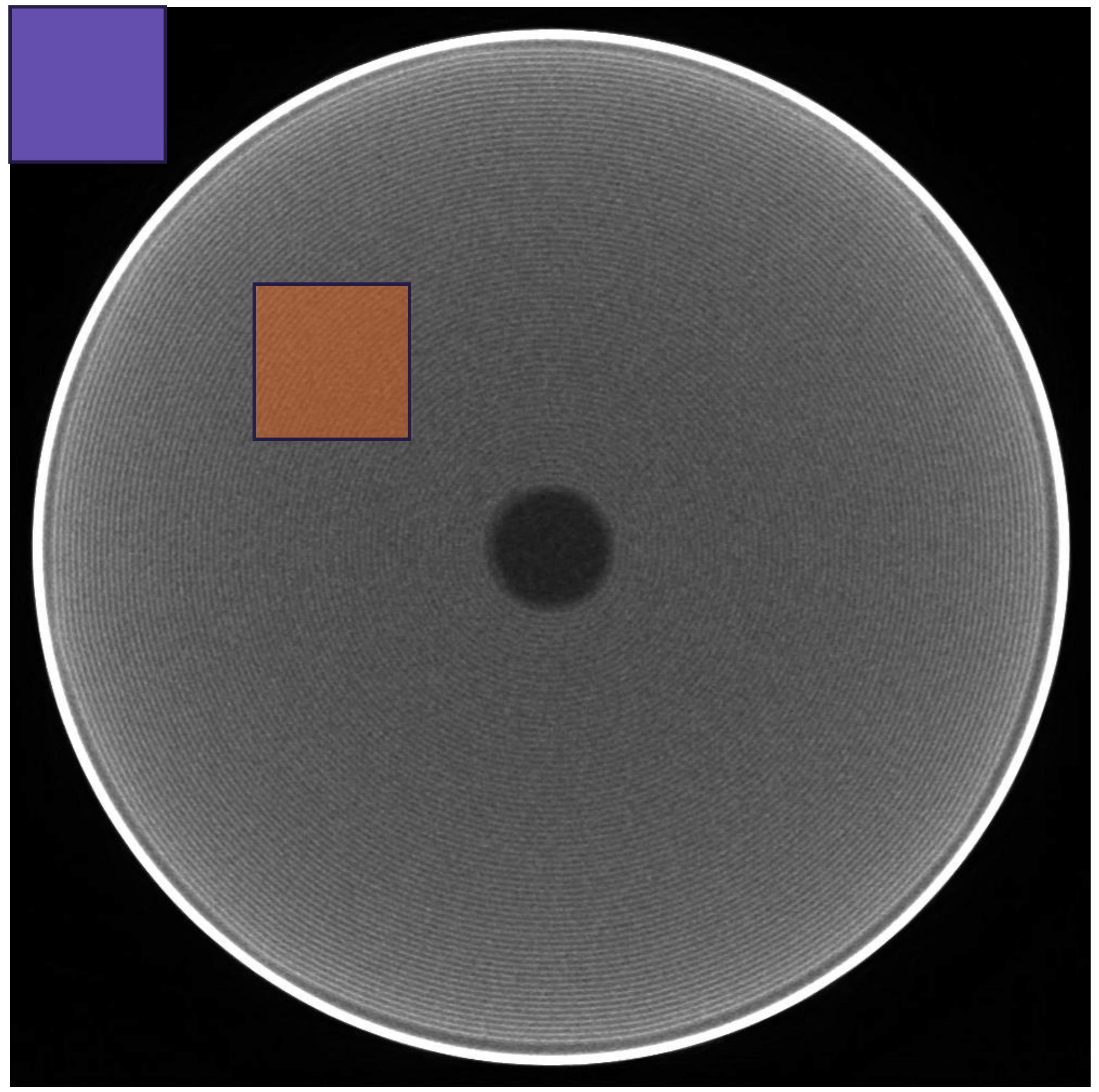
Segmented volume housing



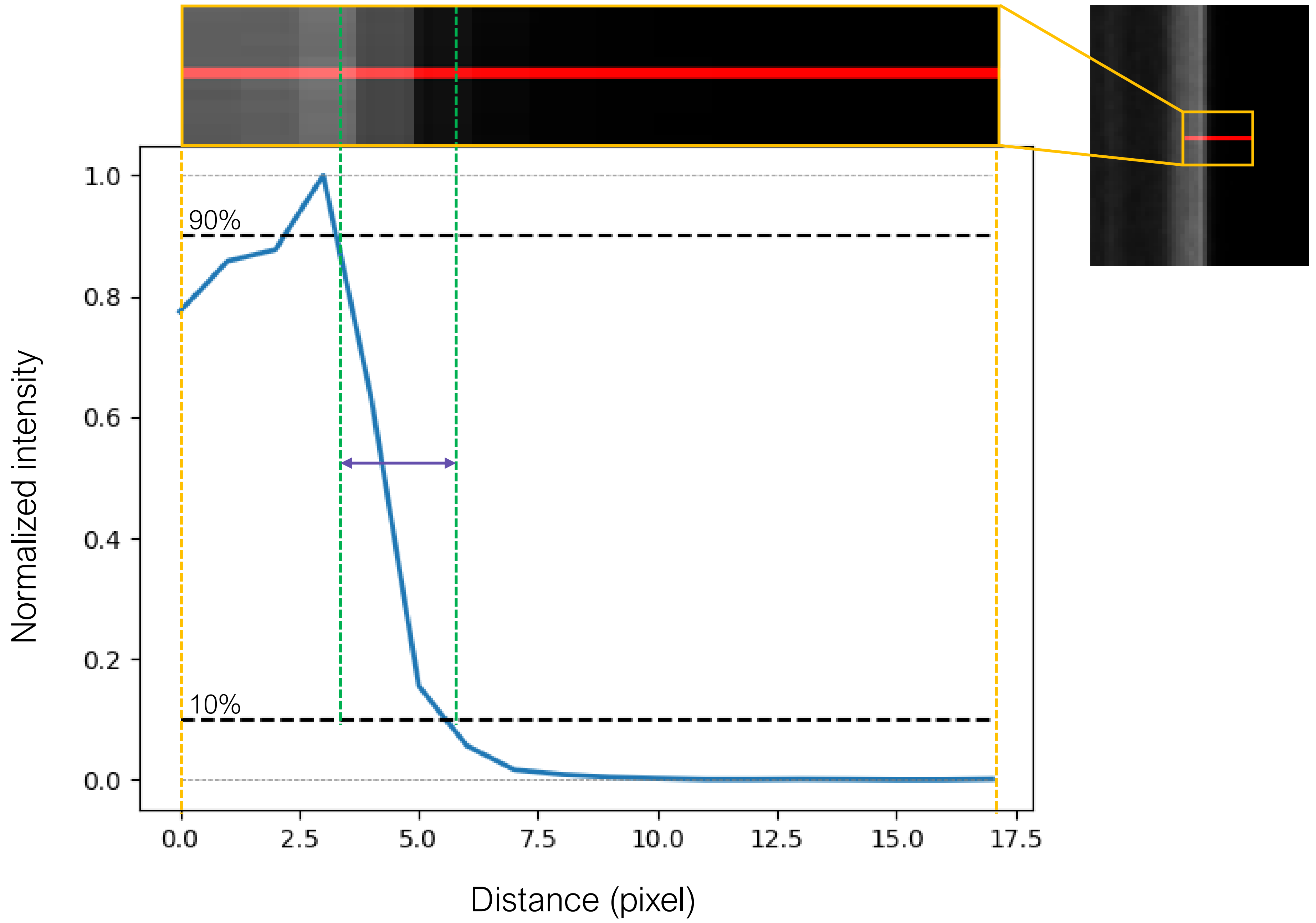
Pre-Processing

Image Quality Assessment

Regions for contrast-to-noise ratio



Example of edge response on the battery can



The CT scan quality is evaluated using dedicated **image quality metrics**.
These include:

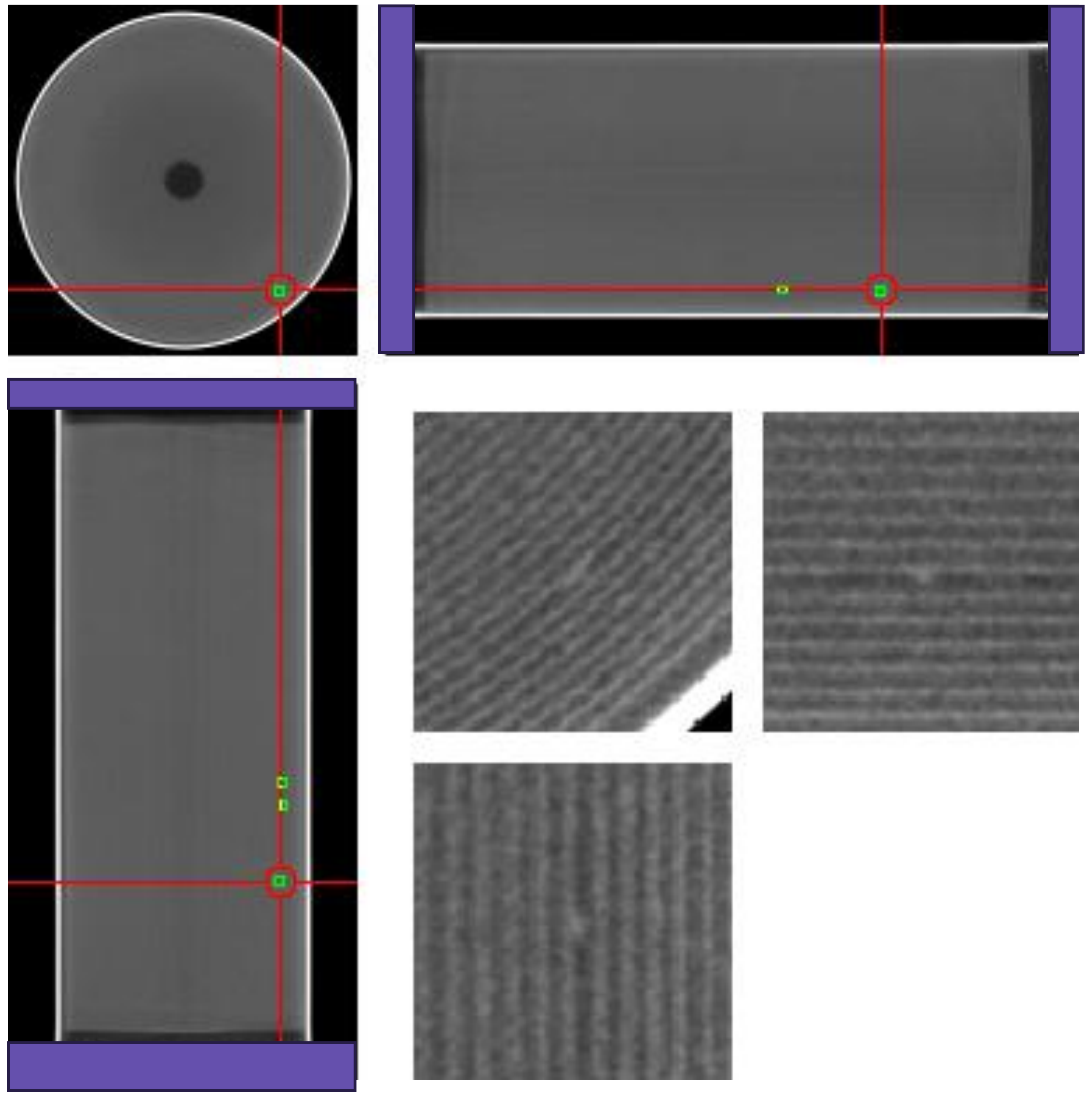
- contrast-to-noise ratio, in selected battery regions,
- and an effective resolution estimate, derived from an edge response at the battery housing.
- background mean and region mean

