Laboratory x-ray micro imaging: Sources, optics, systems and applications

2009 J. Phys.: Conf. Ser. 186 012027

(http://iopscience.iop.org/1742-6596/186/1/012027)

Laboratory x-ray micro imaging: Sources, optics, systems and applications

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Abstract. We summarize the recent progress in laboratory-scale soft and hard x-ray micro imaging in Stockholm. Our soft x-ray work is based on liquid-jet laser-plasma sources which are combined with diffractive and multilayer optics to form laboratory x-ray microscopes. In the hard x-ray regime the imaging is based on a liquid-metal-jet electron-impact source which provides the necessary coherence to allow phase-contrast imaging with high fidelity.

1. Introduction

The Stockholm group is focused on laboratory-scale micro imaging in both the soft x-ray and hard x-ray regimes. The work includes sources, optics, imaging systems, and applications. In the soft x-ray regime the target area is laboratory microscopy. The microscopes described in section 2 are now approaching a maturity and reliability that allows real-world applications. Here thin samples in an aqueous environment have been imaged with high resolution and contrast. In the hard x-ray regime work is focused on a new small spot/high flux source and applications of the source. This microfocus source is based on a liquid-metal-jet-anode, which shows promise to significantly increase brightness compared to existing sources. It enables high-resolution imaging of thick samples with high resolution and adequate exposure times. A high spatial coherence allows significant contrast enhancement by phase imaging. The hard x-ray and soft x-ray projects share the goal to provide unique laboratory imaging solutions. Both rely on our optics fabrication capacity.

2. Soft x-ray sources, optics and microscopy

Here we briefly summarize our work in the soft x-ray regime. It is described in more detail in several contributions in this volume. We demonstrated the first sub-visible-resolution laser-plasma laboratory water-window x-ray microscope [1]. The present version operates at λ=2.48 nm or 3.37 nm and is based on a nitrogen or methanol liquid-jet laser-plasma source, respectively [2]. High-resolution 20 nm and 25-nm Ni zone plates are fabricated in-house, cf. figure 1 [3]. Here

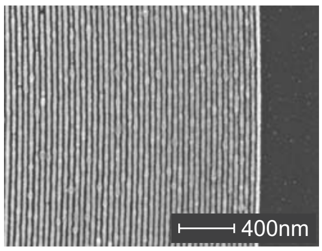

Figure 1. 20 nm Ni zone plate

high process control in, e.g., the electroplating step has been found to be of outmost importance for producing high-efficiency narrow-line width zone plates with decent yield. Recent experimental and theoretical development also involves the fabrication and application of novel diffractive optical elements for DIC and Zernike phase-contrast microscopy [4]. The condenser is either a normal-incidence multilayer optic or diffractive optics.

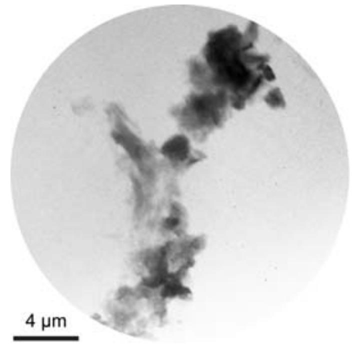

Figure 2. Example of a soil science sample imaged with the compact XRM.

The microscopes now have the reliability and user-friendliness that allows serious work on real-world applications. An early application is soil science, where the instrument demonstrates synchrotron-quality imaging and user-friendliness by taking hundred pictures per day [5]. Figure 2 shows an example. The same type of samples have been used to demonstrate stereo-imaging [6]. Finally, the first tomography on a laboratory water-window microscope has been demonstrated [7]. In the near future the microscope will be equipped with a cryo stage to allow biological imaging. Furthermore, a new high-power laser will result in significantly reduced exposure times, hopefully below 10 s for wet samples.

3. Hard x-ray sources and imaging

3.1. The liquid-jet-anode electron-impact x-ray source

We have developed a microfocus source based on a novel type of anode, the liquid-metal jet. [8]. This electron-impact source concept shows potential for a 100-1000× increase in brightness compared to present systems. The concept has been demonstrated with a tin-jet anode [8] (for 25 keV line emission), with a gallium-jet anode [9] (for 9 keV line emission) and also on non-metal jets such as methanol [10]. As an example, figure 3 shows the source emission with a tin anode. We typically operate with a 5-10 µm x-ray spot and up to a few 100 W of 50-100 keV electron beams.

