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Implementation of a Computed Tomography System based on a laboratory-based nanofocus X-ray source.

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Laboratory-based X-ray computed tomography (CT) with resolutions around 100nm per line pair is technically feasible since a few years [1]. However, this measurement principle is still not widely used - especially not for industrial and medical applications. Reasons for this are high costs, the complex operation of systems based on optical elements, as well as the restricted flexibility of their field-of-view. As applied development center for X-ray technology, the Fraunhofer EZRT is currently developing an easy-to-handle, flexible setup for industrial use. The setup uses standard projection geometry, a small X-ray source and large detector pixel; thus it operates using high geometric magnification. Due to significant advances made on the component side combined with a high stability of the setup, we are able to resolve in standard operation 150nm lines and spaces. Compared to modified SEM X-ray sources, the sample does not need to be placed in vacuum [3]. Moreover, due to the source's peak energy of 60kV, sample diameter and material can be chosen relatively flexible.

For our setup we utilize an X-ray tube developed by *Excillum* in the framework of the NanoXCT Project, which is now commercially available as "NanoTube". In our acquisition geometry, the penumbral blurring of the source's focal spot defines the achievable resolution. Besides a thin transmission target combined with a suited design of the electron optics to guarantee a small source size, also high spatial spot stability is required for computed tomography. The latter is established by advanced temperature and noise control. In order to provide good heat dissipation, the transmission target is made of tungsten deposited on a 100µm diamond window. With this, we reach a source size diameter of a few hundred nanometers.

Although the brightness of the spot is high, the total emitted flux is still relatively low, which is a major drawback compared to an optics-based setup [4]. Thus, we need an efficient detector and a large solid angle to achieve reasonably short exposure times. Therefore, we use 750µm CdTe as sensor material with a quantum efficiency greater than 80% over the full spectrum. The Hybrid Photon Counting "SANTIS" detector possesses 2048 x 514 pixel with 75µm edge length, and was provided by *DECTRIS*. Each pixel of a dedicated readout chip is directly bonded to a semiconducting X-ray sensor [2]. Besides the high efficiency due to the photon counting technique, it possesses virtually zero noise. Furthermore, two energy thresholds enable us to perform dual-energy computed tomography without additional filters. Moreover, the quasi-rectangular point spread function of the detector supersedes oversampling.

Large solid angles are obtained by a short source-detector-distance of minimum 380mm. This also requires small distances between the source and sample. Therefore, an optical collision avoidance system is implemented to be able to adjust source-object-distances below 500µm without risking a damage of the source's window. In combination with this, the system is designed to acquire projections from arbitrary perspectives with different magnifications. This is useful for elongated or flat objects, *e.g.* MEMS.

For reconstruction, we use our own total variation regularized iterative SART software, which keeps the number of required radiographs low and allows to perform a full scan within one day. Thereby, the 3D reconstruction is done automatically.

For an optimal stability, the whole setup is mounted on a 2.2m x 1.1m air-damped granite block with a lead shielded housing on top of the granite. Thus, we do not need any additional lead cabin. Within the shielding, the air temperature is constant at ±0.1°C, which is important to guarantee stable operation for CT. By this stable system design, time-dependent drifts are widely avoided, and only small drifts occur which can be corrected by software.

In Figure 1, we demonstrate the ability to resolve 150nm lines and spaces. For a 1.5µm thick tungsten Siemensstar, the innermost 150nm and the second innermost 300nm features are separable. Moreover, we have also performed a first CT scan of a mineral skeleton radiolaria with 200µm diameter; a corresponding slice is displayed in Figure 2. In total, 621 radiographs were taken with a voxel size of 350nm and 100s exposure time, leading to a total acquisition time of 18h. In this time window, we did not observe any relevant drift. The detector's lower threshold was set to 7 keV**.** As a next step, we will reduce the voxel size further to explore the full capability of our setup.

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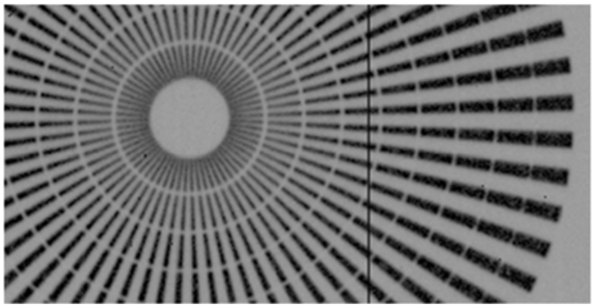

Figure. 1. Siemensstar made of 1.5µm thick tungsten. The innermost features possess 150nm line width, the next ring 300nm lines and spaces. The exposure time was 600s; the tube energy 60keV.

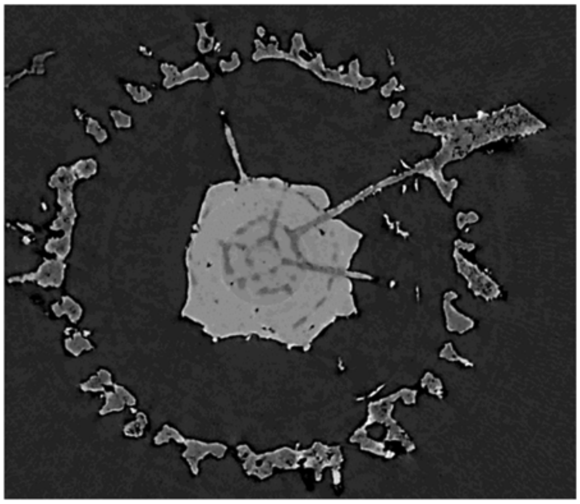

Figure. 2. Slice of a CT scan of a mineral skeleton radiolaria with 200µm diameter. Voxel size was 350nm, tube energy 60keV, total scan time 18h for 621 projections.