From Wafer to Package:
High Performance X-Ray Sources Driving Semiconductor Progress

Julius Hållstedt, T. Dreier, D. Nilsson

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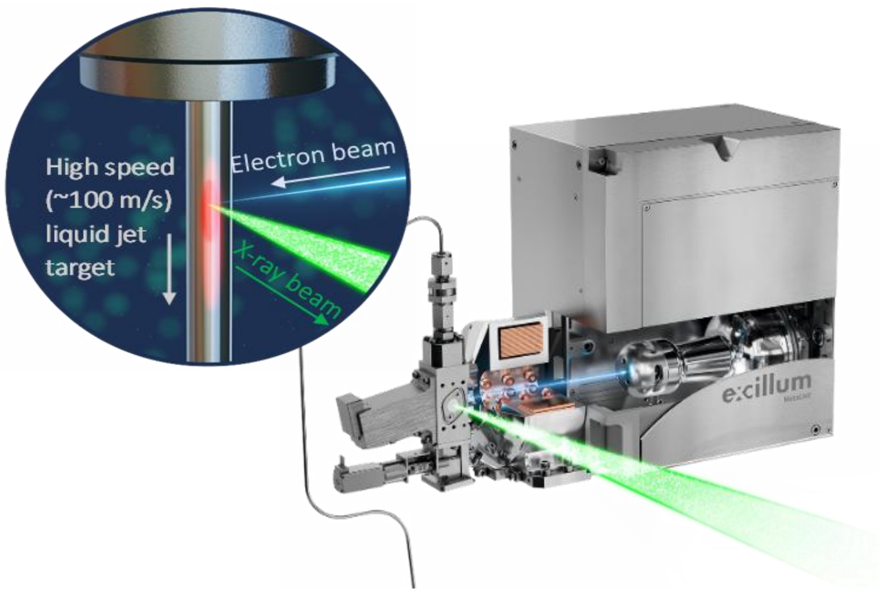
Challenges with X-rays

From Lab to Fab challenges with X-ray applications:
- Speed
- Resolution
- Signal to noise

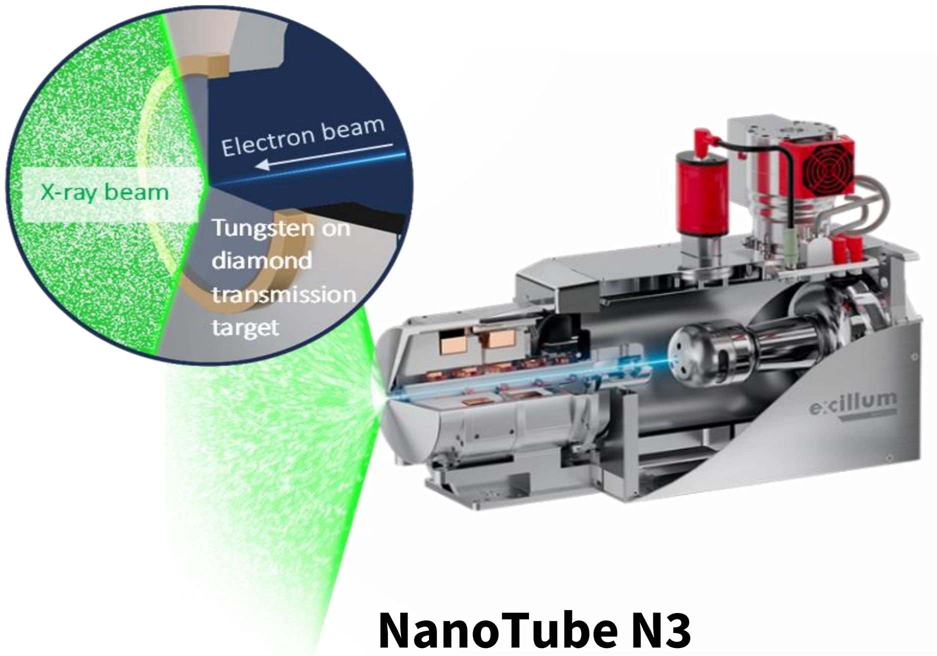
Simply put - too few photons available!

For most applications the
X-ray source is thereby the main limiting factor.

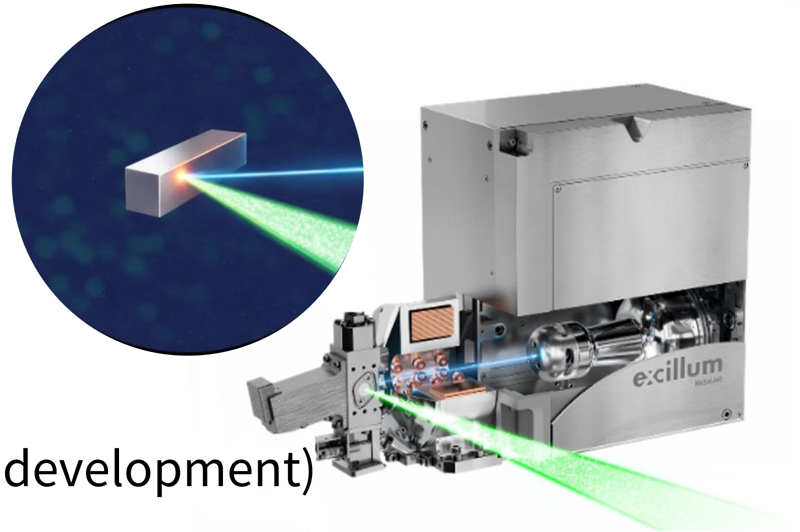
What we do – X-ray sources!



MetalJet F
Extreme brightness

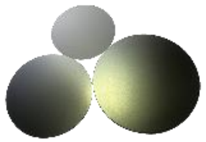


NanoTube N3
Worlds *Smallest spot*



Coming Solid source (in development)

Excillum in semiconductor metrology/inspection

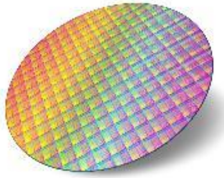


FEOL – front end of line (device fabrication)

Epitaxial layers (HRXRD)

Critical dimensions (CD-SAXS, XRR)

Contamination and composition (XRF, XPS)



BEOL – back end of line (connection of devices via metal layers)

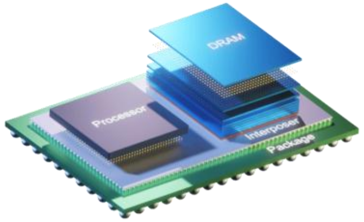
Contamination, composition and thickness (µXRF, XPS)

Critical dimensions (CD)

Crystallinit (XRD)

MetalJet F 1016
High brightness - 1600 W @ 30 um X-ray spot

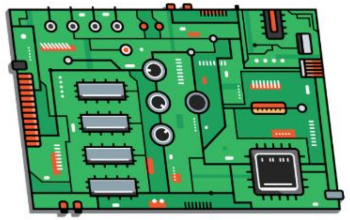
Solid
Target (anode) and spot shape flexibility



Packaging

Advanced packaging (2.5D/3D X-ray)
Detect smallest defects in e.g. TSV, Cu Pillar, micro bump and hybrid bonding

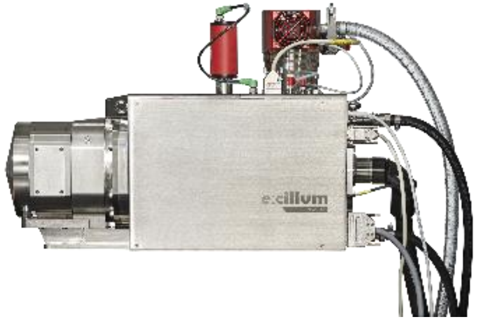
2D/3D X-raywith unique resolution of NanoTube
Optics based solution with MetalJet



PCB surface mount

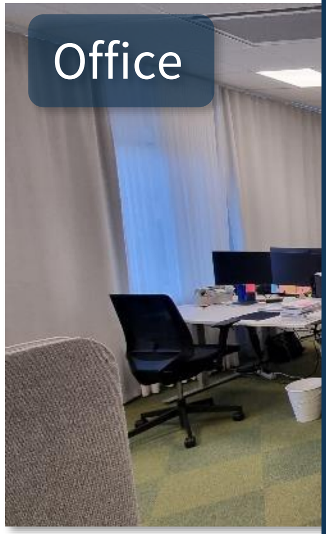
Electronics inspection (2D/2.5D X-ray)
Extreme throughput and defect detectability

Laminography or 2D with unmatched X-ray source power and spot precision of NanoTube



NanoTube N3
High resolution - down to 150 nm

Virtual welcome to Excillum



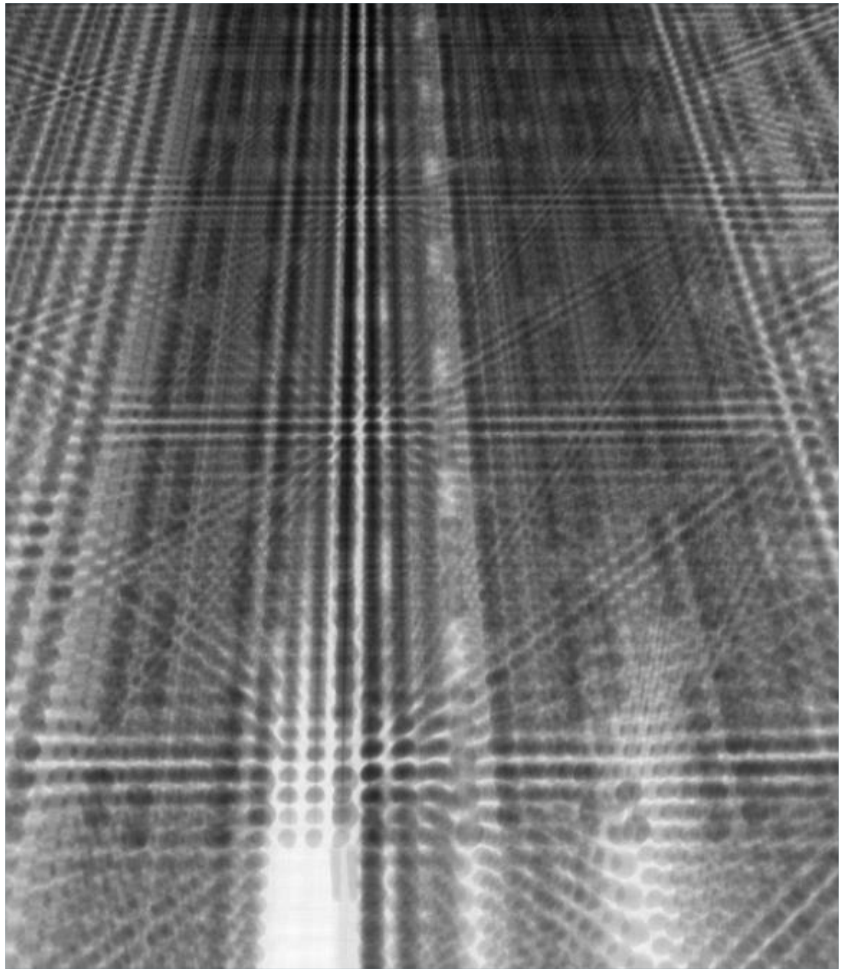
Quick facts

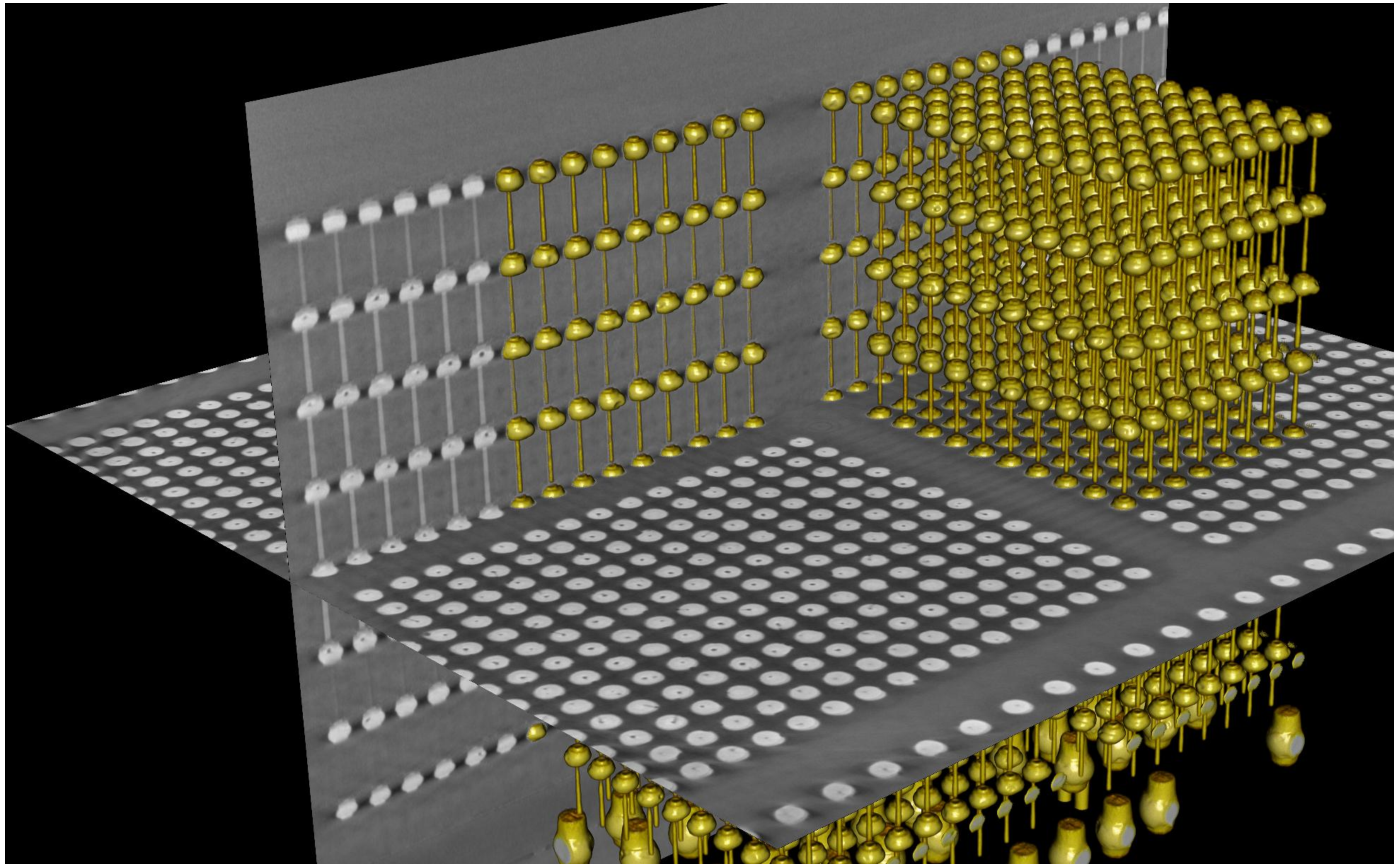
- Founded 2007
- Entirely devoted to making the worlds best X-ray sources
- ~90 people
- >250 sources shipped

3D X-ray

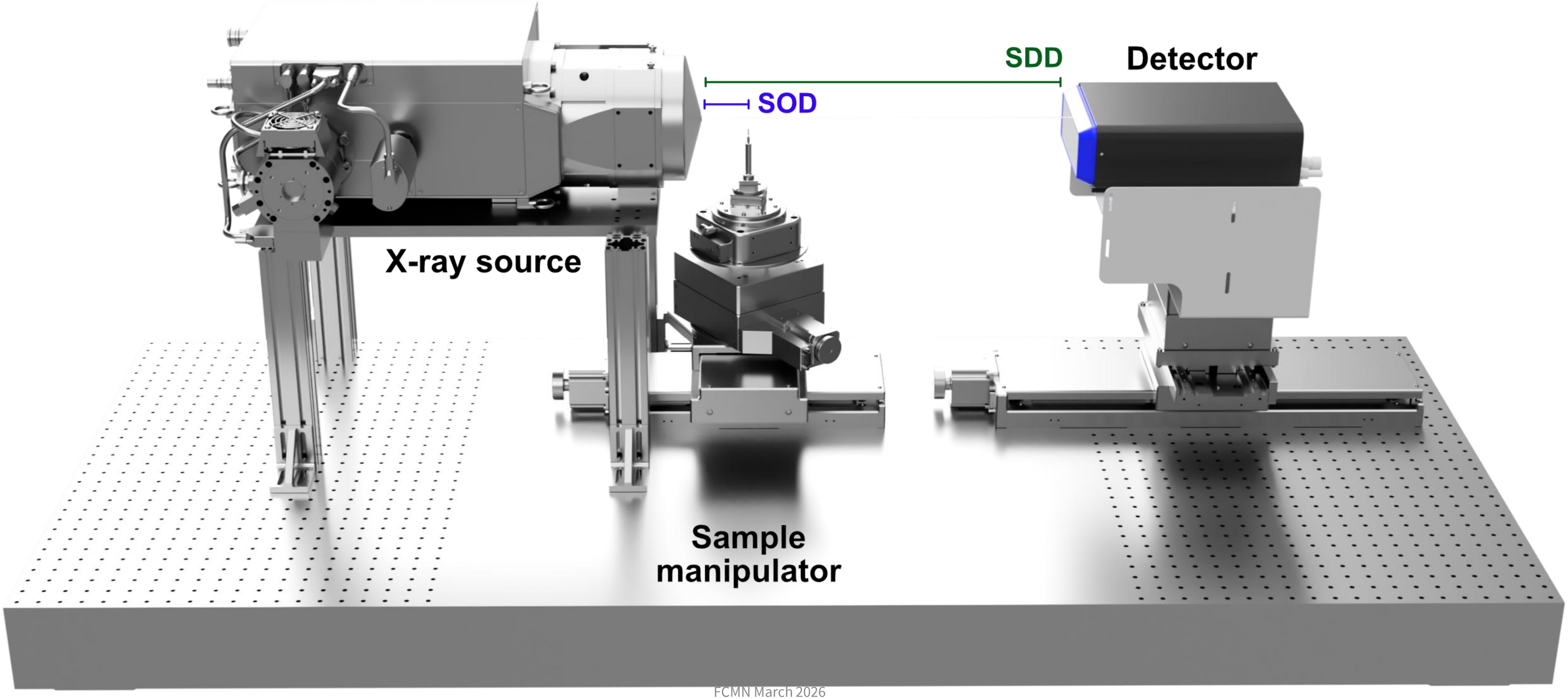
(Nano CT)

