White Paper

Nanoscale Resolution at 0.35µm with the

Apex-Hybrid

Laminography and Tomography System

The Sigray Apex-Hybrid combines ultrahigh-resolution x-ray microscopy and a patented laminography technique in one flexible system. It allows users to choose between scanning large, flat samples efficiently or achieving high-quality images of smaller samples.

This white paper will review the design innovations behind Apex-Hybrid.

Quantum Design
1 avenue de l'Atlantique
Bâtiment Fuji-Yama
91940 Les Ulis - France

Tél. : +33 1 69 19 49 49
france@qd-europe.com
www.qd-europe.com

Nanoscale Resolution at 0.35µm with the Apex-Hybrid

Authors: Sylvia Lewis, Dr. Wenbing Yun, Jeff Gelb | Sigray, Inc.

System Overview: Sigray Apex-Hybrid is a dual-mode x-ray system designed for both the laminography of large, flat samples and ultrahigh-resolution microtomography of conventional samples. It offers several key advantages:

- **Highest resolution:** Achieves <400 nm resolution with high throughput in both modes.
- **Superior image quality:** Minimizes laminography artifacts with Precision Angle Laminography™ (PAL) technology.
- **Fast imaging:** Performs 3D x-ray scans in as little as a few minutes for samples ranging from small components to large PCBs.

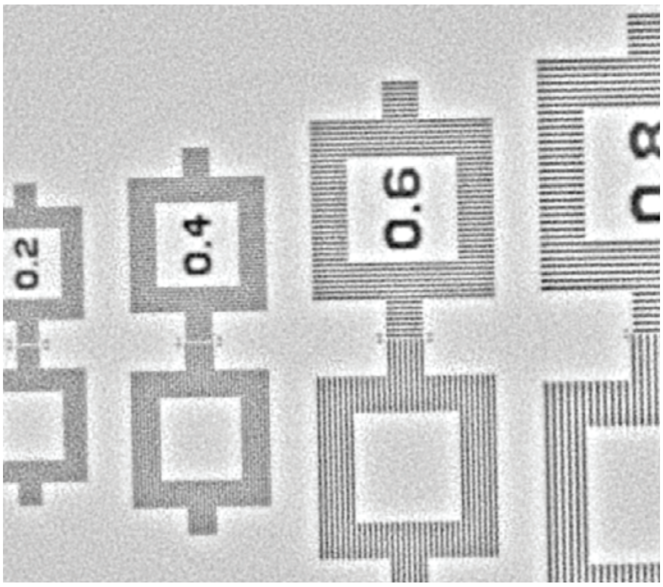

Figure 1: A cross-sectional slice from a 3D tomography dataset of an NTT resolution standard with line pairs, showing <0.4 µm (<400 nm) spatial resolution capabilities. The image was acquired in laminography mode on the Apex-Hybrid.

