High-resolution X-ray imaging for lab-based materials research

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Abstract
The extension of limits of X-ray imaging techniques – in terms of spatial and temporal resolution as well as of material contrast – in the energy range from 5 to 70 keV has long exclusively taken place at third generation synchrotron beamlines. Yet, by using the latest generation of lab-sources together with novel X-ray detectors, results from micro- as well as sub-micrometer imaging are obtained with the same accuracy and quality as known from the state-of-the-art synchrotron experiments. In particular phase contrast imaging, which was long exclusively used at synchrotrons, is now an inherent feature of laboratory X-ray images, the origin and optimization of which will be discussed. This report shows both concepts and first results of two new imaging stations which are built at the University of Würzburg, as well as results from the current state-of-the-art CT experiments at the Fraunhofer Center Development X-ray Technology (EZRT, Fuerth). Based on state-of-the-art SEM machines, the XRM I and XRM II feature highest spatial resolution, so called nano-sources operating in the range from 10 keV to 30 keV. Depending on the target, source sizes of 100 nm and smaller can be realized. Comparing the XRM I with a sub-micrometer transmission tube as well as with imaging experiments from the BAMline (BESSY-II light source) we demonstrate the phase-contrast imaging capability of these setups. Shorter exposure times as well as higher X-ray energies (up to 70 keV), are available with a liquid-metal X-ray source, which when combines with a high-resolution detector is also capable of producing phase contrast images.

Keywords: X-ray nano sources, liquid metal anode, phase contrast imaging

1 Introduction
Upon his discovery of X-rays in 1895, W.C. Röntgen did not reach the conclusion that this part of the electromagnetic spectrum was suited to produce phase contrast, since he found that X-rays could neither be refracted nor diffracted by solid matter, as it was known from visible light [1]. Fortunately, Röntgen’s first conclusions were wrong, and only the result of the extremely weak refraction and diffraction that X-rays show when interacting with matter, making these phenomena difficult to detect [2]. Not until the 1950s, when researchers began to record shadow radiographs of sub-micrometer resolution, the manifestation of X-ray Fresnel propagation was discovered as an inherent feature in those images [3]. As today, back then, modified electron microscopes were used to create very small X-ray sources [4]. Hence, the explanation of phase contrast fringes was ready at hand, since the same phenomenon was observed in transmission electron micrographs (TEM) [5]. When later, X-ray imaging became one of the major fields of application at third generation synchrotron facilities, phase contrast images were used to numerically retrieve projections of the optical phase, again in perfect analogy to transmission electron microscopy [6].

Despite these parallels, the phase imaging capacity of modern X-ray laboratories is still no match for synchrotron beamlines. Why is this? Both kinds of facilities have reached similar limits in terms of spatial resolution and X-ray energy (around 80 nm at 30 keV) and one might think that only time-resolution would remain an exclusivity of the synchrotrons, due to their far-superior brilliance.
To the exception of X-ray microscopes which employ Fresnel zone-plates, laboratory CT uses geometric magnification, hence cone beam, which makes the setup relatively simple and not fixed in terms of acceleration voltage, and thus photon energy. Conventional X-ray tubes operate with an electron beam which is focused onto a target metal, thus creating X-rays through both bremsstrahlung and fluorescence. While for high power sources a reflection target (e.g. a rotating anode) is preferred, setups which provide high spatial resolution use transmission geometry. This is because the resolution limit of the resulting radiographic images is determined mainly through the source size, hence the electron interaction volume in the target material. For focal spots smaller than ca. 2 - 4 µm, this interaction volume is larger than the actual electron beam diameter. By using transmission targets (i.e., thin metal foils) this limit can be avoided down to several hundred nanometers by using very thin target layers and electron guns and optics with sufficiently good focusing power [7].

