Real-time X-ray microimaging using hard synchrotron radiation

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Abstract

Hard X-ray imaging with high spatial resolution is a valuable tool as it allows for an insight into opaque and dense specimens in a widely non-destructive way. Outstanding performance in terms of spatial and/or temporal resolution can be reached when synchrotron light sources are used for illumination. The substantially increased photon flux density gives access to exposure times ultimately given only by the length of one X-ray flash (several 100 ps) during pulsed source operations in so-called timing modes. Furthermore, due to the quasi-parallel beam propagation source-to-sample distances of more than 100 m are feasible which introduce a certain level of coherence to the hard X-ray radiation at the position of the experiment: more sophisticated contrast modalities such as X-ray phase contrast can be used to increase the sensitivity while relaxing the demands on the raw photon flux. This review shall outline how indirect detection schemes combined with commercial high-speed cameras can be used to acquire X-ray movies in a radioscopic mode with frame rates ranging from kHz to MHz range. Selected applications from various fields of research such as biology, materials research or engineering underline the huge potential of real-time hard X-ray microimaging.

Keywords: X-ray imaging, radioscopy, synchrotron radiation, X-ray phase contrast, in situ

1. INTRODUCTION

The ability of recording images in motion gives access to a wealth of information compared to static pictures. Still, capturing such images is challenging. The outstanding scientific benefit when dynamic process can be recorded by a series of images acquired in a continuous manner is demonstrated by the early motion pictures showing the famous collapse of the Tacoma Narrows Bridge (7th November 1940, USA). In order to depict phenomena which take place on a time scale much shorter than for example video frame rate, high image acquisition rates are required: going back in history to the beginning of the last century, scientists like Lucien Bull established techniques for real-time visible light imaging to follow, e.g., the individual fast motions of living insects(1). Acquiring movies with a similar frame rate but using penetrating radiation is more challenging due to the limited available photon flux density.

Outstanding X-ray flux density is available at insertion device beamlines of so-called third generation synchrotron light sources. This holds especially true when pink or white beam configurations are considered. Thus this enables one to record time-resolved movies of aperiodic processes combined with the benefits of X-ray radiography: depicting the interior of an opaque specimen in a non-destructive way and with high spatial resolution. Indirect detectors combined with ultra high speed cameras are capable of coping with the excessive heat load induced by the intense ration as well as dose and hence, allow for progressing from radiography to cineradioscopy(2).

A further advantage of synchrotron light sources is the (partial spatial) coherence of the radiation at the position of the experiment. The former is commonly related to the nearly parallel beam propagation which allows for large source-sample distances and therefore reduces the influence of the finite source size on the image formation. As a consequence, interference effects on interfaces can be exploited as more sophisticated contrast mode, commonly labeled propagation-based phase contrast(3). Phase contrast combined with hard X-rays increases substantially the sensitivity while reducing the demands on raw photon flux density(2).

2. INDIRECT X-RAY IMAGING DETECTORS

The concept of indirect detection for hard X-ray (diffraction) imaging was introduced in the middle of the 1970s in order to perform live topography(4). A scintillator screen is used to convert X-ray photons into visible light. This luminescence image is captured by visible light optics and a camera. Standard configurations nowadays widely in use are sketched in Fig. 1. High-resolution systems commonly place a microscope objective with large numerical aperture directly downstream of the scintillator. Such a design ensures high spatial resolution and light collection efficiency while the large numerical aperture limits the depth of field and therefore the maximal thickness of the scintillator screen applicable. The latter is the dominant driver for the detector efficiency. Furthermore, intense hard radiation can easily damage the objective. In order to improve the radiation hardness, commonly objectives with long working distances are used which can be placed above the X-ray optical beam path. The folded periscope-like design leaves only the scintillator and the mirror as mandatory optical elements in the direct intense radiation. An indirect detector in such configuration frequently is equipped with fast single-crystal scintillator screens (such as Ce-doped Lu_2SiO_5 (LYSO:Ce) or Ce-doped $Lu_3Al_5O_{12}$ (LuAG:Ce)). Its radiation hardness is only limited by the heat load the screen can stand before mechanical cracking occurs(6).

