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Multibeam 3D X-ray microscopy with polycapillary optics and EIGER2 R detector

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Application Note

Introduction

Due to their ability to penetrate deeply into matter, short wavelength X-rays provide a unique means to visualize internal structures of objects with a high spatial resolution. Recently, submicron spatial resolution was achieved in a novel 3D imaging setup, developed by the X-ray optics laboratory (optiXlab) at Jagiellonian University in Kraków. This new lab instrument for high-resolution 3D imaging relies on polycapillary optics [1] and a photon-counting hybrid pixel detector to generate and detect up to 1000 X-ray beams that simultaneously illuminate a sample from slightly different directions. The use of this multiple X-ray beam setup has several advantages over the classical approaches:

i. Improved signal-to-noise ratio of the collected data at shortened exposure times.
ii. Possibility to obtain a depth resolved image of an object inside the focal spot of polycapillary optics from a single exposure [2]. That is, tomographic slices at various depths near the focal plane can be reconstructed in a way similar to tomo-synthesis but from a single X-ray exposure.
iii. High-resolution micro-tomographic scans can be performed without sample translations, truncations of the field of view, or limitations of the angular range [3].

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High-resolution experimental geometry

The newly developed setup for high-resolution 3D imaging in a lab relies on three basic elements: an X-ray tube to generate X-rays, a compound polycapillary element with a multipinhole mask to shape the generated X-rays, and a photon counting hybrid (HPC) pixel detector for detecting a high resolution signal coming from the sample (Figure 1).

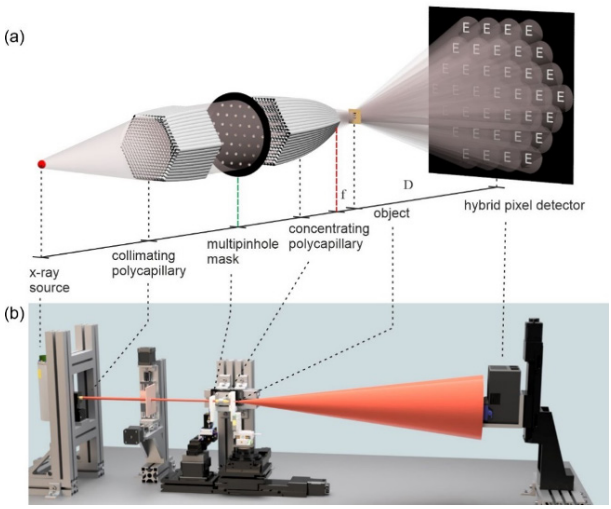

Figure 1 Multibeam X-ray microscopy: from an idea ***(a)*** *to the table-top 3D imaging instrument, developed for the use in laboratories* ***(b).***

X-rays are generated from a microfocus anode, usually Cu or W, with an effective energy 8-10 keV. Photons emitted from the tube are shaped with the so-called polycapillary optics, built from hundreds of thousands of glass microcapillaries that are stacked into hexagonal arrays. They are fabricated using a repeated stack-and-draw process from fiber optics technology and enable to collimate or concentrate X-rays from laboratory (or synchrotron) sources by means of multiple external reflections. The first polycapillary element (collimating polycapillary) is used to form a quasi-parallel X-ray beam. Further down the beam path, a multi-pinhole aperture is used to select a well-defined set of X-ray beams, which are focused by a second polycapillary optics (concentrating polycapillary). The process results in multiple X-ray beams, which simultaneously illuminate the object of interest, placed near the focal plane ($f \approx 2.5$ mm). In order to achieve a high geometrical magnification and high-resolution data collection, a hybrid photon-counting hybrid pixel detector (DECTRIS EIGER2 R 500K) is placed on a large sample-detector distance ($D \approx 300$ mm – 700 mm).

3D imaging principle

If an object is placed in the focal spot of the focusing polycapillary optics, each microbeam forms a replicated X-ray projection of the object. To obtain a high signal-to-noise ratio of a single projection a long acquisition time of almost 1 hour is required (Figure 2(a)). However, by virtue of image multiplexing it is possible to average of multiple projections and drastically improve the signal-to-noise ratio and decrease the acquisition times (Figure 2(b)). This image averaging procedure relies on two features of HPC pixel detectors: no noise performance and a sharp point spread function. In the first step of the procedure, each projection (resulting from each microbeam) yields only a few photons per pixel, which can be detected only by eliminating readout noise of the detector and signals arising from high-energy photons. In this case, this was achieved by using a HPC detector with two thresholds. Secondly, the averaging procedure requires a precise alignment of individual projections, which is possible thanks to the sharp point-spread function of the HPC pixel detector.

