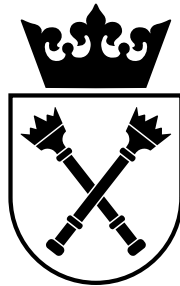


X-ray plenoptic microscopy

by

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Oświadczenie

Ja niżej podpisana *Katarzyna Maria Sowa*, (nr albumu: 1064427) doktorantka Wydziału Fizyki, Astronomii i Informatyki Stosowanej Uniwersytetu Jagiellońskiego, oświadczam, że przedłożona przeze mnie rozprawa doktorska pt. *X-ray plenoptic microscopy* jest oryginalna i przedstawia wyniki badań wykonanych przeze mnie osobiście, pod kierunkiem prof. dr hab. *Pawła Koreckiego*. Pracę napisałam samodzielnie.

Oświadczam, że moja rozprawa doktorska została opracowana zgodnie z Ustawą o prawie autorskim i prawach pokrewnych z dnia 4 lutego 1994 r. (Dziennik Ustaw 1994 nr 24 poz. 83 wraz z późniejszymi zmianami).

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Kraków, 28.05.2020r.

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Abstract

In contrast to a conventional camera, which records only the intensity of the incoming light, a plenoptic camera additionally records directions that the light rays are travelling in space. A standard plenoptic camera consists of a main lens and a micro lens array in front of a sensor. Hence, a plenoptic camera is capable of capturing multiple images of the same scene from slightly different perspectives in a single compound image. As a result, it is possible to numerically refocus on different image planes and to estimate the depth values in the imaged scene. However, until now, plenoptic cameras have been successfully exploited only in the visible light regime.

The aim of this Thesis was to design and construct a first X-ray microscope which realizes plenoptic imaging in the hard X-ray domain. Visible light plenoptic cameras take advantage of large angular apertures of lenses to capture multi-view images. Due to the fact that hard X-ray lenses have small angular apertures (at the level of milliradians), the construction of a plenoptic camera for X-rays was up to now held back by technical limitations. This Thesis presents a workaround of this problem and shows that plenoptic imaging can be extended to X-rays by using arrays of micro capillaries instead of micro lenses.

The X-ray plenoptic microscope was realized in two steps. Firstly, a novel multipoint-projection X-ray imaging geometry was proposed as described in K.M. Sowa et al., *Optica* 5, 577 (2018). The multipoint-projection X-ray imaging was realized with an X-ray tube and a compound structured micro capillary optics that generated nearly one thousand sub-micrometer secondary X-ray sources. The generated micro beams were multiplexed at the object plane. Demultiplexing of the transmitted beams, magnification, and phase contrast were achieved by the free-space propagation. A huge improvement in the signal-to-noise ratio, relative to a single capillary, was achieved without a loss in spatial resolution. Hence, X-ray projections of highly absorbing samples could be recorded with only a few photons per the detector pixel. An almost noise-free detection was accomplished by using modern hybrid pixel detectors. For weakly absorbing samples, the multipoint-projection method enabled recording, in a parallel way, replicated in-line X-ray holograms with incoherent radiation from an X-ray tube. However, all experiments were limited to thin, quasi-planar samples.

In the second step (K.M. Sowa et al., *Appl. Phys. Lett.* 116, 014103 (2020)), the multipoint-projection geometry was extended to 3D imaging. Plenoptic X-ray imaging took advantage of the fact that in the focal spot region of

the polycapillary optics all micro beams illuminate the object from different viewing angles. Hence, the constructed microscope enabled plenoptic X-ray imaging of small sub-volumes of large samples placed in the focal spot region. The angular aperture of almost 10 degrees permitted depth-resolved imaging from a single exposure with a lateral resolution of $0.5\ \mu\text{m}$ and the depth resolution of $\sim 10\ \mu\text{m}$. Depth resolved imaging was optimal in the vicinity of the focal plane ($\pm 60\ \mu\text{m}$). For larger defocusing distances ($\pm 120\ \mu\text{m}$) significant truncation effects could be observed. For even larger defocusing the image formation resembled an apposition compound eye, i.e. each region of the sample was illuminated by a different micro beam. Although, the depth-resolution was lost in this regime, a large field of view of several hundreds of microns could be achieved.

The Thesis also demonstrates that plenoptic X-ray microscopy can be combined with conventional tomographic scans and X-ray fluorescence spectroscopy for multi-modal X-ray analysis with a single polycapillary lens. In future, the plenoptic X-ray microscope can be used at the PolyX beamline, which is constructed at SOLARIS National Synchrotron Radiation Centre.

Streszczenie

W przeciwieństwie do klasycznego aparatu fotograficznego, kamera plenoptyczna rejestruje nie tylko intensywność światła padającego na piksele sensora, ale również kierunek promieni padających na sensor. W skład standardowego układu optycznego kamery plenoptycznej wchodzi soczewka główna oraz maczyca mikrosoczewek ustawionych tuż nad sensorem. Tego typu konstrukcja pozwala na akwizycję wielu obrazów sceny z nieco innych perspektyw w obrębie jednej fotografii. W efekcie możliwa jest zmiana ostrości fotografii już po jej wykonaniu oraz wyznaczenie tzw. mapy głębi obrazowanej sceny.

Do tej pory kamery plenoptyczne były z powodzeniem wykorzystywane dla światła widzialnego. Celem niniejszej rozprawy było zaprojektowanie i skonstruowanie pierwszego mikroskopu plenoptycznego pracującego w reżimie twardego promieniowania rentgenowskiego. W kamerach plenoptycznych dla światła widzialnego obrazy sceny są rejestrowane przy pomocy soczewek o dużych aperturach kątowych. Rentgenowskie elementy optyczne posiadają natomiast zwykle bardzo małe apertury kątowe (rzędu miliradianów), dlatego też konstrukcja plenoptycznej kamery rentgenowskiej nie była do tej pory możliwa. Praca przedstawia rozwiązanie powyższego problemu, w którym zamiast maczyca mikrosoczewek zastosowano maczyce mikrokapilar.

Konstrukcję rentgenowskiego mikroskopu plenoptycznego wykonano dwuetapowo. Po pierwsze opracowano nową geometrię obrazowania, tzw. wielowiązkową mikroskopię rentgenowską, opisaną w K.M. Sowa et al., *Optica* 5, 577 (2018). Zaproponowany układ optyczny składał się z lampy rentgenowskiej oraz strukturyzowanego polikapilarnego elementu optycznego, dzięki któremu otrzymano maczyce około tysiąca sub-mikrometrowych wtórnych źródeł promieniowania rentgenowskiego. Powstałe w tej geometrii mikrowiązki były całkowicie zmultipleksowane w płaszczyźnie obiektu, jednocześnie oświetlały obiekt pod różnymi kątami i generowały około tysiąca obrazów obiektu w płaszczyźnie detektora. Demultipleksowanie, powiększenie i kontrast fazowy uzyskano poprzez swobodną propagację promieniowania rentgenowskiego. W rezultacie uzyskano znaczącą poprawę stosunku sygnału do szumu w porównaniu do pojedynczej kapilary, bez utraty rozdzielczości przestrzennej. Geometria wielowiązkowa umożliwiła rejestrowanie projekcji silnie absorbujących próbek na podstawie zliczeń pojedynczych fotonów. Wydajną, praktycznie bezszumową detekcję umożliwiło zastosowanie nowoczesnych detektorów z hybrydowymi pikselami. W przypadku słabo absorbujących próbek, metoda mikroskopii wielowiązkowej umożliwiła równoległe rejestrowanie powielonych hologramów rentgenowskich

z użyciem niekoherentnego promieniowania z lampy rentgenowskiej. Wszystkie eksperymenty były jednak ograniczone do cienkich, kwazi-płaskich próbek.

W drugim etapie (K.M. Sowa et al., Appl. Phys. Lett. 116, 014103 (2020)) wielowiązkową mikroskopię rentgenowską zaadaptowano tak, aby możliwe było obrazowanie obiektów trójwymiarowych. W plenoptycznym obrazowaniu rentgenowskim wykorzystano fakt, że w obszarze ogniska optyki polikapilarnej, wszystkie mikrowiązki oświetlają obiekt pod różnymi kątami widzenia. Mikroskop umożliwił obrazowanie plenoptyczne małych obszarów dużych próbek znajdujących się w ognisku optyki. Apertura katowa optyki polikapilarnej, sięgająca prawie 10° , umożliwiła przeprowadzenie obrazowania z rozdzielczością głębokościową na podstawie pojedynczej ekspozycji. Uzyskano rozdzielczość w płaszczyźnie wynoszącą $0.5 \mu\text{m}$ i rozdzielczość głębokościową na poziomie $10 \mu\text{m}$. Trójwymiarowe obrazowanie przebiegało optymalnie w pobliżu płaszczyzny ogniskowej ($\pm 60 \mu\text{m}$). Dla większych odstrojeń od płaszczyzny ogniskowej ($\pm 120 \mu\text{m}$) zaobserwowano znaczące efekty tzw. odcięcia (ang. *truncation effects*). Dla jeszcze większych odstrojeń, formowanie obrazu przypominało formowanie obrazu w tzw. apozycyjnym oku zespolonym: tzn. każdy obszar próbki był oświetlony inną mikrowiązką. Pomimo, że w tym reżimie utracono rozdzielczość głębokościową, uzyskiwano dużo większe pole widzenia wynoszące nawet kilkaset mikrometrów.

W rozprawie wskazano również, że plenoptyczną mikroskopię rentgenowską można łączyć z konwencjonalnymi skanami tomograficznymi i rentgenowską spektroskopią fluorescencyjną, co umożliwiło wielomodalną analizę rentgenowską z użyciem pojedynczego rentgenowskiego elementu optycznego - soczewki polikapilarnej. W przyszłości, planowane jest wykorzystanie plenoptycznego mikroskopu rentgenowskiego na linii PolyX, która powstaje w Narodowym Centrum Promieniowania Synchrotronowego SOLARIS.

First and foremost, I would like to thank my Supervisor, prof. dr hab. Paweł Korecki, for his incredible help, for plenty of hints and suggestions, and his motivation in the moments when the equipment refuses to cooperate.

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INTRODUCTION

A plenoptic camera consists of a main lens and a lenslet array placed just above a photodetector sensor (Adelson & Wang 1992). The presence of the lenslet array makes it possible to record the light-field - a 4D vector function describing a radiance at a given point and direction (Levoy & Hanrahan 1996). Hence, in contrast to a conventional camera, the plenoptic camera records both spatial and directional information about the incoming light, which enables depth estimation as well as the numerical refocusing of the image after it was captured (Ng et al. 2005). The main principle of plenoptic imaging is based on the idea that each micro-lens in the lenslet array 'sees' the scene from a different point of view and creates a compound image at the photodetector plane. This idea, to capture in a single exposure different perspectives of the same scene, was firstly introduced by Lippmann and named integral photography (Lippmann 1908).

Many approaches to both construction of plenoptic setups and the light-field data treatment have been suggested. Among them, it is worthwhile mentioning the construction of a standard plenoptic camera (Ng et al. 2005) and its upgraded version, namely the focused plenoptic camera or plenoptic camera 2.0 (Goergiev & Lumsdaine 1996). The main difference is the position of the micro-lens array with respect to the photodetector. In lieu of Micro Lens Array (MLA) one can also use an attenuating mask (Veeraraghavan et al. 2007). Plenoptic imaging can be used not only for light scattered or emitted from objects but also in the context of light absorption (Lanman et al. 2008).

Due to the fact that capturing multi-view images requires large angular apertures, the plenoptic imaging has been so far exploited mainly in the visible light regime. For X-rays, the refractive index decrement is very small and X-ray refraction effects are very weak. As a consequence, optical elements for X-rays have small angular apertures and therefore, a construction of X-ray plenoptic camera has been suppressed by technical issues.

So far, the only attempt to construct X-ray plenoptic microscope was made by Longo (2018) within the VOXEL framework (VOlumatic X-ray Extremely Low dose).

Longo's microscope is dedicated for imaging in the water window region, i.e. energy range between the oxygen and carbon absorption K-edges. The setup utilizes an array of Fresnel Zone Plates to realize plenoptic geometry. Nevertheless, the setup is under further tests and still no experimental results have been provided.

Recently, a similarity between plenoptic imaging and limited angle tomography has been shown by [Vigano et al. \(2018\)](#). A single sub-aperture image produced by an individual micro lens corresponds to one tomographic projection. Therefore, well-established tomographic algorithms can be successfully used to reconstruct 3D data obtained by a plenoptic camera.

This Thesis presents the road to a successful realization of the first plenoptic microscope that works in the X-ray range. The main idea was to replace an array of refractive lenses with an array of capillaries, which very efficiently guide X-rays via total external reflections and to perform plenoptic imaging in the transmission geometry, and not in scattering geometry as it is usually performed in the visible light plenoptic devices. While single capillaries have narrow angular apertures of milliradians, commercially available polycapillary devices have angular apertures which are larger than 10° . The plenoptic X-ray microscope constructed during realization of this Thesis was composed of two polycapillary devices and a multi-pinhole mask that was used for a controlled choice of the image forming capillaries.

The plenoptic microscopy was realized in two stages. Firstly, a novel multipoint-projection X-ray imaging geometry was proposed as described in [Sowa et al. \(2018\)](#). Secondly, this geometry was extended to plenoptic imaging as shown in [Sowa et al. \(2020\)](#). The constructed X-ray plenoptic microscope had an angular aperture of almost 10 degree and permitted single-exposure depth-resolved imaging with a lateral resolution of $0.5\ \mu\text{m}$ and a depth resolution of $10\ \mu\text{m}$. Depth resolved imaging was optimal in the vicinity of the focal plane ($\pm 60\ \mu\text{m}$). For larger defocusing distances ($\pm 120\ \mu\text{m}$) significant truncation effects could be observed. For even larger defocusing, the image formation resembled the image formation in an apposition compound eye i.e. each region of the sample was illuminated by a different micro-beam. Although in this regime, the depth-resolution was lost, a large field of view of several hundreds of microns could be achieved. In the Thesis plenoptic X-ray imaging is applied for imaging of artificial phantoms as well as complex biological objects.

The Thesis is organized into 6 chapters.

In Chapter 1 the concept of light field or plenoptic imaging is reviewed. A description of a standard plenoptic camera is illustrated with images captured by the author with the Lytro first generation plenoptic camera for visible light. A brief description of a previous attempt to transfer plenoptic microscopy into X-ray domain is also presented (Longo 2018). Chapter 1 ends with a description of the link between plenoptic imaging and limited angle X-ray tomography in the point-projection geometry. This link was established in a recent work of Vigano et al. (2018).

Chapter 2 reviews basic elements of X-ray optics, which are important in the context of this Thesis. First, the image formation in propagation based imaging is described and, next, various X-ray optical elements are reviewed with an emphasis on (poly)capillary optics.

Chapter 3 begins with a discussion of the defect-assisted X-ray microscopy with polycapillary optics described in *P. Korecki, K. M. Sowa, B. R. Jany, and F. Krok, Phys. Rev. Lett., 116, 233902 (2016)*. The defect-assisted microscopy was the subject of the master thesis of the author and stimulated the studies on X-ray plenoptic microscopy. The main part of Chapter 3 describes the idea and contains experimental results on the so-called multi-point projection microscopy. The multi-point projection microscopy is an extension of the defect-assisted imaging, in which the beam generating capillaries are selected in a controlled manner. The multi-point projection geometry enables to obtain almost one thousand X-ray projections of small objects placed in the focal spot of the polycapillary optics, and to massively increase the signal-to-noise ratio of high-resolution desktop X-ray imaging. This part of the Thesis contains results presented in *K. M. Sowa, B.R. Jany, P. Korecki, Optica 5, 577 (2018)*. Multi-point projection microscopy was a first step towards plenoptic X-ray microscopy, but all experiments described in Chapter 3 were limited to small and thin (quasi 2D) samples.

Chapter 4 reports the final design and the successful realization of the plenoptic microscopy in the X-ray range, which was partially described in *K. M. Sowa, M. Kujda and P. Korecki, Appl. Phys. Lett. 116, 014103 (2020)*. The microscope enabled to realize plenoptic X-ray imaging of small sub-volumes of large samples placed in the focal spot region of the polycapillary optics. Plenoptic X-ray imaging takes advantage from the fact that, in the focal spot region of the polycapillary optics, all micro beams illuminate the object from different viewing angles. In the last part of Chapter 4 it is demonstrated that plenoptic X-ray microscopy can be very efficiently combined with conventional medium-resolution tomographic scans and X-ray fluorescence spec-

troscopy for multi-modal X-ray analysis of weakly absorbing artificial and biological samples. All these techniques use a single X-ray optics device, i.e. the concentrating polycapillary optics.

Chapter 5 concludes the Thesis and presents perspectives related e.g. to applications at the PolyX beamline, which is constructed at SOLARIS National Synchrotron Radiation Centre.

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PLENOPTIC IMAGING

1.1 PLENOPTIC CAMERA FOR VISIBLE LIGHT

1.1.1 BRIEF HISTORY OF PLENOPTIC (OR LIGHT FIELD) IMAGING

Capturing and displaying 3D images has its origins in the stereoscopy ([Wheatstone 1838](#)). An exemplary picture of a stereoscope camera is presented in Fig. 1.1(a). A stereoscopic setup usually consists of two adjacent cameras, which capture pictures of the same scene but from two different perspectives. Next, the impression of three-dimensionality is obtained by presenting these images to the left and right eye separately. A device used to observe these images is called a stereoscope (Fig. 1.1(b)). Nevertheless, stereoscopic pictures are both captured and displayed as two-dimensional arrays and the depth illusion is produced in the brain of the observer.

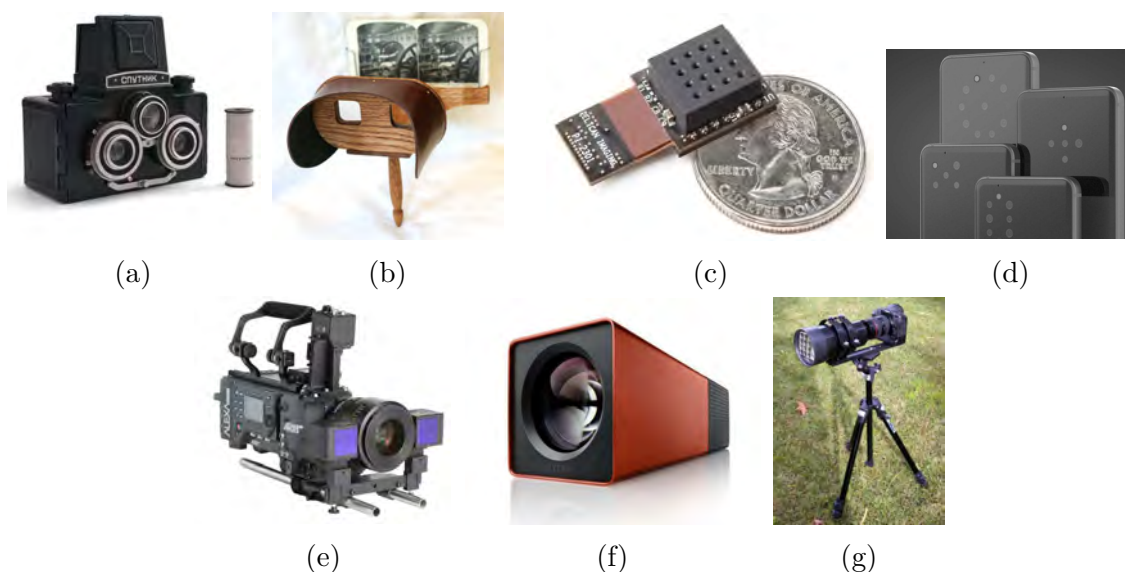


Figure 1.1: Examples of different 3D camera technologies connected with light-field imaging. (a) The Sputnik stereo camera ([wikiwand.com 2020](#)), (b) the Holmes stereoscope ([wikipedia.org 2020](#)), (c) multi-camera array ([Venkataraman et al. 2013](#)), (d) multi-camera setup in mobile phones ([Cardinal 2019](#)), (e) Time-of-Flight Camera (TOF) ([Hach & Steurer 2013](#)), (f) Lytro first generation plenoptic camera ([Kučera 2020](#)), (g) Adobe plenoptic camera ([Georgiev & Intwala 2003](#)).

Over the time the stereoscopy setups evolved naturally into multi-camera systems (Venkataraman et al. 2013). An example of such a camera sensor is depicted in Fig. 1.1(c). The larger number of cameras caused the enhancement in the quality of the depth information. Moreover, multi camera setups are gaining more popularity in the cell phone industry (Cardinal 2019). However, they are not used in the context of capturing 3D scenes, but mainly to increase the resolution and quality of a captured 2D image. Figure 1.1(d) presents several configurations of cameras in cell phones.

An alternative approach to extract depth information is the so-called Time-of-Flight Camera depicted in Fig. 1.1(e) (Hach & Steurer 2013). The depth of the scene is estimated by measuring the time between emitting an infrared light ray from the camera and capturing a ray reflected from the objects surface. The 3D information is obtained by combining time measurement with a conventional photograph of the same scene.

Another approach to capture 3D information about the light is a plenoptic (or light field) camera (Adelson & Wang 1992). Such a device consists of a main lens and a micro lens array (MLA) which is placed in the front of the sensor. Therefore, the camera is able to capture multiple images of the same scene from slightly different viewing angles, which together comprise a single compound image. In addition, it is possible to numerically reconstruct the image at various planes (Ng et al. 2005) without the necessity of acquiring several images with different focus as it is for conventional cameras. So far, the plenoptic camera geometry have been employed in many applications varying from microscopy (Levoy et al. 2005), through medicine (Pégard et al. 2016, Taylor et al. 2018, Bedard et al. 2016) and even in automated optical inspection systems (raytrix.de 2020a). Apart from technical applications, there were also attempts to use the plenoptic camera in motion picture arts (Streuer et al. 2011, Aggoun et al. 2013). It is worth to mention that the first light-field action movie was produced in 2016 (iss.fraunhofer.de 2016, 2020).

The idea to use an array of micro lenses for capturing different perspectives of the scene was reinvented for several times and each time it was named differently. Nevertheless, this concept was firstly introduced in 1908 by Lippmann and named integral photography (Lippmann 1908). In 1930 Lippmann’s design was improved by Ives by inserting a main lens with a large diameter (Ives 1930). However, because of the limitation of the photographic films, the Lippmann’s camera was able to capture images only for objects close to the camera. Hence, this method was not developed for several decades and rediscovered at the end of 20th century with the invention of

digital cameras.

The first theoretical model which was able to describe Lippmann’s integral camera was proposed in 1936 by Gershun ([Gershun 1936](#)). In his work, Gershun describes the properties of the light in three-dimensional space and for the first time defines the term light-field as the vector indicating the irradiance at a given point and direction. In 1991, Adelson and Bergen proposed an extended theory under the name of plenoptic function ([Adelson & Bergen 1991](#)). The name *plenoptic* comes from Latin *plenum* - full, *opticus* - view. The model describes the irradiance as a function of angle, wavelength, time, and viewing position. A year later Adelson and Wang constructed the first model of plenoptic camera ([Adelson & Wang 1992](#)). In 1996, Levoy and Hanrahan proposed a simplification of the plenoptic function from 7 dimensions to 4 dimensions and called this function a light-field ([Levoy & Hanrahan 1996](#)).

The first pocket-sized plenoptic camera was constructed by Ng in 2005 during his Ph.D. research ([Ng et al. 2005](#)). He also developed a fast computational refocusing method. Later on, Ng founded the Lytro Inc. company which aimed to produce commercial plenoptic cameras. A photograph of the first generation Lytro camera, which is available in our laboratory, is presented in Fig. 1.1(f). In Section 1.1.3 an example of visible light plenoptic images acquired with this camera are presented.

In 2009 a new class of plenoptic cameras was designed, known as Focused Plenoptic Cameras or Plenoptic Cameras 2.0 ([Goergiev & Lumsdaine 1996](#)). In contrast to the Ng’s camera, where the MLA is placed one focal length away from the sensor, plenoptic cameras 2.0 have their MLA positioned before or behind the focal plane of the main lens. This modification allows to acquire a higher spatial resolution at the expense of the angular resolution. Nevertheless, the lowering of the angular resolution introduced some artefacts in the resulting images.

There are several other companies which develop light-field imaging, except from the Lytro Inc., which ceased operations in 2018. Among them the leading ones are Raytrix GmbH ([raytrix.de 2020b](#)) and Adobe Systems ([Georgiev & Intwala 2003](#)). A photo of Adobe light field camera is presented in Fig. 1.1(g).

Apart from the classical plenoptic camera setup which utilizes micro lens arrays, an attenuating mask can be also applied ([Veeraraghavan et al. 2007](#)). The patterned mask is placed in the optical path of a main lens of the camera. The rays are attenuated instead of being focused, and the attenuation pattern encodes the direction of the ray at the 2D camera sensor. Therefore, the light-field can be recovered by rearranging pixels, as in the case of conventional plenoptic setup. This was an inspiration

for experiment with 3D occluders by [Lanman et al. \(2008\)](#), in which it is shown, that plenoptic imaging can be also applied in the case of the light absorption, in contrast to the Ng’s setup, where a scattered or emitted light field is recorded.

1.1.2 THEORY OF LIGHT-FIELD IMAGING

In this section a background necessary to understand the image formation in the plenoptic camera geometry is provided based on [Adelson & Wang \(1992\)](#) and [Lam \(2015\)](#).

Consider an incoherent light travelling in all directions in a homogenous medium (free space) and obeying the rules of geometrical optics ([Saleh & Teich 2007](#)). The radiance of the light in every point in space, for every propagation direction, for every wavelength and every point in time can be described by the plenoptic function ([Adelson & Bergen 1991](#)):

$$P(\theta, \phi, \lambda, t, x, y, z), \quad (1.1)$$

where (θ, ϕ) are angular parameters which denote the direction of an incoming ray, λ is the wavelength of the light ray, t is time, (x, y, z) are spatial coordinates of a point in space that the ray passes through. However, for capturing the light field in cameras one can reduce the dimensionality of the above function arguing the following ([Levoy & Hanrahan 1996](#)). Firstly, the time parameter t can be omitted because of capturing a static scene (photographs). Secondly, the location of the ray can be described by two parameters (x, y) due to the fact that unless the ray came across an obstacle, the radiance value along the direction of propagation of the ray is constant. Therefore, the parameter z can be left out of consideration. Finally, digital cameras acquire three colour channels (RGB). In other words they record a monochromatic wave of one of three colours independently. Therefore, the parameter λ can be omitted. Apart from that, the angular coordinates (θ, ϕ) are often replaced with Cartesian ones (u, v) and hence, Eq. (1.1) transforms into a four dimensional function, called the *light field* ([Levoy & Hanrahan 1996](#)) or *lumigraph* in the computer graphics ([Gortler et al. 1996](#)):

$$L(u, v, x, y). \quad (1.2)$$

By employing the two-planes parametrization, it is possible to clearly determine the direction of the light ray by the intersection of the ray with two 2D planes separated by a known distance Z , as depicted in Fig. 1.2. The ray travels from left to right

and intersects the first plane (u, v) at coordinates (u', v') and the second plane (x, y) at point (x', y') . Hence, the angular direction can be recovered from these coordinates of intersections.

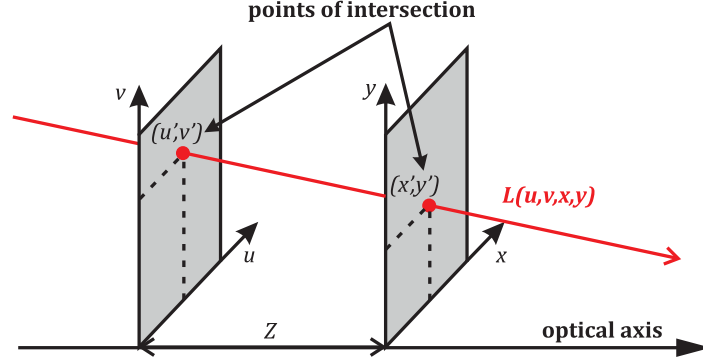


Figure 1.2: Two-planes parametrization. A light ray (red line) travels from left to right, intersecting two planes separated by a distance Z , perpendicular to the optical axis, at coordinates (u', v') and (x', y') respectively. The direction of incoming ray is determined by these coordinates. After [Levoy & Hanrahan \(1996\)](#).

The light-field described by Eq. (1.2) can be plotted by using ray-space diagrams. An example of such a diagram is depicted in Fig. 1.3. For the clarity, instead of dealing with 4D light field, a 2D simplification of $L(u, x)$ is considered. A ray from Fig. 1.3(a) is represented as a point (x, u) on the ray-space diagram in Fig. 1.3(b).

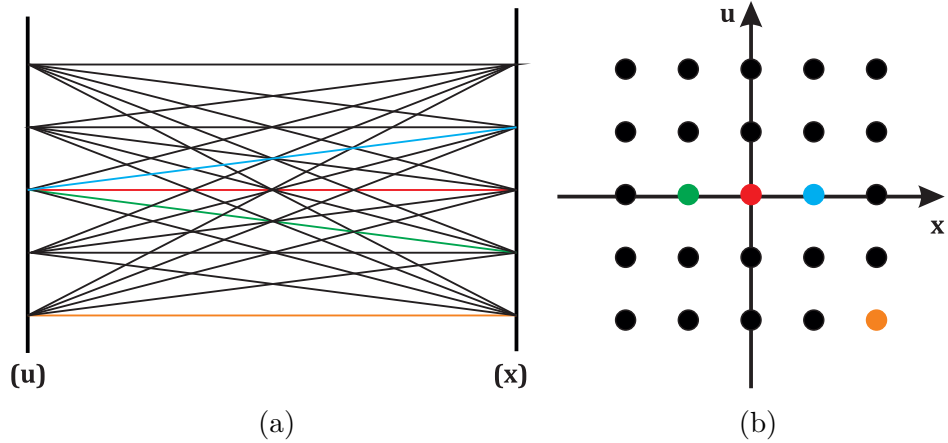


Figure 1.3: Ray-space diagram representation. Every ray from (a) corresponds to a different point on the ray-space diagram from (b). The function defined over the ray-space diagram is 2D light field. Plot adapted from [Lam 2015](#) with minor changes.

A conventional camera consists of a lens and a photodetector sensor placed in the focus of the lens and the image is formed on the photodetector plane. Such arrangement is depicted in Fig. 1.4(a) with the use of the ray-space diagram. For the clarity only one coordinate from each plane is plotted. The cone of the rays from

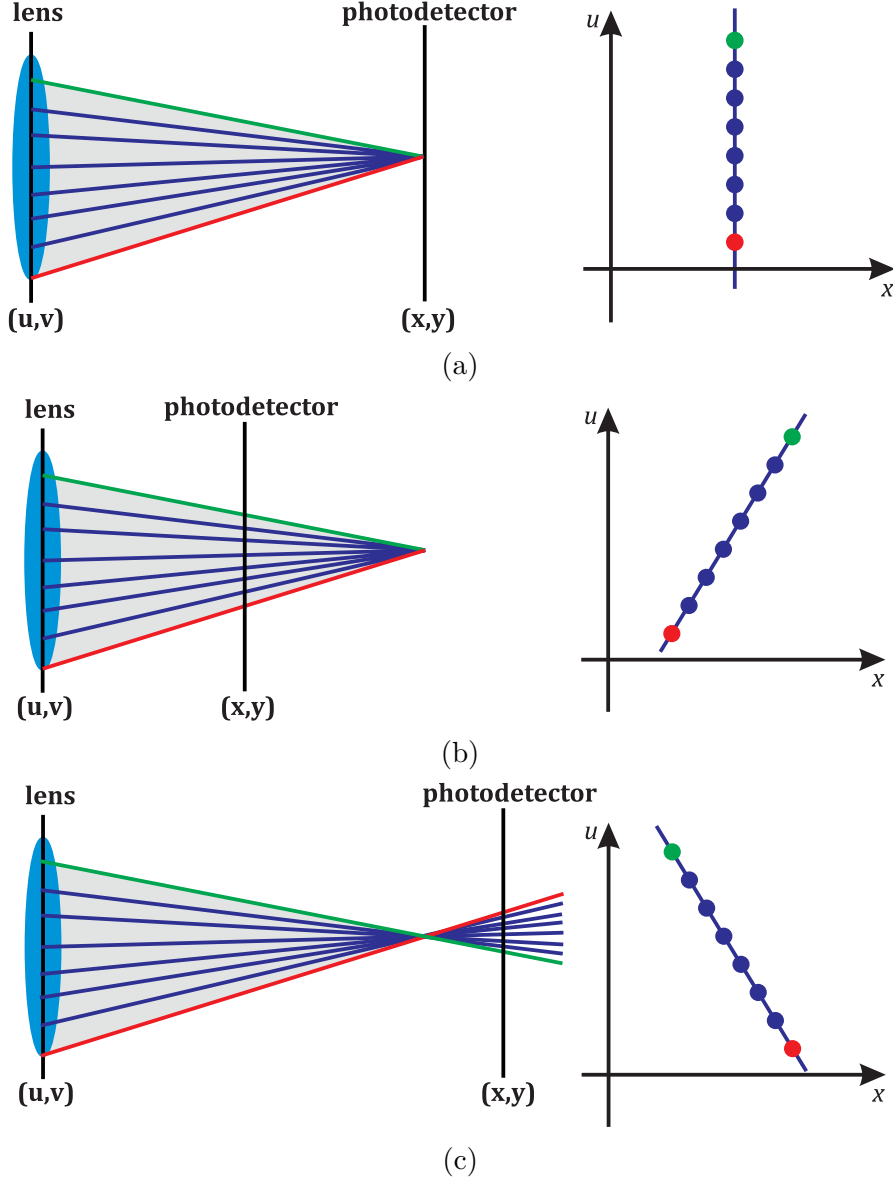


Figure 1.4: Examples of the ray-space diagrams. A collection of rays with different (u, v) positions is: **(a)** focused on the same point in the (x, y) plane (left), which corresponds to a vertical line in the ray-space diagram (right), **(b)** striking the plane (x, y) which is closer to the main lens (left) or **(c)** striking the plane (x, y) which is further to the main lens (left). The rays have different x values, which corresponds to a line tilted to the right or left in the ray-space diagram (right).

lens is converged to one pixel on the photodetector and as the rays with different u share the same x , the spatial information of the rays is preserved but the directional information is lost. In other words, the 4D light field is projected on a 2D photodetector. If the lens was focused closer or further than the photodetector plane, the line on the ray-space diagram would undergo a tilt to the right or left, respectively (Fig. 1.4(b) and 1.4(c)) as the rays from the cone strike at different z positions.

For the conventional camera, the irradiance in photodetector pixel is mathematically described as an integration of the light field over angular coordinates:

$$E(x, y) = \frac{1}{Z^2} \int \int_{-\infty}^{\infty} L(u, v, x, y) T(u, v) du dv, \quad (1.3)$$

where $E(x, y)$ is the irradiance on the (x, y) position on the detector, Z is the distance between the lens and the photodetector, $T(u, v)$ represents the aperture. As a consequence, the image on the detector is a projection of the light field onto the (x, y) axes. If the camera is focus on a new plane $Z' = \alpha Z$, the imaging equation for photodetector pixel values (x', y') at this plane becomes (Ng 2006):

$$E(x', y') = \frac{1}{(\alpha Z)^2} \int \int_{-\infty}^{\infty} L\left(u\left(1 - \frac{1}{\alpha}\right) + \frac{x'}{\alpha}, v\left(1 - \frac{1}{\alpha}\right) + \frac{y'}{\alpha}, u, v\right) T(u, v) du dv \quad (1.4)$$

The above equation contends that imaging can be thought of as shearing the 4D light field and then projecting it down to 2D. Therefore, if it was be possible to capture the light field itself instead of its projections, it would be possible to reconstruct the light field at any plane by projecting it at various angles (Isaken 2000). Moreover, this equation implies that it is possible to digitally refocus the image after it has been already taken by performing a shear of the light field in the ray space diagram: $\psi = \tan^{-1}(1 - \alpha)$, where ψ is the angle of shear.