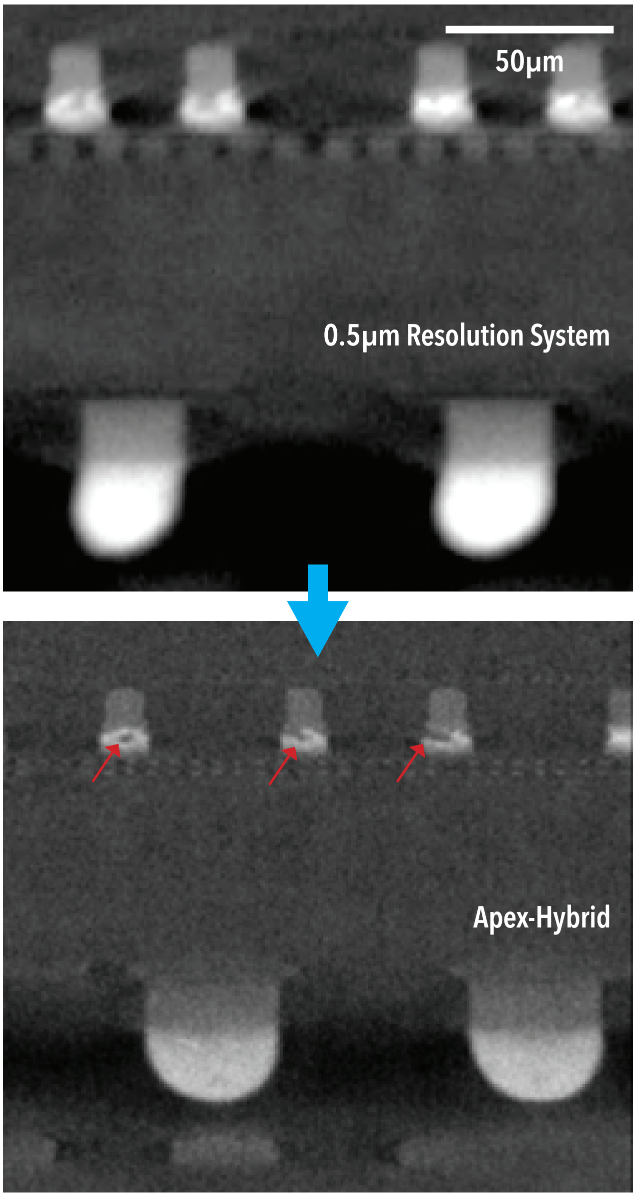

Figure 2: The Apex-Hybrid system delivers superior image quality and resolution compared to other leading systems. This image shows the same sample captured in laminography mode on the Apex-Hybrid at a low slant angle (15 degrees). Red arrows highlight defects clearly detected with the Apex-Hybrid.

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Background

The Apex-Hybrid was originally developed to address challenges in semiconductor failure analysis, where laboratories work with everything from large PCB boards and heterogeneous packages to small, trimmed samples. It seamlessly switches between two imaging modes to enable:

- **Laminography mode** for imaging intact, large samples.
- **Tomography mode** for high-resolution, artifact-free imaging of smaller samples.

Beyond semiconductors, the system also benefits biological and geological research (handling both thin sections and cylindrical/amorphous samples), as well as central research labs, where sample diversity is a constant challenge.

Figure 3A

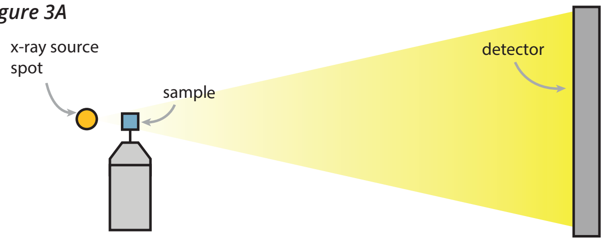

Figure 3B

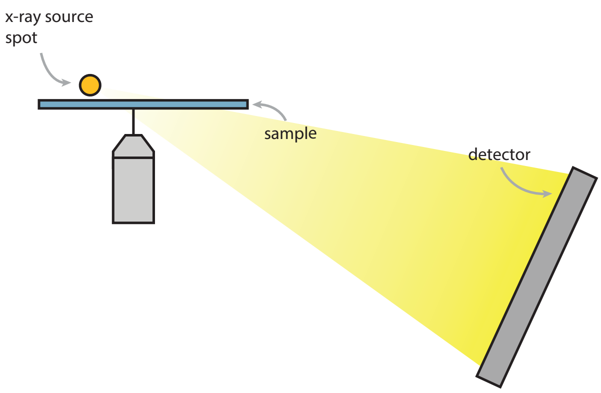

Figure 3: *The Apex-Hybrid switches between tomography (Fig. 3A) and laminography (Fig. 3B) modes. The source and detector are both on rotating gantries, allowing the x-ray beamline to pivot around the sample. The two-in-one design provides enhanced capabilities without the added cost of a second x-ray source and detector.*

