X-ray Tomographic Microscopy at TOMCAT

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Abstract. Synchrotron-based X-ray Tomographic Microscopy is a powerful technique for fast non-destructive, high resolution quantitative volumetric investigations on diverse samples. At the TOMCAT (TOmographic Microscopy and Coherent rAdiology experimenTs) beamline at the Swiss Light Source, synchrotron light is delivered by a 2.9 T superbend. The main optical component, a Double Crystal Multilayer Monochromator, covers an energy range between 8 and 45 keV. The standard TOMCAT detector offers field of views ranging from 0.75x0.75 mm² up to 12.1x12.1 mm² with a pixel size of 0.37 μm and 5.92 μm, respectively. In addition to routine measurements, which exploit the absorption contrast, the high coherence of the source also enables phase contrast tomography, implemented with two complementary techniques (Modified Transport of Intensity approach and Grating Interferometry). Typical acquisition times for a tomogram are in the order of few minutes, ensuring high throughput and allowing for semi-dynamical investigations. Raw data are automatically post-processed online and full reconstructed volumes are available shortly after a scan with minimal user intervention.

1. Introduction

X-ray tomographic microscopy is a powerful technique for fast non-destructive, high resolution, quantitative 3D investigations on an ample variety of samples. Absorption based and "edge-enhanced" tomographic experiments have been routinely performed at TOMCAT [1] since its kick off in June 2006. At TOMCAT we also perform phase contrast tomography. We offer to the user community two complementary techniques based on a Modified Transport of Intensity approach [2] and a Differential Phase Contrast method (DPC) with a grating interferometer [3]. The first phase contrast approach yields a good approximation of the 3D distribution of the refractive index decrement of a weakly absorbing object from a single tomographic dataset without need of additional hardware. It is particularly suited for small specimens when high resolution is required. The second phase contrast technique, the Differential Phase Contrast (DPC) method [3] is characterized by a higher sensitivity, by moderate resolution and gives the best results with larger samples. During the past year, considerable efforts have been spent on fully integrating this approach at the beamline, both in terms of fast acquisition and reconstruction. TOMCAT is one of the few beamlines in the world offering this new feature to the user community.
2. Beamline overview

Synchrotron light is delivered to the beamline by a 2.9 T superbend, with a critical energy of 11.1 keV. In terms of optics, TOMCAT has been kept simple, to prevent degradation of the beam profile. The only optical elements present are a Chemical Vapor Deposited (CVD) diamond window, separating the UHV sector of the machine from the HV of the beamline and a fixed-exit double crystal multilayer monochromator (DCMM), which covers an energy range from 8 to 45 keV (energy bandwidth: 2-3% with multilayers, 0.018% with Si111) and it is located at approximately 7 m from the source in the front end. This unusual location guarantees a beam size in the experimental hutch, at 20 m from the source, of 40 mm horizontally and 7-4 mm vertically (for energies between 10 and 30 keV).

The TOMCAT endstation, in its standard setup features the beam conditioner block, the sample manipulator unit and the microscope. The standard TOMCAT detector offers field of views ranging from 0.75x0.75 mm² up to 12.1x12.1 mm² with a pixel size of 0.37 μm and 5.92 μm, respectively. A more efficient second system, based on a high-aperture tandem 1:1 configuration and accepting a diagonal up to 40 mm, is also available. The CCD camera (PCO2000) has a 2048x2048 pixels chip (7.4x7.4 μm² pitch). This standard setup is mostly used for routine absorption experiments and when the Modified Transport of Intensity approach [2] is applied.

For the DPC method, ad-hoc hardware is required (figure 1). The hard X-ray interferometer works with 2 gratings, a phase grating and an absorption grating, positioned at uneven Talbot distances. A phase stepping approach is used to transform the local fringes position of the interference pattern into signal intensity variations, containing information on the phase gradient of the object. The required grid translation for this phase stepping approach is performed with a piezo stage [4], since speed, accuracy and reproducibility are mandatory. The 2 gratings are mounted, at 25 m from the source, on a massive support completely decoupled from the sample stage to avoid vibrations during sample rotation and translation. Phase matching is usually necessary to avoid large phase jumps: the sample needs to be scanned in a wet environment. For this purpose we developed an aquarium [4], consisting of an aluminum tank with entrance and exit Kapton windows along the beam path. The sample holder comes into the aquarium through a hole at its bottom. A gasket system at the bottom of the tank ensures smooth sample rotation, translation and centering.

3. Software

Fast acquisition of high quality data at TOMCAT is achieved by the combination of a continuous scanning protocol with an optimized acquisition software, where the sample rotates continuously over a 180 degrees range, while images are simultaneously collected by the camera. The optimized acquisition software [5] implemented at TOMCAT exploits the 4 GB internal RAM memory of the detector, where acquired images are transferred at very high rates (up to 14.7 fps at full frame) and its First In First Out (FIFO) buffer acquisition mode. The same approach with continuous sample rotation...
and FIFO acquisition mode is also used for DPC experiments, where a complete continuous scan is acquired for each phase step. Our new acquisition scheme makes high throughput phase contrast studies possible.

During acquisition, a selection of sinograms is computed on the fly, allowing quality check of the recorded tomogram right after the end of a scan through a user friendly web based application [5]. This application is also used to select and fine tune the reconstruction parameters (e.g. center of rotation and filter).

The complete reconstruction of tomographic datasets, from the raw projections to the 3D volume, occurs on a 5 node Linux cluster (2 dual core Xeon processors clocked at 3.0 GHz per node). Such job can be submitted to the cluster directly from the mentioned web application, with just one mouse click. Each single step of this reconstruction pipeline has been optimized for speed, to be able to fully exploit the advantages of our fast acquisition protocol. A high resolution 2048x2048 (1501 projections) dataset is reconstructed on the cluster in less than 12 minutes.

4. Application

The different sensitivity and resolution achieved with the two phase contrast imaging approaches implemented at TOMCAT is illustrated in figure 2. Two tomograms of the same post-transplant human myocardium biopsy have been acquired with the two techniques and the same coronal slice is shown. The higher sensitivity of the DPC method and the higher resolution achieved with the Modified Transport of Intensity approach are clear. The resolution of the DPC method depends on the Talbot distance and is limited by the grating pitch [3]. In contrast, for the propagation method [2], Fresnel fringes need to be detected and therefore high resolution radiographs are imperative. The best results are obtained with a 10x magnification objective, a 1.5x1.5 mm² field of view and a 0.74x0.74 μm² pixel size.

Figure 2. Comparison of two tomograms of a post-transplant human myocardium, embedded in solid paraffin (Sample courtesy of Dr. S. De Marchi, Inselspital, Bern, Switzerland and Dr. M. Gugger, Pathologisches Institut, University of Bern, Switzerland) obtained with the two phase contrast techniques implemented at TOMCAT - (a) DPC tomogram (1.4 μm pixel size, 500 projections, 25 keV, 3rd Talbot distance, 9 phase steps, 3.981 and 2 μm pitch for the phase and absorption gratings, respectively). (b) Tomogram acquired and reconstructed using the Modified Transport of Intensity approach (0.7 μm pixel size, 1500 projections, 20 keV, 32 mm sample-detector distance). (c) Magnification of the region enclosed in the black box in (b).

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