Fast and High-resolution Micro-XCT and Nano-XCT Imaging of Advanced Packaging Structures Using New X-ray Sources

Dr. Björn Hansson, CTO

FCMN 2022, 23 June, Monterey, CA, USA

excillum

Content

- X-ray source basics
- X-ray imaging basics
- Some product mentioning, can’t help it
- Imaging examples, not only advanced packaging

The source for X-ray innovation

Entirely devoted to advanced microfocus and nanofocus X-ray sources

… (and some pure e-beam sources)

Based in Stockholm, Sweden

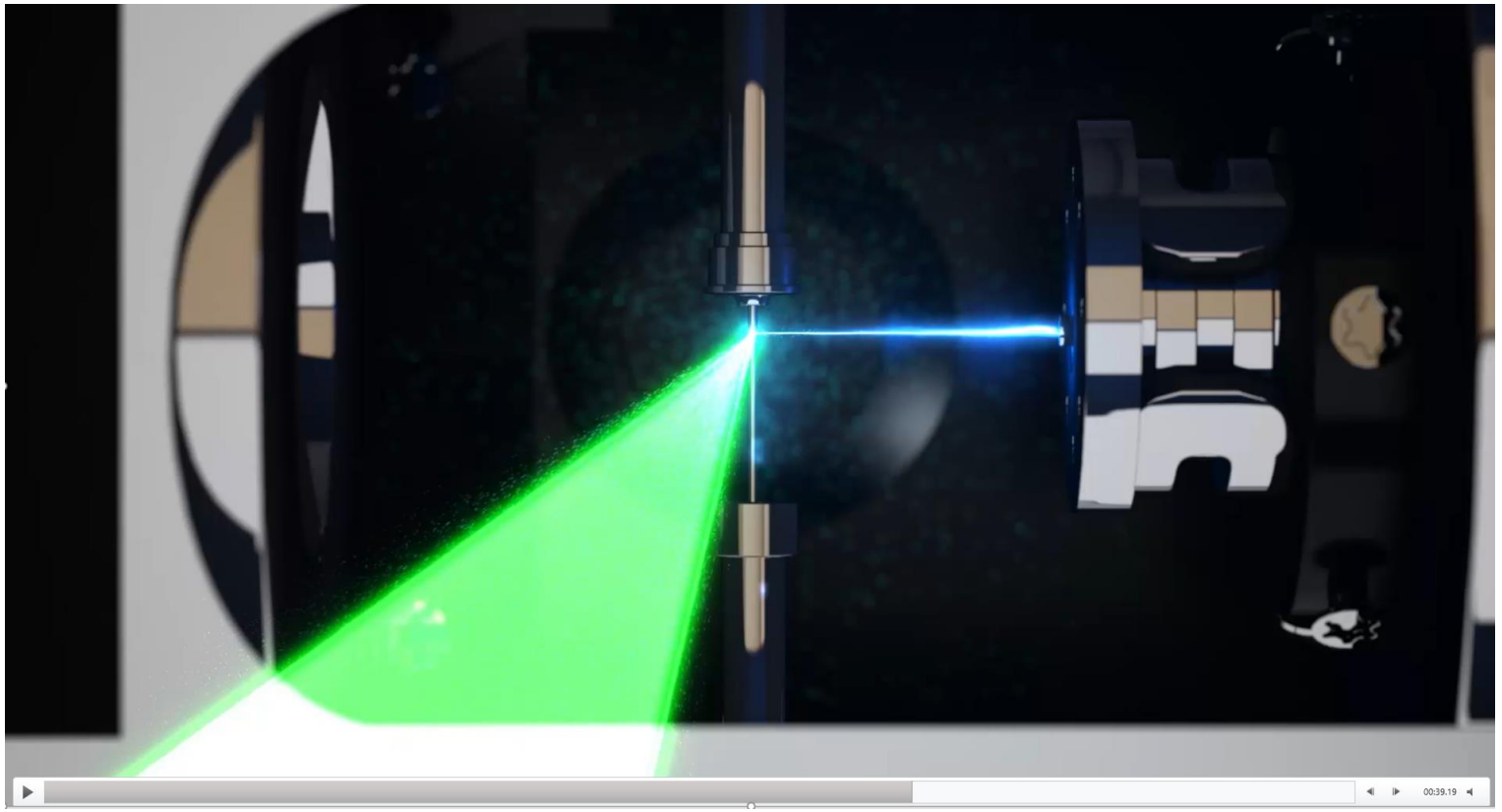
Established 2007

65+ colleagues

- >35 in R&D
- >10 nationalities

Come and see us in Stockholm!

Video



https://www.excillum.com/the-excillum-metaljet-x-ray-source-technology/

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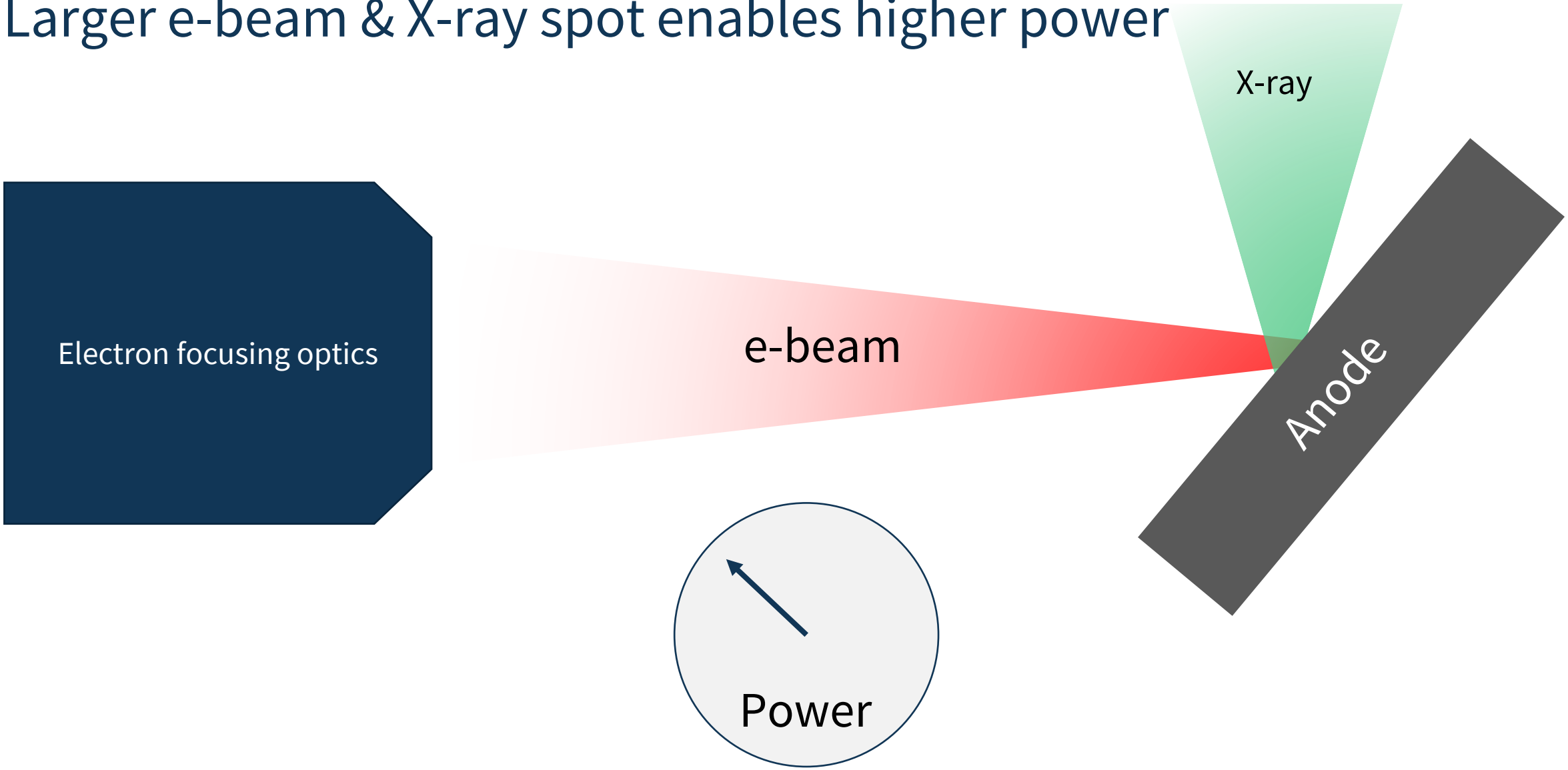
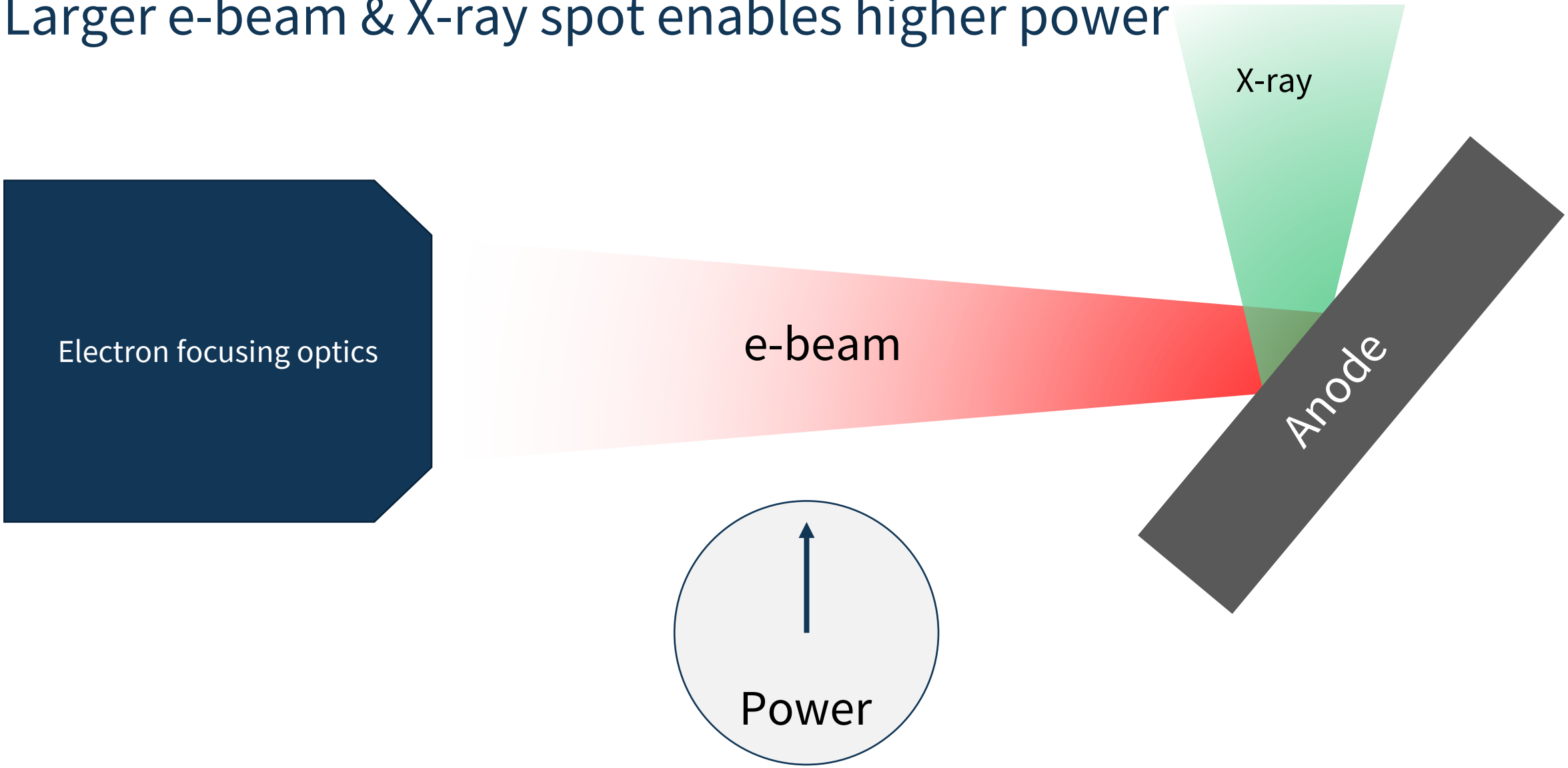
Some X-ray source and X-ray imaging basics

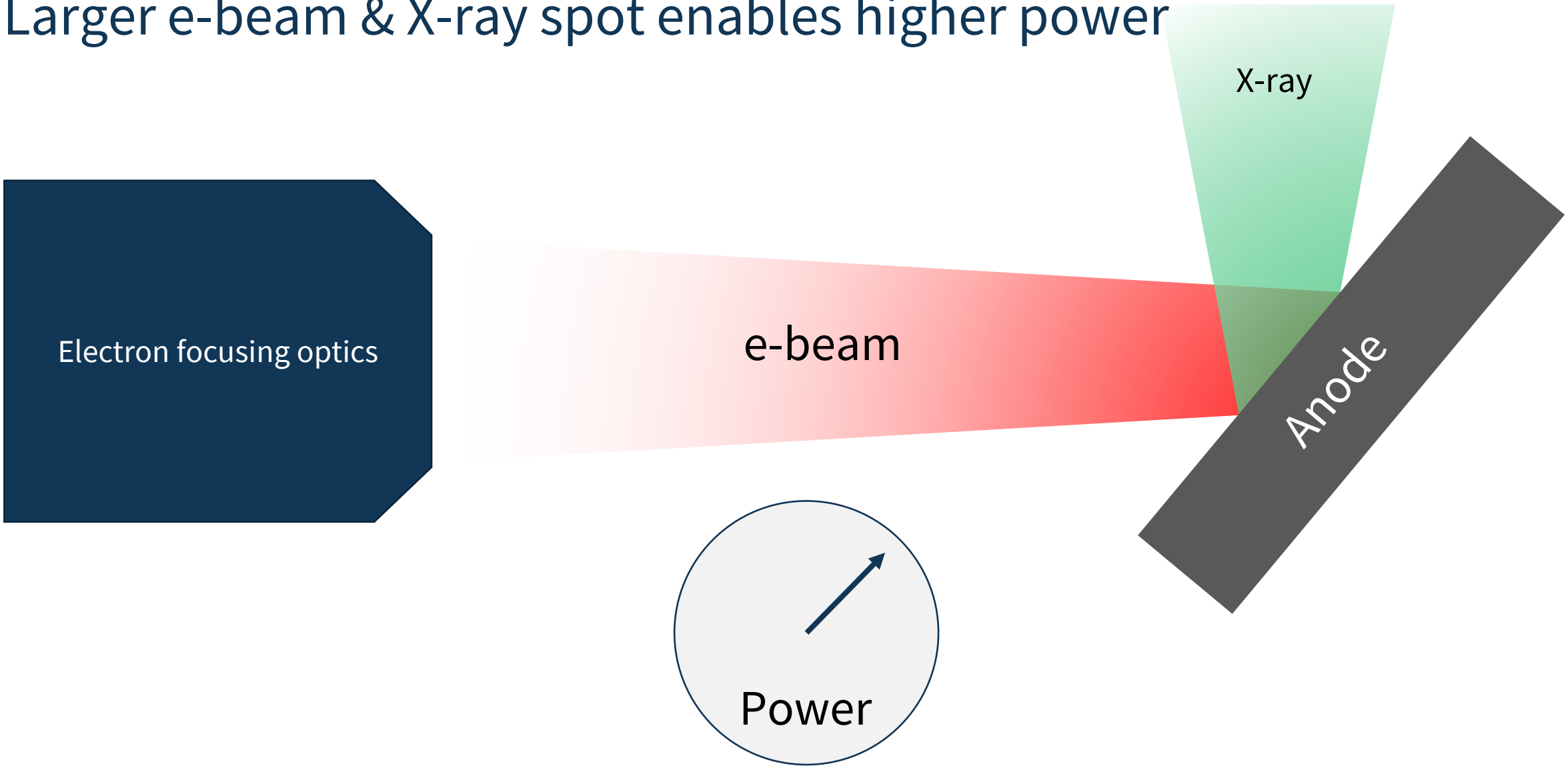
Larger e-beam & X-ray spot enables higher power



Larger e-beam & X-ray spot enables higher power

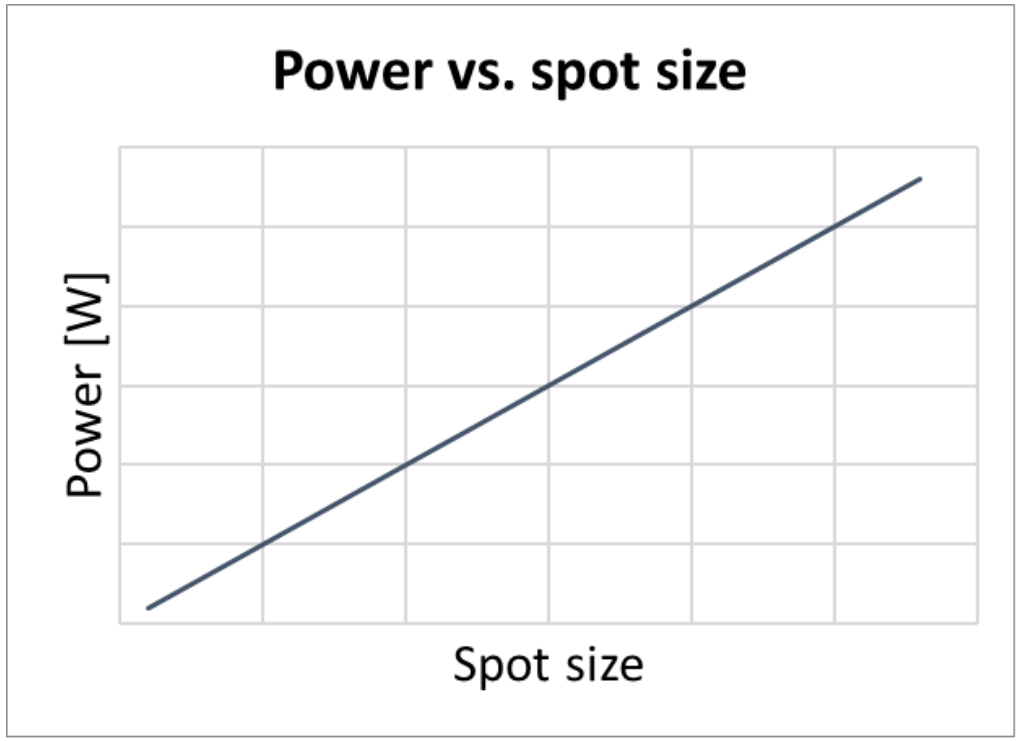


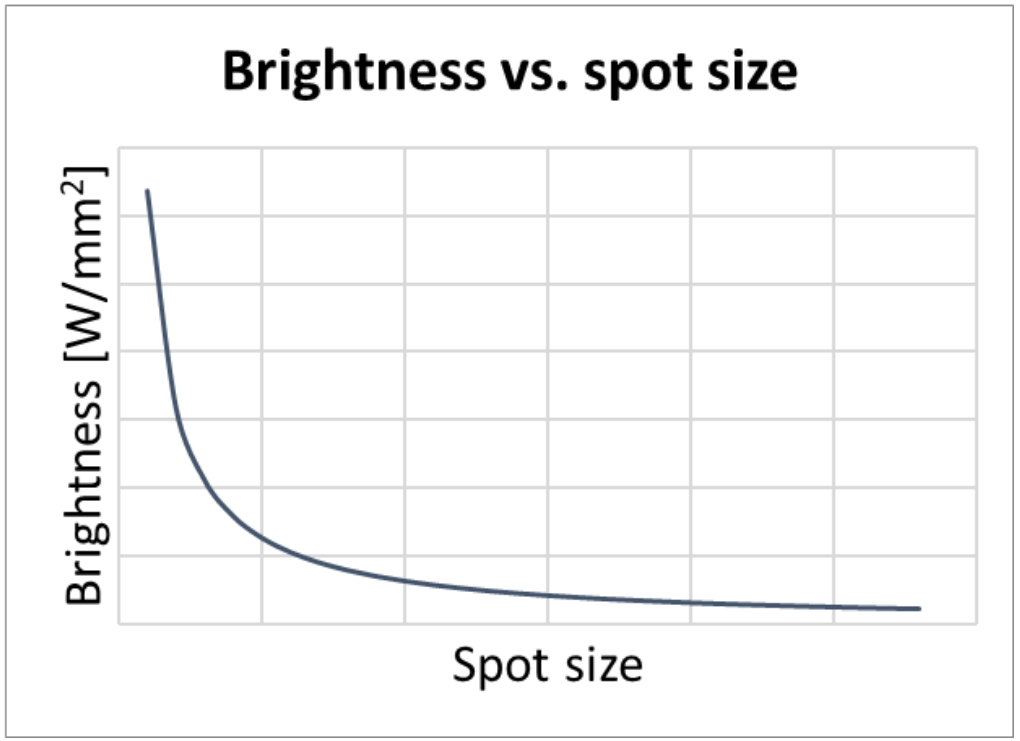
Larger e-beam & X-ray spot enables higher power



Smaller spots are typically brighter

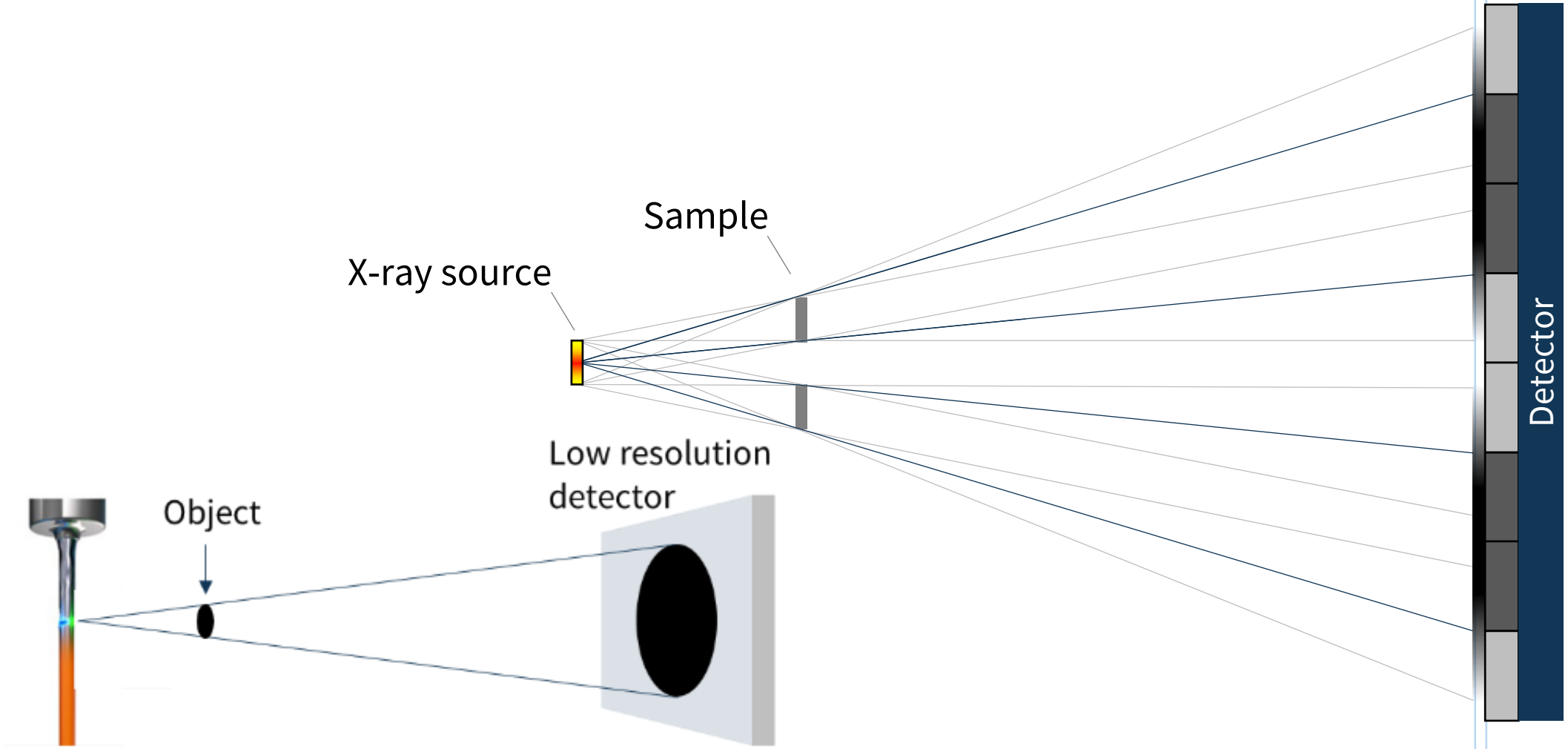
As rule of thumb, power capability is proportional to spot diameter.
And since spot area scale as square of diameter…



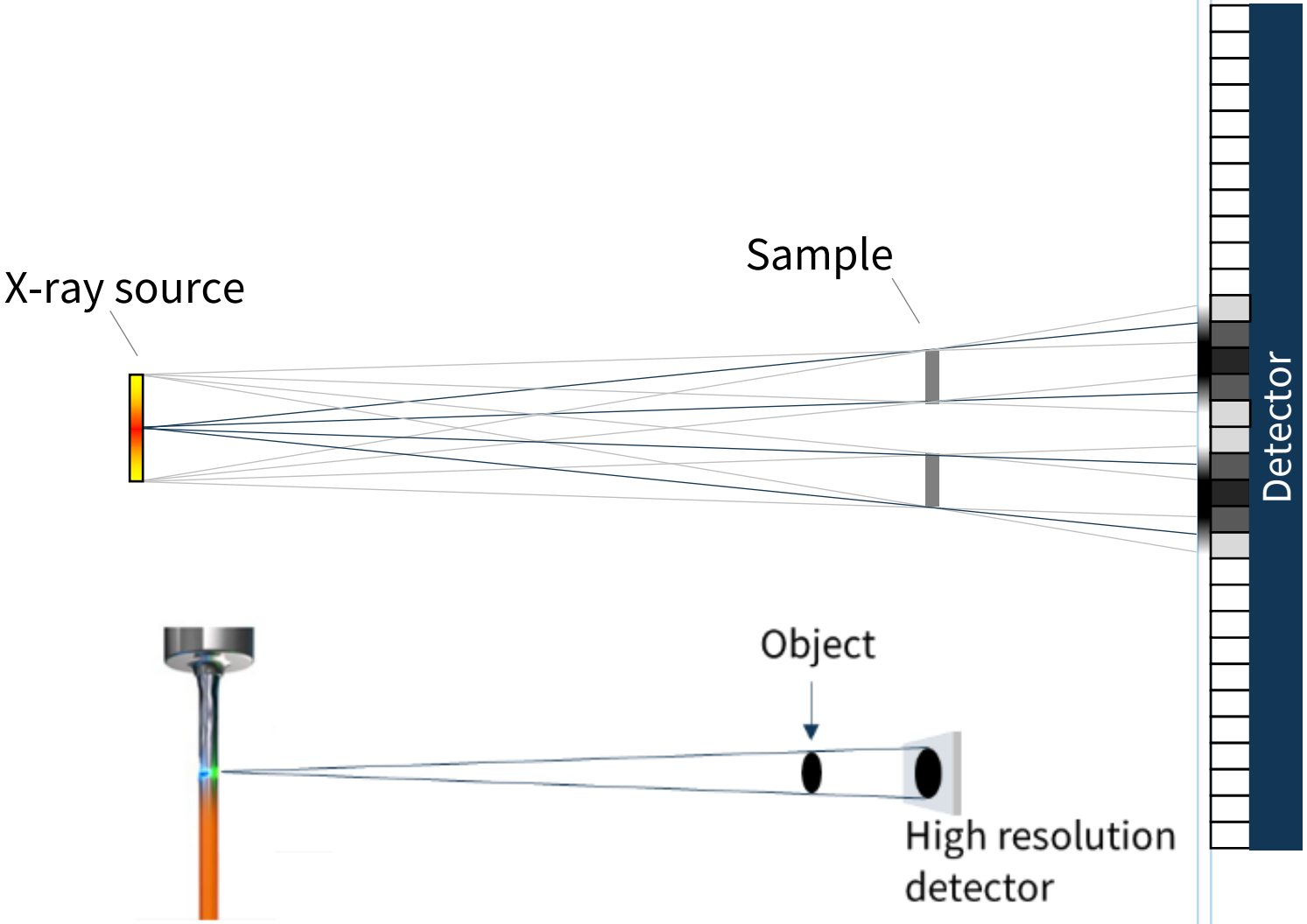


3 ways to acheive high-resolution X-ray imaging

#1 - High resolution through high magnification



#2 - High resolution through high-resolution detector



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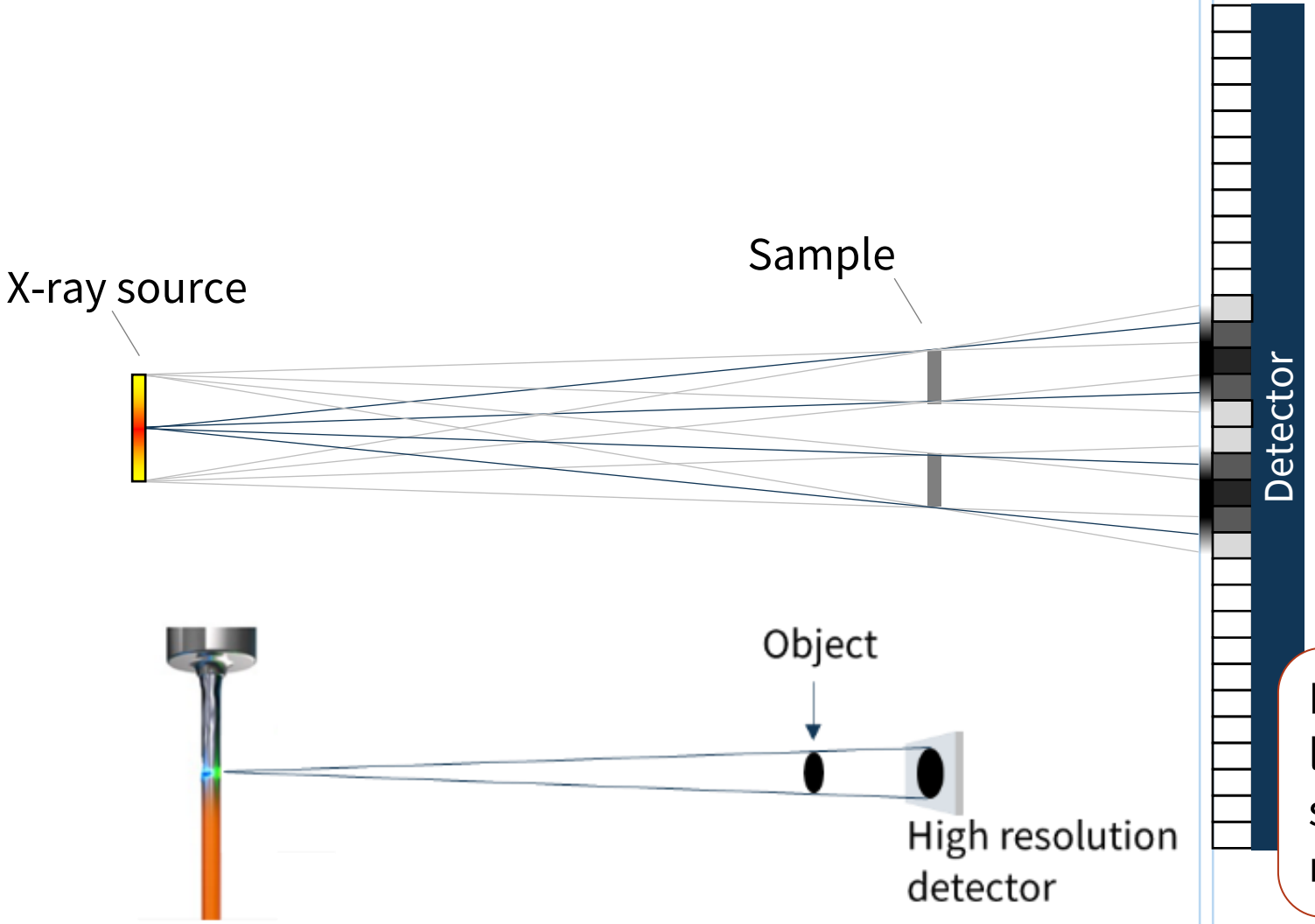
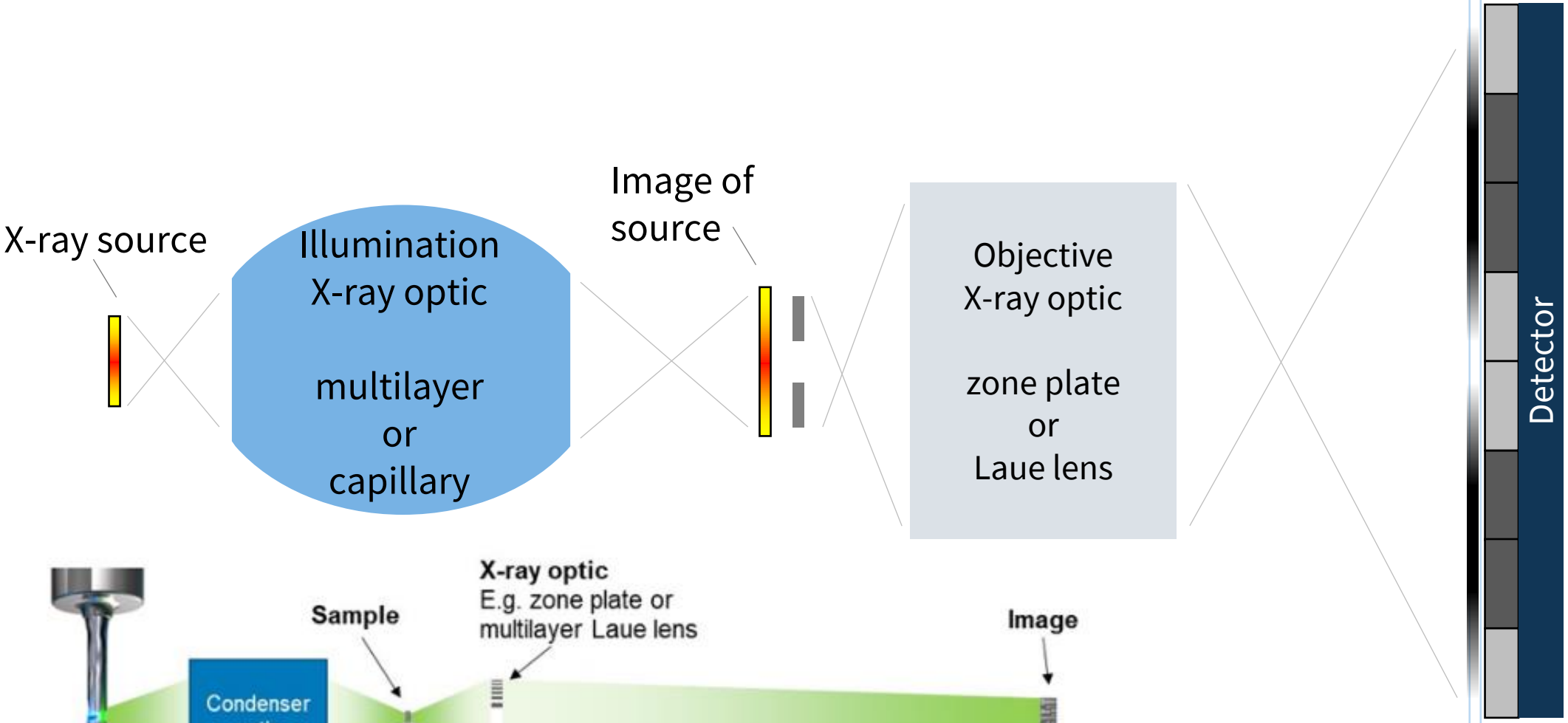