Yet, recording X-ray images with 150 nm resolution and better is also possible by using reflection targets. Therefore, the target has to be a needle with a tip curvature radius of the order of the desired source spot size. High magnification (up to 1000x) is achieved by placing the sample very close to the (sub-micrometer) source, whereby the detector is typically a flat array with pixels of 55 µm (e.g. Medipix2) to 127 µm (Flat-panel detector, e.g. Varian PaxScan©) pitch. Considering a typical source-to-detector distance of one meter, propagation is thus dominated by the smaller source-to-sample distance (approx. 1 mm). Transformation from cone beam to plane-wave illumination leads to the effective distance of Fresnel propagation $D$ which equals

$$D = R_1 \cdot \frac{R_2}{R_1 + R_2} = \frac{R_2}{M}$$

Here, $R_1$ is the source-to-sample, $R_2$ the sample-to-detector distance and $M = (R_1 + R_2)/R_1$ the magnification of the setup [8]. Hence, $D$ is never larger than the smaller of these two distances, and the image’s phase contrast downscales a lot for strong magnifications. To overcome this problem and increase the phase contrast for microscopy, one would have to build a much longer experiment or downscale the detector pixels to allow for weaker magnifications, or both. In addition, the transverse coherence length $L_{\text{trans}} = \lambda/2\theta$, which depends on the X-ray wavelength $\lambda$ and the beam divergence $\theta$, is also an order of magnitude smaller (few µm) compared to synchrotron beamlines [9].

The latter feature the exact opposite proportions, i.e., a very large $R_1$ (30 m – 150 m) and a moderate $R_2$ (typically 5 mm to 1 m). Consequently, it is $R_2$ which determines the magnitude of the phase contrast and several images can be recorded at different distances $R_2$, hence propagation lengths $D$ without changing the magnification, which always remains close to unity. In other words, the correction by the coordinate transform Eq. (1) is only marginal and one works in quasi plane-wave illumination. Despite this simplification, when recording phase contrast images at synchrotron beamlines, one encounters two limitations: i. the finite source size (typically 10 µm – 100 µm) which is demagnified but nevertheless destroys the beam coherence when $R_2$ becomes too large, and ii. the resolution of the detector screen. It is generally acknowledged that the latter is the most stringent limitation to synchrotron imaging. Thin monocrystalline scintillator screens convert the X-rays into visible light. Hence, the resulting images, which are transferred through microscope optics onto a CCD have a diffraction limited resolution of the same magnitude. In order to overcome this limitation, X-ray optics (e.g. KB mirrors, capillary optics or zone lenses) have to be employed, focusing the quasi-parallel beam to a sub-micrometer spot, behind which the images are recorded in conventional cone-beam geometry, only with monochromatic radiation. It is the use of nano-focusing optics which makes these experiments so delicate and limits the available photons to 29 keV, which is the highest energy reported till today for 80 nm resolution [10]. It is worth noting that for this purpose Requena et al. used a standard synchrotron detector with 2.4 µm sampling of the scintillator screen, which is very similar to what we used for first phase contrast experiments at the liquid metal jet anode. Through the use of
liquid metal jets as a reflection target, the brilliance of lab-sources can be increased by one order of magnitude. The latest generation of these sources is being used by our chair to make a platform for high-speed in situ imaging and phase-contrast CT, by using two different X-ray detectors.

2 Material and Methods

2.1 Nano-Imaging stations

First, we will show results of experiments at the Fraunhofer Development Center X-ray Technology (EZRT), a joint department of the Institutes IIS (Erlangen, Germany) and IZPF (Saarbrücken, Germany). The X-ray microscopy setup XRM I which is based on a modified Electron Probe Micro-Analyzer (EPMA, CAMECA SAS, France) works at 100 nA current and 30 kV acceleration (hence, 3 mW power) in transmission through a thin tungsten foil (< 1 µm) and employs the Quad version of the Medipix2 MXR detector (512 x 512 array) [11]. The Medipix2 is a second generation direct photon converter with 55² µm² pixels of monocrystalline silicon, in which electron-hole pairs are generated upon irradiation and the resulting pulses are directly counted [12]. An energy threshold (for pulse height) is responsible for the zero dark current in these detectors, which makes them very favorable for long exposure times (for the present results either 10 min or 30 min were used).

