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Phase-Contrast X-Ray Computed Tomography

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1. Background

Since their discovery by Wilhelm Röntgen in 1895 (Figure 1), X-rays have become ubiquitous in the non-invasive imaging of internal structures. However, in the subsequent 126 years, the basic principle of imaging with X-rays has remained unchanged – with the contrast being provided by absorption.

A new method of imaging with X-rays has been developed where the phase of the X-rays is used to provide the contrast instead. This method promises improved contrast for biological soft tissues. Until recently, this technique has been confined to use at synchrotron facilities. This project aims to use a laboratory X-ray source to take 3D phase-contrast images of a complex object.

Figure 1. The first absorption contrast X-ray image. Taken in 1895 by Wilhelm Röntgen [1].

2. Set-up

Currently, it is not possible to directly measure the phase of electromagnetic radiation at or above optical frequencies. Therefore, a phase-contrast imaging technique is needed to transform the phase perturbations into measurable intensity perturbations. The technique used in this project achieves this through the Talbot effect (Figure 2).

The set-up used is called a Talbot-Lau interferometer (Figure 3) which consists of two absorption gratings (G_0 and G_2) and a phase grating (G_1). To ensure each of the line sources produced by G_0 contributes constructively, the set-up needs to satisfy $p_0 = p_2\, l/d$, where $p_{0,1,2}$ are the periods of the respective gratings. The separation of G_1 and G_2 should be equal to the first Talbot distance, meaning $d = p_1^2/8\lambda$. The imaging resolution of the system is given by wd/l.

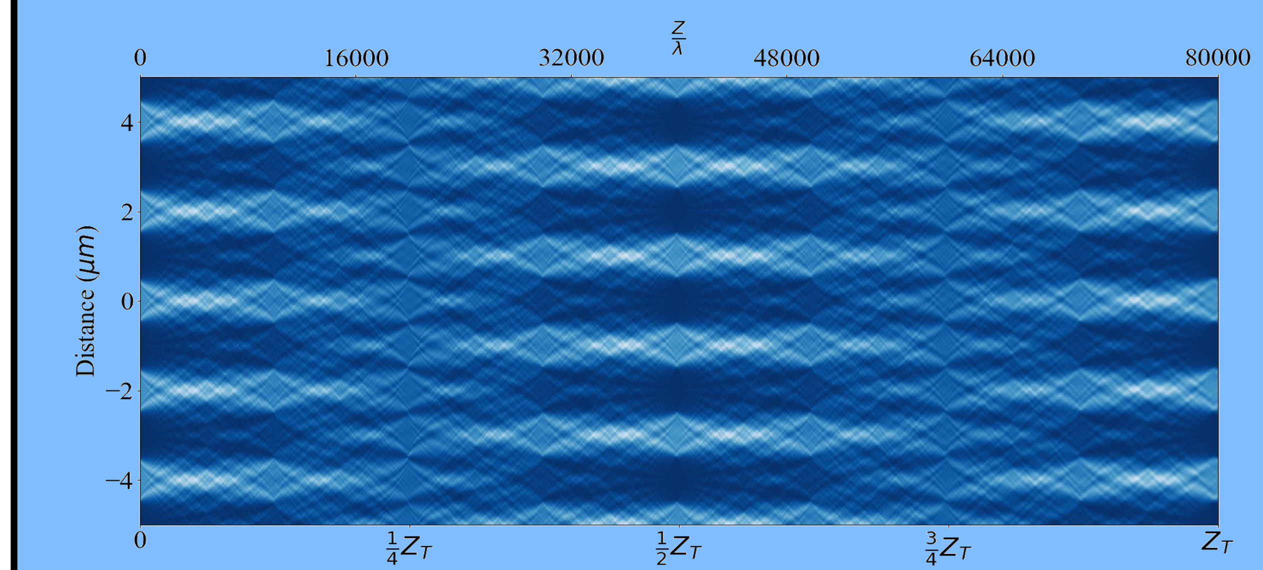

Figure 2. Simulated Talbot Carpet. Grating period = 2 μm, duty-cycle = 0.5, wavelength = 0.1 nm.