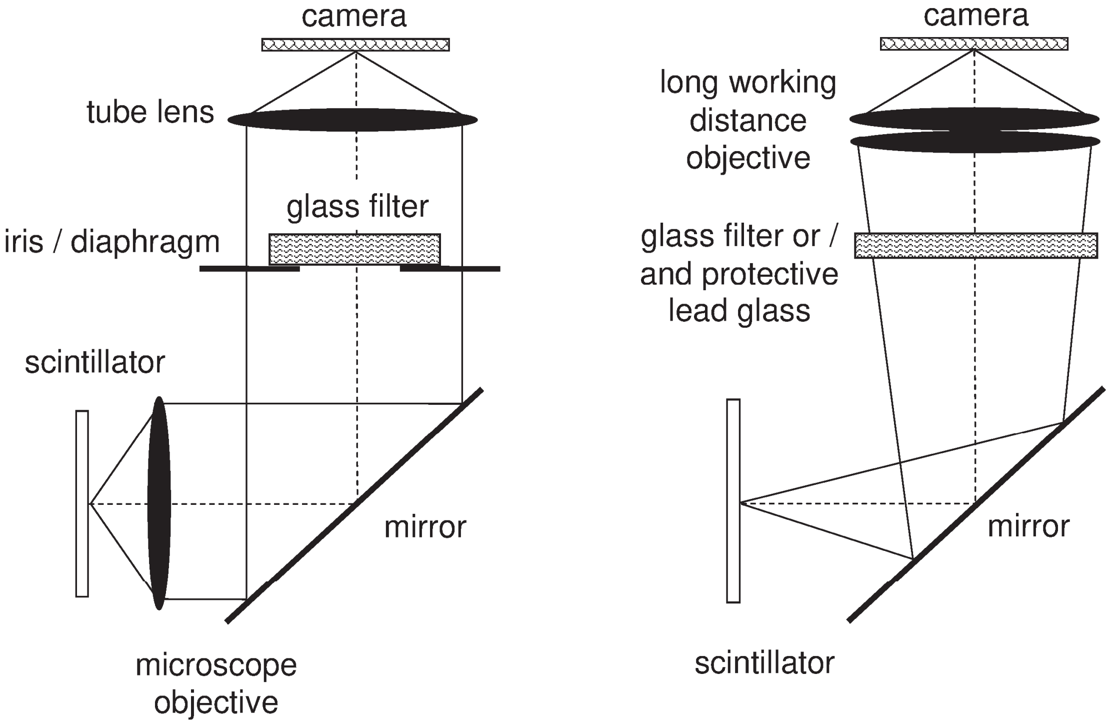

Figure 1: The indirect detection scheme: (left) high-resolution design with the lens placed directly downstream of the scintillator; (right) radiation-hard design with only the scintillator and the mirror in the X-ray optical beam path.(4,5) Adapted from Rack et al., Journal X-ray Science & Technology 13, 429-441 (2010).

Indirect detectors equipped with high-speed CMOS-based cameras can easily reach for acquisition rates in the kHz to MHz regime. Besides radioscopy with (ultra-)high speed a common application is time-resolved microtomography where complete tomographic scans have been recorded as fast as 5 ms.

3. IN-VIVO CINERADIOSCOPY

X-ray phase-contrast imaging has the potential to reduce the dose to the sample as the signal is relying on the refraction of the radiation and not on the absorption. A simple application example is a movie of the chewing and biting mouthparts of the cockroach Periplaneta americana (Linné). Cockroaches have rather primitive mouthparts and therefore act as model system. Descriptive studies of the kinematics of the entire mouthpart are challenging due to an overlap of the involved opaque objects.