A comparison between a conventional camera and the optical system able to record light field (a plenoptic camera) is presented in Fig. 1.5. The light rays travel from left to right. For the conventional camera (Fig. 1.5(a)) it is possible to distinguish 3 planes of interest: the object plane (i, j) , the main lens (aperture) plane (u, v) and the photodetector plane (k, l) , whereas for the plenoptic camera (Fig. 1.5(b)) an additional fourth plane is present: the micro lens array (or imaging) plane (x, y) .

The MLA is in focus of the main lens, where, in the case of conventional camera, there would be a sharp image of the scene. The red lines in Fig. 1.5(b) denote the light rays that travel from the object to the photodetector. As the rays are converged at the MLA plane, the lens equation becomes:

$$\frac{1}{f_1} = \frac{1}{z_0} + \frac{1}{z_1}, \quad (1.5)$$

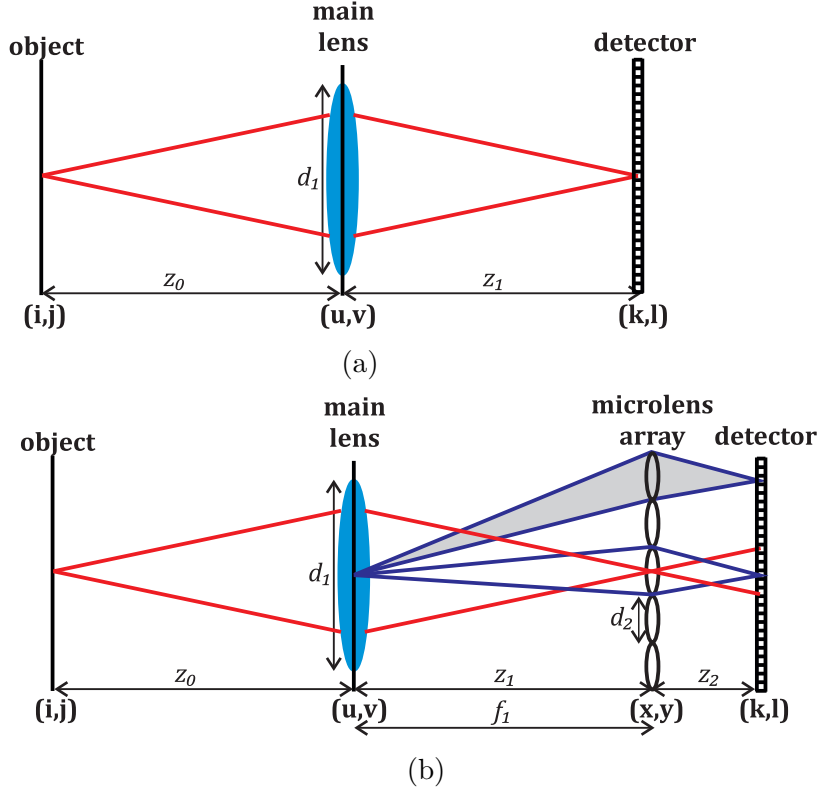


Figure 1.5: A comparison between optical systems of (a) a conventional and (b) a plenoptic camera. For the plenoptic camera is possible to distinguish an additional imaging plane (x, y) compared to the conventional one. This change allows to record light field. For the sake of clarity, the scheme is not in scale. The distance between MLA and the photodetector is microscopic. Adapted from [Lam \(2015\)](#).

where f_1 is the focal length of the main lens, z_0 is the object to the main lens distance and z_1 is the distance between the main lens and MLA. Next, the light rays diverge again and strikes at different point on the photodetector. Hence, the image created at the photodetector provides the directional information about the impinging rays.

On the other hand, since the MLA is in focus of the main lens, it also provides the sharpest images as denoted by the blue lines on the same figure. Due to the fact that the aperture diameter of each micro lens is very small compared to the main lens, MLA is focused at the optical infinity with the focal length of $f_2 = z_2$ and each micro lens produces at the photodetector a small fragment of the scene seen from different viewing angle and thus, encodes the direction of incoming light rays. In addition, the spatial resolution is limited by the size of an individual micro lens. In order to avoid overlapping between these sub-images at the detector the relative distances between main lens, MLA and the photodetector as well as the apertures of main lens and MLA fulfil the condition $\frac{d_1}{z_1} = \frac{d_2}{z_2}$.

1.1.3 LYTRO PLENOPTIC CAMERA

The visualization of the data provided by the plenoptic camera can be only realized by flattening the 4D light field into 2D arrays of images. Therefore, there are three types of representing the light field: raw light field image, sub-aperture images and sub-array or epipolar images. All photographs provided in this section were acquired with the first generation Lytro Camera available in our laboratory. The raw images were extracted from camera with the Lytro Desktop software as well as with the third-party software (Lytro Compatible Viewer) both available from [Kučera \(2020\)](#). Next, images were partly analysed with the MATLAB toolbox provided by [Dansereau et al. \(2013\)](#).

The main and the most useful ability of the plenoptic camera is the possibility to refocus the photograph after it had been already taken. Figures 1.6 (a)-(c) present a photograph numerically refocused on different planes of the scene calculated with the Lytro Desktop software. Originally, the camera was focused approximately 1 m behind the hand watch, as shown in Fig. 1.6(b). In addition, with the plenoptic camera it is possible to obtain a photograph with all planes in focus as shown in Fig. 1.6(d).

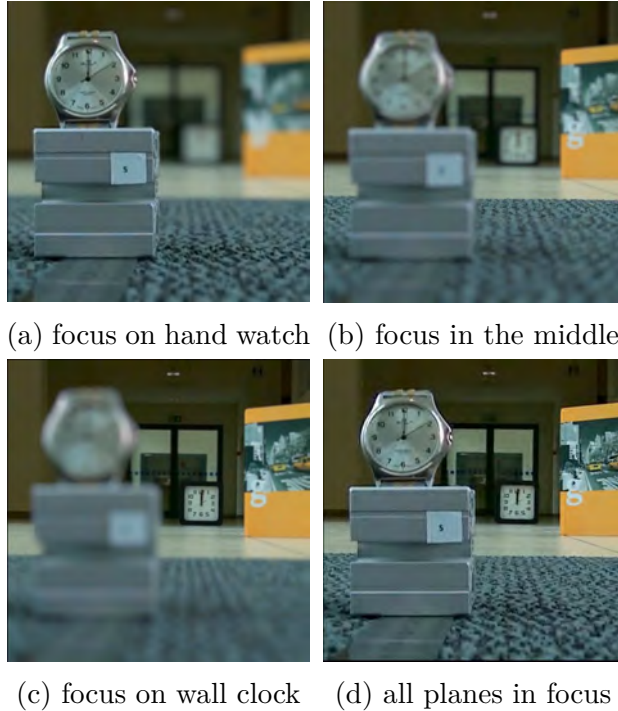


Figure 1.6: The refocused Lytro images. The scene is composed of a hand watch placed at ~ 10 cm from the camera, a laboratory notebook placed at ~ 1.5 m and a wall clock at ~ 5 m. Images (a)-(c) are focused on a different plane of the scene from close to far (clock-wise). Image (d) is a recalculated image with all planes in focus.

RAW LIGHT FIELD IMAGE

A raw image read out from the photo sensor is presented in Fig. 1.7(a). Macroscopically, the image appears like a conventional photograph focused ~ 1 m behind hand watch near the notebook. However, a more close look on the raw sensor image reveals that it is composed of an array of circles and each circle is the image formed underneath a single micro lens (Fig. 1.7(b)). In other words, the raw light field image is an (x, y) grid of images, where each image shows the light arriving at a detector point from different (u, v) positions across the lens.

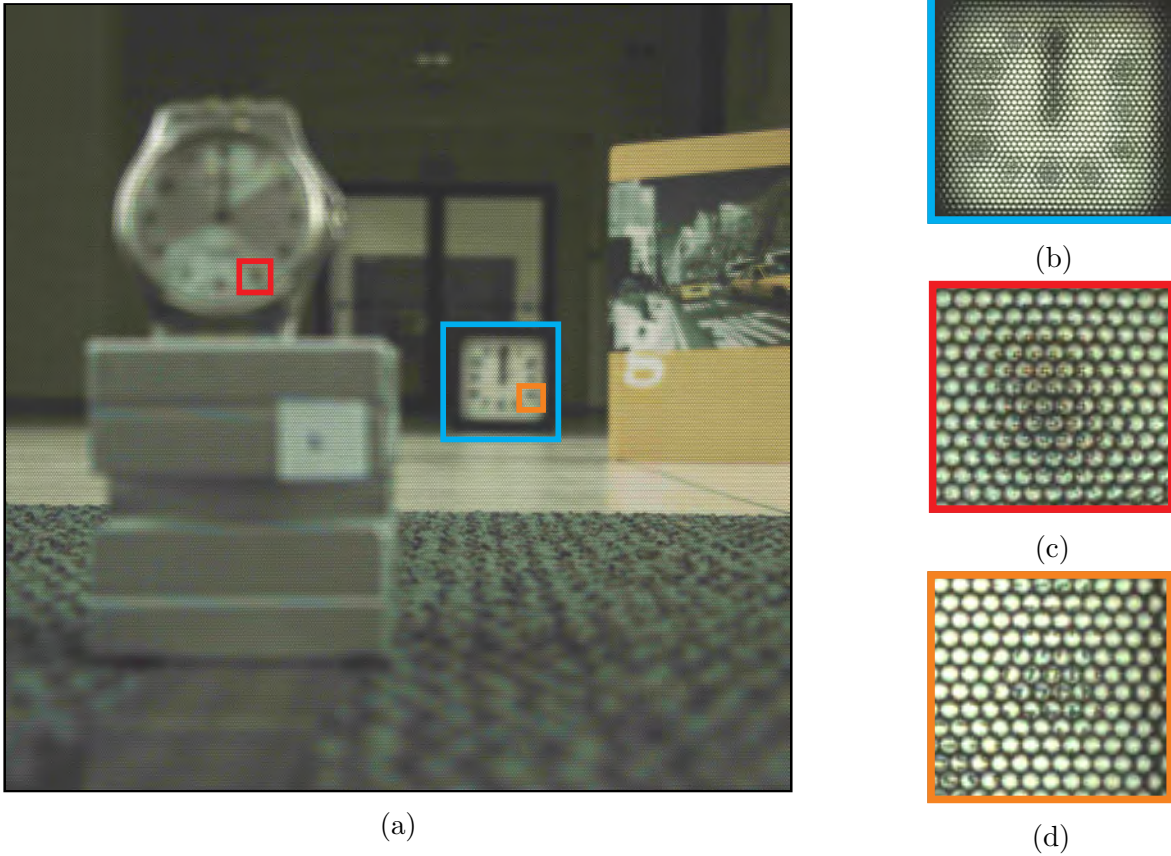


Figure 1.7: A raw photodetector image taken with Lytro Camera. **(a)** The raw image focused ~ 1 m behind the hand watch. **(b)** A close-up on the wall clock reveals the structure of the raw image: an array of circles denoting a sub-image formed by a single micro lens. **(c)** and **(d)** close-ups on symbol 5 from the hand watch and symbol 4 from the wall clock. Note that the image behind the focus is inverted.

The zoomed images of the clock's faces show details of the micro lens images at two depths: the face of the hand watch in the region near the 5 symbol (Fig. 1.7(c)), which is in front of the focus, and the face of the wall clock in the region near the 4 symbol (Fig. 1.7(d)), which is behind the focus. By comparing these images it is

possible to arrive with a conclusion that each micro lens "sees" a different part of the symbols. Note that, for symbol 4 the image became inverted.

SUB-APERTURE IMAGES

The second way of presenting light-field data was called by Ng (2006) as sub-aperture images. An example of such an image is depicted in Fig. 1.8(a). Each sub-aperture image is a result of taking the same pixel under each micro lens which corresponds to the same sub-part u, v of the main lens aperture. In other words, a sub-aperture image can be considered as a set of light field $L(u, v, x, y)$ with fixed (u, v) but different (x, y) . Thus, (u, v) are the indexes of an individual sub-aperture image and (x, y) are the outer indexes of whole sub-aperture array of images.

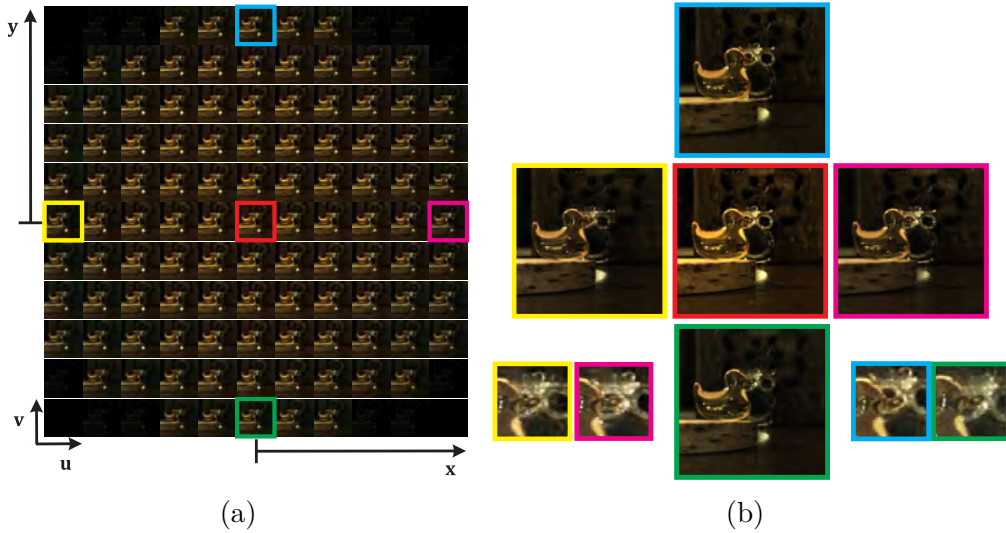


Figure 1.8: Sub-aperture images. The scene is composed of a glass duck in the front plane and an owl pendant in the back plane. **(a)** A sub-aperture image array. The circular global vignetting of the image is due to the fact that the aperture of the lens is also circular. **(b)** Images from the edges and the centre of (a). Comparison between yellow and pink as well as between blue and green images reveals a parallax shift between duck's beak and owl's eye.

The whole sub-aperture array has circular boundaries because of the circular aperture of the lens. Several selected images from the edges and the centre of the sub-aperture array are compared in Fig. 1.8(b). For example, comparison between blue- and green-marked images reveals a parallax shift between the duck's beak and owl's eye. In a conventional camera such disparity is the reason for blur since the image formation is equivalent to sum over the whole array of sub-aperture images.

SUB-ARRAY (OR EPIPOLAR) IMAGES

The disparity between multiple views shown in Fig. 1.8(b) leads to the third approach of displaying the light-field data. In this method, a point from the scene is projected to different position from different views. As a result, those projections create line segments in epipolar images as shown in Fig. 1.9. Therefore, each epipolar image is again a collection of light field $L(u, v, x, y)$ with fixed y and v parameters but varying x and u . Fig. 1.9(a) presents an array of horizontal epipolar images, where y varies up and v varies horizontally to the right through the array and within each epipolar image x increases horizontally to the right, and u varies up the image as indicated in the bottom close-up image.

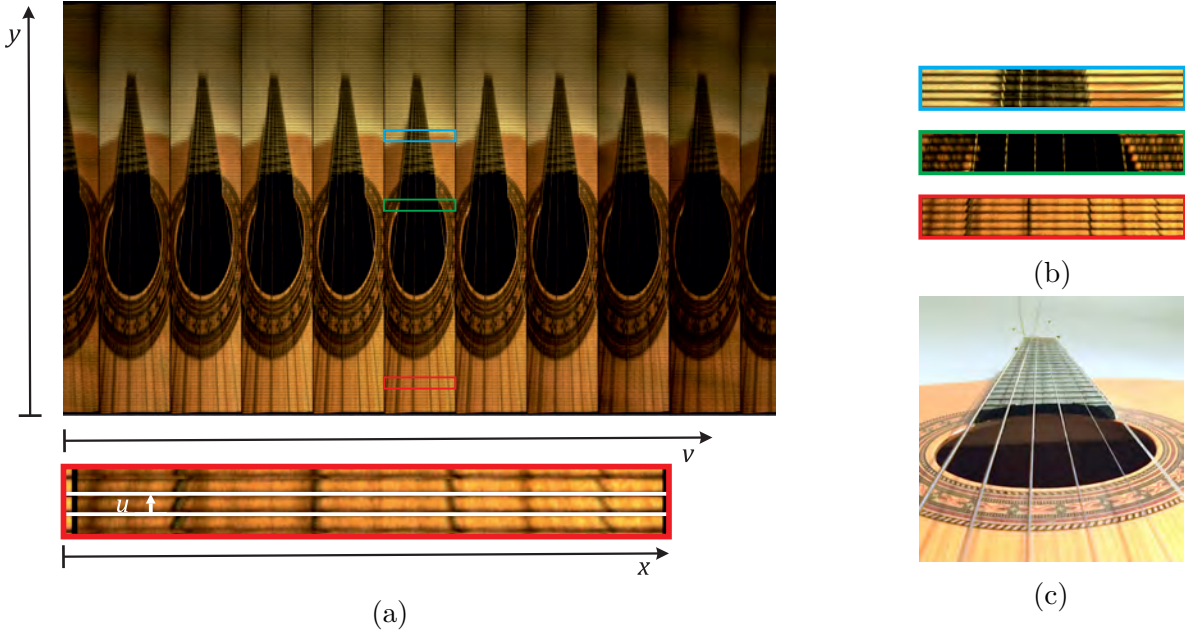


Figure 1.9: Epipolar image of a guitar neck with strings. **(a)** Upper image: an array of horizontal epipolar images, bottom image: a close-up showing a single epipolar image (white rectangle). **(b)** A comparison of epipolar images for different focal planes. The slope of the segment is varying with the change of focus. **(c)** A reconstructed image of the guitar with all planes in focus.

The focus of the image is concentrated approximately in the middle of the sound-hole. As depicted in Fig. 1.9(b), the slope of the segments is different for the areas that are in or out of the focus. Therefore, the depth value can be estimated based on the direction and steepness of the slope. Fig. 1.9(c) shows a reconstructed image of the guitar with all planes in focus.

1.2 TOMOGRAPHIC APPROACH TO LIGHT FIELD IMAGING

Computed tomography (CT) is a widely used imaging technique that allows 3D visualization of the samples based on 2D projections. In the conventional tomographic setups, i.e. cone-beam or conical beam tomography (Fig. 1.10(a)), the X-ray source and the detector synchronously rotate around the object, or equivalently the object can rotate while the source and detector are fixed. If the source is distant enough from the object, so that the divergence is negligible, a parallel-beam approximation can be applied (Fig. 1.10(b)). The results collected from the tomographic experiments are a set of projections from all angles of views, which next are combined to produce a cross-sectional images or 3D reconstruction of the object (Hsieh 2009). The tomographic scan is usually performed over 180° instead of full 360° , as the collected volume projections are integrated over a line connecting each detector pixel with the source position. However, in some situations, i.e. non-destructive imaging, the object cannot be investigated in the full angular range. In that case, any lack of the data results in artefacts or forms ambiguity in the reconstructed image. Nevertheless, with the newer techniques and algorithms a reconstruction that proves sufficient object's features is still possible, and this technique is referred to as the limited angle tomography (Kak & Slaney 2001).

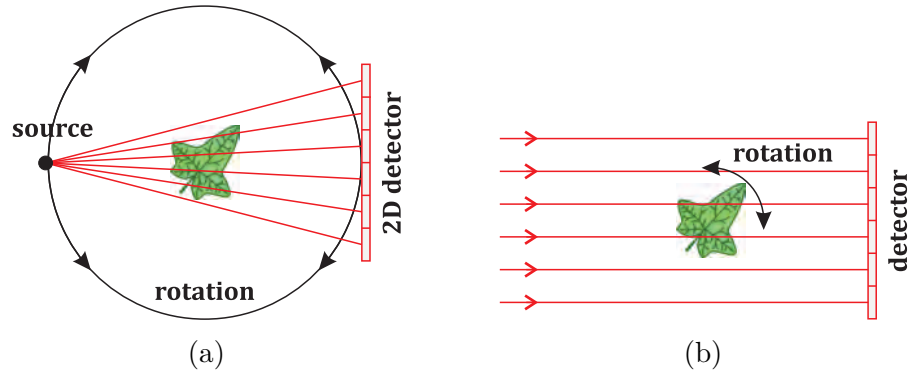


Figure 1.10: Comparison of several tomographic scanning geometries: **(a)** cone-beam and **(b)** parallel beam geometry.

The similarity between light-field imaging and tomography has been demonstrated in the context of light field microscopy (Levoy et al. 2005, Broxton et al. 2013). Recently, a new approach to reconstruct light field images has been proposed by Vigano et al. (2018), which utilizes algorithms and techniques known from the limited angle cone-beam tomography. According to the authors, a single sub-

aperture image of the light field corresponds to one tomographic projection. Consider a diagram presented in Fig. 1.11. Firstly, assume that the light is travelling from left to right. Then, the light originating from the object plane is collected by a main lens at point P (which can be considered as a virtual pinhole) and then is guided further, towards the MLA array. On the other hand, if the light is travelling from right to left, the light originating in point P (which can be considered as a point source) travels towards the sample and can be collected by a detector located behind the sample. In the case of tomography, the direction of propagation becomes of no consideration because of the fact that the Radon transform makes the projections direction-independent.

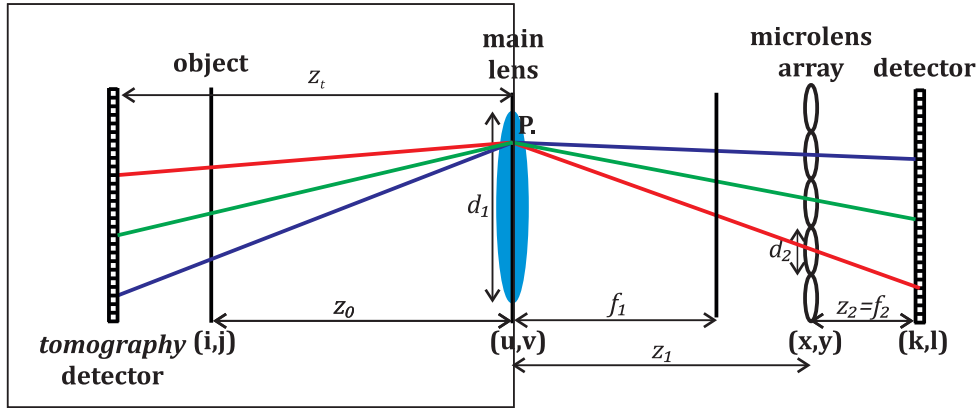


Figure 1.11: Comparison of ray tracing geometry for individual sub-aperture image (rays travelling from left to right) and tomographic geometry (rays travelling from right to left, marked with a black rectangle). After [Vigano et al. \(2018\)](#).

Tomography is usually used for imaging semi-transparent objects and opaque objects give rise to artefacts in reconstruction algorithms. On the contrary, digital photography is typically associated with surface-scattered light. However, [Lanman et al. \(2008\)](#) showed that the light field imaging can be also applied in the case of light absorption, which is important in terms of X-ray imaging.

1.3 SOFT X-RAY PLENOPTIC MICROSCOPE WITH FRESNEL ZONE PLATES

A previous attempt to construct X-ray plenoptic microscope was made by E. Longo during her Ph.D. studies ([Longo 2018](#)) as a part of a European FET project VOXEL (Volumetrix X-ray Extremely Low dose). In her thesis, Longo worked on

the "water window" prototype of desktop-size plenoptic soft X-ray microscope based on a soft X-ray desktop water microscope principle proposed by Wachulak and collaborators (Wachulak et al. 2015). Water window is a spectral range between oxygen K-shell and carbon K-shell, in which water is transparent for soft X-rays whereas carbon-based and thus organic molecules are strongly absorbing. Therefore it is very suitable for imaging i.e. hydrated cells.

A scheme of Longo's setup is depicted in Fig. 1.12. Soft X-rays (SXR) were produced as follows. Nitrogen plasma was produced by focusing a Nd:YAG pumping laser with pulses of 5 ns duration and energy of 1 J by an $f = 300$ mm focal length lens onto a nitrogen puff target. The SXR radiation was collected and focused on the sample by a nickel-coated condensed mirror from Rigaku. The nitrogen plasma radiates in a broad range of wavelengths, including visible light, thus, the produced SXR is incoherent and polychromatic. Therefore, for producing monochromatic radiation, a Ti filter was applied. Thus, the SXR wavelength was close to $\lambda = 2.88$ nm.

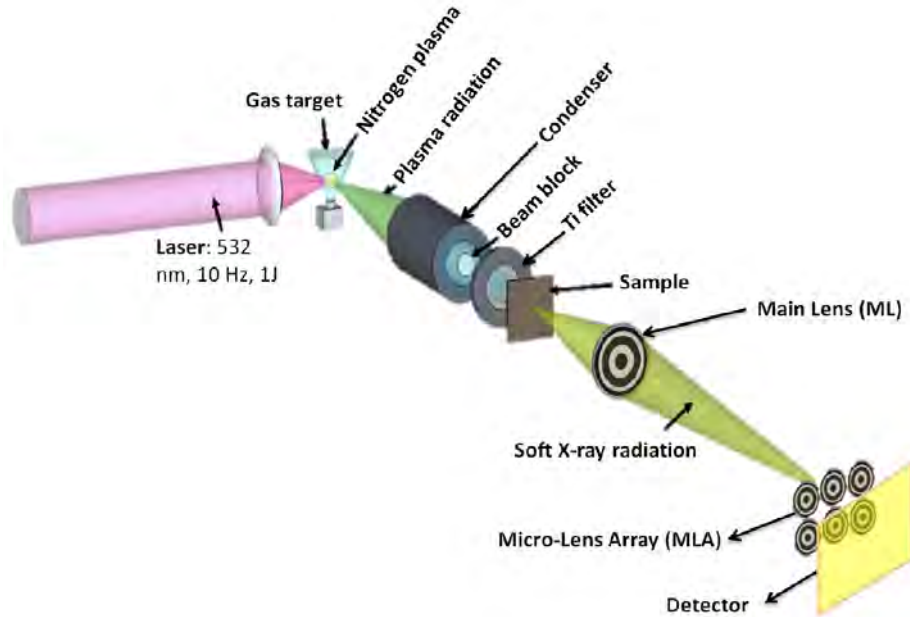


Figure 1.12: A scheme of soft X-ray plenoptic microscope proposed by Longo et al. The plenoptic camera geometry is realized by employing a $320\ \mu\text{m}$ diameter Fresnel zone plate as a main lens and an 20×20 array of small $32\ \mu\text{m}$ diameter zone plates. Image from (Longo 2018).

The plenoptic camera geometry was calculated according to the design of a standard plenoptic camera and designed by employing a Fresnel zone plate as a main lens and an array of small FZPs as a micro lens array. This FZP has a diameter of $320\ \mu\text{m}$,

first ring diameter of $4\text{ }\mu\text{m}$ and outer zone width equal to 18 nm . Thus, an intrinsic resolution was about 18 nm . The focal length of this FZP was 2 mm . An array of 20×20 Fresnel zone plates was employed as a lenslet array. An individual zone plate was composed of 5 zones, has 17.78 mm focal length, $32\text{ }\mu\text{m}$ diameter and outer zone width equal to $1.689\text{ }\mu\text{m}$. The distance between individual ZPs was $37\text{ }\mu\text{m}$. In their prototype, they used a 2048×2048 CCD camera with a pixel size of $13.5\text{ }\mu\text{m}$.

The setup is still under development. Longo and collaborators plan to replace current CCD camera with a crystal coupled to visible CCD camera with pixel size of $1\text{ }\mu\text{m}$. The crystal would convert X-rays into a green light and collect radiation on CCD via a 10x objective microscope. Additionally, the FZP main lens is planned to be replaced with a spherical mirror and adaptive optics. Moreover, the array of FZPs could be also replaced with an array of pinholes. Although the setup looks very promising and is under further tests, still no experimental results have been presented.

X-RAY IMAGING

2.1 X-RAY PROPAGATION IMAGING

The basic principles of plenoptic imaging and X-ray radiography rely on geometrical optics, which is wavelength-independent. However, in the experiments reported in this Thesis, a clear phase-contrast could be observed in X-ray images which, in most cases, requires wave optics description. In principle, the concept of a plenoptic camera can be generalized to wave optics ([Lam 2015](#)). Here, we skip such a non-trivial generalization. Instead of this, the following Sections show that under scalar, paraxial and projection approximations, X-ray images formed due to propagation based phase-contrast can be described in terms of geometrical optics. The phase contrast is manifested just as an edge enhancement effect. Following Sections are mainly based on [Paganin \(2006\)](#).

2.1.1 PARAXIAL AND PROJECTION APPROXIMATIONS

A propagating wave is mathematically described in the notion of a field. For X-rays a scalar approximation of the electromagnetic field ($\Psi(x, y, z)$) is usually employed, and the wave equation (or d’Alembert equations) in vacuum can be written as:

$$\left(\frac{1}{c^2}\partial_t^2 - \nabla^2\right)\Psi(x, y, z, t) = 0. \quad (2.1)$$

Here c represents the speed of light, and ∇^2 is the Laplacian operator in Cartesian coordinate system. In order to reduce the complexity, the separation of variables is performed, resulting in the so-called Helmholtz equation:

$$(\nabla^2 + k^2)\psi(x, y, z) = 0, \quad (2.2)$$

where $k = \frac{\omega}{c}$ is the wave vector and $\psi(x, y, z)$ is a time-independent monochromatic wave. If the normal vectors of the wave’s wavefront form small angles with respect to the propagation direction, the wave is called paraxial. Thus, the Helmholtz equation can be further reduced to the so-called paraxial wave equation by separating the

propagating wave into a rapidly oscillating plane wave e^{ikz} along the optical axis z and a slowly varying envelope $\psi_0(x, y, z)$:

$$\psi(x, y, z) = \psi_0(x, y, z)e^{ikz}. \quad (2.3)$$

Inserting Eq. (2.3) into the Helmholtz equation (Eq. (2.2)) and neglecting the second order derivative in z , the homogenous paraxial Helmholtz equation is obtained:

$$(\partial_{x,y}^2 + 2ik\partial_z)\psi_0(x, y, z) = 0. \quad (2.4)$$

Here, the Laplacian was split into the lateral: $\partial_{x,y}^2 = \partial_x^2 + \partial_y^2$ and axial ∂_z^2 part. Such a procedure is called the paraxial approximation and is a fine description for waves or beams propagating in one direction and varying mainly along the direction of propagation, such as spherical, parabolical or Gaussian waves. The latter are well suited for characterizing waveguide-based imaging (Fuhse et al. 2006). In the presence of matter Eq. (2.2) becomes the inhomogeneous Helmholtz equation:

$$(\nabla^2 + k^2 n^2(x, y, z))\psi(x, y, z) = 0, \quad (2.5)$$

where $n(x, y, z) = \sqrt{\frac{\epsilon(x, y, z)}{\epsilon_0}}$ is the refractive index, which, in case of X-rays, is slightly smaller than unity and is often expressed as the complex refractive index:

$$n(x, y, z) = 1 - \delta(x, y, z) + i\beta(x, y, z), \quad (2.6)$$

Here, δ is the refractive index decrement responsible for phase shifts in the material and β is governing the absorption effects. For X-rays, both δ and β are positive numbers, typically on the order of 10^{-5} and 10^{-6} , respectively. The parameter $\delta(x, y, z)$ can be described away from the absorption edges as:

$$\delta(x, y, z) = \frac{2\pi r_e \rho_e(x, y, z)}{k^2}, \quad (2.7)$$

where r_e is the classical electron radius and $\rho_e(x, y, z)$ is the electron density. The parameter $\beta(x, y, z)$ can be approximated by:

$$\beta(x, y, z) = \frac{\mu(x, y, z)}{2k}, \quad (2.8)$$

where $\mu(x, y, z)$ is the absorption coefficient. For a weakly interacting objects placed in a paraxial beam (Fig. 2.1), the paraxial approximation allows to rewrite the inhomogeneous Helmholtz equation (Eq. (2.5)) as:

$$(2ik\partial_z + \partial_{x,y}^2 + k^2(n^2(x, y, z) - 1))\psi(x, y, z) = 0. \quad (2.9)$$

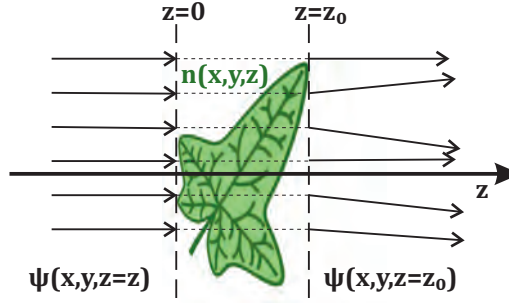


Figure 2.1: The projection approximation. A plane wave $\psi(x, y, z = 0)$ is incident on an object at plane $z = 0$, undergoes scattering, and exits the object at the plane $z = z_0$. According to the projection approximation, the wave field at the $\psi(x, y, z = z_0)$ plane after passing through the object is determined by the phase and amplitude shifts accumulated along the straight rays as the beam paths remains undisturbed in the sample.