High resolution detectors are typically less efficient due to needing very thin scintillators to achieve the high resolution

#3 - High resolution through X-ray optics

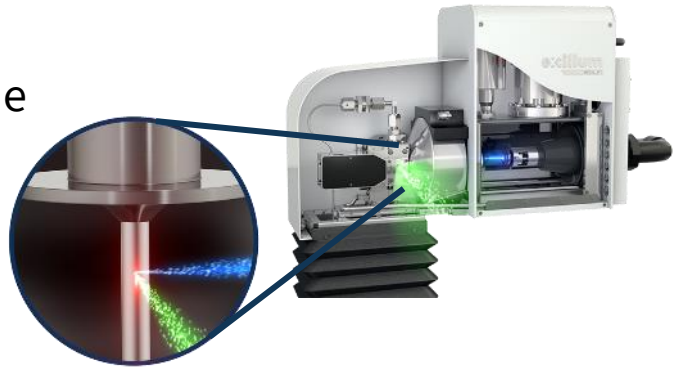


Two different X-ray sources

MetalJet

World's brightest microfocus X-ray source

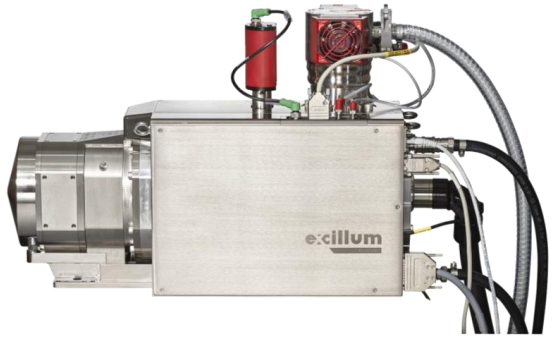
Liquid metal-jet anode technology

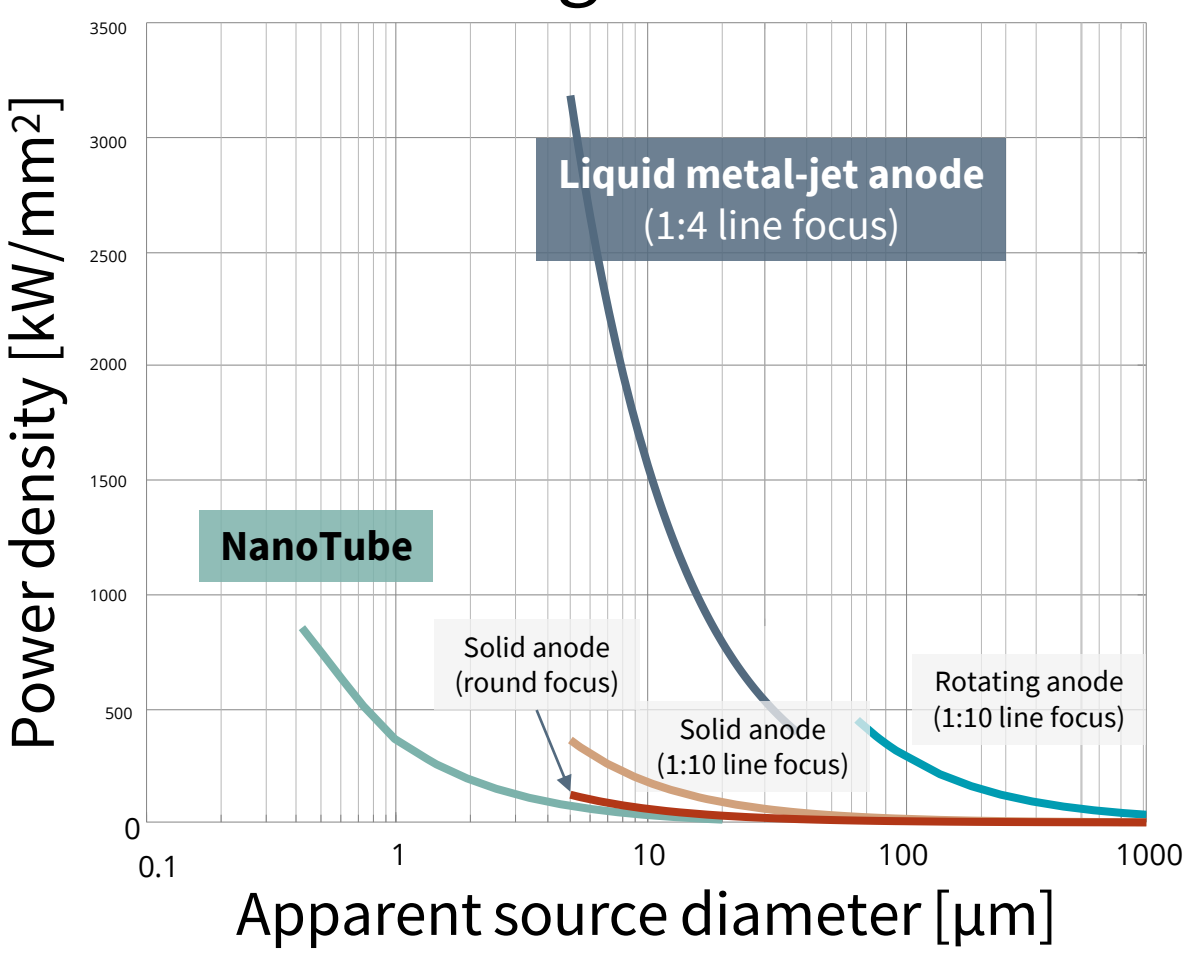


NanoTube

World's smallest X-ray nanospot

Advanced electron beam technology





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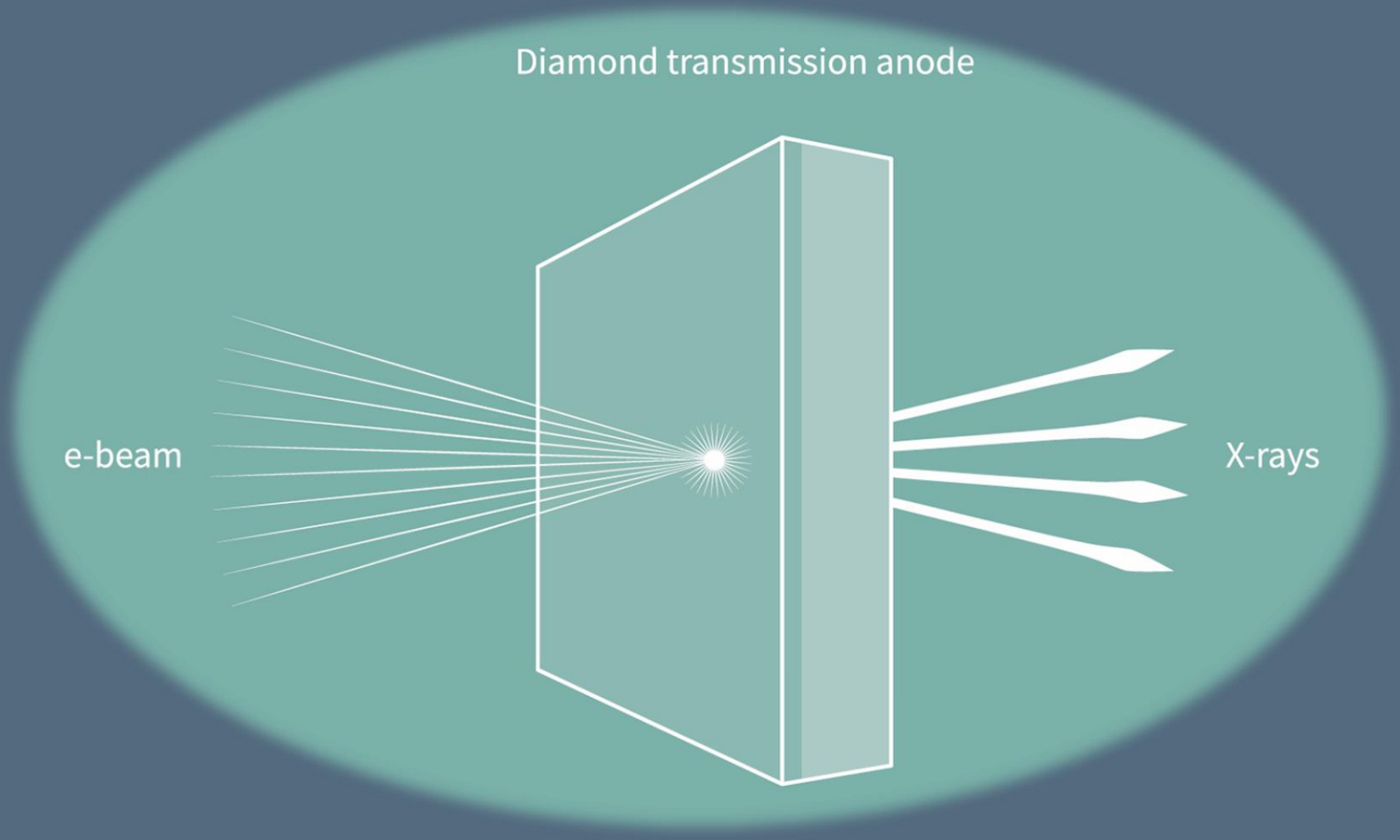
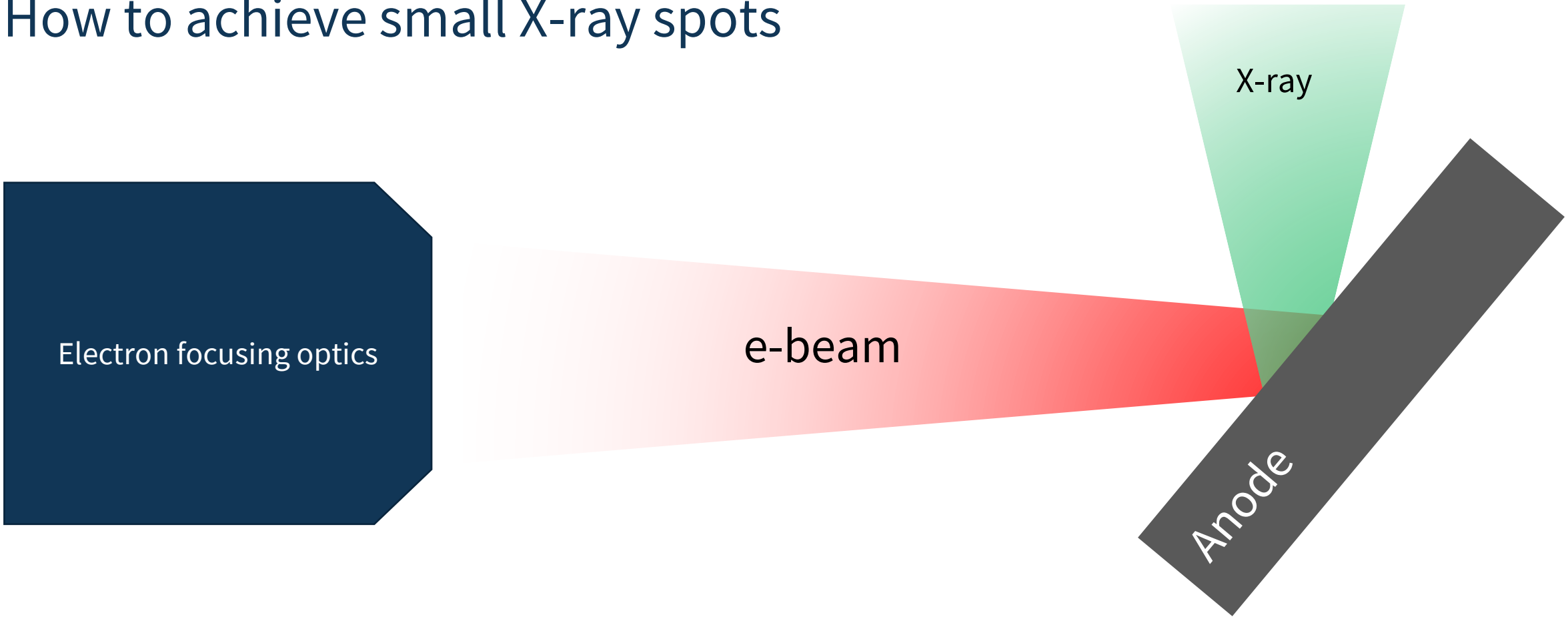
NanoTube Technology



How to achieve small X-ray spots



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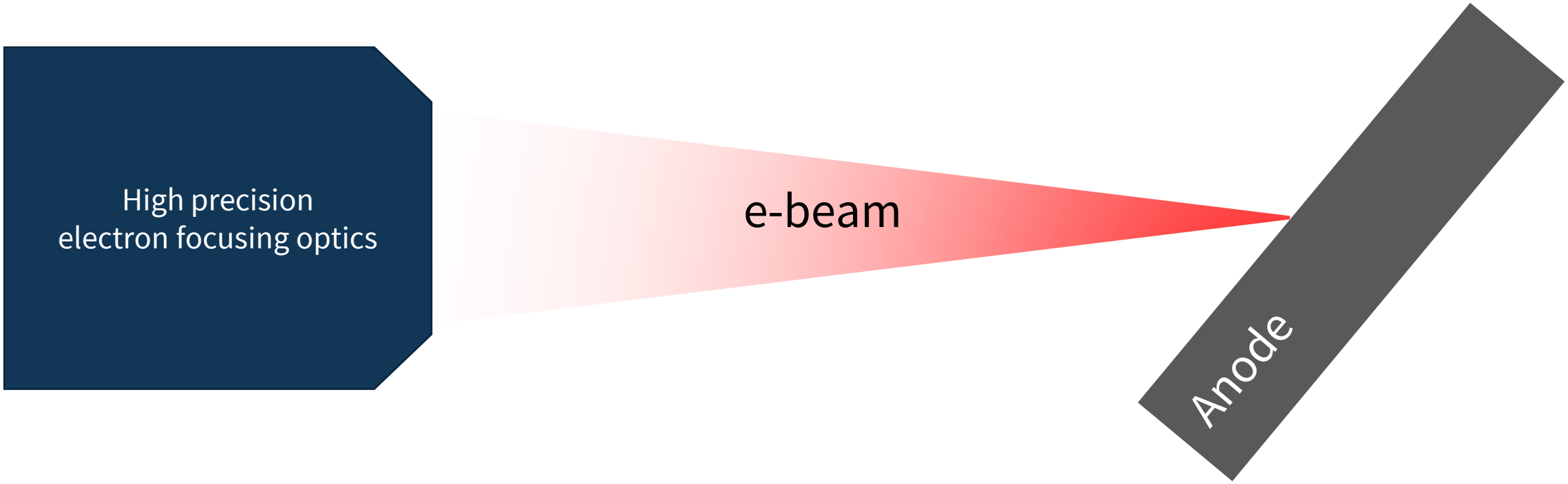

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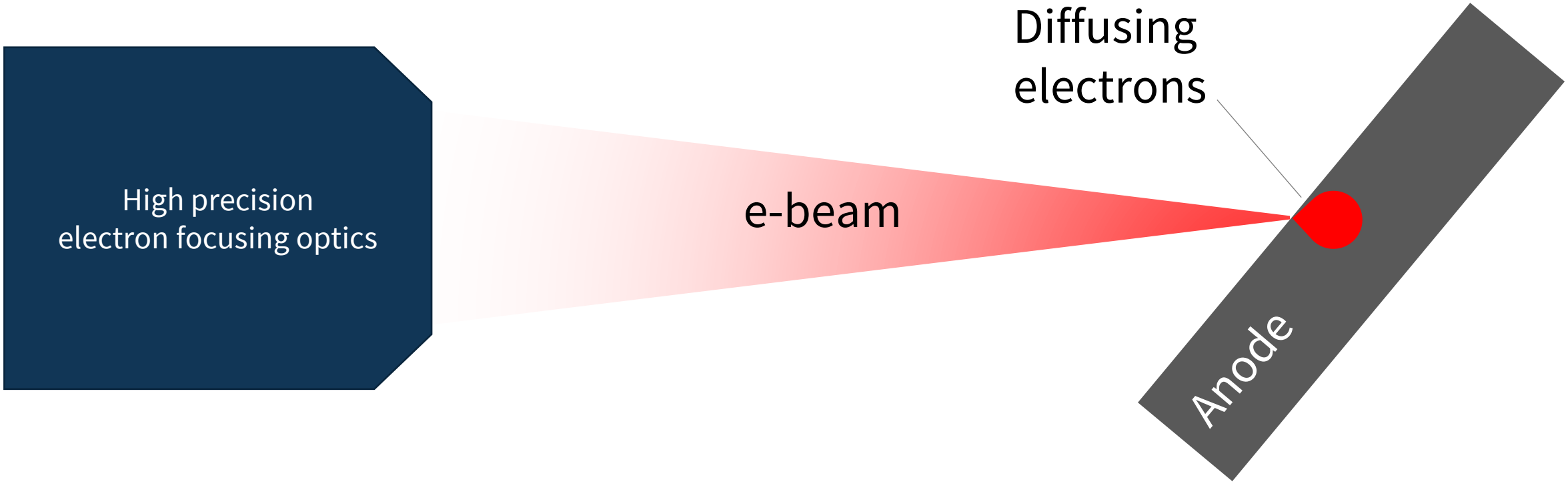

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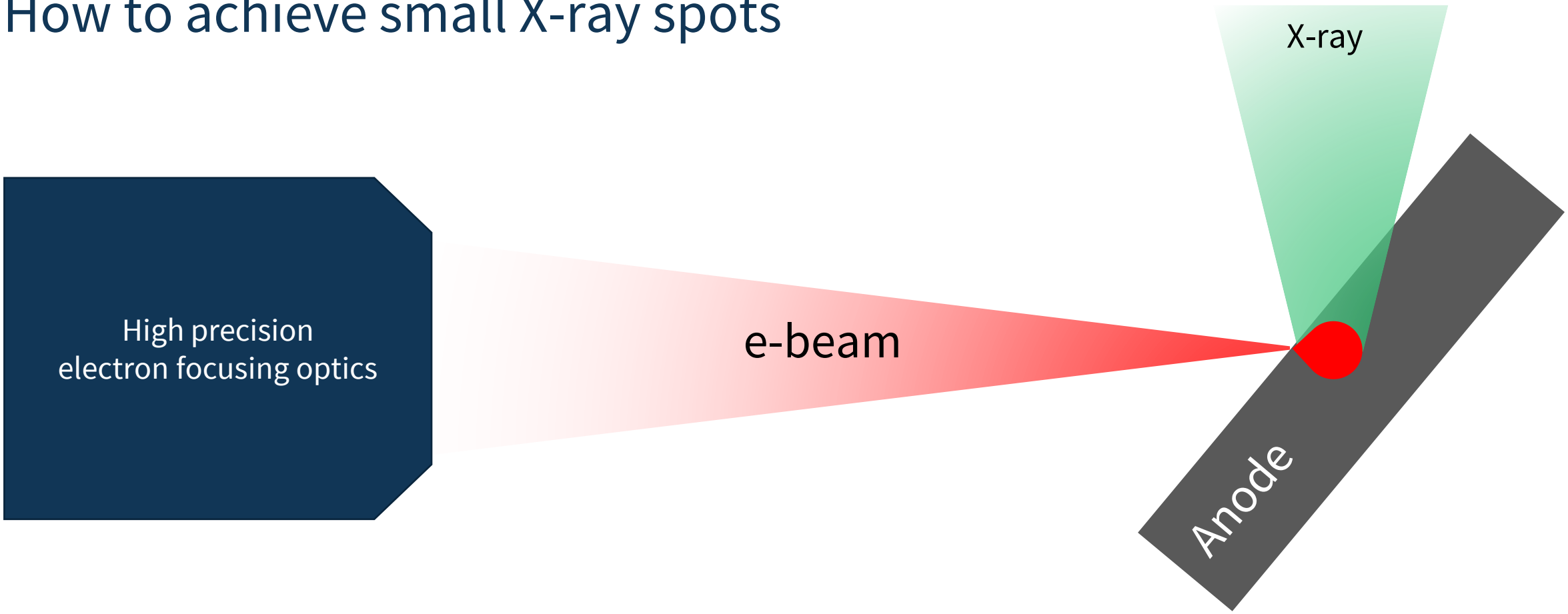

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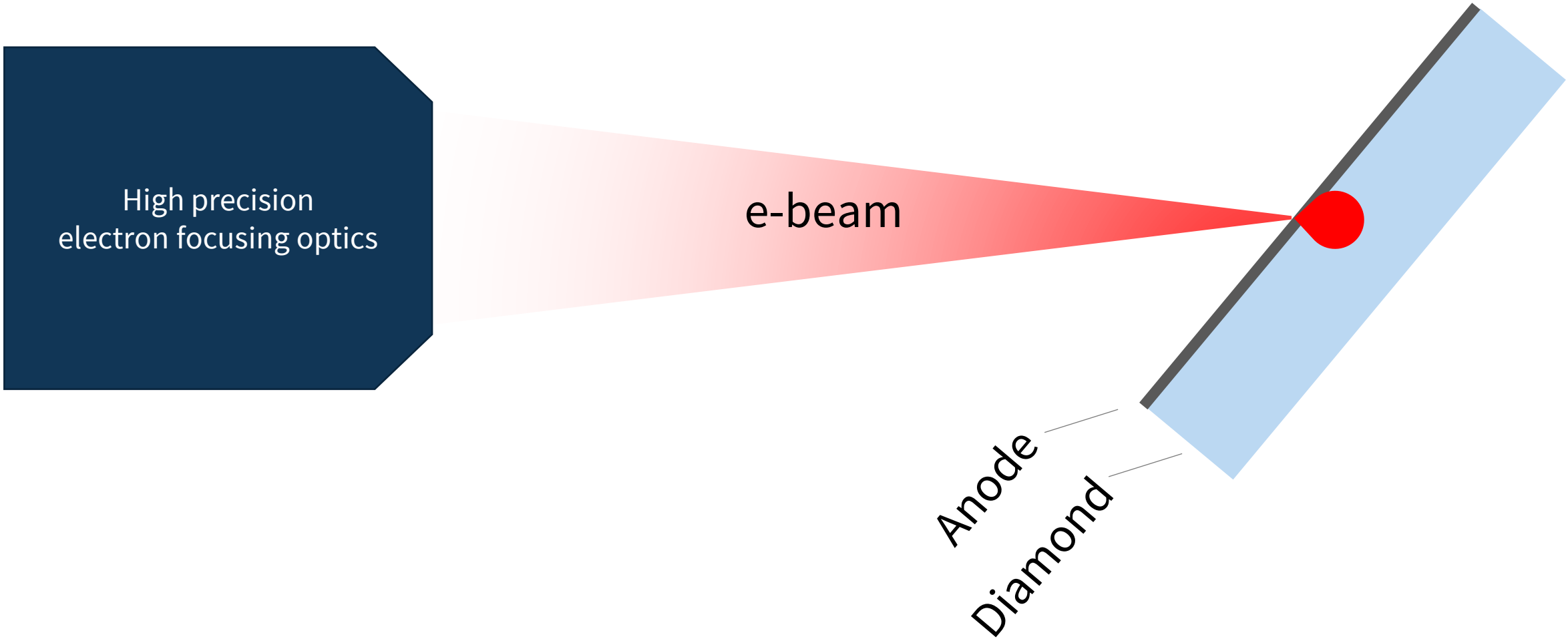

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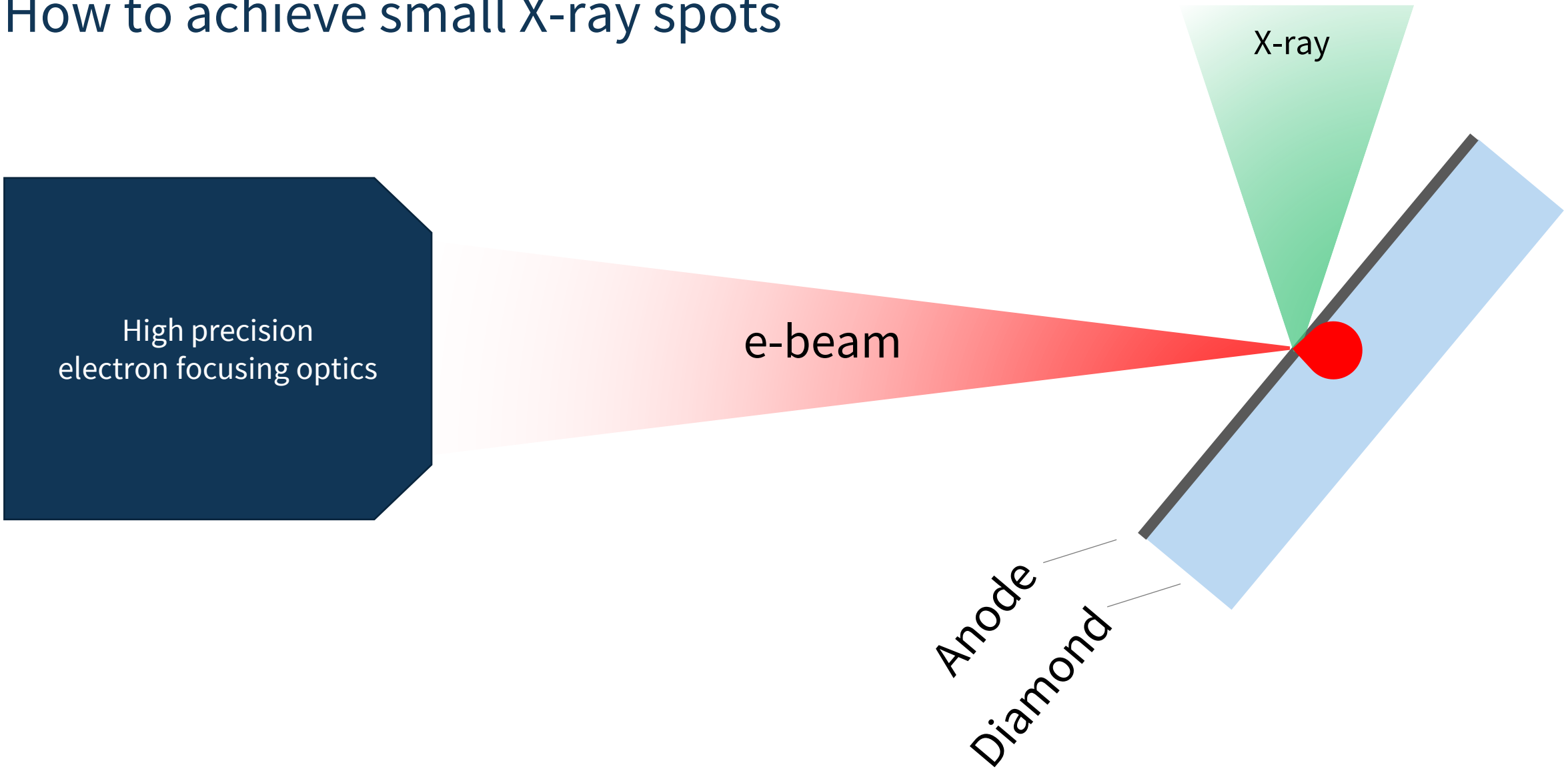

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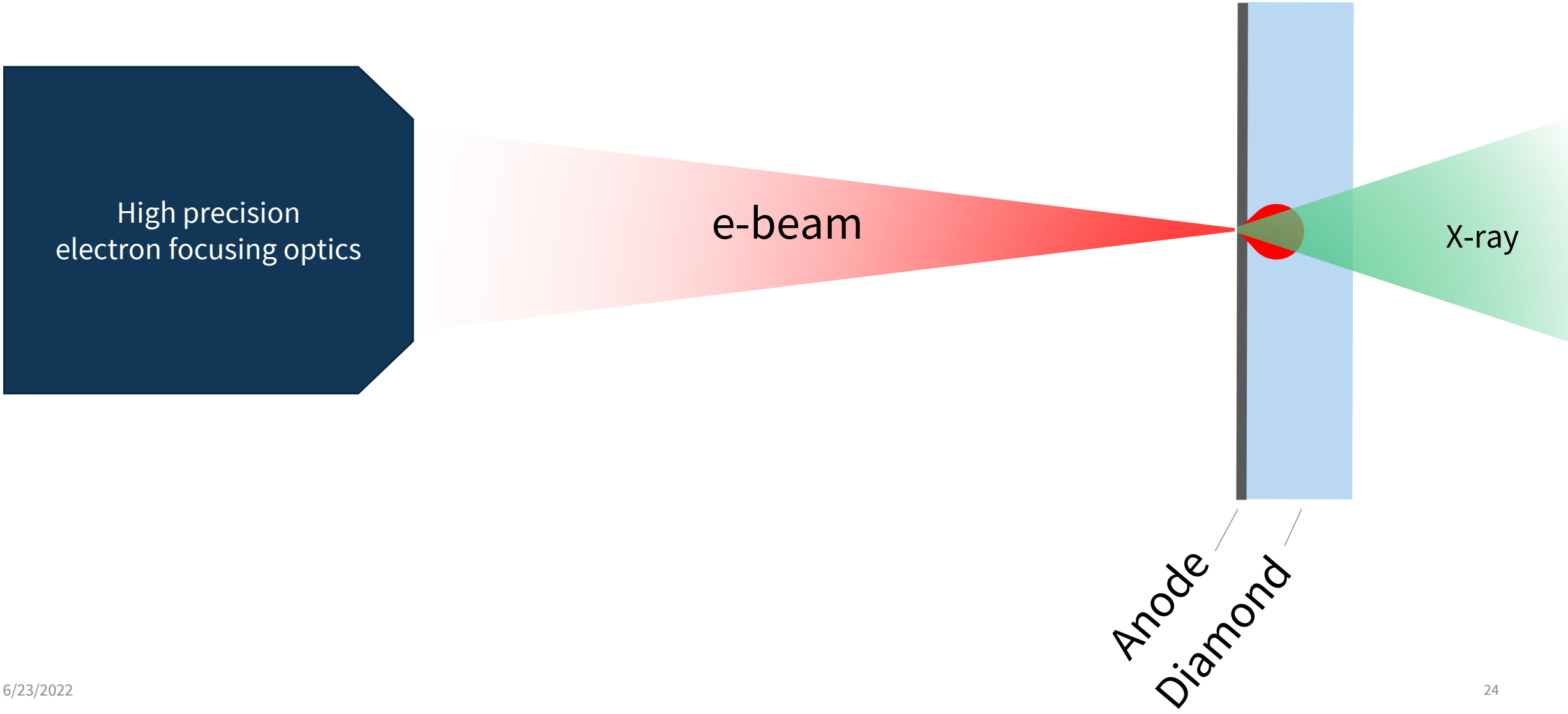
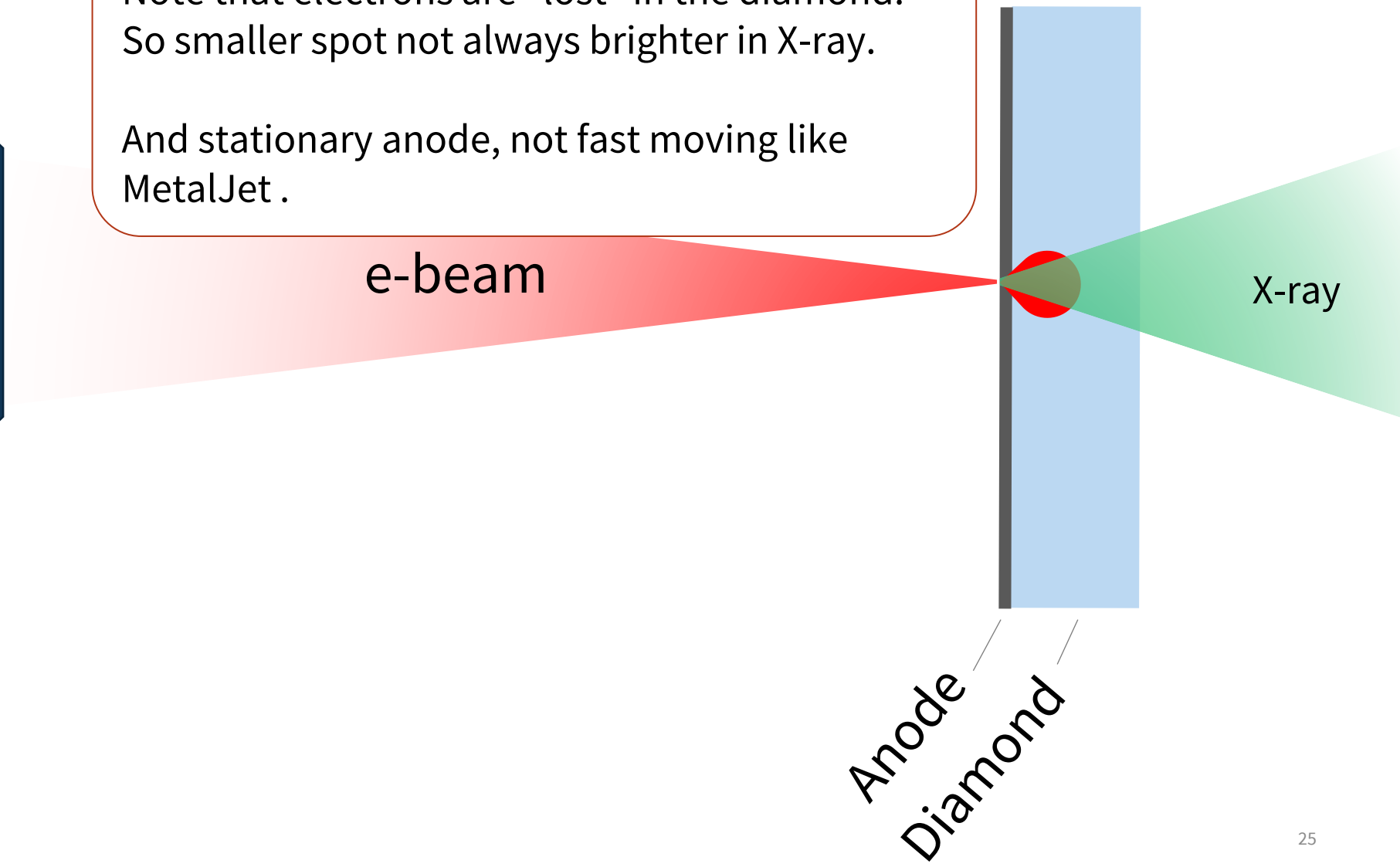


How to achieve small X-ray spots

Note that electrons are ”lost” in the diamond.
So smaller spot not always brighter in X-ray.

