Industrial X-ray Computed Tomography Scanners

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46.1 Introduction: Background and Current Technological Trends

It is certainly safe to say that for any computed tomography (CT) scanner “the system is more than the mere sum of its components.” The surprisingly large variety of industrial CT (iCT) scanners that we encounter today brings about the demand to classify them into a limited number of groups, in order to allow the users of these machines to better compare their results. Yet, to date, there is no complete manifest which can assign a well-defined system group to each existing scanner, and there are new scanners being developed and built every year that do not fit into any of the, even provisional, schemes. Therefore, this chapter will try to make the desperate attempt to provide a new larger set of system groups which—to our belief—are categorized by clear definitions and encompass almost any of the existing iCT scanners worldwide (see Section III, Chapter 45, for a description of industrial CT).

The designation “industrial X-ray CT scanner” defines a machine which is, both in software and hardware, based on the original invention of medical CT by Hounsfield (1973). Yet, unlike medical scanners, iCT does not serve a diagnostic purpose and is not applied to a human being or an animal (these scanners are discussed in other chapters). Nevertheless, many iCT scanners still strikingly resemble their medical counterparts and they even use components from the same manufacturing lines (i.e., X-ray anodes and X-ray detectors). On the other hand, some iCT scanners (e.g., those employed by the automotive industry) hardly show any resemblance to the original; some of them involve robot arms and sophisticated data processing to acquire the 3D data required. More and more iCT tasks are shifted to dedicated synchrotron beamlines (e.g., the European Synchrotron Radiation Facility, ESRF) where the highly brilliant X-ray sources allow for extremely short scan times, thus being able to process large numbers of samples in a short time or even applying in situ tomography, that is, observing a dynamic process over time without having to interrupt the continuous recording of CT scans (see Section I, chapter 8). The client, who generally purchases the data or the information that is extracted from it, is not always interested in the type of scanner by which the data was recorded, provided the results are of good quality (signal-to-noise ratio (SNR), material contrast). Therefore, the need to classify existing scanners into well-defined groups is limited to a relatively small community: (a) researchers who develop novel methods of iCT, (b) companies that build and sell iCT scanners, and (c) university chairs or application centers who host one or more iCT scanners in their own labs. Worldwide speaking, there are about two dozen iCT companies who share an annual market of approximately US$100M, which results in some thousand labs at universities and industry that host and use these machines. Surprisingly little change has been observed over the past 20 years in system design and also in the choice of components from which iCT scanners are built, possibly because the community of research labs that actively develops this technology is very small; the Fraunhofer Development Center for X-ray Technology (EZRT) being one of the key players in this field. Now, one might argue that the lack of development in the field of iCT scanners appears because this technology has reached its point of optimal performance, which can only
be improved on by more computing power, and that all physical components (source, mechanics, and detector) already operate at their limits. This chapter will show that quite the opposite is the case and that further developing iCT is indeed a promising field of applied research (see Zabler et al. 2012).

Three approaches are common to subdivide iCT scanners into groups:

• Classification through optical resolution: this approach is found when one speaks of micro-CT, sub-µCT and nano-CT scanners, the highest resolution generally being defined through the basic spatial resolution derived from X-ray images of line patterns.

• Classification through object type and size: for example, drill-core CT, XXL-CT, or plant-CT.

• Classification through the choice of the different components constituting each iCT scanner.

In this chapter, we propose a combination of all three criteria. While creating a new group for each new combination of components will certainly result in too large a number of groups, alternatively restricting the division to types of objects or spatial resolution will allow for a better arranged set of iCT groups: for example, a drill-core CT generally involves a rotating gantry, which is a very unique choice of motor component and which is also required in scanning diffusion and solidification in gases and liquids; the corresponding group will therefore be called “Gantry-CT scanners.” Some of our groups will be referred to as Nano-CT and Micro-CT, yet this labeling—despite being compliant with the commercial labels—does not so much refer to the spatial resolution of the 3D images, as to the choice of the system components (hence the division between “lens-based” and “scanning electron microscope (SEM)-based” Nano-CT) and the applications at hand. The mere grouping of iCT scanners into Nano-CT and Micro-CT, as is custom for iCT manufacturers, is strongly misleading (e.g., by calling a standard sub-µCT machine “nanotom”) and far too general to allow for the discussion of the subtle, yet important, differences between these systems.

As previously implied, the “components” of an iCT system fall into three categories (source, mechanics, and detector) each allowing an iCT system to mark its specifics:

• The X-ray anode (see also Section I, Chapter 2):

  • Conventional anodes, be they “open” or “closed” vacuum tubes, employ a filament cathode, a Wehnelt cylinder, and a bulk metal target—in most cases tungsten. These sources feature the lowest price but also the lowest brightness (low flux, large focal spot). The available voltages may range from 80 to 600 kV.

  • Rotating anodes follow the same working principle but the bulk metal is now disk shaped and revolving at very high speed (up to 6000 rpm). Thus the focal spot power is distributed onto a ring-shaped surface on the anode, thereby increasing applicable thermal charge and hence brightness of the source. Because rotating anodes were developed in medical imaging, their acceleration voltages do not surpass 160 kV.

  • Micro-focus transmission anodes: The term micro-focus refers to additional magnetic lenses and apertures, which may focus and collimate the electron beam down to an area of less than 0.025 µm² and seldom larger than 250 µm², similar to electron beam focusing optics in SEM machines. When this focused beam is directed onto a thin-film anode, which may be a tungsten sputter coated X-ray exit window, a very small X-ray spot is generated in transmission. Depending on the acceleration voltage and the coating thickness (electron interaction zone), the spot size changes. The latter is at least of the order of the coating thickness. If thermally conducting diamond windows are employed, the brightness of these sources is comparable to a state-of-the-art rotating anode. They are also equally expensive and mostly “open” tubes, hence they require continuous pumping. The additional heat from magnetic coils makes the stability of the small focal spot a very serious issue. So far, the highest acceleration voltage applied by this source type is 300 kV, while the smallest spot size is 150 nm round (Excillum NanoTube®).

• Micro-focus reflection anodes: Here, electromagnetic lenses are employed too, but the electron beam is focused onto a bulk metal target, thus using more interaction volume, thereby creating a larger X-ray spot of the order 100–250 µm². The reflection mode sometimes comes as an exchangeable head with the transmission tube. In one product line (Comet), the acceleration voltage reaches up to 450 kV. In terms of brightness, a very particular reflection anode, based on a liquid metal target, reaches outstandingly high values. Here, either gallium or gallium—indium alloys are pumped through a closed circuit in order to form a cylinder-shaped “jet” crossing the point of electron focus. Similar to a rotating anode, the rapid motion of the metal target leads to a much more efficient dissipation of heat (here, evaporation is the limit to power) so the source brightness surpasses even rotating anodes. Highest brightness was measured for a focal spot of approximately 10 × 40 µm round. The liquid metal jet anode is available with up to 160 kV acceleration voltages (Excillum SA).