Due to the fact that both $\delta(x, y, z)$ and $\beta(x, y, z)$ are much smaller than unity, the second order terms in calculating $n^2(x, y, z) - 1$ from Eq. (2.6) can be neglected. As a result the inhomogeneous paraxial equation becomes:

$$(2ik\partial_z + \partial_x^2 + \partial_y^2 + 2k^2(\delta(x, y, z) - i\beta(x, y, z)))\psi(x, y, z) = 0. \quad (2.10)$$

Therefore, the wave field at the plane $z = 0$ (where the beam is impinging an weakly absorbing object, see Fig. 2.1) is related with the wave field at plane $z = z_0$ (where the wave is exiting the object) as follows:

$$\psi(x, y, z = z_0) = e^{\frac{k}{2i} \int_0^{z_0} 1 - (\delta(x, y, z) - i\beta(x, y, z)) dz} \psi(x, y, z = 0). \quad (2.11)$$

Eq. (2.11) is called the projection approximation and is obtained by solving the boundary problem of the inhomogeneous paraxial equation. The projection approximation assumes that the scattering inside the object is weak, and the beam paths inside the sample are undisturbed. Hence, amplitude changes and phase shifts are accumulated along straight rays. The intensity of the beam (squared modulus of Eq. (2.11)) is similar to the Beer's law of absorption:

$$\begin{aligned} I(x, y, z = z_0) &= e^{-2k \int \beta(x, y, z) dz} I(x, y, z = 0) \\ &= e^{-\mu^T(x, y)} I(x, y, z = 0), \end{aligned} \quad (2.12)$$

where $T(x, y)$ is the projected thickness of the object and the phase shifts $\phi(x, y, z)$ and absorption $\mu(x, y, z)$ of the object are defined as follows:

$$\phi(x, y, z) = -k \int_{-d}^0 \delta(x, y, z) dz, \quad (2.13)$$

$$\mu(x, y, z) = 2k \int_{-d}^0 \beta(x, y, z) dz. \quad (2.14)$$

2.1.2 FRESNEL APPROXIMATION OF FREE SPACE PROPAGATION

The plane wave at the plane $z = 0$ (Fig. 2.1) can be decomposed in lateral Fourier components:

$$\psi(x, y, z = 0) = \frac{1}{2\pi} \iint \tilde{\psi}(k_x, k_y, z = 0) e^{i(k_x x + k_y y)} dk_x dk_y, \quad (2.15)$$

where $\tilde{\psi}(k_x, k_y, z = 0)$ denotes the Fourier transform of $\psi(k_x, k_y, z = 0)$ and (k_x, k_y) are components of the wave vector $\mathbf{k}$. In order to propagate this wave to any plane $z = \Delta > 0$ one needs to insert the Eq. (2.15) into Helmholtz equation and solve it for $\tilde{\psi}(k_x, k_y, z = \Delta)$:

$$\tilde{\psi}(k_x, k_y, z = \Delta) = \tilde{\psi}(k_x, k_y, z = 0) e^{i\Delta \sqrt{k^2 - k_x^2 - k_y^2}}. \quad (2.16)$$

Therefore, Eq. (2.15) becomes:

$$\psi(x, y, z = \Delta) = \frac{1}{2\pi} \iint \tilde{\psi}(k_x, k_y, z = 0) e^{i\Delta \sqrt{k^2 - k_x^2 - k_y^2}} e^{i(k_x x + k_y y)}, \quad (2.17)$$

which is called the angular spectrum representation of the propagated wave field and describes the propagation of the wave field to a given distance Δ . Moreover, it is possible rewrite Eq. (2.17) using the Fourier transform ($\mathcal{F}$):

$$\psi(x, y, z = \Delta) = \mathcal{F}^{-1} \left[e^{i\Delta \sqrt{k^2 - k_x^2 - k_y^2}} \mathcal{F} [\psi(x, y, z = 0)] \right], \quad (2.18)$$

and thus a free space propagation operator acting on a given wave field $\psi(x, y, z = 0)$ can be introduced:

$$\hat{D}_z = \mathcal{F}^{-1} e^{iz \sqrt{k^2 - k_x^2 - k_y^2}} \mathcal{F} \quad (2.19)$$

Since the wave field is paraxial, k_x and k_y components of the wave vector are much less than k_z and also $k_x^2 + k_y^2 \ll k^2$. As a result a following approximation can be applied:

$$\sqrt{k^2 - k_x^2 - k_y^2} \approx k - \frac{k_x^2 + k_y^2}{2k}, \quad (2.20)$$

and the propagating wave field (Eq. (2.18)) becomes:

$$\psi(x, y, z = \delta) \approx \hat{D}_\Delta \psi(x, y, z = 0) = e^{ik\Delta} \mathcal{F}^{-1} \left[e^{-\frac{i\Delta(k_x^2 + k_y^2)}{2k}} \mathcal{F} [\psi(x, y, z = 0)] \right]. \quad (2.21)$$

Eq. (2.21) is called the Fresnel approximation of free space propagation or Fresnel diffraction with the corresponding Fresnel free space propagation operator:

$$\hat{D}_z^F = e^{ikz} \mathcal{F}^{-1} e^{-\frac{iz(k_x^2 + k_y^2)}{2k}} \mathcal{F}. \quad (2.22)$$

2.1.3 FRESNEL SCALING THEOREM

Consider a situation depicted in Fig. 2.2(a). A monochromatic point source emits radiation in a paraxial divergent beam and illuminates the object placed at a distance R from the source.

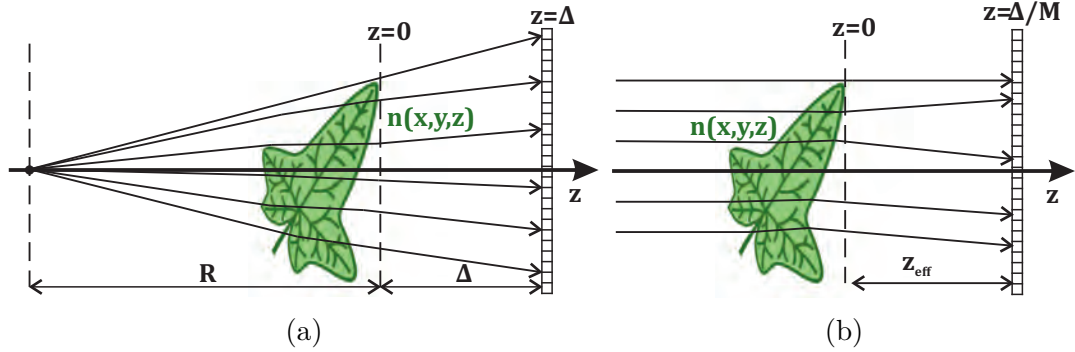


Figure 2.2: Illustration of Fresnel scaling theorem. **(a)** A point source emits radiation in a divergent beam and illuminates an object placed at the distance R . The image of the object is magnified ($M = \frac{R+\Delta}{R}$) at the detector plane at distance $R + \Delta$. **(b)** A plane wave illuminates the object and the image of the object is formed at the detector plane at effective distance z_{eff} from the object. The Fresnel scaling theorem states that both images are identical if the paraxial and projection approximations are valid. Adopted from Paganin (2006).

The propagation of such a wave field from the source to the detector plane $z = \Delta$ can be calculated as follows:

$$\begin{aligned} \psi^{\text{div}}(x, y, z = \Delta) &= \\ &= -\frac{ik}{2\pi\Delta} e^{ik\Delta} e^{\frac{ik(x^2 + y^2)}{2\Delta}} \iint \psi^{\text{div}}(x', y', z = 0) e^{\frac{ik(x'^2 + y'^2)}{2}} e^{-ik\frac{xx' + yy'}{\Delta}} dx' dy'. \end{aligned} \quad (2.23)$$

According to the paraxial and projection approximations, the propagated divergent wave can be expressed in terms of the plane wave:

$$\psi^{\text{div}}(x, y, z = 0) = \psi^{\text{plane}}(x, y, z = 0) e^{\frac{ik}{2R}(x^2 + y^2)}, \quad (2.24)$$

and therefore, Eq. (2.24) becomes:

$$\begin{aligned}\psi^{div}(x, y, z = 0) = \\ = -\frac{ik}{2\pi\Delta} e^{ik\Delta} e^{\frac{ik}{2\Delta}(x^2+y^2)} \iint \psi^{plane}(x', y', z = 0) e^{\frac{ik(x'^2+y'^2)}{2\Delta}(\frac{1}{\Delta}+\frac{1}{R})} e^{-\frac{ik(xx'+yy')}{\Delta}} dx' dy'.\end{aligned}\quad (2.25)$$

The geometrical magnification can be deduced from Fig. 2.2(a) with the use of the principle of similar triangles:

$$M = \frac{R + \Delta}{R}, \quad (2.26)$$

and therefore the effective propagation distance can be introduced:

$$\frac{1}{z_{eff}} = \frac{1}{R} + \frac{1}{\Delta} = \frac{M}{\Delta}. \quad (2.27)$$

The intensity of the propagated wave field can be calculated by substituting Eq. (2.27) into Eq. (2.26) and taking the squared modulus:

$$\begin{aligned}I^{div}(x, y, z = \Delta) = \\ = \frac{k^2}{4\pi^2\Delta^2} \left| \iint \psi^{plane}(x', y', z = 0) \exp \left[\frac{ikM}{2\Delta}(x'^2 + y'^2) - \frac{ik}{\Delta}(xx' + yy') \right] dx' dy' \right|^2.\end{aligned}\quad (2.28)$$

For R approaching ∞ , the magnification is going to the unity and therefore the intensity for plane wave case becomes:

$$\begin{aligned}I^{plane}(x, y, z = \Delta) = \\ = \frac{k^2}{4\pi^2\Delta^2} \left| \iint \psi^{plane}(x', y', z = 0) \exp \left[\frac{ik}{2\Delta}(x'^2 + y'^2) - \frac{ik}{\Delta}(xx' + yy') \right] dx' dy' \right|^2.\end{aligned}\quad (2.29)$$

The comparison of equations (2.29) and (2.30) allows one to conclude that:

$$I^{div}(x, y, z = \Delta) = \frac{1}{M^2} I^{plane}\left(\frac{x}{M}, \frac{y}{M}, z = \frac{\Delta}{M}\right) \quad (2.30)$$

Hence, the propagation of a divergent (or cone-beam) wave field is equivalent to a plane wave propagation with the object demagnified by the geometric magnification M . The prefactor $\frac{1}{M^2}$ scales the intensity and is responsible for energy conservation. Eq. (2.30) is called the Fresnel scaling theorem.

2.1.4 CONTRAST FORMATION

The classical X-ray images that we usually think of, i.e. radiographs, are based on measuring the absorption of the sample. The phase distribution is not easy to

record, due to the fact that the electric field oscillate too fast. However, phase contrast imaging is a better choice for low absorption samples (i.e. biological samples) as it provides better contrast and detection sensitivity compared to conventional absorption images. To describe a contrast formation, the wave field is described in terms of phase distribution $e^{i\phi(x,y,z)}$ and measurable intensity $I(x, y, z)$ as follows:

$$\psi(x, y, z) = \sqrt{I(x, y, z)}e^{i\phi(x,y,z)}. \quad (2.31)$$

Inserting Eq. (2.31) into the homogenous Helmholtz equation (Eq. (2.4)) and performing simplifications yields:

$$\partial_{x,y}(I(x, y, z)\partial_{x,y}\phi(x, y, z)) = -k\partial_z I(x, y, z) \quad (2.32)$$

which is known as the Transport-of-Intensity Equation (TIE) (Paganin & Pelliccia 2019) and states that the changes of the wave field along the optical axis can be calculated from small steps in z -axis, with known intensity and phase at some initial point. If we consider a small propagation distance Δz , we can approximate the TIE equation to:

$$\partial_{x,y}^2 \phi(x, y, 0) \approx -k \frac{I(x, y, \Delta z) - I_0}{I_0 \Delta z}, \quad (2.33)$$

and therefore:

$$\frac{I(x, y, \Delta z)}{I_0} \approx 1 - \frac{\Delta z \partial_{x,y}^2 \phi(x, y, 0)}{k}, \quad (2.34)$$

which is called the near field TIE. Eq. (2.34) indicates that in the propagation based imaging the intensity pattern is proportional to the Laplacian of the object's phase shifts. The effect of the Laplacian operator is manifested as an clear edge-enhancement of the imaged features.

2.1.5 PAGANIN PHASE RETRIEVAL ALGORITHM

One of the phase reconstruction algorithms based on the near field TIE was proposed by Paganin (2006). The algorithm assumes that the object is homogenous, and therefore phase and absorption are proportional to each other (Burvall et al. 2011). If the projected thickness of an object $T(x, y)$ is known, the projection approximation with Eq. (2.13) and (2.14) describe the intensity of the wave after passing through the object as follows:

$$I(x, y, 0) = |\psi(x, y, 0)| = I_0 e^{\mu_{LB} T(x,y)}, \quad (2.35)$$

where $\mu_{LB} = 2k\beta$ is the linear absorption coefficient from Lambert-Beer's law. Substituting Eq. (2.35) to the TIE yields:

$$\left(1 - \frac{\delta\Delta z}{\mu}\nabla^2\right)e^{-\mu T(x,y)} = \frac{I(x,y,\Delta z)}{I_0}. \quad (2.36)$$

The above differential equation can be solved using the pseudo differential operators. As a result, an expression for the object thickness $T(x,y)$ is obtained. Moreover, the phase shifts can be calculated via:

$$\phi(x,y,0) = \frac{\delta}{2\beta} \cdot \ln \mathcal{F}^{-1} \left(\frac{\mathcal{F}\left(\frac{I(x,y,\Delta z)}{I_0}\right)}{1 + \frac{\delta}{2k\beta}(k_x^2 + k_y^2)} \right), \quad (2.37)$$

which is called the Paganin reconstruction or the Paganin filter (Paganin et al. 2002). The algorithm depends on the δ/β ratio. This ratio is frequently chosen based on a visual assessment of the quality of the reconstruction, i.e. the presence of the blurring or edges enhancement.

2.2 X-RAY OPTICS

2.2.1 OVERVIEW OF X-RAY OPTICAL ELEMENTS

COMPOUND REFRACTIVE LENS

Since the refractive index in the X-ray regime is only slightly smaller than unity, the fabrication of efficient refractive optics is a challenging task. Until 1990s it was alleged that refractive lens for hard X-ray regime are hard to produce (Kirkpatrick & Baez 1948, Michette 1991, Yang 1993). The complex refractive index for X-rays is commonly described as (Paganin 2006):

$$n = 1 - \delta + i\beta, \quad (2.38)$$

where δ is the refractive index decrement responsible for phase shifts in the material and it is on the order of 10^{-6} and β is governing the absorption effects. Because of the negative refractive index decrement, an X-ray converging lens has a concave shape, in contrast to converging lens for visible light of convex shape. Fig. 2.3(a) presents a scheme of a single refractive lens for X-rays: biconcave lens with a curvature radius R in material slab. Such a lens focuses rays at a distance (Paganin 2006):

$$f = \frac{R}{2\delta}. \quad (2.39)$$

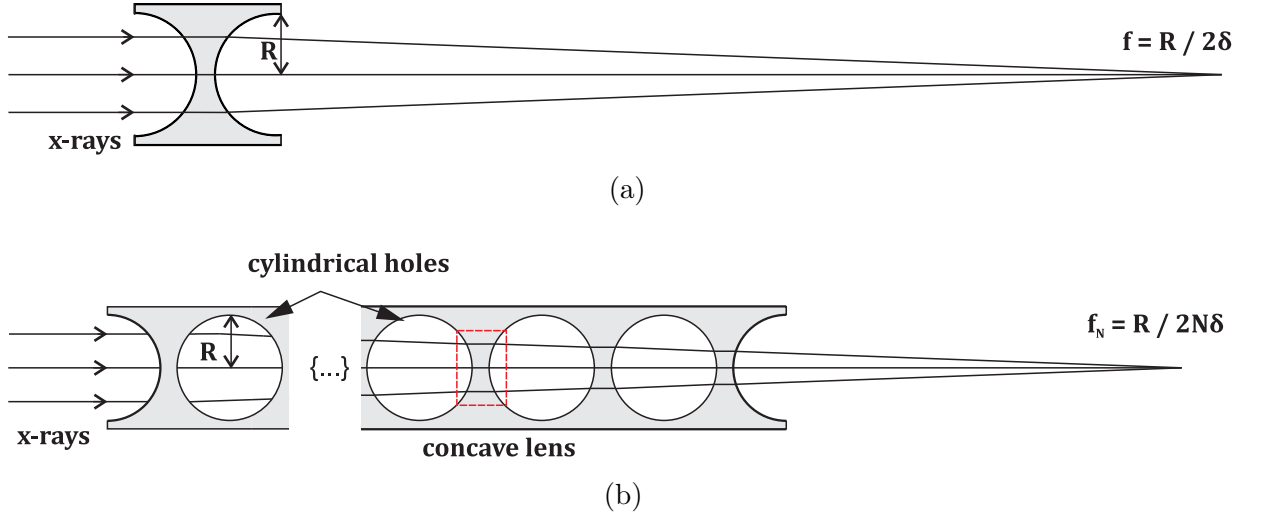


Figure 2.3: A scheme of converging refractive lenses for X-rays. **(a)** A single refractive lens. **(b)** A compound refractive lens with N holes, which focuses X-rays on a focal length N times shorter than single refractive lens. A red dashed square marks an individual biconcave lens.

Consider a typical value of δ for hard X-rays as $\leq 10^{-6}$. The focal length of a single lens ($R \approx 1$ mm) will be on the order of 25 m, making this kind of lens unpractical for performing experiments. On the other hand, to achieve a focal length in the order of 10 cm, the radius of individual lens must be on the order of $2 \mu\text{m}$, which still is hard to manufacture. In 1996 Snigirev proposed to increase a number of holes, which directly leads to the shortening of the focal length. Therefore, his compound lens with N holes has a focal length N times smaller than the single lens (Snigirev et al. 1996):

$$f_N = \frac{R}{2\delta N}. \quad (2.40)$$

A scheme of such compound refractive lens is presented in Fig. 2.3(b). However, another problem occurred as the increasing thickness of the material caused the increase of the absorption effects and as a consequence the attenuation of the beam while travelling through the lens. Therefore, typically low- Z elements, such as aluminium, beryllium or boron are chosen for the lens material.

FRESNEL ZONE PLATES

Fresnel zone plates are widely used diffractive focusing elements not only for X-rays but also for neutrons, where refractive lenses are inappropriate due to the high

absorption in material (Kearney et al. 1980). As presented in Fig. 2.4 a FZP consists of thin circular opaque and transparent gratings, called Fresnel zones, on which X-rays undergoes diffraction. The zones are numbered consecutively from the most inner one and they are spaced in such a way that rays constructively interfere at the focus f . A given zone plate can be specified by its radius r_N and outermost zone width Δr_N , from which the resolution, focal length, and numerical aperture at a given wavelength can be easily calculated. The optical path of the rays going through the transparent zones differ by one wavelength and the condition on the zone radii is given by (Jacobsen et al. 2019):

$$f^2 + r_n^2 = \left(f + \frac{n\lambda}{2}\right)^2, \quad (2.41)$$

where r_n is the radius of n^{th} zone given by:

$$r_n = \sqrt{n\lambda \left(f + \frac{n\lambda}{4}\right)} \simeq \sqrt{n\lambda f}. \quad (2.42)$$

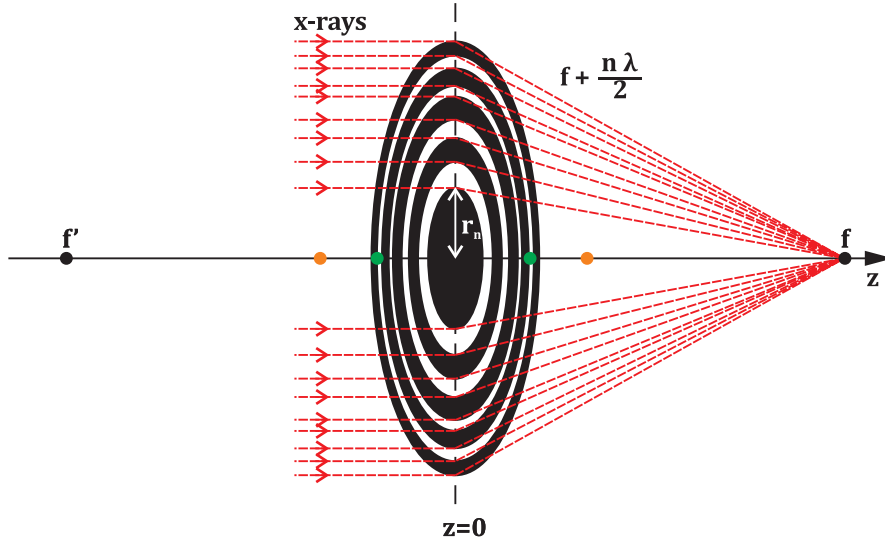


Figure 2.4: A scheme of a Fresnel zone plate at a plane $z = 0$. It consists of several opaque and transparent concentric rings (Fresnel zones) on which X-rays are diffracting. A monochromatic plane waves are focused at a focal distance $f + \frac{n\lambda}{2}$, where n is a number of Fresnel zones and r_n is a radius of n^{th} zone. A virtual focus is located at f' . Additional virtual and real foci lay at distances $\pm f/3$ (orange dots) and $\pm f/5$ (green dots). After Als-Nielsen & McMorrow (2011).

The width of the outermost zone N is calculated as a difference of the above equation taken for n and $(n - 1)$:

$$\Delta r_n = \frac{\lambda f}{2r_N}. \quad (2.43)$$

Moreover, all the zones have equal area and, with the grating equation, the numerical aperture of Fresnel zone plate can be expressed as:

$$NA = \sin \theta = \frac{r_N}{f} = \frac{\lambda}{2\Delta r_N}. \quad (2.44)$$

The Rayleigh criterion for minimum resolvable details is given by:

$$\Delta x = \frac{0.61\lambda}{NA} = 1.22r_N. \quad (2.45)$$

Nowadays, zone plates are fabricated mainly using techniques based on electron beam lithography with the diameter of 10 – 20 nm ([Chao et al. 2009](#), [Lider 2017](#)).

MULTI LAYER LENSES

Multi layer lenses consist of a series of alternating layers of high and low density materials (Fig. 2.5(a)). X-rays incident at the angle θ are reflected from multilayer lens if the Bragg condition is fulfilled, i.e the path-length difference marked by red lines is an integer multiple m of the wavelength λ :

$$m\lambda = 2d \sin \theta, \quad (2.46)$$

where d is the period of multilayer, typically ranging from 2 nm to 20 nm.

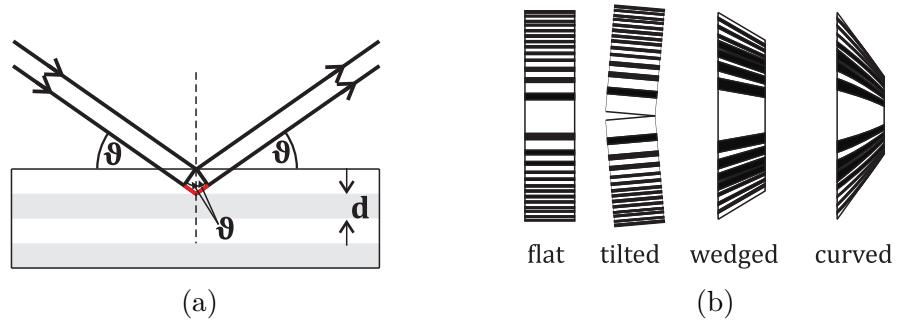


Figure 2.5: Examples of multilayer lenses. **(a)** A scheme of multilayer optics. The X-rays are reflected if the Bragg condition is fulfilled: if the path-length difference marked by red lines is an integer multiple of the wavelength. After [Als-Nielsen & McMorrow \(2011\)](#). **(b)** Types of multilayer Laue lens (MLL) after [Yan et al. \(2007\)](#).

It is worth to mention a special type of zone plates, called multilayer Laue lenses (MLL). They consist of thousand of alternating layers grown by the magnetron sputter deposition technique ([Yan et al. 2010](#)). This manufacturing technique allows the

growth of very thin zones and overcoming the difficulties present for FZP. Multilayer optics can be used both to monochromatise and collimate the X-ray beam, by continuously adapting the reflection angle along the optics. This property leads to the four types of MLL as shown in Fig. 2.5(b) (Yan et al. 2007).

A flat MLL is equivalent to an one dimensional zone plate and follows the same rules, i.e. equation (2.42). In a second type of the MLL, tilted one, the Bragg condition is fulfilled at particular lens region because the varying zone width. In the third type, a wedged one, zones are tilted gradually to the incident rays. Lastly, a parabolical or elliptical zone profile (curved MLL) enables to achieve focus size on the order of the wavelength.

2.2.2 CAPILLARY OPTICS

TOTAL EXTERNAL REFLECTION

The total external reflection of X-rays was discovered and described by Compton (Compton 1923). To begin with, consider a situation depicted in Fig. 2.6. An incident ray is travelling in the medium with higher refractive index n_i (i.e. vacuum) and impinges a medium with lower refractive index n_t . The Snells's law for such situation is defined as:

$$\Re(n_i) \sin \theta_i = \Re(n_t) \sin \theta_t, \quad (2.47)$$

$$\sin \theta_i = (1 - \delta) \sin \theta_t. \quad (2.48)$$

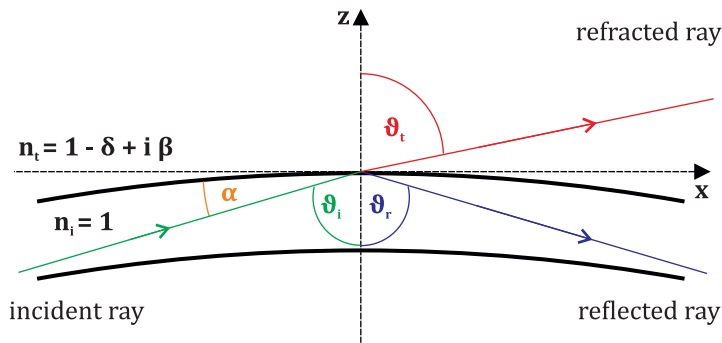


Figure 2.6: A scheme of reflection in a single capillary. The capillary is typically hollow inside ($n_i = 1$ for vacuum) and made of borosilicate glass ($n_t = 1 - 1.66 \cdot 10^{-6} + i \cdot 3.88 \cdot 10^{-9}$) (Henke et al. 1993). The incident ray impinge the media border at angle θ_i , reflects and refracts at angles θ_r and θ_t , respectively. The angle α is the incidence angle but measured with respect to the surface that the ray strikes.

If θ_i is such that $\theta_t \rightarrow \pi/2$, a critical angle θ_c for which the total reflection occurs is obtained:

$$\sin \theta_c = (1 - \delta) \sin \frac{\pi}{2} = 1 - \delta. \quad (2.49)$$

In X-ray optics angles are measured with respect to the surface that a light ray strikes, therefore the critical angle α_c can be expressed as $\alpha_c = \pi/2 - \theta_c$, and Eq. (2.49) can be rewritten as:

$$\cos \alpha_c = 1 - \delta. \quad (2.50)$$

By employing the second order Taylor expansion for cosine at zero angle we end with the well known equation for the critical angle:

$$\alpha_c = \sqrt{2\delta}. \quad (2.51)$$

If the angle α on Fig. 2.6 is less or equal to this critical value, the ray is totally reflected from the surface. Since for X-rays $n_t < n_i$, this phenomenon is called total *external* reflection, whereas the reverse situation ($n_i < n_t$) for visible light is called total internal reflection. For a known material, Eq. (2.51) can be transformed into:

$$\alpha_c E = \frac{eh}{2\pi} \sqrt{\frac{\rho_e}{\epsilon_0 m_e}}, \quad (2.52)$$

where $E = \frac{hc}{\lambda}$ is energy, e is the charge of electron, c is speed of light in vacuum, ρ_e is the number of electrons per unit volume in material, ϵ_0 is the electrical permittivity of free space, m_e is the rest mass of the electron. Eq. (2.52) points out that the critical angle is an energy dependent value. Additionally, α_c increases proportionally to $\sqrt{\rho_e}$, and as a consequence, materials of higher atomic number will have a higher critical angle. However, the main conclusion from Eq. (2.52) is that the shorter the wavelength is, the lower the critical angle becomes. For X-rays, δ is on the order of 10^{-6} , thus the critical critical angle is on the order of milliradians (Als-Nielsen & McMorrow 2011).

SINGLE CAPILLARY OPTICS

The idea to guide X-rays through a single capillary by total external reflection was firstly proposed by Hirsch & Kellar (1951) and then developed further by Marton (1966) and Mosher & Stephanakis (1976). A capillary is a hollow glass tube in a conical, parabolical or elliptical shape that is used to concentrate X-rays to a small spot

with an increase in the intensity of 10-1000 times (Stern et al. 1988, Engström et al. 1989, Rindby et al. 1989, Thiel et al. 1989). X-rays are travelling through the glass capillary via total external reflection on the inner walls. There are two types of mono-capillaries, as depicted in Fig. 2.7.

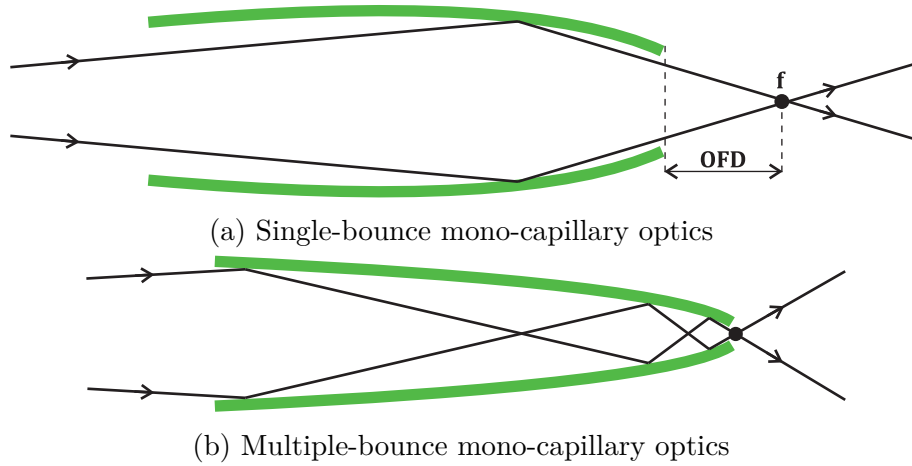


Figure 2.7: Types of mono-capillary optics. Adopted from Bilderback et al. (1996).

In the first type of capillary optics, X-rays are reflecting only once from the surface (Fig. 2.7(a)) and image the source on to the sample position. The incoming rays are focused at the point f at the distance OFD from the capillary exit. This distance is often called working distance or output focal distance of the optical element. For a single-bounce mono-capillary, OFD is typically on the order of millimetres or centimetres and the typical focal spot size at a level of several microns. (Balaic et al. 1995).

In the second type of mono-capillary X-rays are reflected more than once from the surface (Fig. 2.7(b)). The beam size is determined by the exit diameter of the capillary (typically 50 nm - 10 μm (Bilderback et al. 1996)). In contrast to single-bounce capillaries, a true focus is not produced and as a consequence, the multiple-bounce mono-capillaries are often called as concentrating optics rather than focusing ones. Additionally, the working distance of such elements is very short and the exiting beam is the smallest at the capillary exit surface. As a consequence, the sample has to be positioned close to the capillary exit surface.

POLYCAPILLARY

In 1990, inspired by ion channelling experiments, Kumahkov designed a first polycapillary optical element (Kumakhov 1990) which can accept about 60 times larger

angle of incident rays than the mono-capillaries (Lider 2018). Since then, polycapillary optics became well suited for various laboratory-based techniques such as spectroscopy (Adams et al. 2016), imaging (Sun & McDonald 2013) and diffraction techniques (Ullrich et al. 1994, Zhou et al. 2010) as well as in medicine (Kim et al. 2006).

A polycapillary optical element consists of over a dozen hundreds of thousands hollow glass capillaries bundled together with an appropriate curvature which enables to collimate or concentrate X-rays (Fig. 2.8). What is more, a polycapillary provides much higher intensity in the focal spot compared to other X-ray optical elements.

Since in our experiments we used a polycapillary optics, it is worth to discuss several of its properties. To begin with, there is a phenomenological simplification of equation (2.52) for a polycapillary optics made of borosilicate glass:

$$\alpha_c[\text{mrad}] = \frac{30[\text{keV}]}{E}, \quad (2.53)$$

which results in an energy-dependent transmission of the polycapillary element. As a result, it is possible to employ polycapillary as a low pass filter. In chapter 3.3.2 we provide comparison of spectra acquired for the same polycapillary element but with X-ray tubes of different anodes.

The second important parameter is the the maximum source diameter that can be captured by the optic, which at the focal point can be expressed as:

$$D_{source} \approx 2IFD \cdot \alpha_c, \quad (2.54)$$

where IFD is the input focal distance of the element. Rays coming from a source which is larger than D_{source} are impinging the optics at angles too high to be reflected. Moreover, if the source is placed closer than the IFD to the optics, it is not efficiently captured by the optics because only a few individual capillaries can transmit X-rays. Nonetheless, the position of the focal spot does not depend on the position of the source (Vincze et al. 2002).

The third parameter is the divergence. A polycapillary optics has two types of divergence. The first type, a global divergence γ , is determined by the exit diameter of polycapillary D_{out} and OFD:

$$\gamma = 2 \tan^{-1} \left(\frac{D_{out}}{2 \cdot OFD} \right). \quad (2.55)$$

A shorter OFD will result in a smaller spot and increase the global divergence. The second type, the local divergence of each of individual capillaries β , is always greater

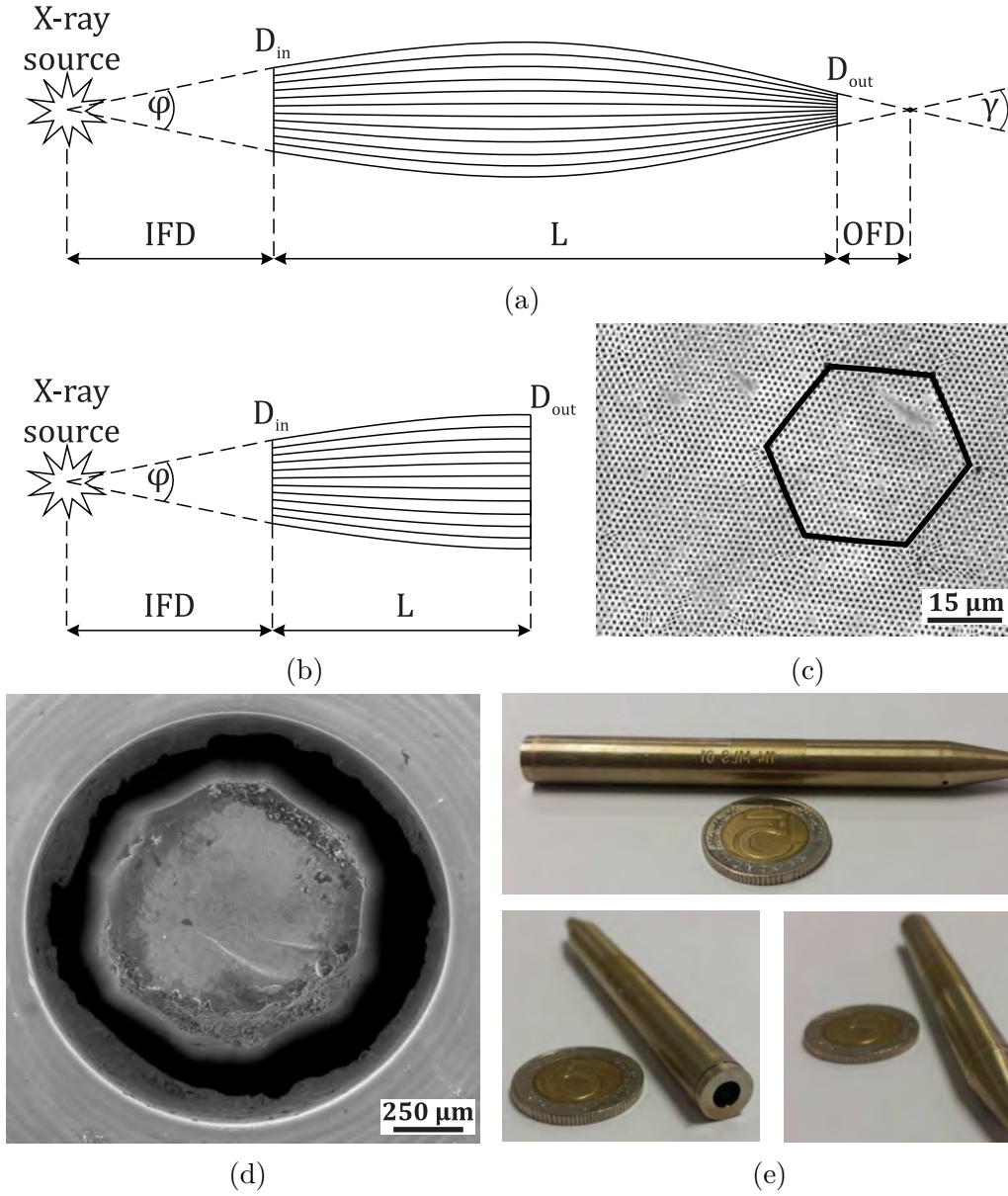


Figure 2.8: Polycapillary optical element. Schemes of (a) concentrating and (b) collimating polycapillary, respectively. Here, IFD denotes the input focal distance, L is the length of the optical element, OFD is the output focal distance, φ is collecting angle, D_{in} and D_{out} are diameters of the input and exit surface of the optics, respectively, γ is the global divergence of the element. (c) and (d): SEM images of polycapillary structure at the exit of concentrating optical element (images were acquired by dr B.R. Jany). A single hexagonal bundle of capillaries is marked as a black hexagon. (e) Photographs of concentrating polycapillary optics in our laboratory.

than zero (even for collimating optics, for which $\gamma = 0$) and is limited by the critical angle, and is an energy-dependent value:

$$\beta = 2\alpha_c. \quad (2.56)$$

Taking the above into consideration, the total divergence of a polycapillary is a sum of γ and β (McDonald 2017).