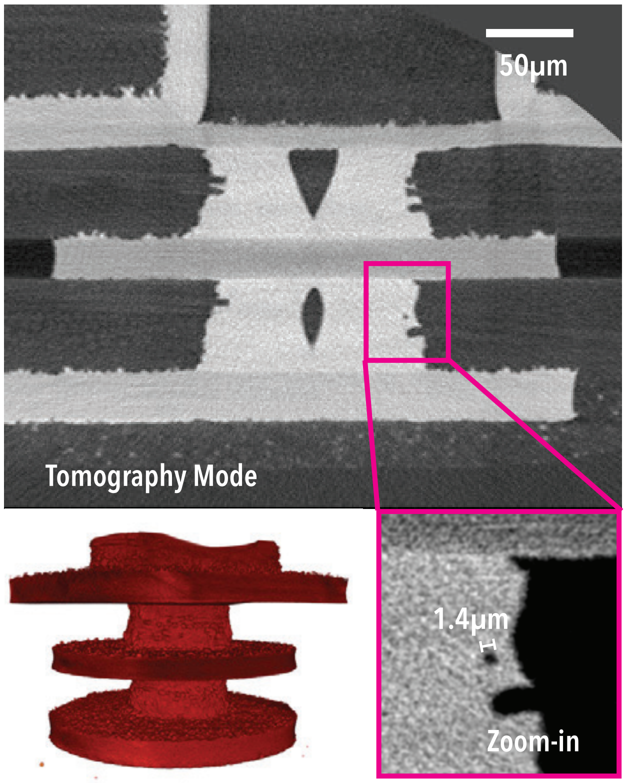

Figure 4: *A memory device was acquired at 0.27 µm in tomography mode on the Apex-Hybrid. Fine details, such as burrs, are visible, and a ~1 µm defect is clearly resolved.*

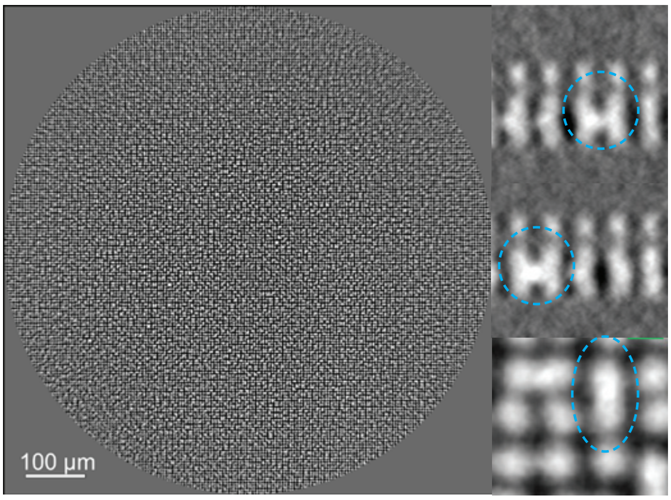

Figure 5: *A large array of 5 µm diameter TSVs on a 300 mm wafer is shown. The full FOV appears in the left image, while bridging—highlighted with teal dotted circles—is visible in the three zoomed-in images on the right.*

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A New Architecture: Precision Angle Laminography (PAL)

For laminographic acquisitions, the Apex-Hybrid employs its patented [1] Precision Angle Laminography (PAL) method, which significantly enhances image quality compared to traditional laminography.

PAL achieves superior performance through two key design advantages:

- **Smaller slant angles** to minimize artifacts.
- **Precise motion control** to enhance mechanical resolution.

Conventional Laminography Approaches: To understand how PAL differs from traditional laminography, it's important to first review two common designs:

1. **Fixed Source, Rotating Sample** (Fig. 6): An x-ray source is placed beneath a rotating stage that moves the sample during imaging. Achieving shallow slant angles requires a large rotary stage aperture, but this weakens structural integrity due to mechanical and machining constraints. Accommodating large samples, like 300 mm wafers, would demand an impractically large aperture and system footprint. As a result, most manufacturers use smaller apertures, significantly limiting achievable slant angles (measured from the sample surface to the optical axis, as shown in Fig. 6).

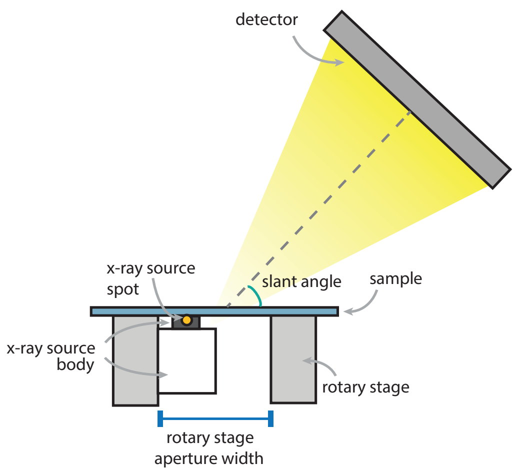

Figure 6: Conventional geometry, in which the sample moves, uses a rotary sample stage. This approach limits acquisitions to larger slant angles due to the restricted rotary stage aperture width.

2. **Moving Source and Detector, Fixed Sample** (Fig. 7): In this approach, the sample remains stationary while the x-ray source and/or detector move around it. This allows for an x-ray-transparent sample stage but requires heavy components (e.g., the x-ray source) to rotate at high speeds, making submicron precision difficult. The mechanical instability from these rapid movements reduces resolution and limits how close the source and detector can get to the sample, restricting the minimum slant angle.