• Linear accelerators: This type of X-ray source reaches from 600 kV up to 9 MeV and stems from medical radiation therapy. When used for iCT scanners (e.g., XXL-CT), these sources have a relatively low brightness and a larger focal spot size (the working principle is that of a conventional tube with a bulk tungsten target), which can only be reduced through two-axis blade collimation.

• The system’s motor axes: One iCT system may be comprised of up to 30 motors. It is therefore helpful to define broad categories. For reasons of convenience, a global coordinate system, which shall be valid for all further explanations on iCT, is fixed: the x-axis...
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coincides with the vector from source center to detector center, whereas the z-axis is the vertical coordinate on earth; hence y designs lateral motion in the horizontal direction.

- **Scanning axis**: In the case of a Gantry-CT, this axis makes source and detector revolve around the object (similar to medical CT) whereas in all other iCT machines it is a mere 360° object rotation. The “scan” may be made by stop-and-go moving the scan axis or by driving the axis continuously at relatively slow speed (sometimes called “fly-by scan mode”). The object rotation may also be accompanied by incremental z-steps, the so called helical scan mode. The number of intervals at which projection images are recorded is, however, independent of the scanning mode and must only relate to the available scan time and to the number of horizontal detector pixels. We shall call a scan “normal axial CT” when the scan axis coincides with z and intersects—in projection—the center of the detector’s field-of-view (FOV). For flat extended objects, the scan axis is inclined with respect to z, for example, having an angle of 30° to z and 60° to x while remaining orthogonal to y. It is called the computed laminography (CL) angle, referring to the well-known laminography scan mode. Some older iCT machines perform a zig-zag or random y-motion of object or detector during the scan, which is later reversed prior to reconstruction by image processing. This “max-shift” is applied to reduce “ring artifacts” in the reconstructed volume image, but it is adding more complications than benefits; therefore, modern iCT machines do not employ it. For the case of “robot-CT” detectors, the X-ray anode, even the object, may be mounted on multi-axial robotic arms which do not generally follow the script of an axial rotation but take a number of arbitrary positions around the region-of-interest (ROI). This Robo-CT scan mode constitutes an exception within the group of macro-CT scanners.

- **Alignment axes**: These axes constitute the large majority of motors in iCT machines. They may serve to vertically align the scan axis or they may move source, object, or detector along x. This x-motion defines two principal lengths: the source-detector distance (SDD) and the source-object distance (SOD). The object voxel magnification is simply defined as the ratio \( M = \frac{SDD}{SOD} \). If the detector is a two-dimensional pixel array, the cone-angle of a scan is defined as \( \alpha = 2 \cdot \text{atan}(h_{\text{cen}}/2 \cdot \text{SDD}) \) with \( h_{\text{cen}} \) the vertical size of the effective detector screen. A larger cone angle (>40°) brings about certain constrains but guarantees short scan times, which are required, for example, for unstable focal spots. Object and detector may be equipped with additional y-motors, which allows for extending the FOV of the scan (a) by shifting the scan axis aside, or (b) by shifting the detector screen. If the latter is done to record more than one scan, the recorded data may be “stitched” prior to 3D volume reconstruction. In order to cover a larger z-range of the object (e.g., drill cores), both detector and source can move up and down synchronously, or the object may do so. Any remaining tilt or misalignment of the scan must later be corrected through image processing. State-of-the-art iCT machines therefore come with calibration routines and special alignment objects to guarantee reproducible and accurate results while avoiding time-consuming data-processing.

- **Axes for X-ray optics**: Two iCT systems will be presented here, each being its own group, which comprise X-ray optics. (A) The transmission X-ray microscope (TXM), a lens-based Nano-CT machine comprising condenser optics, pinhole, and a Fresnel lens, each of which has to be aligned individually with minute precision in parallel and onto the x-axis. (B) The Talbot–Lau interferometer comprises three line gratings in addition to the standard CT components. Like the TXM optics, these line gratings must all be aligned parallel to z and the scan axis as well as orthogonal to x. The third grating will generally perform a step-wise y-motion during the scan, thereby defining a new axial CT scan mode, the “grating-based phase-contrast mode.”

- **The X-ray detector**: Note, one iCT system may comprise more than one detector. Two very rare detectors shall not be discussed here because of their lack of relevance to iCT: (A) Image intensifiers are large, bulb-shaped medical detectors which comprise an inverted cathode ray tube which serves to de-magnify and intensify the X-ray image by converting it to an electron image first, then later on to a visible light image at the expense of dynamic range. (B) Multi-Channel-Plate (MCP) detectors are a modern form of image intensifiers replacing the cathode ray tube with one or more MCPs serving as electron multiplier. MCP detectors were originally not designed to intensify X-ray images, consequently their use is problematic.

- **Digital detector array**: Surprisingly, the large majority of iCT systems are based on these DDAs (often called flat-panel detectors FPD), which have not evolved far since their introduction in the eighties to the medical imaging sector. The sensor is a simple multi-layer arrangement with large pixel-arrays of 48–200 µm pixel pitch. Below a protective window (aluminum or carbon), a polycrystalline scintillator screen—some hundreds of micrometers thick—is converting the X-rays into visible photons with a relatively high gain. Columnar cesium iodide (CsI) is the most commonly used material followed by ceramic or powder gadolinium oxy-sulfide. The visible light
is received by a semiconducting layer, generally amorphous silicon, thereby forming charge clouds which are collected by an underlying thin-film transistor (TFT) pixel array. These DDAs come in different sizes, ranging from 5–40 cm square panels. They had been designed to operate well in medical imaging, hence at 60–160 kV acceleration voltages and for objects of the size of a human skull, jaw, knee, or torso. When used with iCT machines, DDAs perform just as well but there are issues of long term stability (the electronics are not inert to X-radiation) and sensitivity to high-energy X-rays. Spatial resolution is another problematic issue that is often neglected when discussing DDAs. Because the image quality, and thus the resolving power, of medical CT scanners is always limited by the patient dose, these machines operate far below the theoretical optimum of what can be achieved in terms of SNR and resolution (system modulation transfer function [MTF]). Consequently, X-ray projection images are commonly oversampled by a factor of three or four; the resulting high frequency noise is later cancelled out by adaptive filter kernels yielding the best image quality for a tolerable patient dose. For iCT, however, dose is not an issue and the strong detector blurring caused by DDAs remains highly inconvenient.