Smart Battery Cell Inspection

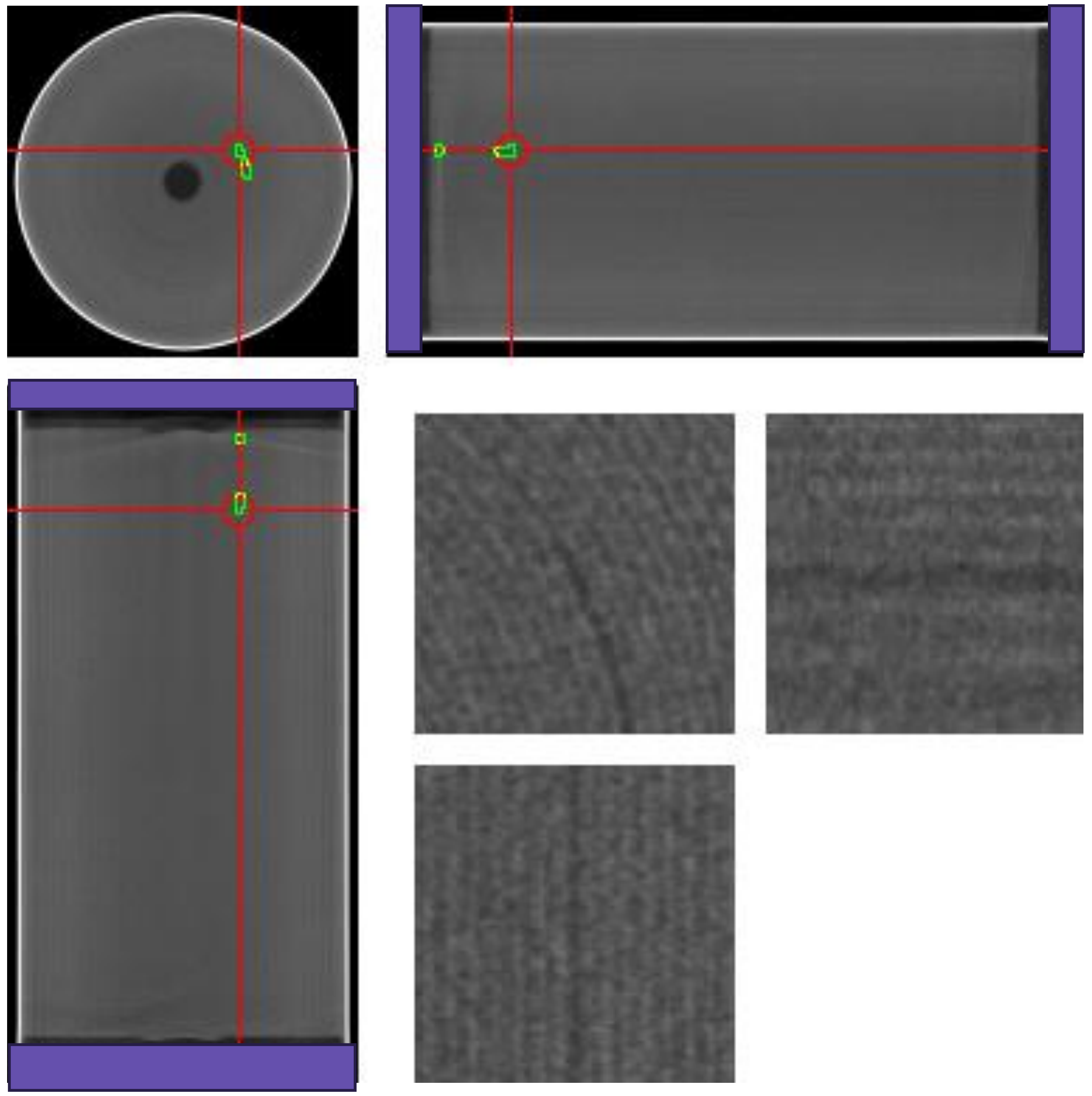
Inclusion Detection

Analytical Detection

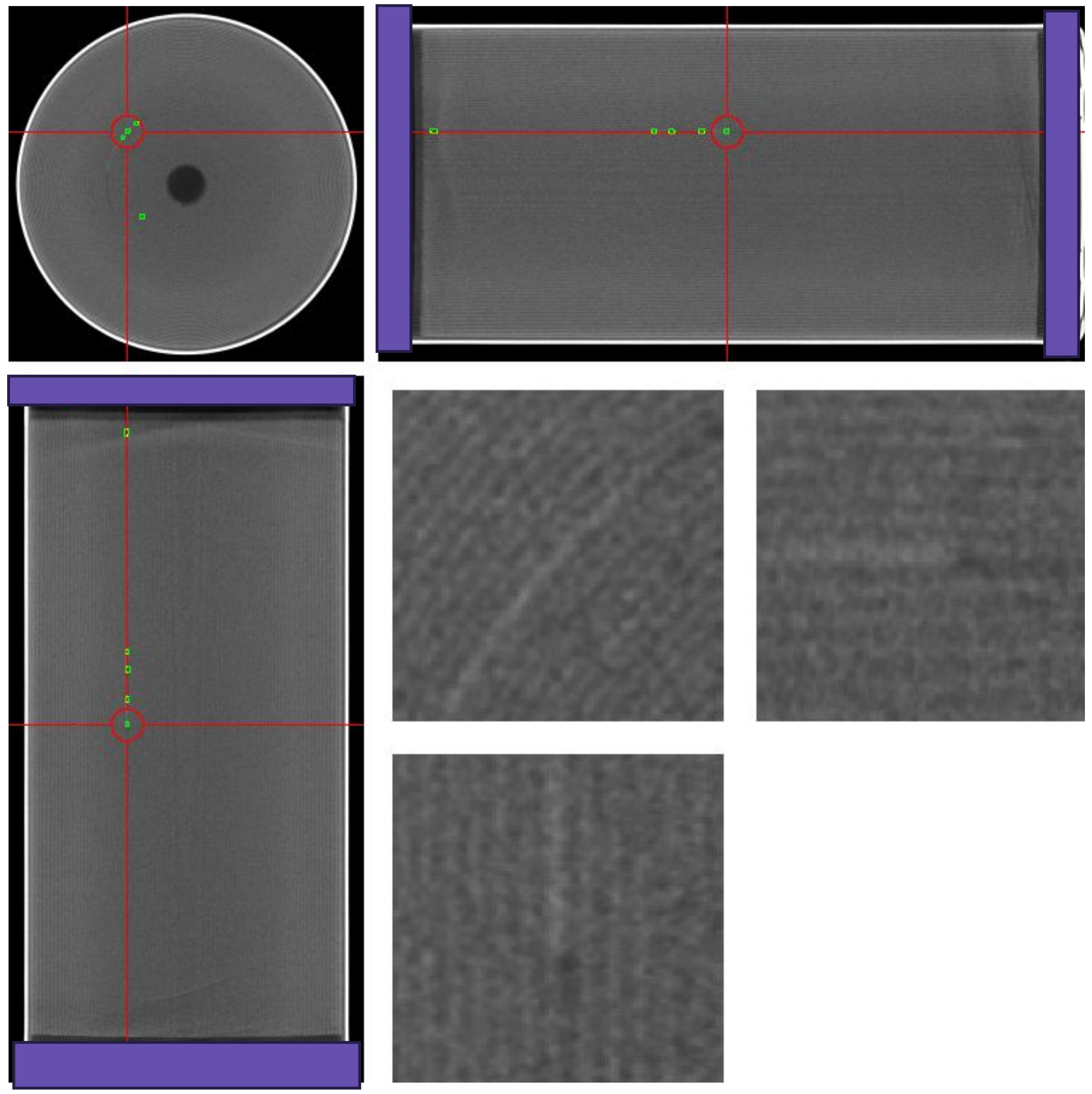
Example of detected inclusion



Example of detected *delamination*



Example of detected cathode



Inclusion Detection

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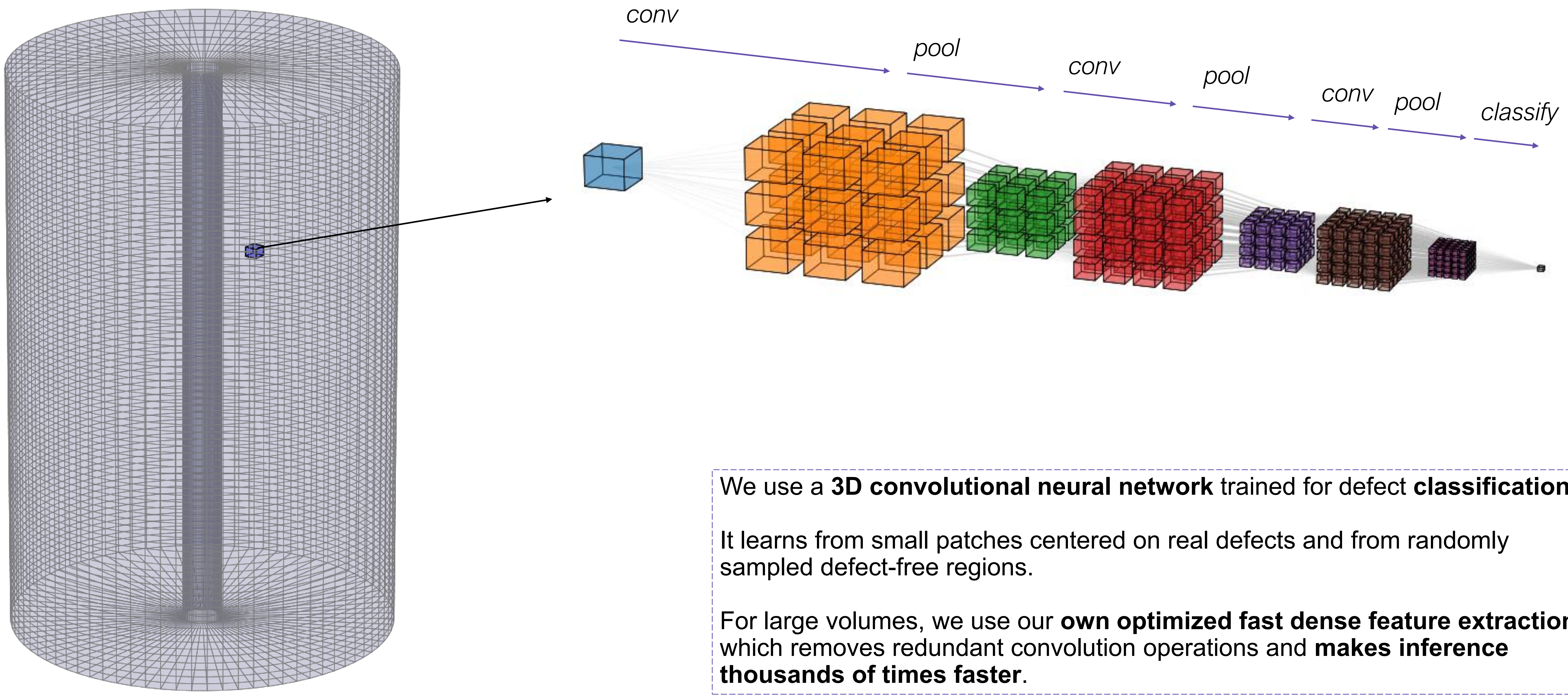
Classification Network