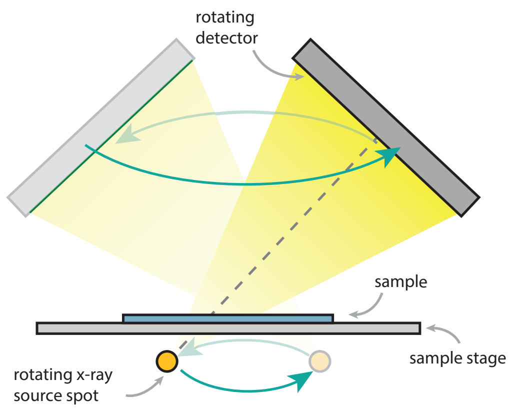

Figure 7: Conventional geometry that involves moving the source and/or detector faces challenges due to their heavy weight. This makes it difficult to achieve submicron smooth motion, thereby limiting resolution.

Apex-Hybrid's PAL Architecture

The patented PAL architecture overcomes these limitations by using a **fixed** x-ray source and detector, with the sample placed on a **high-precision air-bearing rotary stage**. Unlike standard mechanical rotary stages, which rely on bearings, are prone to wobble, and require maintenance, air-bearing stages use a cushion of compressed air for near-zero wobble.

To maximize the benefits of the air-bearing stage, Apex-Hybrid positions the x-ray source above the sample, which is mounted on a carbon fiber holder. This design elevates the sample above the rotary stage (Fig. 8), allowing for:

- **Shallow slant angles (10–20°)**: The elevated sample avoids aperture constraints.
- **Close source proximity:** Enhances spatial resolution.
- **Stable imaging:** A stationary source and detector prevent mechanical limitations on resolution.

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91940 Les Ulis - France
Tél. : +33 1 69 19 49 49
france@qd-europe.com
www.qd-europe.com
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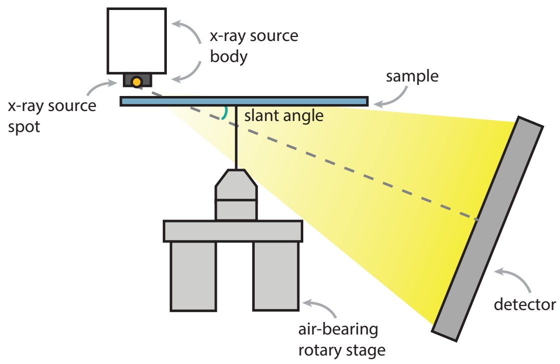

Figure 8: *Sigray's PAL geometry enables the use of an air-bearing rotary stage by employing a sample mount that offsets the sample from the stage. This design allows for slant angles as shallow as 10°.*

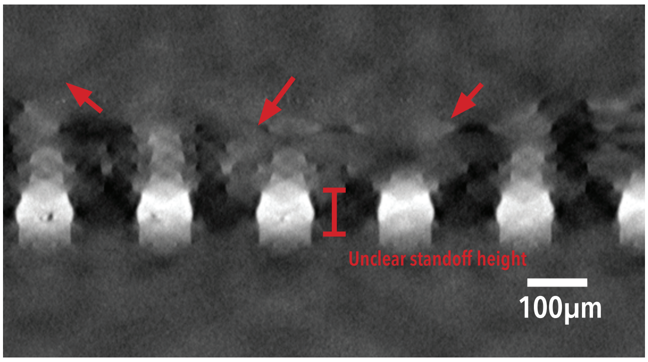

Figure 10A: *Laminography at a standard 30° slant angle: Angled "streak" artifacts (red arrows) are present, making it difficult to measure stand-off heights (SOH) and distinguish RDL layers.*

Why are Small Slant Angles Desirable?

Shallow angles reduce laminographic artifacts, particularly the **"missing cone" effect** in Fourier space (Fig. 9). The cone's angle relative to the Y-axis corresponds to the slant angle—shallower angles result in less missing data.

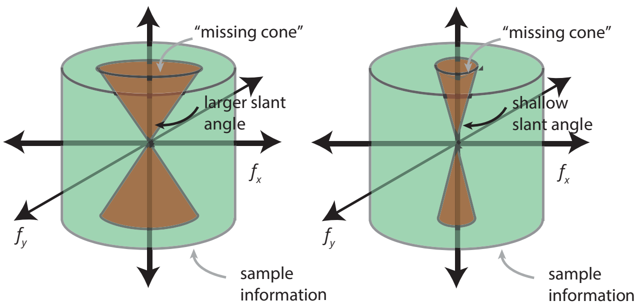

Figure 9: *Laminographic acquisition creates a "missing cone" in Fourier space, similar to the "missing wedge" in limited-angle tomography [2]. Shallower slant angles result in a smaller "missing cone" (right). The missing cone angle depends on the slant angle.*

Laminographic artifacts primarily affect vertical cross-sections rather than horizontal ones, as shown in Figure 10:

- **Fig. 10A:** Conventional laminography, which typically achieves only 30–40° slant angles, shows significant limitations.
- **Fig. 10B**: PAL's low slant angles provide clearer imaging.

