X-ray nano-tomography enables high-resolution investigations from micro-bumps to hybrid bonding in advanced packaging

Dr. Till Dreier
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NANOTS 2024, Osaka, Japan

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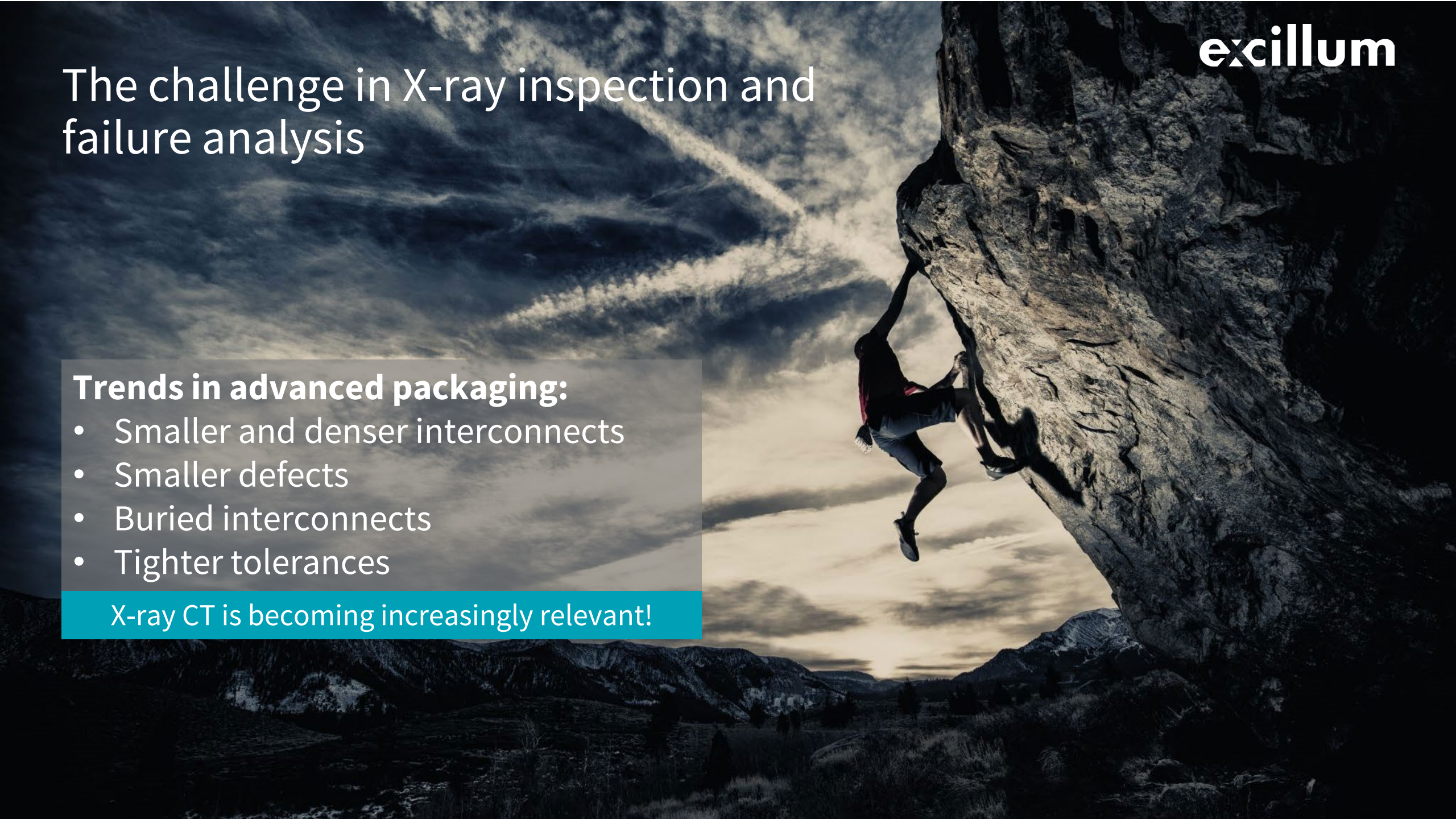
The challenge in X-ray inspection and failure analysis



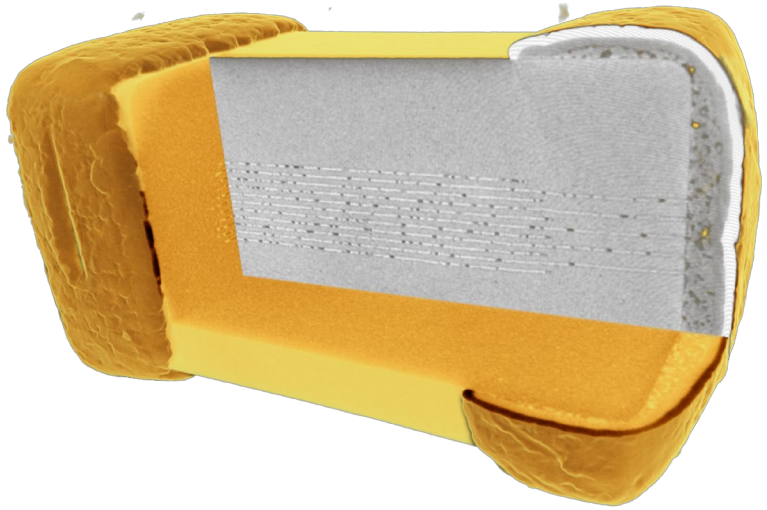
Trends in advanced packaging:

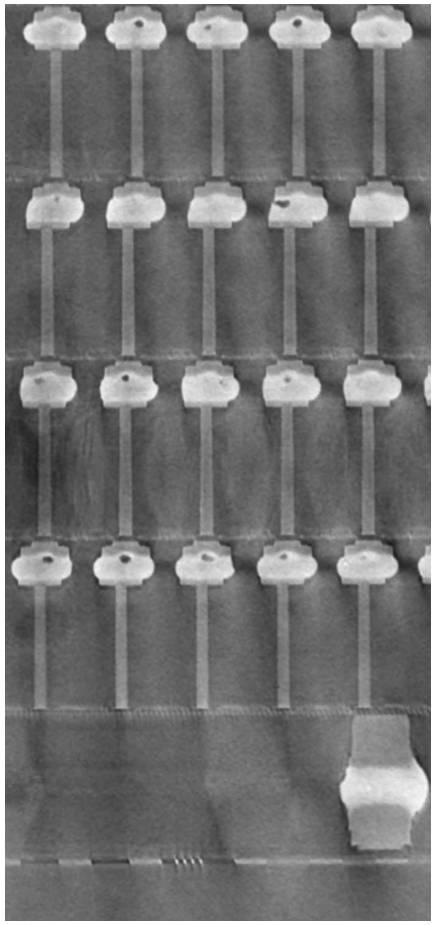
- Smaller and denser interconnects
- Smaller defects
- Buried interconnects
- Tighter tolerances

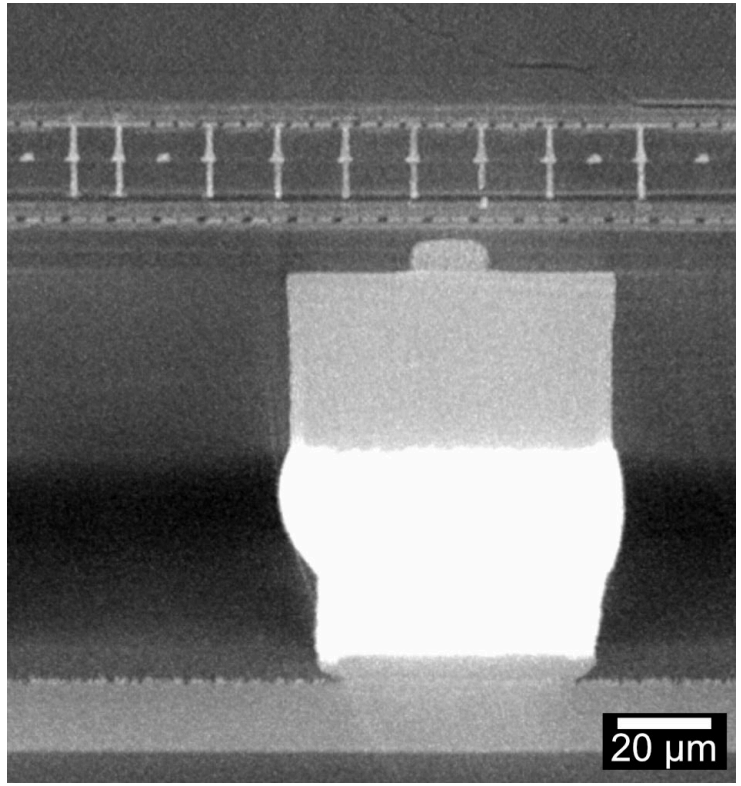
X-ray CT is becoming increasingly relevant!

Sharper scans – faster ramp up

Improved x-ray inspection to drive development and boost yield







The source for X-ray innovation

Entirely devoted to advanced microfocus and nanofocus X-ray sources

Based in Stockholm, Sweden

Established 2007

80+ colleagues

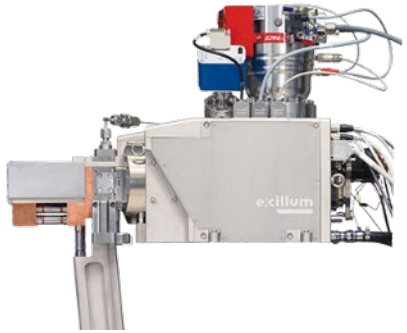
- >40 in R&D
- >10 nationalities

Collaborating with leading system integrators

Our technology and product lines

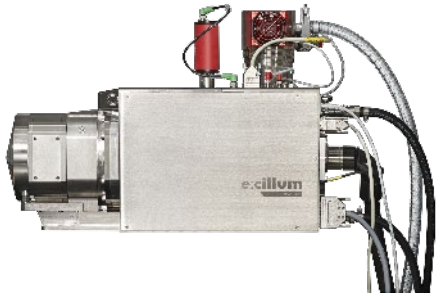
MetalJet
World's brightest microfocus X-ray source

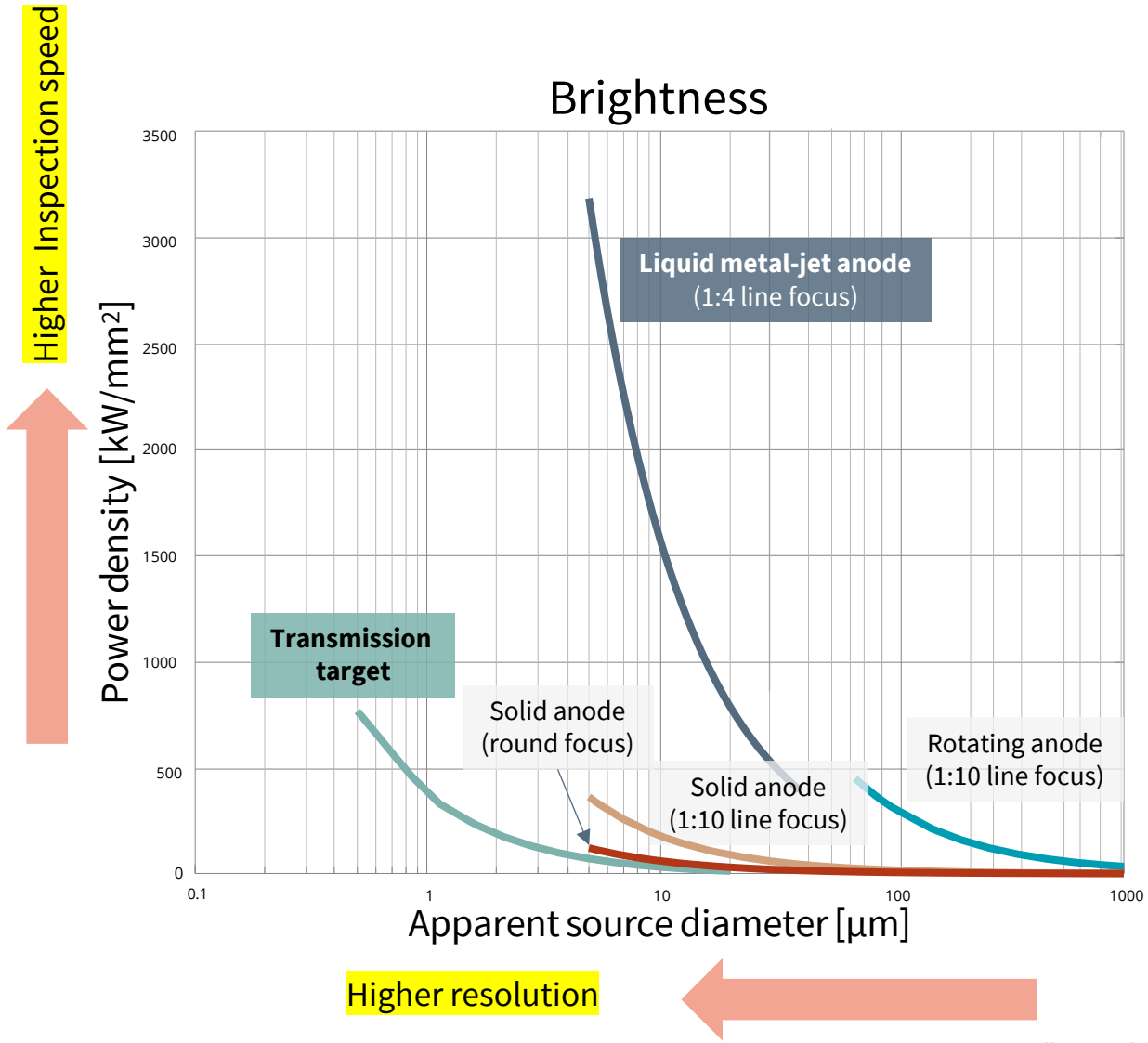
Liquid metal-jet anode and advanced electron beam technologies