- **Indirect scintillation detectors:** Two types of these detectors are available: (A) taper-coupled detectors, and (B) lens-coupled detectors. Almost any commercial complementary metal-oxide semiconductor (CMOS) or charge-coupled device (CCD) chip/camera can be employed to build these detectors. Depending on the size of the actual sensor and the magnification of the optical coupling, the effective image area ranges from 1 mm to 5 cm, subdivided onto an array of up to 16 Mio. Pixels. Lens-based coupling is less efficient than optical taper-coupling and therefore preferred only for higher optical magnification (>2×). For lower magnification, and sometimes de-magnification, optical tapers are joined to the scintillator screen on the one side and to the CCD or CMOS chip on the other side. While taper-coupled cameras cover larger FOVs, lens-coupled scintillators can yield spatial resolutions down to 0.5 µm, which is the equivalent of an optical microscope. To our surprise, indirect scintillation detectors are employed only in very few iCT installations, the large majority of them using DDAs exclusively, even when the object sizes never actually exceed the 5 cm limit of indirect detectors. Those installations which are using indirect detectors, however, clearly achieve better scan quality in terms of spatial resolution and material contrast, at similar scan times and SNR values. We have therefore dedicated an extra group to this type of sub-µ CT systems. Note that both synchrotron CT and lens-based TXM also rely on indirect scintillation detectors.

- **Photon counting detectors:** That semiconductors can be used to detect, count, and discriminate X-rays is a well-known fact. Photon-counting detectors apply this very principle to a pixelated matrix underneath a silicon or compound semiconductor (GaAs or CdTe). The challenge is to create application-specific integrated circuits (ASICs) which do not suffer from residual radiation transmitted by the semiconductor. Also, the stopping power of these semiconductors is currently restricted to 90 keV for CdTe and to 10 keV for silicon. On the other hand, the pulse-discrimination allows for cancelling out any dark current, and for setting energy thresholds pixel-wise. Photon-counting detectors are available under the labels “Medipix, Widepix, Pixirad, Maxipix, Pilatus, and Eiger.” Larger FOVs can be obtained by tiled arrays providing up to 2048 pixels in width, the pixel pitch always being of the order 55 µm or larger. The price of these detectors is higher than for DDAs but their image quality is far superior in terms of SNR and resolution. They are used in SEM-based Nano-CT as well as for grating-based phase-contrast.

- **High-energy line detectors:** High-energy photons emitted by X-ray sources at 450 kV acceleration voltages and beyond cannot be efficiently detected by any of the aforementioned X-ray detectors, which hardly have any stopping power in this range. Consequently, thick scintillating material (>4 mm) has to be employed, which maintains a significant photon conversion yield even above 1 MeV. Line detectors with 0.8 mm pixel pitch consisting of an array of photo-diodes, each coupled to 4 mm or more cadmium tungstate (CWO) scillator, are currently the only option. iCT scanners using X-ray linear accelerators (e.g., by XXL-CT) are therefore very time-demanding because projection images have to be scanned line-by-line.

Table 46.1 gives an overview of the iCT systems presented in the following sections with regard to their technical specifications and their application purposes.

### 46.2 XXL-CT

At present, conventional iCT systems pose significant limitations regarding the size and composition of objects that can be examined. The main reasons are the insufficient penetration power of X-ray tubes for, for example, steel above 55 mm or aluminum above 165 mm, and simply the lack of space and sensitive detector area for objects bigger than 1.0 × 1.0 × 1.0 m³ in conventional CT systems. The goal of the development and implementation of the Fraunhofer EZRT XXL-CT scanner was to overcome the limitations in object size and composition and to provide the possibility of performing 3D-CT scans on a much
bigger variety of object scales, for example, up to standard 10 ft sea freight containers or complete automobiles. To cope with the new challenges resulting from objects with those voluminous measurements, one has to scale the radiation source, manipulation system, and detector device in an appropriate way.

In Figure 46.1, the schematic setup of the Fraunhofer XXL-CT system is depicted. The manipulation system consists of two towers and a rotation stage. The two 8 m high steel framework towers are equipped with a slide system that carries the radiation source and detector. The slides are guided by a precisely aligned guide rail that allows a vertical manipulation of both components in a range of nearly 5 m in the vertical direction. The absolute positioning in the vertical direction can be measured optically with a metal tape measure. The rotation stage is a steel table with a diameter of 3.0 m and can hold up to 10 tons in weight. A rotary encoder attached to the rotation axis delivers the angular information.

The general properties for a suitable radiation source are, in a very rudimentary sense, to deliver a high photon flux—to shorten measurement times and to cope with focus detector distances (FDD) of up to 12 m—and high photon energies for maximum material penetration. Conventional X-ray tubes deliver only spectra with maximum photon energies up to 800 keV that result in too low penetration capabilities for huge objects like complete automobiles. Besides linear accelerators, another category of high-energy photon sources are Betatrons. Despite their capability of generating high X-ray energies of up to 7.5 MeV, they are lacking in dose rate output and deliver only about 0.2 Gy/min in 1 m distance from the focal spot. The best combination of high X-ray energy and high dose rate for this application is linear accelerators (linac) that originate from cancer treatment in the medical field. In the XXL-CT system, a 9 MV SIEMENS SILAC is used ([https://www.oem-products.siemens.com/linear-accelerator](https://www.oem-products.siemens.com/linear-accelerator)). The SILAC is capable of delivering a dose rate up to 25 Gy/min in 1 m distance from the focal spot at a maximum X-ray spectrum energy of 8.2 MeV. The energy of a 9 MV linac is, in a certain regime, tunable down to lower MeV values, but then the dose output decreases drastically, for example, 10 Gy/min at 7.0 MeV. One crucial characteristic of a linac is the relatively big focal spot sizes in comparison to standard X-ray tubes: the diameter of the linac spot sizes varies between 1.4 mm (7.0 MeV spectrum) and up to 2.0 mm (8.2 MeV spectrum). This has to be taken into account regarding geometrical blur in the acquired radiographic images. For the XXL setup, the focus-detector distance (FDD) is roughly 12 m and the focus-object distance (FOD) is 10 m. The magnification M, therefore, is about M = 1.2. The expected value of the geometrical blur is in the order of 0.4 mm.

The basic features of the used detector system are a high efficiency for high photon energies up to 9 MeV and a span length of several meters. The 2D DDAs usually used in ICT are not suitable for the purposes of the XXL-CT: the available sensor thicknesses of some several hundred microns result in a much too low detection efficiency. The maximum edge length of flat panel arrays is, in general, in the order of 40–50 cm. It would need several distinct, continuously stacked detectors to cover a length of several meters and the costs would be enormous. Therefore, the preferred detector type is a line detector array (LDA). The line