And stationary anode, not fast moving like MetalJet .

High precision
electron focusing optics



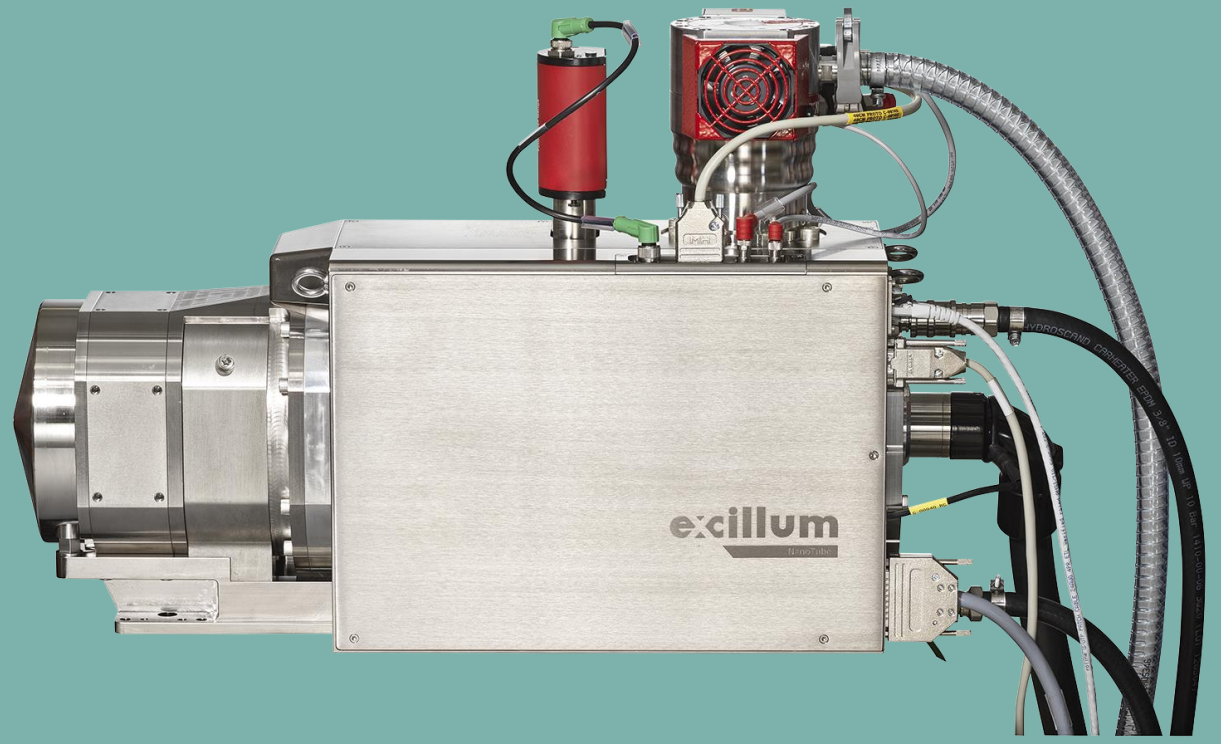
Excillum NanoTube N3 160 kV

NanoTube N3

The world’s smallest X-ray nanospot

Up to 160 kV

24/7 operation



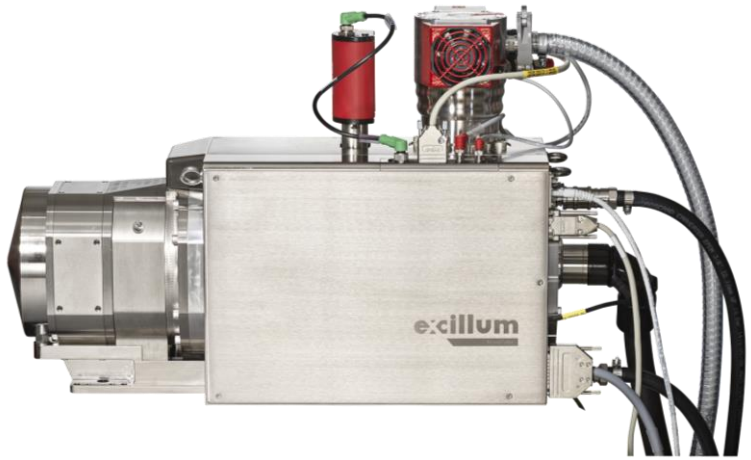
The road to NanoTube N3

NanoTube N1

- ❑ Launched Aug 2016
- ❑ **60 kV**
- ❑ Semi-automated operation

NanoTube N2

- ❑ Launched Feb 2020
- ❑ 60 kV & **110 kV**
- ❑ Increased power
- ❑ Automated operation



NanoTube N3

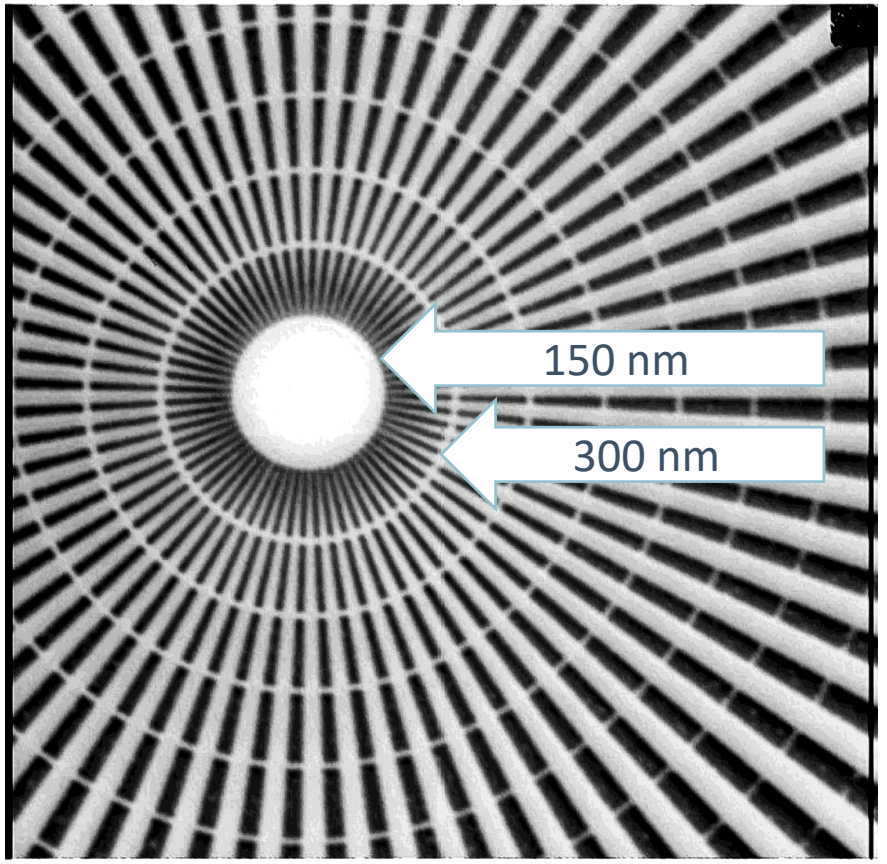
- ❑ Launched Dec 2021
- ❑ 60 kV, 110 kV & **160 kV**
- ❑ Automated startup and commissioning after service
- ❑ Optimized for 24/7 in-line inspection and metrology

Performance of available three versions

NanoTube N3 60 kV	
Voltage	40-60 kV
Min. resolution	150 nm
Max. power on target	2.4 W

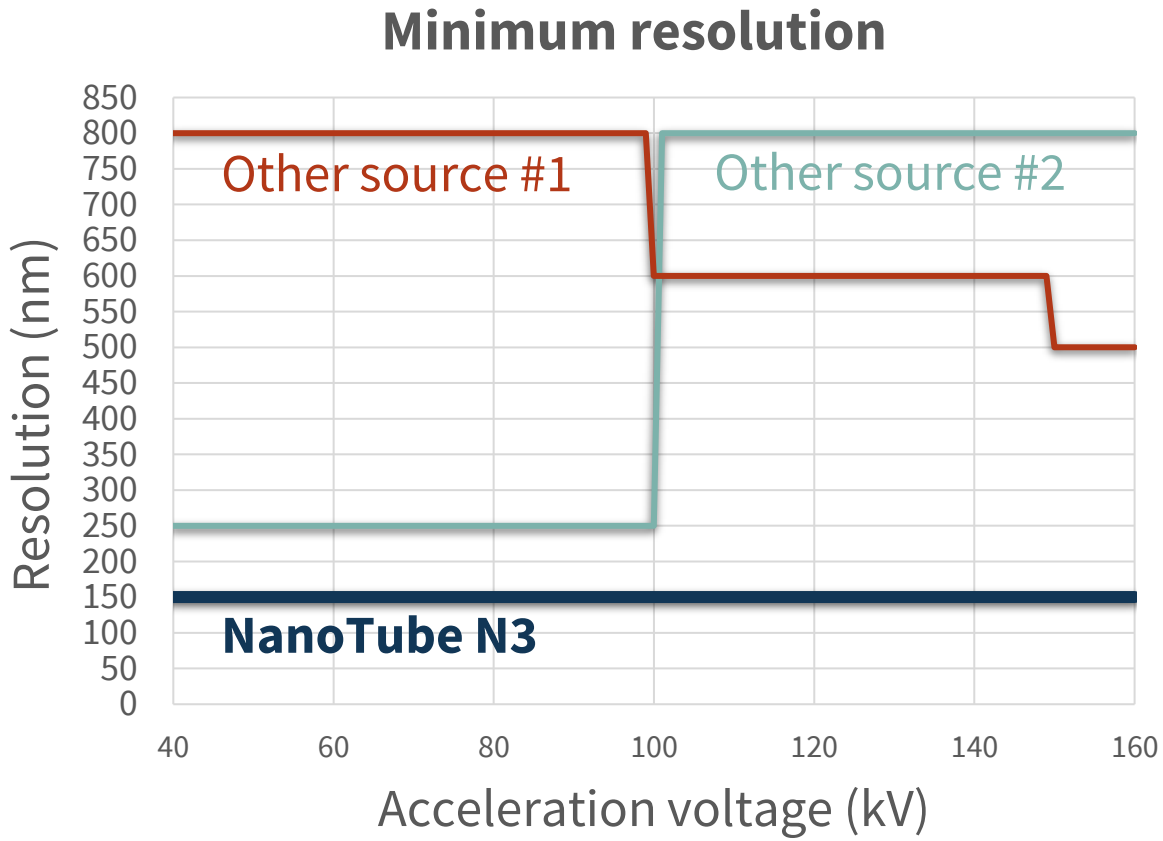
NanoTube N3 110 kV	
Voltage	40-110 kV
Min. resolution	150 nm
Max. power on target	6.1 W

NanoTube N3 160 kV	
Voltage	40-160 kV
Min. resolution	150 nm
Max. power on target	11 W



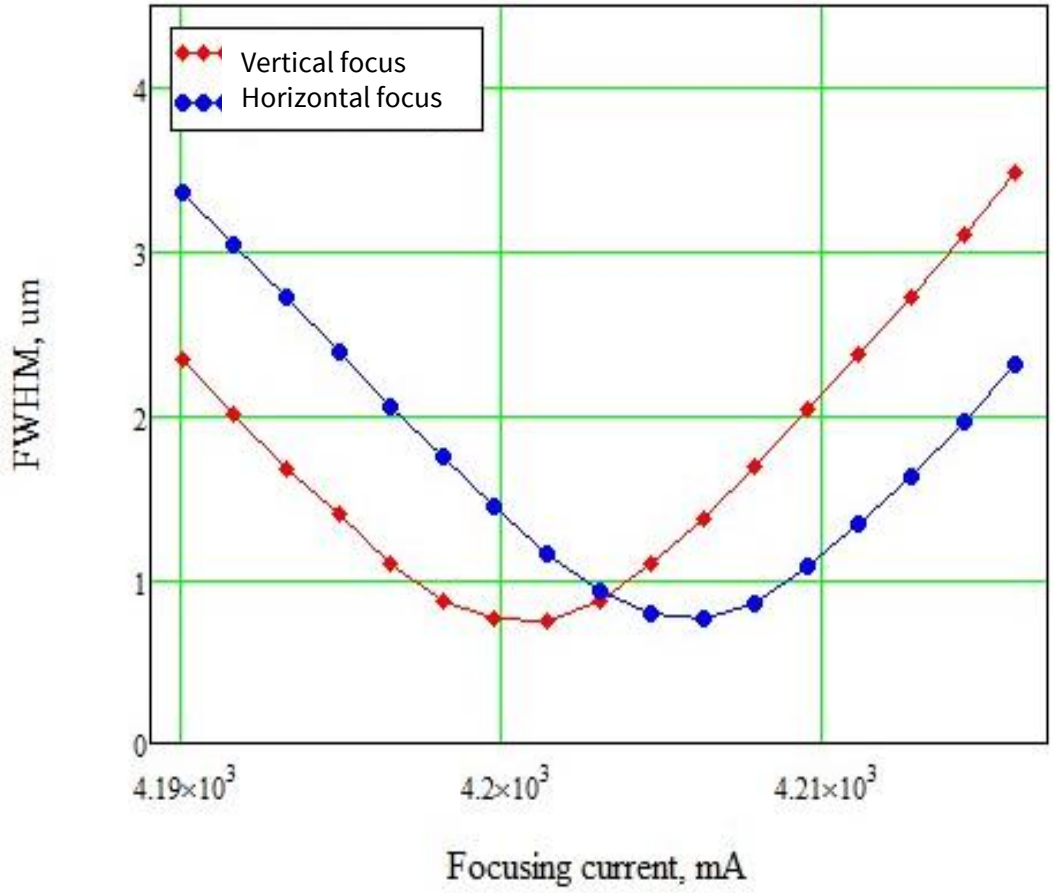
The right resolution and power – all the time, every day!

- The NanoTube N3 can consistently reach 150 nm minimum resolution across the full voltage range
- The power at a certain resolution and kV is always the same over the full cathode lifetime
- Performance is identical between different individual NanoTube N3s

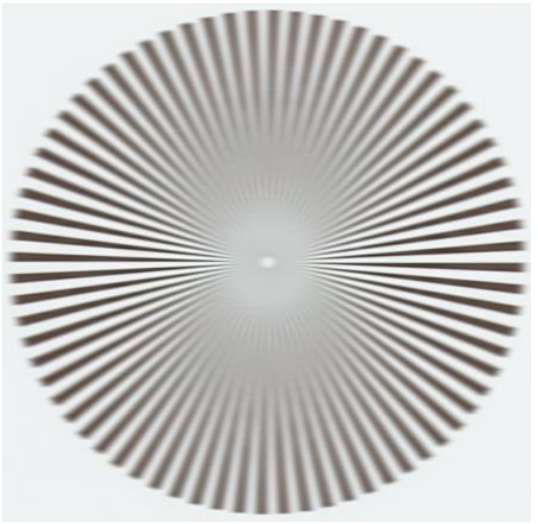


Symmetric resolution thanks to astigmatism correction

Before astigmatism correction

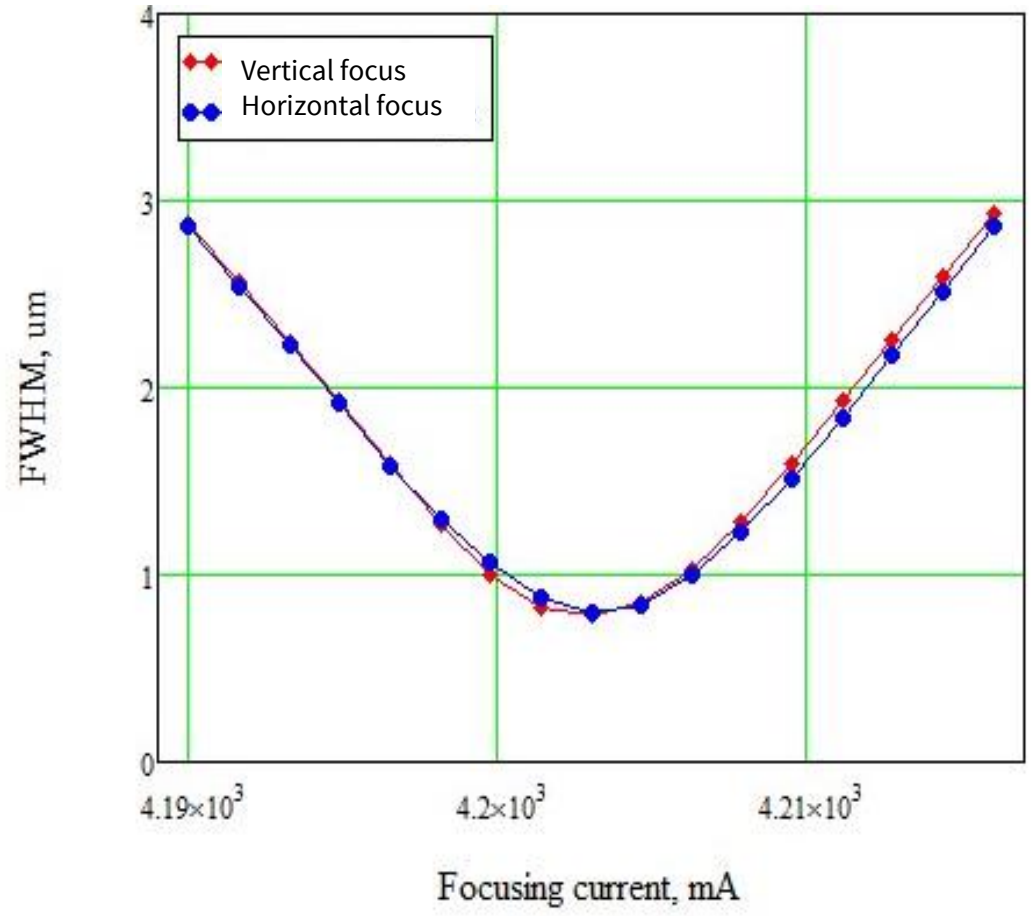


Elliptical spot

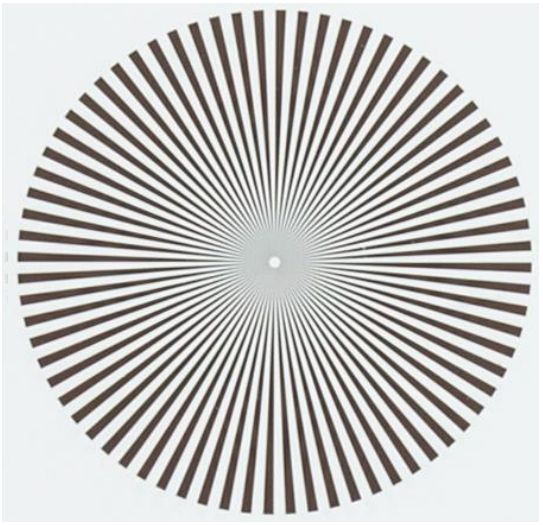


Symmetric resolution thanks to astigmatism correction

After astigmatism correction



Round spot



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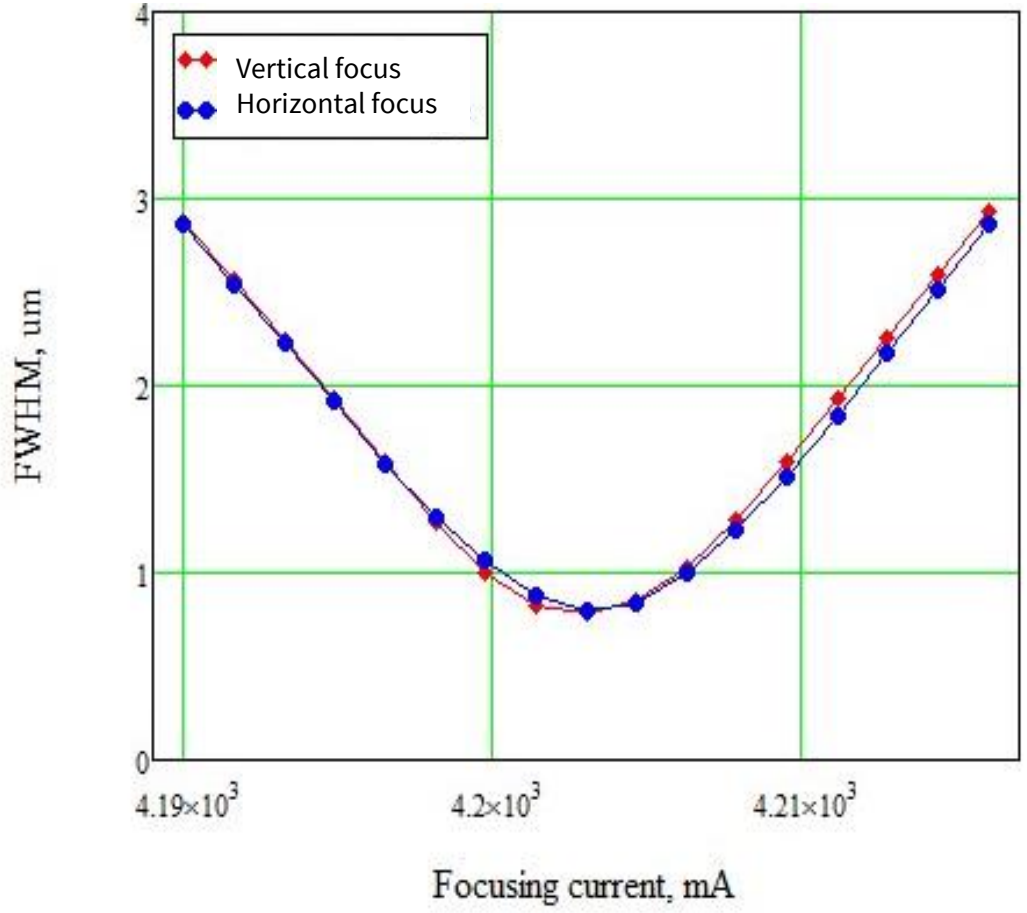
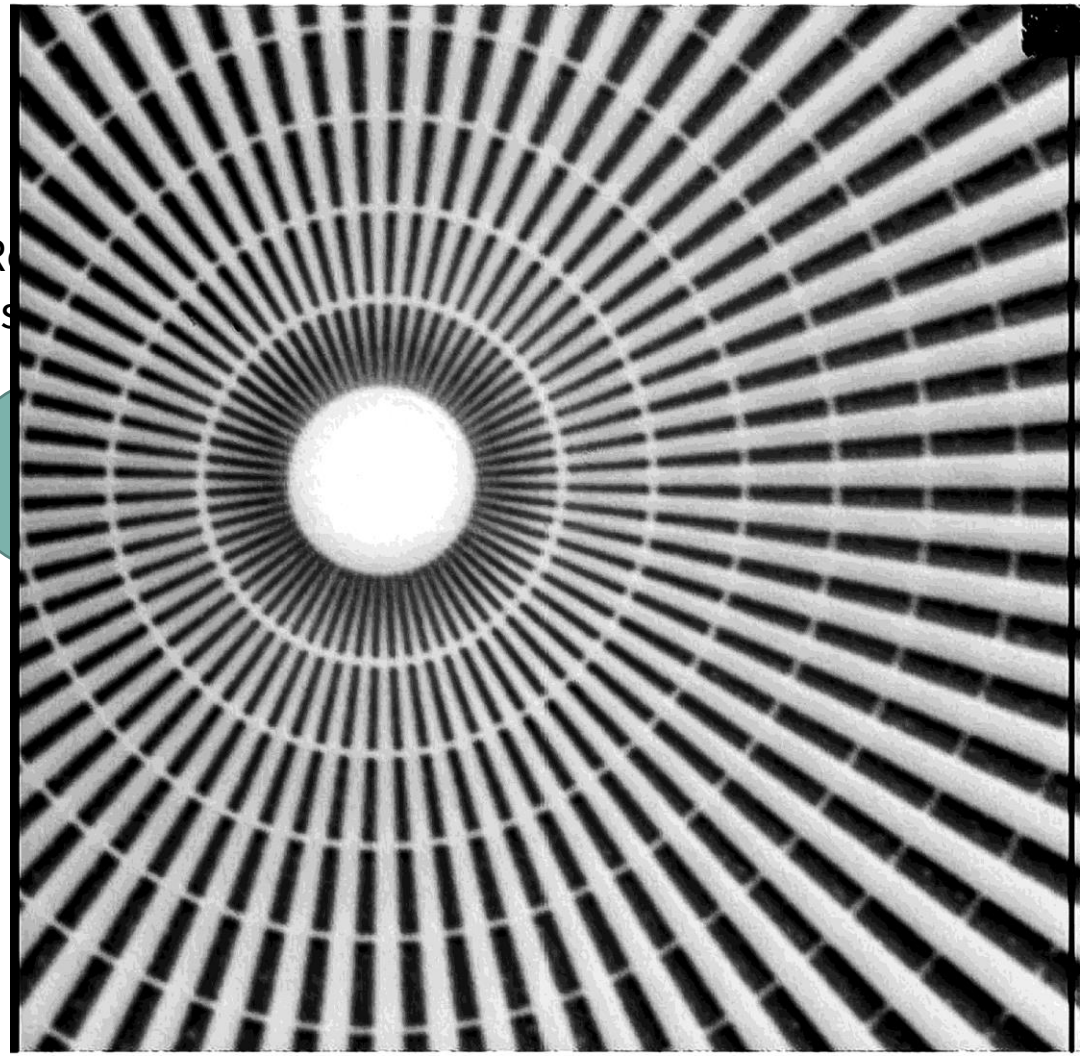
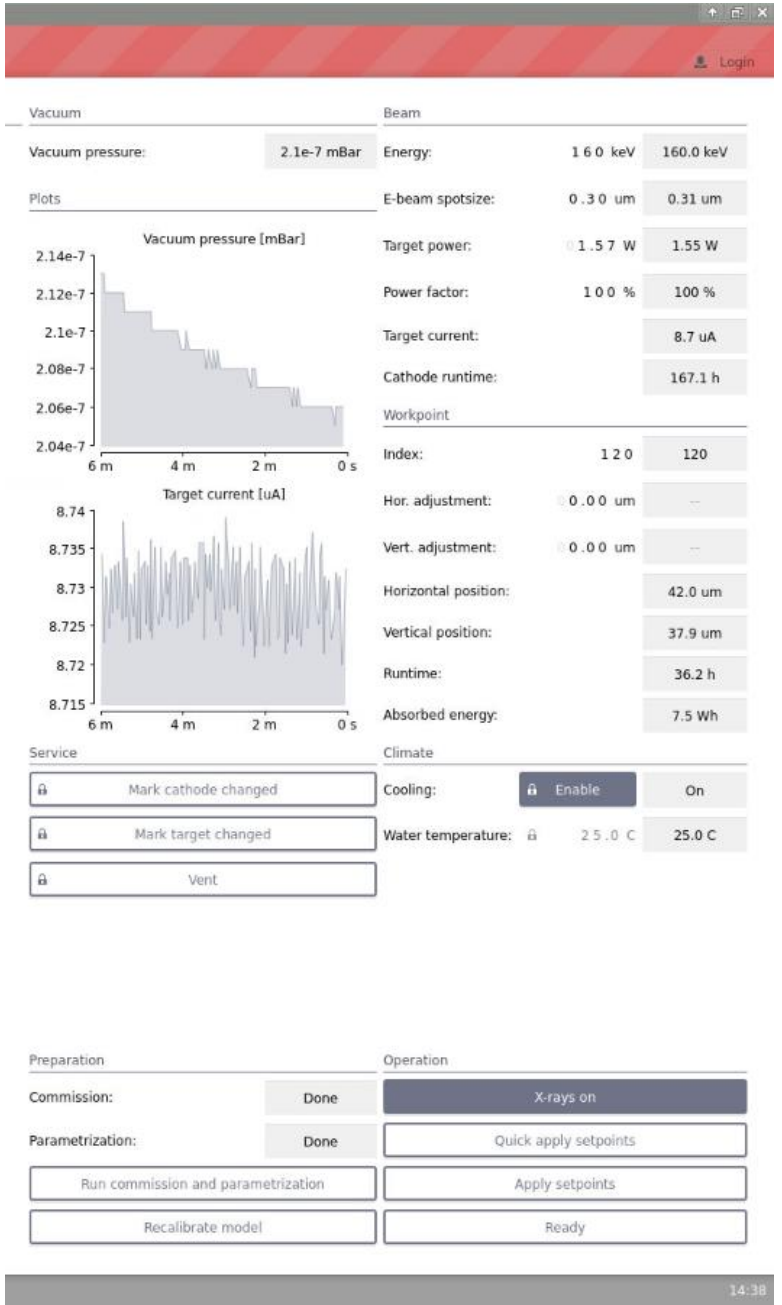




Control and automation

- Controlling the tube can be done either through the source GUI or through the API with text commands over TCP/IP
- The NanoTube N3 lets the user directly control:
  - Acceleration voltage
  - Spot size
  - Target Power
  - Spot position on target
- Parameters automatically set and verified
  - No manual fine tuning
- Same performance within cathode lifetime
  - No gradual loss of performance