The last but not least parameter is a spot size, which is preferred to be as small as possible for many applications in order to focus and investigate objects with sizes on the order of micrometres. The spot size at the focal point is determined by the diameter of an individual capillary d , OFD and a local divergence β (Shields et al. 2002):

$$d_{spot} \approx \sqrt{d^2 + (OFD \cdot \beta)^2} \approx 2 \cdot OFD \alpha_c + d, \quad (2.57)$$

where d is usually very small compared to d_{spot} and can be neglected. Combining equations (2.53) and Eq. (2.57):

$$d_{spot}[\text{mm}] \approx \frac{60[\text{keV}] \cdot OFD[\text{mm}]}{E[\text{keV}]}. \quad (2.58)$$

MULTIPOINT-PROJECTION X-RAY MICROSCOPY

The multipoint-projection microscope was the first step towards the X-ray plenoptic microscope. The inspiration for both microscopes comes from a previous experiment performed in our group, namely defect-assisted hard X-ray microscopy (Korecki et al. 2016). It revealed that although polycapillaries are not classical imaging optics (Paganin 2006, Vincze et al. 2002), individual intrinsic point defects of the polycapillary surface lead to the formation of the multiple projections of the object. Unluckily, defects are randomly distributed along the polycapillary surface which makes this defect-assisted technique inconvenient for routine applications.

The natural next step was to use tailored polycapillary elements with a predefined distribution of capillaries. However, the fabrication of such elements is a hard and demanding task. As a retort we proposed to use a compound polycapillary element combined with a multipinhole mask. By means of this combination it was possible to obtain a predefined source distribution and simultaneously collect over 1000 projections of small planar objects placed in the focal spot of polycapillary optics. However, depth resolved imaging has not been obtained at this stage.

In the first part of this Chapter a brief description of defect-assisted microscopy is provided. In the second part, the multipoint-projection X-ray microscopy is described. Part of results from the following sections were published in K. Sowa, B.R. Jany and P. Korecki, *Multipoint-projection X-ray microscopy*, Optica 5, 577 (2018).

3.1 DEFECT-ASSISTED HARD X-RAY MICROSCOPY

A scheme of experimental setup for the defect-assisted microscopy is presented in Fig. 3.1 whereas the full description of the experiment is provided in Korecki et al. (2016) and the Master Thesis of the author. The experimental setup consisted of an X-ray tube with a tungsten anode (operating at 50 kV voltage and 1 mA current), a hybrid photon counting FitPix detector (Kraus et al. 2011) and a polycapillary concentrating optics.

The detector had 256×256 pixels of $55 \mu\text{m}$ pitch forming a total area of 14.08×14.08 mm. The polycapillary had a structure of hexagonal bundles formed from

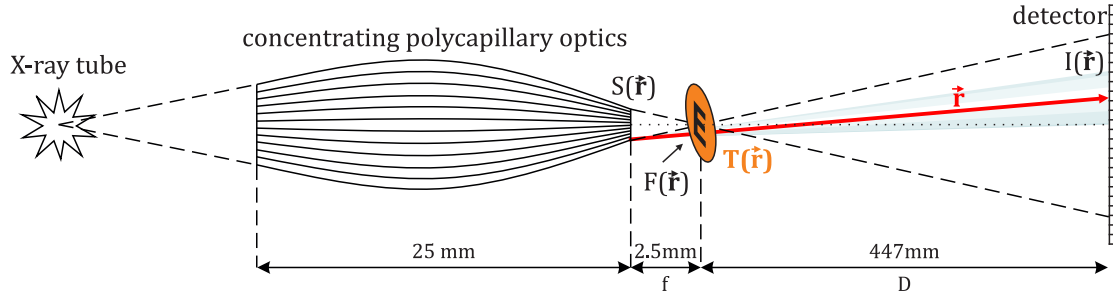


Figure 3.1: A scheme of defect-assisted hard X-ray microscopy. X-rays from an X-ray tube are concentrated by a polycapillary optical element on the object placed in the focal spot of the optics. The intensity at the detector can be described as a convolution between the transmission through polycapillary and the transmission through the object. For the clarity, the scheme is not in scale.

approximately 3.3×10^5 individual capillaries of $1.2 \mu\text{m}$ diameter each. The SEM image of the exit surface is presented in Fig. 2.8, and a X-ray image of the fragment of the structure is presented in Fig. 3.3(a).

Two types of defects are marked in circles, i.e. slightly bigger (green circle) or broken (red circle) capillaries. Broken capillaries appears mostly on the edges of the bundles. The focal spot of the optics had an approximate Gaussian shape with FWHM of $11.8 \pm 0.8 \mu\text{m}$ and total flux was $2.9 \times 10^8 \frac{\text{ph.}}{\text{s}}$. The object (Fig. 3.2(a)) was symbol E milled in an $4 \mu\text{m}$ gold electron microscopy grid by focused ion beam and placed in the focal spot of the polycapillary optic with XYZ piezo-positioner (Mechonics MS30CL).

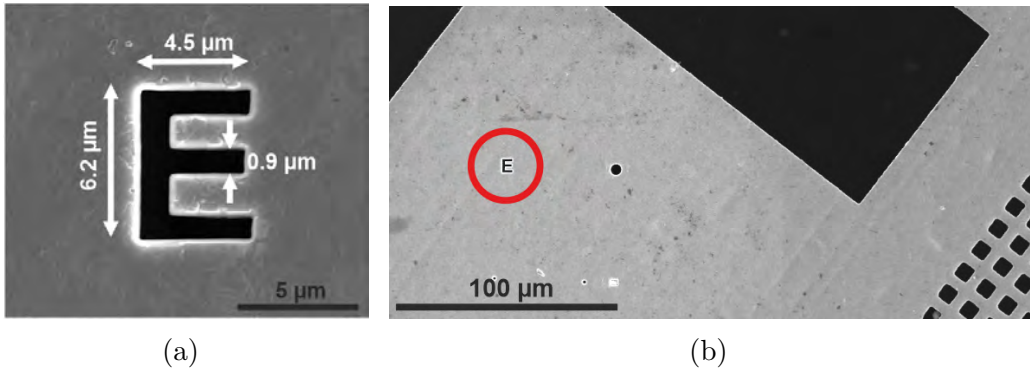


Figure 3.2: A SEM image of the test object. (a) Symbol E milled by focused ion beam in gold electron microscopy grid. (b) A general view of the sample, symbol E marked in red circle. Both the object and SEM images were made by dr hab. B. R. Jany.

According to the model of X-ray coded aperture microscopy (Korecki et al. 2015, Dąbrowski et al. 2013) the image formation at the detector plane can be described as:

$$I(\vec{r}) = \frac{1}{S_0 M^2} [T_M(\vec{r}) F_M(\vec{r})] * S_M(\vec{r}), \quad (3.1)$$

where S_0 is the total number of photons in focal spot of the optics, $M = \frac{f-D}{f}$ is the magnification factor, $T_M(\vec{r})$ is the transmission function of an object magnified by a factor of $(1 - M)$, $F_M(\vec{r})$ is the spatial distribution of radiation in focal spot at magnification M , $S_M(\vec{r})$ is the spatial distribution of radiation at the exit plane of the optics at magnification M , the symbol $*$ stands for convolution operation. The relation between $F_M(\vec{r})$ and the angular distribution of radiation emitted from capillaries $G(\vec{r})$ can be described as:

$$G(\vec{r}) = \frac{D^2}{S_0} F_M(\vec{r}). \quad (3.2)$$

Therefore, the intensity recorded at the detector plane without the presence of an object can be defined as:

$$I_0(\vec{r}) = \frac{1}{S_0 M^2} F_M(\vec{r}) * S_M(\vec{r}) \quad (3.3)$$

and describes a magnified and blurred image of the capillary structure S .

For a perfect polycapillary structure (Fig. 3.3(b), red rectangle), the convolution operation smears out the information about the object, because the focal spot of the polycapillary is much larger than the spatial period of capillaries. However, the presence of defects breaks the periodicity and leads to the formation of multiple images of the object at the positions of defects (circles in Fig. 3.3(b)). If the distribution of defects is known, it is possible to decode (or deconvolve) object's image (Fig. 3.4(a)).

Images presented in Fig. 3.3 were recorded in a 200 min. exposure in order to acquire clear images of the defects, but for the reconstruction of the object such a long exposure times are not necessary, because the decoding procedure sums up the multiple images of the objects.

With this technique it was possible to obtain a resolution at sub-micrometer level. The main disadvantage of this method is the random distribution of defects on the polycapillary surface. Although, we proposed that tailored optics will be the best option for improving this method, manufacturing of such an element is still a demanding task, even though the technology known for photonic crystal fibres could

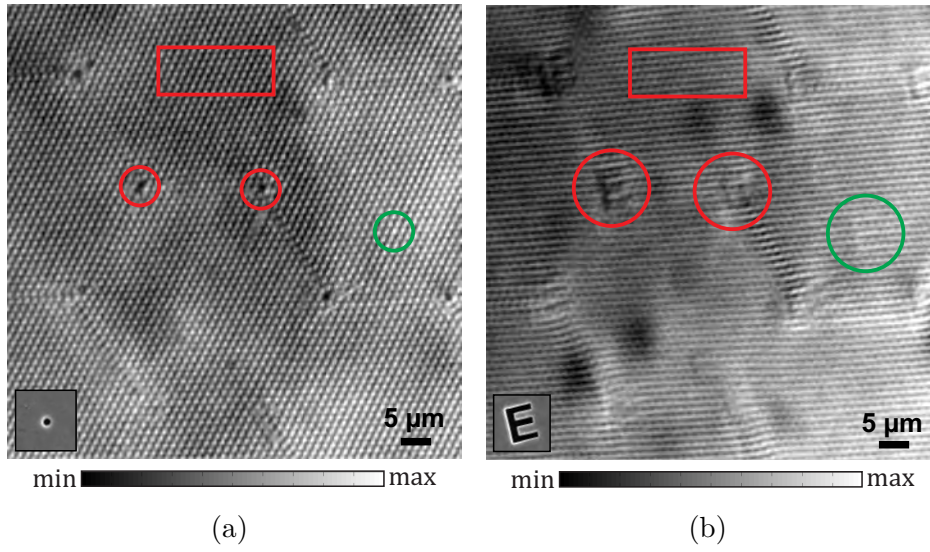


Figure 3.3: Raw results from the defect-assisted microscopy experiment. **(a)** An X-ray image of the polycapillary structure obtained by placing a $0.8 \mu\text{m}$ diameter pinhole in the focal spot of the optics. Red circles marks broken capillaries, green circle marks a slightly bigger capillary. Red rectangle marks non-defected polycapillary structure. **(b)** An X-ray image of the polycapillary structure with an object placed in the focal spot of the optics. Several object's images are clearly seen imposed on the polycapillary structure. Circles and rectangles corresponds to the same regions as in (a). Insets show SEM images of the pinhole and the object.

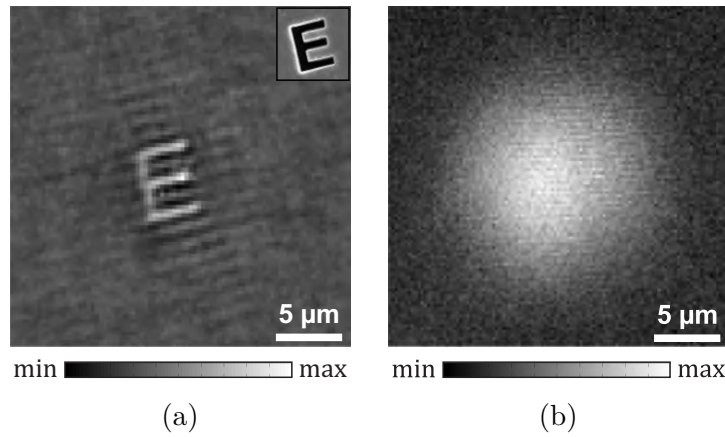


Figure 3.4: A comparison of **(a)** the reconstructed object with **(b)** a conventional projection of the same object. Reconstruction was based on the image 3.3(b). Inset shows SEM image of the object.

be a good place to start with (Russel 2003). Yet, with this experiment we have learned that polycapillary can be used for point projection imaging and this experiment was a starting point for the construction of plenoptic X-ray microscope.

3.2 IMAGE FORMATION & PHASE RETRIEVAL IN MULTIPOINT-PROJECTION X-RAY MICROSCOPY

The point-projection geometry is the simplest and most common way of coherent X-ray imaging (Cosselett & Nixon 1951, Paganin et al. 2002). The setup consists only of a point source and a detector, and a small X-ray source size is required to obtain high resolution images. Nowadays, commercially available X-ray sources can easily achieve focal spot sizes below $10\ \mu\text{m}$ or even less than $1\ \mu\text{m}$ (Eckermann et al. 2020). However, the production of such small sources require the machines to work with low power X-rays and sometimes the vacuum conditions are necessary (Mayo et al. 2002, Eckermann et al. 2020). The point-projection microscopy can be also realized with secondary nano- and micro-sources, which can be generated by X-ray waveguides (Giewekemeyer et al. 2010) or tapered glass capillaries (Bilderback et al. 1996). Therefore, to realize a spatially multiplexed version of point-projection geometry, we propose to employ a polycapillary optical element (Sowa et al. 2018).

The general concept of multipoint-projection X-ray microscopy is presented in Fig. 3.5. The radiation from X-ray source is collected by a compound polycapillary element and concentrated at a working distance f . A secondary X-ray micro-source is generated at the exit of each micro-capillary (Dąbrowski et al. 2013), and emits radiation in a narrow cone, defined by the critical angle for total external reflection α_c . At the object plane, the beams are spatially multiplexed and the total beam has a width of:

$$w \approx 2f\alpha_c. \quad (3.4)$$

As a result, the object placed in the focal plane is illuminated by all micro-sources, and each micro-beam produces a corresponding image of the object at the detector plane with the magnification:

$$M = \frac{D+f}{f} \gg 1, \quad (3.5)$$

where D is the distance between the object and the detector plane.

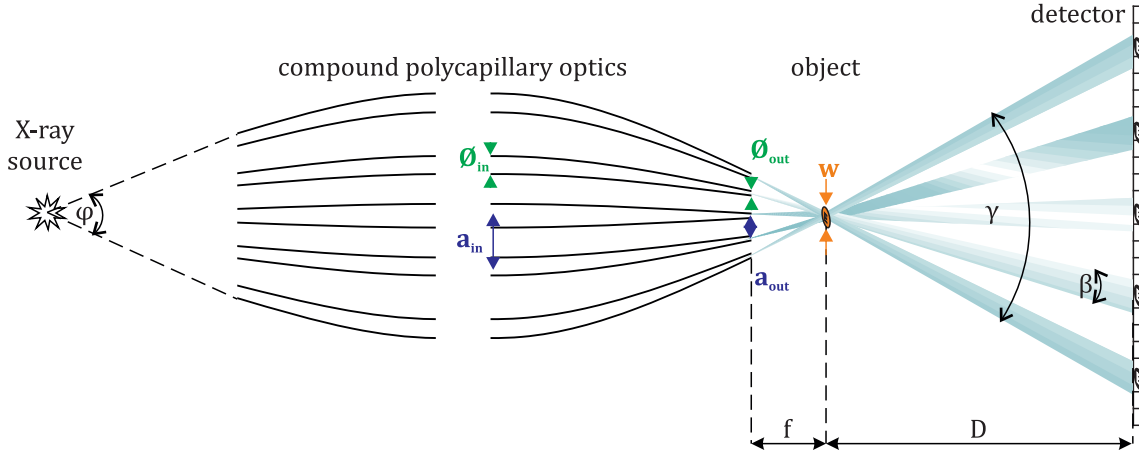


Figure 3.5: A general concept of multipoint-projection microscopy. X-rays from the source are collected by a compound polycapillary optics with collecting angle φ , and directed towards a common focal spot at a distance f from the optics. Therefore, the object placed in the focal spot is illuminated by an array of secondary X-ray micro-sources. Each micro-source produces an image of the object at the detector placed at the distance D from the object. Here, $\varnothing_{in}$ and $\varnothing_{out}$ are diameters of an individual capillary at the beginning and at the exit of the concentrating optics, respectively, a_{in} and a_{out} are the distances between capillaries, γ and β are global and local divergence, w is the total beam size at the focal plane. Images at the detector plane do not overlap if $a_{out} \geq w$. For the clarity, the scheme is not in scale.

In [Korecki et al. \(2016\)](#) it was demonstrated that the distance between individual capillaries (or micro-sources) plays an important role in object imaging: if it is too small, images of the object overlap and the details of the object are smeared out and are not resolvable at all (Fig. 3.3(b)). However, if the micro-sources spacing is greater than the lateral dimension of the beam at the object plane:

$$a_{out} \geq w, \quad (3.6)$$

then the micro-beams do not overlap at the detector position ([Korecki et al. 2015](#)). In effect, the net image of the object can be obtained by bringing individual projections to a common origin and summing up over multiple secondary sources without the need for any decoding procedure. Importantly, the condition for perfectly demultiplexed micro-beams plays an important role in the signal-to-noise ratio (SNR) of the images as explained below.

The relation between the number of photons and the image quality is defined by the Rose model as the signal-to-noise ratio of an object covering the area A of the detector, surrounded by a background with $\bar{I}_b$ photons per unit area ([Cunningham & Shaw](#)

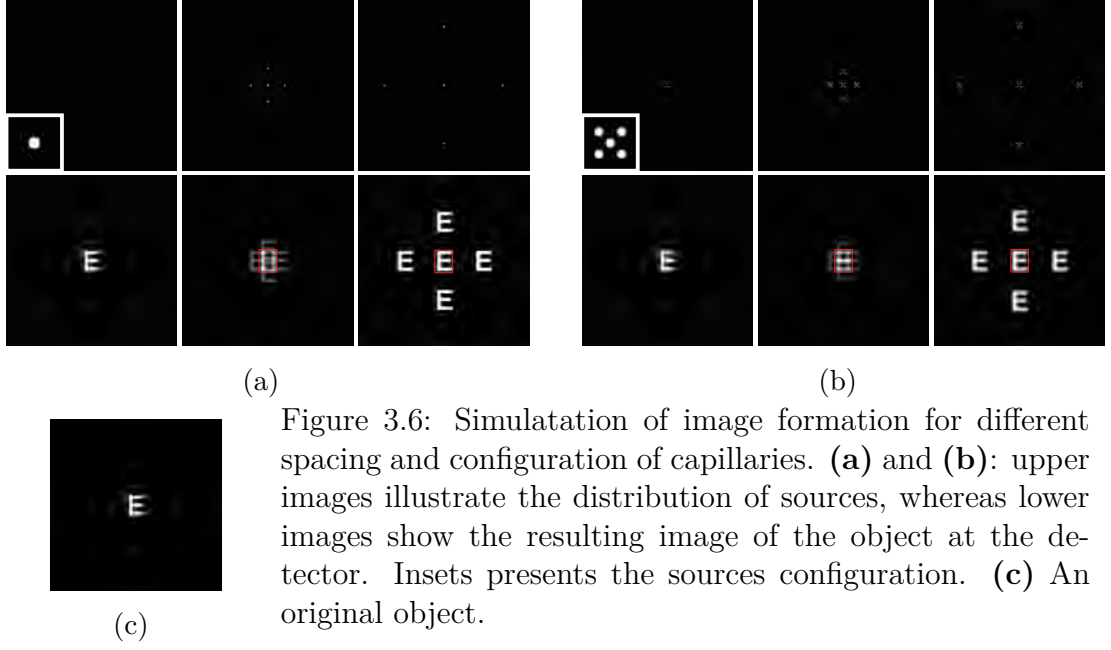


Figure 3.6: Simulation of image formation for different spacing and configuration of capillaries. **(a)** and **(b)**: upper images illustrate the distribution of sources, whereas lower images show the resulting image of the object at the detector. Insets presents the sources configuration. **(c)** An original object.

1999). Therefore, the contrast of the image can be described as:

$$C = \frac{\bar{I}_b - \bar{I}_o}{\bar{I}_b}, \quad (3.7)$$

where $\bar{I}_o$ is the average number of photons per unit area in the region of the object. The noise of the image is described in the terms of Poisson distribution and is denoted as a standard deviation in the number of photons in the background. Thus, the signal-to-noise ratio is defined as:

$$SNR = \frac{A(\bar{I}_b - \bar{I}_o)}{\sqrt{A\bar{I}_b}} = C\sqrt{A\bar{I}_b}. \quad (3.8)$$

Consider a single capillary illuminating an object in a narrow cone. According to Eq. (3.8), the SNR in such a case can be described as:

$$SNR_1 = C\sqrt{I_1 A}, \quad (3.9)$$

where C is the propagation-based phase contrast, I_1 is the number of photons emitted from the capillary. A simulated image at the detector plane is presented in the left column in Fig. 3.6(a).

If n capillaries that illuminate the object fulfil the condition from Eq. (3.6) and hence are perfectly demultiplexed at the detector, the SNR can be described as:

$$SNR_D = C\sqrt{nI_1 A}. \quad (3.10)$$

Therefore, the intensity will be increased by factor of n . A simulation of such image formed at the detector for $n = 5$ is presented in the right column in Fig. 3.6(b), whereas the middle column presents the simulation for an arrangement of capillaries that do not fulfil the condition from Eq. (3.6). However, if the capillaries are distributed less sparsely, and form m sub-beams of n capillary for each beam (i.e. hexagonal bundles of individual capillaries), the signal-to-noise ratio becomes:

$$SNR_M = \frac{C}{m} \sqrt{mnI_1A}, \quad (3.11)$$

and while the intensity is increased due to the number of illuminating capillaries (mnI_1), the contrast is decreased due to the overlap between adjacent capillaries by m . At the same time a decoding procedure is required in order to obtain the resulting image of the object. An example for several configurations and spacings of capillaries for $n = m = 5$ is presented in Fig. 3.6(b). The comparison of Equations (3.10) and (3.11) leads to the conclusion that the SNR_D is $\sqrt{m}$ times grater than SNR_M . Rose also showed that SNR must be approximately equal to or greater than five for reliable detection of an object (Burgess 1999).

Since the X-ray transport in multi-bounce capillary optics is incoherent, the image formation for the multipoint-projection geometry can be described in the terms the scalar theory of Fresnel X-ray diffraction of the free-space propagating wave in the paraxial approximation as described in Section 2. Therefore, for the object characterized by the transmission function $T(x, y)$, the free-space propagated wave field at the plane $z > 0$ is described by Fresnel formula:

$$\Psi(x, y, z > 0) \approx e^{ikz} \mathcal{F}^{-1} \left[e^{\frac{iz(k_x^2 + k_y^2)}{2k}} \mathcal{F} [T(x, y)\Psi(x, y, z = 0)] \right]. \quad (3.12)$$

The intensity at the detector placed at the position $z = D$ can be calculated similarly to Eq. (2.30) and the shape of the exit surface of the polycapillary is taken into account as a convolution:

$$I_\sigma(x, y, z = D) = I(x, y, z = D) * S(x, y), \quad (3.13)$$

where $S(x, y)$ is the distribution of the secondary sources. The phase retrieval was performed with a homogenous object approximation on the basis of Paganin reconstruction algorithm (Eq. (2.37), (Paganin et al. 2002)). It is also worth to mention that the resolution in the case of the multipoint-projection microscopy is limited to the single capillary channel diameter.

3.3 EXPERIMENTAL SETUP

In order to realize the multipoint-projection concept we used a compound polycapillary element which consisted of a collimating and concentrating optics and a multipinhole mask. Such an arrangement simulates a tailored optical element with desired spatial distribution of capillaries, to realize demultiplexing at the detector plane according to Eq. (3.6). A scheme of the experimental setup is presented in Fig. 3.7(a).

The radiation from an X-ray tube irradiated the collimating polycapillary optical element and was directed as a quasi parallel beam through the multipinhole mask. The mask was placed in a near contact with concentrating polycapillary optics. The distance between collimating and concentrating optics was $\Delta Z_0 \approx 420$ mm. The working distance of the concentrating optics was $f = 2.5$ mm and the object-to-detector distance was $D = 447$ mm. The photographs of experimental setup are presented in Fig. 3.7(b). All acquisition was controlled by home-made software in MATLAB environment. Below, detailed descriptions of the set-up elements are provided.

3.3.1 DETECTORS

In this experiment we used two types of detector: for higher-resolution imaging we used a smaller photon-counting FitPix detector by Medipix Collaboration, while for acquiring a large number of object's projections, we used the X-ray $2k \times 2k$ sCMOS Camera by Photonic Science. In Fig. 3.8(a) a comparison between the sizes of detectors' sensors is illustrated.

FITPIX BY MEDIPIX COLLABORATION

FitPix is a nearly noise-free photon-counting hybrid pixel detector. The Si sensor was $300 \mu\text{m}$ thick and had 256×256 pixels of $55 \mu\text{m}$ pitch, therefore a total area of the sensor was 14.08×14.08 mm. The sensor was attached to a FitPIX-2 interface (Kraus et al. 2011). The FitPix detector was developed by an international collaboration in CERN (medipix.web.cern.ch 2016). During measurement, the detector provided three quantities from each pixel: the number of counted particles, energy of incidence particles, and information about arrival time, therefore it could be also used for particle tracking. Detector can achieve up to 90 frames per second. A photograph of the detector is presented in Fig. 3.8(b).

3. MULTIPOINT-PROJECTION X-RAY MICROSCOPY

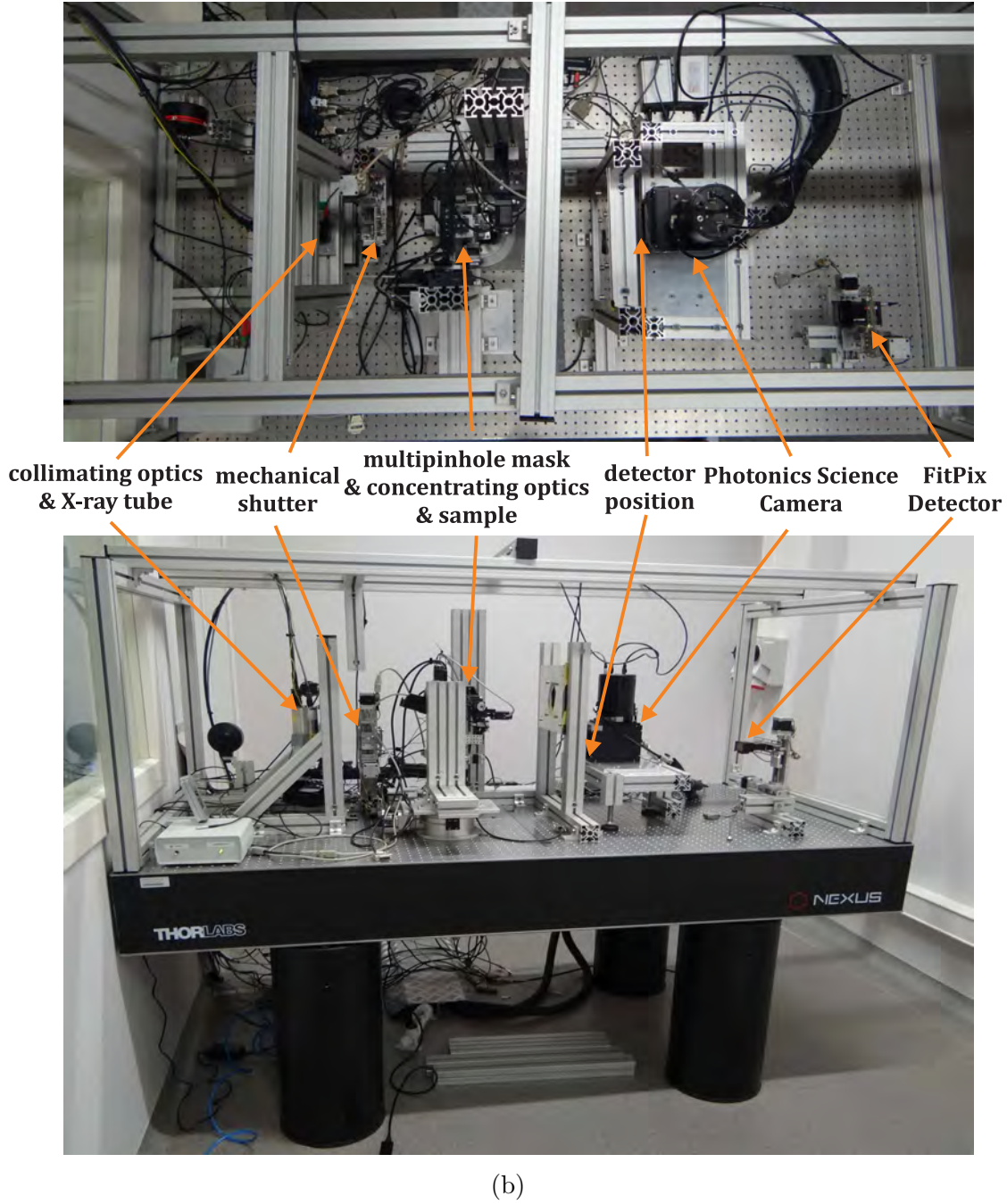
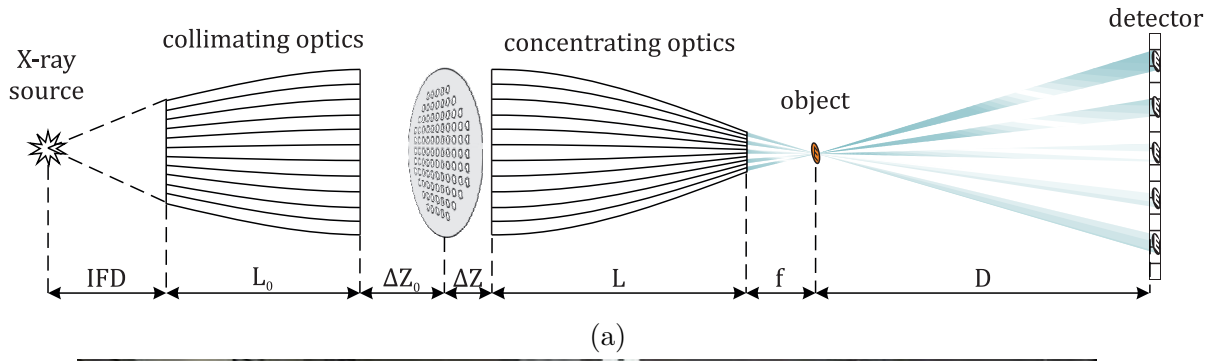


Figure 3.7: Realization of multipoint-projection X-ray microscopy. (a) A scheme of the experimental setup. The scheme is not in scale. (b) Top and side view photographs of the experimental setup.

X-RAY $2\text{k} \times 2\text{k}$ sCMOS CAMERA BY PHOTONIC SCIENCE

The X-ray $2\text{k} \times 2\text{k}$ sCMOS Camera is a water-cooled X-ray sensitive camera with a sCMOS (scientific complementary metal-oxide-semiconductor) sensor consisting of 2048×2048 pixels, $6.5 \mu\text{m}$ each. The sCMOS sensor was lens-coupled to a $80\text{ mm} \times 80\text{ mm}$ Gadox X-ray scintillator. Hence the effective pixel size was $\sim 40 \mu\text{m}$. The scintillator has $\sim 300 \mu\text{m}$ thickness and was optimised for X-ray energies below 50 kV. The camera had a high-speed read-out of the sCMOS sensor which results in a frame rate of 18 Hz. A photograph of the camera is presented in Fig. 3.8(c).

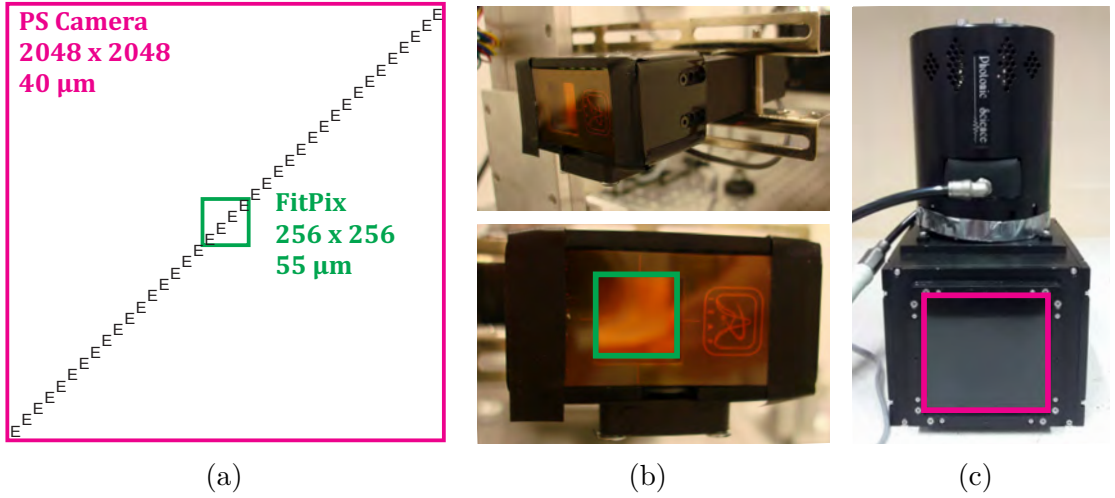


Figure 3.8: Detector used in the experiment. **(a)** A comparison of the sensors' sizes: Photonic Science Camera (magenta square) and FitPix detector (green square). **(b)** Photographs of the FitPix detector. The sensor area is marked by a green square. **(c)** A photograph of the Photonics Science Camera. The sensor is marked by a magenta square

3.3.2 POLYCAPILLARY OPTICS & MULTIPINHOLE MASK

POLYCAPILLARY OPTICS

We used a standard, commercially available polycapillary optics for X-ray fluorescence spectroscopy (IfG Institute of Scientific Instruments GmbH) which consisted of approx. 3.3×10^5 individual capillaries arranged in ~ 463 hexagonal bundles (Fig. 3.9(a) and photographs in Fig. 2.8). The optics had $IFD = 25\text{ mm}$, $f = 2.5\text{ mm}$, diameters of input and output surfaces equal to 2.75 mm and 1.1 mm , respectively, and a collecting angle of $\phi = 6.5^\circ$. At the focal spot, the beam had a width $w \approx 12 \mu\text{m}$.