2D and 3D imaging

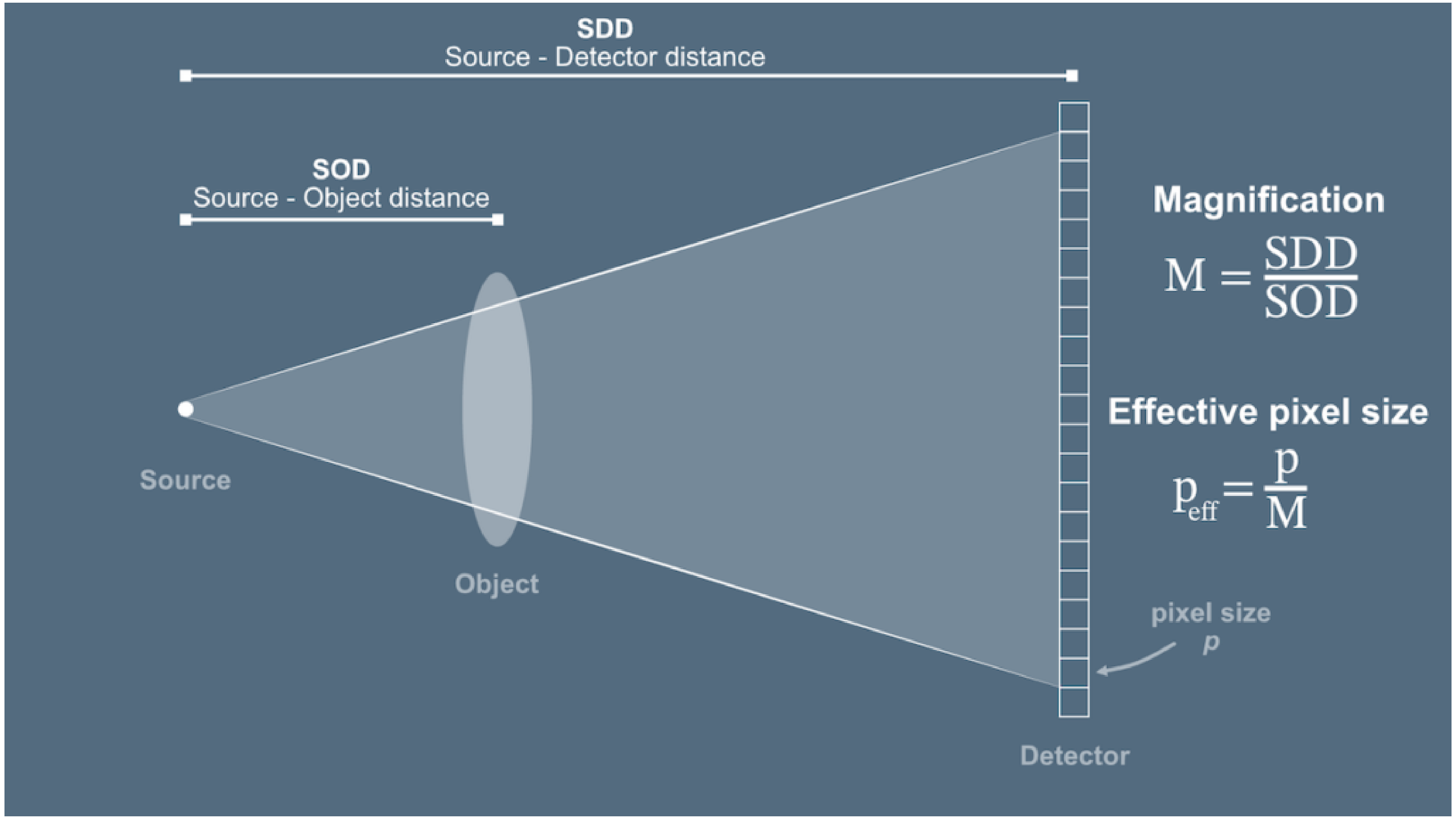




Example of NanoCT setup

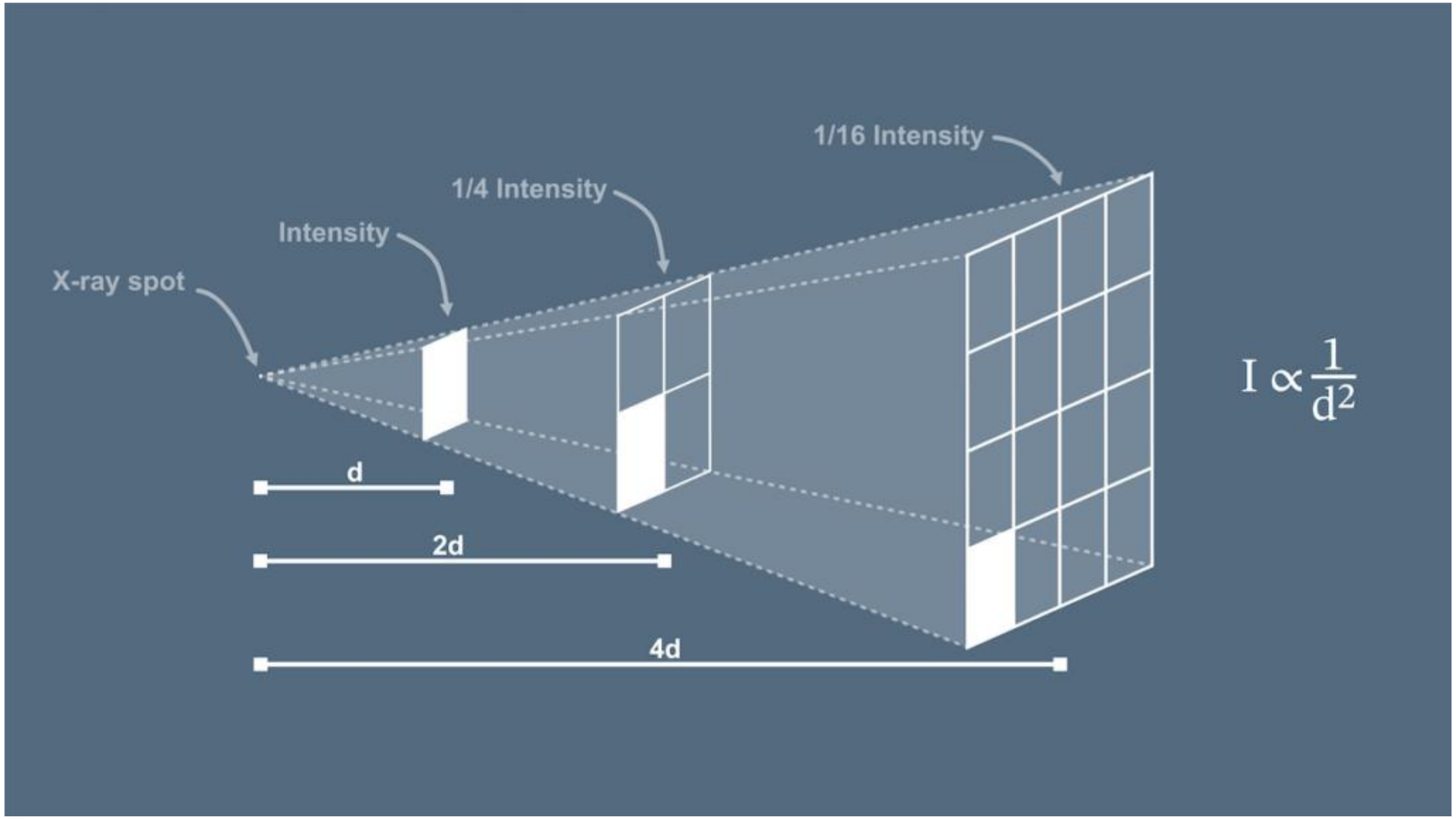


Geometric Magnification



Geometric magnification, the ratio between source-detector distance (SDD) and source-object distance (SOD), defines the achievable resolution.

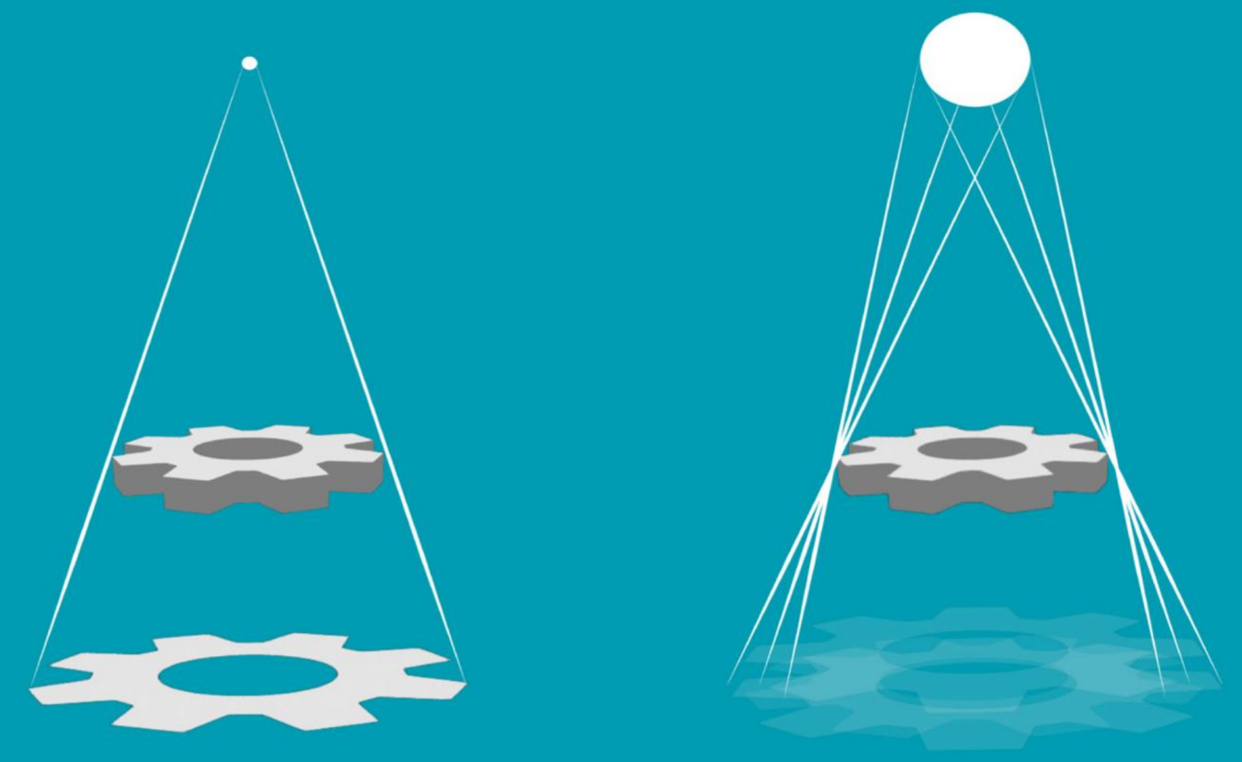
Intensity and inverse square law



The inverse square law states that with increasing distance, the intensity per area is reduced by the square of the distance.

Resolution limit: spot size and penumbral blurring

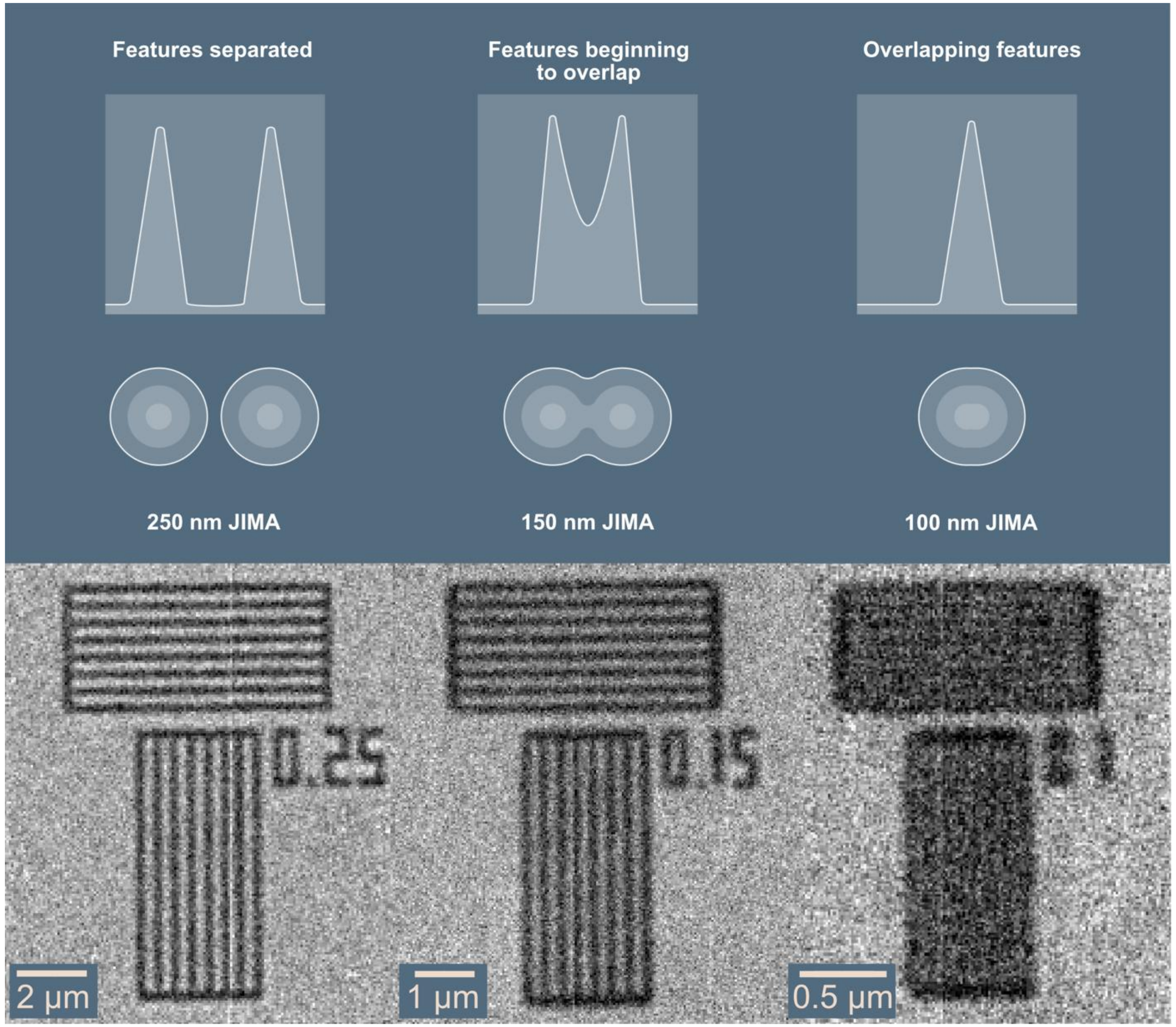
Resolution limit:
½ FWHM of x-ray spot
Assuming a Gaussian-like spot profile



Penumbral blurring:
X-ray spot is projected onto the detector, limiting the achievable resolution

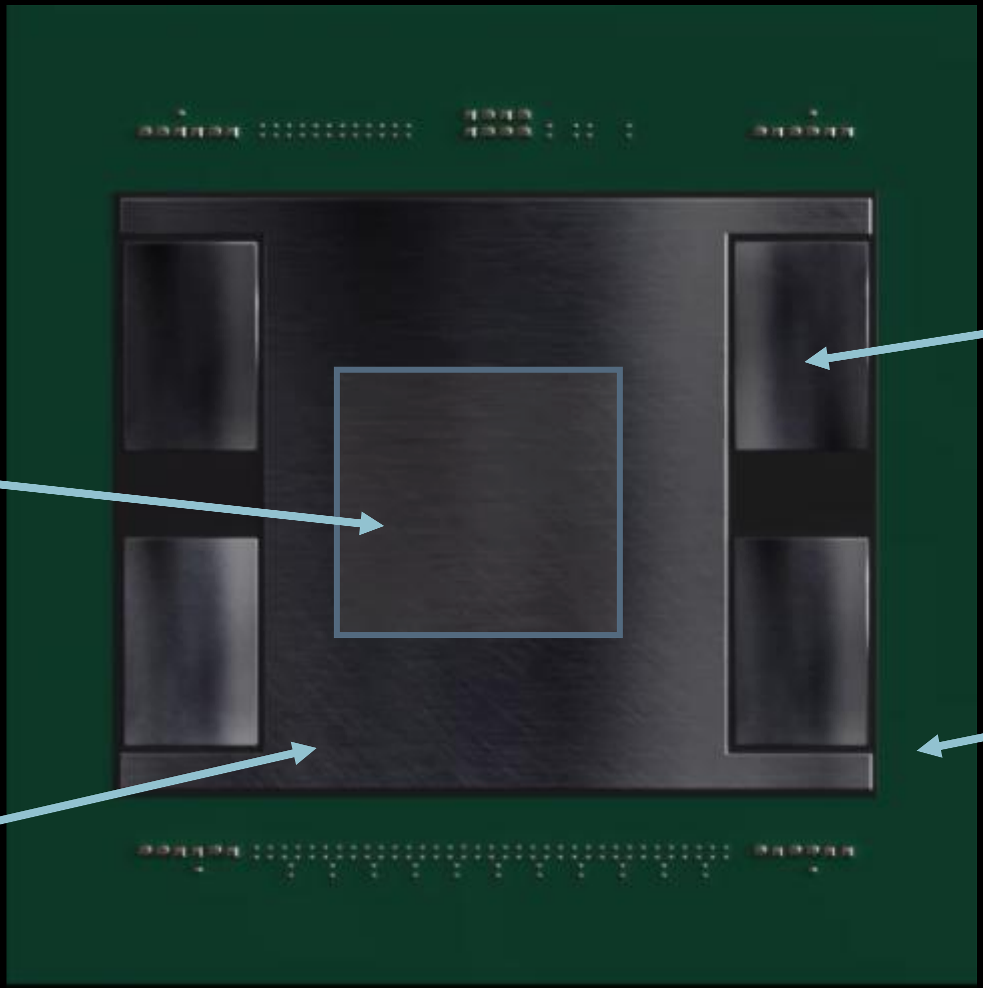
Figure from: J. Hållstedt "*Brightness as key performance metric for X-ray tubes and benchtop X-ray sources*", Excillum AB, 2024