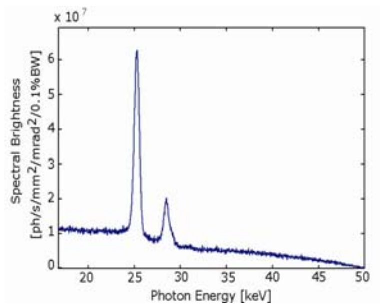

Figure 3. Source spectrum from electron-impact microfocus source based on a liquid-tin-jet anode.

Recent progress includes demonstration of long-term operation of a high-brightness microfocus source based on this concept. The tube uses a Ga/In/Sn alloy with strong line emission at 9.25 keV (comparable to conventional copper anode sources) as well as significant continuum radiation up 100 keV. The spot size is 5-20 µm with an electron-beam power up to 200 W and a power density of ~10 W/µm. This is >10× more than for present state-of-the-art microfocus tubes. This second-generation source incorporates a continuous recycling system for uninterrupted operation as well as reduced footprint and enhanced reliability. This source shows promise to enable many laboratory-scale x-ray applications, today limited by source brightness. Also, for novel imaging modalities, like phase-contrast imaging, source brightness is crucial. The system is now mature enough for scientific and industrial applications. We are therefore making the source commercially available [11].

3.2. High-resolution phase-contrast imaging

Phase-contrast methods increase contrast, detail and selectivity in medical and non-medical x-ray imaging. Such imaging requires a small source spot (to provide high resolution and sufficient spatial coherence) and a high flux (to give reasonable exposure times). To date phase-contrast imaging has therefore primarily been performed at high-brightness synchrotron radiation sources. However, the vast majority of x-ray imaging is performed with compact electron-impact sources in clinics or laboratories. Unfortunately, present compact x-ray sources do not provide the necessary spatial coherence with sufficient power to allow laboratory-scale high-resolution phase-contrast imaging with adequate exposure times.

The liquid-jet anode source is suitable for x-ray imaging, both in conventional absorption and with phase. In both cases the potential for small-spot/high flux operation (high brightness) is the key to provide high-resolution imaging with adequate exposure times. Figure 4 shows absorption imaging of a 20 lp/mm mammography test chart. The contrast is excellent. The observed contrast compares well to theoretical simulations. The source was operated with a tin anode at 50 keV with a 5 μm spot.

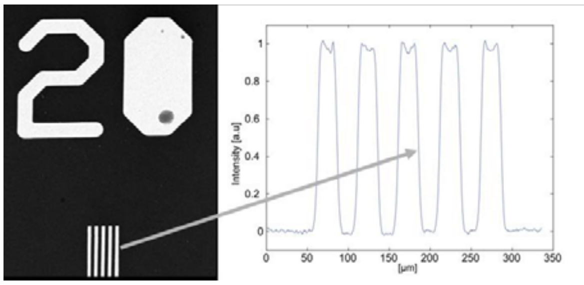

Figure 4. High-resolution absorption imaging of 20 lp/mm mammography test charts.

The small-spot source provides sufficient coherence to allow high-quality high-resolution phase-contrast imaging [11]. Figure 5 shows a phase image of a spider. The sub-5 μm hair on the head and pedipalps are clearly visible. We note that these hair are not observable in absorption imaging. Also for the phase imaging we have excellent comparison between modeling and experiments. The source was operated with a tin anode at 50 keV with a 5 μm spot.

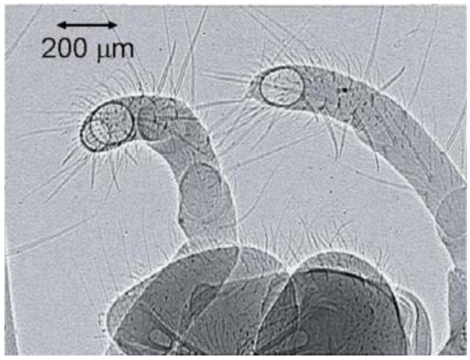

Figure 5. High-resolution phase-contrast image of a spider´s head and pedipalps.

We are presently investigating the source's applicability for small-animal imaging experiments, especially for tumour detection. Here mice with defined human neuroblastoma tumours are imaged with phase-contrast. Preliminary results look encouraging. Finally, we have shown that the source can be scaled to high power, thereby paving the way for laboratory-scale high-contrast and high-resolution x-ray imaging with exposure times comparable with present rotating-anode-based systems.

4. Acknowledgements

The authors gratefully acknowledge the financial support from the Swedish Science Research Council, the Foundation for Strategic Research, the Swedish Agency for Innovation Systems, the EU 6th Framework, the Wallenberg Foundation, the Gustafsson Foundation and KTH-KI Life Science Imaging Consortium.

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