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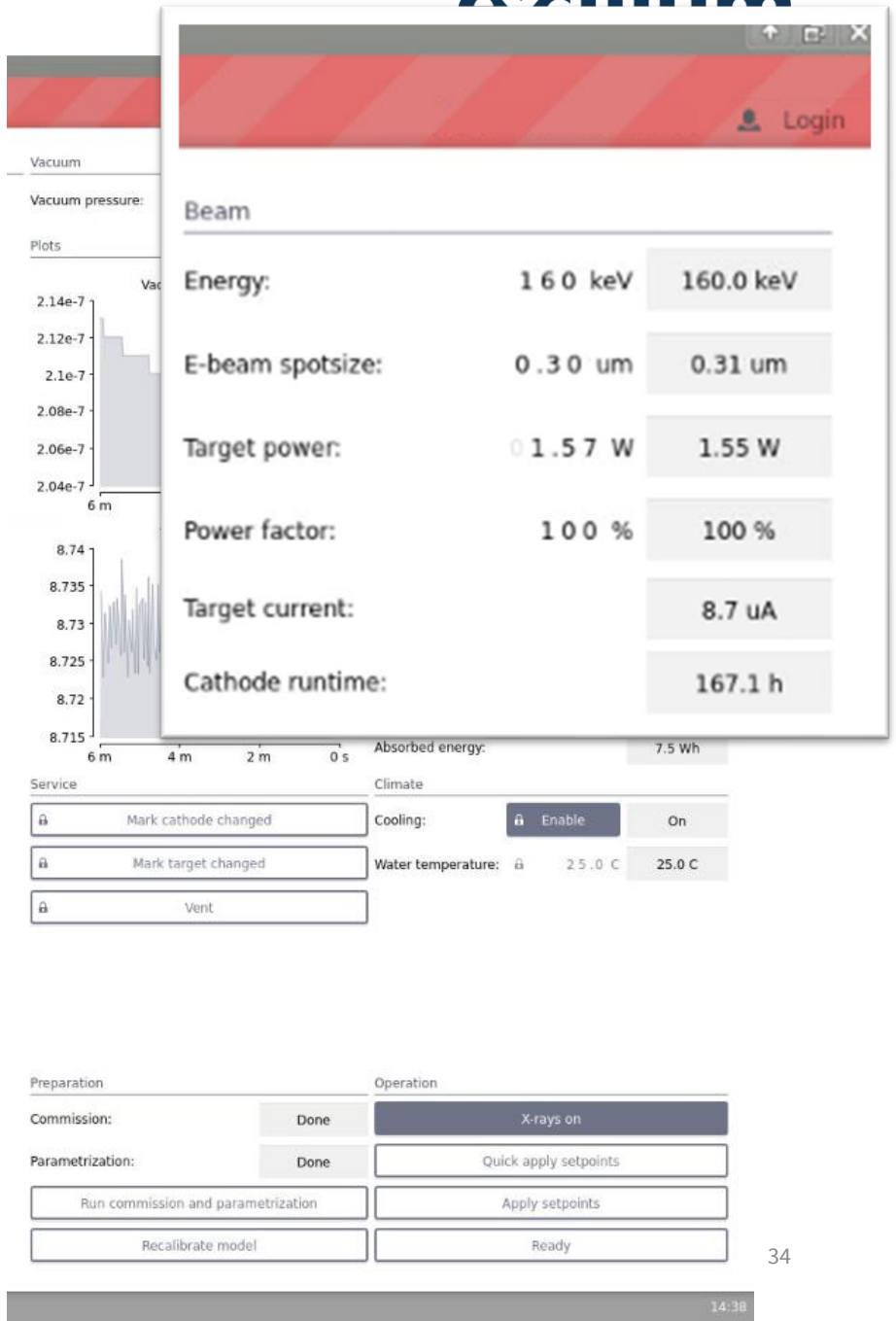
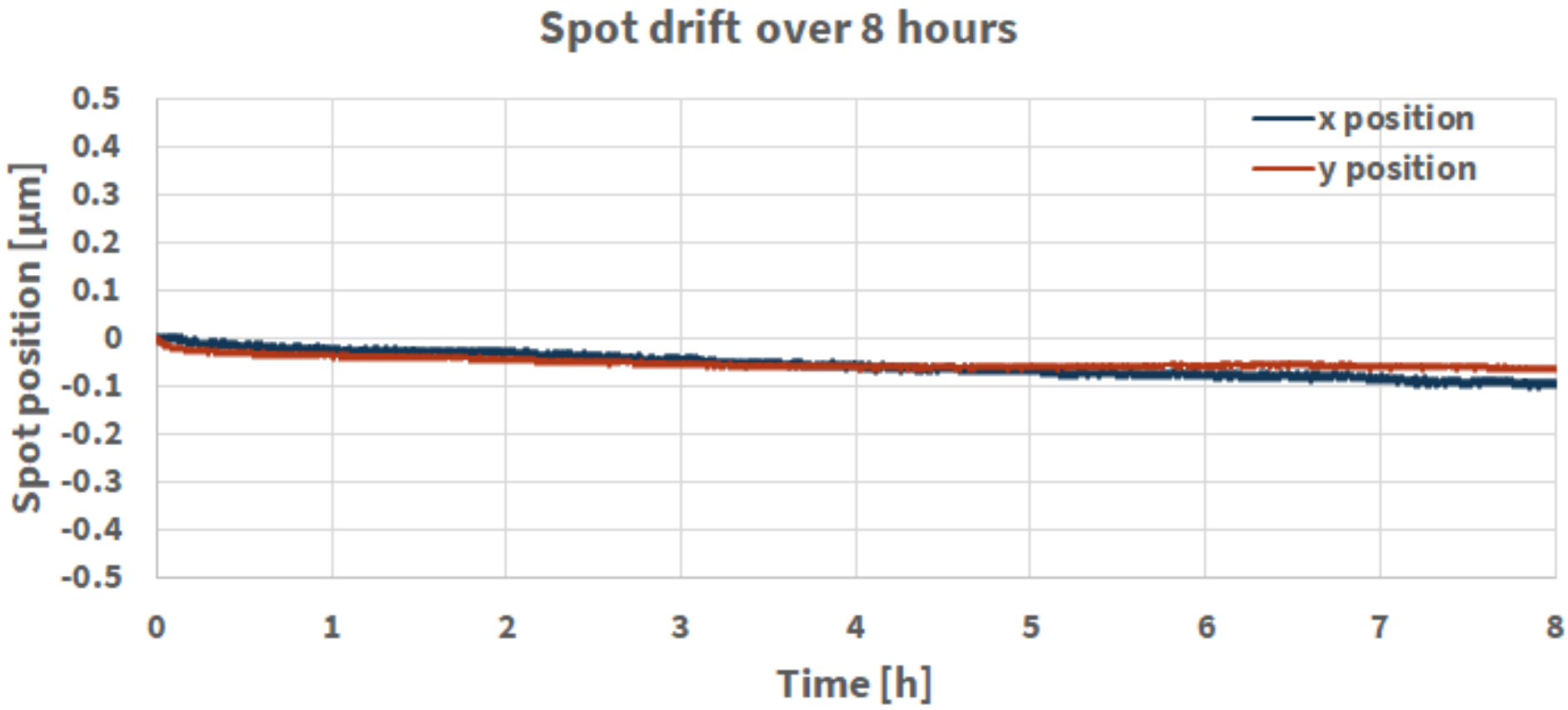
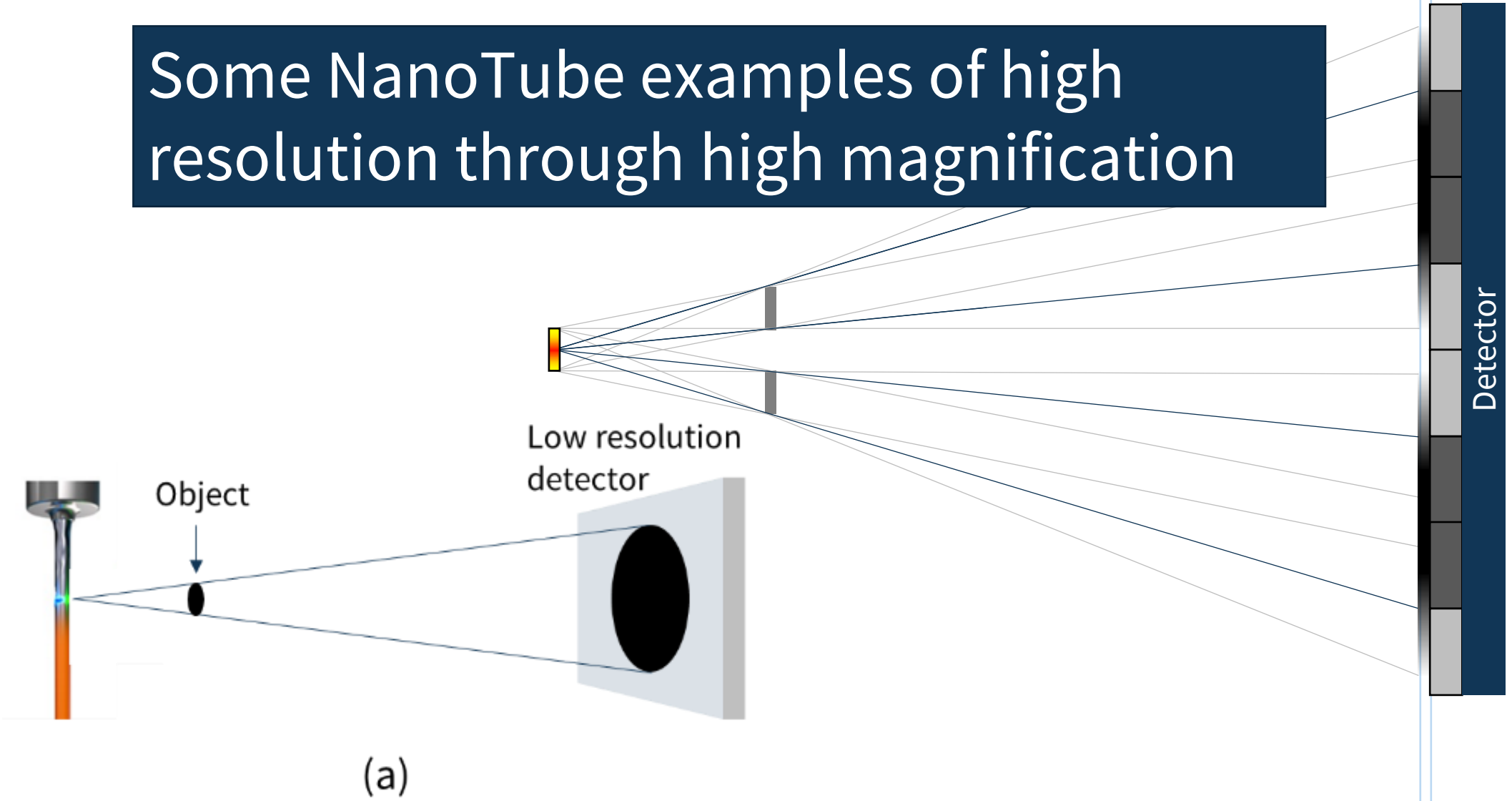


Spot stability is important for long CT exposures



#1 - High resolution through high magnification

Some NanoTube examples of high resolution through high magnification



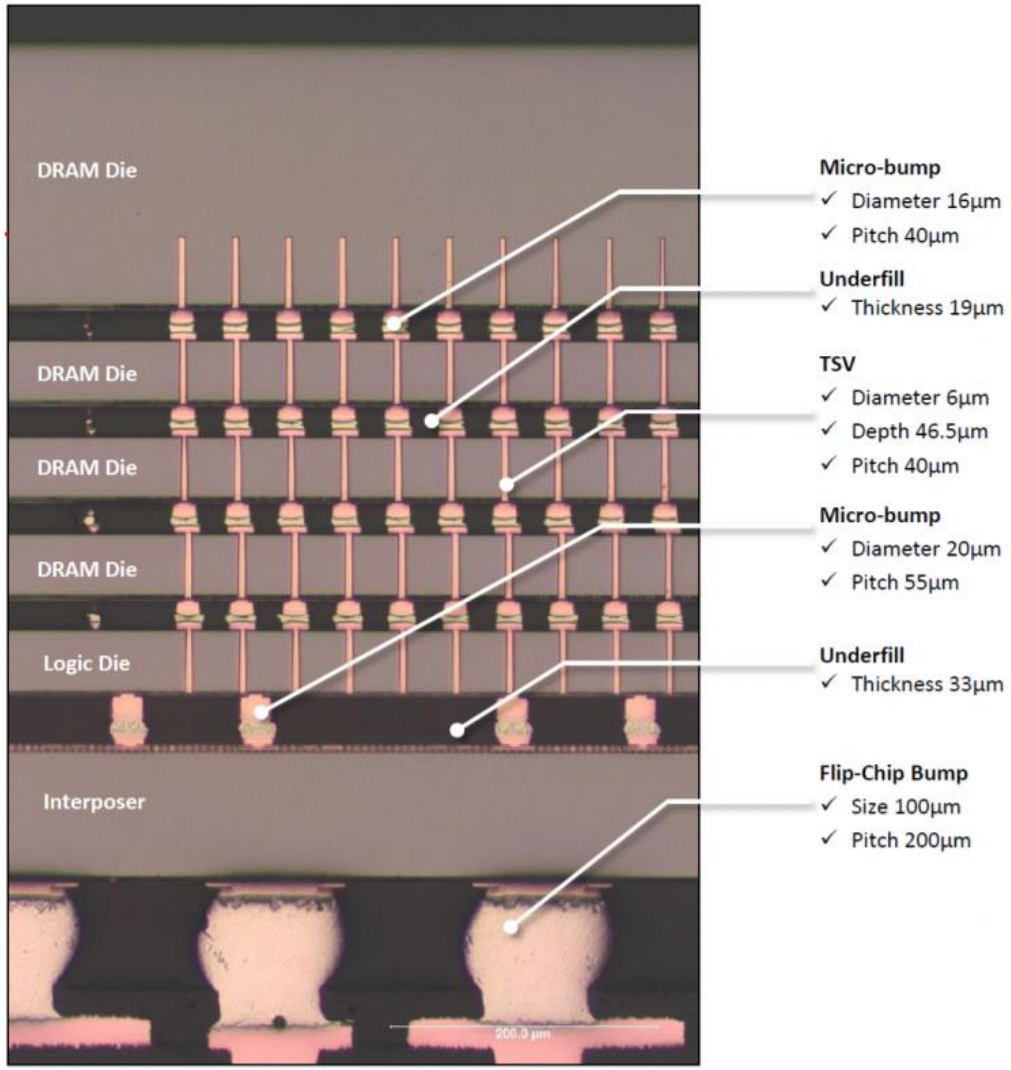
Demo capability #1 – Electronics/SEMI 2D imaging system

A commercial electronics/SEMI inspection system has been converted with a NanoTube N3 and is available to demonstrate 2D and potentially 3D laminography imaging.

HBM memory on Nvidia GV100

NanoTube, 60 kV 0.6 µm 1.45 W, 30 s exposure

Cross section of older HBM from Hynix with only 4 layers

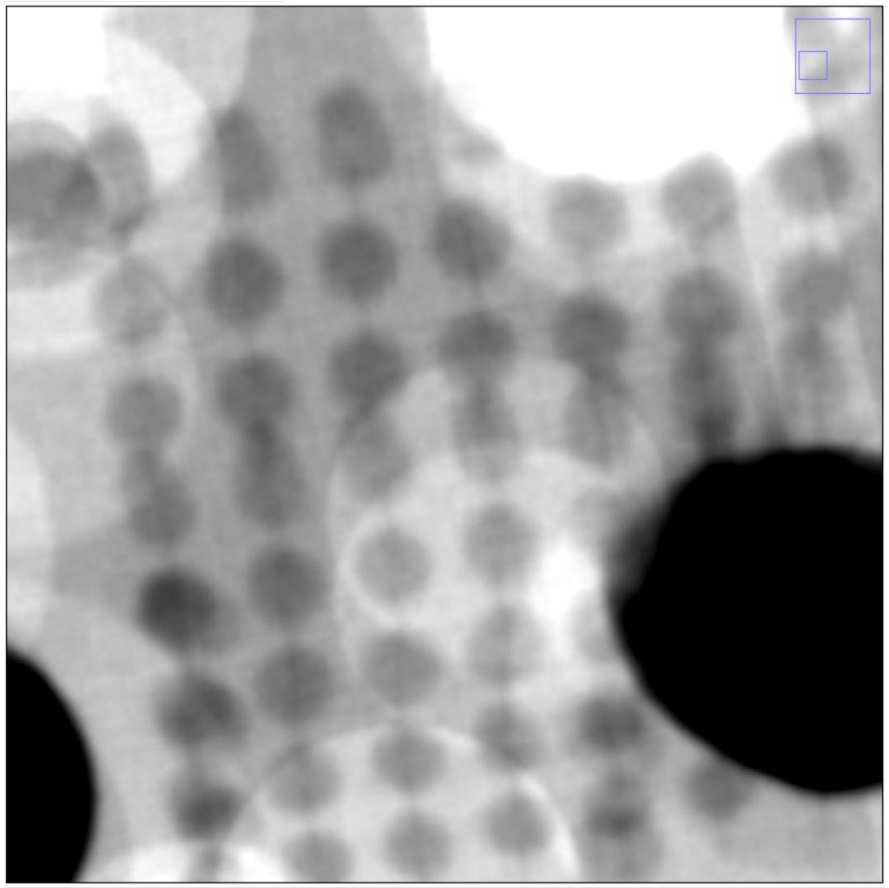


HBM Stack Cross-Section – Optical View

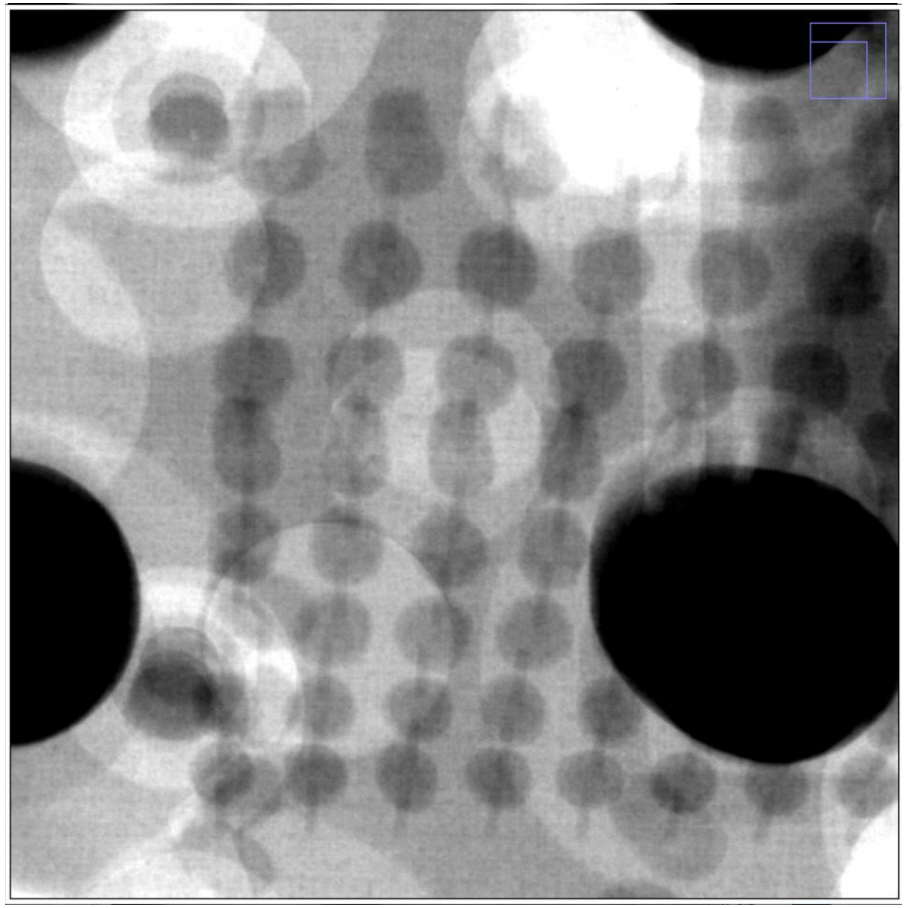
Fig. 6: AMD/SK Hynix HBM Cross-section

HBM memory on Nvidia GV100

Original Transmission Tube 80 kV



NanoTube 60 kV



Demo capability #2 – Nano CT system

A NanoTube N3 powered system with a high precision rotation stage is available at Excillum for demonstration of high-resolution computed-tomography capability.

Various detectors are available, but we are also happy to demo with your own detector.

Apple A15

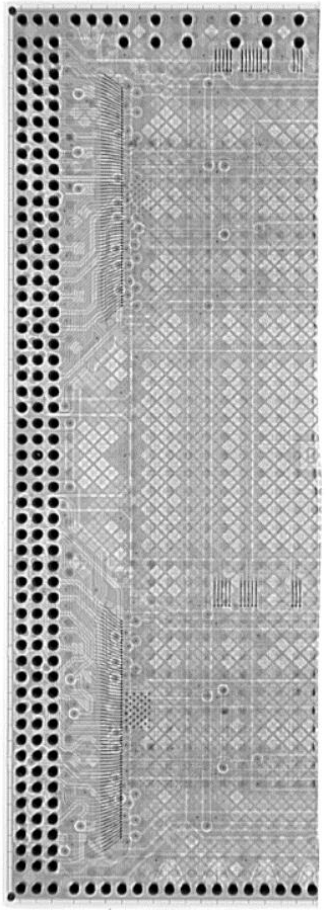
in partnership with
Yole SystemPlus

Apple A15 chip

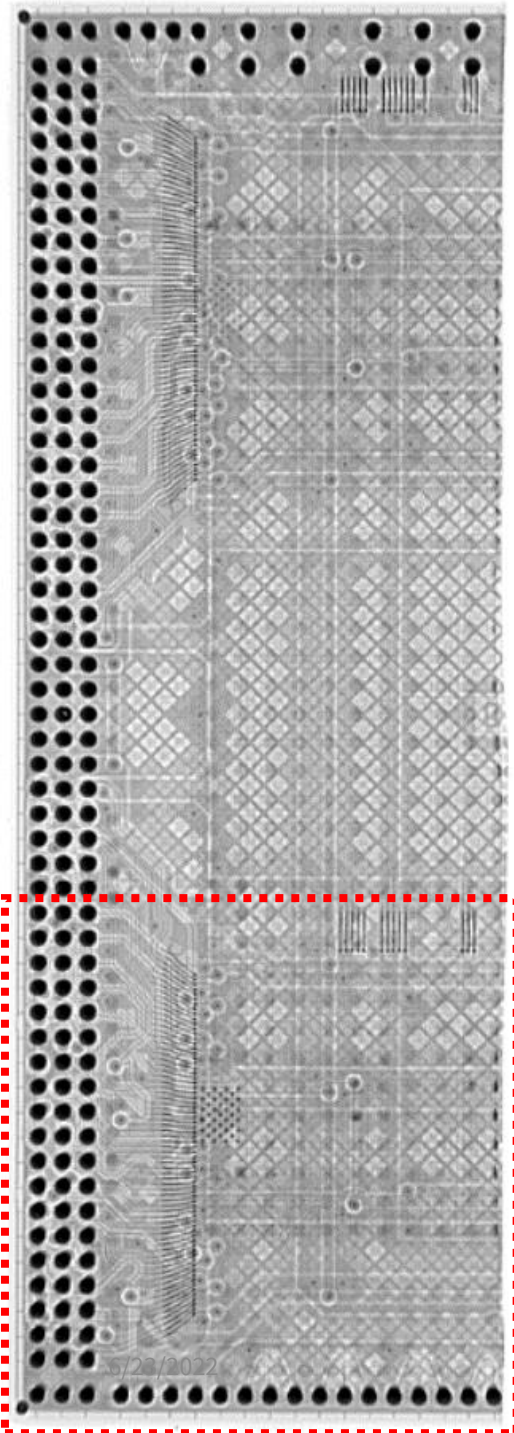
Photo
Side 1

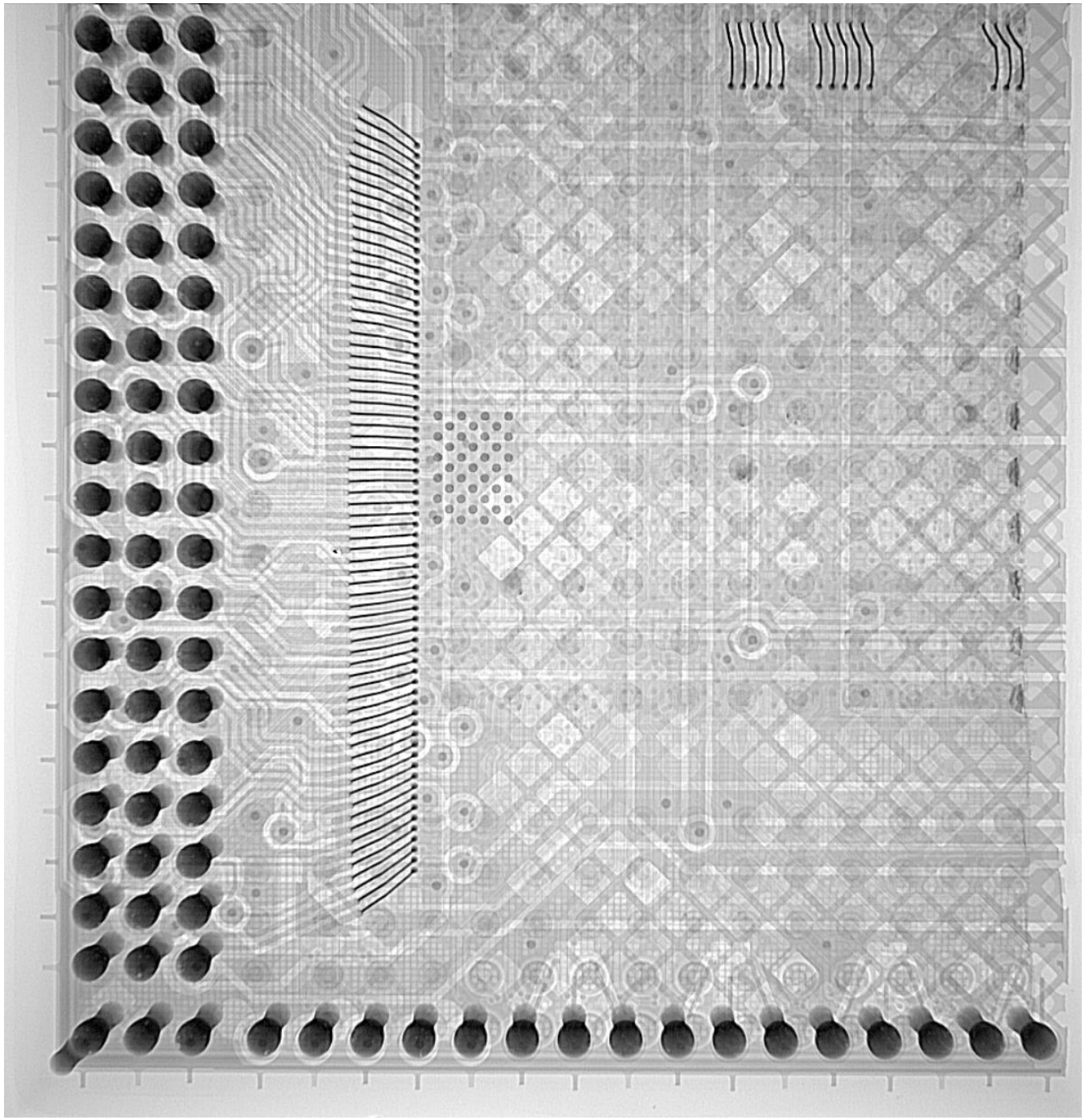
Photo
Side 2

2D X-ray
overview



The sample was cleaved in half by Yole SystemPlus in order to enable higher resolution





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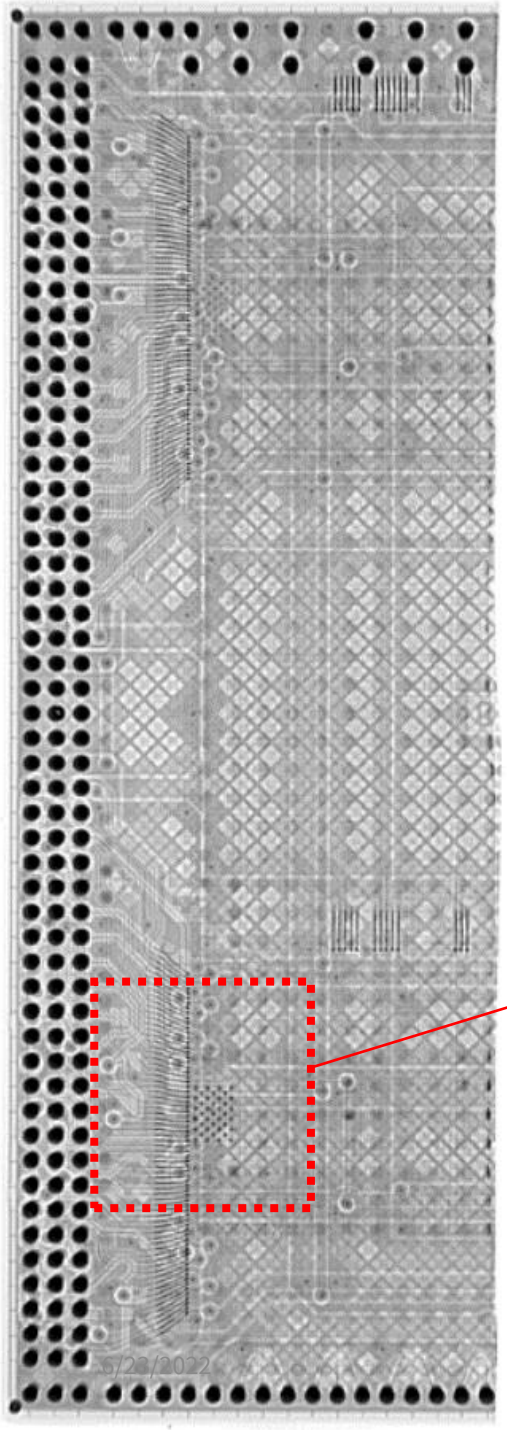

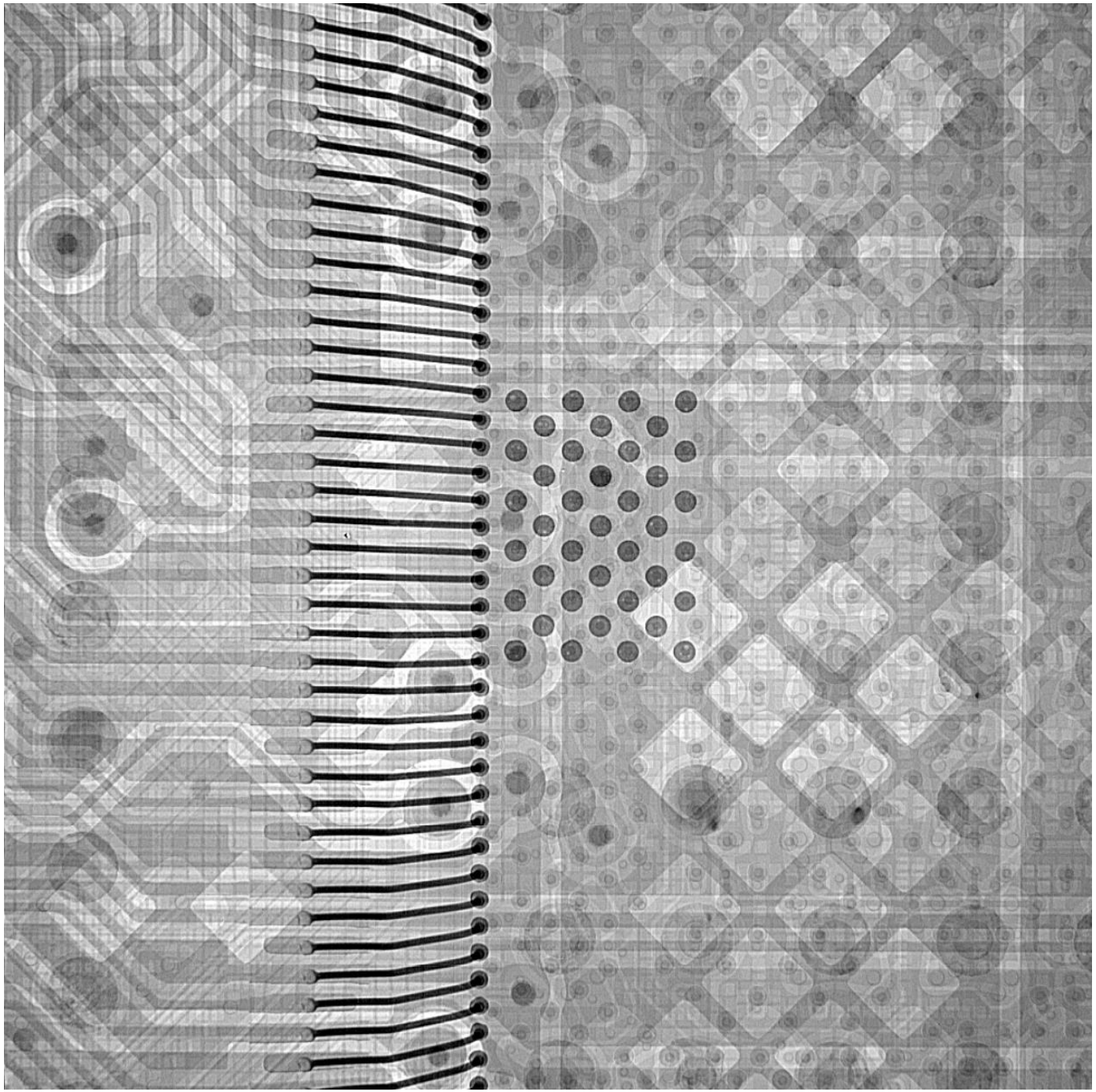

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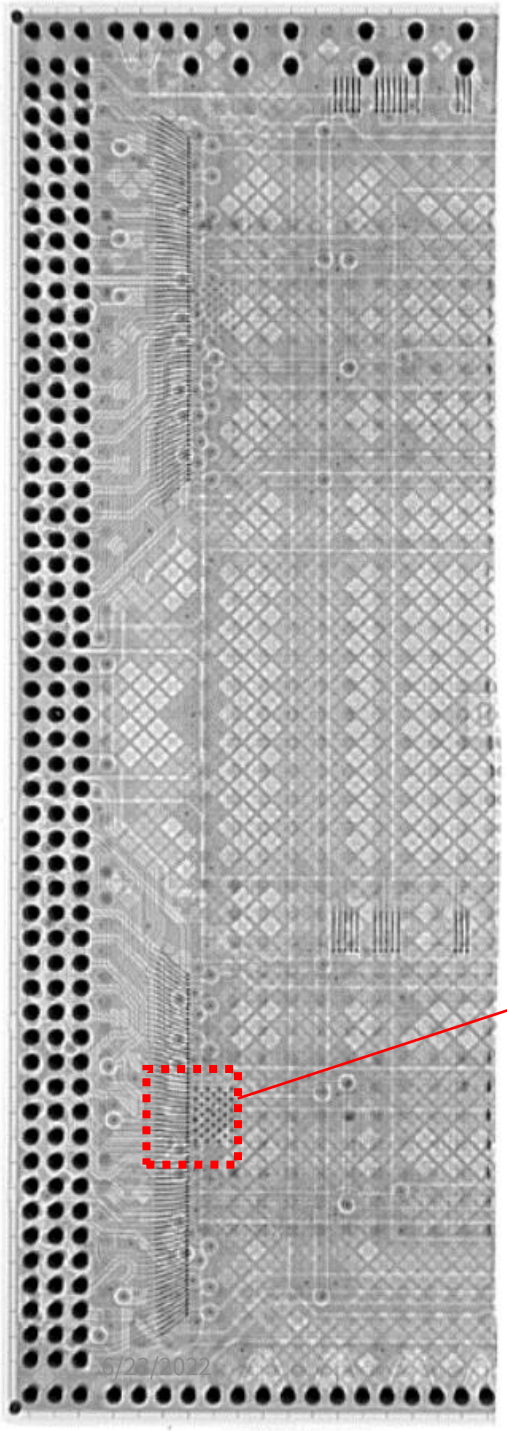