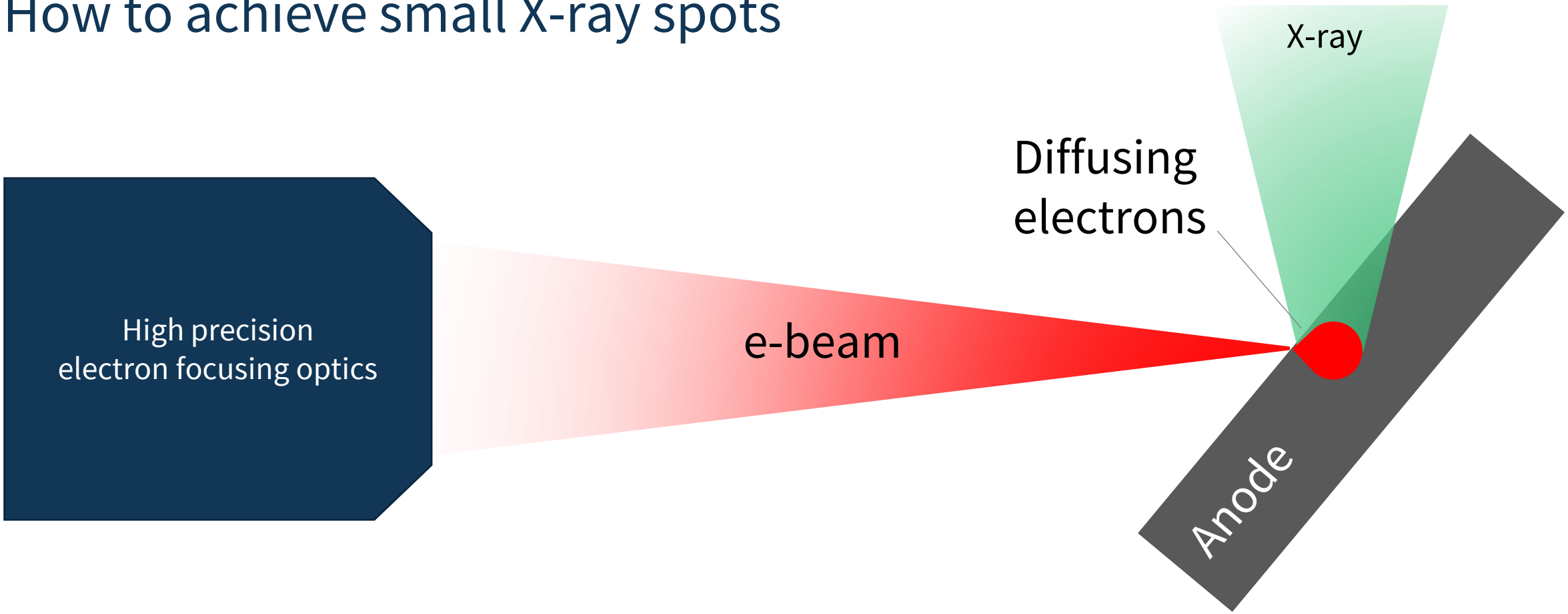
NanoTube
World's smallest X-ray nanospot

Advanced electron beam technology

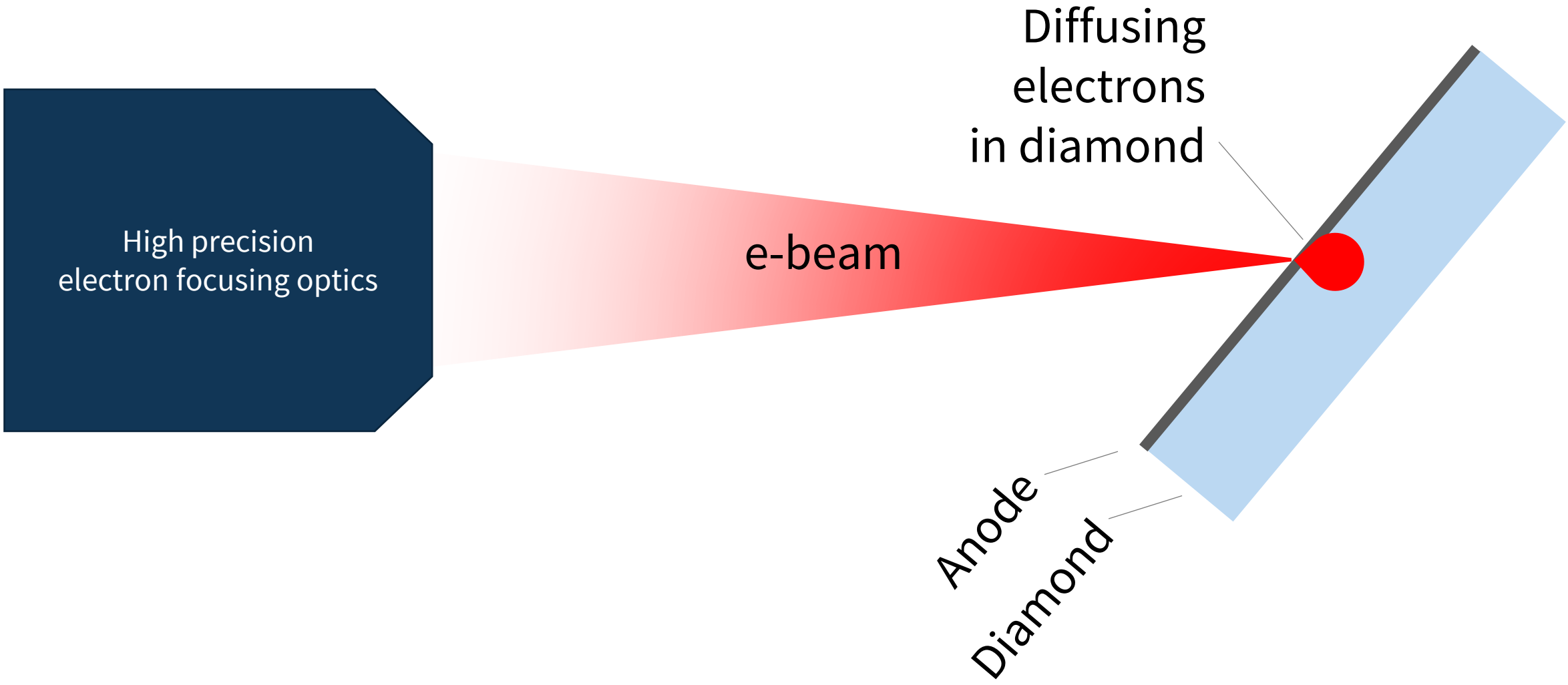




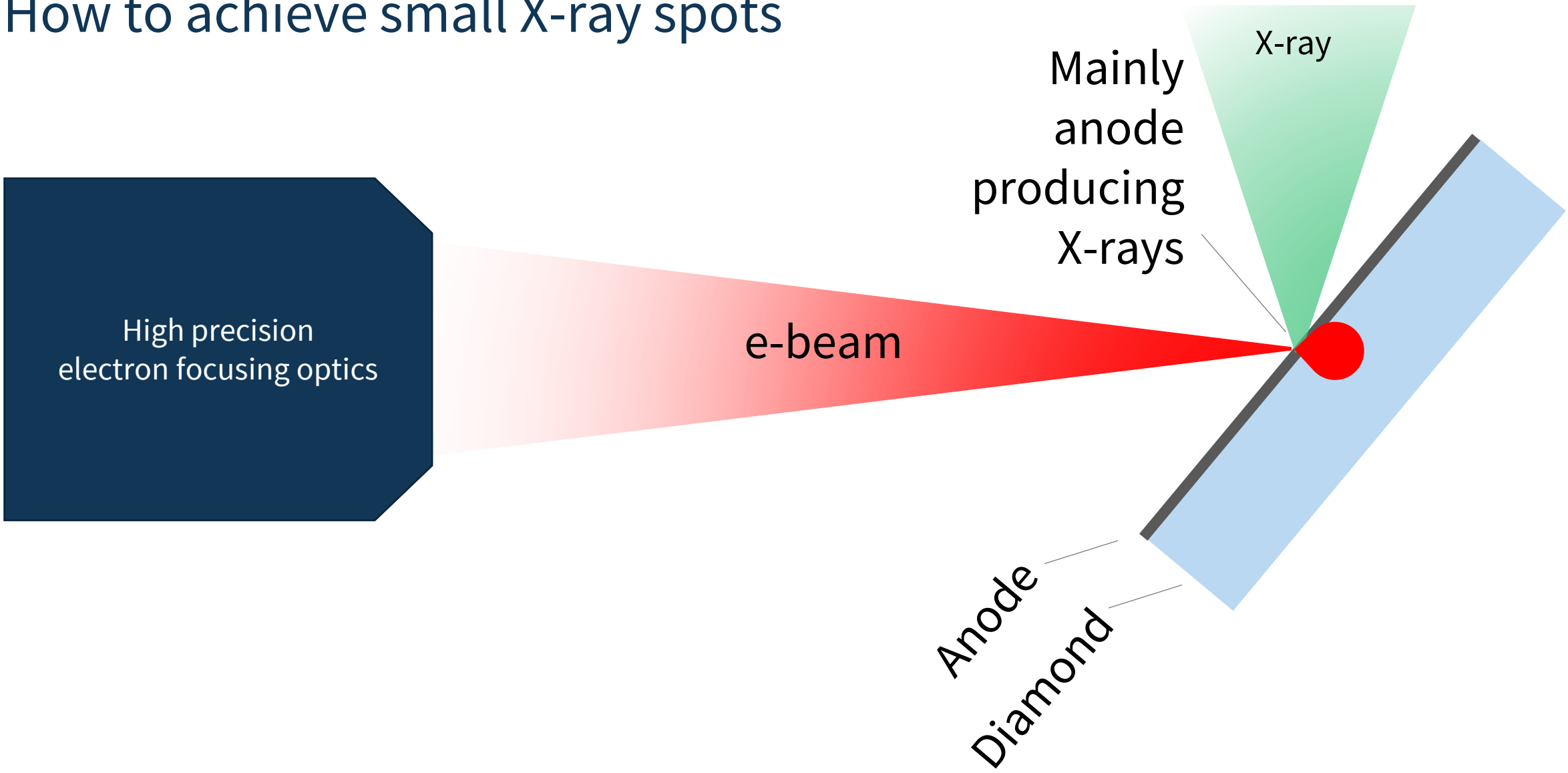
How to achieve small X-ray spots



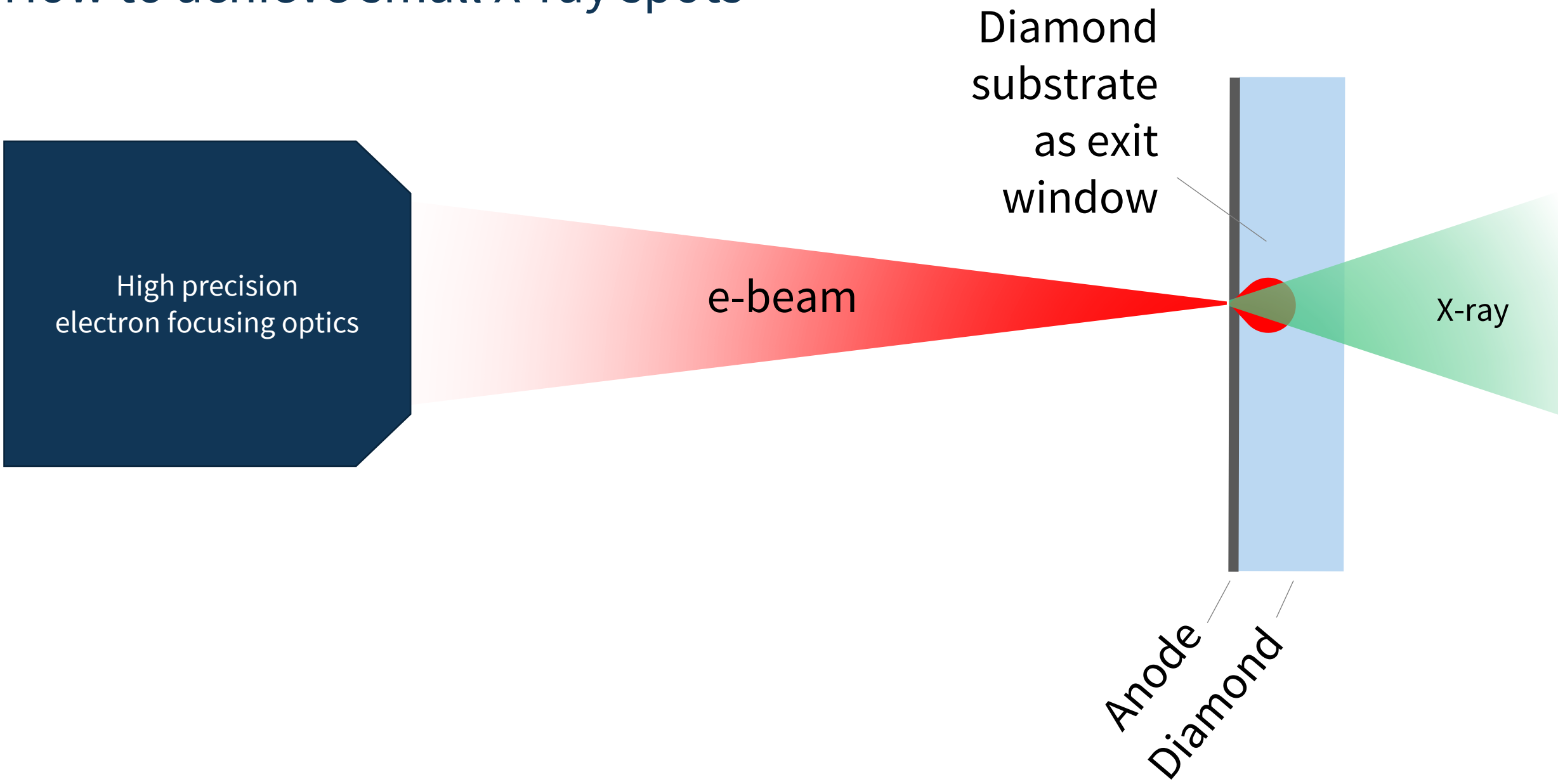
How to achieve small X-ray spots



How to achieve small X-ray spots



How to achieve small X-ray spots



High resolution through geometric magnification

High resolution through geometric magnification $\boldsymbol{M}$:

- Minimise Source-Object distance (**SOD**)
- Select Magnification by adjusting Source-Detector distance (**SDD**)

$$M = \frac{SDD}{SOD}$$

Inverse square law

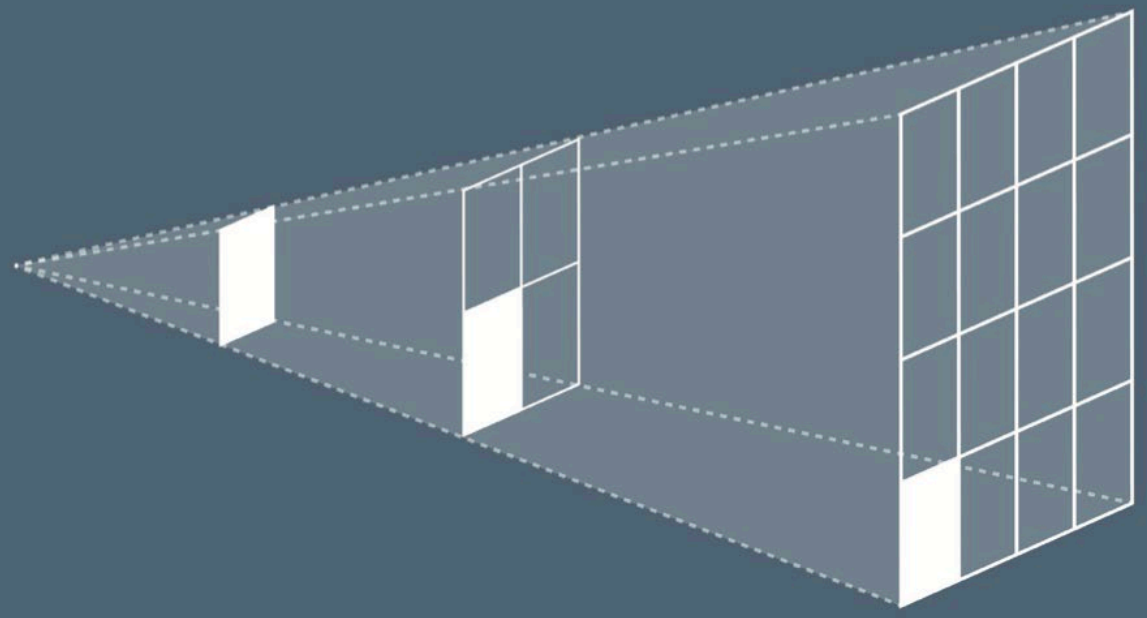
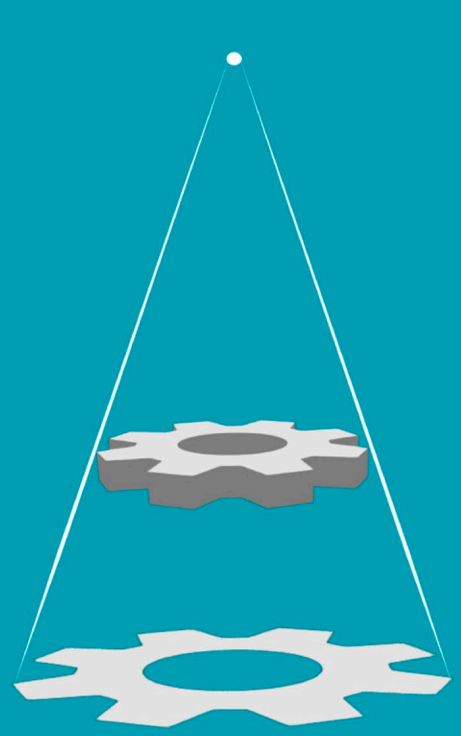
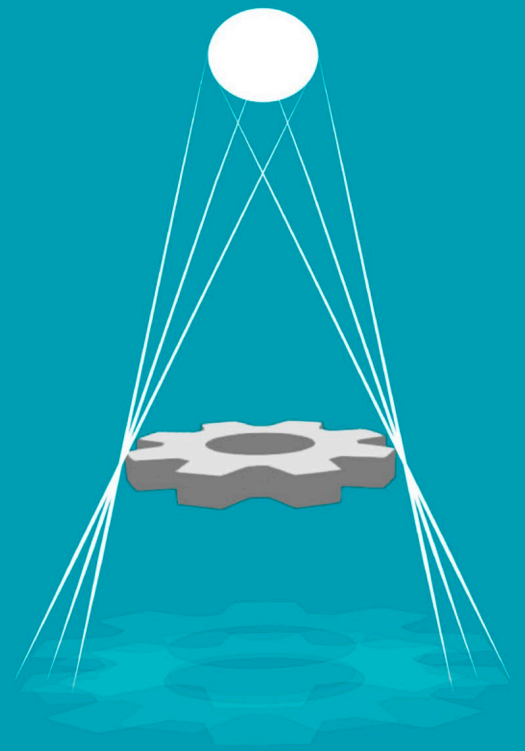


Figure from: J. Hållstedt "*Brightness as key performance metric for X-ray tubes and benchtop X-ray sources*", Excillum AB, 2024

Resolution limit: spot size and penumbral blurring

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



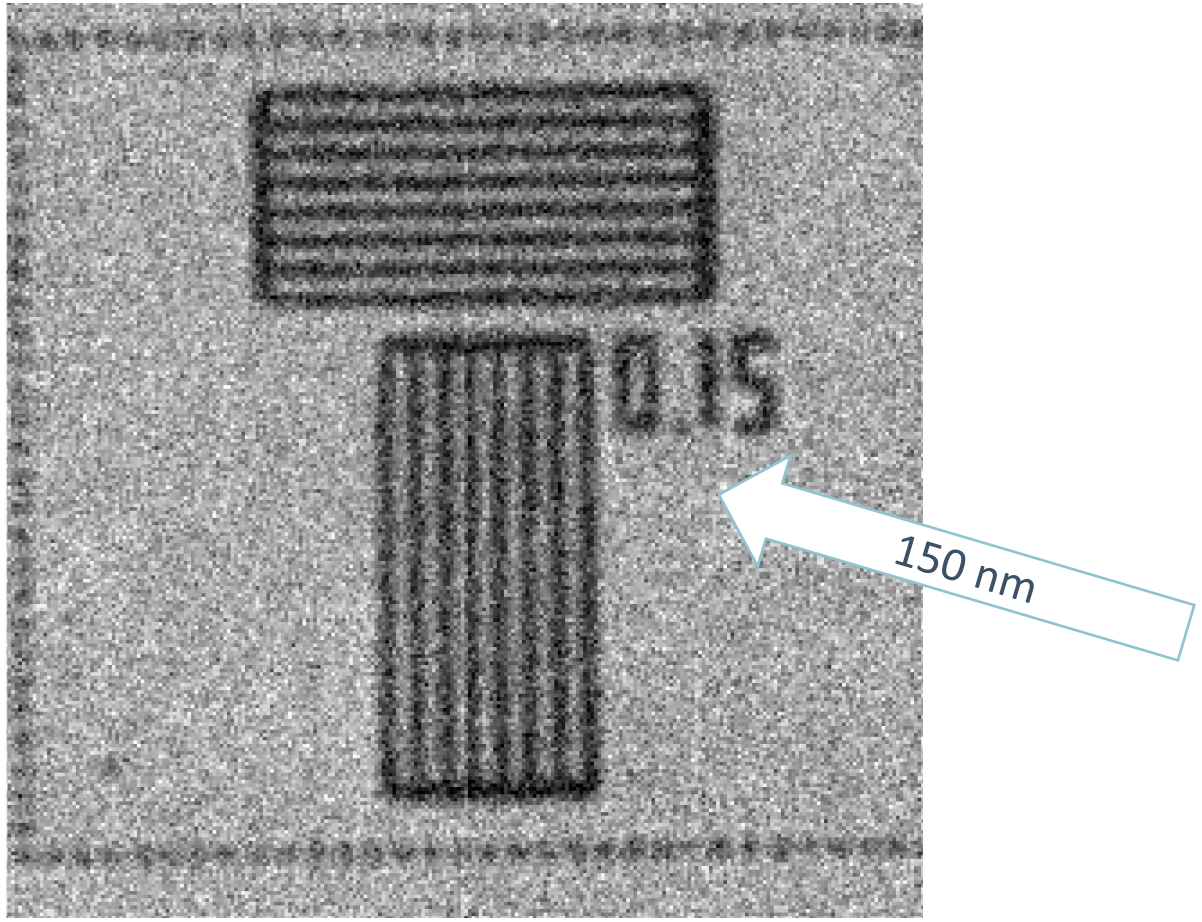


Penumbral blurring:
X-ray spot is projected onto the detector, limiting the achievable resolution

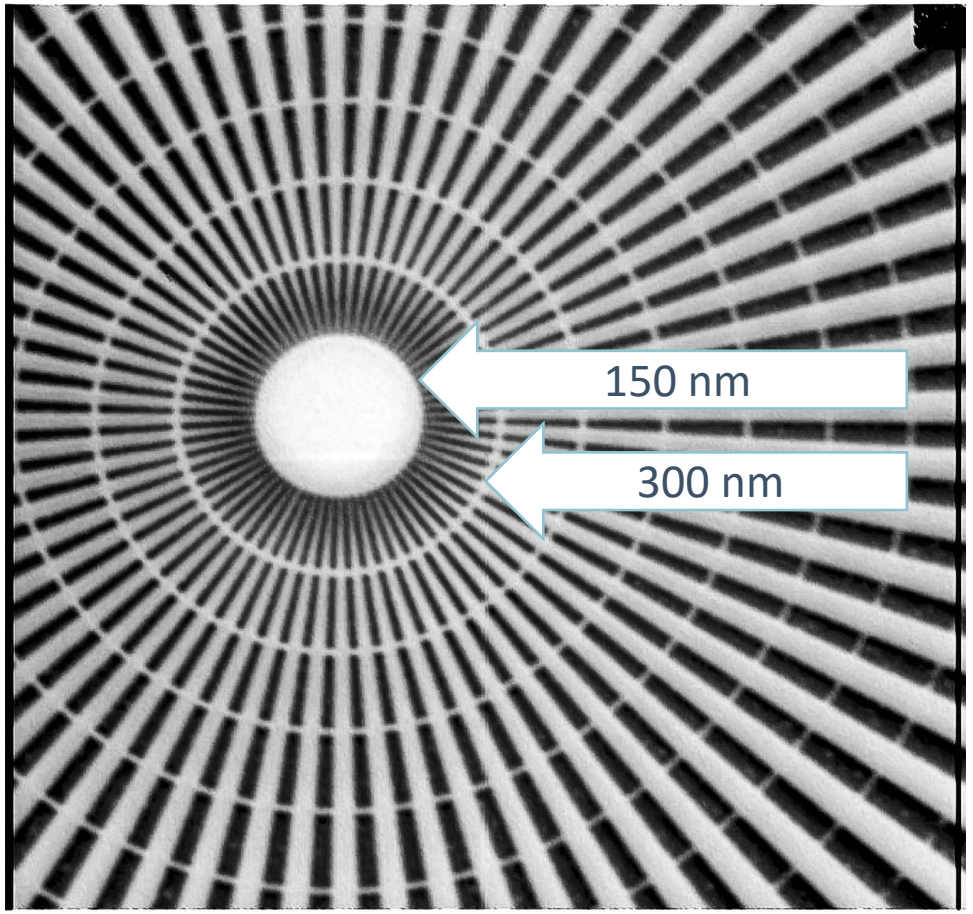
Figure from: J. Hållstedt "*Brightness as key performance metric for X-ray tubes and benchtop X-ray sources*", Excillum AB, 2024

150 nm resolution without optics

JIMA RT RC-04

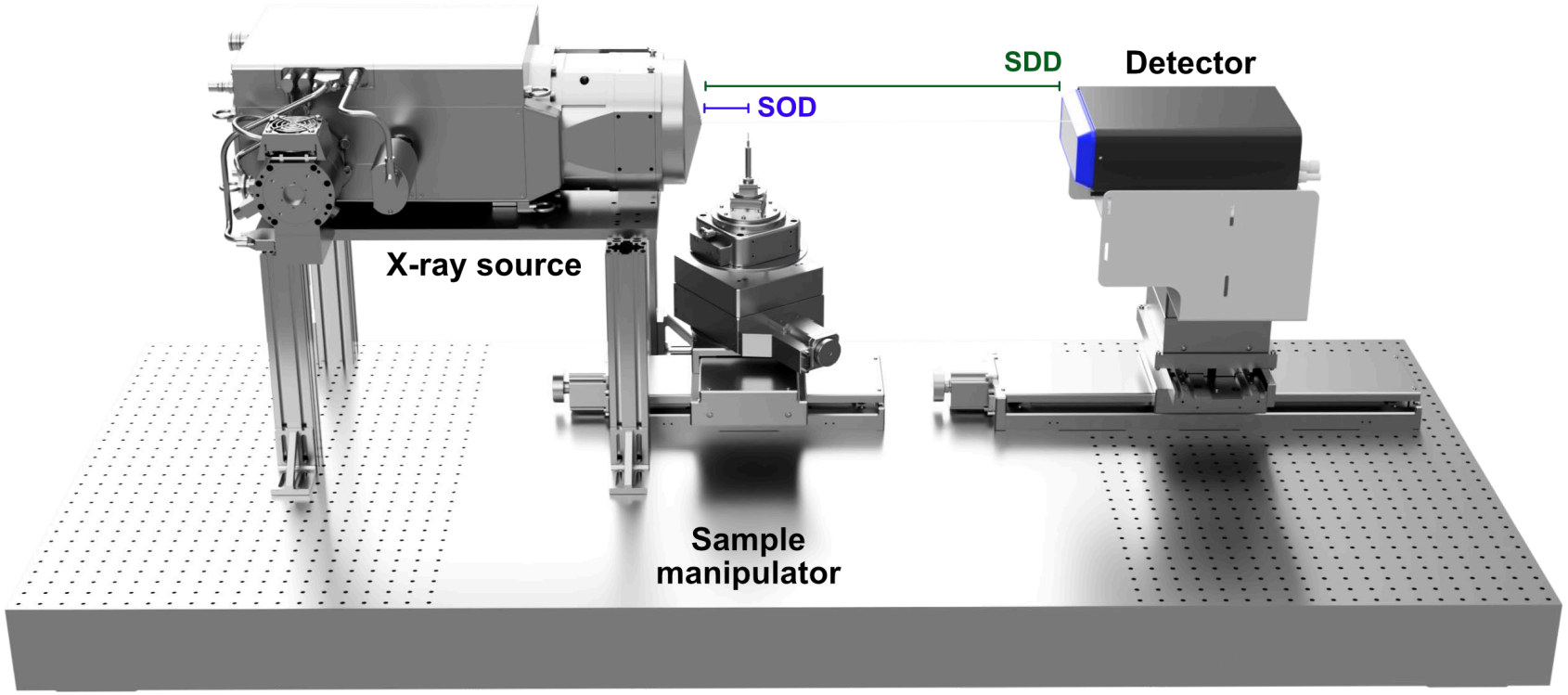


Siemens star



X-ray nano-CT

- Use high efficiency detectors with large pixels
  - Industrial FlatPanels with thick scintillators
  - Photon counting detectors
- Utilise inverse square law
  - Reduction of SOD by ½ increases number of photons on sample by 4x