Figure 1: (a) Schematic drawing of the modified Electron Probe Micro-Analyzer (EPMA) with Medipix2 detector and sample stage, named XRM I. (b) Feinfokus setup with X-ray macroscope from the BESSY-II BAMline

Phase contrast measurements of a single carbon fiber at the XRM I will be compared to the (sub-) micro-CT (EZRT) which, for this purpose, was equipped with the X-ray macroscope kindly provided by the BAMline at the Berlin synchrotron BESSY-II (courtesy Dr. H. Riesemeier). The sub-micro CT features a Feinfokus transmission tube (V_{max} = 160 kV) with a 6 µm tungsten layer as transmission target. Its minimal focal-spot size was determined to approx. 1 µm. For the presented results, the electron acceleration was set to 60 kV and the emitted spectrum was not filtered except for a 0.3 mm glassy carbon window and 1 meter of air. The electron current was 60 µA hence the source was working at 3.6 W power. The detector was placed at the maximum source-detector distance of 1060 mm. The macroscope uses a thin phosphor screen (P43 coating on quartz-glass, Proxivision GmbH, Germany) which is magnified by two lens systems (1. Rodenstock XR-Heliflex f/1.1, 100 mm and 2. Nikkor telephoto lens f/2.8 ED, 180 mm) onto a cooled CCD camera (pco.4000, courtesy W. Tutsch, PCO AG, Germany). The phosphor is thus sampled at 9 µm / 1.8 = 5 µm length and the field of view equals 20 mm x 14 mm (the CCD being a Kodak KAI 4008 x 2672 array). Measurements of the exact pixel size gave a smaller value of 4.7 µm, probably due to the manual focusing of the scintillator
screen, which does not permit to set the rays exactly parallel between the two lens systems. The sample stage was placed in between the detector and the source at 235 mm source-to-sample distance, hence the maximum sample-to-detector distance was 825 mm. At 4.51x magnification the sample is thus scanned in 1.04 µm steps. According to Eq. 1 the effective propagation distance for this setup is \( D = 183 \) mm. Exposure times were 1 – 5 min. The two setups are displayed in Fig. 1.

The measurements of a carbon fibre and of a human hair are further compared to synchrotron images of the same samples. On the BAMline at the BESSY-II light source (Berlin, Germany) a broad X-ray spectrum is generated by a 7-Tesla wavelength-shifter with a peak emittance at 12.4 keV. We used the same macroscope as in the Feinfokus setup but with an Olympus microscope lens (\( f \approx 8 \) mm) instead of the XR-Heliflex and a Princeton VersArray 2048B CCD detector, resulting in 0.58 µm sampling and approx. 1.8 µm FWHM [13]. A high-resolution LuAG scintillator screen was used in place of the P43 powder. The source-to-sample distance is \( R_1 = 35 \) m and the detector can drive to various positions \( R_2 \) ranging from 5 mm to 1.14 m. The incoming beam was filtered by 0.5 mm Aluminum and reflected over two Si-W multilayer mirrors (\( E = 17 \) keV, approx. 1.6 %BW).

Very recently a second generation nano-source (XRM II) has been set up by the Chair of X-ray Microscopy in Wuerzburg, Germany. The XRM II is a modified JEOL high-resolution electron microscope with both sample and reflection target stationed inside the vacuum chamber. The reflection target is a thin needle of either Tungsten or Molybdenum. The needles are being processed inhouse, whereby a tip curvature < 100 nm was achieved for both materials using an electrochemical etching technique. Fig. 2 shows a 50 nm W-needle together with the corresponding resolution test pattern.