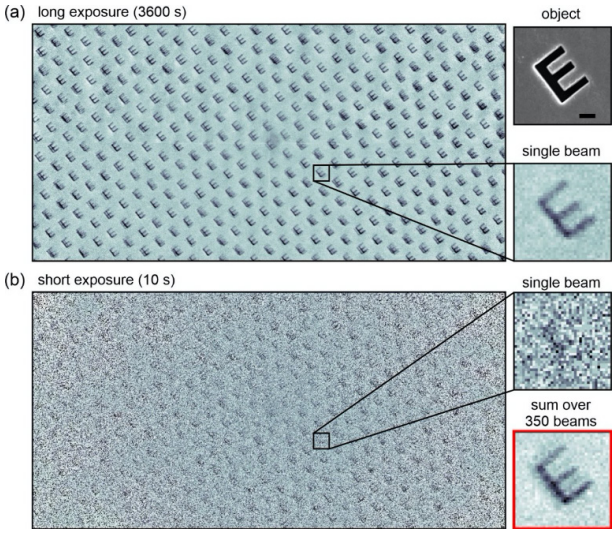

Figure 2 Principle of signal-to-noise reduction in multi-beam X-ray microscopy. ***(a)*** *Multibeam projection of a test object (ion-beam milled letter "E") that is shown in the top right corner. Scale bar: 2 µm. To obtain a high signal-to-noise ratio of a single projection (inset at bottom right) a long (1 hour) exposure is required.* ***(b)*** *Averaging of multiple projections enables to shorten the acquisition by a factor approximately equal to the number of microbeams. The average image acquired with 350 beams in 10 seconds is shown on right bottom corner.*

Application Note

Plenoptic X-ray microscopy with the multibeam setup

Plenoptic cameras use arrays of microlenses to capture multiple views of the same scene in a single compound image [4]. They enable refocusing on different planes and depth estimation. However, until now, all types of plenoptic computational imaging processes have been limited to visible light. The newly developed multibeam X-ray system is capable of recording plenoptic X-ray images that enable depth resolved X-ray imaging from a single exposure (Figure 1), Ref. [2]. Each of the microbeams generated by polycapillary optics illuminate a focal spot region from a slightly different angle. By virtue of this perspective effects, slices at various depths near the focal plane can be reconstructed in a way similar to tomosynthesis. As shown in the Figure 3, the multibeam setup can be even used for a depth-resolved imaging of weakly absorbing objects by means of propagation phase-contrast.

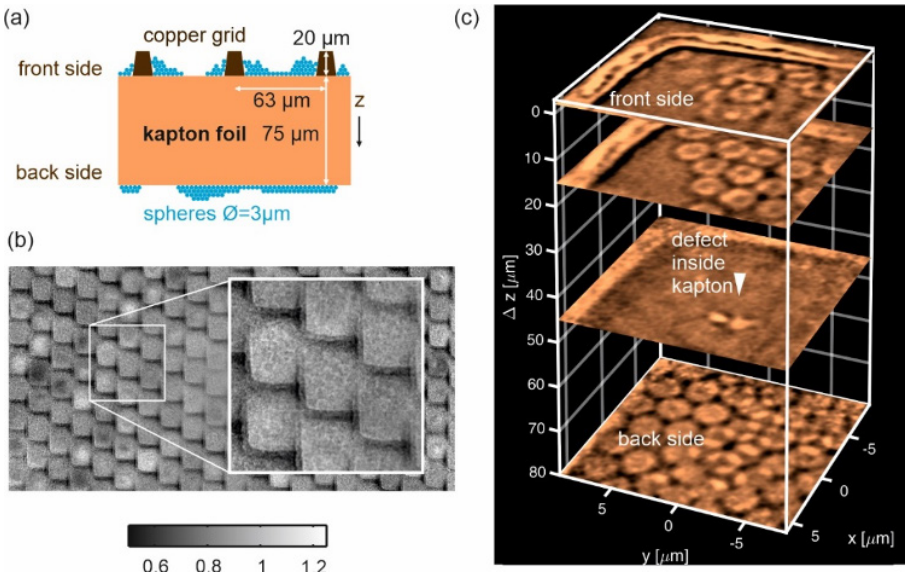

*Figure 3 Plenoptic X-ray imaging in the multibeam geometry: **(a)** Phantom: kapton foil with an attached finder grid and latex spheres on both sides of the foil **(b)** Multibeam X-ray image **(c)** Depth resolved plenoptic reconstruction from a single X-ray exposure. Latex spheres on both sides can be easily resolved. The lateral resolution is better than 0.5 µm, whereas the depth resolution is approximately 10 µm.*

Application Note

X-ray microtomography with multiple ultranarrow beams

Multiple beams generated by polycapillary optics have very narrow cones because their opening is limited by the critical angle for total external reflection (≈ 0.2° – 0.4°). Therefore, objects that are near the focal plane have a limited field-of-view (FOV). Increase of FOV is possible by placing the object further from the focal plane, but this comes with an expense of signal multiplexing (Figure 4). The other possibility to increase the FOV is to use of the whole beam of polycapillary optics (opening angle up to 10°) Such geometry enables to perform full 3D microtomographic imaging with resolution that is almost 10 times higher than the focal-spot limited resolution of standard polycapillary based setups [3].