We use a **3D convolutional neural network** trained for defect **classification**.

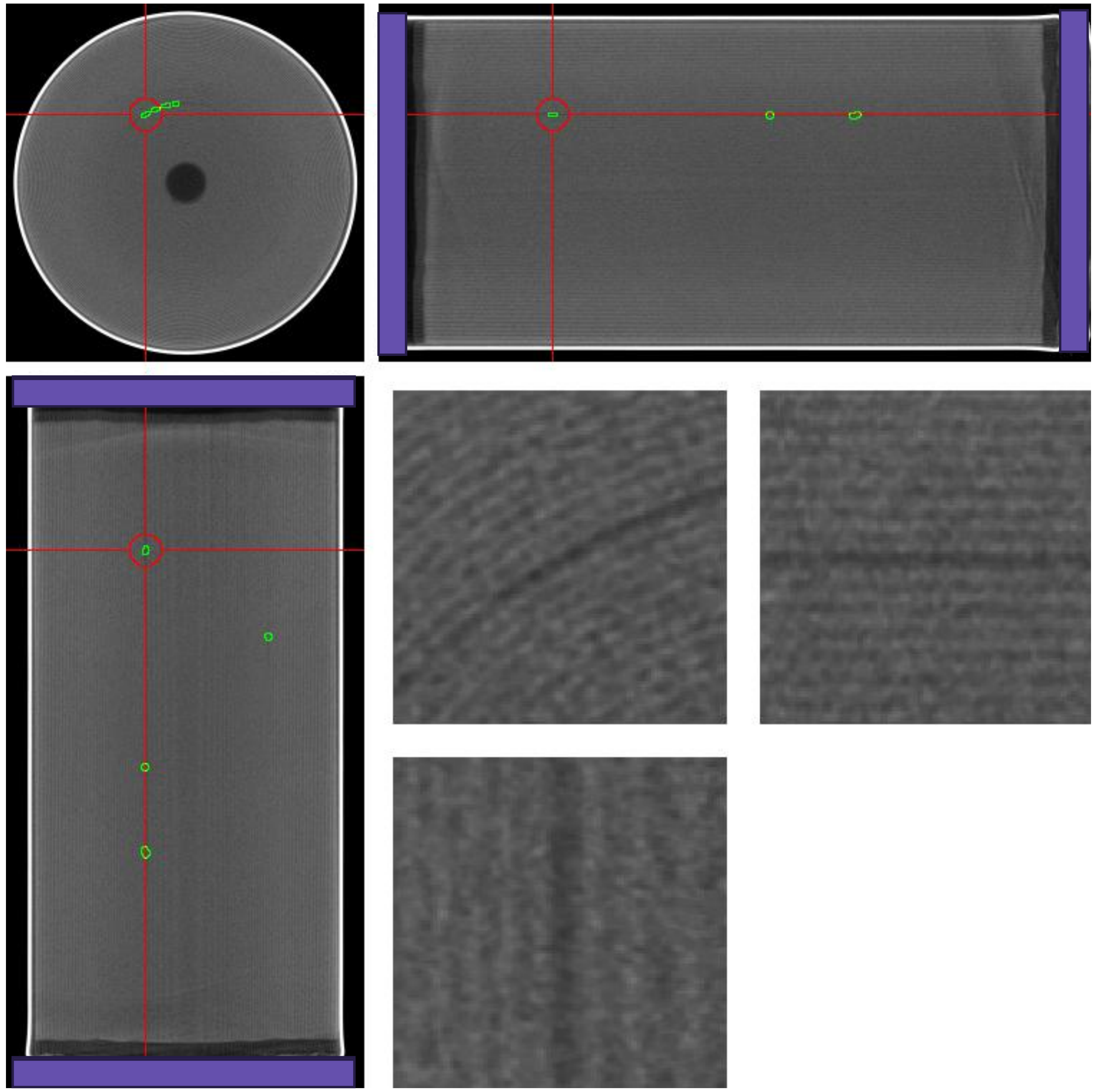
It learns from small patches centered on real defects and from randomly sampled defect-free regions.

For large volumes, we use our **own optimized fast dense feature extraction**, which removes redundant convolution operations and **makes inference thousands of times faster**.