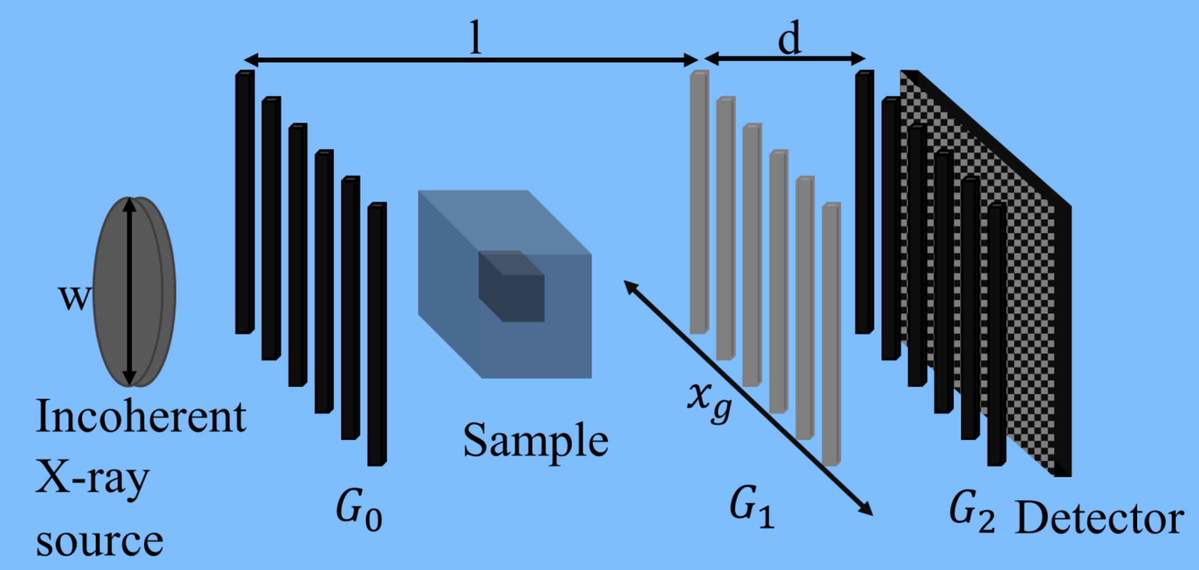

Figure 3. Typical Talbot-Lau Interferometer setup. Inspired by [2].

To obtain images with the Talbot-Lau interferometer, either G_1 or G_2 is scanned in the direction x_g, causing the intensity measured in each pixel to oscillate as a function of x_g. This oscillation is then expressed as a Fourier series from which the offset, amplitude and phase coefficients can be extracted. The difference between these coefficients in the reference image (r) and the sample image (s) gives the normalized image as outlined in Figure 4. Example images taken with a Talbot-Lau interferometer are shown in Figure 5. All three image types can be extended to three dimensions with reconstruction algorithms.