### TABLE 46.1

Overview of the Different Industrial Computed Tomography (iCT) System Groups

<table>
<thead>
<tr>
<th>System Group</th>
<th>Technical Specifications</th>
<th>Application Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>XXL-CT</td>
<td>S: linear accelerator</td>
<td>Cars, freight containers, large paleontological specimen, engines and parts</td>
</tr>
<tr>
<td></td>
<td>A: heavy object rotation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D: high-energy line detector</td>
<td></td>
</tr>
<tr>
<td>Macro-CT (e.g., Robo-, Inline-CT)</td>
<td>S: conventional or rotating anode</td>
<td>Inspection (also in-line) of larger (&gt;10 cm Al or &gt;1 cm Fe) metal parts, mostly automotive</td>
</tr>
<tr>
<td></td>
<td>A: object rotation or robots</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D: DDA or X-eye(^a)</td>
<td></td>
</tr>
<tr>
<td>Gantry-CT</td>
<td>S: micro-focal reflection anode</td>
<td>Drill-cores (rock or ice), diffusion reactors, high-temperature furnaces, plant labs</td>
</tr>
<tr>
<td></td>
<td>A: rotating gantry with z-motor</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D: DDA or X-eye(^a)</td>
<td></td>
</tr>
<tr>
<td>Micro-CT</td>
<td>S: micro-focal reflection anode</td>
<td>Larger light-weight parts (glass and carbon fiber composite), plants, soil, smaller metal parts</td>
</tr>
<tr>
<td></td>
<td>A: object rotation with x and z-motor</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D: DDA</td>
<td></td>
</tr>
<tr>
<td>“Source-based” sub-µ CT</td>
<td>S: micro-focal transmission a</td>
<td>Cellular materials, wood, metals, electronics, composite, additively manufactured parts</td>
</tr>
<tr>
<td></td>
<td>A: object rotation with x-motor</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D: DDA or taper-coupled CCD</td>
<td></td>
</tr>
<tr>
<td>“Detector-based” sub-µ CT</td>
<td>S: micro-focal reflection anode</td>
<td>Cellular materials, wood, metals, rocks, fiber composites, additively manufactured parts</td>
</tr>
<tr>
<td></td>
<td>A: object rotation with z-motor</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D: lens-coupled</td>
<td></td>
</tr>
<tr>
<td>SEM-based nano-CT</td>
<td>S: SEM-focal reflection anode</td>
<td>Microstructures of fossils, metals, electronics, ceramics, additively manufactured parts, rock</td>
</tr>
<tr>
<td></td>
<td>A: object rotation with z-motor</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D: photon-counting + EDX</td>
<td></td>
</tr>
<tr>
<td>Lens-based nano-CT</td>
<td>S: liquid-metal or rot. anode</td>
<td>Biological microstructures, microelectronics, additively manufactured parts, rock</td>
</tr>
<tr>
<td></td>
<td>A: object rotation, FZP, pinhole and condenser</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D: lens-coupled</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) “X-eye” refers to a large area (up to 40 × 50 cm\(^2\)) optics-coupled indirect multi-CCD X-ray detector developed by Fraunhofer EZRT and sold by Meomed, s.r.o. (Czech Republic). S: source; A: axes; D: detector. CCD; charge coupled device; DDA: digital detector array; FZP: Fresnel zone plate.
detector technology allows production of longer 1D structures due to the subsequent placement of single detector modules more easily. Furthermore, LDAs can be equipped with several millimeter thick sensor materials like cadmium tungstate, providing the needed high absorption capability at high energies. A huge advantage of LDAs is also that an effective pre-collimation can reduce most of the scattered radiation generated by the incident beam in the measurement object (the most prominent interaction process of high-energy photons above 500 keV is Compton scattering). For that reason, LDAs are well-known and widely used in the field of 2D cargo scanning devices for freight containers. However, the spatial resolution of state-of-the-art cargo LDAs is in the range of 2 mm and therefore too coarse for our applications.

The XXL-CT detector consists of three custom tailored line detector modules built by Detection Technology (http://www.deetee.com/products/product/x-scan-ihe2-series/). The first sensor is made of 10 mm thick cadmium tungstate with a pixel pitch of 400 µm. The length of the LDA is 4 m, resulting in nearly 10,000 pixels. The overall system is shown in Figure 46.2. The XXL-CT is capable—taking into account the geometrical magnification—of fully capturing a cylindrical measurement volume with a diameter of 3.2 m and a height of 4.8 m. The effective pixel size is about 330 µm (pixel pitch 400 µm and magnification M = 1.2). The vertical sampling is freely adjustable by the parametrization of the feed rate of the tower system and the acquisition rate of the detector.

The majority of applications of the XXL-CT are inspection tasks from the automotive industry. From sub components like fully assembled combustion engines, car bodies, or up to complete cars (see Figure 46.3), the XXL-CT can generate CT datasets to inspect for flaws (pores, cracks, missing parts) or perform more sophisticated tasks like variance analysis, that is, the...
comparison of the original computer-aided design (CAD) construction or simulation data to the actual built product. One specific research topic is to extract precise geometrical information of sub-components from the CT scan of actually crashed vehicles. The extracted data can be used for studying the crash behavior without manually tearing down the vehicle and furthermore to increase prediction accuracy of finite element crash simulations by the car manufacturer (Ciliberti et al. 2016). Further fields of application are shipbuilding, aerospace (jet and rocket engines), and cultural heritage. One rather special application was the CT scan of a 66-million-year-old Tyrannosaurus rex skull, which was still encased in the surrounding sandstone matrix during the CT scan. The extracted CT data of the skull were used to assess the general state of the petrified bones prior to conservation and preparation work (Reims et al. 2016).

46.3 Macro-CT

While the X-ray system components in macro-CT are strictly limited to conventional or rotating anodes (ranging from 90 kV to 600 keV), as well as to large area detectors (DDA or X-eye), the mechanics of such systems sometimes deviate a lot from the typical axial scan.

Figure 46.4 shows a photo of so called Robo-CT, a scan mode for which two robotic arms are employed, positioning source and detector around the object and thus recording arbitrary X-ray views. The Robo-CT scan mode is extremely important for the inspection of frames and wings (aircraft or wind turbines) and requires a lightweight source as well as a sophisticated calibration of the scan path coordinates.

In another macro-CT mode (in-line CT, Figure 46.5), the source and detector have fixed positions while the sample is held by one robotic arm, which performs the scan rotation very quickly with its wrist then deposits the sample and picks up a new one. The source in this super-fast scan mode is preferably a high-power rotating anode, which is pulsed synchronously with the X-ray exposures. Scan times reach down to 8 s in this “Dragonfly” mode.
With the acceleration voltage rising, however, the X-ray contrast is more and more determined through Compton scattering, which often causes problems of both a “forward” and “backward” nature. Although Compton scattering by the object is counted as a photon loss in physics textbooks, the scattered photon is still around after the event and even very likely to reach the detector, particularly when the latter captures a large angle view of the radiation cone. In fact, Compton scattering preferentially occurs forward, decreasing only linearly with atomic number. Consequently, parts of low-Z material (plastics but also aluminum, depending on the energy) are outlined by a broadly extending pseudo edge-contrast in the X-ray images, which is an artifact to tomographic back-projection since it does not relate to Beer’s law of attenuation. Inversely, the transmitted radiation reaching the scintillating layer of the DDA is not fully attenuated by the latter either. The part of the high-energy radiation which transmits both object and scintillator impinges onto the amorphous-silicon layer of the underlying TFT array from which it is likely to be Compton-backscattered onto the scintillator, thereby causing an asymmetric edge profile and further artifacts of volume reconstruction from X-ray images. These perturbations caused by X-ray scattering are most prominent above 200 kV and therefore mostly occur in macro-CT scanners, where they have to be countered by appropriate methods (e.g., restricting the scattering to the horizontal axis by using line detectors, employing anti-scatter gratings from medical imaging, or applying image processing).