![Figure 2: (a) High-resolution SEM image of a W-needle recorded at the XRM II microscope at the University of Wuerzburg (scale bar is 100 nm, tip diameter approx. 50 nm). (b) Sub-micrometre radiograph recorded of X-radia test pattern by using the tip from (a) as reflection target (detector Medipix2, CdTe Hexa-Chip).](image)

### 2.2 High-brilliance liquid metal source

Also very recently we began operating a X-ray imaging experiment which employs a liquid metal jet anode as X-ray source (Excillum SA, Sweden). As compared to conventional X-ray tubes this source has a peak brilliance which is 7-8 times higher. This feature is attributed to the property of the metal being liquid. Hence more electron power can be put onto the target which does no longer suffer from the risk of melting. The source’s pumping circuit is filled with Ga-In-Sn soldering alloy which is liquid at room temperature. The emitted spectrum is composed of bremsstrahlung (\( U_{\text{max}} = 70 \) kV) and characteristic lines at 10 keV (Ga), 24 keV (In) and 27 keV (Sn) with the Ga-line being the most powerful one. To work in phase contrast mode, a scintillator-based indirect detector is used to record images with 5 µm pixels or less. The jet is relatively large (183 µm diameter) and one can choose the
shape of the electron focus as well as its position on the jet (with respect to the jet center) to work either with a line-focus in full power (300 W) or with a small point focus and reduced power (40 W). Both phase contrast imaging and in-situ materials testing (e.g., fatigue) are feasible on this station, and one can switch from one to the other without making many changes. Therefore, a new sCMOS camera is used (Andor NEO), which can record images either at high-speed (max. 100 Hz full frame) or in slow scan mode (the sCMOS chip can be cooled down to \(-40 \, ^\circ C\), reducing the dark current to the of high quality CCD cameras). The camera features 2560 x 2160 pixels with 6.5 \(\mu\)m pitch. For the first imaging tests which will be shown below, we used an inhouse built macroscope (very similar to the BAMline macroscope). A 5 \(\mu\)m thin high-resolution phosphor screen (kindly provided by Proxivision GmbH, Germany) was used to convert the X-rays to a visible light image which is projected onto the NEO sCMOS camera through a combination of a XR-Heliflex lens (the same as mentioned above) and different Nikkor Telephotos (50 mm and 180 mm).

3 Results

3.1 Nano-Imaging stations

![Image](image.png)

Figure 3: (a) Tungsten wedge (50 \(\mu\)m thickness) imaged with the Feinfokus setup at \(R_2 = 10\) mm. (b) JIMA RT RC-02 resolution test pattern imaged with the same setup at \(R_2 = 825\) mm. (c) line profile across (a) and Gaussian fit of its first derivative (line spread function). (d) Horizontal line profile across the 3 \(\mu\)m JIMA test pattern (6 \(\mu\)m pitch, cf. inset in (b)). The 2 \(\mu\)m and smaller patterns were not visible.
Before recording phase contrast images, the spatial resolution was determined for the XRM I and for the sub-micro CT setup at EZRT, using a 50 µm tungsten wedge and a JIMA RT RC-02 test pattern. Radiographs and line profiles of both resolution tests are shown in Fig. 3 for the Feinfokus setup. Blurring was calculated at the Full Width Half Maximum (FWHM) of a Gaussian spreading which was fitted to the derivative of the wedge profile (cf. Fig. 3c [software Qtiplot©]).

Figure 4: (a) Radiographs of a single carbon fiber (6 µm diameter) at increasing magnification on the XRM I setup. (b) Corresponding line profiles (horizontally stacked) drawn on a µm length scale.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>(R_1) [mm]</th>
<th>(R_2) [mm]</th>
<th>(p_{samp}) [µm]</th>
<th>(M)</th>
<th>(w_{tot}) [µm]</th>
<th>(w_{PSF}) [µm]</th>
<th>(S) [µm]</th>
</tr>
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<td>831 – 838</td>
<td>0.13 – 0.6</td>
<td>91 – 382</td>
<td>1.9 – 2.3</td>
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<td>2.1</td>
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<tr>
<td>Feinfokus</td>
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<td>825</td>
<td>1.04</td>
<td>4.51</td>
<td>5.36</td>
<td>16.8</td>
<td>2.1</td>
</tr>
<tr>
<td>BAMline</td>
<td>35000</td>
<td>10 – 1140</td>
<td>0.57 – 0.58</td>
<td>1 – 1.03</td>
<td>1.85 – 6.9</td>
<td>1.8</td>
<td>164</td>
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</table>

Table 1: Experimental parameters and results of resolution tests for the used setups: Resolution of the XRM I setup was determined in [11] to be 0.3 µm for a 100 nm thin W-target and 1.72 µm for a 0.7 µm target. Comparisons with forward simulations on a single C-fiber confirmed that the 0.7 µm were used for the present experiments. For the BAMline setup the horizontal source size was determined in [12] to be 164 µm, whereas the vertical size was only 41 µm. The numbers in the last three columns are FWHM of a Gaussian PSF.