150 nm resolution without optics



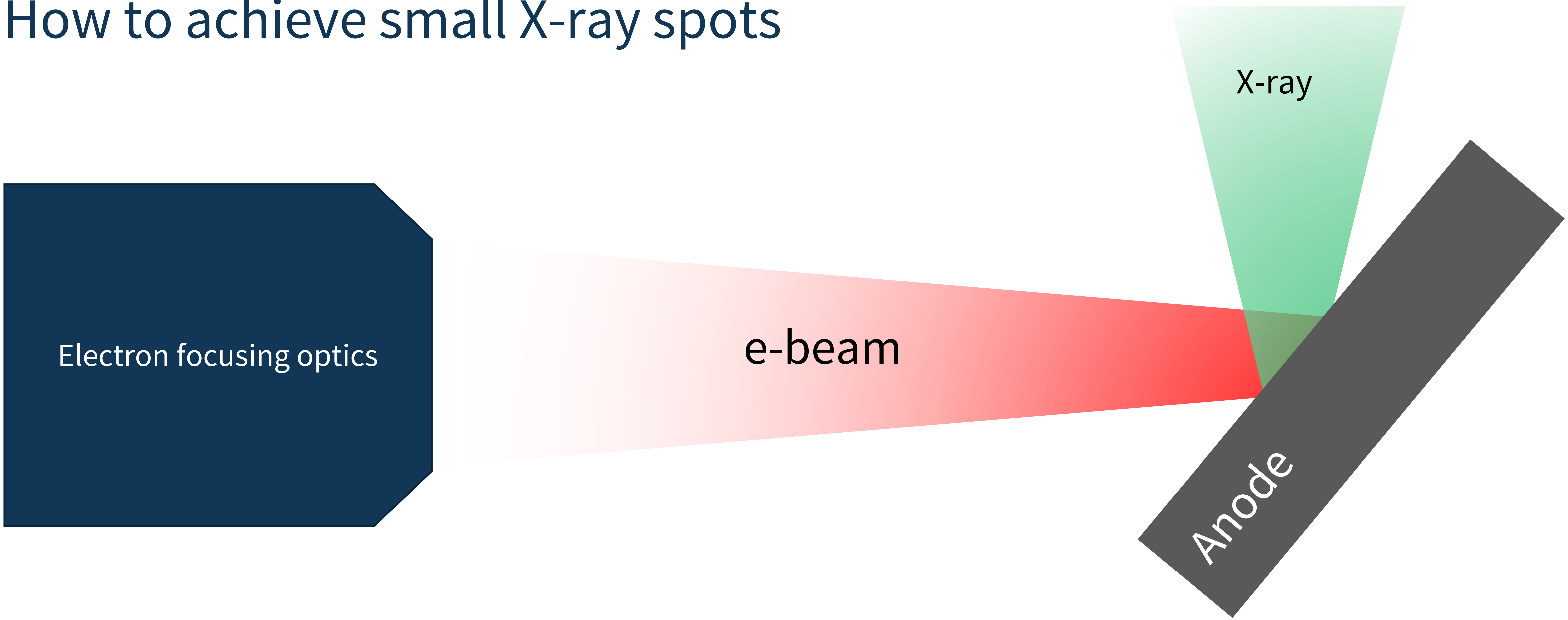
- Schematic illustration of the resolution limit that describes the lower limit of what can be resolved by an imaging system.
- Moving two objects closer together will finally result in them being detected as one.
- As practical example of this effect X-ray images of JIMA test structures was acquired using a 300 nm X-ray spot.

Nano-CT in advanced packaging

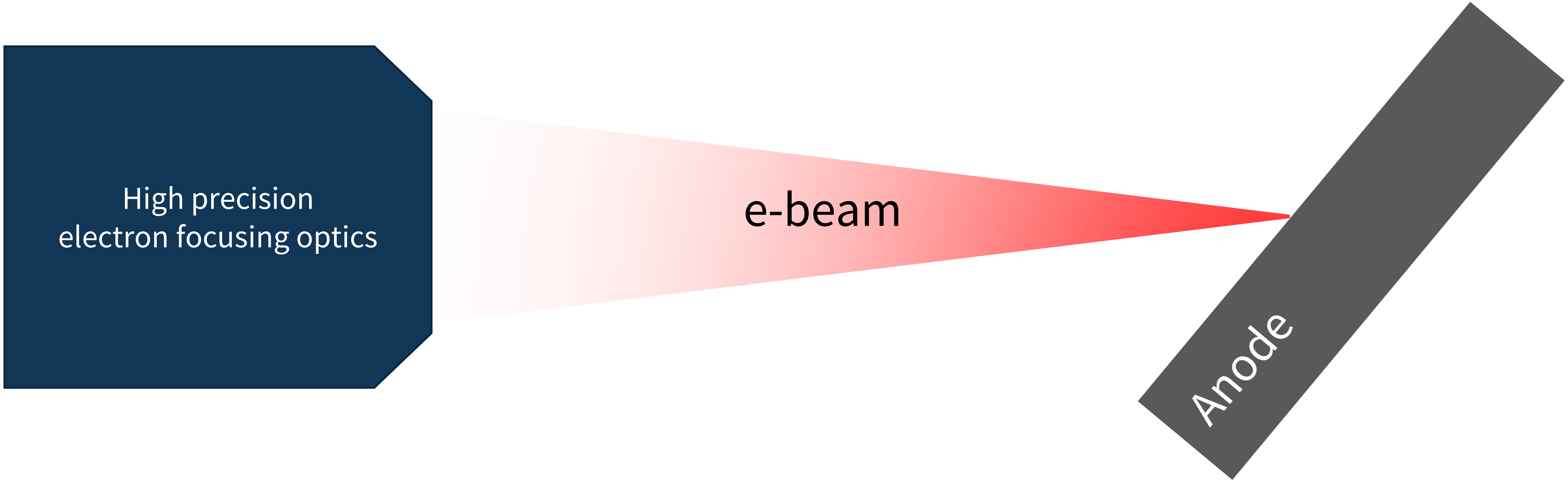


Nvidia GV100 GPU

How to achieve small X-ray spots



How to achieve small X-ray spots



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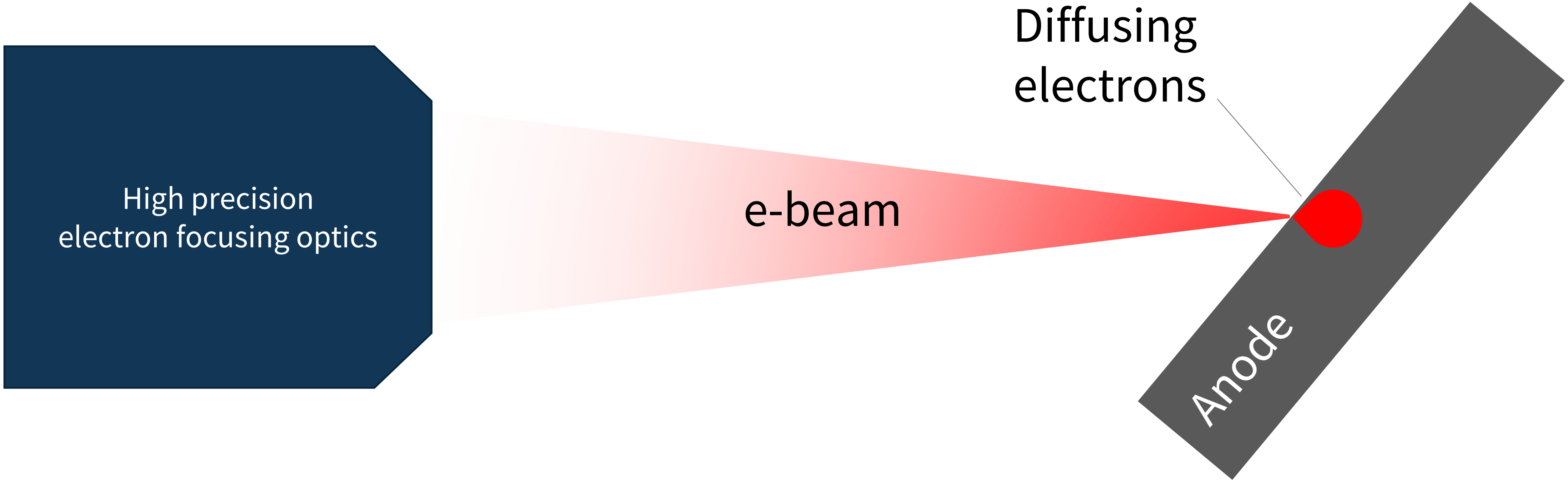
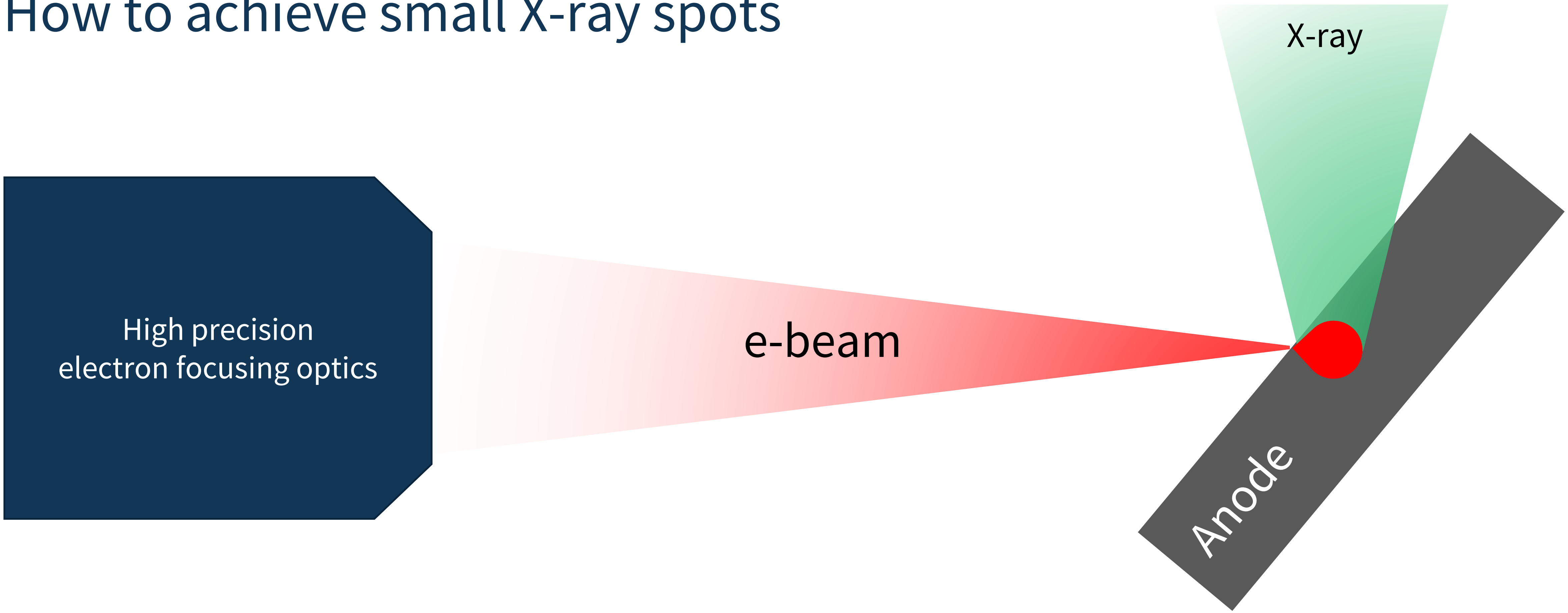
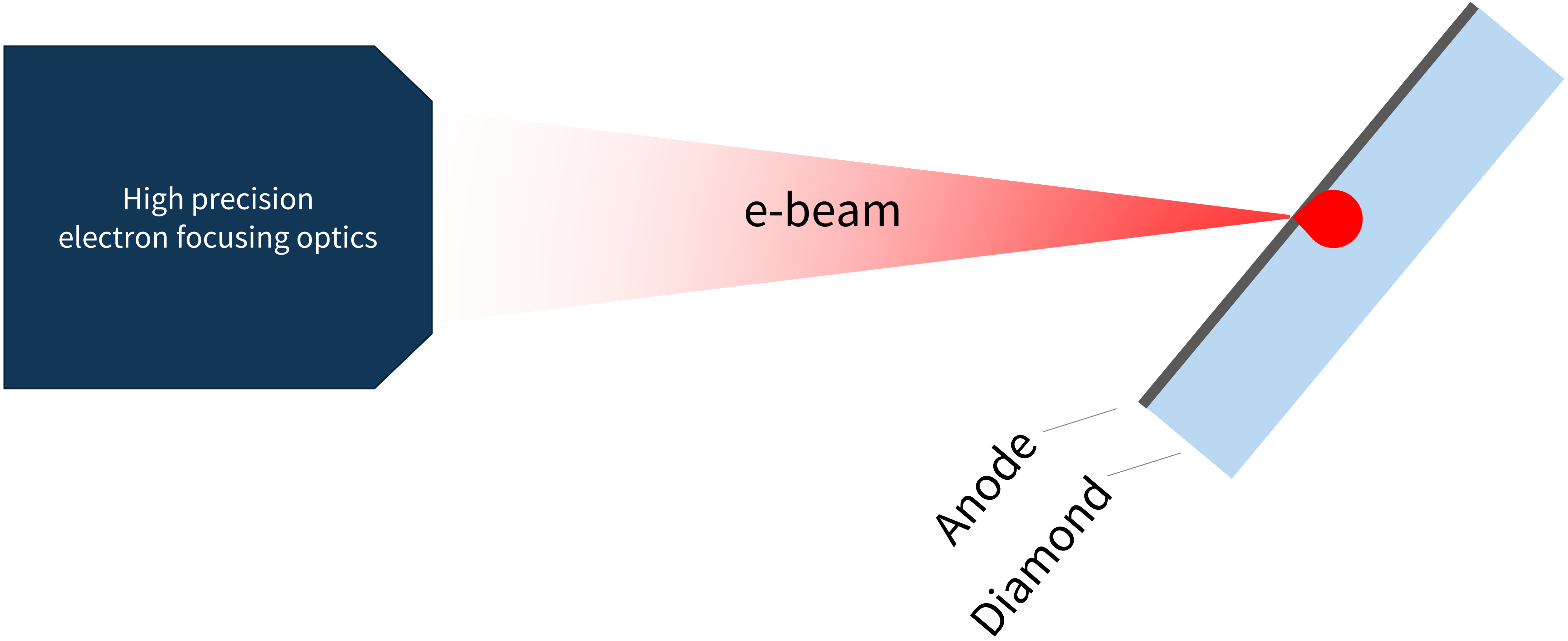
How to achieve small X-ray spots