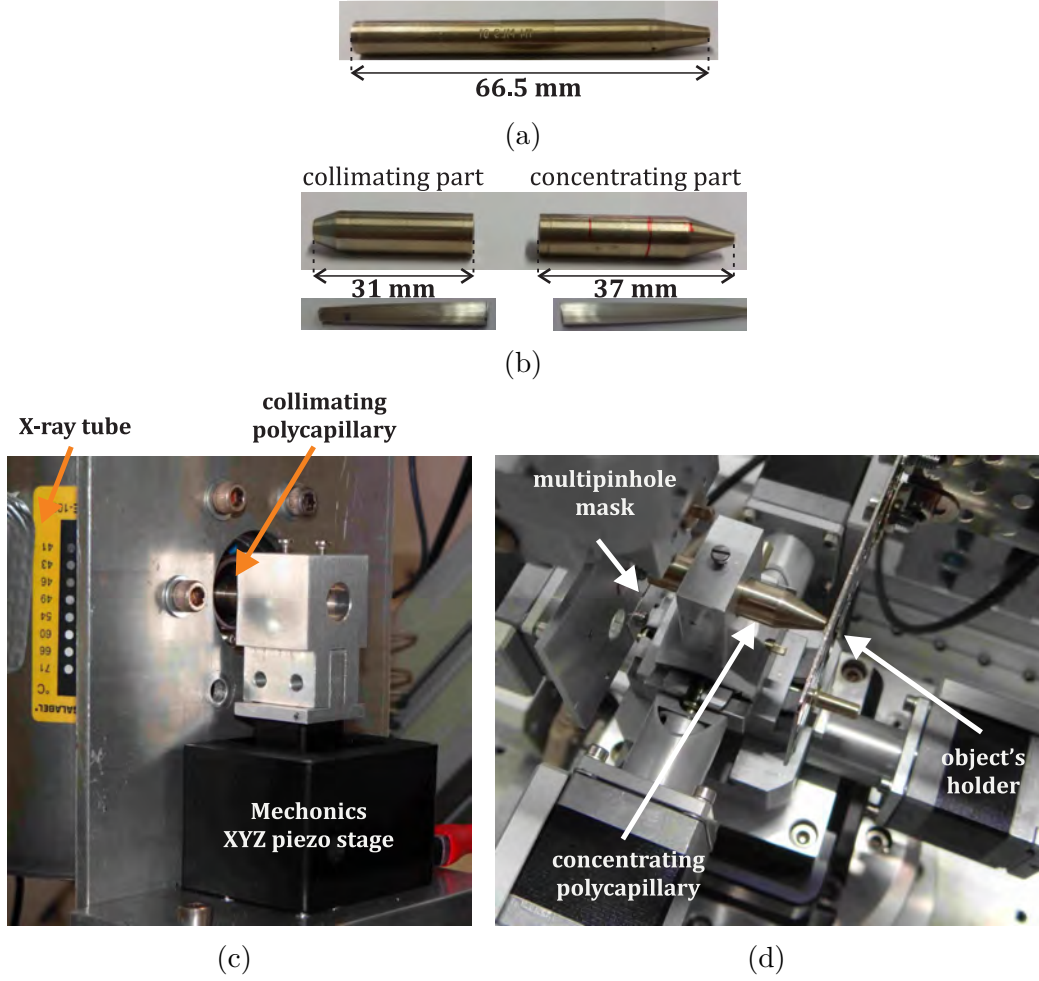


Figure 3.9: Photographs of polycapillary optics. **(a)** Before the cut. **(b)** After the cut. Lower images shows polycapillary without the cover. **(c)** The collimating part of polycapillary in setup. **(d)** The concentrating part of polycapillary in the setup.

For the experiment, the polycapillary was cut into two pieces by the producer, as shown in Fig. 3.9(b). The first (collimating) part of the optics was positioned using an XYZ open-loop piezo translation stage (Mechonics, MX35, range of movement 18 mm) to the focal spot of the X-ray tube as show in Fig. 3.9(c). The second piece of polycapillary (concentrating one) was positioned using six stepper-motor translation stages and goniometers (3.9(d)). Fig. 3.10 presents SEM images of the input and output surface of the concentrating part of polycapillary. The capillaries have a tapered shape with taper ratio of:

$$t = \frac{\varnothing_{in}}{\varnothing_{out}} \approx 5. \quad (3.14)$$

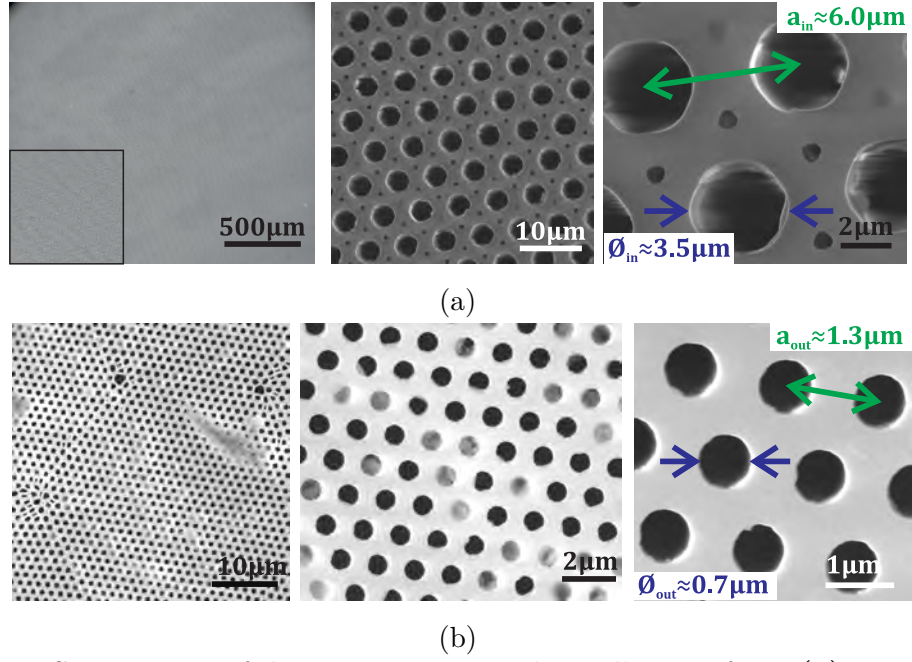


Figure 3.10: SEM images of the concentrating polycapillary surface. (a) Input surface. Inset: zoomed fragment of the surface. (b) Exit surface. The taper ratio $\phi_{in}/\phi_{out} \approx 5$.

In order to investigate the effect of the X-ray tube anode material on the images' signal-to-noise ratio, we recorded spectra for several different configurations of experimental setup by using the MediPix mode of the FitPix detector. A comparison between X-ray tubes with tungsten and copper anode for three configurations is presented in Fig. 3.11(a) and 3.11(b): without any optics (black), with collimating optics (green) and with both collimating and concentrating optics (blue).

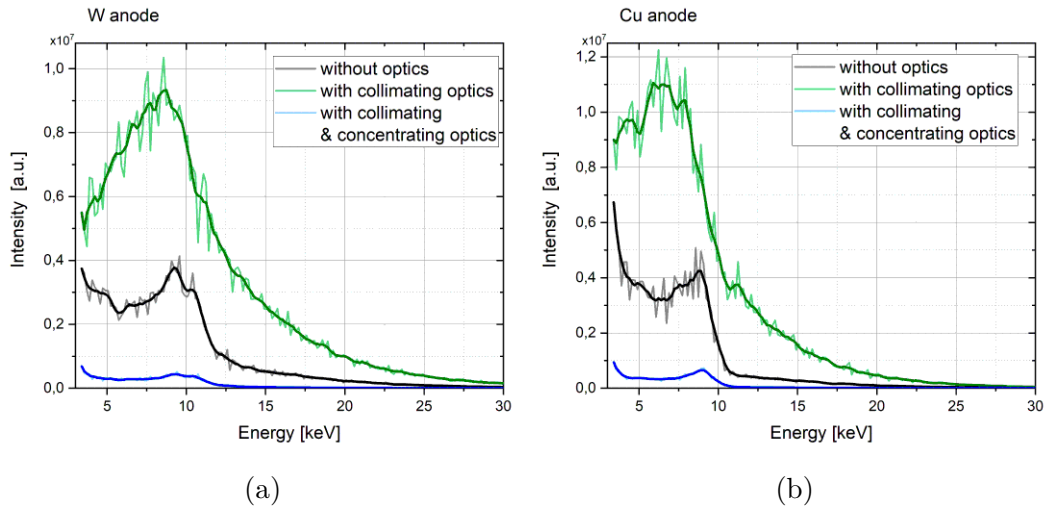


Figure 3.11: A comparison between X-ray tubes with tungsten and copper anode for three configurations of the optics. Thick lines present the data smoothed by adjacent averaging.

Similar comparison between tubes for a selected configuration is presented in Fig. 3.12. The performances for X-ray tubes with W and Cu anode were comparable. Note that the poor quality of spectra is due to the fact that the spectra were collected by simultaneously collecting images and changing the energy threshold of the FitPix detector.

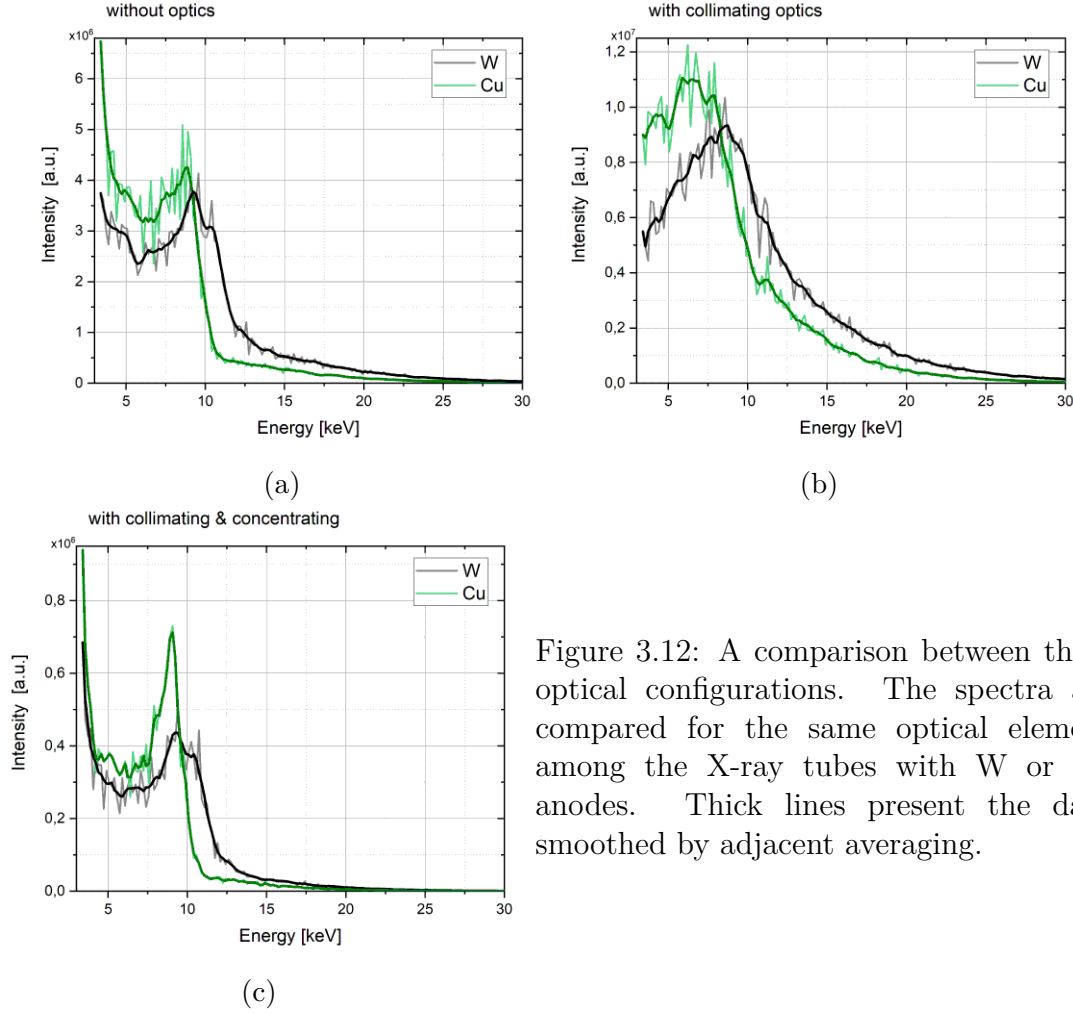


Figure 3.12: A comparison between three optical configurations. The spectra are compared for the same optical element among the X-ray tubes with W or Cu anodes. Thick lines present the data smoothed by adjacent averaging.

MULTIPINHOLE MASK

The multipinhole mask (Lenoxlasers) was laser drilled in a $50 \mu\text{m}$ thick tungsten foil (Fig. 3.13). The individual pinholes had approximately $7 \mu\text{m}$ diameter and were placed on a hexagonal pattern with spacing of $\sim 42 \mu\text{m}$. The mask was positioned using six stepper-motor translation stages and goniometers in nearly contact with the concentrating optics in order to minimize the penumbra blur, as shown in Fig. 3.13(b). SEM images of the multipinhole mask at different magnifications are presented in

Fig. 3.13(c). The mask was placed between collimating and concentrating optics, and hence in a nearly parallel beam, which enabled to use the material of the mask as an efficient X-ray blocker.

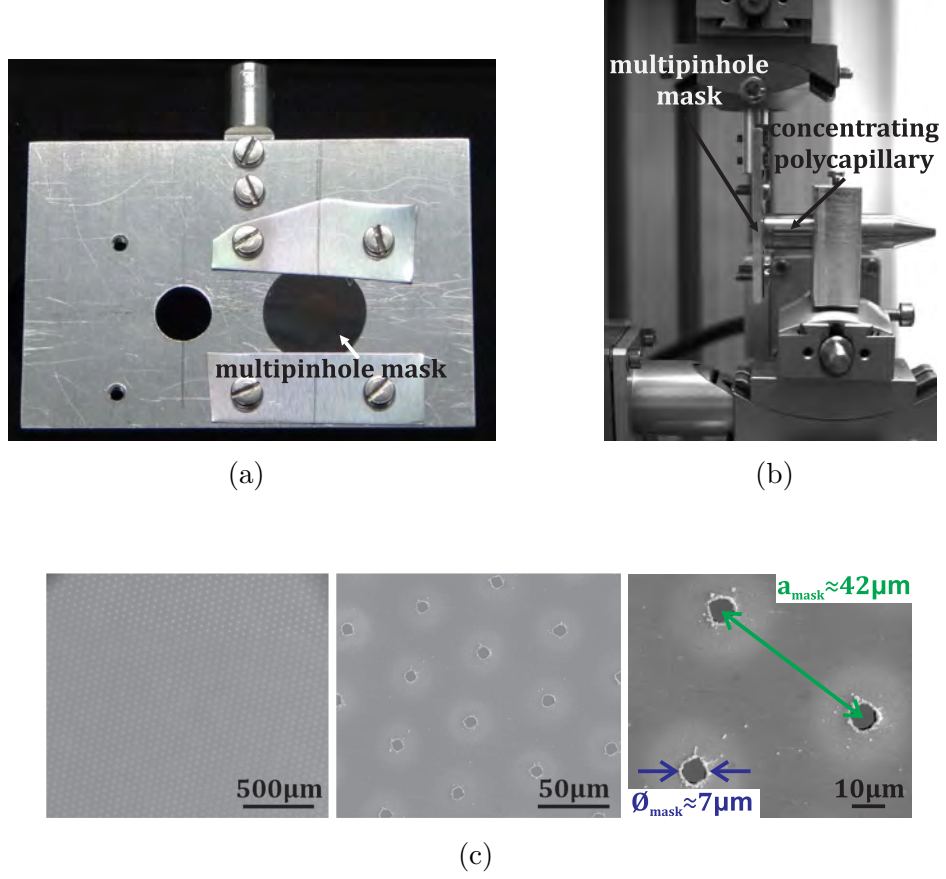


Figure 3.13: Photographs of the multipinhole mask. (a) A general view. (b) Multipinhole mask aligned to concentrating polycapillary optics in nearly contact. (c) SEM images of the mask with different magnifications acquired by dr hab. B.R. Jany.

In order to align the multipinhole mask and the concentrating polycapillary we performed a random matching of pinholes to individual capillaries, as follows. The diameter of pinholes from multipinhole mask was chosen in such a way that, regardless the relative position between the mask and the polycapillary input surface, the radiation coming through a pinhole strikes at least one and at most three capillaries, as depicted in Fig. 3.14. Therefore, some fraction of the secondary sources showed as tripled or doubled as depicted in Fig. 3.14(c). On account of the fact that images generated by these sources slightly decrease the image quality, they were not taken into account during the reconstruction procedure. Due to the fact that capillaries

have a tapered shape, the image of the mask was demagnified at the exit surface of the concentrating optics according to the taper ratio (Eq. (3.14)). Therefore, the pinhole spacing in the mask was chosen to fulfil the condition for perfectly demultiplexed images at the detector plane (Eq. (3.6)):

$$\frac{a_{mask}}{t} \approx w. \quad (3.15)$$

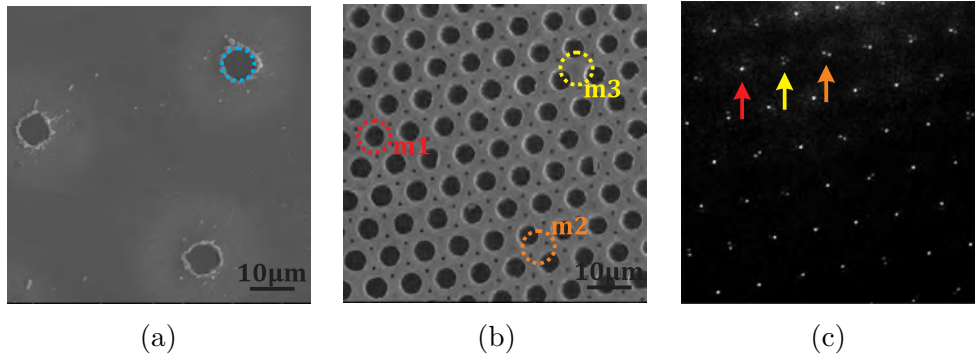


Figure 3.14: Random matching of pinholes to individual capillaries. **(a)** A SEM image of multipinhole mask with a single pinhole denoted as blue dashed circle. **(b)** A SEM image of the input surface of the concentrating polycapillary. Dashed circles denote the pinhole size and present three types of matching between pinholes and individual capillaries: $m1$ - one pinhole matches one capillary, $m2$ one pinhole matches two capillaries, $m3$ one pinhole matches three capillaries. **(c)** Multipoint-projection image of the secondary sources obtained by inserting a $0.5 \mu\text{m}$ pinhole in the focal spot of the optics. Arrows mark three types of the generated secondary sources.

3.3.3 OTHER COMPONENTS OF SETUP

X-RAY TUBE

For the multipoint-projection experiment we used an X-ray tube (Oxford Instruments, XTG 5011 Apogee) with a tungsten anode. The tube operated at 50 kV and 1 mA and had a focal spot of $\sim 37.8 \mu\text{m}$. The total number of photons after each component of the experimental setup measured with FitPix detector is provided in Table 3.1.

Table 3.1: Total number of photons after each optical element measured with FitPix detector.

component	No. of photons [$\frac{\text{photons}}{s}$]
before the cut concentrating polycapillary in one part 	3×10^8
after the cut collimating part of polycapillary 	2×10^9
collimating & concentrating parts of polycapillary 	4.5×10^7
50 μm spacing multipinhole mask between collimating & concentrating parts of polycapillary 	8×10^5

MOTORS

The collimating part of the optics was positioned by an open-loop piezo translation stage (Mechanics MX35) with the movement range of 10 mm (Fig. 3.9(c)). All samples were positioned by closed-loop XYZ piezo translation stage (Mechanics MS30) which had a 100 nm step and a movement range of 18 mm (Fig. 3.15). For aligning of other components of the experimental setup we used Standa and Huber translation stages as well as a Huber goniometer (Huber 410a).

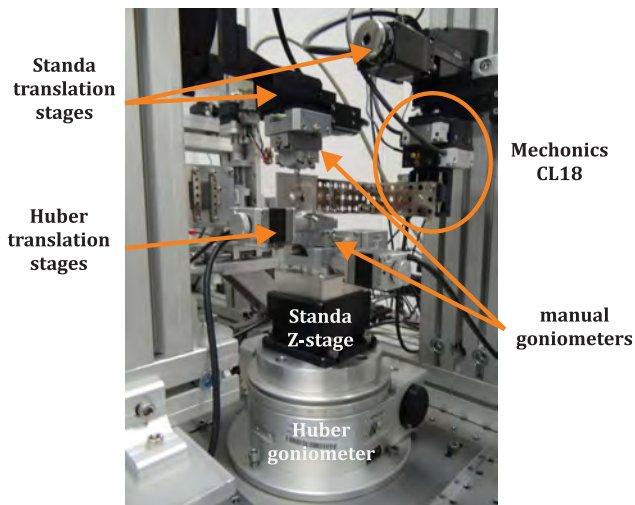


Figure 3.15: A photograph of the main part of the experimental setup which shows the motors used to align key parts of the setup.

3.4 RESULTS

3.4.1 HIGHLY ABSORBING SAMPLES

SYMBOL "E"

The first model object that we investigated was a symbol E milled in a gold electron microscopy grid. A similar object was used in the experiments on the defect-assisted microscopy (Fig. 3.2, (Korecki et al. 2016)). As a result we obtained over one thousand projections of the E demultiplexed at the detector plane and magnified approximately 200 times. Fig. 3.16 presents the experimental data acquired with Photonics Science camera. The acquisition time was 60 min.

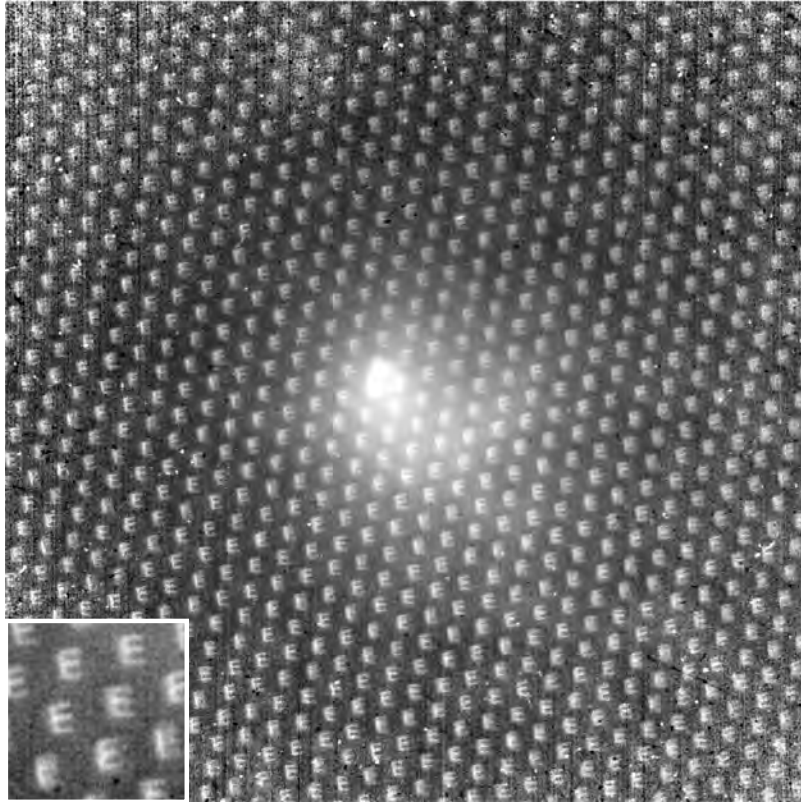


Figure 3.16: Over thousand multipoint projections of the object (symbol E milled with FIB in a gold electron microscopy grid). Inset shows a zoomed fragment of the image. Acquisition time: 60 min.

For higher resolution imaging we used the FitPix detector, which has significantly smaller detecting area compared to the Photonics Science camera and therefore cap-

tures only a small fragment of the radiation cone. Fig. 3.17(a) presents an image of the secondary sources which was acquired by inserting a $0.5\ \mu\text{m}$ pinhole in the focal plane of the optics. The acquisition time was 180s. Three types of the sources, marked with dashed circles, are resolved and correspond directly to the assumed types from the matching procedure (c.f. Fig. 3.14(b)): single sources, doubled, and tripled ones.

Figure 3.17(b) presents the resulting image of approximately 47 projection of the symbol E placed in the focal spot of the optics. Some projections are also doubled or tripled according to the $m2$ and $m3$ types of the secondary sources, as marked in dashed circles. The green rectangle marks a region of an individual projection of the object for which SNR was at the level of 2.45 and was calculated according to Eq. (3.8).

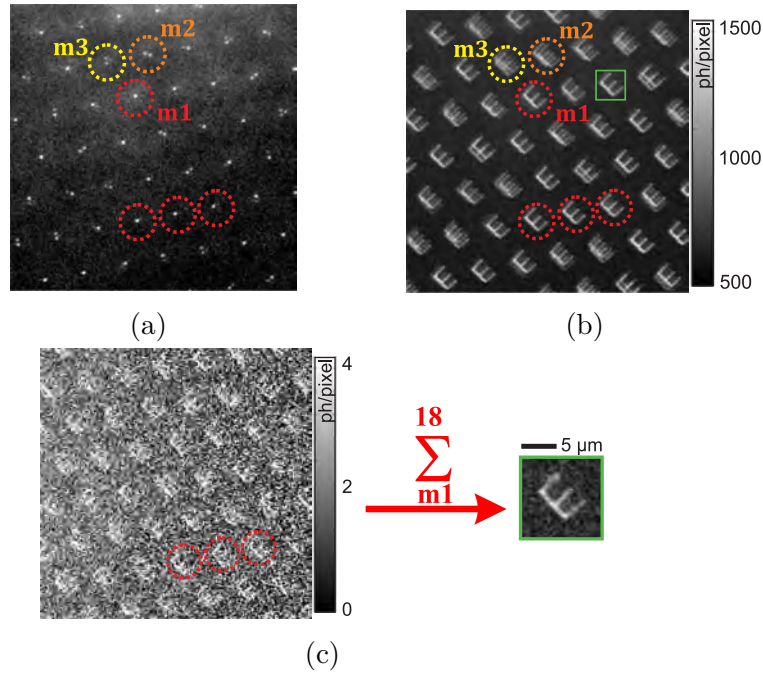


Figure 3.17: Multipoint projections of a $0.5\ \mu\text{m}$ pinhole and a symbol E . (a) An image of the secondary sources obtained by inserting a $0.5\ \mu\text{m}$ pinhole in the focal spot. Acquisition time: 180s. (b) Multipoint projections of the symbol E with acquisition time 180s. (c) Multipoint projections of the symbol E with acquisition time 10s. Right image on (c) shows the reconstructed object's image after summing over 18 individual projections from the left image. Labels $m1$, $m2$ and $m3$ mark three types of secondary sources on (a) and corresponding images of the object on (b) and left image on (c). Red circles marks an exemplary sources and images that were taken into account during the summation procedure. Green rectangle on (b) marks an individual projection for which SNR was calculated. All images were acquired with FitPix detector and normalized with respect to data recorded without the object.

Figure 3.17(c) presents the same object but with the acquisition time of only 10s. The details of the object are hardly resolved in the multipoint projection image, with an average 2 photons per pixel. The summing procedure over 18 projections of the object was performed as follows. After the measurement of the object, a pinhole of $0.5 \mu\text{m}$ diameter was placed in the focal spot of the optics and thus a fine image of the secondary sources was obtained. Based on this image (in this case it was the image depicted in Fig. 3.17(a)), the distribution of the secondary sources was chosen manually and saved with a software written in MATLAB environment. Then, the algorithm summed every projection of the object corresponding to the position of the secondary source.

The same procedure was applied to other results presented in this chapter but with varying number of secondary sources which were taken into account. The procedure of summing over 18 projections of the object (for $m1$ type of secondary source) allows one to obtain a clear image of the object with the SNR at the level of 4.57. The resulting image is presented in Fig. 3.17(c).

JIMA RT RC-02B RESOLUTION CHART

For resolution testing we use a planar JIMA RT RC-02B chart which consists of a set of slits with the width varying from 15 to $0.4 \mu\text{m}$ in an absorbing tungsten material of $1 \mu\text{m}$ thickness. Figures 3.18(a) and 3.18(b) show a photograph and a conventional projection with the chart placed far from the focal plane and exposure time of 600s. The data were normalized with respect to the data recorded without the chart.

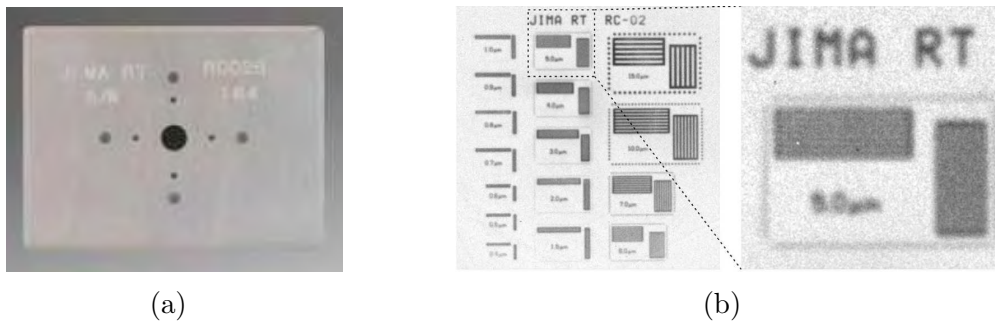


Figure 3.18: JIMA RT RC-02B resolution chart. (a) A photograph. (b) A conventional projection (acquisition time 600s).

Examples of multipoint-projections of horizontal and vertical slits of $1 \mu\text{m}$ width are presented in Fig. 3.19(a). The reconstructed images for $1 \mu\text{m}$, $0.5 \mu\text{m}$ and $0.4 \mu\text{m}$

slits are presented in Fig. 3.19(b)-3.19(d). Red lines denote profiles integrated across the slits. As shown in Fig. 3.19(c), lines with spacing widths of $0.5 \mu\text{m}$ could be resolved.

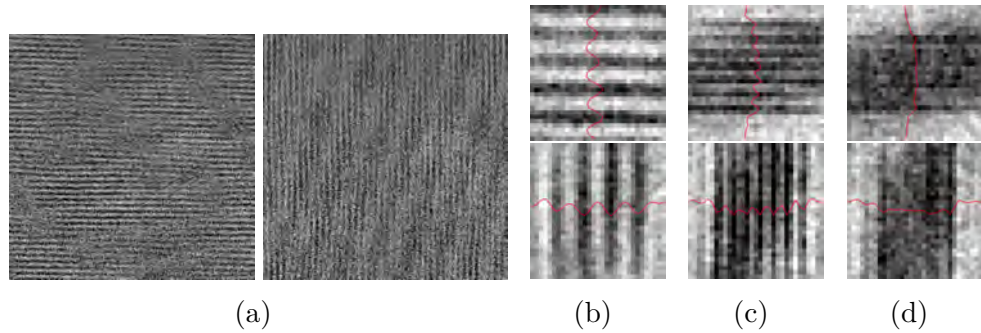


Figure 3.19: JIMA RT RC-02B resolution chart. (a) Exemplary multipoint-projections of horizontal and vertical slits of $1 \mu\text{m}$ width (acquisition time 10 min.). Reconstructed images of horizontal and vertical slits of width: (b) $1 \mu\text{m}$, (c) $0.5 \mu\text{m}$, (d) $0.4 \mu\text{m}$. Red lines denote profiles integrated along the slits.

3.4.2 PHASE CONTRAST IMAGING

AFM CANTILEVER

Phase contrast imaging was tested on an Atomic Force Microscope (AFM) silicon cantilever with a polystyrene sphere of $8 \mu\text{m}$ diameter. Fig. 3.20(a) presents a conventional projection of the cantilever with acquisition time of 60s. The multipoint projection of polystyrene sphere placed in the focal spot of the optics is presented in Fig. 3.20(b) (acquisition time was 80 min.). Figure 3.20(c) presents the image of polystyrene sphere averaged over all projections from Fig. 3.20(b).

In order to extend the field of view of the setup (which is limited by the width of the beam in focal spot, $w \approx 12 \mu\text{m}$) we performed a position scan (3×3 points with pitch of $10 \mu\text{m}$, acquisition time for each position was 1 hour) and therefore, the edges of the cantilever were also visible (Fig. 3.21(a)). Fig. 3.21(b) presents the retrieved phase image (according to Eq. (2.37)).

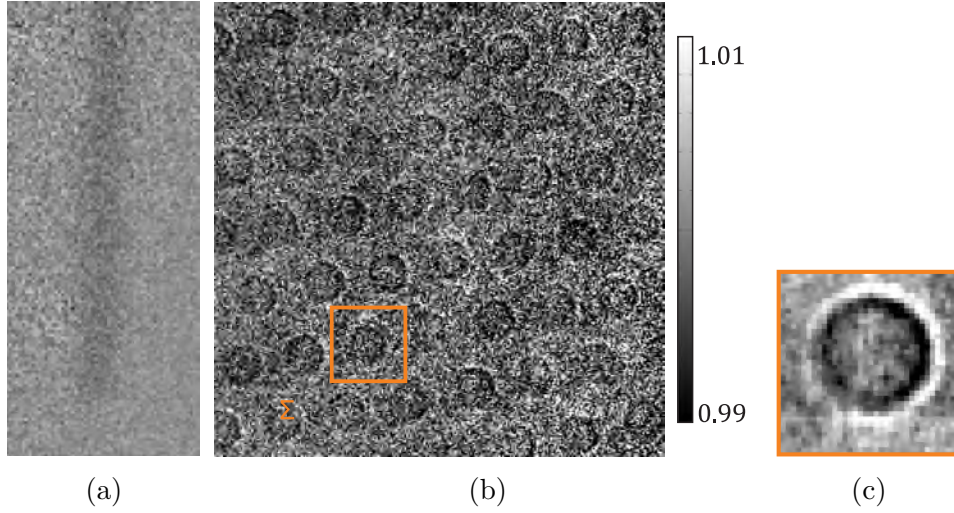


Figure 3.20: AFM cantilever with a polystyrene sphere of $8\ \mu\text{m}$ diameter. (a) A conventional projection of the cantilever. Acquisition time: 60s. (b) Multipoint projections of the sphere. An exemplary individual projection is marked by orange rectangle. Acquisition time: 80 min. (c) The resulting image after summing over all projections of the sphere from (b).

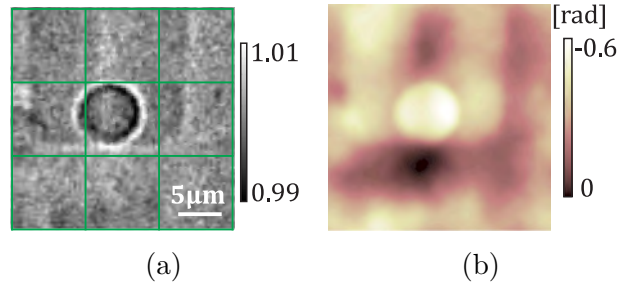


Figure 3.21: A position scan (3×3) of the AFM cantilever. (a) Reconstructed and combined images from the scans. Each green square corresponds to an individual image acquired in subsequent scan positions. Acquisition time: 80 min. (b) Retrieved phase image.

OTHER SAMPLES

Fig. 3.22 presents phase contrast X-ray projections of several almost pure phase objects: a group of polystyrene spheres of $3\ \mu\text{m}$ diameter each (Fig. 3.22(a)), a diatom frustule from diatomaceous earth (Fig. 3.22(b)), and a dandelion (*Taraxacum officinale*) pollen grain (Fig. 3.22(c)). For all of these samples a position scan (3×3 points with pitch of $10\ \mu\text{m}$) was performed. The acquisition time for each scan point was 150 min. giving totally 22.5h for the whole image. Some low frequency artefacts and phase offsets are observed due to the imperfect data analysis (i.e. a small blur

induced in the averaging process) as well as thermal drifts because of the long exposure time. Nevertheless, the phase shift variations (right images on Fig. 3.22) are large enough to observe clear X-ray projections of these weakly absorbing objects with high spatial resolution.