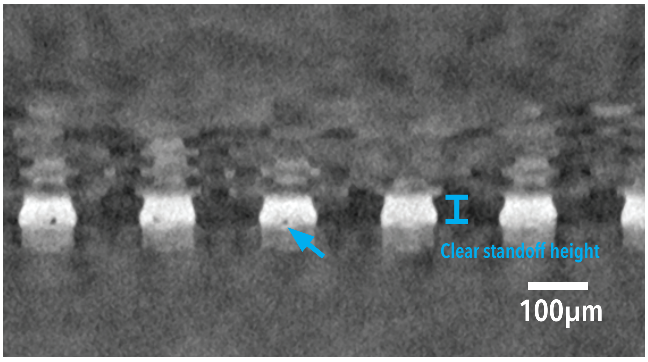

Figure 10B: *Apex XCT image at a low 13° slant angle: Laminographic artifacts are reduced, making RDL layers clearer. A blue arrow highlights a void that is more visible at this angle and might have been missed at a higher slant.*

While shallower angles reduce artifacts, they also increase the material thickness that x-rays must pass through, potentially lowering throughput. However, these artifacts are less problematic for vertical features like TSVs and hybrid bonds, as their Fourier transformation falls outside the "missing cone." A slant angle of around 20° often provides a good balance.

Apex-Hybrid Comparison to Other Sigray Products

Sigray offers three advanced 3D x-ray product lines: Apex, Apex-Hybrid, and EclipseXRM, each with distinct capabilities. Since Apex-Hybrid integrates features from both Apex and EclipseXRM, understanding their differences is essential.

Apex XCT (Laminography) and Apex-Hybrid:

Capability	ApexXCT	Apex-Hybrid
Spatial Resolution	500-600 nm	350 nm
Aqusition Modes	Laminography	Laminography Tomography
Max XYZ Stage Travel	300 mm diameter (Theta-R-Theta Stage)	100 x 20 x 100 mm (XYZ Stage)
EFEM for In-line Use	Yes	On the Roadmap
X-ray Source	Sealed Tube 25 W	Open Tube 16 W

Table 1: *Apex XCT and Apex-Hyrid Comparison.*

The benefits of Apex-Hybrid, outlined in the table, include:

- Higher resolution
- Dual imaging modes: Tomography & laminography
- Lower cost of ownership with an open tube design

Trade-offs include:

- No EFEM integration (yet), but supports an in-system robot for scanning up to ten 100 × 100 mm samples
- Reduced maximum x-ray source power
- Smaller stage travel, but can still scan 300 mm wafers using manual positioning and 100 mm motorized fine-stepping

EclipseXRM (Tomography) and Apex-Hybrid:

Capability	EclipseXRM	Apex-Hybrid
Spatial Resolution	300 nm	350 nm
Aqusition Modes	Tomography	Laminography Tomography
Detector	Dual Detectors (Up to 27 MP)	Single Detector (Up to 13 MP)
Max XYZ Stage Travel	10 x 70 x 100 mm (XYZ Stage)	100 x 20 x 100 mm (XYZ Stage)
X-ray Source	Open Tube	Open Tube
Source-Detector Dist (Geo Mag)	1,300 mm	650 mm

Table 2: *EclipseXRM and Apex-Hyrid Comparison.*

EclipseXRM and Apex-Hybrid are built on distinct system architectures, leading to significant differences:

- **EclipseXRM:** Optimized for high geometric magnification with a long source-detector distance, making it ideal for imaging small samples to large specimens (e.g., monkey skulls). It supports dual detectors—a LFOV detector for wide views and a small-pixel detector for high-resolution imaging at large working distances.
- **Apex-Hybrid:** Designed for maximum flexibility, offering high-quality, high-throughput imaging of large, flat samples while also enabling ultrahigh-resolution tomography.

Summary:

Apex-Hybrid bridges the capabilities of Apex and EclipseXRM, offering higher resolution, dual imaging modes, and cost-efficient operation.