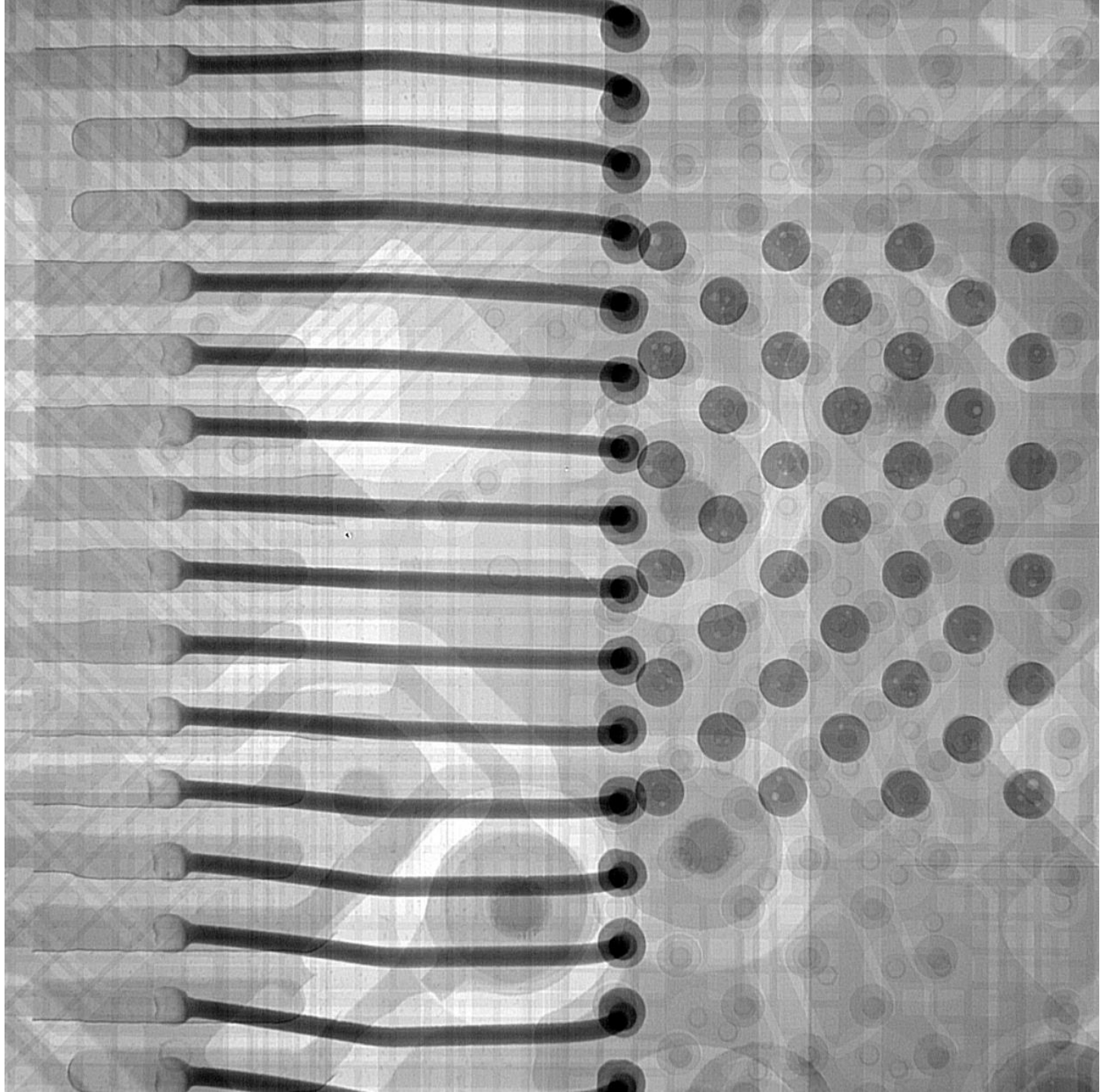

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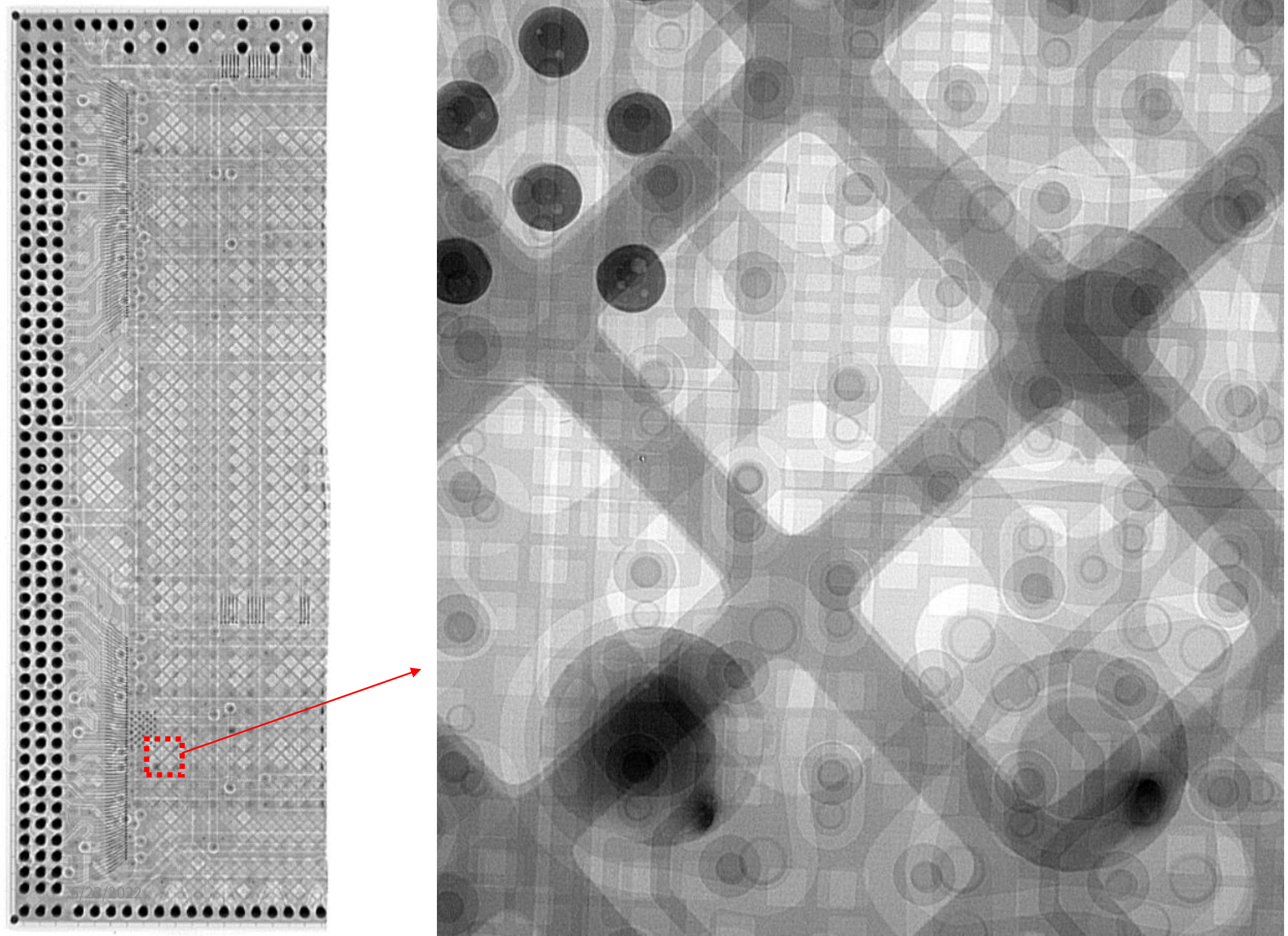

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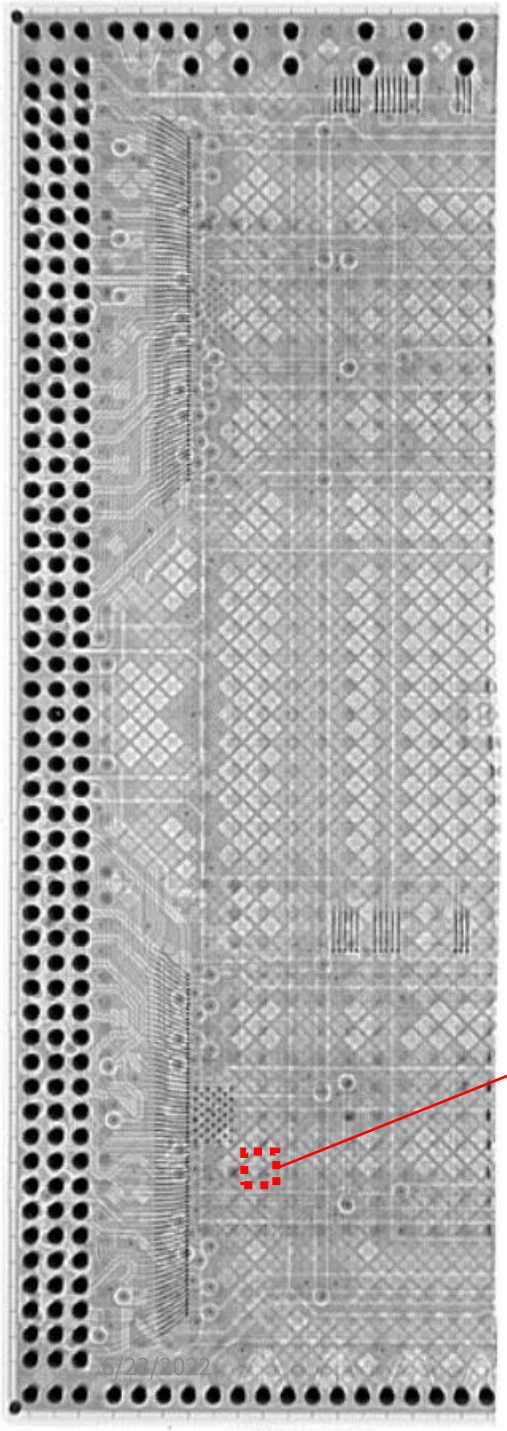

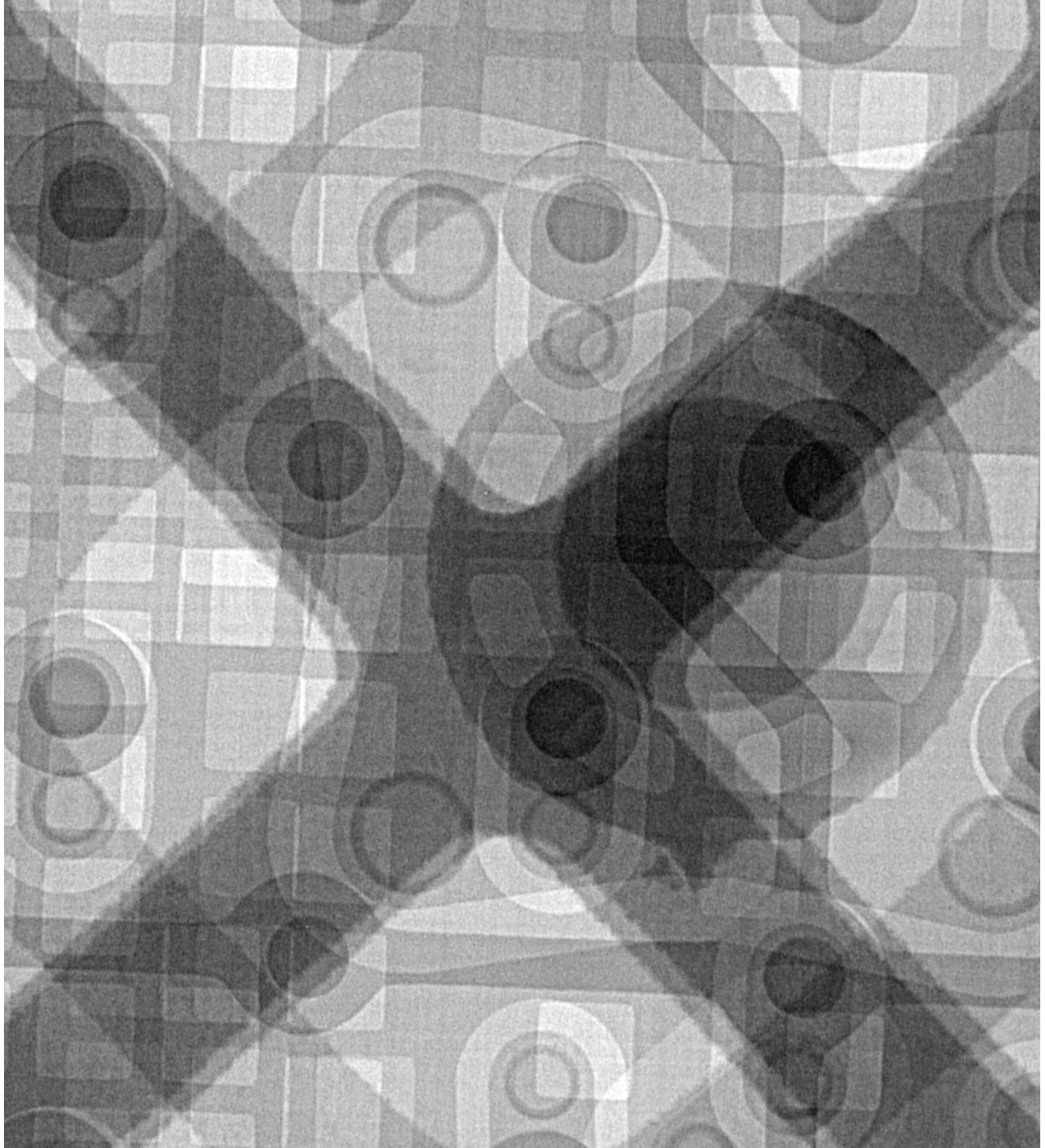

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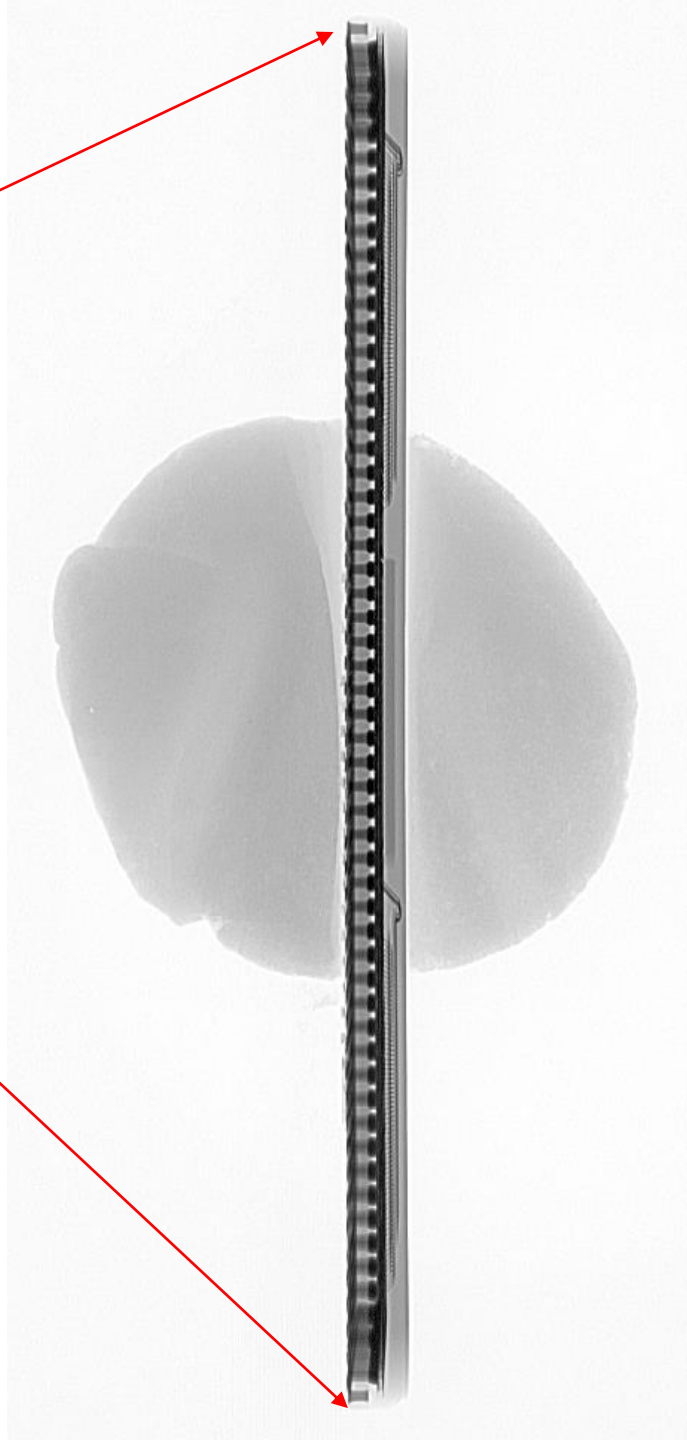
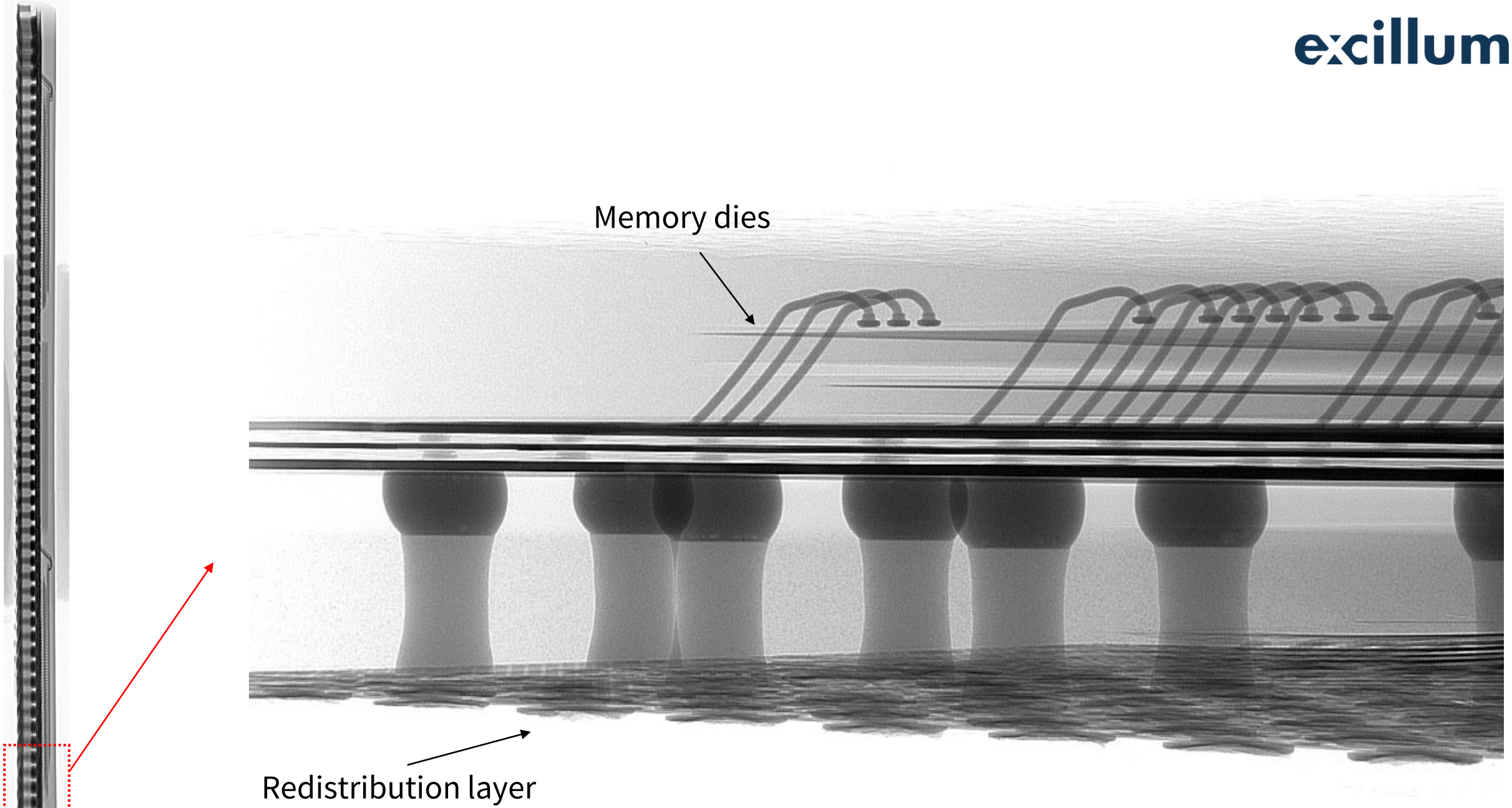
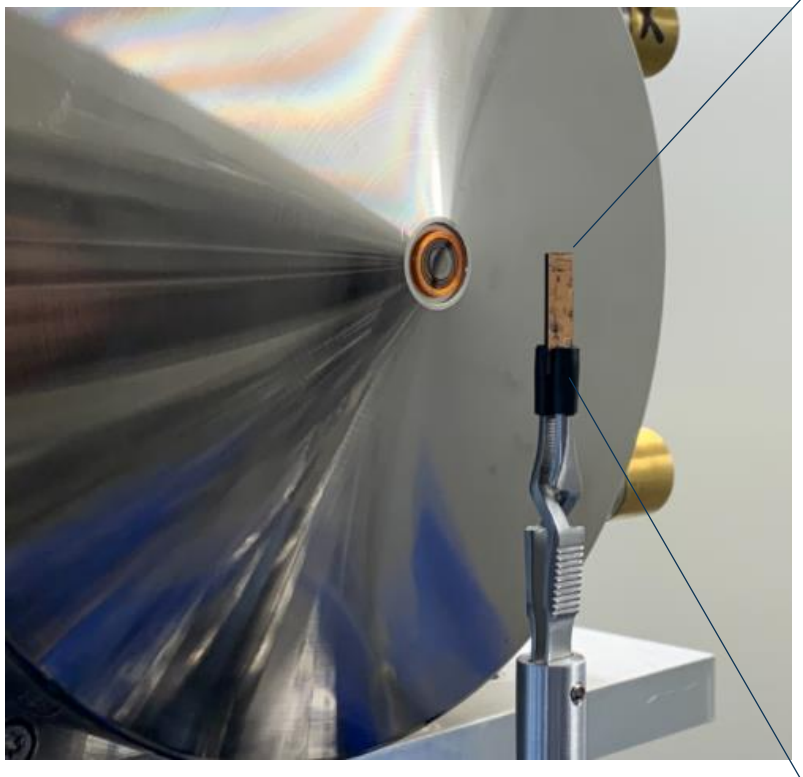
Apple A15 side view

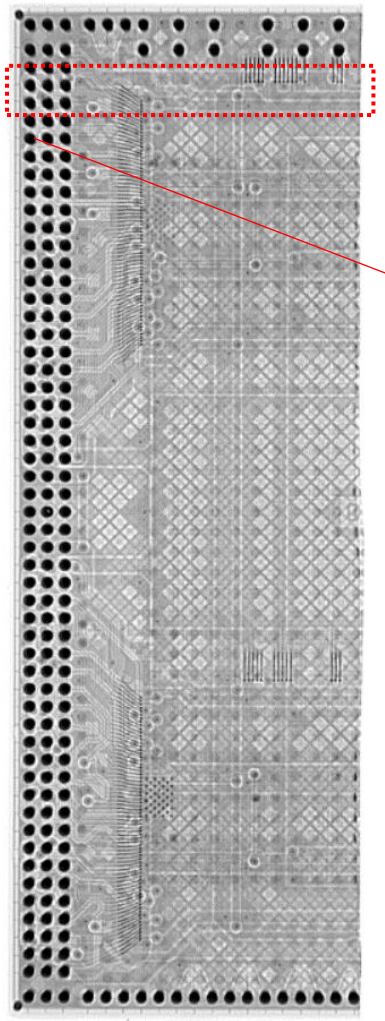
Sample placed standing up using sticky tack.



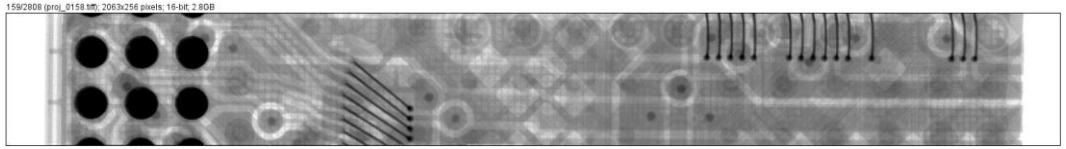

Memory dies
Redistribution layer

Moving to CT

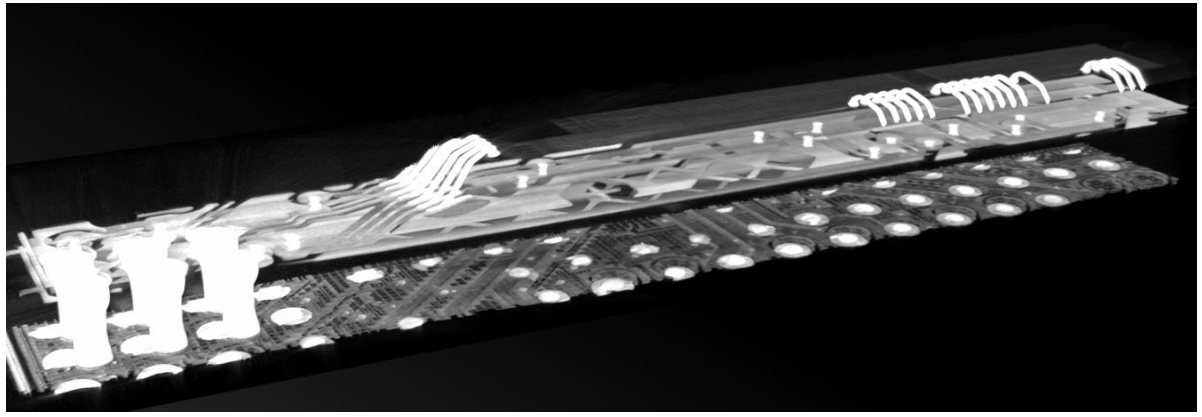




Region of interest scanned due to limited height of detector



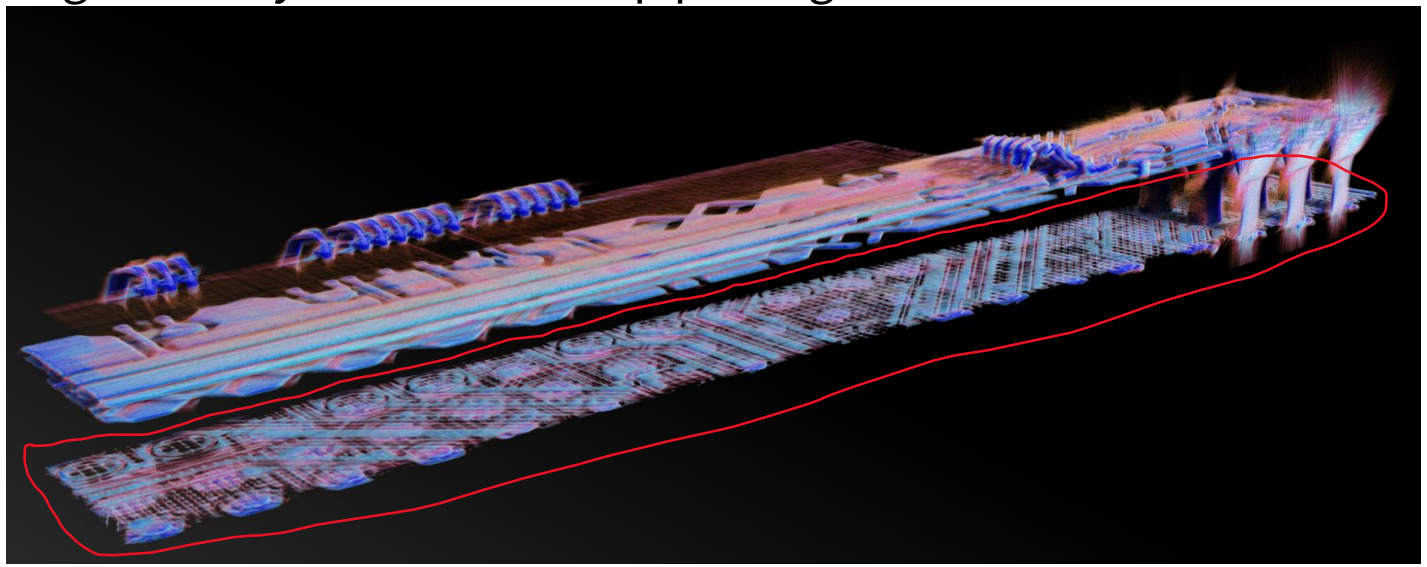
3D reconstruction with 3 µm³ voxels



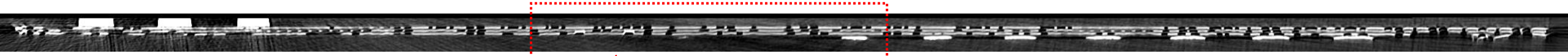
Direct Conversion Thor FX20.256 CdTe photon counting detector
2048 × 256 pixels, 100 µm pixel size

Closer look at the layers at the bottom of the chip.

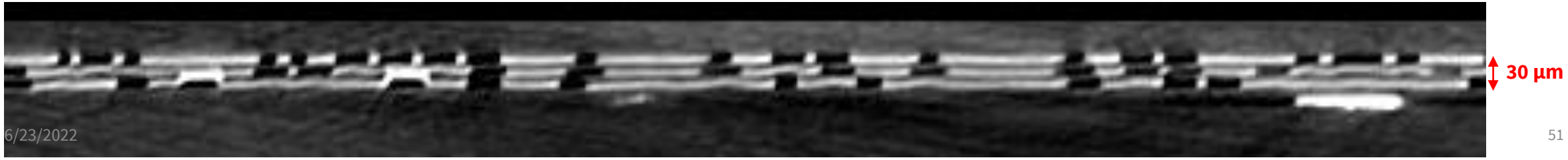
Tracing the circuits in the redistribution layer is a typically challenging task when investigating a high-density wafer-level chip package



Below is a cross section through these layers. The combined thickness of the layers is about 30 µm. The metal traces in each layer appear to be about 6-7 µm thick.



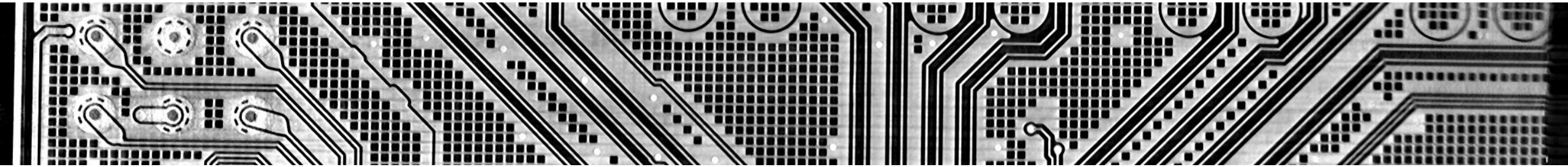
A closer look



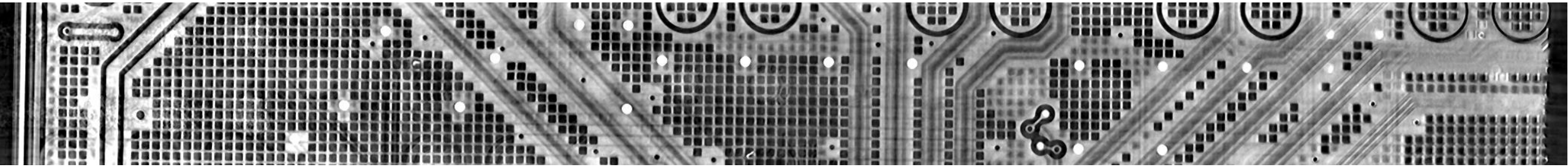
Closer look at the layers at the bottom of the chip.

After correcting for the slight curvature of the chip the three layers can be nicely separated which should allow for full tracing of the redistribution layers if all areas are imaged and stitched or a helical CT scan is performed

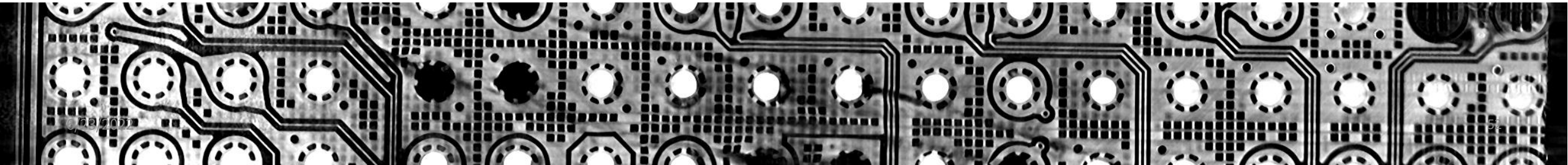
Top layer



Middle layer



Bottom layer



excillum

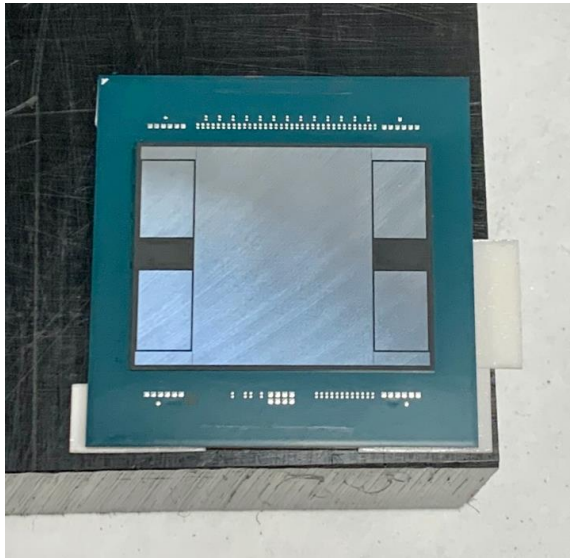
HBM2 memory on Nvidia GV100

Sample preparation

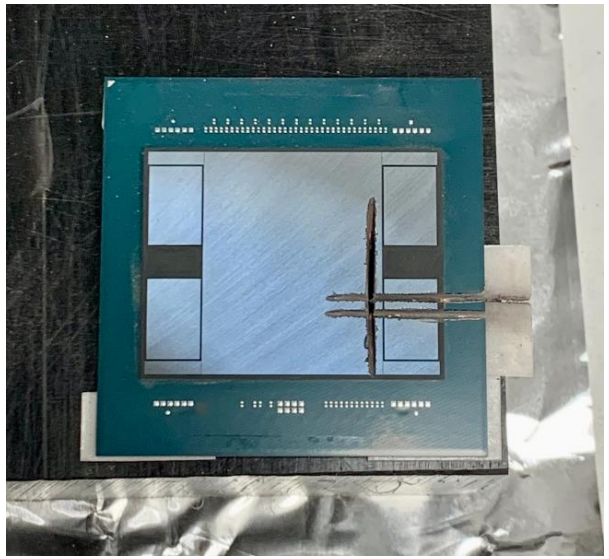
A relatively small piece was cut from the GPU using a Dremel and a diamond cutting wheel.