Note that FWHM = 2.354\(\sigma\), with \(\sigma\) the variance of the Gaussian. Similar tests were carried out on the XRM I setup, which were already published in [13]. The JIMA test pattern gives a rather qualitative impression (the smallest pattern resolved by the Feinfokus setup, were 3 µm bars, hence a structure of 6 µm pitch corresponding to a resolution of 167 lp/mm). By recording images of the W-wedge at two sample-to-detector distances (10 mm and 825 mm) we managed to quantify the contributions of source and detector for the Feinfokus setup separately. By using Eq. (2) and replacing \(p_{phys}\) with the total detector blurring \(p_{PSF}\) (Point Spread Function) we obtain two linear equations, which are then solved to obtain \(p_{PSF} = 16.4\) µm and \(s = 2.1\) µm (both FWHM). Results are summarized in Table 1 along with the values for the synchrotron setup. The total blurring of 1.9 µm for the XRM I setup was estimated from numerical phase contrast simulations of a single carbon fiber, and matches well the value of 1.72 µm FWHM source size, reported for a 0.7 µm tungsten target [14]. Next, radiographs of the 6 µm carbon fiber were recorded, first with the XRM I, at several source-to-sample distances ranging from 2.2 mm to 9.2 mm, from 382x to 91x magnification, or \(p_{samp} = 0.13\) µm to 0.6 µm sampling (cf. Table 1). Figure 4 shows five radiographs plus the resulting line profiles which were averaged over the entire image.
length after applying image rotation to set the fiber vertically straight. One can clearly see, how the phase contrast which outlines the fiber, decreases in amplitude when the magnification increases.

Figure 5: Line profiles of the carbon fiber recorded for various propagation distances at the BESSY-II light source (BAMline) with $R_2$ ranging from 10 mm to 1.14 m. Inset: radiography at $R_2 = 1.14$ m, $E = 17$ keV.

The fiber, which can be considered a quasi-pure phase object is better resolved, yet, less visible. Another fiber was recorded with monochromatic radiation on the BAMline. Several distances $R_2$, ranging from 10 mm to 1140 mm, were used to produce phase contrast images of the carbon fiber, from which line profiles are shown in Fig. 5. Obviously, the fiber phase contrast at the synchrotron is far more pronounced due to the longer propagation distances (which are approximated by $R_2$, since $R_1 = 35$ m $>> R_2$). At $R_2 = 10$ mm (and at $R_1 = 9.2$ mm for the XRM I), the BAMline and the XRM I line profiles match well in resolution and detector sampling, as well as in amplitude of phase contrast, thus illustrating that both images are a manifest of Fresnel propagation. Yet, larger $D$ and stronger phase contrast appear unreachable for the XRM I setup due to the conflict with the magnification.

Figure 6 shows the radiograph of a carbon fiber next to two strains of intersecting hair, recorded with the macroscope and the Feinfokus transmission tube (inset shows the corresponding synchrotron radiography of the same hair).