46.4 Gantry-CT

The main difference between a medical CT and industrial Gantry-CT scanners is the rotating part. Contrary to the medical scanner, standard iCT machines rotate the object, allowing for a much simpler CT system setup requiring only one sample rotation stage. The free adjustable position of the rotation stage allows for an easy magnification adjustment, whereas in medical CT this has to be done by replacing the tube and detector position on the rotating gantry, taking the risk of imbalance at the rotating gantry. Gantry-CTs, where source and detector rotate around the object, are solely employed by iCT if the sample cannot be moved, for example, because it is liquid. Also, for large objects, such as drill cores, the manipulation capabilities of the sample stage are limited and rotating gantry systems are better suited. Typical application fields are therefore inspection tasks of objects with motion resilient structure, which would cause position inconsistencies if sample rotation was applied. Some objects (e.g., plants) have to be attached to auxiliary structures (e.g., soil), thus making sample rotation impossible. A good example of the first type of application for resilient structures is the CT scanner integrated fully into a greenhouse, allowing for the three-dimensional surveillance of the growth stadium of complete plants, revealing internal data from the pot to the leaves. Contrary to standard iCT, capable of scanning a pot with soil and root structures, this gantry based setup also allows the resilient structures above the ground—like the stem, the fruits, and the leaves—to be scanned to get the most complete phenotype data. The choice of the components applicable for a gantry operation is limited by different boundary conditions: the transmission of electrical power as well as cooling liquids and data cable to the anode head being the most important conditions, which have to be met at a given revolution. Therefore, the gantry solution is strongly optimized to the application at hand by minutely selecting components at the price of versatility. The most common industrial X-ray sources require a high voltage supply through a HV-cable, and a cooling unit. The X-ray tubes are generally large and bulky, which makes their integration onto the gantry difficult, sometimes slowing down the maximum applicable speed of rotation to some ten seconds, which is slow enough not to require endless revolution. For this kind of Gantry-CT scanner, integrated X-ray units are available, allowing for a compact system design by integrating the HV-generator, the anode, and an oil supply for cooling into the gantry. This integrated approach strongly reduces the periphery and requires a minimum installation space. However, the power of the X-ray anode is limited and a power reduction factor of 0.5 has to be considered due to the less effective heat dissipation compared to fixed industrial X-ray anodes. The fields of application for gantry X-ray scanners include baggage or food inspection as well as the emerging market of dental CT, all requiring high reliability, little user interaction, and ultimately, a comparatively low price of the employed components. On the detector side, depending on the speed of a rotation and the requirements of the size of the analyzed object, line or area detectors can be applied. For fast applications at rotation rates of 1 Hz, line detectors with a frame rate of 1 kHz are typically suitable, providing a full 360° dataset every second consisting of 1000 images. In process tomography applications, this allows processes with duration times of some dozens of seconds like, for example, diffusion or liquid flow, to be visualized.

Figure 46.6 shows a setup aimed for application in process tomography for the surveillance of liquid–gas transfer phenomena or flow observation in chromatographic columns.

The resolution of these fast scans is typically defined by the detector’s pixel size due to a significantly larger focal spot size resulting from the high power applied between 0.5 and 1 kW. The line detectors actually applied provide a pixel size down to 80 µm, yielding an effective resolution power for structures of approx. 200 µm size in the reconstructed cross-sections. When the imaging speed is not essential, DDAs in combination with micro focus X-ray sources can be applied. From a time frame of approximately 10 s per scan, higher resolved 3D volumes can be acquired. Figure 46.7 shows an application for the tomography of plants and root systems in an automated greenhouse environment working at a voxel-size of 300 µm using a helical trajectory for scanning a cylindrical volume of 120 mm diameter and 300 mm height within 20 s. While the gantry revolves endlessly at 9.6 rpm, each plant is transported by a top-mounted conveyor which is anchored into the CT system. After placing the plant in the center of rotation, the gantry is quickly lifted to the scan position and the scan is performed with a slow elevation along the scan range on the analyzed plant.

The full process—including the outfeed of the plant after the scan—takes 30 s, allowing for almost 1000 plant scans per shift. In the full process, all further data processing steps have to be automated, to allow the data to be processed adequately and to extract significant features like the root architecture, the total biomass, and other dimensional phenotype characteristics.
Before micro-CT scanners are introduced in the following section, we have to point the reader’s attention to a special hybrid case of iCT, the ultra-fast CT. Several such devices have been introduced, for example, for baggage scanning or for the in situ monitoring of chemical liquid–vapor reactions (Fischer et al. 2008). Similar to the Gantry-CT systems, the objects remain motionless during the scan while, instead of using a rotating gantry, multiple anodes are positioned on a source ring. A high-power electron beam is focused onto each point anode for only several microseconds then the e-beam is scanned at high-speed over the entire target array. In conjunction with the source ring, a detector ring (mostly line- or multi-line detectors for the sake of speed) is positioned around the same center, and the recording of intensities is synchronized with the cascade of X-ray flashes from the multiple source spots. Recording times for a single CT-slice can be as short as 60 µs with these devices, which have only two drawbacks: the constant CT-geometry (fixed magnification) and the overall moderate spatial sampling of 0.1 mm and larger. While ultra-fast CT is currently limited to 150 kV, there is no technical hindrance for developing this technology to 1 MeV and beyond. In the long term, this technique may be far more reliable and cost-efficient than gantry-based iCT.

46.5 Micro-CT

The micro-CT concept is a straightforward use of micro-focus reflection anodes for reaching scan resolutions in the order of 10 µm. iCT scanners of this category are produced by Werth Messtechnik GmbH, Bruker Skyscan, GE (v|tome|x) and Rayscan. The scanning volume can be rather big, larger than 30 cm if 40 cm square DDAs are used. Source voltages may reach up to 330 kV. Micro-CT scans may be applied to investigate glass fiber plastic composites or aluminum castings, in search of cracks and pores. Some micro-CT scanners allow for geometric calibration of the system magnification, thereby extending the confidence in voxel size to below 1% (instead of the general 10% of an uncalibrated system). Calibrated micro-CT scans may serve as comparative to CAD models, for example, for assessing production processes. Micro-CT scanners can be relatively easily equipped with in situ loading devices, for example, for tensile or compression testing. Figure 46.8 shows the example of an in situ tensile test on two glued polyetheretherketon (PEEK) parts compared to finite element modeling (FEM) simulation. Other
more recent fields of application for micro-CT are the scanning of airplane or automotive parts, soil, and rock drill cores.