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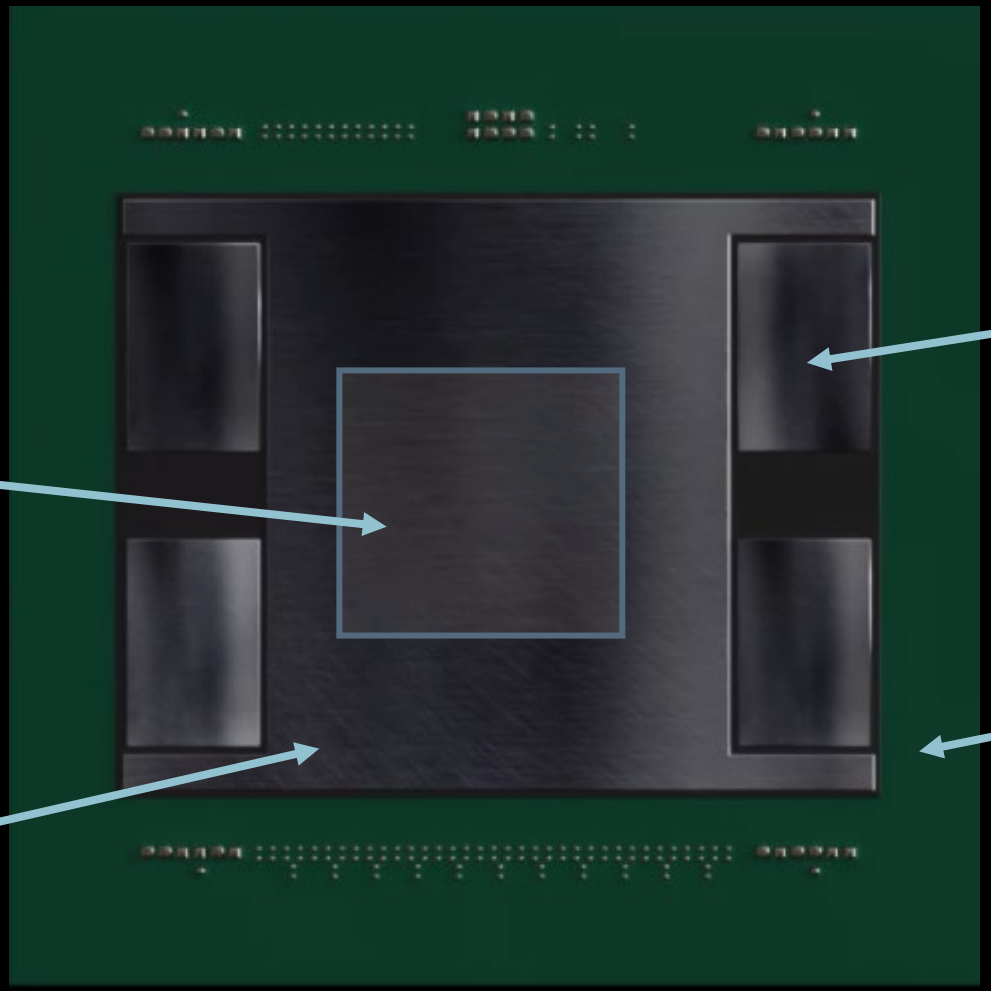
High-Bandwidth Memory (HBM)

Nano-CT in advanced packaging



Nvidia GV100 GPU

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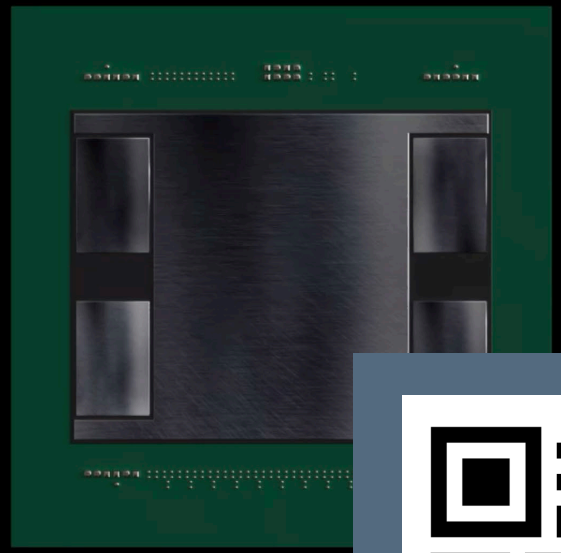
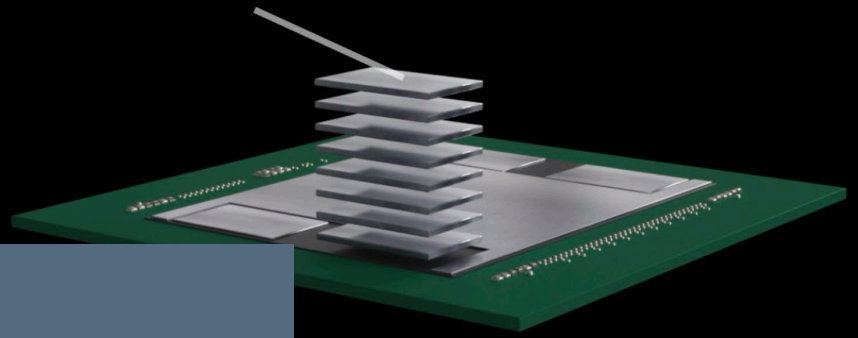
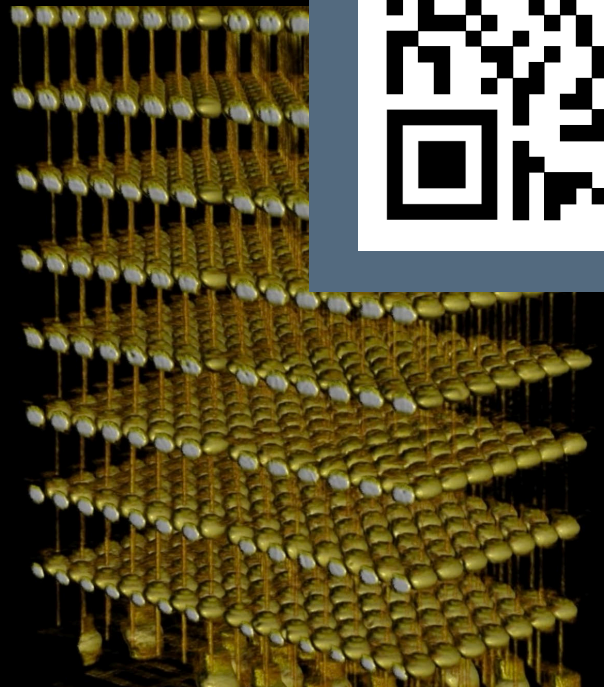


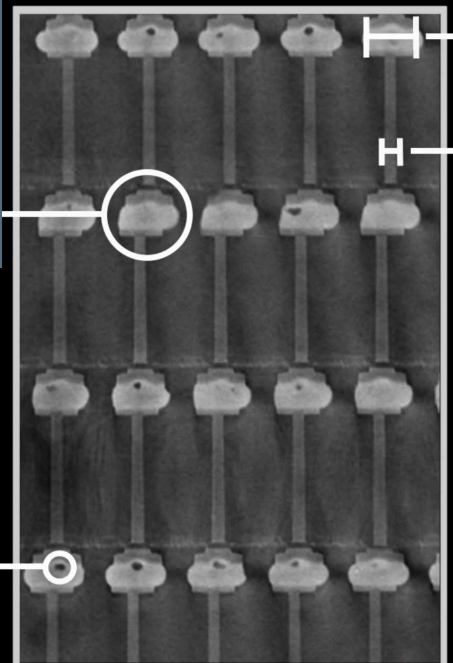
Commercially available
GPU with HBM



Video available at:

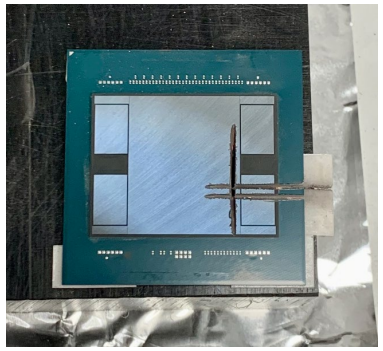
https://youtu.be/OT9j3JvEn80?si=0MSejJPhyMm2PqHw



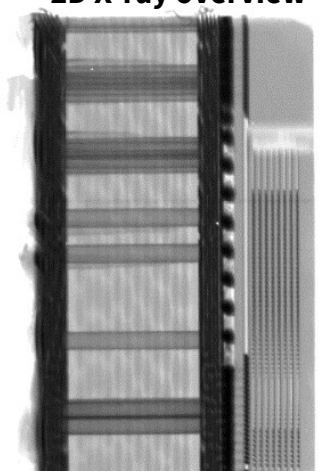


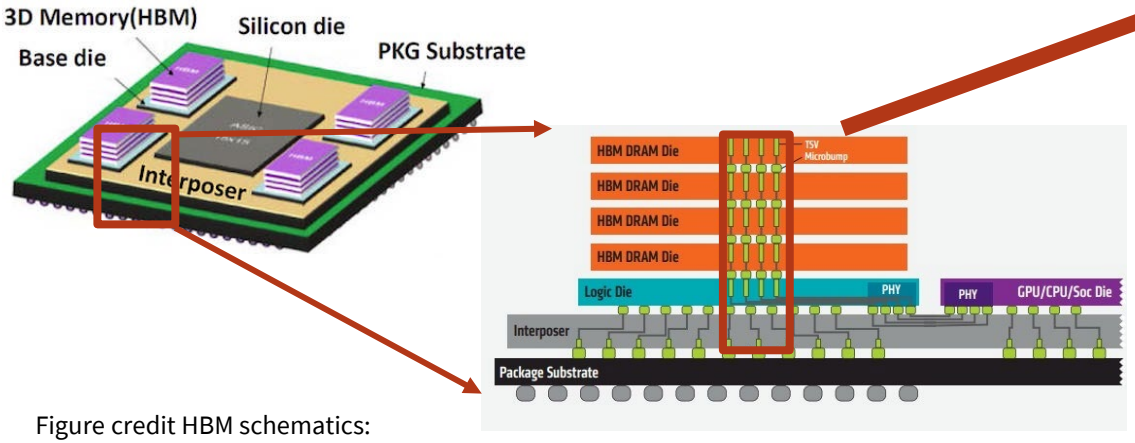
Nano-CT in advanced packaging

Commercially available GPU with HBM



2D X-ray overview





30 s overview scan

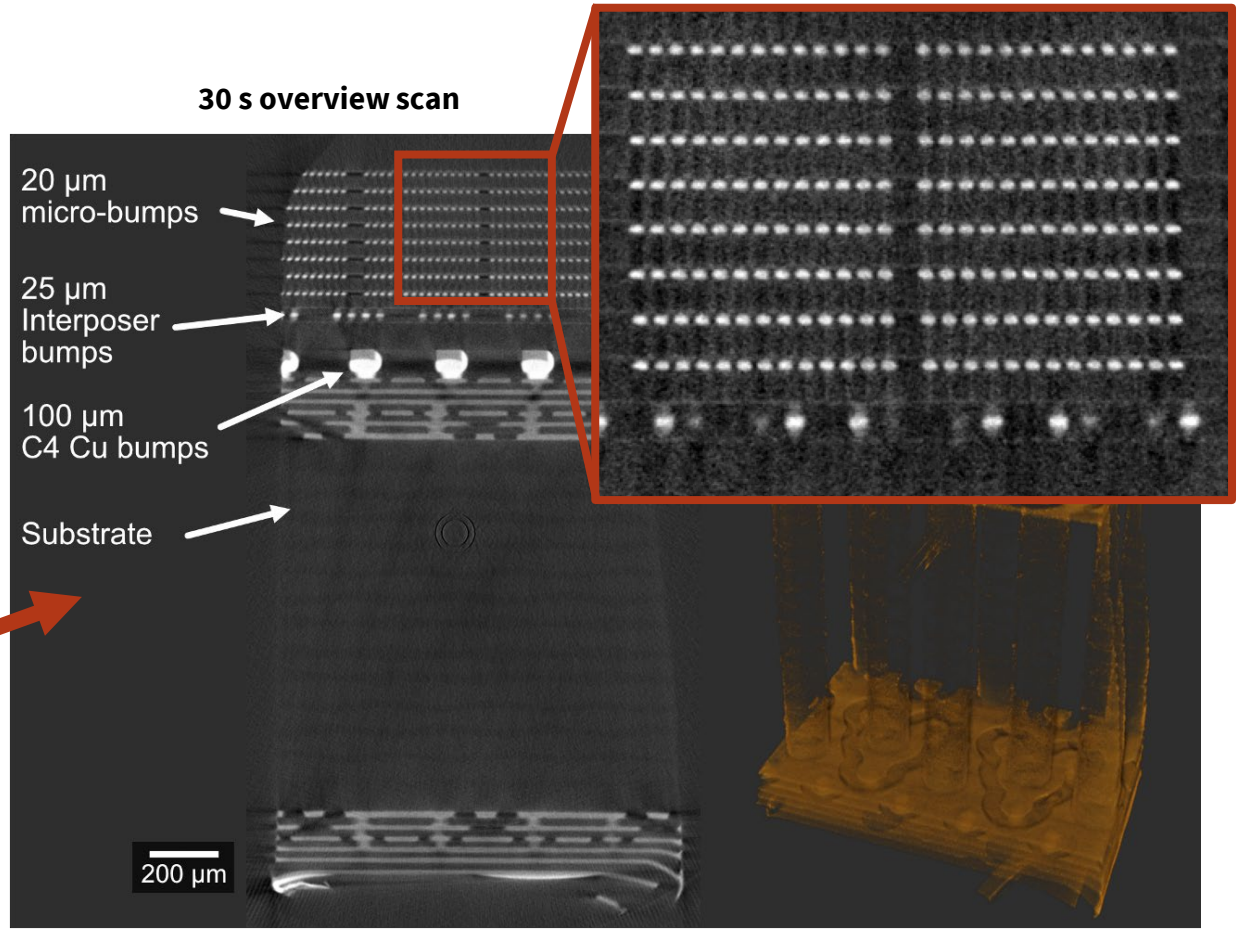
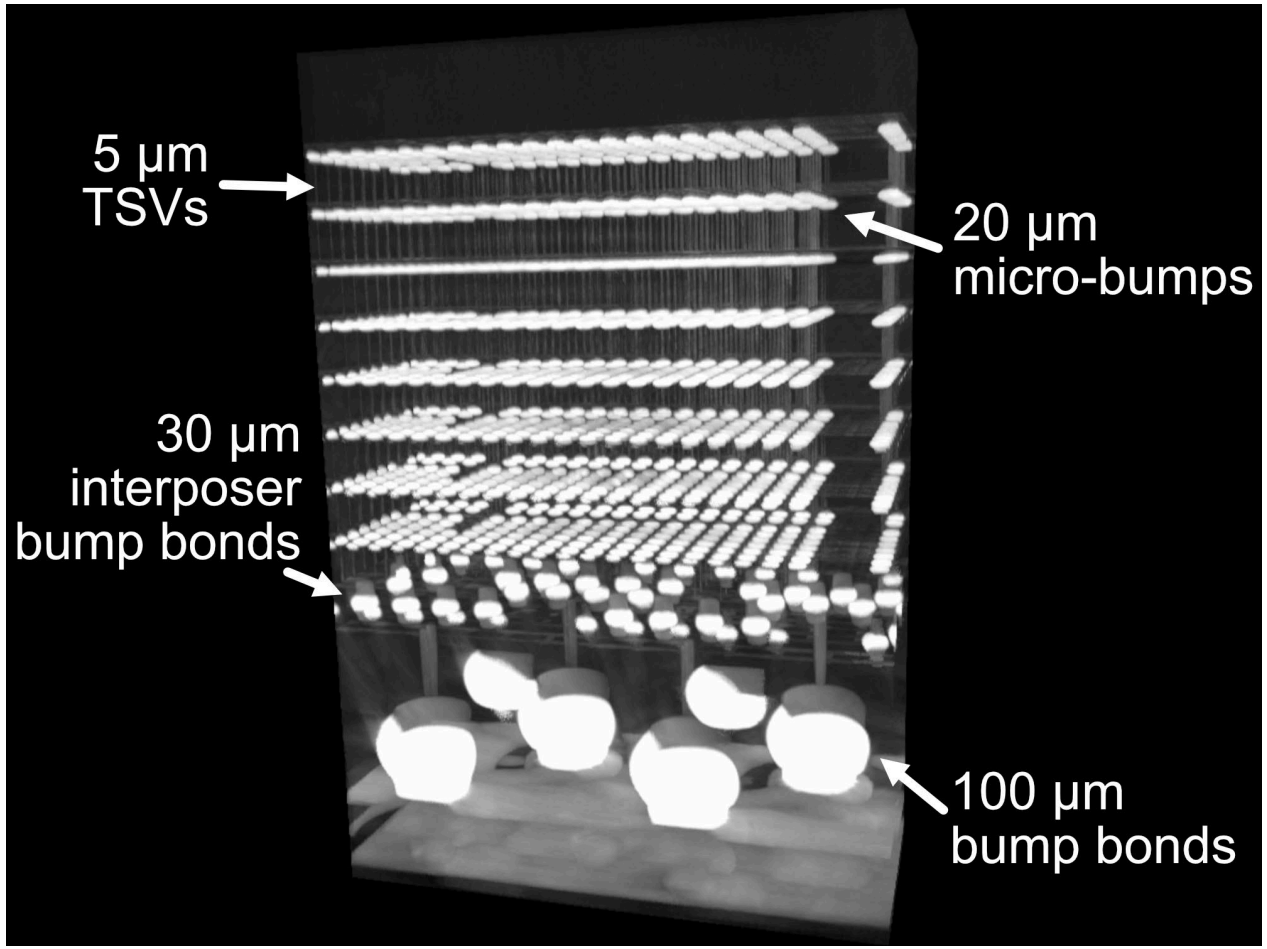