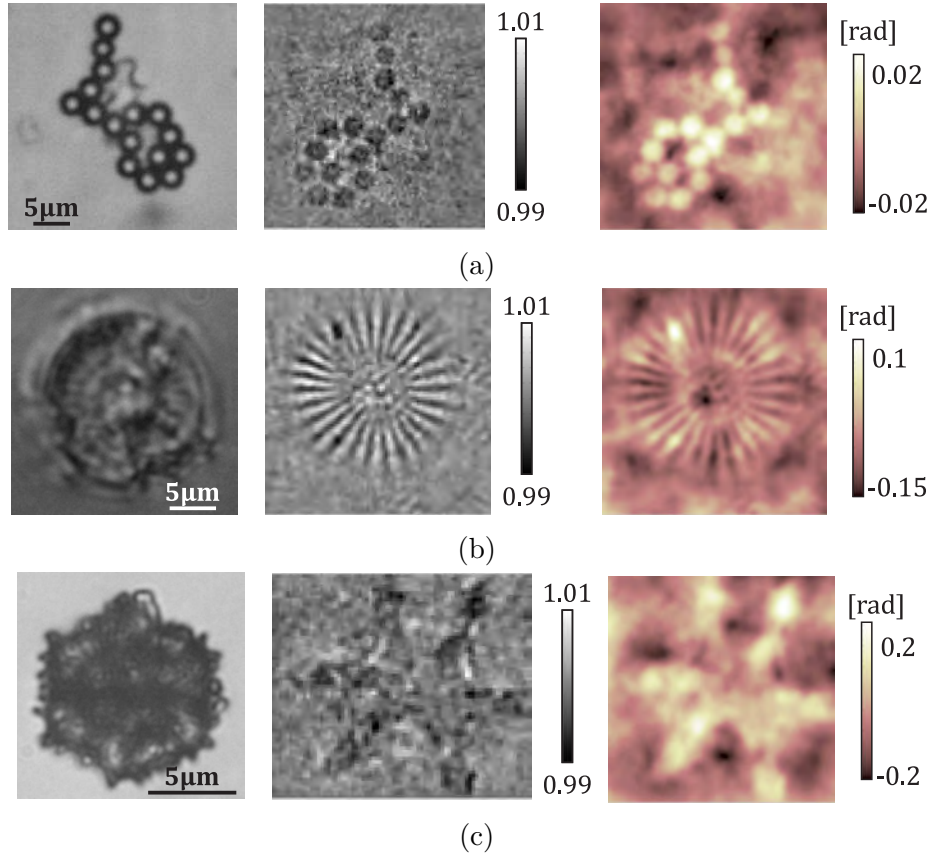


Figure 3.22: A set of weakly absorbing samples. **(a)** a group of polystyrene spheres of $3\mu\text{m}$ diameter each, **(b)** a diatom frustule from diatomaceous earth, and **(c)** a dandelion pollen grain. Left column shows optical microscope images, the middle one presents images reconstructed from a 3×3 point scan, acquisition time for each point of the scan: 150 min, the right column shows retrieved phase maps.

3.4.3 SUMMARY

Within this Chapter the defect-assisted hard X-ray microscopy and the multipoint-projection microscopy were described. During the latter experiment a compound polycapillary optical element was built. This element consisted of collimating and concentrating parts of the same polycapillary cut into two parts. In between this two parts of optics, a multi-pinhole mask was placed in which an array of secondary

micro-sources was created. The parameters of the mask were chosen in a way that enabled to realize multiplexing at the focal plane and perfect demultiplexing of micro-beams at the detector plane. As a result, it was possible to record over a thousand projections of an object placed in the focal spot of the optics, which were summed up afterwards to obtain the resulting object's image.

For higher resolution imaging, a nearly noise-free detector was used and the technique allowed to reconstruct clear image of a highly absorbing planar object with average 2 photons per detector pixel. The setup achieved sub-micron resolution (tested on a JIMA-RT RC-02B resolution chart). Phase contrast imaging was also performed on several weakly absorbing phantoms as well as biological objects.

PLENOPTIC X-RAY MICROSCOPE

The developed multi-point projection microscope was a starting point for the development of the plenoptic X-ray microscope for single-exposure depth resolved imaging of 3D objects. Within this Chapter an upgraded version of the multipoint-projection setup is described. The modified setup enabled to perform 3D imaging. The prime difference is the EIGER 2R detector with an area approximately 8 times larger than the FitPix detector. This change had an impact on the SNR ratio which depends on the number of projections recorded by the detector in a single exposure as described in Section 3.2. Within this Chapter we investigated large 3D biological samples and therefore the second change was made within the multi pinhole mask. We have chosen a mask with larger spacing between individual pinholes in order to be sure that we avoided overlapping between multipoint projections. Moreover we introduce three imaging regimes depending on the distance from the focal plane. Lastly, the X-ray plenoptic microscope is combined with conventional tomography as well as X-ray fluorescence spectroscopy. Part of results from Chapter part were published in K. Sowa and P. Korecki, Plenoptic X-ray microscopy, Appl. Phys. Lett. 116(014103), 2020.

4.1 IMAGE FORMATION

To begin with, similarly to the visible light plenoptic camera, the ray-space diagrams for different X-ray imaging geometries are presented in Fig. 4.1. The convention is adopted from the usual ray model (Levoy & Hanrahan 1996). For clarity, 2D simplification of the X-ray field (short wavelength counterpart of the light-field field) is depicted in this figure. Also, note that the close relation of the plenoptic function or the light-field with the Radon transform, which is a basis of X-ray tomography (Goergiev et al. 2014).

In the case of parallel beam projection geometry (Fig. 4.1(a)), the relation between u and x or x' is linear and the ray-space diagram is independent on the propagation distance, i.e, every point from a virtual plane (u, v) corresponds to the same point at planes (x, y) and (x', y') .

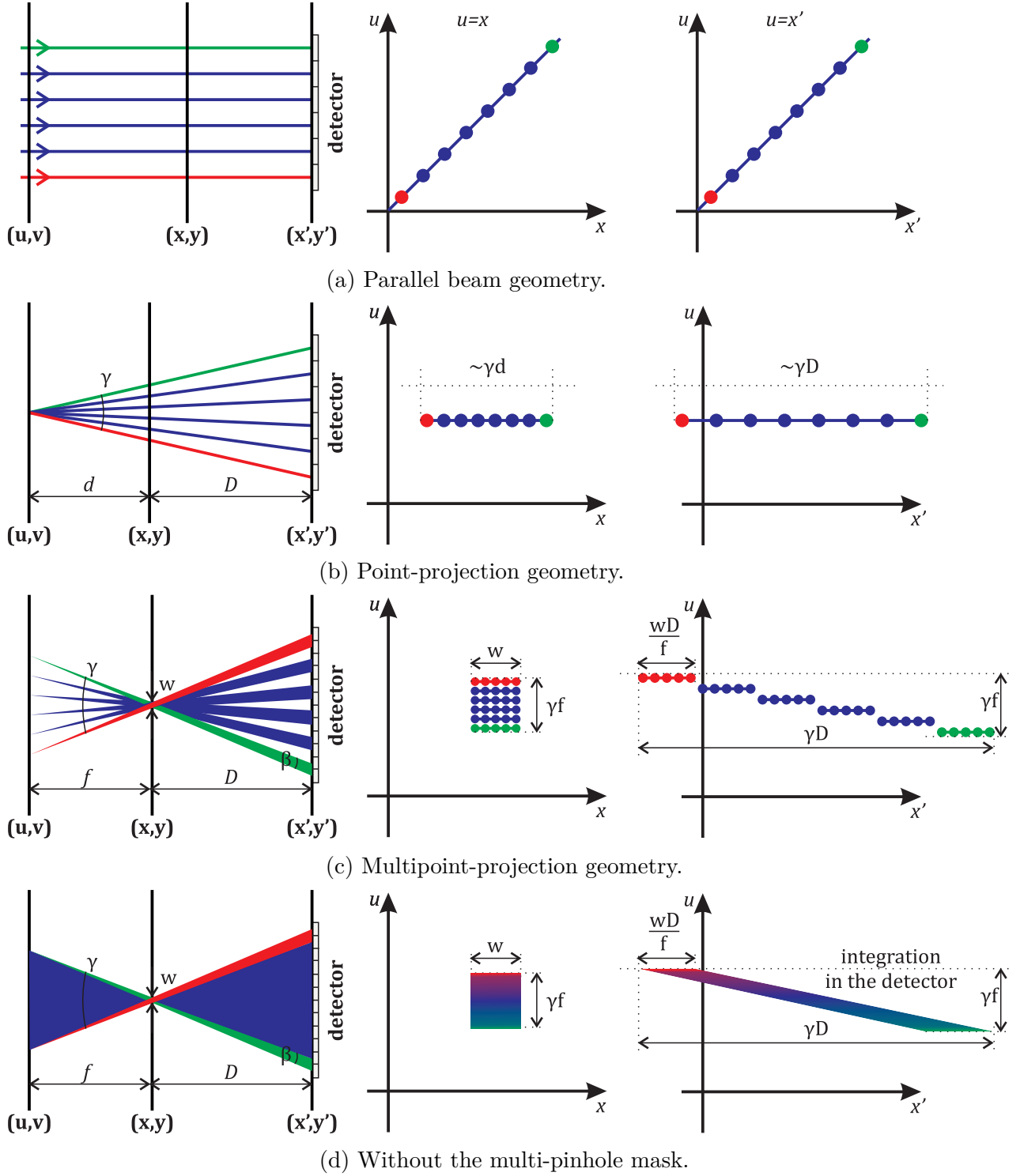


Figure 4.1: Ray-space diagrams of X-ray field for standard X-ray projection geometries and multipoint projection geometry. In standard X-ray geometries single lines in the ray-space diagrams are measured for a given sample orientation. Uniform sampling of the x-ray field at the (x, y) focal plane and demultiplexing at the detector (x', y') plane enables to interpret multi-point projections in terms of plenoptic imaging.

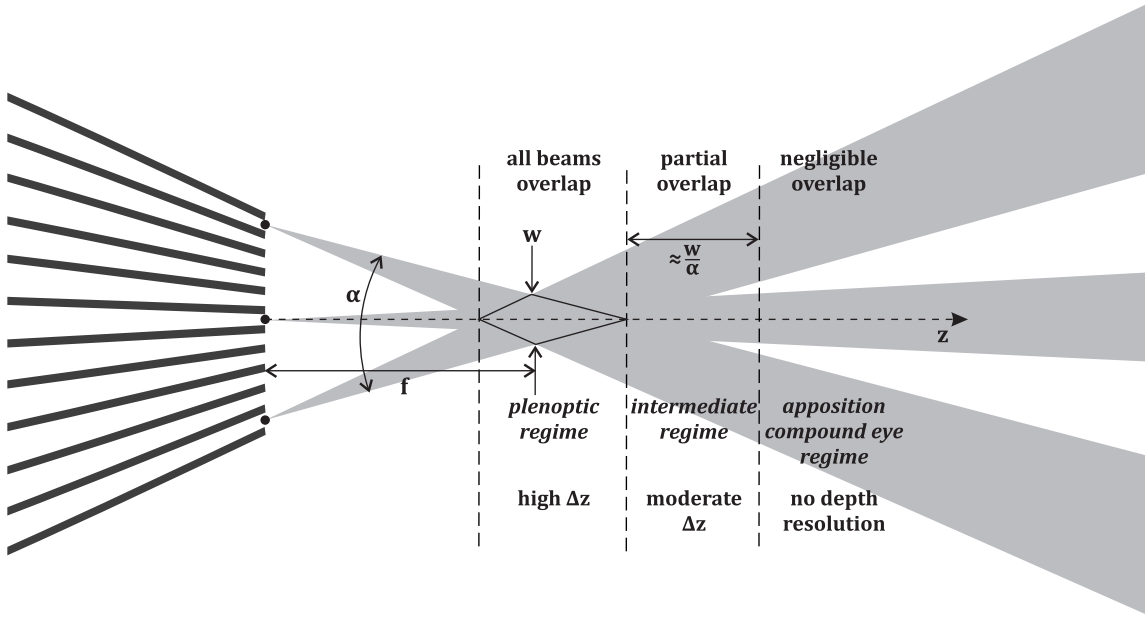
For the point-projection geometry (Fig. 4.1(b)), the (u, v) plane contains a single point-source with a divergence γ . Therefore, the ray space diagram corresponds to a horizontal line: all rays have a common origin at the (u, v) plane. Propagation along optical axis reduces from a shear (see Eq. (1.4)) to a simple scaling governed by the magnification factor. The ray space diagram for point-projection geometry is similar to the one for visible-light camera setup consisted of a main lens and a photodetector from Fig. 1.4(a) (ray space diagram was a vertical line). The only difference is the rays' direction of propagation.

The multipoint-projection geometry can be considered as a set of individual point sources, which are separated according to Eq. (3.6). Therefore, apart from the global divergence γ a local divergence β of individual capillaries also exists. As a result, the ray space diagram (Fig. 4.1(c)), at the focal plane (x, y) , where all micro-beams overlap, is a set of horizontal lines with width determined by the beam width and height determined by γf . On the other hand, at the detector plane (x', y') , the lines are sheared and scaled, as an effect of perfectly demultiplexed micro-beams. Each of the lines has a width scaled by the magnification factor D/f .

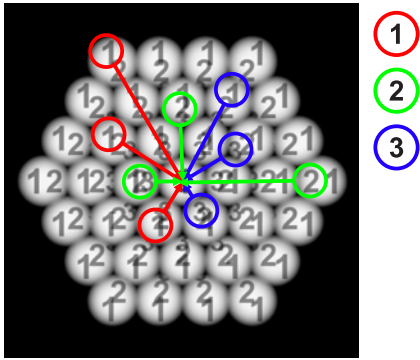
In standard X-ray geometries only single lines or profiles of the ray-space diagrams are measured for a given sample orientation. In multipoint projection geometry the light field enables a uniform sampling at the (x, y) focal plane and due to demultiplexing at the detector (x', y') , in which it can be directly measured. This feature set the basis for the interpretation of multi-point projection geometry in terms of plenoptic imaging. This also means that a single exposure in the multipoint projection geometry encodes a 3D information.

It is worthwhile mentioning that a bare polycapillary concentrating element without the multi-pinhole mask (Fig. 4.1(d)) does not encode any directional information about the light field as the microbeams generated by individual capillaries are too densely packed and overlap at the detector plane. Thus, the image at the detector is an integration over all overlapping micro-images. Similarly, to the conventional camera, the light field cannot be captured with such a setup.

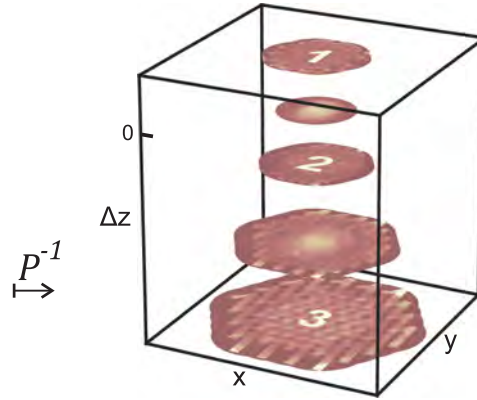
For a more detailed description of X-ray plenoptic principle, Fig. 4.2(a) shows a magnified fragment of multi-point projection geometry, near the focal plane. X-rays are guided through a compound polycapillary element with multipinhole mask that generates a distribution of micro-sources illuminating an object. Here, the object is three-dimensional: symbols 1, 2 and 3 placed at various distances Δz from the focal spot of the optics. As the microscope utilizes the multipoint-projection geometry, the



(a)



(b)



(c)

Figure 4.2: Principle of the plenoptic X-ray microscope. **(a)** Key point of the plenoptic microscope setup. A 3D object, symbols 1, 2 and 3 placed at various distances Δz from the focal spot of the optics, are illuminated by micro-beams that fulfils Eq. (3.6). Three imaging regimes can be marked out: plenoptic, intermediate and the apposition compound eye regime. The latter must not be confused with the multipoint-projection regime, where the sample was placed in the focal spot of the optics. **(b)** The idea of plenoptic reconstruction which is based on the depth-dependent affine transformation. The transformation involves the translation of sub-images and scaling operation. Translation vectors for three different Δz are shown with red, green and blue colours. **(c)** The plenoptic reconstruction at various depths.

image at the detector can be also described by Eq. (2.30), but the simple convolution from Eq. (3.13) is not valid for $D \neq f$.

If the condition from Eq. (3.6) is fulfilled, i.e. the spacing between micro-beams is approximately equal to the beam width w at the focal plane, all micro-beams overlap at the focal plane, and they do not overlap at the detector plane. In such a case, the image at the detector plane can be interpreted as a set of limited angle tomographic projections but acquired in a single exposure. Therefore, it is possible to reconstruct a tomographic-like slices at various depths Δz by a plenoptic reconstruction P^{-1} , which is equivalent to the refocusing procedure in plenoptic cameras for visible light (Vigano et al. 2018).

The reconstruction procedure is performed as follows. The first step of reconstructing the image at the plane $z = d$ is to multiply the sub-image that was generated by a single secondary source by a two-dimensional Gaussian function. Secondly, this image is back-projected from the detector plane $z = D$ to the desired plane $z = d$ by the affine transform:

$$\begin{bmatrix} \frac{D}{d} & 0 & 0 \\ 0 & \frac{D}{d} & 0 \\ (1 - \frac{D}{d})x_i & (1 - \frac{D}{d})y_i & 1 \end{bmatrix}^{-1} \quad (4.1)$$

by the *imwarp* function in MATLAB Image Processing Toolbox. This routine is performed for all images generated by the micro-beams and then, the back-projections for all of such images are summed up. A scheme of the reconstruction procedure is depicted in Fig. 4.2(b), whereas Fig. 4.2(c) presents an exemplary reconstruction of tomographic-like slices.

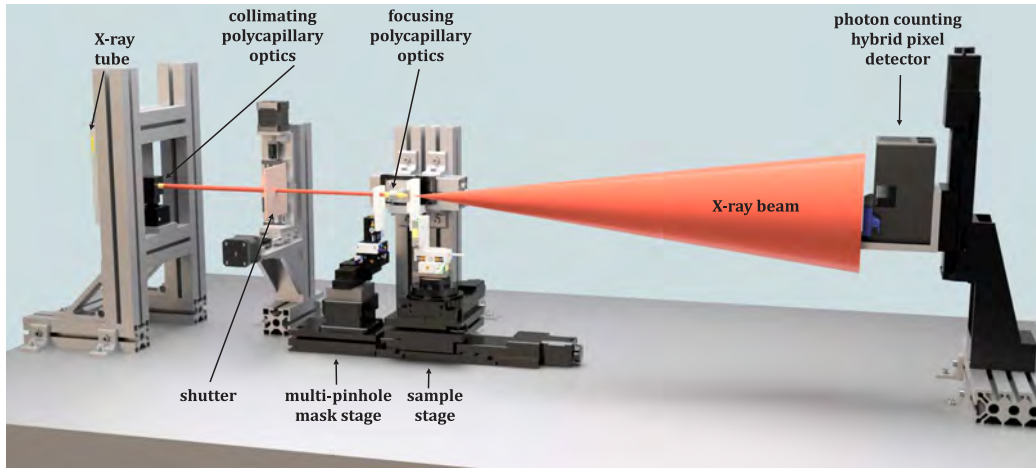
Similarly to the limited angle tomography, the depth resolution is lower than the lateral one, and thus three imaging regimes can be marked out (as depicted in Fig. 4.2(a)). Firstly, the highest resolution (or the plenoptic regime) in our microscope is obtained in the focal spot of the optics, i.e if:

$$\Delta z < \frac{w}{\alpha}, \quad (4.2)$$

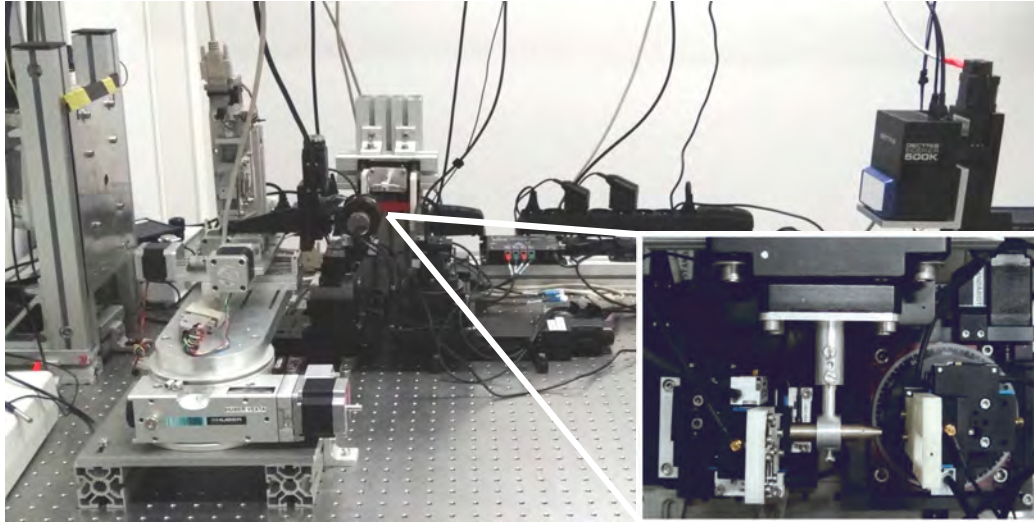
which is $\pm 60 \mu\text{m}$ in case of our setup. Secondly, For larger Δz , the depth resolution is progressively decreasing (intermediate regime). Lastly, it is not possible to resolve the depth of field but the high lateral resolution is still kept for large field of views (up to several hundreds of microns). The last regime can be referred to as a apposition compound eye regime, as each micro-beam 'sees' a different part of the object.

4.2 EXPERIMENTAL SETUP

The setup from Fig. 3.7 was upgraded but the concept remains the same. Fig. 4.3 presents the 3D model and a photograph of the upgraded setup. The setup consisted of an X-ray tube (Oxford Instruments, XTG5011 Apogee) with a tungsten anode that was operated at 50 kV and 1 mA. A polycapillary optical element (IfG Institute of Scientific Instruments GmbH, micro-lens array for X-ray fluorescence spectroscopy) was placed near to the window of the X-ray tube.



(a)



(b)

Figure 4.3: Experimental realization of the plenoptic X-ray microscope. (a) A 3D model (author: M. Kujda). (b) A photograph of the existing setup. The inset shows the key part of the setup.

The collimating polycapillary generated a quasi parallel beam with a mean energy of $\approx 9\text{keV}$. In this experiment we used a multi-pinhole mask with $75\ \mu\text{m}$ spacing between pinholes. Both multi-pinhole mask and the object were attached to a 3D printed holders and aligned using a multi-axis alignment stages (stepper-motor-driven Standa stages). The precise translations were realized by two closed-loop XYZ piezo stages (Mechonics MS30). Tilt, tip and rotation were realized by stepper-motor Standa stages. The concentrating polycapillary optical element was aligned with an open-loop 4-axis piezo stage (8071M Picomotor, Newport). X-rays were acquired with a photon-counting hybrid pixel detector EIGER2 R 500K Dectris. All acquisition was controlled by home-made software in MATLAB environment. Below, a description of the new setup elements is provided.

4.2.1 DETECTOR: EIGER2 R 500K DECTRIS

In this experiment we used a photon counting hybrid pixel detector from Dectris: EIGER2 R 500K. The detector had a $450\ \mu\text{m}$ thick Si sensor and 1030×514 pixels of $75\ \mu\text{m}$ size, forming a total detecting area of $77.25 \times 38.6\ \text{mm}^2$. The detector could achieve a frame rate up to 40 Hz. A photograph of the detector is presented in Fig. 4.4(a). A comparison of the active area of the EIGER2 detector sensor and other detectors sensors that we used in the previous setup is illustrated in Fig. 4.4(b). The detector was placed at a distance 680 mm from the optics for higher resolution imaging.

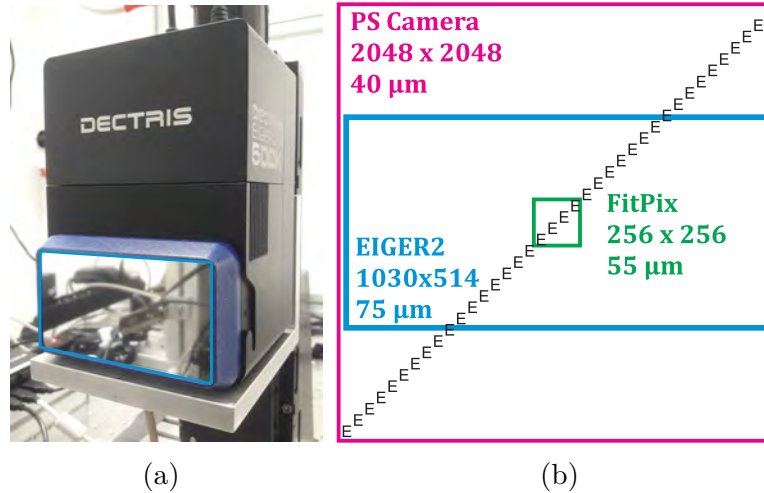


Figure 4.4: EIGER2 detector from Dectris **(a)** A photograph. The detector sensor is marked by a blue rectangle. **(b)** A comparison of dimensions of Photonic Science Camera (pink square), FitPix detector (green square) and EIGER2 detector (blue rectangle).

4.2.2 POLYCAPILLARY OPTICS & MULTIPINHOLE MASK

We used the same polycapillary optical element as in previous experiment (Section 3.3.2). However, the aligning system was completely modified. The concentrating part of the polycapillary was attached to an aluminium holder and aligned using an open-loop 4-axis piezo stage (8071M Picomotor, Newport). For this experiment we used a new multipinhole mask (Lenoxlaser) that was laser drilled in a $50\text{ }\mu\text{m}$ thick tungsten foil. The individual pinholes had $\sim 7\text{ }\mu\text{m}$ diameter and were placed on a hexagonal pattern with spacing of $\sim 75\text{ }\mu\text{m}$.

A comparison of images obtained with $42\text{ }\mu\text{m}$ and $75\text{ }\mu\text{m}$ spacing is presented in Fig. 4.5. The image of the secondary sources was obtained by inserting a $0.5\text{ }\mu\text{m}$ pinhole in the focal spot of the optics. Due to the sparse distribution of pinholes in multi-pinhole mask, the number of secondary sources was approximately 21 (for the $42\text{ }\mu\text{m}$ spacing mask it was 47), as illustrated in Fig. 4.5(a) and 4.5(b). Figures 4.5(c) and 4.5(d) present a comparison of multi-point projection images for a low absorbing object (carbon fiber of $8\text{ }\mu\text{m}$ diameter) that was placed in the focal spot of the optics.

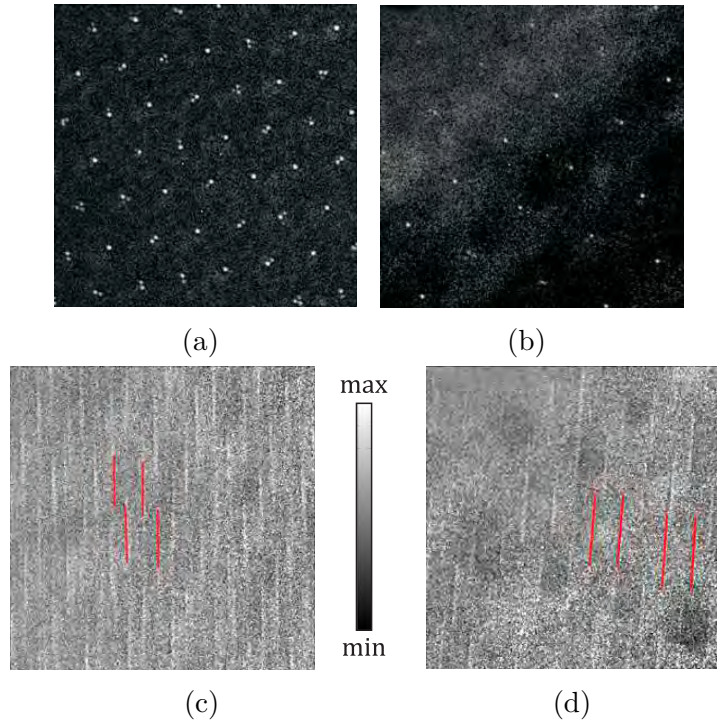


Figure 4.5: A comparison of images obtained with multipinhole masks of spacing: $42\text{ }\mu\text{m}$ (left column) and $75\text{ }\mu\text{m}$ (right column). **(a)**, **(b)** The distribution of secondary sources ($0.5\text{ }\mu\text{m}$ pinhole in focal spot of the optics). **(c)**, **(d)** Multiple projections of the carbon fiber ($8\text{ }\mu\text{m}$ diameter) obtained in the experiment. Red lines mark the edges of the fiber. Images were recorded with FitPix detector.

A small overlap of the fiber's projections is observed for the aperture with smaller spacing. Although, the high number of object's projections has a positive impact on the SNR, the overlapping can cause ghosting and complicate the summing procedure. The overlap is not observed for the aperture with larger spacing (Fig. 4.5(d)) but the number of projections is half as big as for mask with smaller spacing between pinholes.

4.2.3 X-RAY BEAM GENERATED BY THE THE PLENOPTIC MICROSCOPE

Figures 4.6 and 4.7 present the X-ray beam generated by the plenoptic microscope for two geometries used during experiments. The beam had a full opening angle of 15° and a FWHM of $\sim 5^\circ$. In the first geometry, the detector-to-object distance was 200 mm. The detector captured the whole beam (981 micro beams, Fig. 4.6(d)). Because of a small miscut of the polycapillary input surface, a fine structure on the right side of the beam could be resolved (Fig. 4.6(d)). Nevertheless, after the normalization procedure, the structure vanished and did not influence imaging of the objects.

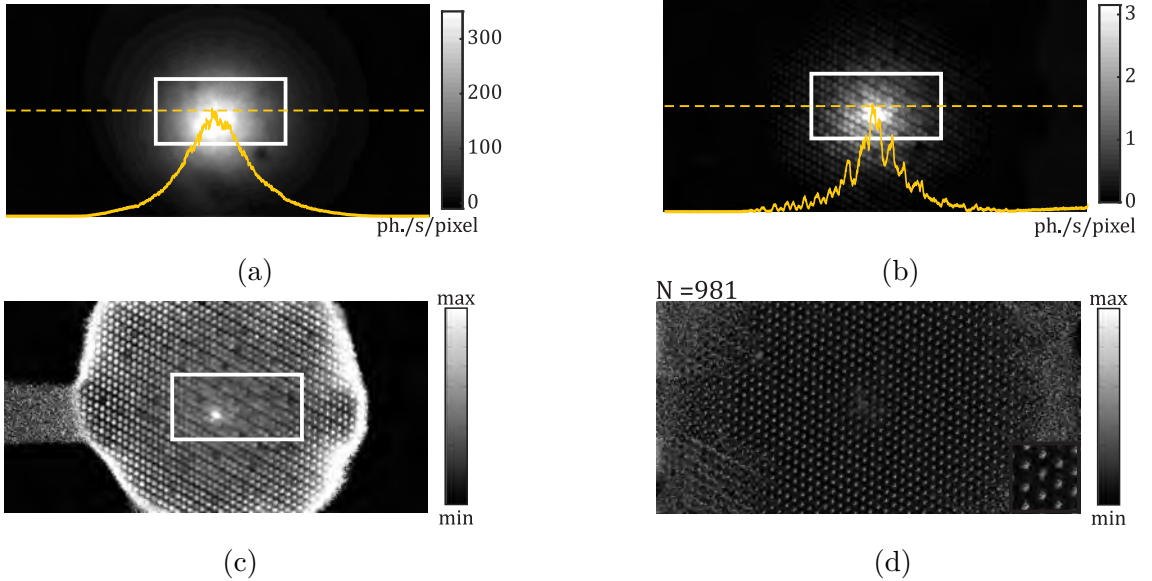


Figure 4.6: X-ray beam generated by the plenoptic microscope for the detector placed at the distance $D = 200$ mm from the object. **(a)** Without the multipinhole mask. **(b)** With the multipinhole mask. **(c)** Ratios of the images from (a) and (b). The white rectangle marks the small fragment of the beam that we used in the experiments. **(d)** Source distribution. Inset: zoomed fragment of the source distribution. The whole beam contains ~ 981 micro beams.

In the second geometry, the detector was placed at a distance 680 mm from the object and thus, it covered only a small fragment of the beam (161 secondary sources, Fig. 4.7(d)). This geometry was routinely used by us for high resolution imaging.

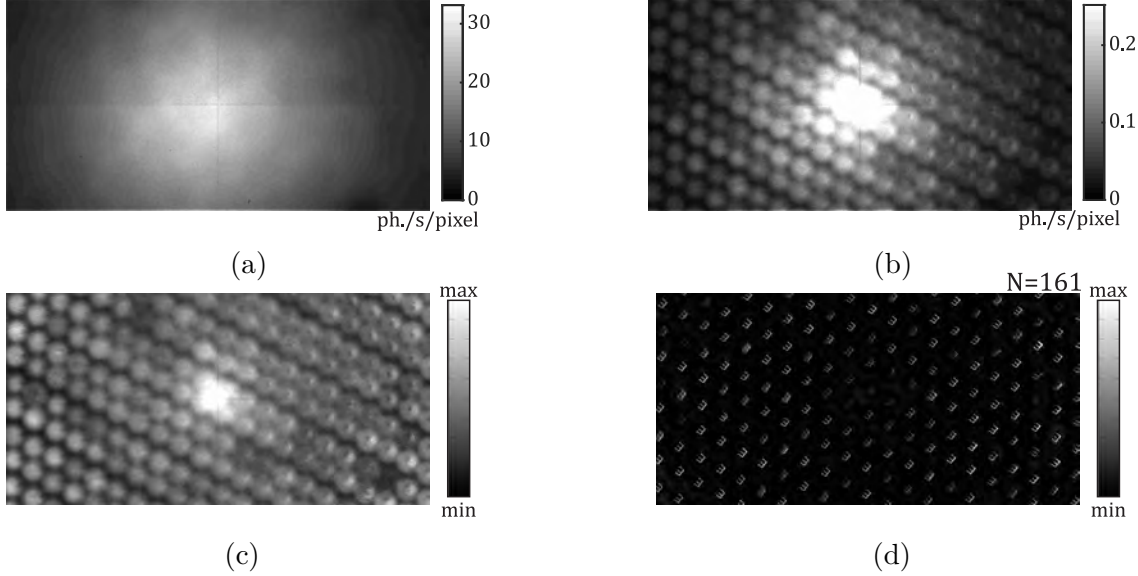


Figure 4.7: X-ray beam generated by the plenoptic microscope for the detector placed at the distance $D = 680$ mm from the object. **(a)** Without the multipinhole mask. **(b)** With the multipinhole mask. **(c)** Ratios of the images from (a) and (b). **(d)** Source distribution. The whole beam contains ~ 161 micro beams.

During this experiment we decided to use a planar and highly absorbing object (symbol E , Fig. 3.2) to determine the distribution of the secondary sources. The procedure is presented in Fig. 4.8. For $\Delta z = 0$, the image at the detector (according to Eq. (2.30)) is a convolution of the secondary source distribution and the object transmission function. As presented in Fig. 4.8(a), an object placed in the focal plane of the optics produces identical images for each of the generated micro beams. To obtain high-fidelity images of the object, the acquisition time was 1h. However, during the experiments shorter acquisition times, i.e. 10 min. also allowed to precisely determine the position of the sources. Figures 4.8(b) and 4.8(c) presents data normalized by the image without the object and after applying the high-pass filter, respectively. Inset in Fig. 4.8(c) presents a chosen sub-image which was used to calculate correlation with the image 4.8(c). The 2D correlation function is presented in Fig. 4.8(d). Therefore, by automatic finding the positions of the highest intensity peaks one can determine the position of secondary sources (Fig. 4.8(e), peaks are indicated by white circles). Fig. 4.8(f) shows comparison of the image 4.8(c) with calculated sources distribution.