X-ray Detector Options

Options for FOV and Resolution

Apex-Hybrid offers three detector choices (Fig. 11), each optimized for specific imaging needs:

- **HyperCapture (Standard 7MP):** Provides a fast 15 fps readout with a thick, ultra-high efficiency structured scintillator for optimal imaging performance.
- **HyperCapture-XL (13MP):** An extended version with ~2X the field of view (FOV) while maintaining the same 15 fps readout speed. The larger detector improves metrology precision for features like microbumps by increasing statistical accuracy.
- **UltraVision (16MP):** A small-pixel detector designed for the highest-resolution applications, such as single-digit micron TSVs. While it enables ultrasmall voxels, it has lower efficiency at higher x-ray energies compared to HyperCapture. As a result, UltraVision is typically operated in BIN2 mode, reducing its pixel count from 16MP to an effective 4MP, which impacts FOV at resolution.

Due to system space constraints, only one detector can be selected per system. For assistance in choosing the right option for your applications, contact your local Sigray representative.

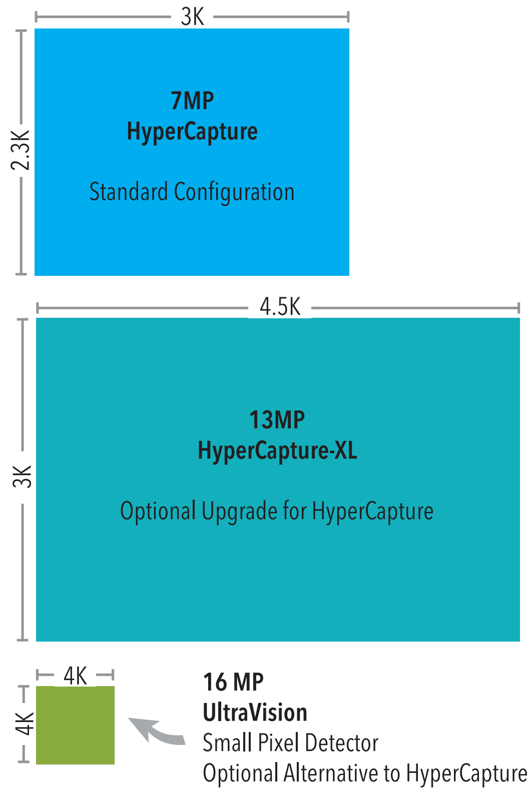

Figure 11: *Multiple detector options are available on Apex-Hybrid. The standard 7MP HyperCapture provides a large FOV. Two optional detectors include HyperCapture-XL (13MP) and UltraVision, a small-pixel detector. Sizes are provided to illustrate scale.*

MegaView Montage Package

For applications requiring a large field of view (FOV) at high resolution—such as reverse engineering 100 mm boards at micron-scale resolution—Sigray offers the MegaView™ montage package. This feature stitches multiple FOVs to create seamless, large-scale 3D datasets.

Example (Fig. 12): A PCB was imaged in 20 fast acquisitions and **seamlessly stitched** using MegaView. More details are available in Sigray's application note, "*Montage Imaging of Large Fields of View*" [3].

Note: Due to the large dataset sizes produced by MegaView (often hundreds of gigabytes), Sigray recommends upgrading computer RAM to 512 GB or 1 TB.

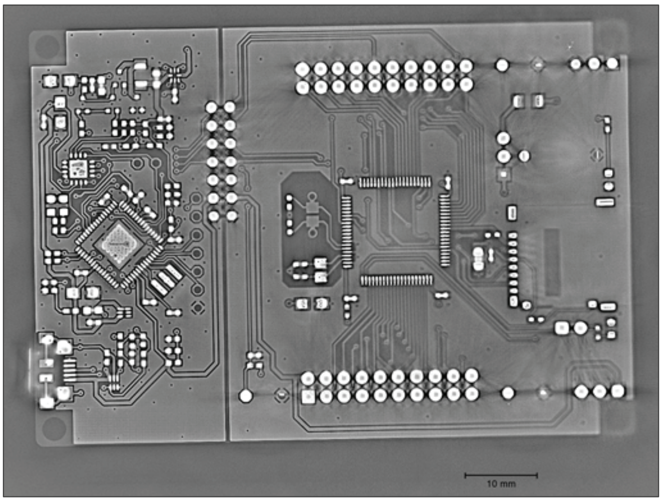

Figure 12: *An intact PCB was imaged at high resolution using Sigray's Montage Package. Additional details can be found it in the associated applications note [Ref. 3].*

X-ray Source Advantages

Always Know Your Resolution: X-ray Source Calibration

One challenge for metrology-focused users of x-ray microscopes is that, while the ***voxel*** size of a scan is easily determined, the actual ***spatial resolution*** is often unknown. For instance, a scan with a voxel size of 0.1 μm can have a spatial resolution up to 50 times worse—around 5 μm—due to penumbral blur caused by a larger x-ray source spot size. Thus, accurately determining the x-ray source spot size and astigmatism is critical. Unfortunately, this is a difficult task.