Figure 6: Radiography at $R_2 = 825$ mm ($D = 183$ mm), taken on the Feinfokus setup along with a carbon fiber (left). Inset: Corresponding radiography from the synchrotron ($R_2 = 340$ mm, $E = 17$ keV, $D = 336$ mm).
The effective propagation distance for the Feinfokus setup was $D = 183 \text{ mm}$ (at $p_{\text{samp}} = 1.04 \mu\text{m}$ sampling), compared to $R_2 = 340 \text{ mm}$ for the synchrotron image. Line profiles across one hair are depicted in Fig. 7a for the synchrotron and for the Feinfokus setup. Both profiles match in amplitude, but the latter lacks the smaller interference lobes which are visible in the synchrotron measurement, while it has only one broad lobe (dark-bright). Our resolution tests show that this effect must be attributed mostly to the polychromaticity of the X-ray tube, and only little to differences in sharpness – the Feinfokus image being nevertheless slightly less sharp than the synchrotron image ($5.36 \mu\text{m}$ vs. $3.36 \mu\text{m}$ FWHM). The same effect can be observed by comparing the profiles across the carbon fiber (Fig. 7b). Again, the outer interference lobes are smeared out through the polychromaticity of the lab source, while shape and amplitude of the principal lobes are preserved.

### 3.2 High-brilliance liquid metal source

For recording phase-contrast radiographs the spectrum of the liquid metal jet anode was used unfiltered. Fig. 8a shows a corn flower for which a Rodenstock XR-Heliflex (f/1.1, 100 mm) was combined with a 50 mm telephoto (f/2.0) to yield 13 µm pixels. By placing the sample half-way between source and detector ($R_1 = 33 \text{ cm}$ and $R_2 = 47.5 \text{ cm}$) an effective pixel sampling of 5.3 µm was realized at an effective propagation distance $D = 19.5 \text{ cm}$. For recording a smaller object (a cat claw) the 50 mm telephoto was replaced by the 180 mm Nikkor, yielding a 1.5 µm pixel sampling (Fig. 8b).

It is interesting to note that for both examples the liquid metal source operated at 117 W power and a 80 µm x 20 µm line focus, impinging onto the cylindrical jet sideways, 40 mm from its center. The penubral blurring should hence be 8 µm at least, according to the manufacturer the detector screen has a resolution of 100 lp/mm, viz. a point spread of 5 µm.

### 4 Discussion

With the development of sub-micrometer imaging at modern laboratory X-ray sources unusually high magnifications of up to 1000 x are achieved. Therefore, some groups have to make use of very large source-to-detector distances in order to maintain reasonable propagation distances for phase contrast and / or diffraction imaging: e.g., Hertz et al. use 2.4 m beam path and a 15 µm detector sampling to reach values of $D$ of 0.36 m, whereas Salditt et al. had to use the total length of their experimental hutch at the PETRA-III synchrotron source (5.3 m) to resolve their sample at $p_{\text{samp}} = 60 \text{ nm}$ and ($R_1 = 2 \text{ mm}$), with a Pilatus detector of 172 µm pitch [15-17]. Using an indirect X-ray detector based on a thin phosphor screen and macroscope optics, we could demonstrate that it is possible to extend the...
available propagation distances from few mm to some 10 cm for lab based micro- and sub-micrometer tomography, while keeping moderate source-to-detector distances of approx. 1 m.

Figure 8: (a) Radiograph of a corn flower recorded with 5.3 µm sampling (X-ray macroscope and Andor NEO). Scale bar equals 2 mm. Exposure time was 2 s. (b) Cat claw recorded with the same macroscope at 1.5 µm sampling. Scale bar equals 1 mm, exposure time was 3 s.