Figure credit HBM schematics:
https://www.eenewseurope.com/en/closing-the-memory-gap-can-advanced-fab-and-packaging-finally-realize-in-memory-processing/
https://www.amd.com/en/technologies/hbm
X-ray image and 3D render: T. Dreier et al., ESREF 2024, Submitted to Microelectronics Reliability.

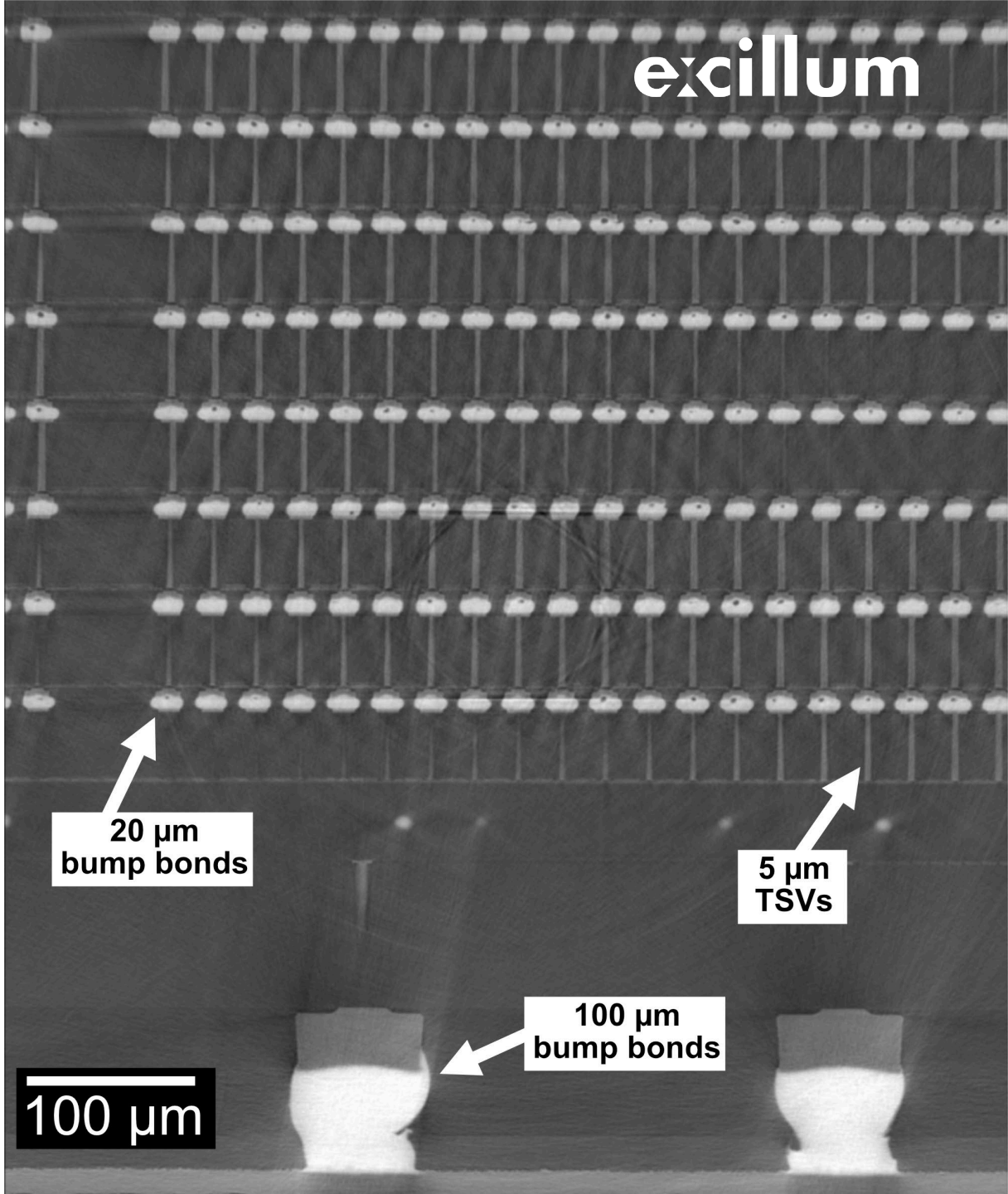
High-bandwidth memory

- Geometry
  - SOD = 3.65 mm
  - SDD = 390 mm
  - p_{eff} = 700 nm
- Scan settings
  - Projections: 2600
  - Rotation: 216 degrees
  - Exposure time: 10 s
  - Scan time: 7.2 h
- Source settings
  - Voltage: 100 kV
  - Spot size: 600 nm



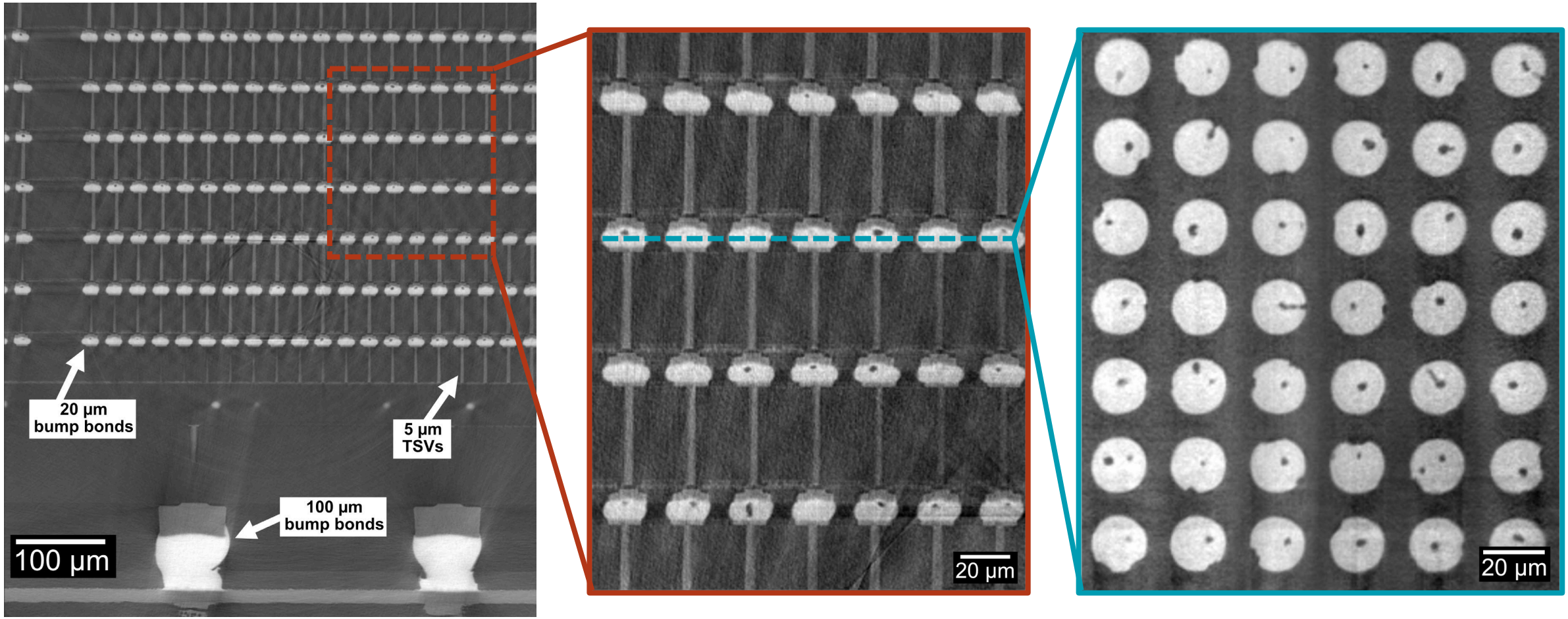
High-bandwidth memory

- 8 layer DRAM stack at sub-micron resolution
- Imaging of 5 µm TSVs
- Uniform resolution in all directions
- Capture >1000 individual bump bonds and voids[1]



[1] T. Dreier et al., ESREF 2024, submitted to Microelectronics Reliability.

High-bandwidth memory



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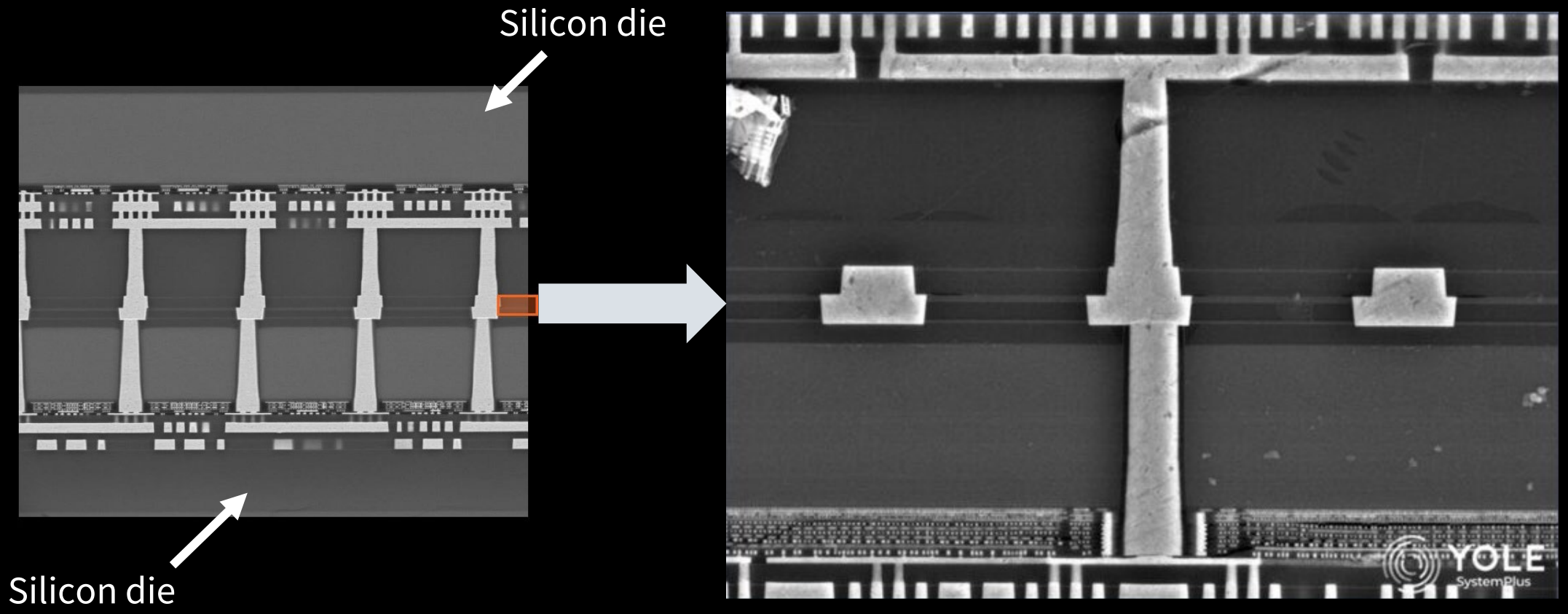
Hybrid Bonding