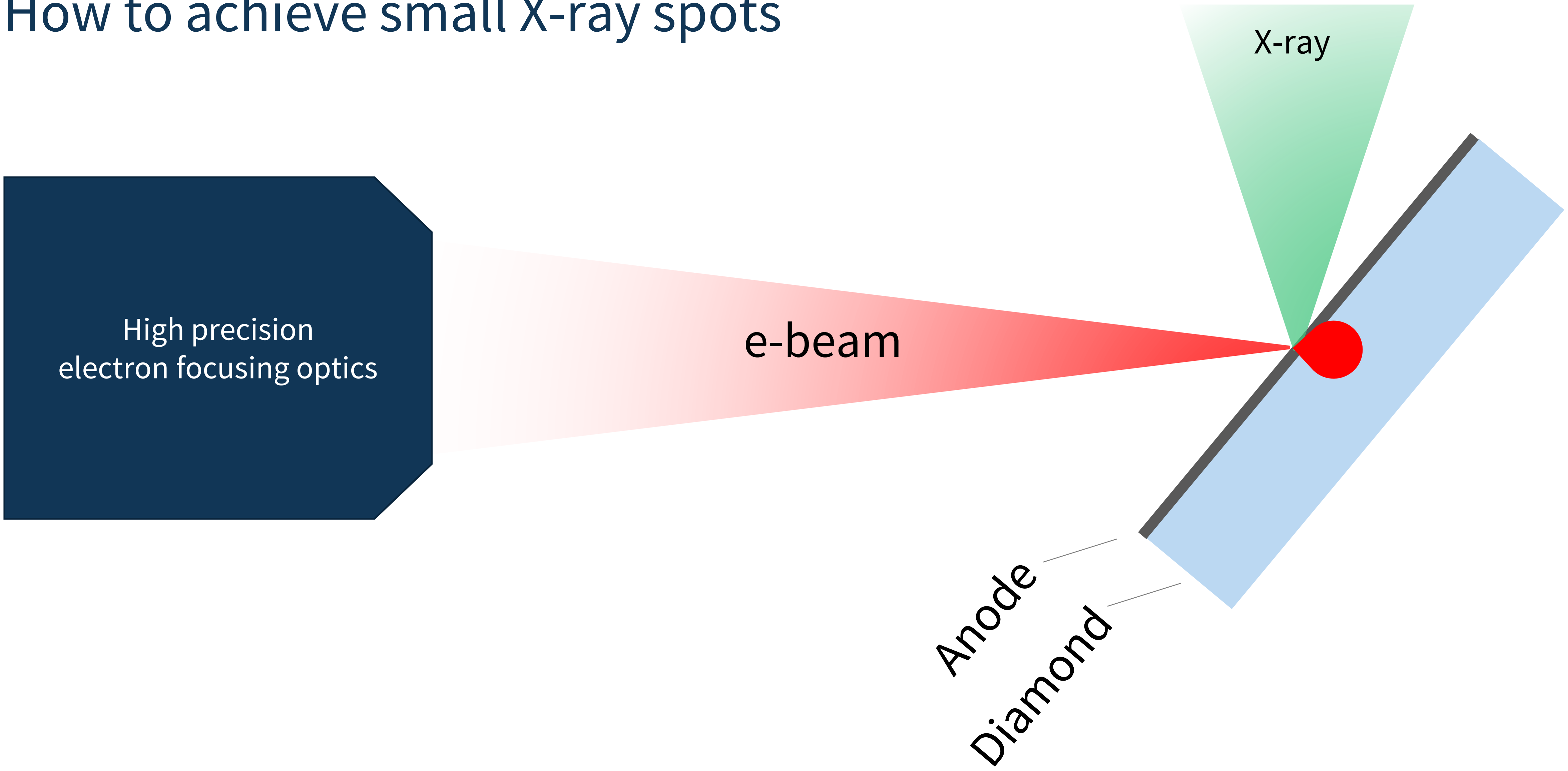
How to achieve small X-ray spots



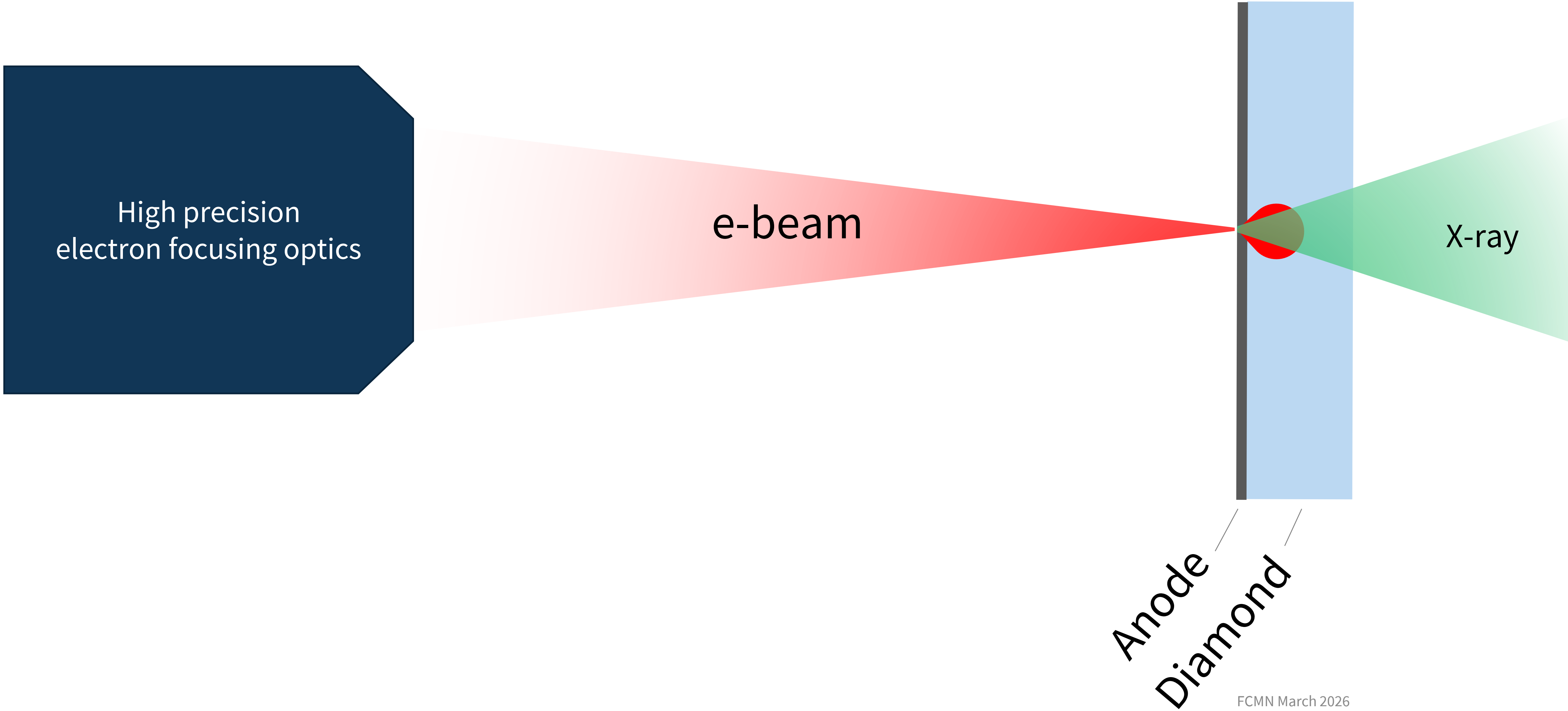
How to achieve small X-ray spots



How to achieve small X-ray spots



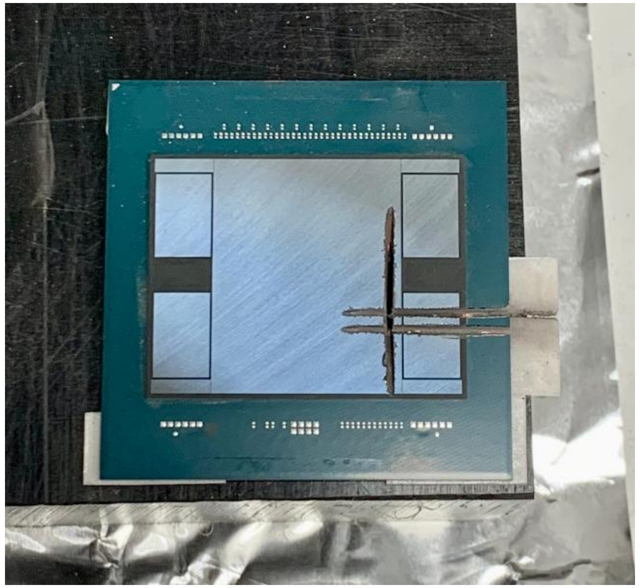
How to achieve small X-ray spots

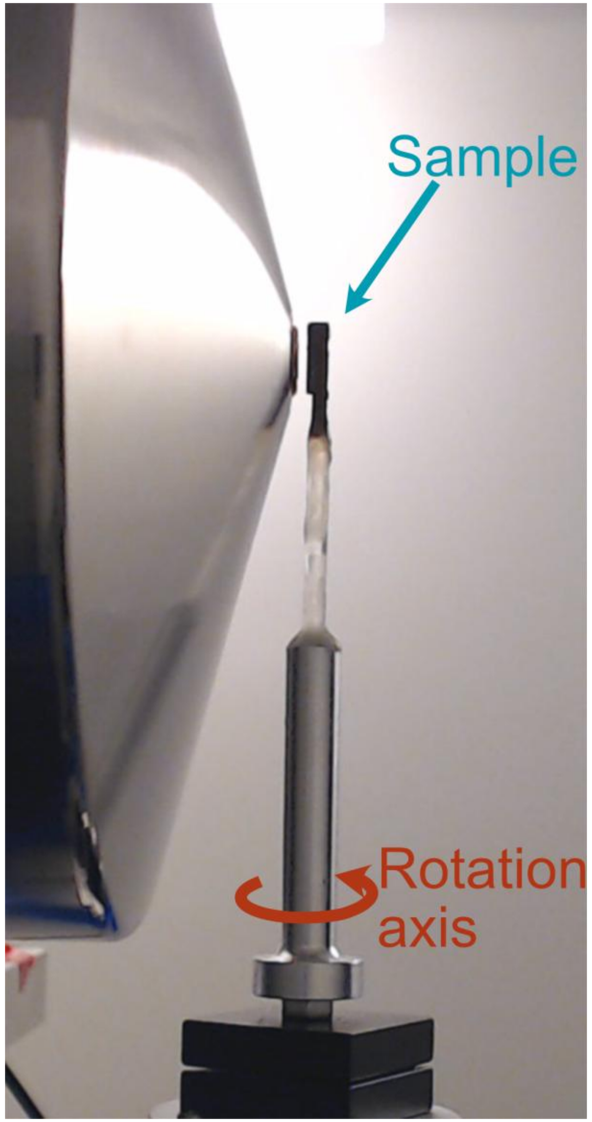


CT examples in advanced packaging

CT sample prep. in advanced packaging

Commercially available
GPU with HBM

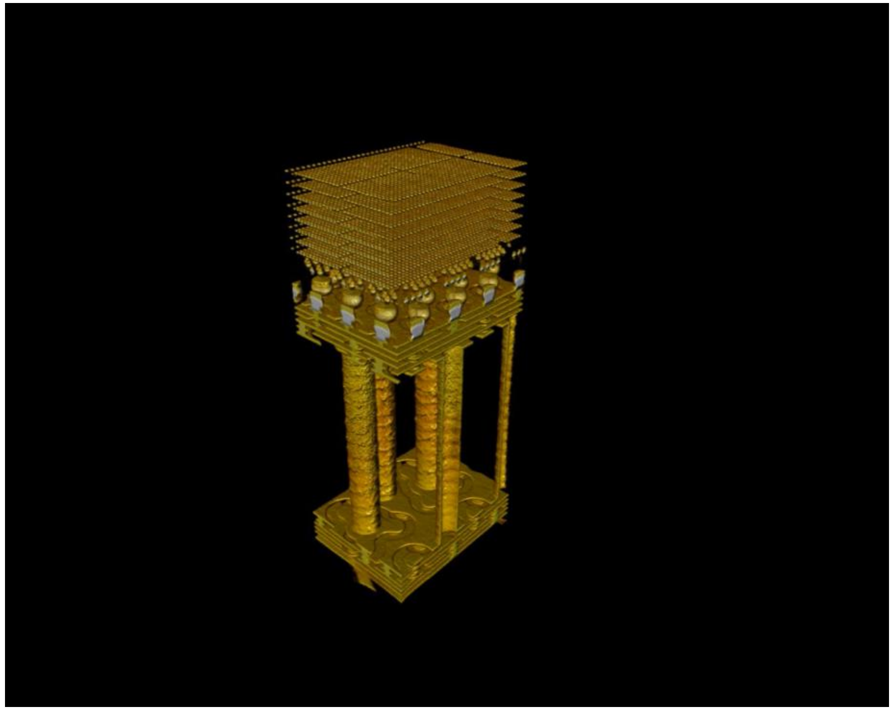


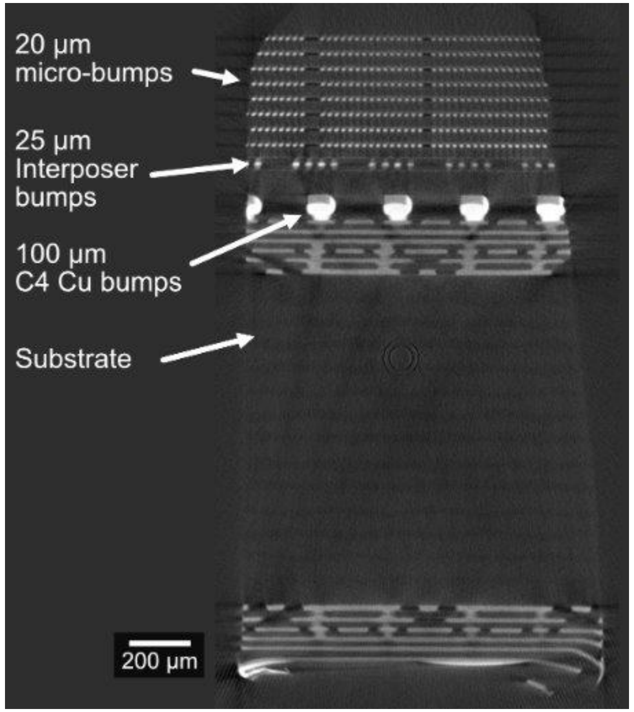


T. Dreier et al., Microelectronics Reliability 168 (2025)

Overview fast CT of HBM microbumps

Very fast overview of sample: **total scan time 30 seconds**





Scan parameters

Geometry

- SOD = 5.8 mm
- SDD = 444 mm
- M = 76.55 → p_{eff} = 2.6 µm

Source

- 80 kVp
- 2 µm x-ray spot

Acquisition

- 900 projections
- 33.3 ms exposure
- 12 deg/s continuous rotation

T. Dreier et al., Microelectronics Reliability 168 (2025)

Detailed ROI study – analysis of individual bump bonds

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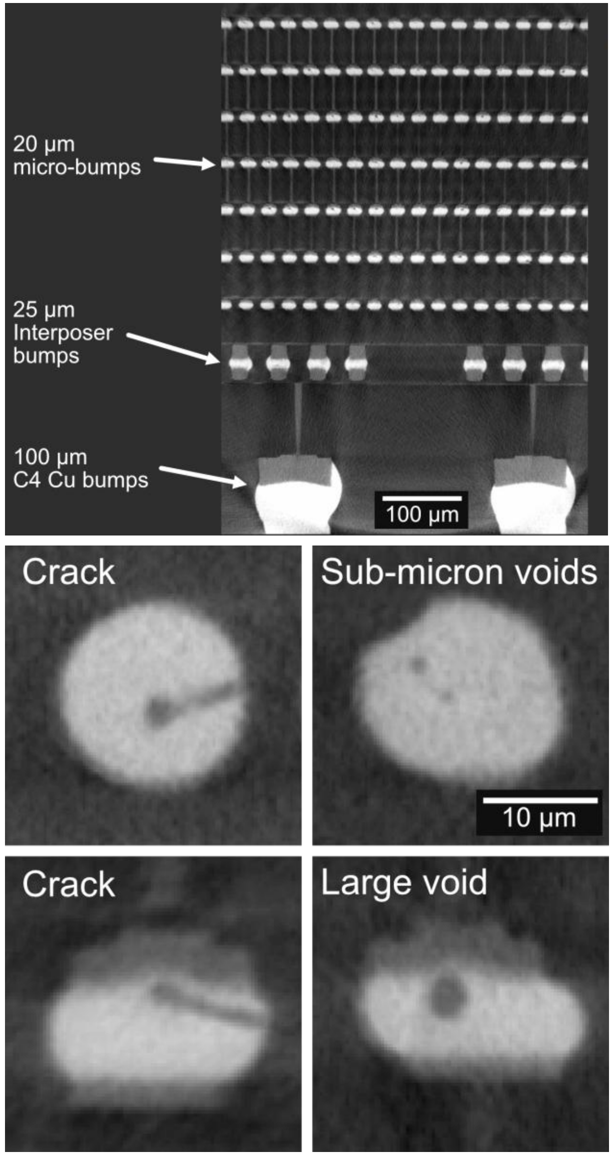
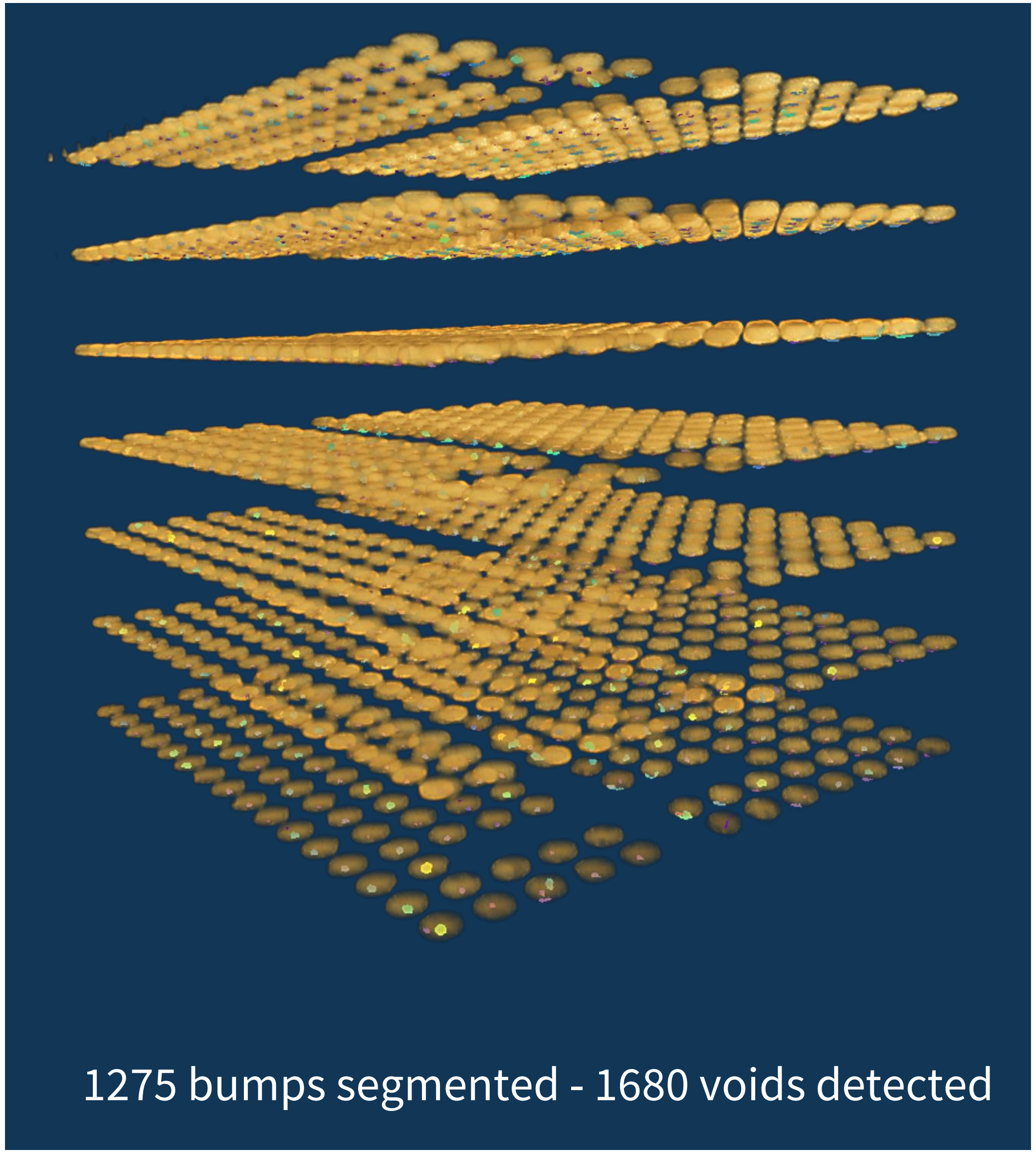
- Geometry
  - SOD = 2.1 mm
  - SDD = 644 mm
  - M = 306.7 → p_{eff} = 0.65 µm
- Source
  - 80 kVp
  - 0.7 µm x-ray spot
- Acqusition
  - 3000 projections
  - 5 x 300 ms exposure
  - 210 degree rotation