- 1.5 X 2.95 X 15 mm

Before cutting

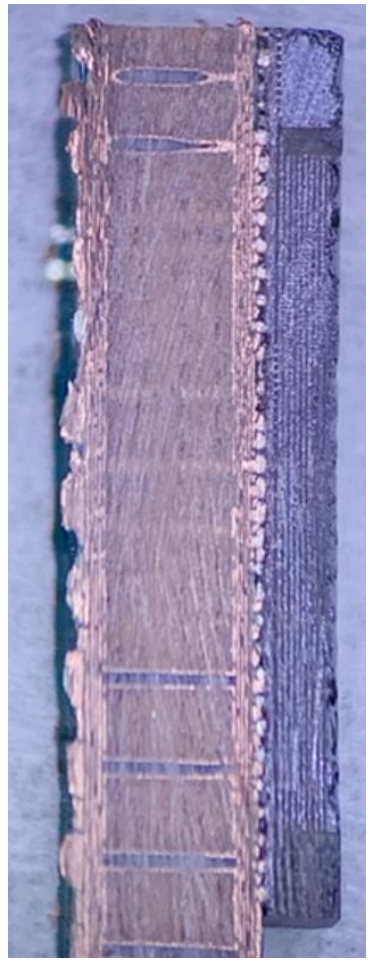


After cutting

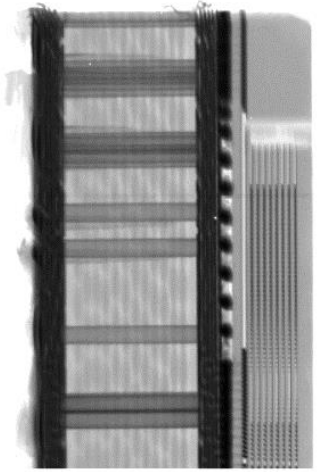


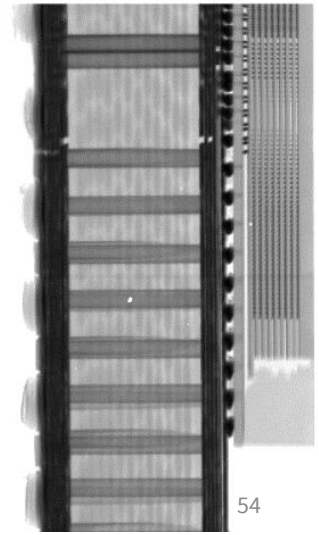
Mounted on sample holder
(black carbon rod has 2 mm diameter)

Stereo microscope



X-ray overview

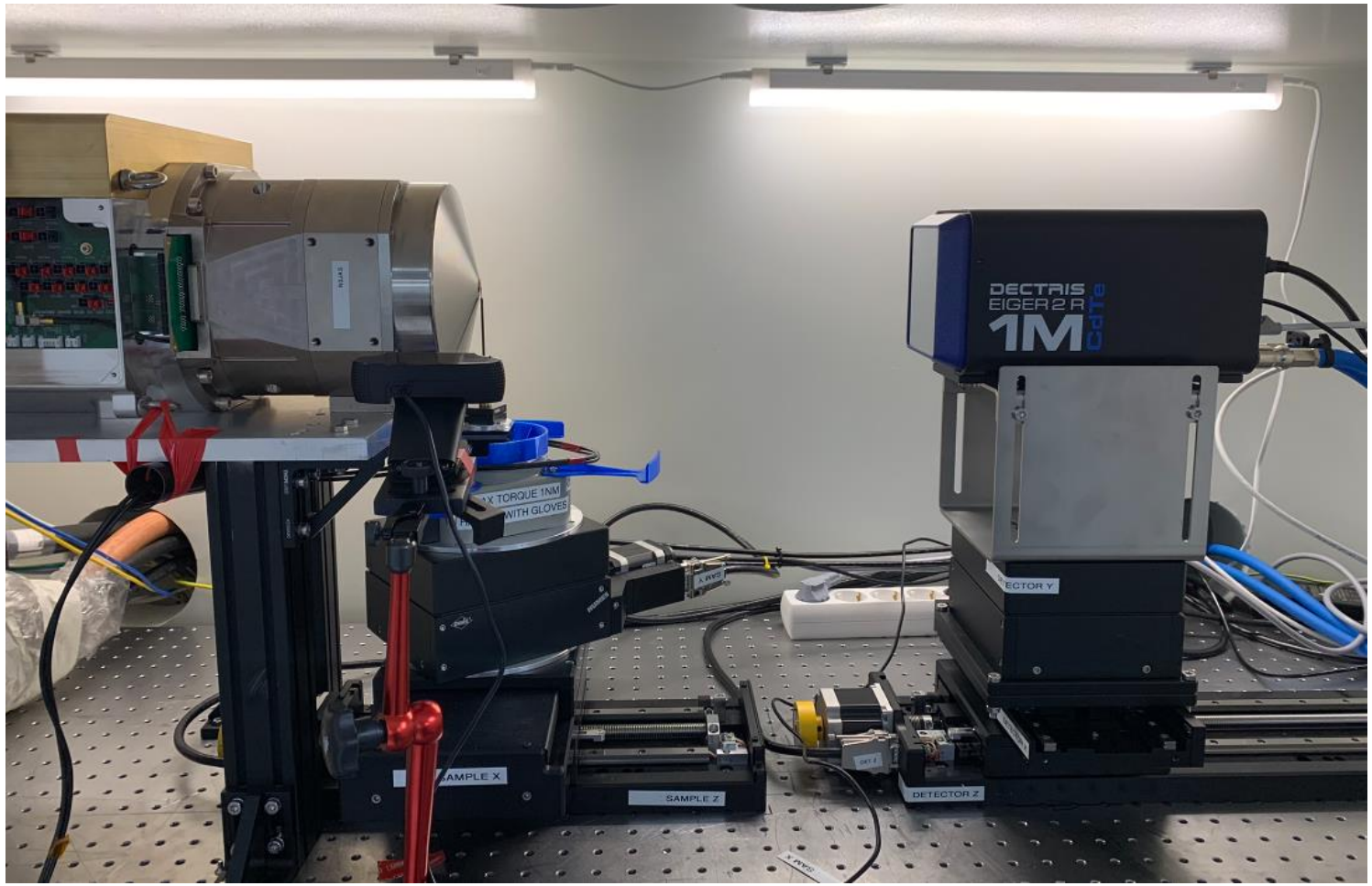




Experimental arrangement

- Source: NanoTube N3
- Detector: Dectris Eiger 1M CdTe, 75 µm, 1028 x 1063
- LAB RT100-S rotation stage

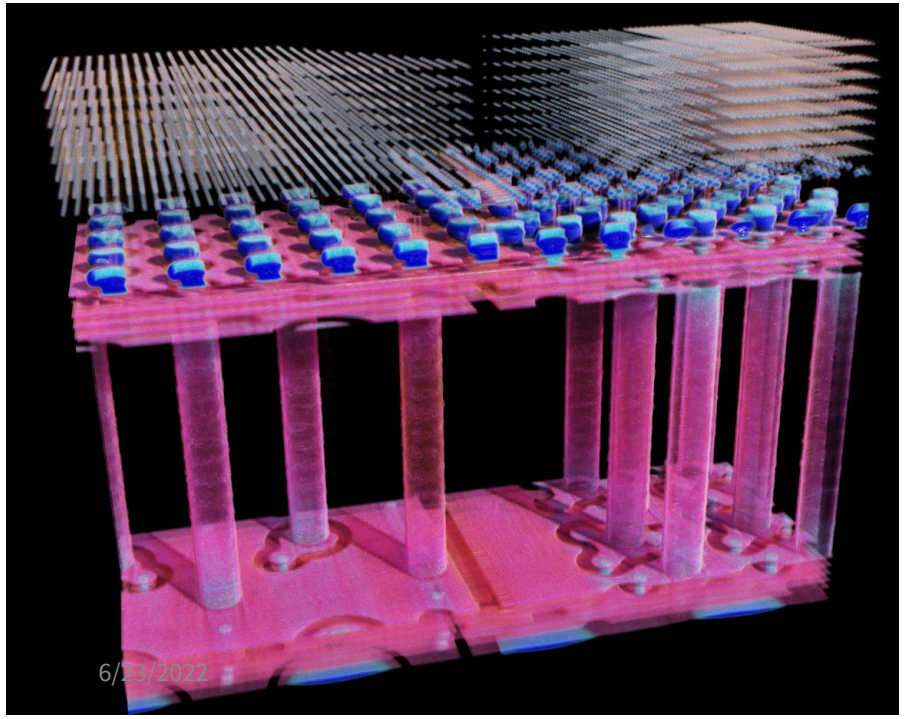
- Source-to-Detector: 343 mm
- Source-to-Sample: between 16.6 mm and 1.9 mm.



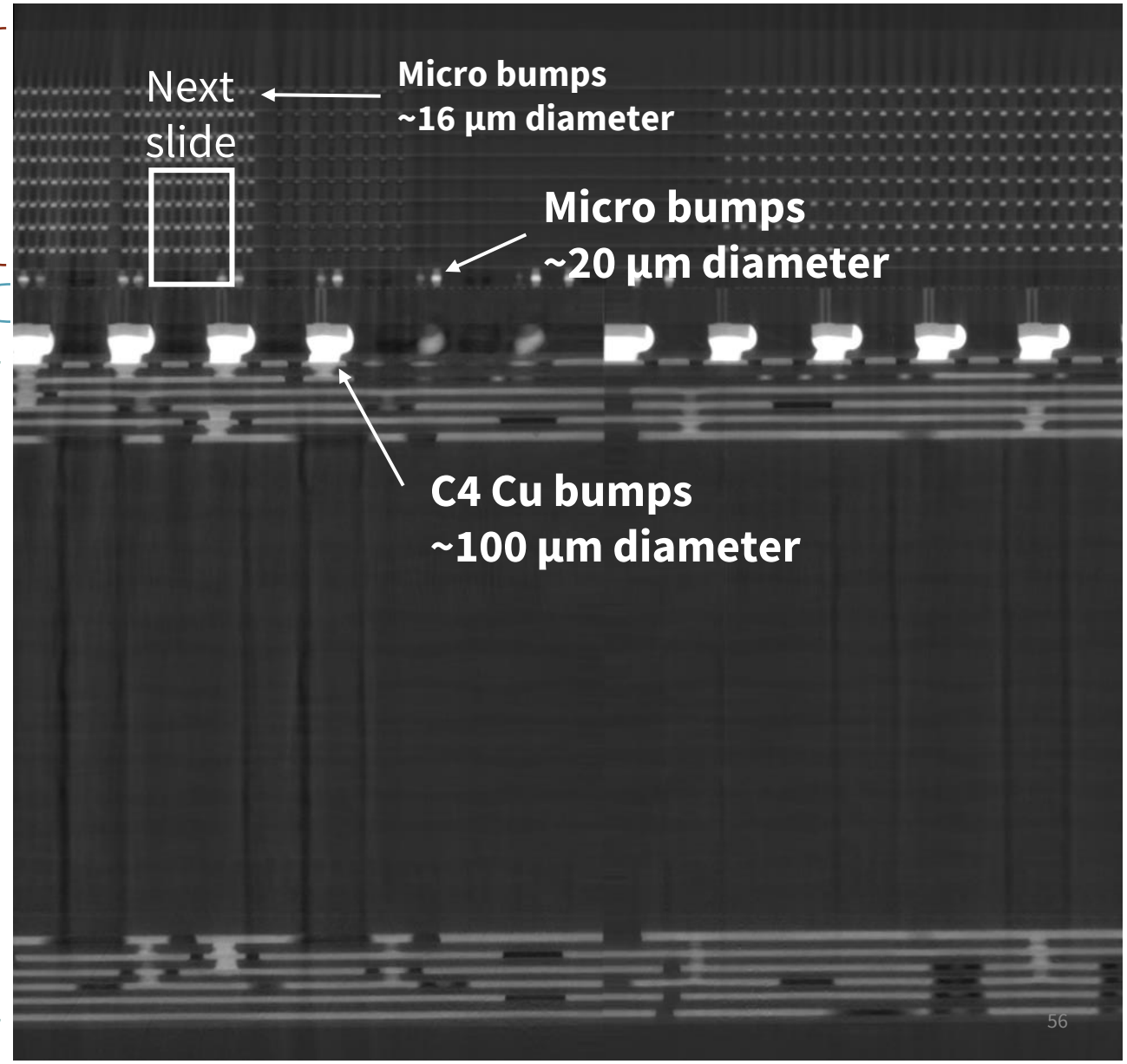
Overview scan

- 16.6 mm source-detector distance, 1.2 µm X-ray spot
- Reconstruction to 3.5 µm voxels clearly show all layers and dumps inside the sample, even the smallest 16 µm bumps in the HBM2 memory.

3D render of reconstructed volume

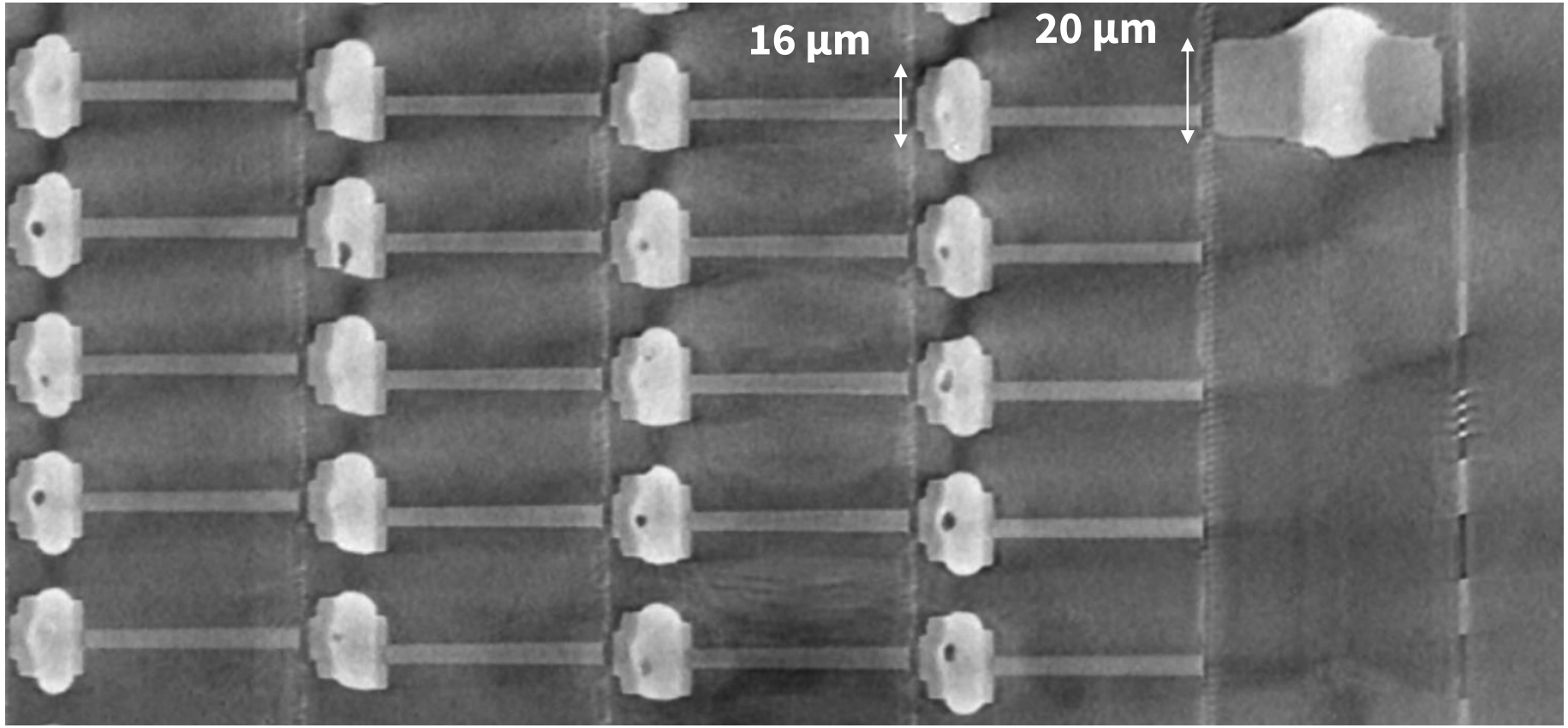


Slice through volume showing all layers



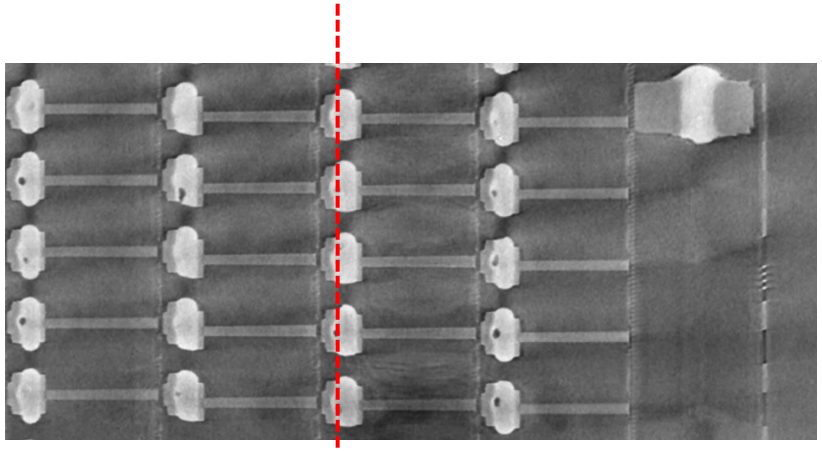
ROI scan of HBM2

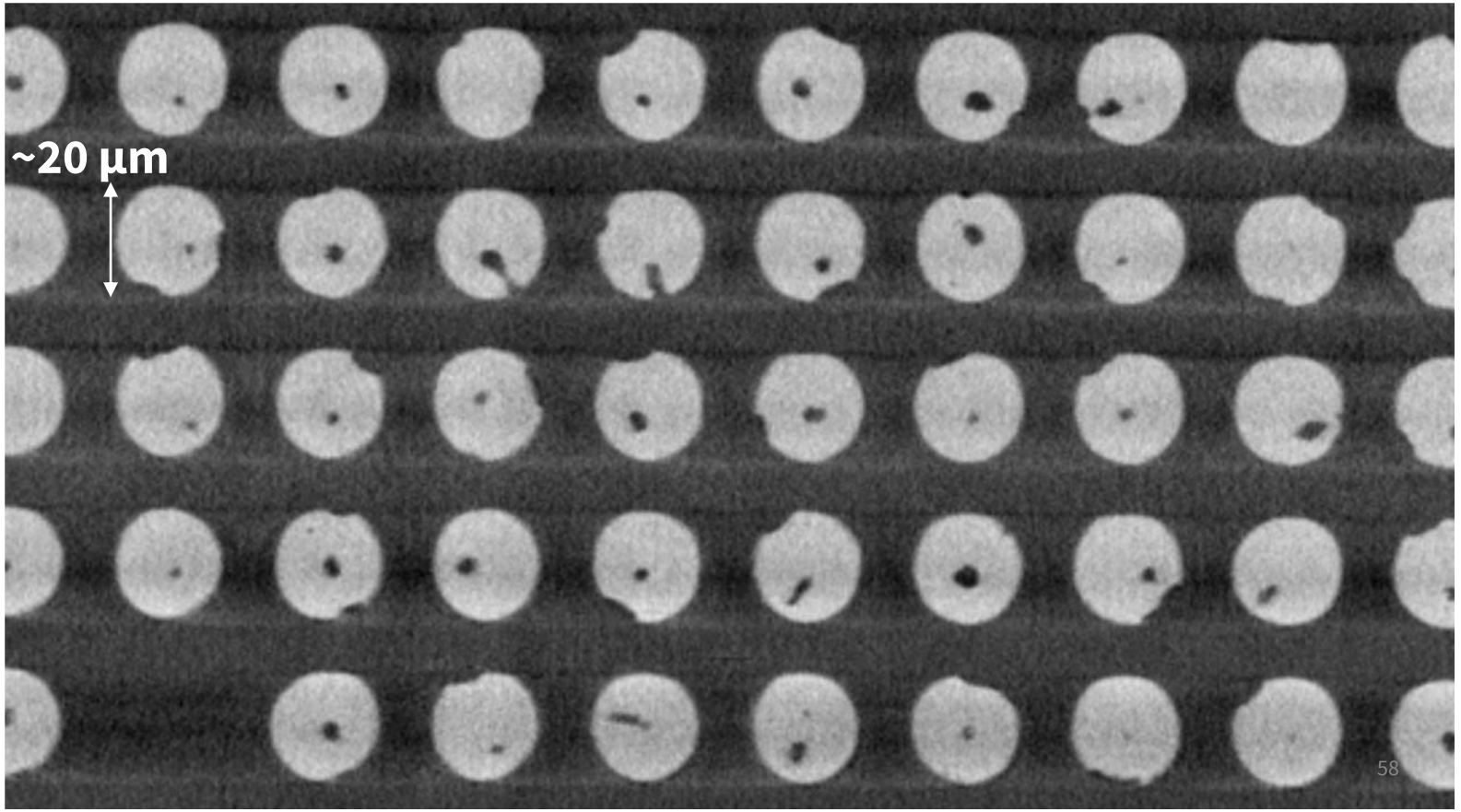
- 1.9 mm source detector distance, 500 nm X-ray spot
- Slice through volume showing 4 layers of micro bumps and TSV in the HBM2 memory.
- To the upper right one of the micro bumps connecting the memory to the interposer is seen.



ROI scan of HBM2

- A slice through one of the planes filled with micro bumps connecting the memory dies show voids in detail. The smallest voids are less than 1 µm.





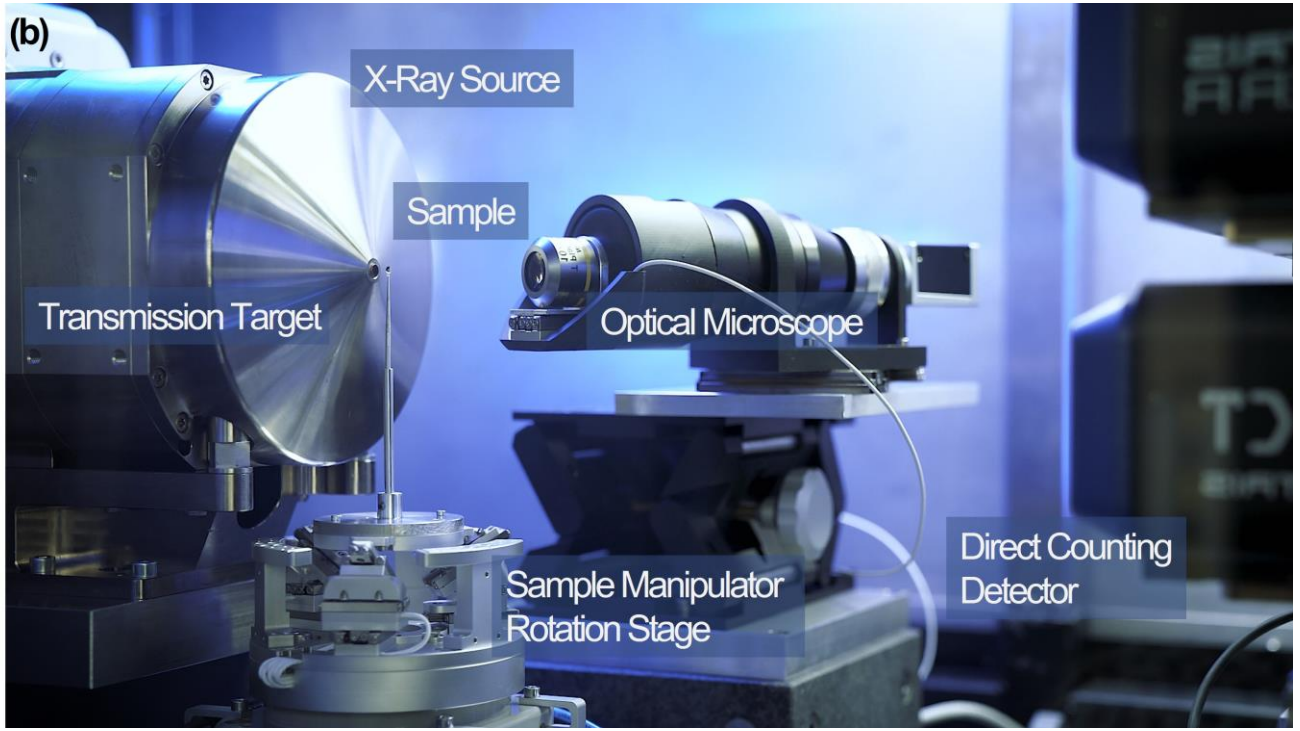
excillum

3D NAND memory

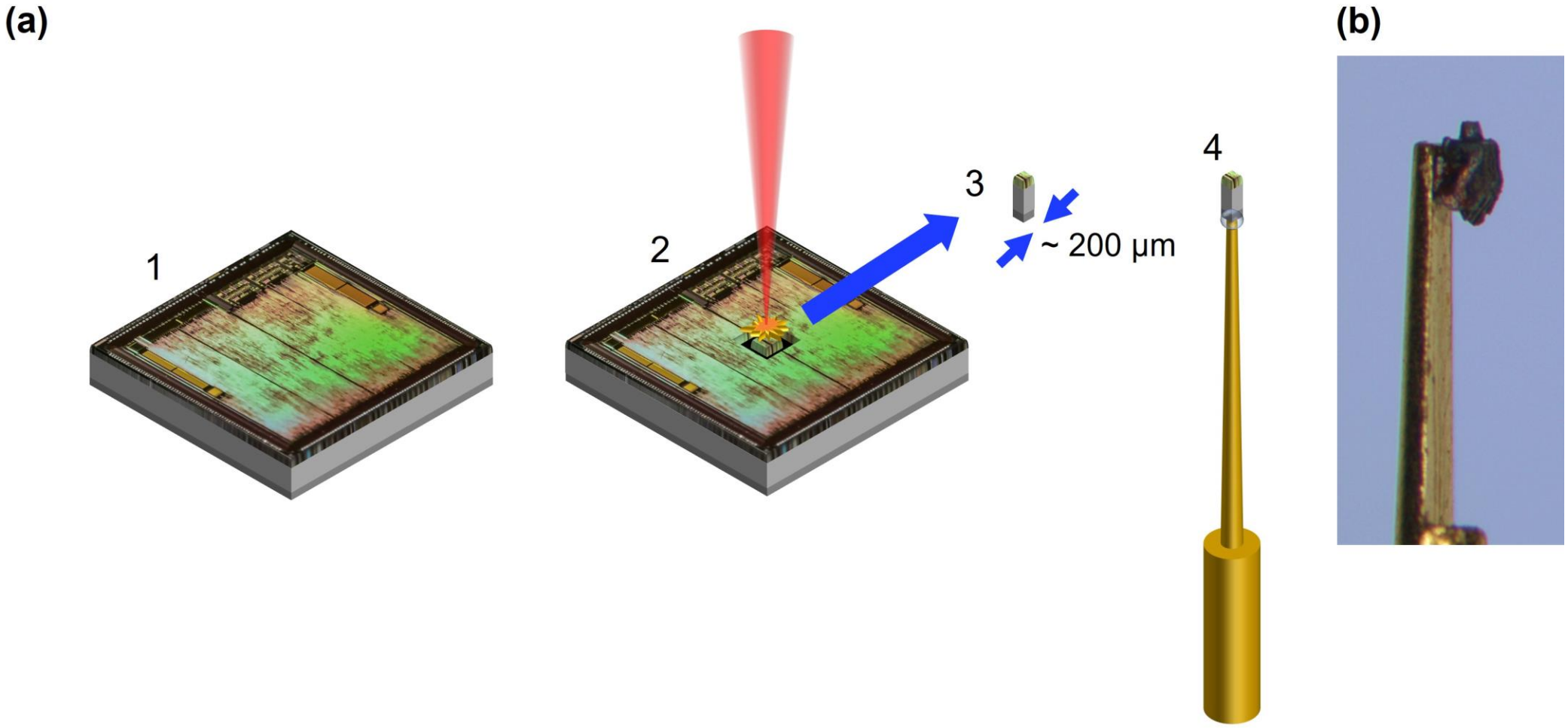
from

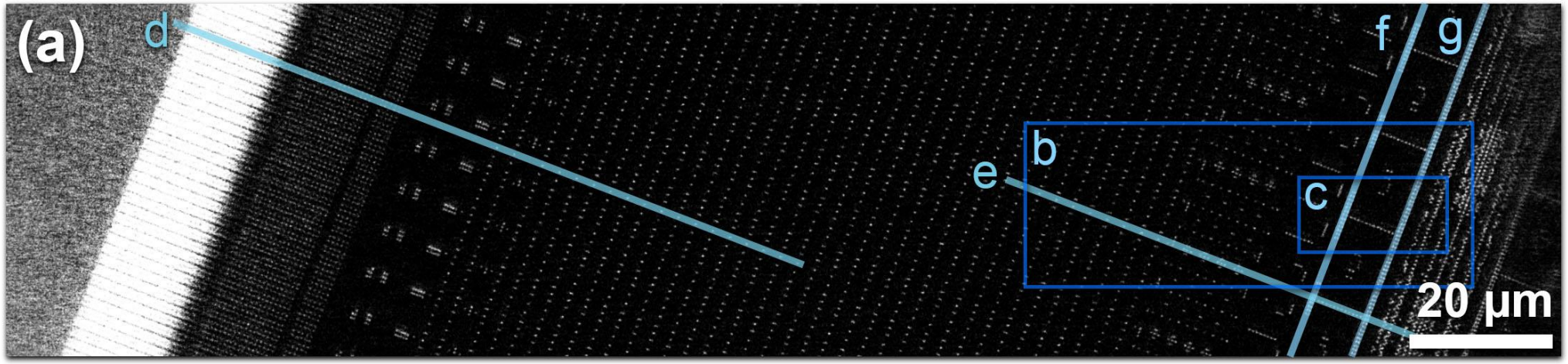
SanDisk 32 Gb microSDHC UHS-I

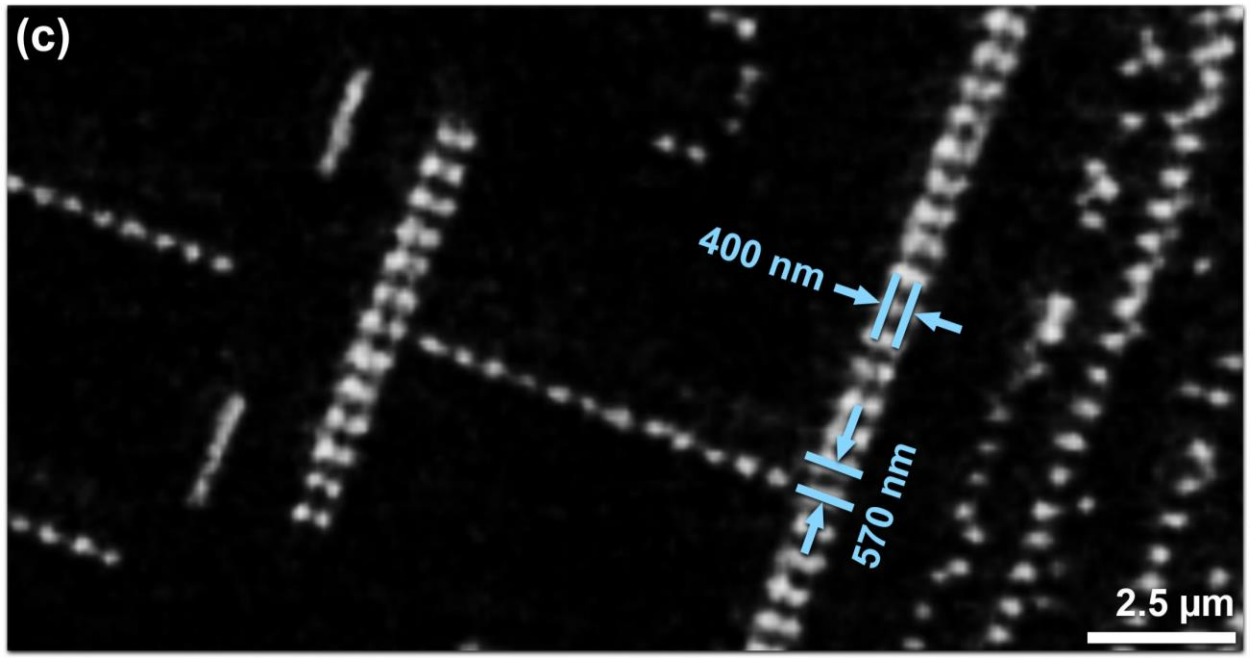
ntCT @ Fraunhofer EZRT (Würzburg)
Commercialized by ProCon X-ray GmbH