46.6 “Source-Based” Sub-µ CT

The commercially available source-based sub-µ CT systems are one of the most numerous types of iCT scanners: GE nanotom|m and nanotom|s, Bruker Skyscan 1272, RX Solution micro-CT, and CT-alpha (PCX GmbH). Figure 46.9 shows a photo of its core setup: the X-ray transmission tube and a large area DDA. In order to reach a high spatial resolution of 1 µm or less, the sample must be placed in extreme close proximity to the X-ray source; therefore, the minimum focal distance (MFD) has to be 1–2 mm at most. The DDA, on the other hand, features pixels of 100–200 µm pitch. This condition imposes a strict limit on the geometric magnification of the object and hence on the ratio between object size and voxel sampling (approximately 1000:1). Applying ROI CT with these machines is not much of an option; the samples have to be cut down to the size of the measurement volume. In modern source-based sub-µ CT systems, the DDA is therefore often replaced with a tapered CCD detector (e.g., Bruker Skyscan 1272 and RX Solution Micro-CT) which features smaller pixels, thereby relaxing the ROI limit for high-resolution scans. While the X-ray energy of source-based sub-µ CT ranges from 20 to 300 kV, the size and temporal stability of the X-ray focal spot are critical issues. While any high-resolution iCT system will be sensitive to in-plane (y–z) motion of some µm, systems operating in high magnification M > 100 will suffer from out-of-plane (x) motion as well. Generally, different target foils are used: 7 µm tungsten for “high-power” illumination and

FIGURE 46.8 Comparison of finite element analysis (FEA) simulation with in situ-computed tomography measurement of the glue joint between two plastic parts (Polyetheretherketon [PEEK]) at two different loads (500 N and 750 N); color scale corresponds to +0.15 mm and −0.15 mm. (© Fraunhofer IIS.)

FIGURE 46.9 Photo of a typical source-based sub-µ CT setup (Courtesy of Pierre Luissier, SIMAP Grenoble France). The system EASYTOM XL Nano is realized by the company RX solution and comprises both a micro-focal transmission anode and a reflection anode (upper part) facing a tapered CCD detector produced by the company Princeton Instruments Ltd.
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FIGURE 46.10 Axial slice from a high-resolution iCT (GE nanotom|m) scan of structured bio minerals. (Courtesy Dirk Linde, University clinic Jena). Total scan time was 1 h at 80 kV and 9.6 W emission power. The voxel sampling equals 2.222 µm/voxel (SOD = 5 mm, SDD = 225 mm, M = 45).

1 µm tungsten or less for the “high-resolution” mode. The exact size of the focal spot further depends on the applied acceleration whereby higher voltages tend to create smaller foci because the electron scattering inside the anode is mainly forward. However, the rule of thumb is “target thickness ≤ focal spot width.” Figure 46.10 shows a CT slice through a biocomposite material acquired with a GE nanotom|m at 2.2 µm/voxel sampling. Even at this high-resolution, there is no trace of phase-contrast effects in the images, which is considered a disadvantage when compared to synchrotron CT scans. The reason for the absence of phase-contrast enhancement is twofold: firstly, the optical propagation effectively takes place only over a very short SOD, which is 5 mm in this case; secondly, the detector blurring of the DDA is significantly larger (generally three pixels full width at half maximum [FWHM]) than that known from optics-coupled synchrotron detectors.

When the volume is sampled at <1 µm/voxel with these systems, the focal spot stability inevitably causes deviations from the ideal circular scan path. The spot drift is mainly caused by heating of (a) the source housing, and (b) the target and the substrate. For a better cooling of the latter, synthetic diamond replaces beryllium windows; meanwhile, active cooling is applied to the housing, making the whole employment of high-resolution X-ray transmission tubes a costly venture. The NanoTube, which was introduced in 2014 by the Swedish company Excillum, certainly excels in the range of very small and very stable focal spots. Figure 46.11a shows a resolution test pattern acquired downstream of a 350 nm thin transmission tungsten anode at a geometric magnification of M = 1340 (5 min exposure). The temporal stability of the source spot is depicted in Figure 46.11b and shows that the spot is stable in the range of 100 nm over a period of 12 hours. However, the maximum acceleration voltage of this source is currently limited to 60 kV. The Swiss company Yxlon is meanwhile introducing a 160 kV source, which is based on such an ultra-thin target.

Finally, considering that equivalently high spatial resolution can be reached with less effort by detector-based sub-µ CT systems (see the following paragraph), the main advantage of the source-based systems lies in their capacity to extend their scan range to much larger objects, typically 10 cm wide or more. Source-based sub-µ CT is more versatile than any other iCT scanner.

46.7 “Detector-Based” Sub-µ CT

While for source-based sub-µ CT the spatial resolution of the scan is limited by the X-ray focal spot dimensions, the detector-based version relies on high-resolution X-ray cameras—either taper-coupled or lens-coupled indirect scintillation detectors—whose pixel pitch ranges from 24 µm (Roper Scientific) down to 0.3 µm (e.g., Hamamatsu Photonics). The X-ray focal spot space may be small (transmission tube) or very large (rotating anode); it is either magnified or de-magnified to match the detector point spread function (PSF) through a magnification M < 2. Commercial iCT systems which incorporate this working principle are Rigaku nano3DX, Zeiss X-radia Versa, and customized systems from RX-solution. Furthermore, synchrotron-based imaging setups rely entirely on these detectors since the geometric magnification there is M ~ 1 by default.

Similar to some iCT micro-CT systems, which propose an optional sub-µ CT mode by adding a second—micro-focus transmission—source to the setup (e.g., GE, Rayscan, and Yxlon), the largest producer of detector-based sub-µ CT systems, Zeiss X-radia, promotes the addition of a DDA to their Versa system as a “large FOV” option. Inversely, Procon X-ray (PCX) advertises...

FIGURE 46.11 Resolution test pattern images with the Excillum nanoTube anode; right: a stability test over 12 hours shows faint focal drifts in the vertical (y) and horizontal (x) directions.
the addition of a high-resolution X-ray camera as a secondary detector to their iCT systems. Combining the high-resolution mode with the large FOV clearly has the advantage of making an iCT system more versatile, but also more expensive and more complex since source, mechanics, and shielding have to be laid-out to cover both cases: high-energy and large objects as well as small objects that have to be handled with very high precision.

Table 46.2 covers the basic instrument and measurement parameters of source-based sub-\( \mu \)CT systems (e.g., GE nanotom|\( m \)) compared to detector-based sub-\( \mu \)CT systems (e.g., Zeiss Versa).