The example pictures shown in Fig. 2 were acquired at the beamline TopoTomo of the German synchrotron light source ANKA. TopoTomo was operated in the white beam mode, using solely a 0.5 mm thick Be window between the sample and the source (30 m distance) and 1 mm thick Si attenuator (peak photon flux density around 20 keV, the integral photon flux density of ca. 10^{11} Ph/s/mm^2. As detector, a so-called BAMline macroscope was utilized (Rodenstock right-angle in combination with a Nikkor 180/2.8 ED as tube lens, similar to Fig. 1, left). The scintillator screen was made of $CdWO_4$ (CWO) or LYSO:Ce (single crystal). The camera used was a Photron Fastcam SA1 (Photron Inc., USA, 1024 × 1024 pixel CMOS chip, 20 µm pixel size, peak quantum efficiency of 42% at 640 nm, dynamic range of 10bit (800:1). The camera can acquire up to 5 400 full-frame images per second. In order to maximize the contribution of inline phase contrast to the image formation, the X-ray detector was positioned approximately 0.5 m downstream from the specimen.

In Fig. 2, a selected series of example images extracted from one movie showing a feeding cockroach are shown. They were acquired with a frame rate of 125 images/s. For this movie the detector was equipped with a bulk LYSO:Ce crystal. The effective pixel size was around 13.5 µm. The complete movie is available online(2,7). The contrast is dominated by refraction due to the low absorption signal of the specimen. The temporal resolution is sufficient to sample a chewing cycle with around 40 images. Reducing the demands on spatial resolving power and/or signal-to-noise ratio allows one to reach higher image frame rates. Movies with 250 images/s were acquired during the very same experiment(7). Hence, the image rate is limited by the dose the living specimen can stand: frame rates up to 1 000 images are imaginable.

Employing radiation with broad bandwidth is a valuable tool in order to apply in vivo cineradiography at synchrotron light sources where the photon flux density is not sufficient enough to use monochromatic radiation. Despite the polychromatic nature of the impinging radiation, refraction by means of propagation-based X ray phase contrast is available. One of the drawbacks is the higher dose involved.