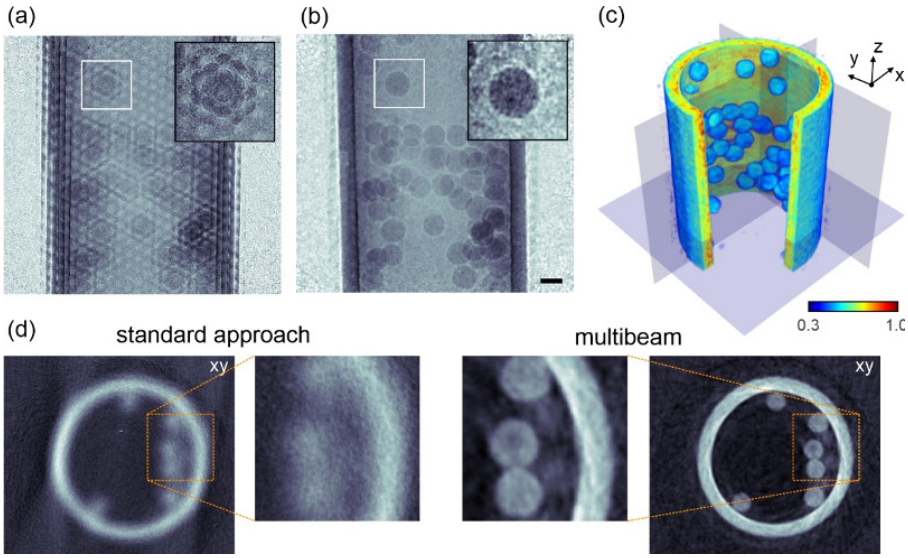

*Figure 4 X-ray microtomography with multiple ultranarrow beam. Object is a 0.21 mm diameter capillary filled with 25 µm diameter glass spheres. **(a)** Multibeam projection for a single sample orientation. Image of a single sphere is multiplexed only among neighboring microbeams. **(b)** Reconstructed high-resolution projection. **(c)** 3D reconstruction from 180 projections. **(d)** Axial slices. Comparison of standard approach with multibeam tomography.*

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Outlook

Although still in the development phase, multibeam X-ray microscopy is a promising tool for 3D X-ray imaging as it allows for high-resolution data to be collected at decreased exposure times. Experiments presented in this application note have been performed using a low power X-ray tube (50W), which resulted in exposure times of several hours. In future, combination of a large area hybrid pixel detector and more powerful X-ray tubes (rotating anode or metal jest sources) can result in much attractive acquisition times. Multibeam X-ray microscopy will be also tested at a constructed beamline PolyX at SOLARIS synchrotron radiation center.

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Technical specifications

EIGER2 R series technical specifications

EIGER2	500K	1M	4M
Number of detector modules	1	1x2	2x4
Active area: width × height [mm²]	77.3 × 38.6	77.1 × 79.7	155.1 × 162.2
Pixel size [µm²]		77.1 × 79.7	
Point-spread function		1 pixel (FWHM)	
Energy-discriminating thresholds		2	
Threshold range [keV]	4-11	3.5-30	3.5-30
Maximum count rate [cps/mm²]*	3.6×10^8	6.9×10^8	6.9×10^8
Counter depth [bit/threshold]		2 x 16	
Acquisition mode		simultaneous read/write with zero dead time	
Image bit depth [bit]		32	
Optional vacuum compatibility?		yes	
Cooling	Air-cooled	Water-cooled	Water-cooled
Dimensions (WHD) [mm3]	100 × 140 × 93	114 × 133 × 240	235 × 237 × 372
Weight [kg]	1.8	3.9	15

* Values are for Cu radiation. Instant Retrigger and higher count rates for EIGER2 R 500K will be available in 2021.

All specifications are subject to change without notice

For details, please visit https://www.dectris.com/products/eiger2/eiger2-r-for-laboratory/

[1] References

[1] C. A. MacDonald (2017) Structured X-Ray Optics for Laboratory-Based Materials Analysis, Annu. Rev. Mater. Res. 47(1), 115–134 (2017).
[2] K. M. Sowa, M.P. Kujda, P. Korecki (2020) Plenoptic X-ray microscopy, Applied Physics Letters 116, 014103.
[3] K. M. Sowa, P. Korecki, X-ray tomography with multiple ultranarrow cone beams (2020) Optics Express 28, 23223.
[4] E. Y. Lam (2015) Computational photography with plenoptic camera and light field capture: tutorial, J. Opt. Soc. Am. A 32, 2021.

This product family is also available with a high-energy CdTe sensor.