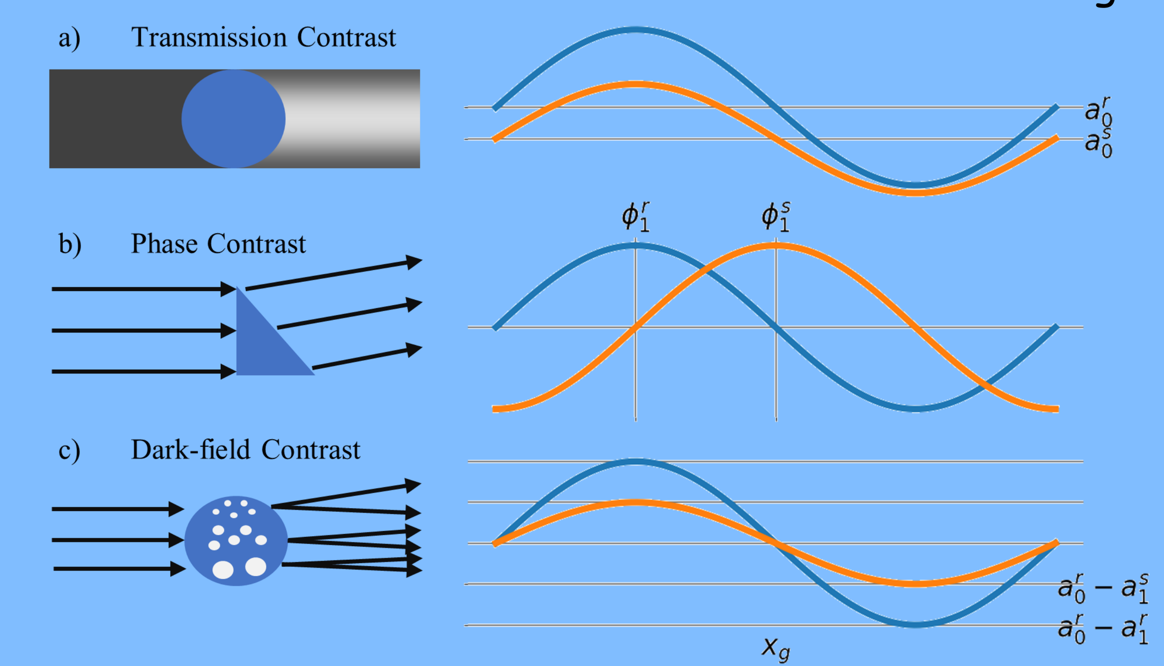

Figure 4. Imaging modalities of a Talbot-Lau interferometer. a) Transmission contrast, b) Phase contrast & c) Dark-field contrast. Inspired by [3].

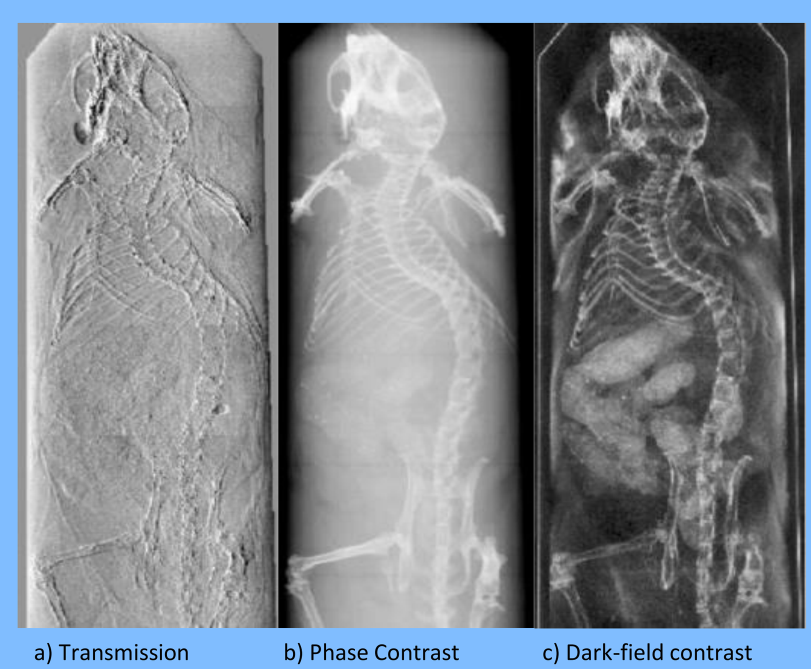

Figure 5. Comparison of the three different imaging modalities. Adapted from [3].

3. X-Ray Source

The X-ray source used in this experiment is a third generation microfocus X-ray source developed by researchers at Kings College London (Figure 6).

Electrons are emitted through thermionic emission at the cathode and then accelerated by a fixed potential difference towards the anode. After passing the anode, the electron beam is focussed by an electromagnetic lens onto a metal target. As the electrons hit the target they decelerate and emit X-rays.

The power and source size can be altered by varying the current in the cathode and electromagnetic lens respectively. Whilst the spectrum can be changed by altering the material of the target.