Figure 46.12 shows a high-resolution CT slice recorded with a voxel sampling of 0.7\( \mu \)m/voxel from (a) a source-based sub-\( \mu \)CT and (b) a detector-based sub-\( \mu \)CT system. Both scans were acquired with the same total amount of exposure time (2 h 20') and reconstructed by the same software from 720 projection images. Why is the scan quality (SNR and detail visibility) in the detector-based scan so much better than in the source-based system, since both systems claim a nominal resolution of 0.7\( \mu \)m judging from 2D projection images? The reasons for this quality difference are subtle and cannot be deduced from specifications in Table 46.2 alone. First of all, the better material contrast (the object was a splint of sapwood) mostly stems from the lower energy photons (\( \sim \)10 keV), which are best converted by the high-resolution scintillator of the detector-based system. Secondly, the spatial resolution in the source-based system suffers from strong detector blurring as well as from focal spot drifts, which generally exceed the spot size. Note that in Figure 46.12a a lot of care was taken to thermally stabilize the system, and even linear drift correction was applied (based on correlation of the 0° projection with the final 360° view) but the result is nevertheless inferior to the detector-based sub-\( \mu \)scan. Furthermore, in high-resolution mode the latter system is better equipped to produce in-line phase contrasted images, which add an additional gain to the material contrast thus extending the overall dynamic contrast range of the CT system. Furthermore, unlike for source-based sub-\( \mu \) systems, extremely short SOD is no longer required and the system is ready for high-resolution in situ CT (e.g., by adding a tensile testing device to the setup).

Concerning the large FOV mode, the source-based system has the upper hand, at least at first glance. While it is true that much larger objects can be investigated with such a system, the X-ray settings for this scanning mode are far from the optimum. The emission current of transmission sources, and hence their

<table>
<thead>
<tr>
<th>System Properties</th>
<th>Source-Based Sub-( \mu ) CT</th>
<th>Detector-Based Sub-( \mu ) CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imaging Mode</td>
<td>High-Res</td>
<td>Large FOV</td>
</tr>
<tr>
<td>Min. focal spot/( \mu )m</td>
<td>0.7</td>
<td>5</td>
</tr>
<tr>
<td>Detector pixel PSF/( \mu )m</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Largest object diameter/mm</td>
<td>1.4</td>
<td>180</td>
</tr>
<tr>
<td>Acceleration voltage/kV</td>
<td>100</td>
<td>225</td>
</tr>
<tr>
<td>Typical scan duration/min</td>
<td>120</td>
<td>30</td>
</tr>
<tr>
<td>Tolerable focus drift/( \mu )m</td>
<td>0.7</td>
<td>45</td>
</tr>
<tr>
<td>Typical SOD/mm</td>
<td>4</td>
<td>450</td>
</tr>
<tr>
<td>Typical SDD/mm</td>
<td>550</td>
<td>550</td>
</tr>
</tbody>
</table>


FIGURE 46.12  Sub-\( \mu \) CT slices of sap wood recorded (a) by a detector-based and (b) by a source-based sub-\( \mu \) CT system at equal total exposure times.
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power, is generally limited to 5–10 W. Yet, for scanning larger objects, 100 W could be applied, in order to record scans with much shorter exposures. Manufacturers of micro-focal X-ray sources are therefore pushing larger power bandwidths or dual-target solutions, with success, but thereby making such sources ever more expensive. The detector-based systems designers on the other hand go up to the largest reasonable pixel-size, which is of the order 24 µm, for example, tapered to a 30 µm thick CsI screen, and employ this FOV at magnification M = 2, which is the optimum working distance for X-ray focal spots of similar sizes.

An important fact about detector-based sub-µCT systems is that they do employ more than one scintillator screen. For higher resolution, lens-coupling is realized through exchangeable microscope objectives, three or five of which are commonly mounted on motorized revolvers, each having their own scintillation screen. The smallness of the FOV allows for the use of transparent crystalline thin-film scintillators whose thickness may range from 1 to 300 µm. Unlike powder screens, for which the resolution limit decreases proportionally to the screens’ thickness, transparent scintillators can resolve images with 5 µm detail, even though the screen is 300 µm thick, and much finer details for thinner films. According to Koch et al. (1998), the resolution is determined from the crystal thickness z and the numerical aperture (NA) of the objective

\[ R = \frac{p}{\sqrt{\left(\frac{p}{NA}\right)^2 + (q \cdot z \cdot NA)^2}} \]  

(46.1)

For the Zeiss Versa system, the microscope revolver can furthermore change position with a larger scintillator screen (5 × 5 cm²), which is imaged by a macro-lens for a larger FOV. The entire detector, which thereby covers six different FOVs, each with its own scintillation screen, is nevertheless within the price range of the state-of-the-art DDAs. The reason for this is one single high-quality CCD (or scientific CMOS [sCMOS]) camera which is employed for all available FOVs. The CCD chip is generally extra-shielded against direct X-ray exposure. Compared to DDAs, these detectors therefore have a much longer lifetime, less noise, and higher pixel dynamics. In view of the less stringent requirements on the X-ray source, the overall system costs for a detector-based sub-µCT system are significantly lower than for equivalent source-based systems.

46.8 “SEM-Based” Nano-CT

Nano-CT machines are defined by spatial resolving powers that clearly exceed the power of sub-µCT systems which is in the order of 500 lp/mm. Based on SEMs, which have been redesigned to host not just the object but also a movable X-ray target, a resolution of 2500 lp/mm and better could be demonstrated (Stahlhut et al. 2016). The working principle of these machines is surprisingly simple: while the electron interaction volume (“bulb”) of bulk targets generally extends to some micrometers, using a very pointy needle target will restrict the source of X-ray emission to the size of the tip. Figure 46.13 was recorded in a JEOL JSM-7100F SEM with a tungsten needle of approximately 70 nm tip diameter. While the 100 nm lines can be clearly distinguished in the test pattern (1 µm gold on Si3N4 membrane), the 50 nm lines remain obscure. Unlike lens-based Nano-CT systems, SEM-based Nano-CT comes with adjustable magnification and a polychromatic spectrum (U_{max} = 30 kV). This simple setup was first christened the “X-ray shadow microscope” by von Ardenne (1939). Its projection images feature edge enhancement, which was correctly interpreted by Cosslett and Nixon (1953) as Fresnel (near field diffraction) fringes. Figure 46.14 shows two sagittal slices from an Al–Cu29 alloy before (a) and after (b) application of Paganin-type phase retrieval.

The only drawback of SEM-based Nano-CT is the low photon flux emitted by the tiny source. Typical exposures range from 5 to 30 min, hence days are required to record a full CT dataset (for Figures 46.13 and 46.14, a field emission cathode was employed at 300 nA anode current). In order to shorten the scan time, switching to cathodes of higher power is the only option, while lens based Nano-CT promises faster Nano-CT scans if the efficiency of the employed optical elements can be raised.

46.9 “Lens-Based” Nano-CT

Nowadays, the highest resolution for laboratory-based CTs can be obtained by X-ray microscopy with the help of optical elements. Like this, periodic structures down to 50 nm can be resolved in 2D (Tkachuk et al. 2007). In 3D, the resolution is typically slightly decreased due to high requirements concerning mechanical and thermal stability during scan times of several hours.

As the brightness of laboratory-based sources is typically not high enough for scanning techniques, the remaining approach is a full-field transmission TXM. Figure 46.15 displays a schematic setup for such a TXM. In this case, a sample is illuminated from the backside with a condenser and forms a transmission X-ray image. This image is further magnified by an optical element, such as a Fresnel zone plate (FZP), onto the detector. As the detector possesses a pixel array, the complete spatial sample information is acquired simultaneously, coining the phrase “full-field” microscopy.