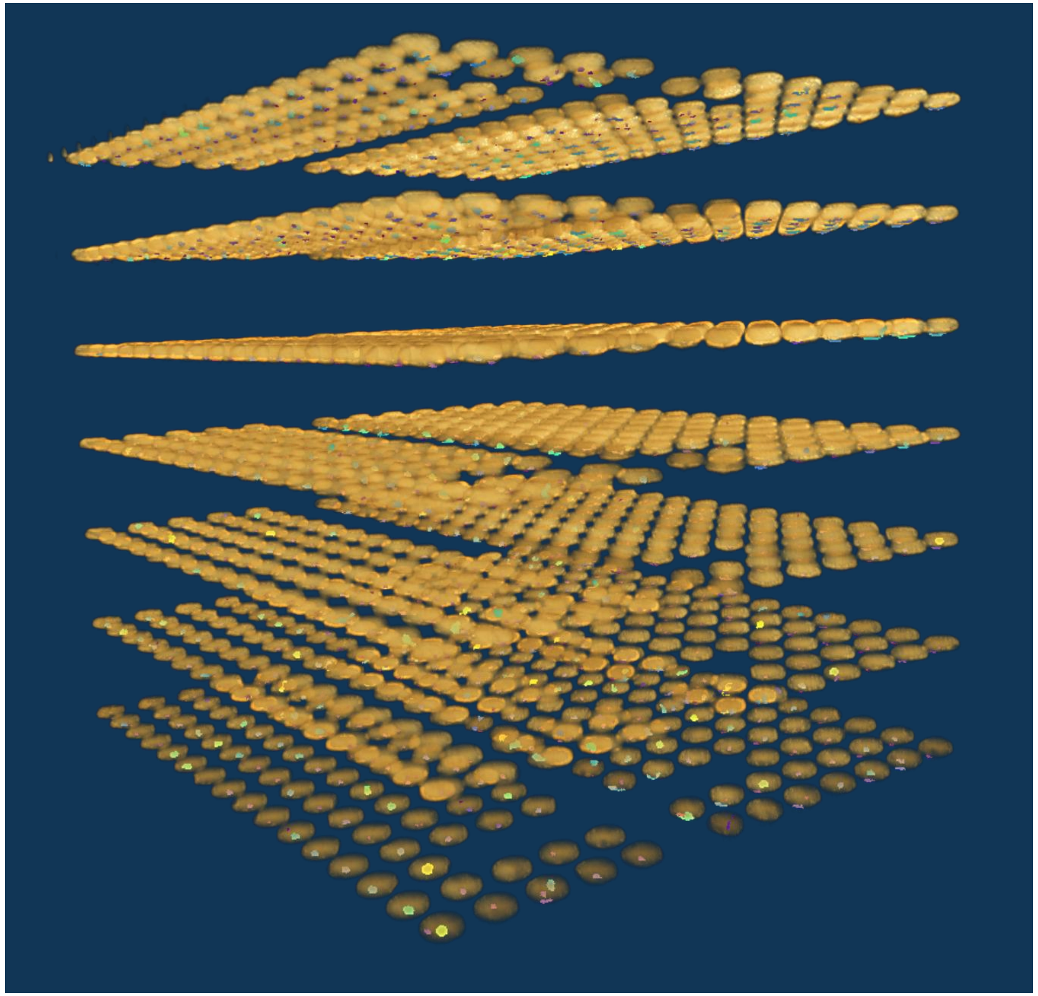
→ 75 min scan

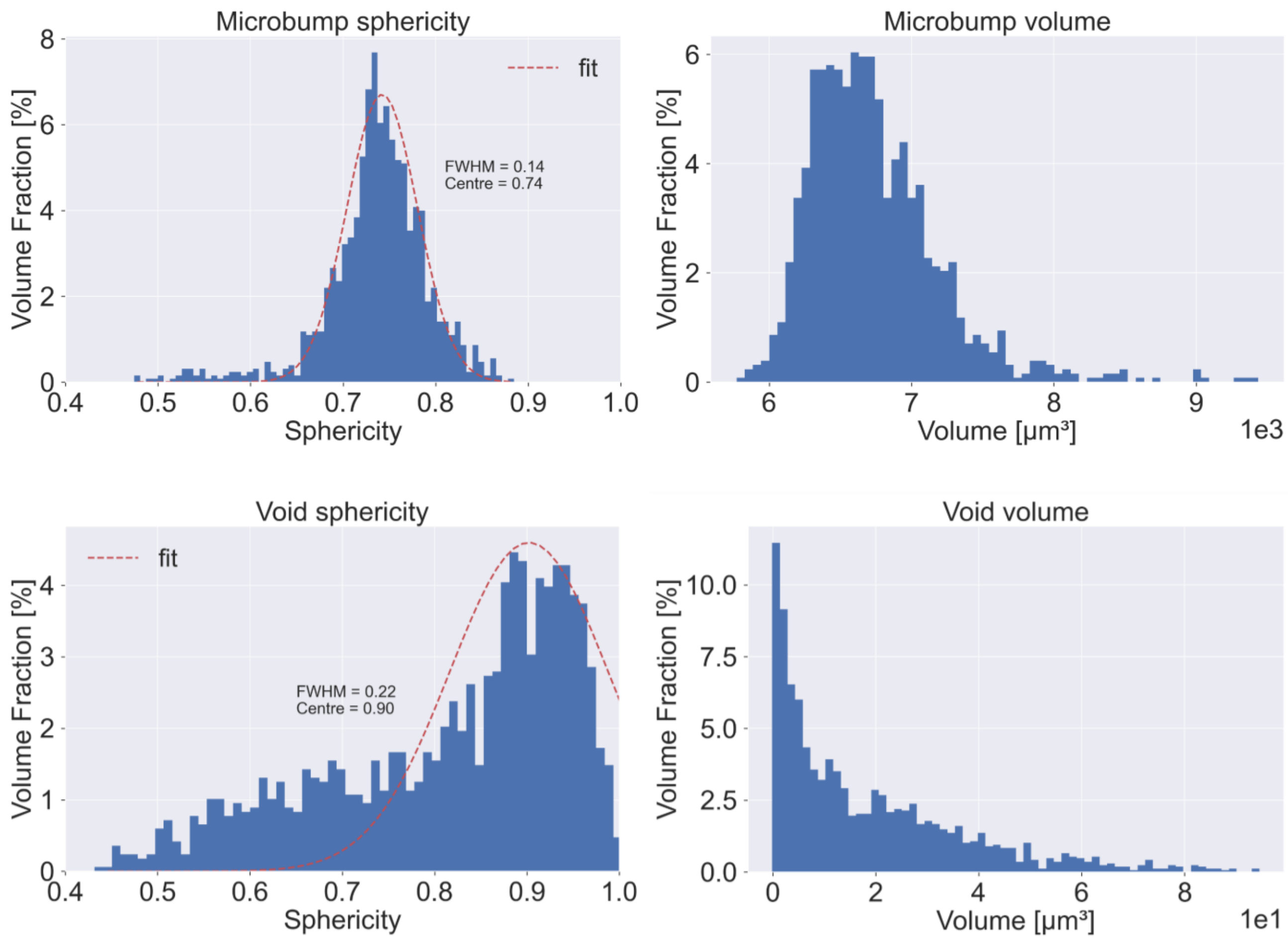




T. Dreier et al., Microelectronics Reliability 168 (2025)

Nano-CT of High-Bandwidth Memory



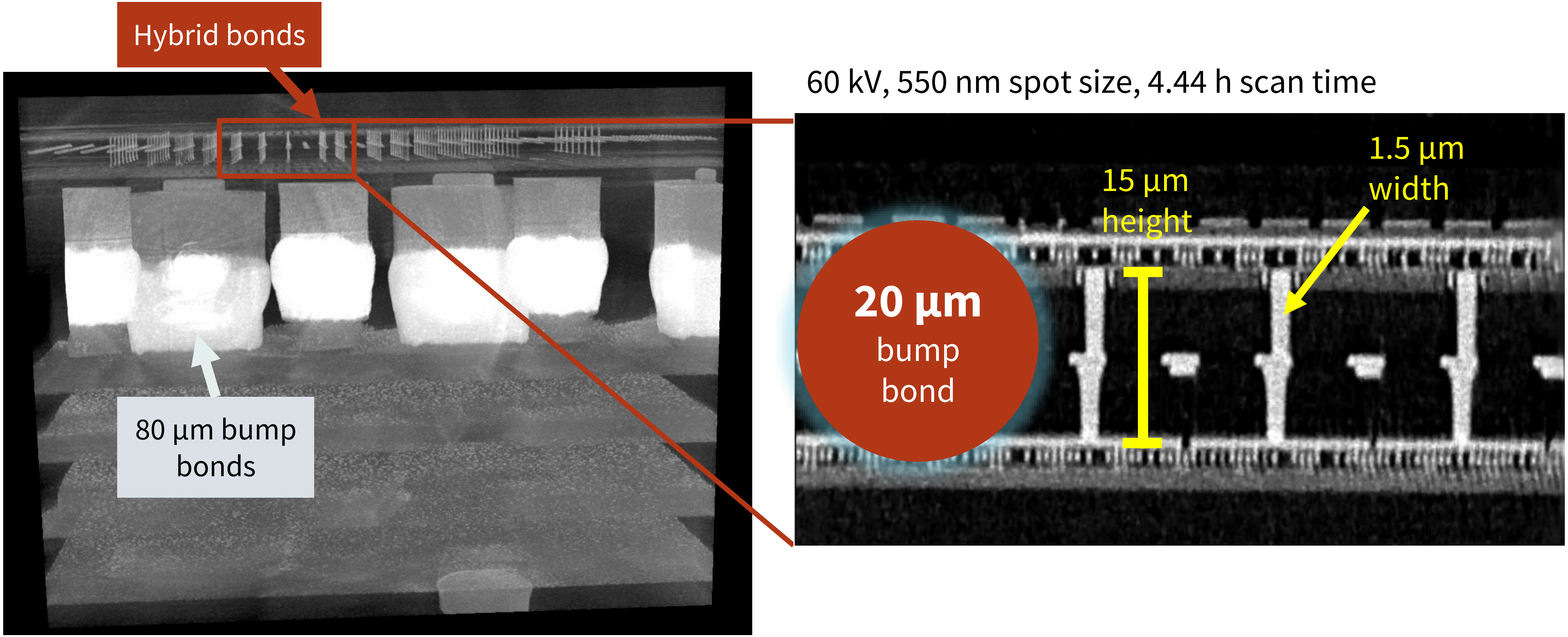


T. Dreier et al., Microelectronics Reliability 168 (2025)

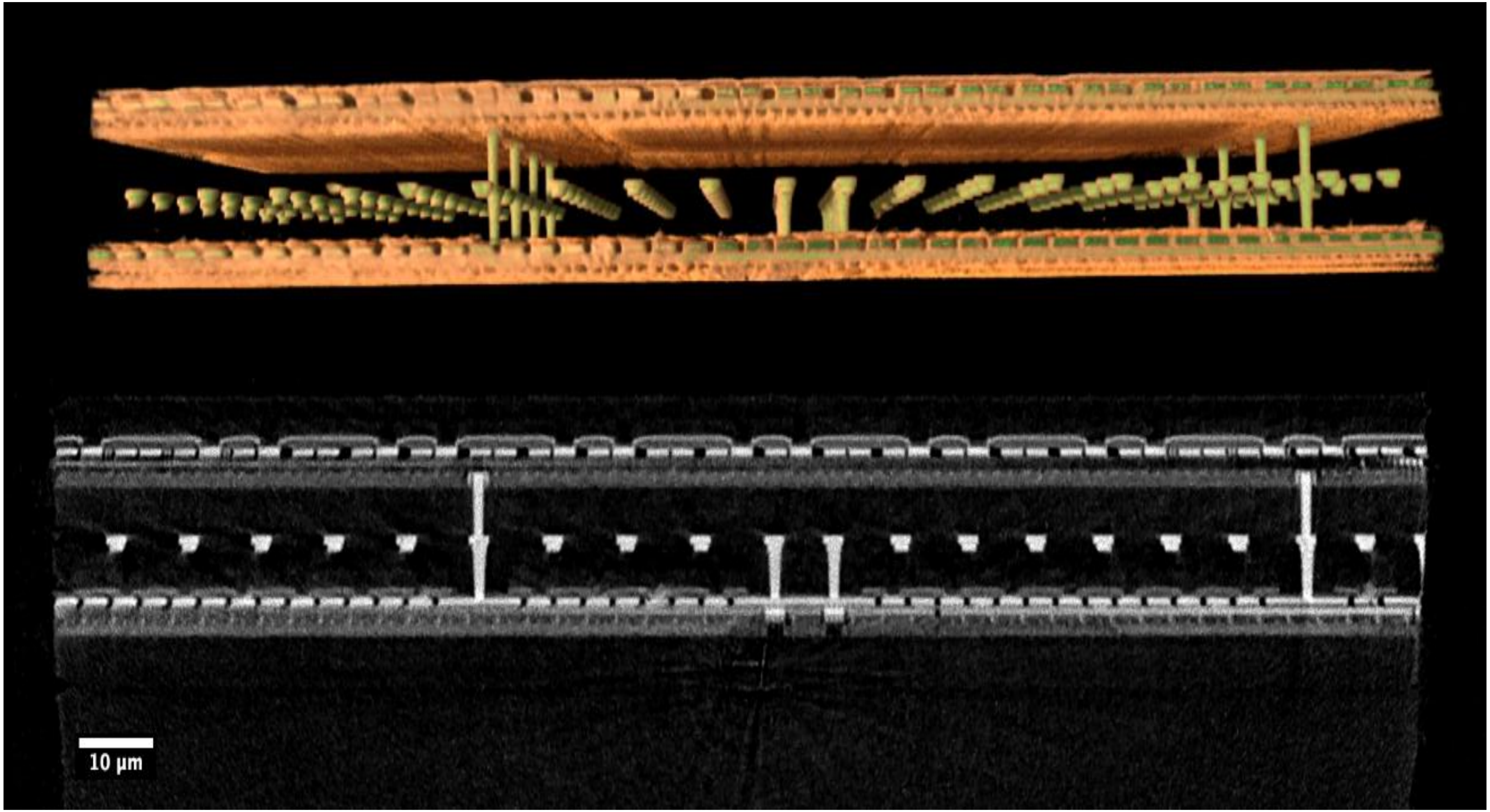
Hybrid bonding examples

-Pushing the resolution!

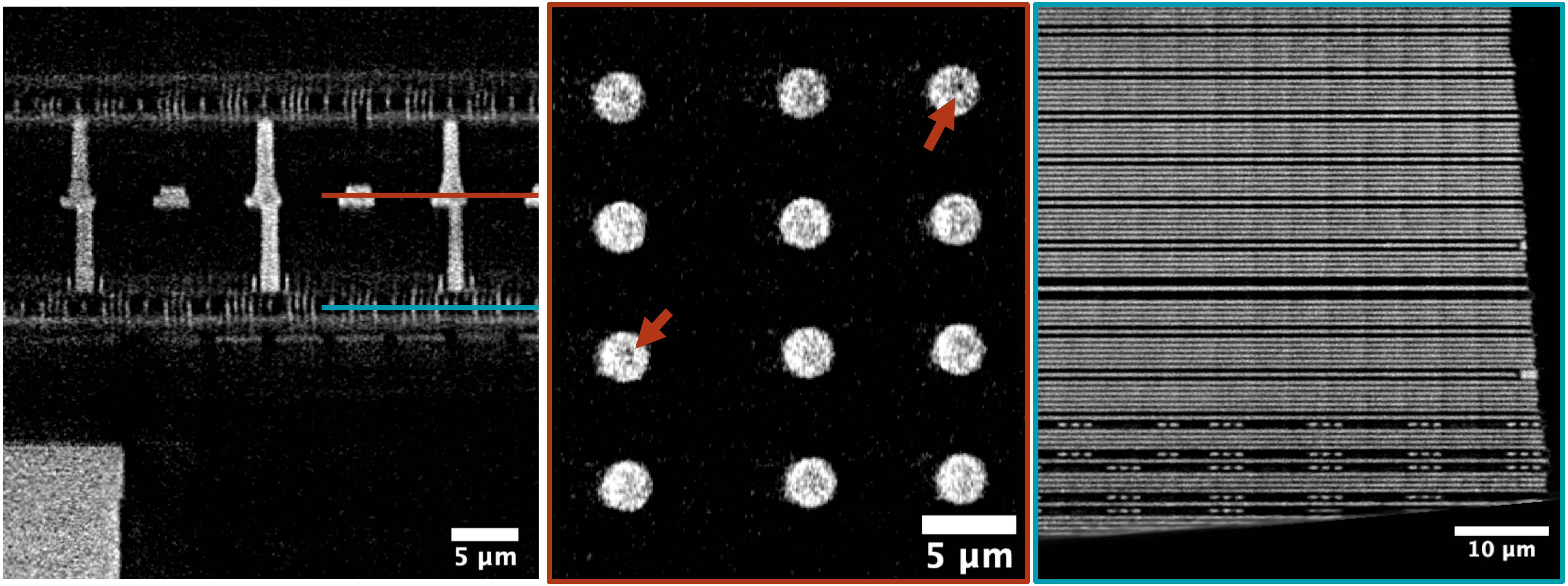
Computed Tomography of hybrid bonds



T. Dreier et al., 44th NANO Testing Symposium, Osaka, Japan (2024)


10 µm

Computed Tomography of hybrid bonds



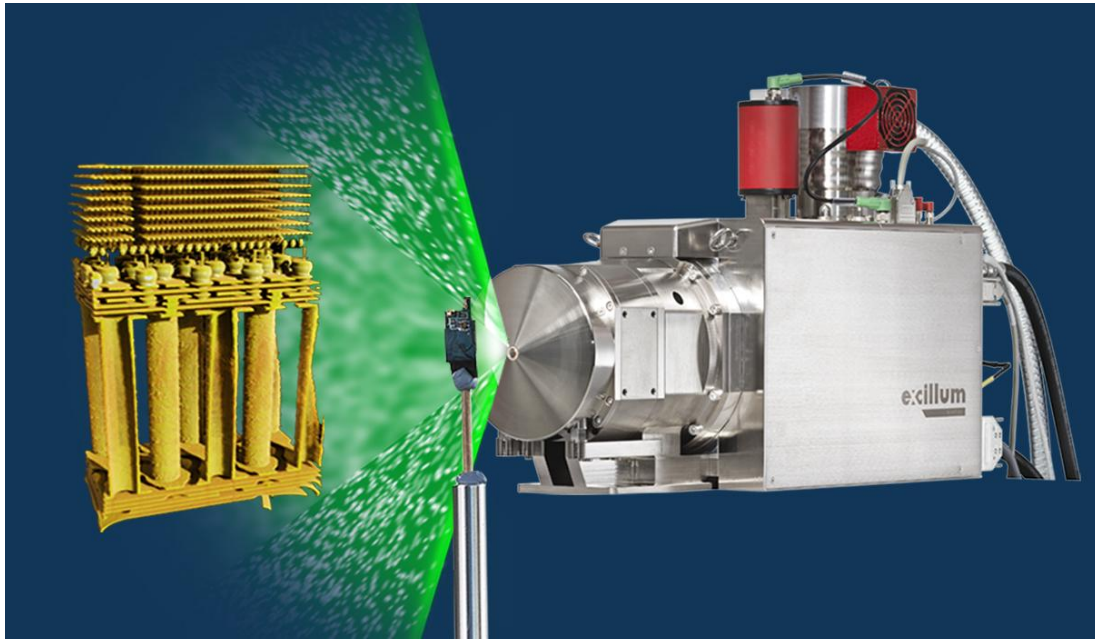
Read more in our whitepapers

Unlock the mystery

- www.3dincites.com/2025/04/unlocking-the-mystery-of-x-ray-imaging-for-electronics-and-semiconductor-inspection/