We compared these results to images from the BESSY-II light source (BAM line) and to a modified EPMA with a Medipix2 detector. In order to realize high magnifications (91x to 382x) the XRM I could not use propagation distances larger than ca. 9 mm, whereas values of $D$ up to 1.1 m can be realized at the synchrotron without changing $M$. Combining the Feinfokus transmission tube with a synchrotron macroscope detector, we reached some intermediate value of $D = 183$ mm. Compared to the XRM I, the phase contrast was enhanced, as expected from the synchrotron measurements, yet two main constrains arose: (a) very long exposure times (several minutes for conventional X-ray transmission tubes), and (b) the inherent polychromaticity of the radiation. The latter appears to blur high-resolution phase contrast images artificially, most likely because it nullifies higher frequencies in the contrast transfer function, i.e. the kernel of the Fresnel propagation. As a result, the laboratory phase contrast radiographs appear less sharp compared to the monochromatic synchrotron images, although both setups feature a similar resolution in absorption mode. The longer exposure times (due to the use of a smaller solid angle) are traded against intensity of phase contrast (i.e., longer propagation distances). Obviously, the smaller the structural details of the object are, the more beneficial this trade will prove. Conventional absorption images require a certain amount of attenuation (either high $\mu$ or large features) in order to render their details visible. In this common situation, the probability of detection (POD) is more important than mere resolution. The latter competing against image noise, it is photon statistics – not penumbral blurring – which usually obscures the details. Phase contrast imaging, on the other hand, highlights these smallest features, and increases their POD. Particularly for sub-micrometer resolution, phase contrast is the only way (at least for reasonable exposure times) to detect details which are too small or too weak in terms of attenuation contrast to be seen in conventional radiographs. We have to admit that both lab sources which were used for this study did not exploit the full resolving power of the corresponding imaging systems: 1. In order to keep the exposure times reasonable, the images on the XRM I were recorded with a 0.7 µm thick target layer of tungsten resulting in an approximate Gaussian penumbral blurring of 1.7 µm FWHM. Using a 0.1 µm target, resolutions of an order of magnitude better (approx. 0.3 µm) have already been demonstrated with this setup, yet for much longer exposure times; 2. The resolution tests
on the macroscope yield an effective source size of 2.1 µm, hence the image resolution was mainly limited by the detector blurring (16.8 µm FWHM were determined for the phosphor, which is in excellent agreement with measurements on this screen at the synchrotron). For a magnification of 4.51 x, 167 lp /mm were estimated from the JIMA test pattern, 5.36 µm FWHM from the W-wedge. This X-ray tube, under ideal circumstances, would operate at a focal spot size of 0.7 µm, yet we could not perform a full automated optimization since we used a non-standard detector. To counter the effect of polychromaticity, the design of sub-micrometer hard X-ray imaging stations should consider lower Z metals as target, e.g. molybdenum or indium, whose spectra are more peaked, due to presence of strong K fluorescence lines. The liquid metal anode from which first radiographs were presented shows distinctive features of phase contrast even at moderate resolution. This phenomenon can be attributed to the strong 10 keV Ga-emission line which dominates the image contrast. Both samples (corn flower and cat claw) have little X-ray absorption and thus represent good phase objects. The shorter exposure times (as compared to the sub-micro CT setup at EZRT) give hope that in situ measurements of deformation and fatigue will be feasible once the setup is fully operational.

5 Conclusions

From our studies we conclude that:

- For any given X-ray lab setup, the propagation distance can be optimized without changing the length of the setup, whereby \(D = (R_1 + R_2)/4\) can be reached at best. Therefore, only the detector sampling has to become smaller. Ideally, source and sampling should be similar and of the order of a few µm or less. Only indirect detectors, e.g. macroscope or microscope optics which are commonly used at synchrotron beamlines fulfill this demand.

- Since micrometer or sub-micrometer source sizes are required for phase contrast imaging, and since these sources generally run at low power (few mW for the XRI, few W for the Feinfokus tube) long exposure times are expected, approx. 10 times longer than usual.

- As shown for the example of the liquid metal anode, X-ray tubes of higher brilliance can be used to shorten the exposure time. For higher energy applications, pure indium should be used as jet material as it has been recently demonstrated by Larsson et al [18].

- In order to record high-resolution phase contrast CT data, the X-ray source has to run under stable conditions for at least 10 hours, preferably one full day of operation.

- Tungsten as material for a transmission target produces a white bremsstrahlung and only little fluorescence at the characteristic L-lines. Consequently, higher order interference lobes are smeared out and the phase contrast radiographs appear blurred when compared to monochromatic images from synchrotron light sources. Therefore, other target metals with lower energy K-lines (in the range of 20 – 25 keV) should be considered (e.g., Mo, Ag, In, Sn), as well as the use of high-resolution reflection targets (needles) of such material.

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