For successful laboratory-based TXM, the most critical factor is the exposure time required for a reasonable SNR. In other
words, the photon flux on the detector needs to be as high as possible. For a certain pixel resolution, this flux results directly from the brightness of the source, as well as the NA and the efficiency of the X-ray optics. Unfortunately, these values are typically very low, as will be discussed in the following section.

46.9.1 Source

As already noted, the brightness of the source should be as high as possible. For this, the heat produced by the electron beam is the limiting factor. One possibility to reach a high electron power load per area is to simply use a very small spot in a microfocus tube (Ihsan et al. 2007, Müller 1927, Zheng et al. 2016): in this case, the spot is small compared to the surrounding area, meaning that the heat can be transferred away efficiently. Another possibility is that the heated material gets constantly renewed, such as in a liquid-metal-jet source (Hemberg et al. 2003), or virtually enlarged, as in the case of a rotating anode. Nowadays, the highest brightness can be reached with the liquid-metal-jet source.

As the X-ray object lens used is strongly chromatic, another general requirement for the source is that it produces monochromatic radiation. Otherwise, a blurred image results. Usually, for low Z materials (e.g., Cr, Cu, Ga), the characteristic radiation from the K\(_\alpha\)-line has much more intensity compared to the bremsstrahlung, meaning that the latter acts only as a background and can be tolerated. However, as the K\(_\beta\) emission line possesses high intensity close to the design energy of the optical element, it should be blocked by a thin absorption filter of the material with the next lower Z-value. For high Z materials (e.g., In), the ratio of characteristic lines and bremsstrahlung decreases and a multilayer should be used to obtain monochromatic radiation.

46.9.2 Optical Elements

The aim of the condenser is to illuminate the object with low loss of brightness and fill the NA of the objective (i.e., the zone plate). Moreover, it has to magnify the source to illuminate the complete FOV on the sample. High efficiencies can be reached by mono- and polycapillaries as well as multilayer Montel optics. While the former two options work on the basis of total external reflection, and thus act as a low pass filter, the functionality of

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**FIGURE 46.14** Reconstruction results of the AlCu29 alloy sample. Uncorrected reconstruction results are shown as well as their phase retrieved equivalents. The line plots (following the white line marked in the phase retrieved images) show the phase contrasted contours in the uncorrected (dashed line) and the smoothed result in the Paganin-filtered (solid line) reconstruction. Taken from Stahlhut et al. (2016 SPIE).

**FIGURE 46.15** Schematic setup for a full-field transmission X-ray microscope (TXM). The components are (from left to right): a source, which illuminates the sample via a condenser. The transmitted light is magnified by an optical element onto the detector, which possesses a pixel array.
the latter is based on Bragg reflection and therefore behaves like a bandpass filter. Additionally, a central beam stop and apertures can shape the beam.

For a high-resolution image, the image of the sample needs to be magnified beyond the detector resolution. For this, FZPs are commonly used, which are circular diffraction gratings where, in the simplest case, the zones vary in a way that light transmitted by the transparent zones creates constructive interference at the focal length (see Figure 46.16). The focusing efficiency of such a zone plate is determined by its thickness; its NA is indirectly proportional to the reachable resolution, which is basically equivalent to the width of the outermost (smallest) zone. Thus, good zone plates require a high aspect ratio, which is challenging in terms of production. For an Au zone plate with a 50 nm outermost zone width, a design energy of 8 keV (i.e., the Cu Kα-line), and an optimal thickness of 1500 nm, the theoretically reachable efficiency is about 30%. However, as such an aspect ratio of 30 is very challenging, in reality the efficiency is between 5 and 15%. For energies above 10 keV, even higher aspect ratios are needed.

As an alternative, compound refractive lenses (CRLs) can be used for magnification (see Figure 46.16). Their working principle resembles that of lenses in the visible. However, due to the small refraction, very small curvature radii and a stack of several lenses are needed. Their efficiency depends mainly on the material via its ratio of refraction and absorption, leading for example, in the case of SU8 photoresist and 9.2 keV, to an efficiency of approximately 30%. As the NA of the CRLs is limited by absorption within the lens material, in the 10 keV energy range, the NA of CRLs is typically smaller than that of FZPs. Therefore, the reachable resolution is currently slightly smaller (∼300 nm). However, in contrast to zone plates, CRLs also allow microscopy at high energies.

### 46.9.3 Applications

For X-ray microscopy, the energy has to be adapted to the investigated sample specimen. This is more critical than working with the bremspectrum, as this energy is fixed by the source’s anode material. Lower energy means a higher absorption contrast, but on the other hand, a smaller possible sample diameter. However, absorption also varies strongly in the vicinity of element-specific absorption edges, which can thus also be exploited. For instance, when imaging typical electronic components which consist, for example, of Cu and Si, the Ga Kα-line has the advantage that

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**FIGURE 46.16** Scanning electron microscopy (SEM) image of a zone plate (left, fabricated by P. Charalambous) and optical microscope image of crossed 1D compound refractive lenses (CRLs) made of SU8 photoresist (right, fabricated by A. Last, KIT).

**FIGURE 46.17** (a) Spatial resolution of Xradia Ultra, demonstrated using a Siemens star resolution target. The innermost features are 50 nm wide (50 nm lines, 50 nm spaces). Image pixel size is 16 nm. (b) Polymer fibers in a desalination membrane, imaged in phase-contrast. (Images taken from White paper X-ray Nanotomography in the Laboratory with ZEISS Xradia Ultra 3D X-ray Microscopes, by Zeiss X-ray Microscopy, June 2015.)
both Cu contrast and transmission through Si are high; in contrast, the absorption would be much lower for Cu anodes. In addition, Zernike phase-contrast can also be used to enhance contrast (Sakdinawat and Attwood 2010).

### 46.9.4 Current Status

Nowadays, only a few laboratory-based X-ray microscopes are realized in research facilities. One example is a setup based on a copper transmission tube, which is situated at the Institute for X-Optics at the University of Applied Sciences Koblenz. Another approach, based on a liquid-metal-jet source, is realized at the Chair of X-ray Microscopy at the University of Würzburg; in this case, a hybrid setup is realized that allows micro- and nano-imaging. Since 2007, Xradia (now Zeiss) has offered commercial optic-based X-ray microscopes based on a rotating anode (Cu or Cr) source. With the Zeiss X-radia Ultra TXM, resolutions up to 50 nm have been demonstrated in 2D (see Figure 46.17).

### 46.9.5 Outlook

In order to establish high-resolution laboratory-based microscopes for a broader audience, the quality of X-ray optical elements in particular needs to be further increased. Here, both technical optimization and affordable prices are requirements to strengthen X-ray microscopes on the market. In this regard, novel sources show potential for further improving the image quality of such microscopes under moderate exposure time. Therefore, we are confident that the vision of compact X-ray microscopes as standard instruments for any laboratory can soon be turned into reality.

### REFERENCES