Nano-CT performance examples

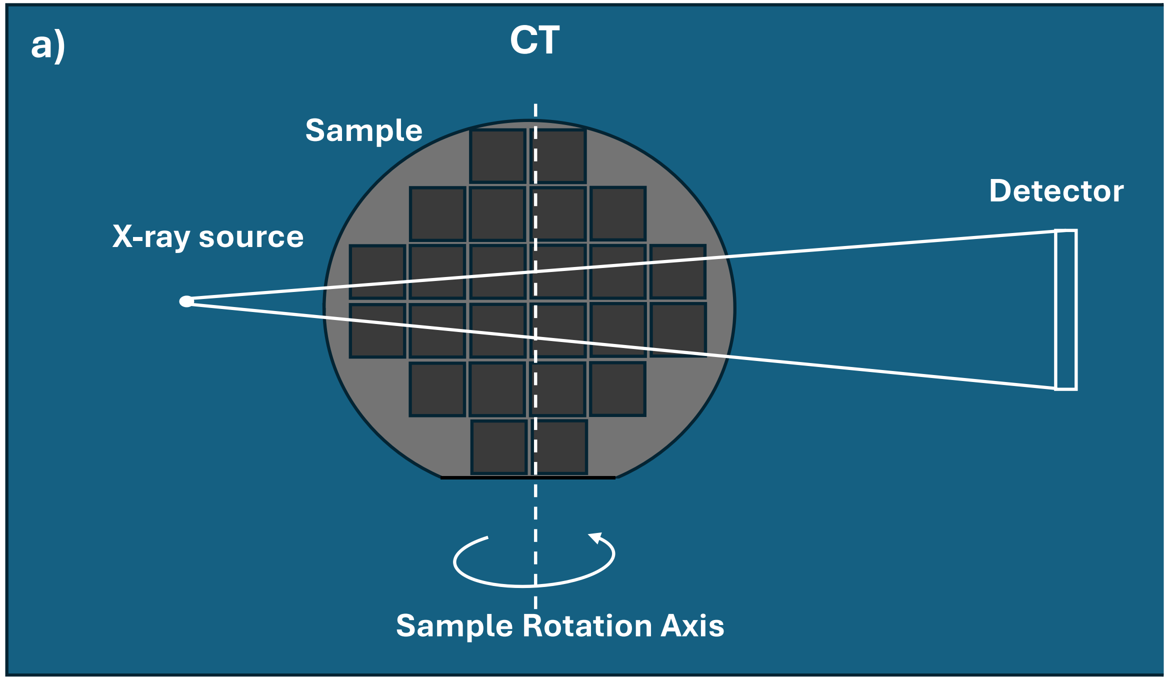
- www.3dincites.com/2025/07/revealing-the-invisible-optimized-nano-ct-case-studies-in-advanced-packaging/



Non destructive 3D X-ray with Laminography

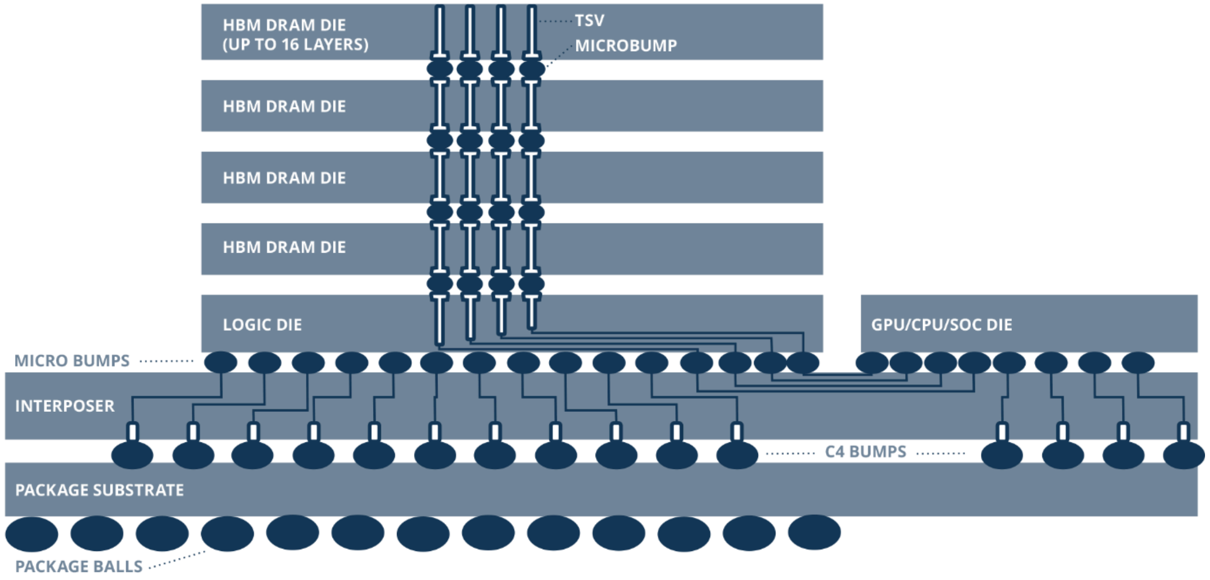
Non destructive X-ray - CT

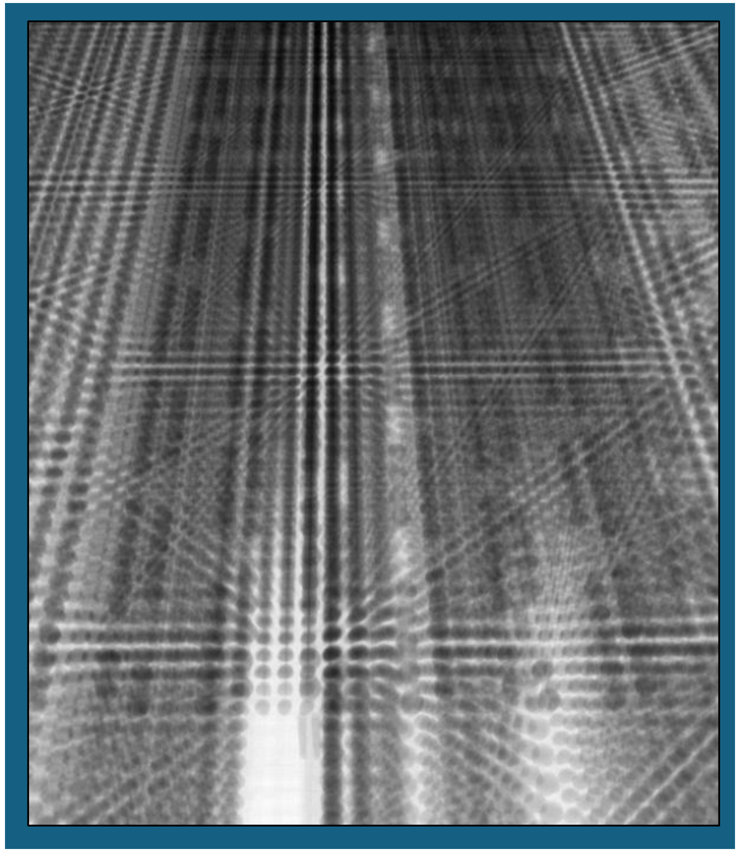
- CT is very difficult on large samples as you need to be able to rotate object in the X-ray beam.



Non destructive 2D X-ray of HBM stack

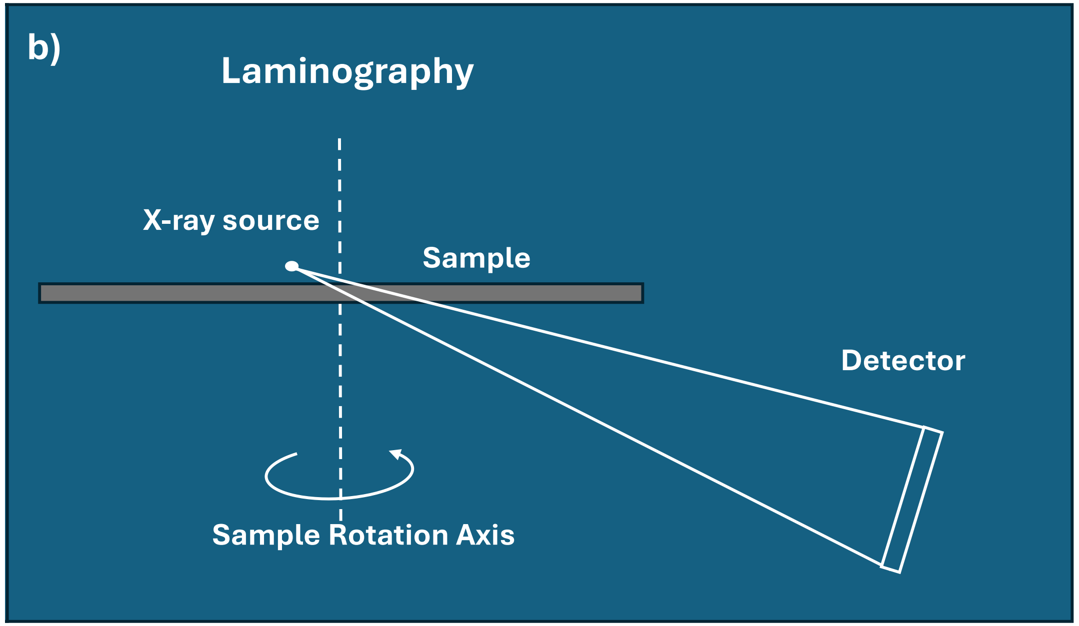
- 2D X-ray of HBM stack
- Very complex and difficult to interpret with 2D X-ray





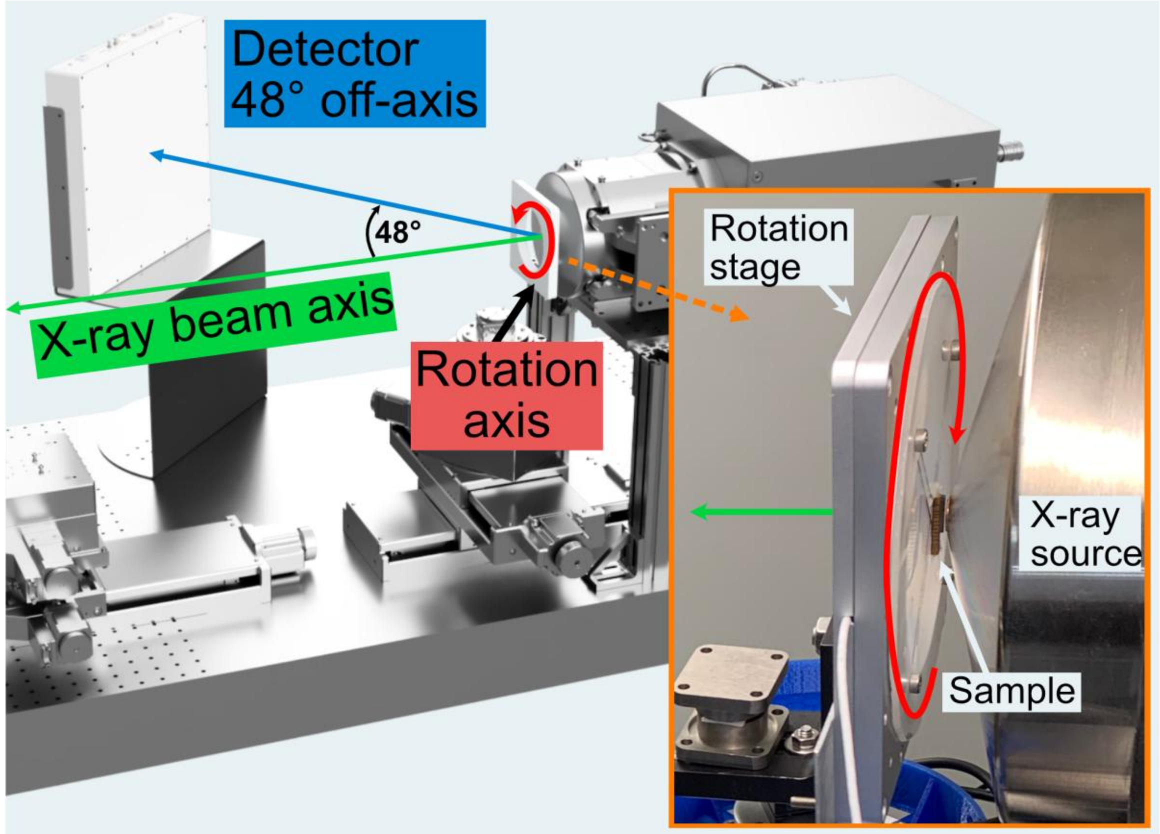
Non destructive X-ray - Laminography

- Laminography is an attractive method for large flat samples
  - Enables high magnification and high X-ray intensity with sample close to source

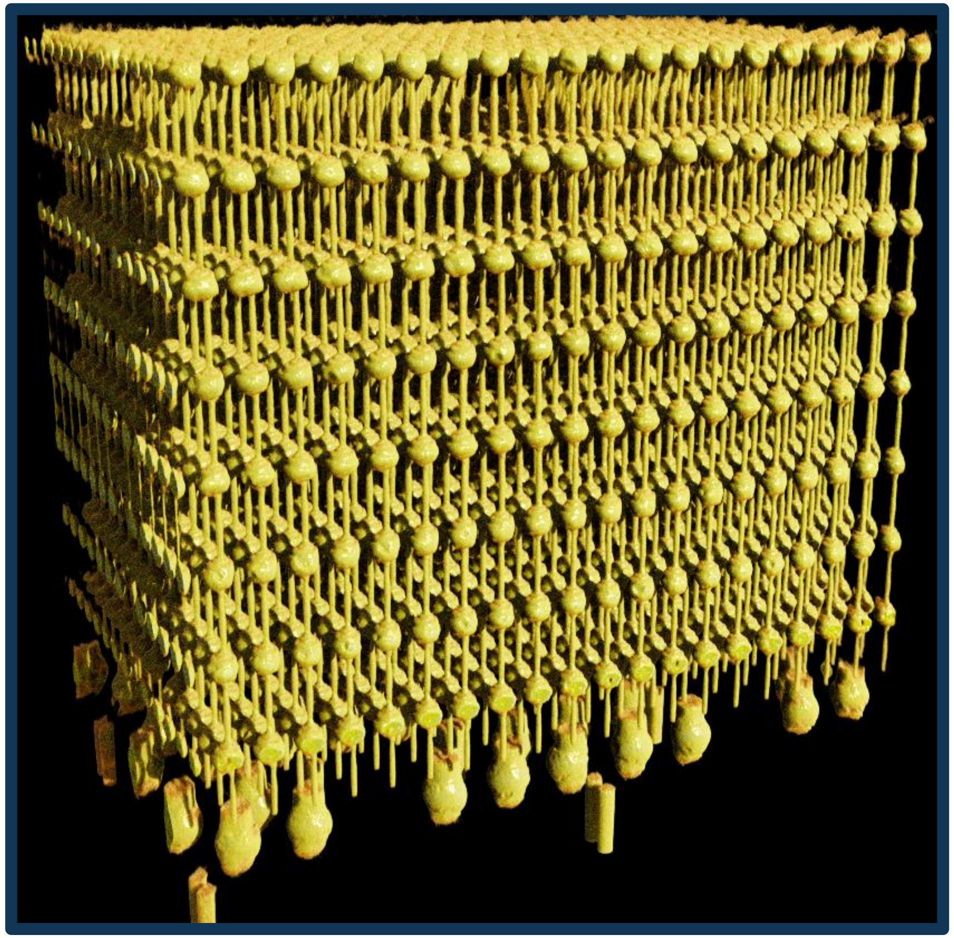


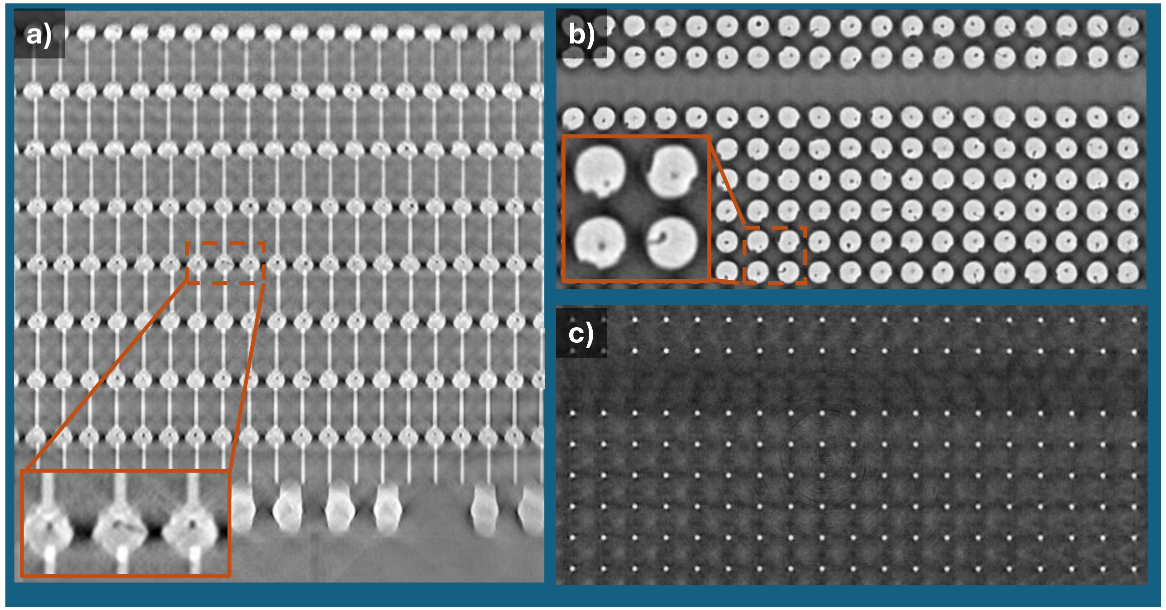
T. Dreier et al., Microelectronics Reliability 168 (2025)