Hybrid bonding

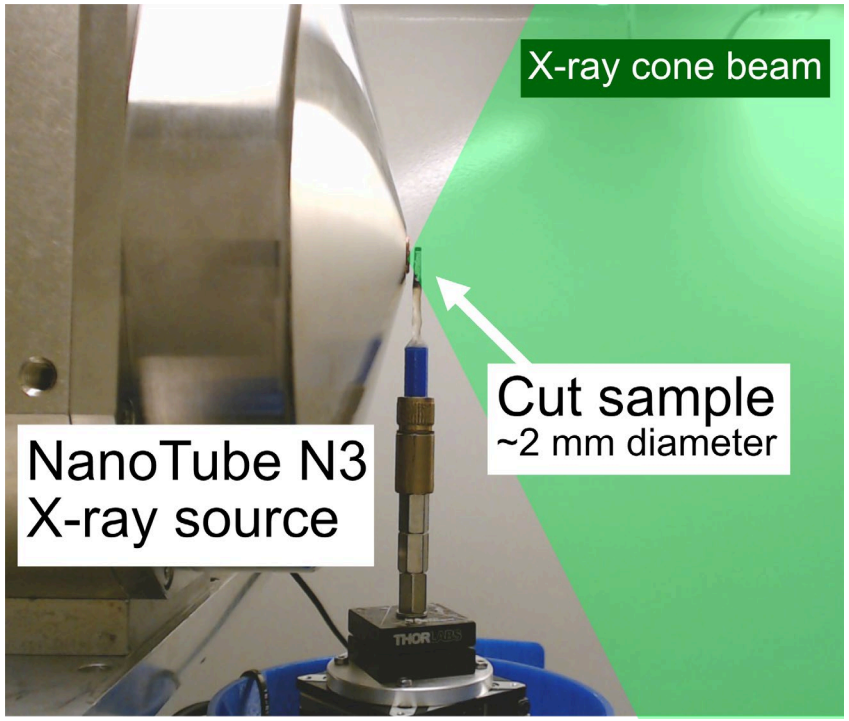


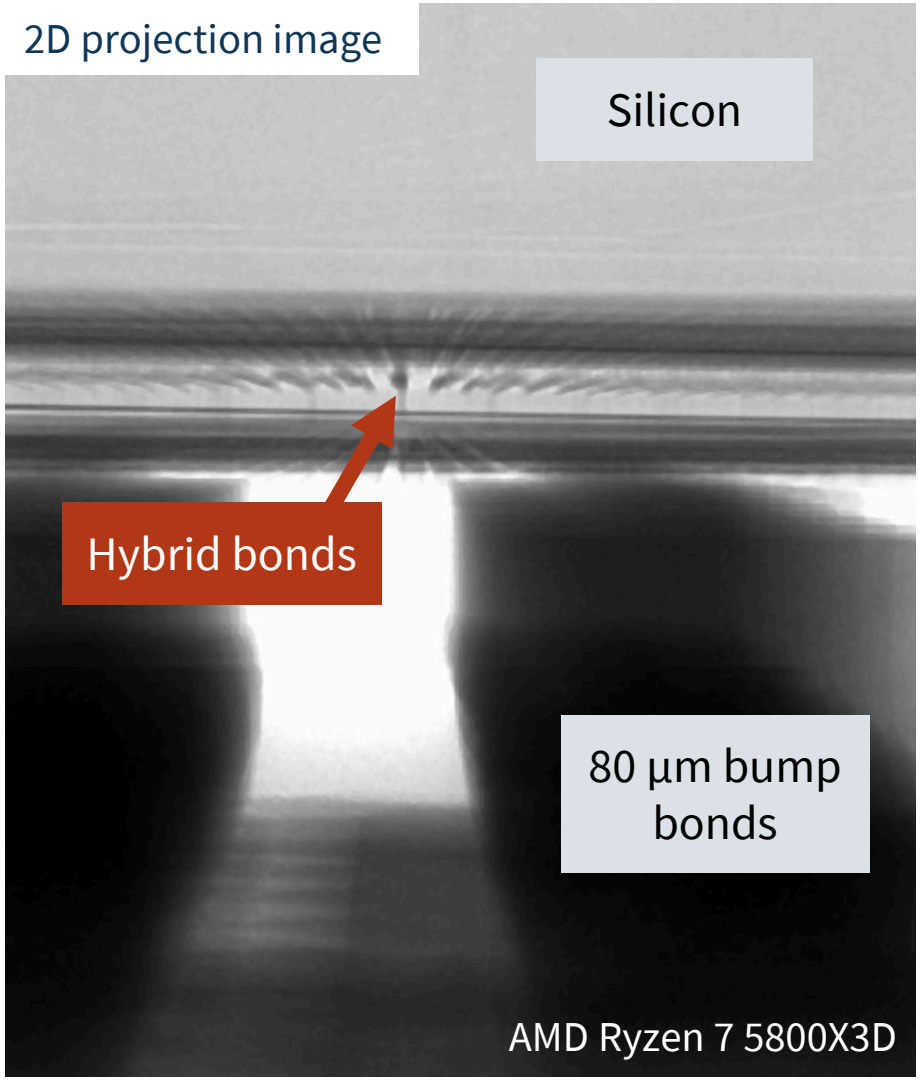
Direct Cu-Cu bonding of 2 Silicon dies

Image credit: https://www.servethehome.com/amd-milan-x-delivers-amd-epyc-caches-to-the-gb-era/amd-epyc-7003x-milan-x-hybrid-bonding/
and: https://www.yolegroup.com/strategy-insights/innovation-beyond-moores-law-advanced-packaging-explores-new-frontiers/

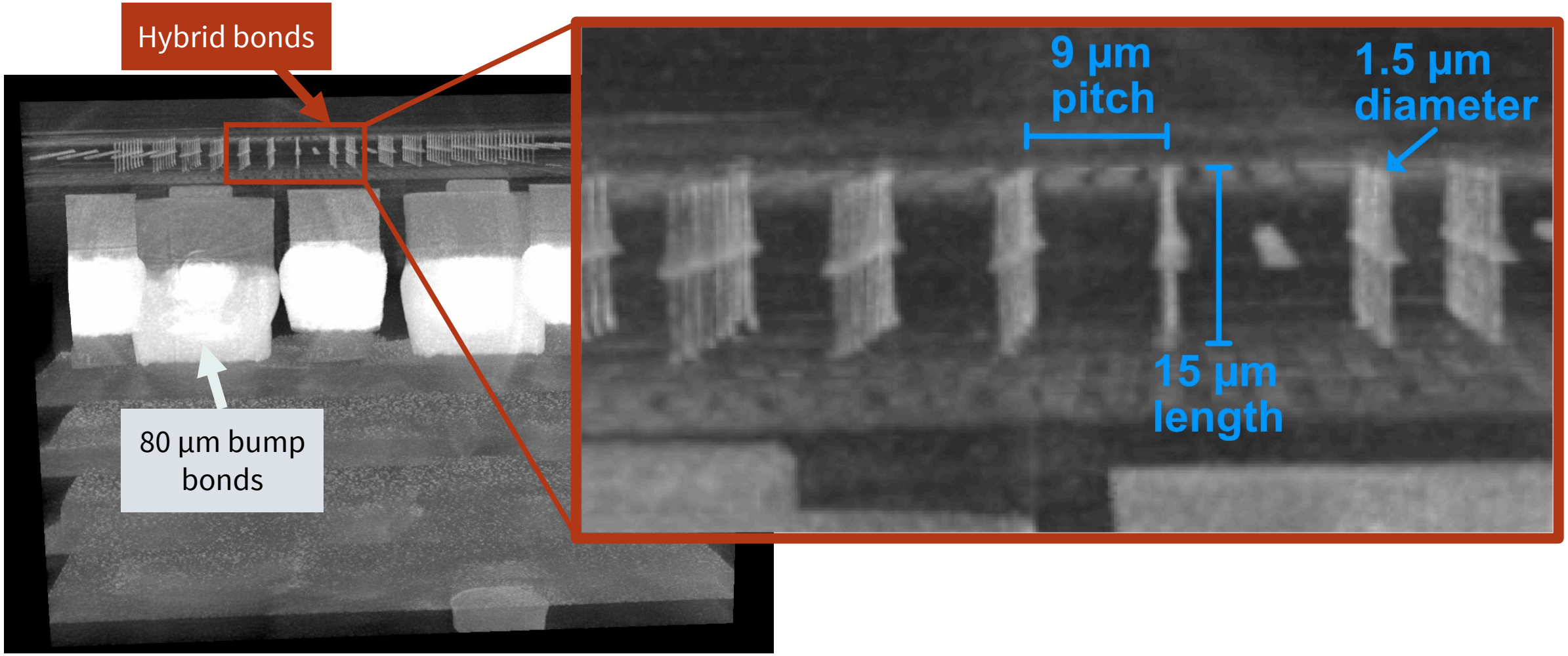
Hybrid bonding

- Geometry
  - SOD = 2.29 mm
  - SDD = 490 mm
  - p_{eff} = 350 nm
- Scan settings
  - Projections: 2160
  - Rotation: 216 degrees
  - Exposure time: 10 s
  - Scan time: 6 h
- Source settings
  - Voltage: 80 kV
  - Spot size: 500 nm