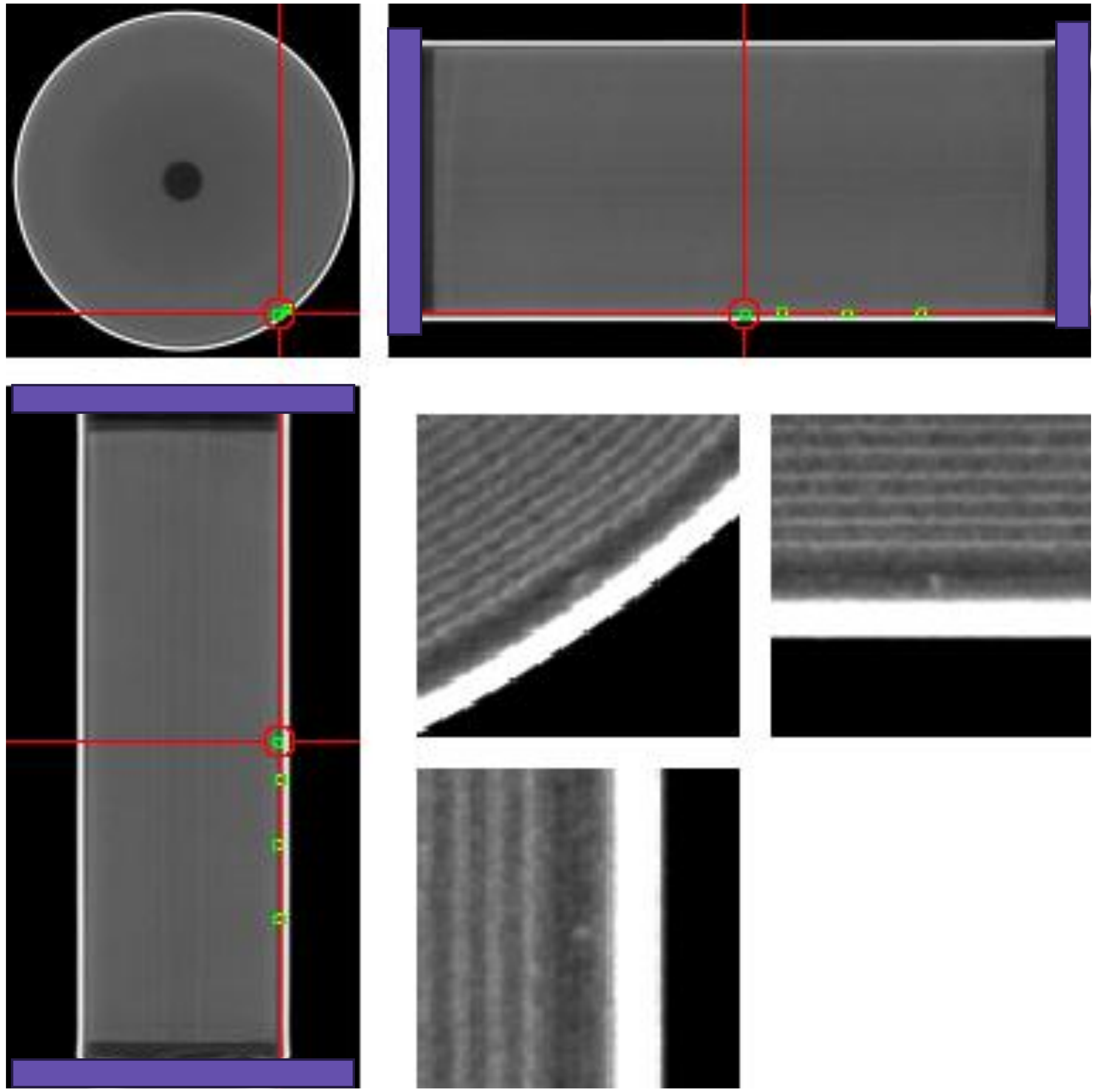
Inclusion Detection

Classification Network

Example of detected *delamination*



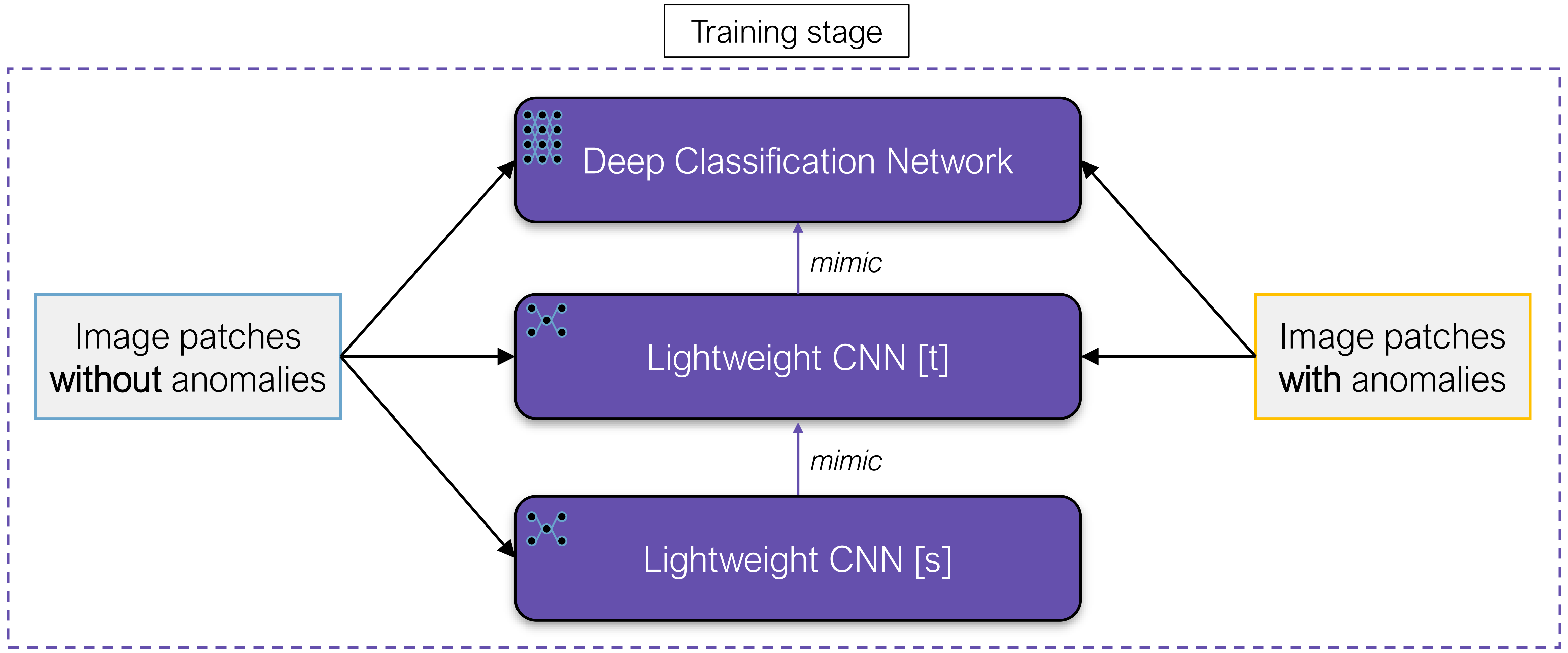
Example of detected inclusion

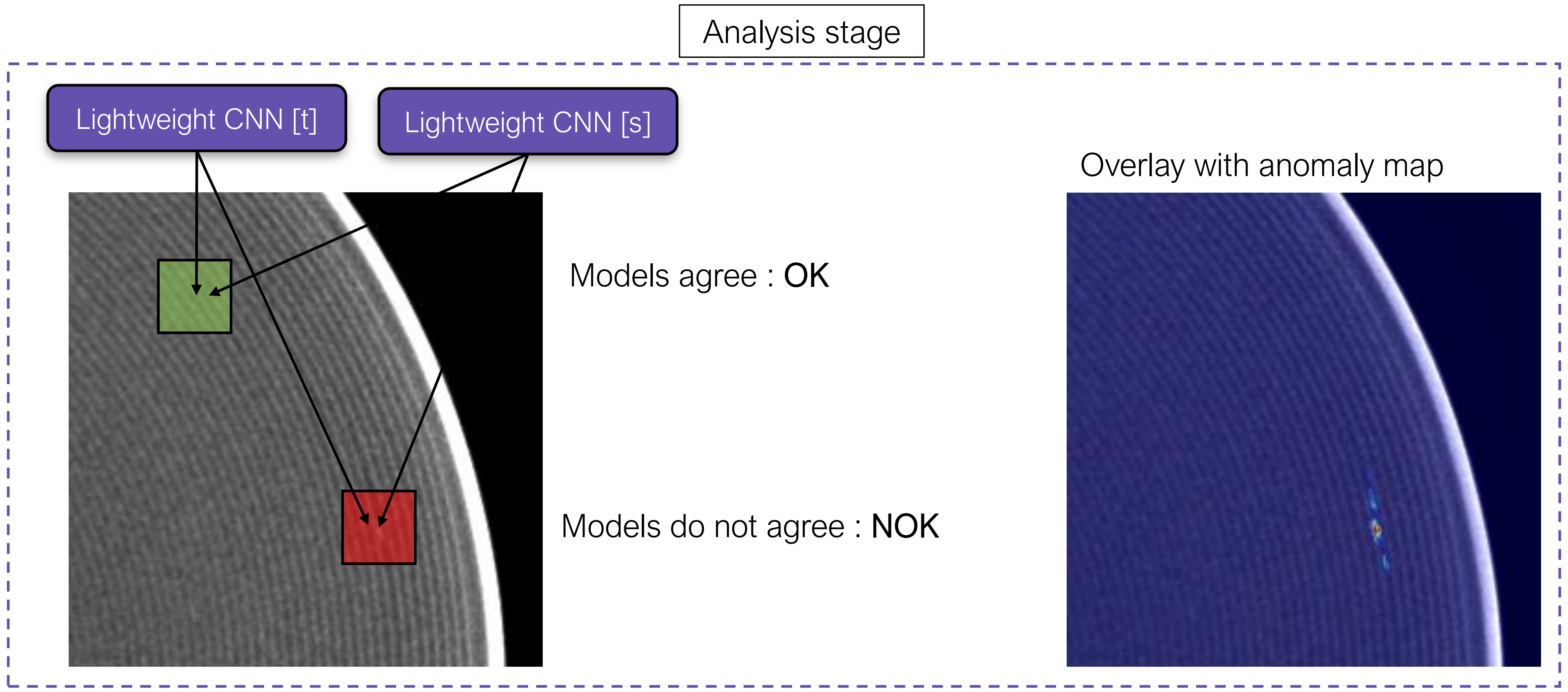


Smart Battery Cell Inspection

Inclusion Detection

Anomaly Detection Network





We **use small, lightweight networks** so inference stays fast, even on large images.

These networks are trained to copy the feature space of a deeper, more complex model, but with different training conditions.

One focuses on learning from all data, while another focuses on normal, defect-free examples.

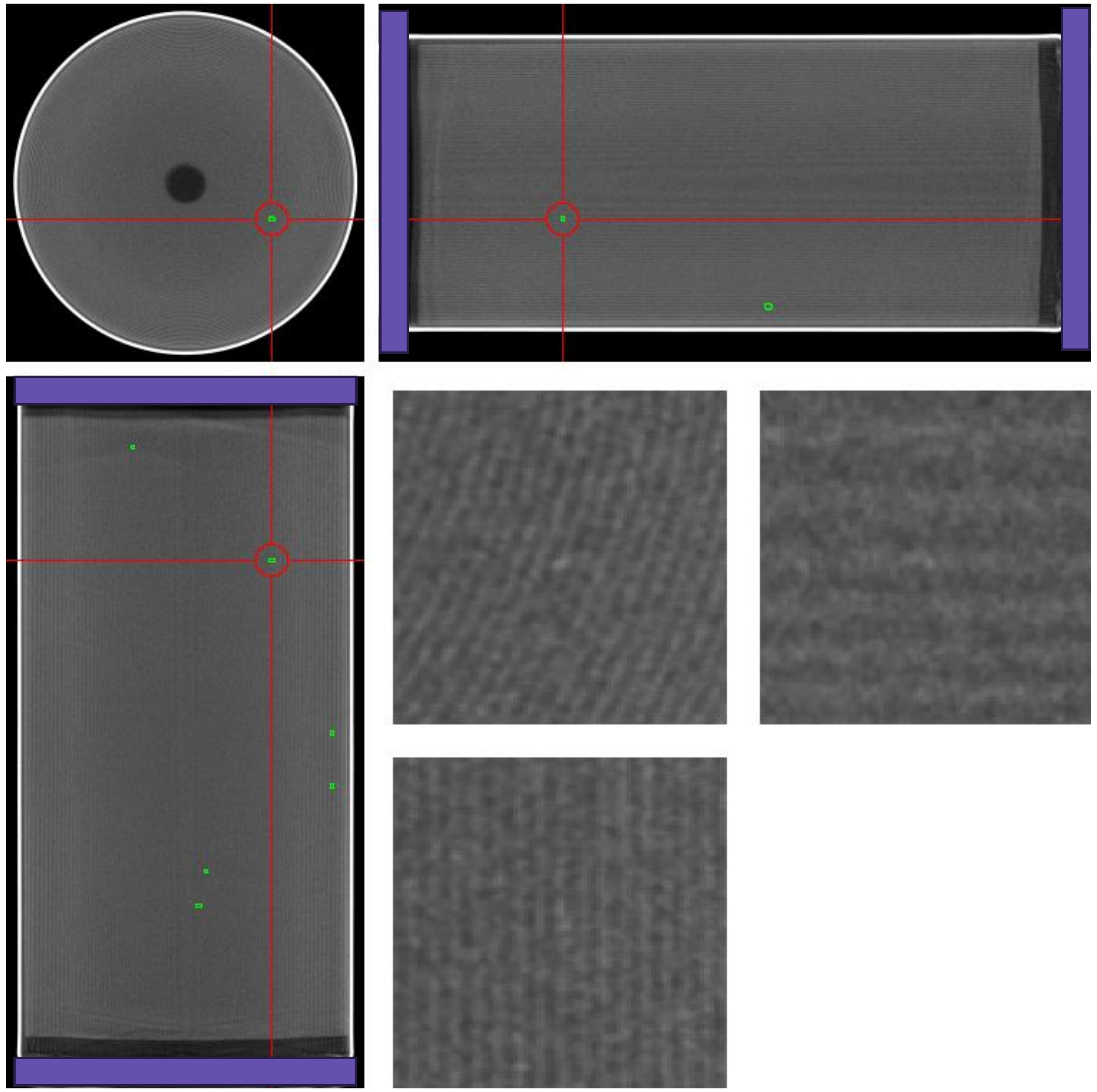
By **comparing their feature outputs**, we can spot regions that behave differently and mark them as possible anomalies.