- Example setup:



Laminography of HBM stack





T. Dreier, J. Hållstedt: “Laminography: a Non-destructive 3D X-ray Breakthrough for Advanced Packaging” in 3D inCites, 7th October 2025

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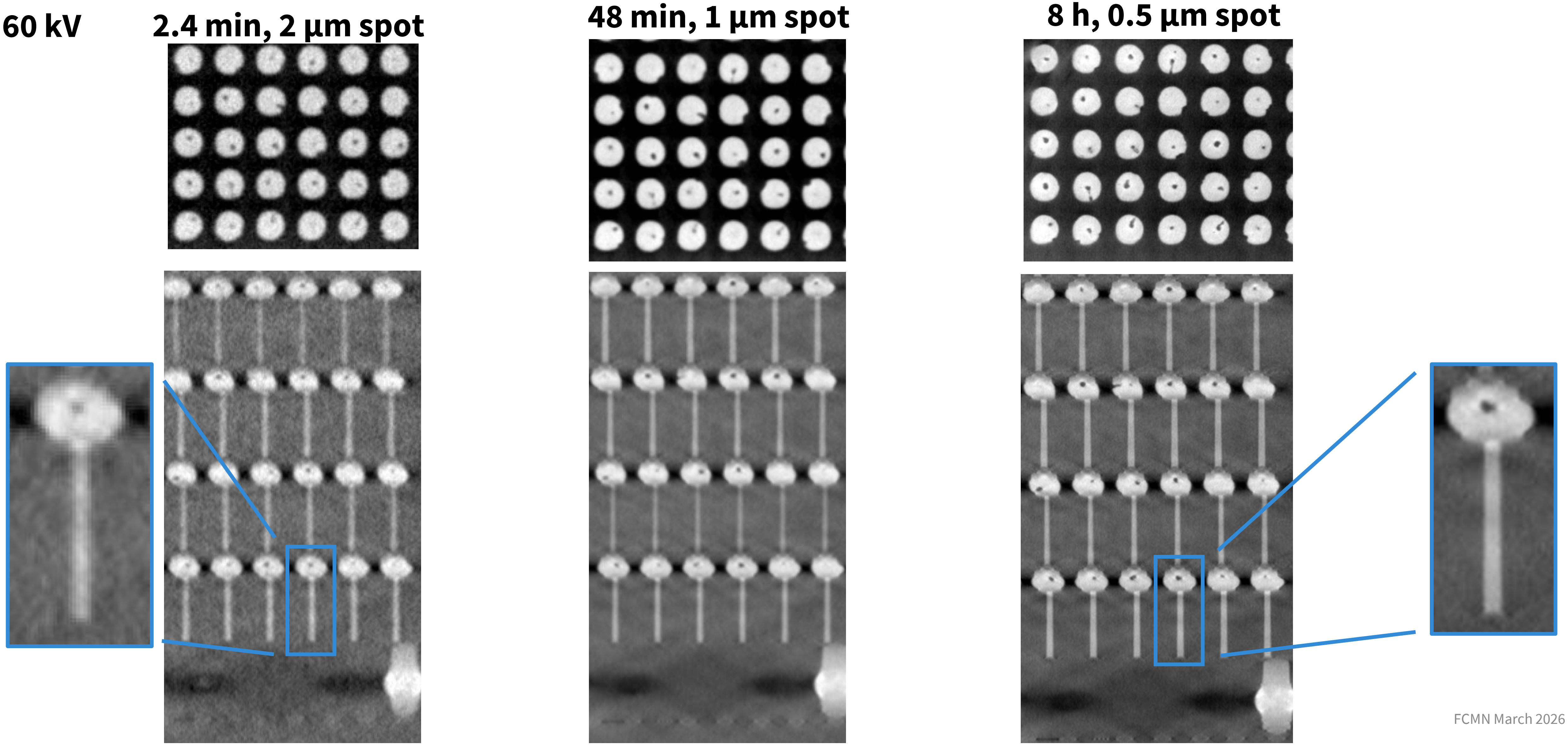
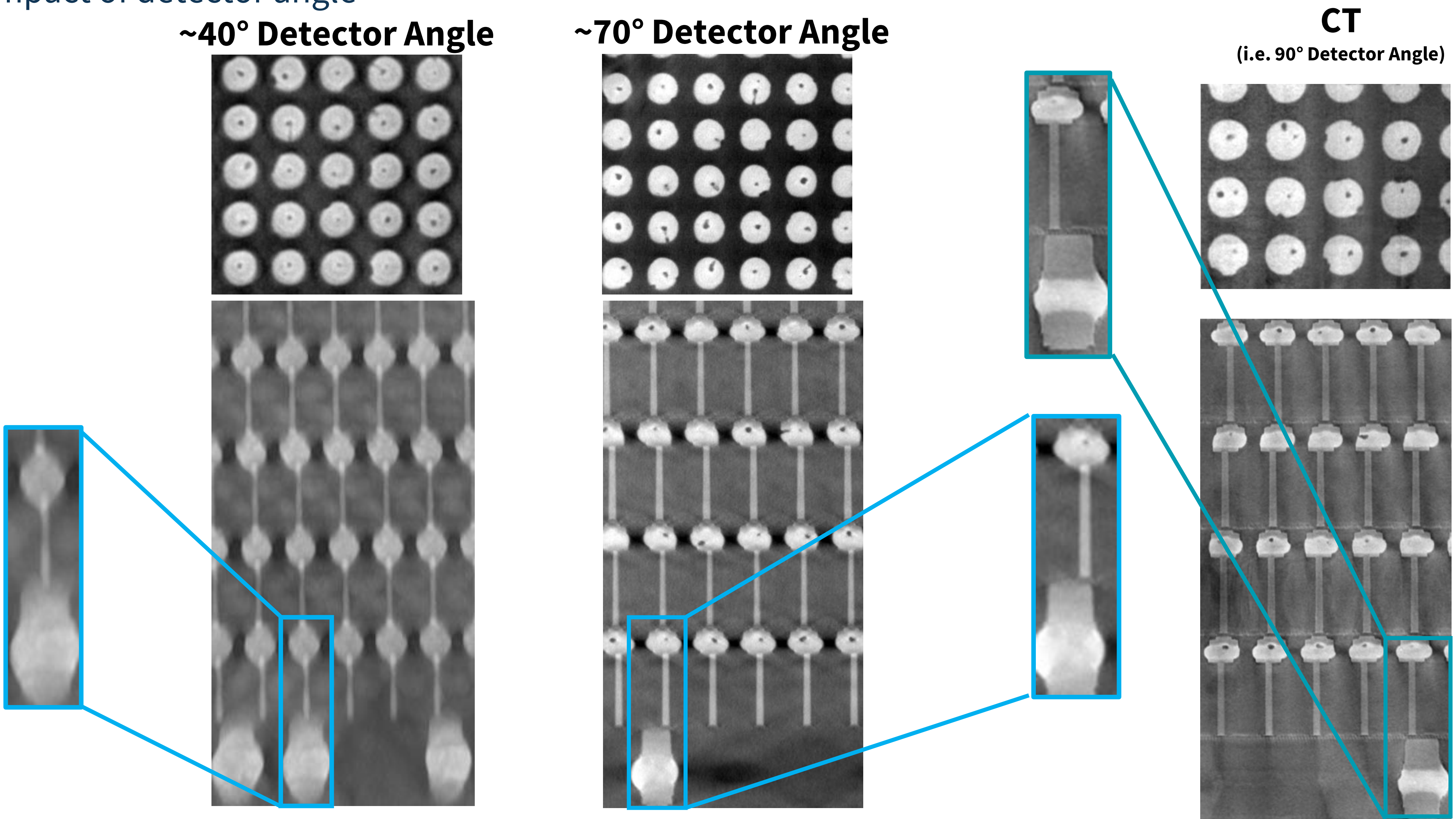
Laminography of High-Bandwidth Memory

Impact of spot size and measurement time

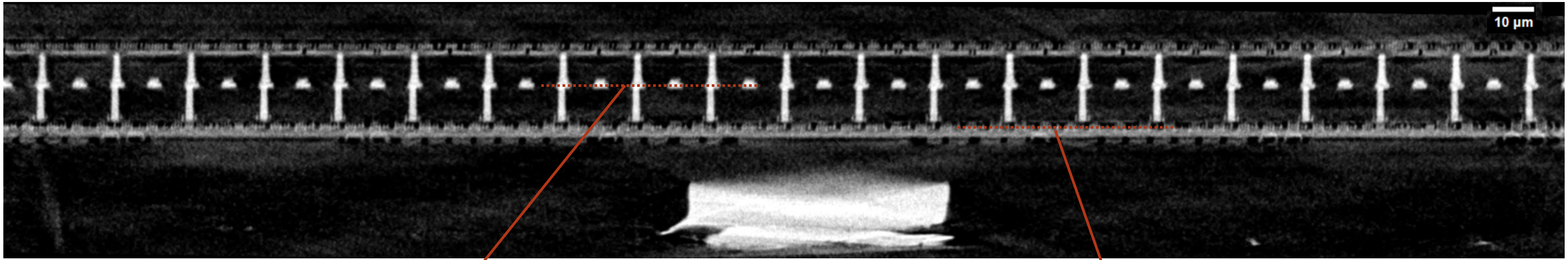


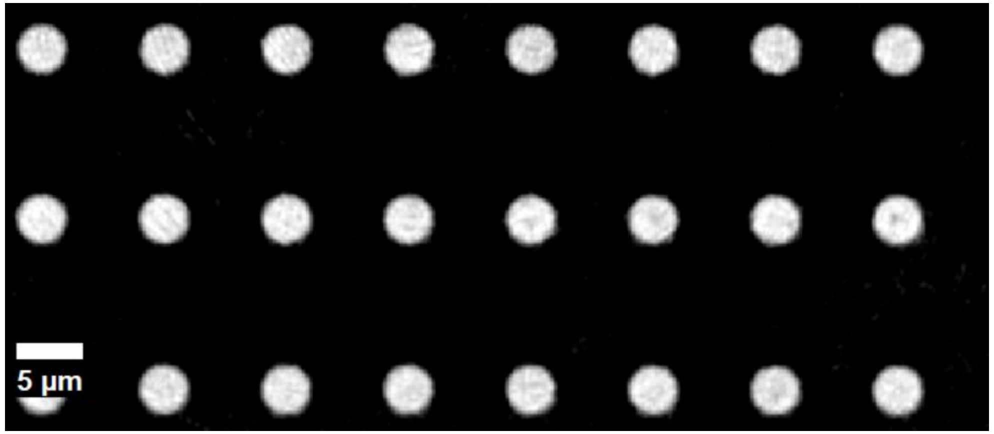
Laminography of High-Bandwidth Memory

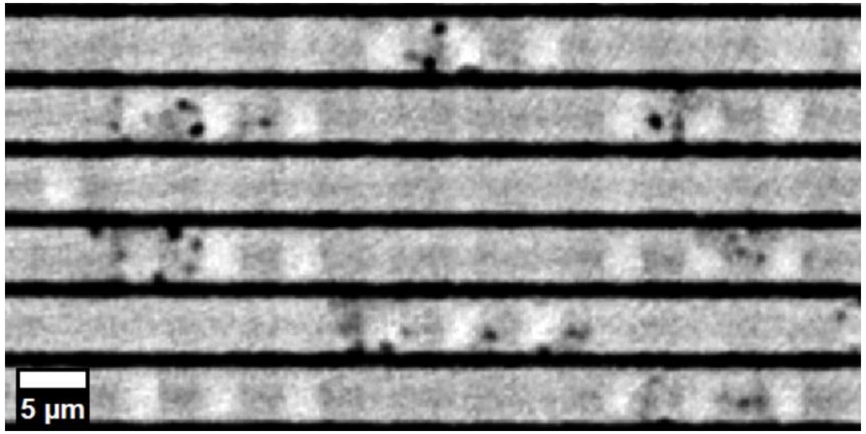
Impact of detector angle



Laminography of hybrid bonding







Geometry
- SOD = 0.75 mm
- SDD = 405 mm
- Voxel size = 150 nm

Scan settings
- Projections: 2880
- Rotation: 360 degrees
- Exposure time: 10 s
- Scan time: 8 h

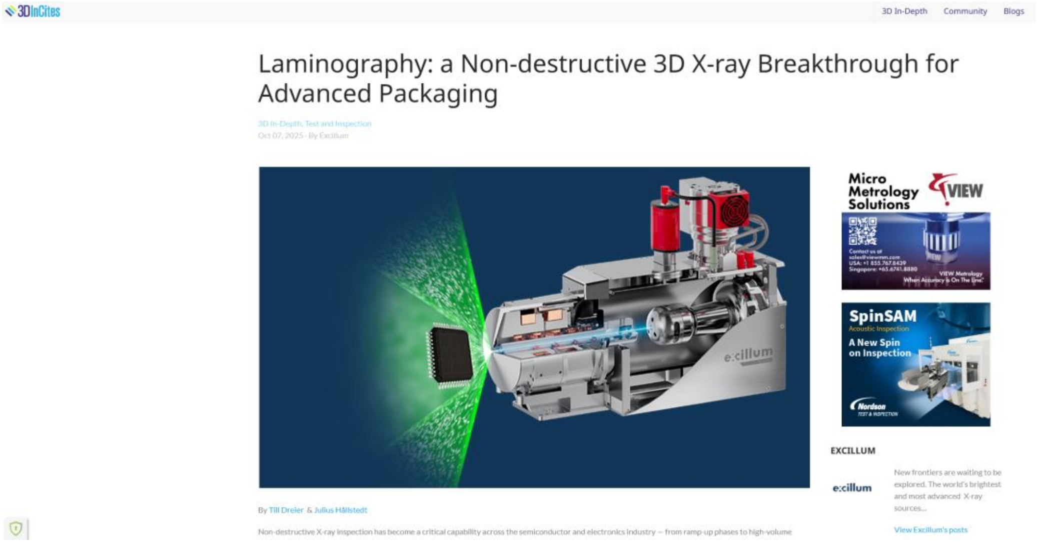
- **Source settings**
- Voltage: 60 kV
- Spot size: 500 nm

More details to be presented at ICEP-HBS 2026

Whitepaper

Link:

https://www.3dincites.com/2025/10/laminography-a-non-destructive-3d-x-ray-breakthrough-for-advanced-packaging/