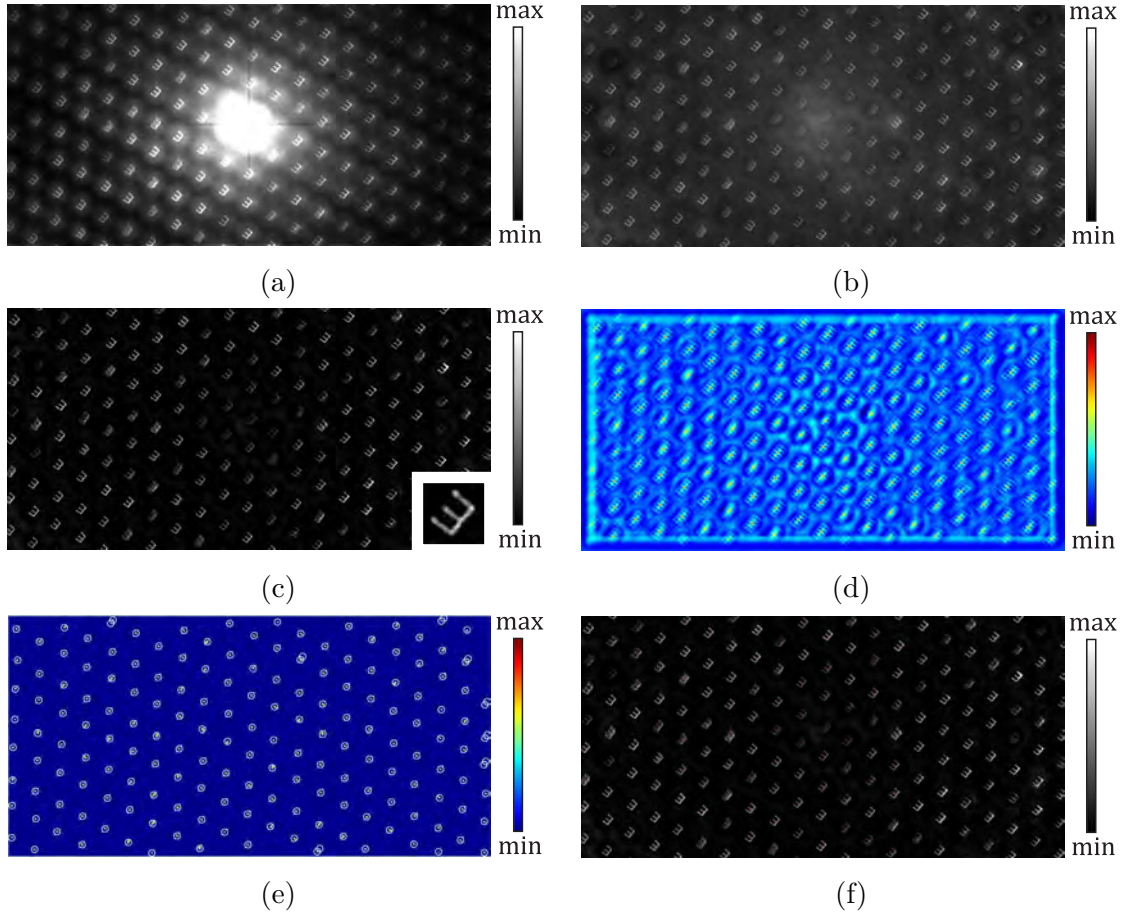


Figure 4.8: A procedure for determining the source distribution. Acquisition time: 1h. **(a)** A multipoint-projection image of a highly absorbing planar object (symbol E) placed in the focal spot of the optics. **(b)** The image normalized by an image recorded without the object. **(c)** After high-pass filter. Inset shows a single sub-image. **(d)** The calculated correlation of the image (c) with the single sub-image (inset). **(e)** The positions of the secondary sources generated at the tips of capillaries. The positions are determined by finding the positions of the highest intensity peaks in the thresholded correlation, which are indicated by white circles. **(f)** An overlap of (c) with the determined source distribution.

INSPECTION MICROSCOPES

Two optical inspection microscopes (Dino-Lite AM7915MZTL) with long working distance were used in order to simplify the procedure of bringing the biological samples into focal spot of the optics. Microscopes are observing the sample from two perpendicular directions (Fig. 4.9).

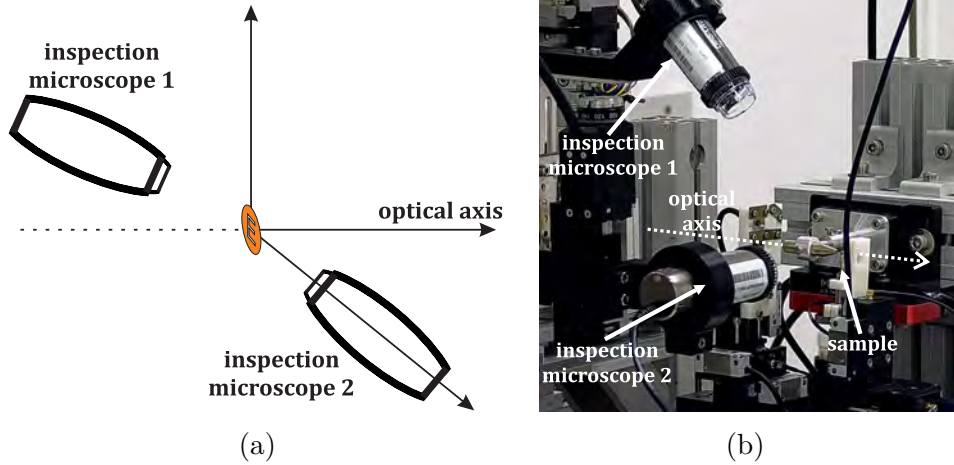


Figure 4.9: Optical inspection microscopes for aligning the sample. (a) A scheme and (b) a photograph of the inspection setup.

The focal spot of the optics was determined firstly by inserting a high absorbing object (symbol E) into focal spot. Then, by using the software provided with the microscopes, the position of the focal spot was marked and therefore, while aligning a complex biological sample it was easier to roughly bring the object into the focal spot of the optics. Fig. 4.10 presents images from inspection microscope during aligning the symbol E .

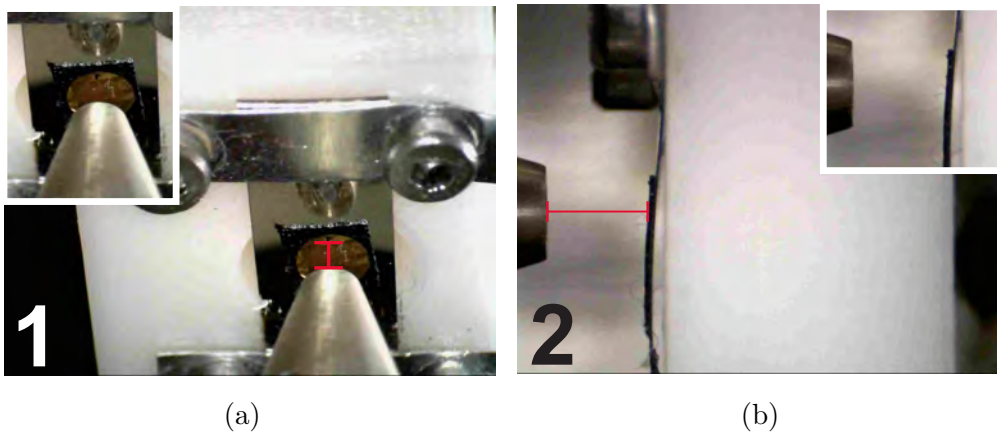


Figure 4.10: Images from optical inspection microscopes during aligning the symbol E . (a) Microscope 1 and (b) microscope 2. The focal length is marked by red line. Insets present raw microscopes' images.

4.3 RESULTS

4.3.1 TEST SAMPLES

2D OBJECT - JIMA RT RC-02B RESOLUTION CHART

The resolution of the plenoptic X-ray microscope was tested on JIMA resolution chart, described in section 3.4.1. Images of the $0.5\ \mu\text{m}$ and $0.4\ \mu\text{m}$ slits were recorded at two Δz positions. The raw data acquired in the experiment are presented in Fig. 4.11(a). Figure 4.11(b) depicts the data after the normalization with the image without any object in the focal spot of the optics.

Note that these images are similar to the images of 4 and 5 symbols obtained with the Lytro camera for visible light (Fig. 1.7). The internal structure of the image in both X-ray and visible light cases consists of circles (which denotes the boundaries of

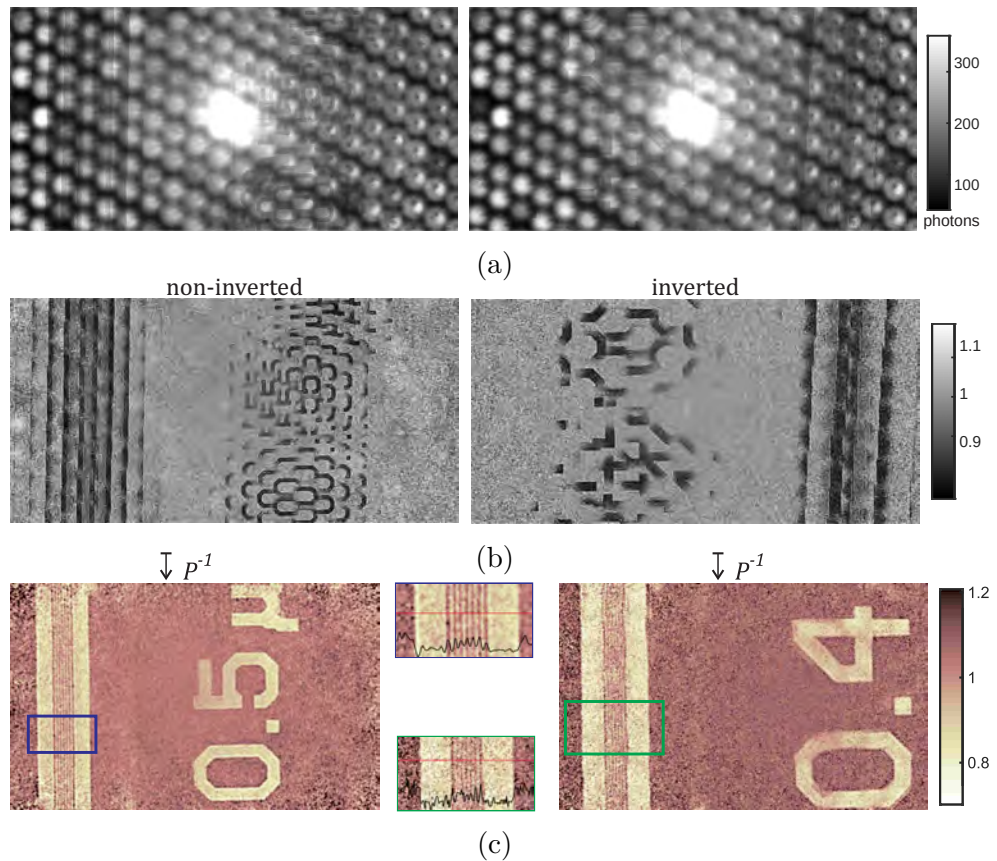


Figure 4.11: Test of the lateral resolution. (a) Raw images obtained for $0.5\ \mu\text{m}$ (left, $\Delta z \approx 1\ \text{mm}$) and $0.4\ \mu\text{m}$ slits (right, $\Delta z \approx -1\ \text{mm}$). Acquisition time: 1h. (b) Data after the normalization. (c) The plenoptic reconstruction. The middle images are zoomed areas with profiles along the red lines.

the secondary sources and micro-lenses, respectively) and also a typical inverted image for $\Delta z < 0$ and non-inverted for $\Delta z > 0$ are clearly seen. Figure 4.11(c) shows the plenoptic reconstruction for the slits. Our microscope resolves the $0.4 \mu\text{m}$ line width on the JIMA chart (profiles in Fig. 4.11(c)) and the lateral resolution is also limited by the individual micro-source size, as it was in the case of multipoint-projection microscopy.

2D OBJECT - STM TIP

An electrochemically etched Pt-Ir scanning tunneling microscopy (STM) tip was used to visualize image formation at various distances Δz in front and behind the focal plane of our setup (Fig. 4.12). For distances closer to the focal spot of the optics, images of the tip can be reconstructed in the terms of plenoptic reconstruction. Note, that for $\Delta z = 15000 \mu\text{m}$, the image of the tip is imposed on the image of the secondary sources structure without any marks of plenoptic image (i.e. it appears as a conventional X-ray projection).

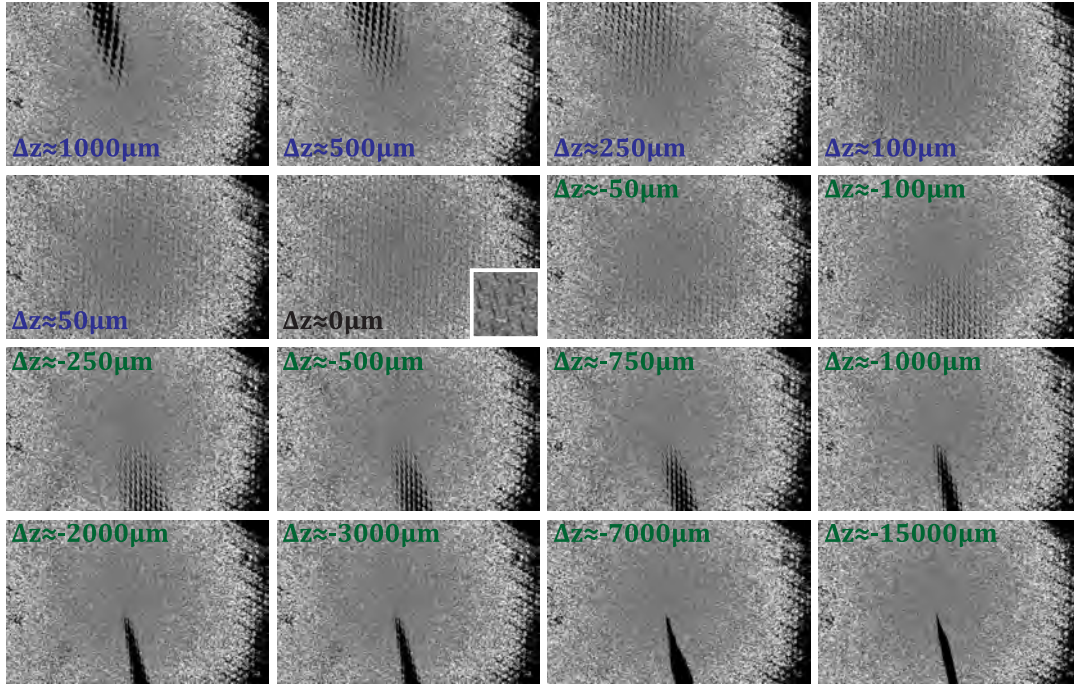


Figure 4.12: Plenoptic images of the STM tip at various Δz . Images were normalized with respect to the image without the object in the focal spot. Acquisition time: 600s for each position.

Figure 4.13(a) presents a microscopic image of the tip, whereas Fig. 4.13(b) presents the plenoptic reconstruction for the tip in focal spot of the optics ($\Delta z = 0$). The ghost images in Fig. 4.13(b) are a result of the reconstruction procedure.

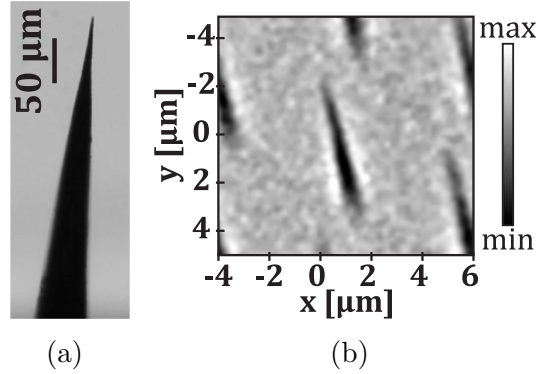


Figure 4.13: STM tip. (a) An optical microscope image of the tip. (b) A plenoptic reconstruction for the tip at $\Delta z = 0$. Ghost images are a result of reconstruction procedure.

3D OBJECT - LATEX SPHERES SANDWICH

The ability of three-dimensional imaging of our microscope was tested on a model sample as depicted in Fig. 4.14(a). A copper finder grid with thickness of $20\ \mu\text{m}$ was fixed on a $75\ \mu\text{m}$ kapton foil with sticky tape in its edges. Next, a $\sim 0.2\%$ water solution of latex spheres with $3\ \mu\text{m}$ diameter (polystyrene latex beads, LB30, Sigma Aldrich) was dispensed on both sides of the sample and left for drying for 24h. Optical microscope images of the ROI on the sample at various depths are presented in Fig. 4.14(b).

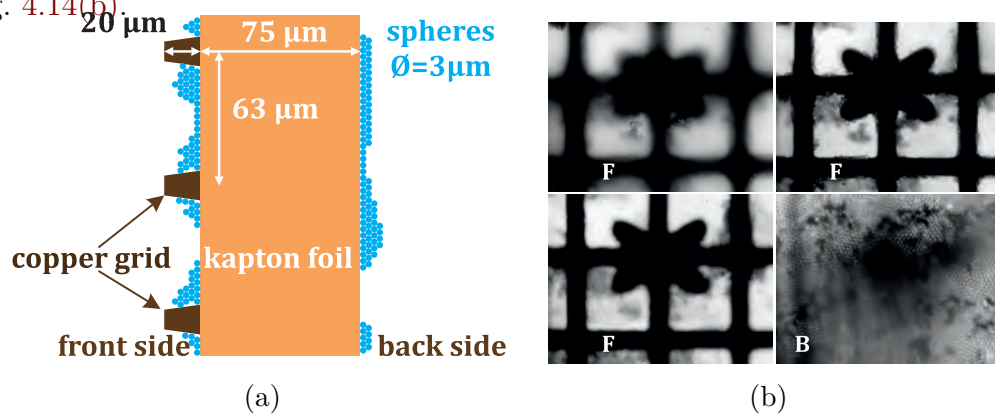


Figure 4.14: Model sample. (a) A scheme of the model object. (b) Optical microscope images of the region on the sample at various depths. F and B denote the front and the back side of the sample, respectively.

Figure 4.15(a) illustrates conventional X-ray projections of the sample without the multi-pinhole mask. Figure 4.15(b) depicts an image recorded for $\Delta z \approx 1.5$ mm with the multi-pinhole mask upstream of the optics. Due to the fact that $\Delta z \gg 0$, the imaging was realized in the apposition compound eye regime. Therefore, it was possible to only reconstruct a high resolution projection of the sample (Fig. 4.15(c)), without depth resolution.

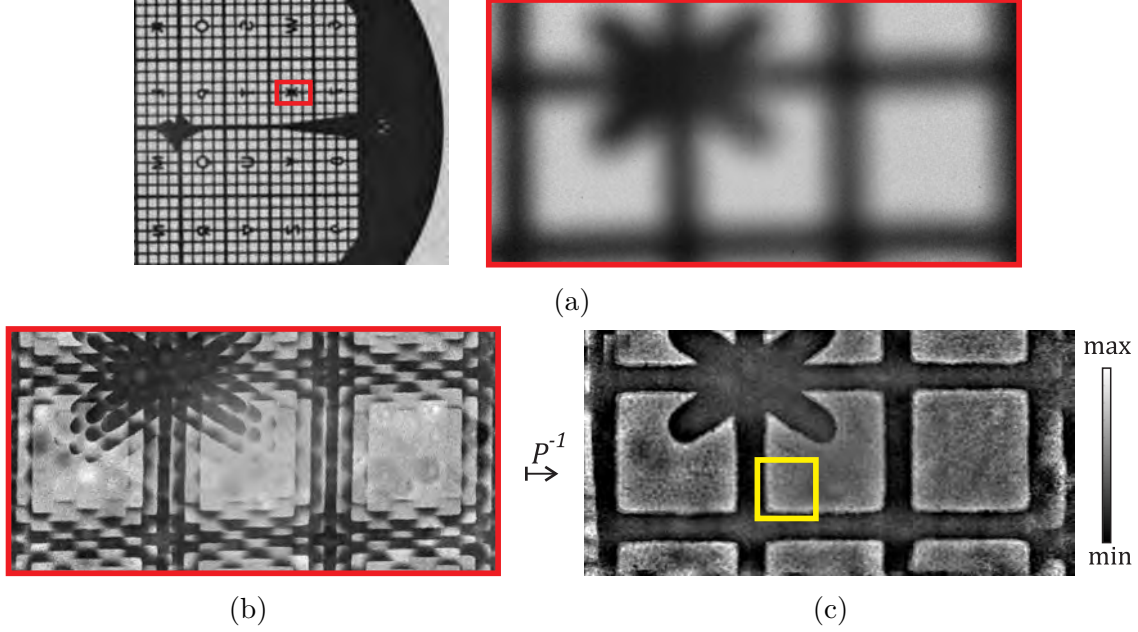


Figure 4.15: Model sample in the apposition compound eye regime. (a) A set of conventional X-ray projections of the sample at various magnifications. ROI marked as a red rectangle. Acquisition time: 300s. (b) A plenoptic image recorded with the multi-pinhole mask for $\Delta z \approx 1.5$ mm and $M \approx 170$. Acquisition time: 60 min. (c) A plenoptic reconstruction of image b). Yellow rectangle marks the next region of interest (ROI2).

In the next step, the sample was moved to $\Delta z \approx 0$ at $M \approx 270$ and the ROI denoted as yellow rectangle in Fig. 4.15(c) was brought into the plenoptic regime. The plenoptic image of this ROI is depicted in Fig. 4.16(a). The image consists of multiple projections of the same region but illuminated from slightly different angles. This image is a counterpart of the sub-aperture image in the plenoptic camera for visible light (Fig. 1.8(a)). Based on this image, it was possible to reconstruct slices of the object at various depths as depicted in Fig. 4.16(c). Since the lateral resolution is limited by the individual micro-source diameter to 400 nm (Fig. 4.11), spheres from both sides of the kapton foil are easily distinguished. Moreover, a defect inside the

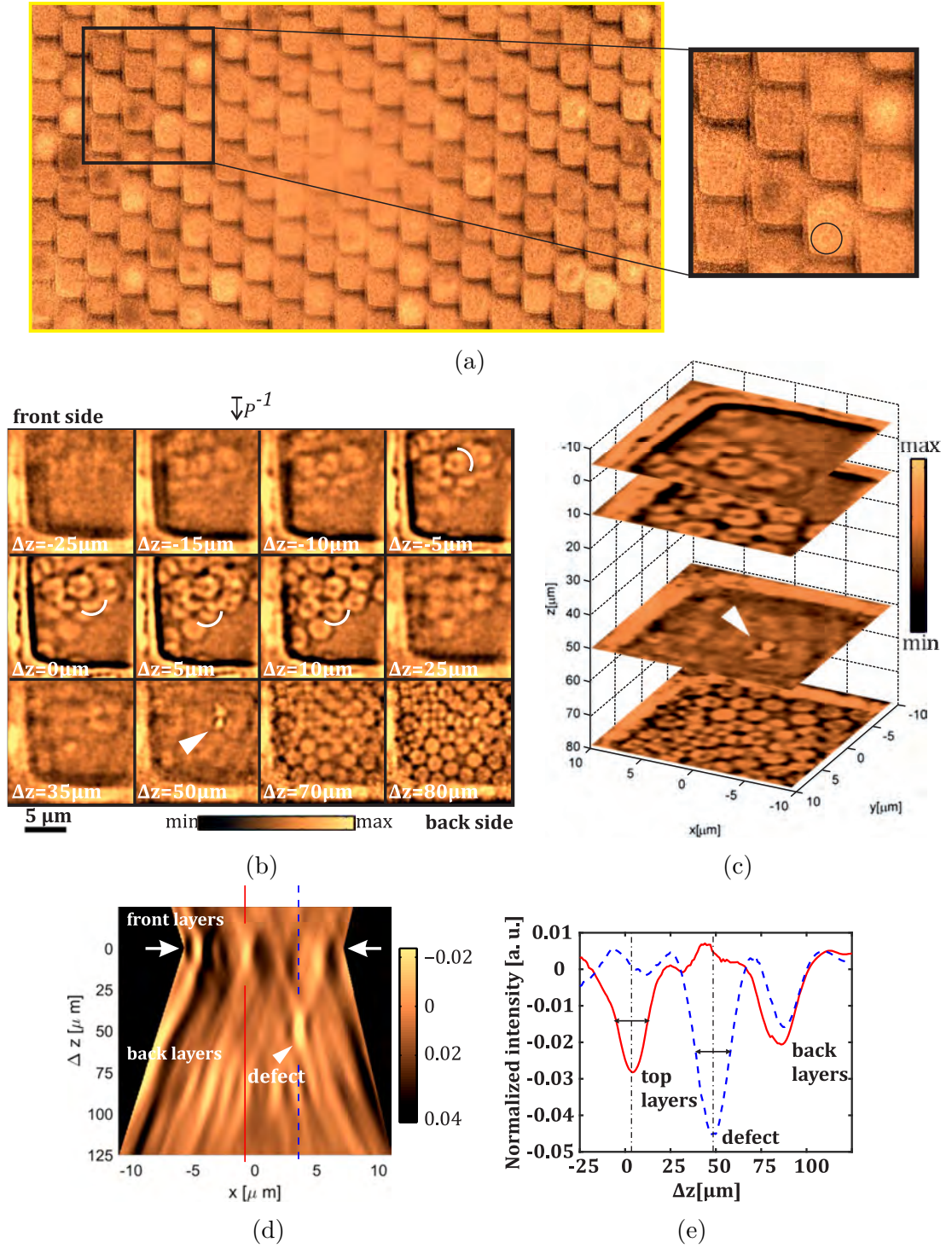


Figure 4.16: X-ray images of the ROI2 in the plenoptic imaging regime. (a) A plenoptic image for ROI2 at $\Delta z \approx 0$ and $M \approx 270$. Black circle marks the image of a well resolved single latex sphere. Acquisition time: 2h. This image is a counterpart of the sub-aperture image in the plenoptic camera for visible light (Fig. 1.8(a)). (b) Plenoptic reconstruction at various depth based on (a). (c) Pseudo-3D visualization of several reconstructed layers. (d) z -axis axial scan in plenoptic reconstruction. (e) Profiles along the lines from (d).

foil was also captured. The depth resolution was sufficient to distinguish layers of the spheres in the front of the sample as marked by white arrows. However, as the depth resolution decreases with increasing Δz , layers at the bottom side of the sample are not resolved. Fig. 4.16(c) presents pseudo-3D image of several reconstructed layers, which reflects the spheres arrangement from the scheme (Fig. 4.14(a)).

A more precise illustration of the depth resolution is presented in Fig. 4.16(d) where plenoptic slices in the depth directions are depicted similarly to a tomographic axial scan. The reconstructed region has a shape determined by the width of the X-ray beam. Therefore, as for the limited-angle tomography, the best resolution is acquired in the focal spot region, according to Eq. (4.2) (marked by white arrows) and here, individual layers of spheres were resolved. Moreover, for large Δz , an elongation of reconstruction appears along the illumination direction of individual capillaries. Fig. 4.16(e) presents the profiles along the lines marked in Fig.4.16(d).

4.3.2 BIOLOGICAL SAMPLE - IVY LEAF

An ivy leaf (*Hedera helix*) was imaged in order to demonstrate the abilities of our plenoptic microscope to image biological samples at cellular level as well as to demonstrate the imaging regimes of the microscope. The leaf (Fig. 4.17(a)) was collected during winter at the temperature below 0°. A $10 \times 20 \text{ mm}^2$ fragment of the leaf was cut off and attached to a 3D printed sample holder and measured after 24h. Fig. 4.17(b) depicts a conventional X-ray projection of the leaf fragment. Red rectangle denotes the desired ROI1 in which a trichome (leaf hair) is present on the bottom side of the leaf.

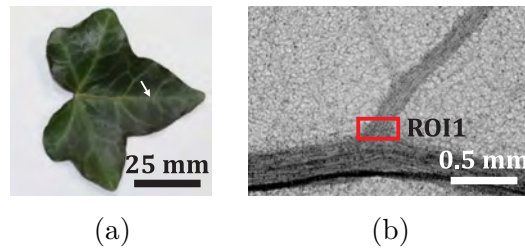


Figure 4.17: Ivy leaf (*Hedera helix*). **(a)** A photograph of the leaf. Arrow points to fragment that was cut off. **(b)** A conventional projection of the leaf fragment with ROI1 denoted as red rectangle.

Fig. 4.18(a) presents the plenoptic image of the ROI1 at $\Delta z \approx 2.5 \text{ mm}$, which lies in the apposition compound eye regime. Therefore, a high resolution 2D pro-

jection of a large area was obtained from the plenoptic reconstruction, as shown in Fig. 4.18(b). A complex structure of the leaf is visible: vascular bundles, druses (Franceschi & Nakata 2005) and a trichome (Ackerfield 2001).

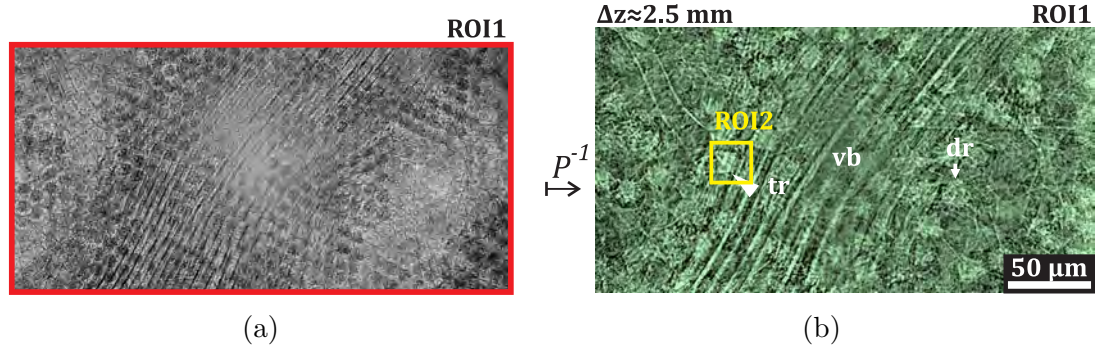


Figure 4.18: Ivy leaf in the apposition compound eye regime. (a) An X-ray image of the ROI1 for $\Delta z = 2.5 \text{ mm}$. Acquisition time: 1h. (b) A plenoptic reconstruction of image (a). Labels: tr - trichome, vb - vascular bundle, dr - druses. Red rectangle marks ROI2.

Some fragments from reconstructed images of the sample acquired for various Δz are depicted in Fig. 4.19. In particular a central part of the trichome (Fig. 4.19(a), optical microscope image Fig. 4.19(b)) and the position of the druses in hexagonal cells (Fig. 4.19(c)). For reference, calcium oxalate druses were isolated from ivy leaves according to the procedure of da Costa et al. (2009) and imaged with the SEM microscope (Fig. 4.19(d)).

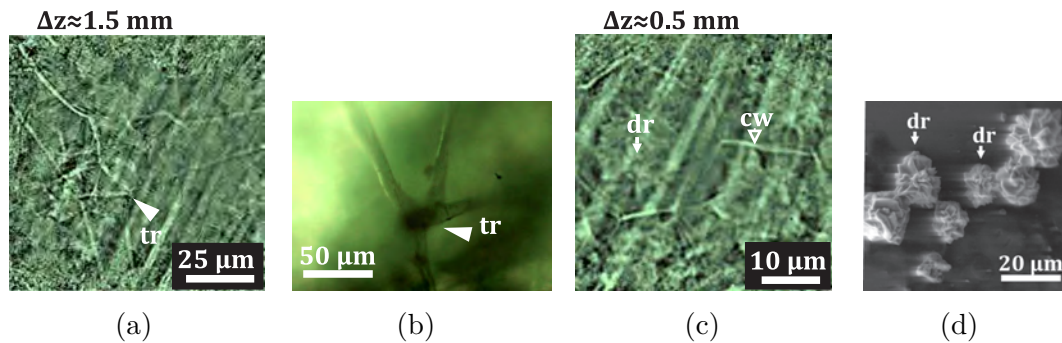


Figure 4.19: Fragments from reconstructed image of the sample acquired for several Δz (a) Plenoptic reconstruction for $\Delta z = 1.5 \text{ mm}$ of the central part of the trichome. (b) An optical microscope image of a trichome. (c) Plenoptic reconstruction for $\Delta z = 0.5 \text{ mm}$ of druses in hexagonal cells. (d) SEM image of calcium oxalate druses present in ivy leaves. Labels: tr - trichome, vb - vascular bundle, dr - druses, cw - cell wall.

Next, ROI2 was brought near to the focal spot of the optics (plenoptic imaging regime). Figure 4.20(a) presents the plenoptic image of the ROI2 and a virtual paradermal sectioning that could be performed as depicted in Figures 4.20(b) and 4.20(c).

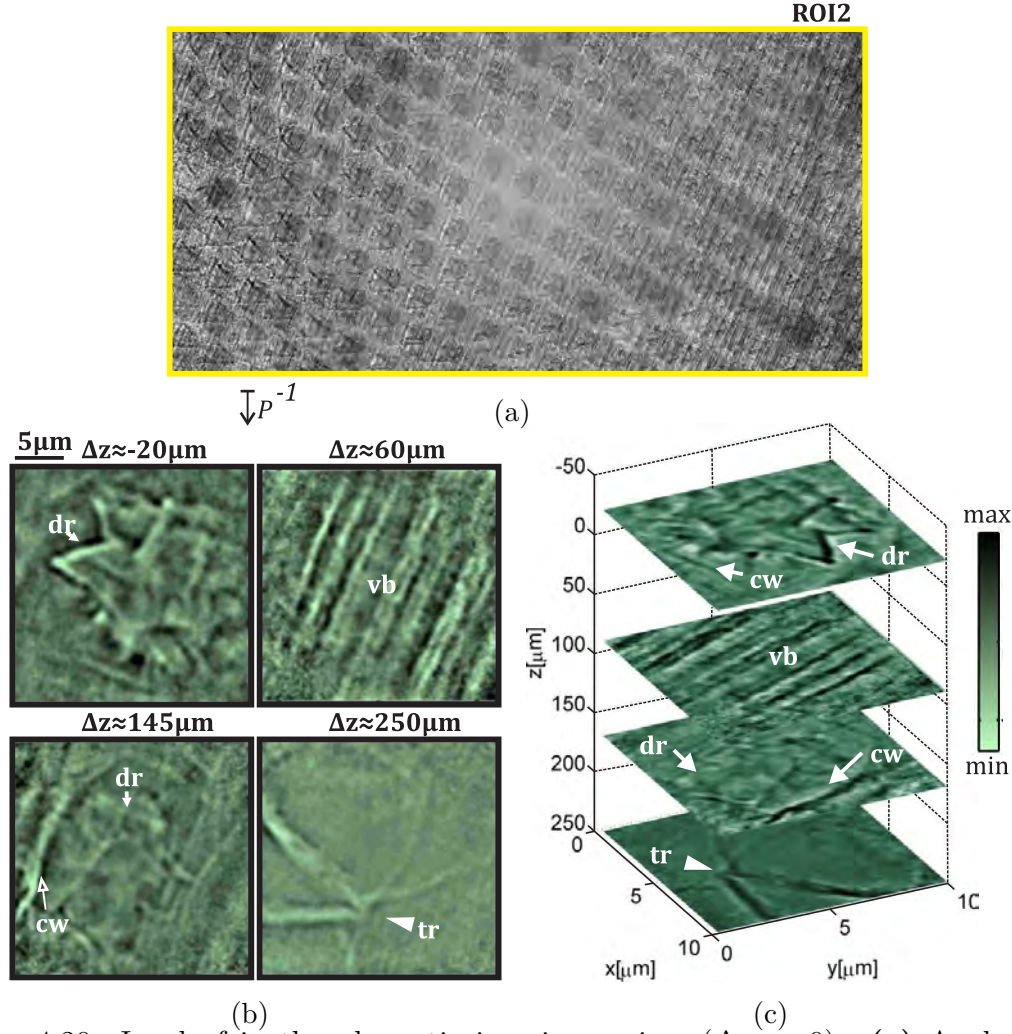


Figure 4.20: Ivy leaf in the plenoptic imaging regime ($\Delta z \approx 0$). (a) A plenoptic image of ROI2. (b) Reconstructions of (a) for various depths. (c) Quasi-3D image of several layers of the leaf. Labels: tr - trichome, vb - vascular bundle, dr - druses, cw - cell wall.