To address this, many x-ray imaging users traditionally rely on purchasing and using x-ray resolution calibration targets. These targets are used to measure resolution as the x-ray source ages and may change in resolution. However, this approach requires additional scans and analysis time, reducing the time available for scanning other samples.

Apex-Hybrid solves this challenge with a novel x-ray source that incorporates microstructured x-ray targets as internal calibration patterns. This innovation enables precise determination of the x-ray spot size for each scan. Users can simply select a desired x-ray spot size in the software to optimize both resolution and scan time. Since the x-ray spot size, detector pixel size, and distances are all known, the exact spatial resolution can be accurately calculated.

Long X-ray Source Lifetime

A key advantage of Apex-Hybrid's x-ray source is its innovative electron optics design, which extends cathode life to several thousand hours—far longer than the few hundred hours of standard open tubes. Since cathode replacements are much cheaper than replacing an entire x-ray tube, this makes Apex-Hybrid's unique open tube more cost-effective than nanofocus sealed tubes. Additionally, open tubes allow for x-ray target replacements, and in principle, their bodies can last indefinitely.

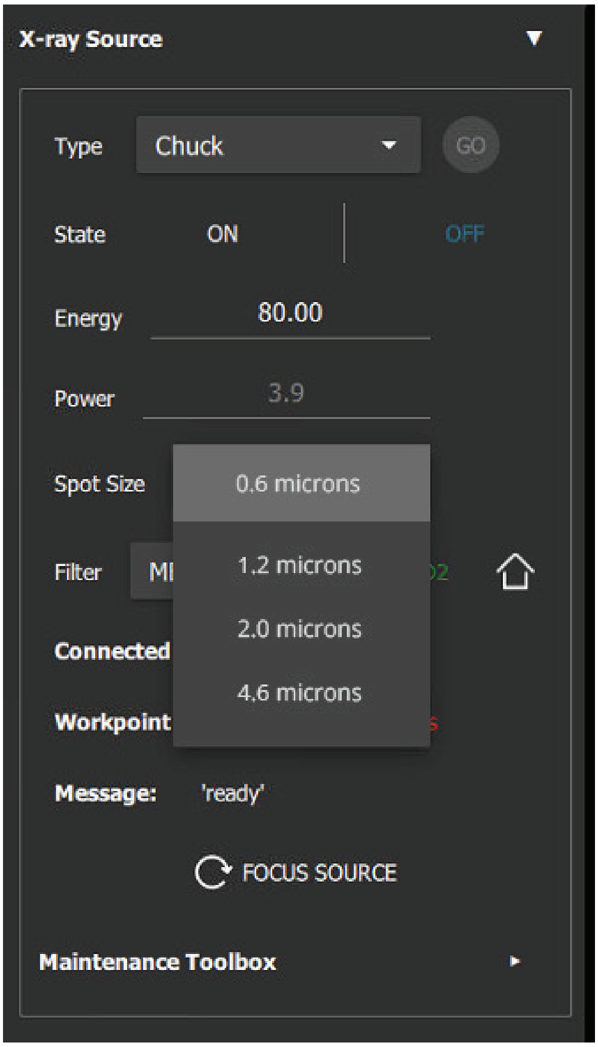

Figure 13: *Users can select from different preset x-ray source spot sizes. A patented internal calibration procedure within the x-ray source ensures that the spot size is accurate.*

Automation and Software Features

Automation for Operatorless Sample Exchange

Apex-Hybrid offers two automation options for unattended, recipe-driven scanning:

1. **Sample Handling Robot** – A robot and 10-slot cassette (for samples up to 100 × 100 mm) are mounted inside the chamber for automated sample handling.
2. **Virtual Robot** – For smaller samples, Apex-Hybrid uses its large stage travel to shift between positions, enabling automated scanning without a physical robot. The standard XYZ stage provides 100 × 20 × 100 mm travel.