3DInCites
3D In-Depth Community Blogs

Laminography: a Non-destructive 3D X-ray Breakthrough for Advanced Packaging

3D In-Depth, Test and Inspection
Oct 07, 2025 · By Excillum

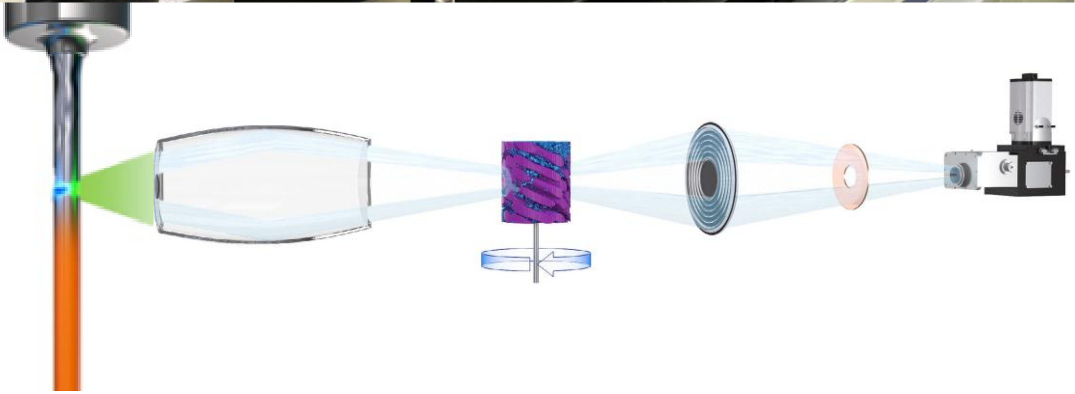
By Till Dreier & Julius Hållstedt

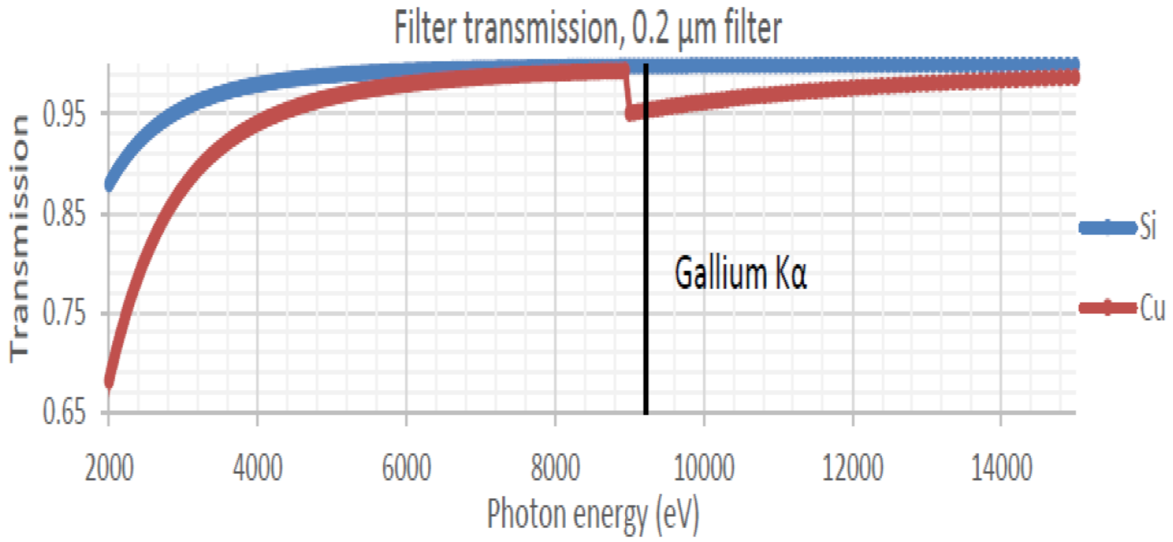
Non-destructive X-ray inspection has become a critical capability across the semiconductor and electronics industry – from ramp-up phases to high-volume

Beyond geometric magnification

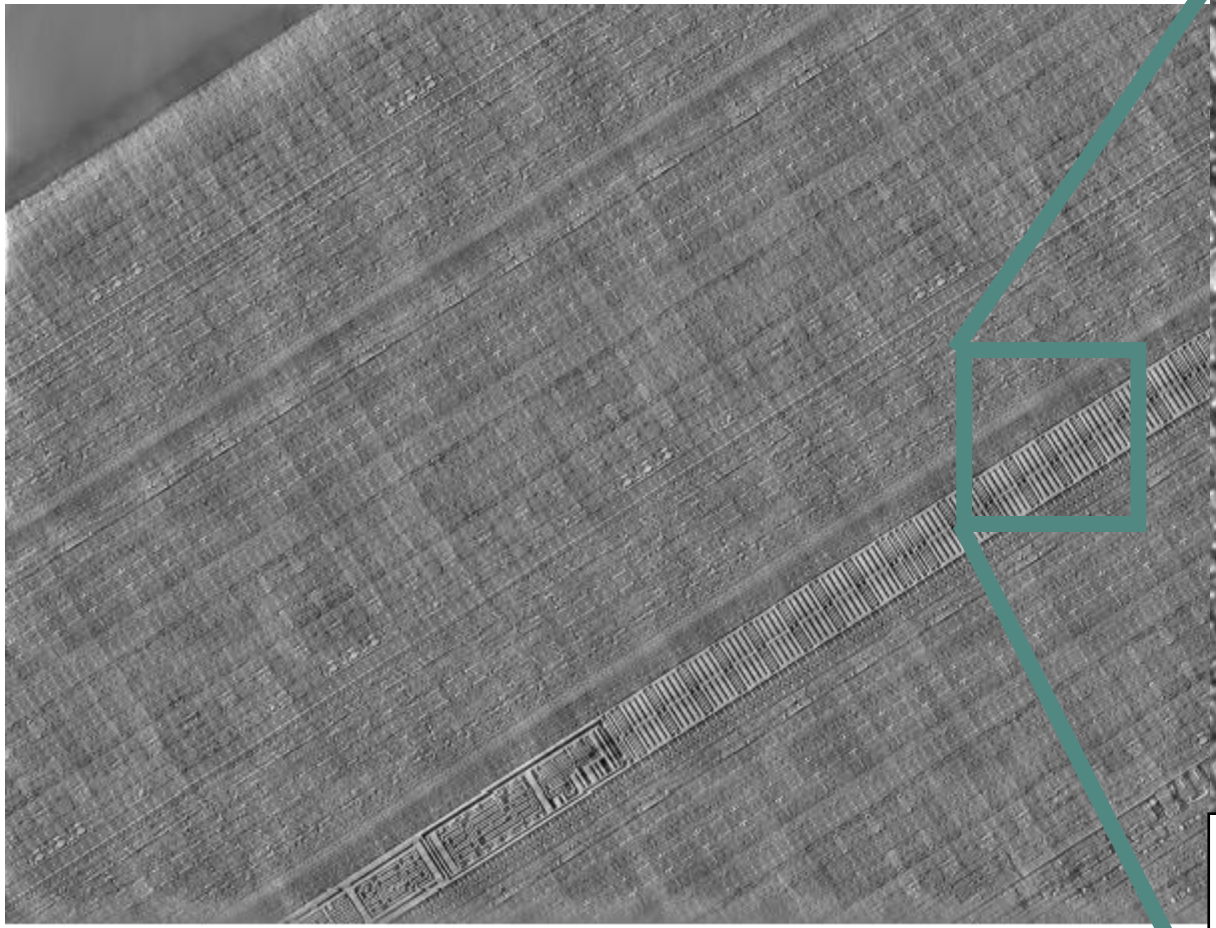
X-ray optics based imaging

Nanotomography with a 9.2 KeV MetalJet

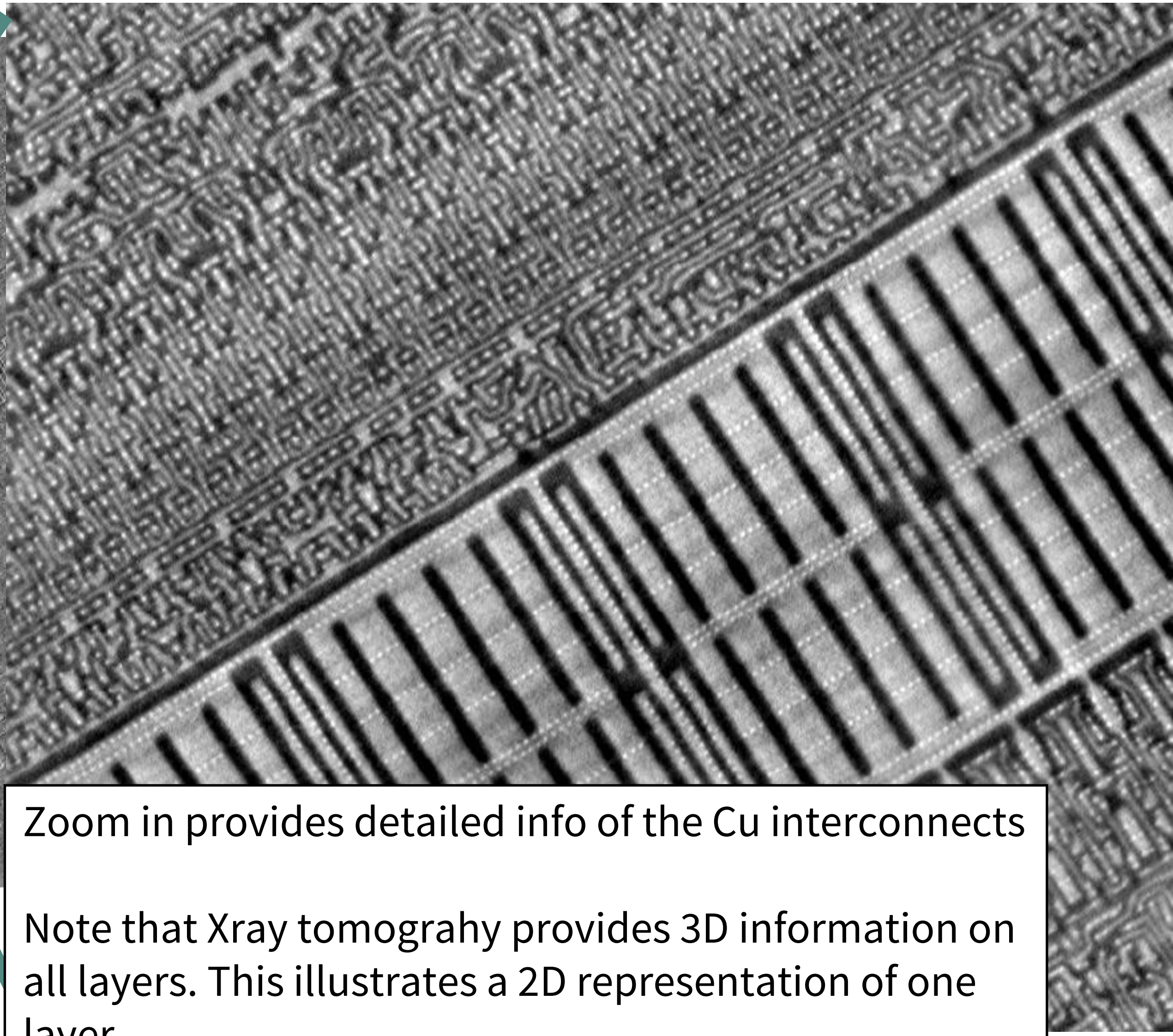




X-ray Tomography of a 90 nm Cu process (18x7 stitched overlapping tomographies)



Xray micrograph of one of the reconstructed layers



Zoom in provides detailed info of the Cu interconnects

Note that Xray tomograhy provides 3D information on all layers. This illustrates a 2D representation of one layer

XRM2018 M. Sutherland (DMEA) et al.

X-ray Tomography Cu interconnects (18x7 stitched overlapping tomographies)

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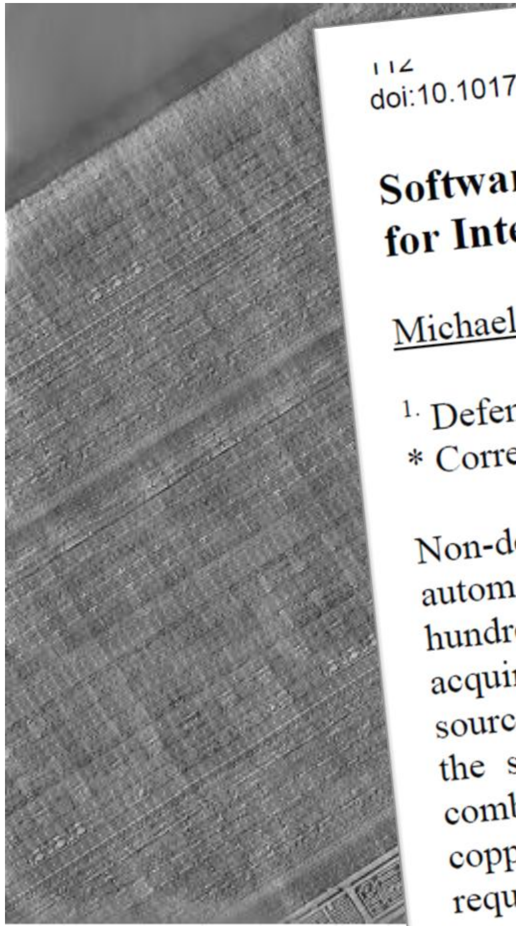


Microsc. Microanal. 24 (Suppl 2), 2018

doi:10.1017/S1431927618012953

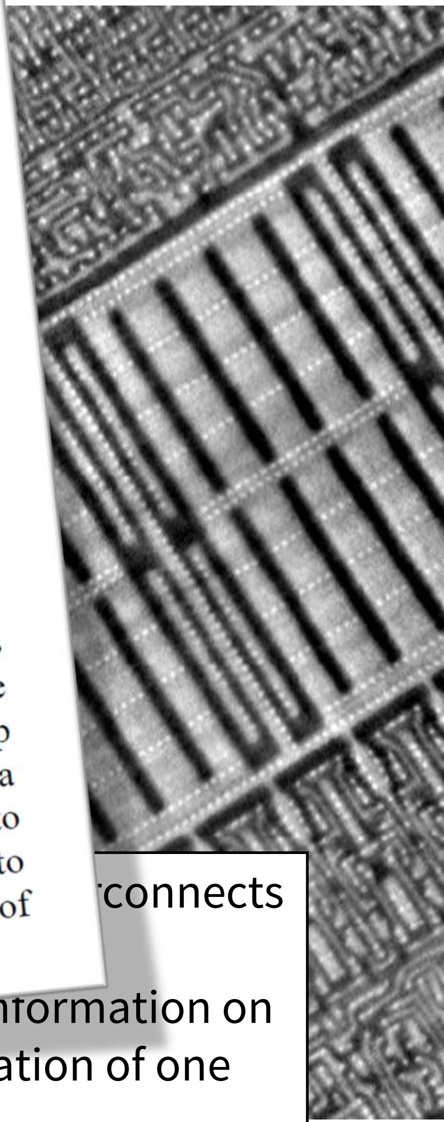
Software Automation and Optimization of an X-ray Microscope Custom Designed for Integrated Circuit Inspection

Michael Sutherland[1*], Christopher Powell[1], Skylar Downes[1]

1. Defense Microelectronics Activity, McClellan Park, USA
* Corresponding author, michael.sutherland@dmea.osd.mil

Non-destructive X-ray tomography of the interconnect structure of microelectronics requires extensive automation for both scanning and reconstruction. Integrated circuits (ICs) are very large (one to hundreds of mm^2) compared to their smallest metal interconnects (in the tens of nm). DMEA has acquired a unique Zeiss Ultra X-ray microscope that has been customized with a D2+ liquid metal jet source from Excillum [1]. The D2+ utilizes gallium (K-α 9.2keV) which has a ~9x better contrast than the standard copper (K-α 8.04keV) rotating anode source when viewing Cu against SiO_2. This combined with the ~10x increased brightness over the standard source makes it ideal for imaging the copper interconnect structures of ICs. However, imaging a single mm^2 on our system with a 5% overlap requires ~700 fields of view, or ~700 tomographies to get the 3D dataset. Imaging any significant area requires the system to run for multiple days and the reconstruction needs to be automated to be able to process the large datasets in a reasonable amount of time. These requirements have led DMEA to develop software to optimize our microscope, automate long term scans, and automate the process of reconstructing our data on a cluster

Xray micrograph of



...rconnects

...3D information on ...layers. This illustrates a 2D representation of one layer

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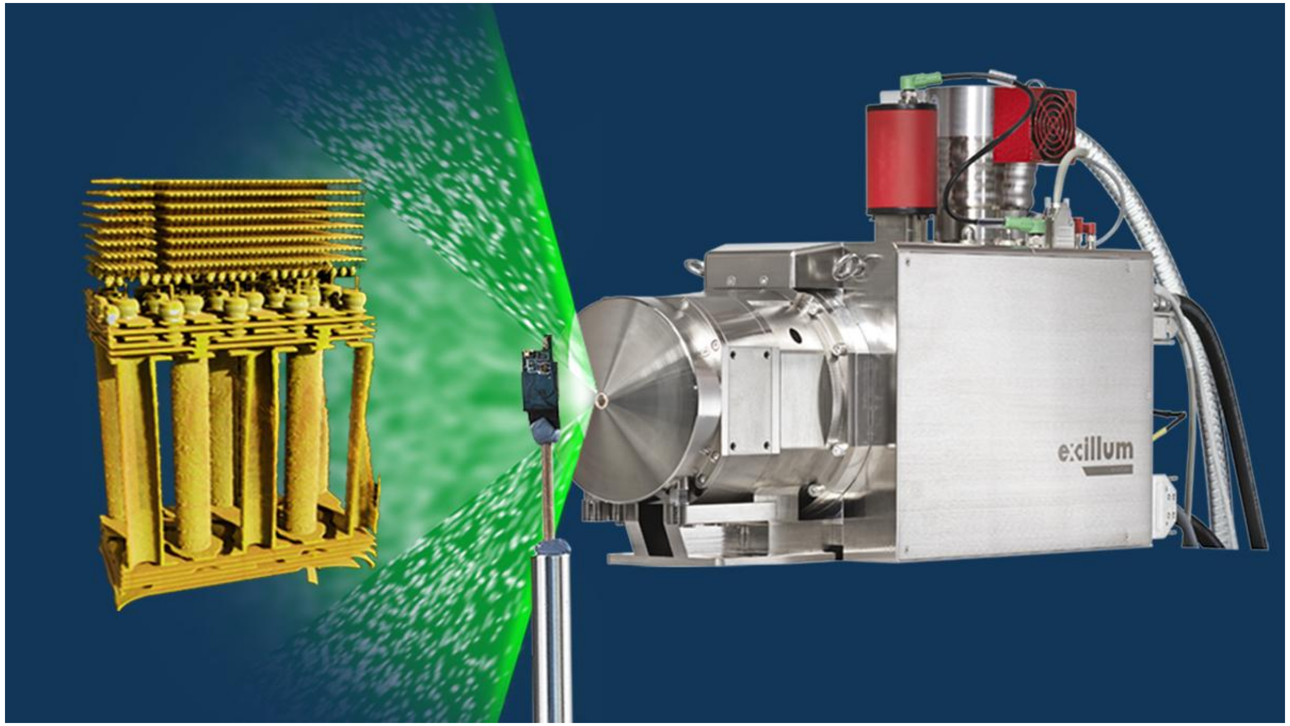
Summary and concluding remarks

Key take aways

- Increasing demands of X-ray methods across semiconductor value chain
- X-ray source is a major limitation but developments are pushing boundaries
- New nano focusing sources enabling inspection of:
  - HBM microbumps
  - TSVs
  - Hybrid bonds
  - etc



Thank you for your attention

More info:
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