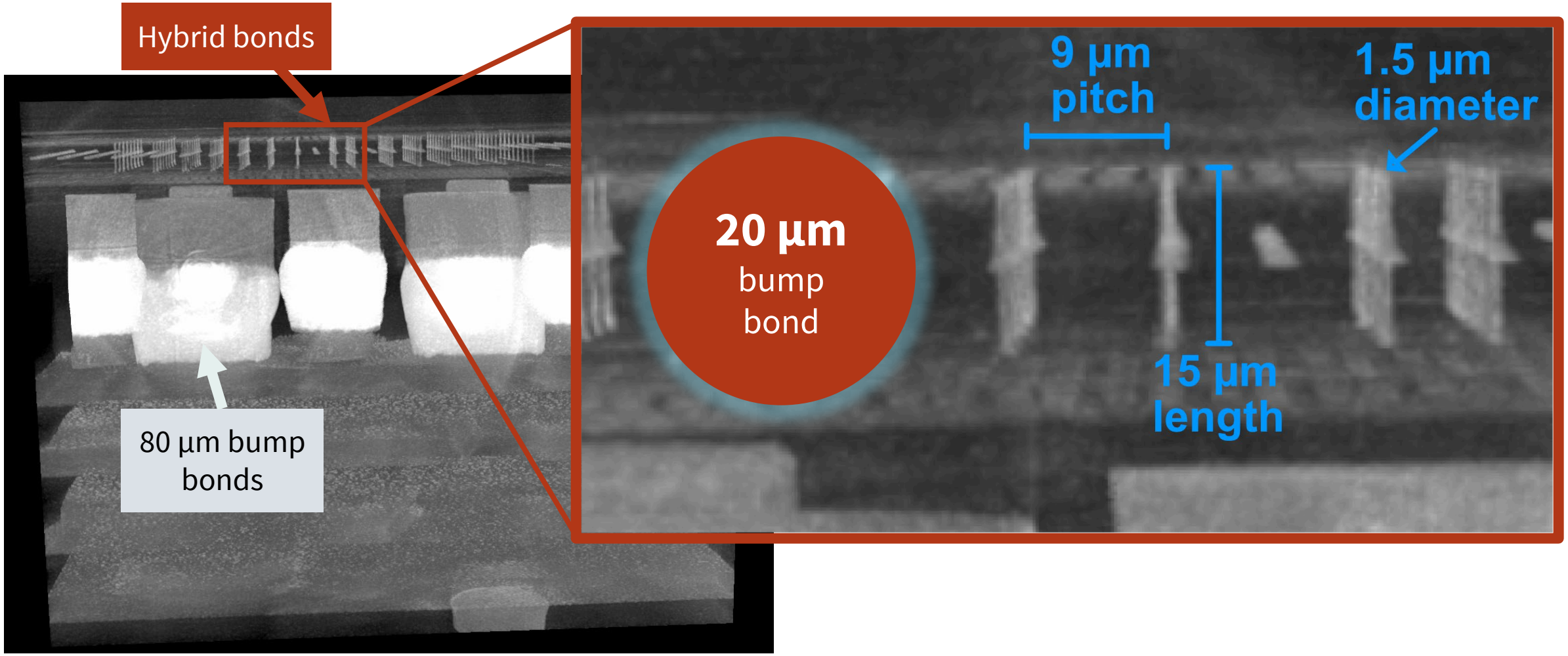




Hybrid bonding



Hybrid bonding



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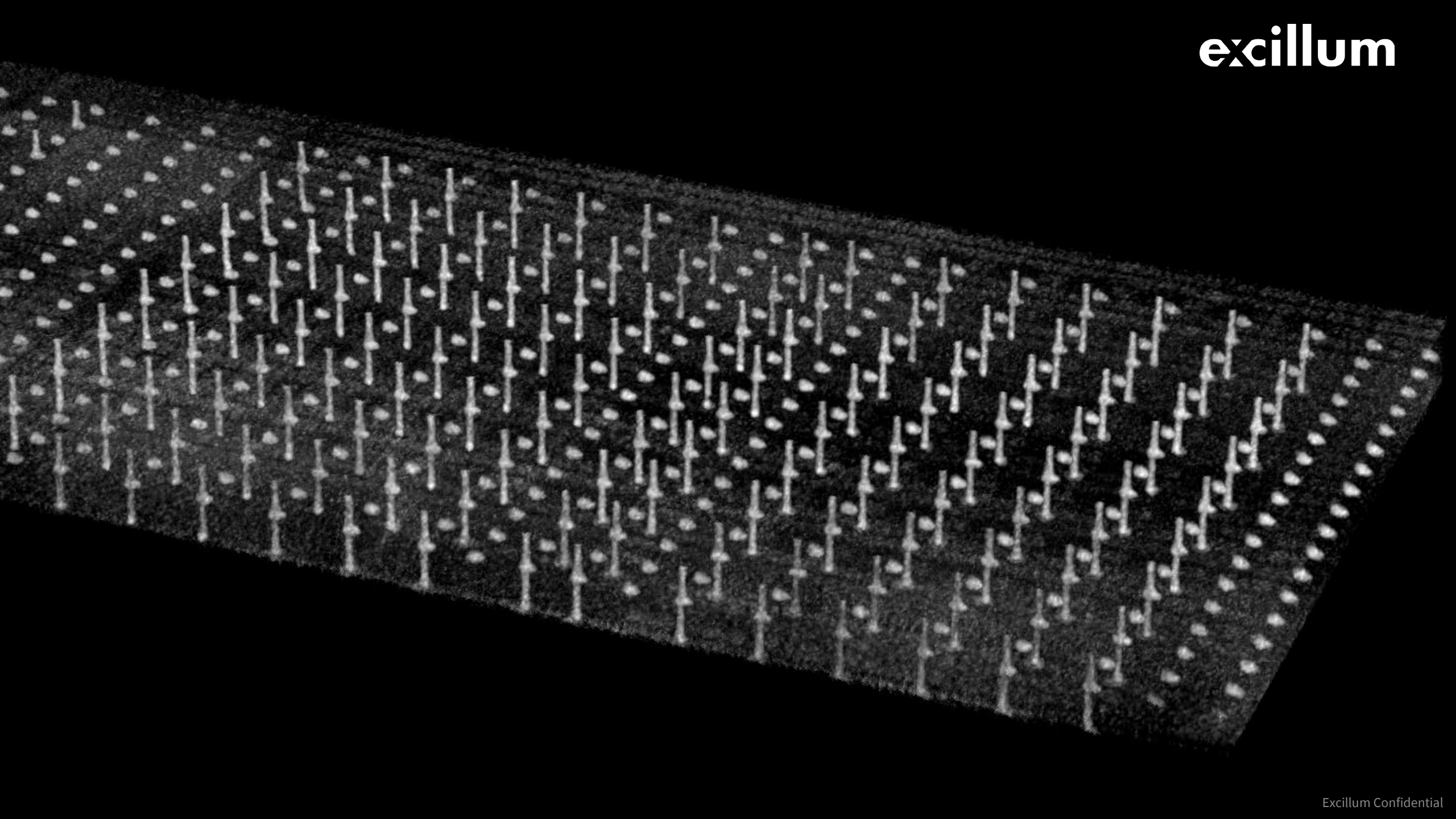
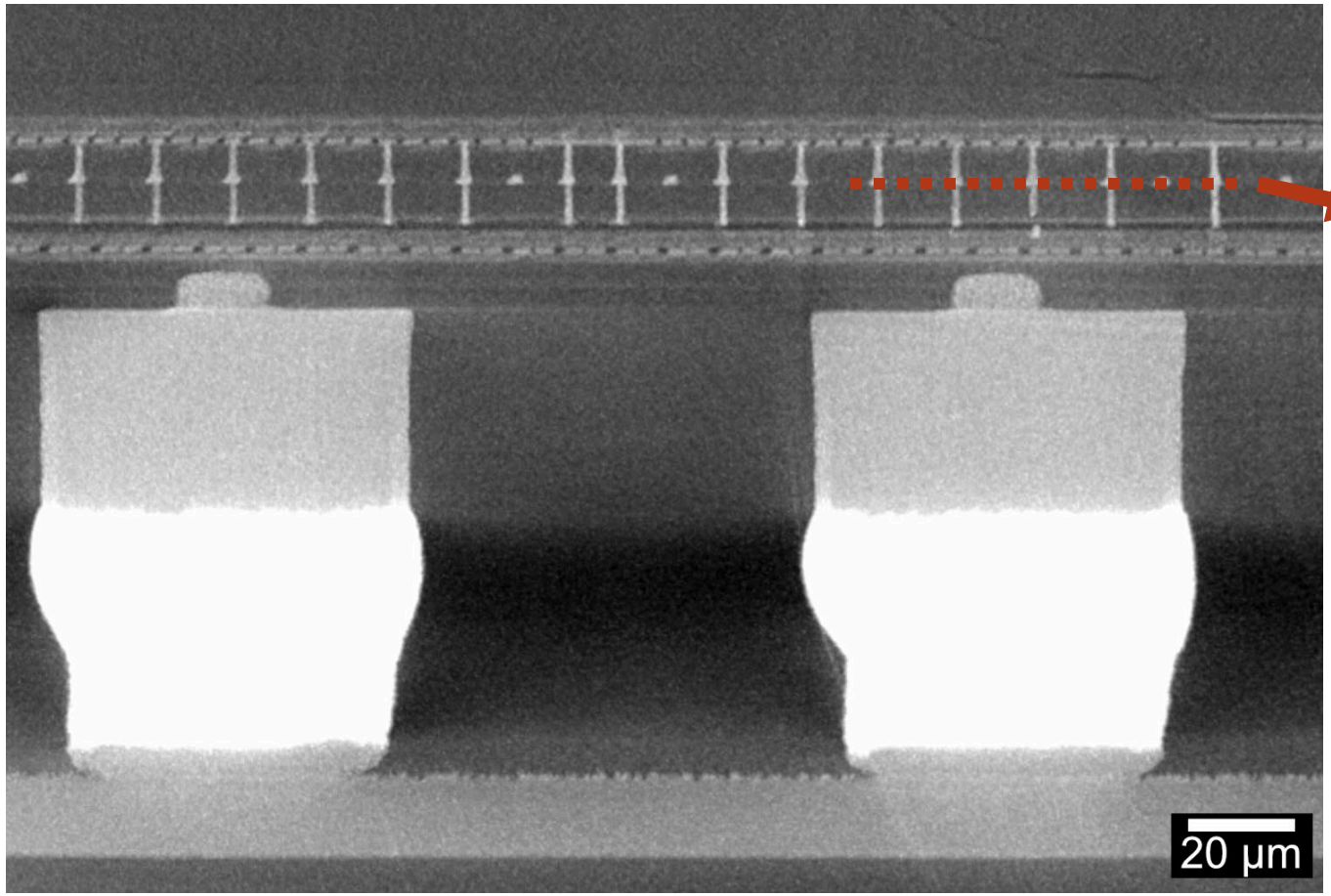
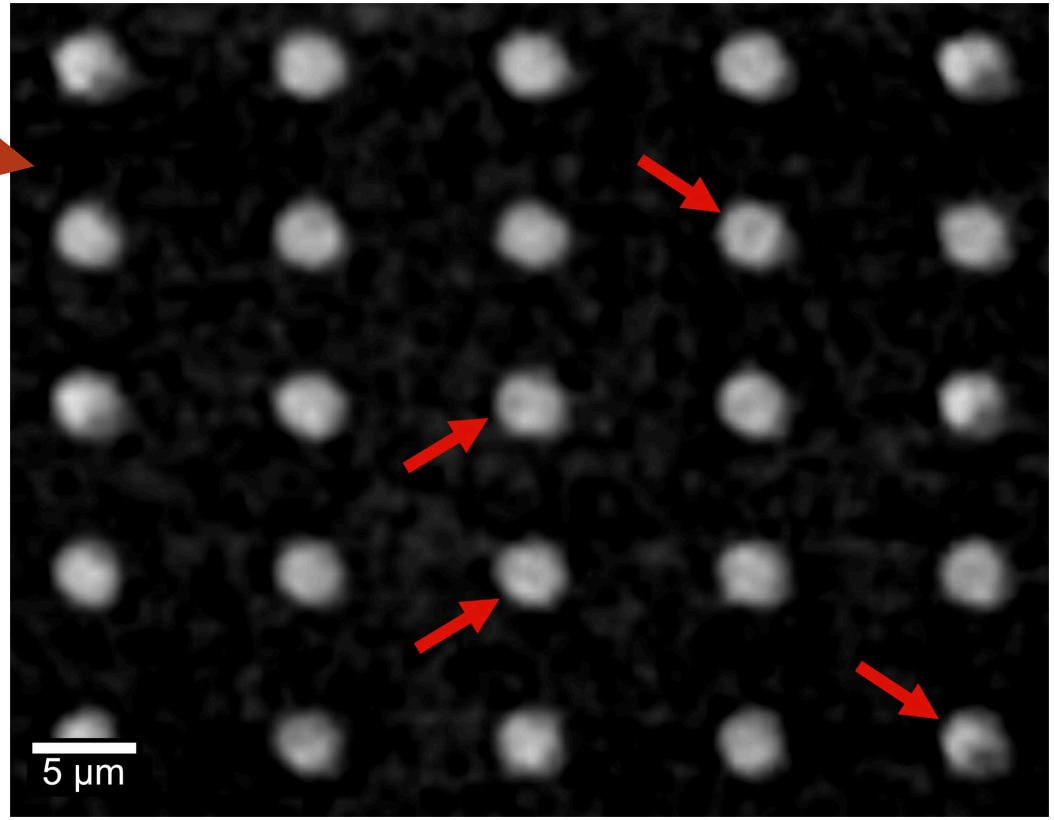


Hybrid bonding





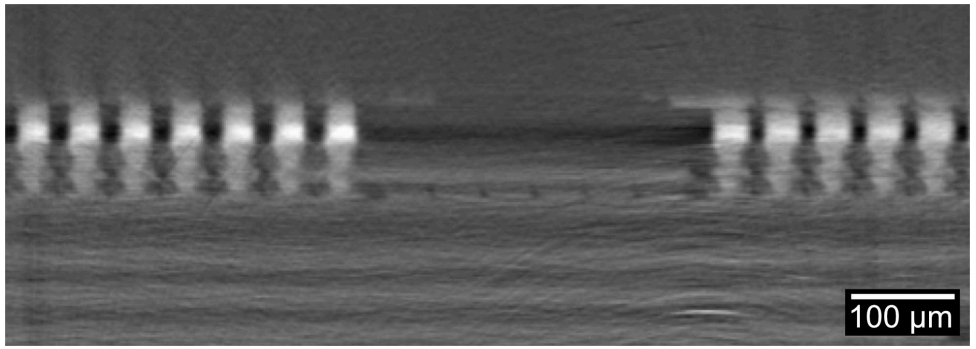
Conclusions

High resolution X-ray CT without optics

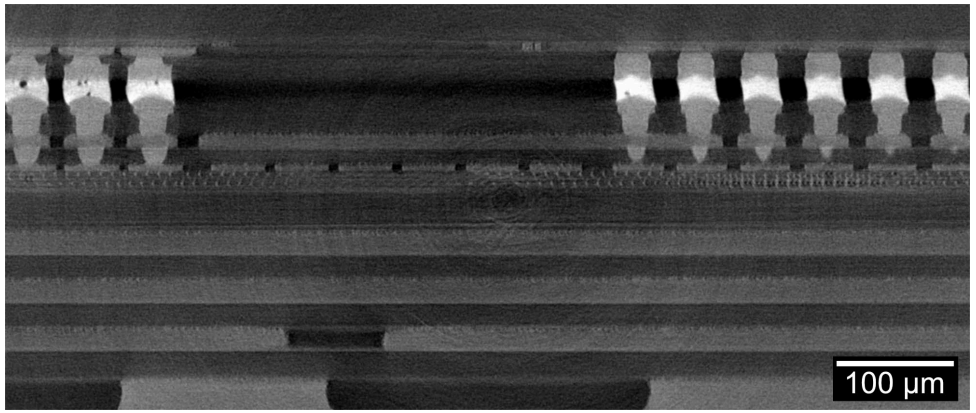
Imaging of micro-bumps and hybrid bonding

Package level failure analysis enabled by X-ray CT

Intel EMIB scanned using a Waygate Nanomex



Intel EMIB scanned using a NanoTube-based system



Acknowledgements

DECTRIS Ltd. is acknowledged for providing the used detector and their support.

HiCONNECTS project has received funding from Chips Joint Undertaking (Chips JU) under grant agreement No 101097296. Chips JU receives support from the European Union's Horizon Europe research and innovation programme and Austria, Italy, Germany, Netherlands, Israel, Finland, Switzerland, Hungary, Sweden, Turkey, France, Denmark and Romania.

The source for X-ray innovation

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Application Scientist
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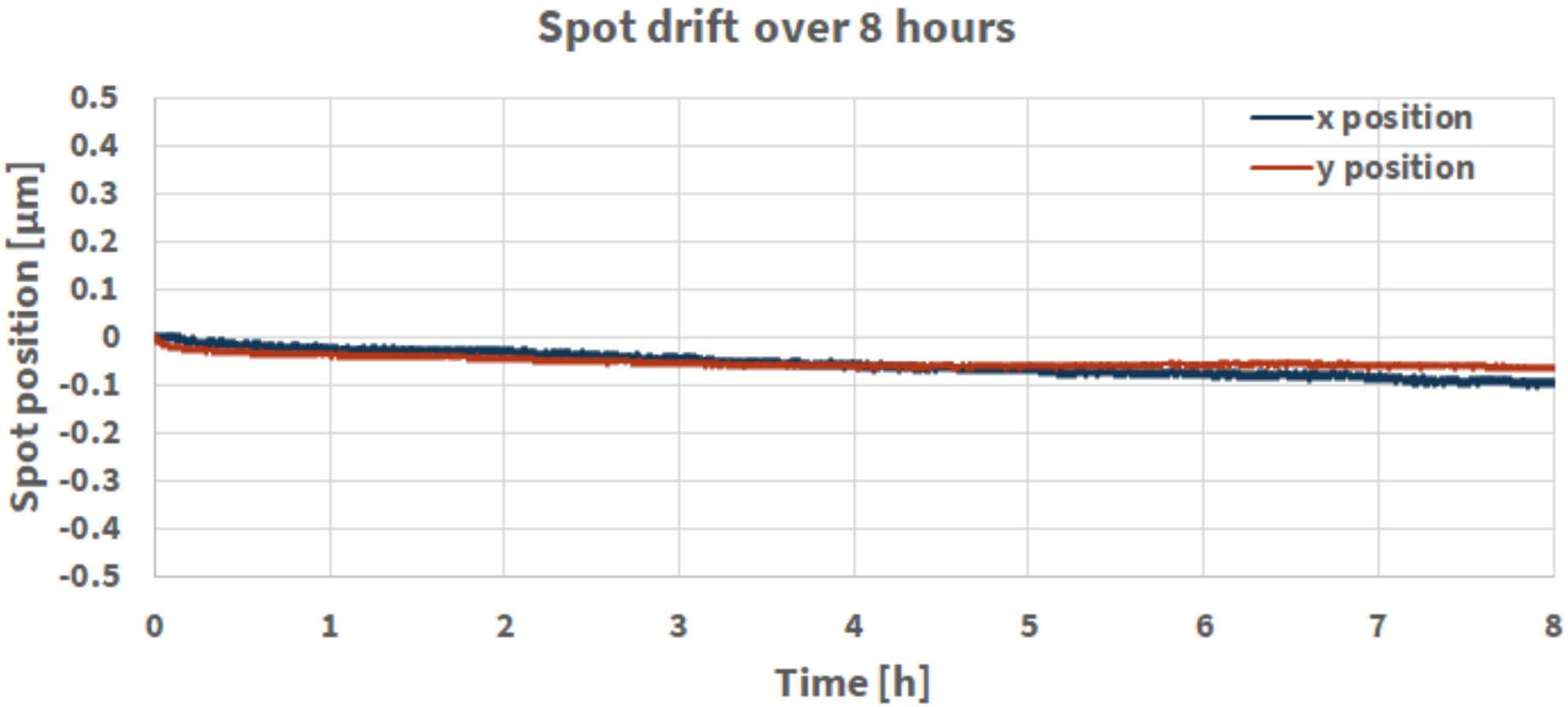
Appendix