This keeps computation light while still being robust to noise and unseen variations.

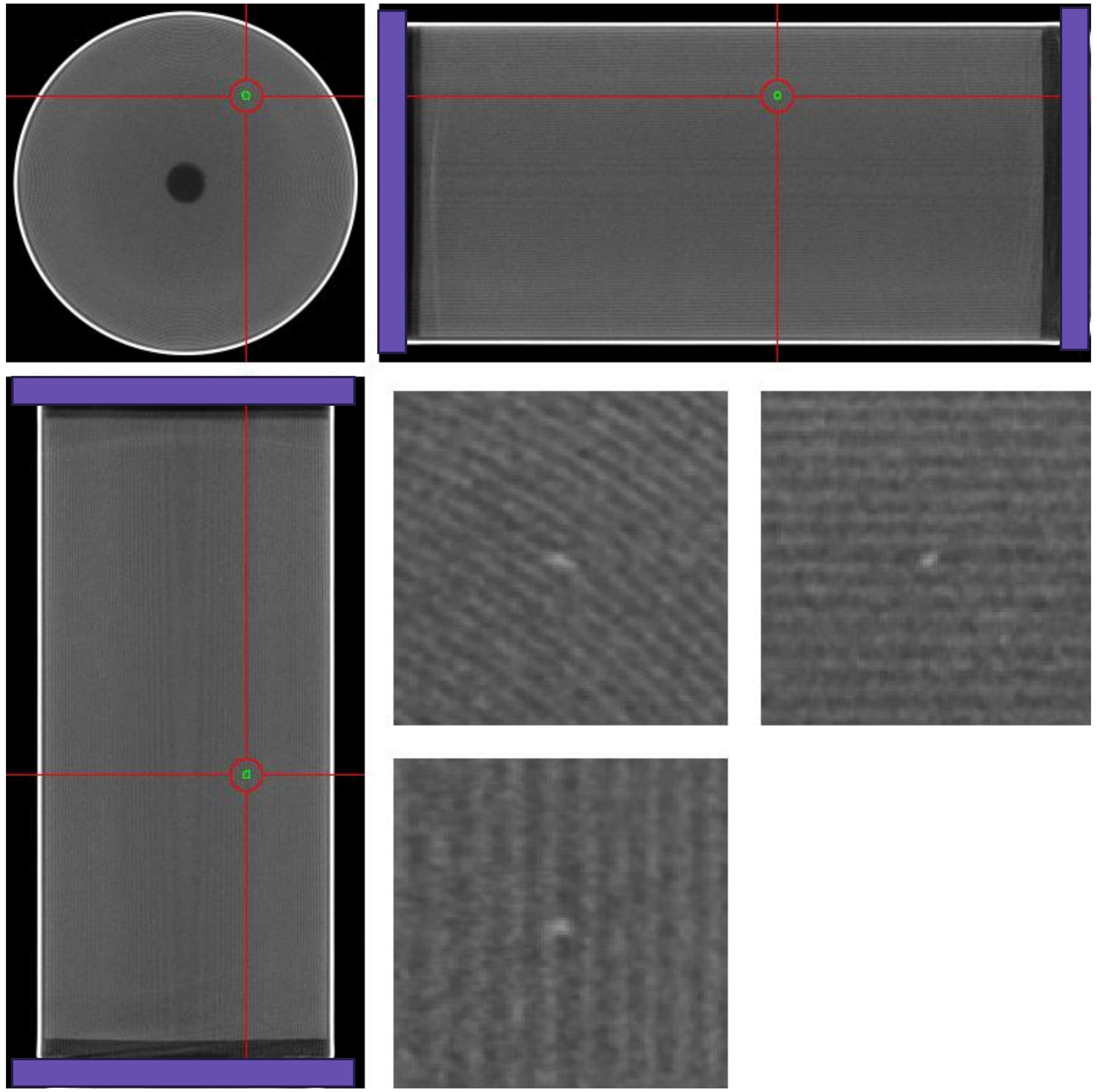
Inclusion Detection

Anomaly Detection Network

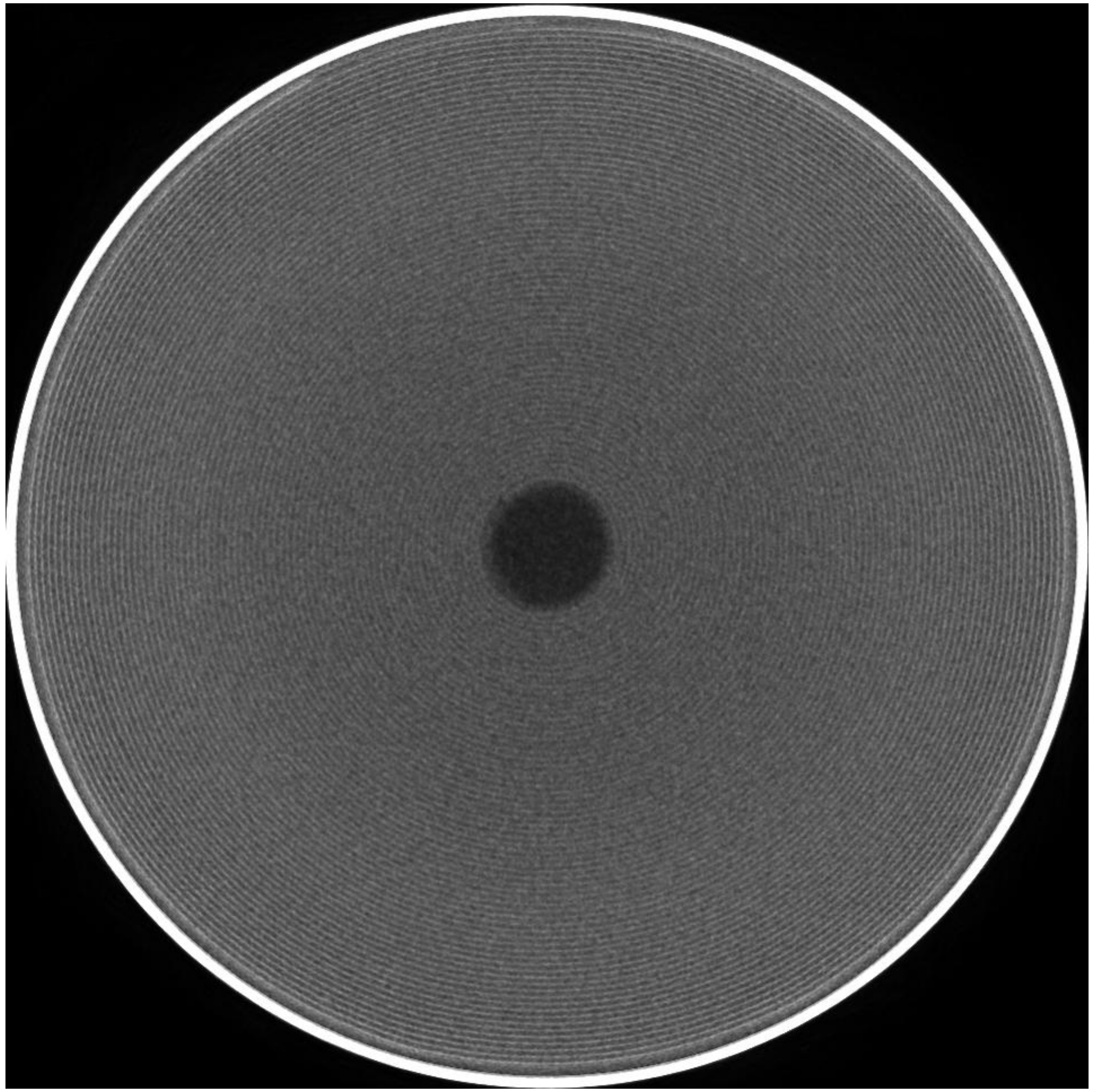
Example of detected inclusion

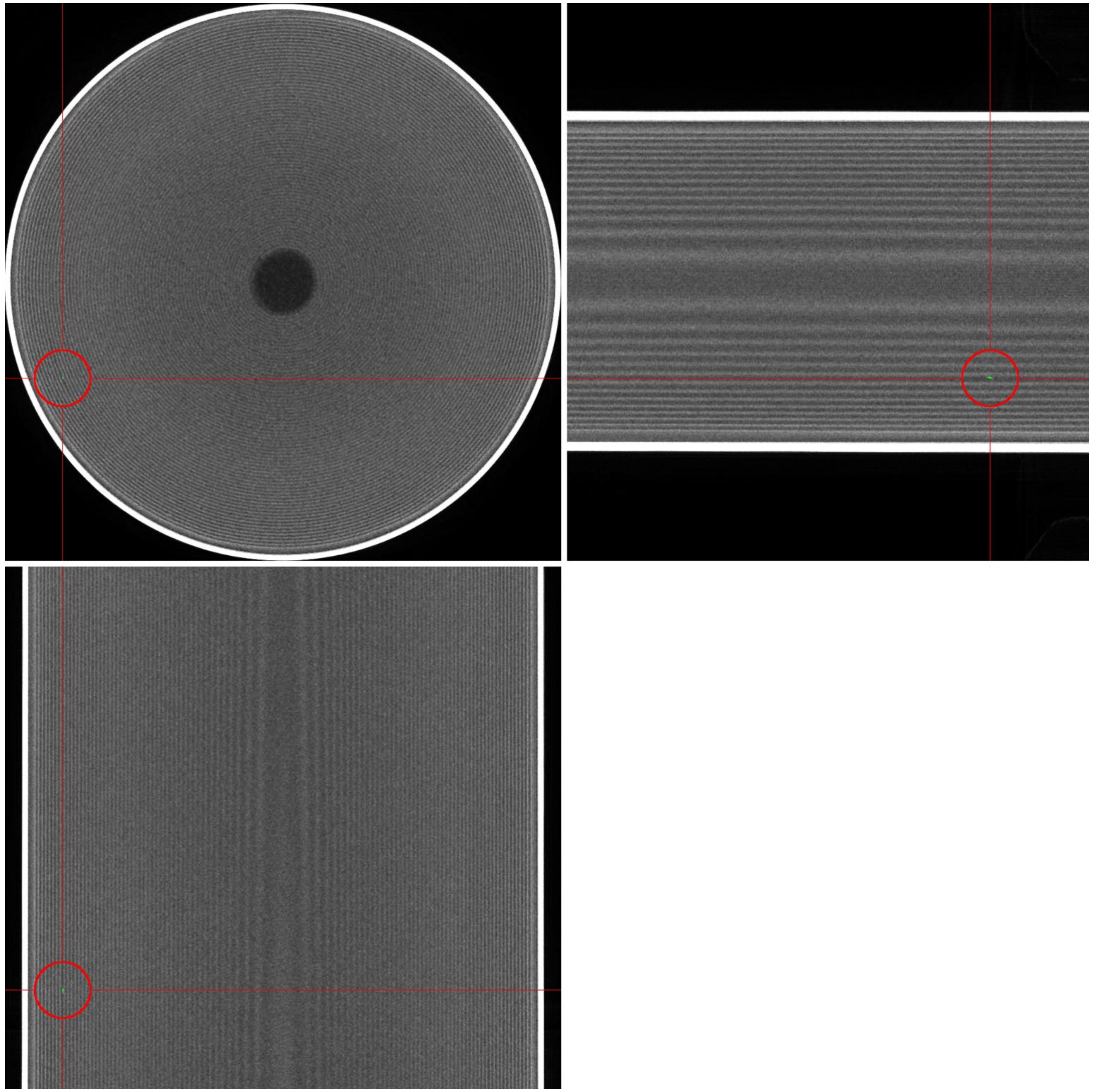


Example of detected inclusion

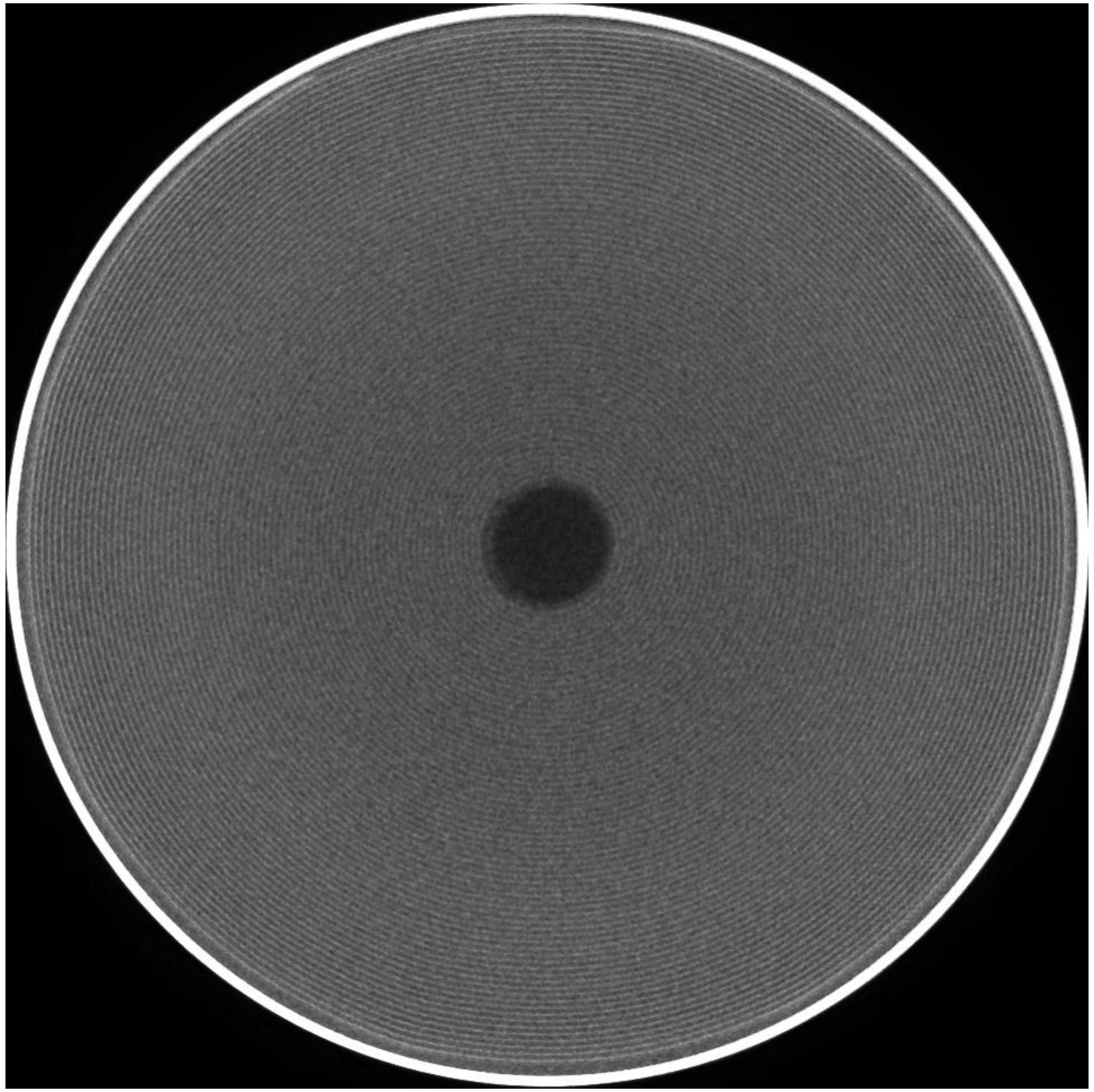


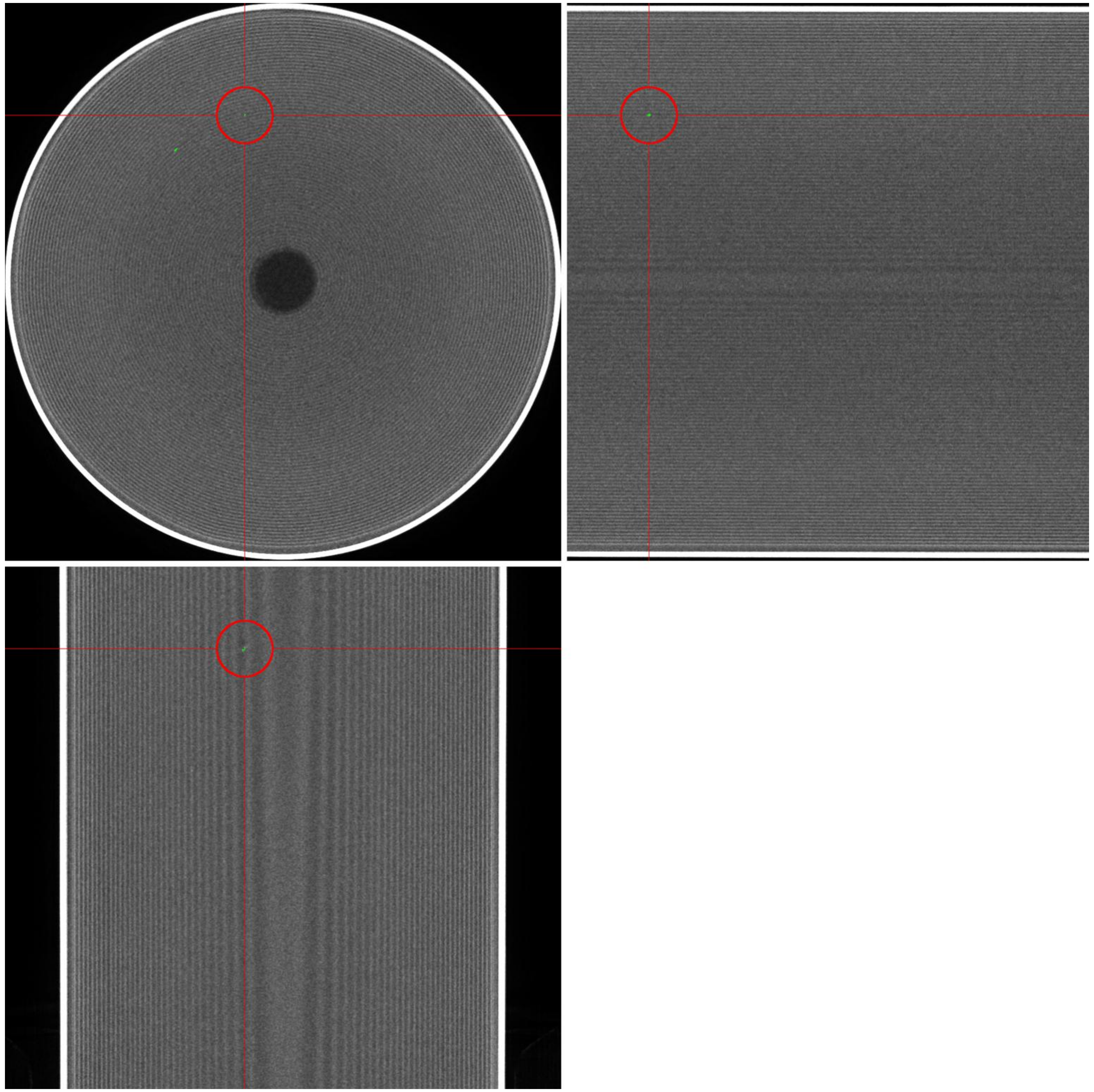