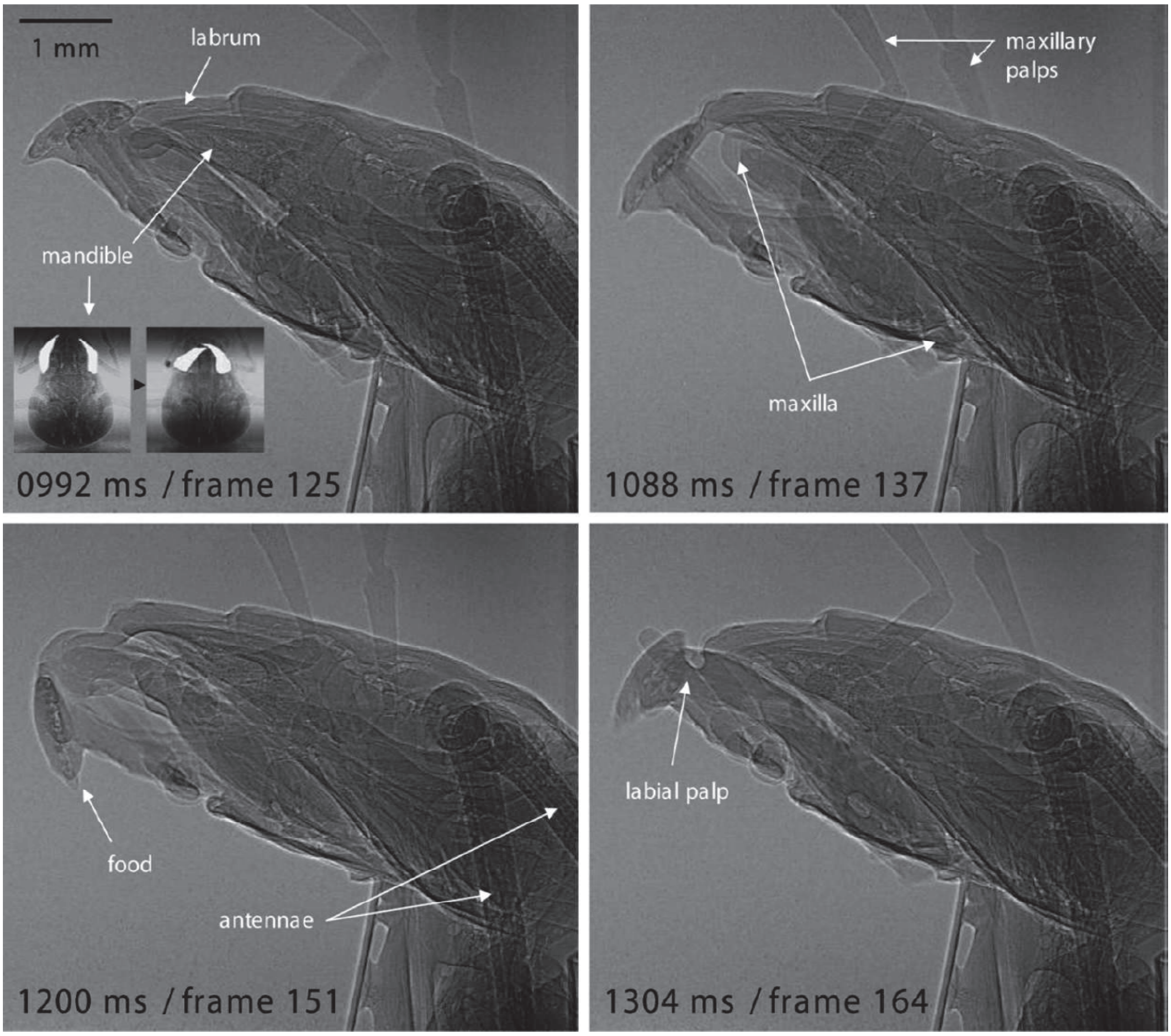

Figure 2: Sequence of consecutive in vivo radiographs depicting the head of Periplaneta americana during ingestion (TopoTomo beamline, ANKA light source, Germany). By using the lateral perspective the multilayered assembly is easily explained: labrum, mandibles, maxillae and labium (from dorsal to ventral). During food intake these mouthparts interact in a periodic way. A small picture inset in the upper left quarter illustrates the position of the mandibles (white) as can be seen in the dorsal view. The movie was acquired with 125 images/s frame rate (effective pixel size approximately 13.5 µm). Adapted from Rack et al., Journal X-ray Science & Technology 13, 429-441 (2010).

4. RADIOSCOPY WITH SPATIO-TEMPORAL MICRORESOLUTION

Substantially higher frame rates are accessible with polychromatic synchrotron radiation when dose to the sample issues do not need to be considered. Frequently, in situ experiments tackling materials science allow for higher dose (rates), commonly only limited by potential heat load issues. The example shown in Fig. 3 depicts a coalescence event in a liquid aluminum foam (AlSi6Cu4). The images were acquired at beamline ID19 of the European Synchrotron Radiation Facility (ESRF) in Grenoble, France. In order to reach sufficient photon flux density the beamline was operated in white beam mode with the radiation of a wiggler insertion device only filtered by aluminum attenuators. The camera on the indirect detector was Photron Fastcam SA5 (Photron Inc., USA). Compared to the model in the previous section this camera can reach up to 7 000 images/s without restricting the field-of-view. For the pictures shown a frame rate of 105 000 images/s was applied. In order to reach this speed, a region-of-interest of 233 × 163 pixels had to be set (18.1 µm effective pixel size). Again, the weakly attenuating cell walls of the aluminum foam are visible by means of X-ray phase contrast (8 m propagation distance between sample and detector).