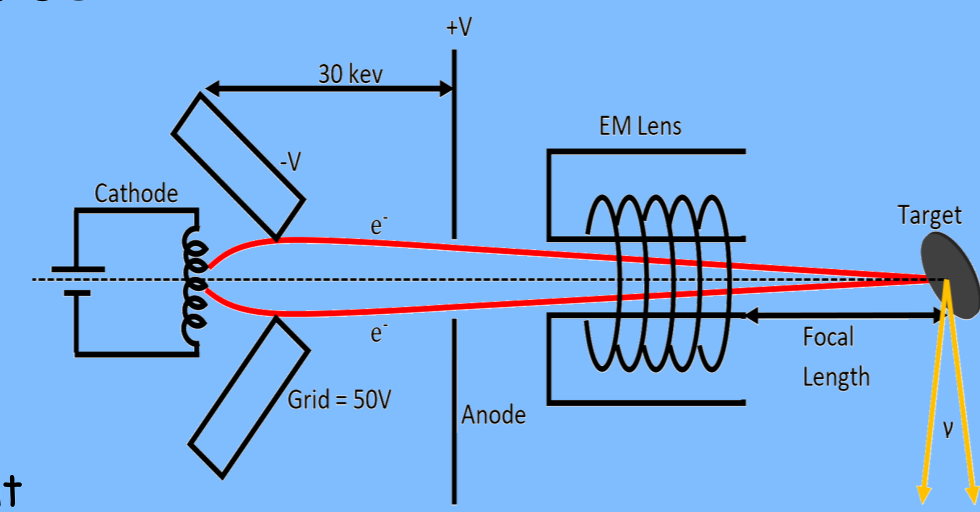

Figure 6. Diagram of the X-ray source used.

3.1. Size

To measure the size of the source, the knife-edge method was used. This involves blocking half of the beam with a sharp opaque object (Figure 7). The resulting intensity distribution is known as the edge-spread function - taking the spatial derivative yields the line-spread function (Figure 8). The source size is then the FWHM of the line spread function. This resulted in a minimum source size of $34.3 \pm 0.5\ \mu m$.

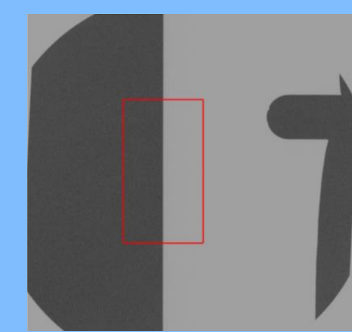

Figure 7. Image with a knife-edge in the beam path.

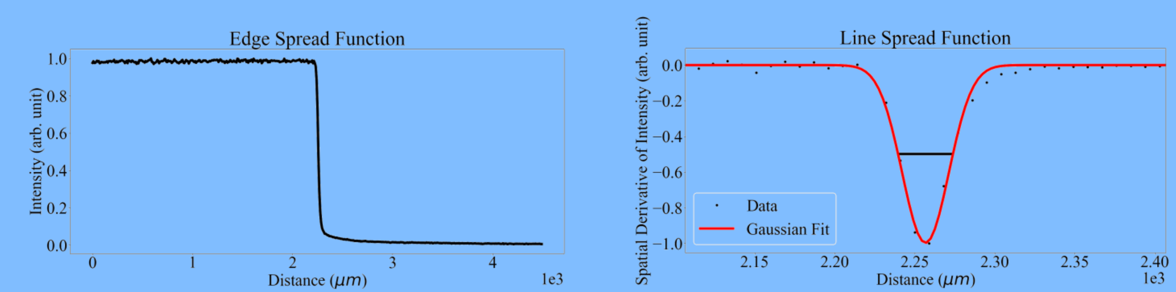

Figure 8. Graphs showing the method to determine the source size.

3.2. Spectrum

A curved crystal spectrometer was used to measure the spectrum. This splits the beam into its spectrum according to the Bragg condition: $2d\sin\theta = n\lambda$. Therefore, from the angle the beam is deflected, the wavelengths present in the beam can be determined. An example image is shown in Figure 9 whilst the spectra for Cu and Zr are shown in Figure 10.

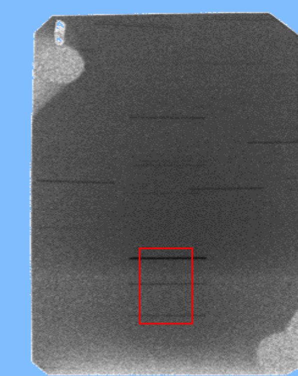

Figure 9. Example image from the crystal spectrometer.