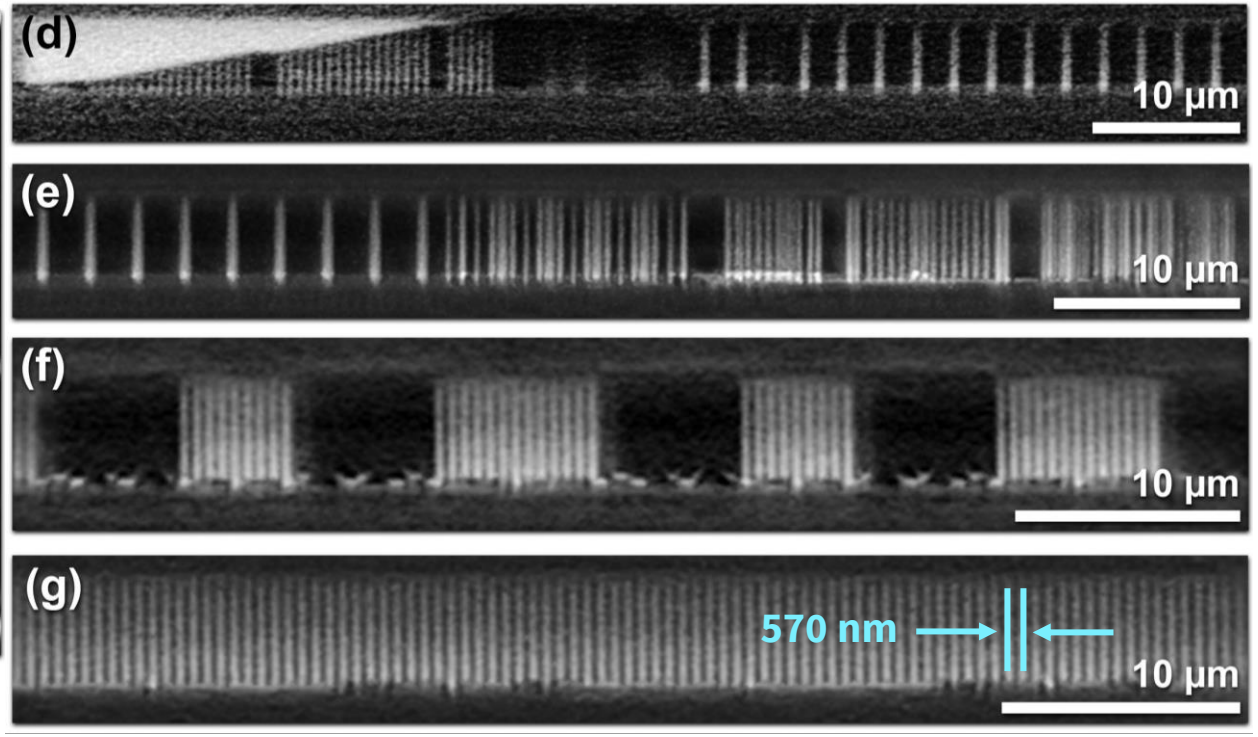


More serious sample preparation

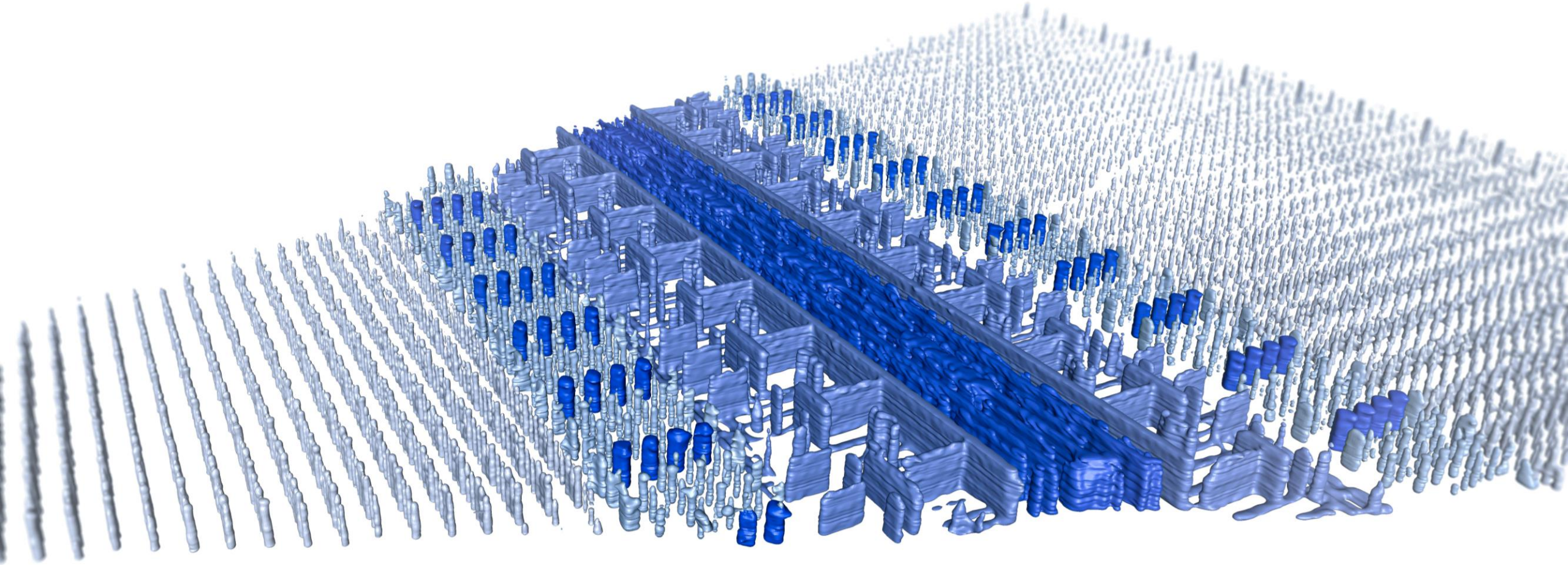








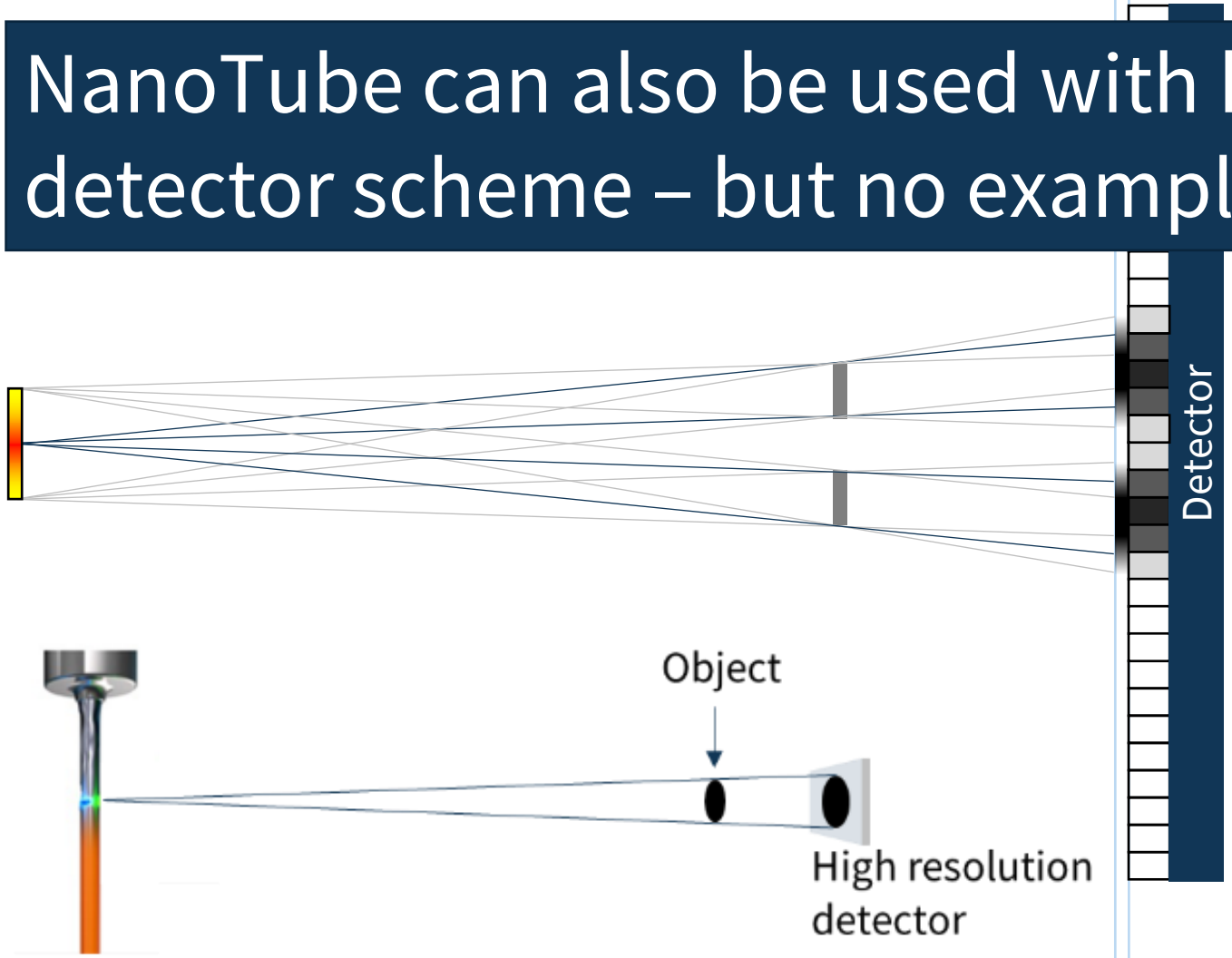
Dominik Müller et. al., *Crystals* **2021**, *11*, 677



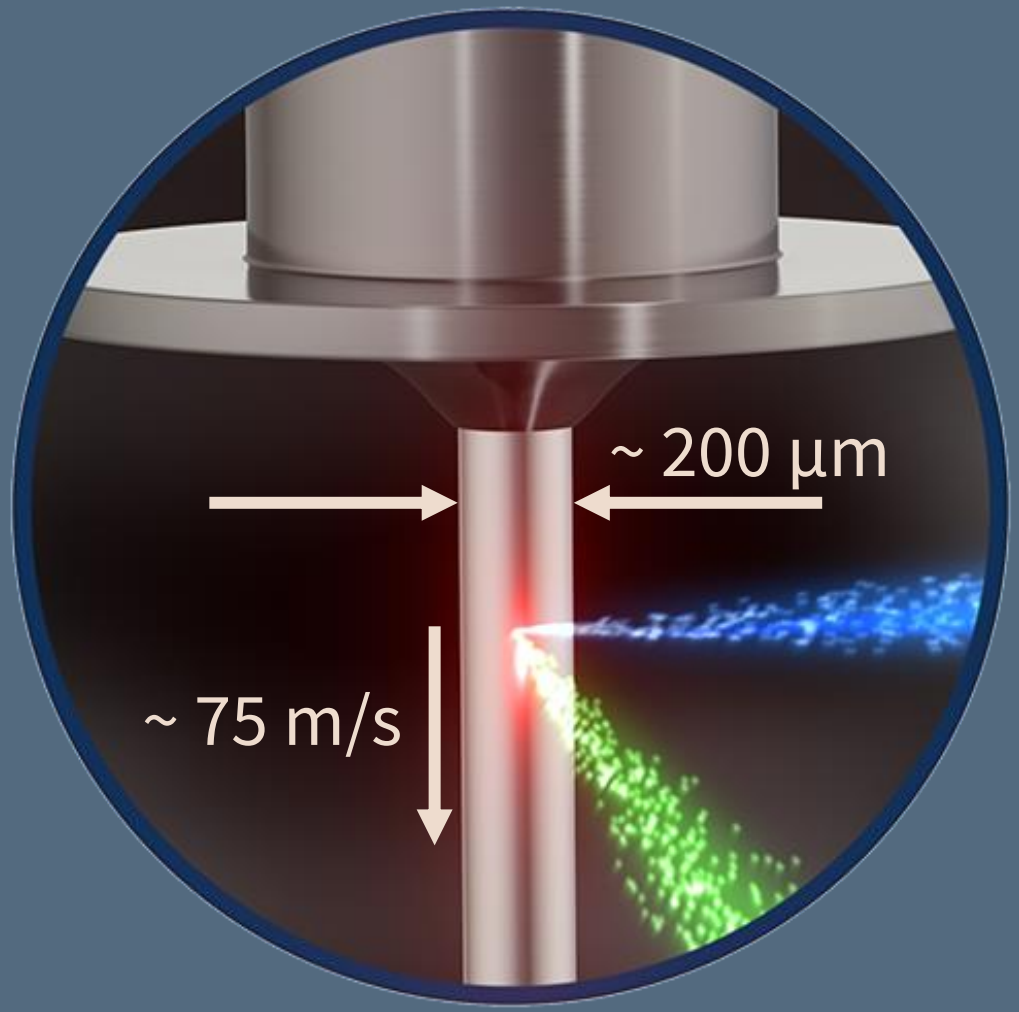
Dominik Müller et. al., *Crystals* **2021**, *11*, 677

#2 - High resolution through high-resolution detector

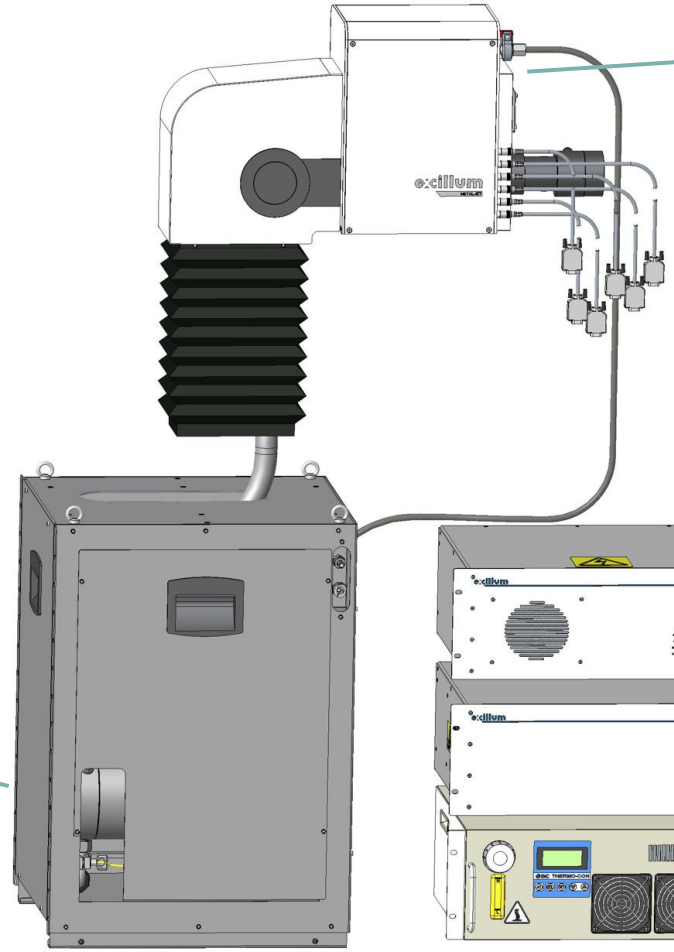
NanoTube can also be used with high resolution detector scheme – but no examples, sorry.



MetalJet technology



MetalJet source details

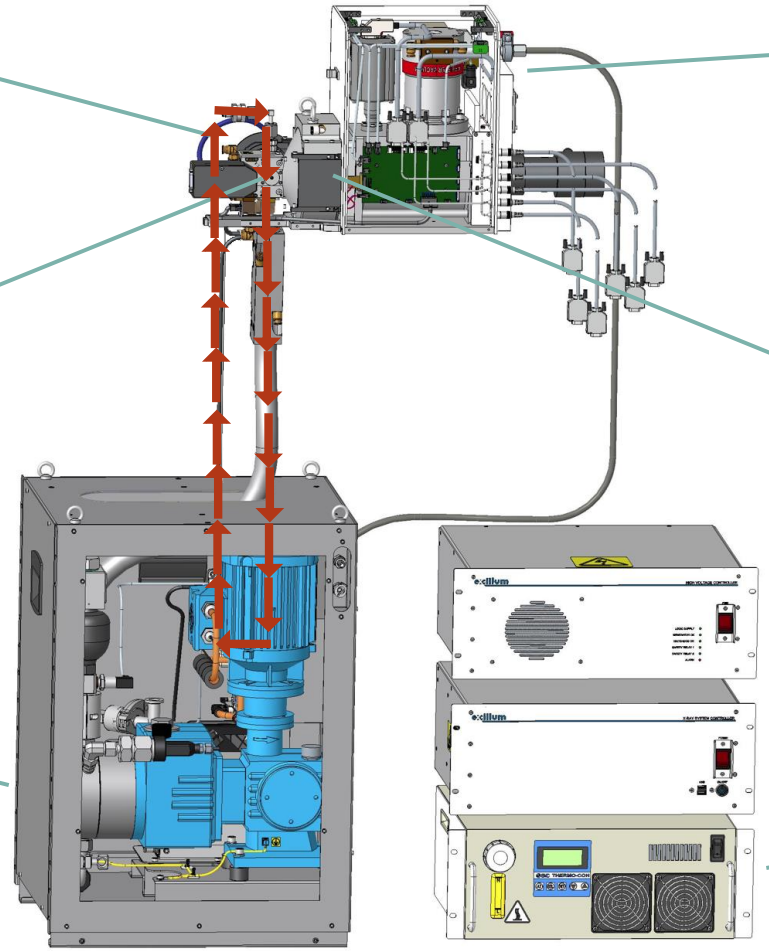


MetalJet source details

The path of the continuously recycled liquid alloy

X-rays are emitted from the interaction point between the metal-jet and the e-beam

Pumps etc. are housed in a 19” box



X-ray head

Advanced electromagnetic focusing and correctional optics together with a high brightness LaB_6 cathode results in a very high-quality e-beam focus

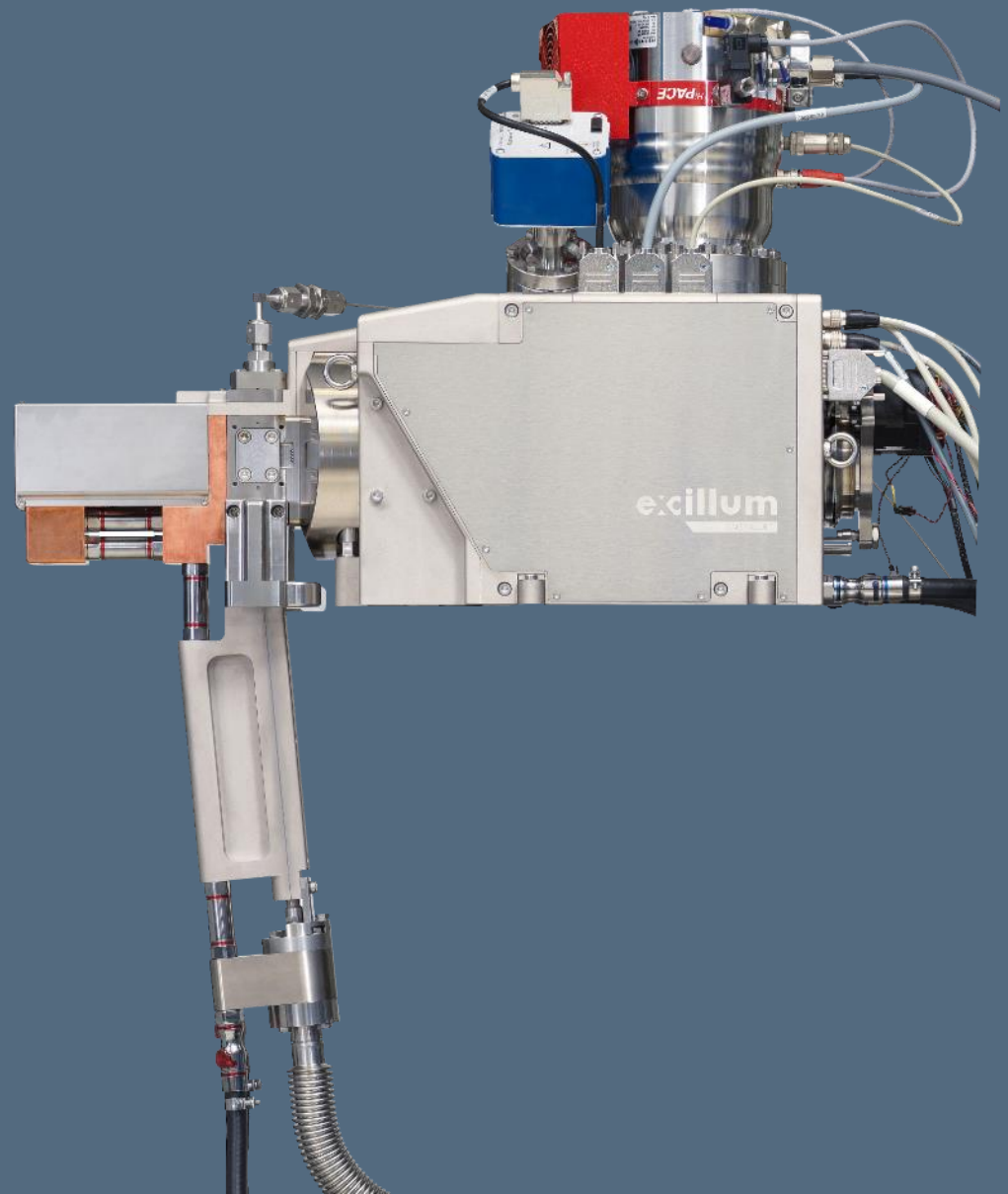
Electronics are housed in two 19” boxes

Chiller, 19” rack mount or floor standing

Excillum MetalJet E1+ 160 kV

Kilowatt microfocus performance with submicron stability.

Built for 24/7 operation with 100% duty cycle.

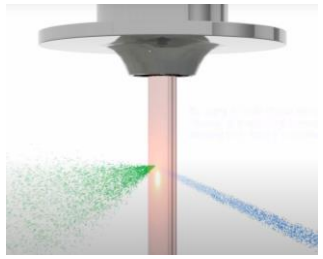


MetalJet E1+ compared to conventional microfocus tube

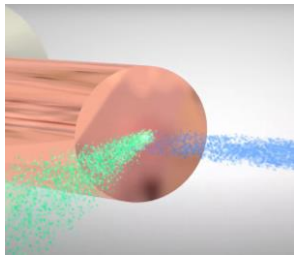
1000 W, 30 µm spot MetalJet E1+ 160 kV

vs.

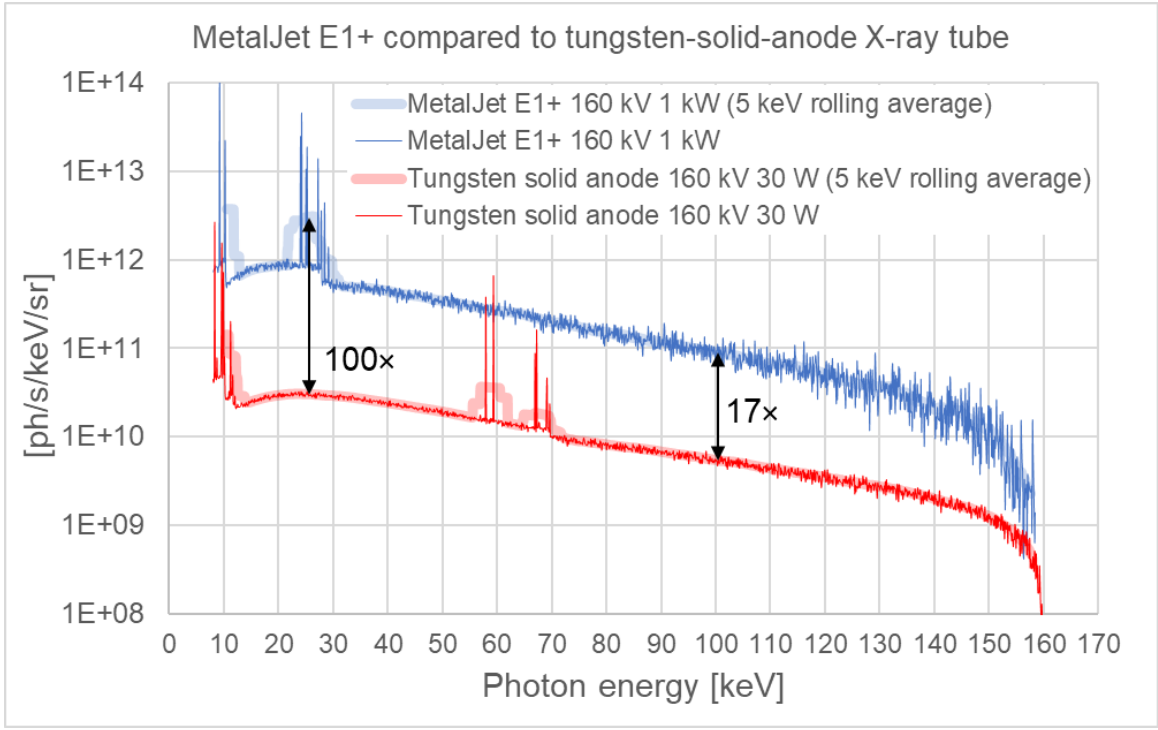
30 W, 30 µm spot tungsten solid anode

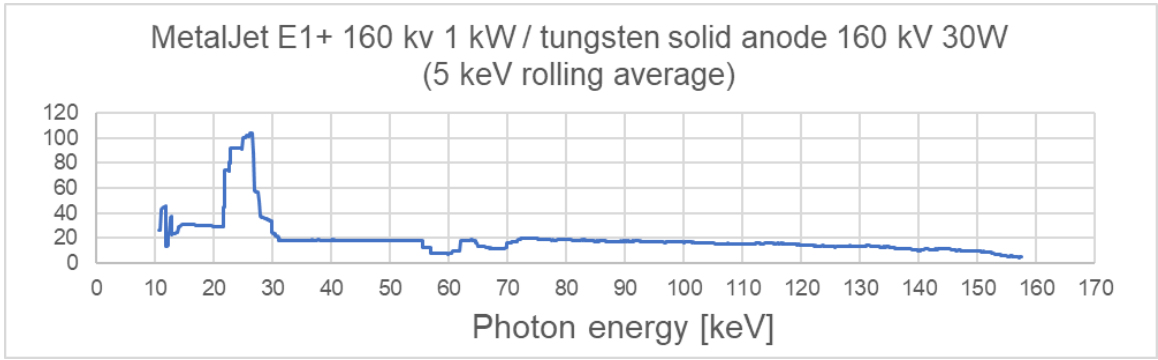


vs.



- 17× more X-ray flux over a broad spectral range
- 100× more X-ray flux in the spectral range of 24-29 keV where the indium and tin characteristic emission lines are present

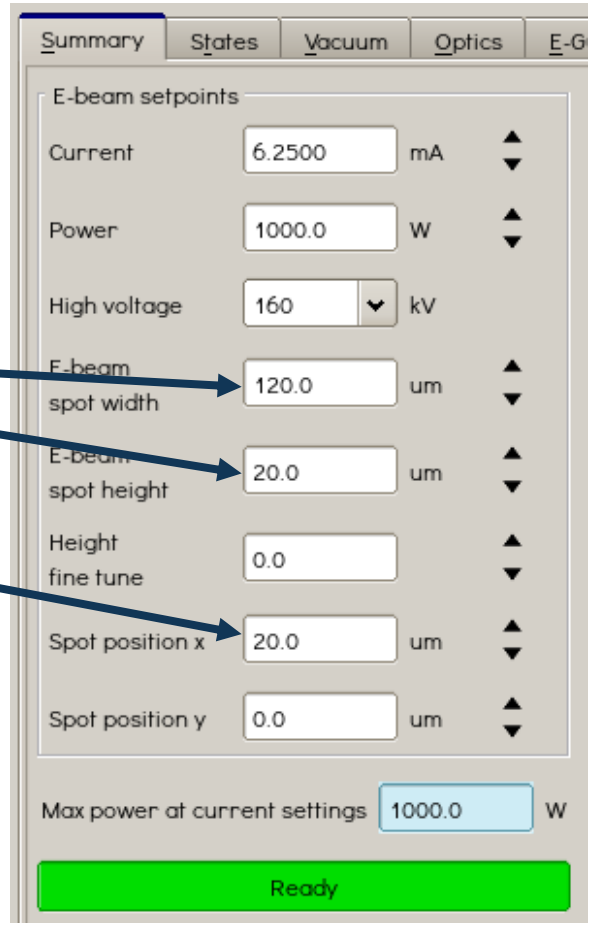




Fully automated for 24/7 operation

As all Excillum MetalJet sources, the MetalJet E1+ features fully automated X-ray spot control.

Simply dial in
desired e-beam spot dimensions
and
desired impact position on the jet
and the source will automatically set and internally verify those settings.



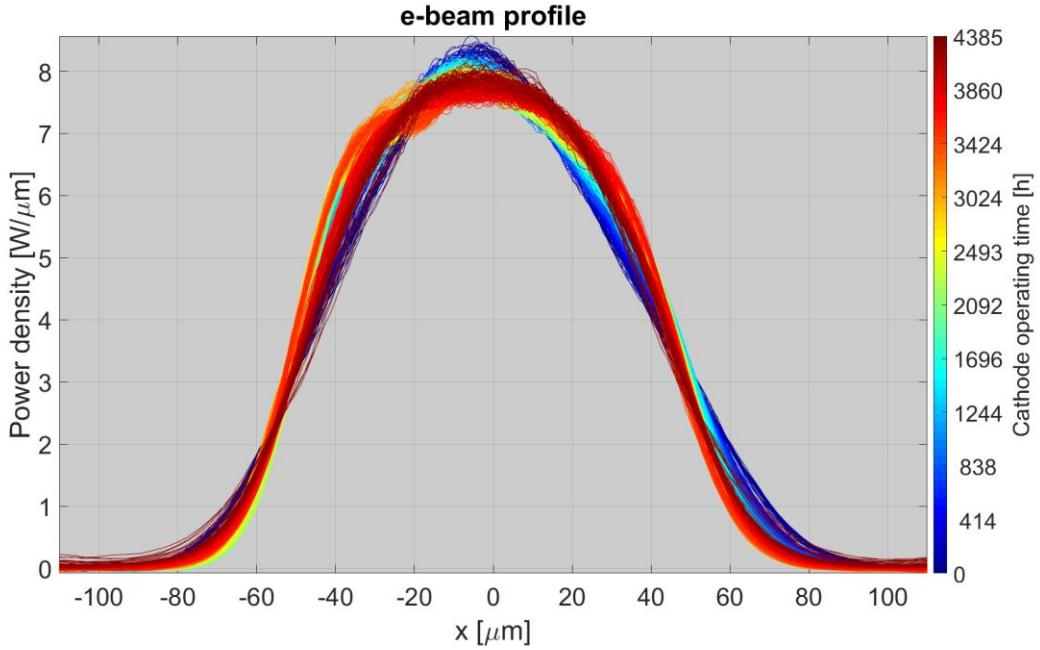
Up to once-per-year maintenance cycles

The MetalJet E1+ is designed for 100% duty-cycle 24/7 operation at high power.

Maintenance cycles are typically driven by cathode aging. The cathode aging cycle can be tracked for optimal planned maintenance timing.

Typical cathode-replacement intervals:

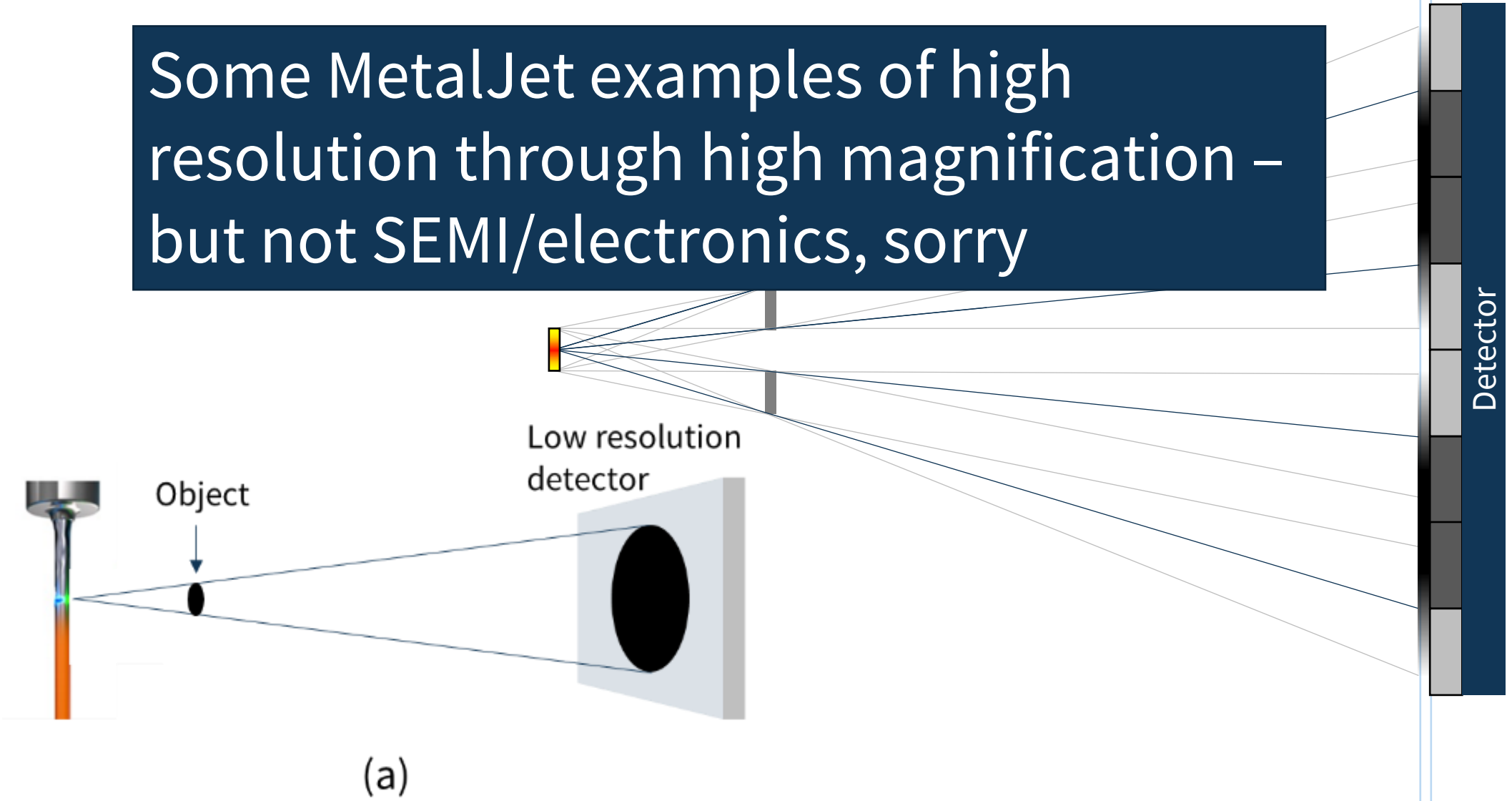
- 1000 W, 30 µm spot size: 3-4 months
- 700 W, 30 µm spot size: 9-12 months

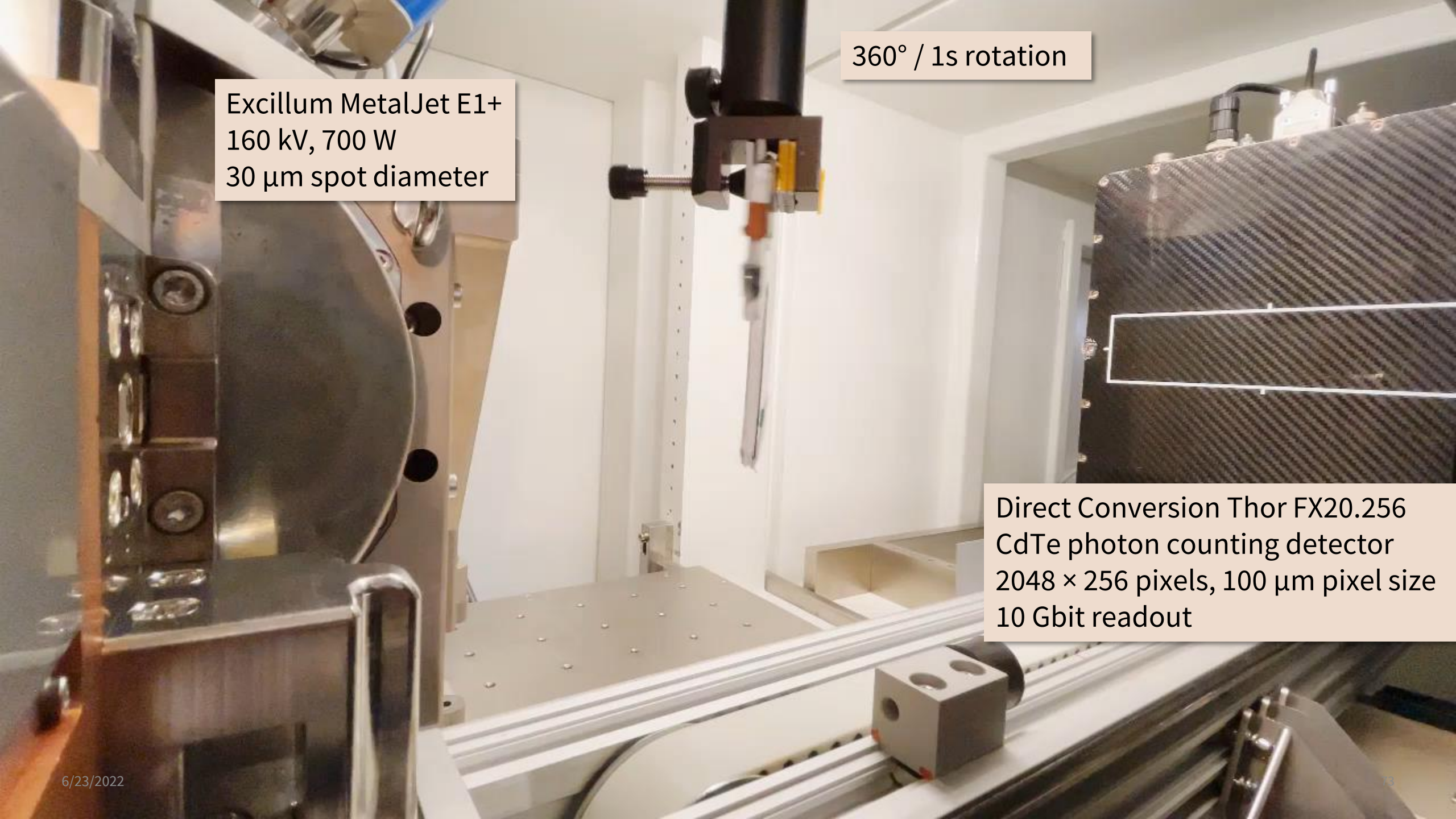


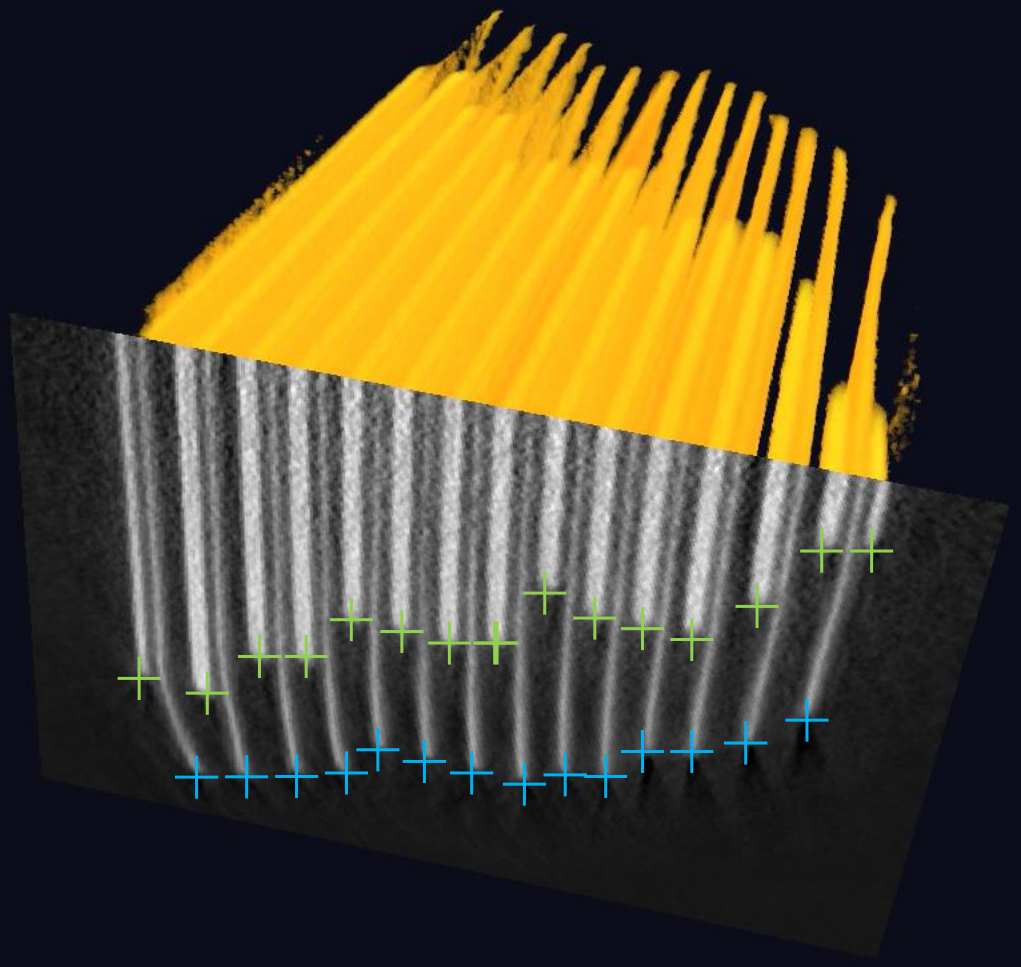
Example of e-beam focus shape evolution during 6 months continuous operation at 700 W.