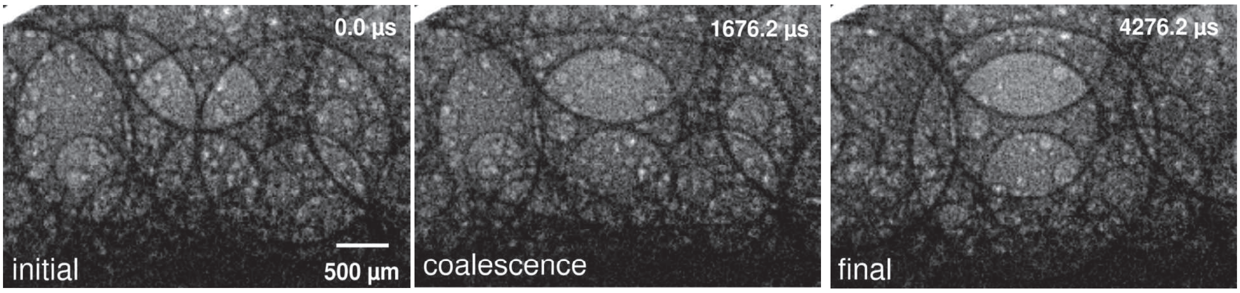

Figure 3: Coalescence event in an expanding liquid aluminum foam (AlSi6Cu4 at a temperature of 640°C). Movie taken with an image acquisition rate of 105 000 images/s. Timestamps refer to the first frame. Adapted from Rack et al., Applied Optics 52, no. 33, 8122 (2013).

5. MHz RADIOSCOPY

Since MHz frame cameras became commercially available it is possible now to progress synchrotron-based radioscopy using indirect detection schemes in terms of image acquisition rates. The fact that photon flux densities available at synchrotron light sources are sufficient to reach sub-microsecond exposure times with good image quality had already been proven with lower image acquisition rates(9). Care in case of MHz radioscopy has to be taken to choose a scintillator material with a decay time compatible with the exposure times only lasting a few 100 ns. Commonly, LYSO:Ce is the material of choice as it is commercially widely available as single-crystal screen. A first demonstration of MHz radioscopy was carried out at beamline ID19 of the ESRF. The camera chosen is a Shimadzu HPV-X2 (up to 10 MHz recording speed, 128/256 images ring buffer, 400 × 250 pixels, 32 µm pixel size)(8). Combined with a custom-made 4× lens (OptiquePeter, Lentilly, France) this camera allows for 5 MHz acquisition rate at 8 µm effective pixel size in a routine manner. The example pictures shown in Fig. 4 reveal details during breakdown of a commercial electrical fuse.

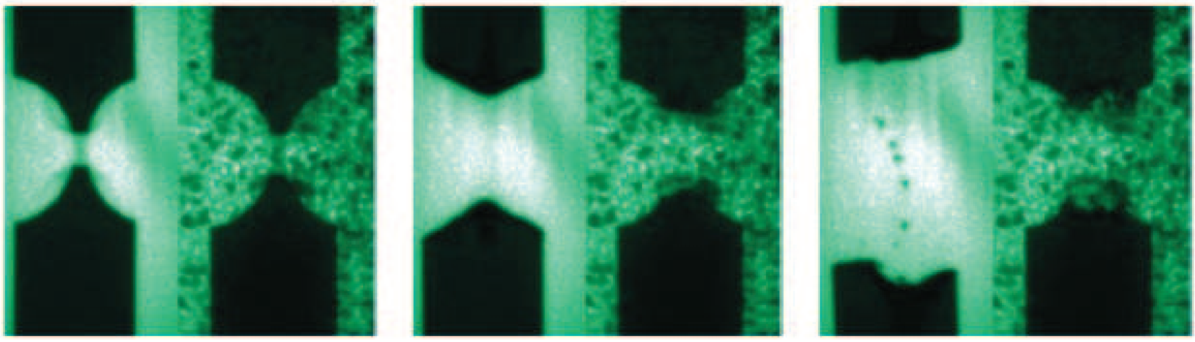

Figure 4: Breakdown of an electrical fuse (images acquired 25 µs, 100 µs and 500 µs following a current spike). The left picture of the pairs is always with reduced sand-grain housing, on the right the standard housing in order to show the effect on sand and arc-quenching channels. Adapted from ESRFnews, July 2016, No. 73, p. 28.

6. SUMMARY

Using indirect detection schemes combined with high speed cameras, radioscopy with frame rates from kHz to MHz can be applied in a routine manner. Commonly, this requires the use of polychromatic synchrotron radiation and propagation-based X-ray phase contrast.

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