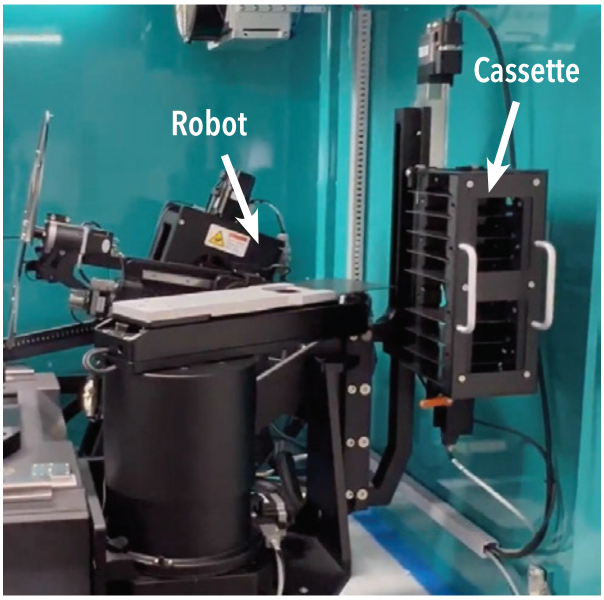

Figure 14: *An in-system sample handling robot (SHR) enables unattended, recipe-based scanning for up to ten 100 × 100 mm samples.*

Software

Apex-Hybrid provides a powerful suite of software that includes:

- **XRM Companion:** User-friendly software for setting scan parameters.
- **3D Viewer:** Includes five licenses per system, allowing multiple users to render 3D images, view 2D cross-sections, and analyze dimensions.
- **GigaRecon:** The fastest multi-GPU reconstruction software, using standard and iterative methods with artifact suppression. More details in Sigray's white paper on Advanced X-ray Software [3].
- **Open Source Controls:** Supports Python scripting (PyEpics) for reconstruction and hardware integration. More details in Sigray's white paper on Advanced X-ray Software [3].

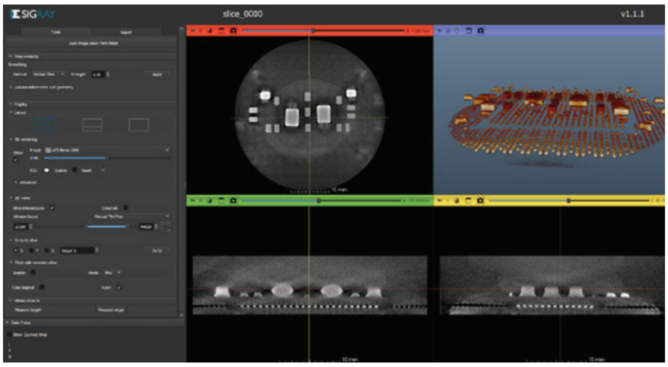

Figure 15: *Sigray 3DViewer offers a user-friendly interface for analyzing Apex-Hybrid's 3D data.*

Apex-Hybrid Specifications

Parameter	Specification
Spatial Resolution	<100 nm pixel resolution 400 nm spatial resolution (350 nm achievable)
Imaging Modes	Transmission PAL (Precision Angle Laminography)
Source(s)	Open transmission x-ray tube with long-lifetime and internal resolution calibration
Target	Microstructured Tungsten on diamond
Power & Max Voltage	16W, 160 kV
X-ray Detectors	HyperCapture - Standard Flat Panel detector: 7MP with 50 µm pixels Larger format (13MP) or smaller pixel (16MP) available (options).
Stages	State-of-the-art Air Bearing rotary stage with minimal runout Sample positioning stage with 100 x 20 x 100 mm XYZ travel
Automation	In-system Sample Robot | 10 samples of 100 x 100 mm dimensions
Workstations	Windows II Pro User PC Linux-based Control System
Software	Acquisition: XRM Companion User Friendly GUI Reconstruction: Sigray GigaRecon - Fastest reconstruction algorithm on the market. Open-source Controls and Open File Formats Optional Auto-Recon Package and MegaView Montage Advanced Analysis: Optional Dragonfly 3D World and/or Avizo Data Analysis

References

1. Patents: US 11/686,692; 12/153,001; 11/992,350.
2. M Holler. Nature Electronics 2019.
3. Sigray White Paper*: D Vine et al. Advanced 3D X-ray Software: GigaRecon.

Quantum Design

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Bâtiment Fuji-Yama
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