#1 - High resolution through high magnification

Some MetalJet examples of high resolution through high magnification – but not SEMI/electronics, sorry

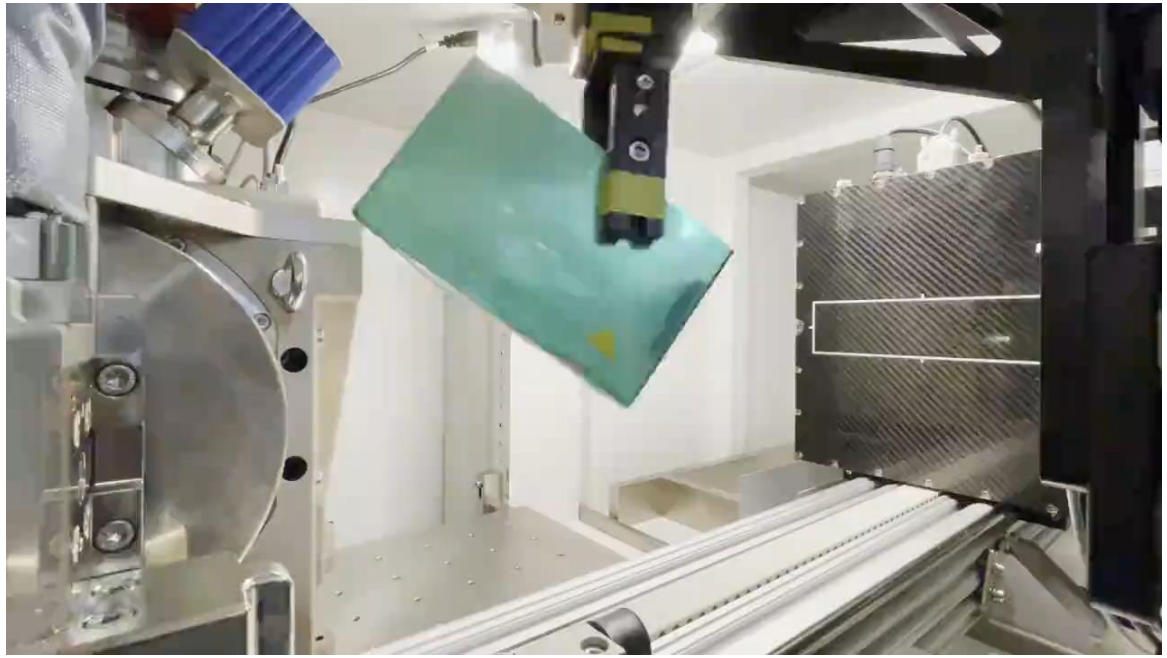



Excillum MetalJet E1+
160 kV, 700 W
30 µm spot diameter
360° / 1s rotation
Direct Conversion Thor FX20.256
CdTe photon counting detector
2048 × 256 pixels, 100 µm pixel size
10 Gbit readout

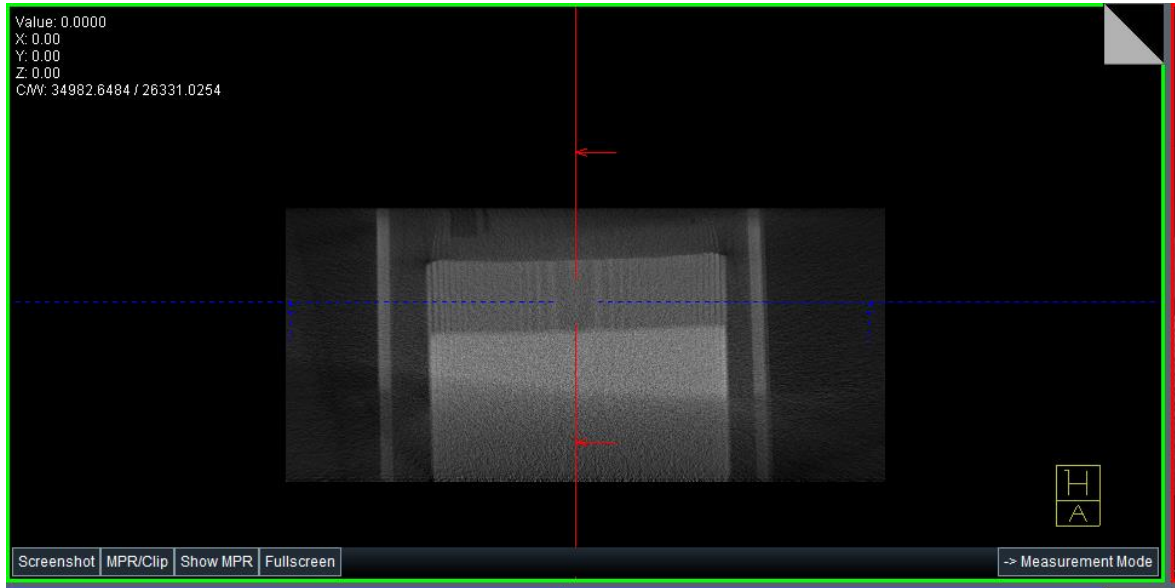


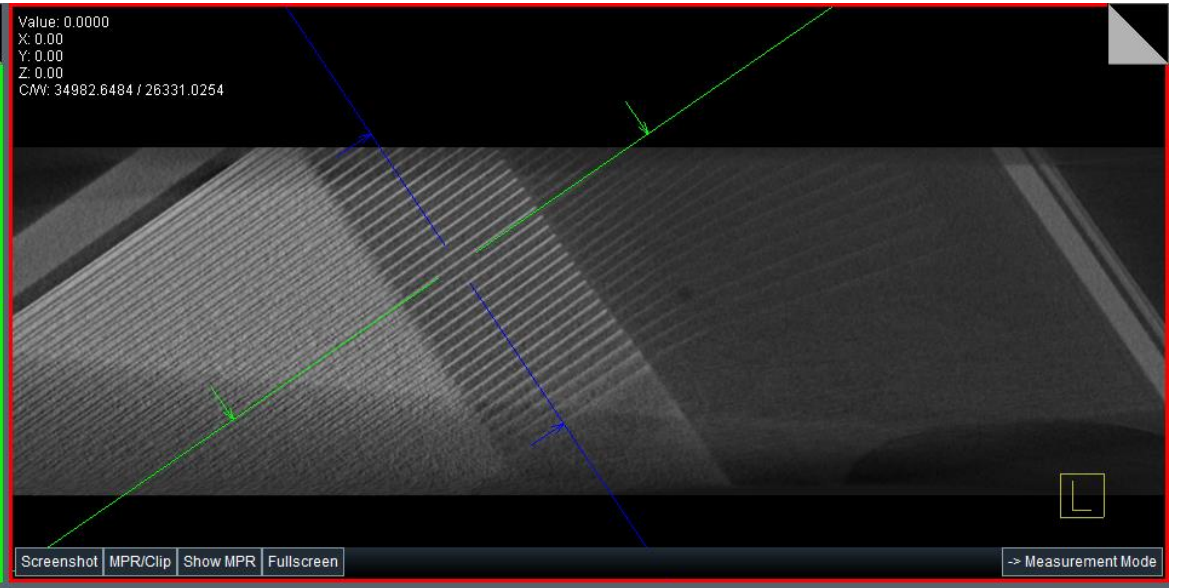
Electrical vehicle-cell

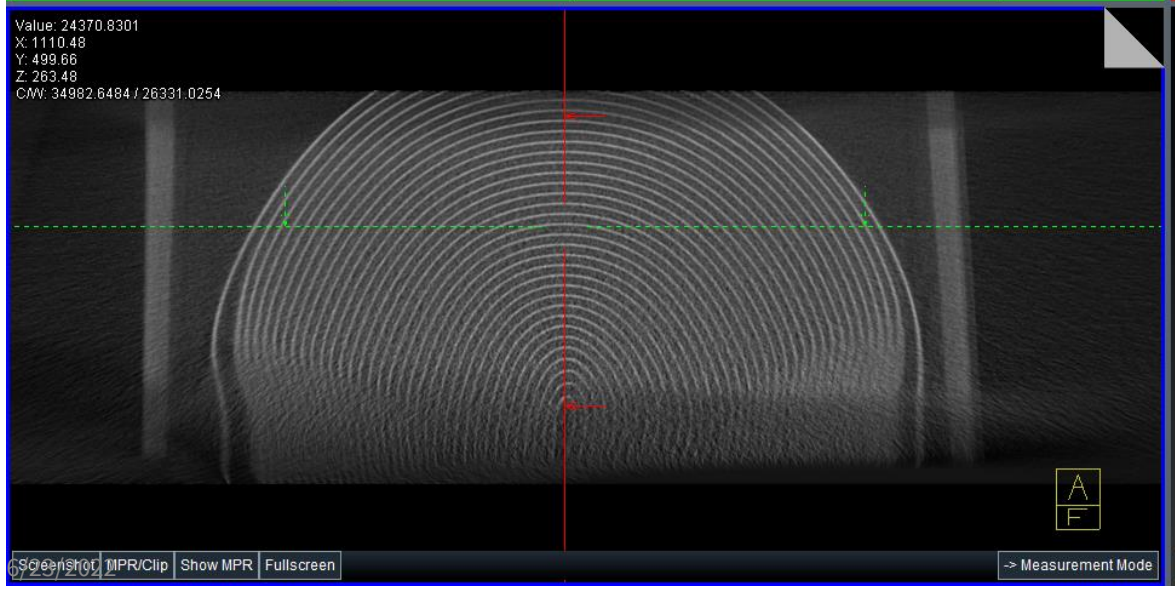
- Focusing on corner to study overhang
- Same experimental setup
- EV-cell from Golf GTE
  - 148mm x 95mm x 26mm
  - Panasonic prismatic lithium cell 25ah

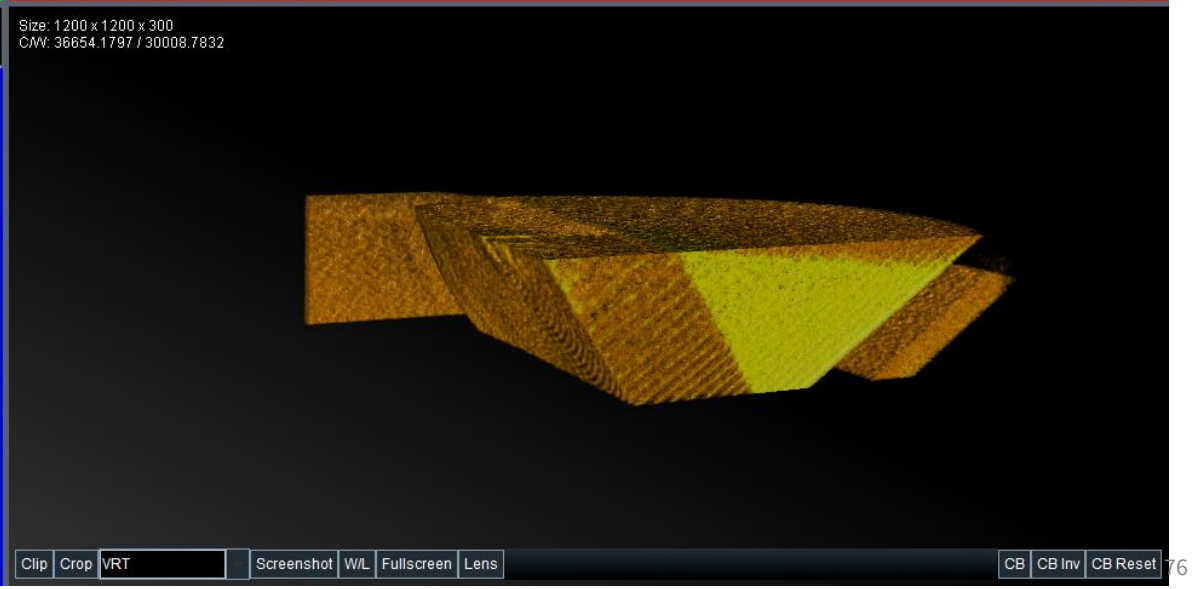


Results


Value: 0.0000
X: 0.00
Y: 0.00
Z: 0.00
C/W: 34982.6484 / 26331.0254
H
A
Screenshot
MPR/Clip
Show MPR
Fullscreen
-> Measurement Mode

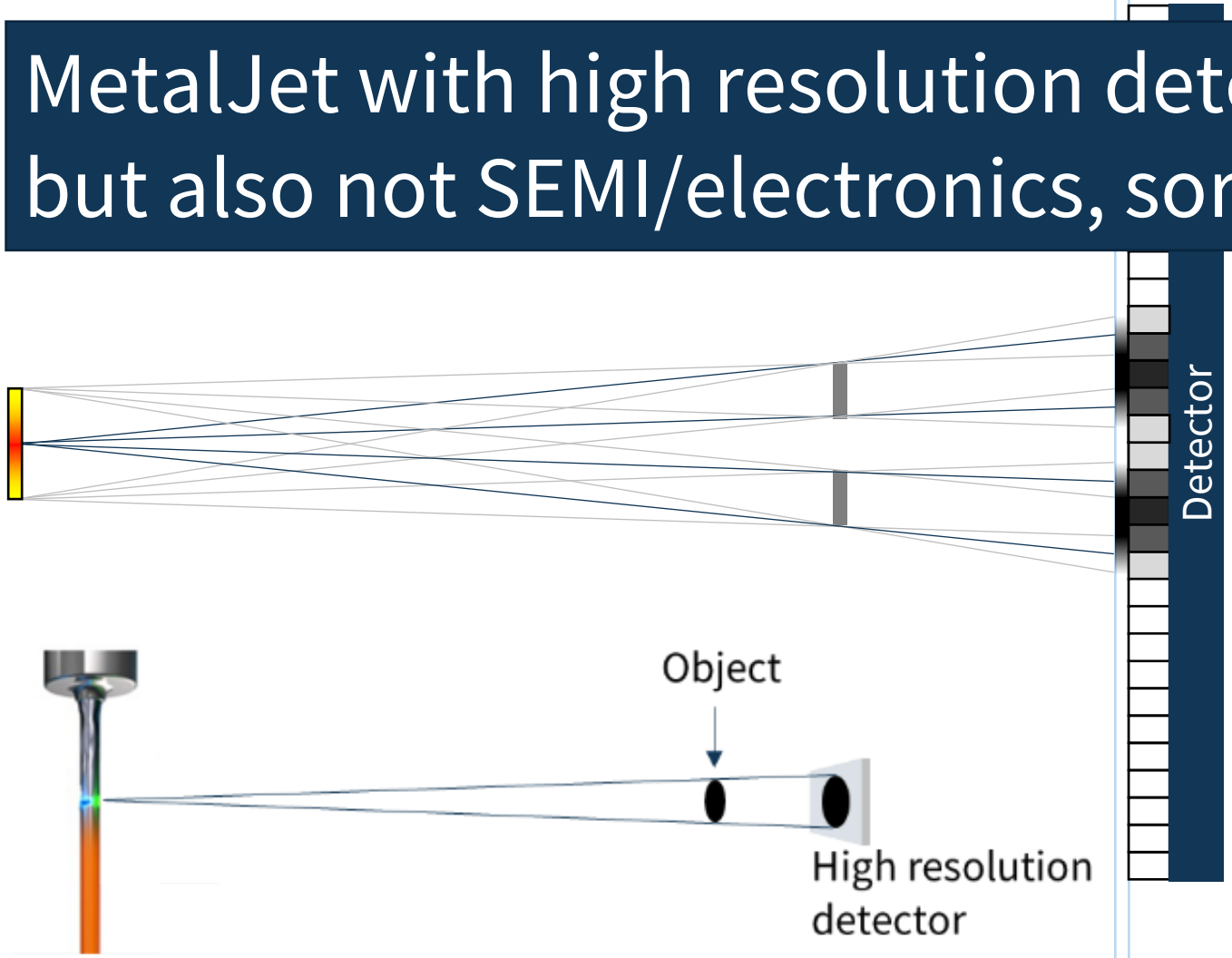

Value: 0.0000
X: 0.00
Y: 0.00
Z: 0.00
C/W: 34982.6484 / 26331.0254
L
Screenshot
MPR/Clip
Show MPR
Fullscreen
-> Measurement Mode


Value: 24370.8301
X: 1110.48
Y: 499.66
Z: 263.48
C/W: 34982.6484 / 26331.0254
A
F
Screenshot
MPR/Clip
Show MPR
Fullscreen
-> Measurement Mode


Size: 1200 x 1200 x 300
C/W: 36654.1797 / 30008.7832
Clip
Crop
VRT
Screenshot
W/L
Fullscreen
Lens
CB
CB Inv
CB Reset

#2 - High resolution through high-resolution detector

MetalJet with high resolution detector scheme – but also not SEMI/electronics, sorry



MetalJet enables phase-contrast microscopy

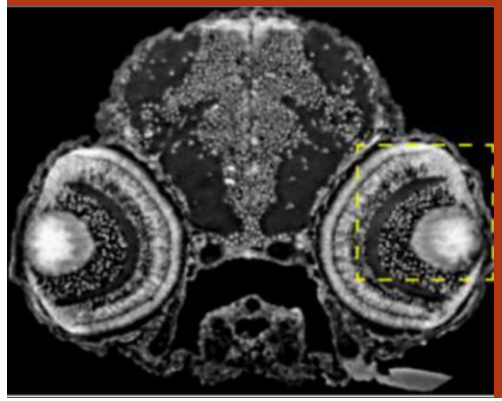
In the imaging system offered by EXCISCOPE, the MetalJet sources enable high-resolution phase-contrast imaging with reasonable exposure times

Phase contrast image on Exciscope system

0.6 µm voxel size
1.0 µm system resolution
(determined by phantom)
6 h scan time

Sample courtesy: University of Basel

Syncrotron benchmark at TOMCAT beamline (PSI)



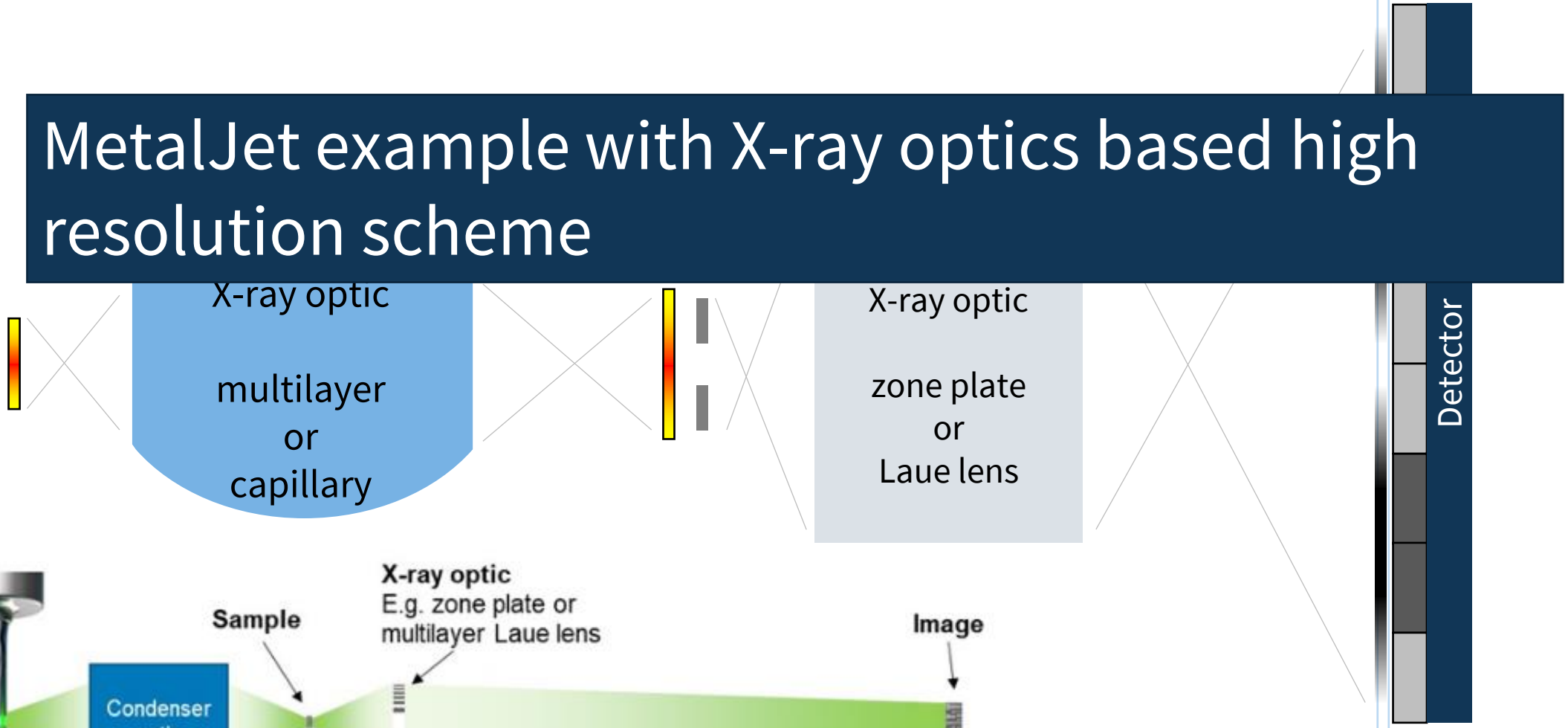
0.325 µm voxel size
1.8 µm image resolution
(fourier domain estimation)
0.15 h scan time

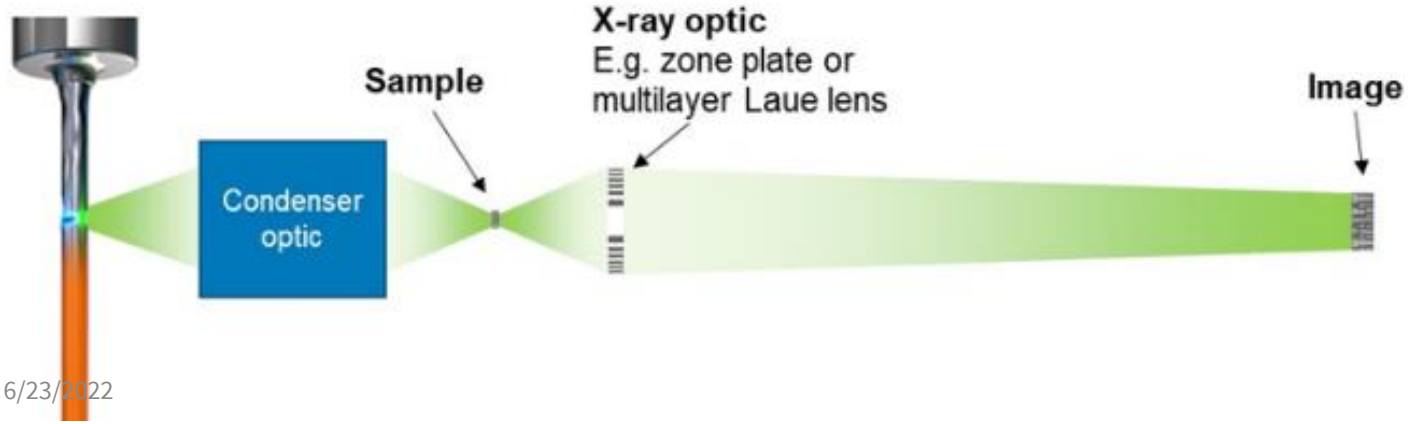
A. Migga, et. al. Proc. SPIE 11840

The zebrafish is an important and widely used vertebrate model organism.

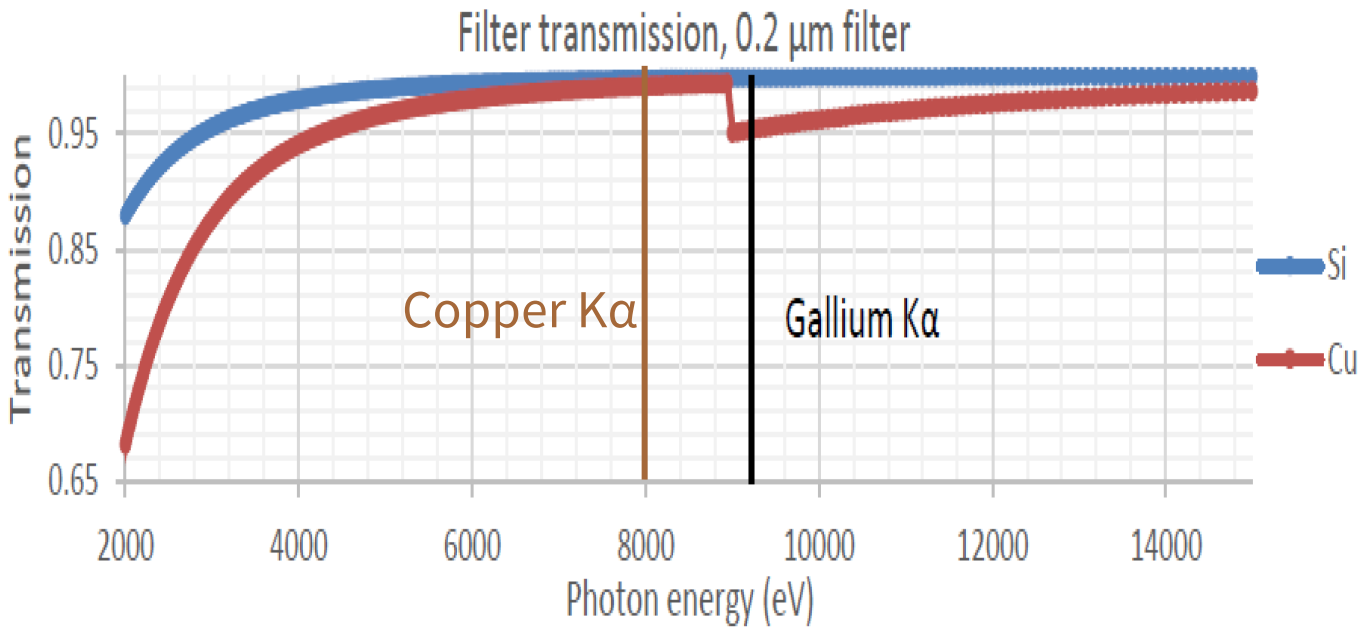
#3 - High resolution through X-ray optics

MetalJet example with X-ray optics based high resolution scheme





Ga gives excellent Si/Cu contrast



MetalJet D2+ installed in Zeiss Xradia Ultra

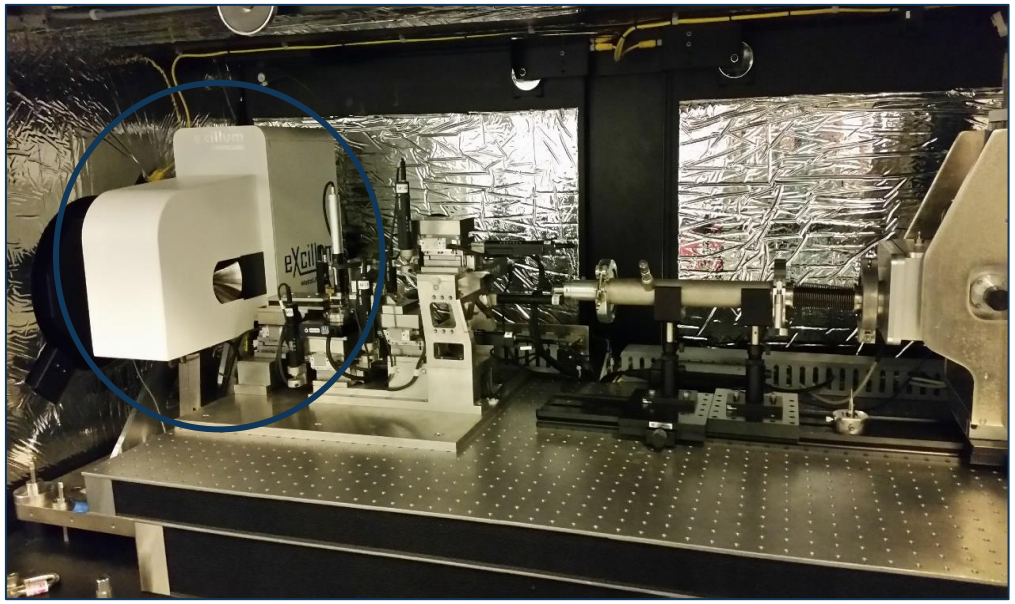
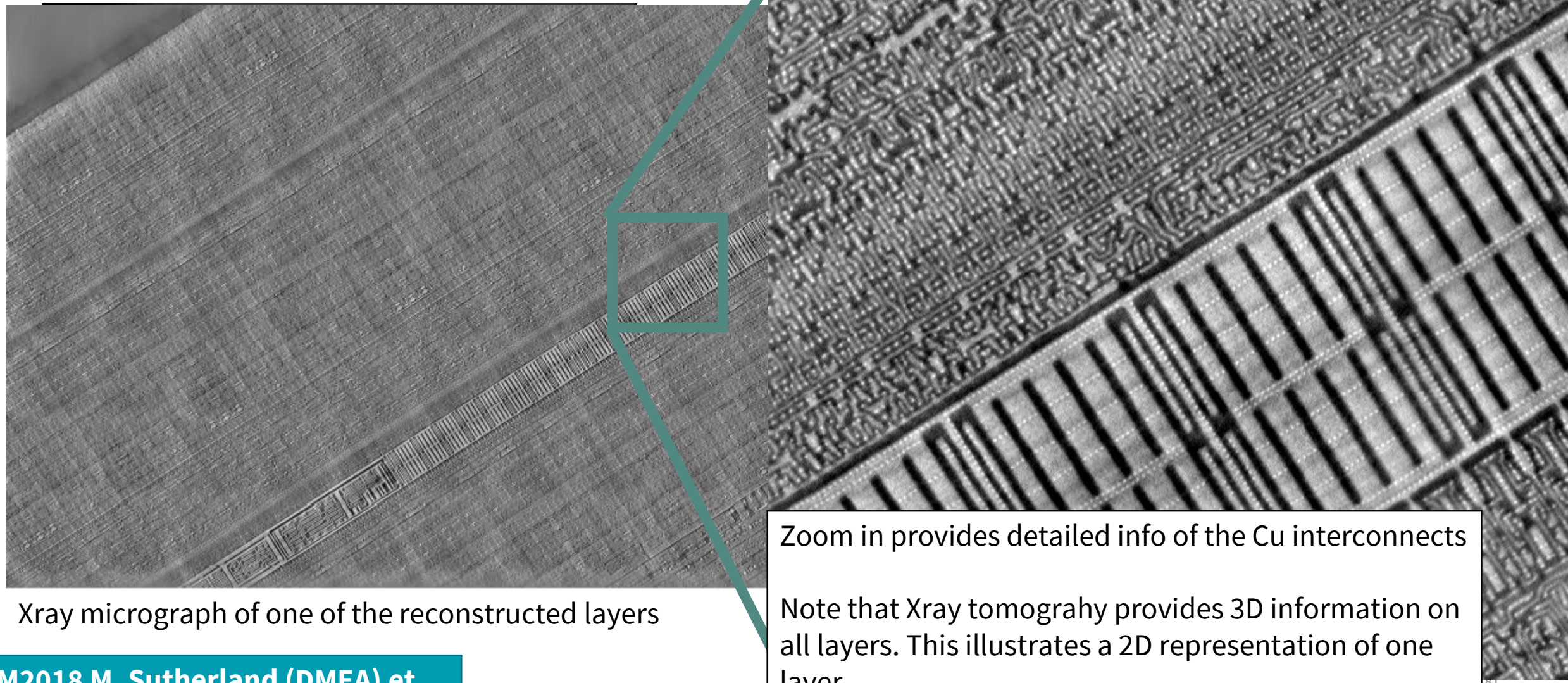


Image courtesy of Carsten Gundlach of Imaging at DTU, Denmark

Xray Tomography of a 90 nm Cu process (18x7 stitched overlapping tomographies)

excillum



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

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Thank you for listening!

bjorn.hansson@excillum.com

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Detectors
Direct Conversion
Dectris

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