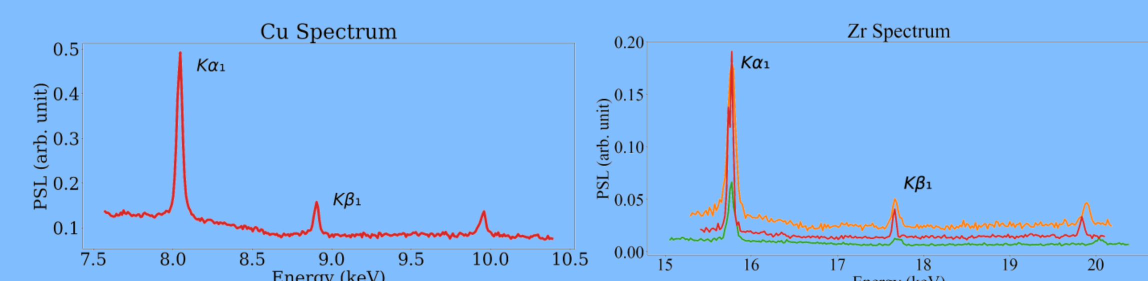

Figure 10. Spectra of the source with Cu and Zr targets respectively.

4. Simulations

As the laboratory has been closed, simulations have replaced experiment. Figure 11 shows a simulation of the knife-edge method for both a coherent and an incoherent X-ray source, whilst Figures 12 and 13 show a simulation of an absorption contrast experiment.

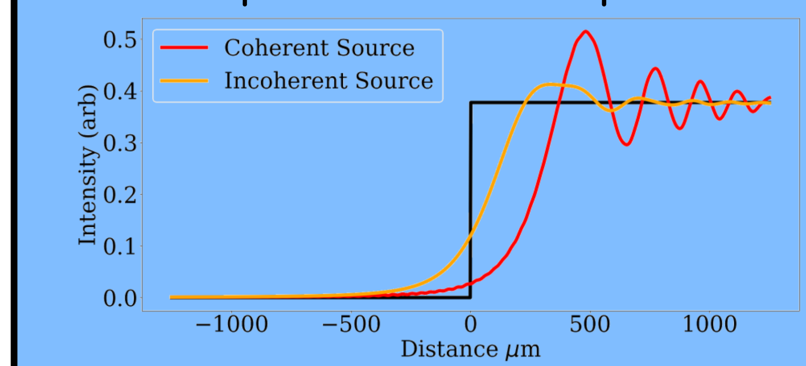

Figure 11. Simulated knife-edge experiment

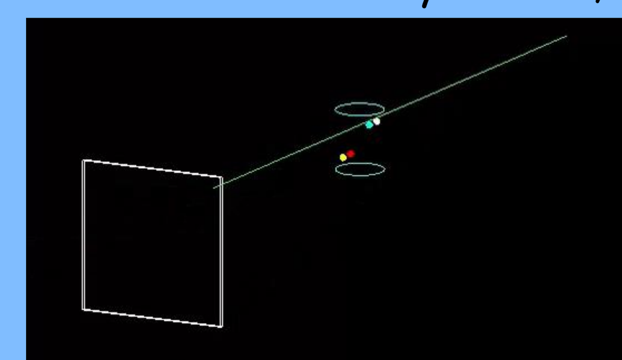

Figure 12. Ray diagram of the absorption contrast simulation.

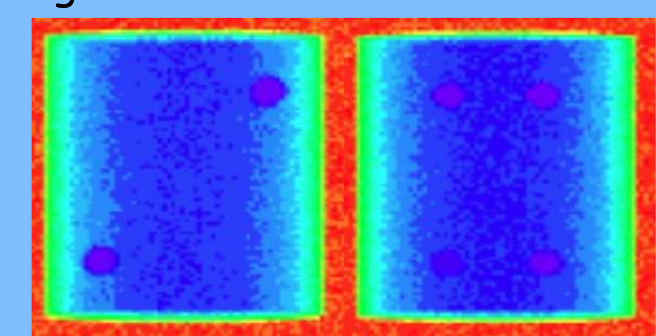

Figure 13. Images resulting from the simulation with different rotations of the phantom

5. Conclusions

To conclude, the X-ray source has been successfully characterised and can now be used to take 3D phase contrast images, which can then be compared to the simulated imaging experiments once they are extended to include phase effects and 3D.

References

[1] W. Röntgen, "On a New Kind of Rays", Nature, vol. 53, no 1369, pp. 274—276, 1896
[2] F. Pfeiffer, T. Weitkamp, O. Bunk et al, 'Phase retrieval and differential phase-contrast imaging with low-brilliance X-ray sources', Nature Phys, vol. 2, pp. 258-261, 206
[3] F. Pfeiffer et al. 'Grating-based X-ray phase contrast for biomedical imaging applications', Zeitschrigt für Medizinishce Physik, vol. 23, no. 3, pp. 176-185, 201