Inclusion Detection





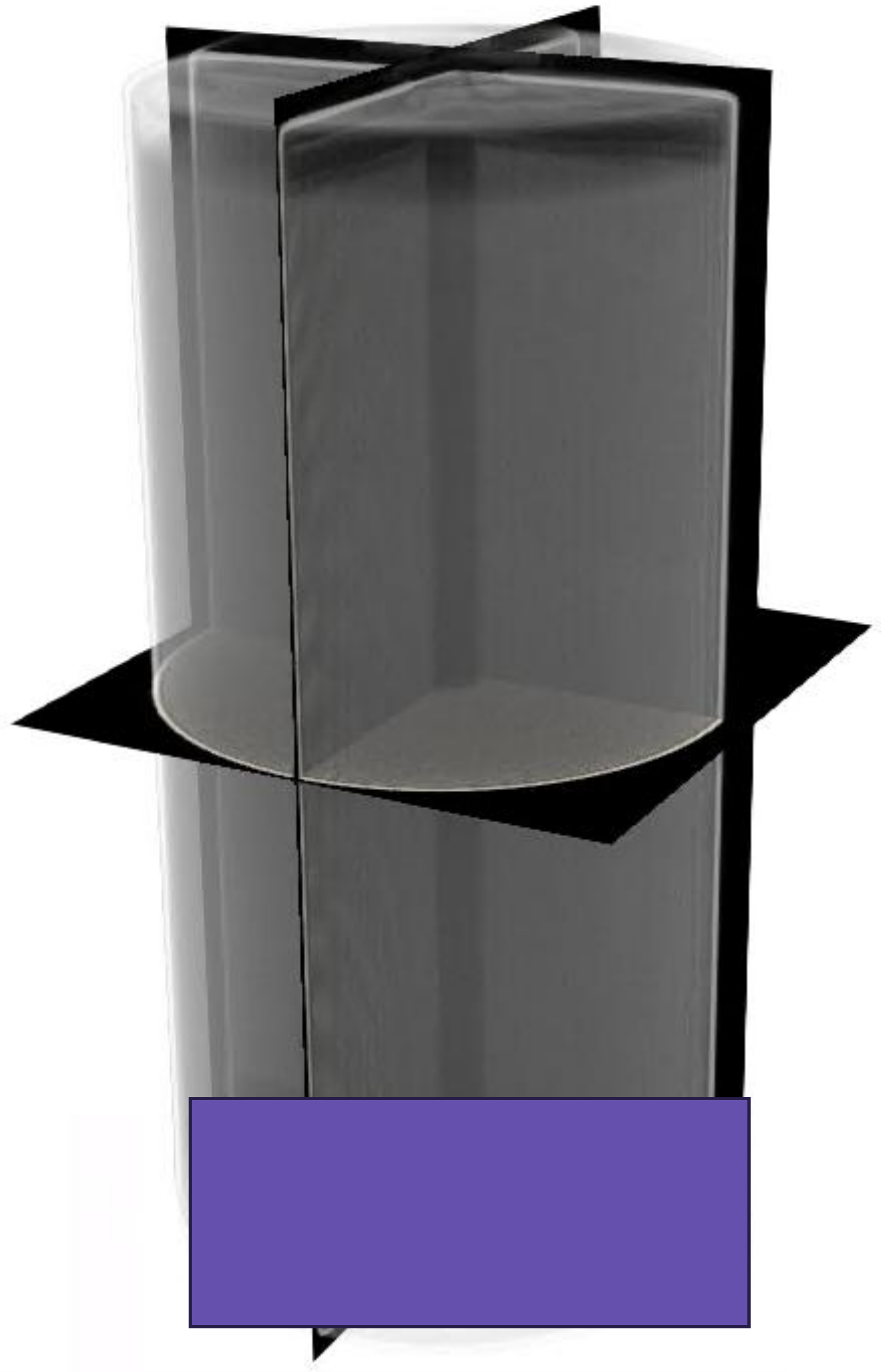
Inclusion Detection

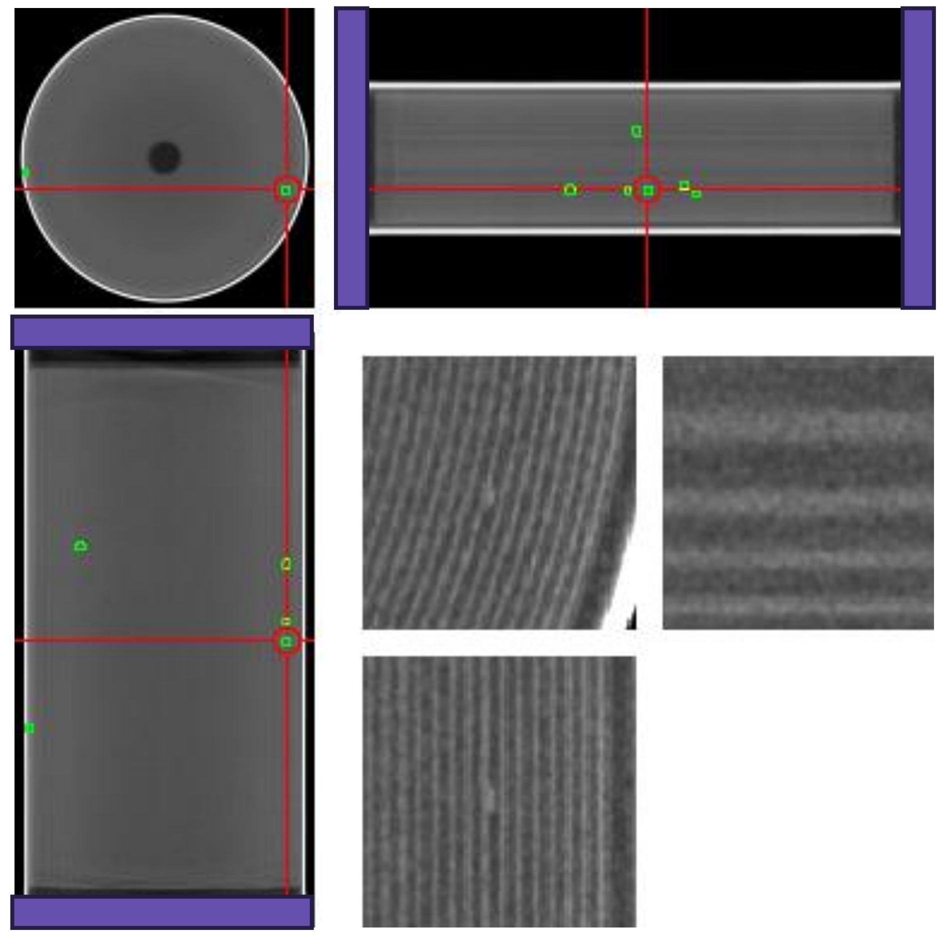


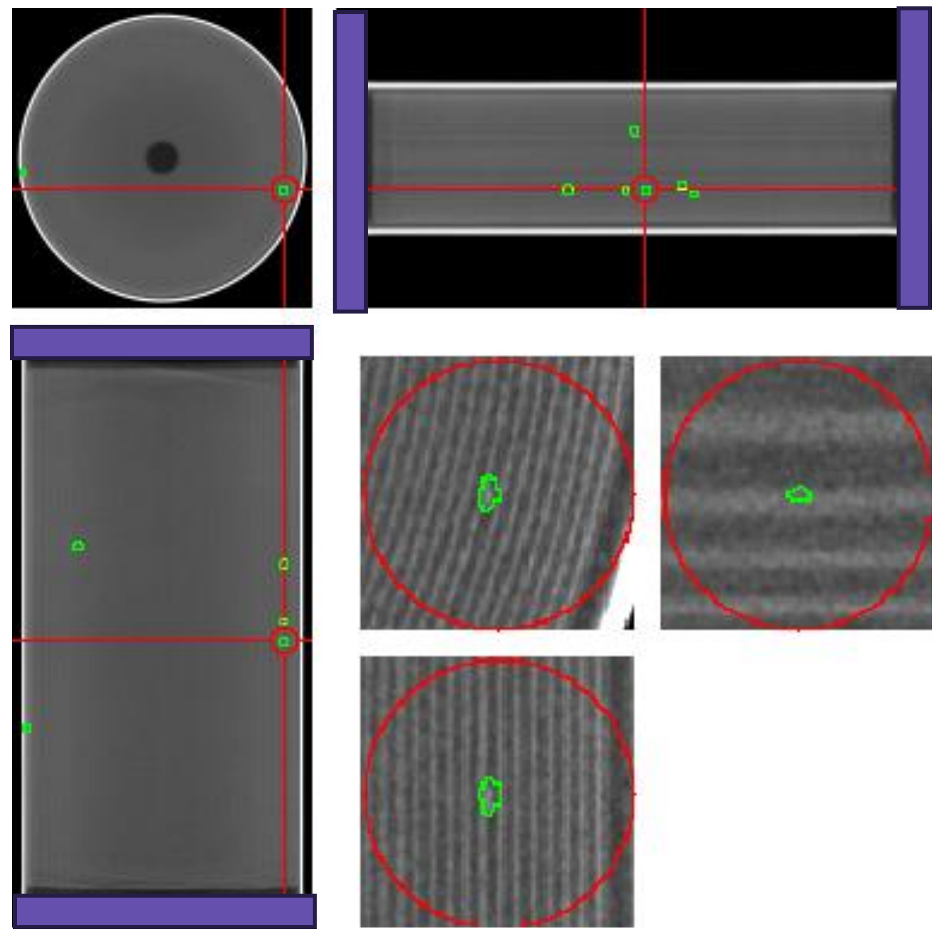


Smart Battery Cell Inspection

Post-Processing







- Merge segmentations
- Measure size of inclusions and delaminations
- Compute centroids
- Create annotations in the original coordinate systems
- Create tables and structured files for reporting