4.3.3 MULTIMODAL IMAGING - COMBINATION OF PLENOPTIC MICROSCOPY WITH μCT AND XRF

This section describes combined experiments of the plenoptic X-ray microscopy with conventional tomography and X-ray fluorescence spectroscopy (XRF). In both

samples described below, the procedure of the experiment was as follows. Firstly, a tomographic scan (for polycapillary optics without the multi pinhole mask) was performed in order to find regions of interest. Secondly, X-ray plenoptic images of the interesting regions were acquired (polycapillary optics with the multi pinhole mask). Then, these plenoptic images were used to bring interesting features of samples into the focal plane of the optics and perform XRF.

DANDELION ACHENE

A dandelion (*Taraxacum officinale*) achene (Meng et al. 2014) was separated from the pappus beak and glued vertically to a sample holder and placed on a top of a 6 mm diameter stepper motor with a 256:1 gearhead (Faulhaber DM0620). Images from the inspection microscopes are presented in Fig. 4.21(a).

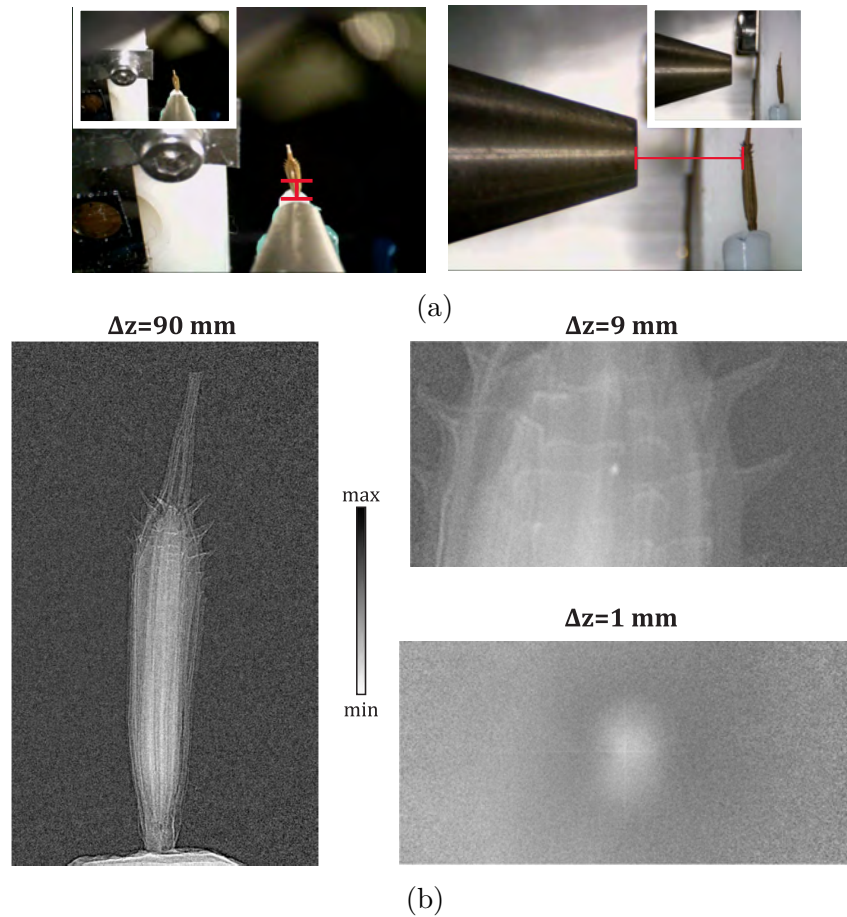


Figure 4.21: Dandelion (*Taraxacum officinale*) achene. (a) Images from the inspection microscopes. (b) Conventional projections of the achene with an iron filling (white spot) accidentally put on the surface. Acquisition time for each projection: 180s.

An iron filling was accidentally put on the surface of the achene. This motivated us to test the combination of plenoptic X-ray microscopy with XRF for multi-modal imaging. Figure 4.21(b) presents conventional X-ray projection of the achene at various Δz . The filling is visible as a white spot, nevertheless, no details of the filling are resolved.

A conventional tomographic experiment with the same polycapillary optics but without the multi-pinhole mask was performed in the cone-beam geometry. In this type of geometry, the focal spot plays the role of the secondary X-ray source and the resolution is limited to approx. $10\ \mu\text{m}$. A tomographic scan within the range of 200° and step of 0.2° was performed with the use of the stepper motor. Each scan point was acquired for 60s giving together a total time of 8.3 h. The tomographic reconstruction was performed with the open source ASTRA Toolbox for MATLAB environment (astra.toolbox.com 2019) and the visualization of the 3D data was done with the Tomviz software (tomviz.org 2020). The 3D reconstruction of the achene is presented in Fig. 4.22.

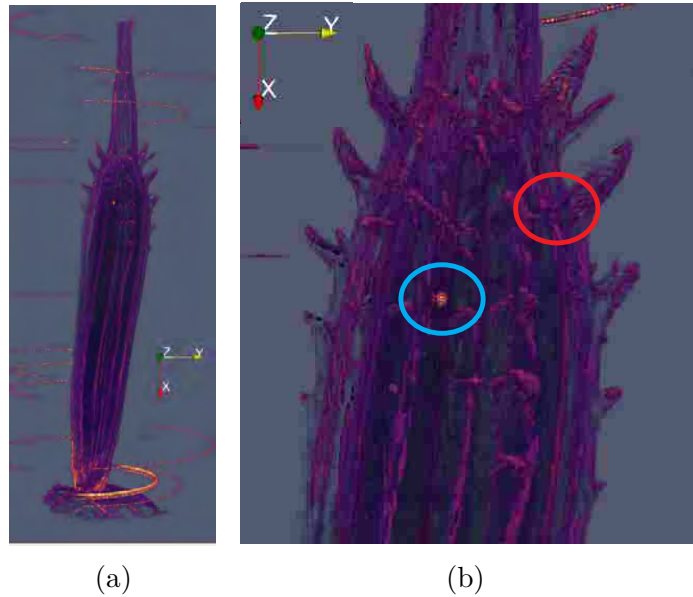


Figure 4.22: Low resolution ($\sim 10\ \mu\text{m}$) conventional tomographic reconstruction of the dandelion achene. **(a)** The whole achene. **(b)** A zoom on the filling (blue circle) and spike (red circle).

Firstly, the spikes of the achene (marked with red circle on 4.22(b)) were investigated in the apposition compound eye regime. Figure 4.23 presents a conventional X-ray projection of the spikes at $\Delta z = 2.5\ \text{mm}$. No detail of the spike structure were resolved.

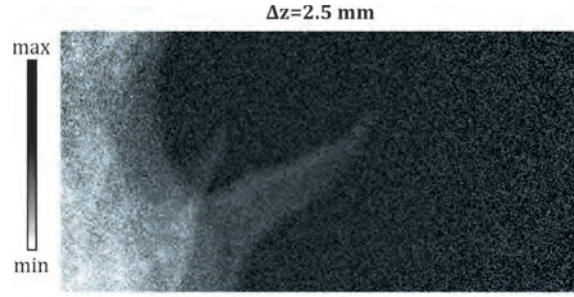


Figure 4.23: A conventional projection of dandelion spikes at $\Delta z = 2.5 \mu\text{m}$. No details of the spike are resolved. Acquisition time: 180s.

A plenoptic image for $\Delta z = 1.9 \mu\text{m}$ corresponding reconstructed image are depicted in Fig. 4.24. A stringy structure is clearly seen on the surface of the spikes.

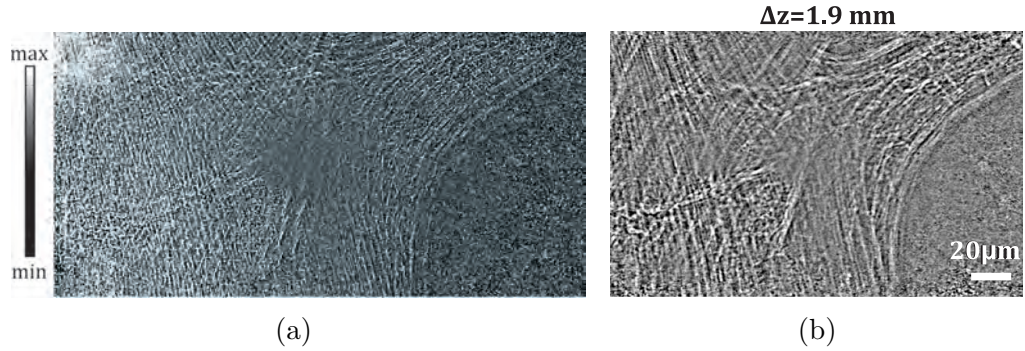


Figure 4.24: Dandelion spikes in the apposition compound eye regime. (a) A plenoptic image at $\Delta z = 1.9 \mu\text{m}$. Acquisition time: 1h. (b) A plenoptic reconstruction. An individual spike with details is resolved.

Next, the iron filling was brought into the focal spot of the optics and investigated in the regime of plenoptic imaging. Figure 4.25(a) and 4.25(b) presents the plenoptic image and the reconstruction of the iron filling at $\Delta z = 100 \mu\text{m}$ respectively.

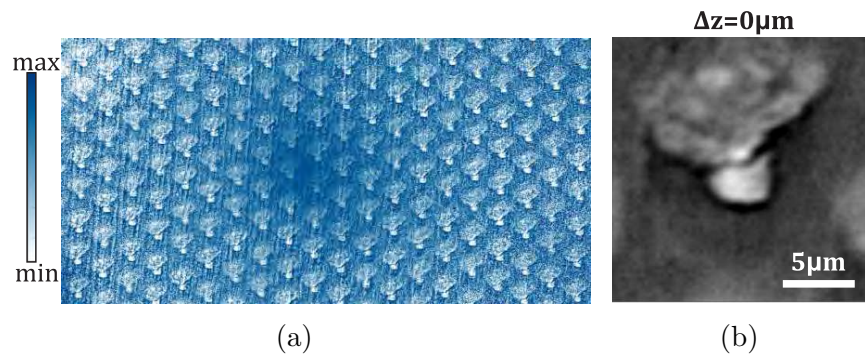


Figure 4.25: Plenoptic images of the iron filling. (a) Plenoptic image. Acquisition time: 1h. (b) Reconstruction for the original position.

Additionally, the setup was extended by an Amptek X-123 spectrometer with a 25 mm² silicon drift detector and DP4 digital pulse processor, in order to perform X-ray fluorescence experiments and test the ability of our microscope to perform multi-modal experiments. Note that the setup was not optimized for XRF yet. Therefore, we have to deal with a considerable large background levels. Figure 4.26(b) shows the spectra obtained in the presence of the iron filling (red), at another position on the sample (blue) and in the total absence of the sample (black). In the presence of the filling, peaks in the energy range corresponding to the iron K_α and K_β fluorescence lines appear. However, there are also peaks corresponding to the calcium K_α and K_β and antimony L_1 , which can be identified as a component of dust (antimony is used as a hardener in lead alloys and since we use lead for blocking the radiation, the presence of this element can be justified).

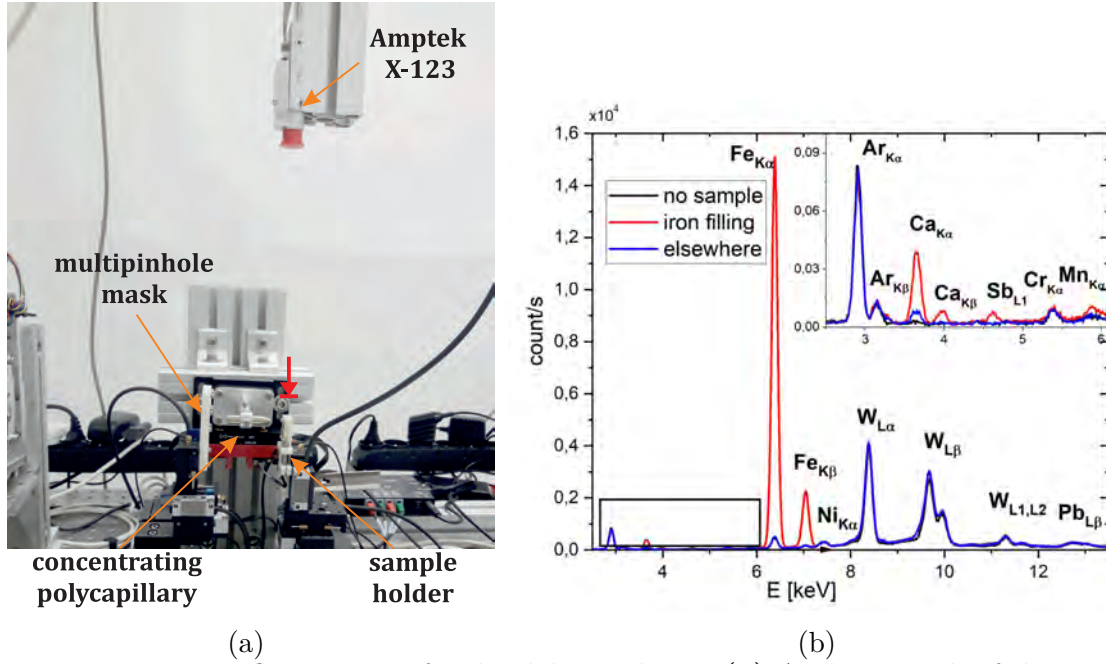


Figure 4.26: X-ray fluorescence for dandelion achene. **(a)** A photograph of the setup. Red arrow marks the position of Amptek X-123 during the experiment. **(b)** X-ray fluorescence spectra obtained in the presence of iron filling (red), on other position on the achene (black) and with the total absence of the sample (black). The inset shows a zoomed area for 2-6keV.

DROSOPHILA MELANOGASTER

A model organism i.e. a fruit fly (*Drosophila melanogaster*, (Chyb & Gompel 2013)) was found dead in our laboratory, glued into a 3D printed sample holder and put at the top of the Faulhaber stepper motor as it was in the case of the dandelion achene. Optical microscope images of the fly are presented in Fig. 4.27(a). The orange rectangle marks dust crystals in the leg of the fly. A fly positioned in the setup is illustrated in Fig. 4.27(b).

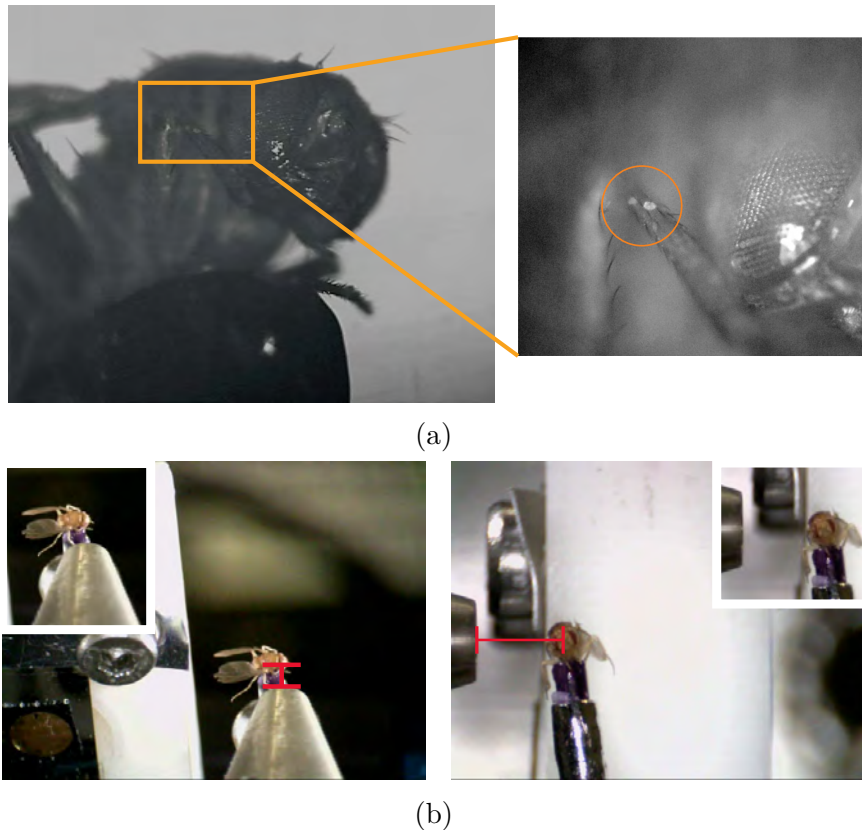


Figure 4.27: *Drosophila Melanogaster*. (a) Optical microscope images. Orange circle marks dust crystals on the leg of the fly. (b) Images from inspection microscopes while positioning of the fly in the setup. The red lines denotes the position of the focal spot of the optics. Black arrow point to the leg with dust crystals. Insets presents raw images from the microscopes.

A conventional medium-resolution tomographic scan (without the multi pinhole mask) was performed in the range of 0° - 200° with a step of 0.2° . Each tomographic projection was acquired with 60s exposure giving a total scan time of 8.3h. The data were reconstructed with the ASTRA Toolbox for MATLAB environment and displayed

with the Tomviz software (Fig. 4.28). The fly was covered in dust crystals. We chose two of them, marked as blue circles, to perform plenoptic imaging.

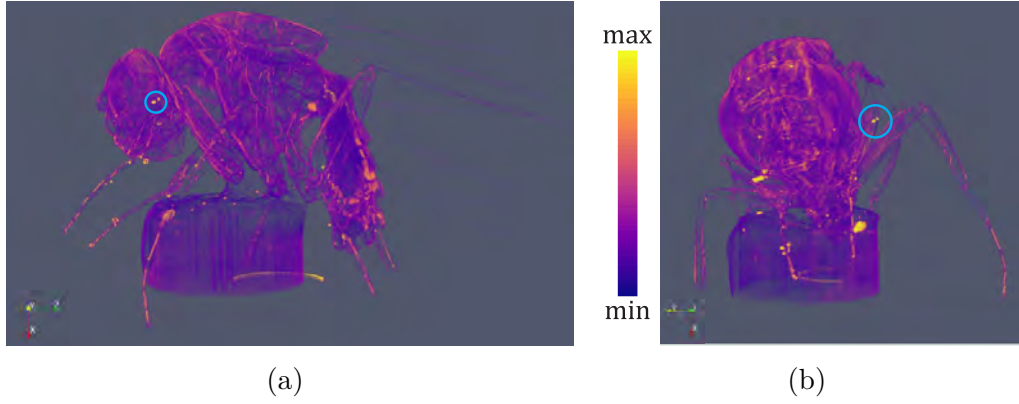


Figure 4.28: Conventional tomography of *Drosophila Melanogaster* with polycapillary optics. The tomographic reconstruction **(a)** from the front and **(b)** from the side of the fly. Blue circle marks the selected crystals.

Figure 4.29 presents a conventional X-ray projections of the fly at different Δz . Blue circles indicates chosen crystals.

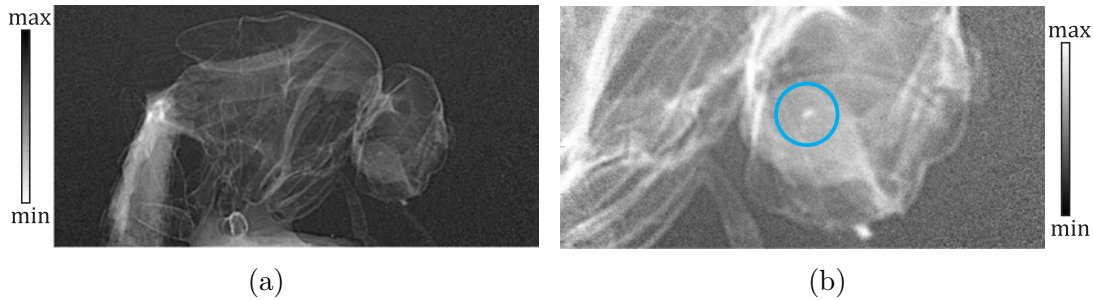


Figure 4.29: Conventional X-ray projections of *Drosophila Melanogaster*. Orange and blue circles indicates chosen crystals. Acquisition time: 300s.

Firstly, the crystals present on the leg of the fly (orange circle in Fig. 4.29) were brought into the plenoptic imaging regime. The thorax of the fly was centred at the focal spot of the optics with the fly's leg aligned approximately along the optical axis of the system. Therefore, the incoming radiation firstly penetrated the thorax and then the leg of the fly was exposed (see Fig. 4.27(b)). The plenoptic image for such a configuration is presented in Fig. 4.30(a). Several slices at various depths were reconstructed as depicted in Fig. 4.30(b). In a way, a structure very similar to sinews is visible and further, the dust crystals are resolved.

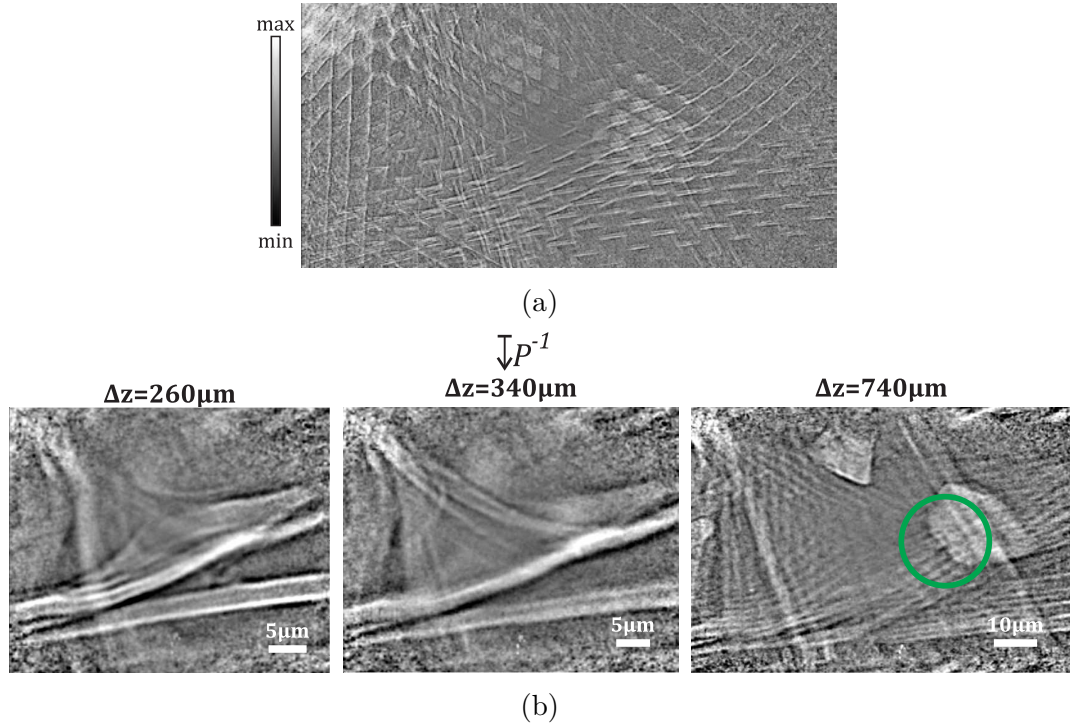


Figure 4.30: The dust crystal on the leg of the fly in intermediate regime. **(a)** A plenoptic image. Acquisition time: 1h. **(b)** The reconstruction at various depths Δz . Green circle marks ROI of crystal brought into the focus.

Next, the crystal marked in green circle was brought into the focus. The plenoptic image is presented in Fig. 4.31(a). Besides the shape of the crystal, a structure of the sinews is resolved, as they are closer to the focal spot of the optics. A reconstructed image at plane $\Delta z = 0$ is presented in Fig. 4.31(b).

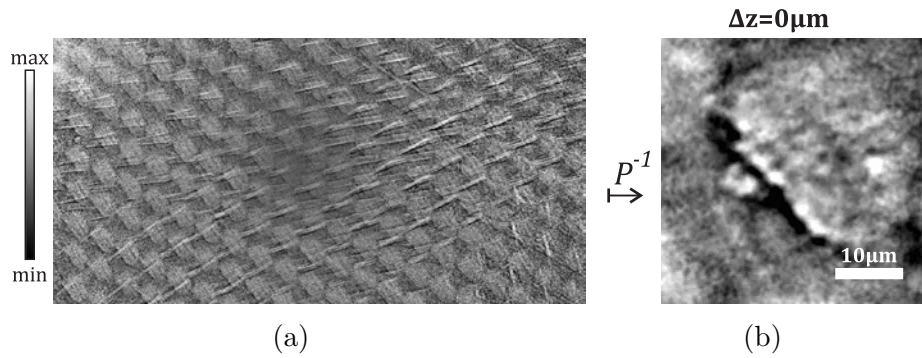
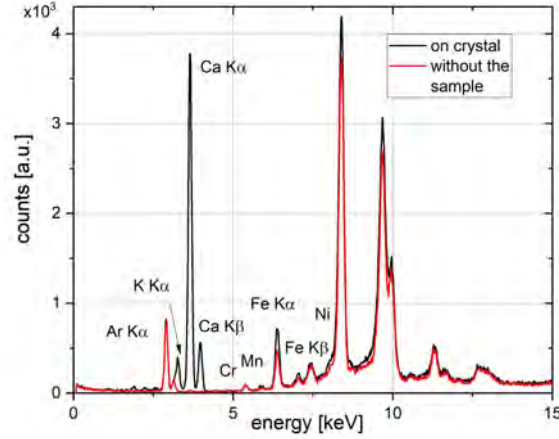


Figure 4.31: The dust crystal on the leg of the fly in the imaging regime. **(a)** A plenoptic image. Acquisition time: 1h. **(b)** The reconstruction for the dust crystal in the focal spot.

In order to determine the element composition of the dust crystal, X-ray fluo-

rescence experiment was performed in the same manner as for the iron filling on the dandelion achene. Figure 4.32(a) depicts the fluorescence spectra obtained in the presence of the dust and without the sample. The dust consisted mainly of calcium.



(a)

Figure 4.32: X-ray fluorescence spectra in the presence of the dust crystal and with the absence of the whole sample.

4.3.4 SUMMARY

This Chapter described the construction of the first X-ray plenoptic microscope and its applications. The microscope utilizes the multipoint-projection geometry and instead of micro-lens array uses an array of micro-capillaries from polycapillary optical element. The distribution of capillaries was defined by a multi pinhole mask placed between two polycapillary elements. Hence, an array of secondary micro sources was created. If the spacing between secondary sources is bigger or equal to the beam width at the focal plane, all microbeams are perfectly demultiplexed at the detector plane and therefore, the image at the detector could be interpreted as a set of limited angle tomographic projection acquired in a single exposure (Vigano et al. 2018). Therefore, tomographic-like slices at various depths could be successful reconstructed with the plenoptic reconstruction (analogously to the refocusing procedure in visible light plenoptic cameras).

Three imaging regimes were introduced. The first one, plenoptic regime, is characterized by a high depth resolution and lies closely to the focal plane of the optics (in the case of our configuration it was $\pm 60 \mu\text{m}$). The field of view in the plenoptic regime was approximately $10 \times 10 \mu\text{m}$. We tested the depth resolution on a phantom

sample (sandwich consisted of 3 μm) polystyrene spheres. In the plenoptic region it was possible to resolve individual layers of the spheres.

Additionally, on the example of an ivy leaf, we tested the possibility of single-exposure depth-resolved imaging of complex biological samples. In the plenoptic regime a virtual paradermal sectioning of the leaf was possible. However, the sample reveal that the depth resolution is decreasing with the distance to the focal plane. Therefore the second intermediate region could be characterized as with a moderate depth-resolution but a larger field of view.

For samples placed far away from the focal plane ($> 120 \mu\text{m}$) the depth resolution decreased drastically but a high resolution multipoint projections could be obtained. In this region, each micro beam illuminates a different part of the sample and therefore we called this region an apposition compound eye regime.

In the last part of this Chapter a preliminary attempt to combine the X-ray plenoptic microscope with other imaging techniques was made. The experiments combined conventional tomography with the X-ray fluorescence microscopy. Two large biological samples were investigated: a dandelion achene with an iron filling and a fruit fly with dust crystals on the leg. For both samples, the first step was to perform tomography to roughly locate regions of interest. Next, the plenoptic imaging was performed and high-resolution images of filling and dust crystals were obtained. Finally, the X-ray plenoptic microscopy allowed to perfectly align crystals and filling in the focal spot of the optics and perform X-ray fluorescence spectroscopy.

CONCLUSIONS & PERSPECTIVES

This Thesis reports a first realization of the X-ray plenoptic microscope in which the compound polycapillary optical element is the equivalent of MLA in conventional plenoptic camera for visible light.

In the Thesis the concept of light field imaging was reviewed, accompanied by the description of the standard plenoptic camera setup for visible light and plenoptic images taken by the author with the Lytro camera. The previous attempt to construct X-ray plenoptic microscope made by Longo and collaborators was briefly presented. Additionally, the relation between plenoptic imaging and limited angle X-ray tomography was shown. The image formation in propagation based imaging was delineated followed by the description of several primary X-ray optical elements with a focus on the polycapillary optics as the key element of the X-ray plenoptic microscope.

The defect-assisted hard X-ray microscopy was described as the inspiration for the construction of the X-ray plenoptic microscope. The defects in polycapillary surface break the periodicity of the capillary structure and give rise to X-ray projection of the object imposed on the image of the polycapillary surface.

In the extension of the defect-assisted imaging, namely the multipoint-projection microscopy, a compound polycapillary element was proposed, containing collimating and concentrating part with a multipinhole mask with desired pinhole distribution in between. Therefore, it was possible to control the distribution of the micro beams generated by individual capillaries. The parameters of the mask were chosen to enable multiplexing at the focal plane and perfect demultiplexing of micro beams at the detector plane. Over thousand projections of the object placed in the focal spot of the optics were obtained. The reconstruction procedure was based on the summation of individual projections of the object. It was possible to reconstruct a clear image of the object from a multipoint projection image with average 2 photons per detector pixel. The lateral resolution of $0.5 \mu\text{m}$ was tested on the JIMA resolution chart. The phase contrast imaging was performed for several weakly absorbing and biological objects. However, all experiments in this part were limited to a quasi planar objects.

The upgraded version of the multipoint-projection setup was proposed to realize the plenoptic imaging in the hard X-ray regime. The prime difference was the detector with larger detecting area. The spacing between the pinholes in the multipinhole mask (and hence the spacing between the secondary sources) was chosen to obtain a perfectly demultiplexed multiple projections of the object at the detector plane. The resulting compound image could be interpreted as a set of limited angle tomographic projections acquired in the single exposure. The reconstruction algorithm was based on the depth dependent affine transformation. As a result, tomographic-like slices at various depths were obtained. The depth resolution was tested on a phantom model composed of several layers of polystyrene spheres of $3\text{ }\mu\text{m}$ diameter attached to both sides of a kapton foil. Individual layers of the spheres were resolved.

Additionally, three imaging regimes were proposed and presented on several exemplary complex biological samples. The depth resolution of our microscope is decreasing with the increasing distance to the focal plane. Hence, the first regime, namely the plenoptic imaging regime, lied in the vicinity of the focal plane ($\pm 60\mu\text{m}$) and had approximately $10 \times 10\mu\text{m}$ field of view. The second region was characterized by a moderate depth resolution with slightly larger field of view. Away from the focal plane ($> 120\mu\text{m}$), the depth resolution was lost, however a high resolution multipoint projections were obtained. Here, each micro beam illuminated a different part of the object, and therefore we called this regime an apposition compound eye regime.

The plenoptic X-ray microscopy was also successfully combined with other imaging methods, i.e. μCT or X-ray fluorescence microscopy forming together a multimodal imaging microscope. Two complex biological samples, a dandelion achene and a fruit fly, were examined in order to test the routine procedure of multimodal imaging. Firstly, a conventional tomography experiment were performed to find interesting region on the samples. The tomography reconstruction revealed small regions on both samples characterised by high absorption which later we identified as an iron filling and a dust crystal. Secondly, a high resolution 2D multipoint-projection imaging were performed followed by the 3D X-ray plenoptic imaging of selected ROIs and revealed the structure of the filling and dust crystal. Lastly, X-ray fluorescence spectroscopy was performed which yielded the information about the element composition of the filling and dust crystal.

To conclude, within this Thesis, the plenoptic imaging was extended into hard X-ray regime. The penetrating nature of X-rays enabled 3D imaging of opaque samples. However, due to limited angular apertures of polycapillaries, the depth resolution is

always worse than the lateral one.

Future improvements in this X-ray plenoptic microscope would require a more powerful X-ray source, such as a rotating anode or metal jet source. On the other hand, the setup is compatible with parallel beam illumination and therefore, it could be used on synchrotron beamlines. In particular, we plan to implement the setup on POLYX beamline at the SOLARIS National Synchrotron Radiation Centre. The synchrotron source would also enable time resolved single-shot studies. The optimisation of the XRF part of the setup could also enable 3D chemical mapping.

LIST OF SYMBOLS AND ABBREVIATIONS

Abbreviations used throughout the text:

μ CT	X-ray Microtomography
2D	two dimensional
3D	three dimensional
4D	four dimensional
7D	seven dimensional
AFM	Atomic Force Microscope
CCD	Charge Coupled Device
CRL	Compound Refractive Lens
CMOS	Complementary metal–oxide–semiconductor
CT	Computed Tomography
DoF	Depth of Field
FoV	Field of View
FWHM	Full Width at Half Maximum
FZP	Fresnel Zone Plate
IFD	Input Focal Distance
RGB	red-green-blue colour model
MLA	Micro Lens Array
MLL	Multilayer Laue Lens
OFD	Output Focal Distance
sCMOS	scientific Complementary metal–oxide–semiconductor
SEM	Scanning Electron Microscope
SNR	Signal-to-Noise Ratio
STM	Scanning Tunneling Microscopy
SXR	Soft X-Ray
TIE	Transport of Intensity Equation
TOF	Time-of-Flight Camera
UV	Ultraviolet
XRF	X-ray Fluorescence

Some useful symbols used throughout the text:

α_c	the critical angle for total external reflection
β	the local divergence of the polycapillary optics determined by the divergence of individual capillaries
γ	the global divergence of the polycapillary optics
φ	the collecting angle of the polycapillary optics
a_{in}	distance between individual capillaries at the input surface of concentrating polycapillary part
a_{mask}	distance between individual pinholes in the multipinhole mask
a_{out}	distance between individual capillaries at the exit surface of concentrating polycapillary part
f	output focal distance of the polycapillary optics (OFD)
D	object-to-detector distance
t	taper ratio
w	lateral dimension of the beam at the object plane
Δz	object-to-focal plane distance
$\varnothing_{in}$	diameter of an individual capillary at the input surface of concentrating polycapillary part
$\varnothing_{mask}$	diameter of an individual pinhole in the multipinhole mask
$\varnothing_{out}$	diameter of an individual capillary at the exit surface of concentrating polycapillary part

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