NanoTube N3 の優れた安定性

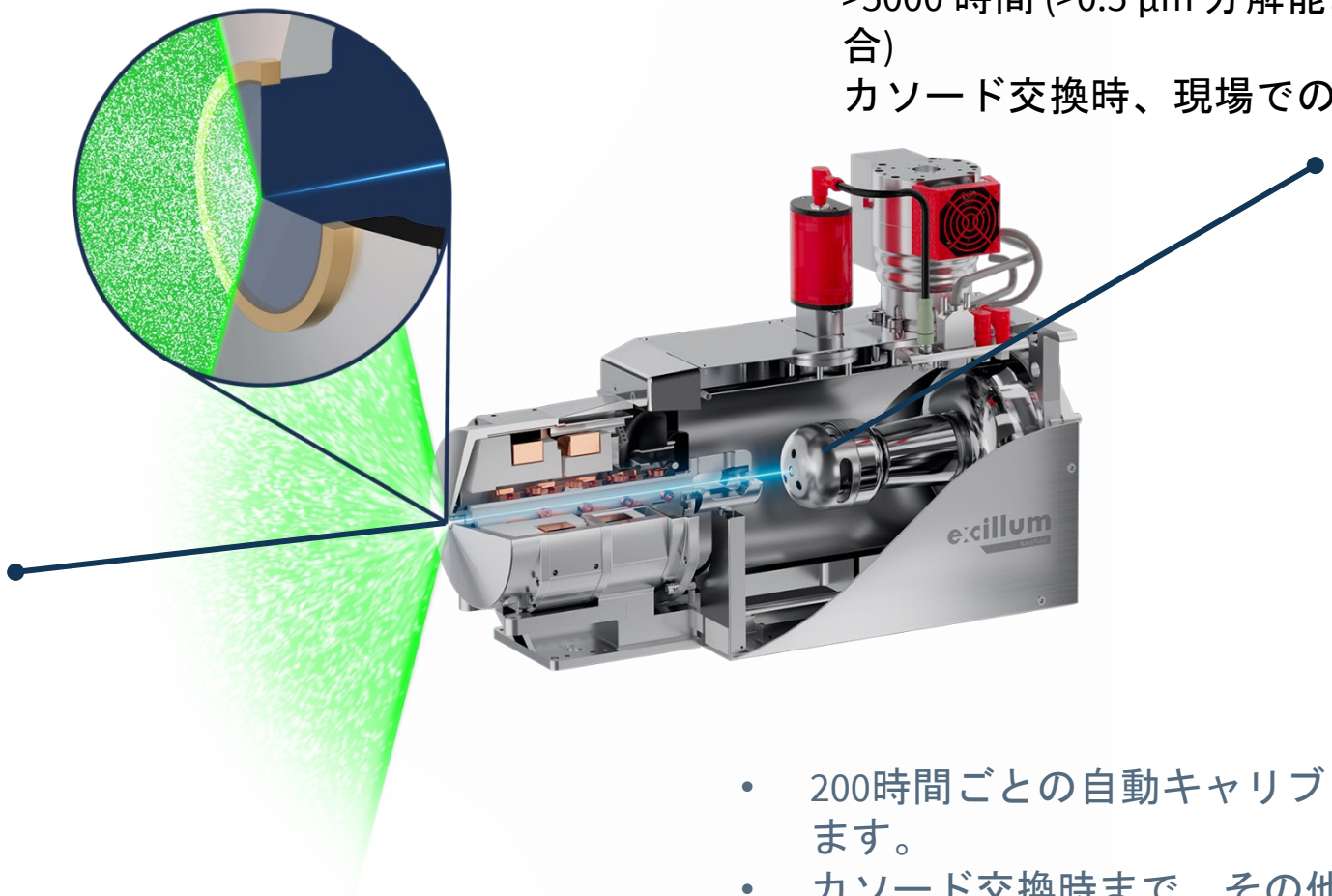


Excillum Confidential

メンテナンスが最小限の開放型X線管！

Long lifetime and minimal maintenance

ダイヤモンド上のタングステン透過ターゲットの寿命は5 年以上。



平均寿命が 2500 時間以上のカソード

>5000 時間 (>0.5 µm 分解能および >100 kV で動作する場合)

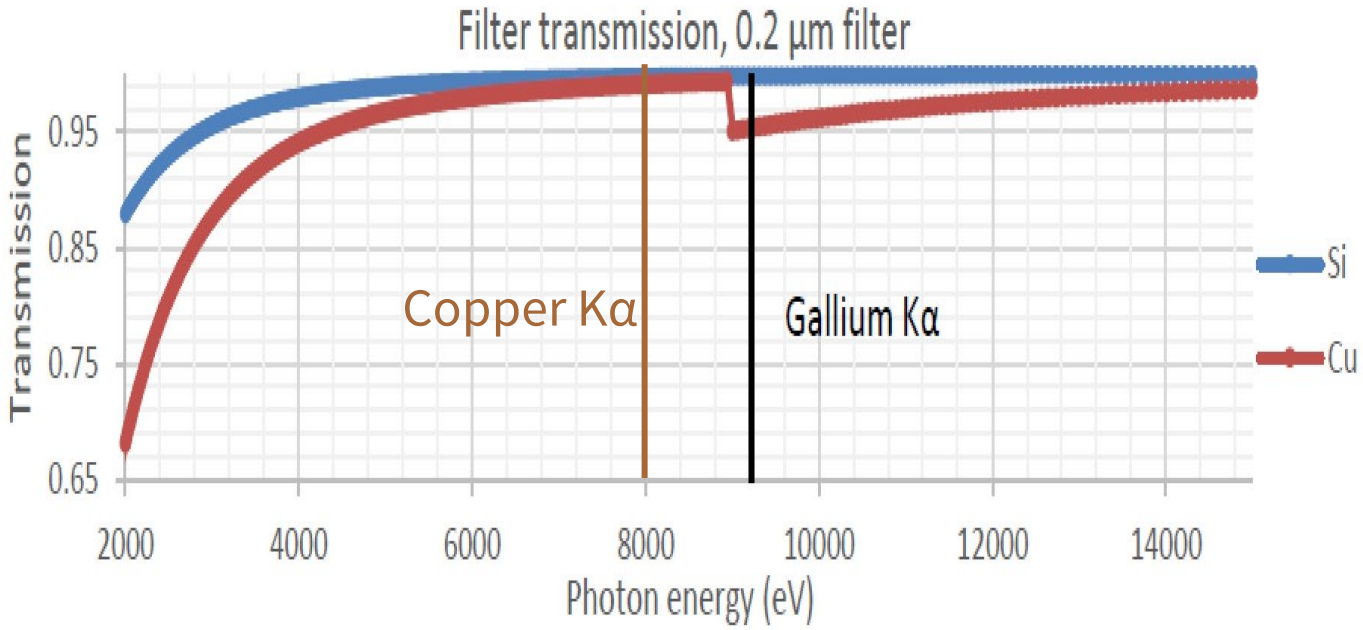
カソード交換時、現場での**ダウンタイムは 4 時間未満**

カソードの全寿命にわたり、X線管の性能は一定です。

- 200時間ごとの自動キャリブレーションを推奨しています。
- カソード交換時まで、その他のメンテナンスは必要ありません。

MetalJetを用いたX線顕微鏡

Ga による優れた Si/Cu コントラスト



Zeiss Xradia Ultraに搭載されたMetalJet D2+

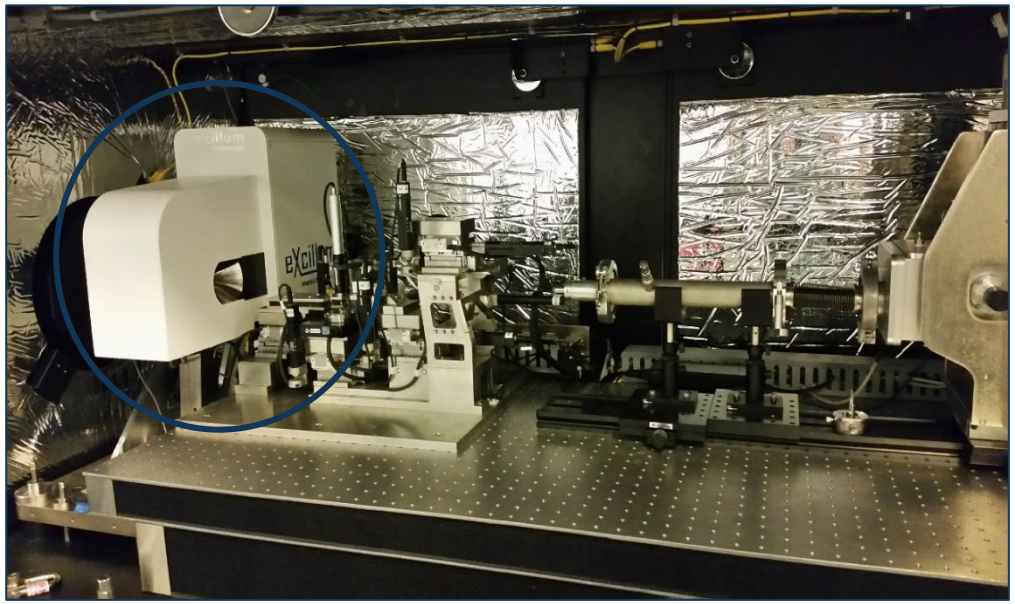
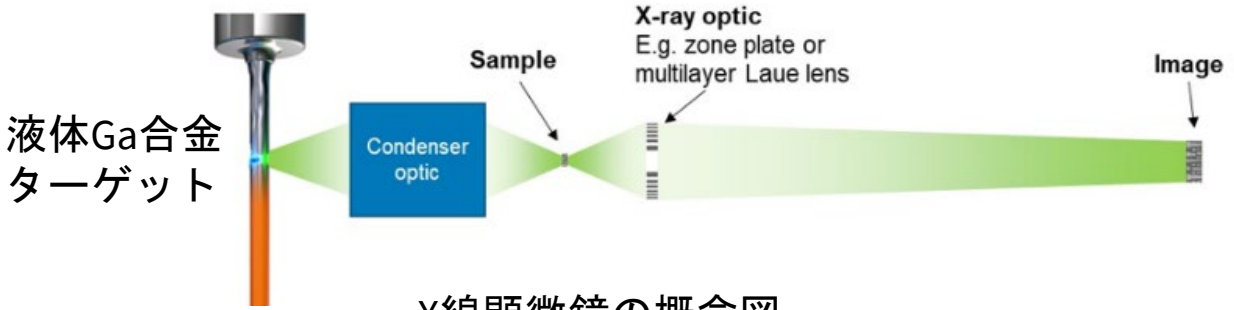
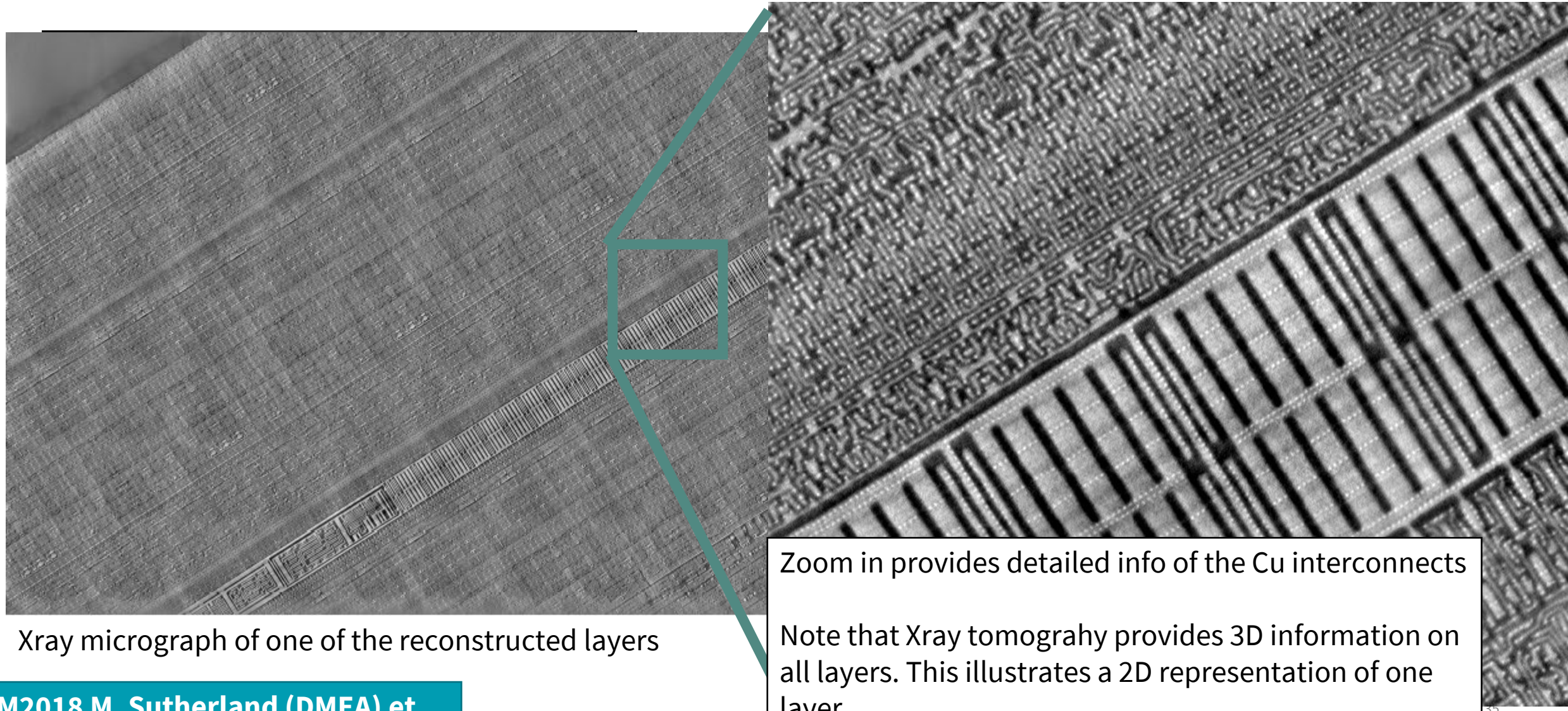


Image courtesy of Carsten Gundlach of Imaging at DTU, Denmark



X線顕微鏡の概念図

Ｘ線ＣＴによる90 nm ノードCu配線の観察 (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

パートナー企業*

ターンキーシステム販売企業

VC battery by VisiConsult *Battery inspection systems*	EXCISCOPE *Phase-contrast imaging systems*	Rigaku *Nano CT systems*
PXR PROCON X-RAY *Nano CT systems*	PROTO *High pressure XRD systems*	marXperts *Single crystal X-ray diffraction systems (protein/macro molecule)*
BRUKER *Single crystal X-ray diffraction systems (small & protein/macro molecule)*	STOE SINCE 1887 *Single crystal X-ray diffraction systems (small molecule & powder)*	Anton Paar *Small angle X-ray scattering (SAXS) systems*
xenocs Exploring the very small *Small angle X-ray scattering (SAXS) systems*	ELDICO SCIENTIFIC *Electron diffraction systems*	scientaomicron *HAXPES systems*

カスタムシステム販売企業

PROTO *Custom X-ray analytical systems (worldwide)*	Pinnacle X-Ray Solutions *Custom X-ray imaging systems (North America)*
UNITE 优纳珂科技 *Custom X-ray analytical systems (China)*	SGService *Custom X-ray systems (Taiwan)*

X線源販単体　販売代理店

PROTO *North America*	Quantum Design CHINA *China*
NanoLab KOREA *Korea*	RAD Device *Japan*

*公開可能な企業のみ掲載

デモ測定をご利用ください！

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（1）サンプルをお送りください。
　　弊社で測定して結果をお送りいたします。
（2）弊社へお越しください。
　　サンプルや普段お使いの検出器などをお持ちください。測定をお手伝いいたします。

ナノ CT

2D ナノ測定

MetalJet 高速 CT