- Save images

Typical Realization and Implementation offered by Xnovo

Load management balancing

Different analysis types are performed

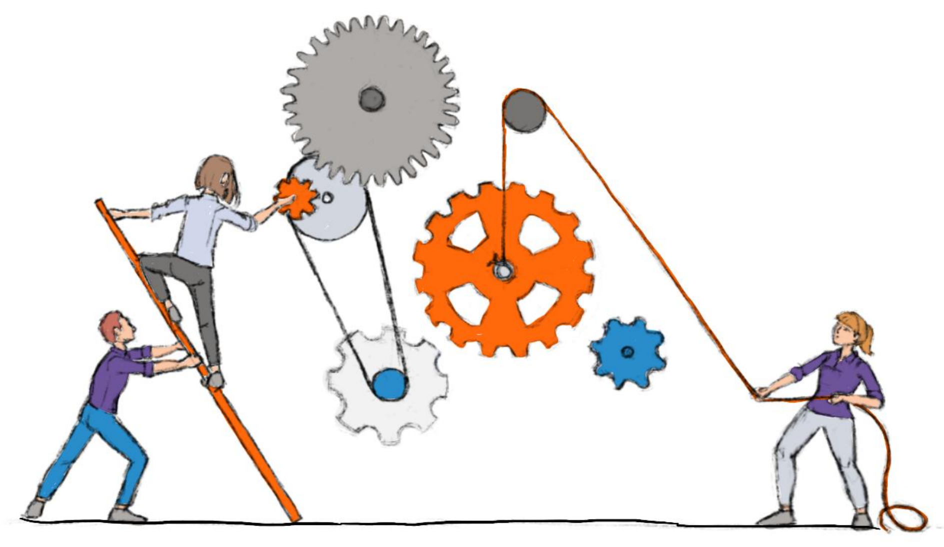
- Initial scan quality surveil
- Analytical methods (CPU)
- Anomaly detection (GPU)
- Classification network (GPU)
- Segmentation and geometrical analyses (GPU and CPU)
- Pre- and postprocessing (mainly CPU)

Analyses are distributed over different workstation with multiple GPUs

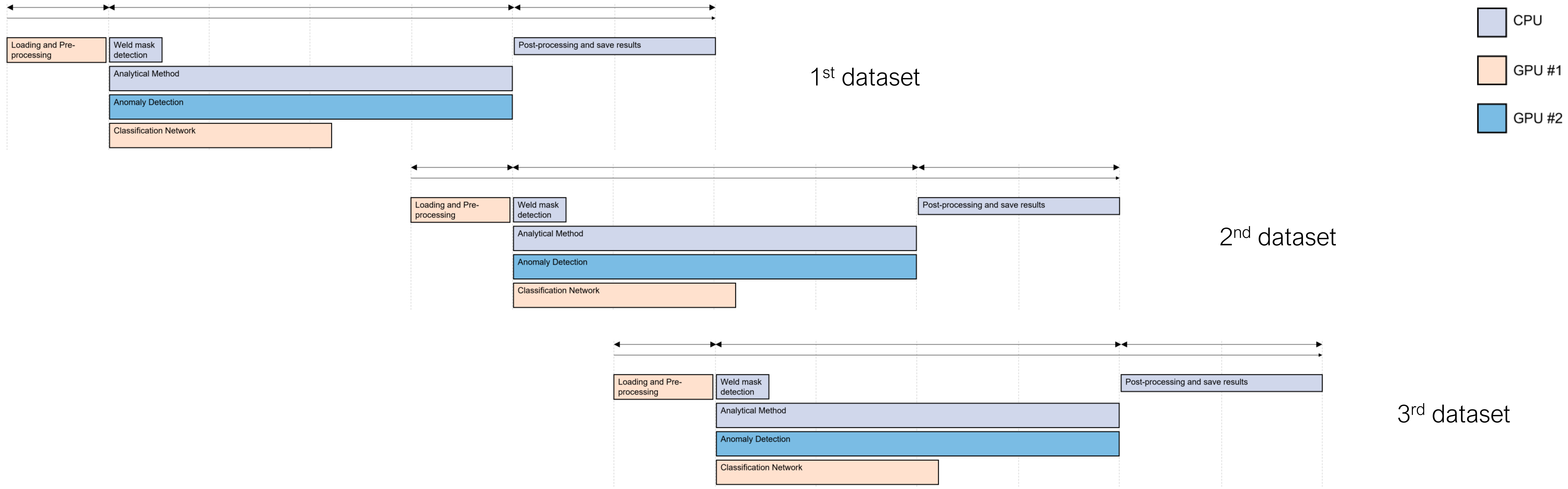
- Each available CPU and GPU in the local analysis network can be addressed separately
- Volumes can be split if necessary and loaded into dedicated CPUs and GPUs to perform analyses
- Status of each analysis is surveilled
- Results are collected and merged
- Data and reports are stored on NAS

Some interfaces

- OPC UA Server to communicate with process control system and PLC
- HMI for SW control, offline analysis and training of models
- Web-based status dashboard
- Interface to statistical process control SW (e.g. Q-DAS)
- Automatic data parsing and compression for archiving
  - Uncompressed for cells with defects
  - Lossless compression
  - Lossy compression
  - Preserve reports, images and metadata
- …



Workflow on a single Workstation

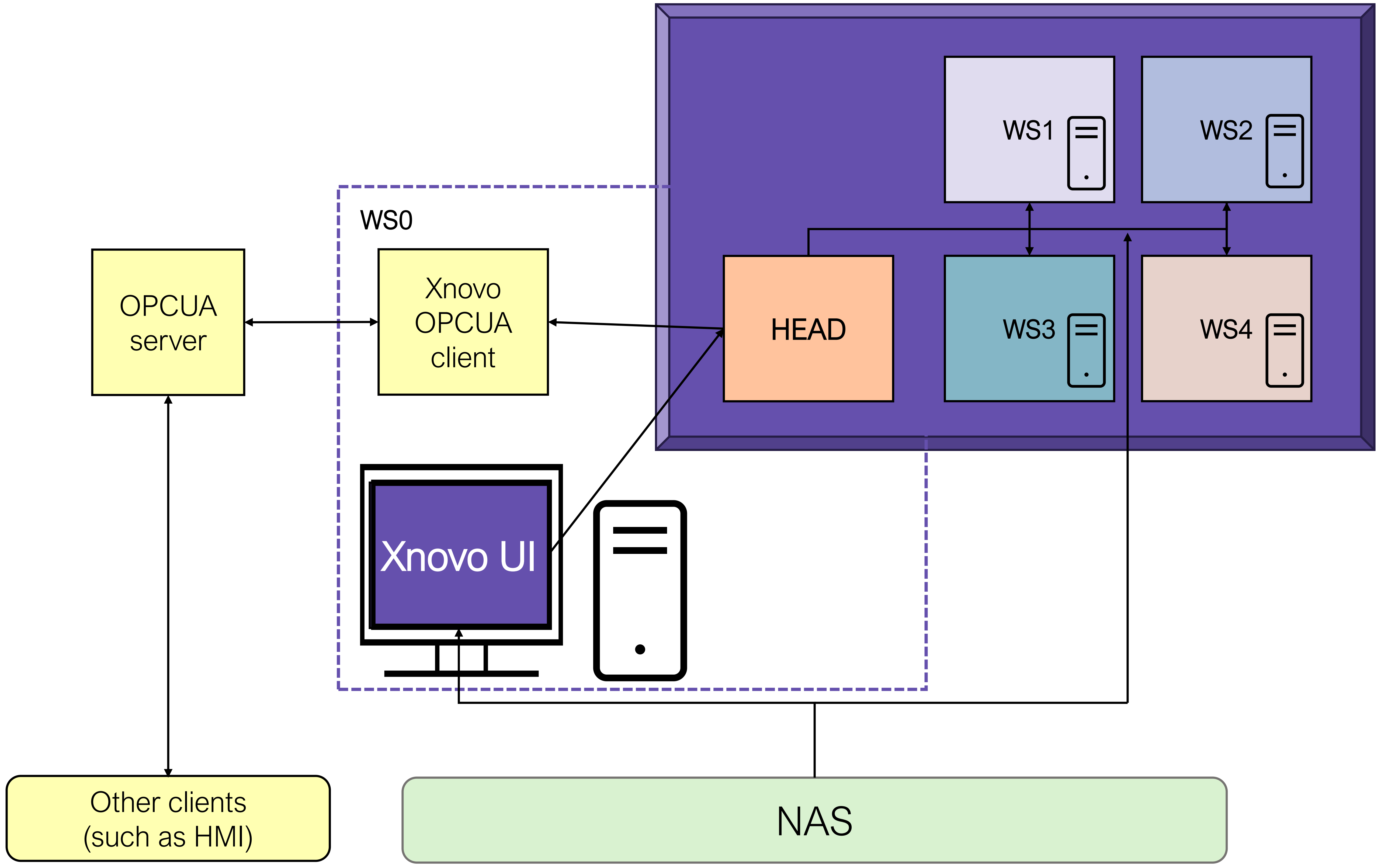


Optimized usage of available CPUs and GPUs to

- minimize throughput time – catch up with cycle time.
- limit total duration of analysis – reduce needed buffer time.

Realization: Parallelization using multiple Workstations

Load Management – Task Distribution system



Realization: Parallelization using multiple Workstations

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NODES

Auto Refresh:

Request Status: Node summary fetched.

Node Statistics

TOTAL x 3 ALIVE x 3

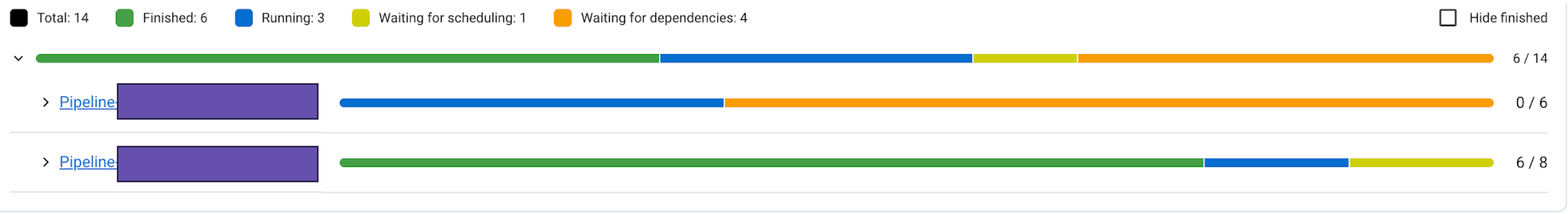
Node List

Host | IP | Node ID | State | Page Size | Sort By | Reverse: | TABLE | CARD

1

	Host / Worker Process name	State	State Message	ID	IP / PID	Actions	CPU	Memory	GPU	GRAM
>	LAPTOP-S77D20T5	ALIVE	-	be90a...	10.1.227.150 (Head)	Log	3%	7.42GB/15.84GB(46.8%)	N/A	N/A
>	XNOVOWS07	ALIVE	-	8fd45...	10.1.223.11	Log	0.8%	77.21GB/255.88GB(30.2%)	[0]: 0.0%	[0]: 1542MiB/8192MiB
>	XNOVOWS06	ALIVE	-	a7955...	10.1.223.10	Log	3.9%	30.33GB/255.66GB(11.9%)	[0]: 0.0% [1]: 0.0%	[0]: 10190MiB/16384MiB [1]: 1121MiB/16384MiB

Realization: Web based Dashboard



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Thank you!